#### WELCOME

### **CERN Courier – digital edition**

Welcome to the digital edition of the March/April 2025 issue of CERN Courier.

It's remarkable that the estimated age of the universe could be revised downward by over half a billion years – a possibility that now looms for cosmologists. For particle physicists, the implications of a couple of parts per billion on the predicted magnetic moment of the muon are no less dramatic. These are the stakes in this edition of *CERN Courier*, which sheds light on two of the most intriguing anomalies in fundamental science: the "Hubble tension" (p28) and "muon g-2" (p21).

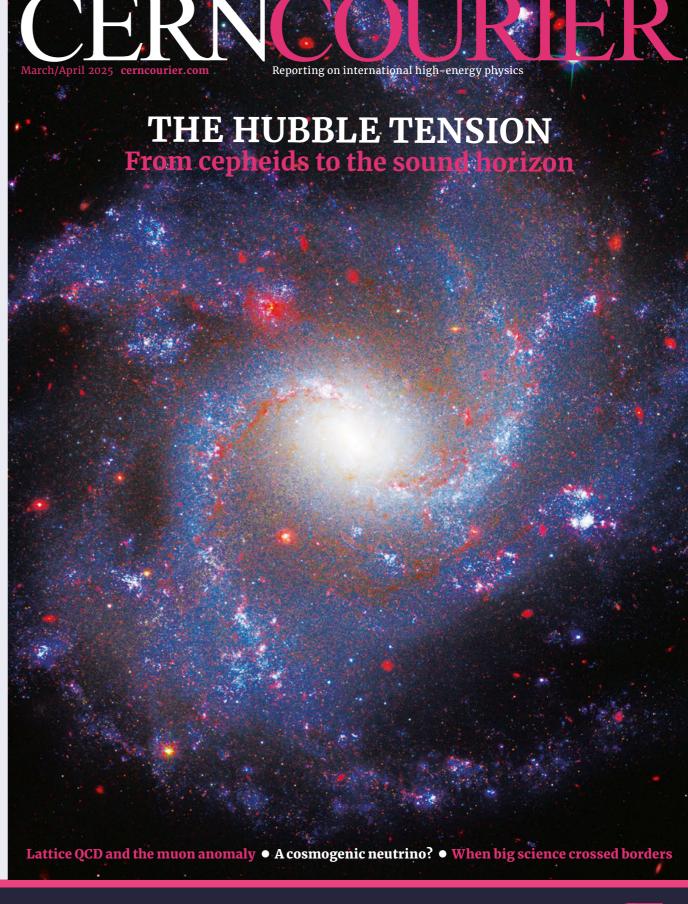
Both anomalies unite experimentalists and theorists in a race for precision. One spans the largest scales, and the other the smallest. One tests the  $\Lambda CDM$  model of cosmology, the other the Standard Model of particle physics. Both are currently the subjects of rapid global developments and both could have implications for new particles and interactions.

Elsewhere in the magazine: Ugo Amaldi remembers his father Edoardo's foundational contributions to European cooperation in science (p33); KM3NeT smashes records for neutrino energy (p7); CERN accelerates superconductor technology (p8); CDF stands by the W-mass anomaly (p9); the relationship between particle physics and art (p41); upgrading triggers for the HL-LHC (p17); how to get a job in computer-game design (p48); and much more.

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EDITOR: MARK RAYNER





















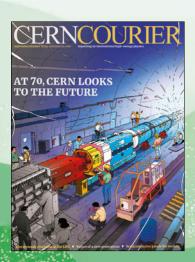


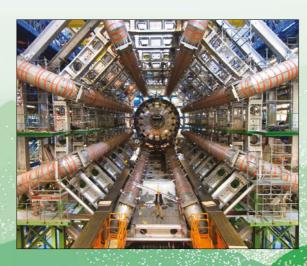
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### FROM THE EDITOR

### Anomalies of the largest and smallest scales



t's remarkable that the estimated age of the universe could be revised downward by over half a billion years - a L possibility that now looms for cosmologists. For particle physicists, the implications of a couple of parts per billion on the predicted magnetic moment of the muon are no less dramatic. These are the stakes in this edition of CERN Courier, which sheds light on two of the most intriguing anomalies in fundamental science: the "Hubble tension" and "muon g-2".

Both anomalies unite experimentalists and theorists in a race for precision. One spans the largest scales, and the other the smallest. One tests the ACDM model of cosmology, the other the Standard Model of particle physics. Both are currently the subjects of rapid global developments and both could have implications for new particles and interactions.

The age of the universe is 13.8 billion years. This is the consistent prediction of the ACDM model - a remarkably successful six-parameter model that explains the evolution of the universe from the era of cosmic inflation until the present day. The most precise prediction is derived from measurements of the cosmic microwave background by the

from a team led by Nobel prize winner Adam Riess suggest that the age of the universe is less than 13.1 billion years. Put most starkly, this is a  $5\sigma$  tension between direct and indirect measurements of the Hubble constant – a tension between our understanding of local astrophysics and models of the early universe. Are we simply miscalibrating cepheid stars or does new physics decrease the sound horizon – the distance travelled by inflationary perturbations in the primordial plasma? This is the question addressed by Vivian Poulin in our cover feature (p28).

On muon g-2 we hand the pen to members of the BMW-DMZ collaboration. In 2020, a team originally from Budapest, Marseille and Wuppertal (BMW) brought lattice QCD to bear on the question of quantum corrections to the magnetic moment of the muon, challenging the anomaly indicated triggers for the HL-LHC (p17); how to get a job in computerby comparing direct measurements from Fermilab to the game design (p48); and much more.



Megamaser NGC 4258 is a geometric anchor for cosmic distance measurements

Yet measurements of supernova distances and redshifts reference, data-driven Standard Model prediction of the Muon g-2 Theory Initiative. Last year, BMW joined forces with Davier, Malaescu and Zhang (DMZ) to tame the challenging "long-distance" component of the lattice calculation with a pragmatic data-driven approach, further undermining the anomaly. In their featured article, the authors survey the experimental and lattice inputs currently available to theorists as they seek to align on a new consensus prediction in advance of an updated measurement from Fermilab (p21).

Elsewhere in the magazine: Ugo Amaldi remembers his father Edoardo's foundational contributions to European cooperation in science (p33); KM3NeT smashes records for neutrino energy (p7); CERN accelerates superconductor technology (p8); CDF stands by the W-mass anomaly (p9); the relationship between particle physics and art (p41); upgrading

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# NEWS ANALYSIS

### Cosmogenic candidate lights up KM3NeT

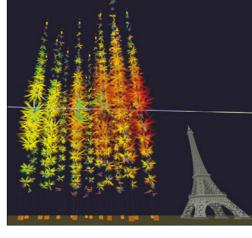
On 13 February 2023, strings of photodetectors anchored to the seabed off the coast of Sicily detected the most energetic neutrino ever observed, smashing previous records. Embargoed until the publication of a paper in Nature last month, the KM3NeT collaboration believes their observation may have originated in a novel cosmic accelerator, or may even be the first detection of a "cosmogenic" neutrino.

"This event certainly comes as a surprise," says KM3NeT spokesperson Paul de Jong (Nikhef). "Our measurement converted into a flux exceeds the limits set by IceCube and the Pierre Auger Observatory. If it is a statistical fluctuation, it would correspond to an upward fluctuation at the  $2.2\sigma$  level. That is unlikely, but not impossible." With an estimated energy of a remarkable 220 PeV, the neutrino observed by KM3NeT surpasses IceCube's record by almost a factor of 30.

The existence of ultra-high-energy cosmic neutrinos has been theorised since the 1960s, when astrophysicists began to conceive ways that extreme estimated energy astrophysical environments could generate particles with very high energies. At about the same time, Arno Penzias and Robert Wilson discovered "cosmic microwave background" (CMB) photons emitted in the era of recombination, when the primordial plasma cooled down and the universe became electrically neutral. Cosmogenic neutrinos were soon hypothesised to result from ultra-high-energy cosmic rays interacting with the CMB. They are expected to have energies above 100 PeV (1017 eV), however, their abundance is uncertain as it depends on cosmic rays, whose sources are still cloaked in intrigue (CERN Courier July/August 2024 p24).

#### A window to extreme events

But how might they be detected? In this regard, neutrinos present a dichotomy: though outnumbered in the cosmos only by photons, they are notoriously elusive. However, it is precisely their weakly interacting nature that makes them ideal for investigating the most extreme regions of the universe. Cosmic neutrinos travel vast cosmic distances



Making a splash detected by

without being scattered or absorbed, providing a direct window into their origins, and enabling scientists to study phenomena such as black-hole jets and neutron-star mergers. Such extreme astrophysical sources test the limits of the Standard Model at energy scales many times higher than is possible in terrestrial particle accelerators.

Because they are so weakly interacting, studying cosmic neutrinos requires giant detectors. Today, three large-scale neutrino telescopes are in operation: IceCube, in Antarctica; KM3NeT, under construction deep in the Mediterranean Sea; and Baikal-GVD, under construction in Lake Baikal in southern Siberia. So far, IceCube, whose construction was completed over 10 years ago, has enabled significant advancements in cosmic-neutrino physics, including the first observation of the Glashow resonance, wherein a 6 PeV electron antineutrino interacts with an electron in the ice sheet to form an on-shell W boson, and tor, but they are numerous; high-energy the discovery of neutrinos emitted by "active galaxies" powered by a supermassive black hole accreting matter. The previous record-holder for the highest recorded neutrino energy, IceCube has also searched for cosmogenic neutrinos but has not yet observed neutrino candidates above 10 PeV.

league, KM3NeT, consists of two subdetectors: ORCA, designed to study neutrino properties, and ARCA, which made this detection, designed to detect highenergy cosmic neutrinos and find their astronomical counterparts. Its deep-sea arrays of optical sensors detect Cherenkov light emitted by charged particles created when a neutrino interacts with a quark or electron in the water. At the time of the 2023 event, ARCA comprised 21 vertical detection units, each around 700 m in length. Its location 3.5km deep under the sea reduces background noise, and its sparse set up over one cubic kilometre optimises the detector for neutrinos of higher energies.

The event that KM3NeT observed in 2023 is thought to be a single muon created by the charged-current interaction of an ultra-high-energy muon neutrino. The muon then crossed horizontally through the entire ARCA detector, emitting Cherenkov light that was picked up by a third of its active sensors. "If it entered the sea as a muon, it would have travelled some 300 km waterequivalent in water or rock, which is impossible," explains de Jong. "It is most likely the result of a muon neutrino interacting with sea water some distance from the detector."

The best estimate for the neutrino energy of 220 PeV hides substantial uncertainties, given the unknown interaction point and the need to correct for an undetected hadronic shower. The collaboration expects the true value to lie between 110 and 790 PeV with 68% confidence. "The neutrino energy spectrum is steeply falling, so there is a tug-of-war between two effects," explains de Jong. "Low-energy neutrinos must give a relatively large fraction of their energy to the muon and interact close to the detecneutrinos can interact further away, and give a smaller fraction of their energy to the muon, but they are rare."

More data is needed to understand the sources of ultra-high-energy neutrinos such as that observed by KM3NeT, where construction has continued in the two years since this remarkable early

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#### **NEWS ANALYSIS**

fully constructed, we will have three network will monitor the full sky with

detection. So far, 33 of 230 ARCA detection large-scale neutrino telescopes of about **The network** units and 24 of 115 ORCA detection units the same size in operation around the will improve have been installed. Once construction is world," adds Mauricio Bustamante, complete, likely by the end of the decade, theoretical astroparticle physicist at of detecting KM3NeT will be similar in size to IceCube. the Niels Bohr Institute of the Univer-"Once KM3NeT and Baikal-GVD are sity of Copenhagen. "This expanded

nearly equal sensitivity in any direction, improving the chances of detecting new neutrino sources, including faint ones in the chances new regions of the sky." new neutrino

#### **Further reading**

The KM3NeT Collab. 2025 Nature 638 376

### **CERN** gears up for tighter focusing

High-Luminosity LHC (HL-LHC) will feel like a new collider. The hearts of the ATLAS and CMS detectors, and 1.2 km of the 27 km-long Large Hadron Collider (LHC) ring will have been transplanted with cutting-edge technologies that will push searches for new physics into uncharted territory.

On the accelerator side, one of the most impactful upgrades will be the brandnew final focusing systems just before the proton or ion beams arrive at the interaction points. In the new "inner triplets"; particles will slalom in a more focused and compacted way than ever before towards collisions inside the detectors.

To achieve the required focusing strength, the new quadrupole magnets will use Nb<sub>3</sub>Sn conductors for the first corrector package time in an accelerator. Nb<sub>3</sub>Sn will allow fields as high as 11.5 T, compared to 8.5 T separation and for the conventional NbTi bending mag- recombination nets used elsewhere in the LHC. As they are a new technology, an integrated test the inner-tripletstand of the full 60 m-long inner-triplet string test stand assembly is essential - and work is now at CERN. in full swing.

#### Learning opportunity

"The main challenge at this stage is the interconnections between the magnets, particularly the interfaces between the magnets and the cryogenic line," explains Marta Bajko, who leads work on the inner-triplet-string test facility. "During this process, we have encountered nonconformities, out-of-tolerance components, and other difficulties expected challenges given that these connections are being made for the first time. This phase is a learning opportunity for everyone involved, allowing us to refine the installation process."

The last magnet - one of two built in the US - is expected to be installed in May. Before then, the so-called N lines, which enable the electrical connections between the different magnets, will be pulled through the entire magnet chain to prepare for splicing the cables together. Individual system tests and shortcircuit tests have already been success-



sources

#### Dress rehearsal

Preparing to integrate the (yellow) with the dipole (blue) at

fully performed and a novel alignment Cosmotron and CERN's Proton Synchromagnets are ongoing, while electrical superconducting link.

in the tunnel," says Bajko. "The sur- to experimental analyses. face installation, located in a closed and easily accessible building near the a time-honoured technique, Nb<sub>3</sub>Sn teams' workshops and laboratories, brings new challenges. The HL-LHC offers an invaluable opportunity for them magnets are the first accelerator to learn how to perform their tasks effec- magnets to be built at lengths of up to tively. This training often takes place 7 m, and the technical teams at CERN alongside other teams, under real instal- and in the US collaboration - each of lation constraints, allowing them to gain which is responsible for half the total hands-on experience in a controlled yet authentic environment.

a separation and recombination dipole, and testing infrastructure. a corrector-package assembly and a quadrupole triplet. The dipole combines tor physicists have been hard at work the two counter-rotating beams into a designing and testing the new magnets single channel; the corrector package and their associated powering, vacuum, fine-tunes beam parameters; and the alignment, cryogenic, cooling and proquadrupole triplet focuses the beam onto tection systems. Each component of the interaction point.

of accelerator physics since they were however, this is only half the story as first implemented in the early 1950s at all components must be integrated and

system developed for the HL-LHC is being tron. Quadrupole magnets are like lenses installed on each magnet. Mechanical that are convex (focusing) in one transtransfer function measurements of some verse plane and concave (defocusing) in the other, transporting charged particles integrity tests in a helium environment like beams of light on an optician's bench. have been successfully completed, along In a quadrupole triplet, the focusing plane with the pressure and leak test of the alternates with each quadrupole magnet. The effect is to precisely focus the "Training the teams is at the core of particle beams onto tight spots within our focus, as this setup provides the most the LHC experiments, maximising the comprehensive and realistic mock-up number of particles that interact, and before the installations are to be done increasing the statistical power available

Though quadrupole triplets are "cold mass" production - have decided to produce two variants, primarily driven The inner triplet string is composed of by differences in available production

Since 2011, engineers and accelerathe HL-LHC will be individually tested Quadrupole triplets have been a staple before installation in the LHC tunnel, synchrotrons such as the Brookhaven operated within the machine, where  $\triangleright$ 

they will all share a common electri- opers. The test programme has been Nb<sub>2</sub>Sn is will test the integration of all these relevant stakeholders. components, evaluating them in terms of their collective behaviour, in preparation for hardware commissioning and While Nb<sub>3</sub>Sn offers significant advannominal operation.

efforts and testing them as if operating tection system. from the control room - launching tests

cal and cooling circuit. Throughout the integrated into a sequencer, and testing strategically rest of 2025, the inner-triplet string procedures are being approved by the

#### Return on investment

tages over NbTi, manufacturing magnets high-energy "We aim to replicate the operational with it presents several challenges. It processes of the inner-triplet string using requires high-temperature heat treatthe same tools planned for the HL-LHC ment after winding, and is brittle and machine," says Bajko. "The control sys- fragile, making it more difficult to handle tems and software packages are in an than the ductile NbTi. As the HL-LHC advanced stage of development, prepared Nb<sub>3</sub>Sn magnets operate at higher current through extensive collaboration across and energy densities, quench protection CERN, involving three departments is more challenging, and the possibility and nine equipment groups. The inner- of a sudden loss of superconductivity triplet-string team is coordinating these requires a faster and more robust pro-

The R&D required to meet these in short-circuit mode and verifying sys- challenges will provide returns long tem performance to provide feedback to into the future, says Susana Izquierdo the technical teams and software devel- Bermudez, who is responsible at CERN

important because it lays the foundation for future

colliders

for the new HL-LHC magnets.

"CERN's investment in R&D for Nb, Sn is strategically important because it lays the foundation for future high-energy colliders. Its increased field strength is crucial for enabling more powerful focusing and bending magnets, allowing for higher beam energies and more compact accelerator designs. This R&D also strengthens CERN's expertise in advanced superconducting materials and technology, benefitting applications in medical imaging, energy systems and industrial technologies."

The inner-triplet string will remain an installation on the surface at CERN and is expected to operate until early 2027. Four identical assemblies will be installed underground in the LHC tunnel from 2028 to 2029, during Long Shutdown 3. They will be located 20 m away on either side of the ATLAS and CMS interaction points.

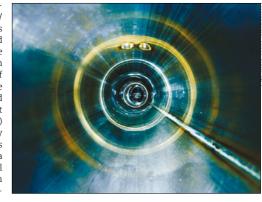
#### STRONG INTERACTIONS

### Isospin symmetry broken more than expected

In the autumn of 2023, Wojciech Brylinski was analysing data from the NA61/ SHINE collaboration at CERN for his thesis, when he noticed an unexpected anomaly - a strikingly large imbalance between charged and neutral kaons in argon-scandium collisions. Instead of producing roughly equal numbers, he found that charged kaons were produced 18.4% more often. This suggested that the "isospin symmetry" between up (u) and down (d) quarks might be broken by more than expected due to the differences in their electric charges and masses - a discrepancy that existing theoretical models would struggle to explain. Known sources of isospin asymmetry only predict deviations of a few percent.

"When Wojciech got started, we Fixed target thought it would be a trivial verification NA61/SHINE's of the symmetry," says Marek Gaździcki lead-scintillator of Jan Kochanowski University of Kielce, calorimeter. spokesperson of NA61/SHINE at the time of the discovery. "We expected it to be closely obeyed - though we had previously measured discrepancies at NA49, they had large uncertainties and were not significant."

Isospin symmetry is one facet of flavour symmetry, whereby the strong interaction treats all quark flavours identically, except for kinematic differences arising from their different masses. Strong interactions should therefore generate nearly equal yields of charged  $K^{+}$  (u $\overline{s}$ ) and  $K^{-}$  ( $\overline{u}$ s), and neutral  $K^{0}$  (d $\overline{s}$ ) and  $K^{0}$  ( $\overline{d}$ s), given the similar masses of



the two lightest quarks. NA61/SHINE's data contradict the hypothesis of equal yields with  $4.7\sigma$  significance.

"I see two options to interpret the results," says Francesco Giacosa, a theoretical physicist at Jan Kochanowski University working with NA61/SHINE. "First, we substantially underestimate the role of electromagnetic interactions in creating quark-antiquark pairs. Second, strong interactions do not obey flavour symmetry - if so, this would falsify QCD." Isospin is not a symmetry of the electromagnetic interaction as up and down quarks have different electric charges.

While the experiment routinely measures particle yields in nuclear collisions, finding a discrepancy in isospin sym- Further reading metry was not something researchers NA61/SHINE Collab. 2024 arXiv:2312.06572.

were actively looking for. NA61/SHINE's primary focus is studying the phase diagram of high-energy nuclear collisions using a range of ion beams. This includes looking at the onset of deconfinement, the formation of a quark-gluon plasma fireball, and the search for the hypothesised QCD critical point where the transition between hadronic matter and quark-gluon plasma changes from a smooth crossover to a first-order phase transition. Data is also shared with neutrino and cosmic-ray experiments to help refine their models.

The collaboration is now planning additional studies using different projectiles, targets and collision energies to determine whether this effect is unique to certain heavy-ion collisions or a more general feature of high-energy interactions. They have also put out a call to theorists to help explain what might have caused such an unexpectedly large asymmetry.

"The observation of the rather large isospin violation stands in sharp contrast to its validity in a wide range of physical systems," says Rob Pisarski, a theoretical physicist from Brookhaven National Laboratory. "Any explanation must be special to heavy-ion systems at moderate energy. NA61/SHINE's discrepancy is clearly significant, and shows that QCD still has the power to surprise our naive expectations."

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#### **DETECTOR PHYSICS**

**NEWS ANALYSIS** 

### CDF addresses W-mass doubt

It's tough to be a lone dissenting voice, but the CDF collaboration is sticking to its guns. Ongoing cross-checks at the Tevatron experiment reinforce its 2022 measurement of the mass of the W boson, which stands seven standard deviations above the Standard Model (SM) prediction. All other measurements are statistically compatible with the SM, though slightly higher, including the most recent by the CMS collaboration at the LHC, which almost matched CDF's stated precision of 9.4 MeV (CERN Courier November/December 2024 p7).

With CMS's measurement came fresh scrutiny for the CDF collaboration, which had established one of the most inter- On track esting anomalies in fundamental science - a higher-than-expected W mass might reveal the presence of undiscovered in the CDF II heavy virtual particles. Particular scru- experiment. tiny focused on the quoted momentum resolution of the CDF detector, which the  $collaboration\, claims\, exceeds\, the\, precision$ of any other collider detector by more than a factor of two. A new analysis by CDF verifies the stated accuracy of 25 parts per million by constraining possible biases using a large sample of cosmic-ray muons.

"The publication lays out the 'warts and all' of the tracking aspect and explains



The central outer

why the CDF measurement should be taken seriously despite being in disagreement with both the SM and silicontracker-based LHC measurements," says stability of the CDF drift chamber and its spokesperson David Toback of Texas insensitivity to radiation damage." A&M University. "The paper should be seen as required reading for anyone milab's Tevatron collider from 1999 to who truly wants to understand, without 2011. Its cylindrical drift chamber was bias, the path forward for these incredibly difficult analyses."

sively used information from CDF's drift yielded track parameters. chamber - a descendant of the multiwire proportional chamber invented at CERN Further reading by Georges Charpak in 1968 - and dis- AV Kotwal 2025 Phys. Rev. Res. 7 013128.

carded information from its inner silicon vertex detector as it offered only marginal improvements to momentum resolution. The new analysis by CDF collaborator Ashutosh Kotwal of Duke University studies possible geometrical defects in the experiment's drift chamber that could introduce unsuspected biases in the measured momenta of the electrons and muons emitted in the decays of W bosons.

"Silicon trackers have replaced wirebased technology in many parts of modern particle detectors, but the drift chamber continues to hold its own as the technology of choice when high accuracy is required over large tracking volumes for extended time periods in harsh collider environments," opines Kotwal, "The new analysis demonstrates the efficiency and

The CDF II detector operated at Fercoaxial with the colliding proton and antiproton beams, and immersed in an The 2022 W-mass measurement excluary axial 1.4 T magnetic field. A helical fit

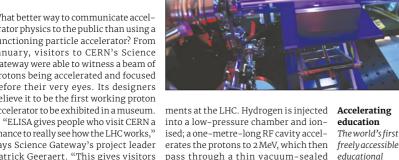
### EDUCATION AND OUTREACH **Educational** accelerator open to the public

What better way to communicate accelerator physics to the public than using a functioning particle accelerator? From January, visitors to CERN's Science Gateway were able to witness a beam of protons being accelerated and focused before their very eyes. Its designers believe it to be the first working proton accelerator to be exhibited in a museum.

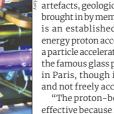
chance to really see how the LHC works," says Science Gateway's project leader Patrick Geeraert. "This gives visitors pass through a thin vacuum-sealed educational a unique experience: they can actually see a proton beam in real time. It then means they can begin to conceptualise ducing visible light, allowing members the experiments we do at CERN."

The model accelerator is inspired by a component of LINAC 4 - the first stage in the chain of accelerators used to ELISA - the Experimental Linac for prepare beams of protons for experi- Surface Analysis - will also be used

10



ised; a one-metre-long RF cavity accelwindow. In dim light, the protons in proton accelerator the air ionise the gas molecules, proof the public to see the beam's progress before their very eyes (see "Accelerating education" figure)



The world's first

to analyse the composition of cultural artefacts, geological samples and objects brought in by members of the public. This is an established application of lowenergy proton accelerators: for example, a particle accelerator is hidden 15 m below the famous glass pyramids of the Louvre in Paris, though it is almost 40 m long and not freely accessible to the public.

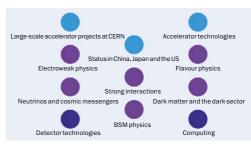
"The proton-beam technique is very effective because it has higher sensitivity and lower backgrounds than electron beams," explains applied physicist and lead designer Serge Mathot. "You can also perform the analysis in the ambient air, instead of in a vacuum. making it more flexible and better suited to fragile objects."

For ELISA's first experiment, researchers from the Australian Nuclear Science Technology Organisation and from Oxford's Ashmolean Museum have proposed a joint research project about the optimisation of ELISA's analysis of paint samples designed to mimic ancient cave art. The ultimate goal is to work towards a portable accelerator that can be taken to regions of the world that don't have access to proton beams.

### Strategy symposium shapes up

Registration is now open for the Open Symposium of the 2026 update to the European Strategy for Particle Physics (ESPP). It will take place from 23 to 27 June at Lido di Venezia in Italy, and see scientists from around the world debate the inputs to the ESPP (see p39).

The symposium will begin by surveying the implementation of the last strategy process, whose recommendations were approved by the CERN Council in June 2020. In-depth working-group technology will follow.



discussions on all areas of physics and Symposium sessions The plenary sessions foreseen for the Open Symposium of the ESPP in Venice in June.

The rest of the week will see plenary sessions on the different physics and technology areas, starting with various proposals for possible large accelerator projects at CERN, and the status and plans in other regions of the world. Open questions, as well as how they can be addressed  $by \, the \, proposed \, projects, will \, be \, presented$ in rapporteur talks. This will be followed by longer discussion blocks where the full community can get engaged. On the final day, members of the European Strategy Group will summarise the national inputs and other overarching topics to the ESPP.

### Boost for compact fast radio bursts

powerful bursts of radio waves that are believed to be emitted by dense astrophysical objects such as neutron stars or black holes. They were discovered by Duncan Lorimer and his student David Narkevic in 2007 while studying archival data from the Parkes radio telescope in Australia Since then, more than a thousand FRBs have been detected, located both within and without the Milky Way. These bursts usually last only a few milliseconds but can release enormous amounts of energy - an FRB detected in 2022 gave off more energy in a millisecond than the Sun does in 30 years - however, the exact mechanism underlying their creation remains a mystery.

Inhomogeneities caused by the presence of gas and dust in the interstellar medium scatter the radio waves coming from an FRB. This creates a stochastic interference pattern on the signal, called scintillation - a phenomenon akin to the twinkling of stars. In a recent study, astronomer Kenzie Nimmo and her colleagues used scintillation data from FRB 20221022A to constrain the size of its emission region. FRB 20221022A is a 2.5 millisecond burst from a galaxy about 200 million light-years away. It was detected on 22 October 2022 by the Canadian Hydrogen Intensity Mapping Experiment Fast Radio Burst project (CHIME/FRB).

The CHIME telescope is currently the world's leading FRB detector, discovering an average of three new FRBs every day. It consists of four stationary 20 m-wide and 100 m-long semi-cylindrical paraboloidal reflectors with a focal length of 5 m (see "Right on CHIME" figure). 256 dual-



Right on CHIME Hydrogen Intensity Experiment.

polarisation feeds suspended along each axis gives it a field of view of more than 200 square degrees. With a wide bandwidth, high sensitivity and a high-performance correlator to pinpoint where in al. independently support this concluthe sky signals are coming from, CHIME is an excellent instrument for the detection and mechanisms that power FRBs. of FRBs. The antenna receives radio waves in the frequency range of 400 to 800MHz.

to explain the emission mechanisms of understand their environments. FRBs. Near-field models hypothesise that emission occurs in close proximity to the turbulent magnetosphere of a central engine, while far-away models hypothesise that emission occurs in relativistic shocks that propagate out to large radial distances. Nimmo and her team measured two distinct scintillation scales in the frequency spectrum of FRB 20221022A: one originating from its host galaxy or using these scattering sites as astrophysical lenses, they were able to constrain the size of the FRB's emission region to Further reading better than 30,000 km. This emission size K Nimmo et al. 2025 Nature 637 48. contradicted expectations from far-away R Mckinven et al. Nature 637 43.

models. It is more consistent with an emission process occurring within or just beyond the magnetosphere of a central compact object - the first clear evidence for the near-field class of models.

Additionally, FRB 20221022A's detection paper notes a striking change in the burst's polarisation angle - an "S-shaped" swing covering about 130° over a mere 2.5 milliseconds. They interpret this as the emission beam physically sweeping across our line of sight, much like a lighthouse beam passing by an observer, and conclude that it hints at a magnetospheric origin of the emission, as highly magnetised regions can twist or shape how radio waves are emitted. The scintillation studies by Nimmo et sion, narrowing the possible sources Moreover, they highlight the potential of the scintillation technique to explore Two main classes of models compete the emission mechanisms in FRBs and

The field of FRB physics looks set to grow by leaps and bounds. CHIME can already identify host galaxies for FRBs, but an "outrigger" programme using similar detectors geographically displaced from the main telescope at the Dominion Radio Astrophysical Observatory near Penticton, British Columbia, aims to strengthen its localisation capabilities to a precision of tens of millocal environment, and another from a liarcsecond. CHIME recently finished scattering site within the Milky Way. By deploying its third outrigger telescope in northern California.

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# ENERGY FRONTIERS

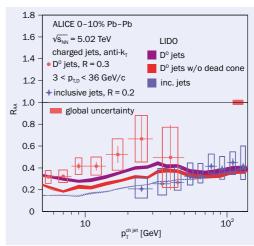
Reports from the Large Hadron Collider experiments

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### Charm jets lose less energy

Collisions between lead ions at the LHC generate the hottest and densest system ever created in the laboratory. Under these extreme conditions, quarks and gluons are no longer confined inside hadrons but instead form a quark-gluon plasma (QGP). Being heavier than the more abundantly produced light quarks. charm quarks play a special role in probing the plasma since they are created in the collision before the plasma is formed and interact with the plasma as they traverse the collision zone. Charm jets, which are clusters of particles originating from charm quarks, have been investigated for the first time by the ALICE collaboration in Pb-Pb collisions at the LHC using the Do mesons (that carry a charm quark) as tags.

The primary interest lies in measuring the extent of energy loss experienced by different types of particles energy loss specifically depends on the particle type and particle mass, varying between quarks and gluons. Due to their larger mass, charm quarks at low makes the charm quark an ideal probe gluon radiation by massive quarks is quark and its colour charge. suppressed: the so-called "dead-cone effect". Additionally, gluons, which carry



**Fig. 1.** Nuclear modification factor (R<sub>AA</sub>) of D<sup>o</sup> jets (red markers) as they traverse the plasma, referred and inclusive jets (blue markers). The statistical and systematic LIDO model calculations (Ke et al. 2018 arXiv:1810.08177) for D° jets (with and without the dead-cone effect) and inclusive jets are shown.

transverse momentum do not reach the for studying the QGP properties. ALICE speed of light and lose substantially less is well suited to study the in-medium energy than light quarks through both energy loss of charm quarks, which is collisional and radiative processes, as dependent on the mass of the charm

The production yield of charm jets tagged with fully reconstructed Do a larger colour charge than quarks, expemesons ( $D^0 \rightarrow K^-\pi^*$ ) in central Pb-Pb rience greater energy loss in the QGP as collisions at a centre-of-mass energy of quantified by the Casimir factors C<sub>A</sub> = 3 5.02 TeV per nucleon pair during LHC Run for gluons and  $C_F = 4/3$  for quarks. This 2 was measured by ALICE. The results are reported in terms of nuclear modification factor (RAA), which is the ratio of the particle production rate in Pb-Pb collisions to that in proton-proton collisions, scaled by the number of binary nucleon-nucleon collisions. A measured nuclear modification factor of unity would indicate the absence of final-state effects.

The results, shown in figure 1, show a clear suppression (R<sub>AA</sub><1) for both charm iets and inclusive iets (that mainly originate from light quarks and gluons) due to energy loss. Importantly, the charm jets exhibit less suppression than the inclusive jets within the transverse momentum range of 20 to 50 GeV, which is consistent with mass and colour-charge dependence.

The measured results are compared with theoretical model calculations that include mass effects in the in-medium energy loss. Among the different models, LIDO incorporates both the dead-cone effect and the colour-charge effects, which are essential for describing the energy-loss mechanisms. Consequently, it shows reasonable agreement with experimental data, reproducing the observed hierarchy between charm jets and inclusive jets.

The present finding provides a hint of the flavour-dependent energy loss in the QGP, suggesting that charm jets lose less energy than inclusive jets. This highlights the quark-mass and colourcharge dependence of the in-medium energy-loss mechanisms.

#### **Further reading**

ALICE Collab. 2024 arXiv:2409.11939.

### Breaking new ground in flavour universality

A new result from the LHCb collaboration supports the hypothesis that the rare decays  $B^{\pm} \rightarrow K^{\pm}e^{+}e^{-}$  and  $B^{\pm} \rightarrow K^{\pm}\mu^{+}\mu^{-}$  occur at the same rate, further tightening constraints on the magnitude of lepton flavour universality (LFU) violation in rare B decays. The new measurement is the most precise to date in the high-q2 region and the first of its kind at a hadron collider.

is the most precise to date in the

The new measurement

Standard Model (SM). Under LFU, each ward ratio to measure is that between should be unity except for kinematic

generation of lepton  $\ell^{\pm}$  (electron, muon the muon and electron decay modes, and tau lepton) is equally likely to inter- known as R<sub>K</sub>. Any significant deviation act with the W boson in decay processes from R<sub>K</sub> = 1 could only be explained by the such as  $B^{\pm} \to K^{\pm} \ell^{+} \ell^{-}$ . This symmetry leads existence of new physics (NP) particles to the prediction that the ratio of branch- that preferentially couple to one lepton ing fractions for these decay channels generation over another, violating LFU.

 $B^{\pm} \rightarrow K^{\pm} \ell^{+} \ell^{-}$  decays are a powerful probe effects due to the different masses of the for virtual NP particles. These decays LFU is an accidental symmetry of the **high-q² region** charged leptons. The most straightfor—involve an underlying b-to-s quark

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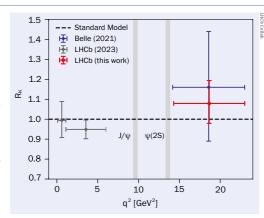




#### ENERGY FRONTIERS

transition - an example of a flavourchanging neutral current (FCNC). FCNC transitions are extremely rare in the SM, as they occur only through higher-order Feynman diagrams. This makes them particularly sensitive to contributions from NP particles, which could significantly alter the characteristics of the decays. In this case, the mass of the NP particles could be much larger than can be produced directly at the LHC. "Indirect" searches for NP, such as measuring the precisely predicted ratio  $R_{\mbox{\tiny K}},$  can probe mass scales beyond the reach of direct-production searches with current experimental resources.

In the decay process  $B^{\pm} \rightarrow K^{\pm} \ell^{+} \ell^{-}$ , the final-state leptons can also originate such as a J/ $\psi$  or  $\psi$ (2S). These resonant Feynman diagrams. Their contribu-inthehigh-g<sup>2</sup> region. tions significantly outnumber the nonresonant FCNC processes and are not exclude these resonances, to preserve therefore measured in ranges of dilepton invariant mass-squared (q2), which



from an intermediate resonant state, Fig. 1. Measurements of the lepton flavour universality ratio  $R_K$  conducted previously by LHCb in the low- $q^2$  region, by channels occur through tree-level the Belle collaboration in the high-q2 region, and now by LHCb

expected to be affected by NP. R<sub>K</sub> is sensitivity to potential NP effects in FCNC processes

The new result from the LHCb collabo-

ration measures R<sub>K</sub> in the high-q<sup>2</sup> region, above the  $\psi(2S)$  resonance. The high-q<sup>2</sup> region data has a different composition of backgrounds compared to the low-q2 data, leading to different strategies for their rejection and modelling, and different systematic effects. With R<sub>v</sub> expected to be unity in all domains in the SM, low-q2 and high-q2 measurements offer powerfully complementary constraints on the magnitude of LFU-violating NP in rare B decays

The new measurement of R<sub>K</sub> agrees with the SM prediction of unity and is the most precise to date in the high-q2 region (figure 1). It complements a refined analysis below the I/ψ resonance published by LHCb in 2023, which also reported R<sub>v</sub> consistent with unity. Both results use the complete proton-proton collision data collected by LHCb from 2011 to 2018. They lay the groundwork for even more precise measurements with data from Run 3 and beyond.

#### **Further reading**

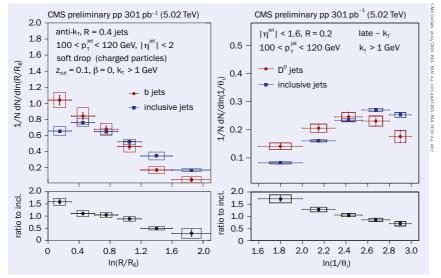
LHCb Collab. 2025 LHCb-PAPER-2024-056.

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### CMS peers inside heavy-quark jets

Ever since quarks and gluons were discovered, scientists have been gathering clues about their nature and behaviour. When quarks and gluons - collectively called partons - are produced at particle colliders, they shower to form jets sprays of composite particles called hadrons. The study of jets has been indispensable towards understanding quantum chromodynamics (QCD) and the description of the final state using parton shower models. Recently, particular focus has been on the study of the jet substructure, which provides further input about the modelling of parton showers.

Jets initiated by the heavy charm (c-jets) or bottom quarks (b-jets) provide insight into the role of the quark mass, as an additional energy scale in QCD calculations. Heavy-flavour jets are not only used to test QCD predictions, they are also a key part of the study of other particles, such as the top quark and the Higgs boson. Understanding the thus crucial for both the identification of these heavier objects and the interpretation of QCD properties. One such property is the presence of a "dead cone" around the heavy quark, where collinear gluon emissions are suppressed in the direction of motion of the quark.



internal structure of heavy-quark jets is  $\mathbf{Fig. 1}$ . The per-jet angular distributions for the soft-drop and late- $k_T$  angles in b-jets (left) and c-jets (right). The blue histograms represent the distributions of inclusive jets, dominated by light-quark and gluon jets. The red histograms represent the distributions of heavy-flavour jets. The bottom panel presents the ratio of heavy-flavour to the inclusive jets.

two new results focusing on c- and b-jets, and decay at a small but measurable

CMS has shed light on the role of the respectively. Heavy-flavour hadrons quark mass in the parton shower with in these jets are typically long-lived,

distance from the primary interaction shower process. Substructure techniques CMS has shed vertex. In c-jets, the Do meson is reconare then employed to decompose the jet structed in the  $K^{\pm}\pi^{\mp}$  decay channel by into two subjets, which correspond to the combining pairs of charged hadrons that heavy quark and a gluon being emitted do not appear to come from the primary from it. Two of those algorithms are soft interaction vertex. In the case of b-jets, drop and late-k<sub>T</sub>. They select the first a novel technique is employed. Instead and last emission in the jet clustering of reconstructing the b hadron in a given tree, respectively, capturing different decay channel, its charged decay daugh- aspects of the QCD shower. Looking at ters are identified using a multivariate the angle between the two subjets (see analysis. In both cases, the decay daugh-figure 1), denoted as  $R_e$  for soft drop and  $\theta_e$ ters are replaced by the mother hadron for late-k<sub>1</sub>, demonstrates the dead-cone

particles in a pairwise manner, leading to pressed compared to the inclusive jet

effect, as the small angle emissions of Jets are reconstructed by clustering b-jets (left) and c-jets (right) are supa clustering tree that mimics the parton case. The effect is captured better by the

light on the role of the quark mass in the parton late-k<sub>T</sub> algorithm than soft drop in the case of c-iets.

ENERGY FRONTIERS

These measurements serve to refine the tuning of Monte Carlo event generators relating to the heavy-quark mass and strong coupling. Identifying the onset of the dead cone in the vacuum also opens up possibilities for substructure studies in heavy-ion collisions, where emissions induced by the strongly interacting quark-gluon plasma can be isolated.

#### **Further reading**

CMS Collab. 2024 CMS-PAS-HIN-24-005. CMS Collab. 2024 CMS-PAS-HIN-24-007.

### A new record for precision on B-meson lifetimes

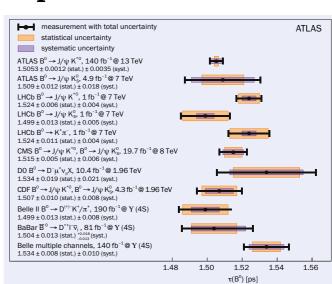
As direct searches for physics beyond the Standard Model continue to push frontiers at the LHC, the b-hadron physics sector remains a crucial source of insight for testing established theoretical models

The ATLAS collaboration recently published a new measurement of the Bo lifetime using  $B^{\scriptscriptstyle 0}\!\to\! J/\psi K^{*\scriptscriptstyle 0}$  decays from the entire Run-2 dataset it has recorded at 13 TeV. The result improves the precision of previous world-leading measurements by the CMS and LHCb collaborations by a factor of two

Studies of b-hadron lifetimes probe our understanding of the weak interaction. The lifetimes of b-hadrons can be systematically computed within the heavy-quark expansion (HQE) framework, where b-hadron observables are expressed as a perturbative expansion in inverse powers of the b-quark mass.

ATLAS measures the "effective" Bolife $time, which \, represents \, the \, average \, decay$ time incorporating effects from mixing and CP contributions, as  $\tau(B^{\circ}) = 1.5053 \pm$  $0.0012(stat.) \pm 0.0035(syst.)$ ps. The result is consistent with previous measurements published by ATLAS and other experiments, as summarised in figure 1. It also aligns with theoretical predictions from HQE and lattice QCD, as well as with the experimental world average.

The analysis benefitted from the large Run-2 dataset and a refined trigger selection, enabling the collection of an extensive sample of 2.5 million  $B^0 \rightarrow J/\psi K^{*0}$ decays. Events with a J/ $\psi$  meson decaying into two muons with sufficient transverse momentum are cleanly identified in the ATLAS Muon Spectrometer by the first-level hardware trigger. In the nextlevel software trigger, exploiting the full detector information, these muons are



A comparison of the current ATLAS result for the B° lifetime with the previous ATLAS result in the  $B^{\circ} \rightarrow J/\psi K_{\circ}^{\circ}$  channel, and with those from other experiments.

then combined with two tracks meas- tematic uncertainties, with the largest ured by the Inner Detector, ensuring they originate from the same vertex.

The B°-meson lifetime is determined through a two-dimensional unbinned maximum-likelihood fit, utilising the measured B°-candidate mass and decay time, and accounting for both signal and the light and heavy B<sub>s</sub>-meson mass background components. The limited hadronic particle-identification capability of ATLAS requires careful modelling of the significant backgrounds from (syst.) ± 0.0057 (ext.). The result is conother processes that produce  $J/\psi$  mesons. The sensitivity of the fit is increased by gent test of QCD predictions, which also estimating the uncertainty of the decaytime measurement provided by the ATLAS tracking and vertexing algorithms on a Further reading per-candidate basis. The resulting life- ATLAS Collab. 2024 arXiv:2411.09962. time measurement is limited by sys- ATLAS Collab. 2021 Eur. Phys. J. C 81 342

contributions arising from the correlation between B° mass and lifetime, and ambiguities in modelling the mass distribution.

ATLAS combined its measurement with the average decay width ( $\Gamma_s$ ) of eigenstates, also measured by ATLAS, to determine the ratio of decay widths as  $\Gamma_{1}/\Gamma_{1} = 0.9905 + 0.0022 \text{ (stat.)} + 0.0036$ sistent with unity and provides a strin-

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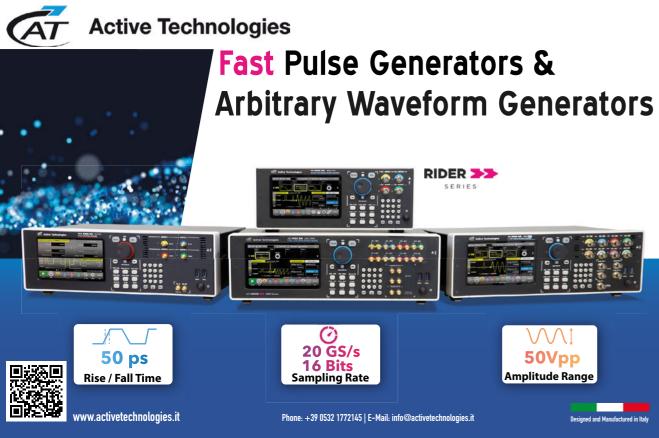












### FIELD **NOTES**

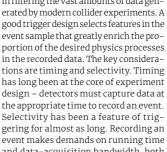
Reports from events, conferences and meetings

TRIGGERING DISCOVERIES IN HIGH-ENERGY PHYSICS

### The triggering of tomorrow

The third edition of Triggering Discoveries in High Energy Physics (TDHEP) attracted 55 participants to Slovakia's High Tatras mountains from 9 to 13 December 2024. The workshop is the only conference dedicated to triggering in high-energy physics, and follows previous editions in Jammu, India in 2013 and Puebla, Mexico in 2018. Given the upcoming High-Luminosity LHC (HL-LHC) upgrade, discussions focused on how trigger systems can be enhanced to manage high data rates while preserving physics sensitivity.

Triggering systems play a crucial role in filtering the vast amounts of data genthe appropriate time to record an event. Selectivity has been a feature of trigand data-acquisition bandwidth, both of which are limited.



#### **Evolving architecture**

Thanks to detector upgrades and major changes in the cost and availability of fast data links and storage, the past 10 years have seen an evolution in LHC triggers away from hardware-based decisions using coarse-grain information.

Detector upgrades mean higher granularity and better time resolution, improving the precision of the trigger algorithms and the ability to resolve the problem of having multiple events in a single LHC bunch crossing ("pileup"). Such upgrades allow more precise initial-level hardware triggering, bringing the event rate down to a level where events can be recon- in filtering structed for further selection via highlevel trigger (HLT) systems.

To take advantage of modern computer architecture more fully, HLTs use both graphics processing units (GPUs) and central processing units (CPUs) to collider process events. In ALICE and LHCb this experiments

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**Timing and selectivity** The TDHEP 2024 workshop took place in Slovakia's High Tatras mountains.

leads to essentially triggerless access to all events, while in ATLAS and CMS hardware selections are still important. All HLTs now use machine learning (ML) algorithms, with the ATLAS and CMS experiments even considering their use trigger and data-acquisition systems. at the first hardware level.

to search for new physics. At the end of collisions and several MHz for protonand time resolution to handle the highluminosity environment of the HL-LHC, collisions the data is filtered. which will deliver up to 200 interactions per LHC bunch crossing. Both experiments achieved efficient triggering in Run 3, but higher luminosities, diffiupgraded detectors and increasingly between input and output - to 10 µsec in ATLAS and 12.5 usec in CMS.

lelised processing to crunch huge data streams efficiently in real time. Both will be two-level triggers: a hardware trigger followed by a software-based HLT. The ATLAS hardware trigger will utilise full-granularity calorimeter and muon signals in the global-trigger-event processor, using advanced ML techniques for real-time event selection. In addition to calorimeter and muon data, CMS will introduce a global track trigger, enabling real-time tracking at the first trigger level. All information will be integrated within the global-correlator trigger, which will extensively utilise ML to enhance event selection and background suppression.

#### **Substantial upgrades**

The other two big LHC experiments already implemented substantial trigger upgrades at the beginning of Run 3. The ALICE experiment is dedicated to studying the strong interactions of the quark-gluon plasma - a state of matter in which quarks and gluons are not confined in hadrons. The detector was upgraded significantly for Run 3, including the The ALICE continuous readout can cope ATLAS and CMS are primarily designed with 50 kHz for lead ion-lead ion (PbPb) Run 3, upgrades to both experiments proton (pp) collisions. In PbPb collisions will significantly enhance granularity the full data is continuously recorded and stored for offline analysis, while for pp

Unlike in Run 2, where the hardware trigger reduced the data rate to several kHz, Run 3 uses an online software trigger that is a natural part of the common cult-to-distinguish physics signatures, online-offline computing framework. The raw data from detectors is streamed ambitious physics goals call for advanced continuously and processed in real new techniques. The step change will be time using high-performance FPGAs significant. At HL-LHC, the first-level and GPUs. ML plays a crucial role in the hardware trigger rate will increase from heavy-flavour software trigger, which the current 100 kHz to 1 MHz in ATLAS is one of the main physics interests. and 760 kHz in CMS. The price to pay is Boosted decision trees are used to idenincreasing the latency - the time delay tify displaced vertices from heavy quark decays. The full chain from saving raw data in a 100 PB buffer to selecting events The proposed trigger systems for of interest and removing the original raw ATLAS and CMS are predominantly data takes about three weeks and was

systems play a crucial role the vast amounts of data generated by modern

Triggering

FPGA-based, employing highly paral-fully employed last year.

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FIELD NOTES

#### FIELD NOTES

The LHCb experiment focuses on pre-output rate to 20 kHz. This represents **The third** cision measurements in heavy-flavour 10 GB/s written to disk for later analysis. physics. A typical example is measuring the probability of a particle decaying into a ments differ considerably. Contributions certain decay channel. In Run 2 the hard- from other areas covered heavy-ion ware trigger tended to saturate in many hadronic channels when the luminosity was instantaneously increased. To solve (RHIC), fixed-target physics at CERN is only set to this issue for Run 3 a high-level software and future experiments at the Facility trigger was developed that can handle 30MHz event readout with 4TB/s data flow. Darmstadt and Brookhaven's Electron- $A\,GPU-based\,partial\,event\,reconstruction \quad Ion\,Collider\,(EIC).\,NA62\,at\,CERN\,and\,STAR$ and primary selection of displaced tracks at RHIC both use conventional trigger and vertices (HLT1) reduces the output strategies to arrive at their final event data rate to 1MHz. The calibration and samples. The forthcoming CBM experdetector alignment (embedded into the iment at FAIR and the ePIC experiment trigger system) are calculated during data at the EIC deal with high intensities but taking just after HLT1 and feed full-event aim for "triggerless" operation. reconstruction (HLT2), which reduces the

Away from the LHC, trigger requirephysics at Brookhaven National Laboratory's Relativistic Heavy Ion Collider in this field for Antiproton and Ion Research at GSI

Requirements were reported to be even

edition of **TDHEP** suggests that innovation

accelerate

more diverse in astroparticle physics. The Pierre Auger Observatory combines local and global trigger decisions at three levels to manage the problem of trigger distribution and data collection over 3000 km2 of fluorescence and Cherenkov detectors

These diverse requirements will lead to new approaches being taken, and evolution as the experiments are finalised. The third edition of TDHEP suggests that innovation in this field is only set to accelerate.

Marek Bombara Pavol Jozef Šafárik University in Košice Roman Lietava CERN and University of Birmingham, and Orlando Villalobos Baillie  ${\it University} \ of {\it Birmingham}.$ 

#### **BCVSPIN PROGRAMME**

### Salam's dream visits the Himalayas

After winning the Nobel Prize in Physics in 1979, Abdus Salam wanted to bring world-class physics research opportunities to South Asia. This was the beginning of the BCSPIN programme, encompassing Bangladesh, China, Sri Lanka, Pakistan, India and Nepal. The goal was to provide scientists in South and Southeast Asia with new opportunities to learn from leading experts about developments in particle physics, astroparticle physics and cosmology. Together with Jogesh Pati, Yu Lu and Oaisar Shafi, Salam initiated the programme in 1989. This first edition was hosted by Nepal. Vietnam joined in 2009 and BCSPIN became BCVSPIN. Over the years, the conference has been held as far afield as Mexico

The most recent edition attracted more than 100 participants to the his- University. toric Hotel Shanker in Kathmandu, Nepal, from 9 to 13 December 2024. The conference aimed to facilitate interactions between researchers from BCVSPIN countries and the broader international community, covering topics such as collider physics, cosmology, gravitational waves, dark matter, neutrino physics, particle astrophysics, physics beyond the Standard Model and machine learning. Participants ranged from renowned professors from across the globe to aspiring students.

Speaking of aspiring students, the main event was preceded by the BCVSPIN-2024 Masterclass in Particle Physics and Workshop in Machine Learning, hosted at Tribhuvan University from 4 to 6 December. The workshop provided 34 undergraduate and graduate students from around Nepal with a comprehen-



#### Nepali brainpower

The BCVSPIN-2024 Masterclass took place at Tribhuvan

them for future careers in HEP.

started the following Monday. In the how – in the midst of the ongoing rev-

sive introduction to particle physics, spirit of BCVSPIN, the first plenary seshigh-energy physics (HEP) experiments sion featured an insightful talk on the and machine learning. In addition to lec- status and prospects of HEP in Nepal, protures, the workshop engaged students viding valuable insights for both locals in hands-on sessions, allowing them to and newcomers to the initiative. Then, experience real research by exploring the latest and the near-future physics core concepts and applying machine- highlights of experiments such as ATLAS, learning techniques to data from the ALICE, CMS, as well as Belle, DUNE and ATLAS experiment. The students' enthu- IceCube, were showcased. From physics siasm was palpable as they delved into performance such as ATLAS nailing bthe intricacies of particle physics and tagging with graph neural networks, to the machine learning. The interactive ses- most elaborate mass measurement of the sions were particularly engaging, with W boson mass by CMS, not to mention students eagerly participating in dis- ProtoDUNE's runs exceeding expeccussions and practical exercises. High- tations, the audience were offered lights included a special talk on artificial comprehensive reviews of the recent intelligence (AI) and a career development breakthroughs on the experimental session focused on crafting CVs, applica-side. The younger physicists willing to tions and research statements. These ses- continue or start hardware efforts surely sions ensured participants were equipped appreciated the overview and schedule with both academic insights and practical of the different upgrade programmes. guidance. The impact on students was The theory talks covered, among others, profound, as they gained valuable skills dark-matter models, our dear friend the and networking opportunities, preparing neutrino and the interactions between the two. A special talk on AI invited the The BCVSPIN conference officially audience to reflect on what AI really is and olution - it impacts the fields of physics BCVSPIN and physicists themselves. Overviews of long-term future endeavours such as the Electron-Ion Collider and the Future Circular Collider concluded the programme.

A special highlight of the conference was a public lecture "Oscillating Neutrinos" by the 2015 Nobel Laureate from the Takaaki Kajita. The event was held near the historical landmark of Patan Durbar Square, in the packed auditorium of the Rato Bangala School. This centre of excellence is known for its innovative teaching methods and quality instruction. More

offers younger scientists precious connections with physicists international community

than half the room was filled with excited allowed, he was swept up in a crowd of students from schools and universities, eager to listen to the keynote speaker. After a very pedagogical introduction explaining the "problem of solar neutrinos", Kajita shared his insights on the discovery of neutrino oscillations and its affordable for students, it is a stepping in Kamioka, Japan, as well as his partici- national community. pation at BCVSPIN in 1994. After encouraging the students to become scientists Claire David AIMS South Africa and

passionate Nepali youth, thrilled to be in the presence of such a renowned physicist.

The BCVSPIN initiative has changed the landscape of HEP in South and Southeast Asia. With participation made implications for our understanding of the stone for the younger generation of universe. His presentation included his-scientists, offering them precious contorical photographs of the experiments nections with physicists from the inter-

and answering as many questions as time Joe Haley Oklahoma State University.

HARD AND ELECTROMAGNETIC PROBES

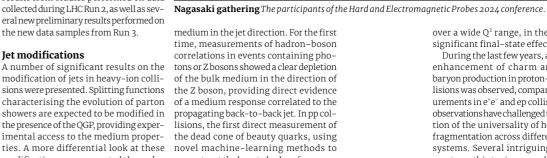
### Probing the quark-gluon plasma in Nagasaki

The 12th edition of the International Conference on Hard and Electromagnetic Probes attracted 346 physicists to Nagasaki, Japan, from 22 to 27 September 2024. Delegates discussed the recent experimental and theoretical findings on perturbative probes of the quark-gluon plasma (QGP) - a hot and deconfined state of matter formed in ultrarelativistic heavy-ion collisions.

The four main LHC experiments played a prominent role at the conference, presenting a large set of newly published results from studies performed on data collected during LHC Run 2, as well as sev $eral\,new\,preliminary\,results\,performed\,on$ the new data samples from Run 3.



A number of significant results on the scales on the observable



tial decay information, was also shown.

Several new results from studies of particle production in ultraperipheral These studies allow us to investigate the possible onset of gluon saturation at low the properties of jet modification in the Bjorken-x values. In this context, new medium might be imprinted at different results of charm photoproduction, with measurements of incoherent and coher-The first measurements of the ent I/w mesons, as well as of D<sup>o</sup> mesons. were released. Photonuclear production tors in p-Pb and Pb-Pb collisions were cross-sections of di-jets, covering a large presented, showing modifications in interval of photon energies to scan over both the small- and large-angle corre- different regions of Bjorken-x, were also lations for both systems compared to pp presented. These measurements pave the collisions. A long-sought after effect of way for setting constraints on the gluon energy exchanges between the jet and the component of nuclear parton distribumedium is a correlated response of the tion functions at low Bjorken-x values, conference over a wide Q2 range, in the absence of significant final-state effects.

During the last few years, a significant enhancement of charm and beautybaryon production in proton-proton collisions was observed, compared to measurements in e<sup>+</sup>e<sup>-</sup> and ep collisions. These observations have challenged the assumption of the universality of heavy-quark fragmentation across different collision systems. Several intriguing measurements on this topic were released at the conference. In addition to an extended set of charm meson-to-meson and barvon-to-meson production yield ratios, the first measurements of the production of  $\Sigma_{c}^{0,++}$  (2520) relative to  $\Sigma_{c}^{0,++}$  (2455) at the LHC, obtained exploiting the new Run 3 data samples, were discussed. New insights on the structure of the exotic  $\chi_{ci}(3872)$  state and its hadronisation mechanism were garnered by measuring the ratio of its production yield to that of  $\psi(2S)$  mesons in hadronic collisions.

Additionally, strange-to-non-strange production-yield ratios for charm and beauty mesons as a function of the collision multiplicity were released, pointing toward an enhanced strangeness production in a higher colour-density envi-

modification of jets in heavy-ion collishowers are expected to be modified in the presence of the QGP, providing experimental access to the medium propermodifications was presented through a reconstruct the beauty hadron from parcorrelated measurement of the shared momentum fraction and opening angle of the first splitting satisfying the "soft drop" condition in jets. Additionally, heavy-ion collisions were discussed. energy-energy correlators have recently emerged as promising observables where

two-particle energy-energy correla-

The four main LHC experiments played a prominent role at the

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ronment. Several theoretical approaches imental opportunities in this field was New implementing modified hadronisation also provided. A new and intriguing set mechanisms with respect to in-vacuum of physics observables for a complete fragmentation have proven to be able to characterisation of the QGP with hard reproduce at least part of the measure- probes will become accessible with the ments, but a comprehensive description of the heavy-quark hadronisation, in particular for the baryonic sector, is the next long LHC shutdown and in the still to be reached.

Aglimpse into the future of the exper- at CERN, such as NA60+, or in other

planned upgrades of the ALICE, ATLAS, CMS and LHCb detectors, both during more distant future. New experiments

facilities like the Electron-Ion Collider in the US and J-PARC-HI in Japan, will experiments explore higher-density regions of the will explore QCD-matter phase diagram. higher-density regions of the

QCD-matter

phase diagram

The next edition of this conference series is scheduled to be held in Nashville, US, from 1 to 5 June 2026.

Fabio Colamaria and Nima Zardoshti

CHAMONIX WORKSHOP 2025

### Chamonix looks to CERN's future

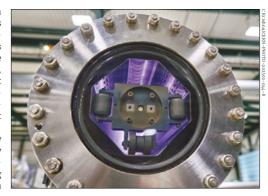
The Chamonix Workshop 2025, held from 27 to 30 January, brought together CERN's accelerator and experimental communities to reflect on achievements, address challenges and chart a course for the future. As the discussions made clear, CERN is at a pivotal moment. The past decade has seen transformative developments across the accelerator complex, while the present holds significant potential and opportunity.

The workshop opened with a review of accelerator operations, supported by input from December's Joint Accelerator Performance Workshop. Maintaining current performance levels requires an extraordinary effort across all the facilities. Performance data from the ongoing Run 3 shows steady improvements in availability and beam delivery. These results are driven by dedicated efforts from system experts, operations teams has greatly and accelerator physicists, all working to ensure excellent performance and high availability across the complex.

#### Electron clouds parting

Attention is now turning to Run 4 and the High-Luminosity LHC (HL-LHC) era. Several challenges have been identified, including the demand for high-intensity beams, radiofrequency (RF) power limitations and electron-cloud effects. In the latter case, synchrotron-radiation photons strike the beam-pipe walls, releasing electrons which are then accelerated by proton bunches, triggering a cascading electron-cloud buildup. Measures to address these issues will be implemented during Long Shutdown 3 (LS3), ensuring CERN's accelerators continue to meet the demands of its diverse physics community.

LS3 will be a crucial period for CERN. In addition to the deployment of the HL-LHC and major upgrades to the ATLAS and CMS experiments, it will see a widespread programme of consolidation, maintenance and improvements across the accelerator complex to secure future exploitation over the coming decades.



**Avoiding electron** clouds CERN's Vacuum, Surfaces and Coatings group improved its amorphous carbon coating technique.

Progress on the HL-LHC upgrade was reviewed in detail, with a focus on key FCC-ee injector complex would fit into systems - magnets, cryogenics and the broader strategic picture was exambeam instrumentation - and on the construction of critical components such as deliverables of the pre-technical design crab cavities. The next two years will be report (pre-TDR) phase that is planned to decisive, with significant system testing scheduled to ensure that these technolo-

has been key to aligning complex interalls, the potential of a muon collider and are making strong progress in shaping a resource-loaded plan. The scale of LS3 field magnets and superconducting RF will require meticulous coordination, but it also represents a unique opportunity to future accelerator-based facilities. build a more robust and adaptable accelerator complex for the future. Looking 4, implementing the LS3 upgrade probeyond LS3, CERN's unique accelerator complex is well positioned to support an increasingly diverse physics programme. essential. CERN's future will be shaped This diversity is one of CERN's greatest by how well we seize these opportunities. strengths, offering complementary

discussions highlighted the importance for decades to come of balancing these demands while ensuring that the full potential of the acceler- Mike Lamont CERN

ator complex is realised.

Future opportunities such as those highlighted by the Physics Beyond Colliders study will be shaped by discussions being held as part of the update of the European Strategy for Particle Physics (ESPP). Defining the next generation of physics programmes entails striking a careful balance between continuity and innovation, and the accelerator community will play a central role in setting the priorities.

workshop focused on the Future Circular Collider (FCC) Feasibility Study and the next steps. The physics case was presented alongside updates on territorial implementation and civil-engineering investigations and plans. How the ined in detail, along with the goals and follow the Feasibility Study's conclusion.

While the FCC remains a central focus,

The next steps - preparing for Run grammes and laying the groundwork for future projects - are ambitious but

The shared expertise and dedication of opportunities across a wide range of fields. CERN's personnel, combined with a clear The high demand for beam time at strategic vision, provide a solid foundation ISOLDE, n TOF, AD-ELENA and the for success. The path ahead is challenging, North and East Areas underscores the but with careful planning, collaboration need for a well-balanced approach that and innovation, CERN's accelerator comsupports a broad range of physics. The plex will remain at the heart of discovery

A forward-looking session at the

gies meet ambitious performance targets. other future projects were also discussed Planning for LS3 is already well advan- in the context of the ESPP update. These ced. Coordination between all stakeholders include mature linear-collider proposdependencies, and the experienced teams plasma wakefield acceleration. Development of key technologies, such as highsystems, will underpin the realisation of

## DO MUONS WOBBLE FASTER THAN EXPECTED?

With a new measurement imminent, the Courier explores the experimental results and theoretical calculations used to predict 'muon g-2' - one of particle physics' most precisely known quantities and the subject of a fast-evolving anomaly.

undamental charged particles have spins that wobble in a magnetic field. This is just one of the insights that emerged from the equation Paul Dirac wrote down in 1928. Almost 100 years later, calculating how much they wobble - their "magnetic moment" - strains the computational sinews of theoretical physicists to a level rarely matched. The challenge is to sum all the possible ways in which the quantum fluctuations of the vacuum affect their wobbling.

The particle in question here is the muon. Discovered in cosmic rays in 1936, muons are more massive but ephemeral cousins of the electron. Their greater mass is expected to amplify the effect of any undiscovered new particles shimmering in the quantum haze around them, and measurements have disagreed with theoretical predictions for nearly 20 years. This suggests a possible gap in the Standard Model (SM) of particle physics, potentially providing a glimpse of deeper truths beyond it.

In the coming weeks, Fermilab is expected to present the final results of a seven-year campaign to measure this property, reducing uncertainties to a remarkable one part in 1010 on the magnetic moment of the muon, and 0.1 parts per million on the quantum corrections. Theorists are racing to match this with an updated prediction of comparable precision. The calculation is in good shape, except for the incredibly unusual eventuality that the muon briefly emits a cloud of quarks and gluons at just the moment it absorbs a photon from the magnetic field. But in quantum mechanics all possibilities count all the time, and the experimental precision is such that the fine details of "hadronic vacuum polarisation" (HVP) could be the difference between reinforcing the SM and **Vacuum fluctuation** The fine details of "hadronic vacuum polarisation" challenging it.

#### **Quantum fluctuations**

was a surprise and was named the magnetic anomaly or the anomalous magnetic moment.



FEATURE MUON g-2 ANOMALY

could be the difference between reinforcing the SM and challenging it.

between experiment and theory. It became clear that The Dirac equation predicts that fundamental spin  $s = \frac{1}{2}$  a relativistic field theory like the developing quantum particles have a magnetic moment given by g(eħ/2m)s, electrodynamics (QED) could produce quantum fluctuwhere the gyromagnetic ratio (g) is precisely equal to ations, shifting g from two. In 1948, Julian Schwinger two. For the electron, this remarkable result was soon calculated the first correction to be a =  $\alpha/2\pi \approx 0.00116$ , confirmed by atomic spectroscopy, before more precise aligning beautifully with 1947 experimental results. The experiments in 1947 indicated a deviation from g = 2 of a emission and absorption of a virtual photon creates a few parts per thousand. Expressed as a = (g-2)/2, the shift cloud around the electron, altering its interaction with the external magnetic field (see "Quantum fluctuation" figure). Soon, other particles would be seen to influence This marked the beginning of an enduring dialogue the calculations. The SM's limitations suggest that undis-

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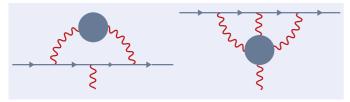




#### FEATURE MUON g-2 ANOMALY



**Quantum fluctuation** Julian Schwinger calculated the effect of adding an extra photon line (right) to Dirac's q = 2 interaction between a photon from a magnetic field and an electron (left).



Hadronic contributions Feynman diagrams illustrating contributions to muon g-2 from hadronic vacuum polarisation (HVP, left) and hadronic light-by-light scattering (HLbL, right). The muon line enters from the left and interacts with a photon from the magnetic field arriving from below. Additional photon lines connect the process with a complex swarm of quarks and gluons that can only be evaluated using data-driven or lattice-QCD methods (grey circles).

> covered particles could also affect these calculations. Their the SM prediction for a particle's anomalous magnetic moment and its measured value.

than the electron, as its sensitivity to physics beyond disparate, the production of hadrons in these processes QED is generically enhanced by the square of the ratio of their masses: a factor of around 43,000. In 1957, inspired by Tsung-Dao Lee and Chen-Ning Yang's proposal that parity is violated in the weak interaction, Richard Garwin, Leon Lederman and Marcel Weinrich studied the decay of muons brought to rest in a magnetic field at the Nevis QCD" requires hundreds of millions of processor-core hours cyclotron at Columbia University. As well as showing on the world's largest supercomputers. that parity is broken in both pion and muon decays, they found g to be close to two for muons by studying their "precession" in the magnetic field as their spins circled around the field lines.

This iconic experiment was the prototype of muonprecession projects at CERN (see CERN Courier September/ was obtained with a precision of a few parts per thousand October 2024 p53), later at Brookhaven National Laboratory and now Fermilab (see "Precision" figure). By the end of the Brookhaven project, a disagreement between the measured value of "a<sub>u</sub>" - the subscript indicating methods. Though even more complex to compute, HLbL g-2 for the muon rather than the electron - and the SM prediction was too large to ignore, motivating the present is smaller. round of measurements at Fermilab and rapidly improving theory refinements.

#### g-2 and the Standard Model

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particles. The leading contributions are from electrons,

where each successive term contributes only around 1% of the previous one. QED effects have been computed to fifth order, yielding an extraordinary precision of 0.9 parts per billion - significantly more precise than needed to match measurements of the muon's g-2, though not the electron's. It took over half a century to achieve this theoretical tour de force

The weak interaction gives the smallest contribution to a<sub>u</sub>, a million times less than QED. These contributions can also be computed in an expansion. Second order suffices. All SM particles except gluons need to be taken into account.

Gluons are responsible for the strong interaction and appear in the third and last set of contributions. These are described by QCD and are called "hadronic" because quarks and gluons form hadrons at the low energies relevant for the muon g-2 (see "Hadronic contributions" figure). HVP is the largest, though 10,000 times smaller than the corrections due to QED. "Hadronic light-by-light scattering" (HLbL) is a further 100 times smaller due to the exchange of an additional photon. The challenge is that the strong-interaction effects cannot be approximated by a perturbative expansion. QCD is highly nonlinear and different methods are needed.

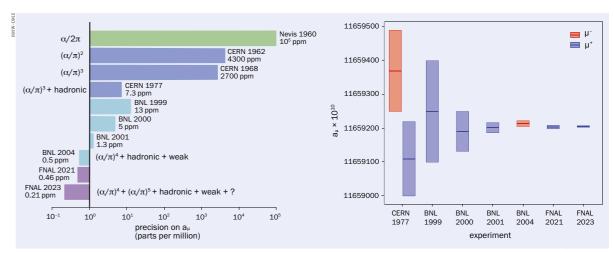
#### Data or the lattice?

Even before QCD was formulated, theorists sought to existence might be revealed by a discrepancy between subdue the wildness of the strong force using experimental data. In the case of HVP, this triggered experimental investigations of e<sup>+</sup>e<sup>-</sup> annihilation into hadrons As noted, the muon is an even more promising target and later hadronic tau-lepton decays. Though apparently can be related to the clouds of virtual quarks and gluons that are responsible for HVP.

> A more recent alternative makes use of massively parallel numerical simulations to directly solve the equations of QCD. To compute quantities such as HVP or HLbL, "lattice

> In preparation for Fermilab's first measurement in 2021, the Muon g-2 Theory Initiative, spanning more than 120 collaborators from over 80 institutions, was formed to provide a reference SM prediction that was published in a 2020 white paper. The HVP contribution using a compilation of measurements of e<sup>+</sup>e<sup>-</sup> annihilation into hadrons. The HLbL contribution was determined from a combination of data-driven and lattice-QCD is needed only to 10% precision, as its contribution

After summing all contributions, the prediction of the 2020 white paper sits over five standard deviations below the most recent experimental world average (see "Landscape of muon g-2" figure). Such a deviation would usually Today, a prediction for a<sub>u</sub> must include the effects of all be interpreted as a discovery of physics beyond the SM. three of the SM's interactions and all of its elementary However, in 2021 the result of the first lattice calculation of the HVP contribution with a precision comparable to muons and tau leptons interacting electromagnetically. that of the data-driven white paper was published by the  $These\,QED\,contributions\,can\,be\,computed\,in\,an\,expansion\quad Budapest-Marseille-Wuppertal\,collaboration\,(BMW).\,These\,CED\,contributions\,can\,be\,computed\,in\,an\,expansion$ 



**Precision** Left: the precision of successive experiments to measure the muon anomaly has dipped below 1 part per million of  $a_{ij}$  (black line).  $The electromagnetic, hadronic and weak couplings \ probed \ at this \ precision \ are \ also \ indicated. For FNAL 2023, although the \ prediction \ includes \ the \ prediction \ the \ predic$  $(\alpha/\pi)^5$  contribution, the experiment is not yet sensitive to it. Right:  $a_\mu$  and its uncertainty in successive measurements using  $\mu^-$  (red) and  $\mu^+$  (blue).

result, labelled BMW 2020 as it was uploaded to the preprint archive the previous year, is much closer to the experimental average (green band on the figure), suggesting that the SM may still be in the race. The calculation relied on methods developed by dozens of physicists since the seminal work of Tom Blum (University of Connecticut) in 2002 (see CERN Courier May/June 2021 p25).

In 2020, the uncertainties on the data-driven and lattice-QCD predictions for the HVP contribution were still large enough that both could be correct, but BMW's 2021 paper showed them to be explicitly incompatible in an "intermediate-distance window" accounting for approximately 35% of the HVP contribution, where lattice QCD is most reliable.

This disagreement was the first sign that the 2020 consensus had to be revised. To move forward, the sources of the various disagreements - more numerous now and the relative limitations of the different approaches must be understood better. Moreover, uncertainty on HVP already dominated the SM prediction in 2020. As well as resolving these discrepancies, its uncertainty must be even more critical than before, as elsewhere the theory of heavier quarks is subtracted using BMW 2020 lattice house is in order: Sergev Volkov (KITP) recently verified the fifth-order QED calculation of Tatsumi Aoyama, Toichiro lattice calculations that do not include those effects. Kinoshita and Makiko Nio, identifying an oversight not numerically relevant at current experimental sensitivi- including all other relevant contributions. Agreement ties; new HLbL calculations remain consistent; and weak is excellent and the verdict is clear: the disagreement enough for the foreseeable future.

#### News from the lattice

Since BMW's 2020 lattice results, a further eight lattice-QCD computations of the dominant up-and-down-quark (u + d) contribution to HVP's intermediate-distance window have disagreement is observed. been performed with similar precision, with four also

FHM 2024 -BMW-DMZ 2024 RBC/UKOCD 2023 ETM 2022 Mainz 2022 Aubin 2022 χQCD 2022 Lehner 2020 BMW 2020 e+e- & lattice BMW 2020 200 203 206 209 1010 × intermediate-window (u+d)

is clear: the disagreement between the lattice and data-driven approaches is confirmed

The verdict

FEATURE MUON g-2 ANOMALY

**Intermediate window** The up-and-down-quark intermediate-distance component of the HVP contribution to  $a_u \times 10^{10}$ . Lattice-QCD calculations (blue circles) are compared reduced by a factor of three to fully leverage the coming to a data-driven estimate (green square). As the data-driven measurement from Fermilab. Work on the HVP is therefore estimate incorporates all quark contributions, the small effect results, to also allow a comparison with the more numerous

contributions have already been checked and are precise between the lattice and data-driven approaches is confirmed (see "Intermediate window" figure).

> Work on the short-distance window (about 10% of the HVP contribution) has also advanced rapidly. Seven computations of the u + d contribution have appeared, with four including all other relevant contributions. No significant

The long-distance window (around 55% of the total) is

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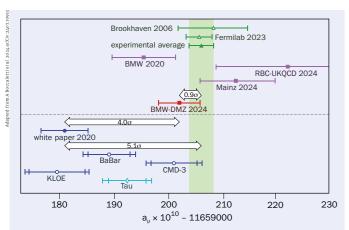




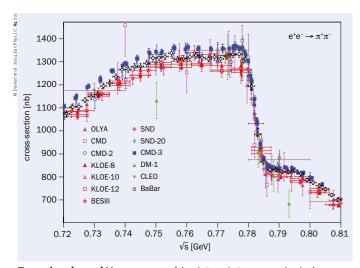




#### FEATURE MUON g-2 ANOMALY



Landscape of muon g-2 Measurements of a, (green triangles) compared to SM predictions using lattice QCD (purple squares), data-driven predictions using  $e^+e^-$  annihilation to hadrons (blue circles), tau–lepton decays (cyan diamond) and a hybrid approach (red square). Statistical compatibility or incompatibility is indicated by arrows between the latest experimental average (filled green triangle), News from electron-positron annihilation the 2020 white paper (filled blue circle) and the most precise prediction (red square).



**Two-pion channel** Measurements of the  $e^+e^- \rightarrow \pi^+\pi^-$  cross-section in the  $\rho$ - $\omega$  interference region.

by far the most challenging, with the largest uncertainties. In recent weeks three calculations of the dominant u + d contribution have appeared, by the RBC-UKQCD, Mainz and FHM collaborations. Though some differences CLEO experiments at B factories, under very different are present, none can be considered significant for the time being.

With all three windows cross-validated, the Muon g-2 shape measurement. Theory Initiative is combining results to obtain a robust far from the 0.2% ultimately needed.

presented new results for the full HVP contribution to au, and the RBC-UKQCD collaboration, which first proposed the multi-window approach, is also in a position to make a full calculation. (The corresponding result in the "Landscape of muon g-2" figure combines contributions reported in their publications.) Mainz obtained a result with 1% precision using the three windows described above. BMW-DMZ divided its new calculation into five windows and replaced the lattice-QCD computation of the longest distance window - "the tail", encompassing just 5% of the total - with a data-driven result. This pragmatic approach allows a total uncertainty of just 0.46%, with the collaboration showing that all e\*e\* datasets contributing to this long-distance tail are entirely consistent. This new prediction differs from the experimental measurement of au by only 0.9 standard deviations.

These new lattice results, which have not yet been published in refereed journals, make the disagreement with the 2020 data-driven result even more blatant. However, the analysis of the annihilation of e<sup>+</sup>e<sup>-</sup> into hadrons is also evolving rapidly.

Many experiments have measured the cross-section for  $e^+e^-$  annihilation to hadrons as a function of centre-of-mass energy ( $\sqrt{s}$ ). The dominant contribution to a data-driven calculation of au, and over 70% of its uncertainty budget, is provided by the  $e^+e^- \rightarrow \pi^+\pi^-$  process, in which the final-state pions are produced via the  $\rho$  resonance (see "Two-pion channel" figure).

The most recent measurement, by the CMD-3 energy-scan experiment in Novosibirsk, obtained a cross-section on the peak of the  $\rho$  resonance that is larger than all previous ones, significantly changing the picture in the  $\pi^+\pi^-$  channel. Scrutiny by the Theory Initiative has identified no

CMD-3's approach contrasts that used by KLOE, BaBar and BESIII, which study e'e- annihilation with a hard photon emitted from the initial state (radiative return) at facilities with fixed √s. BaBar has innovated by calibrating the luminosity of the initial-state radiation using the μ<sup>+</sup>μ<sup>-</sup> channel and using a unique "next-to-leading-order" approach that accounts for extra radiation from either the initial or the final state - a necessary step at the required

In 1997, Ricard Alemany, Michel Davier and Andreas Höcker proposed an alternative method that employs  $\tau^- \rightarrow \pi^- \pi^0 \nu$  decay while requiring some additional theoretical input. The decay rate has been precisely measured as a function of the two-pion invariant mass by the ALEPH and OPAL experiments at LEP, as well as by the Belle and conditions. The measurements are in good agreement. ALEPH offers the best normalisation and Belle the best

KLOE and CMD-3 differ by more than five standard lattice-QCD determination of the HVP contribution. The deviations on the  $\rho$  peak, precluding a combined analysis final uncertainty should be slightly below 1%, still quite of  $e^+e^- \rightarrow \pi^*\pi^-$  cross-sections. BaBar and  $\tau$  data lie between them. All measurements are in good agreement at low The BMW-DMZ and Mainz collaborations have also energies, below the  $\rho$  peak. BaBar, CMD-3 and  $\tau$  data

### The prospect of testing the limits of the SM through high-precision measurements generates considerable impetus

careful study of radiative corrections to  $e^+e^- \to \pi^+\pi^-$ . That study points to the possible underestimate of systematic uncertainties in radiative-return experiments that rely on Monte Carlo simulations to describe extra radiation, as opposed to the in situ studies performed by BaBar.

#### The future

g-2 are under control at the level of precision required to weeks. The ultimate aim is to reach a level of precision match the forthcoming Fermilab measurement, in trying in the SM prediction that allows us to fully leverage the to reduce the uncertainties of the HVP contribution to a potential of the muon anomalous magnetic moment in commensurate degree, theorists and experimentalists the search for new fundamental physics, in concert with shattered a 20 year consensus. This has triggered an intense the final results of Fermilab's Muon g-2 experiment and Sorbonne University collective effort that is still in progress.

New analyses of e<sup>+</sup>e<sup>−</sup> are underway at BaBar, Belle II, Japan, which will implement a novel technique. •

BES III and KLOE, experiments are continuing at CMD-3, and Belle II is also studying  $\tau$  decays. At CERN, the longer term "MUonE" project will extract HVP by analysing how muons scatter off electrons - a very challenging endeavour regarding the unusual accuracy required both in the control of experimental systematic uncertainties and also theoretically, for the radiative corrections.

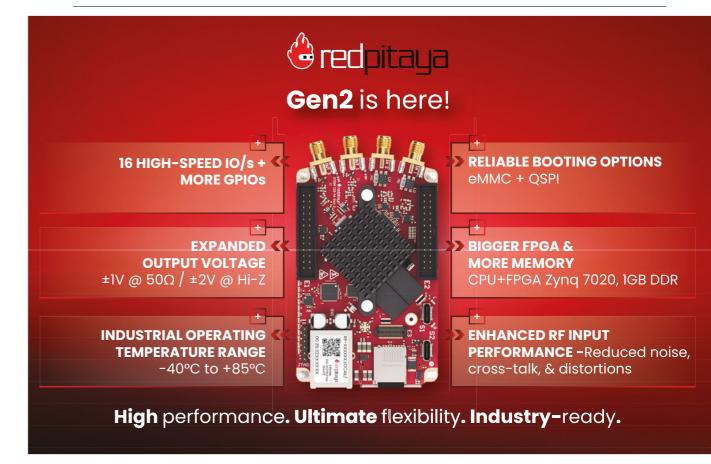
At the same time, lattice-QCD calculations have made enormous progress in the last five years and provide a are also in agreement above the  $\rho$  peak. To help clarify very competitive alternative. The fact that several groups this unsatisfactory situation, in 2023 BaBar performed a are involved with somewhat independent techniques is allowing detailed cross checks. The complementarity of the data-driven and lattice-QCD approaches should soon provide a reliable value for the g-2 theoretical prediction at unprecedented levels of precision.

There is still some way to go to reach that point, but IJCLabOrsay, the prospect of testing the limits of the SM through CNRS/IN2P3 and high-precision measurements generates considerable While most contributions to the SM prediction of the muon impetus. A new white paper is expected in the coming the projected Muon g-2/EDM experiment at J-PARC in and Paris Cité

#### THE AUTHORS

FEATURE MUON g-2 ANOMALY

Michel Davier and **Zhiqing Zhang** Paris-Saclay University, Laurent Lellouch CPT, CNRS and Aix-Marseille University, and Bogdan Malaescu LPNHE, CNRS/IN2P3, University.



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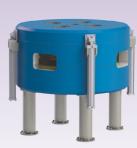
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FEATURE COSMOLOGY

# THE HUBBLE TENSION

Vivian Poulin asks if the tension between a direct measurement of the Hubble constant and constraints from the early universe could be resolved by new physics.

> Tust like particle physics, cosmology has its own standard This can be tested against direct measurements in our mysteries and profound implications. The first was "The Hubble tension" figure). the realisation in 1917 that a homogeneous and isotropic universe must be expanding. This led Einstein to modify his general theory of relativity by introducing a cosmological constant ( $\Lambda$ ) to counteract gravity and achieve a static universe – an act he labelled his greatest blunder when Edwin Hubble provided observational proof of the tion of distance. The gradient is Ho. universe's expansion in 1929. Sixty-nine years later, Saul Perlmutter, Adam Riess and Brian Schmidt went further. Their observations of Type Ia supernovae (SN Ia) showed that the universe's expansion was accelerating. A was to be precisely measured using the redshifts (z) of atomic revived as "dark energy", now estimated to account for 68% of the total energy density of the universe.

not from theory but from 50 years of astrophysical sleuthing. From the "missing mass problem" in the Coma galaxy cluster in the 1930s to anomalous galaxy-rotation curves

On large scales the dominant motion of galaxies is the Hubble flow, the expansion of the fabric of space itself

THE AUTHOR

**Vivian Poulin** 

et Particules de

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Montpellier and CNRS.

Laboratoire Univers

in the 1970s, evidence built up that additional gravitational we observe today. The 1980s therefore saw the proposal of

the energy density of the universe, and actively sought by diverse experiments across the globe and in space.

Dark energy and CDM supplement the remaining 5% can be used to calibrate them. of normal matter to form the  $\Lambda$ CDM model.  $\Lambda$ CDM is a remarkable six-parameter framework that models 13.8 billion years of cosmic evolution from quantum fluctuations during an initial phase of "inflation" - a hypothesised expansion of the universe by 26 to 30 orders of magnitude built a "distance ladder" to calibrate the luminosity of in roughly 10<sup>-36</sup> seconds at the beginning of time. ACDM 42 SN Ia within 37 host galaxies. The SN Ia are calibrated successfully models cosmic microwave background (CMB) anisotropies, the large-scale structure of the universe, and the redshifts and distances of SN Ia. It achieves this despite big open questions: the nature of dark matter, the nature of dark energy and the mechanism for inflation.

Cosmologists are eager to guide beyond-ΛCDM model-building efforts by testing its end-to-end predic- (right) The usual suspects The SHoES and CCHP teams tions, and the model now seems to be failing the most have so far used the James Webb Space Telescope to

One of the main predictions of  $\Lambda$ CDM is the average energy density of the universe today. This determines its using the Hubble Space Telescope. The galaxies are shown current expansion rate, otherwise known as the Hubble constant ( $H_0$ ). The most precise  $\Lambda$ CDM prediction comes tional 2009 to 2013), which yields  $H_0 = 67.4 \pm 0.5 \, \mathrm{km/s/Mpc}$ . (Credit: NASA, ESA and the Hubble Heritage Team)

model. It is also powerful in prediction, and brings new local universe, revealing a surprising discrepancy (see

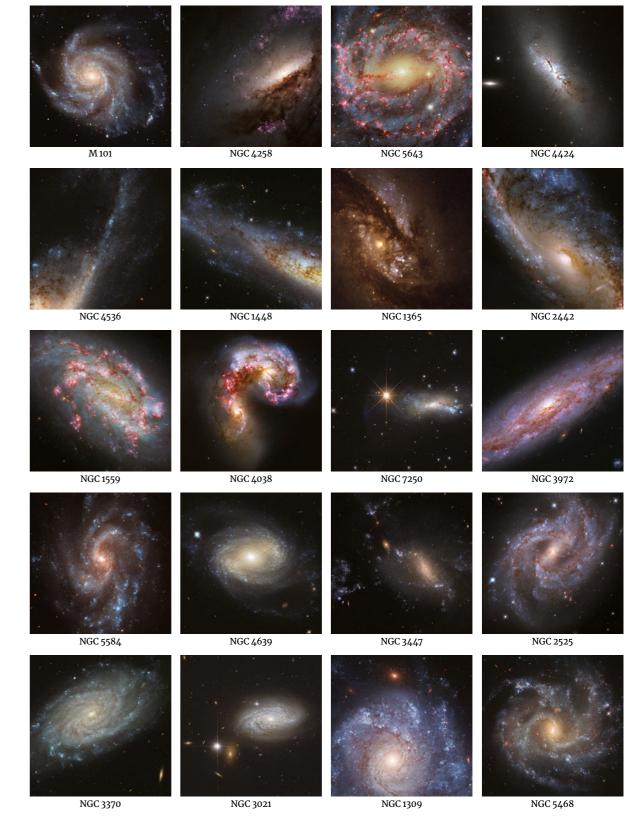
At sufficiently large distances, the dominant motion of galaxies is the Hubble flow - the expansion of the fabric of space itself. Directly measuring the expansion rate of the universe calls for fitting the increase in the recession velocity of galaxies deep within the Hubble flow as a func-

#### Receding supernovae

While high-precision spectroscopy allows recession velocity spectra, it is more difficult to measure the distance to astrophysical objects. Geometrical methods such as parallax are The second dominant component of the model emerged imprecise at large distances, but "standard candles" with somewhat predictable luminosities such as cepheids and SN Ia allow distance to be inferred using the inverse square-law. Cepheids are pulsating post-main-sequence stars whose radius and observed luminosity oscillate over a period of one to 100 days, driven by the ionisation and recombination heft was needed to explain the of helium in their outer layers, which increases opacity and formation of the large-scale traps heat; their period increases with their true lumistructure of galaxies that nosity. Before going supernova, SN Ia were white dwarf stars in binary systems; when the white dwarf accretes enough mass from its companion star, runaway carbon cold dark matter (CDM), now fusion produces a nearly standardised peak luminosity for estimated to account for 27% of a period of one to two weeks. Only SN Ia are deep enough in the Hubble flow to allow precise measurements of H<sub>0</sub>. When cepheids are observable in the same galaxies, they

> At present, the main driver of the Hubble tension is a 2022 measurement of H<sub>0</sub> by the SH<sub>0</sub>ES (Supernova H<sub>0</sub> for the Equation of State) team led by Adam Riess. As the SN Ia luminosity is not known from first principles, SH₀ES against intermediate-distance cepheids, and the cepheids are calibrated against four nearby "geometric anchors" whose distance is known through a geometric method (see "Distance ladder" figure). The geometric anchors are: Milky Way parallaxes from ESA's Gaia mission; detached eclipsing

important: predicting the expansion rate of the universe. recalibrate the distances to 20 of the 37 galaxies used by the SHoES team to calibrate their direct measurement of H<sub>0</sub> in order of their distance, from the Pinwheel Galaxy M101, approximately 29.2 Mpc away, to NGC 5468, roughly 33.1 Mpc from a fit to CMB data from ESA's Planck satellite (opera- distant. The second galaxy is the geometric anchor NGC 4.258.



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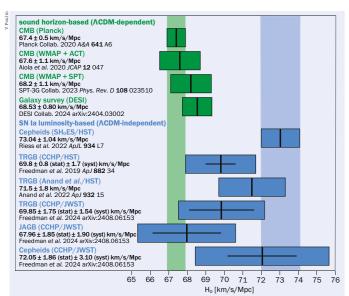




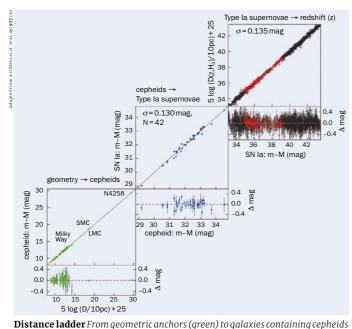




#### FEATURE COSMOLOGY



**The Hubble tension** The measurements of the Hubble constant described in this article.  $\Lambda$ CDM predictions (green) are labelled by the method of measuring the scale of baryon acoustic oscillations and the instrument(s) used. Direct measurements are labelled by the means of calibrating the distance to SN Ia, the analysis team and the instrument used for the calibration.



(blue) to 42 SN Ia used by SH<sub>0</sub>ES to calibrate their full measurement of H<sub>0</sub> (red), the distances on the abscissa calibrate a relative distance indicator on the ordinate, based on a population of cepheids also existing in the geometric anchor or the SN Ia host galaxy. D is a geometrical distance in Mpc. The corresponding distance measure m-M (mag) is the difference between the observed (m) and absolute (M) magnitudes of cepheids and SN Ia, with M fitted to align with the line of equality.

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binaries in the large and small magellanic clouds (LMC and SMC); and the "megamaser" galaxy host NGC4258, where water molecules in the accretion disk of a supermassive black hole emit Doppler-shifting microwave maser photons.

The great strength of the SH<sub>0</sub>ES programme is its use of NASA and ESA's Hubble Space Telescope (HST, 1990-) at all three rungs of the distance ladder, bypassing the need for cross-calibration between instruments. SN Ia can be calibrated out to 40 Mpc. As a result, in 2022 SH<sub>0</sub>ES used measurements of 300 or so high-z SN Ia deep within the Hubble flow to measure  $H_0 = 73.04 \pm 1.04 \text{ km/s/Mpc}$ . This is in more than 5σ tension with Planck's ΛCDM prediction of  $67.4 \pm 0.5 \,\text{km/s/Mpc}$ .

#### The sound horizon

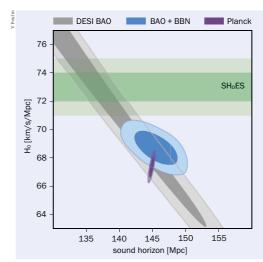
The value of H<sub>0</sub> obtained from fitting Planck CMB data has been shown to be robust in two key ways.

First, Planck data can be bypassed by combining CMB data from NASA's WMAP probe (2001–2010) with observations by ground-based telescopes. WMAP in combination with the Atacama Cosmology Telescope (ACT, 2007-2022) yields  $H_0 = 67.6 \pm 1.1 \text{km/s/Mpc}$ . WMAP in combination with the South Pole Telescope (SPT, 2007-) yields  $H_0 = 68.2 \pm 1.1 \text{km/}$ s/Mpc. Second, and more intriguingly, CMB data can be bypassed altogether.

In the early universe, Compton scattering between photons and electrons was so prevalent that the universe behaved as a plasma. Quantum fluctuations from the era of inflation propagated like sound waves until the era of recombination, when the universe had cooled sufficiently for CMB photons to escape the plasma when protons and electrons combined to form neutral atoms. This propagation of inflationary perturbations left a characteristic scale known as the sound horizon in both the acoustic peaks of the CMB and in "baryon acoustic oscillations" (BAOs) seen in the large-scale structure of galaxy surveys (see "Baryon acoustic oscillation" figure). The sound horizon is the distance travelled by sound waves in the primordial plasma.

While the SH<sub>0</sub>ES measurement relies on standard candles, ACDM predictions rely instead on using the sound horizon as a "standard ruler" against which to compare the apparent size of BAOs at different redshifts, and thereby deduce the expansion rate of the universe. Under  $\Lambda$ CDM, the only two free parameters entering the computation of the sound horizon are the baryon density and the dark-matter density. Planck evaluates both by studying the CMB, but they can be obtained independently of the CMB by combining BAO measurements of the dark-matter density with Big Bang nucleosynthesis (BBN) measurements of the baryon density (see "Sound horizon" figure). The latest measurement by the Dark Energy Spectroscopic Instrument in Arizona (DESI, 2021-) yields  $H_0 = 68.53 \pm 0.80 \,\text{km/s/Mpc}$ , in 3.4 $\sigma$  tension with SH<sub>0</sub>ES and fully independent of Planck.

The next few years will be crucial for understanding the Hubble tension, and may decide the fate of the ΛCDM model. ACT, SPT and the Simons Observatory in Chile (2024-) will release new CMB data. DESI, the Euclid space telescope (2023-) and the forthcoming LSST wide-field optical survey in Chile will release new galaxy surveys. "Standard siren" measurements from gravitational waves



Sound horizon The degeneracy of DESI measurements of H<sub>o</sub> with the sound horizon (grey) can be resolved by measurements of Big Bang nucleosynthesis (blue), yielding a  $\Lambda$ CDM fit compatible with measurements of the CMB by Planck. SH<sub>o</sub>ES data (green) implies a lower value for the sound horizon, suggesting beyond- $\Lambda$ CDM physics.

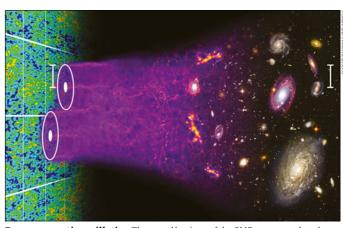
with electromagnetic counterparts may also contribute to the debate, although the original excitement has dampened with a lack of new events after GW170817. More accurate measurements of the age of the oldest objects may also provide an important new test. If Ho increases, the age of the universe decreases, and the SH<sub>0</sub>ES measurement favours less than 13.1 billion years at  $2\sigma$  significance.

The SH<sub>0</sub>ES measurement is also being checked directly. helium fusion in low-mass stars. The TRGB is bright enough to be seen in distant galaxies that host SN Ia, though at distances smaller than that of cepheids.

#### Settling the debate

using the TRGB within the LMC and NGC4258 to determine three rows of "The Hubble tension" figure).  $H_0 = 69.8 \pm 0.8$  (stat)  $\pm 1.7$  (syst). An independent reanaly-

of the 37 hosts galaxies home to the 42 SNIa studied by SH<sub>0</sub>ES anchor NGC 5468 (see "The usual suspects" figure). and the geometric anchor NGC4258.



Baryon acoustic oscillation The sound horizon of the CMB corresponds today to the separation of galaxies.



So far, all observations suggest good agreement with the Webb of intrigue previous observations by HST. SH<sub>0</sub>ES used JWST observations A key approach is to test the three-step calibration by to obtain up to a factor 2.5 reduction in the dispersion of the Space Telescope is seeking alternative intermediate standard candles besides period-luminosity relation for cepheids with no indication recalibrating the cepheids. One candidate is the peak-luminosity "tip" of of a bias in HST measurements. Most importantly, they were distances to SN Ia.  $the\ red\ giant\ branch\ (TRGB)\ caused\ by\ the\ sudden\ start\ of \\ able\ to\ exclude\ the\ confusion\ of\ cepheids\ with\ other\ stars\ as$ being responsible for the Hubble tension at  $8\sigma$  significance.

Meanwhile, the CCHP team provided new measurements based on three distance indicators: cepheids, the TRGB and a new "population based" method using the J-region of the asymptotic giant branch (JAGB) of carbon-rich stars, In 2019 the Carnegie-Chicago Hubble Program (CCHP) led for which the magnitude of the mode of the luminosity by Wendy Freedman and Barry Madore calibrated SN Ia function can serve as a distance indicator (see the last

The new CCHP results suggest that cepheids may show a sis including authors from the SHoES collaboration later bias compared to JAGB and TRGB, though this conclusion  $reported \ H_0 = 71.5 \pm 1.8 \ (stat + syst) \ km/s/Mpc. \ The \ difference \\ was \ rapidly \ challenged \ by \ SH_0ES, \ who \ identified \ a \ missing$ in the results suggests that updated measurements with the source of uncertainty and argued that the size of the sample James Webb Space Telescope (JWST) may settle the debate. of SN Ia within hosts with primary distance indicators is Launched into space on 25 December 2021, JWST is per- too small to provide competitive constraints: they claim  $fectly\ adapted\ to\ improve\ measurements\ of\ the\ expansion \\ that\ sample\ variations\ of\ order\ 2.5\ km/s/Mpc\ could\ explain$ rate of the universe thanks to its improved capabilities in the why the JAGB and TRGB yield a lower value. Agreement near infrared band, where the impact of dust is reduced (see may be reached when JWST has observed a larger sample "Improved resolution" figure). Its four-times-better spatial of galaxies – across both teams, 19 of the 37 calibrated by resolution has already been used to re-observe a subsample SH<sub>0</sub>ES have been remeasured so far, plus the geometric

At this stage, no single systematic error seems likely to fully

The James Webb

FEATURE COSMOLOGY

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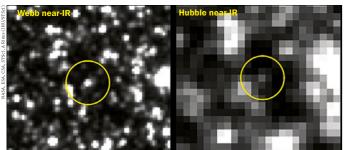








#### FEATURE COSMOLOGY



#### **Improved** resolution Comparison of JWST (left) and HST (right) views of a cepheid star in NGC 5468.

explain the Hubble tension, and the problem is more severe than it appears. When calibrated, SN Ia and BAOs constrain universe, boosting the expansion rate at just the right time. not only  $H_0$ , but the entire redshift range out to  $z \sim 1$ . This imposes strong constraints on any new physics introduced in the late universe. For example, recent DESI results suggest that the dynamics of dark energy at late times may not be features. Future data will be decisive in testing them. exactly that of a cosmological constant, but the behaviour needed to reconcile Planck and SH<sub>0</sub>ES is strongly excluded. Further reading

most proposals now focus on altering the calibration of either AGRiess et al. 2022 ApJL 934 L7. SN Ia or BAOs. For example, an unknown systematic error WL Freedman et al. 2024 arXiv:2408.06153. could alter the luminosity of SN Ia in our local vicinity, but AGRiess et al. 2024 ApJ 977 120. we have no indication that their magnitude changes with V Poulin et al. 2024 arXiv:2407.18292.

redshift, and this solution appears to be very constrained.

The most promising solution appears to be that some new physics may have altered the value of the sound horizon in the early universe. As the sound horizon is used to calibrate both the CMB and BAOs, reducing it by 10 Mpc could match the value of Ho favoured by SHoES (see "Sound horizon" figure). This can be achieved either by increasing the redshift of recombination or the energy density in the pre-recombination universe, giving the sound waves less time to propagate.

The best motivated models invoke additional relativistic species in the early universe such as a sterile neutrino or a new type of "dark radiation". Another intriguing possibility is that dark energy played a role in the pre-recombination The wide variety and high precision of the data make it hard to find a simple mechanism that is not strongly constrained or finely tuned, but existing models have some of the right

Rather than focusing on the value of the expansion rate, L Verde et al. 2024 Ann. Rev. Astrophys. 62 287.

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EDOARDO AMALDI AND

distinguished career at CERN, Ugo Amaldi offers deeply personal insights into his father Edoardo's foundational contributions to international cooperation in science.

#### nould we start with your father's involvement in the founding of CERN?

I began hearing my father talk about a new European laboratory while I was still in high school in Rome. Our lunch table was always alive with discussions about science, physics and the vision of this new laboratory. Later, I learned that between 1948 and 1949, my father was deeply engaged in these conversations with two of his friends: Gilberto Bernardini, a well-known cosmic-ray expert, and Bruno Ferretti, a professor of theoretical physics at Rome University. I was 15 years old and those table discussions remain vivid in my memory.

#### So, the idea of a European laboratory was already being discussed before the 1950 UNESCO meeting?

Yes, indeed. Several eminent European physicists, including my father, Pierre Auger, Lew Kowarski and Francis Perrin, recognised that Europe could only be competitive in nuclear physics through collaborative efforts. All the actors wanted to create a research centre that would stop the post-war exodus of physics talent to North America and these scientists back and rebuild European physics. help rebuild European science. I now know that my father's involvement began in 1946 when he travelled to Cambridge, Massachusetts, for a conference. There, he met Nobel Prize In 1950 my father was corresponding with Gilberto Berwinner John Cockcroft, and their conversations planted in his mind the first seeds for a European laboratory.

political initiative led by Swiss philosopher and writer Denis contact with other prominent figures in this decentralde Rougemont. After spending the war years at Princeton ised and multi-centered initiative. Together with Norman University, he returned to Europe with a vision of fostering Ramsay, Rabi had previously succeeded, in 1947, in perunity and peace. He established the Institute of European suading nine northeastern US universities to collaborate Culture in Lausanne, Switzerland, where politicians from under the banner of Associated Universities, Inc, which led France, Britain and Germany would meet. In December to the establishment of Brookhaven National Laboratory. 1949, during the European Cultural Conference in Lausanne, French Nobel Prize winner Louis de Broglie sent a famous speech at the fifth assembly of UNESCO in Florence Interview by Panos



FEATURE CULTURE AND HISTORY

from across the continent could work together peacefully. My father strongly believed in the importance of accelerators to advance the new field that, at the time, was at the crossroads between nuclear physics and cosmic-ray physics. Before the war, in 1936, he had travelled to Berkeley to learn about cyclotrons from Ernest Lawrence. He even of the driving attempted to build a cyclotron in Italy in 1942, profiting forces behind from the World's Fair that had to be held in Rome. Moreover, he was deeply affected by the exodus of talented Italian physicists after the war, including Bruno Rossi, Gian Carlo Wick and Giuseppe Cocconi. He saw CERN as a way to bring

#### How did Isidor Rabi's involvement come into play?

nardini, who was spending a year at Columbia University. There Bernardini mentioned the idea of a European Parallel to scientific discussions, there was an important laboratory to Isidor Rabi, who, at the same time, was in

What is not generally known is that before Rabi gave his **THE AUTHOR** letter advocating for a European laboratory where scientists in June 1950, he came to Rome and met with my father. They Charitos CERN.

Father and son Uao Amaldi beside a portrait of his father

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CERN COURIER MARCH/APRIL 2025

# **CERNCOURIER**





















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#### FEATURE CULTURE AND HISTORY

Our lunch table was always alive with discussions about science, physics and the vision of a new European laboratory

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Family values The Amaldi family in 1948, from left, Ugo, Ginestra, Francesco, Daniela and Edoardo.

discussed how to bring this idea to fruition. A few days later, Rabi's resolution at the UNESCO meeting calling for **Eminent friends** On vacation in Pera di Fassa in the Dolomites regional research facilities was a crucial step in launching in 1954: (clockwise from bottom left) Enrico and Giulio Fermi, the project. Rabi considered CERN a peaceful compensation Ginestra Amaldi, Laura Fermi, Edoardo and Ugo Amaldi. for the fact that physicists had built the nuclear bomb.

#### How did your father and his colleagues proceed after the UNESCO resolution?

Following the UNESCO meeting, Pierre Auger, at that time director of exact and natural sciences at UNESCO, and my signed, and my father was nominated secretary general father took on the task of advancing the project. In September 1950 Auger spoke of it at a nuclear physics conference in Oxford, and at a meeting of the International Union of  $Pure\ and\ Applied\ Physics\ (IUPAP), my\ father-\ one\ of\ the\ vice \\ In\ particular,\ the\ UK\ was\ reluctant\ to\ participate\ fully.$ presidents - urged the executive committee to consider how They had their own advanced facilities, like the 40 MeV best to implement the Florence resolution. In May 1951, Auger cyclotron at the University of Liverpool. In December 1952 and my father organised a meeting of experts at UNESCO my father visited John Cockcroft, at the time director of headquarters in Paris, where a compelling justification for the European project was drafted.

any single nation. This led to an intergovernmental conference under the auspices of UNESCO in December 1951, where the foundations for CERN were laid. Funding, totalling \$10,000 for the initial meetings of the board of experts, came his temper and passionately defended the project. During from Italy, France and Belgium. This was thanks to the financial support of men like Gustavo Colonnetti, president of the Italian Research Council, who had already - a year the UK contributed to CERN, albeit initially as a series of before - donated the first funds to UNESCO.

#### Were there any significant challenges during this period?

Not everyone readily accepted the idea of a European laboratory. Eminent physicists like Niels Bohr, James Chadwick and Hendrik Kramers questioned the practicality of starting a new laboratory from scratch. They were concerned about the feasibility and allocation of resources, and preferred the



my father incorporated some of the concerns raised by the sceptics into a modified version of the project, ensuring broader support. In February 1952 the first agreement setting up a provisional council for CERN was written and of the provisional CERN.

He worked tirelessly, travelling through Europe to unite the member states and start the laboratory's construction. the Harwell Atomic Energy Research Establishment, to discuss this. There's an interesting episode where my The cost of such an endeavour was beyond the means of father, with Cockcroft, met Frederick Lindemann and Baron Cherwell, who was a long-time scientific advisor to Winston Churchill. Cherwell dismissed CERN as another "European paper mill." My father, usually composed, lost the following visit to Harwell, Cockcroft reassured him that his reaction was appropriate. From that point on, donations rather than as the result of a formal commitment. It may be interesting to add that, during the same visit to London and Harwell, my father met the young John Adams and was so impressed that he immediately offered him a position at CERN.

#### What were the steps following the ratification of CERN's convention?

Robert Valeur, chairman of the council during the interim coordination of many national laboratories and institutions. period, and Ben Lockspeiser, chairman of the interim Through skilful negotiation and compromise, Auger and finance committee, used their authority to stir up early initiatives and create an atmosphere of confidence that attracted scientists from all over Europe. As Lew Kowarski noted, there was a sense of "moral commitment" to leave secure positions at home and embark on this new scientific endeavour.

During the interim period from May 1952 to September 1954, the council convened three sessions in Geneva whose primary focus was financial management. The organisation began with an initial endowment of approximately 1 million Swiss Francs, which - as I said - included a contribution from the UK known as the "observer's gift". At each subsequent session, the council increased its funding, reaching around 3.7 million Swiss Francs by the end of this period. When the permanent organisation was established, an initial sum of 4.1 million Swiss Francs was made available.

In 1954, my father was worried that if the parliaments didn't approve the convention before winter, then construction would be delayed because of the wintertime. So he took a bold step and, with the approval of the council president, authorised the start of construction on the main site before the convention was fully ratified.

This led to Lockspeiser jokingly remarking later that Werner Heisenberg at CERN in 1960. council "has now to keep Amaldi out of jail". The provisional council, set up in 1952, was dissolved when the cist who had led the synchrocyclotron group, as the new came into being in 1954, though the acronym CERN (Conseil Européen pour la Recherche Nucléaire) was the initial phase of CERN. Tragically though, Bakker died had grown significantly. A critical moment occurred on how hard my father was hit by this loss. 29 September 1954, when a specific point in the ratification procedure was reached, rendering all assets temporarily How did the development of accelerators at ownerless. During this eight-day period, my father, serving as secretary general, was the sole owner on behalf of council, marking the end of CERN's formative years.

#### Did your father ever consider becoming CERN's Director-General?

People asked him to be Director-General, but he declined for two reasons. First, he wanted to return to his students and position. He believed in the project for its own sake.

Bloch, a Swiss-American physicist and Nobel Prize winner for his work on nuclear magnetic resonance. Bloch accepted but insisted that my father serve as his deputy. My father, of the engineers, who often don't receive the same level of dedicated to CERN's success, agreed to this despite his recognition as physicists. They are the ones who make the desire to return to Rome full time.

#### How did that arrangement work out?

in Europe. He insisted on bringing all his instruments 
The experimentalists are those fellows on the ships who from Stanford so he could continue his research on nuclear sailed to the other side of the world and wrote down what magnetic resonance at CERN. He found it difficult to adapt they saw. The theoretical physicists are those who stayed to the demands of leading CERN and soon resigned. The behind in Madrid and told Columbus that he was going endeavour council then elected Cornelis Jan Bakker, a Dutch physi- to land in India.



FEATURE CULTURE AND HISTORY

Holding council (from left) Giuseppe Fidecaro, Edoardo Amaldi and

European Organization for Nuclear Research officially Director-General. From the beginning, he was the person my father thought would have been the ideal director for retained. By the conclusion of the interim period, CERN in a plane crash a year and a half later. I well remember

### CERN progress?

The decision to adopt the strong focusing principle for the the newly forming permanent organisation. The interim Proton Synchrotron (PS) was a pivotal moment. In August phase concluded with the first meeting of the permanent 1952 Otto Dahl, leader of the Proton Synchrotron study group, Frank Goward and Rolf Widerøe visited Brookhaven just as Ernest Courant, Stanley Livingston and Hartland Snyder were developing this new principle. They were so excited by this development that they returned to CERN determined to incorporate it into the PS design. In 1953 Mervyn Hine, a long-time friend of John Adams with his cosmic-ray research in Rome. Second, he didn't want whom he had moved to CERN, studied potential issues people to think he had done all this to secure a prominent with misalignment in strong focusing magnets, which led to further refinements in the design. Ultimately, the When the convention was finally ratified in 1954, the PS became operational before the comparable acceleracouncil offered the position of Director-General to Felix tor at Brookhaven, marking a significant achievement for European science.

It's important here to recognise the crucial contributions work of experimental physicists and theorists possible. "Viki" Weisskopf, Director-General of CERN from 1961 to 1965, compared the situation to the discovery of America. My father agreed but Bloch wasn't at that time rooted The machine builders are the captains and shipbuilders.

There was a sense of 'moral commitment' to leave secure positions at home and embark on this new scientific in Geneva

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Science has

always been a

cultures and

nations, and

bridge between

CERN's history

is a testimony

of what this

brings to

humanity



Steering the ship Edoardo Amaldi and Victor Weisskopf in 1974.

#### Your father also had a profound impact on the development of other Big Science organisations in Europe

Yes, in 1958 my father was instrumental, together with Pierre Auger, in the founding of the European Space Agency. In a letter written in 1958 to his friend Luigi Crocco, who was environment is one of the main goals of us scientists. It's professor of jet propulsion in Princeton, he wrote that "it is not just about achieving results but also about how we work now very much evident that this problem is not at the level of the single states like Italy, but mainly at the continental level. Therefore, if such an endeavour is to be pursued, it must be **Looking ahead, what are your thoughts on the** done on a European scale, as already done for the building of the large accelerators for which CERN was created... I think it is absolutely imperative for the future organisation to be neither military nor linked to any military organisation. It must be a purely scientific organisation, open – like CERN countries." This document reflects my father's vision of peaceful and non-military European science.

#### How is it possible for one person to contribute so profoundly to science and global collaboration?

son with a clear vision and unwavering dedication. I hope shifts delay or complicate these plans, we should consider that by sharing these stories, others might be inspired to pushing hard on alternative strategies like developing the pursue their goals with the same persistence and passion.

#### Could we argue that he was not only a visionary but also a relentless advocate?

He travelled extensively, talked to countless people, and was always cheerful and energetic. He accepted setbacks but atoms. Back at CERN, he developed the Roman pots kept moving forwards. In this connection, I want to mention Eliane Bertrand, later de Modzelewska, his secretary in Rome who later became secretary of the CERN Council for left a memoir about those early days, highlighting how my and led LEP's DELPHI Collaboration. Today, he advances the father was always travelling, talking and never stopping. It's use of accelerators in cancer treatment as the founder of the a valuable piece of history that, I think, should be published.

#### International collaboration has been a recurring theme in your own career. How do you view its importance today?

International collaboration is more critical than ever in today's world. Science has always been a bridge between This interview first appeared in the newsletter of CERN's exper-



Advocate Eliane de Modzelewska, who assisted Edoardo in the early stages that led to CERN, talked about he was always travelling, talking and never stopping.

of what this brings to humanity. It transcends political differences and fosters mutual understanding. I hope CERN and the broader scientific community will find ways to maintain these vital connections with all countries. I've always believed that fostering a collaborative and inclusive together and support each other along the way.

### future of CERN and particle physics?

I firmly believe that pursuing higher collision energies is essential. While the Large Hadron Collider has achieved remarkable successes, there's still much we haven't uncovered – especially regarding supersymmetry. Even - to all forms of cooperation and outside the participating though minimal supersymmetry does not apply, I remain convinced that supersymmetry might manifest in ways we haven't yet understood. Exploring higher energies could reveal supersymmetric particles or other new phenomena.

Like most European physicists, I support the initiative of the Future Circular Collider and starting with an elec-My father's ability to accept defeats and keep pushing tron-positron collider phase so to explore new frontiers at forward was key to his success. He was an exceptional per- two very different energy levels. However, if geopolitical technologies for muon colliders.

**Ugo Amaldi** first arrived at CERN as a fellow in September 1961. Then, for 10 years at the ISS in Rome, he opened two new lines of research: quasi-free electron scattering on nuclei and experimental technique, was a co-discoverer of the rise of the proton-proton cross-section with energy, measured the polarisation of muons produced by neutrinos, proposed the about 20 years, serving under several Director–Generals. She concept of a superconducting electron–positron linear collider, TERA Foundation for hadron therapy and as president emeritus of the National Centre for Oncological Hadrontherapy (CNAO) in Pavia. He continues his mother and father's legacy of authoring high-school physics textbooks used by millions of Italian pupils. His motto is: "Physics is beautiful and useful."

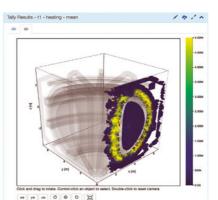
cultures and nations, and CERN's history is a testimony imental physics department. It has been edited for concision.

### Leading the industry in Monte Carlo simulations for accelerator applications

Particle-beam technology has wide applications in science and industry. Specifically, high-energy x-ray production is being investigated for FLASH radiotherapy, I4MeV neutrons are being produced for fusion energy production, and compact electron accelerators are being built for medicaldevice sterilisation. In each instance it is critical to guarantee that the particle beam is delivered to the end user with the correct makeup, and also to ensure that secondary particles created from scattering interactions are shielded from technicians and sensitive equipment. There is no precise way to predict the random walk of any individual particle as it encounters materials and alloys of different shapes within a complicated apparatus. Monte Carlo methods simulate the random paths of many millions of independent particles, revealing the tendencies of these particles in aggregate. Assessing shielding effectiveness is particularly challenging computationally, as the very nature of shielding means simulations produce low particle rate.

A common technique for shielding calculations takes these random walk simulations a step further by applying variance reduction techniques. Variance reduction techniques are a way of introducing biases in the simulation in a smart way to increase the number of particles emerging from the shielding, while still staying true to the total conservation of matter. In some regions within the shielding, particles are split into independent "daughter" particles with independent pathways but some common history. They are given a weight value, so the overall flux of parpossible to predict the behaviour of a one-in-a-million event without having to simulate one million particle trajectories. The performance of these techniques is shown in figure 2.

These kinds of simulations take on new importance with the global race most deeply shielded regions.



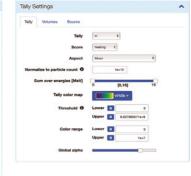


Fig. 1. RadiaSoft's Sirepo – OpenMC is a browser-based interface for running neutron and photon nte Carlo simulations

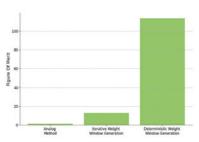


Fig. 2. Variance reduction techniques reduce the mputational cost of achieving convergence.

to develop fusion reactors for energy production. Materials will be exposed to conditions they've never seen before, mere feet from the fusion reactions that sustain stars. It is imperative to understand the neutron flux from fusion reactions and how they affect critical components in the sustained operation of fusion facilities if they are going to operate to meet our ever-growing energy needs. Monte Carlo simulation packages are capable of both distributed memory (MPI) and shared memory (OpenMP) parallel computation on the ticles is kept constant. In this way, it is world's largest supercomputers, engaging hundreds of thousands of cores at once. This enables simulations of billions of particle histories. Together with variance reduction, these powerful simulation tools enable precise estimation of particle fluxes in even the

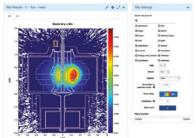


Fig. 3. Many 2D and 3D plotting options are available to gain insights from your simulations right away.

RadiaSoft offers browser-based modelling of neutron radiation transport with parallel computation and variance reduction capabilities running on Sirepo, their browser-based interface. Examples of fusion tokamak simulations can be seen above. RadiaSoft is also available for comprehensive consultation in x-ray production, radiation shielding and dose-delivery simulations across a wide range of applications.

#### RadiaSoft LLC

6525 Gunpark Dr. Ste. 370411 Boulder CO 80301-3346 Tel: 1-720-502-3928 Meet our expert, Stephen Coleman, coleman@radiasoft.net www.radiasoft.net



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# OPINION VIEWPOINT

### A call to engage

The secretary of the 2026 European strategy update, Karl Jakobs, talks about the strong community involvement needed to reach a consensus for the future of our field



Karl Jakobs is secretary of the 2026 update to the European strateay for particle physics. A professor at the University of Freiburg, Jakobs served as spokesperson of theATLAScollaboration from 2017 to 2021 and as chairman of the European Committee for Future Accelerators from 2021 to 2023.

It is anticipated that a number of proposals for largescale research projects will be submitted as input to the strategy

The European strategy for particle physics is the cornerstone of Europe's decision-making process for the longterm future of the field. In March 2024 CERN Council launched the programme for the third update of the strategy. The European Strategy Group (ESG) and the strategy secretariat for this update were established by CERN Council in June 2024 to organise the full process. Over the past few months, important aspects of the web pages at europeanstrategyupdate. web.cern.ch/welcome

will play an important role in distilling the community's scientific input September 2024, CERN Council appointed eight members of the PPG, four on the committee and four on the recommenthe Americas and Asia.

 $to form \, nine \, working \, groups \, to \, cover \, the \quad has \, put \, together \, a \, set \, of \, guidelines.$ full range of physics topics as well as the



Into the future À la recherche de l'Anti-Motti by artist Gianni Motti.

is available on the strategy web pages. parison of projects, we therefore request

ments must be no more than 10 pages nical description. long and provide a comprehensive and The Physics Preparatory Group (PPG) self-contained summary of the input. Additional information and details collected by March 2025 and to the can be submitted in a separate backup and scientific discussions at the open document that can be consulted on by communities are offered further opporsymposium in Venice in June 2025 into a the PPG if clarification on any aspect 'physics briefing book". At its meeting in is required. A backup document is not, however, mandatory.

A major component are inputs by recommendation of the scientific policy national high-energy physics communities, which are expected to be collected dation of the European Committee for individually by each country, and in some Future Accelerators (ECFA). In addition, cases by region. The information collected the PPG has one representative from from different countries and regions will CERN and two representatives each from be most useful if it is as coherent and outcome of the process will provide the uniform as possible when addressing the basis for the decision by CERN Council The strategy secretariat also proposed key issues. To assist with this, the ECFA

It is anticipated that a number of protechnology areas of accelerators, detec- posals for large-scale research projects tors and computing. The work of these will be submitted as input to the strategy groups will be co-organised by two con- process, including, but not limited to, veners, with one of them being a member particle colliders and collider detectors. of the PPG. In addition, an early-career These proposals are likely to vary in researcher has been appointed to each scale, anticipated timeline and technigroup to act as a scientific secretary. Both cal maturity. In addition to studying the the appointments of the co-conveners scientific potential of these projects, the and of the early-career researchers are ESG wishes to evaluate the sequence of by the broader community in the cur- ciated with delivery, and to understand rent update. The full composition of the how each project could fit into the wider PPG, the co-conveners and the scien- roadmap for European particle physics. Further reading tific secretaries of the working groups In order to allow a straightforward comeuropeanstrategyupdate.web.cern.ch

The strategy secretariat has also that all large-scale projects submit a process have been set up, and these are devised guidelines for input by the standardised set of technical data in described in more detail on the strategy community. Any submitted docu-addition to their physics case and tech-

> To allow the community to take into account and to react to the submissions content of the briefing book, national tunities for input: first ahead of the open symposium (see p11), with a deadline of 26 May 2025; and then ahead of the drafting session, with a deadline of 14 November 2025

> In this strategy process the community must converge on a preferred option for the next collider at CERN and identify a prioritised list of alternative options. The in 2027 or 2028 on the construction of the next large collider at CERN, following the High-Luminosity LHC. Areas of priority for exploration complementary to colliders and for other experiments to be considered at CERN and other laboratories in Europe will also be identified, as well as priorities for participation in projects outside Europe.

Given the importance of this process and its outcomes, I encourage strong community involvement throughout important to increase the engagement delivery steps and the challenges asso- to reach a consensus for the future of

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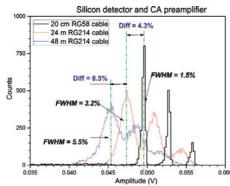


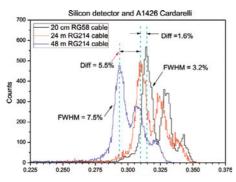


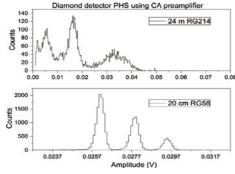
Since many decades CAEN provides complete range of High/Low Voltage Power Supply systems and Front-End/Data Acquisition modules for Nuclear and Particle Physics. CAEN instrumentation has demonstrated to be well suited for CERN highly demanding needs. A typical issue with high energy measurements is the need to avoid those front-end electronics is exposed to high level of radiation.

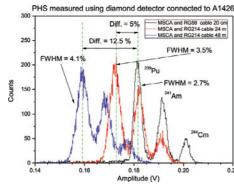
Recently a paper where CAEN Front-End/Data Acquisition modules were used has been published on Journal of Instrumentation [1]. In this paper the distance between solid state detectors (high-quality Diamond and Silicon detectors) and two CAEN preamplifiers, models A1426-Cardarelli fast amplifier (FA) and charge sensitive A1422 (CA), respectively, was varied up to 48 m and the spectrometric performance of detectors (Pulse Height Spectra PHS) of a multi-peaks alpha source (239Pu,241Am,236Cm) studied versus cable length. Two commercial double-shielded 50  $\Omega$  RG214 coaxial cables were used of 24 m and 48 m long, respectively. The used CAEN preamplifiers feature 50  $\Omega$  input impedance thus matching the RG214 cable impedance. PHS were recorded by CAEN DT5751 digitizer. All the measured PHS were compared in terms of energy resolution (FWHM) and peak amplitude with a reference PHS measured when the diamond/silicon preamplifier system was connected via a just 20 cm long RG58 coaxial cable. For the sake of the measurements both detectors and alpha source were placed inside a vacuum chamber kept at a pressure of 1\*10-6 mbar. The results are reported graphically in the next figures.

With A1426-Cardarelli FA connected to Silicon detector a reduction of the FWHM is observed already when using 20 cm long RG58 coaxial cable. This is not surprising since FA was designed for use with Diamond detectors and its gain was optimized for the small signal amplitude of Diamond detectors. When using Silicon detector, the reduction of the FWHM, for all the used cables, is more pronounced with A1426 with respect to A1422 preamplifier.









Diamond detector connected to CA preamplifier works well for the case of the 20 cm long RG58 cable. However, both FWHM and peak amplitude are strongly reduced already with 24 m of RG214 double screened cable indicating that this type of coupling is not recommended for long Diamond detector to CA distances (with 48 m long RG214 a very poorly resolved signal was measured).

The FA A1426 Cardarelli, in turn, works well with Diamond detector. The FWHM when Diamond detector is connected through 20 cm RG58 cable to A1426 is around 2.7%, comparable with that obtained using CA (1.5%). The effect of the long RG214 cable is to reduce of a few percent (with respect to 20 cm RG58) both FWHM and peak amplitude. The latter result is demonstrating the effectiveness of A1426 when connected to Diamond detector through long transmission lines (see last figure). Therefore, this effectiveness is verified only when high quality coaxial cable is used. To mention that using RG58 cables up to 5 m long to connect both detectors to CA and FA, respectively, very poor signals were recorded.

In conclusion, CAEN CA A1422 allows to perform nuclear spectroscopy using Silicon detectors also with long RG214 cables while CAEN FA A1426-Cardarelli works well with Diamond detectors. More complete results together with a description of A1426-Cardarelli fast amplifier performances and characteristics can be found in the references 1, 2 and 3.

#### References

 Study of the effect of detector to front-end electronics distance on the spectrometric performances of solidstate detectors. Authors: M. Angelone, M. Morichi and M. Pillon, Journal of Instrumentation, Volume 19, P08008, August 2024

### THE ARTICLE IS OPEN ACCESS https://doi.org/10.1088/17/8-0221/19/08/P08008

- 2. Development of a low-noise amplifier for neutron detection in harsh environment. Authors: M. Angelone, R. Cardarelli, L. Paolozzi and M. Pillon, Eur. Phys. J. Plus 129 (2014) 205.
- 3. https://www.caen.it/products/a1426-cardarelli/



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### OPINION INTERVIEW

### **Encounters with artists**

Over the past 10 years, Mónica Bello facilitated hundreds of encounters between artists and scientists as curator of the Arts at CERN programme. As she steps down, she shares her reflections on the symbiotic relationship between two disciplines united by insatiable curiosity.

### Why should scientists care about art? Throughout my experiences in the

laboratory, I have seen how art is an important part of a scientist's life. By being connected with art, scientists recognise that their activities are very embedded in contemporary culture. Science is culture. Through art and dialogues with artists, people realise how important science is for society and for culture in general. Science is an important cultural pillar in our society, and these interactions bring scientists meaning.

### Are science and art two separate cultures?

Today, if you ask anyone: "What is nature?" they describe everything in scientific terms. The way you describe things, the mysteries of your research: you are actually answering the questions that are present in everyone's life. In this case, scientists have a sense of responsibility. I think art helps to open this dialogue from science into society.

### Do scientists have a responsibility to communicate their research?

All of us have a social responsibility in everything we produce. Ideas don't belong to anyone, so it's a collective endeavour. I think that scientists don't have the responsibility to communicate the research themselves, but that their research cannot be isolated from society. I think it's a very joyful experience to see that someone cares about what you do.

### Why should artists care about science?

If you go to any academic institution, there's always a scientific component, very often also a technological one. A scientific aspect of your life is always present. This is happening because we're all on the same course. It's a consequence of this presence of

**Synergy** Mónica Bello, longtime curator of Arts at CERN, says that art helps to open a dialogue from science into society.

# Creativity and curiosity are the parameters and competencies that make up artists and scientists

science in our culture. Artists have an important role in our society, and they help to spark conversations that are important to everyone. Sometimes it might seem as though they are coming from a very individual lens, but in fact they have a very large reach and impact. Not immediately, not something that you can count with data, but there is definitely an impact. Artists open these channels for communicating and thinking about a particular aspect of science, which is difficult to see from a scientific perspective. Because in any discipline, it's amazing to see your activity from the eves of others

A few years back we did a little survey, and most of the scientists

thought that by spending time with artists, they took a step back to think about their research from a different lens, and this changed their perspective. They thought of this as a very positive experience. So I think art is not only about communicating to the public, but about exploring the personal synergies of art and science. This is why artists are so important.

### Do experimental and theoretical physicists have different attitudes towards art?

Typically, we think that theorists are much more open to artists, but I don't agree. In my experiences at CERN, I found many engineers and experimental physicists being highly theoretical. Both value artistic perspectives and their ability to consider questions and scientific ideas in an unconventional way. Experimental physicists would emphasise engagement with instruments and data, while theoretical physicists would focus on conceptual abstraction.

By being with artists, many experimentalists feel that they have the opportunity to talk about things beyond their research. For example, we often talk about the "frontiers of knowledge". When asked about this, experimentalists or theoretical physicists might tell us about something other than particle physics – like neuroscience, or the brain and consciousness. A scientist is a scientist. They are very curious about everything.

### Do these interactions help to blur the distinction between art and science? Well, here I'm a bit radical because I

Well, here I'm a bit radical because I know that creativity is something we define. Creativity and curiosity are the parameters and competencies that make up artists and scientists. But to become a scientist or an artist you

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Small details... **Great differences** 

















#### **OPINION INTERVIEW**

need years of training - it's not that you can become one just because you are a curious and creative person.

Not many people can chat about particle physics, but scientists very often chat with artists. I saw artists speaking for hours with scientists about the Higgs field. When you see two people speaking about the same thing, but with different registers, knowledge and background, it's a precious moment.

When facilitating these discussions between physicists and artists, we don't speak only about physics, but about everything that worries them. Through that, grows a sort of intimacy that often becomes something else: a friendship. This is the point at which a scientist stops being an information point for an artist and becomes someone who deals with big questions alongside an artist - who is also a very knowledgeable and curious person. This is a process rich in contrast, and you get many interesting surprises out of these interactions

But even in this moment, they are still artists and scientists. They don't become this blurred figure that can do anything.

#### Can scientific discovery exist without art?

That's a very tricky question. I think that art is a component of science, therefore science cannot exist without art - without the qualities that the artist and scientist have in common. To advance science, you have to create a question that needs to be answered experimentally.

#### Did discoveries in quantum mechanics affect the arts?

Everything is subjected to quantum mechanics. Maybe what it changed was an attitude towards uncertainty: what we see and what we think is there. There was an increased sense of doubt and general uncertainty in the arts.

#### Do art and science evolve together or separately?

I think there have been moments of convergence - you can clearly see it in any of the avant garde. The same applies to literature; for example, modernist writers showed a keen interest in science. Poets such as T S Eliot approached poetry with a clear resonance of the first scientific revolutions of the century. There are references to the contributions of

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**Evolution** Art and science is inextricably intertwined, as depicted in this work of art – Chroma VII – at the  $CERN Science \ Gateway. \ It was inspired \ by \ the \ connections \ between \ space, energy \ and \ matter.$ 

Faraday, Maxwell and Planck. You can tell these artists and poets were informed and eager to follow what science was revealing about the world.

You can also note the influence of science in music, as physicists get a better understanding of the physical aspects of sound and matter. Physics became less about viewing the world through a lens, and instead focused on the invisible: the vibrations of matter, electricity, the innermost components of materials. At the end of the 19th and 20th centuries, these examples crop up constantly. It's not just representing the world as you see it through a particular lens, but being involved in the phenomena of the world and these uncensored realities.

From the 1950s to the 1970s you can see these connections in every single moment. Science is very present in the work of artists, but my feeling is that we don't have enough literature about it. We really need to conduct more research on this connection between humanities and science.

#### What are your favourite examples of art influencing science?

Feynman diagrams are one example Feynman was amazing - a prodigy. Many people before him tried to represent things that escaped our intuition visually and failed. We also have the Pauli Archives here at CERN. Pauli was not the most popular father of quantum mechanics, but he was determined to not only understand mathematical equations but to visualise them, and share them with his friends and colleagues. This sort of endeavour goes beyond just writing - it is about the possibility of creating a tangible experience. I think scientists do that all the time by building machines, and then by trying to understand these machines statistically. I see that in the laboratory constantly, and it's very revealing because usually people might think of these statistics as something no one cares about - that the visuals are clumsy and nerdy. But they're not.

Even Leonardo da Vinci was known as a scientist and an artist, but his anatomical sketches were not discovered until hundreds of years after his other works. Newton was also paranoid about expressing his true scientific theories because of the social standards and politics of the time. His views were unorthodox, and he did not want to ruin his prestigious reputation.

Today's culture also influences how we interpret history. We often think of Aristotle as a philosopher, yet he is also recognised for contributions to natural history. The same with Democritus,

whose ideas laid foundations for scientific thought

So I think that opening laboratories to artists is very revealing about the influence of today's culture on science.

#### When did natural philosophy branch out into art and science?

I believe it was during the development of the scientific method: observation, analysis and the evolution of objectivity. The departure point was definitely when we developed a need to be objective. It took centuries to get where we are now, but I think there is a clear division: a line with philosophy. natural philosophy and natural history on one side, and modern science on the other. Today, I think art and science have different purposes. They convene at different moments, but there is always this detour. Some artists are very scientific minded, and some others are more abstract, but they are both bound to speculate massively.

For example, at our Arts at CERN programme we have had artists who were interested in niche scientific aspects. Erich Berger, an artist from Finland, was interested in designing a detector, and scientists whom he met kept telling him that he would need to calibrate the detector. The scientist and the artist here had different goals. For the scientist, the most important thing is that the detector has precision in the greatest complexity. And for the artist, it's not. It's about the process of creation, not the analysis.

#### Do you think that science is purely an objective medium while art is a subjective one?

No. It's difficult to define subjectivity and objectivity. But art can be very objective. Artists create artefacts to convey their intended message. It's not that these creations are standing alone without purpose. No, we are beyond that. Now art seeks meaning that is, in this context, grounded in scientific and technological expertise.

#### How do you see the future of art and science evolving?

There are financial threats to both disciplines. We are still in this moment where things look a bit bleak. But I think our programme is pioneering, because many scientific labs are developing their own arts programmes inspired by the example of Arts at

It's really good news for everyone that labs want to include non-scientists

CERN. This is really great, because unless you are in a laboratory, you don't see what doing science is really about. We usually read science in the newspapers or listen to it on a podcast - everything is very much oriented to the communication of science, but making science is something very specific. It's really good news for everyone that laboratories want to

include non-scientists. Arts at CERN works mostly with visual artists, but you could imagine filmmakers, philosophers, those from the humanities, poets or almost anyone at all, depending on the model that one wants to create in the lab.

**OPINION INTERVIEW** 

Interview by Alex Epshtein editorial assistant.



Feynman was

amazing – a

prodigy. He

represented

things that

escaped our

intuition

visually

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# A match for the pressure

The SEN range of pressure sensors from KOBOLD Messring GmbH, based in Hofheim, Germany, are extremely compact and can be used in a variety of applications. The approved measuring principle uses a thick-film ceramic measuring cell, has excellent repeatability and is very reliable. Automatic temperature compensation provides great accuracy, and as these robust devices are so well protected against overloading and cope very well with pressure peaks, they are highly suitable for use in hydraulic systems. Other typical applications are in compressor and pump engineering, and cooling circuits.

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# **OPINION REVIEWS**

### **Beyond Bohr and Einstein**

**Quantum Drama** 

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By Jim Baggott and John L Heilbron

Oxford University Press

When I was an undergraduate physics student in the mid-1980s, I fell in love with the philosophy of quantum mechanics. I devoured biographies of the greats of early-20th-century atomic physics - physicists like Bohr, Heisenberg, Schrödinger, Pauli, Dirac, Fermi and Born. To me, as I was struggling with the formalism of quantum mechanics, there seemed to be something so exciting, magical even, about that era, particularly those wonder years of the mid-1920s when its mathematical framework was being developed and the secrets of the quantum world were revealing themselves.

I went on to do a PhD in nuclear reaction theory, which meant I spent most of my time working through mathematical derivations, becoming familiar with S-matrices, Green's functions and scattering amplitudes, scribbling pages of angular-momentum algebra and coding in Fortran 77. And I loved that stuff. There certainly seemed to be little time for worrying about what was really going on inside atomic nuclei. Indeed, I was learning that even the notion of something "really going on" was a vague one. My generation of theoretical physicists were still being very firmly told to "shut up and calculate", as many adherents of the Copenhagen school of quantum mechanics were keen to advocate. To be fair, so much progress has been made over the past century, in nuclear and particle physics, quantum optics, condensed-matter physics and quantum chemistry, that philosophical issues were seen as an unnecessary distraction. I recall one senior colleague, frustrated by my abiding interest in interpretational matters, admonishing me with: "Jim, an electron is an electron is an electron. Stop trying to say more about it. "And there certainly seemed to bevery little in the textbooks I was reading about unresolved issues arising from such topics as the EPR (Einstein-Podolsky-Rosen) paradox and the measurement problem, let alone any analysis of the work



One hundred years of insights Jim Baggott and John Heilbron don't neglect later quantum pioneers like John Bell (pictured).

of Hugh Everett and David Bohm, who were regarded as mavericks. The Copenhagen hegemony ruled supreme.

What I wasn't aware of until later in my career was that a community of physicists had indeed continued to worry and think about such matters. These physi- to finally emerge from the shadows into cists were doing more than just debating mainstream debate again. and philosophising - they were slowly advancing our understanding of the **A new narrative** quantum world. Experimentalists such So, what makes Quantum Drama stand a lot about how we are only now acknowledging their contribution. Meanwhile, - even advanced undergraduate ones should contain their new insights.

All of which brings me to Quantum as such, will probably be of most inter-

tries to be all things. On occasion, it has wonderful biographical detail, often of less well-known but highly deserving characters. It is also full of wit and new insights. But then sometimes it can get mired in technical detail, such as in the lengthy descriptions of the different Bell tests, which I imagine only professional physicists are likely to fully appreciate.

Having said that, the book is certainly timely. This year the world celebrates the centenary of quantum physics, since the publication of the momentous papers of Heisenberg and Schrödinger on matrix and wave mechanics, in 1925 and 1926, respectively. Progress in quantum information theory and in the development of new quantum technologies is also gathering pace right now, with the promise of quantum computers, quantum sensing and quantum encryption getting ever closer. This all provides an opportunity for the philosophy of quantum mechanics

as Alain Aspect, John Clauser and Anton out from other books that retell the story Zeilinger were devising ingenious exper- of quantum mechanics? Well, I would iments in quantum optics - all three of say that most historical accounts tend whom were only awarded the Nobel Prize to focus only on that golden age between for their work on tests of John Bell's 1900 and 1927, which came to an end at famous inequality in 2022, which says the Solvay Conference in Brussels and those well-documented few days when Einstein and Bohr had their debate about theorists such as Wojciech Zurek, Erich what it all means. While these two giants Joos, Deiter Zeh, Abner Shimony and of 20th-century physics make the front Asher Peres, to name just a few, were cover of the book, Quantum Drama takes formalising ideas on entanglement and the story on beyond that famous condecoherence theory. It is certainly high ference. Other accounts, both popular time that quantum-mechanics textbooks and scholarly, tend to push the narrative that Bohr won the argument, leaving generations of physicists with the idea that the interpretational issues Drama, a new popular-science book and had been resolved - apart that is, from collaboration between the physicist and the odd dissenting voices from the likes science writer Jim Baggott and the late of Everett or Bohm who tried, unsuchistorian of science John L Heilbron. In cessfully it was argued, to put a spanterms of level, the book is at the higher ner in the Copenhagen works. All the end of the popular-science market and, real progress in quantum foundations after 1927, or so we were told, was in the est to, for example, readers of CERN development of quantum field theories, Courier. If I have a criticism of the book such as QED and QCD, the excitement it is that its level is not consistent. For it of high-energy physics and the birth  $\triangleright$ 

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at centre stage. Quantum Drama takes up Debate to the Riddle of Entanglement. the story after 1927, showing that there has been a lively, exciting and ongoing

of the Standard Model, with the likes of In fact, the period up to Solvay 1927 is all **The Bohr**-Murray Gell-Mann and Steven Weinberg dealt with in Act I of the book. The sub- **Einstein debate** replacing Heisenberg and Schrödinger title puts it well: From the Bohr-Einstein

All in all, Quantum Drama delivers something remarkable, for it shines a and kicking dispute over what it all means, long after light on all the muddle, complexity and the death of those two giants of physics. confusion surrounding a century of

is still very much alive

debate about the meaning of quantum mechanics and the famous "Copenhagen spirit", treating the subject with thoroughness and genuine scholarship, and showing that the Bohr–Einstein debate is still very much alive and kicking.

process, gain a deeper understanding of

Massive gravity, the focus of this part of

Jim Al-Khalili University of Surrey.

#### The Beauty of Falling

#### By Claudia de Rham

Princeton University Press

A theory of massive gravity is one in which the graviton, the particle that is believed to mediate the force of gravity, has a small mass. This contrasts with general relativity, our current best theory of gravity, which predicts that the graviton is exactly massless. In 2011, Claudia de Rham (Imperial College London), Gregory Gabadadze (New York University) and Andrew Tolley (Imperial College London) revitalised interest in massive gravity by uncovering the structure of the best possible (in a technical sense) theory of massive gravity, now known as the dRGT theory, after these authors.

Claudia de Rham has now written a popular book on the physics of gravity. The Beauty of Falling is an enjoyable and relatively quick read: a first-hand and personal glimpse into the life of a theoretical physicist and the process of discovery.

De Rahm begins by setting the stage with the breakthroughs that led to our current paradigm of gravity. The Michelson-Morley experiment and special relativity, Einstein's description of gravity as geometry leading to general relativity and its early experimental triumphs, black holes and cosmology are all described in accessible terms using familiar analogies. De Rham grips the reader by weaving in

Space Oddities: The Mysterious **Anomalies Challenging Our** Understanding of the Universe

#### By Harry Cliff

Penguin Random House

Space Oddities takes readers on a journey through the mysteries of modern physics, from the smallest subatomic particles to the vast expanse of stars and space. Harry Cliff - an experimental particle physicist at Cambridge University - unravels some of the most perplexing anomalies chalbehind-the-scenes scoops from eight difstories concern lepton universality and the magnetic moment of the muon.

2 THE BEAUTY

a deeply personal account of her own life the process of thought and discovery in and upbringing, illustrating what inspired theoretical physics. When reading the her to study these ideas and pursue a latest outrageously overhyped clickbait career in theoretical physics. She has led headlines coming out of the world of an interesting life, from growing up in fundamental physics, it is easy to get the various parts of the world, to learning to wrong impression about what theoretical dive and fly, to training as an astronaut physicists do. This part of the book illusand coming within a hair's breadth of trates how ideas come about: by asking becoming one. Her account of the train-questions of established theories and tug-

this latter discovery underlies much of the understanding of the structure of general interest in massive gravity; there remains relativity. And, as has occurred countless the lingering possibility that general rel-times before with intriguing mathematativity may need to be modified to account ical structures, it may ultimately prove for the observed accelerated expansion. useful for something completely differ-

In the second part of the book, de Rham ent and unforeseen – something that its warns us that we are departing from the originators did not have even remotely realm of well tested and established in mind. Here, de Rahm offers invaluaphysics, and entering the world of more ble insights both into uncovering a new uncertain ideas. A pet peeve of mine is theoretical structure and what happens popular accounts that fail to clearly make next, as the results are challenged and this distinction, a temptation to which built upon by others in the community. this book does not succumb.

Here, the book offers something that Kurt Hinterbichler Case Western

ing and selection process for European ging on their loose threads, we uncover Space Agency astronauts is fascinating, new mathematical structures and, in the and worth the read in its own right. Moving closer to the present day, de the structures we have. Rahm discusses the detection of gravitational waves at gravitational-wave obserthe book, is a prime example: by starting vatories such as LIGO, the direct imaging with a basic question, "does the graviton of black holes by the Event Horizon Tel- have to be massless?", a new structure was escope, and the evidence for dark matter revealed. This structure may or may not and the accelerating expansion of the uni- have any direct relevance to gravity in verse with its concomitant cosmological the real world, but even if it does not, our constant problem. As de Rham explains, study of it has significantly enhanced our

is hard to find: a first-hand account of Reserve University.

Theoretical predictions have demonstrated an extremely precise value for the muon's magnetic moment, experimentally verified to an astonishing 11 significant figures. Over the last few years, however, experimental measurements have suggested a slight discrepancy - the devil lying in the 12th digit. 2021 measurements at Fermilab disagreed with theory predictions at  $4\sigma$ . Not enough to cause a "scientific earthquake", as Cliff puts it, but enough to suggest that new physics might be at play.

Just as everything seemed to be edging lenging the Standard Model (SM), with towards a new discovery, Cliff introduces the "villains" of the piece. Groundbreakferent experiments. The most intriguing ing lattice-QCD predictions from the Budapest-Marseille-Wuppertal collaboration were published on the same day



as a new measurement from Fermilab If correct, these would destroy the anomaly by contradicting the data-driven theory consensus. ("Yeah, bullshit," said one experimentalist to Cliff when put to him that the timing wasn't intended to steal the experiment's thunder.) The situation is still unresolved, though many new theoretical predictions have been made and a new theoretical consensus is imminent (see p21). Regardless of the outcome, Cliff emphasises that this research will pave the way for future discoveries, and none of it should be taken for granted even if the anomaly disappears.

"One of the challenging aspects of being part of a large international project is that your colleagues are both collaborators and competitors," Cliff notes. ▷

"When it comes to analysing the data with One day we each research group will fight to claim ownership of the most interesting topics."

This spirit of spurring collaboratorcompetitors on to greater heights of precision is echoed throughout Cliff's **clutches of** own experience of working in the LHCb the SM collaboration, where he studies "lepton universality". All three lepton flavours electron, muon and tau - should interact almost identically, except for small differences due to their masses. However, over the past decade several experimental results suggested that this theory might not hold in B-meson decays, where muons seemed to be appearing less frequently than electrons. If confirmed, this would point to physics beyond the SM.

Having been involved himself in a complementary but less sensitive analysis of B-meson decay channels involving strange quarks, Cliff recalls the emotional rollercoaster experienced by some of the key protagonists: the "RK" team from Imperial College London. After a year of rigorous testing, RK unblinded a sanity check of their new computational toolkit: a reanalysis of the prior measurement that yielded a perfectly consistent R value of 0.72 with an uncertainty of about 0.08, upholding a 3σ discrepancy. Now was the time to put the data collected since then through the same pasta machine: if it agreed, the tension between the SM and their overall measurement would cross the 5σ threshold. After an anxious wait while the numbers were crunched, the team received the results for the new data: 0.93 with an uncertainty of 0.09.

"Dreams of a major discovery evaporated in an instant," recalls Cliff. "Anyone who saw the RK team in the CERN cafeteria that day could read the result from their faces." The lead on the RK team, Mitesh Patel, told Cliff that they felt "emotionally train wrecked".

With both results combined, the ratio averaged out to 0.85 ± 0.06, just shy of  $3\sigma$  away from unity. While the experimentalists were deflated, Cliff notes that for theorists this result may have been more exciting than the initial anomaly, as it was easier to explain using new particles or forces. "It was as if we were spying the footprints of a great, unknown beast as it crashed about in a dark jungle," writes Cliff.

Space Oddities is a great defence of irrepressible experimentation. Even "failed" anomalies are far from useless: if they evaporate, the effort required to investigate them pushes the boundaries of experimental precision, enhances collaboration between scientists across

right mistake and escape the claustrophobic

excitement of near breakthroughs, the the claustrophobic clutches of the SM. heartbreak of failed experiments, and the dynamic interactions between theoretical myths that physicists are cold, calculating figures working in isolation, Cliff sheds light on a community driven by curiosity, Alex Epshtein CERN.

the world, and refines theoretical frame- ambition and (healthy) competition. His the ultimate goal of making discoveries, might make the works. Through retellings and interviews, book is a story of hope that one day we Cliff helps the public experience the might make the right mistake and escape

> "I've learned so much from my mistakes," read a poster above Cliff's and experimental physicists. Thwarting undergraduate tutor's desk. "I think I'll make another."

### **ETH** zürich

#### **Professor** of Accelerator Physics





→ The Department of Physics (www.phys.ethz.ch) at ETH Zurich and the Center for Accelerator Science and Engineering (CAS) at the Paul Scherrer Institute (PSI) invite applications for a joint professorship in Accelerator

→ The new professor will lead the PSI department Accelerator Technologies within the Center for Accelerator Science and Engineering (CAS). She/he will conduct forefront research in accelerator science and technology and will engage in R&D projects for the PSI accelerator facilities and for the Swiss Accelerator Research and Technology Program (CHART). The broad diversity of PSI facilities with advanced light sources, advanced muon and neutron sources, and specialized accelerators for medical applications offers a range of opportunities for frontier research on particle accelerators.

→ At ETH Zurich, the Institute for Particle Physics and Astrophysics (IPA) will host the professorship, ensuring fruitful exchanges and synergies with particle physics, which remains the main driver of new developments in accelerator technology. The new professor will participate in the teaching activities of the ETH Physics Department, in particular with specialized courses on accelerator physics. Courses at Master's and doctoral level are taught in English. Supervision of Master's and doctoral students is also expected.

→ The successful candidate for this position will be an internationally renowned scientist in a field related to accelerator physics. She/he will have extensive experience in accelerator science and technology development and implementation for cutting-edge accelerator facilities, along with excellent leadership and teaching skills.

→ ETH Zurich is an equal opportunity and family-friendly employer, values diversity, and is responsive to the needs of dual-career couples.

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-> Applications should include a curriculum vitae, a list of publications, a statement of future research and teaching interests, a description of the leadership philosophy, a description of the three most important achievements, and a certificate of the highest degree. The letter of application should be addressed to the President of ETH Zurich, Prof. Dr. Joël Mesot. The closing date for applications is 23 March 2025.

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# **PEOPLE CAREERS**

### Game on for physicists

Raphael Granier de Cassagnac discusses opportunities for particle physicists in the gaming industry.

"Confucius famously may or may not have said: 'When I hear, I forget. When I see, I remember. When I do, I understand.' And computer-game mechanics can be inspired directly by science. Study it well, and you can invent game mechanics that allow you to engage with and learn about your own reality in a way you can't when simply watching films or reading books."

So says Raphael Granier de Cassagnac, a research director at France's Centre national de la recherche scientifique and member of the CMS collaboration at the LHC. Granier de Cassagnac is also the creative director of Exographer, a science-fiction computer game that draws on concepts from particle physics and is available on Steam, Switch, PlayStation 5 and Xbox.

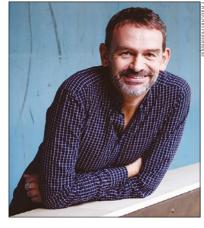
"To some extent, it's not too different from working at a place like CMS, which is also a super complicated object," explains Granier de Cassagnac. Developing a game often requires graphic artists, sound designers, programmers and science advisors. To keep a detector like CMS running, you need engineers, computer scientists, accelerator physicists and funding Creative direction Raphael Granier de agencies. And that's to name just a few. Even Cassagnac is a research director at CNRS and if you are not the primary game designer or creative director of Exographer, a computer principal investigator, understanding the game that uses concepts from particle physics. fundamentals is crucial to keep the project running efficiently.

#### Root skills

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Most physicists already have some familiarity with structured programming and data handling, which eases the transition into game Structure, coherence and the ability to guide development. Just as tools like ROOT and Geant 4 an audience through complex information are serve as libraries for analysing particle colli- also required. sions, game engines such as Unreal, Unity or Godot provide a foundation for building games. game mechanics.

mind, which helps when it comes to organising me came naturally." a game's software," explains Granier de Casand you never have to code anything super com-





sections to optimise the engine itself."

While coding is an essential skill for game production, it is not enough to create a compelling game. Game design demands storytelling, character development and world-building.

focus more on the adventure or world-building," Prebuilt functionalities are used to refine the says Granier de Cassagnac. "I've always enjoyed reading science fiction and playing role-playing "Physicists are trained to have an analytical games like Dungeons and Dragons, so writing for

sagnac. "The engine is merely one big library, key skills, as it is increasingly rare for developers to create games independently. Universities and plicated, you just need to know how to use the startup incubators can provide valuable support building blocks you have and code in smaller through funding and mentorship. Incubators Interview by Alex Epshtein editorial assistant.

### Though challenging to break into, opportunity abounds for those willing to upskill

can help connect entrepreneurs with industry experts, and bridge the gap between scientific research and commercial viability.

"Managing a creative studio and a company, as well as selling the game, was entirely new for me," recalls Granier de Cassagnac. "While working at CMS, we always had long deadlines and low pressure. Physicists are usually not prepared for the speed of the industry at all. Specialised offices in most universities can help with valorisation - taking scientific research and putting it on the market. You cannot forget that your academic institutions are still part of your support network."

The industry is fiercely competitive, with more games being released than players can consume, but a well-crafted game with a unique vision can still break through. A common mistake made by first-time developers is releasing their game too early. No matter how innovative the concept or engaging the mechanics, a game riddled with bugs frustrates players and damages its reputation. Even with strong marketing, a rushed release can lead to negative reviews and refunds - sometimes sinking a project entirely.

"In this industry, time is money and money is time," explains Granier de Cassagnac. But though challenging to break into, opportunity abounds for those willing to upskill, with the gaming industry worth almost \$200 billion a year and reaching more than three billion players worldwide by Granier de Cassagnac's estimation. The most important aspects for making a successful game are originality, creativity, "Some games are character-driven, others marketing and knowing the engine, he says.

"Learning must always be part of the process; without it we cannot improve," adds Granier de Cassagnac, referring to his own upskilling for the company's next project, which will be even more ambitious in its scientific coverage. "In the next Entrepreneurship and collaboration are also game we want to explore the world as we know it, from the Big Bang to the rise of technology. We want to tell the story of humankind."

#### Appointments and awards



#### Interim director for Fermilab On 13 January, experimental particle physicist Young-Kee Kim was appointed interim director at Fermilab, taking over from Lia Merminga. Kim brings extensive experience to the position, having served as Fermilab's deputy director from 2006 to 2013, as well as co-spokesperson of the Tevatron's CDF experiment from 2004 to 2006. In addition to her responsibilities at Fermilab, Kim is Michelson Distinguished

Service Professor of Physics at the

#### Going down in history

University of Chicago.

Michael Riordan (Santa Cruz Institute for Particle Physics) has been awarded the 2025 Abraham Pais Prize for History of Physics by the American Physical Society. He is recognised for his "significant contributions to documenting the history of post-World War II physics, particularly in areas such as the discovery of quarks, the invention and development of the transistor, and the search for the Higgs boson". The award also highlights his work to make particle physics accessible to both academic



and general audiences. Riordan has authored multiple books, including The Hunting of the Quark and Crystal Fire: The Birth of the Information Age, co-authored with Lillian Hoddeson, on the invention of the transistor. The award includes a \$10,000 prize.

#### New STFC chair

Michele Dougherty, space physicist at Imperial College London, has been appointed executive chair of the Science and Technology Facilities Council (STFC) starting in January, succeeding Mark Thomson, who has been appointed Director-General designate of CERN (CERN Courier January/February 2025 p38). Dougherty has led uncrewed exploratory missions to Saturn and Jupiter, served as the principal investigator for the magnetometer instrument on the Cassini-Huygens mission to Saturn, and currently holds the same role for the Jupiter Icv Moons Explorer of the European Space Agency, which launched in April 2023 (CERN Courier



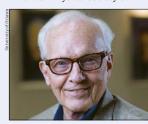
January/February 2025 p26). Dougherty also succeeds Thomson as one of the UK's two delegates to the CERN Council, alongside Shabana Haque of the Department for Science, Innovation and Technology

#### National Medal for Freedman Wendy Freedman, of the University

of Chicago, was awarded the National Medal of Science on 3 January, in recognition of her research on the Hubble constant (p28). As part of the Telescope Key Project in 2001, Freedman's team made a refined measurement of the Hubble constant, helping to establish the age of the universe at about 13.7 billion years old. Freedman initiated the Giant Magellan Telescope project, now one of the world's largest optical telescopes, and served as chair of its board of directors from 2003 to 2015. The award was presented in the Eisenhower Executive Office Building of the White House.

#### Every (atto)second counts

Experimental physicist Paul Corkum (University of Ottawa) has been awarded the American Physical Society's



2025 APS Medal for Exceptional Achievement in Research for his work in attosecond science. Corkum combined concepts from plasma physics, strong-field spectroscopy and electron scattering, to create a new form of strong-field physics, which spans atomic to solid-state physics. Notably, at the Joint Attosecond Science Laboratory, Corkum and his colleagues captured an image of an electron orbiting an atom using ultrafast light pulses. This discovery enabled the visualisation of electron motion at attosecond (a billionth of a billionth of a second) timescales, which was previously impossible.

#### New leadership at FAIR and GSI

Experimental physicist Thomas Nilsson has been appointed scientific managing director of GSI Helmholtzzentrum für Schwerionenforschung and of the Facility for Antiproton and Ion Research (FAIR). which is under construction at the German laboratory. Before starting his position in Darmstadt, Nilsson was head of the physics department at Chalmers University of Technology in Gothenburg. He is a member of the physics class of the prestigious Royal Swedish Academy of Sciences, which is responsible for selecting Nobel Prize laureates. Nilsson will play a leading role in shaping FAIR. He succeeds Paolo Giubellino, the president of the Scientific Commission at INFN, Italy.

#### Kanungo to TRIUMF

TRIUMF welcomes former Saint Mary's University professor Rituparna Kanungo as Physical Sciences Division director. Kanungo will direct the division's six departments (Particle Physics, Nuclear Physics, Molecular and Materials Sciences, Theory, Scientific Computing and Science Technology) to advance operational excellence, support TRIUMF's researchers, students and users, and explore new ways to leverage the Canadian lab's infrastructure. A nuclear physicist with broad experience



at TRIUMF, RIKEN in Japan and GSI in Germany, Kanungo is the recipient of numerous awards and recognitions, including fellowships of the Canadian Association of Physicists and the American Physical Society, the Alexander von Humboldt Fellowship, and the CAP-TRIUMF Vogt Medal.

#### Swiss Academy appoints Beck

Hans Peter Beck (University of Bern) has been appointed a full member of the Swiss Academy of Engineering Sciences (SATW) in recognition of his longstanding contributions to the ATLAS collaboration, and his election as outreach coordinator in 2024. Beck previously served as chair of the International Particle Physics Outreach Group and was president of the Swiss Physical Society. He has also spearheaded several young-talent programmes, and been involved in numerous knowledge-transfer initiatives, including co-authoring The Economics of Big Science in 2021. He plans to contribute to SATW through fundamental research, innovation and technology transfer, as well as building bridges between science, industry and politics.

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#### PEOPLE OBITUARIES

# PEOPLE OBITUARIES

### A physicist of extraordinary creativity

Guido Barbiellini Amidei, who passed away on 15 November 2024, made fundamental contributions to both particle physics and astrophysics.

In 1959 Guido earned a degree in physics from Rome University with a thesis on electron bremsstrahlung in monocrystals under Giordano Diambrini, a skilled experimentalist and excellent teacher. Another key mentor was Marcello Conversi, spokesperson for one of the detectors at the Adone electronpositron collider at INFN Frascati, where Guido became a staff member and developed the first luminometer based on small-angle electronpositron scattering - a technique still used today. Together with Shuji Orito, he also built the first double-tagging system for studying gamma-ray collisions.

Guido later spent several years at CERN, collaborating with Carlo Rubbia, first on the study of K-meson decays at the Proton Synchro- Guido Barbiellini had an insatiable scientific tron and then on small-angle proton-proton curiosity and passion for physics. scattering at the Intersecting Storage Rings. field for him: neutrino-electron scattering, during the transition to LEP's higher-energy approved during this period. Launched in 2007, a fundamental but extremely rare phenomenon known from a handful of events seen in students and senior colleagues Gargamelle. To distinguish electromagnetic showers from hadronic ones, the CHARM collaboration built a "light" calorimeter made of he co-organised a workshop, with Konrad 150 tonnes of Carrara marble. From 1979 to Kleinknecht and Walter Hoogland, exploring 1983, 200 electron–neutrino scattering events  $\phi$  the possibility of an electron–positron  $\phi$ -factory

Amaldi: "Why don't we start our own collaboration for LEP instead of joining others?" This collider in Frascati. suggestion sparked the genesis of the DELPHI collaboration, in which Guido played a pivotal Firstly, he became a professor at the University as director of INFN Trieste. Intellectually free role in defining its scientific objectives and overseeing the construction of the barrel electromagnetic calorimeter. He also contributed ter, published in Nature in collaboration with dedication to nurturing young talents. He will significantly to the design of the luminosity Giuseppe Cocconi, in which it was established be deeply missed. monitors. Above all, Guido was a constant that neutrinos have a charge smaller than 10-1 driving force within the experiment, offer- elementary charges. Thirdly, Guido presented His friends and colleagues.

Iosif Khriplovich 1937-2024 **Electroweak** connections

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Khriplovich passed away on 26 September 2024, professorial position at Petersburg University aged 87. Born in 1937 in Ukraine to a Jewish and was a corresponding member of the Russian family, he graduated from Kiev University and Academy of Sciences from 2000.

In 1974 he proposed an experiment in a new ing innovative ideas for fundamental physics co-principal investigator, was conceived and

phase, and engaging tirelessly with both young

extended to CP symmetry violation. In 1989 to study CP violation in neutral kaon decays. In 1980 Guido remarked to his friend Ugo Two of his papers, with Claudio Santoni, laid environment that enriched all the projects he the groundwork for constructing the DAPNE took part in. He was not only a brilliant physi-

> of Trieste. Secondly, the detection of neutrinos produced by Supernova 1987A inspired a let- and commitment with grace and a profound

moved to the newly built Academgorodok in Siberia. From 1959 to 2014 he was a prominent Institute of Nuclear Physics. He combined his where he also held a professorship in 1983-2009. Renowned Soviet/Russian theorist Iosif In 2014 he moved to St. Petersburg to take up a

a new idea to mount silicon detectors (which he had encountered through work done in DELPHI by Bernard Hyams and Peter Weilhammer) on the International Space Station or a spacecraft to detect cosmic rays and their showers, which led to a seminal paper.

At the beginning of the 1990s, an international collaboration for a large NASA space mission focused on gamma-ray astrophysics (initially named GLAST) began to form, led by SLAC scientists. Guido was among the first proponents and later was the national representative of many INFN groups. The mission, later renamed Fermi, was launched in 2008 and continues to produce significant insights in topics ranging from neutron stars and black holes to darkmatter annihilation.

Beyond GLAST, Guido was captivated by the application of silicon sensors to a new programme of small space missions initiated by the Italian Space Agency. The AGILE gammaray astrophysics mission, for which Guido was AGILE made numerous discoveries over nearly 17 years, including identifying the origin of had-Guido's insatiable scientific curiosity also ronic cosmic rays in supernova remnants and discovering novel, rapid particle acceleration phenomena in the Crab Nebula

Guido's passion for physics made him inexhaustible. He always brought fresh insights and thoughtful judgments, fostering a collaborative cist but also a true gentleman of calm and mild The year 1987 was a turning point for Guido. manners, widely appreciated as a teacher and and always smiling, he conveyed determination

In a paper published in 1969, Khriplovich was the first to discover the phenomenon member of the theory department at the Budker of anti-screening in the SU(2) Yang-Mills theory by calculating the first loop correction research with teaching at Novosibirsk University, to the charge renormalisation. This immediately translates into the crucial first coefficient (-22/3) of the Gell-Mann-Low function and asymptotic freedom of the theory.

Regretfully, Khriplovich did not follow this interpretation of his result even after >

the key SLAC experiment on deep inelastic scattering and its subsequent partonic interpretation by Feynman. The honour of the discovery of asymptotic freedom in QCD went to three authors of papers published in 1973, who seemingly did not know of Khriplovich's calculations.

In the early 1970s, Khriplovich's interests turned to fundamental questions on the way towards the Standard Model. One was whether the electroweak theory is described by the Weinberg-Salam model, with neutral currents interacting via Z bosons, or the Georgi-Glashow model without them. While neutrino scattering on nucleons was soon confirmed, the electron interaction with nucleons was still unchecked. One practical way to find out was to use atomic spectroscopy to look for any mixing between states of opposite parity. Actively entering He became engaged in this area, Khriplovich and his students worked out quantitative predictions for the rotation of laser polarisation due to the weak interaction between electrons and nucleons. Their predictions were triumphantly confirmed in were interested in them experiments, firstly by Barkov and Zolotorev at the Budker Institute. The same parity violating interaction was later observed at SLAC also derived the first solid limit on the mass of Mikhail Shifman and Arkady Vainshtein in 1978, proving the Z-exchange and the Wein- the charm quark that was unexpectedly disberg-Salam model beyond any doubt. In 1973, covered the following year. together with Arkady Vainshtein, Khriplovich



Iosif Khriplovich was among the first to embrace Yang-Mills theories.

### Yang-Mills theories at a time when very few people

The work of Khriplovich and his group signif- Zelevinsky Michigan State University.

icantly advanced the theory of many-electron atoms and contributed to the subsequent studies of the violation of fundamental symmetries in processes involving elementary particles, atoms, molecules and atomic nuclei. His students and later close collaborators, such as Victor Flambaum, Oleg Sushkov and Maxim Pospelov, grew as strong physicists who made important contributions to various subfields of theoretical physics. He was awarded the Silver Dirac Medal by the University of New South Wales (Sydney) and the Pomeranchuk Prize by the Institute of Theoretical and Experimental Physics (Moscow).

Yulik, as he was affectionately known, had his own style in physics. He was feisty and focused on issues where he could become a trailblazer, unafraid to cut relations with scientists of any rank if he felt their behaviour did not match his high ethical standards. This is why he became engaged in Yang-Mills theories at a time when very few people were interested in them. Yet, Yulik was always graceful and respectful in his interactions with others, and smiling, as we would like to remember him.

University of Minnesota, Edward Shuryak Stony Brook University, and Vladimir

#### Meinhard Regler 1941-2024

### Austrian scientist, innovator, teacher

Meinhard Regler, an expert in detector development and software analysis, passed away on 22 September 2024 at the age of 83.

Born and raised in Vienna, Meinhard studied physics at the Technical University Vienna (TUW) and completed his master's thesis on deuteron acceleration in a linac at CERN. In 1966 he joined the newly founded Institute of High Energy Physics (HEPHY) of the Austrian Academy of Sciences. He settled in Geneva to participate in a counter experiment at the CERN Proton Synchrotron, and in 1970 obtained his PhD with distinction from TUW

In 1970 Meinhard became staff member in CERN's data-handling division. He joined the Split Field Magnet experiment at the Intersecting Storage Rings and, together with HEPHY, contributed specially designed multi-wire proportional chambers. Early on, he realised the importance of rigorous statistical Meinhard Regler was a driving force for the methods for track and vertex reconstruction MedAustron cancer-therapy facility. in complex detectors, resulting in several seminal papers

In 1975 Meinhard returned to Vienna as leader deputy director and responsible for the detector the Vienna Conference on Instrumentation (VCI). development and software analysis groups. As



specialised lectures and practical courses, which contributions to track and vertex reconstrucshaped a generation of particle physicists. In of HEPHY's experimental division. From 1993 1978 Meinhard and Georges Charpak founded until his retirement at the end of 2006 he was the Wire Chamber Conference, now known as published by Cambridge University Press and

Meinhard continued his participation in

Meinhard received several prizes and was rewarded with the highest scientific decoration of Austria

the European Hybrid Spectrometer. After joining the DELPHI experiment at LEP, he realised the emerging potential of semiconductor tracking devices and established this technology at HEPHY. First applied at DELPHI's Very Forward Tracker, this expertise was successfully continued with important contributions to the CMS tracker at LHC, the Belle vertex detector at KEKB and several others.

Meinhard is author and co-author of several hundred scientific papers. His and his group's tion are summarised in the standard textbook Data Analysis Techniques for High-Energy Physics, translated into Russian and Chinese

All that would suffice for a lifetime achievea faculty member of TUW he created a series of experiments at CERN, including WA6, UA1 and ment, but not so for Meinhard. Inspired by the

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# **CERNCOURIER**





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#### PEOPLE OBITUARIES

Vienna region. Initially planned as a spallation organised several accelerator schools and conmuted into a facility for cancer therapy by pro- the European Physical Society's international thinking and constructive criticism. ton and carbon-ion beams, called MedAustron. Financed by the province of Lower Austria and tific efforts and in particular the realisation of crucial scientific and engineering support from and was rewarded with the highest scientific CERN and Austrian institutes, clinical treatment started in 2016.

Meinhard was invited as a lecturer to many

group on accelerators. For his tireless sciendecoration of Austria - the Honorary Cross for Science and Arts of First Class.

He was also a co-founder and long-term pres- HEPHYVienna.

fall of the Iron Curtain, he envisaged the creation international conferences and post-graduate ident of a non-profit organisation in support of of an international centre of excellence in the schools worldwide. He chaired the VCI series, mentally handicapped people. His character was incorruptible, strictly committed to truth and neutron source, the project eventually trans- ferences in Austria, and served on the boards of honesty, and responsive to loyalty, independent

In Meinhard Regler we have lost an enthusiastic scientist, visionary innovator, talented the hosting city of Wiener Neustadt, and with MedAustron, Meinhard received several prizes organiser, gifted teacher, great humanist and good friend. His legacy will forever stay with us.

Rudolf Frühwirth and Winfried Mitaroff

#### Karel Šafařík 1953–2024

### The wise man of ALICE

Karel Šafařík, one of the founding members of the ALICE collaboration, passed away on 7 October 2024.

Karel graduated in theoretical physics in Bratislava, Slovakia (then Czechoslovakia) in 1976 and worked at JINR Dubna for over 10 years, participating in experiments in Serpukhov and doing theoretical studies on the phenomenology of particle production at high energies. In 1990 he joined Collège de France and the heavy-ion programme at CERN, soon becoming one of the most influential scientists in the Omega series of heavy-ion experiments (WA85, WA94, WA97, NA57) at the CERN Super Proton Synchrotron (SPS). In 2002 Karel was awarded the Slovak Academy of Sciences Prize for his contributions to the observation of the enhancement of the production of multi-strange particles in heavyion collisions at the SPS. In 2013 he was awarded the medal of the Czech Physical Society.

a central role in shaping the ALICE experiment, from the definition of physics topics and the He was pivotal in convincing the collaboration to struct decays of charm hadrons only a few tens



Karel Šafařík played a pivotal role in the ALICE experiment.

of microns from the primary vertex in central analytical mind, a legendary memory, a seem-As early as 1991, Karel was part of the small lead-lead collisions at the LHC - an idea conmat, tracking, data storage and data analysis. he also made multiple contributions to ALICE collaborators. We miss him dearly. upgrade studies and became known as the "wise introduce two layers of pixel detectors to reconman" to be consulted on the trickiest questions. His friends and colleagues in the

ingly unlimited set of competences ranging from group who designed the first heavy-ion detector sidered by many to be impossible in heavy-ion higher mathematics to formal theory, and from for the LHC, which later became ALICE. He played collisions, but that is now one of the pillars of detector physics to high-performance computthe ALICE physics programme. He was the ALICE ing. At the same time he was a generous, carphysics coordinator for many years leading up to ing and kind colleague who supported, helped, detector layout to the design of the data for- and including first data taking. Over the years, mentored and guided a large number of ALICE

Karel was a top-class physicist, with a sharp ALICE collaboration.

#### GÜNTER WOLF 1937-2024

### A driving force for collider physics

planning, construction and data analysis of 1961 where the DESY synchrotron was being experiments that were instrumental in estab- built under DESY founder Willibald Jentschke. at the higher energies of the recently completed lishing the Standard Model, passed away on Together with Erich Lohrmann and Martin linear accelerator at Stanford University (SLAC). 29 October 2024 at the age of 86. He significantly Teucher, he was involved in the preparation of He became the spokesperson for an experiment shaped and contributed to the research pro- the bubble-chamber experiments there and at with a polarised gamma beam, which provided gramme of DESY, and knew better than almost the same time took part in experiments at CERN. new insights into the nature of vector mesons. anyone how to form international collaborations and lead them to the highest achievements.

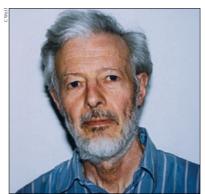
The first phase of experiments with highenergy photons at the DESY synchrotron, in physics in Tübingen. At the urging of his super-recognised results on the electromagnetic inter-life and became a leader in the planning, con-

Günter Wolf, who played a leading role in the visor Helmut Faissner, he went to Hamburg in actions of elementary particles. In 1967 Wolf seized the opportunity to continue this research

In 1971, Jentschke succeeded in bringing Wolf back to Hamburg as senior scientist. He Born in Ulm, Germany in 1937, Wolf studied which he was involved, had produced widely remained associated with DESY for the rest of his

of charmonium in 1975 and thus to the ulti- ments in experimental physics. mate confirmation that quarks are particles. For the next, larger electron-positron storage Günter Wolf was always friendly, helpful, ring, PETRA, he designed the TASSO detector, encouraging and inspiring, but at the same His friends and colleagues. again together with Wiik. In 1979, the TASSO collaboration was able to announce the discovery of the gluon through its spokesperson Wolf, for which he, together with colleagues from TASSO, was awarded the High Energy Particle Physics Prize of the European Physical Society.

In 1982 Wolf became the chair of the experi-



Günter Wolf was a leader of DESY experiments.

### Wolf's negotiating skills and deep understanding of physics and technology served particle physics worldwide

ment selection committee for the planned LEP collider at CERN. His deep understanding of physics and technology, and his negotiating skills, were an essential foundation for the successful LEP programme, just one example of how Wolf has served particle physics worldwide as a  $member\,of\,international\,scientific\,committees.$ 

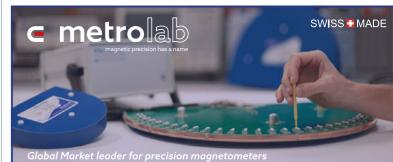
At the same time, Wolf was involved in the planning of the physics programme for the electron-proton collider HERA. The ZEUS general-purpose detector for experiments at HERA was the work of an international collaboration of more than 400 scientists, that Wolf brought together and led as its spokesperson for many years. The experiments at HERA ran from 1992 to 2007, producing outstanding results that include the direct demonstration of the unification of the weak and electromagnetic force at high momentum transfers, the precise measurement of the structure of the proton,

struction and analysis of key DESY experiments. which is determined by quarks and gluons, and time demanding and insistent on precision and Together with Bjørn Wiik, as part of an the surprising finding that there are collisions scientific excellence. He took the opinions of international collaboration, Wolf designed in which the proton remains intact even at the others seriously, but only a thorough and comand realised the DASP detector for DORIS, the highest momentum transfers. In 2011 Wolf was petent analysis could convince him. As a result, first electron-positron storage ring at DESY. awarded the Stern-Gerlach Medal of the German he enjoyed the greatest respect from everyone This led to the discovery of the excited states 

Physical Society, its highest award for achieve 

and became a role model and friend to many. DESY owes its reputation in the international When dealing with colleagues and staff, physics community not least to people like him.

PEOPLE OBITUARIES



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### **BACKGROUND**

Notes and observations from the high-energy physics community

### **Springtime at CERN**

facility took root (CERN Courier November/December 2024 p9), an unexpected discovery nearly nipped them in the bud - 200 wild orchids, thriving in the chosen spot. These finicky flowers don't take kindly to relocation, but losing them would be a blow to biodiversity. Being a flora enthusiast, the lead engineer on the project embarked on a mission to safely replant the orchids at another on-site location, and on 17 February a small team met at the crack of dawn to delicately dig them up. They are now in a prime location on the opposite side of the site.



### Science and symphony



At the 2025 World Economic Forum's annual meeting in Davos, CERN Director-General Fabiola Gianotti and renowned cellist Yo-Yo Ma took to the stage to perform Saint-Saëns' *Le Cygne*. "Arts, science, philosophy – it's all culture, they are what make us human," remarked Gianotti after the performance.



The surprisingly narrow width of the  $\Omega(2012)$  baryon measured by the ALICE collaboration, confirming a prior measurement by Belle (arXiv:2502.18063).

### **Media corner**

"Preventing the construction of a tunnel will change almost nothing in global CO₂ emissions. But without it, we are depriving ourselves of fundamental research and its technological spin-offs, some of which will be positive for the climate, because they will affect society as a whole."

CERN's **Patrick Janot** on the FCC's carbon footprint (*L'Express*, 1 March).

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"If you want an elevator pitch, we've seen a completely new type of matter that doesn't happen very often – and now we're going to use that new type of matter to better understand the universe."

CERN Director–General designate **Mark Thomson** on *The Economist's Babbage* podcast (5 March).

"We're already now doing better with the data that we've collected than we thought we'd be able to do

### From the archive: April 1985

#### Science and technology as time goes by

Technological spin-off from fundamental science has several timescales. Short-term developments are typified by improvements to equipment manufactured by firms in close contact with the research projects. The high rate of innovation produces technology available over a wide range of activities. Medium-term development is led by the need for



A positron camera developed at CERN being used for tomographic imaging at a major Geneva hospital

fundamental science to press technology to the limit. Here, particle physics has an important advantage, as its practitioners are well qualified to invent and exploit the instrumentation required. Such equipment frequently finds extensive application in other research areas as well as in commercial and medical fields. Developments from fundamental studies are unpredictable and the timescale of the resulting technological impact can be lengthy. Long-term spin-off permeates vast areas of technology and affects our whole culture. An outstanding example is the development of the quantum theory to account for the behaviour of matter at the atomic level, which now underlies all technologies involving matter, on the molecular, atomic and nuclear scales, including all of modern electronics.

• Text adapted from CERN Courier April 1985 p91.

#### Compiler's note

Methodist University and the

"The second quantum revolution

will likely provide another leap in

funding from the government and

human civilisation. Sustainable

ATLAS collaboration in

The Guardian (3 February).

private sector is essential."

Always at the vanguard of computing, CERN established the LHC Computing Grid in 2002 to manage the huge volume of data generated by the LHC. Now a global effort, the Worldwide LHC Computing Grid operates around a million computers across 170 sites in more than 40 countries, providing more than three exabytes of storage and processing two million tasks per day. Quantum theory, first formulated in 1925, is now being harnessed to tackle problems beyond the scope of even the most powerful classical computers. In 2020 CERN launched a Quantum Technology Initiative, and since spring 2024 the lab has hosted the Open Quantum Institute (OQI), a three-year programme to unleash the full potential of quantum computing for humanitarian uses.

 with 20 times more data 10 years
 Jian-Wei Pan of the University

 ago. So we've advanced by 20 years
 of Science and Technology of

 at least. A huge part of this has been down to AI."
 China on the International Year of

 Quantum Science and Technology
 Quantum Science and Technology

 Katharine Leney of Southern
 (Physics World, 5 February).

"All the stars will die, even all the black holes that are left – the final end points of the most massive stars – will evaporate away."

> **Brian Cox** is interviewed by Diane Morgan's character Philomena Cunk (*Cunk on Life*, Netflix, 2 January).

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- Novel Particle Sources and Acceleration Techniques
- Hadron Accelerators
- Beam Dynamics and EM Fields
- Beam Instrumentation and Controls, Feedback and Operational Aspects
- Accelerator Technology and Sustainability
- Applications of Accelerators, and Engagement for Industry and Society

#### **ORGANIZING COMMITTEES**

Ming-Chyuan Lin (NSRRC) Organizing Committee Chair Yoichi Sato (KEK/J-PARC) Scientific Program Chair Jui-Che Huang (NSRRC) Local Organizing Committee Chair Stella Su (NSRRC) Scientific Secretariat





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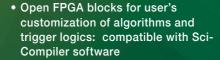
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