WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the April 2018 issue of *CERN Courier*.

This month we delve into the curious world of beauty-quark decays, which play a powerful role in precision tests of the Standard Model. During the past year or two, in addition to results reported by the Belle and BaBar B-factory experiments in Japan and the US, the LHCb experiment at CERN has seen slight deviations from predictions in the way b mesons decay into different types of leptons. If the measurements firm up on collection of further data in the coming months and years, they could challenge a tenet of the Standard Model called lepton universality. In the parallel world of accelerators, high-gradient X-band cavities developed by the CLIC collaboration for fundamental physics exploration at the TeV scale are making their way into other fields including light sources and medical applications. This month's issue also features a report demanding a paradigm shift in computing to cope with the data requirements of high-energy physics into the 2020s, a breakdown of the timeline for the upcoming European strategy update, and a call to the community to talk positively about the discovery of the Higgs boson.

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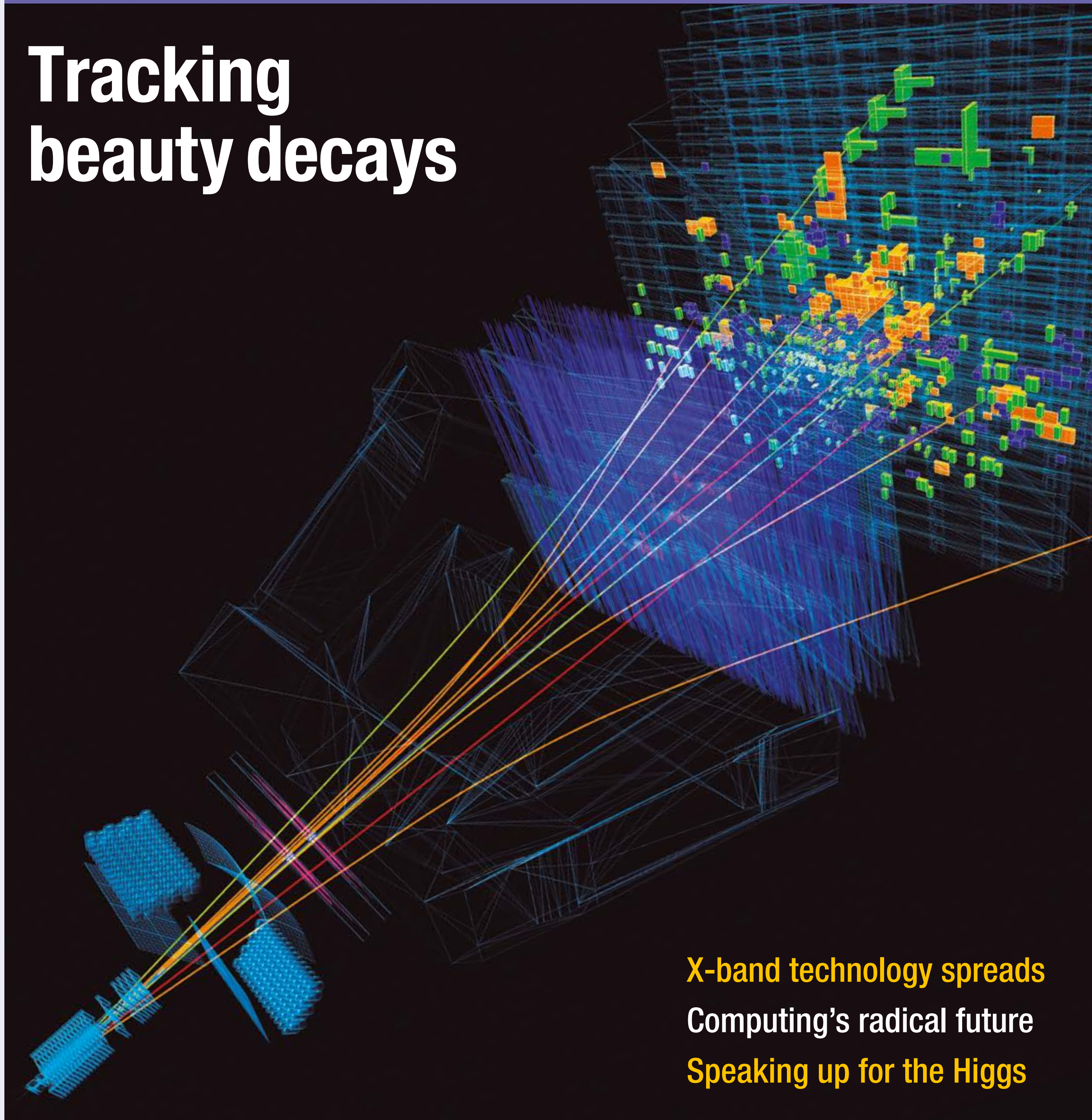

Contents

Covering current developments in high-energy physics and related fields worldwide

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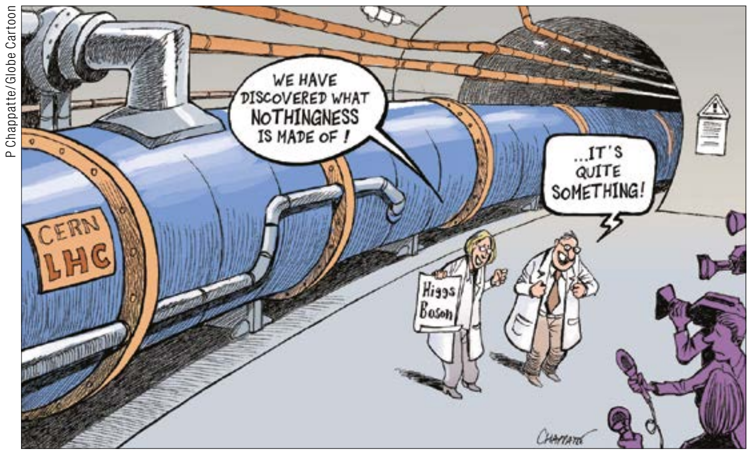
On the cover: A proton–proton collision resulting in the production of pairs of b hadrons and their decay products in the LHCb detector. (Image credit: LHCb collaboration.)

Viewpoint

We need to talk about the Higgs

The discovery of the Higgs boson marks the beginning, not the end, of a fascinating journey.



P Chappatte/Globe Cartoon

The LHC's discovery of the Higgs boson in 2012 captured the world's attention, but is too often said to have closed the door to new physics.

By Tim Gershon

It is just over five years ago that the discovery of the Higgs boson was announced, to great fanfare in the world's media, as a crowning success of CERN's Large Hadron Collider (LHC). The excitement of those days now seems a distant memory, replaced by a growing sense of disappointment at the lack of any major discovery thereafter.

While there are valid reasons to feel less than delighted by the null results of searches for physics beyond the Standard Model (SM), this does not justify a mood of despondency. A particular concern is that, in today's hyper-connected world, apparently harmless academic discussions risk evolving into a negative outlook for the field in broader society. For example, a recent news article in *Nature* led on the LHC's "failure to detect new particles beyond the Higgs", while *The Economist* reported that "Fundamental physics is frustrating physicists". Equally worryingly, the situation in particle physics is sometimes negatively contrasted with that for gravitational waves: while the latter is, quite rightly, heralded as the start of a new era of exploration, the discovery of the Higgs is often described as the end of a long effort to complete the SM.

Let's look at things more positively. The Higgs boson is a totally new type of fundamental particle that allows unprecedented tests of electroweak symmetry breaking. It thus provides us with a novel microscope with which to probe the universe at the smallest scales, in analogy with the prospects for new gravitational-wave telescopes that will study the largest scales. There is a clear need to measure its couplings to other particles – especially its coupling with itself – and to explore potential connections between the Higgs and hidden or dark sectors. These arguments alone provide ample motivation for the next generation of colliders including and beyond the high-luminosity LHC upgrade.

So far the Higgs boson indeed looks SM-like, but some perspective is necessary. It took more than 40 years from the discovery of the neutrino to the realisation that it is not massless and therefore not SM-like; addressing this mystery is now a key component of the global particle-physics programme. Turning to my own main research area, the beauty quark – which reached its 40th birthday last year – is another example of a long-established particle that is now providing exciting hints of new phenomena (see p23). One thrilling scenario, if these deviations from the SM are confirmed, is that the new physics landscape can be explored through both the b and Higgs microscopes. Let's call it "multi-messenger particle physics".

How the results of our research are communicated to the public has never been more important. We must be honest about the lack of new physics that we all hoped would be found in early LHC data, yet to characterise this as a "failure" is absurd. If anything, the LHC has been more successful than expected, leaving its experiments struggling to keep up with the astonishing rates of delivered data. Particle physics is, after all, about exploring the unknown; the analysis of LHC data has led to thousands of publications and a wealth of new knowledge, and there is every possibility that there are big discoveries waiting to be made with further data and more innovative analyses. We also should not overlook the returns to society that the LHC has brought, from technology developments with associated spin-offs to the training of thousands of highly skilled young researchers.

The level of expectation that has been heaped on the LHC seems unprecedented in the history of physics. Has any other facility been considered to have produced disappointing results because only one Nobel-prize winning discovery was made in its first few years of operation? Perhaps this reflects that the LHC is simply the right machine at the right time, but that time is not over: our new microscope is set to run for the next two decades and bring physics at the TeV scale into clear focus. The more we talk about that, the better our long-term chances of success.

Tim Gershon is a professor at the University of Warwick, UK, and a member of the LHCb collaboration, with research interests including flavour physics, CP violation and heavy-quark physics.

News

FUTURE OF THE FIELD

Call for input to European strategy update

The European strategy for particle physics, which is due to be updated by May 2020, will guide the direction of the field to the mid-2020s and beyond. To inform this vital process, the secretariat of the European Strategy Group (ESG) is calling upon the particle-physics community across universities, laboratories and national institutes to submit written input by 18 December 2018.

The update of the European strategy got under way in September when the CERN Council established a strategy secretariat (*CERN Courier* November 2017 p37). Chaired by Halina Abramowicz, former chair of the European Committee for Future Accelerators (ECFA), the secretariat includes Keith Ellis (chair of CERN's Scientific Policy Committee), Jorgen D'Hondt (current ECFA chair) and Lenny Rivkin (chair of the European Laboratory Directors group).

Discussions at the open session of the previous European strategy update, which was held in Kraków in Poland in September 2012.

The ESG secretariat, which has been assigned the task of organising the update process, proposes to broadly follow the steps of the previous two strategy processes concluded in 2006 and 2013. An open symposium, which in previous editions took place in Orsay (France) and Kraków (Poland), will take place in the second half of May 2019, in which the community will be invited to debate scientific input into the strategy update. With the event expected to attract around 500 participants, the secretariat proposes to hold it over a period of four days.

To prepare for the open symposium, the location of which is expected to be decided by the summer, ESG calls for written contributions towards the end of the year. Input should be submitted via a portal on the strategy-update website, which will be available from the beginning of October once the update has been formally launched by the CERN Council. The link will appear on the CERN Council's web pages (https://council.web.cern.ch/en) and will be widely communicated closer to the time.

A "briefing book" based on the discussions will then be prepared by a physics preparatory group and submitted to the ESG for consideration during a five-day-long drafting session in the second half of January 2020. A special ECFA session on 14 July 2019 during the European Physical Society conference on high-energy physics in Ghent, Belgium, will provide another important opportunity for the community to feed into the ESG's drafting session.

Global perspective

The European strategy update takes into account the worldwide particle-physics landscape and developments in related fields, and was initiated to coordinate activities across a large, international and fast-moving community. The third update comes as the scale of particle-physics facilities is leading to increased globalisation of the field and as its research direction evolves.

Understanding the properties of the Higgs boson (which was discovered at CERN just before the previous strategy update) remains a key focus of analysis at the LHC and future colliders, as are precision measurements of other Standard Model (SM) parameters and searches for new physics beyond the SM.

Neutrino physics is another key area of interest, with much experimental activity taking place since the last update. A "physics beyond colliders" programme has also been established by CERN to explore projects complementary to high-energy colliders and projects of national laboratories. The European astroparticle and nuclear-physics communities, meanwhile, recently launched their own strategies (*CERN Courier* September 2017 p6; March 2018 p7), which will also feed into the ESG update.

"After the discovery of the Higgs boson, the field is presented with a number of challenges and opportunities," says Abramowicz. "Guided by the input from the community, the European strategy will determine which of these opportunities will be pursued."

Sommaire en français

TOTEM

Oddball antics in proton–proton collisions

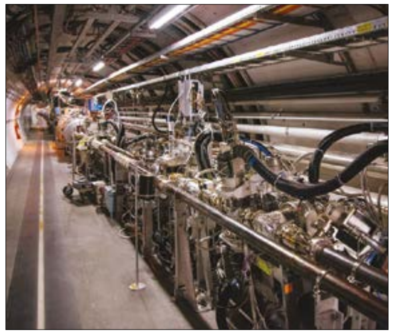
The TOTEM collaboration at CERN has uncovered possible evidence for a subatomic three-gluon compound called an odderon, first predicted in 1973. The result derives from precise measurements of the probability of proton–proton collisions at high energies, and has implications for our understanding of data produced by the LHC and future colliders.

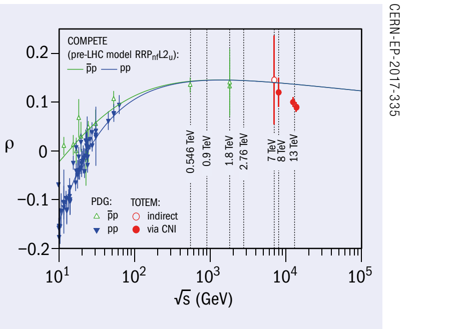
In addition to probing the proton structure, TOTEM is designed to measure the total cross section of proton–proton collisions. Physically it is by far the longest experiment at the LHC, comprising two detectors located 220 m on either side of the CMS experiment. While most proton–proton interactions at the LHC cause the protons to break into their constituent quarks and gluons, TOTEM detects the roughly 25% of elastic collisions that leave the protons intact. Such collisions merely cause the path of the protons to deviate, by around a millimetre over a distance of 200 m.

Elastic scattering at low-momentum transfer and high energies has long been successfully explained by the exchange of a pomeron – a colour-neutral state made up of an even number of gluons – between the incoming protons. But TOTEM's latest results seem to be incompatible with this traditional picture.

The discrepancy came to light via measurements of a parameter called ρ, which represents the ratio of the real and imaginary parts of the nuclear elastic-scattering amplitude when there is minimal gluon exchange between the colliding protons and thus almost no deviation in their trajectories (corresponding to a vanishing squared four-momentum transfer, t). TOTEM measured the differential elastic proton–proton scattering cross section down to $t = 8 \times 10^{-4}\,\text{GeV}^2$ at an energy of 13 TeV during a special LHC run involving "$\beta^* = 2.5$ km" optics and, exploiting Coulomb–nuclear interference, determined ρ with unprecedented precision: 0.09 ± 0.01.

While conventional models based on various pomeron exchanges and related "even-under-crossing" scattering amplitudes can describe ρ and the total proton–proton cross-section in the energy range 0.01–8 TeV, none can describe simultaneously TOTEM's latest ρ measurement (which is lower than predicted by conventional models) and TOTEM's total cross-section measurements ranging from 2.76 to 13 TeV (see figure). Combining the two measurements, TOTEM finds better agreement with models that indicate the exchange of three aggregated gluons.


M Brice/CERN



CERN-EP-2017-335

Left: one side of the TOTEM apparatus in the LHC tunnel. Right: dependence of ρ on energy, showing pp (blue) and $p\bar{p}$ (green) data taken from the Particle Data Group and TOTEM measurements at 13 TeV (red). Contrary to the traditional QCD picture, based on results from the COMPETE collaboration, the rate of growth of ρ slows at high energies.

The odderon started out in the early 1970s as a purely a mathematical concept. After the advent of QCD, however, theorists showed that QCD not just allowed but required the existence of such a three-gluon compound.

Although the new data favour the existence of the odderon, the TOTEM collaboration prefers to emphasise all the possible meanings and consequences its results might have – in particular concerning the behaviour of the total proton–proton cross section at high energies. If it turns out that the odderon is not entirely responsible for the observed decrease in ρ at 13 TeV, then it could be the first observation that the proton–proton cross-section growth slows down at energies beyond this. Either way, claims the TOTEM team, the results would constitute an important discovery.

"The TOTEM result is in a reasonable agreement with what is expected within the QCD picture, and the inclusion of the odderon certainly improves our description of the existing data on the high-energy elastic proton–proton scattering," says theorist and QCD expert Valery Khoze of Durham University in the UK. "Conservatively, I would say that this is a strong indication in favour of the experimental observation of a long-awaited but so far experimentally elusive object predicted by QCD."

Basarab Nicolescu of Babes-Bolyai University in Romania – who co-invented the odderon with the late Leszek Lukaszuk – and Evgenij Martynov of the Bogolyubov Institute for Theoretical Physics in Ukraine go further. In a paper published shortly after the TOTEM result, they write that the new data "can be considered as the first experimental discovery of the odderon".

TOTEM researchers say they will continue to refine their measurements of ρ and explore how this ratio of scattering amplitudes evolves as a function of the squared four-momentum transfer. A similar "forward" experiment at the LHC called ALFA, which is part of the ATLAS experiment, is also taking part in such t-channel studies of the proton–proton cross section.

However, if a three-gluon compound is being produced in proton–proton collisions, it should also appear in other scattering experiments via direct s-channel production. Such a signature of the odderon could be detected, for example, by the LHCb experiment and also the COMPASS experiment at CERN.

"The discovery of the odderon would signal another bright manifestation of the predictive power of the QCD theory and confirm again that perturbative QCD allows for quite fair predictions in the experimentally available domain," says Khoze.

● Further reading

TOTEM Collaboration 2017 CERN-EP-2017-335.
TOTEM Collaboration 2017 CERN-EP-2017-321.
E Martynov and B Nicolescu 2018 *Phys. Lett. B* **778** 414.
V Khoze *et al.* 2017 arXiv:1712.00325.

ANTIMATTER

Antiprotons to hit the road

A project carried out at the Technische Universität (TU) Darmstadt in Germany, funded by the European Commission, aims to build a magnetic trap that allows antiprotons to be transported from one location to another. Launched in January, the ultimate goal of the PUMA (antiProton Unstable Matter Annihilation) project is to transfer antiprotons from CERN's Antiproton Decelerator (AD) to the nearby ISOLDE facility to study exotic nuclear phenomena.

One of PUMA's physics goals is to explore the occurrence of neutron halos and neutron skins in very neutron-rich radioactive nuclei. By measuring pions emitted after the capture of low-energy antiprotons by nuclei, researchers will be able to determine how often the antiprotons annihilate with the constituent nucleons and therefore deduce their relative densities at the surface of the nucleus. It would be the first time that such effects were investigated in medium-mass nuclei, contributing to a better understanding of the complex nature of nuclei and related astrophysical processes. In the future, PUMA might also allow the spectroscopy of single-particle states in heavy-nuclei with atomic numbers above 100, offering new insight into the unknown shell structure at the top of the nuclear landscape.

J Ordan/CERN

The connection between the ELENA ring and the GBAR experiment at CERN's AD, from which PUMA's antiprotons will be extracted.

To make such studies possible, PUMA must trap antiprotons for long enough to be transported by truck for use in nuclear experiments at the ISOLDE facility, located a few hundred metres away from the AD. Keeping the antiprotons from annihilating with ordinary matter during this process is no easy task. The idea is to develop a double-zone trap inside a one-tonne superconducting solenoid magnet and keep it under an extremely high vacuum (10^{-17} mbar) and at a temperature of 4 K. One region of the trap will confine the antiprotons, while a second zone will host collisions between antiprotons and radioactive nuclei that are produced at ISOLDE but decay too rapidly to be transported and studied elsewhere.

PUMA will eventually trap a record one billion antiprotons at CERN's GBAR experiment, which is currently being hooked up to the ELENA facility at the AD (*CERN Courier* December 2016 p16), and keep them for several weeks to allow the measurements to be made. The team plans to build and develop the solenoid, trap and detection apparatus in the next two years, targeting 2022 for first collisions at ISOLDE.

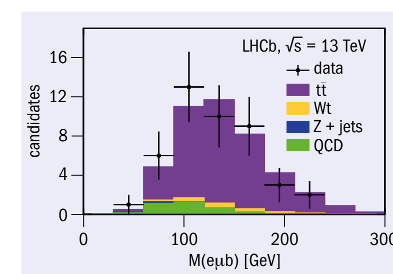
Today, CERN is the only place in the world where low-energy antiprotons are produced, but "this project might lead to the democratisation of the use of antimatter," says project leader Alexandre Obertelli of TU Darmstadt, who was awarded a €2.55 million five-year grant from the European Research Council. Along with researchers from RIKEN in Japan, CEA Saclay and IPN Orsay in France, Obertelli has submitted a letter of intent to CERN's experiment committee concerning the future ELENA and ISOLDE activities. The PUMA apparatus could also, at a later stage, provide antiprotons to experiments beyond CERN. "For example, to universities or nuclear-physics laboratories where specific nuclei can be produced, such as the new SPIRAL2 facilities in Caen, France," says Obertelli.

LHC EXPERIMENTS

Taking top physics forward

Measurements of top-quark production at high rapidity in LHC proton–proton collisions provide a unique probe of the Standard Model of particle physics (SM). In this kinematic region, top-pair production is characterised by sizeable rates of quark–antiquark and quark–gluon scattering processes (in addition to gluon–gluon fusion), potentially enhancing sensitivity to physics beyond the SM. Precision measurements at high rapidity can also be used to probe the inner structure of the proton, constraining parton distribution functions at high "Bjorken-x" values and reducing uncertainties on the background process rates in other measurements. Such a "forward" region is uniquely covered with full instrumentation at the LHC by the LHCb detector.

LHCb has now made its first measurement of top quark production using Run-2 data collected in proton–proton collisions at the energy of 13 TeV. This is the third measurement from LHCb in the sector of top physics and is also the first from the collaboration to study the dilepton channel.



Selected events as a function of the invariant mass of the dilepton and b-jet system, with the signal component shown in purple.

The measurement was performed by reconstructing dilepton decays of the top-pair system, looking for high-momentum electrons, muons and b-jets in the acceptance of the LHCb detector, using data recorded in 2015 and 2016. About 87% of selected events correspond to the signal process, making this the highest purity measurement of top physics at LHCb to date. Within the region covered by LHCb, the production cross-section of top-quark pairs (multiplied by the branching fraction to the measured final state) was determined to be 126 fb with a precision of about 20%, with the uncertainty dominated by statistical effects. The measurement is compatible with the SM predictions.

Such measurements are only now possible at LHCb owing to the increased proton collision energy (13 TeV) of LHC Run 2. While the overall cross section for top-pair production at the LHC has increased by roughly a factor of three with respect to the 8 TeV proton–proton collisions recorded in Run 1, the cross section within the forward coverage of LHCb has increased by about one order of magnitude.

LHCb expects to accumulate, by the end of Run 2, four times more data than that used in the present analysis. With future runs and the upcoming and planned detector upgrades, LHCb will enter a new era of precision studies of forward top physics.

Further reading

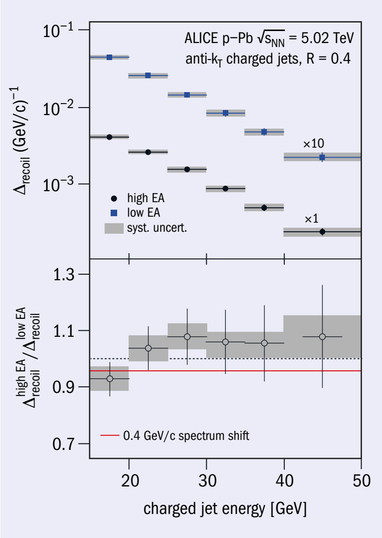
LHCb Collaboration 2017 LHCb-PAPER-2017-050.
LHCb Collaboration 2016 LHCb-PAPER-2016-038.
LHCb Collaboration 2015 LHCb-PAPER-2015-022.

ALICE puts limits on jet quenching in p–Pb collisions

What are the essential requirements for the formation of a quark–gluon plasma (QGP)? Do only the most violent, head-on lead–lead (Pb–Pb) interactions at the LHC provide such conditions? The answer to such questions will provide key insights into the mechanisms driving the QGP towards equilibration, converting kinetic collision energy into a hot and strongly interacting medium.

Recent measurements of proton–lead (p–Pb) and proton–proton (pp) collisions at the LHC have shown intriguing hints of QGP-like behaviour in such systems, which were initially thought to be too small for QGP formation. Experimentalists classify p–Pb collisions by a parameter called the event activity (EA), which is characterised by particle or energy production in the forward Pb-going direction; the most violent p–Pb collisions, with the largest EA, exhibit correlations that are characteristic of the collective flow of the QGP. Verification of this picture requires measurements of other QGP signals, notably the "quenching" of energetic quark and gluon jets as they propagate through the dense QCD medium.

Jets arise from the scattering of quarks and gluons in the incoming projectiles, and are produced predominantly in azimuthally back-to-back pairs. The first jet-quenching measurements in p–Pb collisions looked for suppression of the inclusive production rate of high momentum hadrons and jets by counting all such objects and comparing them to a reference rate from proton–proton (pp) collisions. Some inclusive suppression measurements indicate significant jet suppression in the highest-EA p–Pb collisions. Quantitative comparison to the pp collision reference spectrum requires the assumption that high-EA is correlated with central p–Pb collisions, in which the proton ploughs through the centre of the Pb-nucleus. However, the relation between forward particle and energy production used to measure EA with the geometry of a p–Pb collision may be modified in events containing jets, complicating its interpretation. An approach to jet quenching in p–Pb that does not invoke this assumption is therefore needed.



Background-subtracted recoil jet rates Δ_{recoil} in p–Pb collisions with high and low event activity (EA), top, and the ratio of the two measurements (bottom). The ratio is compatible with unity, indicating no significant energy loss for jets in p–Pb collisions with larger EA.

For this purpose, the ALICE collaboration has reported measurements of the semi-inclusive distribution of jets recoiling from a high-momentum hadron trigger (h+jet) in p–Pb collisions, as a function of EA. The h+jet distribution is self-normalising, due to the back-to-back nature of jet-pair production: jet quenching is observed as a reduction in jet rate per trigger, without comparison to a pp reference spectrum or the assumption that high-EA corresponds to central p–Pb collisions. The analysis applies a data-driven statistical approach to correct the complex uncorrelated background, enabling the accurate measurement of recoil jets over a broad phase space in the complex LHC environment.

The upper panel of the figure shows distributions of this observable, Δ_{recoil}, for p–Pb collisions with high and low EA. Jet quenching corresponds to the transport of energy out of the jet cone, thereby suppressing Δ_{recoil} for high EA. The ratio is however consistent with unity at all jet energies, indicating negligible jet quenching effects within the uncertainties.

These data provide a limit on the magnitude of medium-induced energy transport to large angles due to jet quenching: for events with high EA, medium-induced charged energy transport out of the jet cone is less than 0.4 GeV/c (90% confidence level). This limit is a factor 20 smaller than the magnitude of jet quenching measured using this observable in Pb–Pb collisions, in contrast to some of the current inclusive jet suppression measurements in p–Pb collisions. This result challenges theoretical models that predicted strong jet quenching in p–Pb collisions. Comparison of these data with the surviving models promises new insight into QGP formation in small systems, and the fundamental processes of equilibration in QCD.

Further reading

ALICE Collaboration 2017 arXiv:1712.05603.

ATLAS illuminates the Higgs boson at 13 TeV

The ATLAS collaboration has released a set of comprehensive results that illuminates the properties of the Higgs boson with improved precision, using its decay into two photons with LHC collisions recorded at a centre-of-mass energy of 13 TeV.

The Higgs-to-two-photons decay played a crucial role in the discovery of the Higgs boson in 2012 owing to the excellent mass resolution and well-modelled backgrounds in this channel. Following the discovery, the properties of the Higgs boson can be probed more precisely using the large 13 TeV dataset.

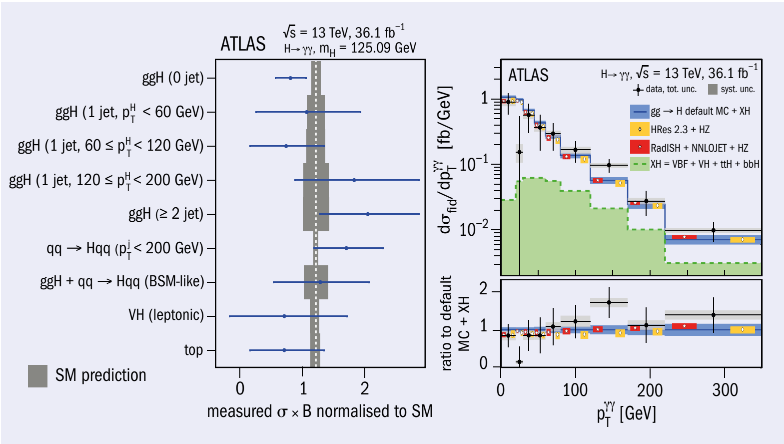
One major result of the new study is the measurement of the signal strength μ, defined as the ratio of the number of observed and expected Higgs boson events. The signal strength is measured to be $\mu = 0.99^{+0.15}_{-0.14}$ – in good agreement with the Standard Model expectation. The precision could be improved by a factor of two with respect to the previous measurements at energies at 7 and 8 TeV. The precision of signal-strength measurements of individual Higgs boson production modes are also improved significantly thanks to a better ▷

understanding of the ATLAS detector, the increased rate of Higgs production at 13 TeV and the extended use of machine-learning techniques to identify specific production processes.

Another key result of the present study are the measurements of nine simplified template cross sections (STXS), which refer to the cross sections of specific Higgs production channels measured in different kinematic regions. Measurements of STXS are corrected for the impact of the Higgs-boson decay and incorporate the acceptance of the experiment, so that they can be combined across Higgs boson channels and experiments (see figure, left).

The properties of the Higgs boson are further investigated by measuring 20 differential and two double-differential cross sections. The Higgs boson transverse momentum (figure, right) and rapidity, the number and properties of jets produced in association with the Higgs boson, and several angular relations that allow us to probe its spin and CP quantum numbers are measured. Five of these distributions are used to search for new CP-even and CP-odd couplings between the Higgs boson and vector bosons or gluons. No significant deviations from the Standard Model predictions are observed.

Collectively, this new set of results at the highest LHC energies sheds light on the fundamental properties of the Higgs boson and extends our knowledge obtained from the first running period of the LHC.



Left: the nine measured simplified template cross sections (blue markers) normalised to the Standard Model expectation (grey bands). Right: measured Higgs boson transverse momentum differential cross section (data points) compared to three predictions for gluon–gluon fusion (coloured bands), and the predicted sum of weak-boson fusion and associated production with vector bosons as well as bottom- and top-quark pairs.

Further reading

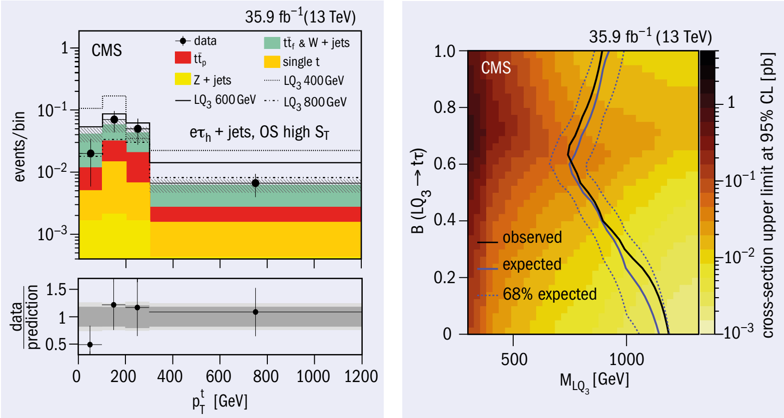
ATLAS Collaboration 2018 arXiv:1802.04146.

CMS searches for third-generation leptoquarks

Anomalies in decays of B mesons, in which a bottom quark changes flavour to become a charmed quark, reported by the LHCb, Belle and Babar collaborations, have triggered considerable excitement in the particle-physics community (see p23). The combined results of these experiments suggest that the decay rates of $\bar{B} \to D\tau\bar{\nu}$ and $\bar{B} \to D^*\tau\bar{\nu}$ differ by more than four standard deviations from the Standard Model (SM) predictions.

Several phenomenological studies have suggested that these differences could be explained by the existence of hypothetical new particles called leptoquarks (LQs), which couple to both leptons and quarks. Such particles appear naturally in several scenarios of new physics, including models inspired by grand unified theories or Higgs-compositeness models. Leptoquarks that couple to the third generation of SM fermions (top and bottom quarks, and the tau lepton and its associated neutrino) are considered to be of particular interest to explain these flavour anomalies.

Leptoquarks coupling to fermions of the first and also the second generation of the SM have been the target of many searches by collider experiments at the successive energy frontiers (SPS, LEP, HERA, Tevatron). The most sensitive searches have been performed at the LHC, resulting in the exclusion of LQs with masses below 1.1 TeV. Searches for third-generation LQs were first performed at the Tevatron, and the baton has now been passed to the LHC. ▷



The distribution of the transverse momentum of the leading top-quark candidate in one of the search categories optimised for the LQ search by CMS (left), and the exclusion limits as a function of LQ mass and branching ratio into top+tau (B = 1) and bottom+neutrino (B = 0), reaching the TeV region (right).

The first investigation by the CMS collaboration used events recorded at an energy of 8 TeV during LHC Run 1, and targeted LQ pair production via the strong interaction with the decay channel of the LQ to a top quark and a tau lepton. The result of this search, reported by CMS in 2015, was that third-generation LQs with masses below 0.685 TeV were excluded. These early results have now been extended using the 2016 dataset at 13 TeV, employing more sophisticated analysis methods. The new search investigates final states containing an electron or a muon, one or two tau leptons that decay to hadrons and additional jets. To achieve sensitivity to the largest possible range of LQ masses, the analysis uses several event categories in which deviations from the SM predictions are searched for. The SM backgrounds mainly consist of top-quark pair production and W+ jets events, whose contributions are derived from the data rather than from simulation.

No significant indication of the existence of third-generation LQs has yet been found in any of the categories studied (see left-hand figure on previous page). The collaboration was therefore able to place exclusion limits on the product of the production cross section and branching fraction as small as 0.01 pb, which translate into lower limits on LQ masses extending above 1 TeV.

Combining the result of a search for the pair-production of supersymmetric bottom squarks, which can be reinterpreted as a search for LQs in the decay mode of a bottom quark and a tau neutrino, results in limits that probe the TeV mass range over all possible LQ branching ratios (see figure, right). Another recent search targets different LQs that decay into a bottom quark and a tau lepton. Using a smaller dataset at 13 TeV, this search excludes masses below 0.85 TeV for a unity branching fraction.

This is the first time that searches at the LHC have achieved sufficient sensitivity to explore the mass range favoured by phenomenological analyses of LQs and the current flavour anomalies. No hints of these states have been found, but analyses are under way using larger datasets and including additional signatures.

Further reading
CMS Collaboration 2015 *JHEP* **7** 42.
CMS Collaboration 2017 *JHEP* **7** 121.
CMS Collaboration 2018 arXiv:1803.02864.

Les physiciens des particules du monde entier sont invités *à apporter leurs contributions au CERN Courier, en français ou en anglais. Les articles retenus seront publiés dans la langue d'origine. Si vous souhaitez proposer un article, faites part de vos suggestions à la rédaction à l'adresse cern.courier@cern.ch.*

CERN Courier welcomes contributions from the international particle-physics community. These can be written in English or French, and will be published in the same language. If you have a suggestion for an article, please send proposals to the editor at cern.courier@cern.ch.

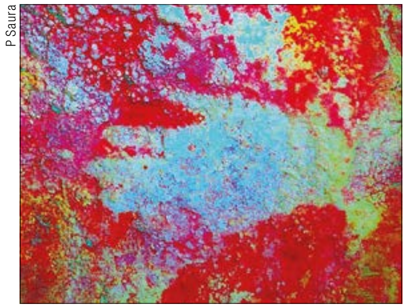
Sciencewatch

Compiled by John Swain, Northeastern University

Neanderthals created Europe's first art

Contrary to common belief, Neanderthals may have been the first cave artists. Dirk Hoffmann of the Max Planck Institute for Evolutionary Anthropology in Dresden and colleagues used uranium–thorium dating of carbonate crusts to show that cave paintings from three sites in Spain must be older than 64,000 years, predating the arrival of modern humans by 20,000 years or more. The paintings are mainly red and black with depictions of animals, linear signs, geometric shapes and stencils, and prints of hands. Together, they suggest a more advanced appreciation of symbols than had previously been thought, and prove that the cognitive abilities of our evolutionary cousins were similar to our own.

P Saura



A colour-enhanced section of the La Pasiega cave wall in Spain showing what is thought to be a hand stencil dating to older than 64,000 years.

● **Further reading**
D Hoffmann *et al.* 2018 *Science* **359** 912.

Introducing the memtransistor

Two-terminal memristors have been getting attention for some time now, both for computer memories and for neuromorphic computing. But their usefulness has been limited, largely owing to the small number of inputs they can take. Now, Vinod Sangwan and colleagues at Northwestern University have announced that they have made multi-terminal memtransistors (hybrids of a memristor and transistor) in molybdenum disulphide (MoS_2). Unlike conventional devices, which require single-crystal MoS_2 flakes, this process can use polycrystalline and all-surface MoS_2 films and be readily scaled up to very-large-area devices, claims the team.

● **Further reading**
V Sangwan *et al.* 2018 *Nature* **554** 500.

Wood as strong as steel

Natural wood has been used for millennia as a structural material, but its mechanical performance is limited. Jianwei Song from the University of Maryland and colleagues have exhibited a simple way to turn natural wood into a new structural material with more than 10 times the strength, toughness and ballistic resistance, as well as improved stability. First, the team partially remove lignin and hemicellulose from the wood cells by boiling wood in a solution of NaOH and Na_2SO_3, and then use a hot press to collapse the cell walls. The technique works well for many woods and the final processed wood has a strength higher than most metals.

● **Further reading**
J Song *et al.* 2018 *Nature* **554** 224.

High-power THz chip

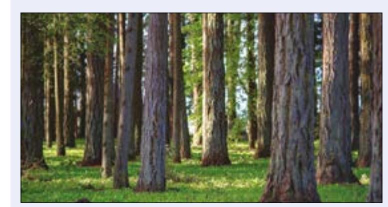
Alan Turing was the first person to demonstrate how stationary periodic patterns could form in biology, but his ideas have been fruitful in other fields. One is pattern formation in continuous-wave-laser-pumped Kerr-active microresonators, which Shu-Wei Huang of UCLA and colleagues have now stabilised via a novel scheme using local-mode hybridisations to set a new record of 45% in power conversion efficiency. Finally, the pattern is turned into terahertz radiation with a plasmonic photomixer for an overall optical-to-THz conversion efficiency of 1.1%. The whole setup can fit on a chip, so would have huge implications for medical imaging, wireless communications and other applications.

● **Further reading**
S-Wei Huang *et al.* 2018 *Phys. Rev. X* **7** 041002.

Pulsating auroras

The auroras, whose striking images wind up on calendars and screensavers across the world, occur a few thousand kilometres above Earth. Pulsating auroras are another, less-well-known phenomenon. These blinking patches of light at altitudes of tens of thousands of kilometres occur at high latitudes when energetic magnetospheric electrons precipitate out and excite air molecules. Many researchers had hoped that the phenomenon was describable by an interaction between magnetospheric electrons and electromagnetic waves called whistler-mode chorus waves. Now, Satoshi Kasahara of the University of Tokyo and colleagues have used the ERG (Exploration of energization and Radiation in Geospace) spacecraft, launched in December 2016 equipped with instruments to measure electrons and electromagnetic radiation, together with ground-based observations of the aurora, to confirm the proposed explanation.

● **Further reading**
S Kasahara *et al.* 2018 *Nature* **554** 337.



The team reports a simple strategy to transform bulk natural wood into a high-performance structural material.

Unstable allotropes made safe

The elemental allotropes white phosphorus and yellow arsenic would be potentially more useful reagents were it not for their extreme instability: the former bursts into flame in air, while the latter turns grey on exposure to light. Many approaches of varying difficulty have been tried to store these materials in a protected way so that they can be used when needed, for synthesis or other applications such as semiconductors. Now, Manfred Scheer of the University of Regensburg and colleagues have found that the substances can be stored safely and inexpensively in the pores inside activated charcoal and released into solutions when needed for a reaction.

● **Further reading**
A Seitz *et al.* 2018 *Nat. Commun.* **9** 361.

Astrowatch

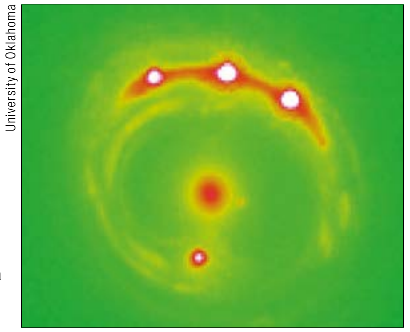
Compiled by Merlin Kole, Department of Particle Physics, University of Geneva

Spotting the first extragalactic planets

Three decades since astronomers first detected planets outside our solar system, exoplanets are now being discovered at a rate of hundreds per year. Although it is reasonable to assume other galaxies than our own contain planets, no direct detections of such objects have been made owing to their small size and their large distances from Earth.

Now, however, radiation emitted around a distant black hole has revealed the existence of extragalactic planets in a galaxy 3.8 billion light years away, located between the black hole and us. The planets, which have no way of being directly detected using any kind of existing telescope, are visible thanks to the small gravitational distortions they inflict on X-rays emanating from the more distant black hole.

The discovery was made by Xinyu Dai and Eduardo Guerras from the University of Oklahoma in the US using data from the Chandra X-ray Observatory. The distant black hole in question, which forms the supermassive centre of the quasar RX J1131-1231, is surrounded by an accretion disk that heats up as it orbits and emits radiation at X-ray wavelengths. Thanks to a fortunate cosmic alignment, this radiation is amplified by gravitational lensing and therefore can be studied accurately. The lensing galaxy positioned between Earth and the quasar causes light from RX J1131-1231 to bend around it, appearing to us not as a normal point-source but as a ring with four bright spots (see figure). The spots are a result of radiation coming from the same location of the quasar, which initially followed different paths but ended up being directed to the Earth.



University of Oklahoma

Image of the quasar RX J1131-1231 gravitationally lensed by the galaxy shown at the centre. The four lensed images of the background quasar helped reveal the presence of trillions of planets in the central galaxy.

Dai and Guerras focused on the spectral features of iron, a strong emission line that reveals details of the accretion disk, and found that this emission line is not just shifted in energy but that the amount of the shift varies with time. Although a shift in the frequency of this line is common, for example due to relative velocities between observers, its position is generally very stable with time when studying a specific object. Based on the 38 times RX J1131-1231 had been observed by the Chandra satellite during the past decade, the Oklahoma duo found that the energy varied significantly between observations in all of the four bright points of the ring.

This feature can be explained using microlensing. The intermediate lensing galaxy is not a uniform mass but rather consists of small point masses, mainly stars and planets. As the relatively small objects within the lensing galaxy move, the light from the quasar passing through it is deflected in slightly different ways, causing different parts of the accretion disk to be amplified at different levels over time. As the different parts of the disk appear to emit at different energies, the measured variations in the energy of this emission line can be explained by the movement of objects within the lensing galaxy. The question is: what objects could cause such changes over time scales of several years?

Stars, being so numerous and massive, are one good candidate explanation. But Dai and Guerras calculated that the chance for a star to cause such short-term variations is very small. A better candidate, suggest fits to analytical models, is unbound planets which do not orbit a star. The Chandra data were best described by a model in which, for each star, there are more than 2000 unbound planets with masses between that of the Moon and Jupiter. Although the exact population of such planets is not well known even for our own galaxy, their number is well within the existing constraints. These observations thus form the best evidence for the existence of extragalactic planets and, by also providing the number of such planets in that galaxy, teach us something about the number of unbound planets we can expect in our own galaxy.

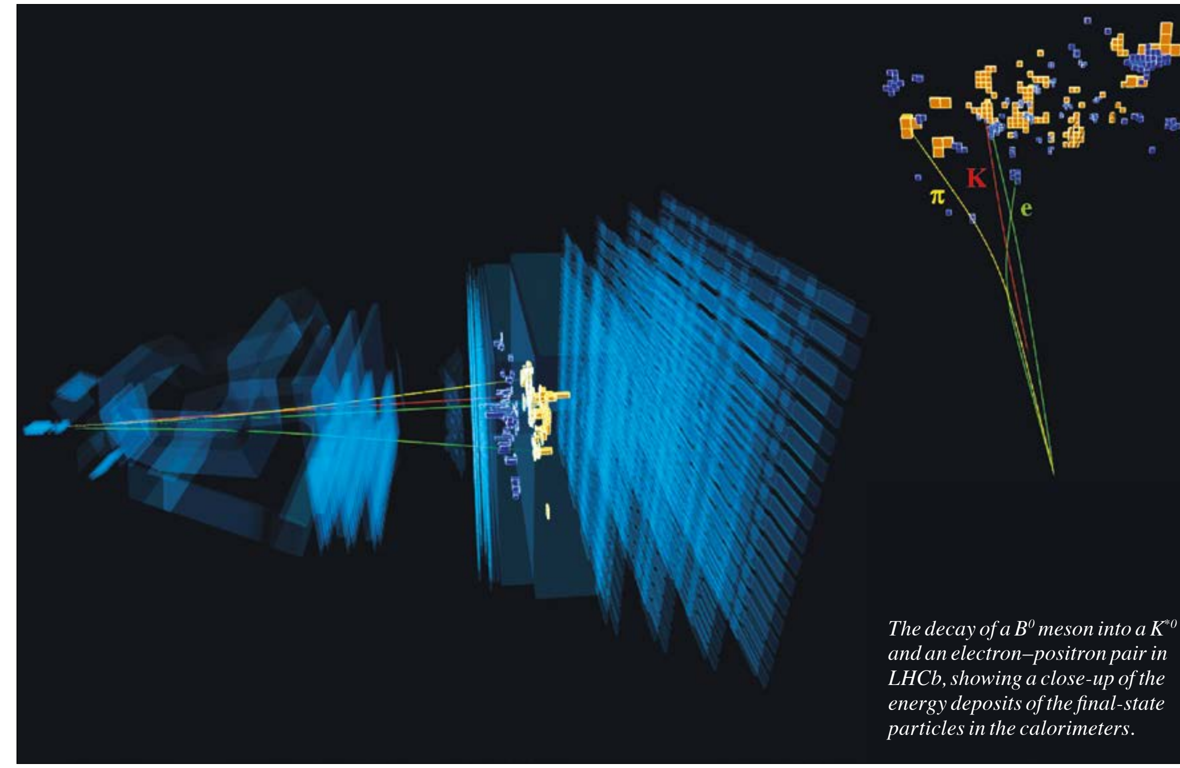
Further reading

X Dai and E Guerras 2018 *ApJL* **853** L27.

Picture of the month

Both objects in this image are blue but very different in nature. On the right is the famous Pleiades, a cluster of extremely bright blue stars 400 light years away that can be seen relatively easily from Earth, while on the left is the bright blue tail produced by comet C/2016 R2. The comet appears to be moving towards the cluster but actually is travelling in the upwards direction, and the blue tail is produced by solar radiation, which causes the unusually high amount of ionised carbon monoxide to emit fluorescent light. One theory about the complex shape of the tail is that the comet contains a rapidly rotating nucleus. If C/2016 R2 survives its passage at the closest point near the Sun in May 2018, it will return to Earth again – but not for another 20,000 years or so.

T Masterson/Transient Astronomer



The decay of a B^0 meson into a K^{*0} and an electron–positron pair in LHCb, showing a close-up of the energy deposits of the final-state particles in the calorimeters.

Beauty quarks test lepton universality

A series of measurements from LHCb and B-factory experiments have tested whether the interactions of charged leptons agree with the Standard Model.

Of all the puzzling features of the Standard Model of particle physics (SM), one of the most vexing is the arrangement of the elementary particles into families or generations. Each pair of fermions comes in three and apparently only three copies: the electron, muon, tau leptons and their associated neutrinos, and three pairs of quarks. The only known difference between generations is the different strengths of their interactions with the Higgs field, known as the Yukawa couplings. This results in different masses for each particle, giving a wide range of experimental signatures.

In the case of the charged leptons (electrons, muons and taus), this pattern also results in one simple post-diction, known as lepton universality (LU): other than effects related to their different masses, all the SM interactions treat the three charged leptons identically. During the past couple of decades, LU has been tested to sub-percent precision in interactions of photons and weak bosons, and in transitions between light quarks. These measurements were made, for example, at the Large Electron–Positron (LEP) collider at CERN in decays of W and Z bosons, by the PIENU and NA62 fixed-target experiments in decays of pions and kaons, and in J/ψ decays by the BES-III, CLEO and KEDR collaborations. However, LU has never been established to such a degree of precision in decays of heavy quarks.

Measurements from Run 1 of decays of beauty hadrons at the LHCb experiment, in addition to earlier results from the B-factories Belle at KEKB and BaBar at PEP-II, have hinted at potential deviations from LU. None is statistically significant on its own but, taken together, the results have led to speculation on whether non-SM forces exist or phenomena that treat leptons differently depending on their flavour are at play. If a deviation from LU was to be confirmed, it would be clear evidence for physics processes beyond the SM and perhaps a sign that we are finally moving towards an understanding of the structure of the fermions.

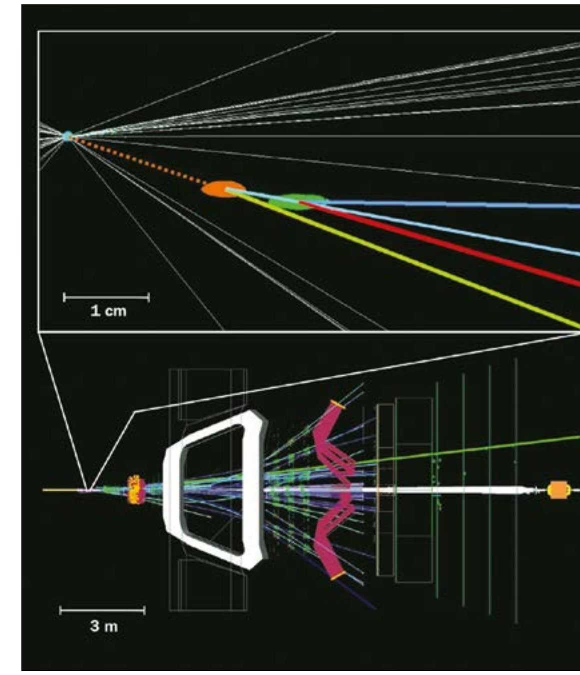
Two classes

The results so far concern two classes of transitions in b-quark hadron decays, exemplified in figure 1. Measurements of highly suppressed flavour-changing neutral-current (FCNC) decays, $b \to s\ell^+\ell^-$, hint at a difference involving muons and electrons, while measurements of the more frequent leading-order or tree-level decays, $b \to c\ell^+\nu_\ell$, hint at a difference between muons and taus. These two classes of decays present very different challenges, both experimentally and theoretically. The latter, semi-leptonic, decays of b-quark hadrons proceed through tree-level diagrams in which a virtual W boson decays into a lepton–neutrino pair. Measurements of decays involving electrons and muons show no deviations with respect to the SM within the current level of precision. In contrast, measurements of decays involving τ leptons are only marginally in agreement with the SM expectation. The quantity that is experimentally measured is the ratio of branching fractions $R_{D^{(*)}} = BF(B \to D^{(*)}\tau^+\nu_\tau)/BF(B \to D^{(*)}\ell^+\nu_\ell)$, with $\ell = e$ or μ. This ratio is precisely predicted in the SM owing to the cancellation of the leading uncertainty that stems from the knowledge of the decay form-factors.

Interest in these decay modes was heightened in 2012 when the BaBar collaboration found values for R_D and R_{D^*} above the SM prediction. This was followed in 2015 by results from the Belle collaboration that were also consistently high. Experimentally, such semi-tauonic beauty decays are extremely difficult to measure because taus are not reconstructed directly and at least two undetected neutrinos are present in the final state. To get around this, the BaBar and Belle experiments used both B mesons produced from Υ(4S) decays. By reconstructing the decay of one B meson in the event, the teams were able to infer the recoil of the other, "signal", B decay. This tagging technique, based on the known momentum of the initial-state positron–electron pair and therefore that of the Υ(4S), allows the determination of the momentum of the B signal, the reconstruction of its decay under the assumption that only neutrinos escape detection, and the separation of signal and background.

The combined world average of R_{D^*} and R_D remains in tension with the Standard Model.

The study of beauty-hadron decays to final states involving τ leptons was deemed not to be feasible at hadron colliders such as the LHC. This is a result of the unknown momentum of the colliding partons and the significantly more complex environment with respect to electron–positron B-factories in terms of particle densities, detector occupancy, trigger and detection efficiencies. However, due to the significant Lorentz boost and the excellent performance of the LHCb vertex locator, the decay vertices of the b-hadrons produced at the LHC are well separated from the proton–proton interaction point. This enables the collaboration to approximate the b-hadron momentum and its decay kinematics with sufficient resolution to preserve the discrimination between signal and background.



Side view of an event in the LHCb detector and an enlarged area close to the interaction point, showing the decay of a B meson produced in the proton–proton interaction.

Exploiting the tau

The first measurement of R_{D^*} at a hadron collider was performed by LHCb researchers in 2015 using the decays of the τ lepton into a muon and two neutrinos. This measurement again came out higher than the SM prediction, thus strengthening the tension between theory and experiment raised by Belle and BaBar.

In 2017, LHCb reported another R_{D^*} measurement by exploiting the decay of the τ lepton into three charged pions and a neutrino. This measurement was considered to be even more difficult than the previous one due to the large backgrounds from B decays and the apparent lack of discriminating variables. Nevertheless, the presence of a τ decay vertex significantly detached from the b-hadron decay vertex allows the most abundant backgrounds to be suppressed. The residual background, due to b-hadrons decaying to a D^* and another charm meson that subsequently gives three pions in a detached vertex topology, is reduced by exploiting the different resonant structure of the three-pion system. The resulting measurement of R_{D^*} is larger than, although compatible with, the

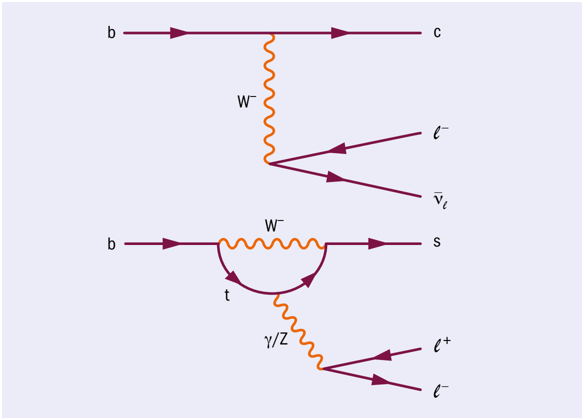


Fig. 1. Feynman diagrams in the Standard Model for two classes of processes relevant to the study of lepton universality in heavy quarks: a charged-current $b \to c\ell^-\bar{\nu}_\ell$ tree-level transition (top) and a neutral-current $b \to s\ell^+\ell^-$ loop-level transition (bottom).

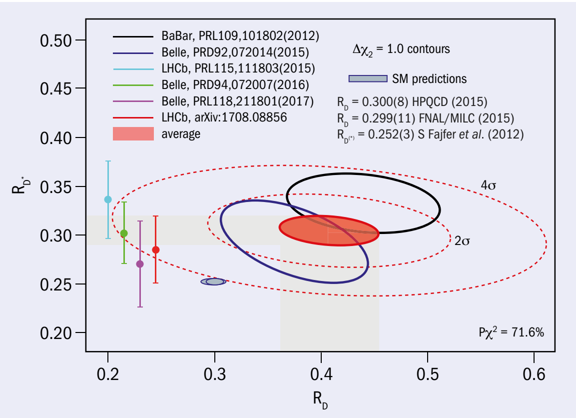


Fig. 2. Status of R_D and R_{D^*} measurements. The red ellipse represents the world average, including both the results from simultaneous measurements of R_D and R_{D^*} (black and blue ellipses) and separate measurements of R_{D^*} (points with error bars).

SM prediction, and consistent with previous determinations.

The combined world average of R_{D^*} and R_D measurements, known to precisions of 5 and 10%, respectively, remains in tension with the SM prediction at a level of four standard deviations (figure 2). This provides solid motivation for further LU tests in semi-tauonic decays of B hadrons. In the next years, the LHCb collaboration will therefore extend the R_{D^*} measurement to the datasets collected in Run 2 and continue to study semi-tauonic decays of other b-quark hadrons.

In early 2018 the first measurement of $R_{J/\psi}$ was performed, probing LU in the B_c sector. While the result was higher than the SM, the current uncertainty is large and the SM prediction is not yet firm. However, it can be an interesting test for the future. An important extension of this already rich physics programme, already being explored by Belle, will consider observables other than branching fractions, such as polarisation and angular distributions of the final-state particles. This will provide crucial insight when interpreting the current anomalies in terms of new-physics models.

The plot thickens

The results described above concern tree-level semi-leptonic decays. In contrast, the other relevant class of transitions for testing LU, $b \to s\ell^+\ell^-$, are highly suppressed because there are no tree-level FCNCs in the SM. This increases the sensitivity to the possible existence of new physics. The presence of new particles contributing to these processes could lead to a sizeable increase or decrease in the rate of particular decays, or change the angular distribution of the final-state particles. Tests of LU in these decays involve measurements of the ratio of branching fractions between muon and electron decay modes $R_{K^{(*)}} = BF(B \to K^{(*)}\mu^+\mu^-)/BF(B \to K^{(*)}e^+e^-)$.

These modes represent a considerable challenge because the highly energetic LHC environment causes electrons to emit a large amount of bremsstrahlung radiation as they traverse the material of the LHCb detector. This effect complicates the analysis procedure, for example making it more difficult to separate the signal and backgrounds where one or more particles have not been reconstructed. Fortunately, there are several control samples in the data that can be used to study electron reconstruction effects, such as the resonant decays $B \to K^{(*)}(J/\psi \to e^+e^-)$, and ultimately the precision is dominated by the statistical uncertainty of the decays involving electrons. Despite this, the LHCb measurements dominate the world precision.

Three measurements of $R_{K^{(*)}}$ have been performed by the LHCb experiment with the Run 1 data: two in the $B^0 \to K^{*0}\ell^+\ell^-$ decay mode (R_{K^*}) and one in the $B^+ \to K^+\ell^+\ell^-$ decay mode (R_K). The results are more precise than those performed at previous experiments, and all have a tendency to sit below the SM predictions (figure 3). The BaBar and Belle experiments have also measured these LU ratios and found them to be consistent with the SM, albeit with a larger uncertainty.

Assuming that rather than being statistical fluctuations these deviations arise from new physics, one can ask the question: what is driving the R_K and R_{K^*} anomalies? Is the electron decay rate being enhanced or the muon suppressed, or both? One could get an answer to this question by looking at the differential branching fractions of the decays $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0_s \to \phi\mu^+\mu^-$. Although with small statistical significance, all these branching fractions consistently sit below the SM predictions, indicating that something could be destructively interfering with the muonic decay amplitude. If a new particle was really contributing to the B decay amplitude, then one would naturally expect it to also influence the angular distribution of the decay products. Intriguingly, by studying the angular distribution of $B^0 \to K^{*0}\mu^+\mu^-$ decays one observes discrepancies that can be interpreted as being compatible with the expectation based on the central values of R_K and R_{K^*}.

Can we conclude it is due to new physics? Unfortunately not. Information such as branching fractions and angular observables are affected by non-perturbative QCD effects. In principle, these

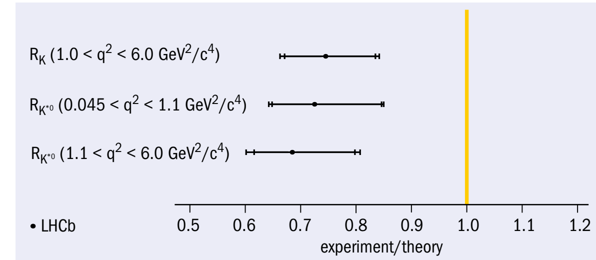


Fig. 3. LHCb measurements of the lepton universality ratios R_K and R_{K^*}. BaBar and Belle have made similar measurements, although with larger uncertainties.

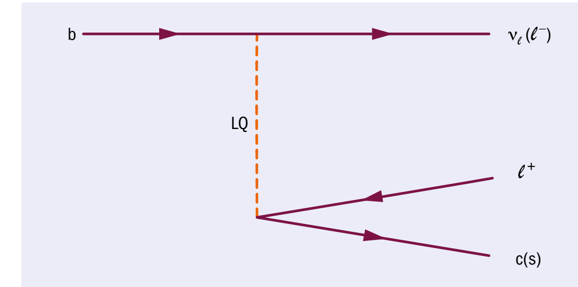


Fig. 4. An example of a Feynman diagram for leptoquark-mediated $b \to c\ell^+\nu_\ell$ and $b \to s\ell^+\ell^-$ singular transitions.

can be controlled, but there is an open question about whether the interference of fully hadronic decays such as $B^0 \to K^{*0} J/\psi$ could mimic some of the discrepancies seen. This contribution is very hard to calculate and will most likely require controlling in the data directly.

All the results so far probing LU at LHCb are based on LHC Run 1 data recorded at a centre-of-mass energy of 7 and 8 TeV. Measurements of the R_K and R_{K^*} ratios can be significantly improved over future years with the analysis of the full Run 2 data at an energy of 13 TeV. LHCb will also broaden its search for LU violation to other types of FCNC decays, such as $B_s \to \phi\mu^+\mu^-$. Another interesting avenue, recently taken up by Belle, is to compare the angular distributions of the decays $B^0 \to K^{*0}\mu^+\mu^-$ and $B \to K^{*0}e^+e^-$. If LU were indeed violated, then one would expect to see differences between the angular distributions of muons and electrons as well as the decay rates.

Potential explanations

It is possible that the anomalies seen in tree-level and FCNC decays are related. The tree-level decays are sensitive to new physics at the TeV scale, whereas the FCNC decays are sensitive to scales of the order 10 TeV on account of the SM suppression of loop-level decays. If one would like to explain both anomalies with a single model, then this must also be suppressed in its contribution to $b \to s\ell^+\ell^-$ decays compared to $b \to c\tau^+\nu_\tau$ decays. This can be done by either forbidding FCNC processes at tree level, like in the SM, or by having a hierarchical flavour structure where the coupling to third-generation leptons is enhanced with respect to muons. Amongst several speculations, the most promising model in this regard introduces the well known concept of leptoquarks, which are particles that carry both lepton and quark quantum numbers (figure 4). The mass scale for such a leptoquark could be around 1 TeV, which is clearly very interesting for direct searches at the LHC.

The theoretical options open up if one would like to explain only one set of anomalies. For example, the loop-level anomalies can be explained with a Z′ boson of a few TeV in mass, although the allowed parameter space for such a model competes with the constraints imposed by B_s matter–antimatter oscillations. Overall, there are many possible models proposed that can explain one or both of these anomalies, and differentiating between them would become an exciting challenge if these were to be confirmed.

In any case, the amount of data analysed for the measurements described here corresponds to just one-third of what will be available by the end of 2018 at LHCb. Meanwhile, following a major overhaul of the KEK accelerator, the Belle-II experiment is about to start operations in Japan and is expected to collect data until 2025 (*CERN Courier* September 2016 p32). The two experiments are designed for the study of heavy-flavour physics, and their complementary characteristics will allow researchers to perform ultra-precise measurements of decays of b-quark hadrons. Hence, the prospects for continuing to test lepton universality in the next decade and beyond are excellent.

Further reading

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BaBar Collaboration 2013 *Phys. Rev. D.* **88** 072012.
Belle Collaboration 2015 *Phys. Rev. D.* **92** 072014.
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LHCb Collaboration 2015 *Phys. Rev. Lett.* **115** 111803.
LHCb Collaboration 2017 *JHEP* **08** 055.
LHCb Collaboration 2014 *Phys. Rev. Lett.* **113** 151601.
G Ciezarek *et al.* 2017 *Nature* **546** 227.
F Archilli *et al.* 2017 *Nature* **546** 221.

Résumé

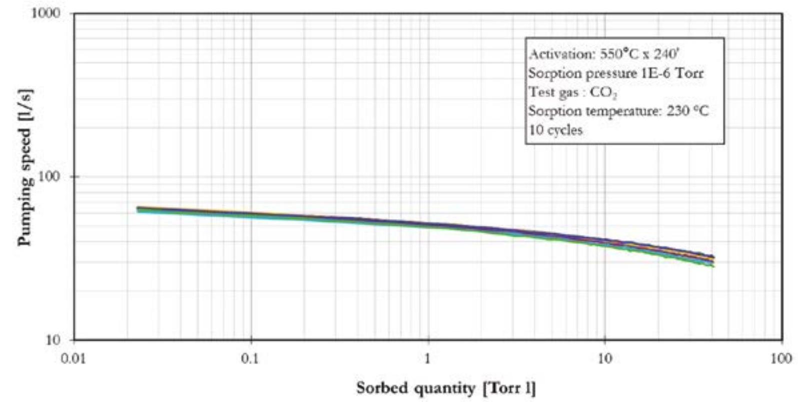
Les quarks beauté bousculent l'universalité leptonique

De récentes mesures des désintégrations de hadrons de beauté effectuées par l'expérience LHCb, venant s'ajouter aux précédents résultats de Belle au KEKB et de BaBar au PEP-II, semblent indiquer de légers écarts par rapport à l'universalité leptonique. Pris individuellement, ces résultats ne sont pas significatifs statistiquement. Considérés tous ensemble, en revanche, ils intriguent, car ils montrent que les forces du Modèle standard ne sont pas insensibles à la saveur leptonique. Si un écart par rapport à l'universalité leptonique était confirmé, il s'agirait d'un indice fort de l'existence d'une physique au-delà du Modèle standard, et cela permettrait de mieux comprendre le classement en trois générations des fermions. Les physiciens attendent donc avec impatience de nouvelles données pour voir si ces effets sont confirmés ou non.

Simone Bifani, University of Birmingham; **Concezio Bozzi**, CERN and INFN; **Gregory Ciezarek**, CERN; and **Patrick Owen**, University of Zurich.

ZAO® non-evaporable getter (NEG) pumps for high-vacuum (HV) applications

SAES® Group is the world leader in the field of getters and it has pioneered this technology for more than 70 years. Non-evaporable getter (NEG) pumps, in particular, are one of the company's core businesses and SAES has steadily contributed to the growth of NEG technology over the years, by introducing a wide range of getter alloys for different applications, as well as by innovating pumps' design, manufacturing processes and testing techniques.



CO2 sorption curves of CapaciTorr HV200 during multiple sorption-reactivation cycles.

Beyond UHV: the new ZAO® alloy for HV applications

While NEG pumps are perfectly suitable for usage in the ultra-high and extremely-high vacuum range (UHV-XHV), one of their main limitations has always been the possibility to effectively use them in the high vacuum (HV) range, corresponding to 10^{-6}–10^{-9} mbar. The main residual gas in typical UHV systems is H_2, for which a NEG pump can provide a high pumping speed and a virtually infinite sorption capacity prior to requiring a reactivation. On the contrary, HV systems are often unbaked and viton-sealed, thus the gas loads and the gas composition are different: H_2 is no more the main residual gas and a key role is played by H_2O, N_2, and O_2 also, as well as by CO and CO_2. In these conditions, the single-run sorption capacity of a NEG pump is often too limited to allow an efficient employment with no need for frequent reactivation.

The latest step forward made by SAES in NEG technology is the recent development of ZAO® alloy (Zr-V-Ti-Al), which gives the possibility to overcome this intrinsic limitation in the usage of NEG pumps. As a matter of fact, ZAO pumps can work either at room temperature or in warm conditions (150–200 °C), enabling their adoption not only in the usual UHV-XHV range but also in HV systems thanks to the following features:

- a lower H_2 equilibrium pressure;
- lower H_2 emission during the activation;
- a larger capacity for all the active gases: by keeping the NEG cartridge at the indicated moderate temperatures, more than 20 sorption cycles in HV conditions are possible;
- better mechanical properties: ZAO disks are intrinsically more robust than St172 ones;
- a higher H_2 embrittlement limit;

NEG pumps made of ZAO elements—such as CapaciTorr® HV200—can be continuously operated at pressures up to 10^{-7} mbar, as they are able to efficiently deal with large air leaks and/or big amounts of carbon contaminants while ensuring a very good mechanical stability over time.

The sorption capacity of a getter can be enhanced by operating it at moderate temperature (e.g., ~200 °C) and moderate power (e.g., 10–50 W, depending on the model), which promotes gas diffusion from the surface to the bulk. However, high-load sorption cycles might be detrimental for traditional St707®-based getter alloys, leading to a progressive efficiency loss in the getter reactivation, as sorbed gases keep accumulating inside the bulk.

Figure 1 is an example of ZAO's ability to continuously work at moderate temperature in HV conditions. Ten CO_2 sorption cycles have been made at $1\text{-}10^{-6}$ Torr with a CapaciTorr HV200 pump working at 200 °C. Each cycle at such pressure corresponds to 1 year of operation at $5\text{-}10^{-8}$ Torr. The pumping performances have been substantially the same all along the series, without any substantial performance variation between the first and the tenth cycles. This demonstrates how ZAO is able to withstand several reactivation cycles under high gas loads while keeping its performance close to the nominal one, thanks to its higher carbon, oxygen, and nitrogen diffusivity to the bulk.

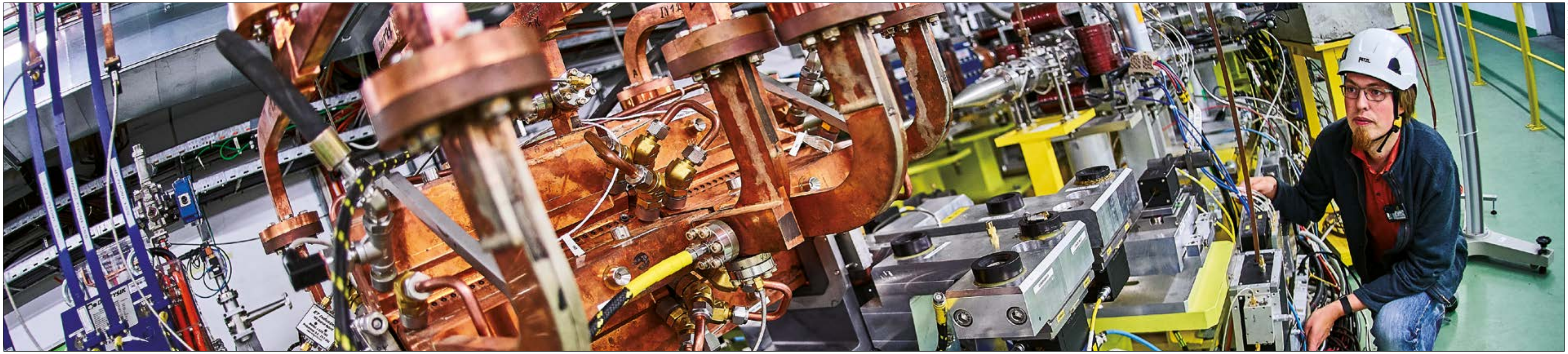
In addition, H_2 could be partially released from standard getter alloys (such as St172 and St707) working at 200 °C, whereas ZAO—having an intrinsically-lower equilibrium pressure—does not release H_2 while operating at 200 °C.

A practical example is given by the Pixel detector of CMS at CERN, where 16 vacuum insulated transfer lines (each ~17 m long) with liquid CO_2 are used. The lines are grouped 4x4 in 4 sectors with 4 vacuum manifolds, originally pumped by a turbomolecular pump. While the goal was to keep the overall pressure below 10^{-4} mbar, the presence of a huge magnetic field in the manifold region did not allow to keep either turbomolecular or sputter-ion pumps permanently running. 4 CapaciTorr HV200 replaced the turbomolecular pumps, succeeded in keeping the Pressure in the 10^{-7}–10^{-8} mbar range for months with no need for any getter reactivation .

1. https://indico.cern.ch/event/469996/contributions/2148165/attachments/1278563/1898196/Forum2016_TransferLines_Tropea.pdf

saes group

Download the full white paper at http://cerncourier.com/cws/article/whitepapers/71254



J Ordan/CERN

High-gradient X-band technology: from TeV colliders to light sources and more

Technologies developed for the Compact Linear Collider promise smaller accelerators for applications outside high-energy physics.

The demanding and creative environment of fundamental science is a fertile breeding ground for new technologies, especially unexpected ones. Many significant technological advances, from X-rays to nuclear magnetic resonance and the Web, were not themselves a direct objective of the underlying research, and particle accelerators exemplify this dynamic transfer from the fundamental to the practical. From isotope separation, X-ray radiotherapy and, more recently, hadron therapy, there are now many categories of accelerators dedicated to diverse user communities across the sciences, academia and industry. These include synchrotron light sources, X-ray free-electron lasers (XFELs) and neutron spallation sources, and enable research that often has direct societal and economic implications.

During the past decade or so, high-gradient linear accelerator technology developed for fundamental exploration has matured to the point where it is being transferred to applications beyond high-energy physics. Specifically, the unique requirements for the Compact Linear Collider (CLIC) project at CERN have led to a new high-gradient "X-band" accelerator technology that is attracting the interest of light-source and medical communities, and which would have been difficult for those communities to advance themselves due to their diverse nature.

Set to operate until the mid-2030s, the Large Hadron Collider (LHC) collides protons at an energy of 13 TeV. One possible path forward for particle physics in the post-LHC, "beyond the Standard Model", era is a high-energy linear electron–positron collider. CLIC envisions an initial-energy 380 GeV centre-of-mass facility focused on precision measurements of the Higgs boson and the top quark, which are promising targets to search for deviations from the Standard Model (*CERN Courier* November 2016 p20). The machine could then, guided by the results from the LHC and the initial-stage linear collider, be lengthened to reach energies up to 3 TeV for detailed studies of this high energy regime. CLIC is overseen by the Linear Collider Collaboration along with the International Linear Collider (ILC), a lower energy electron–positron machine envisaged to operate initially at 250 GeV (*CERN Courier* January/February 2018 p7).

The accelerator technology required by CLIC has been under development for around 30 years and the project's current goals are to provide a robust and detailed design for the update of the European Strategy for Particle Physics, with a technical design report by 2026 if resources permit. One of the main challenges in making CLIC's 380 GeV initial energy stage cost effective, while guaranteeing its reach to 3 TeV, is generating very high accelerating gradients. The gradient needed for the high-energy stage of CLIC is 100 MV/m, which equates to 30 km of active acceleration. For this reason, the CLIC project has made a major investment in developing high-gradient radio-frequency (RF) technology that is feasible, reliable and cheap.

Evading obstacles

Maximising the accelerating gradient leads to a shorter linac and thus a less expensive facility. But there are two main limiting factors: the increasing need of peak RF power and the limitation of accelerating-structure surfaces to support increasingly strong electromagnetic fields. Circumventing these obstacles has been the focus of CLIC activities for several years.

One way to mitigate the increasing demand for peak power is to use higher frequency accelerating structures (figure 1), since the power needed for fixed-beam energy goes up linearly with gradient but goes down approximately with the inverse square root of the RF frequency. The latest XFELs SACLA in Japan and SwissFEL in Switzerland operate at "C-band" frequencies of 5.7 GHz, which enables a gradient of around 30 MV/m and a peak power requirement of around 12 MW/m in the case of SwissFEL. This increase in frequency required a significant technological investment, but CLIC's demand for 3 TeV energies and high beam current requires a peak power per metre of 200 MW/m! This challenge has been under study since the late 1980s, with CLIC first focusing on 30 GHz structures and the Next Linear Collider/Joint Linear Collider community developing 11.4 GHz "X-band" technology. The twists and turns of these projects are many, but the NLC/JLC project ceased in 2005 and CLIC shifted to X-band technology in 2007. CLIC also generates high peak power using a two-beam scheme in which RF power is locally produced by transferring energy from a low-energy, high-current beam to a high-energy, low-current beam. In contrast to the ILC, CLIC adopts normal-conducting RF technology to go beyond the approximately 50 MV/m theoretical limit of existing superconducting cavity geometries.

The second main challenge when generating high gradients is more fundamental than the practical peak-power requirements. A number of phenomena come to life when the metal surfaces of accelerating structures are subject to very high electromagnetic fields, the most prominent being vacuum arcing or breakdown, which induces kicks to the beam that result in a loss of luminosity.

Image: X-band technology at the CLEAR test facility at CERN.

A CLIC accelerating structure operating at 100 MV/m will have surface electric fields in excess of 200 MV/m, sometimes leading to the formation of a highly conductive plasma directly above the surface of the metal. Significant progress has been made in understanding how to maximise gradient despite this effect, and a key insight has been the identification of the role of local power flow. Pulsed surface heating is another troubling high-field phenomenon faced by CLIC, where ohmic losses associated with surface currents result in fatigue damage to the outer cavity wall and reduced performance. Understanding these phenomena has been essential to guide the development of an effective design and technology methodology for achieving gradients in excess of 100 MV/m.

Test-stand physics

Critical to CLIC's development of high-gradient X-band technology has been an investment in four test stands, which allowed investigations of the complex, multi-physics effects that affect high-power behaviour in operational structures (figure 2). The test stands provided the RF klystron power, dedicated instrumentation and diagnostics to operate, measure and optimise prototype RF components. In addition, to investigate beam-related effects, one of the stands was fed by a beam of electrons from the former "CTF3" facility. This has since been replaced by the CLEAR test facility, at which experiments will come on line again next year (*CERN Courier* November 2017 p8).

While the initial motivation for the CLIC test stands was to test prototype components, high-gradient accelerating structures and high-power waveguides, the stands are themselves prototype RF units for linacs – the basic repeatable unit that contains all the equipment necessary to accelerate the beam. A full linac, of course, needs many other subsystems such as focusing magnets and beam monitors, but the existence of four operating units that can be easily visited at CERN has made high-gradient and X-band technology serious options for a number of linac applications in the broader accelerator community. An X-band test stand at KEK has also been operational for many years and the group there has built and tested many CLIC prototype structures.

With CLIC's primary objective being to provide practical technology for a particle-physics facility in the multi-TeV range, it is rather astonishing that an application requiring a mere 45 MeV beam finds itself benefiting from the same technology. This small-scale project, called Smart*Light, is developing a compact X-ray source for a wide range of applications including cultural heritage, metallurgy, geology and medical, providing a practical local alternative to a beamline at a large synchrotron light source. Led by the University of Eindhoven in the Netherlands, Smart*Light produces monochromatic X-rays via inverse Compton scattering, in which X-rays are produced by "bouncing" a laser pulse off an electron beam. The project teams aims to make the equipment small and inexpensive enough to be able to integrate it in a museum or university setting, and is addressing this objective with a 50 MV/m-range linac powered by one of the two standard CLIC test-stand configurations (a 6 MW Toshiba klystron). Funding has been awarded to construct the first prototype system and, once operational, Smart*Light will pursue commercial production.

CLIC technology has the potential to significantly reduce the cost of X-ray facilities.

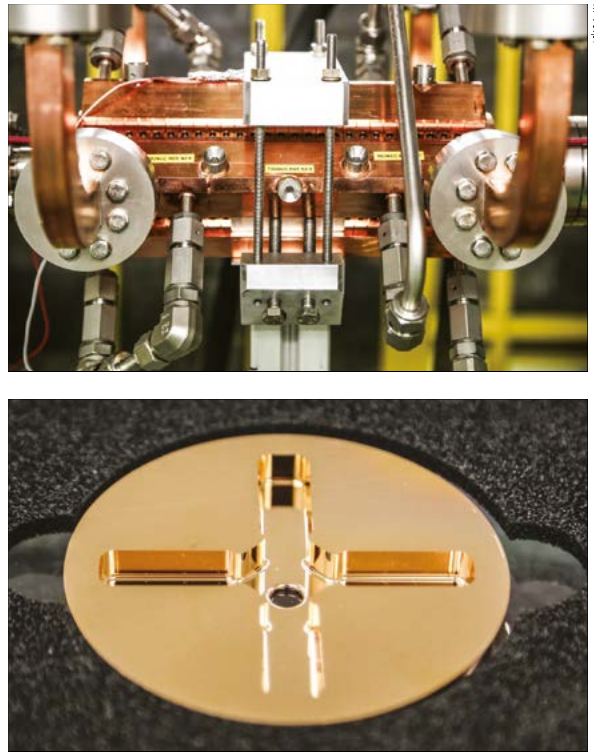

M Volpi

Fig. 1. (Top) A high-gradient structure for CLIC measuring 25 cm across, showing the waveguides (emerging from page) that feed power in and out. The structures are made up of disks (bottom) bonded together to form a series of resonating cells that accelerate the beam. The cells are made to micron-level precision and have a highly optimised geometry to ensure maximum accelerating gradient.

Another Compton-source application is the TTX facility at Tsinghua University in China, which is based on a 45 MeV beam. The Tsinghua group plans to increase the energy of the X-rays by upgrading the energy of their electron linac, which must be done by increasing the accelerating gradient because the facility is housed in an existing radiation-shielded building. The energy increase will occur in two steps: the first will raise the accelerating gradient by upgrading parts of the existing S-band 3 GHz RF system, and the second will be to replace sections with an X-band system to increase the gradient up to 70 MV/m. The Tsinghua X-band power source will also implement a novel "corrector cavity" system to flatten the power compressed pulse that is also now part of the 380 GeV CLIC baseline design. Tsinghua has successfully tested a standard CLIC structure to more than 100 MV/m at KEK, demonstrating that high-gradient technology can be transferred, and has taken delivery of a 50 MW X-band klystron for use in a test stand.

Perhaps the most significant X-band application is XFELs, which produce intense and short X-ray bursts by passing a very low-emittance electron beam through an undulator magnet. The electron linac represents a substantial fraction of the total facility cost and the number of XFELs is presently quite limited. Demand for facilities also exceeds the available beam time. Operational facilities include LCWS at SLAC, FERMI at Trieste and SACLA at Riken, while the European XFEL in Germany, the Pohang Light Source in Korea and SwissFEL are being commissioned (*CERN Courier* July/August 2017 p18), and it is expected that further facilities will be built in the coming years.

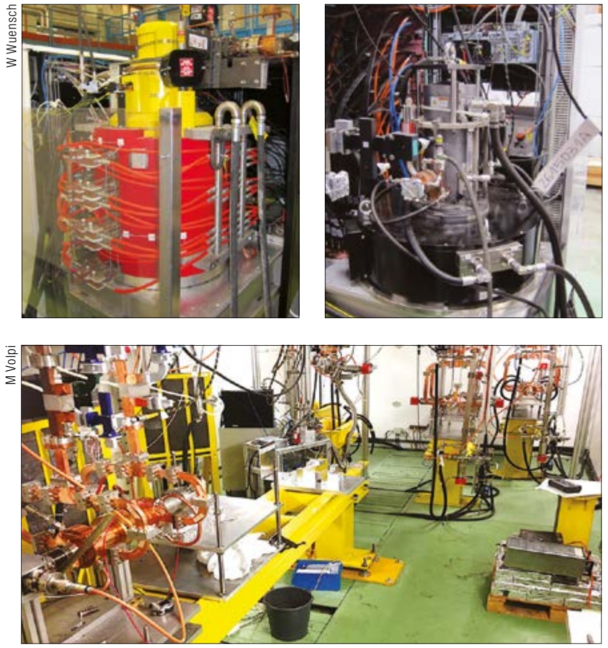

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Fig. 2. The basic power-generating element of the RF system is a klystron driven by a high-voltage pulsed modulator. Pictured top (left and right) are the 50 MW klystron from CPI (left) and the 6 MW high-repetition rate klystron from Canon (formerly Toshiba), right, installed in the CLIC test stands. Swedish firm Scandinova provided solid-state modulators for all four test stands. The output RF power from these units is channelled via a 12 GHz waveguide (copper structure in the top right of the CPI image) to a pulse compressor containing low-loss resonant cavities, and then transported into a shielded bunker and distributed to the accelerating structures (bottom).

XFEL applications

CLIC technology, both the high-frequency and high-gradient aspects, has the potential to significantly reduce the cost of such X-ray facilities, allowing them to be funded at the regional and possibly even university scale. In combination with other recent advances in injectors and undulators, the European Union project CompactLight has recently received a design study grant to examine the benefits of CLIC technology and to prepare a complete technical design report for a small-scale facility (*CERN Courier* December 2017 p8).

A similar type of electron linac, in the 0.5–1 GeV range, is being proposed by Frascati Laboratory in Italy for XFEL development, in addition to the study of advanced plasma-acceleration techniques. To fit the accelerator in a building on the Frascati campus, the group has decided to use a high-gradient X-band for their linac and has joined forces with CLIC to develop it. The cooperation includes Frascati staff visiting CERN to help run the high-gradient test facilities and the construction of their own test stand at Frascati, which is an important advance in testing its capability to use CLIC technology.

In addition to providing a high-performance technology for acceleration, high-gradient X-band technology is the basis for two important devices that manipulate the beam in low-emittance and short-bunch electron linacs, as used in XFELs and advanced development linacs. The first is the energy-spread lineariser, which uses a harmonic of the accelerating frequency to correct the energy spread along the bunch and enable shorter bunches. A few years ago a collaboration between Trieste, PSI and CERN made a joint order for the first European X-band frequency (11.994 GHz) 50 MW klystrons from SLAC, and jointly designed and built the lineariser structures, which have significantly improved the performance of the Elettra light source in Trieste and become an essential element of SwissFEL.

Following the CLIC test stand and lineariser developments, a new commercial X-band klystron has become available, this time at the lower power of 6 MW and supplied by Canon (formerly Toshiba). This new klystron is ideally suited for lineariser systems and one has recently been constructed at the soft X-ray XFEL at SINAP in Shanghai, which has a long-standing collaboration with CLIC on high-gradient and X-band technology. Back in Europe, Daresbury Laboratory has decided to invest in a lineariser system to provide the exceptional control of the electron bunch characteristics needed for its XFEL programme, which is being developed at its CLARA test facility. Daresbury has been working with CLIC to define the system, and is now procuring an RF power system based on the 6 MW Toshiba klystron and pulse compressor. This will certainly be a major step in the ease of adoption of X-band technology.

The second major high-gradient X-band beam manipulation application is the RF deflector, which is used at the end of an XFEL to measure the bunch characteristics as a function of position along the bunch. High-gradient X-band technology is well suited to this application and there is now widespread interest to implement such systems. Teams at FLASH2, FLASH-Forward and SINBAD at DESY, SwissFEL and CLIC are collaborating to define common hardware, including a variable polarisation deflector to allow a full 6D characterisation of the electron bunch. SINAP is also active in this domain. The facility is awaiting delivery of three 50 MW CPI klystrons to power the deflectors and will build a standard CLIC test structure for tests at CERN in addition to a prototype X-band XFEL structure in the context of CompactLight.

The rich exchange between different projects in the high-gradient community is typified by PSI and in particular the SwissFEL. Many essential features of the SwissFEL have a linear-collider heritage, such as the micron-precision diamond machining of the accelerating structures, and SwissFEL is now returning the favour. For example, a pair of CLIC X-band test accelerating structures are being tested at CERN to examine the high-gradient potential of PSI's fabrication technology, showing excellent results: both structures can operate

PSI

SINAP

Fig. 3. The SwissFEL C-band linac at the Paul Scherrer Institute (left) and the injection linac for the SINAP XFEL test facility at the Shanghai Institute of Applied Physics (right). Both projects work closely with CLIC to advance high-gradient RF technology.

at more than 115 MV/m and demonstrate potential cost savings for CLIC. In addition, the SwissFEL structures have been successfully manufactured to micron precision in a large production series – a level of tolerance that has always been an important concern for CLIC. Now that the PSI fabrication technology is established, the laboratory is building high-gradient structures for other projects such as Elettra, which wishes to increase its X-ray energy and flux but has performance limitations with its 3 GHz linac.

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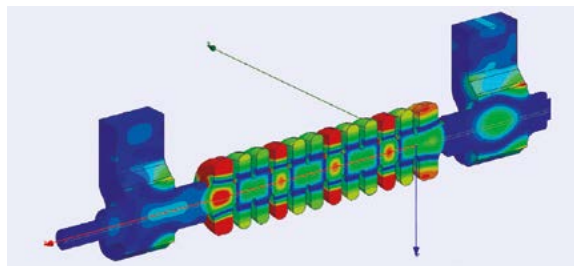


Fig. 4. Simulation of the field inside an RF deflector (red and blue correspond to high and low fields, respectively) used to measure the bunch characteristics at XFELs, which is another application well suited to high-gradient X-band technology.

Beyond light sources

High-gradient technology is now working its way beyond electron linacs, particularly in the treatment of cancer. The most common accelerator-based cancer treatment is X-rays, but protons and heavy ions offer many potential advantages. One drawback of hadron therapy is the high cost of the accelerators, which are currently circular. A new generation of linacs offer the potential for smaller, lower cost facilities with additional flexibility.

The TERA foundation has studied such linac-based solutions and a firm called ADAM is now commercialising a version with a view to building a compact hadron-therapy centre (*CERN Courier* January/February 2018 p25). To demonstrate the potential of high gradients in this domain, members of CLIC received support from the CERN knowledge transfer fund to adapt CLIC technology to accelerate protons in the relevant energy range, and the first of two structures is now under test. The predicted gradient above was 50 MV/m, but the structure has exceeded 55 MV/m and also behaves consistently when compared to the almost 20 CLIC structures. We now know that it is possible to reach high accelerating gradients even for protons, and projects based on compact linacs can now move forward with confidence.

Collaboration has driven the wider adoption of CLIC's high-gradient technology. A key event took place in 2005 when CERN management gave CLIC a clear directive that, with LHC construction limiting available resources, the study must find outside collaborators. This was achieved thanks to a strong effort by CLIC researchers, also accompanied by a great deal of activity in electron linacs in the accelerator community.

We should not forget that the wider adoption of X-band and high-gradient technology is extremely important for CLIC itself. First, it enlarges the commercial base, driving costs down and reliability up, and making firms more likely to invest. Another benefit is the improved understanding of the technology and its operability by accelerator experts, with a broadened user base bringing new ideas. Harnessing the creative energy of a larger group has already yielded returns to the CLIC study, for instance addressing important industrialisation and cost-reduction issues.

The role of high-gradient and X-band technology is expanding steadily, with applications at a surprisingly wide range of scales. Despite having started in large linear colliders, the use of the technology now starts to be dominated by a proliferation of small-scale applications. Few of these were envisaged when CLIC was formulated in the late 1980s – XFELs were in their infancy at the time. As the technology is applied further, its performance will rise even more, perhaps even leading to the use of smaller applications to build a higher energy collider. The interplay of different communities can make advances beyond what any could on their own, and it is an exciting time to be part of this field.

Résumé

La technologie en bande X à gradient élevé

La puissante technologie des accélérateurs linéaires, développée pour la recherche fondamentale, a évolué au point qu'elle est aujourd'hui appliquée dans des domaines autres que la physique des hautes énergies. Les exigences uniques du Collisionneur linéaire compact du CERN ont conduit au développement d'une nouvelle technologie d'accélération « en bande X » à gradient élevé. Celle-ci suscite l'intérêt des chercheurs travaillant sur les sources de lumière et la médecine, qui n'auraient vraisemblablement pas été en mesure de la faire évoluer.

Walter Wuensch, CERN.

Time to adapt for big data

Radical changes in computing and software are required to ensure the success of the LHC and other high-energy physics experiments into the 2020s, argues a new report.

It would be impossible for anyone to conceive of carrying out a particle-physics experiment today without the use of computers and software. Since the 1960s, high-energy physicists have pioneered the use of computers for data acquisition, simulation and analysis. This hasn't just accelerated progress in the field, but driven computing technology generally – from the development of the World Wide Web at CERN to the massive distributed resources of the Worldwide LHC Computing Grid (WLCG) that supports the LHC experiments. For many years these developments and the increasing complexity of data analysis rode a wave of hardware improvements that saw computers get faster every year. However, those blissful days of relying on Moore's law are now well behind us (see panel overleaf), and this has major ramifications for our field.

The high-luminosity upgrade of the LHC (HL-LHC), due to enter operation in the mid-2020s, will push the frontiers of accelerator and detector technology, bringing enormous challenges to software and computing (*CERN Courier* October 2017 p5). The scale of the HL-LHC data challenge is staggering: the machine will collect almost 25 times more data than the LHC has produced up to now, and the total LHC dataset (which already stands at almost 1 exabyte) will grow many times larger. If the LHC's ATLAS and CMS experiments project their current computing models to Run 4 of the LHC in 2026, the CPU and disk space required will jump by between a factor of 20 to 40 (figures 1 and 2).

Even with optimistic projections of technological improvements there would be a huge shortfall in computing resources. The WLCG hardware budget is already around 100 million Swiss francs per year and, given the changing nature of computing hardware and slowing technological gains, it is out of the question to simply throw

Inside the CERN computer centre in 2017. (Image credit: J Ordan/CERN.)

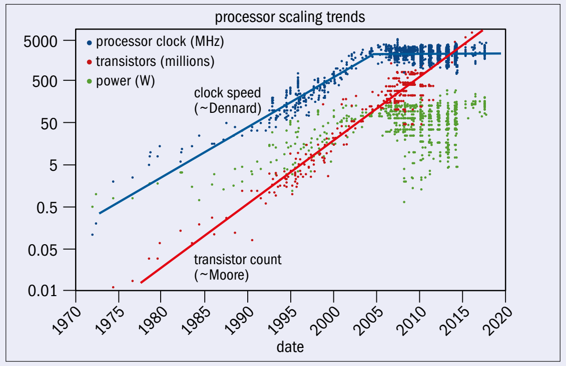
more resources at the problem and hope things will work out. A more radical approach for improvements is needed. Fortunately, this comes at a time when other fields have started to tackle data-mining problems of a comparable scale to those in high-energy physics – today's commercial data centres crunch data at prodigious rates and exceed the size of our biggest Tier-1 WLCG centres by a large margin. Our efforts in software and computing therefore naturally fit into and can benefit from the emerging field of data science.

A new way to approach the high-energy physics (HEP) computing problem began in 2014, when the HEP Software Foundation (HSF) was founded. Its aim was to bring the HEP software community together and find common solutions to the challenges ahead, beginning with a number of workshops organised by a dedicated startup team. In the summer of 2016 the fledgling HSF body was charged by WLCG leaders to produce a roadmap for HEP software and computing. With help from a planning grant from the US National Science Foundation, at a meeting in San Diego in January 2017, the HSF brought community and non-HEP experts together to gather ideas in a world much changed from the time when the first LHC software was created. The outcome of this process was summarised in a 90-page-long community white paper released in December last year.

The report doesn't just look at the LHC but considers common problems across HEP, including neutrino and other "intensity-frontier" experiments, Belle II at KEK, and future linear and circular colliders. In addition to improving the performance of our software and optimising the computing infrastructure itself, the report also explores new approaches that would extend our physics reach as well as ways to improve the sustainability of our software to match the multi-decade lifespan of the experiments.

Almost every aspect of HEP software and computing is presented in the white paper, detailing the R&D programmes necessary to deliver the improvements the community needs. HSF members looked at all steps from event generation and data taking up to final analysis, each of which presents specific challenges and opportunities.

CPU scaling comes to the end of an era



C Legget/LBL

For years, high-energy physics has benefitted from a wave of improvements in computing hardware. Every couple of years the performance of code more than doubled because as transistors became smaller, they could be run faster. Many problems that were faced could be solved simply by waiting for computers to get faster, and this trend was a key part of the plan for LHC computing. However, as can be seen from the plot above, in the mid-2000s this "Dennard scaling" ground to an abrupt halt: while chip makers continued to pack more and more smaller transistors onto silicon following Moore's law (red points), it became impossible to increase the clock speed of the CPU (blue) further due to the increased heat load. With the performance of single CPU cores stalling, manufacturers started to add multiple independent CPU cores to their machines. Instead of doing one thing faster, such architectures could at least do many things together at the same speed. This trend continues today, and is one key change to which high-energy physicists need to adapt to find practical solutions to the big-data challenges of the 2020s.

Souped-up simulation

Every experiment needs to be grounded in our current knowledge of physics, which means that generating simulated physics events is essential. For much of the current HEP experiment programme it is sufficient to generate events based on leading-order calculations – a relatively modest task in terms of computing requirements. However, already at Run 2 of the LHC there is an increasing demand for next-to-leading order, or even next-to-next-to-leading order, event generators to allow more precise comparisons between experiments and the Standard Model predictions (*CERN Courier* April 2017 p18). These calculations are particularly challenging both in terms of the software (e.g. handling difficult integrations) and the mathematical technicalities (e.g. minimising negative event weights), which greatly increase the computational burden. Some physics analyses based on Run-2 data are limited by theoretical uncertainties and, by Run 4 in the mid-2020s, this problem will be even more widespread. Investment in technical improvements of the computation is therefore vital, in addition to progress in our underlying theoretical understanding.

We require new investment and a commitment to solving problems in common

Increasingly large and sophisticated detectors, and the search for rarer processes hidden amongst large backgrounds, means that particle physicists need ever-better detector simulation. The models describing the passage of particles through the detector need to be improved in many areas for high precision work at the LHC and for the neutrino programme. With simulation being such a huge consumer of resources for current experiments (often representing more than half of all computing done), it is a key area to adapt to new computing architectures.

Vectorisation, whereby processors can execute identical arithmetic instructions on multiple pieces of data, would force us to give up the simplicity of simulating each particle individually. The best way to do this is one of the most important R&D topics identified by the white paper. Another is to find ways to reduce the long simulation times required by large and complex detectors, which exacerbates the problem of creating simulated data sets with sufficiently high statistics. This requires research into generic toolkits for faster simulation. In principle, mixing and digitising the detector hits at high pile-up is a problem that is particularly suited for parallel processing

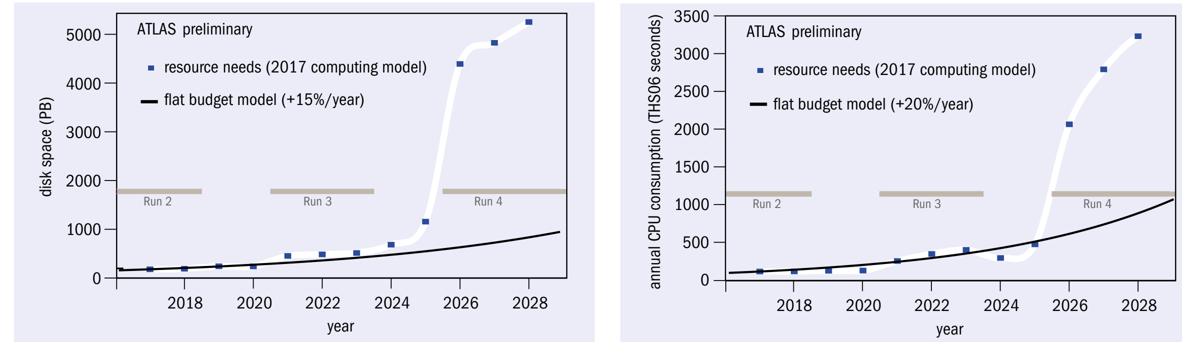


Fig. 1. The estimated disk-space requirements (left) and CPU resources (right) of the ATLAS experiment for period the 2018 to 2028 for both data and simulation processing. The blue points are estimates based on the current software performance estimates, while the solid line shows the amount of resources expected to be available if a flat-funding scenario is assumed, which implies an increase of 20% per year based on the current technology trends.

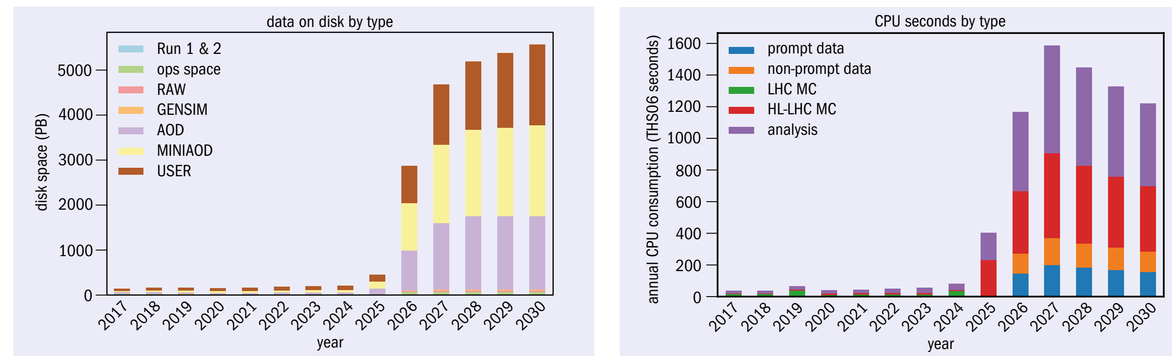


Fig. 2. CMS estimated disk space (left) and CPU resources (right) required for the high-luminosity LHC era, using the current computing model with parameters projected for the next 12 years. The vertical label "THS06" stands for Terra HEP SPEC 06, a standard measure of the performance of a CPU code used in high-energy physics.

on new concurrent computing architectures – but only if the rate at which data is read can be managed.

This shift to newer architectures is equally important for our software triggers and event-reconstruction code. Investing more effort in software triggers, such as those already being developed by the ALICE and LHCb experiments for LHC Run 3, will help control the data volumes and enable analyses to be undertaken directly from initial reconstruction by avoiding an independent reprocessing step. For ATLAS and CMS, the increased pile-up at high luminosity makes charged-particle tracking within a reasonable computing budget a critical challenge (figure 3). Here, as well as the considerable effort required to make our current code ready for concurrent use, research is needed into the use of new, more "parallelisable" algorithms, which maintain physics accuracy. Only these would allow us to take advantage of the parallel capabilities of modern processors, including GPUs (just like the gaming industry has done, although without the need there to treat the underlying physics with such care). The use of updated detector technology such as track triggers and timing detectors will require software developments to exploit this additional detector information.

For final data analysis, a key metric for physicists is "time to insight", i.e. how quickly new ideas can be tested against data. Maintaining that agility will be a huge challenge given the number of events physicists have to process and the need to keep the overall data volume under control. Currently a number of data-reduction steps are used, aiming at a final dataset that can fit on a laptop but bloating the storage requirements by creating many intermediate data products. In the future, access to dedicated analysis facilities that are designed for a fast turnaround without tedious data reduction cycles may serve the community's needs better.

This draws on trends in the data-analytics industry, where a number of products, such as Apache Spark, already offer such a data-analysis model. However, HEP data is usually more complex and highly structured, and integration between the ROOT analysis framework and new systems will require significant work. This may also lend itself better to approaches where analysts concentrate on describing *what* they want to achieve and a back-end engine takes care of optimising the task for the underlying hardware resource. These approaches also integrate better with data-preservation requirements, which are increasingly important for our field. Over and above preserving the underlying bits of data, a fundamental challenge is to preserve knowledge about how to use this data. Preserved

Software and computing

B Lieunard/LAPP

The final touches to the HEP Software Foundation (HSF) white paper were made at a workshop in Annecy in June 2017.

knowledge can help new analysts to start their work more quickly, so there would be quite tangible immediate benefits to this approach.

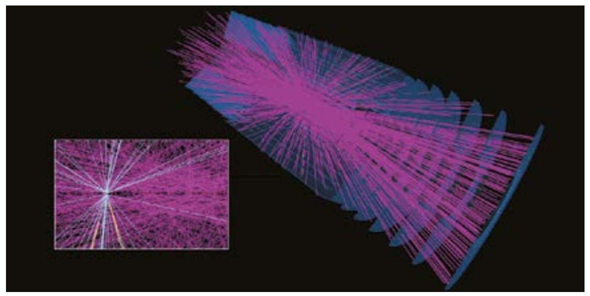
A very promising general technique for adapting our current models to new hardware is machine learning, for which there exist many excellent toolkits. Machine learning has the potential to further improve the physics reach of data analysis and may also speed up and improve the accuracy of physics simulation, triggering and reconstruction. Applying machine learning is very much in vogue, and many examples of successful applications of these data-science techniques exist, but real insight is required to know where best to invest for the HEP community. For example, a deeper understanding of the impact of such black boxes and how they relate to underlying physics, with good control of systematics, is needed. It is expected that such techniques will be successful in a number of areas, but there remains much research to be done.

New challenges

Supporting the computational training phase necessary for machine learning brings a new challenge to our field. With millions of free parameters being optimised across large GPU clusters, this task is quite unlike those currently undertaken on the WLCG grid infrastructure and represents another dimension to the HL-LHC data problem. There is a need to restructure resources at facilities and to incorporate commercial and scientific clouds into the pool available for HEP computing. In some regions high-performance computing facilities will also play a major role, but these facilities are usually not suitable for current HEP workflows and will need more consistent interfaces as well as the evolution of computing systems and the software itself. Optimising storage resources into "data lakes", where a small number of sites act as data silos that stream data to compute resources, could be more effective than our current approaches. This will require enhanced delivery of data over the network to which our computing and software systems will need to adapt. A new generation of managed networks, where dedicated connections between sites can be controlled dynamically, will play a major role.

The many challenges faced by the HEP software and computing community over the coming decade are wide ranging and hard. They require new investment in critical areas and a commitment to solving problems in common between us, and demand that a new generation of physicists is trained with updated computing skills. We cannot afford a "business as usual" approach to solving these problems, nor will hardware improvements come to our rescue, so software upgrades need urgent attention.

The recently completed roadmap for software and computing



ATLAS

Fig. 3. The high-luminosity LHC upgrade will produce around 200 simultaneous proton–proton collisions in a single bunch crossing, illustrated by a simulated event for ATLAS.

R&D is a unique document because it addresses the problems that our whole community faces in a way that was never done before. Progress in other fields gives us a chance to learn from and collaborate with other scientific communities and even commercial partners. The strengthening of links, across experiments and in different regions, that the HEP Software Foundation has helped to produce, puts us in a good position to move forward with a common R&D programme that will be essential for the continued success of high-energy physics.

Further reading

HEP Software Foundation 2017 arXiv:1712.06982.

Résumé

Données massives : l'heure est aux changements

Les défis informatiques du LHC à haute luminosité sont immenses. D'après le nouveau rapport de la Fondation HSF (HEP Software Foundation), la réussite du LHC et d'autres expériences de physique des hautes énergies après 2020 ne sera possible que si des changements radicaux sont opérés dans les domaines de l'informatique et des logiciels. Outre l'amélioration des performances de nos logiciels et l'optimisation de l'infrastructure informatique, ce rapport passe en revue de nouvelles approches qui pourraient permettre d'étendre le potentiel de notre physique et s'intéresse aux moyens d'accroître la durabilité de nos logiciels pour faire face au ralentissement de l'évolution de nos ressources informatiques.

Graeme A Stewart and **Benedikt Hegner**, CERN and the HEP Software Foundation.

Faces & Places

APPOINTMENTS

Brookhaven role to focus on technology transfer

Particle physicist David Asner has been appointed deputy associate laboratory director for strategic program development at Brookhaven National Laboratory (BNL), a new role focused on growing Brookhaven's nuclear and particle physics programme in directions outside its traditional areas. Asner, a former spokesperson of the CLEO collaboration at Cornell and leader of the US participation in Belle at KEK, has also been appointed head of BNL's instrumentation division, succeeding Graham Smith. A focus of the strategic BNL role is to identify opportunities for technology transfer and commercialisation in areas such as national security, space science and materials science.

BNL

David Asner previously led the high-energy physics programme at Pacific Northwest National Laboratory.

DUNE elects co-spokesperson

Stefan Söldner-Rembold of the University of Manchester in the UK has been elected co-spokesperson of the international Deep Underground Neutrino Experiment (DUNE) collaboration, beginning 1 April, succeeding Mark Thomson (*CERN Courier* March 2018 p41). DUNE will use two neutrino detectors placed in an intense neutrino beam produced at Fermilab to measure CP violation in neutrino interactions. Söldner-Rembold is a former spokesperson of the D0 experiment at Fermilab, where he worked on searches for the Higgs boson. He is a member of the MicroBooNE and SBND collaborations at Fermilab's short-baseline neutrino programme, and also of the SuperNEMO and IceCube-GEN2 collaborations.

D D'Souza

Stefan Söldner-Rembold.

Carlin takes the helm at CMS experiment

Roberto Carlin of the INFN and University of Padova in Italy has been elected spokesperson of the CMS experiment for a two-year term beginning in September, taking over from current spokesperson Joel Butler. Carlin, a longstanding CMS collaborator, studied physics at the University of Padova and completed his thesis on the PS170 experiment at CERN in 1989. Prior to joining CMS in 2005 he worked on ZEUS at HERA, DESY. He is currently deputy CMS spokesperson and has also played important roles in the CMS muon drift-tube detector and trigger.

M Bruce/CERN

Roberto Carlin in the CMS control room.

AWARDS

Alfvén Prize for cosmic acceleration

The plasma physics division of the European Physical Society has awarded the 2018 Hannes Alfvén Prize to Tony Bell of the University of Oxford for his seminal contributions to cosmic particle acceleration. Bell, a theoretical plasma physicist, has opened up new research fields in both astrophysical and laboratory plasmas. He also played a leading role in the development of what is now the standard model of astrophysical particle acceleration and cosmic-ray origins and has been one of the main players over three decades in developing the understanding of electron transport in laser-produced plasmas.

Royal Society

Theorist Tony Bell of the University of Oxford (left) won the Hannes Alfvén award for his work in cosmic particle acceleration.

Five young researchers win ATLAS thesis prize

On 22 February the ATLAS collaboration presented the latest winners of its annual thesis awards. Five winners were selected from a total of 31 nominations spanning all areas of ATLAS physics, from detector development and operations to software and performance studies and physics analyses: Pierfrancesco Butti (Nikhef), Johanna Gramling (University of Geneva), Oleh Kivernyk (University of Paris-Saclay), Philip Sommer (Albert Ludwigs University of Freiburg) and Markus Zinser (Johannes Gutenberg University Mainz). PhD students make up almost a fifth of the ATLAS collaboration's 5500 members and contribute greatly to all areas of the experiment while learning valuable skills for their degrees.

K Anthony

Left to right: Katsuo Tokushuku, Pierfrancesco Butti, Oleh Kivernyk, Karl Jakobs (ATLAS spokesperson), Johanna Lena Gramling, Markus Zinser, Philip Sommer and Max Klein.

Meetings

Big science meets industry in Copenhagen

Big science equals big business, whether it is manufacturing giant superconducting magnets for particle colliders or perfecting mirror coatings for space telescopes. The Big Science Business Forum (BSBF), held in Copenhagen, Denmark, on 26–28 February, saw more than 1000 delegates from more than 500 companies and organisations spanning 30 countries discuss opportunities in the current big-science landscape.

Nine of the world's largest research facilities – CERN, EMBL, ESA, ESO, ESRF, ESS, European XFEL, F4E and ILL – offered insights into procurement opportunities and orders totalling more than €12 billion for European companies in the coming years. These range from advisory engineering work and architectural tasks to advanced technical equipment, construction projects and radiation-resistant materials. A further nine organisations also joined the conference programme: ALBA, DESY, ELI-NP, ENEA, FAIR, MAX IV, SCK•CEN – MYRRHA, PSI and SKA, thereby gathering 18 of the world's most advanced big-science organisations under one roof.

The big-science market is currently fragmented by the varying quality standards and procurement procedures of the different laboratories, delegates heard. BSBF aspired to offer a space to discuss the entry challenges for businesses and suppliers – including small- and medium-sized enterprises – who can be valuable business partners for big-science projects.

M Nørulf

CERN director for accelerators and technology, Frédérick Bordry, highlighted material expenditure for the HL-LHC upgrade project worth 950 million Swiss francs in the next few years.

"The vision behind BSBF is to provide an important stepping stone towards establishing a stronger, more transparent and efficient big-science market in Europe and we hope that this will be the first of a series of BSBFs in different European cities," said Agnete Gersing of the Danish ministry for higher education and science during the opening address.

Around 700 one-to-one business meetings took place, and delegates also visited the European Spallation Source and MAX IV facility just across the border in Lund, Sweden. Parallel sessions covered big science as a business area, addressing topics such as the investment potential and best practices of Europe's big-science market.

"Much of the most advanced research takes place at big-science facilities, and their need for high-tech solutions provides great innovation and growth opportunities for private companies," said Danish minister for higher education and science, Søren Pind.

Nanotechnology: from materials to science

Aiming to bring companies and researchers active in nanotechnology together with experts from other research fields, such as high-energy physics or medical science, the CERN-fostered High-Energy Physics Technology Transfer Network (HEPTech) organised an academia–industry matching event on 15–16 February at Charles University in Prague. The forum was part of the HEPTech's programme in nanotechnology and attracted about 60 participants from 11 European countries. It was co-organised by participants of the EU project ACCELERATE, which aims to support the long-term sustainability of large-scale research infrastructures.

Many conventional techniques and methods for nano-scale characterisation and analysis have reached their limit, requiring further development. Research in high-energy physics has allowed the development of accelerator and detector technology that can be applied in other research fields, and nanotechnology is among them.

E Getsova/HEPTech

Delegates at the HEPTech event in Prague.

The Prague event discussed several examples of where particle physics can impact nano-analysis and characterisation, particularly in biological and pharmacological environments. Other examples included X-ray imaging techniques for use in the PETRA III light source to visualise 3D microscopic structures with resolutions down to below 1 μm, while Elettra Sincrotrone Trieste focused on the capabilities for operando characterisation of advanced batteries and fuel cells using X-ray absorption spectroscopy and X-ray photoelectron spectroscopy. The Ruđer Bošković Institute in Croatia shared its experience in the production and analysis of nanostructures using ion beams in the MeV energy range.

● *HEPTech is mandated by and reports to the CERN Council and its programme is aligned with the directives of the European Strategy for Particle Physics.*

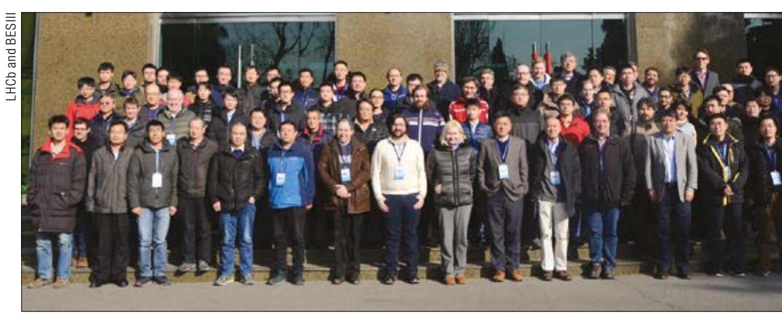
Beauty workshop highlights CERN–China links

At first sight, the LHCb experiment at CERN and the BESIII experiment at the Institute of High Energy Physics (IHEP) in Beijing are different experiments with little in common. The former operates in the fierce environment of 13 TeV proton–proton collisions of the LHC, whereas BESIII collects data from the BEPC accelerator, an electron–positron collider operating at energies of 3–4 GeV. Yet both experiments have been built for flavour physics, which is the study of the properties and decays of hadrons containing a heavy quark (beauty or charm in the case of LHCb; charm in the case of BESIII). As such, there are many topics of common interest between LHCb and BESIII. Moreover, measurements made at one collider can provide useful and essential input to the physics programme at the other.

On 8–9 February a workshop took place at IHEP to explore these synergies – the first such joint meeting between LHCb and BESIII – involving around 70 representatives from the experiments in addition to several invited theorists.

CP violation, which probes the difference in behaviour between matter and antimatter, is a central area of study for LHCb and a clear example of the benefits of closer collaboration with BESIII. Many CP-violation measurements involve decay processes where a beauty hadron decays into a charm meson, which itself subsequently decays. A clean interpretation of the results requires a complete understanding of the characteristics of the charm decay, and this can be provided by BESIII. Furthermore, many LHCb analyses targeted at testing lepton universality, a very hot topic at present (see p23), can be improved by a more complete survey of charm decays that provide potential backgrounds to the signal samples. BESIII is an ideal experiment for performing such a survey.

LHCb and BESIII



Participants at the first joint LHCb–BESIII physics workshop in Beijing.

These and related topics were the subject of lively discussions at the meeting, with attention devoted to both the potential of the current BESIII data and the future running plans of the Beijing experiment. It was concluded that future such events should be organised, and that the two collaborations should work closely together. This will enable us to obtain the best possible sensitivity to the key observables in flavour physics and to explore the full potential of this unique synergy between two major high-energy physics facilities.

Training young researchers in South-East Europe

The Southeastern European Network in Mathematical and Theoretical Physics (SEENET-MTP) organises scientific training and research activities in the Balkan and neighbouring regions. Since it was founded in 2003, the network has promoted the exchange of students and researchers, and contributed to institutional capacity building in physics and mathematics.

In January 2015, with the support of CERN, SEENET-MTP launched a joint PhD training programme aimed at students from southeastern European countries. The main part of the programme was designed to be a series of intense, one-week schools for PhD students, advanced masters students and young postdocs in high-energy physics and related fields. Each school included lectures followed by appropriate exercises, and the programme became part of a general agreement of cooperation between CERN and SEENET-MTP signed in February 2017.

The fourth school, New Trends in High Energy Theory, was held in Sofia, Bulgaria, from 15–22 October 2017, and the main seminar topics were string theory and black holes, with a focus on holography. The opening course, by Timo Weigand of CERN, gave a comprehensive introduction to string theory, starting from the world-sheet formulation of the bosonic and superstrings, and recalling the main properties of D-branes and the low-energy effective supergravity. Other guest lecturers were Atish Dabholkar (ICTP, Trieste), Anastasios Petkou (AU, Thessaloniki), Veselin Filev (DIAS, Dublin) and Nikolay Bobev (KU Leuven, Belgium), who focused on the systematic introduction of the AdS/CFT correspondence.

The 2017 school was organised by the faculty of physics at Sofia University, and moderated by SEENET-MTP president Dumitru Vulcanov (West University of Timisoara) and executive director Goran Djordjevic (University of Niš). A total of 26 participants from six SEENET-MTP countries and Belgium attended. Besides CERN, these activities were supported by the ICTP, the European Physical Society, Sofia University and SEENET-MTP. The next school, High Energy and Particle Physics: Theory and Phenomenology, will be held in Niš, Serbia, on 3–10 June 2018, followed by a workshop on field theory and the early universe, and other events to mark 15 years of the network.

● phd.seenet-mtp.info

M Milosevic

Students at the SEENET mathematical and theoretical physics school.

Visits

J Ordan/CERN

The president of Mozambique, **Filipe Nyusi**, and his delegation were welcomed to CERN on 26 February. President Nyusi visited the LHC tunnel (pictured), the ATLAS control room and the underground experiment area. He also signed the CERN guest book.

Austrian federal president **Alexander Van der Bellen** visited CERN on 27 February, taking in the CMS experiment, the LHC tunnel and the ASACUSA and AEgIS facilities. Van der Bellen also attended a round table with young Austrian scientists. He is pictured (second from left) at CMS with his wife (left) and (right to left) Austria minister for education, science and research Heinz Fassmann and CERN Director-General Fabiola Gianotti.

J Ordan/CERN

On 26 February the governor general of Australia, **Peter Cosgrove**, was welcomed to CERN by Director-General Fabiola Gianotti, director for research and computing Eckhard Elsen, head of associate member and non-member state relations Emmanuel Tsesmelis, and national contact physicist Geoffrey Taylor. Cosgrove visited the ATLAS control room and the underground experiment area, as well as the LHC tunnel.

J Ordan/CERN

Correction: A map showing the location of European hadron-therapy facilities (*CERN Courier* January/February 2018 p34) depicted a centre under construction in Edinburgh that should have been in Northumbria, both in the UK.

OBITUARIES

Aharon Casher 1941–2018

Aharon (Rony) Casher was born in Haifa, Israel, and graduated from the Technion where he performed his thesis work on condensed bosonic systems under Micha Revzen. He then went to Yeshiva University in New York, where he wrote a well-known paper with Joel Lebowitz on heat flow in random harmonic chains. This is also where his longstanding collaborations with Yakir Aharonov and Lenny Susskind began.

The Aharonov–Casher effect, which is dual to the Aharonov–Bohm effect, is textbook material and also led to a beautiful result on the number of zero modes in 2D magnetic fields. With Lev Vaidman, Casher and Aharonov developed the mathematics underpinning weak measurements; and in a separate work with Shimon Yankielowicz they introduced the mechanism of magnetic vacuum condensation for confinement in QCD. The early suggestion by Aharon, Susskind and John Kogut that a vacuum polarisation mechanism can account for quark confinement was extremely influential. Additional, important joint papers on strong interactions, partons and spontaneous chiral symmetry breaking appeared in the early 1970s. The collaboration with Susskind also led to Aharons' familiarity with string theories and to the early paper with Aharonov of a dual string model for spinning particles.

In the high-energy physics community, Aharon is best known for his work on spontaneous chiral symmetry breaking

Casher's work included spontaneous chiral symmetry breaking in QCD.

in QCD. In a singly authored paper he provided a beautiful insight into this subject, followed by a famous paper with Tom Banks that related such breaking to the enhanced density of the low eigenvalues of the Dirac operator. These topics dominated Aharon's interest throughout the 1970s and early 1980s. His deep knowledge of topological field theory and understanding of non-perturbative effects enabled him to make key and long-lasting contributions.

Aharon often visited Brussels, where he worked with François Englert and others on supergravity, quantum gravity and studies of the early universe. Englert, in turn, became a frequent visitor at Tel Aviv University, and non-perturbative effects in quantum gravity and possible connections to the physics of black holes became a shared passion of both. Although Aharon gave a series of influential lectures on string theory at Tel Aviv shortly after the 1984 "string revolution", and published with Englert, Nicolai and Taormina a paper showing that all superstring theories are contained in the bosonic string, he was critical of strings as the ultimate theory of nature. He was an independent thinker, uncompromisingly honest when analysing novel ideas in theoretical physics.

Aharon stayed at Tel Aviv for almost 50 years, his knowledge and remarkable talents enabling him to teach any subject in theoretical physics from memory alone. He was accessible to students and attracted many who subsequently had independent academic careers, including Neuberger, Nissan Itzhaki and Yigal Shamir. Aharon was an avid reader, interested in literature, history, science fiction, sports and politics. One could have an interesting conversation with him on any topic.

Aharon was highly negligent as a self-promoter and was in science for the sheer pleasure of doing it. He rarely gave talks about his work, preferring to think and calculate at his desk, and his collaborators and many others had the deepest respect for him. His ability to keep challenging us and to relentlessly pursue the subtleties that could harbour fatal flaws helped maintain our own scientific integrity. Aharon will be deeply missed.

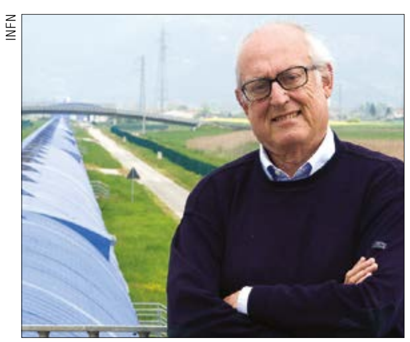
● *Yakir Aharonov, François Englert, Herbert Neuberger and Shmuel Nussinov.*

Adalberto Giazotto 1940–2017

On 17 August 2017 the Virgo and LIGO interferometers recorded the first gravitational-wave signal from the merger of two neutron stars. Their combined data, promptly indicating the direction of the source, made it possible for ground- and space-based telescopes to observe a newly born "kilonova" and for the first time follow its evolution. The data allowed spectroscopic identification of r-process nucleosynthesis, which can explain the abundance of heavy elements such as gold or uranium.

Italian physicist Adalberto Giazotto, who passed away in November, had been a convinced advocate of using gravitational-wave detectors spread around the world as a "single machine" and worked hard to have this vision become reality. Born in 1940 in Genoa, Giazotto graduated in

INFN



Giazotto was a driver of the Virgo interferometer.

Rome with a thesis in theoretical physics and then joined the experimental physics group at the electron synchrotron in Frascati led by Edoardo Amaldi studying π^+ production with an 800 MeV electron beam.

The availability of a higher energy accelerator and the troubled times of 1968 were to prompt his move to Daresbury in the UK with a few colleagues. The NINA electron synchrotron was providing 5 GeV beams, allowing precision studies of the π^+ axial form factor. Subsequently, Giazotto participated at CERN in the NA1 experiment for the photoproduction of charmed particles and lifetime measurements. With the same spectrometer, by scattering π^- off electrons in a liquid hydrogen target, he worked at the NA7 experiment at CERN to measure the π^- and K^- space-like form factor, yielding precise values for their radiuses.

Since the early 1980s, forced to give up travel to Geneva for health reasons, Giazotto ▷

Faces & Places

turned to general relativity, realising that new experimental techniques for the detection of gravitational waves had to be developed. Although pulsars or binary neutron stars could be quite numerous and intense sources, they would produce signals in the range of tens of Hz, where instruments are overwhelmed by microseismic noise. Twenty years of development were necessary for Giazotto and his group to develop an instrument capable of recording those low-frequency oscillations. In the meantime, after joining with Alain Brillet and collaborators, came the proposal to CNRS and INFN to build the Virgo interferometer. In 2002 the infrastructure was delivered, but another 15 years had to pass before the results were seen.

With interests in many fields, Giazotto was also a passionate collector of crystals. He always expressed his wonder at the beauty that can emerge through nature and time, as well as the work of humanity, in particular music. Guided by long-term goals, he was practically impervious to the daily mechanisms of the workings of scientific research and driven only by the search for perfection necessary to undertake "a thing of enormous difficulty".

Adalberto gave us an extraordinary example of how scientific ideas can be carried forward, without compromise, but always respecting nature, to reach unthinkable objectives. His vision and energy will be missed.

● *Francesco Fidecaro, Fulvio Ricci and Federico Ferrini.*

Sandibek Nurushev 1932–2018

Prominent Russian scientist Sandibek Baitemirovich Nurushev passed away on 16 February after a long disease. Nurushev was born on 25 December 1932 and graduated in physics from Moscow Engineering Physics Institute (MEPhI) in 1955, after which he started to work at JINR in Dubna. From the first days he took an active part in the creation of the first polarised proton beam at the JINR synchrocyclotron and in the earliest studies of spin effects in the interaction of protons with atomic nuclei. Nurushev defended his PhD in 1963.

From 1964 up until the last days of his life, he worked at the Institute of High Energy Physics (IHEP) in Protvino.

Nurushev was the father of experimental spin-physics in Russia. With the use of his ideas and under his leadership, many spin experiments were carried out both in Russia and abroad. He was the spokesperson of the first Russian–French polarisation experiment, HERA, at the U-70 accelerator in Protvino in the early 1970s and also of several other spin experiments there.

He was an exceptionally bright figure in the E581 and E704 experiments in Fermilab during the 1980s and 1990s, using polarised proton and antiproton beams with energies near 200 GeV in spin studies, as well as in the spin programme at STAR and the E925 polarisation experiment at Brookhaven National Laboratory. Nurushev left more than 550 scientific papers to his colleagues and followers, many of which added to our understanding of the structure of matter. Those who worked with him, who knew and loved him, will continue his work and develop his ideas.

Nurushev was a patriarch of spin physics.

For many years Nurushev was engaged in teaching activities at MEPhI, and he encouraged many students to deal with polarisation effects and spin physics. He is the author of a textbook on polarisation phenomena and in 1990 was awarded the title of professor in high-energy physics. He also actively participated in the work of the international spin community.

Nurushev died peacefully at home in Protvino, leaving his wife, three children, several grandchildren and great-grandchildren. His last words to his granddaughter a few minutes before his death were: "I fulfilled my programme. I leave, I am satisfied". Sandibek Nurushev will forever live in our memories.

● *His numerous colleagues and students at IHEP and MEPhI.*

Recruitment

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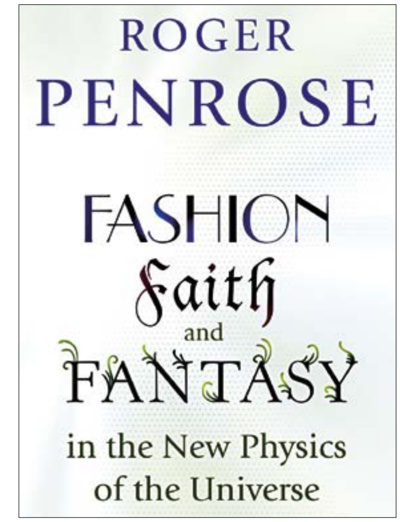
Bookshelf

Compiled by Virginia Greco, CERN

Fashion, Faith and Fantasy in the New Physics of the Universe
By Roger Penrose
Princeton University Press
Also available at the CERN bookshop



The well-known mathematician and theoretical physicist Roger Penrose has produced another popular book, in which he gives a critical overview of contemporary fundamental physics. The main theme is that modern theoretical physics is afflicted by an overdose of fashion, faith and fantasy, which supposedly has led recent research astray.

There are three major parts of the book to which these three f-words relate, corresponding one-to-one with some of the most popular research areas in fundamental physics. The first part, labelled "fashion", deals with string theory. "Faith" refers to the general belief in the correctness of quantum mechanics, while "fantasy" is the verdict for certain scenarios of modern cosmology.

The book starts with an overview of particle physics as a motivation for string theory and quickly focuses on its alleged shortcomings, most notably extra dimensions. Well-known criticisms, for instance linked to the multitude of solutions ("landscape of vacua") of string theory or the postulate of supersymmetry, follow in due course. This material is mostly routine, but there are also previously unheard of concerns such as the notion of "too much functional freedom" or doubts about the decoupling of heavy string states (supposedly excitable, for example from the orbital kinetic energy of Earth).

Next the book turns to quantum mechanics and gives an enjoyable introduction to some of the key notions, such as superposition, spin, measurement and entanglement. The author emphasises, with great clarity, some subtle points such as how to understand the quantum mechanical superposition of space–times. In doing so, he raises some concerns and argues – quite unconventionally – that, to resolve them, it is necessary to modify quantum mechanics. In particular he asks that the postulate of linearity should be re-assessed in the presence of gravity.

The fantasy section gives an exposition of the key ideas of cosmology, in particular of all sorts of scenarios of inflation, big bang, cyclic universes and multiverses. This is all very rewarding to read, and particularly brilliant is the presentation of cosmological aspects of entropy, the second law of thermodynamics and the arrow of time. I consider this third section as the highlight of the book. The author does not hide his suspicion that many of these scenarios should not be trusted and dismisses them as crazy – while saying, as if with a twinkle in the eye: not crazy enough!

There is a brief, additional, final section that has a more personal and historical touch, and which tries to make a case for Penrose's own pet theory: twistor theory. One cannot but feel that some of his resentment against string theory stems from a perceived under-appreciation of twistor theory. In particular, the author admits that his aversion to string theory comes almost entirely from its purported extra dimensions, whereas twistors work primarily in four dimensions.

This touches upon a weak point of the book: the author argues entirely from the direction of classical geometry, and so shares a fixation with extra dimensions in string theory with many other critics. What Penrose misses, however, is that these provide an elegant way to represent certain internal degrees of freedom (needed matter fields). But this is by no means generic – on the contrary, most string backgrounds are non-geometric. For example, some are better described by a bunch of Ising models with no identifiable classical geometry at all, so the agony of how to come to grips with such "compactified" dimensions turns into a non-issue. The point is that due to quantum dualities, there is, in general, no unambiguous objective reality of string "compactification" spaces, and criticism that does not take this "stringy quantum geometry" properly into account is moot.

Somewhat similar in spirit is the criticism of quantum mechanics, which according to Penrose should be modified due to an alleged incompatibility with gravity. Today most researchers would take the opposite point of view and consider quantum mechanics as fundamental, while gravity is a derived, emergent phenomenon. This viewpoint is strongly supported by the gauge-gravity duality and its recent offspring in terms of space–time geometry arising via quantum entanglement.

All-in-all, this book excels by covering a huge range of concepts from particle physics to quantum mechanics to cosmology, presented in a beautifully clear and coherent way (spiced up with many drawings), by an independent and truly deep-thinking master of the field. It also sports a considerable number of formulae and uses mathematical concepts (like complex analysis) that a general audience would probably find difficult to deal with; there are a number of helpful appendices for non-experts, though.

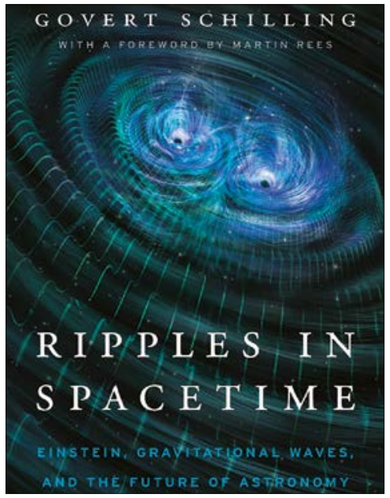
Thus, *Fashion, Faith and Fantasy in the New Physics of the Universe* seems to be suitable for both physics students and experienced physicists alike, and I believe that either group will profit from reading it, if taken with a pinch of salt. This is because the author criticises contemporary fundamental theories through his personal view as a classical relativist, and in doing so falls short when taking certain modern viewpoints into account.

● *Wolfgang Lerche, CERN*

Ripples in spacetime
By Govert Schilling
The Belknap Press of Harvard University Press
In February 2016 the LIGO and Virgo collaborations announced the first detection of gravitational waves from the collision of two black holes. It was a splendid result for a quest that started about five decades ago with the design and construction of small prototypes of laser interferometers. Since this first discovery, at least five other binary black-hole mergers have been found and gravitational waves from two colliding neutron stars have also been detected. Gravitational-wave science is now booming, literally, and will continue to do so for a long time. The upcoming observational progress in this field will impact the development of astrophysics, cosmology and, perhaps, particle physics.

Govert Schilling is an award-winning science journalist with a special interest in astronomy and space science. In this book, he guides the reader through the development of gravitational-wave astronomy, from its very origin deep in

Bookshelf



the early days of general relativity up to the first LIGO discovery. He does so, not only by delving into the key moments of this wonderful piece of history, but also by explaining the main physical and engineering ideas that made it possible.

Moreover, Schilling does a very good job discussing the scientific context in which these events and ideas arose. Far from being a mere collection of events, the book offers the reader a journey that goes beyond its title, exploring and connecting topics such as the cosmic-microwave background and its polarisation, radioastronomy and pulsars, supernovae, primordial inflation, gamma-ray bursts and even dark energy. In addition, the last few chapters of the book discuss the science that may come next, when new interferometers will join LIGO and Virgo in this adventure, observing the sky from Earth (e.g. KAGRA) and space (LISA).

The book clearly aims to target a non-specialist readership and will surely be enjoyed by people lacking a prior knowledge of astrophysics, gravitational waves or cosmology. However, this does not mean that readers more well-versed in these topics will find the book uninspiring. Schilling addresses the reader in a direct, entertaining, almost colloquial manner, managing to explain complex concepts in a few paragraphs while keeping the science sound. Besides, the book gives an interesting (and sometimes surprising) glimpse into the lives, aspirations and mutual interactions of the scientific pioneers in the field of gravitational waves.

If an objection had to be found, it would be that in the first chapter the author belittles general relativity by introducing it as "the theory behind [the movie] *Interstellar*". If this scares you, read on and fear nothing. As always happens, science outshines fiction, and the rest of the book proves why this is so.

● *Guillermo Ballesteros, Instituto de Física Teórica UAM-CSIC, Madrid, Spain*

Books received

Natural Complexity: A Modeling Handbook

By Paul Charbonneau

Princeton University Press

This book aims to introduce readers to the study of complex systems with the help of simple computational models. After showing how difficult it is to define complexity, the author explains that complex systems are an idealisation of naturally occurring phenomena in which the macroscopic structures and patterns generated are not directly controlled by processes at the macroscopic level but arise instead from dynamical interactions at the microscopic level. This kind of behaviour characterises a range of natural phenomena, from avalanches to earthquakes, solar flares, epidemics and ant colonies.

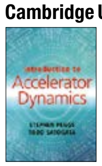
In each chapter the author introduces a simple computer-based model for one such complex phenomenon. As the author himself states, such simplified models wouldn't be able to reliably foresee the development of a real natural phenomenon, thus they are to be taken as complementary to conventional approaches for studying such systems.

Meant for undergraduate students, the book does not require previous experience in programming and each computational model is accompanied by Python code and full explanations. Nevertheless, students are expected to learn how to modify the code to tackle the problems included at the end of each chapter. Three appendices provide a review of Python programming, probability density functions and other useful mathematical tools.

Introduction to Accelerator Dynamics

By Stephen Peggs and Todd Satogata

Cambridge University Press



This concise book provides an overview of accelerator physics, a field that has grown rapidly since its inception and is progressing in many directions. Particle accelerators are becoming more and more sophisticated and rely on diverse technologies, depending on their application.

With a pedagogical approach, the book presents both the physics of particle acceleration, collision and beam dynamics, and the engineering aspects and technologies that lay behind the effective construction and operation of these complex machines. After a few introductory theoretical chapters, the authors delve into the different components and types of accelerators: RF cavities, magnets, linear accelerators, etc. Throughout, they also show the connections between accelerator technology and the parallel development of computational capability.

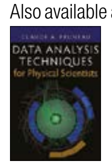
This text is aimed at university students at graduate or late undergraduate level, as well as accelerator users and operators. An introduction to the field, rather than an exhaustive treatment of accelerator physics, the book is conceived to be self-contained (to a certain extent) and to provide a strong starting point for more advanced studies on the topic. The volume is completed by a selection of exercises at the end of each chapter and an appendix with important formulae for accelerator design.

Data Analysis Techniques for Physical Scientists

By Claude A Pruneau

Cambridge University Press

Also available at the CERN bookshop



Since the analysis of data from physics experiments is mainly based on statistics, all experimental physicists have to study this discipline at some point in their career. It is common, however, for students not to learn it in a specific advanced university course but in bits and pieces during their studies and subsequent career.

This textbook aims to present all of the basic statistics tools required for data analysis, not only in particle physics but also astronomy and any other area of the physical sciences. It is targeted towards graduate students and young scientists and, since it is not intended as a text for mathematicians or statisticians, detailed proofs of many of the theorems and results presented are left out.

After a philosophical introduction on the scientific method, the text is presented in three parts. In the first, the foundational concepts and methods of probability and statistics are provided, considering both the frequentist and Bayesian interpretations. The second part deals with the basic and most commonly used advanced techniques for measuring particle-production cross-sections, correlation functions and particle identification. Much attention is also given to the notions of statistical and systematic errors, as well as the methods used to unfold or correct data for the instrumental effects associated with measurements. Finally, in the third section, introductory techniques in Monte Carlo simulations are discussed, focusing on their application to experimental data interpretation.

CERN Courier Archive: 1975

A look back to CERN Courier vol. 15, April 1975, compiled by Peggie Rimmer

News

Directors General appointed

At a special session on 21 March the CERN Council appointed J B Adams and L Van Hove as Directors General for five years beginning 1 January 1976. Dr Adams will be responsible for the administration of CERN, the operation of equipment and services and the construction of buildings and major equipment. Professor Van Hove will be responsible for the research activities.

When Council approved the construction of the 400 GeV super proton synchrotron in 1971, it set up a second Laboratory. The two laboratories were to be unified when the accelerator was completed. The SPS is due to be commissioned during 1976 and Council has decided that the laboratories should be unified from January of that year when the present DG of Laboratory I, Professor W Jentschke, will have completed his five year term.

CERN 261.3.75

Line up of Directors General at the Council Session. On the left is W Jentschke, present Director General of CERN Laboratory I. Centre and right, respectively, are J B Adams and L Van Hove, appointed to lead the combined laboratories from 1 January 1976.

John Adams joined CERN in its earliest days and, after leading the team which built the 28 GeV proton synchrotron, became Director General in 1960 before returning to England. He came back to CERN as Director of the 300 GeV Accelerator Project at the beginning of 1969 and became Director General of Laboratory II in 1971. Leon Van Hove came to CERN in 1961 as Head of the Theoretical Physics Division and has since taken a leading role in the scientific life of the Organization, twice serving as Director of the Theoretical Physics Department (in 1966–68 and 1972–74).

● Compiled from text on p109.

Pastures new

CERN 73.2.75

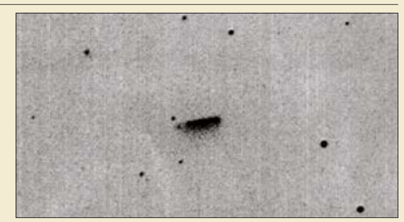
Elliptical mirrors of the large Cherenkov counter used in association with the Omega spectrometer. These mirrors reflect the Cherenkov light onto four sets of parabolic light collectors (sets are visible above and below the white-coated gentleman). The counter, which was built at Saclay, has been working in the CERN West Hall for two years and will also be involved in the first experiments with the 400 GeV proton synchrotron. Meanwhile, it is the essential component of the triggering system in an experiment looking for charmed particles.

● Compiled from text on p111.

ESO: discovery of a comet

A new comet has been identified by the European Southern Observatory (ESO) on a photographic plate exposed on 15 October last year with the ESO Schmidt telescope at La Silla, Chile. This comet has been christened WKI from the names of its three discoverers [R M West at ESO/CERN in January, L Kouhoutek at the Hamburg Observatory in February and T Ikemura, an amateur astronomer, in March in Shinshiro, Japan]. It is the first to be discovered by ESO and the first to be found at the Sky Atlas Laboratory installed at CERN.

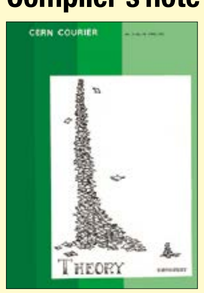
Comets are a kind of contaminated snowball, consisting essentially of ice and various impurities like minerals. They are of special interest because they are probably the remains of the outside fringe of the original gas-cloud that contracted to form the solar system. Comets become visible when they pass close to the Sun, which heats them and produces a halo of incandescent gas (the head) blown by the solar wind (the tail).



First sighting of a new comet by the ESO Schmidt telescope in Chile, baptized WKI. The plate, taken during the "Quick Blue Survey", was processed in the Sky Atlas Laboratory at CERN.

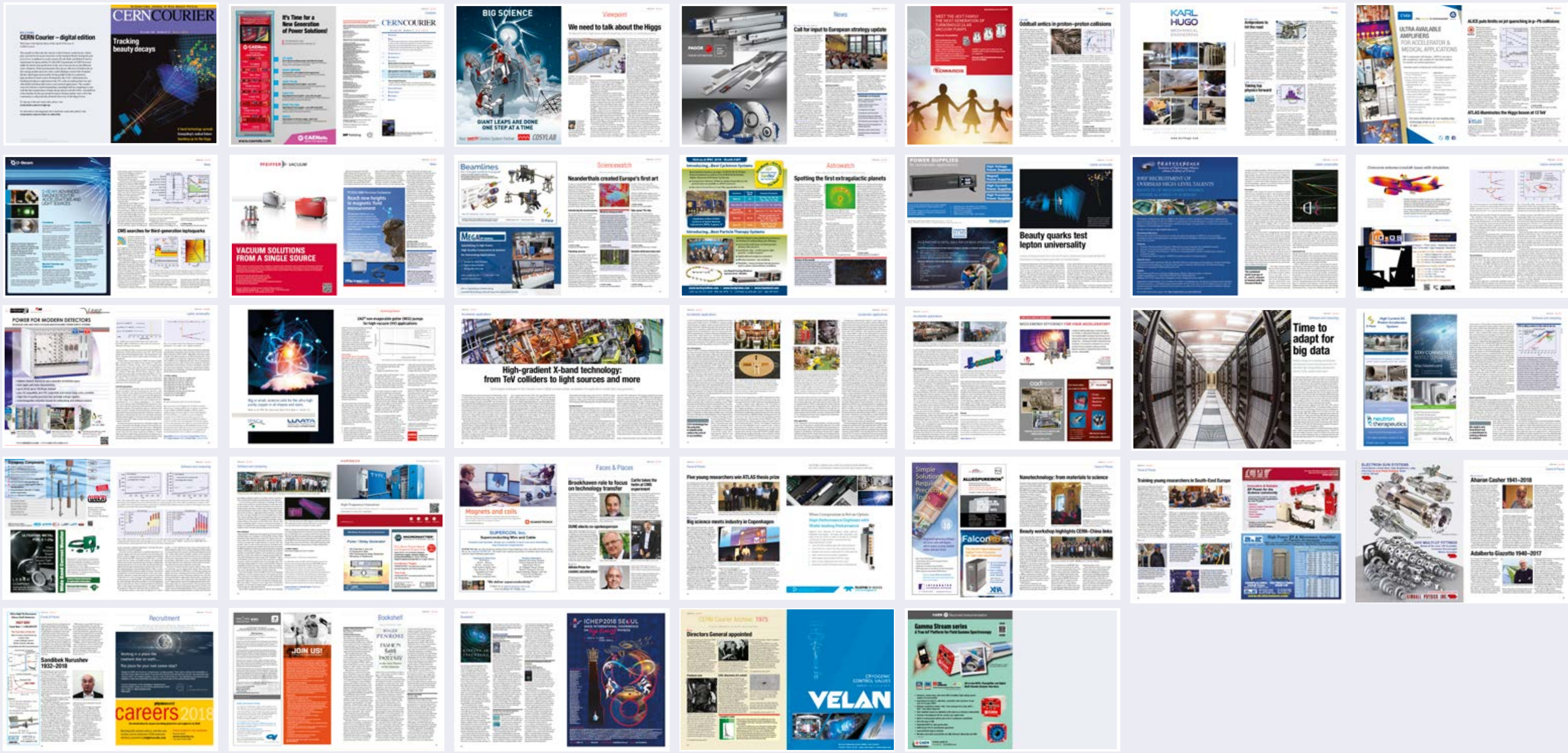
● Compiled from texts on pp111–112.

Compiler's note



Heads or tails? To the uninformed, ESO's sighting of a new comet on a photographic plate could just as well be the sighting of a new micro-organism in a Petri dish. The beauty, and the thrill, is in the eye of the beholder!

The April 1975 *CERN Courier* cover (left) poked fun at the relation between ideas and results in high-energy physics. A different view featured on p109. Eminent theorist V F "Vicki" Weisskopf, CERN Director General from 1961–65, was fond of a Columbus story – "The accelerator physicists and engineers are the ones who built the boat. The experimental physicists are the ones who set sail and discovered America. The theoreticians are the ones who stayed in Madrid and predicted the boat would land in India."



CERNCOURIER

Volume 58 Number 3 April 2018

Contents