WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the January/February 2020 issue of *CERN Courier*.

On the cover of this issue, NASA astronaut Drew Morgan is photographed 400 km above Earth's surface installing a new coolant system for the Alpha Magnetic Spectrometer (AMS) during a crucial spacewalk on 2 December. Masterminded by charm–quark co-discoverer Sam Ting of MIT, and assembled and overseen by an international team at CERN, AMS has been attached to the International Space Station since 2011. Its various subdetectors, which include a silicon tracker embedded in a 0.15 T magnet, have so far clocked up almost 150 billion charged cosmic rays with energies up to the multi-TeV range and produced results that contradict conventional understanding. The new coolant system (which was delivered by an Antares rocket on 2 November) will extend the lifetime of AMS until the end of the decade, allowing more conclusive statements to be made about the origin of the unexpected observations. A full report on the unprecedented AMS intervention – and a taste of the experiment's latest results – will appear on cerncourier.com following the final extravehicular activity by Drew and his colleagues in mid-January.

Meanwhile, in this issue we investigate an intriguing anomaly in nuclear decay rates seen by the "Atomki" experiment, learn about the wider value of anomalies to phenomenologists, talk to theorist John Ellis about the past, present and future of the field, and explore high-level attempts to solve the flavour puzzle. KATRIN's quest for the neutrino mass, outreach for visually impaired audiences, the latest results from the LHC experiments and careers in visual effects are among other highlights of this first issue of the 2020s.

To sign up to the new-issue alert, please visit:
http://comms.iop.org/k/iop/cerncourier

To subscribe to the magazine, please visit:
https://cerncourier.com/p/about-cern-courier

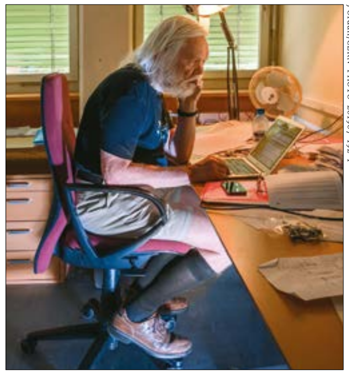
EDITOR: MATTHEW CHALMERS, CERN
DIGITAL EDITION CREATED BY IOP PUBLISHING

IN THIS ISSUE

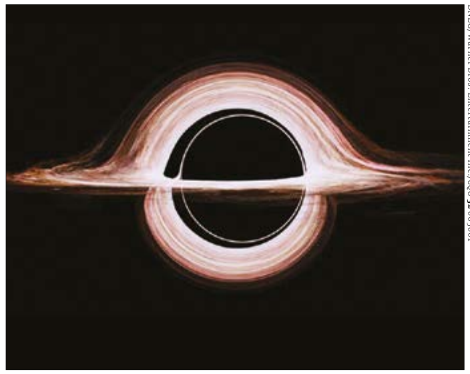
Volume 60 Number 1 January/February 2020


MAGIC

Epic burst *The MAGIC telescope detected photons of unrivalled energy.* **10**


J Ordan/CERN-PHOTO-201907-192-1

Paradigm shift? *John Ellis reflects on the future of the field.* **39**


DNEG/Warner Bros. Entertainment Inc./CQG **32** 065001

Gargantua *The visual effects for* Interstellar *were the fruit of a collaboration with Kip Thorne.* **45**

CERNCOURIER
Volume 60 Number 1 January/February 2020
IOP Publishing
CERN

FROM THE EDITOR

Extending the life of a unique experiment

Matthew Chalmers
Editor

It's not often that *CERN Courier* has the opportunity to feature an astronaut on its cover, but events unfolding 400 km above Earth's surface in recent weeks more than merit such a decision. Photographed on 2 December, NASA astronaut Drew Morgan is seen installing a new coolant system for the Alpha Magnetic Spectrometer (AMS) – the unique cosmic-ray detector masterminded by charm-quark co-discoverer Sam Ting of MIT and assembled by an international team at CERN. AMS has been attached to the International Space Station (ISS) since 2011 and initially was intended to operate for three years. Never designed to be serviceable, some 25 bespoke tools had to be developed for the procedure, which involved four high-profile extravehicular activities (EVAs) and years of preparation involving hundreds of astronauts, engineers and scientists on the ground. It is deemed one of the most complex interventions in space since repairs to the Hubble Space Telescope and will keep AMS operating until the end of the decade.

Equipped with a transition-radiation detector, a silicon tracker embedded in a 0.15 T magnet, a time-of-flight detector, ring-imaging Cherenkov detector and an electromagnetic calorimeter, AMS looks like something you would find underground at the business-end of a particle beam. In the pristine environment of space, the 7.5 tonne apparatus tracks and measures particles from the depths of the universe, and so far its 300,000 channels have clocked up almost 150 billion charged cosmic rays with energies up to the multi-TeV range. Its percent-level results, in particular showing a clear excess in the expected number of positrons at high energies, contradict conventional understanding (*CERN Courier* December 2016 p26). A further 10 years of operation should allow AMS to make conclusive statements on the origin of the unexpected observations.

So far its 300,000 channels have clocked up almost 150 billion charged cosmic rays

To that end, on 2 November 2019 an Antares rocket lifted off from Wallops Island, Virginia, carrying new CO_2 cooling pumps for the AMS tracker, following the failure of three of the four original pumps. On 15 November Morgan and European Space Agency astronaut Luca Parmitano (pictured above right) successfully removed and jettisoned the AMS debris shield, and, one week later, the pair cut through eight stainless-steel lines to isolate the existing cooling box. On 2 December, during the crucial "EVA3", Morgan and Parmitano successfully connected the lines to the new pump system and, as the *Courier* went to press, a final EVA to check the connections was planned for mid-January. The next issue (and on cerncourier.com as events unfold) will feature a full report on the unprecedented AMS intervention and offer a taste of this unique experiment's latest results.

NASA

Virtuoso *Attached to a robotic arm of the ISS on 2 December, ESA's Luca Parmitano handles the new pump system for AMS.*

In this issue

On the subject of intriguing data, this issue takes a closer look at anomalous nuclear-decay results reported recently by the "Atomki" experiment, which have been widely reported to herald the discovery of a fifth force (p7), and explores the wider value of anomalies to phenomenologists (p37). On p39 theorist John Ellis surveys the status and future of the field, while our feature "Who ordered all of that?" describes attempts to solve the flavour puzzle (p23). KATRIN's quest for the neutrino mass (p28), outreach for visually impaired audiences (p33), careers in visual effects (p45) and the latest results from the LHC experiments (p15) are other highlights of this first issue of the 2020s.

Reporting on international high-energy physics

CERN Courier is distributed to governments, institutes and laboratories affiliated with CERN, and to individual subscribers. It is published six times per year. The views expressed are not necessarily those of the CERN management.

IOP Publishing

Editor Matthew Chalmers
Associate editor Mark Rayner
Archive contributor Peggie Rimmer
Astrowatch contributor Merlin Kole
E-mail cern.courier@cern.ch

Advisory board Peter Jenni, Christine Sutton, Claude Amsler, Philippe Bloch, Roger Forty, Mike Lamont, Joachim Kopp

Laboratory correspondents
Argonne National Laboratory Tom LeCompte
Brookhaven National Laboratory Achim Franz
Cornell University D G Cassel
DESY Laboratory Till Mundzeck
Enrico Fermi Centre Guido Piragino
Fermilab Kurt Riesselmann
Forschungszentrum Jülich Markus Buescher
GSI Darmstadt I Peter
IHEP, Beijing Lijun Guo
IHEP, Serpukhov Yu Ryabov
INFN Antonella Varaschin
Jefferson Laboratory Kandice Carter
JINR Dubna B Starchenko
KEK National Laboratory Hajime Hikino
Lawrence Berkeley Laboratory Spencer Klein
Los Alamos National Lab Rajan Gupta
NCSL Ken Kingery
Nikhef Robert Fleischer
Novosibirsk Institute S Eidelman
Orsay Laboratory Anne-Marie Lutz
PSI Laboratory P-R Kettle
Saclay Laboratory Elisabeth Locci
UK STFC Jane Binks
SLAC National Accelerator Laboratory Melinda Baker
SNOLAB Samantha Kuula
TRIUMF Laboratory Marcello Pavan

Produced for CERN by IOP Publishing Ltd Temple Circus, Temple Way, Bristol BS1 6HG, UK
Tel +44 (0)117 929 7481

Head of Media Jo Allen
Head of Media Business Development Ed Jost
Art direction Frédérique Swist
Production editor Ruth Leopold
Technical illustrator Alison Tovey
Advertising sales Tom Houlden
Recruitment sales Chris Thomas
Advertisement production Katie Graham
Marketing and circulation Laura Gillham

Advertising Tel +44 (0)117 930 1026 (for UK/Europe display advertising) or +44 (0)117 930 1164 (for recruitment advertising); e-mail sales@cerncourier.com

General distribution Courrier Adressage, CERN, 1211 Geneva 23, Switzerland; e-mail courrier-adressage@cern.ch

Published by CERN, 1211 Geneva 23, Switzerland
Tel +41 (0) 22 767 61 11

Printed by Warners (Midlands) plc, Bourne, Lincolnshire, UK

ISSN 0304-288X

NEWS ANALYSIS

NUCLEAR PHYSICS

Rekindled Atomki anomaly merits closer scrutiny

A large discrepancy in nuclear decay rates spotted four years ago in an experiment in Hungary has received new experimental support, generating media headlines about the possible existence of a fifth force of nature.

In 2016, researchers at the Institute of Nuclear Research ("Atomki") in Debrecen, Hungary, reported a large excess in the angular distribution of e^+e^- pairs created during nuclear transitions of excited ^{8}Be nuclei to their ground state ($^8\mathrm{Be}^* \rightarrow {}^8\mathrm{Be}\,\gamma;\ \gamma \rightarrow e^+e^-$). Significant peak-like enhancement was observed at large angles measured between the e^+e^- pairs, corresponding to a 6.8σ surplus over the expected e^+e^- pair-creation from known processes. The excess was soon interpreted by theorists as being due to the possible emission of a new boson X with a mass of 16.7 MeV decaying into e^+e^- pairs.

In a preprint published in October 2019, the Atomki team has now reported a similar excess of events from the electromagnetically forbidden "M0" transition in ^{4}He nuclei. The anomaly has a statistical significance of 7.2σ and is likely, claim the authors, to be due to the same "X17" particle proposed to explain the earlier ^{8}Be excess.

Atomki

Future view *Atomki's new high-resolution $LaBr_3$ spectrometer, which will record gamma–gamma pairs from excited nuclei.*

Atomki

X-factor *The Atomki team with the apparatus used for the latest ^{8}Be and ^{4}He results, which detects e^+e^- pairs from the de-excitation of nuclei produced by firing protons at different targets.*

Quality control

"We were all very happy when we saw this," says lead author Attila Krasznahorkay. "After the analysis of the data a really significant effect could be observed." Although not a fully blinded analysis, Krasznahorkay says the team has taken several precautions against bias and carried out numerous cross-checks of its result. These include checks for the effect in the angular correlation of e^+e^- pairs in different regions of the energy distribution, and assuming different beam and target positions. The paper does not go into the details of systematic errors, for instance due to possible nuclear-modeling uncertainties, but Krasznahorkay says that, overall, the result is in "full agreement" with the results of the Monte Carlo simulations performed for the X17 decay.

While it cannot yet be ruled out, the existence of an X boson is not naively expected, say theorists. For one, such a particle would have to "know" about the distinction between up and down quarks and thus electroweak symmetry breaking. Being a vector boson, the X17 would constitute evidence for a new force. It could also be related to the dark-matter problem, write Krasznahorkay and co-workers, and has the right properties to help resolve the discrepancy between measured and predicted values of the muon anomalous magnetic moment.

Last year, the NA64 collaboration at CERN reported results from a direct search for the X boson via the bremsstrahlung reaction $eZ \rightarrow eZX$, the absence of a signal placing the first exclusion limits on the X–e^- coupling in the range $(1.3\text{–}4.2)\times10^{-4}$. "The Atomki anomaly could be an experimental effect, a nuclear-physics effect or something completely new," comments NA64 spokesperson Sergei Gninenko. "Our results so far exclude only a fraction of the allowed parameter space for the X boson, so I'm really interested in seeing how this story, which is only just beginning, will unfold." Last year, researchers used data from the BESIII experiment in China to search for direct X-boson production in electron–positron collisions and indirect production in J/ψ decays – finding no signal. Krasznahorkay and colleagues also point to the potential of beam-dump experiments such as PADME in Frascati, and to the upcoming Dark Light experiment at Jefferson Laboratory, which will search for 10–100 MeV dark photons.

Theorist Jonathan Feng of the University of California at Irvine, who's group proposed the X-boson hypothesis in 2016, says that the new ^{4}He results from Atomki support the previous ^{8}Be evidence of a new particle – particularly since the excess is observed at a slightly different e^+e^- opening angle in ^{4}He (115 degrees) than it is in ^{8}Be (135 degrees). "If it is an experimental error or some nuclear-physics effect, there is no reason for the excess to shift to different angles, but if it is a new particle, this is exactly what is expected," says Feng. "I do not know of any inconsistencies in the experimental data that would indicate that it is an experimental effect."

In 2017, theorists Gerald Miller at the University of Washington and Xilin Zhang at Ohio State concluded that, if the Atomki data are correct, the original ^{8}Be excess cannot be explained by nuclear-physics modelling uncertainties. But they also wrote that a direct comparison to the e^+e^- data is not feasible due to "missing public information" about the experimental detector efficiency. "Tuning the normalisation of our results reduces the confidence level of the anomaly by at least one standard deviation," says Miller. As for the latest Atomki result, the nuclear physics in ^{4}He is more complicated than ^{8}Be because ▷

two nuclear levels are involved, explains Miller, making it difficult to carry out an analysis analogous to the ^{8}Be one. "For ^{4}He there is also a background pair-production mechanism and interference effect that is not mentioned in the paper, much of which is devoted to the theory and other future experiments," he says. "I think the authors would have been better served if they presented a fuller account of their data because, ultimately, this is an experimental issue. Confirming or refuting this discovery by future nuclear experiments would be extremely important. A monumental discovery could be possible."

The Hungarian team is now planning on repeating the measurement with a new gamma-ray coincidence spectrometer at Atomki (see main image), which they say might help to distinguish between the vector and the pseudoscalar interpretation of the X17. Meanwhile, a project called New JEDI will enable an independent verification of the ^{8}Be anomaly at the ARAMIS-SCALP facility (Orsay, France) during 2020, followed by direct searches by the same group for the existence of the X boson, in particular in other light quantum systems, at the GANIL-SPIRAL2 facility in Caen, France.

"Many people are sceptical that this is a new particle," says Feng, who too was doubtful at first. "But at this point, what we need are new ideas about what can cause this anomaly. The Atomki group has now found the effect in two different decays. It would be most helpful for other groups to step forward to confirm or refute their results."

It would be most helpful for other groups to step forward

Further reading

J Feng *et al.* 2016 *Phys. Rev. Lett.* **117** 071803.
J Jiang *et al.* 2019 *Eur. Phys. J. C* **79** 404.
A J Krasznahorkay *et al.* 2019 arXiv:1910.10459.
A J Krasznahorkay *et al.* 2016 *Phys. Rev. Lett.* **116** 042501.

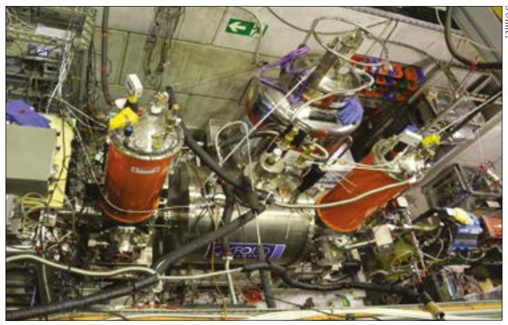
ANTIMATTER

BASE tests antimatter's dark side

A first-of-its-kind experiment at CERN has brought dark matter and antimatter face to face. The fundamental nature of dark matter, inferred to make up around a quarter of the universe, is unknown, as is the reason for the observed cosmic imbalance between matter and antimatter. Investigating potential links between the two, researchers working on the Baryon Antibaryon Symmetry Experiment (BASE) at CERN, in collaboration with members of the Helmholtz Institute at Mainz, have reported the first laboratory search for an interaction between antimatter and a dark-matter candidate: the axion.

Axions are extremely light, spinless bosons that were originally proposed in the 1970s to resolve the strong charge-parity problem of quantum chromodynamics and, later, were predicted by theories beyond the Standard Model. Being stable, axions produced during the Big Bang would still be present throughout the universe, possibly accounting for dark matter or some portion of it. In this case, Earth would experience a "wind" of gravitationally interacting dark-matter particles that would couple to matter and antimatter, and periodically modulate their fundamental properties, such as their magnetic moment. However, no evidence of such an effect has so far been seen in laboratory experiments with ordinary matter, setting stringent limits on the microscopic properties of cosmic axion-like particles.

The BASE team has now searched for the phenomenon in antimatter via measurements of the precession frequency of the antiproton's magnetic moment, which it is able to determine with a fractional precision of 1.5×10^{-9}. The technique relies on single-particle spin-transition spectroscopy – comparable to performing NMR with a single antiproton – whereby individual antiprotons stored in a Penning trap are spin-flipped from one state to another (*CERN Courier* March 2018 p25). An observed variation in the precession frequency over time could provide evidence for the nature of dark matter and, if antiprotons have a stronger coupling to these particles than protons do, such a matter–antimatter asymmetric coupling could provide a link between dark matter and the baryon asymmetry in the universe.



S Ulmer

Mystery meets mystery *The BASE experiment at CERN's Antiproton Decelerator showing two cryostats (orange) flanking a superconducting magnet, in which a multi-Penning trap is used to manipulate antiprotons.*

"We've interpreted these data in the framework of the axion-wind model where light axion-like particles (ALPs) oscillate through the galaxy, at frequencies defined by the ALP mass," explains lead author and BASE co-spokesperson Christian Smorra of RIKEN in Japan. "The particles couple to the spins of Standard Model particles, which would induce frequency modulations of the Larmor precession frequency."

Accruing around 1000 measurements over a three-month period, the team determined a time-averaged frequency of the antiproton's precession of around 80 MHz with an uncertainty of 120 mHz. No signs of regular variations were found, producing the first laboratory constraints on the existence of an interaction between antimatter and a dark-matter candidate. The BASE data constrain the axion–antiproton interaction parameter (a factor in the matrix element inversely proportional to the postulated coupling between axions and antiprotons) to be above 0.1 GeV for an axion mass of 2×10^{-23} and above 0.6 GeV for an axion mass of 4×10^{-17} eV, at 95% confidence. For comparison, similar experiments using matter instead of antimatter achieve limits of above 10 and 1000 TeV for the same mass range – demonstrating that a major violation of established charge-parity-time symmetry would be implied by any signal given the current BASE sensitivity. The collaboration also derived limits on six combinations of previously unconstrained Lorentz- and CPT-violating coefficients of the non-minimal Standard Model extension.

"We have not observed any oscillatory signature, however, our ALP–antiproton coupling limits are much more stringent than limits derived from astrophysical observations," says BASE spokesperson Stefan Ulmer of RIKEN, who is optimistic that BASE will be able to improve the sensitivity of its axion search. "Future studies, with a 10-fold improved frequency stability, longer experimental campaigns and broader spectral scans at higher frequency resolution, will allow us to increase the detection bandwidth."

Further reading

C Smorra *et al.* 2019 *Nature* **575** 310.

POLICY

Physics tops finance in economic impact

Physics-based industries generate over 16% of total turnover and more than 12% of overall employment in Europe, topping contributions from the financial services and retail sectors, according to a report published by the European Physical Society (EPS). The analysis, carried out by UK consultancy firm Cebr (Centre for Economics and Business Research), reveals that physics makes a net contribution to the European economy of at least €1.45 trillion per year, and suggests that physics-based sectors are more resilient than the wider economy.

"To give some context to these numbers, the turnover per person employed in the physics-based sector substantially outperforms the construction and retail sectors, and physics-based labour productivity (expressed as gross value added per employee) was significantly higher than in many other broad industrial and business sectors, including manufacturing," stated EPS president Petra Rudolf of the University of Groningen. "Our hope is that the message conveyed by the EPS through the study performed by Cebr will be inspiring for the future, both at European and national levels, making a convincing case for the support for physics in all of its facets, from education to research, to business and industry."

The Cebr analysis examined public-domain data in 31 European countries for the six-year period 2011–2016. It defined physics-based industries as those where workers with some training in physics would be expected to be employed and where the activities rely heavily on the theories and results of physics to achieve their commercial goals, following the Statistical Classification of Economic Activities in the European Community (NACE). Based on several different measures of economic growth and prosperity, the analysis found that physics-based goods and services contributed an average of 44% of all exports from the 28 European Union (EU) countries during the relevant period. The three major contributions were from manufacturing (42.5%), information and communication (14.1%), and professional, scientific and technical activities in physics-based fields such as architecture, engineering and R&D (14.1%). Germany showed by far the highest percentage of turnover from physics-based industries (29%), followed by the UK (14.2%), France (12.9%) and Italy (10.4%).

Physics flies *The EPS-commissioned report claims that physics makes a net contribution to the European economy of at least €1.45 trillion per year.*

Taking into account "multiplier impacts" that capture the knock-on effect of goods and services on the wider economy, the analysis found that for every €1 of physics-based output, a total of €2.49 is generated throughout the EU economy. The employment multiplier is higher still, meaning that for every job in physics-based industries, an average of 3.34 jobs are supported in the economy as a whole by these industries.

While the report does not assess the impact of different sub-fields of physics, it is clear that high-energy physics is a major contributor, says former EPS president Rüdiger Voss of CERN. "The sheer scale and technological complexity of big-science projects, and the thousands of highly skilled people that they produce, makes particle physics, astronomy and other research based on large-scale facilities significant contributors to the European economy – not to mention the fact that these are the subjects that often draw young people into science in the first place."

ACCELERATORS

CERN updates LHC schedule

The LHC will restart in May 2021, marking the beginning of Run 3, announced the CERN management on 13 December. Beginning two months after the initially planned date, Run 3 will be extended by one year, until the end of 2024, to maximise physics data taking. Then, during long-shutdown three between 2025 and mid-2027, all of the equipment needed for the high-luminosity configuration of the LHC (HL-LHC) and its experiments will be installed. The HL-LHC is scheduled to come into operation at the end of 2027 and to run for up to a decade. Its factor-five or more increase in levelled luminosity is driving ambitious detector upgrade programmes among the LHC experiments. The experiments are replacing numerous components, even entire subdetectors, often working at the limits of current technology, to increase their physics reach. The extra time incorporated into the new schedule will enable the collaborations to ready themselves for Run 3 and beyond.

M Brice/CERN

Breakthrough *Lucio Rossi (HL-LHC project leader), Frédérick Bordry (director for accelerators and technology), Fabiola Gianotti (CERN Director-General) and Oliver Brüning (deputy HL-LHC project leader) celebrate the HL-LHC tunnel breakthrough on 13 December.*

Since the start of long-shutdown two in December 2018, extensive upgrades of CERN's accelerator complex and experiments have been taking place. The pre-accelerator chain is being entirely renovated as part of the LHC Injectors Upgrade project, and new equipment is being installed in the LHC, while development of the HL-LHC's Nb_3Sn magnets continues above ground. On the morning of 13 December, civil engineers made the junction between the underground facilities at Points 1 and 5 of the accelerator – linking the HL-LHC to the LHC, and marking the latest project milestone (see image).

"The HL-LHC is in full swing and the machine and civil engineering is on track," says Lucio Rossi, HL-LHC project leader. "The schedule is drawn up in a global way, taking into account every aspect of the machine, experiment and infrastructure readiness, entirely with the aim to maximise the physics. The overall HL-LHC timetable is flexible in the sense that it will depend on actual results."

CERNCOURIER
VOLUME 60 NUMBER 1 JANUARY/FEBRUARY 2020
IOP Publishing

Astrowatch

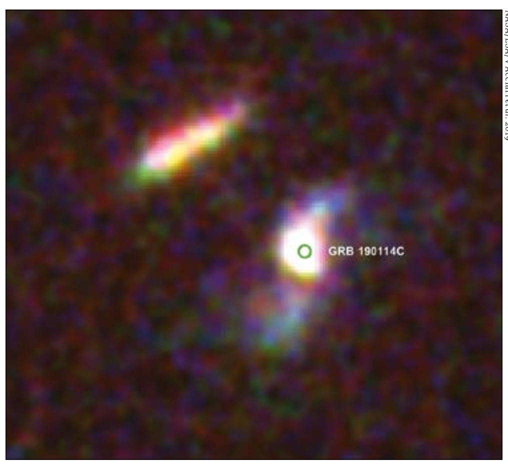
MAGIC spots epic gamma-ray burst

Gamma-ray bursts (GRBs) are the brightest electromagnetic events in the universe since the Big Bang. First detected in 1967, GRBs have been observed about once per day using a range of instruments, allowing astrophysicists to gain a deeper understanding of their origin. As often happens, 14 January 2019 saw the detection of three GRBs. While the first two were not of particular interest, the unprecedented energy of photons emitted by the third – measured by the MAGIC telescopes – provides a new insight into these mysterious phenomena.

The study of GRBs is unique, both because GRBs occur at random locations and times and because each GRB has different time characteristics and energy spectra. GRBs consist of two phases: a prompt phase, lasting from hundreds of milliseconds to hundreds of seconds, which consists of one or several bright bursts of hard X-rays and gamma-rays; followed by a significantly weaker "afterglow" phase that can be observed at lower energies ranging from radio to X-rays and lasts for periods up to months.

ASPERA/R Wagner, MPI Munich

Burning bright *The MAGIC telescope with guidance lasers switched on, and (below) a colour image taken by the Hubble Space Telescope of the location where GRB 190114C took place.*



NASA/ESA/V Acciari et al. 2019

Origins

Since the late 1990s, optical observations have confirmed both that GRBs happen in other galaxies and that longer duration GRBs tend to be associated with supernovae, strongly hinting that they result from the death of massive stars. Shorter GRBs, meanwhile, have recently been shown to be the result of neutron-star mergers thanks to the first joint observations of a GRB with a gravitational wave event in 2017. While this event is often regarded as the start of multi-messenger astrophysics, the recent detection of GRB190114C lying 4.5 billion light-years from Earth adds yet another messenger to the field of GRB astrophysics: TeV photons.

The MAGIC telescopes on the island of La Palma measure the Cherenkov radiation produced when TeV photons induce electromagnetic showers after interacting with the Earth's atmosphere. During the past 15 years, MAGIC has discovered a range of astrophysical sources via their emission at these extreme energies. However, detecting the emission from GRBs has remained elusive, despite more than 100 attempts and the theoretical predictions that such emissions could exist.

On 14 January, based on an alert provided by space-based gamma-ray detectors, the MAGIC telescopes started repointing within a few tens of seconds of the onset of the GRB. In the next half hour, the telescopes had observed around 1000 high-energy photons from the source. This emission, which has long been predicted by theorists, is shown by the collaboration to be the result of the "synchrotron self-Compton" process, whereby high-energy electrons accelerated in the initial violent explosion interact with magnetic fields produced by the collision between these ejecta and interstellar matter. The synchrotron emission from this interaction produces the afterglow observed at X-ray, optical and radio energies. However, some of these synchrotron photons subsequently undergo inverse Compton scattering with the same electrons, allowing them to reach TeV energies. These measurements by MAGIC show, for the first time, that this mechanism does indeed occur. Given the many observations in the past where it wasn't observed, this appears to be yet another feature that differs between GRBs.

The MAGIC results were published in an issue of *Nature* that also reported a discovery of similar emission in a different GRB by another Cherenkov telescope: the High Energy Stereoscopic System (H.E.S.S) in Namibia. While the measurements are consistent, it is interesting to note that the measurements by H.E.S.S were made 10 hours after that particular GRB, showing that this type of emission can also occur at much later time scales. With two new large-scale Cherenkov observatories – the Large High Altitude Air Shower Observatory in China and the global Cherenkov Telescope Array – about to commence data taking, the field of GRB astrophysics can now expect a range of new discoveries.

Further reading

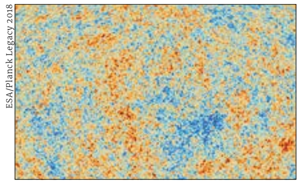
H Abdalla *et al.* 2019 *Nature* **575** 464.
MAGIC Collab. 2019 *Nature* **575** 455.
MAGIC Collab. 2019 *Nature* **575** 459.

CERNCOURIER

Volume 60 Number 1 January/February 2020

IOP Publishing

NEWS DIGEST



ESA/Planck Legacy 2018

Detail of the CMB anisotropy.

Crisis for cosmology?

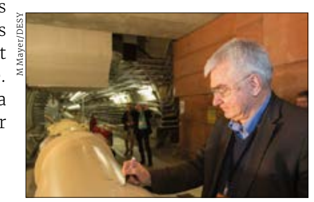
Planck data on the cosmic microwave background (CMB) have been reinterpreted to favour a closed universe at more than 99% confidence, in contradiction with the flat universe favoured by the established ΛCDM model of cosmology (*Nat. Astron.* 2019/arXiv:1911.02087). In their new fit to Planck's 2018 data release, Eleonora Di Valentino (Manchester), Alessandro Melchiorri (La Sapienza) and Joe Silk (Oxford) exchanged an anomalously large lensing amplitude (a phenomenological parameter that rescales the gravitational-lensing potential in the CMB power spectrum) for a higher energy density. In addition to the lensing anomaly, which leads to inconsistencies between large and small scales, the flat interpretation is already plagued by a 4.4σ tension with the latest determination of the Hubble constant using observations of the recession of Cepheid stars (arXiv:1903.07603) – a tension that grows to 5.4σ in a closed universe. The inconsistencies between data sets signal "a possible crisis for cosmology", argue the authors.

ATLAS opens likelihoods up

In a move sure to excite phenomenologists, ATLAS has published "open likelihoods" with full analytical complexity for two recent supersymmetry analyses: a search for bottom-squark pair production (arXiv:1908.03122) and a search for direct stau production in events with two hadronic tau leptons (arXiv:1911.06660). While particle searches by the LHC experiments already provide a wealth of numerical information, theorists will for the first time have access to the full underlying data model used by ATLAS. Although the data-selection requirements are fixed, and results with the open likelihoods cannot include the simulation of possible new physics signals in the detector, they will give theorists a quick assessment of the potential of their new theories. An initially unplanned fruit of rewriting ATLAS software for machine-learning frameworks, the releases should also ensure that analyses survive developments in software and remain repeatable long into the future.

Sendai statement affirms ILC

430 scientists attending the International Workshop on Future Linear Colliders in Sendai, Japan, on 31 October asserted their commitment to building the International Linear Collider (ILC), the strong support of the local community, and the project's maturity and readiness for implementation. The ILC's cost estimate is on a sound technical basis as the key superconducting RF technology has been successfully demonstrated in the European XFEL in Germany, asserted the participants, who argue that the case for a Higgs-boson factory is more compelling than ever given recent LHC results.



M Mayer/DESY

DESY's Joachim Mnich signs the first ALPS II magnet to be installed.

First ALPS II magnet installed

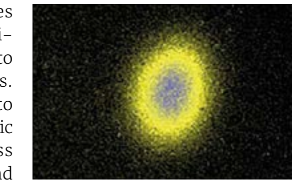
The first magnet has been installed in the upgraded Any-Light-Particle-Search (ALPS II) experiment, which will continue the search for axion-like particles, hidden photons and "mini-charged" particles. Located at DESY in Hamburg, in a straight section of the tunnel where HERA operated until 2007, ALPS II will reuse 24 of that machine's superconducting magnets, with yokes and beam pipes straightened by a delicately calibrated brute-force deformation, to house 120 m-long optical cavities. Should laser light be converted to axion-like particles in the magnetic field, these particles would pass through a light-blocking wall and could then be observed converting back into photons in subsequent superconducting magnets. ALPS II will benefit from both increased length and improved optical technology, in part thanks to work on gravitational-wave interferometers. Data taking will begin in 2021.

Ireland eyes CERN membership

A cross-party committee of the legislature of the Republic of Ireland has unanimously recommended Ireland become an Associate Member State of CERN, to help train the next generation of scientists and engineers, and develop industry opportunities. Alongside Malta and Luxembourg, Ireland is one of only three EU countries that do not have any formal agreement with the laboratory. "Ireland has a strong particle-physics community and CERN would welcome stronger institutional links, which we believe would be mutually beneficial," says Charlotte Warakaulle, CERN's director for international relations.

Beauty baryons enter the fray

LHCb has launched a new offensive in the exploration of lepton-flavour universality (arXiv:1912.08139). Following previous results that hinted that e^+e^- pairs might be produced at a greater rate than $\mu^+\mu^-$ pairs in B meson decays to $K^{(*)}\ell^+\ell^-$, the study brings baryon decays to bear on the subject for the first time. The collaboration measured the ratio of branching fractions for $\Lambda_b^0 \to pK^-e^+e^-$ and $\Lambda_b^0 \to pK^-\mu^+\mu^-$ to be $1.17^{+0.18}_{-0.16}$ (stat) ± 0.07 (syst). Though highly suppressed in the Standard Model, the decays could be affected by the existence of new particles (*CERN Courier* May/June 2019 p9). The study also constitutes the first observation of the decay $\Lambda_b^0 \to pK^-e^+e^-$.



ESRF

The first beam to circulate at ESRF's new storage ring.

Extremely brilliant beginning

Electron beams first circulated in the Extremely Brilliant Source (EBS) on 2 December, almost two years after the installation of the upgraded 844 m-long storage ring began. The first of its kind, with an increased X-ray brightness and coherent flux 100 times higher than before, EBS is the culmination of a decade-long programme to upgrade the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, and ensure Europe's leading position in the light-source world (*CERN Courier* December 2018 p17). The facility also boasts new X-ray beamlines, instrumentation and computing, to facilitate nanometre-scale studies ranging from biology to paleontology. On 15 December, the machine achieved a world-record horizontal beam emittance of 308 pm.

A new era of quantum biology

A natural biomolecule has been caught acting like a quantum wave for the first time (arXiv:1910.14538). Armin Shayeghi of the University of Vienna and colleagues demonstrated quantum interference in molecules of gramicidin – a natural antibiotic made up of 15 amino acids. The team fired a series of short laser pulses to knock the biomolecules into a beam of argon atoms, and used Talbot-Lau interferometry to observe an interference pattern consistent with a de Broglie wavelength for the gramicidin of 350 fm. Though such effects have previously been observed in larger molecules, this is the first demonstration with fragile biomolecules, and paves the way for the optical spectroscopy of enzymes and DNA.

CERNCOURIER
Volume 60 Number 1 January/February 2020
IOP Publishing

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

CMS

Crystal calorimeter hones Higgs mass

Though a free parameter in the Standard Model, the mass of the Higgs boson is important for both theoretical and experimental reasons. Most peculiarly from a theoretical standpoint, our current knowledge of the masses of the Higgs boson and the top quark imply that the quartic coupling of the Higgs vanishes and becomes negative tantalisingly close to, but just before, the Planck scale. There is no established reason for the Standard Model to perch near to this boundary. The implication is that the vacuum is almost but not quite stable, and that on a timescale substantially longer than the age of the universe, some point in space will tunnel to a lower energy state and a bubble of true vacuum will expand to fill the universe. Meanwhile, from an experimental perspective, it is important to continually improve measurements so that uncertainty on the mass of the Higgs boson eventually rivals the value of its width. At that point, measuring the Higgs-boson mass can provide an independent method to determine the Higgs-boson width. The Higgs-boson width is sensitive to the existence of possible undiscovered particles and is expected to be a few MeV according to the Standard Model.

The CMS collaboration recently announced the most precise measurement of the Higgs-boson mass achieved thus far, at 125.35 ± 0.15 GeV – a precision of roughly 0.1%. This very high precision was achieved thanks to an enormous amount of work over many years to carefully calibrate and model the CMS detector when it measures the energy and momenta of the electrons, muons and photons necessary for the measurement.

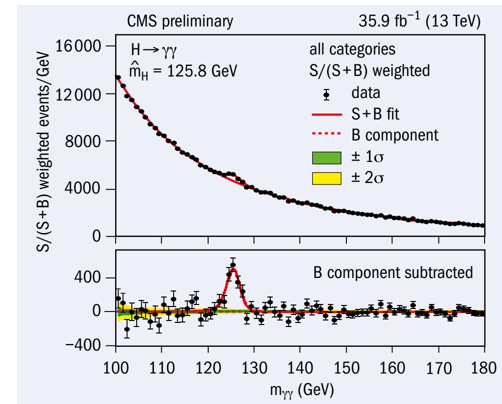


Fig. 1. *The relatively small Higgs-boson resonance can be seen in its decay to two photons, above the falling background of photons from other processes (top) and with the estimated background subtracted (bottom).*

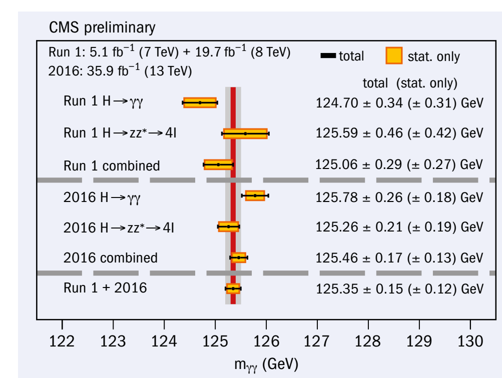


Fig. 2. *Measurements of the Higgs-boson mass by the CMS collaboration. The most recent is the $H\rightarrow\gamma\gamma$ channel with 2016 data.*

The most recent contribution to this work was a measurement of the mass in the di-photon channel using data collected at the LHC by the CMS collaboration in 2016 (figure 1). This measurement was made using the lead–tungstate crystal calorimeter, which uses approximately 76,000 crystals, each weighing about 1.1 kg, to measure the energy of the photons. A critical step of this analysis was a precise calibration of each crystal's response using electrons from Z-boson decay, and accounting for the tiny difference between the electron and photon showers in the crystals.

This new result was combined with earlier results obtained with data collected between 2011 and 2016. One measurement was in the decay channel to two Z bosons, which subsequently decay into electron or muon pairs, and another was a measurement in the di-photon channel made with earlier data. The 2011 and 2012 data combined yield 125.06 ± 0.29 GeV. The 2016 data yield 125.46 ± 0.17 GeV. Combining these yields CMS's current best precision of 125.35 ± 0.15 GeV (figure 2). This new precise measurement of the Higgs-boson mass will not, at least not on its own, lead us in a new direction of physics, but it is an indispensable piece of the puzzle of the Standard Model – and one fruit of the increasing technical mastery of the LHC detectors.

Further reading

CMS Collab. 2019 CMS-PAS-HIG-19-004.

LHCb

Opening gambit for LHCb in the V_{cb} puzzle

There is a longstanding puzzle concerning the value of the Cabibbo–Kobayashi–Maskawa matrix element $|V_{cb}|$, which describes the coupling between charm and beauty quarks in $W^{\pm}$ interactions. This fundamental parameter of the Standard Model has been measured with two complementary methods. One uses the inclusive rate of b-hadron decays into final states containing a c hadron and a charged lepton; the other measures the rate of a specific (exclusive) semileptonic B decay, e.g. $B^0 \rightarrow D^{*-}\mu^+\nu_\mu$. The world average of results using the inclusive approach, $|V_{cb}|^{incl} = (42.19 \pm 0.78) \times 10^{-3}$, differs from the average of results using the exclusive approach, $|V_{cb}|^{excl} = (39.25 \pm 0.56) \times 10^{-3}$, by approximately three standard deviations.

The averages differ by three standard deviations

So far, exclusive determinations have been carried out only at e^+e^- colliders, using B^0 and B^+ decays. Operating at ▷

CERNCOURIER
VOLUME 60 NUMBER 1 JANUARY/FEBRUARY 2020
IOP Publishing

the Υ(4S) resonance, the full decay kinematics can be determined, despite the undetected neutrino, and the total number of B mesons produced, needed to measure $|V_{cb}|$, is known precisely. The situation is more challenging in a hadron collider – but the LHCb collaboration has just completed an exclusive measurement of $|V_{cb}|$ based, for the first time, on B^0_s decays.

The exclusive determination of $|V_{cb}|$ relies on the description of strong-interaction effects for the b and c quarks bound in mesons, the so-called form factors (FF). These are functions of the recoil momentum of the c meson in the b-meson rest frame, and are calculated using non-perturbative QCD techniques, such as lattice QCD or QCD sum rules. A key advantage of semileptonic B^0_s decays, compared to $B^{0/+}$ decays, is that their FF can be more precisely computed. Recently, the FF parametrisation used in the exclusive determination has been considered to be a possible origin of the inclusive-exclusive discrepancy, and comparisons between the results for $|V_{cb}|$ obtained using different parametrisations, such as that by Caprini, Lellouch and Neubert (CLN) and that by Boyd, Grinstein and Lebed (BGL), are considered a key check.

Both parametrisations are employed by LHCb in a new analysis of $B^0_s \to D_s^{(*)-}\mu^+\nu_\mu$ decays, using a novel method that does not require the momentum of particles other than D_s^- and μ^+ to be estimated. The analysis

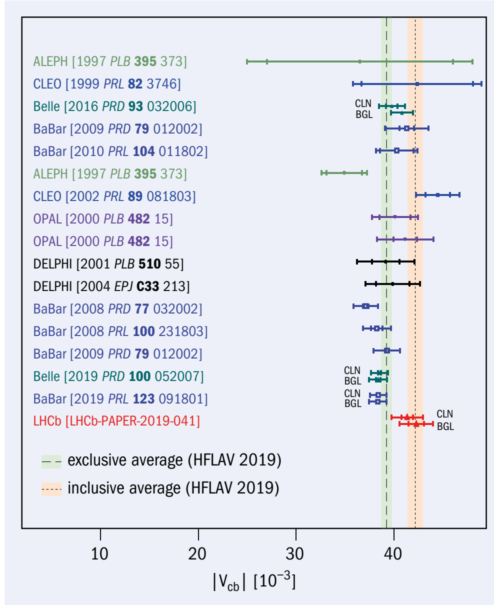


Fig. 1. *Summary of all exclusive measurements of $|V_{cb}|$. The new LHCb measurement (red triangles) uses B^0_s decays, while all others are obtained from B^0 or B^+ decays. The error bars show the total (outer) and statistical (inner, when present) uncertainties. When not stated, the measurement is obtained using the CLN parametrisation. The exclusive average does not include the new LHCb results or BaBar [2019 PRL **123** 091801]. The average of the inclusive determinations is also reported.*

also uses $B^0 \to D^{(*)-}\mu^+\nu_\mu$ as a normalisation mode, which has the key advantage that many systematic effects cancel in the ratio. With the form factors and relative efficiency-corrected yields in hand, obtaining $|V_{cb}|$ requires only a few more inputs: branching fractions that were well measured at the B-factories, and the ratio of B^0_s and B^0 production fractions measured at LHCb.

The values of $|V_{cb}|$ obtained are $(41.4 \pm 1.6) \times 10^{-3}$ and $(42.3 \pm 1.7) \times 10^{-3}$ in the CLN and BGL parametrisations, respectively. These results are compatible with each other and agree with previous measurements with exclusive decays, as well as the inclusive determination (figure 1). This new technique can also be applied to B^0 decays, giving excellent prospects for new $|V_{cb}|$ measurements at LHCb. They will also benefit from expected improvements at Belle II to a key external input, the $B^0 \to D^{(*)-}\mu^+\nu_\mu$ branching fraction. Belle II's own measurement of $|V_{cb}|$ is also expected to have reduced systematic uncertainties. In addition, new lattice QCD calculations for the full range of the D^{*-} recoil momentum are expected soon and should give valuable constraints on the form factors. This synergy between theoretical advances, Belle II and LHCb (and its upgrade, due to start in 2021) will very likely say the final word on the $|V_{cb}|$ puzzle.

Further reading

LHCb Collab. LHCb-PAPER-2019-041.

ATLAS

More plasma quenching seen in wide jets

Hard-scattering processes in hadronic collisions generate parton showers – highly collimated collections of quarks and gluons that subsequently fragment into hadrons, producing jets. In ultra-relativistic nuclear collisions, the parton shower evolves in a hot and dense quark–gluon plasma (QGP) created by the collision. Interactions of the partons with the plasma lead to reduced parton and jet energies, and modified properties. This phenomenon, known as jet quenching, results in the suppression of jet yields – a suppression that is hypothesised to depend on the structure of the jet. High-momentum shower components with a large angular separation are resolved by the medium, however, it is thought that the plasma has a characteristic angular scale below which they are not resolved, but interact as a single partonic fragment.

Using 5.02 TeV lead–lead collision

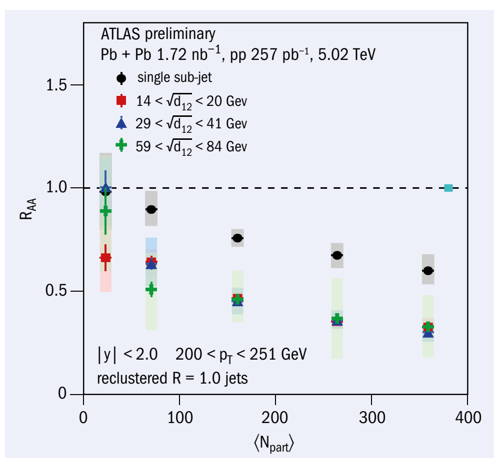


Fig. 1. *Jet quenching in the quark–gluon plasma (the suppression of jet multiplicity in lead–lead collisions relative to pp collisions), as a function of the number of participating nucleons (the centrality of the collision), for different jet substructures.*

data taken at the LHC in 2018 and corresponding pp data collected in 2017, ATLAS has measured large-radius jets by clustering smaller-radius jets with transverse momenta $p_T > 35$ GeV. (This procedure suppresses contributions from the underlying event and excludes soft radiation, so that the focus remains on hard partonic splittings.) The sub-jets are further re-clustered in order to obtain the splitting scale, $\sqrt{d_{12}}$, which represents the transverse momentum scale for the hardest splitting in the jet – a measure of the angular separation between the high-momentum components.

ATLAS has investigated the effect of the splitting scale on jet quenching using the nuclear modification factor (R_{AA}), which is the ratio between the jet yields measured in lead–lead and pp collisions, scaled by the estimated average number of binary nucleon–nucleon collisions. An R_{AA} value of unity ▷

indicates no suppression in the QGP, whereas a value below one indicates a suppressed jet yield. The measurement is corrected for background fluctuations and instrumental resolution via an unfolding procedure.

The figure shows R_{AA} for large-radius jets as a function of the average number of participating nucleons – a measure of the centrality of the collision, as glancing collisions involve only a handful of nucleons, whereas head-on collisions involve a large fraction of the 207 or so nucleons in each lead nucleus. R_{AA} is presented separately for large-radius jets with a single isolated high-momentum sub-jet and for those with multiple sub-jets in three intervals of the splitting scale $\sqrt{d_{12}}$. As expected, jets are increasingly suppressed for more head-on collisions (figure 1). More pertinently to this analysis, and for all centralities, yields of large-radius jets that consist of several sub-jets are found to be significantly more suppressed than those that consist of a single small-radius jet. This observation is qualitatively consistent with the hypothesis that jets with hard internal splittings lose more energy, and provides a new perspective on the role of jet structure in jet suppression. Further progress will require comparison with theoretical models.

Jets with hard internal splittings lose more energy

Further reading

ATLAS Collab. 2019 ATLAS-CONF-2019-056.

ALICE

ALICE probes extreme electromagnetic fields

When two lead nuclei collide in the LHC at an energy of a few TeV per nucleon, an extremely strong magnetic field of the order 10^{14}–10^{15} T is generated by the spectator protons, which pass by the collision zone without breaking apart in inelastic collisions. The strongest yet probed by scientists, this magnetic field, and in particular the rate at which it decays, is interesting to study since it probes unexplored properties of the quark–gluon plasma (QGP), such as its electric conductivity. In addition, chiral phenomena such as the chiral magnetic effect are expected to be induced by the strong fields. Left–right asymmetry in the production of negatively and positively charged particles relative to the collision reaction plane is one of the observables that is directly sensitive to electromagnetic fields. This asymmetry, called directed flow (v_1), is sensitive to two main competing effects: the Lorentz force experienced by charged particles (quarks) propagating in the magnetic field, and the Faraday effect – the quark current that is induced by the rapidly decreasing magnetic field. Charm quarks are produced in the early stages of heavy-ion collisions and are therefore more strongly affected by the electromagnetic fields than lighter quarks.

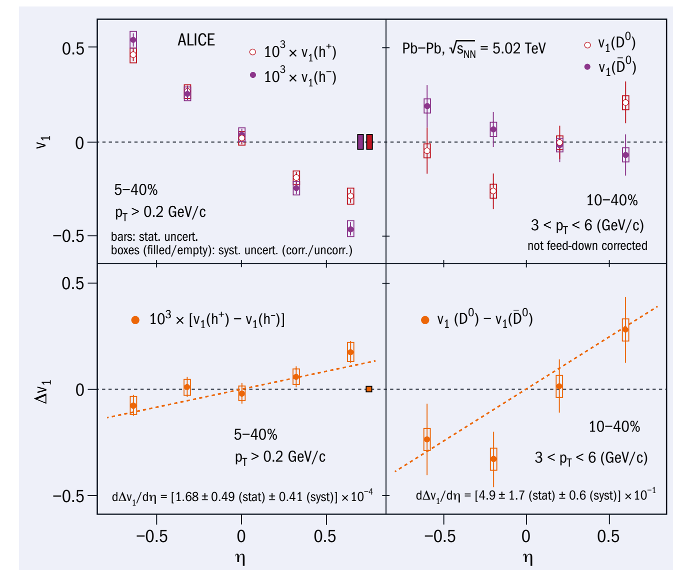


Fig. 1. *The directed flow v_1 of positively and negatively charged hadrons (left, scaled by a factor 10^3 for visibility) is three orders of magnitude smaller than for D^0 and $\bar{D}^0$ mesons (right). In both cases, the difference Δv, between the charge-conjugate species as a function of pseudorapidity η (bottom panels) has an opposite slope to model calculations.*

The ALICE collaboration has recently probed this effect by measuring the directed flow, v_1, for charged hadrons and $D^0/\bar{D}^0$ mesons as a function of pseudorapidity (η) in mid-central lead–lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Head-on (most central) collisions were excluded from the analyses because in those collisions there are very few spectator nucleons (almost all nucleons interact inelastically), which leads to a weaker magnetic field.

The top-left panel of the figure shows the η dependence of v_1 for charged hadrons (centrality class 5–40%). The difference Δv_1 between positively and negatively charged hadrons is shown in the bottom-left panel. The η slope is found to be $d\Delta v_1/d\eta = 1.68 \pm 0.49$ (stat) ± 0.41 (syst) $\times 10^{-4}$ – positive at 2.6σ significance. This measurement has a similar order of magnitude to recent model calculations of the expected effect for charged pions, but with the opposite sign.

The right-hand panels show the same analysis for the neutral charmed mesons D^0 ($c\bar{u}$) and $\bar{D}^0$ ($\bar{c}u$) (centrality class 10–40%). The measured directed flows are found to be about three orders of magnitude larger than for the charged hadrons, reflecting the stronger fields experienced immediately after the collision when the charm quarks are created. The slopes, which are seen to be positive for D^0 and negative for $\bar{D}^0$, are opposite and larger than in the model calculations. The slope of the differences in the directed flows is $d\Delta v_1/d\eta = 4.9 \pm 1.7$ (stat) ± 0.6 (syst) $\times 10^{-1}$ – positive at 2.7σ significance (lower-right panel). Also, in this case, the sign of the observed slope is opposite with respect to model calculations, suggesting that the relative contributions of the Lorentz and Faraday effects in those calculations are not correct.

Together with recent observations at RHIC, these LHC measurements provide an intriguing first sign of the effect of the large magnetic fields experienced in heavy-ion collisions on final-state particles. Measurements with larger data samples in Run 3 will have a precision sufficient to allow the contributions of the Lorentz force and the Faraday effect to be separated.

Further reading

ALICE Collab. 2019 arXiv:1910.14406.

CERNCOURIER

VOLUME 60 NUMBER 1 JANUARY/FEBRUARY 2020

IOP Publishing

CERN

CERNCOURIER.COM

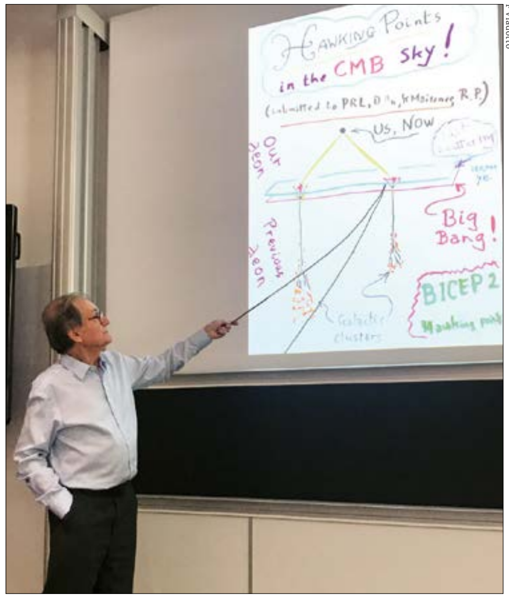
FIELD NOTES

Reports from events, conferences and meetings

TWISTORS AND LOOPS

When twistors met loops

Loop quantum gravity and twistor theory have a lot in common. They both have quantum gravity as a main objective, they both discard conventional space–time as the cornerstone of physics and they have both taken major inspiration from renowned British mathematician Roger Penrose. Interaction between the two communities has been minimal so far, however, due to their distinct research styles: mathematically oriented in twistor theory but focused on empirical support in loop gravity. This separation was addressed in early September 2019 at a conference held at the Centre International de Rencontres Mathématiques (CIRM) at the Luminy campus in Marseille, where around 100 researchers converged for lively debates designed to encourage cross-fertilisation between the two research lines.



Twist and shout *Roger Penrose's talk was the highlight of the Twistors and Loops conference.*

Space–time dissolves

Both twistor theory and loop gravity regard conventional smooth general-relativistic space–time as an approximate and emerging notion. Twistor theory was proposed by Roger Penrose as a general geometric framework for physics, with the long-term aim of unifying general relativity and quantum mechanics. The main idea of the theory is to work on the null rays, namely the space of the possible path that a light ray can follow in space–time, instead of the manifold of the points of physical space–time. Space–time points, or events, are then seen as derived objects: they are given by compact holomorphic curves in a complex three-fold: twistor space. It is remarkable how much the main equations of fundamental physics simplify when formulated in these terms. The mathematics of twistors has its roots in the 19th century Klein correspondence in projective geometry, and modern twistor theory has had a strong impact on pure mathematics, from differential geometry and representation theory to gauge theories and integrable systems.

Loop gravity, on the other hand, is a background-independent theory of quantum gravity. That is, it does not treat space–time as the background on which physics happens, but rather as a dynamical entity itself, satisfying quantum theory. The conventional smooth general relativistic space–time emerges in the classical ($\hbar \rightarrow 0$) limit, in the same manner as a smooth electromagnetic field satisfying the Maxwell equations emerges from the Fock space of the photons in the classical limit of quantum electrodynamics. Similarly, the full dynamics of classical general relativity is recovered from the quantum dynamics of loop gravity in the suitable limit. The transition amplitudes of the theory are finite in the ultraviolet and are expressed as multiple integrals over non-compact groups. The theory provides a compelling picture of quantum space–time. A basis in the Hilbert space of the theory is described by the mathematics of the spin networks: graphs with links labelled by SU(2) irreducible representations, independently introduced by Penrose in the early 1970s in an attempt to a fully discrete combinatorial picture of quantum physical space. Current applications of loop gravity include early cosmology, where the possibility of a bounce replacing the Big Bang has been extensively studied using loop-gravity methods, and black holes, where the theory's amplitudes can be used to study the non-perturbative transition at the end of the Hawking evaporation.

Could allying twistors and loops be dangerous?

A fertile union

The communities working in twistors and loops share technical tools and conceptual pillars, but have evolved independently for many years, with different methods and different intermediate goals. But recent developments discussed at the Marseille conference saw twistors appearing in formulations of the loop-gravity amplitudes, confirming the fertility and the versatility of the twistor idea, and raising intriguing questions about possible deeper relations between the two theories.

The conference was a remarkable success. It is not easy to communicate across research programmes in contemporary fundamental physics because a good part of the field is stalled in communities blocked by conflicting assumptions, ingrained prejudices and seldom-questioned judgments, making understanding one another difficult. The vibrant atmosphere of the Marseille conference cut through this.

The best moment came during Penrose's talk. Towards the end of a long and dense presentation of new ideas towards understanding the full space of the solutions of Einstein's theory using twistors, Roger said rather dramatically that now he was going to present a new, big idea that might lead to the twistor version of the full Einstein equations – but at that precise moment the slide projector exploded in a cloud of smoke, with sparks flying. We all thought for a moment that a secret power of the universe, worried about being unmasked, had interfered. Could allying twistors and loops be dangerous?

Carlo Rovelli *Aix-Marseille University.*

CERNCOURIER
VOLUME 60 NUMBER 1 JANUARY/FEBRUARY 2020
IOP Publishing

Colloquium

CERN's proton synchrotron turns 60

On 24 November 1959, CERN's Proton Synchrotron (PS) first accelerated beams to an energy of 24 GeV. 60 years later, it is still at the heart of CERN's accelerator complex, delivering beams to the fixed-target physics programme and the LHC with intensities exceeding the initial specifications by orders of magnitude. To celebrate the anniversary a colloquium was held at CERN on 25 November 2019, with PS alumni presenting important phases in the life of the accelerator.

The PS is CERN's oldest operating accelerator, and, together with its sister machine, the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory in the US, one of the two oldest still operating accelerators in the world. Both designs are based on the innovative concept of the alternating gradient, or strong-focusing, principle developed by Ernest Courant, Milton Stanley Livingston, Hartland Snyder and John Blewett. This technique allowed a significant reduction in the size of the vacuum chambers and magnets, and unprecedented beam energies. In 1952 the CERN Council endorsed a study for a synchrotron based on the alternating-gradient principle, and construction of a machine with a design-energy range from 20 to 30 GeV was approved in October 1953. Its design, manufacture and construction took place from 1954 to 1959. Protons made first turns on 16 September 1959, and on 24 November beam was accelerated beyond transition and to an energy of 24 GeV. On 8 December the design energy of 28.3 GeV was reached and the design intensity exceeded, at 3×10^{10} protons per pulse.

P.S. I love you *Construction of the tunnel for the Proton Synchrotron took place from 1955 to 1957.*

Margherita *The first combined-function magnet, named after particle-physicist Margherita Cavallaro (pictured here), was completed in 1956, and is still in use today.*

The PS has proven to be a flexible design, with huge built-in potential. Though the first experiments were performed with internal targets, extractions to external targets were soon added to the design, and further innovative extraction schemes were added through the years. On the accelerator side, the intensity was progressively ramped up, with the commissioning of the PS Booster in 1972, the repeated increase of the injection energy, and many improvements in the PS itself. Through the years more and more users requested beam from the PS, for example the EAST area, antiproton physics, and a neutron time-of-flight facility.

With the commissioning of the ISR, SPS, LEP and LHC machines, the PS took on a new role as an injector of protons, antiprotons, leptons and ions, while continuing its own physics programme. A new challenge was the delivery of beams for the LHC: these beams need to be transversely very dense ("bright"), and have a longitudinal structure that is generated using the different radio-frequency systems of the PS, with the PS thereby contributing its fair share to the success of the LHC. And there are more challenges ahead. The LHC's high-luminosity upgrade programme demands beam parameters out of reach for today's injector complex, motivating the ambitious LHC Injectors Upgrade Project (*CERN Courier* October 2017 p33). Installations are now in full swing, and Run 3 will take CERN's PS into a new parameter regime and into another interesting chapter in its life.

Klaus Hanke *CERN.*

CPT'19

Space–time symmetries scrutinised in Indiana

The space–time symmetries of physics demand that experiments yield identical results under continuous Lorentz transformations – rotations and boosts – and under the discrete CPT transformation (the combination of charge conjugation, parity inversion and time reversal). The Standard-Model Extension (SME) provides a framework for testing these symmetries by including all operators that break them in an effective field theory. The first CPT and Lorentz Symmetry meeting, in Bloomington, Indiana, in 1998, featured the first limits on SME coefficients. Last year's event, the 8th in the triennial series, brought 100 researchers together from 12 to 16 May 2019 at the Indiana University Center for Spacetime Symmetries, to sample a smorgasbord of ongoing SME studies.

The SME has revealed uncharted territory that requires theoretical and experimental expertise to navigate

Most physics is described by operators of mass dimension three or four that are quadratic in the conventional fields – for example the Dirac lagrangian contains an operator $\bar{\psi}\,\partial\!\!\!/\,\psi$ (mass dimension $3/2 + 1 + 3/2 = 4$) and an operator $\bar{\psi}\,\psi$ (mass dimension $3/2 + 3/2 = 3$), with the latter controlled by an additional mass coefficient – however, the search for fundamental symmetry violations may need to employ operators of higher mass dimensions and higher order in the fields. One example is the Lorentz-breaking lagrangian-density term $(k_{VV})^{\mu\nu}(\bar{\psi}\,\gamma_\mu\,\psi)(\bar{\psi}\,\gamma_\nu\,\psi)$, which is quartic in the fermion field ψ. The coefficient k_{VV} carries units of GeV^{-2} and controls the operator, which has mass dimension six. Searches for Lorentz-symmetry breaking seek nonzero values for coefficients like k_{VV}. In the 21 years since the first CPT meeting, theoretical studies have uncovered how to write down the myriad operators that describe hypothetical Lorentz violations in both flat and curved space–times. Meanwhile, experiments in particle physics, atomic ▷

Back to Bloomington *The eighth CPT and Lorentz Symmetry meeting took place at Indiana University.*

physics, astrophysics and gravitational physics continue to place exquisitely tight bounds on the SME coefficients, motivated by the intriguing prospect of finding a crack in the Lorentz symmetry of nature (*CERN Courier* December 2016 p21).

Comparisons between matter and antimatter offer rich prospects for testing Lorentz symmetry, because individual SME coefficients can be isolated. The AEgIS, ALPHA, ASACUSA, ATRAP, BASE and gBAR collaborations at CERN, as well as ones at other institutions, are working to develop the challenging technology for such tests. Several presenters discussed Penning traps – devices that confine charged particles in a static electromagnetic field – for storing and mixing the ingredients for antihydrogen, the production of antihydrogen, spectroscopy for the hyperfine and 1S–2S transitions, and the prospects for interferometric measurements of antimatter acceleration. The commissioning of ELENA, CERN's 30 m-circumference antiproton deceleration ring, promises larger quantities of relatively slow-moving antiprotons in support of this work.

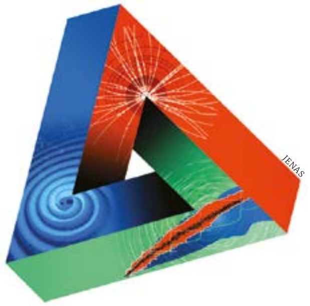
Lorentz violation can occur independently in each sector of the particle world, and participants discussed existing and future limits on SME coefficients based on the muon g-2 experiment at Fermilab, neutrino oscillations at Daya Bay in China, kaon oscillations in Frascati, and on positronium decay using the Jagellonian PET detector (*CERN Courier* November 2018 p17), to name a few. Dozens of Lorentz-symmetry tests have probed the photon sector of the SME with table-top devices such as atomic clocks and resonant cavities, and with astrophysical polarisation measurements of sources such as active galactic nuclei, which leverage vast distances to limit cumulative effects such as the rotation of a polarisation angle. In the gravity sector, SME coefficient bounds were presented from the 2015 gravity-wave detection by the LIGO collaboration, as well as from observations of pulsars, cosmic rays and other phenomena with signals that are proportional to the travel distance. Symmetry-breaking signals are also sought in matter-gravity interactions with test masses, and here CPT'19 included discussions of short-range spin-dependent gravity and neutron-interferometry physics.

The SME has revealed uncharted territory that requires theoretical and experimental expertise to navigate. CPT'19 showed that there is no shortage of physicists with the adventurous spirit to explore this frontier further.

Neil Russell *Northern Michigan University.*

JENAS

APPEC, ECFA and NuPECC join forces



Not impossibly tribal *A Penrose triangle was used to symbolise how astroparticle, particle and nuclear physics are intertwined.*

The first joint meeting of the European Committee for Future Accelerators (ECFA), the Nuclear Physics European Collaboration Committee (NuPECC), and the Astroparticle Physics European Consortium (APPEC) took place on 14–16 October in Orsay, France. Making progress in domains such as dark matter, neutrinos and gravitational waves increasingly requires interdisciplinary approaches to scientific and technological challenges, and the new Joint ECFA-NuPECC-APPEC Seminar (JENAS) events are designed to reinforce links between astroparticle, nuclear and particle physicists.

Jointly organised by LAL-Orsay, IPN-Orsay, CSNSM-Orsay, IRFU-Saclay and LPNHE-Paris, the inaugural JENAS meeting saw 230 junior and senior members of the three communities discuss overlapping interests. Readout electronics, silicon photomultipliers, big-data computing and artificial intelligence were just a handful of the topics discussed. For example, the technological evolution of silicon photomultipliers, which are capable of measuring single-photon light signals and can operate at low voltage and in magnetic fields, will be key both for novel calorimeters and timing detectors at the high-luminosity LHC. They will also be used in the Cherenkov Telescope Array – an observatory of more than 100 telescopes that will be installed at La Palma in the northern hemisphere, and in the Atacama Desert in the southern hemisphere, becoming the world's most powerful instrument for ground-based gamma-ray astronomy.

As chairs of the three consortia, we issued a call for novel expressions of interest

Organisational synergies related to education, outreach, open science, open software and careers were also identified, and a diversity charter was launched by the three consortia, whereby statistics on relevant parameters will be collected at each conference and workshop in the three subfields. This will allow the communities to verify how well we embrace diversity.

As chairs of the three consortia, we issued a call for novel expressions of interest to tackle common challenges in subjects as diverse as computing and the search for dark matter. Members of the high-energy physics and related communities can submit their ideas, in particular those concerning synergies in technology, physics, organisation and applications. APPEC, ECFA and NuPECC will discuss and propose actions in advance of the next JENAS event in 2021.

Jorgen D'Hondt *ECFA chair,* **Marek Lewitowicz** *NuPECC chair and* **Teresa Montaruli** *APPEC chair.*

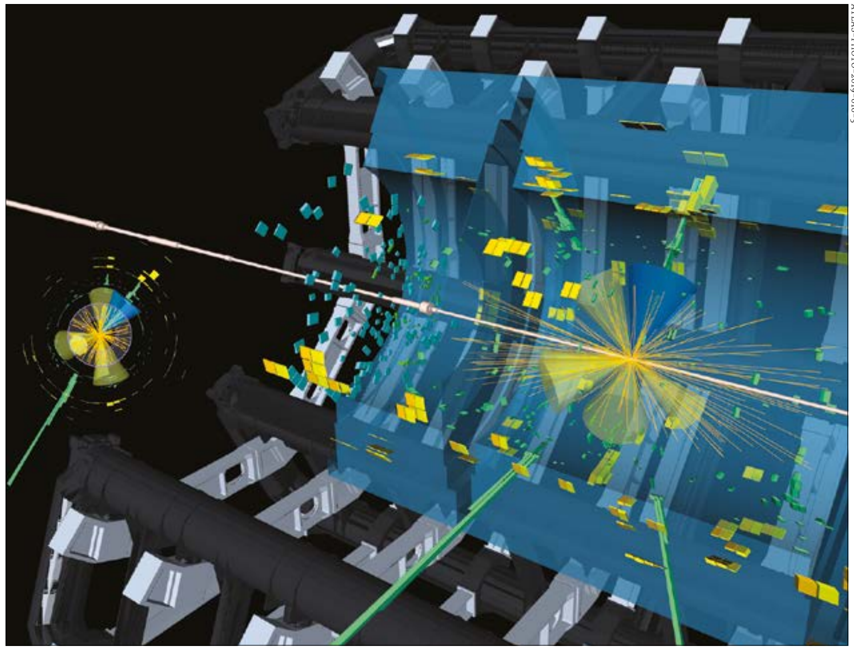
Higgs Couplings 2019

Last stop for the Higgs Couplings workshop

Higgs-boson measurements are entering the precision regime, with Higgs couplings to gauge bosons now measured to better than 10% precision, and its decays to third-generation fermions measured to better than 20%. These and other recent experimental and theoretical results were the focus of discussions at the eighth international Higgs Couplings workshop, held in Oxford from 30 September to 4 October 2019. Making its final appearance with this moniker (it will be rebranded as Higgs 2020), the conference programme comprised 38 plenary and 46 parallel talks attended by 120 participants.

The first two days of the conference reviewed Higgs measurements, including a new ATLAS measurement of ttH production using Higgs-boson decays to leptons, and a differential measurement of Higgs-boson production in its decays to W-boson pairs using all of the CMS data from Run 2. These measurements showed continuing progress in coupling measurements, but the highlight of the precision presentations was a new determination of the Higgs-boson mass from CMS using its decays to two photons. Combining this result with previous CMS measurements gives a Higgs-boson mass of 125.35 ± 0.15 GeV, corresponding to an impressive relative precision of 0.12%. From the theory side, the challenges of keeping up with experimental precision were discussed. For example, the Higgs-boson production cross section is calculated to the highest order of any observable in perturbative QCD, and yet it must be predicted even more precisely to match the expected experimental precision of the HL-LHC.

One of the highest priority targets of the HL-LHC is the measurement of the self-coupling of the Higgs boson, which is expected to be determined to 50% precision. This determination is based on double-Higgs production, to which the self-coupling contributes when a virtual Higgs boson splits into two Higgs bosons. ATLAS and CMS have performed extensive searches for two-Higgs production using data from 2016, and at the conference ATLAS presented an updated self-coupling constraint using a combination of single- and double-Higgs measurements and searches. Allowing only the self-coupling to be modified by a factor κ_λ in the loop corrections yields a constraint on the Higgs self-coupling of $-2.3 < \kappa_\lambda < 10.3$ times the Standard Model prediction at 95% confidence.



ATLAS-PHOTO-2019-016-1

Two towers *ATLAS and CMS data are driving down uncertainties on the Higgs couplings.*

ATLAS presented an updated self-coupling constraint

The theoretical programme of the conference included an overview of the broader context for Higgs physics, covering the possibility of generating the observed matter–antimatter asymmetry through a first-order electroweak phase transition, as well as possibilities for generating the Yukawa coupling matrices. In the so-called electroweak baryogenesis scenario, the cooling universe developed bubbles of broken electroweak symmetry with asymmetric matter–antimatter interactions at the boundaries, with sphalerons in the electroweak-symmetric space converting the resulting matter asymmetry into a baryon asymmetry. The matter-asymmetric interactions could have arisen through Higgs-boson couplings to fermions or gauge bosons, or through its self-couplings. In the latter case the source could be an additional electroweak singlet or doublet modifying the Higgs potential.

The broader interpretation of Higgs-boson measurements and searches was discussed both in the case of specific models and in the Standard Model effective field theory, where new particles appear at significantly higher masses (~1 TeV or more). The calculations in the effective field theory continue to advance, adding higher orders in QCD to more electroweak processes, and an analytical determination of the dependence of the Higgs decay width on the theory parameters. Constraints on the number and values of these parameters also continue to improve through an expanded use of input measurements.

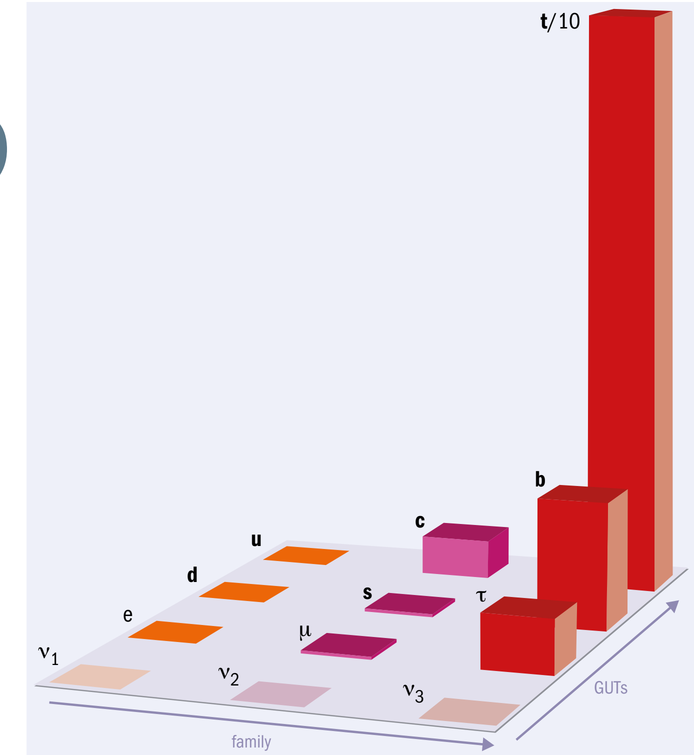
The conference wrapped up with a look into the crystal ball of future detectors and colliders, with a sobering yet inspirational account of detector requirements at the next generation of colliders. To solve the daunting challenges, the audience was encouraged to be creative and explore new technologies, which will likely be needed to succeed. Various collider scenarios were also presented in the context of the European Strategy update, which will wrap up early next year.

The newly minted Higgs conference will be held in late October or early November of 2020 in Stonybrook, New York.

Chris Hays *University of Oxford.*

WHO ORDERED ALL OF THAT?

Explaining the bizarre pattern of fermion types and masses has led theorists to explore more complex symmetry groups than the Standard Model's, with recent work suggesting that the "flavour scale" could be at a much lower energy than previously thought.



A Tovey

Family affair *The Standard Model offers no explanation for why the masses of quarks and leptons (represented by the heights of the towers) span at least 12 orders of magnitude. Grand unified theories (GUTs) or a new "family" symmetry, acting in the directions shown, may provide insights.*

The origin of the three families of quarks and leptons and their extreme range of masses is a central mystery of particle physics. According to the Standard Model (SM), quarks and leptons come in complete families that interact identically with the gauge forces, leading to a remarkably successful quantitative theory describing practically all data at the quantum level. The various quark and lepton masses are described by having different interaction strengths with the Higgs doublet (figure 1, left), also leading to quark mixing and charge-parity (CP) violating transitions involving strange, bottom and charm quarks. However, the SM provides no understanding of the bizarre pattern of quark and lepton masses, quark mixing or CP violation.

In 1998 the SM suffered its strongest challenge to date with the decisive discovery of neutrino oscillations resolving the atmospheric neutrino anomaly and the long-standing problem of the low flux of electron neutrinos from the Sun. The observed neutrino oscillations require at least two non-zero but extremely small neutrino masses, around one ten millionth of the electron mass or so, and three sizeable mixing angles. However, since the minimal SM assumes massless neutrinos, the origin and nature of neutrino masses (i.e. whether they are Dirac or Majorana particles, the latter requiring the neutrino and antineutrino to be related by CP conjugation) and mixing is unclear, and many possible SM extensions have been proposed.

The discovery of neutrino mass and mixing makes the flavour puzzle hard to ignore, with the fermion mass hierarchy now spanning at least 12 orders of magnitude, from the neutrino to the top quark. However, it is not only the fermion mass hierarchy that is unsettling. There are now 28 free parameters in a Majorana-extended SM, including a whopping 22 associated with flavour, surely too many for a fundamental theory of nature. To restate Isidor Isaac Rabi's famous question following the discovery of the muon in 1936: who ordered *all* of that?

A theory of flavour

There have been many attempts to formulate a theory beyond the SM that can address the flavour puzzles. Most attempt to enlarge the group structure of the SM describing the strong, weak and electromagnetic gauge forces: $SU(3)_C \times SU(2)_L \times U(1)_Y$ (see "A taste of flavour in elementary particle physics" panel). The basic premise is that, unlike in the SM, the three families are distinguished by some new quantum numbers associated with a new family or

THE AUTHOR

Stephen F King *School of Physics and Astronomy, University of Southampton, UK.*

CERNCOURIER

Volume 60 Number 1 January/February 2020

IOP Publishing

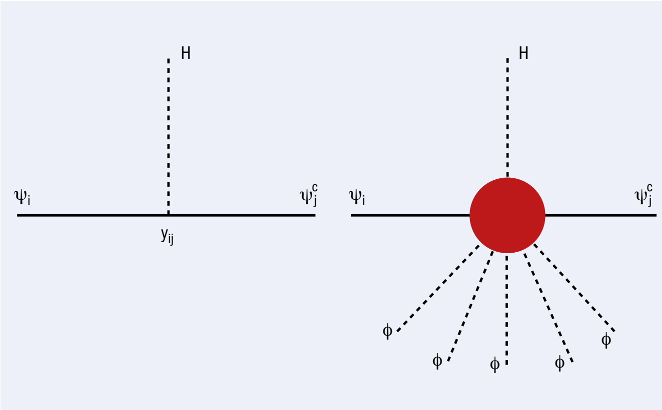


Fig. 1. *Left: Yukawa couplings, y_{ij}, between the Higgs doublet, H, a left-handed fermion, ψ_i, and the CP conjugate of a right-handed fermion, ψ_j^c. Right: how the Yukawa coupling could arise effectively due to a contact interaction involving multiple flavon fields, φ.*

flavour symmetry group, G_{fl}, which is tacked onto the SM gauge group, enlarging the structure to $G_{fl} \times SU(3)_C \times SU(2)_L \times U(1)_Y$. The earliest ideas dating back to the 1970s include radiative fermion-mass generation, first proposed by Weinberg in 1972, who supposed that some Yukawa couplings might be forbidden at tree level by a flavour symmetry but generated effectively via loop diagrams. Alternatively, the Froggatt–Nielsen (FN) mechanism in 1979 assumed an additional $U(1)_{fl}$ symmetry under which the quarks and leptons carry various charges.

To account for family replication and to address the question of large lepton mixing, theorists have explored a larger non-Abelian family symmetry, $SU(3)_{fl}$, where the three families are analogous to the three quark colours in quantum chromodynamics (QCD). Many other examples have been proposed based on subgroups of $SU(3)_{fl}$, including discrete symmetries (figure 2, right). More recently, theorists have considered extra-dimensional models in which the Higgs field is located at a 4D brane, while the fermions are free to roam over the extra dimension, overlapping with the Higgs field in such a way as to result in hierarchical Yukawa couplings. Still other ideas include partial compositeness in which fermions may get hierarchical masses from the mixing between an elementary sector and a composite one. The possibilities are seemingly endless. However, all such theories share one common question: what is the scale, M_{fl}, (or scales) of new physics associated with flavour?

The discovery of neutrino mass and mixing makes the flavour puzzle hard to ignore

Since experiments at CERN and elsewhere have thoroughly probed the electroweak scale, all we can say for sure is that, unless the new physics is extremely weakly coupled, M_{fl} can be anywhere from the Planck scale (10^{19} GeV), where gravity becomes important, to the electroweak scale at the mass of the W boson (80 GeV). Thus the flavour scale is very unconstrained.

To illustrate the unknown magnitude of the flavour scale, consider for example the FN mechanism, where M_{fl} is associated with the breaking of the $U(1)_{fl}$ symmetry. In the SM the top-quark mass of 173 GeV is given by a Yukawa coupling times the Higgs vacuum expectation value of 246 GeV divided by the square root of two. This implies a top-quark Yukawa coupling close to unity. The exact value is not important, what matters is that the top Yukawa coupling is of order unity. From this point of view, the top quark mass is not at all puzzling – it is the other fermion masses associated with much smaller Yukawa couplings that require explanation. According to FN, the fermions are assigned various $U(1)_{fl}$ charges and small Yukawa couplings are forbidden due to a $U(1)_{fl}$ symmetry. The symmetry is broken by the vacuum expectation value of a new "flavon" field $\langle\varphi\rangle$, where φ is a neutral scalar under the SM but carries one unit of $U(1)_{fl}$ charge. Small Yukawa couplings then originate from an operator (figure 1, right) suppressed by powers of the small ratio $\langle\varphi\rangle/M_{fl}$ (where M_{fl} acts as a cut-off scale of the contact interaction).

For example, suppose that the ratio $\langle\varphi\rangle/M_{fl}$ is identified with the Wolfenstein parameter $\lambda = \sin\theta_C = 0.225$ (where θ_C is the Cabibbo angle appearing in the CKM quark-mixing matrix). Then the fermion mass hierarchies can be explained by powers of this ratio, controlled by the assigned $U(1)_{fl}$ charges: $m_e/m_\tau \sim \lambda^5$, $m_\mu/m_\tau \sim \lambda^2$, $m_d/m_b \sim \lambda^4$, $m_s/m_b \sim \lambda^2$, $m_u/m_t \sim \lambda^8$ and $m_c/m_t \sim \lambda^4$. This shows how fermion masses spanning many orders of magnitude may be interpreted as arising from integer $U(1)_{fl}$ charge assignments of less than 10. However, in this approach, M_{fl} may be anywhere from the Planck scale to the electroweak scale by adjusting $\langle\varphi\rangle$ such that the ratio $\lambda = \langle\varphi\rangle/M_{fl}$ is held fixed.

One possibility for M_{fl}, reviewed by Kaladi Babu at Oklahoma State University in 2009, is that it is not too far from the scale of grand unified theories (GUTs), of order 10^{16} GeV, which is the scale at which the gauge couplings associated with the SM gauge group unify into a single gauge group. The simplest unifying group, $SU(5)_{GUT}$, was proposed by Georgi and Glashow in 1974, following the work of Pati and Salam based on $SU(4)_C \times SU(2)_L \times SU(2)_R$. Both these gauge groups can result from $SO(10)_{GUT}$, which was discovered by Fritzsch and Minkowski (and independently by Georgi), while many other GUT groups and subgroups have also been studied (figure 2, left). However, GUT groups by themselves only unify quarks and leptons within a given family, and while they may provide an explanation for why $m_b = 2.4\, m_\tau$, as discussed by Babu, they do not account for the fermion mass hierarchies.

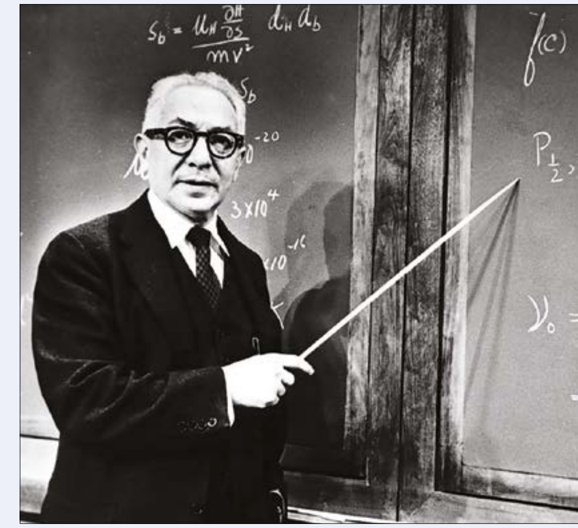
Broken symmetries

A way around this, first suggested by Ramond in 1979, is to combine GUTs with family symmetry based on the product group $G_{GUT} \times G_{fl}$, with symmetries acting in the specific directions shown in the figure "Family affair". In order not to spoil the unification of the gauge couplings, the flavour-symmetry breaking scale is often assumed to be close to the GUT breaking scale. This also enables the dynamics of whatever breaks the GUT symmetry, be it Higgs fields

A TASTE OF FLAVOUR IN ELEMENTARY PARTICLE PHYSICS

The origin of flavour can be traced back to the discovery of the electron – the first elementary fermion – in 1897. Following the discovery of relativity and quantum mechanics, the electron and the photon became the subject of the most successful theory of all time: quantum electrodynamics (QED). However, the smallness of the electron mass ($m_e = 0.511$ MeV) compared to the mass of an atom has always intrigued physicists.

The mystery of the electron mass was compounded by the discovery in 1936 of the muon with a mass of 207 m_e but otherwise seemingly identical properties to the electron. This led Isidor Isaac Rabi to quip "who ordered that?". Four decades later, an even heavier version of the electron was discovered, the tau lepton, with mass $m_\tau = 17\, m_\mu$. Yet the seemingly arbitrary values of the masses of the charged leptons are only part of the story. It soon became clear that hadrons were made from quarks that come in three colour charges mediated by gluons under a $SU(3)_C$ gauge theory, quantum chromodynamics (QCD). The up and down quarks of the first family have intrinsic masses $m_u = 4\, m_e$ and $m_d = 10\, m_e$, accompanied by the charm and strange quarks ($m_c = 12\, m_\mu$ and $m_s = 0.9\, m_\mu$) of a second family and the heavyweight top and bottom quarks ($m_t = 97\, m_\tau$ and $m_b = 2.4\, m_\tau$) of a third family.



Columbia University

Good taste *I I Rabi, who won the Nobel Prize in Physics in 1944 for his discovery of nuclear magnetic resonance.*

It was also realised that the different quark "flavours", a term invented by Gell-Mann and Fritzsch, could undergo mixing transitions. For example, at the quark level the radioactive decay of a nucleus is explained by the transformation of a down quark into an up quark plus an electron and an electron antineutrino. Shortly after Pauli hypothesized the neutrino in 1930, Fermi proposed a theory of weak interactions based on a contact interaction between the four fermions, with a coupling strength given by a dimensionful constant G_F, whose scale was later identified with the mass of the W boson: $G_F \propto 1/m_W^2$.

After decades of painstaking observation, including the discovery of parity violation, whereby only left-handed particles experience the weak interaction, Fermi's theory of weak interactions and QED were merged into an electroweak theory based on $SU(2)_L \times U(1)_Y$ gauge theory. The left-handed (L) electron and neutrino form a doublet under $SU(2)_L$, while the right-handed electron is a singlet, with the doublet and singlet carrying hypercharge $U(1)_Y$ and the pattern repeating for the second and third lepton families. Similarly, the left-handed up and down quarks form doublets, and so on. The electroweak $SU(2)_L \times U(1)_Y$ symmetry is spontaneously broken to $U(1)_{QED}$ by the vacuum expectation value of the neutral component of a new doublet of complex scalar boson fields called the Higgs doublet. After spontaneous symmetry breaking, this results in massive charged W and neutral Z gauge bosons, and a massive neutral scalar Higgs boson – a picture triumphantly confirmed by experiments at CERN.

To truly shed light on the Standard Model's flavour puzzle, theorists have explored higher and more complex symmetry groups than the Standard Model. The most promising approaches all involve a spontaneously broken family or flavour symmetry. But the flavour-breaking scale may lie anywhere from the Planck scale to the electroweak scale, with grand unified theories suggesting a high flavour scale, while recent hints of anomalies from LHCb and other experiments suggest a low flavour scale.

or some mechanism associated with compactification of extra dimensions, to be applied to the flavour breaking. Thus, in such theories, the GUT and flavour/family symmetry are both broken at or around $M_{fl} \sim M_{GUT} \sim 10^{16}$ GeV, as widely discussed by many authors. In this case, it would be impossible given known technology to directly experimentally access the underlying theory responsible for unification and flavour. Instead, we would need to rely on indirect probes such as proton decay (a generic prediction of GUTs and hence of these enlarged SM structures proposed to explain flavour) and/or charged-lepton flavour-violating processes such as $\mu \to e\gamma$ (see *CERN Courier* May/June 2019 p45).

New ideas for addressing the flavour problem continue to be developed. For example, motivated by string theory, Ferruccio Feruglio of the University of Padova suggested in 2017 that neutrino masses might be complex analytic functions called modular forms. The starting point of this novel idea is that non-Abelian discrete family symmetries may arise from superstring theory in compactified extra dimensions, as a finite subgroup of the modular symmetry of such theories (i.e. the symmetry associated with the non-unique choice of basis vectors spanning a given extra-dimensional lattice). It follows that the 4D effective Lagrangian must respect modular symmetry. This, Feruglio observed, implies that Yukawa couplings may be modular forms. So if the leptons transform as triplets under some finite subgroup of the modular symmetry, then the Yukawa couplings themselves must transform also as triplets, but with a well defined structure depending on only one free parameter: the complex modulus field. At a stroke, this removes the need for flavon fields and

CERNCOURIER
Volume 60 Number 1 January/February 2020
IOP Publishing

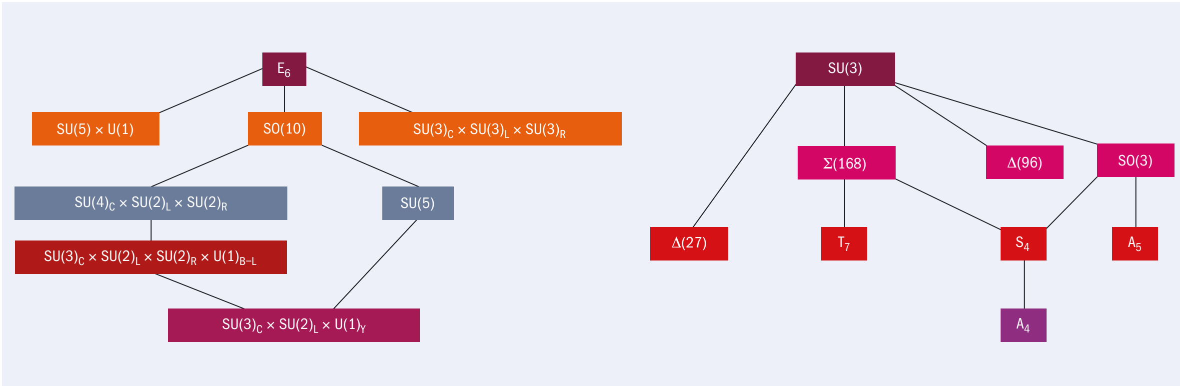


Fig. 2. *Left: some GUT groups based on E_6 or one of its subgroups. Right: some candidate family-symmetry groups based on SU(3) or one of its subgroups, which admit irreducible triplet representations and thereby provide an explanation for three families and large lepton mixing.*

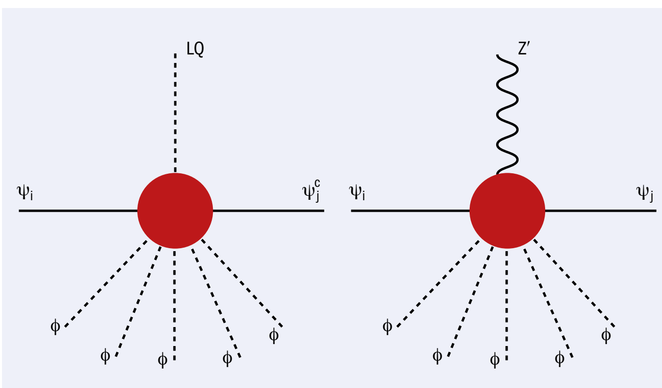


Fig. 3. *The leptoquark (LQ) or Z′ may couple to quarks and leptons via the same kind of effective operators as those responsible for the effective Higgs Yukawa couplings.*

ad hoc vacuum alignments to break the family symmetry, and potentially greatly simplifies the particle content of the theory.

Compactification

Although this approach is currently actively being considered, it is still unclear to what extent it may shed light on the entire flavour problem including all quark and lepton mass hierarchies. Alternative string-theory motivated ideas for addressing the flavour problem are also being developed, including the idea that flavons can arise from the components of extra-dimensional gauge fields and that their vacuum alignment may be achieved as a consequence of the compactification mechanism.

The flavour scale is very unconstrained

Recently, there have been some experimental observations concerning charged lepton flavour universality violation which hint that the flavour scale might not be associated with the GUT scale, but might instead be just around the corner at the TeV scale (*CERN Courier* May/June 2019 p33). Recall that in the SM the charged leptons e, μ and τ interact identically with the gauge forces, and differ only in their masses, which result from having different Yukawa couplings to the Higgs doublet. This charged lepton flavour universality has been the subject of intense experimental scrutiny over the years and has passed all the tests – until now. In recent years, anomalies have appeared associated with violations of charged lepton flavour universality in the final states associated with the quark transitions $b \to c$ and $b \to s$.

Puzzle solving

In the case of $b \to c$ transitions, the final states involving τ leptons appear to violate charged lepton universality. In particular $B \to D^{(*)} \ell \nu_\ell$ decays where the charged lepton ℓ is identified with τ have been shown by Babar and LHCb to occur at rates somewhat higher than those predicted by the SM (the ratios of such final states to those involving electrons and muons being denoted by R_D and R_{D^*}). This is quite puzzling since all three types of charged leptons are predicted to couple to the W boson equally, and the decay is dominated by tree-level W exchange. Any new-physics contribution, such as the exchange of a new charged Higgs boson, a new W′ or a leptoquark, would have to compete with tree-level W exchange. However, the most recent measurements by Belle, reported at the beginning of 2019 (*CERN Courier* May/June 2019 p9), measure R_D and R_{D^*} to be closer to the SM prediction.

In the case of $b \to s$ transitions, the LHCb collaboration and other experiments have reported a number of anomalies in $B \to K^{(*)} \ell^+ \ell^-$ decays such as the R_K and R_{K^*} ratios of final states containing $\mu^+\mu^-$ versus e^+e^-, which are measured deviate from the SM by about 2.5 standard deviations. Such anomalies, if they persist, may be accounted for by a new contact operator coupling the four fermions $b_L s_L \mu_L \mu_L$ suppressed by a dimensionful coefficient M^2_{new}, where M_{new} ~30 TeV, according to a general operator analysis. This hints that there may be new physics arising from the non-universal couplings of leptoquark and/or a new Z′ whose mass is typically a few TeV in order to generate such an operator (where the 30 TeV scale is reduced to just a few TeV after mixing angles are taken into account). However, the introduction of these new particles increases the SM parameter count still further, and only serves to make the flavour problem of the SM worse.

Link-up

Motivated by such considerations, it is tempting to speculate that these recent empirical hints of flavour non-universality may be linked to a possible theory of flavour. Several authors have hinted at such a connection, for example Riccardo Barbieri of Scuola Normale Superiore, Pisa, and collaborators have related these observations to a U(2)[5] flavour symmetry in an effective theory framework. In addition, concrete models have recently been constructed that directly relate the effective Yukawa couplings to the effective leptoquark and/or Z′ couplings. In such models the scale of new physics associated with the mass of the leptoquark and/or a new Z′ may be identified with the flavour scale M_{fl} defined earlier, except that it should be not too far from the TeV scale in order to explain the anomalies. To achieve the desired link, the effective leptoquark and/or Z′ couplings may be generated by the same kinds of operators responsible for the effective Higgs Yukawa couplings (figure 3).

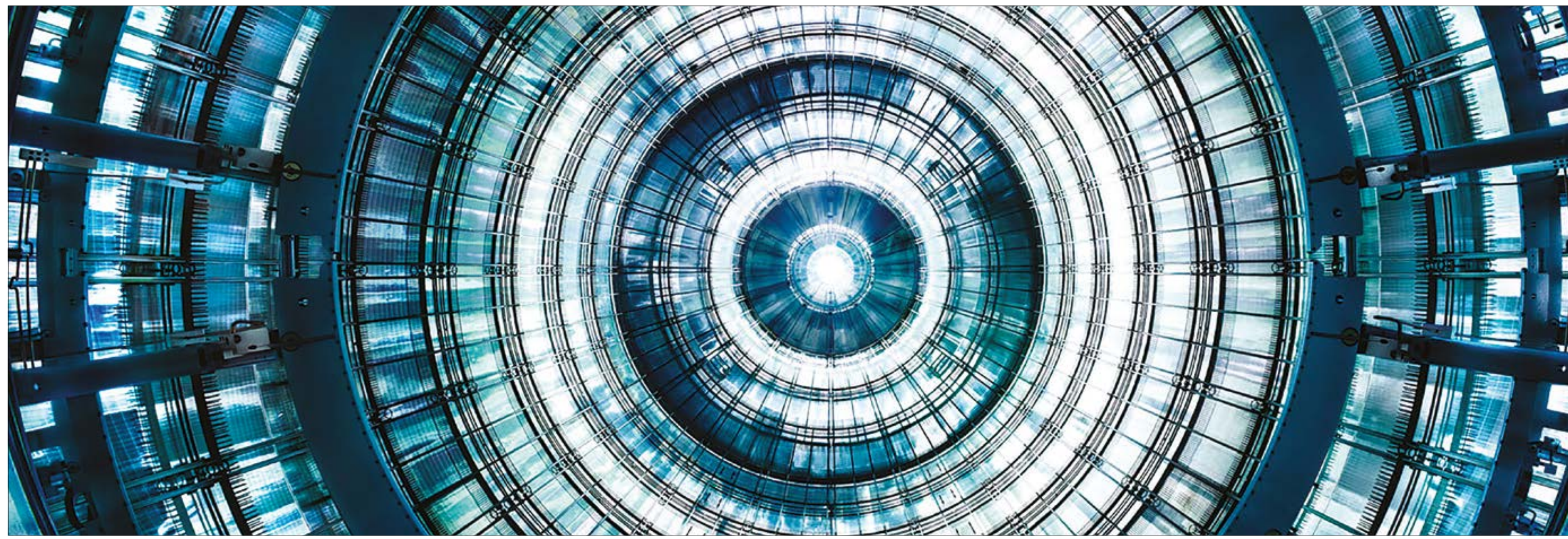
In such a model the couplings of leptoquarks and/or Z′ bosons may be related to the Higgs Yukawa couplings, with all couplings arising effectively from mixing with a vector-like fourth family. The considered model predicts, apart from the TeV scale leptoquark and/or Z′, and a slightly heavier fourth family, extra flavour-changing processes such as $\tau \to \mu\mu\mu$. The model in its current form does not have any family symmetry, and explains the hierarchy of the quark masses in terms of the vector-like fourth family masses, which are free parameters. Crucially, the required TeV scale Z′ mass is given by $M_{Z'} \sim \langle\varphi\rangle \sim$ TeV, which would fix the flavour scale M_{fl} ~ few TeV. In other words, if the hints for flavour anomalies hold up as further data are collected by the LHCb, Belle II and other experiments, the origin of flavour may be right around the corner. ●

In recent years, anomalies have appeared associated with violations of charged lepton flavour universality

Further reading
K S Babu 2009 arXiv:0910.2948.
R Barbieri *et al.* 2016 *Eur. Phys. J. C* **76** 67.
F Feruglio 2017 arXiv:1706.08749.
F Feruglio 2015 *Eur. Phys. J. C* **75** 373.
C D Froggatt and H B Nielsen 1979 *Nucl. Phys. B* **147** 277.
H Georgi and S L Glashow 1974 *Phys. Rev. Lett.* **32** 438.
S F King 2019 arXiv:1905.02660.
S F King and C Luhn 2013 *Rept. Prog. Phys.* **76** 056201.
S F King and G G Ross 2001 *Phys. Lett B* **520** 243.
J C Pati and A Salam 1974 *Phys. Rev. D* **10** 275.

A VOYAGE TO THE HEART OF THE NEUTRINO

The Karlsruhe Tritium Neutrino (KATRIN) experiment has begun its seven-year-long programme to determine the absolute value of the neutrino mass.



Inner space *KATRIN's main spectrometer, the largest ultra-high-vacuum vessel in the world, contains a dual-layer electrode system comprising 23,000 wires to shield the inner volume from charged particles.*

On 11 June 2018, a tense silence filled the large lecture hall of the Karlsruhe Institute of Technology (KIT) in Germany. In front of an audience of more than 250 people, 15 red buttons were pressed simultaneously by a panel of senior figures including recent Nobel laureates Takaaki Kajita and Art McDonald. At the same time, operators in the control room of the Karlsruhe Tritium Neutrino (KATRIN) experiment lowered the retardation voltage of the apparatus so that the first beta electrons were able to pass into KATRIN's giant spectrometer vessel. Great applause erupted when the first beta electrons hit the detector.

In the long history of measuring the tritium beta-decay spectrum to determine the neutrino mass, the ensuing weeks of KATRIN's first data-taking opened a new chapter. Everything worked as expected, and KATRIN's initial measurements have already propelled it into the top ranks of neutrino experiments. The aim of this ultra-high-precision beta-decay spectroscope, more than 15 years in the making, is to determine, by the mid-2020s, the absolute mass of the neutrino.

Massive discovery

Since the discovery of the oscillation of atmospheric neutrinos by the Super-Kamiokande experiment in 1998, and of the flavour transitions of solar neutrinos by the SNO experiment shortly afterwards, it was strongly implied that neutrino masses are not zero, but big enough to cause interference between distinct mass eigenstates as a neutrino wavepacket evolves in time. We know now that the three neutrino flavour states we observe in experiments – ν_e, ν_μ and ν_τ – are mixtures of three neutrino mass states.

Though not massless, neutrinos are exceedingly light. Previous experiments designed to directly measure the scale of neutrino masses in Mainz and Troitsk produced an upper limit of 2 eV for the neutrino mass – a factor 250,000 times smaller than the mass of the otherwise lightest massive elementary particle, the electron. Nevertheless, neutrino masses are extremely important for cosmology as well as for particle physics. They have a number density of around 336 cm^{-3}, making them the most abundant particles in the universe besides photons, and therefore play a distinct role in the formation of cosmic structure. Comparing data from the Planck satellite together with data from galaxy surveys (baryonic acoustic oscillations) with simulations of the evolution of structure yields an upper limit on the sum of all three neutrino masses of 0.12 eV at 95% confidence within the framework of the standard Lambda cold-dark matter (ΛCDM) cosmological model.

Considerations of "naturalness" lead most theorists to speculate that the exceedingly tiny neutrino masses do not arise from standard Yukawa couplings to the Higgs boson, as per the other fermions, but are generated by a different mass mechanism. Since neutrinos are electrically neutral, they could be identical to their antiparticles, making them Majorana particles. Via the so-called seesaw mechanism, this interesting scenario would require a new and very high particle mass scale to balance the smallness of the neutrino masses, which would be unreachable with present accelerators.

As neutrino oscillations arise due to interference between mass eigenstates, neutrino-oscillation experiments are only able to determine splittings between the squares of the neutrino mass eigenstates. Three experimental avenues are currently being pursued to determine the neutrino mass. The most stringent upper limit is currently the model-dependent bound set by cosmological data, as already mentioned, which is valid within the ΛCDM model. A second approach is to search for neutrinoless double-beta decay, which allows a statement to be made about the size of the neutrino masses but presupposes the Majorana nature of neutrinos. The third approach – the one adopted by KATRIN – is the direct determination of the neutrino mass from the kinematics of a weak process such as beta decay, which is completely model-independent and depends only on the principle of energy and momentum conservation.

The direct determination of the neutrino mass relies on the precise measurement of the shape of the beta electron spectrum near the endpoint, which is governed by the available phase space (figure 1). This spectral shape is altered by the neutrino mass value: the smaller the mass, the smaller the spectral modification. One would expect to see three modifications, one for each neutrino mass eigenstate. However, due to the tiny neutrino mass differences, a weighted sum is observed. This "average electron neutrino mass" is formed by the incoherent sum of the squares of the three neutrino mass eigenstates, which contribute to the electron neutrino according to the PMNS neutrino-mixing matrix. The super-heavy hydrogen isotope tritium is ideal for this purpose because it combines a very low endpoint energy, E_0, of 18.6 keV and a short half-life of 12.3 years with a simple nuclear and atomic structure.

Great applause erupted when the first beta electrons hit the detector

KATRIN is born

Around the turn of the millennium, motivated by the neutrino oscillation results, Ernst Otten of the University of Mainz and Vladimir Lobashev of INR Troitsk proposed a new, much more sensitive experiment to measure the neutrino mass from tritium beta decay. To this end, the best methods from the previous

THE AUTHORS
Guido Drexlin *KIT and*
Christian Weinheimer *University of Münster.*

CERNCOURIER
VOLUME 60 NUMBER 1 JANUARY/FEBRUARY 2020
IOP Publishing

TECHNOLOGY TRANSFER DELIVERS ULTIMATE PRECISION

Many technologies had to be pushed to the limits of what was feasible or even beyond. KATRIN became a CERN-recognised experiment (RE14) in 2007 and the collaboration worked with CERN experts in many areas to achieve this. The KATRIN main spectrometer is the largest ultra-high vacuum vessel in the world, with a residual gas pressure in the range of 10^{-11} mbar – a pressure that is otherwise only found in large volumes inside the LHC ring – equivalent to the pressure recorded at the lunar surface.

Even though the inner surface was instrumented with a complex dual-layer wire electrode system for background suppression and electric-field shaping, this extreme vacuum was made possible by rigorous material selection and treatment in addition to non-evaporable getter technology developed at CERN. KATRIN's almost 40 m-long chain of superconducting magnets with two large chicanes was put into operation with the help of former CERN experts, and a ^{223}Ra source was produced at ISOLDE for background studies at KATRIN. A series of ^{83m}Kr conversion electron sources based on implanted ^{83}Rb for calibration purposes was initially produced at ISOLDE. At present these are produced by KATRIN collaborators and further developed with regard to line stability.

Precise *The electron transport and tritium retention system.*

Conversely, the KATRIN collaboration has returned its knowledge and methods to the community. For example, the ISOLDE high-voltage system was calibrated twice with the ppm-accuracy KATRIN voltage dividers, and the magnetic and electrical field calculation and tracking programme KASSIOPEIA developed by KATRIN was published as open source and has become the standard for low-energy precision experiments. The fast and precise laser Raman spectroscopy developed for KATRIN is also being applied to fusion technology.

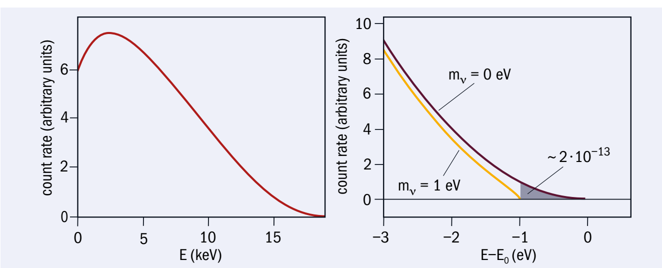


Fig. 1. *The beta spectrum of tritium (left), showing in detail the effect of different neutrino masses on the endpoint (right).*

experiments in Mainz, Troitsk and Los Alamos were to be combined and upscaled by up to two orders of magnitude in size and precision. Together with new technologies and ideas, such as laser Raman spectroscopy or active background reduction methods, the apparatus would increase the sensitivity to the observable in beta decay (the square of the electron antineutrino mass) by a factor of 100, resulting in a neutrino-mass sensitivity of 0.2 eV. Accordingly, the entire experiment was designed to the limits of what was feasible and even beyond (see "Technology transfer delivers ultimate precision" box).

KIT was soon identified as the best place for such an experiment, as it had the necessary experience and infrastructure with the Tritium Laboratory Karlsruhe. The KIT board of directors quickly took up this proposal and a small international working group started to develop the project. At a workshop at Bad Liebenzell in the Black Forest in January 2001, the project received so much international support that KIT, together with nearly all the groups from the previous neutrino-mass experiments, founded the KATRIN collaboration. Currently, the 150-strong KATRIN collaboration comprises 20 institutes from six countries.

It took almost 16 years from the first design to complete KATRIN, largely because many new technologies had to be developed, such as a novel concept to limit the temperature fluctuations of the huge tritium source to the mK scale at 30 K or the high-voltage stabilisation and calibration to the 10 mV scale at 18.6 kV. The experiment's two most important and also most complex components are the gaseous, windowless molecular tritium source (WGTS) and the very large spectrometer. In the WGTS, tritium gas is introduced in the midpoint of the 10 m-long beam tube, where it flows out to both sides to be pumped out again by turbomolecular pumps. After being partially cleaned it is re-injected, yielding a closed tritium cycle. This results in an almost opaque column density with a total decay rate of 10^{11} per second. The beta electrons are guided adiabatically to a tandem of a pre- and a main spectrometer by superconducting magnets of up to 6 T. Along the way, differential and cryogenic pumping sections including geometric chicanes reduce the tritium flow by more than 14 orders of magnitude to keep the spectrometers free of tritium (figure 2).

Filtration

The KATRIN spectrometers operate as so-called MAC-E filters, whereby electrons are guided by two superconducting solenoids at either end and their momenta are collimated by the magnetic field gradient. This "magnetic bottle" effect transforms almost all kinetic energy into longitudinal energy, which is filtered by an electrostatic retardation potential so that only electrons with enough energy to overcome the barrier are able to pass through. The smaller pre-spectrometer blocks the low-energy part of the beta spectrum (which carries no information on the neutrino mass), while the 10 m-diameter main spectrometer provides a much sharper filter width due to its huge size.

The transmitted electrons are detected by a high-resolution segmented silicon detector. By varying the retarding potential of the main spectrometer, a narrow region of the beta spectrum of several tens of eV below the endpoint is scanned, where the imprint of a non-zero neutrino mass is maximal. Since the relative fraction of the tritium beta spectrum in the last 1 eV below the endpoints amounts to just 2×10^{-13}, KATRIN demands a tritium source of the highest intensity. Of equal importance is the high precision needed to understand the measured beta spectrum. Therefore, KATRIN possesses a

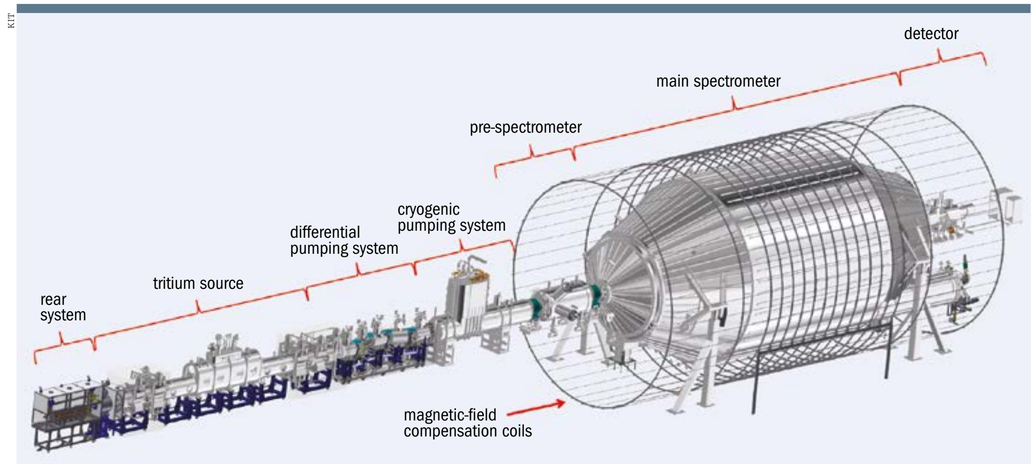


Fig. 2. *The 70 m-long KATRIN setup showing the key stages and components.*

Focus *Operators in the KATRIN control room.*

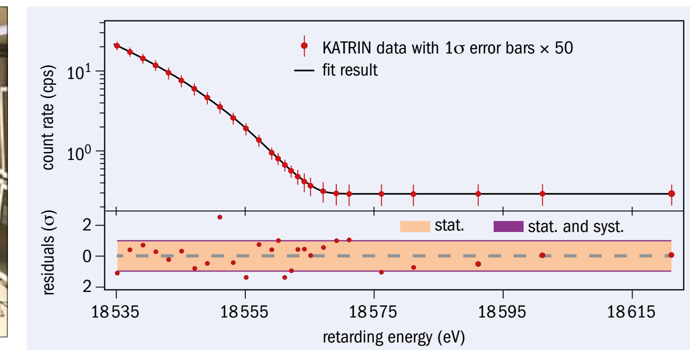


Fig. 3. *The beta-electron spectrum in the vicinity of its endpoint with 50 times enlarged error bars and a best-fit model (top) and fit residuals (bottom).*

complex calibration and monitoring system to determine all systematics with the highest precision *in situ*, e.g. the source strength, the inelastic scattering of beta electrons in the tritium source, the retardation voltage and the work functions of the tritium source and the main spectrometer.

Start-up and beyond

After intense periods of commissioning during 2018, the tritium source activity was increased from its initial value of 0.5 GBq (which was used for the inauguration measurements) to 25 GBq (approximately 22% of nominal activity) in spring 2019. By April, the first KATRIN science run had begun and everything went like clockwork. The decisive source parameters – temperature, inlet pressure and tritium content – allowed excellent data to be taken, and the collaboration worked in several independent teams to analyse these data. The critical systematic uncertainties were determined both by Monte Carlo propagation and with the covariance-matrix method, and the analyses were also blinded so as not to generate bias. The excitement during the un-blinding process was huge within the KATRIN collaboration, which gathered for this special event, and relief spread when the result became known. The neutrino-mass square turned out to be compatible with zero within its uncertainty budget. The model fits the data very well (figure 3) and the fitted endpoint turned out to be compatible with the mass difference between ^{3}He and tritium measured in Penning traps. The new results were presented at the international TAUP 2019 conference in Toyama, Japan, and have recently been published.

This first result shows that all aspects of the KATRIN experiment, from hardware to data-acquisition to analysis, works as expected. The statistical uncertainty of the first KATRIN result is already smaller by a factor of two compared to previous experiments and systematic uncertainties have gone down by a factor of six. A neutrino mass was not yet extracted with these first four weeks of data, but an upper limit for the neutrino mass of 1.1 eV (90% confidence) can be drawn, catapulting KATRIN directly to the top of the world of direct neutrino-mass experiments. In the mass region around 1 eV, the limit corresponds to the quasi-degenerated neutrino-mass range where the mass splittings implied by neutrino-oscillation experiments are negligible compared to the absolute masses.

The neutrino-mass result from KATRIN is complementary to results obtained from searches for neutrinoless double beta decay, which are sensitive to the "coherent sum" $m_{\beta\beta}$ of all neutrino mass eigenstates contributing to the electron neutrino. Apart from additional phases that can lead to possible cancellations in this sum, the values of the nuclear matrix

CERNCOURIER
Volume 60 Number 1 January/February 2020
IOP Publishing

elements that need to be calculated to connect the neutrino mass $m_{\beta\beta}$ with the observable (the half-life) still possess uncertainties of a factor two. Therefore, the result from a direct neutrino-mass determination is more closely connected to results from cosmological data, which give (model-dependent) access to the neutrino-mass sum.

A sizeable influence

Currently, KATRIN is taking more data and has already increased the source activity by a factor of four to close to its design value. The background rate is still a challenge. Various measures, such as out-baking and using liquid-nitrogen cooled baffles in front of the getter pumps, have already yielded a background reduction by a factor 10, and more will be implemented in the next few years. For the final KATRIN sensitivity of 0.2 eV (90% confidence) on the absolute neutrino-mass scale, a total of 1000 days of data are required. With this sensitivity KATRIN will either find the neutrino mass or will set a stringent upper limit. The former would confront standard cosmology, while the latter would exclude quasi-degenerate neutrino masses and a sizeable influence of neutrinos on the formation of structure in the universe. This will be augmented by searches for physics beyond the Standard Model, such as for sterile neutrino admixtures with masses from the eV to the keV scale.

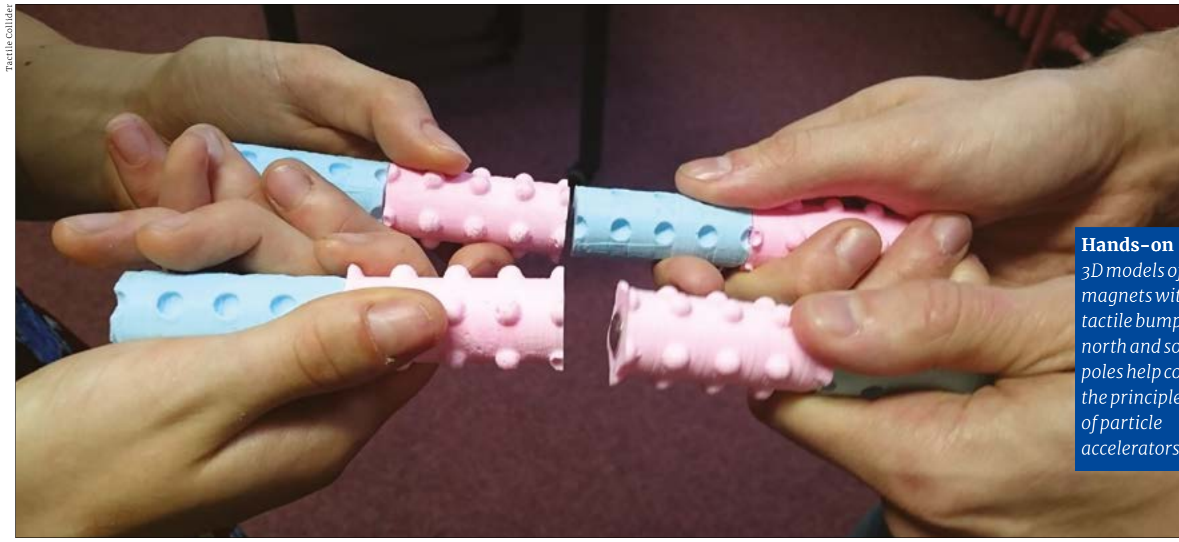
Neutrino-oscillation results yield a lower limit for the effective electron-neutrino mass to manifest in direct neutrino-mass experiments of about 10 meV (50 meV) for normal (inverse) mass ordering. Therefore, many plans exist to cover this region in the future. At KATRIN, there is a strong R&D programme to upgrade the MAC-E filter principle from the current integral to a differential read-out, which will allow a factor-of-two improvement in sensitivity on the neutrino mass. New approaches to determine the absolute neutrino-mass scale are also being developed: Project 8, a radio-spectroscopy method to eventually be applied to an atomic tritium source; and the electron-capture experiments ECHo and HOLMES, which intend to deploy large arrays of cryogenic bolometers with the implanted isotope ^{163}Ho. In parallel, the next generation of neutrinoless double beta decay experiments like LEGEND, CUPID or nEXO (as well as future xenon-based dark-matter experiments) aim to cover the full range of inverted neutrino-mass ordering. Finally, refined cosmological data should allow us to probe the same mass region (and beyond) within the next decades, while long-baseline neutrino-oscillation experiments, such as JUNO, DUNE and Hyper-Kamiokande, will probe the neutrino-mass ordering implemented in nature. As a result of this broad programme for the 2020s, the elusive neutrino should finally yield some of its secrets and inner properties beyond mixing. ●

An upper limit for the neutrino mass of 1.1 eV can be drawn, catapulting KATRIN directly to the top of the world of direct neutrino-mass experiments

Further reading

KATRIN Collaboration 2019 *Phys. Rev. Lett.* **123** 221802.

Tactile Collider



Hands-on *3D models of bar magnets with tactile bumps for north and south poles help convey the principles of particle accelerators.*

ENGAGING WITH THE INVISIBLE

The outreach project Tactile Collider is changing the way particle physicists engage with visually impaired and other important audiences, writes founder Rob Appleby.

We have many fantastic achievements in our wonderful field of research, most recently the completion of the Large Hadron Collider (LHC) and its discovery of a new form of matter, the Higgs boson. The field is now preparing to face the next set of challenges, in whatever direction the European Strategy for Particle Physics recommends. With ambitious goals, this strategy update is the right time to ask: "How do we make ourselves as good as we need to be to succeed?"

Big science has brought more than fundamental knowledge: it has taught us that we can achieve more when we collaborate, and to do this we need to communicate both within and beyond the community. We need to communicate to our funders and, most importantly of all, we need to communicate with wider society to give everyone an opportunity to engage in or become a part of the scientific process. Yet some of the audiences we could and should be reaching are below the radar.

Reaching high-science capital people – those who will attend a laboratory open day, watch a new documentary on dark energy or read a newspaper article about medical accelerators – is a vital part of our work, and we do it well. But many audiences have barriers to traditional modes of outreach and engagement. For example, groups or families with an inherently low science background, perhaps linked to socio-economic grouping, will not read articles in the science-literate mainstream press as they feel, incorrectly, that science is not for them. Large potential audiences with physical or mental disabilities will be put off coming to events for practical reasons such as accessibility or perhaps being unable to read or understand printed or visual media. In the UK alone, millions of people are registered as visually impaired (VI) to some degree. To reach these and other "invisible" audiences, we need to enter their space.

Inspired by the LHC

When it comes to science engagement, which is a predominantly visual interaction, the VI audience is underserved. Tactile Collider is a communication project aimed at addressing this gap. The idea came in 2014 when a major

THE AUTHOR

Rob Appleby
University of Manchester and the Cockcroft Institute, UK

CERNCOURIER
VOLUME 60 NUMBER 1 JANUARY/FEBRUARY 2020
IOP Publishing

Tactile Collider

In the field *Interactive magnet exhibits on display at Tactile Collider.*

LHC exhibition came to Manchester, UK. Joining in panel discussions at a launch party held at the Museum for Science and Industry, it became clear that the accessibility of the exhibition could be improved. Spurring us into action, we also had a request from a local VI couple for an adapted tour. I gathered together some pieces of the ATLAS forward detector and some radio-frequency cavity models, both of which had a pleasing weight and plenty of features to feel with fingers, and gave the couple a bespoke tour of the exhibition. The feedback was fantastic, and making this tactile, interactive and bespoke form of engagement available to more people, be it sighted or VI, was a challenge we accepted.

With the help of the museum staff, we developed the idea further and were soon put in touch with Kirin Saeed, an independent consultant on accessibility and visually impaired herself. Together, we formulated a potential project to a stage where we could approach funders. The UK's Science and Technology Facilities Council (STFC) recognised and supported our vision for a UK-wide project and funded the nascent Tactile Collider for two years through a £100,000 public-engagement grant.

We wanted to design a project without preconceptions about the techniques and methods of communication and delivery. With co-leaders Chris Edmonds of the University of Liverpool and Robyn Watson, a teacher of VI students, our team spent one year listening to and talking with audiences before we even considered producing materials or defining an approach. We spent time in focus groups, in classrooms across the north of England, visiting museums with VI people, and looking at the varied ways of learning and accessing information for VI groups of all ages. Training in skills such as audio description and tactile-map production was crucial, as were the PhD students who got involved to design materials and deliver Tactile Collider events.

None of us can directly engage with the very small or the far or the very massive

Early on, we focused on a science message based around four key themes: the universe is made of particles; we accelerate these particles using electric fields in cavities; we control particle beams using magnets; and we collide particle beams to make the Higgs boson. The first significant event took place in Liverpool in 2017 and since then the exhibition has toured UK schools, science festivals and, in 2019, joined the CERN Open Days for our first Geneva-region event.

Content development

A key aspect of Tactile Collider is content developed specifically for a VI audience, along with training the delivery team in how to sight-guide and educating them about the large range of visual impairments. As an example, take the magnetic field of a dipole – the first step to understanding how magnets are used to control and manipulate charged particle beams. The idea of a bar magnet having a north pole and a south pole, and magnetic field lines connecting the two, is simple enough to convey using pencil and paper. To communicate with VI audiences, by contrast, the magnet station of Tactile Collider contains a 3D model of a bar magnet with tactile bumps for north and south poles, partnered with tactile diagrams. In some areas of Tactile Collider, 3D sound is employed to give students a choice in how to interact.

The lessons learned during the project's development and delivery led us to a set of principles for engagement, which work for all audiences regardless of any particular needs. We found that all science engagement should strive to be authentic, with no dumbing down of the science message and delivered by practicing scientists striving to involve the audience as equals. Alongside this authentic message, VI learners require close interaction with a scientist-presenter in a group of no bigger than four. The scientist should also be trained in VI-audience awareness, sighted guiding, audio description and in the presentation of a tactile narrative linked to the learning outcomes. Coupled with this idea is the need to train presenters to be able to use the differing materials with diverse audience groups.

Tactile Collider toured the UK in 2017 and 2018, visiting many mainstream and specialist schools, and meeting many motivated and enthusiastic students. We have also spent time at music festivals, with a focus on raising awareness of VI issues and giving people a chance to learn about the LHC using senses other than their eyes. One legacy of Tactile Collider is educating our community, and we are planning "VI in science" training events in 2020 in addition to a third community meeting bringing together scientists and communication professionals.

There is now a real interest and understanding in particle physics about the importance of reaching under-represented audiences. Tactile Collider is a step towards this, and we are working to share the skills and insights we have gained in our journey so far. The idea has also appeared in astronomy: Tactile Universe, based at the Institute of Cosmology and Gravitation at the University of Portsmouth, engages the VI community with astrophysics research, for example by creating 3D printed tactile images of galaxies for use in schools and at public events. The first joint Tactile Collider/Universe event will take place in London in 2020 and we have already jointly hosted two community workshops. The Tactile Collider team is happy to discuss bringing the exhibition to any event, lab or venue.

S Eyres

Winning formula *Tactile Collider's Chris Edmonds, Rob Appleby and Robyn Watson (left to right) with the European Physical Society Outreach Award in July 2019. The team also won Innovator of the Year in the 2019 RNIB See Differently awards.*

Fundamental science is a humbling and levelling endeavour. When we consider the Higgs boson and supernovae, none of us can directly engage with the very small or the far or the very massive. Using all of our senses shows us science in a new and fascinating way. ●

CERNCOURIER
VOLUME 60 NUMBER 1 JANUARY/FEBRUARY 2020
IOP Publishing

OPINION VIEWPOINT

Learning to love anomalies

The 2020s will sort current anomalies in fundamental physics into discoveries or phantoms, says Ben Allanach.

Outliers *All surprising discoveries were anomalies at some stage.*

Ben Allanach *is a theorist at the University of Cambridge working on the phenomenology of physics beyond the Standard Model.*

Anomalies, which I take to mean data that disagree with the scientific paradigm of the day, are the bread and butter of phenomenologists working on physics beyond the Standard Model (SM). Are they a mere blip or the first sign of new physics? A keen understanding of statistics is necessary to help decide which "bumps" to work on.

Take the excess in the rate of diphoton production at a mass of around 750 GeV spotted in 2015 by the ATLAS and CMS experiments. ATLAS had a 4σ peak with respect to background, which CMS seemed to confirm, although its signal was less clear. Theorists produced an avalanche of papers speculating on what the signal might mean but, in the end, the signal was not confirmed in new data. In fact, as is so often the case, the putative signal stimulated some very fruitful work. For example, it was realised that ultra-peripheral collisions between lead ions could produce photon-photon resonances, leading to an innovative and unexpected search programme in heavy-ion physics. Other authors proposed using such collisions to measure the anomalous magnetic moment of the tau lepton, which is expected to be especially sensitive to new physics, and in 2018 ATLAS and CMS found the first evidence for (non-anomalous) high-energy light-by-light scattering in lead-lead ultra-peripheral collisions.

Some anomalies have disappeared during the past decade not primarily because they were statistical fluctuations, but because of an improved understanding of theory. One example is the forward–backward asymmetry (A_{FB}) of top–antitop production at the Tevatron. At large transverse momentum, A_{FB} was measured to be much too large compared to SM predictions, which were at next-to-leading order in QCD with some partial next-to-next-to leading order (NNLO) corrections. The complete NNLO corrections, calculated in a Herculean effort, proved to contribute much more than was previously thought, faithfully describing top–antitop production both at the Tevatron and at the LHC.

Other anomalies are still alive and kicking. Arguably, chief among them is the long-standing oddity in the measurement of the anomalous magnetic moment of the muon, which is about 4σ discrepant with the SM predictions. Spotted 20 years ago, many papers have been written in an attempt to explain it, with contributions ranging from supersymmetric particles to leptoquarks. A similarly long-standing anomaly is a 3.8σ excess in the number of electron antineutrinos emerging from a muon–antineutrino beam observed by the LSND experiment and backed up more recently by MiniBooNE. Again, numerous papers attempting to explain the excess, e.g. in terms of the existence of a fourth "sterile" neutrino, have been written, but the jury is still out.

Some anomalies are more recent, and unexpected. The so-called "X17" anomaly reported at a nuclear physics experiment in Hungary, for instance, shows a significant excess in the rate of certain nuclear decays of ^{8}Be and ^{4}He nuclei (see p7) which has been interpreted as being due to the creation of a new particle of mass 17 MeV. Though possible theoretically, one needs to work hard to make this new particle not fall afoul of other experimental constraints; confirmation from an independent experiment is also needed. Personally, I am not pursuing this: I think that the best new-physics ideas have already been had by other authors.

When working on an anomaly, beyond-the-SM phenomenologists hypothesise a new particle and/or interaction to explain it, check to see if it works quantitatively, check to see if any other measurements rule the explanation out, then provide new ways in which the idea can be tested. After this, they usually check where the new physics might fit into a larger theoretical structure, which might explain some other mysteries. For example, there are currently many anomalies in measurements of B meson decays, each of which isn't particularly statistically significant (typically 2–3σ away from the SM) but taken together they form a coherent picture with a higher significance. The exchange of hypothesised Z′ or leptoquark quanta provide working explanations, the larger structure also shedding light on the pattern of masses of SM fermions, and most of my research time is currently devoted to studying them.

Of course, we hope that new anomalies will appear and stick

The coming decade will presumably sort several current anomalies into discoveries, or those that "went away". Belle II and future LHCb measurements should settle the B anomalies, while the anomalous muon magnetic moment may even be settled this year by the g-2 experiment at Fermilab. Of course, we hope that new anomalies will appear and stick. One anomaly from the late 1990s – that type 1a supernovae have an anomalous acceleration at large red-shifts – turned out to reveal the existence of dark-energy and produce the dominant paradigm of cosmology today. This reminds us that all surprising discoveries were anomalies at some stage.

CERNCOURIER
VOLUME 60 NUMBER 1 JANUARY/FEBRUARY 2020
IOP Publishing

OPINION
INTERVIEW

The Higgs, supersymmetry and all that

John Ellis reflects on 50 years spent working at the forefront of theoretical high-energy physics and whether the field is ripe for a change of paradigm.

J Ordan/CERN

Deep thought *John Ellis of King's College London in his office at CERN in July 2019.*

What would you say were the best and the worst of times in your half-century-long career as a theorist?
The two best times, in chronological order, were the 1979 discovery of the gluon in three-jet events at DESY, which Mary Gaillard, Graham Ross and I had proposed three years earlier, and the discovery of the Higgs boson at CERN in 2012, in particular because one of the most distinctive signatures for the Higgs, its decay to two photons, was something Gaillard, Dimitri Nanopoulos and I had calculated in 1975. There was a big build up to the Higgs and it was a really emotional moment. The first of the two worst times was in 2000 with the closure of LEP, because maybe there was a glimpse of the Higgs boson. In fact, in retrospect the decision was correct because the Higgs wasn't there. The other time was in September 2008 when there was the electrical accident in the LHC soon after it started up. No theoretical missing factor-of-two could be so tragic.

Your 1975 work on the phenomenology of the Higgs boson was the starting point for the Higgs hunt. When did you realise that the particle was more likely than not to exist?
Our paper, published in 1976, helped people think about how to look for the Higgs boson, but it didn't move to the top of the physics agenda until after the discovery of the W and Z bosons in 1983. When we wrote the paper, things like spontaneous symmetry breaking were regarded as speculative hypotheses by the distinguished grey-haired scientists of the day. Then, in the early 1990s, precision measurements at LEP enabled us to look at the radiative corrections induced by the Higgs and they painted a consistent picture that suggested the Higgs would be relatively light (less than about 300 GeV). I was sort of morally convinced beforehand that the Higgs had to exist, but by the early 1990s it was clear that, indirectly, we had seen it. Before that there were alternative models of electroweak symmetry breaking but LEP killed most of them off.

To what extent does the Higgs boson represent a "portal" to new physics?
The Higgs boson is often presented as completing the Standard Model (SM) and solving lots of problems. Actually, it opens up a whole bunch of new ones. We know now that there is at least one particle that looks like an effective elementary scalar field. It's an entirely new type of object that we've never encountered before, and every single aspect of the Higgs is problematic from a theoretical point of view. Its mass: we know that in the SM it is subject to quadratic corrections that make the hierarchy of mass scales unstable. Its couplings to fermions: those are what produce the mixing of quarks, which is a complete mystery. The quartic term of the Higgs potential in the SM goes negative if you extrapolate it to high energies, the theory becomes unstable and the universe is doomed. And, in principle, you can add a constant term to the Higgs potential, which is the infamous cosmological constant that we know exists in the universe today but that is much, much smaller than would seem natural from the point of view of Higgs theory. Presumably some new physics comes in to fix these problems, and that makes the Higgs sector of the SM Lagrangian look like the obvious portal to that new physics.

Every single aspect of the Higgs is problematic from a theoretical point of view

In what sense do you feel an emotional connection to theory?
The Higgs discovery is testament to the power of mathematics to describe nature. People often talk about beauty as being a guide to theory, but I am always a bit sceptical about that because it depends on how you define beauty. For me, a piece of engineering can be beautiful even if it looks ugly. The LHC is a beautiful machine from

that point of view, and the SM is a beautiful theoretical machine that is driven by mathematics. At the end of the day, mathematics is nothing but logic taken as far as you can.

Do you recall the moment you first encountered supersymmetry (SUSY), and what convinced you of its potential?
I guess it must have been around 1980. Of course I knew that Julius Wess and Bruno Zumino had discovered SUSY as a theoretical framework, but their motivations didn't convince me. Then people like Luciano Maiani, Ed Witten and others pointed out that SUSY could help stabilise the hierarchy of mass scales that we find in physics, such as the electroweak, Planck and grand unification scales. For me, the first phenomenological indication that indicated SUSY could be related to reality was our realisation in 1983 that SUSY offered a great candidate for dark matter in the form of the lightest supersymmetric particle. The second was a few years later when LEP provided very precise measurements of the electroweak mixing angle, which were in perfect agreement with supersymmetric (but not non-supersymmetric) grand unified theories. The third indication was around 1991 when we calculated the mass of the lightest supersymmetric Higgs boson and got a mass up to about 130 GeV, which was being indicated by LEP as a very plausible value, and agrees with the experimental value.

There was great excitement about SUSY ahead of the LHC start-up. In hindsight, does the non-discovery so far make the idea less likely?
Certainly it's disappointing. And I have to face the possibility that even if SUSY is there, I might not live to meet her. But I don't think it's necessarily a problem for the underlying theory. There are certainly scenarios that can provide the dark matter even if the supersymmetric particles are rather heavier than we originally thought, and such models are still consistent with the mass of the Higgs boson. The information you get from unification of the couplings at high energies also doesn't exclude SUSY particles weighing 10 TeV or so. Clearly, as the masses of the sparticles increase, you have to do more fine tuning to solve the electroweak hierarchy problem. On the other hand, the amount of fine tuning is still many, many orders of magnitude less than what you'd have to postulate without it! It's a question

> **The discovery of gravitational waves almost four years ago was the "Higgs moment" for gravity**

of how much resistance to pain you have. That said, to my mind the LHC has actually provided three additional reasons for loving SUSY. One is the correct prediction for the Higgs mass. Another is that SUSY stabilises the electroweak vacuum (without it, SM calculations show that the vacuum is metastable). The third is that in a SUSY model, the Higgs couplings to other particles, while not exactly the same as in the SM, should be pretty close – and of course that's consistent with what has been measured so far.

To what extent is SUSY driving considerations for the next collider?
I still think it's a relatively clear-cut and well-motivated scenario for physics at the multi-TeV scale. But obviously its importance is less than it was in the early 1990s when we were proposing the LHC. That said, if you want a specific benchmark scenario for new physics at a future collider, SUSY would still be my go-to model, because you can calculate accurate predictions. As for new physics beyond the Higgs and more generally the precision measurements that you can make in the electroweak sector, the next topic that comes to my mind is dark matter. If dark matter is made of weakly-interacting massive particles (WIMPs), a high-energy Future Circular Collider should be able to discover it. You can look at SUSY at various different levels. One is that you just add in these new particles and make sure they have the right couplings to fix the hierarchy problem. But at a more fundamental level you can write down a Lagrangian, postulate this boson-fermion symmetry and follow the mathematics through. Then there is a deeper picture, which is to talk about additional fermionic (or quantum) dimensions of space-time. If SUSY were to be discovered, that would be one of the most profound insights into the nature of reality that we could get.

If SUSY is not a symmetry of nature, what would be the implications for attempts to go beyond the SM, e.g. quantum gravity?
We are never going to know that SUSY is not there. String theorists could probably live with very heavy SUSY particles. When I first started thinking about SUSY in the 1980s there was this motivation related to fine tuning, but there weren't many other reasons why SUSY should show up at low energies. More arguments came later, for example, dark matter, which are nice but a matter of taste. I and my grandchildren will have passed on, humans could still be exploring physics way below the Planck scale, and string theorists could still be cool with that.

How high do the masses of the super-partners need to go before SUSY ceases to offer a compelling solution for the hierarchy problem and dark matter?
Beyond about 10 TeV it is difficult to see how it can provide the dark matter unless you change the early expansion history of the universe – which of course is quite possible, because we have no idea what the universe was doing when the temperature was above an MeV. Indeed, many of my string colleagues have been arguing that the expansion history could be rather different from the conventional adiabatic smooth expansion that people tend to use as the default. In this case supersymmetric particles could weigh 10 or even 30 TeV and still provide the dark matter. As for the hierarchy problem, obviously things get tougher to bear.

What can we infer about SUSY as a theory of fundamental particles from its recent "avatars" in lasers and condensed-matter systems?
I don't know. It's not really clear to me that the word "SUSY" is being used in the same sense that I would use it. Supersymmetric quantum mechanics was taken as a motivation for the laser setup (*CERN Courier* March/April 2019 p10), but whether the deeper mathematics of SUSY has much to do with the way this setup works I'm not sure. The case of topological condensed-matter systems is potentially a more interesting place to explore what this particular face of SUSY actually looks like, as you can study more of its properties under controlled conditions. The danger is that, when people bandy around the idea of SUSY, often they just have in mind this fermion–boson partnership. The real essence of SUSY goes beyond that and includes the couplings of these particles, and it's not clear to me that in these effective-SUSY systems one can talk in a meaningful way about what the couplings look like.

Has the LHC new-physics no-show so far impacted what theorists work on?
In general, I think that members of the theoretical community have diversified their interests and are thinking about alternative dark-matter scenarios, and about alternative ways to stabilise the hierarchy problem. People are certainly exploring new theoretical avenues, which is very healthy and, in a way, there is much more freedom for young theorists today than there might have been in the past. Personally, I would be rather reluctant at this time to propose to a PhD student a thesis that was based solely on SUSY – the people who are hiring are quite likely to want them to be not just working on SUSY and maybe even not working on SUSY at all. I would regard that as a bit unfair, but there are always fashions in theoretical physics.

Following a long and highly successful period of theory-led research, culminating in the completion of the SM, what signposts does theory offer experimentalists from here?
I would broaden your question. In particle physics, yes, we have the SM, which over the past 50 years has been the dominant paradigm. But there is also a paradigm in cosmology and gravitation – general relativity and the idea of a big bang – initiated a century ago by Einstein. The 2016 discovery of gravitational waves almost four years ago was the "Higgs moment" for gravity, and that community now finds itself in the same fix that we do, in that they have this theory-led paradigm that doesn't indicate where to go next. Gravitational waves are going to tell us a lot about astrophysics, but whether they will tell us about quantum gravity is not so obvious. The Higgs boson, meanwhile, tells us that we have a theory that works fantastically well but leaves many mysteries – such as dark matter, the origin of matter, neutrino masses, cosmological inflation, etc – still standing. These are a mixture of theoretical, phenomenological and experimental problems suggesting life beyond the SM. But we don't have any clear signposts today. The theoretical cats are wandering off in all directions, and that's good because maybe one of the cats will find something interesting. But there is still a dialogue going on between theory and experiment, and it's a dialogue that is maybe less of a monologue than it was during the rise of the SM and general relativity. The problems we face in going beyond the current paradigms in fundamental physics are the hardest we've faced yet, and we are going to need all the dialogue we can muster between theorists, experimentalists, astrophysicists and cosmologists.

Interview by **Matthew Chalmers** *editor.*

CERNCOURIER
VOLUME 60 NUMBER 1 JANUARY/FEBRUARY 2020
IOP Publishing

OPINION LETTERS

Operating a future linear collider

After reading your article “Why CLIC?” (*CERN Courier* November/December p41), I felt driven to comment on the issue of the operability of future linear colliders. I was a member of the CLIC study team under Wolfgang Schnell during the early 1990s, and for a short while was responsible for one option of the drive-beam production, the free-electron laser. I began to worry about the operability of the CLIC drive beam which, in all, would carry an electron beam down a very narrow tube; the equivalent power to that consumed by the Ville de Genève! The requirements on beam quality and precision steering to avoid self-destruction seemed to be beyond reasonable requirements.

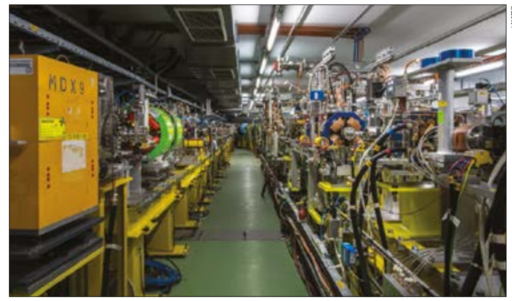
I then spent a year at SLAC during the start-up of the linear collider (SLC), where we were thwarted by operability issues and didn’t see a single electron–positron collision that year. Linear colliders are challenging to operate, as the SLC (the only such facility to date) demonstrated. They must produce collisions with highly focused beams that arrive simultaneously at the collision point. (Circular machines, while not easy, always give the experimenters something to do during tuning, even at low luminosity.) For CLIC to provide collisions that satisfy the needs of waiting experimenters, both of the drive-beam complexes must provide two exceptional, well focused, aligned and very powerful electron beams that are then transported safely through the drive-beam cavities before the tuning of the main accelerating linacs can begin. There are innumerable tweaks to be made to both beams that require feedback and feed-forward adjustments. I know of no attempt to estimate the time requirements to start up such a hideously complicated set of linacs, nor to ensure their operation afterwards. Clearly the CLIC study has advanced considerably during the past two decades, so I would be interested to learn how well the issue of operability has been understood.

Colin Johnson *formerly CERN PS division.*

Author’s reply

As you mention, the CLIC studies have developed in many respects during the past 25 years. For example, the power of the 380 GeV drive beam in its present design is around 18 MW, most of which is converted into RF power for the main beams, and the stored energy of the drive beam is in the per-mill range compared to the LHC beams. The CLIC 380 GeV accelerator complex will have an annual energy consumption corresponding to around two-thirds of CERN’s accelerator complex today. The drive-beam production and operation have been experimentally verified in the CLIC Test Facility 3, which operated until 2015. The recent development, construction and successful operation of synchrotron light sources and free-electron lasers in the past decades have demonstrated many of the CLIC concepts and beam-performance parameters. The SLC, as with many colliders, had its delays and problems but ultimately it produced important physics results. Many lessons were learned and technical solutions developed, and these too have been integrated in the CLIC design.

Steinar Stapnes *linear-collider study leader, CERN.*



CERN

Linear learning *The CTF3 CLIC test facility.*

The rebirth of theory in France

I would like to complement the excellent article “The rise of French particle physics” (*CERN Courier* November/December 2019 p37), in which only the experimental side appears, with a short note about developments in theory. After Louis de Broglie’s fundamental discovery of the wave-particle relation λ = h/mv, which led to the Schrödinger equation, theoretical physics in France became dormant. It is only shortly before 1950 that the signs of a rebirth appeared. There was the “Séminaire Proca” at Institut Henri Poincaré, attended by those who needed some “fresh air” from outside France. In 1951 Cécile DeWitt-Morette founded the Les Houches Summer School of Theoretical Physics, where the best physicists in the world lectured. In Saclay a group of physicists – Albert Messiah and his friends – gave a series of lectures attended mostly, at the beginning, by polytechnicians. In 1952 Maurice Lévy, of whom I am one of the two first students, was invited by Yves Rocard to start a theoretical physics group at the École Normale Supérieure. Lévy also taught at the university, and in this way gathered people from outside, like Jean Iliopoulos who predicted the existence of the charmed quark and received the Dirac Medal.

At École Polytechnique, in around 1952, Louis Michel had some students, one of whom was Raymond Stora who received the Max Planck Medal and the Heineman Prize. Also at École Polytechnique were Jacques Prentki and Bernard d’Espagnat, who later moved to CERN. Worth mentioning too are Roger Nataf and Philippe Meyer. Léon Motchane then founded the Institut des Hautes Études Scientifiques in 1958, the year the Lévy group made the first steps to establish a summer school in Cargèse. Tony Visconti and Daniel Kastler also launched the “Centre de Physique Théorique” in Marseilles in around 1960. All of this produced wonderful results. It is difficult to list all the French particle theorists who received prizes from foreign countries as a consequence.

André Martin *member emeritus of the CERN theory division.*

Speaking up for citizen science

It was gratifying to see your brief mention of the 42,280 citizen scientists who took part in Higgs Hunters (*CERN Courier* November/December p62). As a coordinator of the project, I wanted to add that the exercise yielded fascinating insights into the LHC collision data – such as identifying apparent “muon jets” – which were subsequently found to be the result of calorimeter punch-through – and demonstrated the impressive capability of citizen scientists to search for heavy scalars decaying within the ATLAS tracker. Particular credit is due to the 15 school students who performed further detailed analysis and who presented the results to the ATLAS collaboration. We’re now about to pilot a further study with UK school students, jointly exploring the student’s research questions using the CERN open-data portal.

Alan Barr *University of Oxford.*

OPINION REVIEWS

Ins and outs of collider calorimetry

Calorimetry for Collider Physics, an Introduction

By Michele Livan and Richard Wigmans

Springer

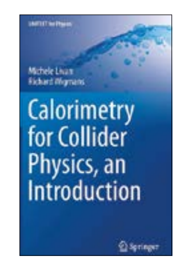
Concise and accessible, *Calorimetry for Collider Physics* is a reference book worthy of the name. Well known experts Michele Livan and Richard Wigmans have written an up-to-date introduction to both the fundamental physics and the technical parameters that determine the performance of calorimeters. Students and senior experts alike will be inspired to deepen their study of the characteristics of these instruments – instruments that have become crucial to most contemporary experiments in particle physics.

Following a light and attractive introductory chapter, the reader is invited to refresh his or her knowledge of the interactions of particles with matter. Key topics such as shower development, containment and profile, linearity and energy resolution are discussed for both electromagnetic and hadronic components. The authors provide illustrations with test-beam results and detailed Monte Carlo simulations. Practical and numerical examples help the reader to understand even counterintuitive effects, stimulating critical thinking in detector designers, and helping the reader develop a feeling for the importance of the various parameters that affect calorimetry.

An important part of the book is devoted to hadron calorimetry. The authors have made a remarkably strong impact in understanding the fundamental problems with large set-ups in test beams, for example the famous lead–fibre sampling spaghetti calorimeter SPACAL. Among other issues, they correct “myths” as to which processes really cause compensation, and discuss quantities that correlate to the invisible energy fraction from hadrons involved in the shower process, for example, to measure the electromagnetic shower fraction event-by-event. The topical development of the dual-readout calorimeter concept follows logically from there – a very promising future direction for this central detector component, as the book discusses in considerable detail. This technology would avoid the question of longitudinal segmentation, which has a particular impact on linearity and calibration.

CERN-EX-9005322

Spaghetti calorimeter *Riccardo de Salvo (left) and Alois Sigrist at CERN in 1990 with a lead–fibre prototype that held the record for energy resolution of single hadrons for 25 years.*



Livan and Wigmans’ book also gives a valuable historical overview of the field, and corrects several erroneous interpretations of past experimental results. The authors do not shy away from criticising calorimetric approaches in former, present and planned experiments, making the book “juicy” reading for experts. The reader will not be surprised that the authors are, for example, rather critical about highly segmented calorimeters aiming at particle flow approaches.

There is only limited discussion about other aspects of calorimetry, such as triggering, measuring jets and integrating calorimeters into an overall detector concept, which may impose many constraints on their mechanical construction. These aspects were obviously considered beyond the scope of the book, and indeed one cannot pack everything into a single compact textbook, though the authors do include a very handy appendix with tables of parameters relevant to calorimetry.

By addressing the fundamentals of calorimetry, Livan and Wigmans have provided an outstanding reference book. I recommend it highly to everybody interested in basic detector aspects of experimental physics. It is pleasant and stimulating to read, and if in addition it triggers critical thinking, so much the better!

Peter Jenni *Albert Ludwig University of Freiburg and CERN.*

ATLAS: A 25-Year Insider Story of the LHC Experiment

By The ATLAS Collaboration

World Scientific

ATLAS: A 25-Year Insider Story of the LHC Experiment is a comprehensive overview of one of the most complex and successful scientific endeavours ever undertaken. 117 authors collaborated to write on diverse aspects of the ATLAS project, ranging from the early days of the proto-collaboration, to the test-beam studies to verify detector concepts, the design, building and installation of the detector systems, building the event selection and computing environment required, forming the organisation, and finally summarising the harvest of physics gathered thus far. Some of the chapters cover topics that are discussed elsewhere – the description of the detector summarises more extensive journal publications, the major physics achievements have been

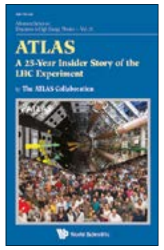
The thrill of the chase for the Higgs boson comes through vividly

covered in recent review articles and the organisational structure is discussed on the web – but this volume usefully brings these various aspects together in a single place with a unified treatment.

Despite the many authors who contributed to this book, the style and level of treatment is reasonably coherent. There are many figures and images that augment the text. Those showing detector elements that are now buried out of sight are important complements to the text descriptions: the pictures of circuit boards are less ▷

CERNCOURIER
Volume 60 Number 1 January/February 2020
IOP Publishing

helpful, besides demonstrating that these electronics exist. A most engaging feature is the inclusion of one-page "stories" at the ends of the chapters, each giving insight into the ups and downs of how the enterprise works. Among these vignettes we have such stories as the ATLAS upgrade week that almost no one attended and the spirit of camaraderie among the experimenters and accelerator operators at the daily 08:30 run meetings.



One could imagine several audiences for this book, and I suspect that, apart from ATLAS collaborators themselves, each reader will find different chapters most suited to their interests. The 26-page chapter "The ATLAS Detector Today" offers a more accessible overview for students just joining the collaboration than the 300-page journal publication referenced in most ATLAS publications. Similarly, "Towards the High-Luminosity LHC" gives a helpful brief introduction to the planned upgrades. "Building up the Collaboration" will be useful to historians of science seeking to understand how scientists, institutions and funding agencies engage in a project whose time is ripe.

Those interested in project management will find "Detector Construction Around the World" illuminating: this chapter shows how the design and fabrication of detector subsystems is organised with several, often geographically disparate, institutions joining together, each contributing according to its unique talents. "From the LoI to the Detector Construction" and "Installation of the Detectors and Technical Coordination" will appeal to engineers and technical managers. The chapters "Towards the ATLAS Letter of Intent" and "From Test Beams to First Physics" catalogue the steps that were necessary to realise the collaboration and experiment, but whose details are primarily interesting to those who lived through those epochs. Finally, "Highlights of Physics Results (2010–2018)" could have offered an exciting story for non-scientists, and indeed the thrill of the chase for the Higgs boson comes through vividly, but with unexplained mentions of leptons, loops and quantum corrections, the treatment is at a more technical level than would be ideal for such readers, and the plots plucked from publications are not best suited to convey what was learned to non-physicists.

Insider story

Given the words in the foreword that the book is "intended to provide an insider story covering all aspects of this global science project," I looked forward to the final chapter, "ATLAS Collaboration: Life and its Place in Society", to get a sense of the human dimensions of the collaboration. While some of that discussion is quite interesting – the collaboration's demographics and the various outreach activities undertaken to engage the public – there is a missing element that I would have appreciated: what makes a collaboration like this tick? How did the large personalities involved manage to come to common decisions and compromises on the detector designs? How do physicists from nations and cultures that are at odds with each other on the world stage manage to work together constructively? How does one account for the distinct personalities that each large scientific collaboration acquires? Why does every eligible author sign all ATLAS papers, rather than just those who did the reported analysis? How does the politics for choosing the collaboration management work? Were there design choices that came to be regretted in the light of subsequent experience? In addition to the numerous successes, were there failures? Although I recognise that discussing these more intimate details runs counter to the spirit of such large collaborations, in which one seeks to damp out as much internal conflict as possible, examining some of them would have made for a more compelling book for the non-specialist.

The authors should be commended for writing a book unlike any other I know of. It brings together a factual account of all aspects of ATLAS's first 25 years. Perhaps as time passes and the participants mellow, the companion story of the *how*, in addition to the *what* and *where*, will also be written.

Paul Grannis *Stony Brook University.*

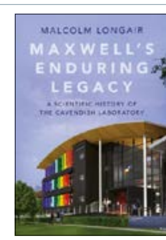
Maxwell's Enduring Legacy: A Scientific History of the Cavendish Laboratory

By Malcom Longair

Cambridge University Press

In 1871, James Clerk Maxwell undertook the titanic enterprise of planning a new physics laboratory for the University of Cambridge from scratch. To avoid mistakes, he visited the Clarendon Laboratory in Oxford and the laboratory of William Thomson (Lord Kelvin) in Glasgow – then the best research institutes in the country – to learn all he could from their experiences. Almost 150 years later, Malcolm Longair, a renowned astrophysicist and the Cavendish Laboratory's head from 1997 to 2005, has written a monumental account of the scientific achievements of those who researched, worked and taught at a laboratory that has become an indispensable part of the machinery of modern science.

The 22 chapters of the book are organised in 10 parts corresponding to the inspiring figures who led the laboratory through the years, most famously Maxwell himself, Thomson, Rutherford, Bragg and Mott. The numerous Nobel laureates who spent part of their careers at the Cavendish are also nicely characterised, among them Chadwick, Appleton, Kapitsa, Cockcroft and Walton, Blackett, Watson and Crick, Cormack and, last but not least, Didier Queloz, Nobel Laureate in 2019 and professor at the universities of Cambridge and Geneva. You may even read about friends and collaborators as the exposition includes the most recent achievements of the laboratory.



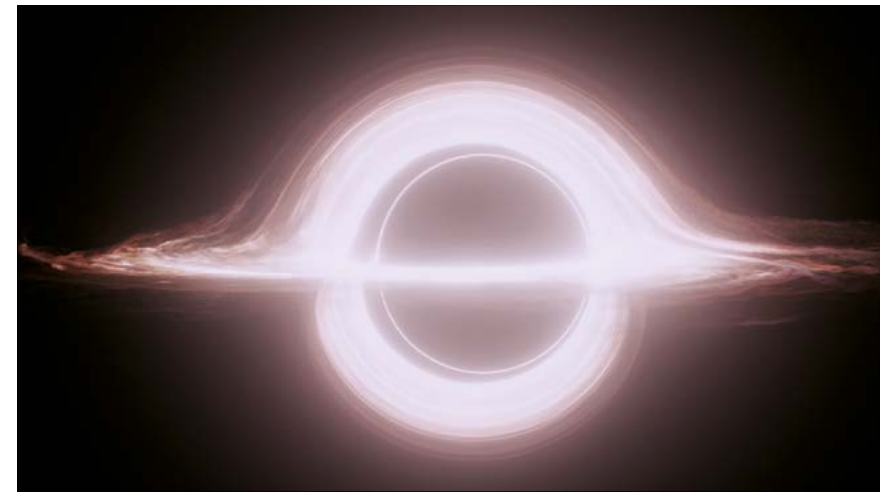
Besides the accuracy of the scientific descriptions and the sharpness of the ideas, this book inaugurates a useful compromise that might inspire future science historians. So far as it was customary to write biographies (or collected works) of leading scientists and extensive histories of various laboratories: here these two complementary aspects are happily married in a way that may lead to further insights on the genesis of crucial discoveries. Longair elucidates the physics with a competent care that is often difficult to find. His exciting accounts will stimulate an avalanche of thoughts on the development of modern science. By returning to a time when Rutherford and Thomson managed the finances of the laboratory almost from their personal cheque book, *Maxwell's Enduring Legacy* will stimulate readers to reflect on the interplay between science, management and technology.

History is often instrumental in understanding where we come from, but it cannot reliably predict directions for the future. Nevertheless the history of the Cavendish shows that lasting progress can come from diversity of opinion, the inclusiveness of practices and mutual respect between fundamental sciences. How can we sum up the secret of the scientific successes described in this book? A tentative recipe might be unity in necessary things, freedom in doubtful ones and respect for every honest scientific endeavour.

Massimo Giovannini *CERN and INFN Milano-Bicocca.*

Generating gargantuan effects

Oliver James of DNEG describes the science underpinning the striking visualisations in *Interstellar*, and discusses trends in the fast-growing visual-effects industry.



DNEG/Warner Bros. Entertainment Inc./CQG **32** 065001

Art meets science *A variant of the black-hole accretion disk seen in the film* Interstellar, *which was created from rigorous general relativistic and other calculations.*

Oliver James is chief scientist of the world's biggest visual-effects studio, DNEG, which produced the spectacular visual effects for the movie *Interstellar*. DNEG's work, carried out in collaboration with theoretical cosmologist Kip Thorne of Caltech, led to some of the most physically accurate images of a spinning black hole ever created, earning the firm an Academy Award and a BAFTA award for best visual effects. For James, it all began with an undergraduate degree in physics at the University of Oxford in the late 1980s. He became interested in atomic physics, quantum mechanics and modern optics. The latter was key, since a great part of visual effects is understanding how light interacts with surfaces and volumes, and eventually enters a camera's lens.

Combining his two other passions – computing and photography – led James to his first job in a small photographic studio in London, where he became familiar with the technical and operational aspects of the industry. Missing the intellectual challenge offered by physics, however, in 1995 he contacted and secured a role in the R&D team of the Computer Film Company – a niche studio specialising in digital film that was part of the emerging London visual-effects industry.

A defining moment came in 2001, when one of his ex-colleagues invited him to join Warner Bros' ESC Entertainment at Alameda, California to work on rigid-body simulations for *The Matrix Reloaded* and *The Matrix Revolutions*. "There's a big fight scene, called the Burly Brawl, where hundreds of digital actors get thrown around like skittles," he says. "We wanted to add realism by simulating the physics of these colliding bodies. The initial tests looked physical, but lifeless, so we enhanced the simulation by introducing torque at every joint, calculated from examples of real locomotion. Suddenly these rag-dolls came to life and you'd find yourself wincing in sympathy as they were battered about." The sequences took dozens of artists and technicians months of work to create just a few seconds of the movie.

Interstellar work

Following his work in ESC Entertainment, James moved back to London and, after a short period at the Moving Picture Company, he finally joined Double Negative in 2004 (renamed DNEG in 2018). He'd been attracted by Christopher Nolan's film *Batman Begins*, for which the firm was creating visual effects, and it was the beginning

> **Suddenly these rag-dolls came to life and you'd find yourself wincing in sympathy as they were battered about**

of a long and creative journey that would culminate in the sci-fi epic *Interstellar*, which tells the story of an astronaut searching for habitable planets in outer space.

The film demanded new imagery for black holes. Given that he hadn't studied general relativity and had only touched upon special relativity, James decided to call Kip Thorne for help in finding an equation that describes the trajectory of light from a distant star, around a black hole and finally into an observer's eye. In total, James and Thorne exchanged some 1000 emails, often including detailed mathematical formalism that DNEG could then use in its code, and the firm was soon able to develop new rendering software to visualise black holes and wormholes. The collaboration was so fruitful that, in 2015, James and his DNEG colleagues published two papers with Thorne on the science and visualisation of black holes (*Am. J. Phys* **83** 486 and *Class. Quantum Grav.* **32** 065001).

"The director had wanted a wormhole with an adjustable shape and size, and thus we designed one with three free parameters, namely the length and radius of the wormhole's interior as well as a third variant describing the smoothness of the transition from its interior to its exteriors," explains James. "The result for the wormhole was like a crystal ball reflecting each point in the universe; imagine a spherical hole in space–time." Simulating a black hole represented a bigger challenge as, by definition, it is an object that doesn't allow light to escape. With his colleagues, he developed a completely new ▷

CERNCOURIER
VOLUME 60 NUMBER 1 JANUARY/FEBRUARY 2020
IOP Publishing

renderer that simulates the path of light through gravitationally warped space–time – including gravitational lensing effects and other physical phenomena that take place around a black hole.

Producing an image for a motion picture requires very high quality standards, and consequently rendering times were up to 100 hours compared to the typical 5–6 hours needed for other films. Contrary to the primary goal of most astrophysical visualisations to achieve a fast throughput, DNEG needed to create images that looked like they might really have been filmed. "This led us to employ a different set of visualisation techniques from those of the astrophysics community – techniques based on propagation of ray bundles (light beams) instead of discrete light rays, and on carefully designed spatial filtering to smooth the overlaps of neighbouring beams," says James.

Another challenge was to capture the fact that the film camera should be traveling at a substantial fraction of the speed of light, meaning that relativistic aberration, Doppler shifts and gravitational redshifts had to be integrated in the rendering code. Things get even more complicated closer to the black hole where space–time is more distorted; gravitational lensing gets more extreme and the computation takes more steps. To simulate the starry background, DNEG used the Tycho-2 star catalogue from the European Space Agency containing about 2.5 million stars, and more recently the team has adopted the Gaia catalogue containing 1.7 billion stars. In total, the movie notched up almost 800 TB of data

Inspired by physics *DNEG chief scientist Oliver James, shown on the right speaking at a colloquium at CERN in March 2019 organised by the Future Circular Collider study in collaboration with CERN's EP department.*

Creative industry

With the increased use of visual effects, not only for sci-fi movies but also in drama or historical films, more and more scientists are working in the field, including mathematicians and physicists. Furthermore, there are a growing number of companies creating tailored simulation packages for specific processes. DNEG alone has increased from 80 people in 2004 to more than 5000 people today. At the same time, this increase in numbers means that software needs to be scalable and adaptable to meet a wide range of skilled artists, James explains. "Developing specialised simulation software that gets used locally by a small group of skilled artists is one thing but making it usable by a wide range of artists across the globe calls for a much bigger effort – to make it robust and much more accessible".

Any increase in computational resources will quickly be swallowed up by artists adding extra detail or creating more complex simulations, he says, and the next big thing on the horizon will be real-time simulation and rendering. "Today, video games are rendered in real-time by the computer's video card, whereas visual effects in movies are almost entirely created as batch-processes and afterwards the results are cached or pre-rendered so they can be played back in real-time," he says. "Moving to real-time rendering means that the workflow will not rely on overnight renders and would allow artists many more iterations during production. We have only scratched the surface and there are plenty of opportunities for scientists." DNEG is currently involved in R&D to use machine learning to enable more natural body movements or facial expressions, and is also embracing open-data movements.

"Visual effects is a fascinating industry where technology and hard-science are used to solve creative problems," says James. "Occasionally the roles get reversed and our creativity can have a real impact on science."

Panos Charitos *CERN.*

Appointments and awards

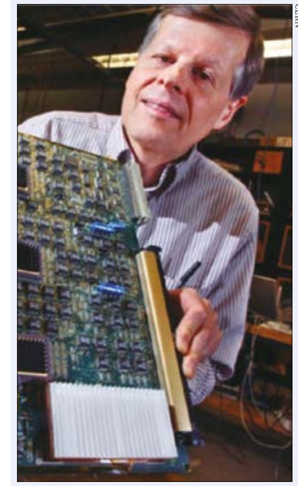
Gianotti elected for second term
On 12 December, the CERN Council unanimously decided to appoint Fabiola Gianotti as Director-General (DG) of CERN for a second term of office of five years, with effect from 1 January 2021. "I am deeply grateful to the CERN Council for their renewed trust," she said in a statement. "The following years will be crucial for laying the foundations of CERN's future projects and I am honoured to have the opportunity to work with the CERN Member States, Associate Member States, other international partners and the worldwide particle-physics community." Gianotti, who is CERN's first female DG, has been a research physicist at CERN since 1994 and was ATLAS spokesperson from March 2009 to February 2013 during the discovery of the Higgs boson.

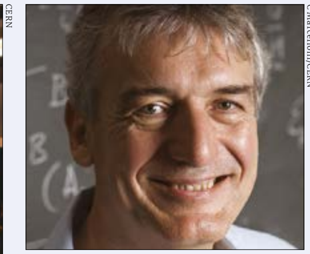
Nikhef reappoints Bentvelsen
Stan Bentvelsen has been reappointed for a second five-year term as director of Nikhef in the Netherlands. Bentvelsen, an experimental physicist on ATLAS and an academic at the University of Amsterdam, first became director in 2014 and has overseen Nikhef's involvement in international projects such as KM3NeT, XENON, Auger and a test facility of the proposed

Einstein Telescope. He plans "to continue to open doors to new physics through diversification of experiments, both accelerator-based and other detectors, from physics to astroparticle physics."

Smith continues at SNOLAB
Astroparticle physicist Nigel Smith has been appointed to a three-year extension as executive director of SNOLAB in Canada. Smith, who has been in the role since 2009, agreed to remain in position until 31 December 2022, with a search for a successor being revisited during 2020.

Appointments and awards

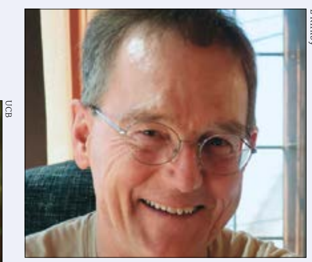




The Sakurai Prize recognises work revealing the potential visibility of the invisible axion

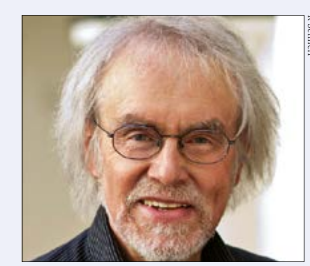
APS announces 2020 prizes
Wesley Smith (top left) of the University of Wisconsin-Madison, and member of the CMS collaboration, has won the American Physical Society (APS) 2020 W K H Panofsky Prize "for the development of sophisticated trigger systems for particle-physics experiments, which enabled measuring the detailed partonic structure of the proton using the ZEUS experiment at HERA and led to the discovery of the Higgs boson and the completion of the Standard Model with the CMS experiment at the LHC". The 2020 J J Sakurai Prize for theoretical particle physics went to Pierre Sikivie (top right) of the University of Florida for seminal work recognising the potential visibility of the invisible axion, devising novel methods to detect it, and for theoretical investigations of its cosmological implications. In the accelerator arena, the 2020 Robert R Wilson Prize was awarded to Bruce Carlsten (bottom left) of Los Alamos National Laboratory for the discovery and subsequent implementation of emittance compensation in photo-injectors "that has enabled the development of high-brightness, X-ray free electron lasers such as the Linac Coherent Light Source". Among several other prizes awarded in the particle, nuclear, astrophysics and related fields, the 2020 Henry Primakoff Award for Early-Career Particle Physics went to Matt Pyle (bottom right above) of the University of California at Berkeley for his development of high-resolution ultra-low-threshold cryogenic detectors for dark-matter searches.

Kirkby bags aerosol award
The 2019 Benjamin Y H Liu Award of the American Association for Aerosol Research, which recognises outstanding contributions to aerosol instrumentation and experimental techniques, has been awarded to CERN's Jasper Kirkby for his investigations into atmospheric new-particle and cloud formation using the unique CLOUD experiment at CERN, which he originated. The award committee described CLOUD as "arguably the most effective experiment to study atmospheric nucleation and growth ever



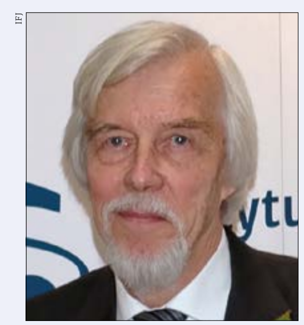
designed and constructed, really by a country mile", and said of Kirkby: "His irrepressible will and determination have adapted the culture of 'big science' at CERN to a major atmospheric science problem. Along the way, Jasper has also become a world-class aerosol scientist."

Max Planck Medal for Buras
Andrzej Buras of the Technical University of Munich has been awarded the Max Planck Medal by the German Physical Society for his outstanding contributions to applied quantum field theory, especially in flavour physics and quantum chromodynamics.



Spiro awarded Lagarrigue Prize
The 2018 André Lagarrigue Prize has been awarded to Michel Spiro, research director emeritus at CEA, for the exemplary nature of his career, from both a scientific and managerial point of view. Spiro contributed, among other things, to the discovery of the W and Z bosons with the UA1 experiment, was the initiator and spokesperson of the EROS experiment, and played a major role in the GALLEX experiment. He has held several senior positions at CEA and CNRS and from 2010–2013 was president of the CERN Council.

Polish honour for Heuer
On 14 October, the Henryk Niewodniczański Institute of Nuclear Physics of the Polish



Academy of Sciences in Kraków (IFJ PAN) granted former CERN Director-General Rolf-Dieter Heuer an honorary professorship "in recognition of his outstanding contribution to the field of experimental particle physics as well as his continuous support of scientific collaboration between IFJ PAN and high-energy European laboratories DESY and CERN".

CERNCOURIER
Volume 60 Number 1 January/February 2020
IOP Publishing

RECRUITMENT

For advertising enquiries, contact *CERN Courier* recruitment/classified, IOP Publishing, Temple Circus, Temple Way, Bristol BS1 6HG, UK.
Tel +44 (0)117 930 1264 E-mail sales@cerncourier.com.
Please contact us for information about rates, colour options, publication dates and deadlines.

ELI Beamlines research centre in Dolní Břežany is part of pan-European infrastructure ELI (Extreme Light Infrastructure) representing a unique tool of support of scientific excellence in Europe by making available its capacities to the best scientific teams across the world. The aim of ELI Beamlines is to establish the most intensive laser system in the world and to operate it on a long-term basis. Due to ultra-high performances of 10 PW (1 petawatt = 1,000,000,000,000,000 watts) and concentrated intensities of up to 1024 W/cm2, we can offer our users a unique source of radiation and beams of accelerated particles. The so called beamlines will enable groundbraking research in the area of physics and science dealing with materials, but also in biomedicine and laboratory astrophysics and many other fields. ELI Beamlines is part of the Institute of Physics of the Czech Academy of Sciences, and it was open in 2015.

The Institute of Physics of the Czech Academy of Sciences is a holder of the HR Excellence in Research Award. It is awarded by the European Commission to institutions which put significant effort into improving their HR strategy and ensuring professional and ethical working conditions.

Ultrafast spectroscopy Researcher

As part of the experimental capabilities at ELI Beamlines, RP4 develops a beamline and multi-purpose user end-station for applications in AMO sciences and CDI (MAC). The MAC user end-station is equipped with electron/ion spectrometers, detectors for coherent diffractive imaging and state-of-the-art sample delivery systems to enable advanced photon science experiments on low density targets (atoms, molecules, clusters, nanometer to micrometer sized organic and inorganic particles, vacuum compatible sub-micrometer size liquid sheets and aerosols).

We are now looking for a researcher/instrumental scientist to contribute to the development of the unique experimental capabilities of the MAC user end-station. The successful candidate will participate in all aspects of the MAC station operations but assume a specific responsibility for the implementation and further development of various sample delivery systems (molecular and cluster beams, gas dynamic virtual nozzle and electrospray nano-particle injection, production of flat liquid sheets). This work also includes the development of characterization methods for samples and sample delivery techniques. Following completion of the ELI Beamlines facility she/he will work both on independent research topics focused on ultrafast spectroscopy and imaging of nano-particles and molecular beams as well as provide support for members of an international user community who come to perform experiments at the scientific end stations.

The work will be predominantly focused on following topics:

- development of experimental capabilities of the MAC user end-station with a strong focus on sample delivery and characterization techniques
- participation in the support of user experiments at the MAC user end-station as well as in-house research and development programmes
- contribution to the relevant research activities of the RP4 group within national and international collaborators at synchrotrons and X-ray free-electron laser facilities

Requirements:

- PhD in physics, biophysics, chemistry or related field is desirable. Highly motivated candidates with a M.Sc. degree are also encouraged to apply (in that case the position will be transferred to a PhD student position)
- strong interests in development and operation of advanced scientific instruments
- programming skills in Phyton, Matlab are beneficial
- experience from working with lasers and/or other pulsed light sources and/or vacuum equipment is beneficial
- strong interests in scientific fields related to biophysics, ultrafast spectroscopy and dynamics, coherent diffractive imaging, physics with ultra-short pulses, interaction of light with matter, atomic and molecular physics
- good networking and communication skills, capability to work in a team
- good knowledge of spoken and written English is necessary as the work environment is highly international

We offer:

- the opportunity to participate in this unique scientific project
- competitive and motivating salary
- flexible working hours
- nice working environment
- career growth
- lunch vouchers, pension contribution and 5 sick days
- support of leisure time activities

Applications, containing CV, cover letter, contacts of references, and any other material the candidate considers relevant, should be sent to Mrs. Jana Ženíšková, HR specialist (jana.zeniskova@eli-beams.eu, +420 - 601560322).

Information regarding the personal data processing and access to the personal data at the Institute of Physics of the Czech Academy of Sciences can be found on: https://www.fzu.cz/en/processing-of-personal-data

eli beamlines | MŠMT MINISTRY OF EDUCATION, YOUTH AND SPORTS | FZU | EUROPEAN UNION

DATA SCIENTIST / SOFTWARE DEVELOPER

EXCITING CAREERS FOR STEM GRADUATES AND POSTGRADUATES

Tessella is a data science, analytics and software consultancy that works with global companies at the forefront of science and technology. We are leaders in the field of data science and analytics, helping clients solve their most complex technical challenges by unlocking the power of their data, enabling them to make better-informed business decisions.

Our projects are varied and typically at the cutting-edge of high-tech R&D, for example:

- Solving computational problems for chemists in drug discovery and development.
- Modelling and simulating new products for FMCG clients and analysing data to improve processes.
- Writing algorithms and solving complex mathematical problems to control satellites and radar systems.
- Solving the computational challenges of oil and gas exploration and production, from reservoir modelling to writing control systems.

We are looking for science, mathematics and engineering graduates and postgraduates to join us. Supported by our extensive training package, you will apply your deep domain knowledge and use a range of skills to create and develop innovative solutions that truly make a difference in the world.

www.tessella.com | jobs@tessella.com

BEST COMPANY 2017 | THE SUNDAY TIMES 100 BEST SMALL COMPANIES TO WORK FOR 2017 | INVESTORS IN PEOPLE Gold Until 2019 | Tessella ALTRAN GROUP

CERN HR Human Resources

CERN's HR Talent Acquisition team wishes you a very happy new year!

2020 will see plenty of new opportunities opening up for students, graduates and experienced professionals. Find out more and apply now: **https://careers.cern**.

You too could experience working in a place like nowhere else on Earth. CERN. **Take part!**

PEOPLE OBITUARIES

Luigi Radicati 1919–2019

Eminence in symmetry

Luigi Radicati, one of the eminent Italian theoretical physicists of the past century, passed away on 23 August 2019 in his home in Pisa, about 50 days before his 100th birthday.

Born in Milan, Radicati received his laurea in physics from the University of Torino under the supervision of Enrico Persico in 1943, and became the assistant professor of Eligio Perucca at Torino Polytechnic in 1948. In between this, during the Second World War he was also a member of a partisan division fighting against German occupation.

The years 1951–1953, which Radicati spent as a research fellow at the University of Birmingham in the group of Rudolf Peierls, had a major impact on his training. Then, in 1953 Radicati became a professor of theoretical physics, first at the University of Naples and two years later at the University of Pisa. In 1962 Radicati was finally called to the Scuola Normale Superiore (SNS) in Pisa as one of two professors in the "Classe di scienze", the other being the great mathematician Ennio De Giorgi. Radicati remained at SNS until 1996, acting as vice-director between 1962 and 1964, and director between 1987 and 1991.


Scuola Normale Superiore

Theorist Luigi Radicati turned his attention to nuclear and particle physics, astrophysics, plasma physics and statistical physics.

Luigi Radicati can be remembered for two main reasons: the special role that he attributed to symmetries; and the broadness of his interests in physics, as in the relations between physics and other disciplines. His most important and well known physics results stem from the early 1960s. After working with Paolo Franzini to show evidence for SU(4) symmetry in the classification of nuclear states, introduced by Wigner in 1937, in 1964 Radicati proposed, together with Feza Gürsey, the enlargement of SU(4) to SU(6) as a useful symmetry of hadrons. Gell-Mann had introduced the SU(3) symmetry in 1962 and at the beginning of 1964 had proposed, simultaneously with George Zweig, the notion of quarks. The SU(6)-subgroup $SU(3) \times SU(2)$ puts together Gell-Mann's SU(3) with the spin SU(2) symmetry, thus unifying in single multiplets the pseudo-scalar together with the vector mesons and the $J = 1/2$ together with the $J = 3/2$ baryons. At a deeper level, SU(6) gave momentum to view the quarks as real entities obeying peculiar statistics, preliminary to the introduction of colour.

Radicati's collaborations brought frequent visits of eminent physicists to Pisa

In the latter part of the 1960s Radicati began turning his attention to astrophysics, gravity, plasma physics and statistical physics. Here it is worth mentioning the long-lasting collaboration with Emilio Picasso, which started in 1977 during a discussion in the CERN cafeteria: the use of a gravitational-wave detector consisting of a system of two radio-frequency cavities, coupled to create a two-level system with a tunable difference between their oscillation frequencies.

Radicati's collaborations brought frequent visits of eminent physicists to Pisa, among them Freeman Dyson, Feza Gürsey, T D Lee, Louis Michel, Rudolf Peierls, David Speiser and John Wheeler. Most of all, Radicati played a prominent role in bringing from CERN to the SNS Gilberto Bernardini, who acted as SNS director from 1964 to 1977, and Emilio Picasso, who was SNS director from 1992 to 1996.

Radicati was a member of the Accademia Nazionale dei Lincei from 1966, named Chevalier de la Légion d'Honneur and Doctor Honoris Causa at the École Normale in Paris in 1994, and was awarded the honour of Cavaliere di Gran Croce of the Italian Republic in 2004. During his career, he also translated and introduced important physics books into Italy, including *The Meaning of Relativity* by Albert Einstein, *A History of Science* by William Dampier and *Quantum Mechanics* by Leonard Schiff.

Luigi Radicati is survived by his wife and four of his sons.

Riccardo Barbieri *Scuola Normale Superiore, Pisa.*

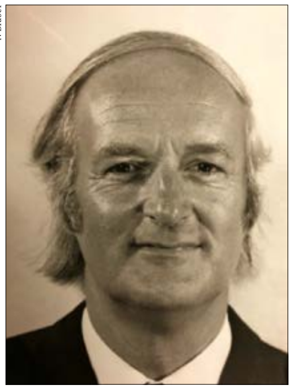
Jean-Pierre Blaser 1923–2019

Pushing cyclotron limits

Jean-Pierre Blaser, a former director of the Swiss Institute of Nuclear Research (SIN), passed away in his home in Switzerland on 29 August 2019 at the age of 96.

In 1948 Blaser finished his physics studies at ETH Zurich, going on to participate in the development of a cyclotron at ETH built by Paul Scherrer during the Second World War. From 1952–1955 he carried out experiments with mesons at the synchrocyclotron in Pittsburgh before becoming director of the observatory in Neuchâtel from 1955–1959. In 1959 he was appointed as Scherrer's successor and inherited from him the planning group for a new cyclotron. Originally, Scherrer wanted to copy the 88-inch cyclotron at Berkeley and use it for research in nuclear physics, but Blaser wanted something more ambitious. After receiving advice from accelerator experts at CERN, among them Pierre Lapostolle, he proposed a 500 MeV cyclotron for the production of mesons.

The key for such a meson factory was to extract the high-intensity proton beam with very low losses. The leader of Blaser's cyclotron group, Hans Willax, realised that a conventional cyclotron would have high losses at extraction and in 1962 had the brilliant idea to break up the cyclotron magnets into separate sectors to leave space for high-voltage cavities. Blaser immediately supported the idea and pushed to get this expensive project approved by the Swiss government. Against all odds and against some strong opposition, he finally succeeded. In 1968 he founded SIN in Villigen and was its director for the next 20 years.


N Blaser

Accelerator physicist Jean-Pierre Blaser was instrumental in getting the Swiss national cyclotron approved.

In a last-minute decision, based on results of CERN experiments which showed that the production of pions would strongly increase with energy, the energy of the SIN cyclotron was increased from 500 to 590 MeV. Even top accelerator specialists like the late Henry Blosser had doubts that the SIN crew would reach the ambitious design goal of a 100 μA beam current. But Blaser and Willax were convinced, anticipating that the original 72 MeV injector cyclotron would be the limiting factor and eventually would have to be replaced. In January 1974 the first protons were extracted from the ring, and at the end of 1976 the design current of 100 μA was reached. More highlights followed, right up to 2009 with 2.4 mA protons at 590 MeV and a new world record of 1.4 MW in average beam power achieved – a record that still holds today. These results gave Blaser great satisfaction, even after his retirement in 1990. Before that date he initiated in 1988 the new Paul Scherrer Institute (PSI), a combination of SIN and the neighbouring reactor institute EIR.

Blaser pioneered the use of pions for the treatment of deep-seated tumours

From the start of the accelerator project, Blaser saw the potential of particle beams to irradiate tumours. The first step, for which a superconducting solenoid was constructed, was to use pions for the treatment of deep-seated tumours. In 1984 the irradiation of eye tumours started, using protons, and to date more than 7000 patients have been treated. Later, a new superconducting cyclotron was acquired and two more gantries are now in operation. Blaser strongly supported all activities in the medical application of cyclotrons, and gave his advice to a new cyclotron project in South Africa – becoming elected as a foreign associate of the Royal Society of South Africa for his efforts.

Jean-Pierre Blaser was blessed with great intuition based on a thorough knowledge of the basic laws of physics. He was open to new and unconventional ideas and he fully motivated young scientists with his trust in their abilities. In his free time he enjoyed exploring the landscapes of Switzerland either by foot or as a pilot with a light aeroplane. But his top priority was his family. He enjoyed enormously the company of his wife Frauke, their two daughters Claudine and Nicole, and their four grandchildren. In Jean-Pierre, his family and the accelerator community loses a great personality.

Werner Joho *Paul Scherrer Institut, Switzerland.*

B V Sreekantan 1925–2019

Remembering a cosmic-ray pioneer

Badanaval Venkatasubba Sreekantan, a pioneering cosmic-ray physicist and a member of Homi Bhabha's team of scientists, who played an important role in the development of post-colonial Indian science, died at his home in Bangalore on 27 October 2019.

Sreekantan was born on 30 June 1925 near Mysore in South India. After receiving his master's degree in physics in 1947 with a specialisation in wireless technology from Mysore University, he joined the Indian Institute of Science at Bengaluru as a research scholar, where he heard about Bhabha and his newly formed Tata Institute of Fundamental Research (TIFR) in Mumbai. Attracted by Bhabha's charisma, he joined TIFR in July 1948 and began a long, illustrious scientific career of almost 44 years.


B Sreekantan

Badanaval Venkatasubba Sreekantan led several key experiments in the Kolar Gold Fields mine.

In 1951 Bhabha sent Sreekantan down the deep Champion Reef Gold Mine at Kolar Gold Fields (KGF) near Bengaluru to measure the flux of cosmic-ray muons at varying depths. This pioneering initiative not only earned Sreekantan a PhD but also paved the way for setting up a deep underground laboratory. A series of follow-up experiments at KGF, carried out during the early 1960s, extended his previous measurements of muon intensity to the deepest level available; finally, after reaching a depth of 2700 m, recording no muons after two months of exposure. Sreekantan and his collaborators realised that such a deep underground site with minimal cosmic-ray muon background would be an ideal site to detect atmospheric neutrinos. A series of seven neutrino telescopes were quickly set up at a depth of 2300 m and in early 1965 they recorded the first atmospheric-neutrino event, contemporaneously with the detection from another underground neutrino experiment set up by Fred Reines in a South African mine. It was an important milestone, given how important the study of neutrinos underground would later become.

During early 1980s Sreekantan and his collaborators built two detectors, one at a depth of 2300 m and the other at 2000 m, to study the stability of the proton. These two experiments ran for more than a decade and put strong limits on the proton lifetime. He was also instrumental in starting a high-altitude cosmic-ray laboratory at Udhagamandalam (Ooty) in the State of Tamil Nadu to study the hadronic components of cosmic-ray showers.

Sreekantan quickly recognised the importance of the emerging field of X-ray astronomy

Sreekantan quickly recognised the importance of the emerging field of X-ray astronomy for probing high-energy processes in the universe. In 1967 he started balloon-borne experiments to study cosmic X-ray sources and built a strong group that went on to develop expertise in the fabrication of highly sophisticated X-ray detectors for space-borne astronomy missions. The multi-wavelength astronomy observatory Astrosat, launched by the Indian Space Research Organisation in September 2015, is a testimony to the strength of the group. A very high-energy gamma-ray observation programme using the atmospheric Cherenkov technique, which was started by Sreekantan and his collaborators in Ooty in the 1970s, is being continued in Ladakh with a low-energy threshold.

Sreekantan became director of TIFR in 1975, and over the next 12 years steered the institute with distinction and left a rich legacy of high-quality research programmes as well as several new TIFR centres and field stations. In 1992, after a long and eventful scientific carrier at TIFR, Sreekantan moved to Bengaluru and was offered a chair at the newly created National Institute of Advance Studies. His research interest shifted from physical sciences to the philosophical aspects of science and in particular to the abstract topic of consciousness and its scientific and philosophical basis. He remained an alert and active researcher and was engaged in his academic activities with great eagerness until the very end. His death marks the end of a glorious chapter of experimental cosmic-ray research in India.

Naba K Mondal *Saha Institute of Nuclear Physics, Kolkata.*

BACKGROUND

Notes and observations from the high-energy physics community

Outreach feels the force


University of Liverpool

Capitalising on the release of *The Rise of Skywalker* last month, UK-based physicists at the Cockroft Institute and the University of Liverpool on 20 November used *Star Wars* to engage local school children with accelerator physics.

"We need more scientists and engineers," said Liverpool's Carsten Welsch. "There has been a fall in interest in these disciplines, and for us today, *Star Wars* is the icebreaker." Welsch linked the proton torpedo used by Luke Skywalker to destroy the death star to hadron therapy, and the hovering speeder bikes seen on the forest moon of Endor to superconductivity and future colliders. Lightsabres provoked discussions on the laser knives used for precision surgery and materials treatment, and students sliced virtual cubes using virtual-reality headsets and controllers. Experiments with liquid nitrogen heightened awareness of Han Solo's precarious situation when frozen in carbonite – and also of the LHC's ultra-low-temperature vacuum pipes. Finally, force telekinesis led to conversations about the Paul traps used to capture antihydrogen ions in experiments such as GBAR at CERN.

Media corner

"To set up mathematical equations where you have a particle that interacts with neutrons and electrons more than with protons and neutrinos turns out to be not so simple to do."

Theorist ***Matt Strassler*** in *Scientific American* (9 December) on the prospects for the existence of the X17 boson (see p7).

"The remarkable progress of underground dark-matter detectors and the LHC has thrown cosmology into a state of major disruption."

Fermilab's ***Dan Hooper*** writing on dark matter's increasing elusiveness in *Time* (6 December).

"CERN's boss Fabiola Gianotti is right to be proud of the spirit of common human purpose her organisation embodies... Is it dewy-eyed idealism to suggest that this is a model we might apply elsewhere?"

From a ***New Scientist*** editorial (23 November) arguing for a research institution dedicated to climate change.

"There they are, theoretical physicists in their natural habitat, sitting at desks deep in contemplation or scrawling indecipherable formulae on whiteboards, trying to figure out where all the dark matter is hiding."

The Observer (1 December) reporting on a visit to CERN.

"The project – known as the Electron-Ion Collider of China, or EICC – will see electrons being fired at the nuclei of heavy elements such as iron or uranium at high speeds."

South China Morning Post (16 December) reports plans to create a "paradise for physicists" in China.

"A hall to house the tank will be dug with explosive charges at a site 8 km from the existing Kamioka facilities, to avoid vibrations disturbing the KAGRA gravitational-wave detector, which is about to start operating."

Nature (16 December) reporting on the green light for construction of the Hyper-Kamiokande experiment in Japan.

From the archive: January/February 1980

STELLAr work


CERN 196.11.79

STELLA—the Satellite Transmission Experiment Linking Laboratories—is taking shape, with a 3-m diameter antenna installed at CERN, right. This pioneering project will allow European physics laboratories to explore the possibility of high-speed data transmission – 1 Mbit/s – over large distances using the European Space Agency's OTS-2 communications satellite, launched in 1978.

STELLA will link CERN, the UK Rutherford Laboratory, DESY in Germany, Saclay in France, Pisa in Italy, Dublin in Ireland and Graz in Austria. It is supported by the European Space Agency (ESA), the European Economic Community (EEC) and the national post and telegraph (PTT) authorities.

CERN experiments will provide the bulk of transmitted data until the "big shutdown", when the SPS stops and work begins on its conversion into a proton–antiproton collider. For the remainder of the year DESY will be the main user, with data for Rutherford and Saclay.

● Compiled from text on pp444–5 of *CERN Courier* Jan/Feb 1980.

Compiler's note

STELLA was a test bed for technologies that would be crucial to the LHC Computing Grid and the Web. STELLA Phase 1, 1978–1981, demonstrated the technical feasibility of accurate high-speed, high-volume data transmission between European laboratories. In STELLA Phase 2, 1981–1983, the Pisa collaborators implemented an interconnection protocol functionally equivalent to the Internet Protocol – while European governments engaged in internecine communication protocols battles, lagging behind the US in adopting TCP/IP. Until 1988, CERN's migration to the internet was heavily criticised; by 1991 the Lab was the hub for 80% of Europe's internet traffic.

1.9 fs

Duration of the shortest ever UV laser pulse, enabling ultrafast spectroscopy of biochemical processes, and one of several superlatives released by DESY to mark its 60th anniversary

Signing for science

Sandbox Studio

ATLAS postdoc Giordon Stark of the University of California, Santa Cruz, in conjunction with sign-language experts, has developed a sign for "particle collision" – one of several being contributed to the lexicon of American Sign Language to help deaf scientists communicate. Stark, who himself is deaf, argued that the sign couldn't just show two fists crashing together and then coming to a stop, since that isn't technically accurate, and settled on the signer sending their hands past one another and then flicking their fingers out to show the resulting sprays of particles.

CERNCOURIER
Volume 60 Number 1 January/February 2020
IOP Publishing
CERN

CAEN Electronic Instrumentation
Save your time, enhance your success!
N1081A - NIM Four-Fold Programmable Logic Unit
The N1081A is a laboratory tool that incorporates in a single NIM module the most common functionalities that you need to implement the logic capabilities of your experiment.
Few taps on the touch screen to attain up to 4 logic units working simultaneously in a single box
Monitor your activity
Configure the input parameters
Set the function of the module
• Wide range of user-selectable functionalities: Logic functions, Counting, Timing, digital pulse generator
• 4 independent sections, each with: 6 NIM/TTL input - 4 NIM/TTL output
• Configuration and control via touch screen display or remotely via web interface
• User-friendly widgets to configure each section, monitor real-time output data and access the online help
Functions
SCALER
COUNTER
RATE METER
PULSE GENERATOR
NEW
A new CAEN Tool in your Laboratory!
N1081A
COUNTERS/TIMERS
DIGITAL PULSE GENERATOR
TIME STAMPING
LOGIC GATES
CHECK THIS OUT!
Complete your NIM Laboratory!
others NIM Family Modules
64/32/8/4/2 Ch.
NIM
Crate Family
DT5495
Programmable Logic Unit