

## WELCOME

# CERN Courier – digital edition

Welcome to the digital edition of the May 2017 issue of *CERN Courier*.

The first meeting at which the Large Hadron Collider (LHC) was officially discussed took place in March 1984, almost a quarter of a century before the first beams circulated in the machine. Following the outcome of the 2013 European Strategy for Particle Physics, CERN launched a Future Circular Collider (FCC) project to help assess what tool should come next after the LHC to continue its journey to the heart of matter. The FCC, which is among a handful of other high-energy colliders currently under consideration, envisages a 100 km-circumference tunnel in which three different collider modes could be realised: an  $e^+e^-$  collider that would improve by orders of magnitude the measurement precision on the Higgs boson and other Standard Model particles; an electron–proton collider that would probe the proton’s substructure with unmatchable precision; and a 100 TeV proton–proton collider with a discovery potential more than five times greater than the LHC. This month’s cover feature describes the enormous physics potential of such a facility, in particular its ability to measure in detail the properties of the Higgs boson. We also describe the history of dark matter, the search for which is another key goal of the LHC and future colliders, and describe how ESA’s Euclid probe will unearth the true nature of the “dark energy” that is driving the accelerating expansion of the universe. Sticking with the darkness theme, we interview theorist Erik Verlinde, who argues that dark matter is not real.

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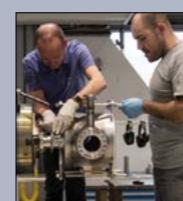
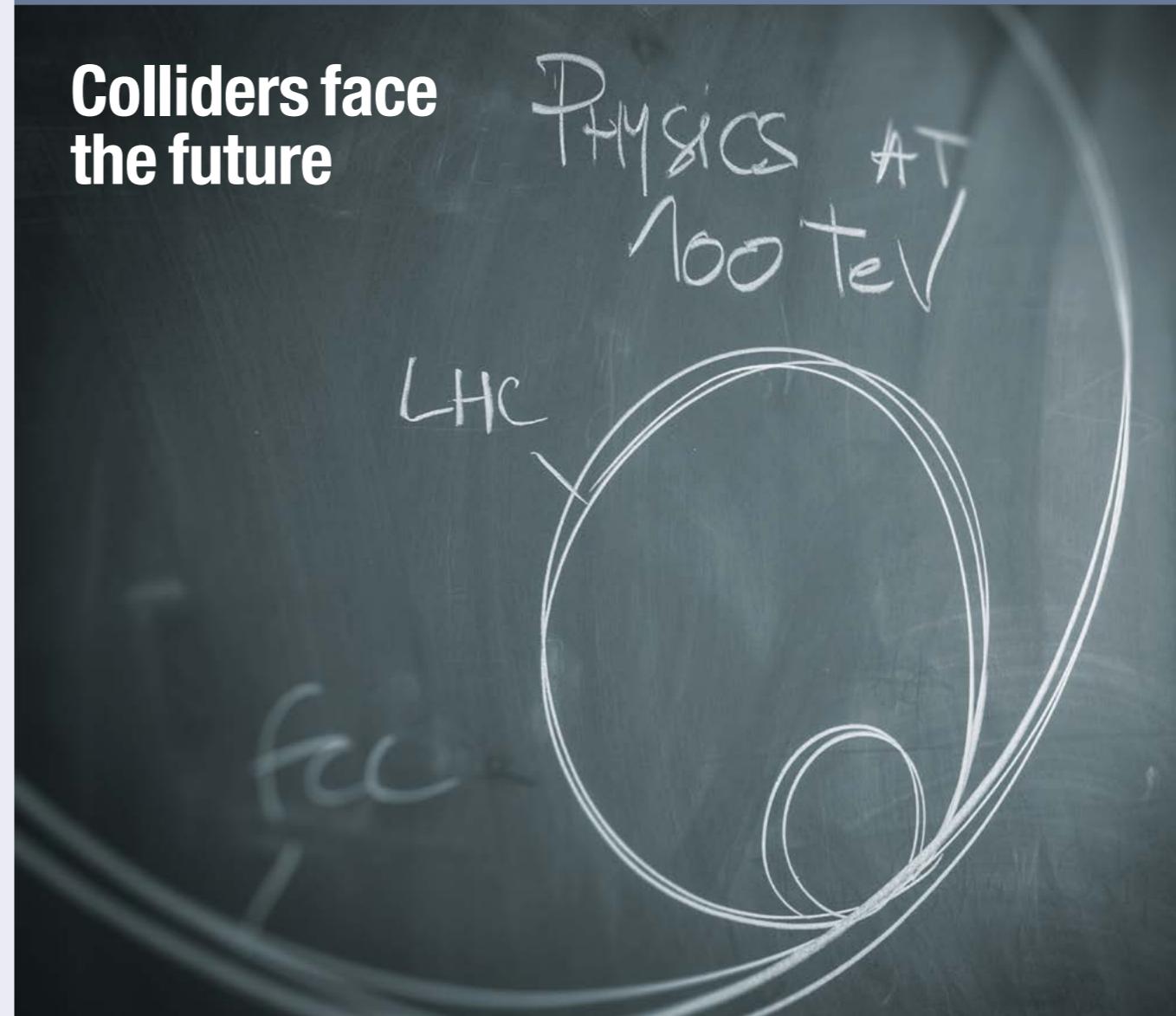
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## Colliders face the future



### CRAB KICKS

Crab cavities for HL-LHC pass high-voltage tests  
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### INTERVIEW

Erik Verlinde explains why dark matter might be an illusion  
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### DARK ENERGY

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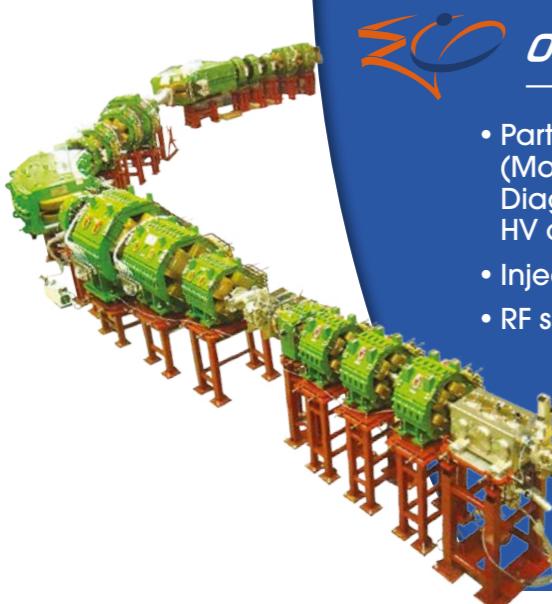


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# CERN COURIER

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

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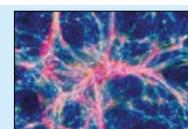
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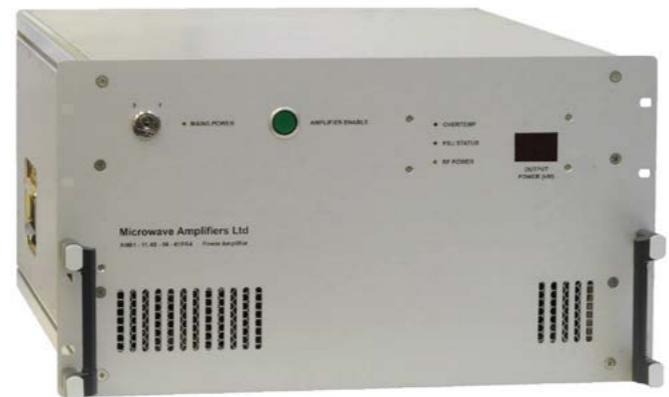


On the cover: CERN's Future Circular Collider (FCC) project. (Image credit: D Dominguez and M Chalmers.)



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## Viewpoint

### Birth of the high-energy network

The CERN Alumni Programme will offer unique networking opportunities for all its members.



S Bennett/CERN  
*A career networking event at CERN organised by the LHC experiment collaborations in 2016.*

By Laure Esteveny

With over 60 years of history and currently more than 13,000 users from all over the world, CERN clearly has great potential to bring together a varied alumni community. Today, CERN alumni are distributed around the world, pursuing their careers and passions across many fields including industry, economics, information technology, medicine and finance. Several have gone on to launch successful start-ups, some of them directly applying CERN-inspired technologies.

Setting up and nurturing this important network is a strategic objective for CERN management. Following 12 months of careful preparation, the new CERN Alumni Programme will be launched in June this year.

The new community, united by a shared pride in having contributed to CERN's scientific endeavours, will provide an opportunity for alumni to maintain links with the Organization. It will allow them to continue to share CERN's values and support its activities, and serve as a valuable resource for members of personnel in the transition to work outside the laboratory. Physicists, in particular, often consider CERN as a "prime environment" that comes just after academia. The prospect of having to leave CERN may be daunting, with no guarantee that one's professional future will offer a similar environment and possibilities. However, preliminary statistics on the CERN alumni community demonstrate that professional experience at CERN nurtures skills and talents that are highly sought after by employers and can aid the development of alumni careers in many different fields.

The CERN Alumni Programme has been purposely designed to be inclusive. Former users, associates,

students, fellows, staff, and any member of personnel who has held a contract of either employment or association with CERN, may join the alumni community simply by registering. Current members of personnel will also be able to register and interact with the alumni, as well as partner companies. The final objective is to establish a dynamic, long-lasting and high-energy network of engaged members.

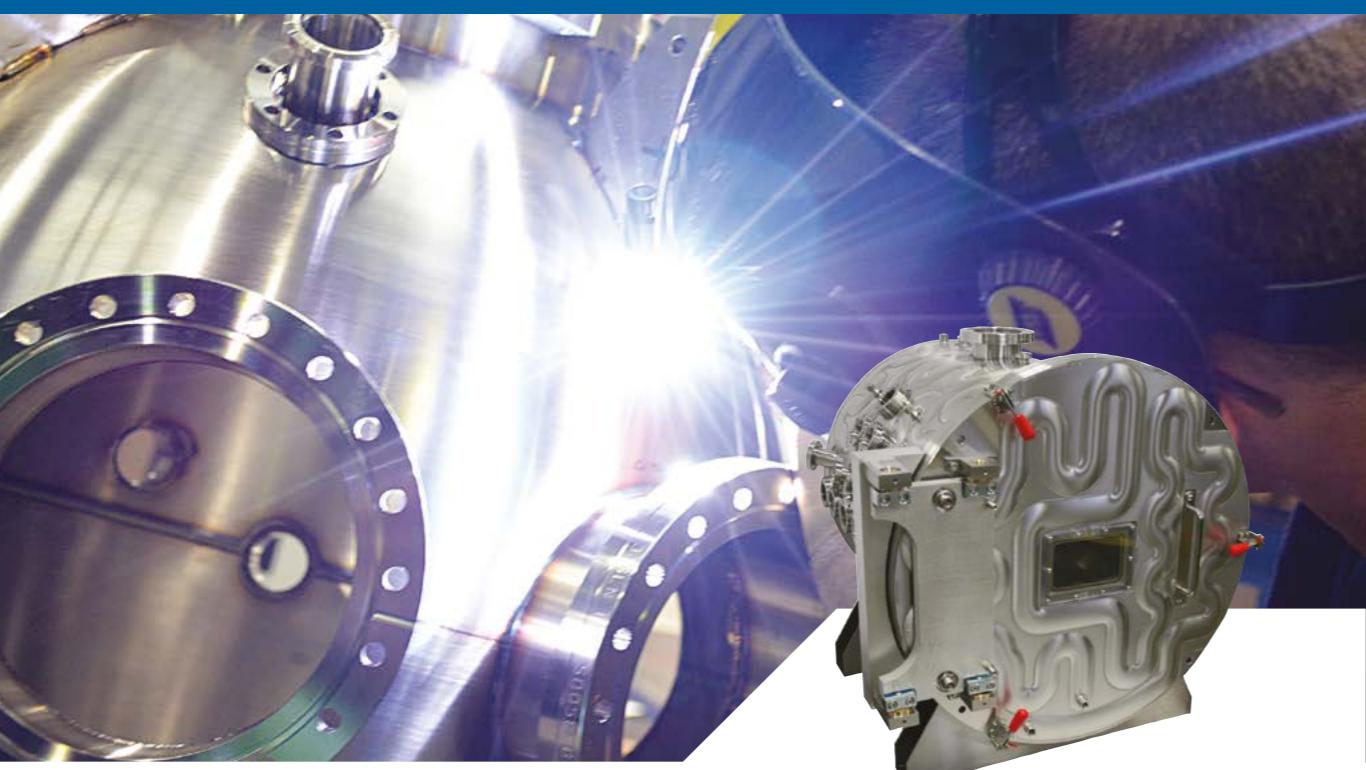
Since November 2016 it has been possible for previous and current members of personnel who wish to become members of the network to leave their contact details on the alumni webpage (see below), which CERN will use to contact them once the new web platform is up and running. Registered members of the CERN alumni community will have access to dedicated editorial content, opportunities to exchange experiences and establish contacts with other alumni, in addition to career development opportunities. The aim is to gather a large number of members, whether they are former colleagues still working in academia, have set up their own businesses, have moved into completely different professional environments, or have retired but wish to stay connected.

CERN alumni will themselves be actively involved in building the community, which will evolve with them. The advisory board of the new programme will include representatives from the community as well as members of CERN management. Alumni will be able to set up thematic groups within the community based on factors such as regional interests and scientific topics. A mobile app will help them to stay connected with news, events and networking activities that are published by the community.

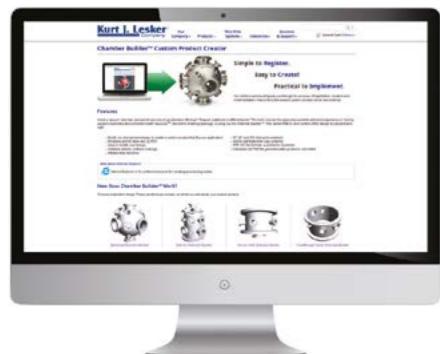
The CERN Alumni Programme kick-off event will be held on 2–3 February 2018. In addition to offering unique networking opportunities, it will be possible to visit the LHC and its experiments as well as experimental areas that are usually not accessible to the public. Inspiring seminars and several panel sessions will complete the programme. The event is designed to be a valuable experience for all different types of alumni, from young scientists who have recently left CERN to those with long-standing careers in different fields, and many others.

We are aware that it will be a challenge to reach all of our alumni spread across the planet over such a long period. If you are one of them, do not hesitate to leave your contact details at <https://alumni.cern/>. It is the best way to show your interest, join the new community and stay connected with CERN. We also invite you to get in touch with any questions by emailing [alumni.relations@cern.ch](mailto:alumni.relations@cern.ch). We will be very happy to welcome you back to CERN again!

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# News

## LHC NEWS

### LHC cold and preparing for beam

Following a longer than usual technical stop, which began in December last year to allow for the replacement of the CMS inner tracker, all eight sectors of the Large Hadron Collider (LHC) have been cooled to their operating temperature of 1.9 K. The machine is now being prepared for the return of proton beams in May.

During the extended year-end technical stop (EYETS), one full sector of the LHC – lying between the ATLAS and ALICE experiments – was warmed up to room temperature to replace one of its 15 m-long superconducting dipoles, which had exhibited abnormal behaviour on a few occasions during the 2016 physics run. The rest of the machine was maintained at 20 K. To make sure none of the LHC's precious liquid-helium coolant would be lost during the EYETS interventions, the machine was emptied and its 130-tonne supply was temporarily stored on the surface.

Following the successful replacement and reconnection of the dipole magnet, pre-cooling of the sector to 80 K started on 17 February using 1200 tonnes of liquid nitrogen carried by 60 thermally insulated trucks, and was completed by 4 March. The re-filling of the arcs with liquid helium started about one week later, with electrical quality-assurance tests taking place at the end of the month. Powering tests took place during April, with the machine check-out



A 360° photo of the LHC tunnel, in which the machine's proportions are distorted. M.Bricq/CERN

scheduled for mid-April and the start of commissioning with beam during the first week of May.

Several other changes were made during the EYETS, not only to the LHC but also to the injectors. The PS Booster (PSB) underwent a massive de-cabling campaign, which has paved the way for the installation of new equipment for the LHC Injector Upgrade (LIU) project in the coming years. In response to a vacuum leak that developed in the SPS internal beam dump in April last year, a new internal beam dump was designed and constructed in record time

and installed in the SPS. This will allow the SPS to reach its full performance again for the 2017 run, and in particular will lift the limit on the number of bunches for the LHC from 96 to 288 per SPS extraction.

With the LHC handed from the engineering department to the operations group on 14 April, the second phase of LHC Run 2 will soon be under way, with first collisions due approximately end of May.

## Sommaire en français

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## HIGH-LUMINOSITY LHC

### Crab cavities promise brighter collisions

As the Large Hadron Collider (LHC) gears up for its 2017 restart, teams in the background at CERN and around the world are making rapid progress towards a major LHC upgrade due to be operational from 2025. A significant milestone towards the High-Luminosity LHC (HL-LHC), which will boost the number of proton–proton collisions, was passed in late February with the first tests of a new accelerator structure called a crab cavity.

Increasing the luminosity of the LHC,

which is a measure of its collision rate, requires new magnets located on either side of the LHC detectors that squeeze the incoming proton beams into tighter bunches and force them to cross one another at a steeper angle. These upgraded inner-triplet quadrupoles for the HL-LHC, prototypes of which have recently been completed at CERN and in the US, have larger apertures than the present LHC magnets and are based on more advanced niobium-tin superconducting technology (*CERN Courier* March 2017 p23).

Crab cavities are essential to fully exploit the inner-triplet upgrade, since they allow the crossing angle of the proton beams to be compensated so as to maximise their overlap at the collision points. Constructed from high-purity niobium sheets, the HL-LHC crab cavities will operate at 2 K to reach

## News

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their nominal performance. Unlike the accelerating RF cavities currently used at the LHC, which accelerate protons in the direction of motion, the crab cavities give the bunches a time-dependent transverse kick in the plane perpendicular to their motion to improve "luminosity levelling".

So far, two superconducting crab cavities have been manufactured at CERN and RF tests at 2 K performed in a superfluid helium bath. The first cavity tests demonstrated a maximum transverse kick voltage exceeding 5 MV, surpassing the nominal operational voltage of 3.4 MV. This kick voltage corresponds to extremely high electric



First niobium crab cavity fabricated at CERN for the High-Luminosity LHC project.

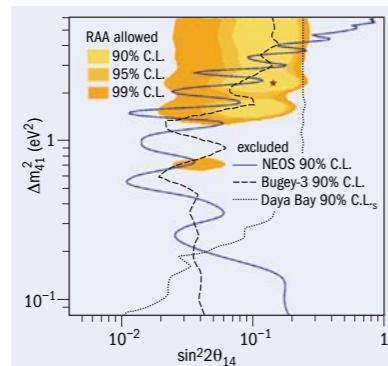
and magnetic fields on the cavity surfaces: 57 MV/m and 104 mT, respectively. By the end of 2017, the two crab cavities will have been inserted into a specially designed cryomodule that will be installed in the Super Proton Synchrotron (SPS) to undergo validation tests with proton beams. This will be the first time that a crab cavity has ever been used for manipulating proton beams, and a total of 16 cavities (eight near ATLAS and eight near CMS) will be required for the HL-LHC project.

## NEUTRINOS

**Sterile neutrinos in retreat**

An experiment in Korea designed to search for light sterile neutrinos has published its first results, further constraining the possible properties of such a particle. Even though the number of light neutrinos cannot exceed three, it is still possible to have additional neutrinos if they are "sterile". Such particles, which are right-handed singlets under the electromagnetic, strong and weak interactions, are predicted by extensions of the Standard Model and would reveal themselves by altering the rate of oscillation between the three standard neutrino flavours. An early hint for such a state came from observations of the mixing between electron and muon neutrinos by the LSND experiment, although more recent results from other experiments are so far inconclusive.

The NEOS detector is a Gd-loaded liquid scintillator located just 24 m from the core of the 2.8 GW Hanbit nuclear power plant in South Korea, which generates a high flux of antineutrinos. Based on precise measurements of an antineutrino energy



Exclusion curves for 3 + 1 neutrino oscillations in the  $\sin^2\theta_{14}$ – $\Delta m_{41}^2$  parameter space. The solid blue curve is based on the comparison with the Daya Bay spectrum, while the dashed grey curve is from Bugey-3, and the dotted curve from Daya Bay. The shaded area is the allowed region from the reactor antineutrino anomaly fit, and the star is its optimum point.

neutrino oscillations, the new results set stringent upper limits on the  $\theta_{14}$  mixing angle (see figure) of  $\sin^2\theta_{14}$  less than 0.1 for  $\Delta m_{41}^2$  ranging from 0.2–2.3 eV<sup>2</sup> at 90% confidence level. The results further improve the constraints to the LSND anomaly parameter space, say the team. With the NEOS experiment now completed, the team is discussing a further reactor neutrino programme using commercial reactors to be built in the near future in Korea.

## Further reading

NEOS Collaboration 2017 *Phys. Rev. Lett.* **118** 121802.

spectrum over an eight-month period, the NEOS team found no evidence for oscillations involving sterile neutrinos. On the other hand, the team recorded a small excess of antineutrinos above an energy of around 5 MeV that is consistent with anomalies seen at longer-baseline neutrino experiments.

With no strong evidence for "3 + 1"

## ANTIMATTER

**GBAR falls into place**

On 1 March, the first component of a new CERN experiment called GBAR (Gravitational Behaviour of Antihydrogen at Rest) was installed: a 1.2 m-long linear accelerator that will be used to generate positrons. Located in the Antiproton Decelerator (AD) hall, GBAR is the first of five experiments that will be connected to the new ELENA deceleration ring and it is specifically designed to measure the effect of gravity on antihydrogen atoms. The experiment will use antiprotons supplied by ELENA and positrons created by the linac



Installation of the GBAR linac in its shielding bunker.

to produce antihydrogen ions, which will be slowed almost to a standstill using lasers and then allowed to fall under gravity over a vertical distance of 20 cm.

Although antimatter is not expected to fall "up", detecting even the tiniest difference between the rate at which matter and antimatter fall would have profound implications for fundamental laws such as Einstein's equivalence principle. Two further experiments that are based at the AD, AEGIS and ALPHA, are also studying the effect of gravity on antimatter. First results on anti-ion production are expected next year, with gravity studies following later.

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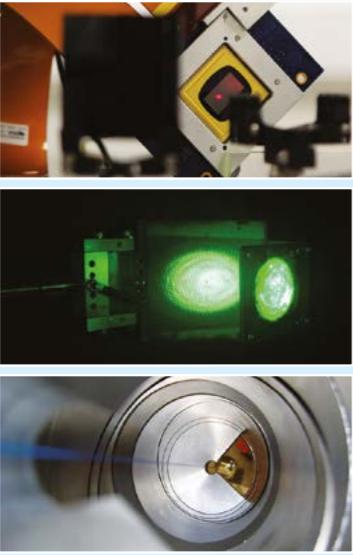
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### LHC EXPERIMENTS

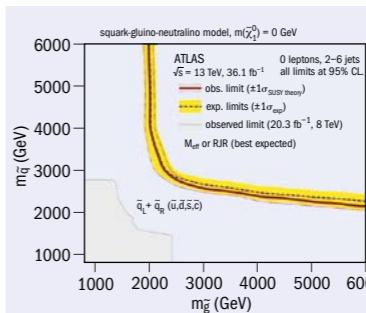
## ATLAS pushes SUSY beyond 2 TeV



The ATLAS experiment has released several new results in its search for supersymmetry (SUSY) using the full 13 TeV LHC data set from 2015 and 2016, obtaining sensitivity for certain new particles with masses exceeding 2 TeV.

SUSY is one of the most studied extensions of the Standard Model (SM) and, if realised in nature, it would introduce partners for all the SM particles. Under the assumption of R-parity conservation, SUSY particles would be pair-produced and the lightest SUSY particle (LSP) would be stable. The strongly produced partners of the gluon and quarks, the gluino and squarks, would decay to final states containing energetic jets, possibly leptons, and two LSPs. If the LSP is only weakly interacting, which would make it a dark-matter candidate, it would escape the detector unseen, resulting in a signature with missing transverse momentum.

A recent ATLAS analysis [1] searched for this signature, while a second [2] targets models where each gluino decays via the partner of the top quark (the "stop"), producing events with many jets originating from a b quark (b jets). Both analyses find consistency with SM expectations, excluding squarks and gluinos from the first two generations at 95% confidence level up to masses of 2 TeV (see figure). Pair-produced stops could decay to final states containing up to six jets, including two b jets, or through the emission of a Higgs or Z boson. Two dedicated ATLAS searches [3, 4] find no evidence for these



*Exclusion limits (95% C.L.) for a SUSY model with production of squarks and gluinos and subsequent decays to quarks and massless neutralinos. The dashed line and yellow band indicate the expected sensitivity and one standard-deviation range of the search, respectively, while the solid red line represents the exclusion based on the observed data yields. The x axis represents the mass of the gluino while the y axis is the mass of the squark.*

processes, excluding stop masses up to 950 GeV.

SUSY might alternatively be manifested in more complicated ways. R-parity violating (RPV) SUSY features an LSP that can decay and hence evade missing transverse momentum-based searches. Moreover, SUSY particles could be long-lived or metastable, leading to unconventional detector signatures. Two dedicated searches [5, 6] for the production of gluino pairs and stop pairs decaying via RPV couplings have recently been studied by ATLAS, both

looking for final states with multiple jets but little missing transverse momentum. In the absence of deviations from background predictions, strong exclusion limits are extracted that complement those of R-parity conserving scenarios.

The production of metastable SUSY particles could give rise to decay vertices that are separated by from the proton–proton collision point in a measurable way. An ATLAS search [7] based on a dedicated tracking and vertexing algorithm has now ruled out large regions of the parameter space of such models. A second search [8] exploited the new layer of the ATLAS pixel tracking detector to identify short track segments produced by particles decaying close to the LHC beam pipe, yielding sensitivity to non-prompt decays of SUSY charginos with lifetimes of the order of a nanosecond. The result constrains an important class of SUSY models where the dark-matter candidate is the partner of the W boson.

The ATLAS SUSY search programme with the new data set is in full swing, with many more signatures being investigated to close in on models of electroweak-scale supersymmetry.

#### Further reading

- [1] ATLAS Collab. 2017 ATLAS-CONF-2017-022.
- [2] ATLAS Collab. 2017 ATLAS-CONF-2017-021.
- [3] ATLAS Collab. 2017 ATLAS-CONF-2017-020.
- [4] ATLAS Collab. 2017 ATLAS-CONF-2017-019.
- [5] ATLAS Collab. 2017 ATLAS-CONF-2017-013.
- [6] ATLAS Collab. 2017 ATLAS-CONF-2017-025.
- [7] ATLAS Collab. 2017 ATLAS-CONF-2017-026.
- [8] ATLAS Collab. 2017 ATLAS-CONF-2017-017.

## CMS inches to the top of the Higgs-coupling mountain



The discovery of the Higgs boson in 2012, a fundamentally new type of scalar particle, has provided the particle-physics community with a new tool with which to search for new physics beyond the Standard Model (SM). Originally discovered via its decay into two photons or four leptons, the SM Higgs boson is also predicted to interact with fermions with coupling strengths proportional to the fermion masses. The top quark, being the heaviest elementary fermion known, has the largest coupling to

the Higgs boson. Precise measurements of such processes therefore provide a sensitive means to search for new physics.

The top-Higgs coupling is crucial for the production of Higgs bosons at the LHC, since the process with the largest production cross-section (gluon–gluon fusion) proceeds via a virtual top-quark loop. In this sense, Higgs production itself provides indirect evidence for the top-Higgs coupling. Direct experimental access to the top-Higgs coupling, on the other hand, comes from the study of the associated production of a Higgs boson and a top-quark pair. This production

mode, while proceeding at a rate about 100 times smaller than gluon fusion, provides a highly distinctive signature in the detector, which includes leptons and/or jets from the decay of the two top quarks.

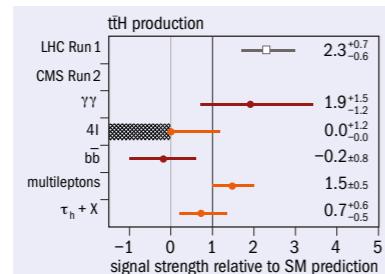
Combined ATLAS and CMS results on ttH production based on the LHC's Run 1 data set showed an intriguing excess: the measured rate was above the SM prediction with a statistical significance corresponding to  $2.3\sigma$ . With the increase of the LHC energy from 8 to 13 TeV for Run 2, the ttH production cross-section is expected to increase by a factor four – putting the ▶

**News****News**

ttH analyses in the crosshairs of the CMS collaboration in its search for new physics.

Compared to the first evidence for Higgs production in 2012, namely Higgs-boson decays into clean final states containing two photons or four leptons, the ttH process is much more rare, and the expected signal yields in these modes are just a few events. For this reason, searches for ttH production have been driven by the higher sensitivity achieved in Higgs decay modes with larger branching fractions, such as  $H \rightarrow bb$ ,  $H \rightarrow WW$ , and  $H \rightarrow \tau\tau$ . The search in the  $H \rightarrow bb$  final state is challenging because of the large background from the production of top-quark pairs in association with jets, and the results are currently limited by systematic and theoretical uncertainties.

A compromise between expected signal yield and background uncertainty can be obtained from final states containing leptons. Such analyses target Higgs decays



The top section summarises the ATLAS and CMS combined analysis of the Run 1 data, which exhibit a 2.3 standard-deviation excess above the SM prediction, while the lower section shows the latest CMS results from Run 2. Results that include the full 2016 data, presented for the first time in March, are indicated in orange.

hadronic  $\tau$ -lepton decays are studied separately.

The latest results of ttH searches at CMS (see figure) show that we are on the verge of measuring this crucial process with sufficient precision to confirm or disprove the previous observed excess. With a larger data set it should be possible to have clear evidence for ttH production by the end of Run 2.

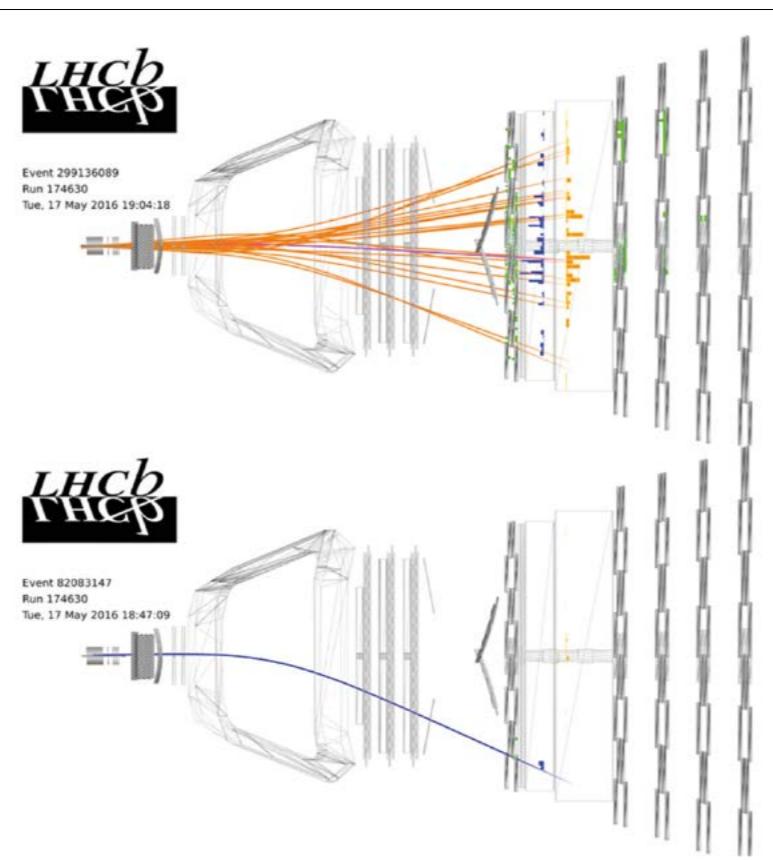
• Further reading

CMS Collaboration 2017 CMS-PAS-HIG-17-003.  
CMS Collaboration 2017 CMS-PAS-HIG-17-004.

## LHCb brings cosmic collisions down to Earth

In an effort to improve our understanding of cosmic rays, the LHCb collaboration has generated high-energy collisions between protons and helium nuclei similar to those that take place when cosmic rays strike the interstellar medium. Such collisions are expected to produce a certain number of antiprotons, and are currently one of the possible explanations for the small fraction of antiprotons (about one per 10,000 protons) observed in cosmic rays outside of the Earth's atmosphere. By measuring the antimatter component of cosmic rays, we can potentially unveil new high-energy phenomena, notably a possible contribution from the annihilation or decay of dark-matter particles.

In the last few years, space-borne detectors devoted to the study of cosmic rays have dramatically improved our knowledge of the antimatter component. Data from the Alpha Magnetic Spectrometer (AMS-02), which is attached to the International Space Station and operated from a control centre at CERN, published last year are currently the most precise and provide the antiproton over proton fraction up to an antiproton energy of 350 GeV (CERN Courier December 2016 p26). The interpretation of these data is currently



(Top) A fully reconstructed proton–helium collision event in the LHCb detector, with the particle identified as an antiproton shown in pink. (Bottom) An event with a single electron elastic scattering.

limited by poor knowledge of the antiproton production cross-sections, however, and no data are available so far on antiproton production in proton–helium collisions.

The LHCb's recently installed internal gas target "SMOG" (System for Measuring Overlap with Gas) provides the unique possibility to study fixed-target proton collisions at the unprecedented energy offered by the LHC, with the forward geometry of the LHCb detector well suited for this configuration. The SMOG device allows a tiny amount of a noble gas to be injected inside the LHC beam pipe near the LHCb vertex detector region. The gas pressure is less than a billionth of atmospheric pressure so as not to perturb LHC operations, but this is sufficient to observe hundreds of millions of beam–gas

collisions per hour. By operating SMOG with helium, LHCb physicists were able to mimic cosmic collisions between 6.5 TeV protons and at-rest helium nuclei – a configuration that closely matches the energy scale of the antiproton production observed by space-borne experiments. Data-taking was carried out during May 2016 and lasted just a few hours.

LHCb's advanced particle-identification capabilities were used to determine the yields of antiprotons, among other charged particles, in the momentum range 12–110 GeV. A novel method has been developed to precisely determine the amount of gas in the target: events are counted where a single electron elastically scattered off the beam is projected inside the detector acceptance. Owing to their distinct signature, these events could

be isolated from the much more abundant interactions with the helium nuclei. The cross-section for proton–electron elastic scattering is very well known and allows the density of atomic electrons to be computed.

The result for the antiproton production has been compared to the most popular cosmic-ray models describing soft hadronic collisions, revealing significant disagreements with their predictions. The accuracy of the LHCb measurement is below 10% for most of the accessible phase space, and is expected to contribute to the continuous progress in turning high-energy astroparticle physics into a high-precision science.

• Further reading

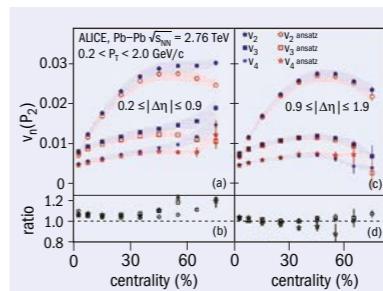
LHCb Collaboration LHCb-CONF-2017-002.

## ALICE reveals dominance of collective flow



The study of the anisotropic flow in heavy-ion collisions at the LHC, which measures the momentum anisotropy of the final-state particles, has been effective in characterising the extreme states of matter produced in such collisions. Much evidence of collective anisotropic flow and the production of a quark–gluon plasma (QGP) in heavy-ion collisions has already been reported. However, ALICE recently devised a new technique to test for the collective nature of the flow using measurements of differential transverse-momentum correlators,  $P_2$ . These quantities measure the degree of correlation between the momenta of produced particles and are used to probe the evolution of the QGP fireball produced in heavy-ion collisions. For specific dynamic processes, one can derive how the shape and strength of momentum correlations is related to those of particle-number correlations.

Collective-flow models posit that the enormous energy density achieved in heavy-ion collisions generates large pressure gradients that drive the expansion of the QGP fireball. In non-central collisions, the nuclear overlap region is anisotropic and approximately almond shaped, with the longer axis oriented perpendicular to the reaction plane



Flow coefficients for two rapidity ranges plotted as a function of centrality (top), with ratios of the coefficients from experimental data and corresponding flow ansatz values (bottom).

scaling relation between  $v_n[P_2]$  coefficients of momentum correlations and the regular flow coefficients  $v_n$ . The presence of other sources of particle correlation, generically called non-flow, are expected to break this simple scaling, however.

ALICE has now found that the scaling relation between  $v_n[P_2]$  and regular  $v_n$  coefficients is well verified for particle pairs with a minimum separation of 0.9 unit of rapidity (figure, right panel), but breaks down for shorter intervals (left panel) where non-flow effects such as resonance decays and jet fragmentation play an important role. The observed scaling at rapidity greater than 0.9 thus confirms that collective flow determined by the geometry of the collision system dominates the correlation dynamics in heavy-ion collisions at the LHC. ALICE also observed, in the five per cent most central collisions, that the third-order coefficients  $v_3[P_2]$  are larger than the second-order coefficients,  $v_2[P_2]$ . Such coefficient hierarchy is also observed in particle-number correlations but only for the two per cent most central collisions. The observable  $P_2$  thus provides better sensitivity to initial state fluctuations that engender finite third-harmonic values.

• Further reading

ALICE Collaboration 2017 arXiv:1702.02665.

*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](mailto:cern.courier@cern.ch).

# Spanish Science Industry at IPAC 2017

Spanish industrial companies are relevant partners in developing, building and maintaining scientific facilities, components and instruments, specially in the field of accelerators and matter sciences. High precision manufacturing, superconductive magnets, special power supplies, detectors, mechatronic systems, vacuum and cryogenic chambers and structures, highly specialized engineering services, encoders and synchronizing equipment...are just a few of their capabilities that will be presented at IPAC 2017 in Copenhagen.

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# Sciencewatch

COMPILED BY JOHN SWAIN, NORTHEASTERN UNIVERSITY

## Data-storage record for DNA

Until recently, attempts to store information in DNA strands have only been able to reach a fraction of the theoretical maximum storage capacity. A new method developed by Yaniv Erlich and Dina Zielinski of the New York Genome Center goes much further towards this goal. Based on a class of computer code called a fountain, the researchers were able to approach the so-called Shannon capacity while protecting against data corruption. As a result, they were able to store  $2.14 \times 10^6$  bytes of information (including a full computer operating system, a short French film from 1895, a \$50 Amazon gift card,



The new study improves the amount of data stored in DNA by a factor 10.

a Pioneer plaque and a 1948 work by Claude Shannon, after compression) in DNA oligonucleotides, which they could then perfectly retrieve using a process that allows  $2.18 \times 10^{15}$  retrievals. The results indicate that perfect data storage and retrieval is feasible at a density of 215 petabytes per gram of DNA, improving on previous work by an order of magnitude.

● Further reading  
Y Erlich and D Zielinski 2017 *Science* **355** 950.

### Supersolid firms up

A supersolid is a bizarre quantum state that is rigid like a solid, yet can flow like a zero-viscosity liquid (a superfluid). After many years of theoretical arguments as to whether this sort of material could even exist, two groups have now reported making it. Jung-Ru Li and colleagues of MIT started with sodium atoms configured in a Bose-Einstein condensate such that lasers could nudge them to line up spatially as if they were in a crystal. Julian Léonard and colleagues of ETH Zürich also began with an atomic superfluid, but placed it in an optical cavity and excited the atoms with a laser causing them to emit photons into the cavity and thus create a standing wave that guides the atoms into orderly positions. The two studies open up a new field of investigation in which many interesting questions, even including whether or not supersolids are in thermodynamic equilibrium, remain open.

● Further reading  
J Léonard et al. 2017 *Nature* **543** 87.  
J-R Li et al. 2017 *Nature* **543** 91.

### Helium joins chemistry

Long thought to be chemically inert, helium has now been coaxed into forming a stable compound. Artem Oganov and colleagues of Stony Brook University in New York put thin pieces of sodium together with helium gas under pressures up to 155 GPa and found that at pressures above 113 GPa the

### Fluorescent frogs

Fluorescence is rare in land animals, being largely limited to parrots and marine turtles. Now, for the first time, it has been found in a frog. Carlos Taboada of CONICET in Buenos Aires and colleagues studied South American polka-dot tree frogs (*Hypsiboas punctatus*) collected near Santa Fe in Argentina. The colours of these frogs are normally a combination of muted greens, yellows and reds, but in dim light and UV illumination they glow bright blue and green. This is genuine fluorescence, not the more common bioluminescence in which organisms make their own light. The fluorescent molecules are unlike those in any other animals, being derived from dihydroisoquinoline. In twilight or night-time conditions, the fluorescence contributes 18–29% of the total emerging light, enhancing a creature's visibility, particularly for amphibians, but the reasons for the fluorescence are still not known.

● Further reading  
CTaboada et al. 2017 *PNAS* doi:10.1073/pnas.1701053114.



Meet the fluorescing South American polka-dot tree frog. (Image credit: C Taboada and J Faivovich.)

two elements formed a compound ( $\text{Na}_2\text{He}$ ). The compound, which is expected to be stable up to at least 1000 GPa, has a crystal structure made of cubes of eight sodium atoms, half of them filled with helium and the rest filled with an electron pair that binds the sodium atoms together.

● Further reading  
XDong et al. 2017 *Nature Chemistry* doi:10.1038/nchem.2716.

### Tools for bees

Tool use was originally thought to be uniquely human, although it has since been reported in primates, marine mammals and birds. Now, Olli Loukola and colleagues of Queen Mary University in London have found that bees also use tools. The team trained bees to know a "correct" location for a small ball, after which the bees were able to move a ball to the correct location to obtain a sucrose-solution reward. The bees learnt better from watching a live or model demonstrator than from a "ghost demonstrator" in the form of a magnet moving the ball, the results showed. The creatures also knew that in cases where more than one ball was present they had to move the closest one, even if it was a different colour, indicating an unprecedented neural flexibility. Apparently, novel behaviour in simple animals can emerge quickly in response to environmental pressures.

● Further reading  
OLoukola et al. 2017 *Science* **355** 833.

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# Astrowatch

COMPILED BY MARC TÜRLER, ISDC AND OBSERVATORY OF THE UNIVERSITY OF GENEVA, AND CHIPP, UNIVERSITY OF ZURICH

## Dark-matter surprise in early universe

New observations using ESO's Very Large Telescope (VLT) in Chile indicate that massive, star-forming galaxies in the early universe were dominated by normal, baryonic matter. This is in stark contrast to present-day galaxies, where the effects of dark matter on the rotational velocity of spiral galaxies seem to be much greater. The surprising result, published in *Nature* by an international team of astronomers led by Reinhard Genzel at the Max Planck Institute for Extraterrestrial Physics in Germany, suggests that dark matter was less influential in the early universe than it is today.

Whereas normal matter in the cosmos can be viewed as brightly shining stars, glowing gas and clouds of dust, dark matter does not emit, absorb or reflect light. This elusive, transparent matter can only be observed via its gravitational effects, one of which is a higher speed of rotation in the outer parts of spiral galaxies. The disc of a spiral galaxy rotates with a velocity of hundreds of kilometres per second, making a full revolution in a period of hundreds of millions of years. If a galaxy's mass consisted entirely of normal matter, the sparser outer regions should rotate more slowly than the dense regions at the centre. But observations of nearby spiral galaxies show that their inner and outer parts actually rotate at approximately the same speed.

It is widely accepted that the observed "flat rotation curves" indicate that spiral galaxies contain large amounts of non-luminous matter in a halo surrounding the galactic disc. This traditional view is based on observations of numerous galaxies in the



Schematic representation of rotating disc galaxies in the local (left) and the distant, early universe (right). The effect of dark matter (shown in red) is to increase the rotation speed of the outer regions of local galaxies.

local universe, but is now challenged by the latest observations of galaxies in the distant universe. The rotation curve of six massive, star-forming galaxies at the peak of galaxy formation, 10 billion years ago, was measured with the KMOS and SINFONI instruments on the VLT, and the results are intriguing. Unlike local spiral galaxies, the outer regions of these distant galaxies seem to be rotating more slowly than regions closer to the core – suggesting they contain less dark matter than expected. The same decreasing velocity trend away from the centres of the galaxies is also found in a composite rotation curve that combines data from around 100 other distant galaxies, which have too weak a signal for an individual analysis.

Genzel and collaborators identify two probable causes for the unexpected result. Besides a stronger dominance of normal matter with the dark matter playing a much smaller role, they also suggest that early

disc galaxies were much more turbulent than the spiral galaxies we see in our cosmic neighbourhood. Both effects seem to become more marked as astronomers look further back in time into the early universe. This suggests that three to four billion years after the Big Bang, the gas in galaxies had already efficiently condensed into flat, rotating discs, while the dark-matter halos surrounding them were much larger and more spread out. Apparently it took billions of years longer for dark matter to condense as well, so its dominating effect is only seen on the rotation velocities of galaxy discs today.

This explanation is consistent with observations showing that early galaxies were much more gas-rich and compact than today's galaxies. Embedded in a wider dark-matter halo, their rotation curves would be only weakly influenced by its gravity. It would be therefore interesting to explore whether the suggestion of a slow condensation of dark-matter halos could help shed light on this mysterious component of the universe.

- **Further reading**  
R Genzel et al. 2017 *Nature* **543** 397.

### Editor's note

After 13 years as the *Courier's* Astrowatch contributor, astronomer Marc Türler is moving to pastures new. We thank him for his numerous lively columns keeping readers up to date with the latest astro results.

### Picture of the month

Thirty years ago, a massive stellar explosion sent shock waves not only through space but also through the astronomical community. Detected on 23 February 1987 in the Large Magellanic Cloud – a satellite galaxy of the Milky Way – SN 1987A was the nearest supernova explosion observed in hundreds of years. Since its launch in 1990, the Hubble Space Telescope has observed the expanding dust cloud of SN 1987A several times to give astronomers a better understanding of these cosmic explosions. Its latest image, shown here, was taken earlier this year to celebrate the 30th anniversary of the supernova. Supernova 1987A is visible in the centre of the image amid a backdrop of stars and surrounded by gaseous clouds. The bright ring around the remains of the exploded star is about one light-year across and was probably ejected about 20,000 years before the star exploded. The origin of the two fainter rings, which extend like mirror images in an hourglass-shaped structure, is still not fully understood.





A new Large Research Infrastructure based on a linac with unprecedented reliability requirements



Since 1998 SCK•CEN is developing the MYRRHA project as an **accelerator driven system (ADS)** based on the lead-bismuth eutectic (LBE) as a coolant of the reactor and a material for its spallation target. MYRRHA is a flexible fast-spectrum pool-type research irradiation facility, also serving since the FP5 EURATOM framework as the backbone of the **Partitioning & Transmutation (P&T) strategy** of the European Commission concerning the ADS development in the third pillar of this strategy.

MYRRHA is proposed to the international community of nuclear energy and nuclear physics as a pan-European large research infrastructure in ESFRI to serve as a multipurpose fast spectrum irradiation facility for various fields of research.

The subcritical core of the MYRRHA reactor ( $\sim 100 \text{ MW}_{\text{th}}$ ) has to be driven by a **600 MeV proton beam** with a maximum **intensity of 4 mA**. The ADS application requires this beam to be delivered in a continuous regime — the resulting beam power of 2.4 MW classifies the driver machine as a High Power Proton Accelerator.

Already in the early design phase of MYRRHA the choice for linac has been endorsed, motivated to a large extent by the **unprecedented reliability requirements**.

The design of the MYRRHA linac has been conducted through an intense European

collaborative effort and supported by several consecutive Euratom FP's. Today the design effort is pursued under the H2020 MYRTE project complemented by several bilateral collaboration agreements.

The MYRRHA linac consists of 2 fundamental entities: (i) the injector and (ii) the main linac. The injector is fully normal conducting and brings the proton beam from the source through a 4-rod RFQ followed by a series of CH-type multigap cavities to 17 MeV.

A MEBT line matches the beam into the main linac, which is fully superconducting and operated at 2K.

**2 families of spoke cavities** prepare the beam for final acceleration in a sequence of 5-cell elliptical cavities. The 600 MeV proton beam is then transported through an achromatic line for vertical injection from above into the reactor. A beam window centered in the subcritical core closes the line.

**A specific requirement for ADS application** is the high level of the proton beam reliability, in other words the absence of unwanted beam trips. In the case of MYRRHA it is defined as follows: during a 3-months operational period the number of beam trips longer than 3s should be limited to 10. Shorter beam trips, on the other hand, are tolerated in large numbers. It has been

acknowledged from the early design stage that such a level of availability/reliability clearly requires a coherent approach to all accelerator components, but also that it compels to implement a global fault tolerant concept.

This has since been confirmed by extensive reliability modeling. The final design of the linac introduces the possibility of fault tolerance at the level of the superconducting cavities through conservative nominal conditions on beam dynamics and on cavity set points.

A similar fault tolerant concept is applied in the solid state RF amplifiers, which may therefore continue feeding the accelerating cavities even in case of failing components. However, such a scheme, based on redundancy from modularity, may not be applied in the injector. Fault tolerance is then recovered by a mere duplication of the injector: 1 active, 1 hot standby.

**The phased approach of MYRRHA** will primarily concentrate on its linac limited to 100 MeV (first spoke family), albeit with 1 injector only. This installation will be a relevantly sized test platform of various fault tolerance mechanisms, and thereby it will allow for a thorough investigation and extrapolation of the realistic capabilities of the full size 600 MeV linac.



[www.sckcen.be/MYRRHA](http://www.sckcen.be/MYRRHA)



# Euclid to pinpoint nature of dark energy

Due for launch in 2020, the European Space Agency's Euclid probe will use its unprecedented sensitivity and reach to identify what is causing the expansion of the universe to accelerate.

The accelerating expansion of the universe, first realised 20 years ago, has been confirmed by numerous observations. Remarkably, whatever the source of the acceleration, it is the primary driver of the dynamical evolution of the universe in the present epoch. That we are unable to know the nature of this so-called dark energy is one of the most important puzzles in modern fundamental physics. Whether due to a cosmological constant, a new dynamical field, a deviation from general relativity on cosmological scales, or something else, dark energy has triggered numerous theoretical models and experimental programmes. Physicists and astronomers are convinced that pinning down the nature of this mysterious component of the universe will lead to a revolution in physics.

Based on the current lambda-cold-dark-matter ( $\Lambda$ CDM) model of cosmology – which has only two ingredients: general relativity with a nonzero cosmological constant and cold dark matter – we identify at this time three dominant components of the universe: normal baryonic matter, which makes up only 5% of the total energy density; dark matter (27%); and dark energy (68%). This model is extremely successful in fitting observations, such as the Planck mission's measurements of the cosmic microwave background, but it gives no clues about the nature of the dark-matter or dark-energy components. It should also be noted that the assumption of a nonzero cosmological constant, implying a nonzero vacuum energy density, leads to what has been called the worst prediction ever made in physics: its value as measured by astronomers falls short of what is predicted by the Standard Model for particle physics by well over 100 orders of magnitude.

Depending on what form it takes, dark energy changes the dynamical evolution during the expansion history of the universe as predicted by cosmological models. Specifically, dark energy modifies the expansion rate as well as the processes by which cosmic structures form. Whether the acceleration is produced by a new scalar field or by modified laws of gravity will impact differently on these observables, and the two effects can be



An artist view based on industry drawings of the Euclid spacecraft showing the large sunshield covered by solar cells and the telescope baffle on the payload module containing the cold parts of the instruments. Also visible is the K-band antenna to transmit the large amount of data from the second Earth–Sun Lagrangian point, located 1.5 million kilometres from Earth. The spacecraft measures approximately 4.5 m tall and will have a launch mass of around 2100 kg. (Image credit: ESA/C Carreau.)

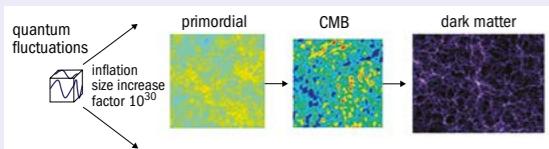
coupled using several complementary cosmological probes. Type Ia supernovae and baryon acoustic oscillations (BAO) are very good probes of the expansion rate, for instance, while gravitational lensing and peculiar velocities of galaxies (as revealed by their redshift) are very good probes of gravity and the growth rate of structures (see panel overleaf). It is only by combining several complementary probes that the source of the acceleration of the universe can be understood. The changes are extremely small and are currently undetectable at the level of individual galaxies, but by observing many galaxies and treating them statistically it is possible to accurately track the evolution and therefore get a handle on what dark energy physically is. This demands new observing facilities capable of both measuring individual galaxies with high precision and surveying large regions of the sky to cover all cosmological scales.

## Euclid science parameters

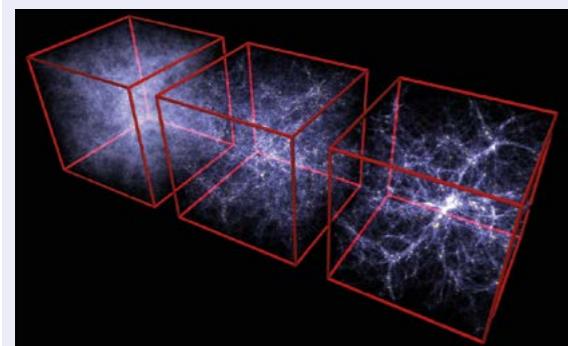
Euclid is a new space-borne telescope under development by the European Space Agency (ESA). It is a medium-class mission ▶

## Dark energy

### The geometry of the universe



The evolution of structure is seeded by quantum fluctuations in the very early universe, which were amplified by inflation. These seeds grew to create the cosmic microwave background (CMB) anisotropies after approximately 100,000 years and eventually the dark-matter distribution of today. In the same way that supernovae provide a standard candle for astronomical observations, periodic fluctuations in the density of the visible matter called baryon acoustic oscillations (BAO) provide a standard cosmological length scale that can be used to understand the impact of dark energy. By comparing the distance of a supernova or structure with its measured redshift, the geometry of the universe can be obtained.



Hydrodynamical cosmological simulations of a  $\Lambda$ CDM universe at three different epochs (left-to-right above), corresponding to redshift  $z=6$ ,  $z=2$  and our present epoch. Each white point represents the concentration of dark matter, gas and stars, the brightest regions being the densest. The simulation shows the growth rate of structure and the formation of galaxies, clusters of galaxies, filaments and large-scale structures over cosmic time. Euclid uses the large-scale structures made out of matter and dark matter as a standard yardstick: starting from the CMB, we assume that the typical scale of structures (or the peak in the spatial power spectrum) increases proportionally with the expansion of the universe. Euclid will determine the typical scale as a function of redshift by analysing power spectra at several redshifts from the statistical analysis of the dark-matter structures (using the weak lensing probe) or the ordinary matter structures based on the spectroscopic redshifts from the BAO probe. The structures will evolve with redshift also due to the properties of gravity. Information on the growth of structure at different scales in addition to different redshifts is needed to discriminate between models of dark energy and modified gravity. (Image credit: MPA Garching/Millennium.)

of ESA's Cosmic Vision programme and was selected in October 2011 as the first-priority cosmology mission of the next decade. Euclid will be launched at the end of 2020 and will measure the

20

accelerating expansion of our universe from the time it kicked in around 10 billion years ago to our present epoch, using four cosmological probes that can explore both dark-energy and modified-gravity models. It will capture a 3D picture of the distribution of the dark and baryonic matter from which the acceleration will be measured to per-cent-level accuracy, and measure possible variations in the acceleration to 10% accuracy, improving our present knowledge of these parameters by a factor 20–60. Euclid will observe the dynamical evolution of the universe and the formation of its cosmic structures over a sky area covering more than 30% of the celestial sphere, corresponding to about five per cent of the volume of the observable universe.

The dark-matter distribution will be probed via weak gravitational-lensing effects on galaxies. Gravitational lensing by foreground objects slightly modifies the shape of distant background galaxies, producing a distortion that directly reveals the distribution of dark matter (see panel overleaf). The way such lensing changes as a function of look-back time, due to the continuing growth of cosmic structure from dark matter, strongly depends on the accelerating expansion of the universe and turns out to be a clear signature of the amount and nature of dark energy. Spectroscopic measurements, meanwhile, will enable us to determine tiny local deviations of the redshift of galaxies from their expected value derived from the general cosmic expansion alone (see image p24). These deviations are signatures of peculiar velocities of galaxies produced by the local gravitational fields of surrounding massive structures, and therefore represent a unique test of gravity. Spectroscopy will also reveal the 3D clustering properties of galaxies, in particular baryon acoustic oscillations.

Together, weak-lensing and spectroscopy data will reveal signatures of the physical processes responsible for the expansion and the hierarchical formation of structures and galaxies in the presence of dark energy. A cosmological constant, a new dark-energy component or deviations to general relativity will produce different signatures. Since these differences are expected to be very small, however, the Euclid mission is extremely demanding scientifically and also represents considerable technical, observational and data-processing challenges.

By further analysing the Euclid data in terms of power spectra of galaxies and dark matter and a description of massive nonlinear structures like clusters of galaxies, Euclid can address cosmological questions beyond the accelerating expansion. Indeed, we will be able to address any topic related to power spectra or non-Gaussian properties of galaxies and dark-matter distributions. The relationship between the light- and dark-matter distributions of galaxies, for instance, can be derived by comparing the galaxy power spectrum as derived from spectroscopy with the dark-matter power spectrum as derived from gravitational lensing. The physics of inflation can then be explored by combining the non-Gaussian features observed in the dark-matter distribution in Euclid data with the Planck data. Likewise, since Euclid will map the dark-matter distribution with unprecedented accuracy, it will be sensitive to subtle features produced by neutrinos and thereby help to constrain the sum of the neutrino masses. On these and other topics, Euclid will provide important information to constrain models.

The definition of Euclid's science cases, the development of ▶

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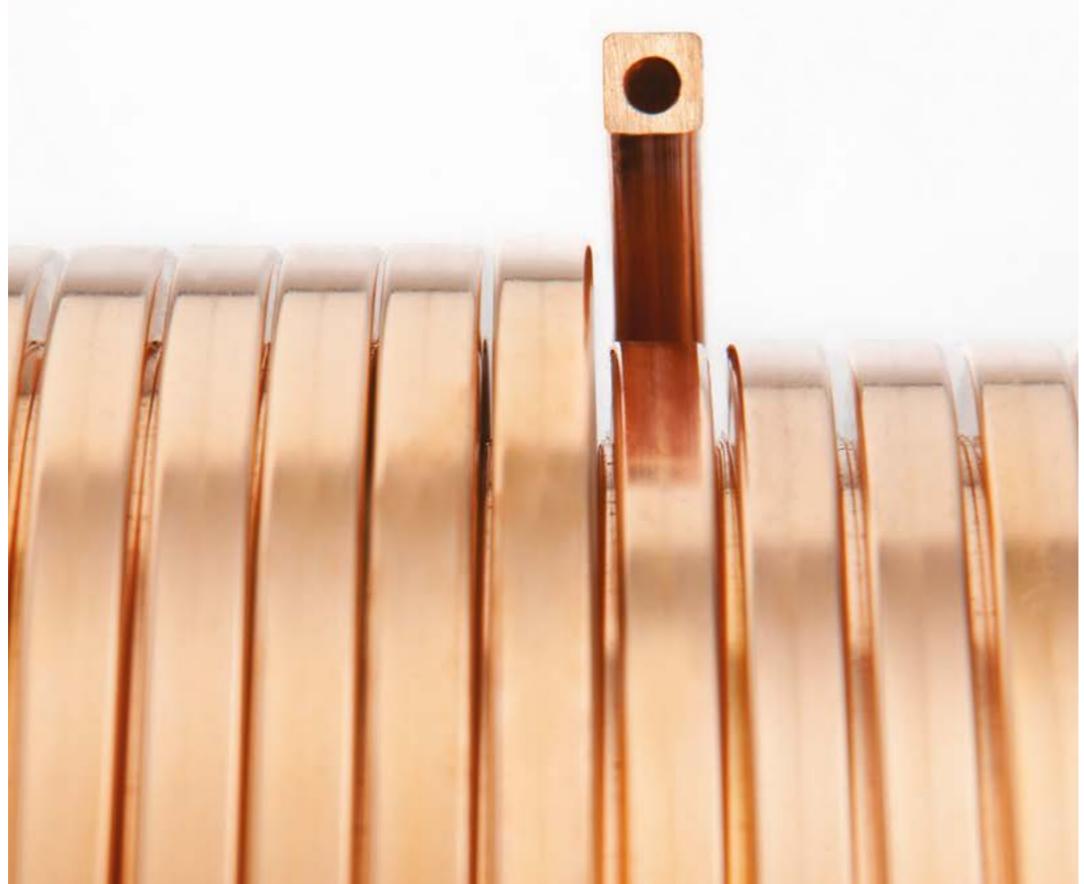
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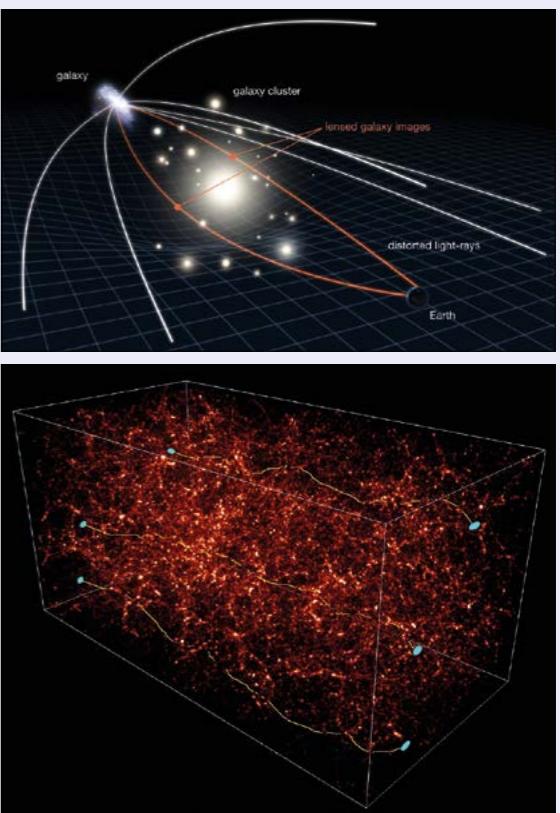
the scientific instruments and the processing and exploitation of the data are under the responsibility of the Euclid Consortium (EC) and carried out in collaboration with ESA. The EC brings together about 1500 scientists and engineers in theoretical physics, particle physics, astrophysics and space astronomy from around 200 laboratories in 14 European countries, Canada and the US. Euclid's science objectives translate into stringent performance requirements. Mathematical models and detailed complete simulations of the mission were used to derive the full set of requirements for the spacecraft pointing and stability, the telescope, scientific instruments, data-processing algorithms, the sky survey and the system calibrations. Euclid's performance requirements can be broadly grouped into three categories: image quality, radiometric and spectroscopic performance. The spectroscopic performance in particular puts stringent demands on the ground-processing algorithms and demands a high level of control over cleanliness during assembly and launch.

### Dark-energy payload

The Euclid satellite consists of a service module (SVM) and a payload module (PLM), developed by ESA's industrial contractors Thales Alenia Space of Turin and Airbus Defence and Space of Toulouse, respectively. The two modules are substantially thermally and structurally decoupled to ensure that the extremely rigid and cold (around 130 K) optical bench located in the PLM is not disturbed by the warmer (290 K±20 K) and more flexible SVM. The SVM comprises all the conventional spacecraft subsystems and also hosts the instrument's warm electronics units. The Euclid image-quality requirements demand very precise pointing and minimal "jitter", while the survey requirements call for fast and accurate movements of the satellite from one field to another. The attitude and orbit control system consists of several sensors to provide sub-arc-second stability during an exposure time, and cold gas thrusters with micronewton resolution are used to actuate the fine pointing. Three star trackers provide the absolute inertial attitude accuracy. Since the trackers are mounted on the SVM, which is separate from the telescope structure and thus subject to thermo-elastic deformation, the fine guidance system is located on the same focal plane of the telescope and endowed with absolute pointing capabilities based on a reference star catalogue.

The PLM is designed to provide an extremely stable detection system enabling the sharpest possible images of the sky. The size of the point spread function (PSF), which is the image of a point source such as an unresolved star, closely resembles the Airy disc, the theoretical limit of the optical system. The PSF of Euclid images is comparable to those of the Hubble space telescope's, considering Euclid's smaller primary mirror, and is more than three times smaller compared with what can be achieved by the best ground-based survey telescopes under optimum viewing conditions. The telescope is composed of a 1.2 m-diameter three-mirror "anastigmatic Korsch" arrangement that feeds two instruments: a wide-field visible imager (VIS) for the shape measurement of galaxies, and a near-infrared spectrometer and photometer (NISP) for their spectroscopic and photometric redshift measurements. An important PLM design driver is to maintain a high and stable image quality over a large field of view. Building on the heritage of previous European high-stability telescopes such as Gaia,

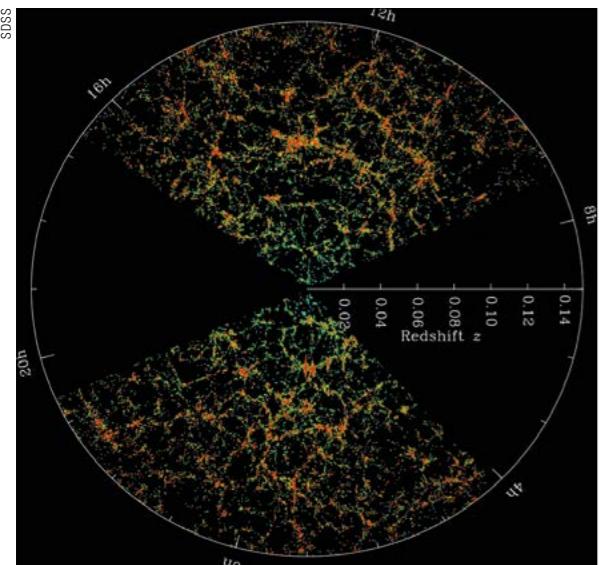
### Tracking cosmic structure



Gravitational-lensing effects produced by cosmic structures on distant galaxies (top; image credit: NASA/ESA & Calçada). Numerical simulations (above) show the distribution of dark matter (filaments and clumps with brightness proportional to their mass density) over a line of sight of one billion light-years. The yellow lines show how light beams emitted by distant galaxies are deflected by mass concentrations located along the line of sight. Each deflection slightly modifies the original shape of the lensed galaxies, increasing their original intrinsic ellipticity by a small amount. Since all distant galaxies are lensed, all galaxies eventually show a coherent ellipticity pattern projected on the sky that directly reveals the projected distribution of dark matter and its power spectrum. The 3D distribution of dark matter can then be reconstructed by slicing the universe into redshift bins and recovering the ellipticity pattern at each redshift. The growth rate of cosmic structures derived from this inversion process strongly depends on the nature of dark energy and gravity, and will be detected by the outstanding image quality of Euclid's VIS instrument. (Image credit: CNRS/UPMC/IAP/S Colombi/Y Mellier.)

which is mapping the stars of the Milky Way with high precision, all mirrors, the telescope truss and the optical bench are made of silicon carbide, a ceramic material that combines extreme stiffness with very good thermal conduction. The PLM structure ▷

## Dark energy

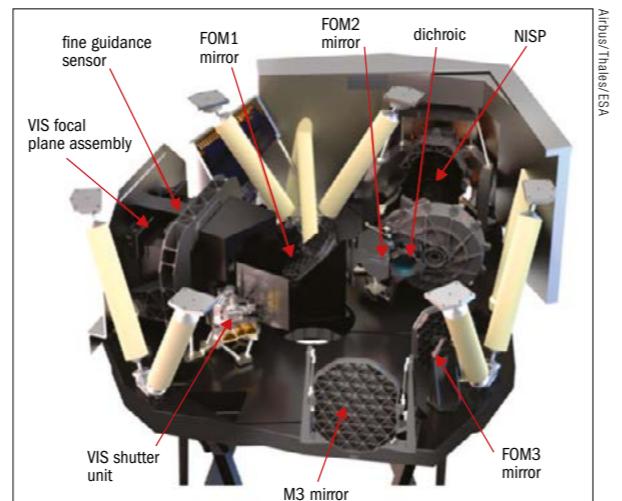


**2D map of the large-scale galaxy distribution observed by the Sloan Digital Sky Survey (SDSS).** Our galaxy is at the centre. Regions with redder colour have a higher density of galaxies; regions of greener colour have lower galaxy densities, and black regions have no galaxies. The elongated structures of a higher density of galaxies pointing toward the centre are signatures of the peculiar redshifts (or velocities) of galaxies. Euclid will measure structures as far out as  $z=2$  over a larger area of the sky.

is passively cooled to a stable temperature of around 130 K, and a secondary mirror mechanism will be employed to refocus the telescope image on the VIS detector plane after launch and cool down.

The VIS instrument receives light in one broad visible band covering the wavelength range 0.55–0.90  $\mu\text{m}$ . To avoid additional image distortions, it has no imaging optics of its own and is equipped with a camera made up of 36 4 k  $\times$  4 k-pixel CCDs with a pixel scale of 0.1 arc second that must be aligned to a precision better than 15  $\mu\text{m}$  over a distance of 30 cm. Pixel-wise, the VIS camera is the second largest camera that will be flown in space after Gaia's and will produce the largest images ever generated in space. Unlike Gaia, VIS will compress and transmit all raw scientific images to Earth for further data processing. The instrument is capable of measuring the shapes of about 55,000 galaxies per image field of 0.5 square degrees. The NISP instrument, on the other hand, provides near-infrared photometry in the wavelength range 0.92–2.0  $\mu\text{m}$  and has a slit-less spectroscopy mode equipped with three identical grisms (grating prisms) covering the wavelength range 1.25–1.85  $\mu\text{m}$ . The grisms are mounted in different orientations to separate overlapping spectra of neighbouring objects, and the NISP device is capable of delivering redshifts for more than 900 galaxies per image field. The NISP focal plane is equipped with 16 near infrared HgCdTe detector arrays of 2 k  $\times$  2 k pixels with 0.3 arcsec pixels, which represents the largest near-infrared focal plane ever built for a space mission.

The exquisite accuracy and stability of Euclid's instruments will provide certainty that any observed galaxy-shape distortions are



*The cold compartment of the Euclid payload module, into which light comes from the telescope primary and secondary mirrors (not shown). The beam is then folded by two flat mirrors (FOM1 and FOM2) and converged by an elliptical mirror (M3) to a dichroic plate, which transmits the near-infrared light to the entrance pupil of the NISP instrument and reflects the visible light to a third flat mirror (FOM3), which finally bends the light towards the focal plane of the VIS instrument. The entire structure, including mirrors and most of the support brackets, is made of silicon-carbide ceramic material (dark grey). The compartment, irregularly shaped, about 2.5 m diameter, is thermally controlled, with a large radiator (light grey) transferring excess heat to space, and is separated structurally and thermally from the rest of the spacecraft by six struts made of glass fibre and titanium (yellow). To get an impression of the physical dimensions: the size of M3 is 54  $\times$  40 cm.*

caused by gravitational lensing and are not a result of artefacts in the optics. The telescope will deliver a field of view of more than 0.5 square degrees, which is an area comparable to two full Moons, and the flat focal plane of the Korsch configuration places no extra requirements on the surface shape of the sensors in the instruments. As the VIS and NISP instruments share the same field of view, Euclid observations can be carried out through both channels in parallel. Besides the Euclid satellite data, the Euclid mission will combine the photometry of the VIS and NISP instruments with complementary ground-based observations from several existing and new telescopes equipped with wide-field imaging or spectroscopic instruments (such as CFHT, ESO/VLT, Keck, Blanco, JST and LSST). These combined data will be used to derive an estimate of redshift for the two billion galaxies used for weak lensing, and to decouple coherent weak gravitational-lensing patterns from intrinsic alignments of galaxies. Organising the ground-based observations over both hemispheres and making these data compatible with the Euclid data turns out to be a very complex operation that involves a huge data volume, even bigger than the Euclid satellite data volume.

## Ground control

One Euclid field of 0.5 square degrees will generate 520 Gb/day of VIS compressed data and 240 Gb/day of NISP compressed data, and one such field is obtained in an observing period lasting about 1 hour and 15 minutes. All raw science data are transmitted to the ground via a high-density link. Even though the nominal mission will last for six years, mapping out the 36% of the sky at the required sensitivity and accuracy within this time involves large amounts of data to be transmitted at a rate of around 850 Gb/day during just four hours of contact with the ground station. The complete processing pipeline from Euclid's raw data to the final data products is a large IT project involving a few hundred software engineers and scientists, and has been broken down into functions handled by almost a dozen separate expert groups. A highly varied collection of data sets must be homogenised for subsequent combination: data from different ground and space-based telescopes, visible and near-infrared data, and slit-less spectroscopy. Very precise and accurate shapes of galaxies are measured, giving two orders of magnitude improvement with respect to current analyses.

Based on the current knowledge of the Euclid mission and the present ground-station development, no showstoppers have been identified. Euclid should meet its performance requirements at all levels, including the design of the mission (a survey of 15,000 square degrees in less than six years) and for the space and ground segments. This is very encouraging and most promising, taking into account the multiplicity of challenges that Euclid presents.

On the scientific side, the Euclid mission meets the precision and accuracy requested to characterise the source of the accelerating expansion of the universe and decisively reveal its nature. On the technical side, there are difficult challenges to be met in achieving the required precision and accuracy of galaxy-shape, photometric and spectroscopic redshift measurements. Our current knowledge of the mission provides a high degree of confidence that we can overcome all of these challenges in time for launch.

### Further reading

- L Amendola *et al.* 2016 arXiv:1606.0018.
- R Laureijs *et al.* 2011 arXiv:1110.3193.
- G Racca *et al.* 2016 Proc. SPIE **9904** 9904-19, arXiv:1610.05508.

### Résumé

*Euclid sur la piste de l'énergie noire*

*Nous savons depuis près de 20 ans que l'expansion de l'Univers s'accélère, mais nous ignorons toujours ce qu'est l'« énergie noire » à l'origine de cette accélération. La sonde Euclid de l'Agence spatiale européenne, qui sera lancée en 2020, utilisera sa sensibilité et sa portée inédites pour identifier la nature de l'énergie noire. Selon sa forme, l'énergie noire modifie légèrement l'historique de l'expansion de l'Univers prédicté par les modèles cosmologiques ; détecter de si petites différences exigera des dispositifs capables de mesurer des galaxies individuelles avec une haute précision et d'étudier de vastes régions du ciel, afin de couvrir toutes les échelles cosmologiques.*

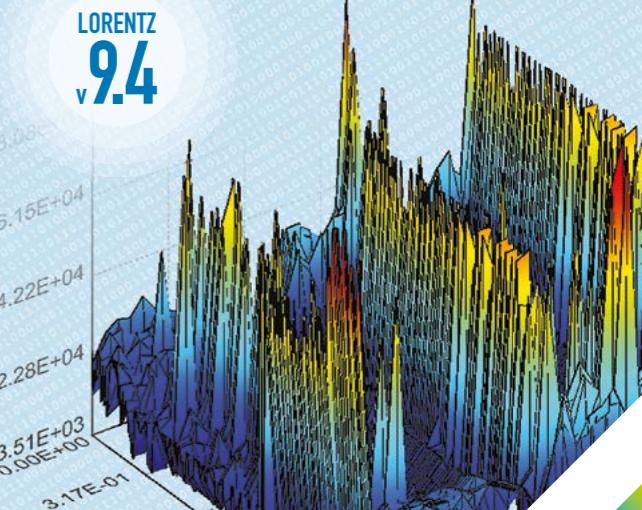
**Yannick Mellier**, CNRS-UMPC/IAP and CEA/IRFU, on behalf of the Euclid Consortium, and **Giuseppe Racca** and **Rene Laureijs**, ESA.

## Dark energy

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[Dark-matter history](#)

# How dark matter became a particle

It took decades for dark matter to enter the lexicon of particle physics. Today, explaining the nature and abundance of dark matter is one of the most pressing problems in the field.

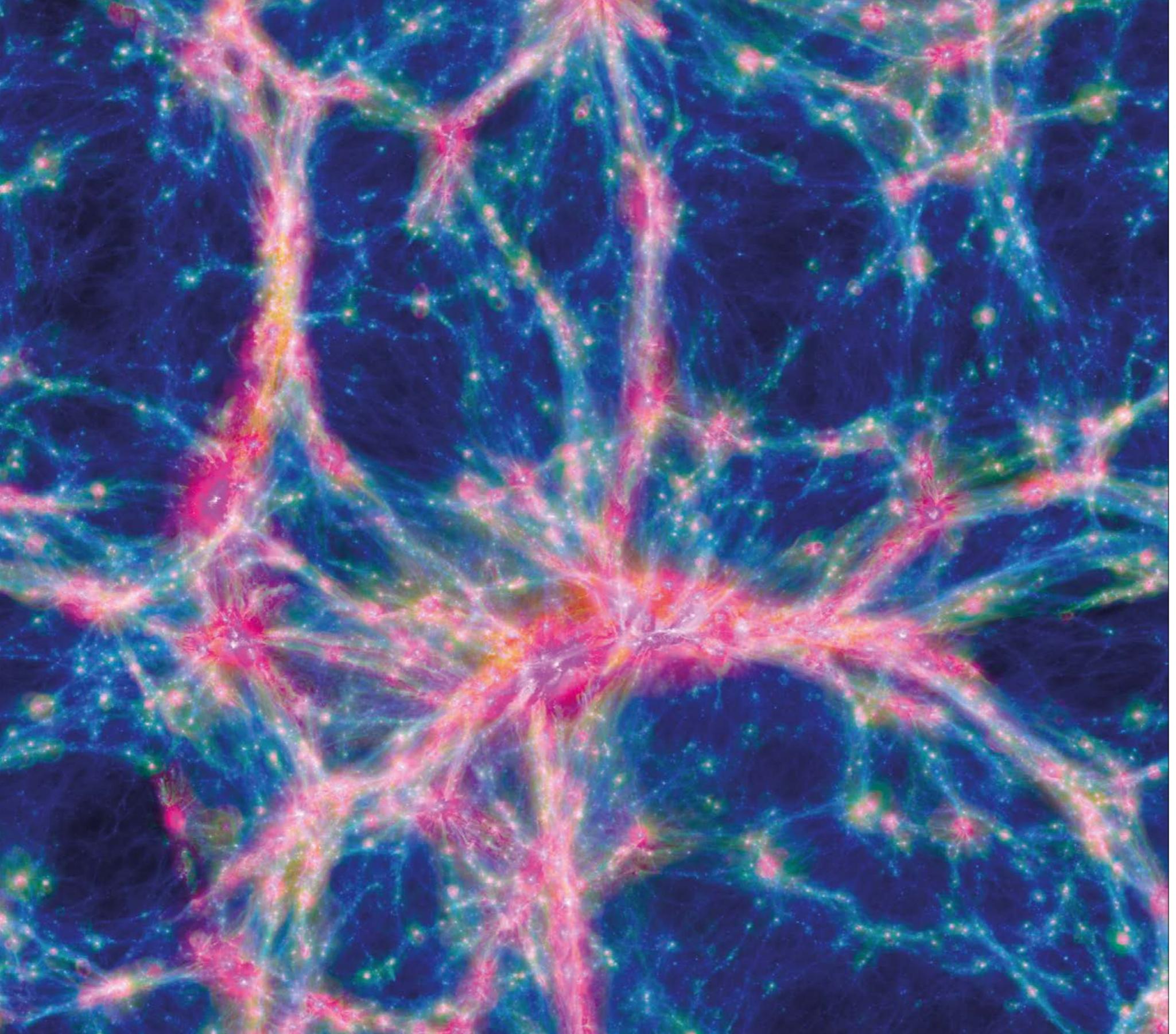
Astronomers have long contemplated the possibility that there may be forms of matter in the universe that are imperceptible, either because they are too far away, too dim or intrinsically invisible. Lord Kelvin was perhaps the first, in 1904, to attempt a dynamical estimate of the amount of dark matter in the universe. His argument was simple yet powerful: if stars in the Milky Way can be described as a gas of particles acting under the influence of gravity, one can establish a relationship between the size of the system and the velocity dispersion of the stars. Henri Poincaré was impressed by Kelvin's results, and in 1906 he argued that since the velocity dispersion predicted in Kelvin's estimate is of the same order of magnitude as that observed, "there is no dark matter, or at least not so much as there is of shining matter".

The Swiss-US astronomer Fritz Zwicky is arguably the most famous and widely cited pioneer in the field of dark matter. In 1933, he studied the redshifts of various galaxy clusters and noticed a large scatter in the apparent velocities of eight galaxies within the Coma Cluster. Zwicky applied the so-called virial theorem – which establishes a relationship between the kinetic and potential energies of a system of particles – to estimate the cluster's mass. In contrast to what would be expected from a structure of this scale – a velocity dispersion of around 80 km/s – the observed average velocity dispersion along the line of sight was approximately 1000 km/s. From this comparison, Zwicky concluded: "If this would be confirmed, we would get the surprising result that dark matter is present in much greater amount than luminous matter."

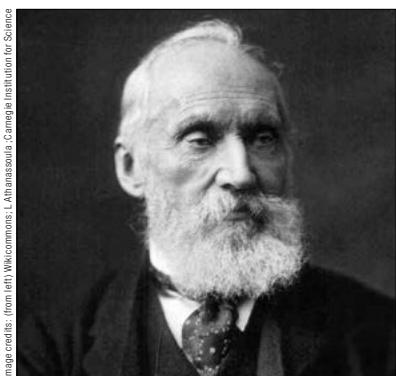
In the 1950s and 1960s, most astronomers did not ask whether the universe had a significant abundance of invisible or missing ▶

*The large-scale structure of the universe is thought to be dominated by vast filaments of dark matter, as simulated by the EAGLE (Evolution and Assembly of GaLaxies and their Environments) project. (Image credit: EAGLE Project.)*

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## Dark-matter history



(Left) Lord Kelvin was perhaps the first, in 1904, to attempt a dynamical estimate of the amount of dark matter in the universe. Albert Bosma (middle), currently at the Laboratoire d'Astrophysique de Marseille, and Vera Rubin (right), who died at the age of 88 in December 2016, played an important role in convincing the scientific community of the presence of dark matter around galaxies.

mass. Although observations from this era would later be seen as evidence for dark matter, back then there was no consensus that the observations required much, or even any, such hidden material, and certainly there was not yet any sense of crisis in the field. It was in 1970 that the first explicit statements began to appear arguing that additional mass was needed in the outer parts of some galaxies, based on comparisons between predicted and measured rotation curves. The appendix of a seminal paper published by Ken Freeman in 1970, prompted by discussions with radio-astronomer Mort Roberts, concluded that: "If [the data] are correct, then there must be in these galaxies additional matter which is undetected, either optically or at 21 cm. Its mass must be at least as large as the mass of the detected galaxy, and its distribution must be quite different from the exponential distribution which holds for the optical galaxy." (Figure 1 overleaf.)

Several other lines of evidence began to appear that supported the same conclusion. In 1974, two influential papers (by Jaan Einasto, Ants Kaasik and Enn Saar, and by Jerry Ostriker, Jim Peebles and Amos Yahil) argued that a common solution existed for the mass discrepancies observed in clusters and in galaxies, and made the strong claim that the mass of galaxies had been until then underestimated by a factor of about 10.

By the end of the decade, opinion among many cosmologists

and astronomers had crystallised: dark matter was indeed abundant in the universe. Although the same conclusion was reached by many groups of scientists with different subcultures and discourses, many individuals found different lines of evidence to be compelling during this period. Some astronomers were largely persuaded by new and more reliable measurements of rotation curves, such as those by Albert Bosma, Vera Rubin and others. Others were

swayed by observations of galaxy clusters, arguments pertaining to the stability of disc galaxies, or even cosmological considerations. Despite disagreements regarding the strengths and weaknesses of these various observations and arguments, a consensus nonetheless began to emerge by the end of the 1970s in favour of dark-matter's existence.

### Enter the particle physicists

From our contemporary perspective, it can be easy to imagine that scientists in the 1970s had in mind halos of weakly interacting particles when they thought about dark matter. In reality, they did not. Instead, most astronomers had much less exotic ideas in the form of comparatively low-luminosity versions of otherwise ordinary stars and gas. Over time, however, an increasing number of particle physicists became aware of and interested in the problem of dark matter. This transformation was not just driven by new scientific results, but also by sociological changes in science that had been taking place for some time.

Half a century ago, cosmology was widely viewed as something of a fringe science, with little predictive power or testability. Particle physicists and astrophysicists did not often study or pursue research in each other's fields, and it was not obvious what their respective communities might have to offer one another. More than any other problem in science, it was dark matter that brought particle physicists and astronomers together.

As astrophysical alternatives were gradually ruled out one by one, the view that dark matter is likely to consist of one or more yet undiscovered species of subatomic particle came to be held almost universally among both particle physicists and astrophysicists alike.

Perhaps unsurprisingly, the first widely studied particle dark-matter candidates were neutrinos. Unlike all other known particle species, neutrinos are stable and do not experience electromagnetic or strong interactions – which are essential characteristics for almost any viable dark-matter candidate. The earliest discussion of the role of neutrinos in cosmology appeared in a 1966 paper by Soviet physicists Gershtein and Zeldovich, and several years later the topic began to appear in the West, beginning in 1972 with a paper by Ram Cowsik and J McClelland. Despite the very ▷

**An increasing number of particle physicists became aware of and interested in the problem of dark matter.**

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Best 20u/25	20–15, 25–15	Best 15 + I <sup>123</sup> , In <sup>111</sup> , Ge <sup>68</sup> /Ga <sup>68</sup>
Best 28u (Upgradeable)	28–15	Best 15 + I <sup>123</sup> , In <sup>111</sup> , Ge <sup>68</sup> /Ga <sup>68</sup>
Best 35	35–15	Greater production of Best 15, 20u/25 isotopes plus Tl <sup>201</sup> , Rb <sup>81</sup> /Kr <sup>81</sup>
Best 70	70–35	Sr <sup>89</sup> /Rb <sup>82</sup> , I <sup>123</sup> , Cu <sup>67</sup> , Kr <sup>81</sup> + research

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interesting and important results of these and other papers, it is notable that most of them did not address or even acknowledge the possibility that neutrinos could account for the missing mass that had been observed by astronomers on galactic and cluster scales. An exception included the 1977 paper by Lee and Weinberg, whose final sentence reads: "Of course, if a stable heavy neutral lepton were discovered with a mass of order 1–15 GeV, the gravitational field of these heavy neutrinos would provide a plausible mechanism for closing the universe."

While this is still a long way from acknowledging the dynamical evidence for dark matter, it was an indication that physicists were beginning to realise that weakly interacting particles could be very abundant in our universe, and may have had an observable impact on its evolution. In 1980, the possibility that neutrinos might make up the dark matter received a considerable boost when a group studying tritium beta decay reported that they had measured the mass of the electron antineutrino to be approximately 30 eV – similar to the value needed for neutrinos to account for the majority of dark matter. Although this "discovery" was eventually refuted, it motivated many particle physicists to consider the cosmological implications of their research.

Although we know today that dark matter in the form of Standard Model neutrinos would be unable to account for the observed large-scale structure of the universe, neutrinos provided an important template for the class of hypothetical species that would later be known as weakly interacting massive particles (WIMPs). Astrophysicists and particle physicists alike began to experiment with a variety of other, more viable, dark-matter candidates.

### Cold dark-matter paradigm

The idea of neutrino dark matter was killed off in the mid-1980s with the arrival of numerical simulations. These could predict how large numbers of dark-matter particles would evolve under the force of gravity in an expanding universe, and therefore allow astronomers to assess the impact of dark matter on the formation of large-scale structure. In fact, by comparing the results of these simulations with those of galaxy surveys, it was soon realised that no relativistic particle could account for dark matter. Instead, the paradigm of *cold* dark matter – i.e. made of particles that were non-relativistic at the epoch of structure formation – was well on its way to becoming firmly established.

Meanwhile, in 1982, Jim Peebles pointed out that the observed characteristics of the cosmic microwave background (CMB) also seemed to require the existence of dark matter. If just baryons existed, then one could only explain the observed degree of large-scale structure if the universe started in a fairly anisotropic or "clumpy" state. But by this time, the available data already set an upper limit on CMB anisotropies at a level of  $10^{-4}$  – too meagre to account for the universe's structure. Peebles argued that this problem would be relieved if the universe was instead dominated by massive weakly interacting particles whose density fluctuations begin to grow prior to the decoupling of matter and radiation during which the CMB was born. Among other papers, this received enormous attention within the scientific community and helped establish cold dark matter as the leading paradigm to describe the structure and evolution of the universe at all scales.

## Dark-matter history

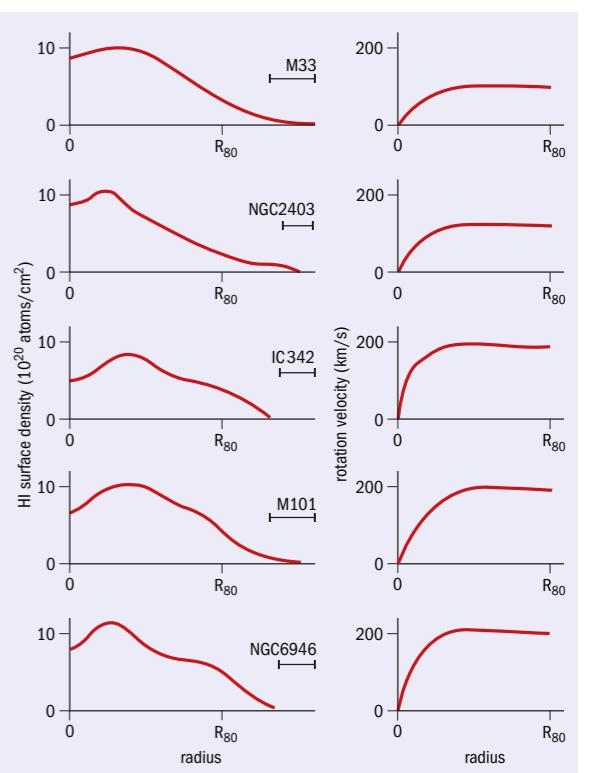
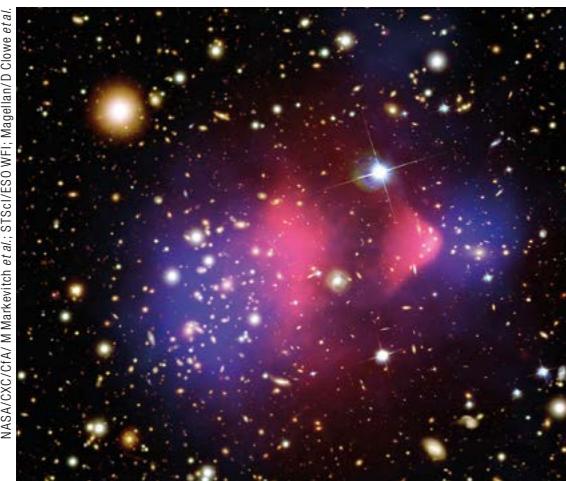


Fig. 1. Flat rotation curves for galaxies, which indicate they are spinning faster than expected if they were made purely from baryonic matter, began to emerge from 21 cm observations in the early 1970s. Shown are the hydrogen surface density profile (left) and rotation curves (right) of five galaxies as obtained by Rogstad and Shostak in 1972, where the bars under the galaxy names indicate their average radial diameter and  $R_{80}$  corresponds to the radius containing 80% of the observed hydrogen.

### Solutions beyond the Standard Model

Neutrinos might be the only known particles that are stable, electrically neutral and not strongly interacting, but the imagination of particle physicists did not remain confined to the Standard Model for long. Instead, papers started to appear that openly contemplated many speculative and yet undiscovered particles that might account for dark matter. In particular, particle physicists began to find new candidates for dark matter within the framework of a newly proposed space-time symmetry called supersymmetry. The cosmological implications of supersymmetry were discussed as early as the late 1970s. In Piet Hut's 1977 paper on the cosmological constraints on the masses of neutrinos, he wrote that the dark-matter argument was not limited to neutrinos or even to weakly interacting particles. The abstract of his paper mentions another possibility made within the context of the supersymmetric partner of the graviton, the spin-3/2 gravitino: "Similar, but much more severe, restrictions follow for particles that interact only gravitationally. This seems of importance □

## Dark-matter history



*The Bullet Cluster is a system of two colliding galaxy clusters that is dominated by sources of gravitational potential beyond what normal baryonic matter can explain.*

with respect to supersymmetric theories," wrote Hut.

In their 1982 paper, Heinz Pagels and Joel Primack also considered the cosmological implications of gravitinos. But unlike Hut's paper, or the other preceding papers that had discussed neutrinos as a cosmological relic, Pagels and Primack were keenly aware of the dark-matter problem and explicitly proposed that gravitinos could provide the solution by making up the missing mass. In many ways, their paper reads like a modern manuscript on supersymmetric dark matter, motivating supersymmetry by its various attractive features and then discussing both the missing mass in galaxies and the role that dark matter could play in the formation of large-scale structure. Around the same time, supersymmetry was being further developed into its more modern form, leading to the introduction of R-parity and constructions such as the minimal supersymmetric standard model (MSSM). Such supersymmetric models included not only the gravitino as a dark-matter candidate, but also neutralinos – electrically neutral mixtures of the superpartners of the photon, Z and Higgs bosons.

Over the past 35 years, neutralinos have remained the single most studied candidate for dark matter and have been the subject of many thousand scientific publications. Papers discussing the cosmological implications of stable neutralinos began to appear in 1983. In the first two of these, Weinberg and Haim Goldberg independently discussed the case of a photino (a neutralino whose composition is dominated by the superpartner of the photon) and derived a lower bound of 1.8 GeV on its mass by requiring that the density of such particles does not overclose the universe. A few months later, a longer paper by John Ellis and colleagues considered a wider range of neutralinos as cosmological relics. In Goldberg's paper there is no mention of the phrase "dark matter" or of any missing mass problem, and Ellis *et al.* took a largely similar approach by simply requiring only that the cosmological abundance of neutralinos not be so large as to overly slow or reverse the universe's expansion rate. Although most of the papers on stable cosmological relics

written around this time did not yet fully embrace the need to solve the dark-matter problem, occasional sentences could be found that reflected the gradual emergence of a new perspective.

During the years that followed, an increasing number of particle physicists would further motivate proposals for physics beyond the Standard Model by showing that their theories could account for the universe's dark matter. In 1983, for instance, John Preskill, Mark Wise and Frank Wilczek showed that the axion, originally proposed to solve the strong CP problem in quantum chromodynamics, could account for all of the dark matter in the universe. In 1993, Scott Dodelson and Lawrence Widrow proposed a scenario in which an additional, sterile neutrino species that did not experience electroweak interactions could be produced in the early universe and realistically make up the dark matter. Both the axion and the sterile neutrino are still considered as well-motivated dark-matter candidates, and are actively searched for with a variety of particle and astroparticle experiments.

### The triumph of particle dark matter

In the early 1980s there was still nothing resembling a consensus about whether dark matter was made of particles at all, with other possibilities including planets, brown dwarfs, red dwarfs, white dwarfs, neutron stars and black holes. Kim Griest would later coin the term "MACHOs" – short for massive astrophysical compact halo objects – to denote this class of dark-matter candidates, in response to the alternative of WIMPs. There is a consensus today, based on searches using gravitational microlensing surveys and determinations of the cosmic baryon density based on measurements of the primordial light-element abundances and the CMB, that MACHOs do not constitute a large fraction of the dark matter.

An alternative explanation for particle dark matter is to assume that there is no dark matter in the first place, and that instead our theory of gravity needs to be modified. This simple idea, which was put forward in 1982 by Mordehai Milgrom, is known as modified Newtonian dynamics (MOND) and has far-reaching consequences. At the heart of MOND is the suggestion that the force due to gravity does not obey Newton's second law,  $F = ma$ . If instead gravity scaled as  $F = ma^2/a_0$  in the limit of very low accelerations ( $a \ll a_0 \sim 1.2 \times 10^{-10} \text{ m/s}^2$ ), then it would be possible to account for the observed motions of stars and gas within galaxies without postulating the presence of any dark matter.

In 2006, a group of astronomers including Douglas Clowe transformed the debate between dark matter and MOND with the publication of an article entitled: "A direct empirical proof of the existence of dark matter". In this paper, the authors described the observations of a pair of merging clusters collectively known as the Bullet Cluster (image above left). As a result of the clusters' recent collision, the distribution of stars and galaxies is spatially separated from the hot X-ray-emitting gas (which constitutes the majority of the baryonic

**In the early 1980s there was still no consensus about whether dark matter was made of particles.**

mass in this system). A comparison of the weak lensing and X-ray maps of the bullet cluster clearly reveals that the mass in this system does not trace the distribution of baryons. Another source of gravitational potential, such as that provided by dark matter, must instead dominate the mass of this system.

Following these observations of the bullet cluster and similar systems, many researchers expected that this would effectively bring the MOND hypothesis to an end. This did not happen, although the bullet cluster and other increasingly precise cosmological measurements on the scale of galaxy clusters, as well as the observed properties of the CMB, have been difficult to reconcile with all proposed versions of MOND. It is currently unclear whether other theories of modified gravity, in some yet-unknown form, might be compatible with these observations. Until we have a conclusive detection of dark-matter particles, however, the possibility that dark matter is a manifestation of a new theory of gravity remains open.

Today, the idea that most of the mass in the universe is made up of cold and non-baryonic particles is not only the leading paradigm, but is largely accepted among astrophysicists and particle physicists alike. Although dark-matter's particle nature continues to elude us, a rich and active experimental programme is striving to detect and characterise dark-matter's non-gravitational interactions, ultimately allowing us to learn the identity of this mysterious substance. It has been more than a century since the first pioneering attempts to measure the amount of dark matter in the universe.

Perhaps it will not be too many more years before we come to understand what that matter is.

### • Further reading

G Bertone and D Hooper 2016 arXiv:1605.04909.  
J de Swart *et al.* 2017 *Nature Astronomy* **1** 59.

### Résumé

*Comment la matière noire est devenue une particule*

*La matière noire, prédicta dans les années 1930, est essentielle dans notre connaissance de l'Univers. Pendant des décennies, on la croyait composée d'objets tels que des versions à faible luminosité d'étoiles et de gaz habituels. Au fil du temps, toujours plus de physiciens des particules ont néanmoins pris conscience du problème de la matière noire et s'y sont intéressés, en raison de nouveaux résultats scientifiques mais aussi des changements sociologiques qui avaient lieu dans le monde des sciences.*

*Aujourd'hui, l'idée selon laquelle la masse de l'Univers est composée principalement de particules froides et non baryoniques, dont nous ne connaissons pas la nature, est largement acceptée parmi les astrophysiciens et les physiciens des particules.*

**Gianfranco Bertone**, University of Amsterdam, and **Dan Hooper**, Fermi National Accelerator Laboratory and the University of Chicago.

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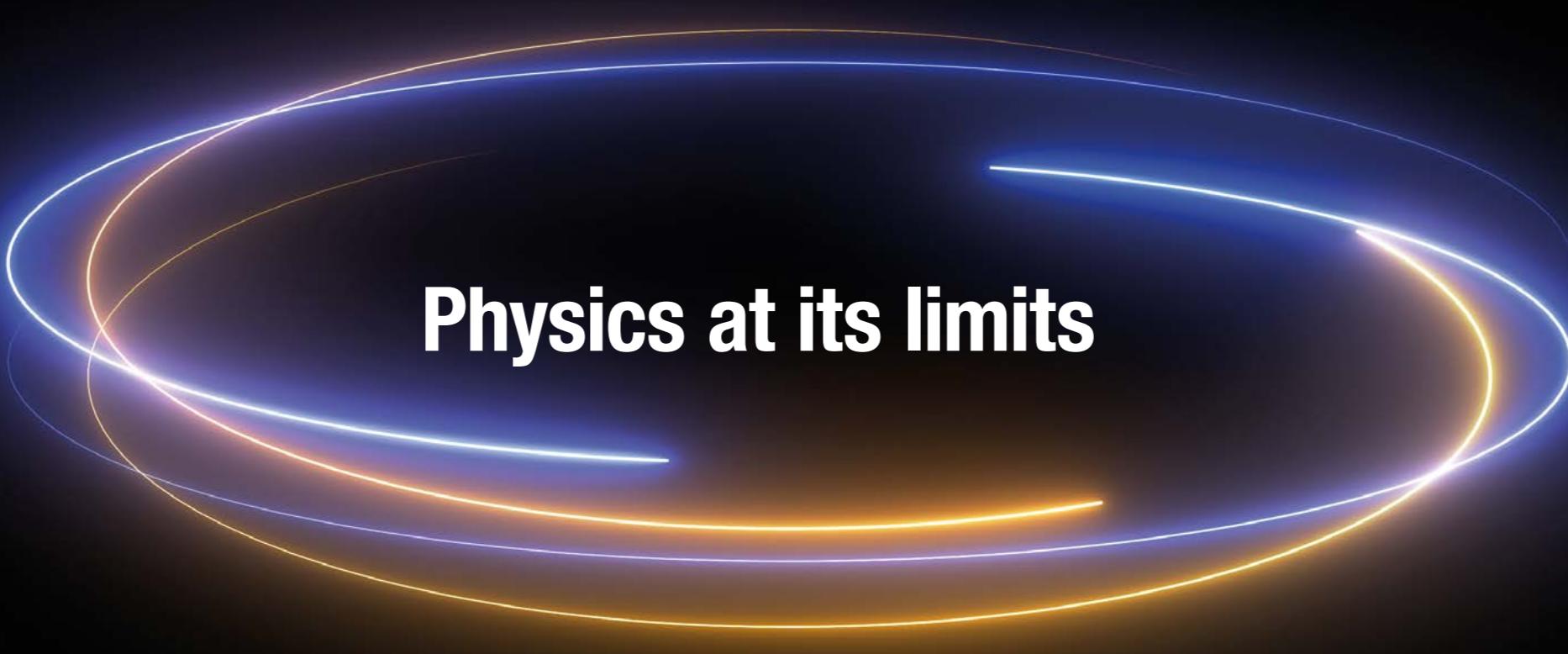
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# Physics at its limits

A 100 km-circumference collider would address many of the outstanding questions in modern particle physics and secure our exploration of the microscopic world for generations.

Since Democritus, humans have wondered what happens as we slice matter into smaller and smaller parts. After the discovery almost 50 years ago that protons are made of quarks, further attempts to explore smaller distances have not revealed tinier substructures. Instead, we have discovered new, heavier elementary particles, which although not necessarily present in everyday matter are crucial components of nature's fundamental make-up. The arrangement of the elementary particles and the interactions between them is now well described by the Standard Model (SM), but furthering our understanding of the basic laws of nature requires digging even deeper.

Quantum physics gives us two alternatives to probe nature at smaller scales: high-energy particle collisions, which induce short-range interactions or produce heavy particles, and high-precision measurements, which can be sensitive to the ephemeral influence of heavy particles enabled by the uncertainty principle. The SM was built from these two approaches, with a variety of experi-

ments worldwide during the past 40 years pushing both the energy and the precision frontiers. The discovery of the Higgs boson at the LHC is a perfect example: precise measurements of Z-boson decays at previous lepton machines such as CERN's Large Electron–Positron (LEP) collider pointed indirectly but unequivocally to the existence of the Higgs. But it was the LHC's proton–proton collisions that provided the high energy necessary to produce it directly. With exploration of the Higgs fully under way at the LHC and the machine set to operate for the next 20 years, the time is ripe to consider what tool should come next to continue our journey.

Aiming at a high-energy collider with a clean collision environment, CERN has for several years been developing an e<sup>+</sup>e<sup>-</sup> linear collider called CLIC. With an energy up to 3 TeV, CLIC would combine the precision of an e<sup>+</sup>e<sup>-</sup> collider with the high-energy reach of a hadron collider such as the LHC. But with the lack so far of any new particles at the LHC beyond the Higgs, evidence is mounting that even higher energies may be required to fully explore the next layer of phenomena beyond the SM. Prompted by the outcome of the 2013 European Strategy for Particle Physics, CERN has therefore undertaken a five-year study for a Future Circular Collider (FCC) facility built in a new 100 km-circumference tunnel (see image overleaf).

Such a tunnel could host an e<sup>+</sup>e<sup>-</sup> collider (called FCC-ee) with an energy and intensity much higher than LEP, improving by orders of magnitude the precision of Higgs and other SM measurements. It could also house a 100 TeV proton–proton collider (FCC-hh) with

a discovery potential more than five times greater than the 27 km-circumference LHC. An electron–proton collider (FCC-eh), furthermore, would allow the proton's substructure to be measured with unmatchable precision. Further opportunities include the collision of heavy ions in FCC-hh and FCC-eh, and fixed-target experiments using the injector complex. The earliest that such a machine could enter operation is likely to be the mid 2030s, when the LHC comes to the end of its operational lifetime, but the long lead times for collider projects demand that we start preparing now (see timeline overleaf). A Conceptual Design Report (CDR) for a 100 km collider is expected to be completed by the end of 2018 and hundreds of institutions have joined the international FCC study since its launch in 2014. An independent study for a similar facility is also under way in China.

The CDR will document the accelerator, infrastructures and experiments, as well as a plethora of physics studies proving FCC's ability to match the long-term needs of global high-energy-physics programmes. The first FCC physics workshop took place at CERN in January to review the status of these studies and discuss the complementarity between the three FCC modes.

## The post-LHC landscape

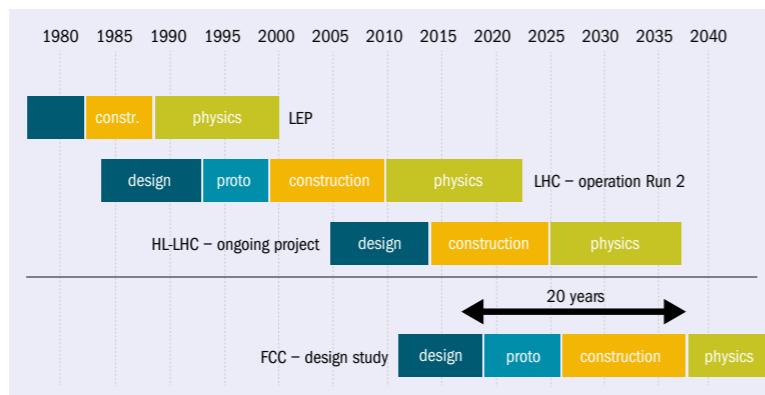
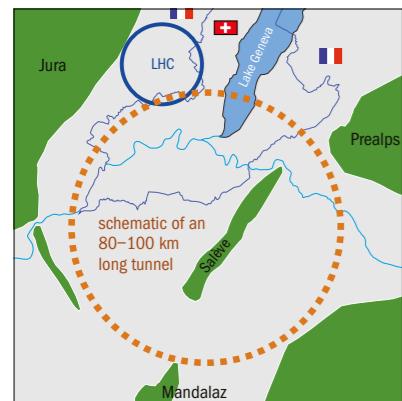
To chart the physics landscape of future colliders, we must first imagine what questions may or may not remain at the end of the LHC programme in the mid-2030s. At the centre of this, and

perhaps the biggest guaranteed physics goal of the FCC programme, is our understanding of the Higgs boson. While there is no doubt that the Higgs was the last undiscovered piece of the SM, it is not the closing chapter of the millennia-old reductionist paradigm. The Higgs is the first of its kind – an elementary scalar particle – and it therefore raises deep theoretical questions that beckon a new era of exploration (figure 1, p39).

Consider its mass. In the SM there is no symmetry that protects the Higgs mass from large quantum corrections that drag it up to the mass scale of the particles it interacts with. You might conclude that the relatively low mass of the Higgs implies that it simply does not interact with other heavy particles. But there is good, if largely theoretical, evidence to the contrary. We know that at energies 16 orders of magnitude above the Higgs mass where general relativity fails to provide a consistent quantum description of matter, there must exist a full quantum theory that includes gravity. The fact that the Higgs is so much lighter than this scale is known as the hierarchy problem, and many candidate theories (such as supersymmetry) exist that require new heavy particles interacting with the Higgs. By comparing precise measurements of the Higgs boson with precision SM predictions, we are indirectly searching for evidence of these theories. The SM provides an uncompromising script for the Higgs interactions and any deviation from it would demand its extension.

Even setting to one side grandiose theoretical ideas such as quantum gravity, there are other physical reasons why the Higgs may

## Future colliders



provide a window to undiscovered sectors. As it carries no spin and is electrically neutral, the Higgs may have so-called “relevant” interactions with new neutral scalar particles. These interactions, even if they take place only at very high energies, remain relevant at low energies – contrary to interactions between new neutral scalars and the other SM particles. The possibility of new hidden sectors already has strong experimental support: although we understand the SM very well, it does not account for roughly 80% of all the matter in the universe. We call the missing mass dark matter, and candidate theories abound. Given the importance of the puzzle, searches for dark-matter particles will continue to play a central role at the LHC and certainly at future colliders.

Furthermore, the SM cannot explain the origin of the matter-antimatter asymmetry that created enough matter for us to exist, otherwise known as baryogenesis. Since the asymmetry was created in the early universe when temperatures and energies were high, we must explore higher energies to uncover the new particles responsible for it. With the LHC we are only at the beginning of this search. Another outstanding question lies in the origin of the neutrino masses, which the SM alone cannot account for. As with dark matter, there are numerous theories for neutrino masses, such as those involving “sterile” neutrinos that are in the reach of lepton and hadron colliders. These and other outstanding questions might also imply the existence of further spatial dimensions, or larger symmetries that unify leptons and quarks or the known forces. The LHC’s findings notwithstanding, future colliders like the FCC are needed to explore these fundamental mysteries more deeply, possibly revealing the need for a paradigm shift.

### Electron–positron potential

The capabilities of circular  $e^+e^-$  colliders are well illustrated by LEP, which occupied the LHC tunnel from 1989 to 2000. Its point-like collisions between electrons and positrons and precisely known beam energy allowed the four LEP experiments to test the SM to new levels of precision. Putting such a machine in a 100 km tunnel and taking advantage of advances in accelerator technology such as superconducting radio-frequency cavities would offer even greater levels of precision on a larger number of processes. We would be able to change the collision energy in the range 91–350 GeV, for example, allowing data to be collected at the Z pole, at the WW production threshold, at the peak of ZH

production, and at the top–antitop quark threshold. Controlling the beam energy at the 100 keV level would allow exquisite measurements of the Z- and W-boson masses, while the high luminosity of FCC-ee will lead to samples of up to  $10^{13}$  Z and  $10^8$  W bosons, not to mention several million Higgs bosons and top-quark pairs. The experimental precision would surpass any previous experiment and challenge cutting-edge theory calculations.

FCC-ee would quite literally provide a quantum leap in our understanding of the Higgs. Like the W and Z gauge bosons, the Higgs receives quantum electroweak corrections typically measuring a few per cent in magnitude due to fluctuations of massive particles such as the top quark. This aspect of the gauge bosons was successfully explored at LEP, but now it is the turn of the Higgs – the key-stone in the electroweak sector of the SM. The millions of Higgs bosons produced by FCC-ee, with its clinically precise environment, would push the accuracy of the measurements to the per-mille level, accessing the quantum underpinnings of the Higgs and probing deep into this hitherto unexplored frontier. In the process,  $e^+e^- \rightarrow HZ$ , the mass recoiling against the Z has a sharp peak that allows a unique and absolute determination of the Higgs decay width and production cross-section. This will provide an absolute normalisation for all Higgs measurements performed at the FCC, enabling exotic Higgs decays to be measured in a model-independent manner.

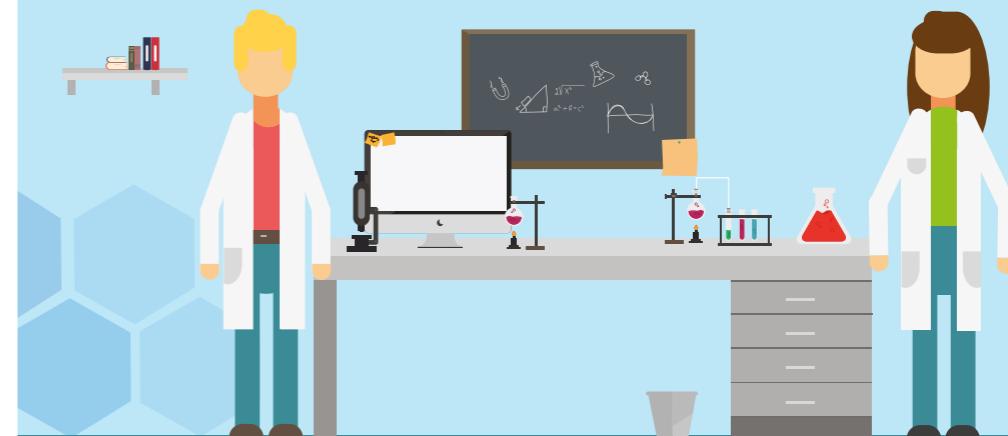
The high statistics promised by the FCC-ee programme go far beyond precision Higgs measurements. Other signals of new physics could arise from the observation of flavour-changing neutral currents or lepton-flavour-violating decays by the precise measurements of the Z and H invisible decay widths, or by direct observation of particles with extremely weak couplings such as right-handed neutrinos and other exotic particles. Given the particular energy and luminosity of a 100 km  $e^+e^-$  machine, the precision of the FCC-ee programme on electroweak measurements would allow new physics effects to be probed at scales as high as 100 TeV. If installed before FCC-hh, it would therefore anticipate what the hadron machine must focus on.

### The energy frontier

The future proton–proton collider FCC-hh would operate at seven times the LHC energy, and collect about 10 times more data. The discovery reach for high-mass particles – such as Z' or W' gauge bosons corresponding to new fundamental forces, or gluinos and squarks in supersymmetric theories – will increase by a factor five or ▷

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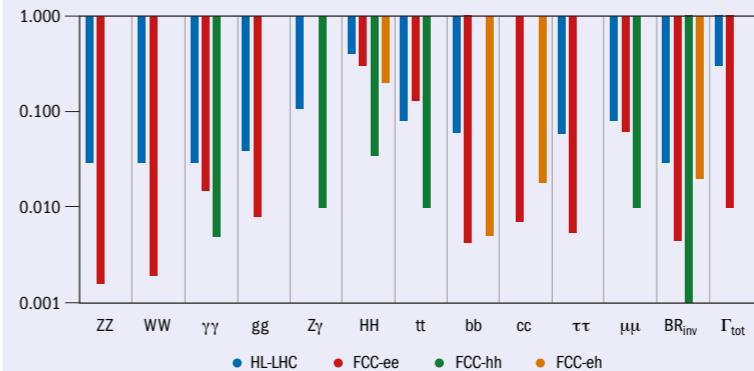
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(Far left). The FCC accelerator complex in the Geneva region, showing the LHC for comparison. (Middle) Technical timeline of the FCC project shown in comparison with previous and existing CERN colliders.

(Left) Fig. 1. Together, FCC-ee, hh and eh can provide detailed measurements on the Higgs properties. The figure shows indicative precision in the determination of couplings to gauge bosons, quarks and leptons, as well as of the Higgs self-coupling, of its total width and of the invisible decay rate. Firmer estimates will appear in the CDR.

more, depending on the luminosity. The production rate of particles already within the LHC reach, such as top quarks or Higgs bosons, will increase by even larger factors. During its planned 25 years of data-taking, more than  $10^{10}$  Higgs bosons will be created by FCC-hh, which is 10,000 times more than collected by the LHC so far and 100 times more than will be available by the end of LHC operations. These additional statistics will enable the FCC-hh experiments to improve the separation of Higgs signals from the huge backgrounds that afflict most LHC studies, overcoming some of the dominant systematics that limit the precision attainable from the LHC.

While the ultimate precision on most Higgs properties can only be achieved with FCC-ee, several demand complementary information from FCC-hh. For example, the direct measurement of the coupling between the Higgs and the top quark necessitates that they be produced together, requiring an energy beyond the reach of the FCC-ee. At 100 TeV, almost  $10^9$  of the  $10^{12}$  produced top quarks will radiate a Higgs boson, allowing the top-Higgs interaction to be measured with a statistical precision at the 1% level – a factor 10 improvement over what is hoped for from the LHC. Similar precision can be reached for Higgs decays that are too rare to be studied in detail at FCC-ee, such as those to muon pairs or to a Z and a photon. All of these measurements will be complementary to those obtained with FCC-ee, and will use them as reference inputs to precisely correlate the strength of the signals obtained through various production and decay modes.

One respect in which a 100 TeV proton–proton collider would come to the fore is in revealing how the Higgs behaves in private. The Higgs is the only particle in the SM that interacts with itself. As the Higgs scalar potential defines the potential energy contained in a fluctuation of the Higgs field, these self-interactions are neatly

defined as the derivatives of the scalar electroweak potential. With the Higgs boson being an excitation about the minimum of this potential, we know that its first derivative is zero. The second derivative of the potential is simply the Higgs mass, which is already known to sub-percent accuracy. But the third and fourth derivatives are unknown, and unless we gain access to

Higgs self-interactions they could remain so. The rate of Higgs pair-production events, which in some part occur through Higgs self-interactions, would grow precipitously at FCC-hh and enable this unique property of the Higgs to be measured with an accuracy of 5% per cent. Among many other uses, such a measurement would comprehensively explore classes of baryogenesis models that rely on modifying the Higgs potential, and thus help us to understand the origin of matter.

FCC-hh would also allow an exhaustive exploration of new TeV-scale phenomena. Indirect evidence for new physics can emerge from the scattering of W bosons at high energy, from the production of Higgs bosons at very large transverse momentum, or by testing the far “off-shell” nature of the Z boson via the measurement of lepton pairs with invariant masses in the multi-TeV region. The plethora of new particles predicted by most models of symmetry-breaking alternative to the SM can be searched for directly, thanks to the immense mass reach of 100 TeV collisions. The search for dark matter, for example, will cover the possible space of parameters of many theories relying on weakly interacting massive particles, guaranteeing a discovery or ruling them out. Theories that address the hierarchy problem will also be conclusively tested. For supersymmetry, the mass reach of FCC-hh pushes beyond the regions motivated by this puzzle alone. For composite Higgs theories, the precision Higgs coupling measurements and searches for new heavy resonances will fully cover the motivated territory. A 100 TeV proton collider will even confront exotic scenarios such as the twin Higgs, which are nightmarishly difficult to test. These theories predict very rare or exotic Higgs decays, possibly visible at FCC-hh thanks to its enormous Higgs production rates.

Beyond these examples, a systematic effort is ongoing to categorise the models that can be conclusively tested, and to find the loopholes that might allow some models to escape detection. This work will influence the way detectors for the new collider are designed. Work is already starting in earnest to define the features of these detectors, and efforts in the FCC CDR study will focus on comprehensive simulations of the most interesting physics signals. The experimental environment of a proton–proton collider is difficult due to the large number of background sources and the additional noise caused by the occurrence of multiple interactions among the hundreds of billions of protons crossing each other at the same time. This pile-up of events will greatly exceed those observed ▷

## Future colliders

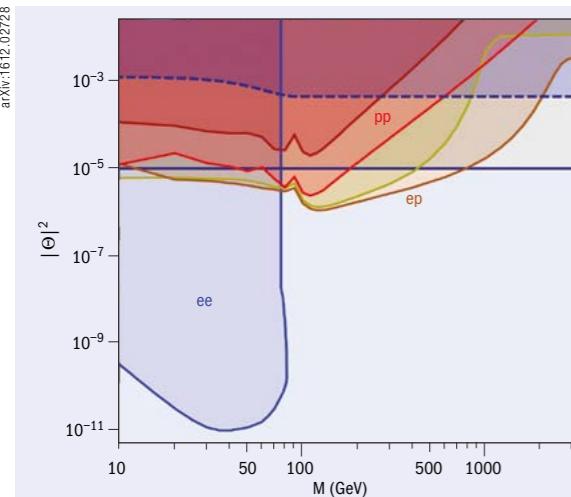


Fig. 2. The complementary role of the ee, pp and ep colliders in probing a sterile neutrino of mass  $M$  and mixing angle  $\theta$  with ordinary neutrinos.

at the LHC, and will pose a significant challenge to the detectors' performance and to the data-acquisition systems. The LHC experience is of immense value for projecting the scale of the difficulties that will have to be met by FCC-hh, but also for highlighting the increasing role of proton colliders in precision physics beyond their conventional role of discovery machines.

### Asymmetric collisions

Smashing protons into electrons opens up a whole different type of physics, which until now has only been explored in detail by a single machine: the HERA collider at DESY in Germany. FCC-eh would collide a 60 GeV electron beam from a linear accelerator, external and tangential to the main FCC tunnel, with a 50 TeV proton beam. It would collect factors of thousands more luminosity than HERA while exhibiting the novel concept of synchronous, symbiotic operation alongside the pp collider. The facility would serve as the most powerful, high-resolution microscope to examine the substructure of matter ever built, with high-energy electron-proton collisions providing precise information on the quark and gluon structure of the proton.

This unprecedented facility would enhance Higgs studies, including the study of the coupling to the charm quark, and broaden the new-physics searches also performed at FCC-hh and FCC-ee. Unexpected discoveries such as quark substructure might also arise. Uniquely, in electron–proton collisions new particles can be created in lepton–quark fusion processes or may be radiated in the exchange of a photon or other vector boson. FCC-eh could also provide access to Higgs self-interactions and extended Higgs sectors, including scenarios involving dark matter. If neutrino oscillations arise from the existence of heavy sterile neutrinos, direct searches at the FCC-eh would have great discovery prospects in kinematic regions complementary to FCC-hh and FCC-ee, giving the FCC complex a striking potential to shine light on the origin of neutrino masses.

### Unknown unknowns

In principle, the LHC could have – and still could provide – answers to many of these outstanding questions in particle physics. That no new particles beyond the Higgs have yet been found, or any significant deviations from theory detected, does not mean that these questions have somehow evaporated. Rather, it shows that any expectations for early discoveries beyond the SM at the LHC – often based on theoretical, and in some cases aesthetic, arguments – were misguided. In times like this, when theoretical guidance is called into question, we must pursue experimental answers as vigorously as possible. The combination of accelerators that are being considered for the FCC project offer, by their synergies and complementarities, an extraordinary tool for investigating these questions (figure 2).

There are numerous instances in which the answer nature has offered was not a reply to the question first posed. For example, Michelson and Morley's experiment designed to study the properties of the ether ended up disproving the existence of the ether and led to Einstein's theory of special relativity. The Kamiokande experiment in Japan, originally built to observe proton decays, instead discovered neutrino masses. The LHC itself could have disproven the SM by discovering that the Higgs boson is not an elementary but a composite particle – and may still do so, with its future more precise measurements.

The possibility of unknown unknowns does not diminish the importance of an experiment's scientific goals. On the contrary, it demonstrates that the physics goals for future colliders can play the crucial role of getting a new facility off the ground, even if a completely unanticipated discovery results. This is true of all expeditions into the unknown. We should not forget that Columbus set sail to find a westerly passage to Asia. Without this goal, he would not have discovered the Americas.

### Further reading

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### Résumé

*La physique poussée dans ses limites*

*Un collisionneur de 100 km de circonférence, tel qu'imaginé par l'étude du CERN sur un futur collisionneur circulaire, pourrait répondre à plusieurs questions de la physique des particules moderne. Une machine électron-position permettrait d'améliorer considérablement la précision des mesures du Higgs et d'autres particules du Modèle standard, un collisionneur proton-proton de 100 TeV aurait plus de cinq fois le potentiel de découverte du LHC, et un collisionneur électron-proton permettrait de mesurer la sous-structure du proton avec une précision inégalée.*

**Michelangelo Mangano**, CERN, **Patrizia Azzi**, INFN Sezione di Padova, **Monica D'Onofrio**, University of Liverpool, and **Matthew McCullough**, CERN.



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Interview: Erik Verlinde

# Doubting darkness

Theorist Erik Verlinde argues that dark matter is an illusion caused by our incomplete understanding of gravity.

#### What is wrong with the theory of gravity we have?

The current description of gravity in terms of general relativity has various shortcomings. Perhaps the most important is that we cannot simply apply Einstein's laws at a subatomic level without generating notorious infinities. There are also conceptual puzzles related to the physics of black holes that indicate that general relativity is not the final answer to gravity, and important lessons learnt from string theory suggesting gravity is emergent. Besides these theoretical issues, there is also a strong experimental motivation to rethink our understanding of gravity. The first is the observation that our universe is experiencing accelerated expansion, suggesting it contains an enormous amount of additional energy. The second is dark matter: additional gravitating but non-luminous mass that explains anomalous galaxy dynamics. Together these entities account for 95 per cent of all the energy in the universe.

#### Isn't the evidence for dark matter overwhelming?

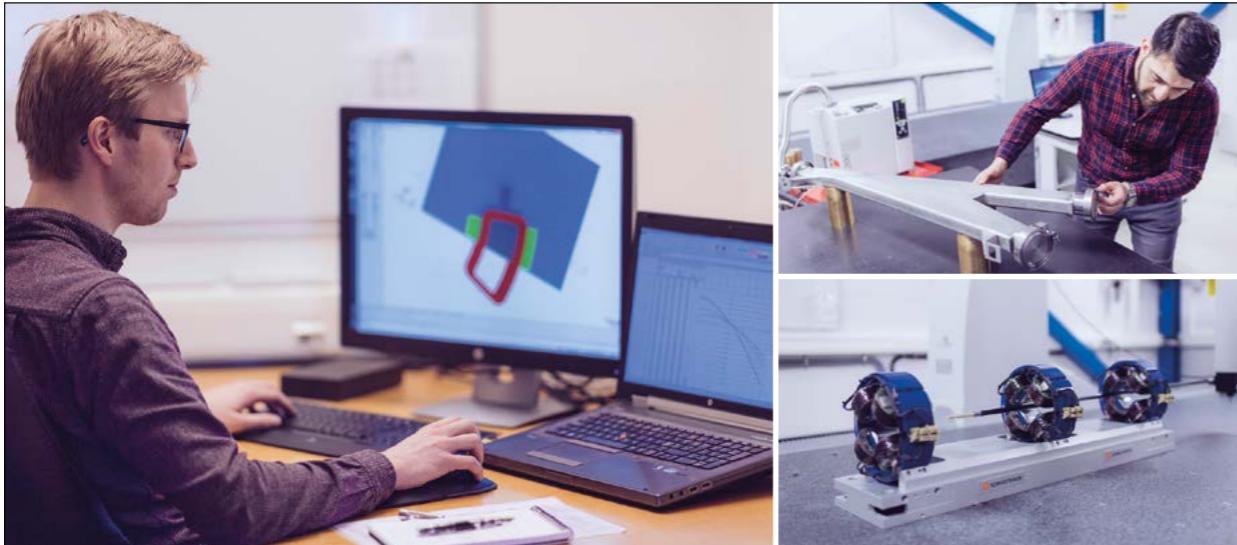
It depends who you ask. There is a lot of evidence that general relativity works very well at length scales that are long compared to the Planck scale, but when we apply general relativity at galactic and cosmological scales we see deviations. Most physicists regard this as evidence that there exists an additional form of invisible matter that gravitates in the same way as normal matter, but this assumes that gravity itself is still described by general relativity. Furthermore, although the most direct evidence for the existence of dark matter comes from the study of galaxies and clusters, not all astronomers are convinced that what they observe is due to particle dark matter – for example, there appears to be a strong correlation between the amount of ordinary baryonic matter and galactic rotation velocities that is hard to explain with particle dark matter. On the other hand, the physicists who are carrying out numerical work on particle dark matter are trying to explain these correlations by including complicated baryonic feedback mechanisms and tweaking the parameters that go into their models. Finally, there is a large community of experimental physicists who simply take the evidence for dark matter as a given.

#### Is your theory a modification of general relativity, or a rewrite?

The aim of emergent gravity is to derive the equations that govern gravity from a microscopic quantum, while using ingredients from quantum-information theory. One of the main ideas



Erik Verlinde of the University of Amsterdam in the Netherlands photographed at CERN in April following his seminar on emergent gravity.



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presence of positive dark energy, the derivation of the Einstein equations breaks down precisely in the circumstances where we observe the effects of "dark matter".

### How did the idea emerge?

The idea of emergent gravity from thermodynamics has been lingering around since the discovery by Hawking and Bekenstein of black-hole entropy and the laws of black-hole thermodynamics in the 1970s. Ted Jacobson made an important step in 1996 by deriving the Einstein equations from assuming the Bekenstein-Hawking formula, which expresses the microscopic entropy in terms of the area of the horizon measured in Planck units. In my 2010 paper [arXiv:1001.0785] I clarified the origin of the inertia force and its relation to the microscopic entropy in space, assuming that this is given by the area of an artificial horizon. After this work I started thinking about cosmology, and learnt about the observations that indicate a close connection between the acceleration scale in galaxies and the acceleration at the cosmological horizon, which is determined by the Hubble parameter. I immediately realised that this implied a relation between the observed phenomena associated with dark matter and the presence of dark energy.

### Your paper is 50 pages long. Can you summarise it here?

The idea is that gravity emerges by applying an analogue of the laws of thermodynamics to the entanglement entropy in the vacuum. Just like the normal laws of thermodynamics can be understood from the statistical treatment of microscopic molecules, gravity can be derived from the microscopic units that make up space-time. These "space-time molecules" are units of quantum information (qubits) that are entangled with each other, with the amount of entanglement measured by the entanglement entropy. I realised that in a universe with a positive dark energy, there is a contribution to the entanglement entropy that grows in proportion to area. This leads to an additional force on top of the usual gravity law, because the dark energy "pushes back" like an elastic medium and results in the phenomena that we currently attribute to dark matter. In short, the laws of gravity differ in the low-acceleration regime that occurs in galaxies and other cosmological structures.

### How did the community react to the paper?

Submitting work that goes against a widely supported theory requires some courage, and the fact that I have already demonstrated serious work in string theory helped. Nevertheless, I do experience some resistance – mainly from researchers who have been involved in particle dark-matter research. Some string theorists find my work interesting and exciting, but most of them take a "wait and see" attitude. I am dealing with a number of different communities with different attitudes and scientific backgrounds. A lot of it is driven by sociology and past investments.

### How often do you work on the idea?

Emergent gravity from quantum entanglement is now an active field worldwide, and I have worked on the idea for a number of years. I mostly work in the evening for around three hours and perhaps one hour in the morning. I also discuss these ideas with my PhD students, colleagues and visitors. In the Netherlands we have

quite a large community working on gravity and quantum entanglement, and recently we received a grant together with theorists from the universities of Groningen, Leiden, Utrecht and Amsterdam, to work on this topic.

### Within a month of your paper, Brouwer et al. published results supporting your idea. How significant is this?

My theory predicts that the gravitational force due to a centralised mass exhibits a certain scaling relation. This relation was already known to hold for galaxy rotation curves, but these can only be measured up to distances of about 100 kilo-parsec because there are no visible stars beyond this distance. Brouwer and her collaborators used weak gravitational lensing to determine the gravitational force due to a massive galaxy up to distances of one mega-parsec and confirmed that the same relation still holds. Particle dark-matter models can also explain these observations, but they do so by adjusting a free parameter to fit the data. My prediction has no free parameters and hence I find this more convincing, but more observations are needed before definite conclusions can be drawn.

### Is there a single result that would rule your theory in or out?

If a dark-matter particle would be discovered that possesses all the properties to explain all the observations, then my idea would be proven to be false. Personally I am convinced this will not happen, although I am still developing the theory further to be able to address important dynamical situations such as the Bullet Cluster (see pp26–33) and the acoustic oscillations that explain the power spectrum of the cosmic microwave background. One of the problems is that particle dark-matter models are so flexible and can therefore easily be made consistent with the data. By improving and extending the observations of gravitational phenomena that are currently attributed to dark matter, we can make better comparisons with the theory. I am hopeful that within the next decade the precision of the observations will have improved and the theory will be developed to a level that decisive tests can be performed.

### How would emergent gravity affect the rest of physics?

Our perspective on the building blocks of nature would change drastically. We will no longer think in terms of elementary particles and fundamental forces, but units of quantum information. Hence, the gauge forces responsible for the electroweak and strong interactions will also be understood as being emergent, and this is the way that the forces of nature will become unified. In this sense, all of our current laws of nature will be seen as emergent.

### Résumé

*Des doutes sur l'obscurité*

*Selon le théoricien Erik Verlinde, si l'espace, le temps et la gravité n'existent pas aux échelles les plus petites, la matière et l'énergie noires pourraient être une illusion due à une compréhension incomplète de la gravité. En mars, après un séminaire au CERN sur la gravité émergente, Erik Verlinde a évoqué avec le Courier les réactions suscitées par son travail et l'avenir de cette idée.*

**Matthew Chalmers, CERN.**

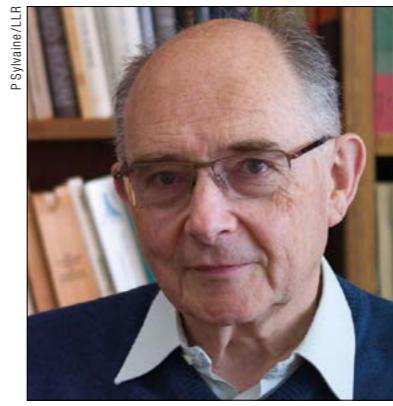
# Faces & Places

## AWARDS

### André Lagarrigue Prize 2016

Bernard Degrange, emeritus director of research at CNRS, has been awarded the 2016 André Lagarrigue Prize in acknowledgement of his exemplary career in experimental particle physics. Co-financed by the CNRS, the University Paris Sud, Linear Accelerator Laboratory (LAL), École Polytechnique, CERN and CEA, with the support of the French Physical Society, the prize was created in 2005 in honour of André Lagarrigue. Director of LAL from 1969 to 1975, Lagarrigue played a leading role in the discovery of weak neutral currents in the Gargamelle bubble-chamber experiment at CERN, thus paving the way for electroweak theory.

After completing his thesis in 1969, Degrange joined the Gargamelle

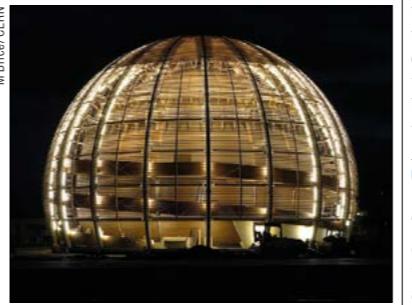


Bernard Degrange worked on bubble chambers and gamma-ray astronomy.

collaboration where he contributed to the first measurement of the ratio of the neutrino and antineutrino cross-sections on nucleons and studied exclusive channels produced in neutral or charged-current interactions. In the early 1980s he moved into the study of cosmic rays and high-energy gamma-ray astronomy, helping to discover several "blazars" in the Crab Nebula with the CAT experiment. For the simultaneous observation of gamma and X-rays during the major bursts of these extragalactic sources, Degrange was awarded the silver medal of the CNRS in 1997. Anticipating the detection power of stereoscopy associated with fast high-granularity imagery, he made major contributions to the design and the results of the HESS experiment.

## CERN communications make the grade

The Czech Republic's Academia Film Olomouc has decided to give its 2017 Award for Contribution to Science Communication to CERN, for its "long-lasting commitment not only to research in the edge of science but also to communication of its results and science in general to broader public". The committee described CERN as a pioneer in developing new ways to communicate science via social media, film, traditional media and events such as CineGlobe. The award ceremony will take place on 29 April at Palacký University Interactive Science Centre in Olomouc.



CineGlobe is one of the many ways that CERN communicates its science.

## EVENT Hidden Figures premiered



The panel recalled awkward moments in their careers that highlighted attitudes to women in science.

On 2 March, in collaboration with CERN and 20th Century Fox, the Pathé cinema in Geneva hosted an advance screening of the film *Hidden Figures*, followed by a debate on the position of women in science. The film tells the story of three African-American female scientists who played key roles in the US space conquest, contributing in particular to the preparations for putting astronaut John Glenn into orbit. After the film, Maite Barroso Lopez of CERN's IT department, Stéphanie Beauceron and Anne-Marie Magnan from CMS, and Andry Rakotozafindrabe from ALICE shared their experiences of science careers with the audience in a debate. They answered questions about the alleged rivalry among women, about whether there is a link between CERN and NASA as pictured in the film, and about their mentors.

## CORRECTION

There was an error in the Compiler's Note on the Archive page of the March issue of the *Courier* (p54) concerning the g-2 value of the muon. The discrepancy between Standard Model theory and experimental data was not evident in the CERN

**Periodic Table of the Elements**

Element Name	Atomic No.	Symbol
Hydrogen	1	H
Lithium	3	Li
Beryllium	4	Be
Sodium	11	Na
Magnesium	12	Mg
Potassium	19	K
Calcium	20	Ca
Rubidium	37	Rb
Sodium	38	Sr
Cesium	55	Cs
Francium	87	Fr
Radium	88	Ra

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18	He
13	Boron
14	Carbon
15	Nitrogen
16	Oxygen
17	Fluorine
5	Neon
6	Carbon
7	Nitrogen
8	Oxygen
9	Fluorine
10	Neon
11	Hydrogen
12	Boron
13	Carbon
14	Nitrogen
15	Oxygen
16	Fluorine
17	Neon
18	Argon
19	Silicon
20	Phosphorus
21	Sulfur
22	Chlorine
23	Ar
24	Yttrium
25	Scandium
26	Titanium
27	Vanadium
28	Chromium
29	Manganese
30	Iron
31	Cobalt
32	Nickel
33	Copper
34	Zinc
35	Gallium
36	Germanium
37	Indium
38	Aluminum
39	Thallium
40	Zinc
41	Nickel
42	Molybdenum
43	Tungsten
44	Ruthenium
45	Rhenium
46	Pd
47	Rh
48	Pt
49	Ru
50	Ir
51	Os
52	Os
53	Te
54	Xe
55	Lu
56	Hf
57	Ta
58	W
59	Ta
60	Os
61	Os
62	Os
63	Os
64	Os
65	Os
66	Os
67	Os
68	Os
69	Os
70	Os
71	Lu
72	Hf
73	Ta
74	W
75	Ta
76	Os
77	Ir
78	Pt
79	Ir
80	Ho
81	Tl
82	Pb
83	Bi
84	Po
85	At
86	Rn

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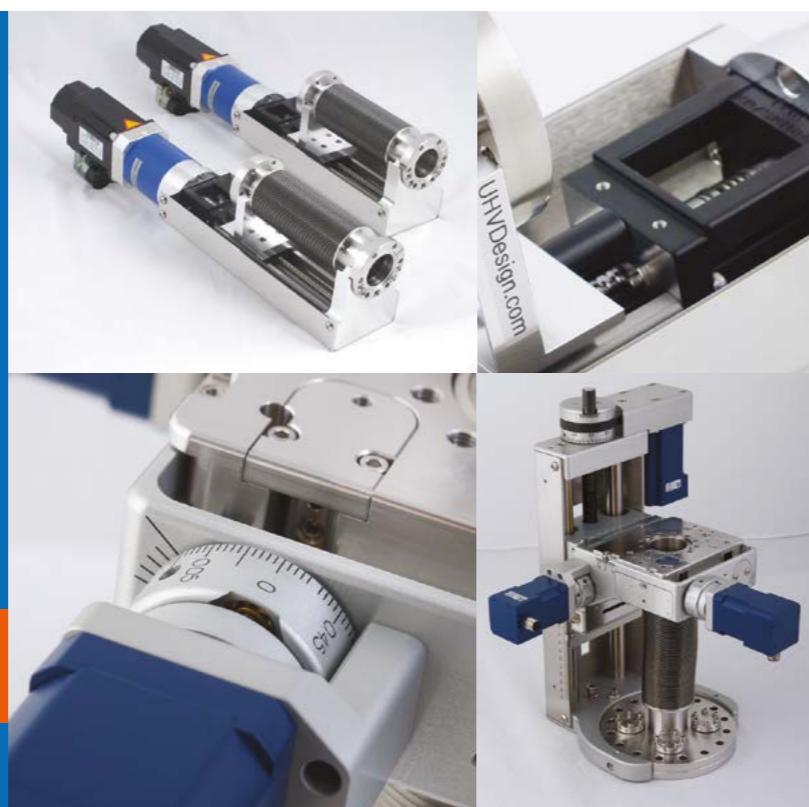
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# CERN COURIER

VOLUME 57 NUMBER 4 MAY 2017



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Faces & Places

## CONFERENCES

# A wealth of new results at Moriond

The 2017 Rencontres de Moriond conference took place in La Thuile, Italy, from 18 March to 1 April, with around 270 participants attending the two-week-long event. The four main LHC experiments presented many fresh results, ranging from precise measurements of the Standard Model (SM) to searches for new physics, including the first obtained with the full 13 TeV data set collected during 2016. Numerous results from experiments outside CERN were also presented, especially in the neutrino field, and participants heard some of the latest developments in theory.

Analyses of the Higgs boson presented by CMS included a precise new measurement of the Higgs mass. CMS also showed results from searches for associated Higgs-top production in final states with multiple leptons, which provides direct evidence for the existence of a top-quark Higgs coupling with a measured signal strength consistent with the SM. Both CMS and ATLAS showed new measurements of total and differential cross-sections of the Higgs boson decaying into four leptons or two photons, which agree with the SM. ATLAS also showed preliminary results from searches for the rare Higgs-boson decay to two muons, which are now approaching the sensitivity required to observe a signal.

Concerning other SM particles, ATLAS presented its first measurement of the mass of the W boson with similar precision to the previous best result from a single experiment. The D0 and CDF collaborations at the former Tevatron collider, meanwhile, presented precise measurements of the



Moriond is the traditional winter meeting for particle physicists.

top-quark mass.

Among the highlights of searches for physics beyond the SM were new limits on supersymmetric particles from ATLAS, which now exclude models with particle masses above 2 TeV (see p11). ATLAS also showed searches for new heavy particles decaying to jets of hadron particles, excluding non-elementary quarks with masses as large as 6 TeV. Both ATLAS and CMS are also looking for new heavy resonances decaying to a vector and a Higgs boson: ATLAS sees a 3.3 standard deviation local excess for a  $W \rightarrow WH$  decay at masses around 3 TeV, whereas CMS sees a similar local excess but at a lower mass.

Exotic searches from CMS using the full 2016 data sample place new limits on many scenarios including dark matter, new types of quarks, vector bosons and gravitons. No significant deviations from SM predictions have been observed so far by CMS and ATLAS.

Results of searches for bottomonium states at the Belle experiment and charmonium-like states at BESIII were also shown. In particular, the analysis of the  $Y(4260)$  appears to be inconsistent with a single peak at more than seven standard deviations.

The heavy-flavour field also saw several new results presented by LHCb. Besides an update of the measurement of the rarest decay of a particle containing a b quark ever observed, and the recent observation of a new system of five particles all in a single analysis, LHCb presented the most precise single measurement of the CP-violating phase  $\phi_s$ . The LHCb collaboration is also putting in place new analyses to shed light on two flavour anomalies:  $R(D^*)$  and  $R(K)$ , which remain around three standard deviations away from their SM values. A measurement of the angular coefficient  $P_5$  in the flavour-changing neutral current decay of B mesons was also presented by ATLAS, CMS and Belle, and was found to be compatible with previous LHCb results.

In the dedicated heavy-ion session, ALICE showed recent results from large samples of proton-proton, lead-lead, and proton-lead collisions collected in 2015 and 2016. One of the new results, concerning the azimuthal asymmetry of the production of  $J/\psi$  mesons, shows that heavy quarks directly "feel" the shape and size of the asymmetric quark-gluon plasma produced in the interaction region.

With LHC Run 2 about to get under way with a similar integrated-luminosity target as achieved in 2016, the search for new physics is in full swing at CERN and elsewhere.

## Madagascar event marks 15 years

The 8th High-Energy Physics (HEP) Madagascar International Conference (HEPMAD 2016) was held in Antananarivo, Madagascar, from 13 to 18 October. It was the event's 15th anniversary and some 50 participants – including 15 invited high-energy physicists from abroad – were present. It is the only conference series in high-energy physics and indeed across all science held in sub-Saharan countries, and aims to be both pedagogical and topical, reviewing the latest experimental and theoretical results in high-energy physics.

Recent results from the LHC, including



HEPMAD is an opportunity for foreign participants to discover the richness of Malagasy science, nature and culture.

precision tests of the Standard Model, Higgs properties and searches for new physics, were presented by ATLAS and CMS. Theory talks, meanwhile, covered topics including the status of the muon anomalous magnetic moment and determinations of the masses and couplings of charmonium and

bottomonium states using QCD spectral sum rule. The high-energy physics talks were complemented by national contributions about climate science and sustainable technologies for energy.

The next HEP MAD event will take place in Antananarivo on 21–27 September 2017.

## Faces &amp; Places



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## Celebrating 90 years of quantum mechanics

In the digital era, where we are surrounded by ever more technological innovations, it is interesting to reflect on the enormous progress that modern physics has made following the quantum-mechanics revolution 90 years ago. The story began in 1900, with Max Planck's suggestion that light is quantised, which Albert Einstein was the first to fully comprehend and exploit. Then, in the mid 1920s, a revolution in physics took place: quantum mechanics was formulated by Werner Heisenberg, Erwin Schrödinger, Paul Dirac and a handful of other young geniuses under the supervision of Niels Bohr and with Einstein as a critical voice. At the famous Fifth Solvay Conference in 1927, where 17 of the participants either already were or were to be Nobel laureates, much of the basic elements of quantum mechanics were ready and discussed. Never in the history of physics has so much been achieved by so few in such a short time.

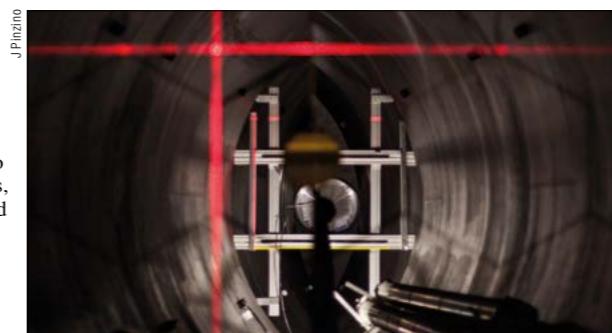
To commemorate the beginning of this revolution and its impact on the modern world, a special conference titled 90 Years of Quantum Mechanics was held at the Institute of Advanced Study at Nanyang University in Singapore on 23–26 January. The event gathered leading experts in the foundations of quantum mechanics, quantum cosmology, quantum gravity, quantum field theory, quantum condensed matter, quantum optics, quantum information and technology, and quantum chemistry. Altogether there were 30 talks, with six speakers being Nobel laureates. Some 300 participants attended from all over the world, with a strong emphasis on South East Asia and China.

Luminaries of the physics world gathered to mark 90 years of quantum progress.

## Physics at the intensity frontier

The Standard Model of particle physics has proved to be a consistent description of nature's fundamental constituents and their interactions, and its predictions have been confirmed by numerous experiments, most recently with the discovery of the Higgs boson at the LHC. However, the model fails to explain several phenomena in particle physics, astrophysics and cosmology, and it is expected that yet unknown particles or interactions are needed to explain these puzzles.

Our inability to observe new particles possibly lies in their extremely feeble interactions. If true, this would imply that experiments are needed not just at the high-energy frontier but also at the "intensity frontier", by increasing the number of collisions to search for rare events. In 2016, CERN created a Physics Beyond Colliders study group with a mandate to explore opportunities offered by the CERN accelerator complex to address outstanding questions in particle physics through projects complementary to high-energy colliders



(CERN Courier November 2016 p28).

A two-week-long "theory institute" took place at CERN from 20 February to 3 March to discuss the theory and phenomenology of possible new physics at low energy scales. More than 100 participants from 21 countries discussed the theoretical landscape, predicting new light particles and "dark forces". The potential for the new physics reach of existing and planned

intensity-frontier experiments – SHiP, NA62, DUNE, MATHUSLA and many others – was discussed. These future experiments are at different stages today, ranging from the preparation of a comprehensive design report (SHiP) to a letter of intent (MATHUSLA). The time is therefore ripe to ensure that any necessary changes to the experiment designs can still be made to the physics reach of intensity-frontier experiments.

a realistic option that is compatible with the level of resources available at CERN.

Another highlight was the summary of the successful demonstration of key CLIC concepts obtained by the recently completed CTF3 test programme at CERN. Part of the CTF3 facility has now been approved for conversion into an electron accelerator facility called CLEAR (CERN Linear Electron Accelerator for Research), providing an open user facility for accelerator R&D, irradiation and training. The future CLEAR programme will include CLIC high-gradient and instrumentation studies.

The successful operation of high-gradient accelerating structures and experience with advanced beam-dynamics techniques, developed for the small dimensions of these structures, have inspired a growing number of applications outside of particle physics. Applications of high-gradient and X-band technology include compact linacs and advanced diagnostics for photon sources, as well as medical applications. Many of the technologies under study for the CLIC detector are also of interest to the HL-LHC, where the high granularity and time-resolution needed for CLIC are equally crucial. Other communities also benefit: for example, software reconstruction techniques developed for particle flow at linear colliders have been applied to current and next-generation neutrino experiments.



Acceleration in the two-beam module at the CTF3 facility was thoroughly tested in 2015–2016, verifying power production and energy gain while operating at the nominal CLIC gradient of around 100 MV/m.

The annual Compact Linear Collider (CLIC) workshop took place at CERN on 6–10 March, attracting 220 collaborators from 26 countries to discuss the latest status of the CLIC accelerator and detector studies. CLIC is a future multi-TeV electron–positron linear collider at CERN envisaged for the era beyond the High-Luminosity LHC (HL-LHC). First beams in CLIC could be foreseen in 2035 and be the starting point of a 20–25 year-long physics programme.

During the workshop particular focus was placed on the recently published updated staging scenario for the CLIC accelerator, where construction and operation are pursued in three stages with collision energies of 0.38, 1.5 and 3 TeV, respectively (CERN Courier November 2016 p20). At its initial energy, CLIC is optimised for Higgs and top measurements and enables a scan at the top-quark pair-production threshold, while the higher-energy stages provide the best sensitivity to new physics through direct and indirect searches. High-energy operation also provides access to rare processes such as double Higgs production, which is sensitive to the important Higgs self-coupling.

## Faces & Places



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## RuPAC16 demonstrates international outlook

For many years the biennial Russian conference on accelerator physics and technology, RuPAC, was viewed by the international accelerator community as an internal event for representatives of the Soviet accelerator school. Although representatives of the latter have actively been working in accelerator centres around the world since the beginning of perestroika in the late 1980s, it is indeed rare to see a foreign specialist invited to a prominent position in Russia. But that situation is changing, and RuPAC16 held at St Petersburg State University (SPbSU) in November last year saw the world's largest accelerator projects represented and more than 60 reports by participants from outside Russia. For the first time, the event also provided simultaneous translation from Russian to English.

Today, RuPAC has become an excellent platform for information exchange between researchers working in accelerator science and technology and related issues. More than 40 reports from SPbSU students were presented at RuPAC16, and the geographical reach of the event extended to 260 participants from 67 institutions in 13 countries. In addition to traditional participants Ukraine, Belarus and Armenia, the event was attended by experts from China, South Africa, UK, Germany, Italy, Canada, US, Japan, Poland, Sweden and Switzerland.

CERN's High-Luminosity LHC and Future Circular Collider projects were presented, and several other reports were devoted to mutual research between Russian and European scientists. A particular focus was the FAIR-NICA collaboration concerning production and testing of superconducting accelerator magnets. Two new facilities have been commissioned at the Joint Institute for Nuclear Research (JINR) in Dubna for the international FAIR and NICA projects in Germany and Russia, respectively. The first is a high-tech assembly and testing hall for superconducting magnets, while the second is a heavy-ion linear accelerator that accelerates ions up to Au<sup>31+</sup> to an energy of 3.2 MeV per nucleon.

Status reports from all accelerator facilities of JINR were presented, as were activities at other major accelerator centres. The National Research Centre Kurchatov Institute carries out a broad range of activities, among them the development of a synchrotron radiation source and operation of the U-70 facility, Russia's largest accelerator complex, with its new facility for carbon-beam medical applications and plans to attain high-power neutron fluxes. Important work also continues at the Institute for Nuclear Research of the Russian Academy of Sciences and the Budker Institute of Nuclear Physics (BINP). The latter facility has established itself as a manufacturer and supplier of high-tech accelerator facilities to the

international market, such as electronic cooling systems, electron accelerators for industrial applications, components and synchrotron systems, magnetic systems and power systems, for example for the European X-FEL. BINP is also actively involved in the construction of FAIR and NICA, while continuing to develop domestic projects including a free electron laser, two electron–positron colliders (VEPP 2000 and VEPP4M) and facilities for radioisotope analysis.

The conference concluded with a satellite meeting devoted to NICA, for which most Russian accelerator centres are already involved in manufacturing elements. Backed by the Russian government since 2016, NICA is a major factor driving current

trends in the country's accelerator science and technology. The success of this project will influence government support of other accelerator projects, such as the super C-tau factory project at BINP.

Although Russia has a highly developed scientific infrastructure and potential to design complex accelerator facilities, the corresponding market is underestimated. Applied research projects such as medical beams for Russia's first proton-therapy facility, along with the Russian "mega-science" projects, are thus a vital factor for accelerating Russian industry. As is clear, such projects are reinforcing the international outlook of Russian accelerator science and technology. The next RuPAC event will be held in autumn 2018.

## Visits

Jordan/CERN



**Marianne Thyssen**, MEP and European commissioner for employment, social affairs, skills and labour mobility, toured CERN on 10 March, during which she visited CMS, ISOLDE and the new MEDICIS facility. She is pictured signing the guestbook with CERN Director-General Fabiola Gianotti.

S Bennett/CERN



**Enrique Cabrero Mendoza**, director-general of CONACYT in Mexico, visited CERN on 23 March, immediately following the 9th CERN–Latin American School held in San Juan del Rio. He visited the ALICE experiment and the LHC tunnel before signing the guestbook with CERN's head of relations with associate members and non-Member States, Emmanuel Tsesmelis, and director of international relations Charlotte Warakaulle.



UK minister of state for universities, science, research and innovation **Jo Johnson** (top) came to CERN on 29 March, during which he visited the underground area at CMS. Two days later, chief scientific adviser to the UK government **Mark Walport** (bottom) also visited CERN, taking in the computing centre, ATLAS and the Antiproton Decelerator.

Image credits: S Bennett/CERN

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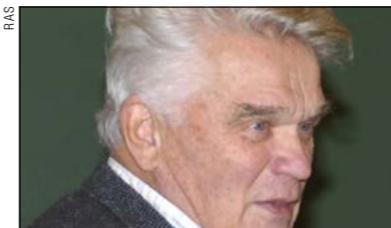
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## OBITUARIES

**Ludwig Faddeev 1934–2017**

Ludwig Dmitrievich Faddeev was an outstanding scientist who made exceptional contributions to modern theoretical and mathematical physics. He was born in 1934 in what is now St Petersburg, Russia, and attended Leningrad University. His name is well known in theoretical physics in connection with the quantum three-body system, and he made decisive contributions to the quantisation of the Yang–Mills theory and gravitational fields. The Faddeev–Popov covariant prescription for quantisation of non-Abelian gauge theories ("Faddeev–Popov ghosts", discovered in 1966–1967) laid some of the foundations for the Standard Model of strong, weak and electromagnetic interactions.

Faddeev is one of the creators of modern mathematical physics, and he believed that mathematical beauty is the most important guiding principle in physics. As predecessors of this point of view, he cited Dirac, Weyl and Fock – the latter having been one of his teachers at Leningrad. In the 1970s, Faddeev was one of the first to recognise the importance of the newly discovered solutions of nonlinear partial differential equations – solitons, and he believed that they would reduce the number of fields in Lagrangians.



Mathematical physicist Ludwig Faddeev.

His work stimulated the widespread application of solitons in relativistic quantum field theory.

Work by Faddeev and his group on the so-called quantum method of inverse scattering is now the basis of a flourishing branch of mathematics and mathematical physics involving quantum groups and their representations. In 1980, Faddeev also clarified the group-theoretical origin of anomalies in the context of "cocycles", after which he continued his work on multidimensional solitons and Yang–Mills theory in the 1990s until his retirement.

Faddeev created a very special atmosphere at the Leningrad Steklov Mathematics Institute in the 1970s and 1980s, during

which he supervised several currently world-renowned mathematicians and theoretical physicists. He visited the theory department at CERN for the first time in 1973 and made several further visits.

The importance of Faddeev's work has been recognised with awards for both physics and mathematics, including the 1975 Dannie Heineman Prize for Mathematical Physics of the American Physical Society; the 1990 ICTP Dirac Medal; the 2002 Pomeranchuk Prize; the 1996 Max Planck Medal; the 1995 and 2004 Russian Federation State Prizes; the 2006 Henri Poincaré Prize; and the 2008 Shaw Prize. Faddeev was a member of the Russian Academy of Sciences from 1976, as well as a number of foreign academies including the US National Academy of Sciences and the French Academy of Sciences. From 1976 to 2000 he was deputy director of the Steklov Mathematical Institute and was the founding director of the Euler International Mathematical Institute, which he led until his death.

Ludwig Faddeev was a man of great honesty who was always ready to discuss new ideas. We will miss him very much.

• Irina Aref'eva and Andrey Slavnov,  
Steklov Mathematics Institute.

**Victor Kryshkin 1939–2017**

Victor Kryshkin was a member of the CMS collaboration.

Victor Kryshkin of the Institute for High Energy Physics (IHEP) in Protvino passed away on 16 January after a long illness. He was a long-standing member of the CMS collaboration and made several important contributions to the CMS detector.

After graduation from Voronezh University, Kryshkin started work as an experimental physicist in Tomsk Institute for Nuclear Physics. There he carried out his first experiment: measuring the lifetime of the neutral  $\pi$  meson, which was included in the *Review of Particle Physics*. Since 1973 he worked at IHEP in Protvino, and was one of the key people who proposed and then established the two-arm magnetic spectrometer, with the main aim to study hadron production with high-momentum transfer in proton–proton and proton–nuclear interactions. Many important scientific results revealing the structure of elementary particles were obtained using

this apparatus. The most important result of these studies was the observation of a kink in the dependence of the cross-section for the production of meson pairs on the sum of transverse momenta in proton–proton interactions at an energy of 70 GeV.

In 1991 Kryshkin became professor of physics at IHEP, and since 1992 he was an

active participant in the CMS experiment at CERN's Large Hadron Collider. He was a technical co-ordinator of the CMS hadron-endcap calorimeter and made major contributions to the design of the detector. Under his leadership, the Protvino group assembled all of the active elements of the hadron-endcap calorimeters. More recently, Kryshkin performed several original studies on gas-discharge detectors, which he was planning to use in calorimetry. The novelty of his research has been confirmed by 21 registered patents.

Victor Kryshkin was not only a prominent scientist, he was also a very interesting companion, possessing an encyclopedic knowledge in many fields. His main hobby was studying astrophysics and space science and he was also interested in history and art. He read a lot, particularly Russian and English literature, and liked to tell jokes and anecdotes. Living in

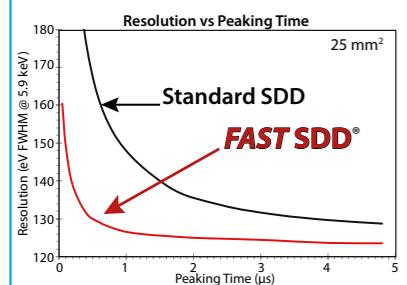
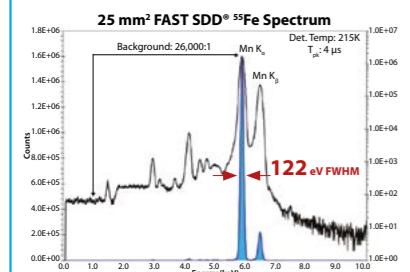
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## Faces & Places

Leningrad after the Second World War, Kryshkin learnt how to paint, and never missed an opportunity to visit an art gallery or museum. He could not imagine his life without music, especially jazz. He loved his family very much and leaves

behind his wife Galina, a son and three granddaughters.

On behalf of the CMS collaboration, we offer our condolences to his family and colleagues.

• His friends and colleagues.

## Heinrich Leutz 1928–2017



Leutz was an active member of CERN's "LAA" programme.

Heinrich Leutz, who joined CERN in 1966 as leader of the BEBC physics aspects group, passed away on 26 February, aged 89, following several years of serious health problems. During his long and active career in experimental physics he took part in three main research fields: nuclear spectroscopy; high-energy physics with bubble chambers; and detector technologies for hadron colliders. In each of these areas, Leutz was responsible for original inventions that led to improved physics results.

During his first active research period in the 1950s and 1960s, based at the University of Heidelberg, Leutz led a research group studying colour centres in crystals, nuclear beta decay, electron capture, polarisation and photon spectroscopy. One of his remarkable contributions during this period concerned the idea to grow scintillation crystals doped with radioactive isotopes, which allowed precise spectroscopy to be performed while avoiding source-thickness and scattering-correction effects. Important publications from this period demonstrate excellent research results in nuclear physics during the 1950s and 1960s.

His move to high-energy physics started in the 1970s when he joined the French-German-CERN programme to design and construct the Big European Bubble Chamber (BEBC) at CERN as the SPS started up. Responsible for the physics aspect of the BEBC project, Leutz soon became well known in the bubble-chamber community around the world. His team developed a track-sensitive liquid-hydrogen-filled, optically transparent target box to observe primary particle interactions, surrounded by a heavy-liquid neon-hydrogen mixture to provide improved photon conversion. His bold proposal was no less than to operate a "bubble chamber inside a bubble chamber" by finding a temperature and pressure regime such that the pressure cycle was transmitted from the heavy liquid to the hydrogen volume for primary interactions, allowing interactions and tracks in both media to be visualised on the same photo. A further step was the construction of a high-resolution fast-cycling bubble

chamber (LEBC activity) that was used for charm physics and allowed one of the first definitive studies of charm production at a proton facility.

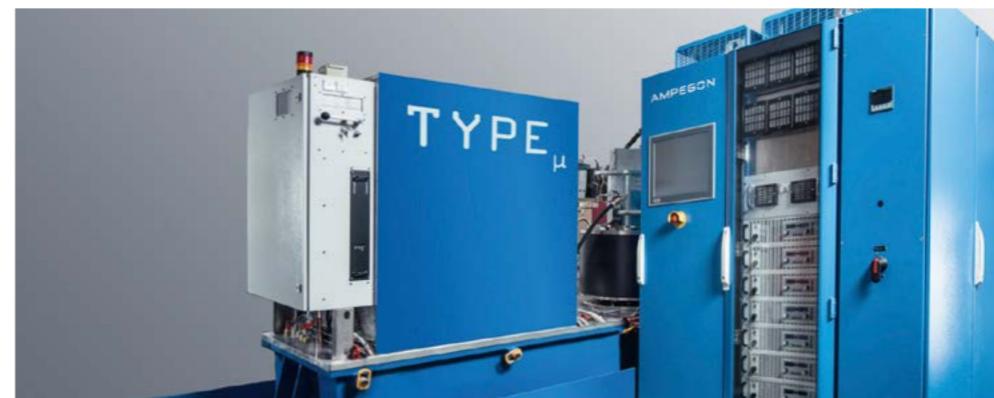
After the closure of bubble chambers around 1984, Leutz concentrated on promoting detector technologies for high-energy colliders within the CERN LAA (Lepton Asymmetry Analyser) programme. In particular, he dedicated his efforts to the development of plastic scintillating fibres and new photodetectors called hybrid photon detectors for particle tracking in LHC-like environments and for non-high-energy physics applications. In this last phase of his professional career, he particularly enjoyed being surrounded by motivated and motivating young people: a new generation that he endeavoured to shape and which had the great opportunity to be mentored by him. Books and publications testify to his outstanding contributions to experimental physics, even beyond his retirement from CERN in 1993.

Throughout his professional life, Leutz developed his exceptional talents to promote original ideas, establish collaborations with physics teams worldwide, motivate high-level technical support in his own team and – last but not least – make friends to whom he always offered great hospitality at his home, together with his wife Ingrid. Whenever they meet at CERN, friends and former colleagues recall the great times they spent with Heinrich Leutz.

• His friends and colleagues.

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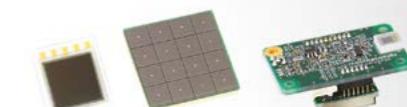
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VOLUME 57 NUMBER 4 MAY 2017



## Bookshelf

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### Challenges and Goals for Accelerators in the XXI Century

By Oliver Brüning and Stephen Myers (eds)

World Scientific

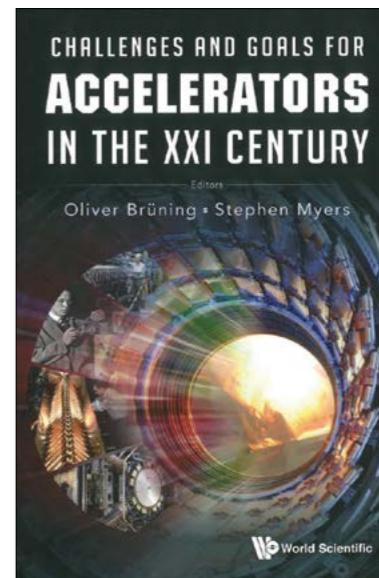
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This mighty 840 page book covers an impressive range of subjects divided into no less than 45 chapters. Owing to the expertise and international reputations of the authors of the individual chapters, few if any other books in this field have managed to summarise such a broad topic with such authority. While too numerous to list in the space provided, the full list of authors – a veritable “who’s who” of the accelerator world – can be viewed at [worldscientific.com/worldscibooks/10.1142/8635#toc](http://worldscientific.com/worldscibooks/10.1142/8635#toc).

The book opens with two chapters devoted to a captivating historical review of the Standard Model and a general introduction to accelerators, and closes with two special sections. The first of these is devoted to novel accelerator ideas: plasma accelerators, energy-recovery linacs, fixed-field alternating-gradient accelerators, and muon colliders. The last section describes European synchrotrons used for tumour therapy with carbon ions and covers, in particular, the Heidelberg Ion Therapy Centre designed by GSI and the CERN Proton Ion Medical Machine Study. The last chapter describes the transformation of the CERN LEIR synchrotron into an ion facility for radiobiological studies.

Concerning the main body of the book, 17 chapters look back over the past 100 years, beginning with a concise history of the three first lepton colliders: AdA in Frascati, VEP-1 in Novosibirsk and the Princeton-Stanford electron-electron collider. A leap in time then takes the reader to CERN’s Large Electron-Positron collider (LEP), which is followed by a description of the Stanford Linear Collider. Unfortunately, this latter chapter is too short to do full justice to such an innovative approach to electron-positron collisions.

The next section is devoted to beginnings, starting from the time of the Brookhaven Cosmotron and Berkeley Bevatron. The origin of alternating-gradient synchrotrons is well covered through a description of the Brookhaven AGS and the CERN Proton Synchrotron. The first two hadron colliders at CERN – the Intersecting Storage Rings (ISR) and the Super Proton Synchrotron (SPS) proton-antiproton collider – are then



and more than 90% of the world’s total man-made quantity of nuclear antimatter. This section of the book concludes with a description of the lepton-proton collider HERA at DESY, the GSI heavy-ion facility, and the rare-isotope facility REX at ISOLDE. Space is also given to the accelerator that was never built, the US Superconducting Super Collider (SSC), of which “the hopeful birth and painful death” is recounted.

The following 25 chapters are devoted to accelerators for the 21st century, with the section on “Accelerators for high-energy physics” centred on the Large Hadron Collider (LHC). In the main article, magisterially written, it is recalled that the 27 km length of the LEP tunnel was chosen having already in mind the installation of a proton-proton collider, and the first LHC workshop was organised as early as 1984. The following chapters are dedicated to ion-ion collisions at the LHC and to the upgrades of the main ring and the injector. The high-energy version of the LHC and the design of a future 100 km-circumference collider (with both electron-positron and proton-proton collision modes) are also covered, as well as the proposed TeV electron-proton collider LHeC. The overall picture is unique, complete and well balanced.

Other chapters discuss frontier accelerators: super B-factories, the BNL Relativistic Heavy Ion Collider (RHIC) and its electron-ion extension, linear electron-positron colliders, electron-positron circular colliders for Higgs studies and the European Spallation Source. Special accelerators for nuclear physics, such as the High Intensity and Energy ISOLDE at CERN and the FAIR project at GSI, are also discussed. Unfortunately, the book does not deal with synchrotron light sources, free electron lasers and high-power proton drivers. However, the latter are discussed in connection with neutrino beams by covering the CERN Neutrinos to Gran Sasso project and neutrino factories.

•

The book is aimed at engineers and physicists who are already familiar with particle accelerators and may appreciate the technical choices and stories behind existing and future facilities. Many of its chapters could also be formative for young people thinking of joining one of the described projects. I am convinced that these readers will receive the book very positively.

• Ugo Amaldi, TERA Foundation.

## Bookshelf

### Big Data: Storage, Sharing, and Security

By Fei Hu (ed.)

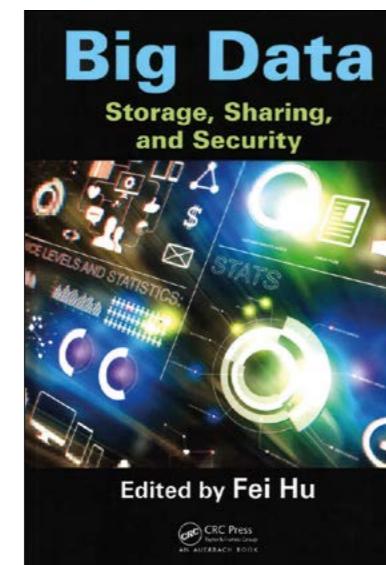
CRC Press

Nowadays, enormous quantities of data in a variety of forms are generated rapidly in fields ranging from social networks to online shopping portals to physics laboratories. The field of "big data" involves all the tools and techniques that can store and analyse such data, whose volume, variety and speed of production are not manageable using traditional methods. As such, this new field requires us to face new challenges. These challenges and their possible solutions are the subject of this book of 17 chapters, which is clearly divided into two sections: data management and security.

Each chapter, written by different authors, describes the state-of-the-art for a specific issue that the reader may face when implementing a big-data solution. Far from being a manual to follow step-by-step, topics are treated theoretically and practical uses are described. Every subject is very well referenced, pointing to many publications for readers to explore in more depth.

Given the diversity of topics addressed, it is difficult to give a detailed opinion on each of them, but some deserve particular mention. One is the comparison between different communication protocols, presented in depth and accompanied by many graphs that help the reader to understand the behaviour of these protocols under different circumstances. However, the black-and-white print makes it difficult to differentiate between the lines in these graphs. Another topic that is nicely introduced is the SP (simplicity and power) system, which makes use of innovative solutions to aspects such as the variety of data when dealing with huge amounts. Even though the majority of the topics in the book are clearly linked to big data, some of them are related to broader computing topics such as deep-web crawling or malware detection in Android environments.

Security in big-data environments is widely covered in the second section of the book, spanning cryptography, accountability and cloud computing. As the authors point out, privacy and security are key: solutions are proposed to successfully implement a reliable, safe and private platform. When managing such amounts of data, privacy needs to be carefully treated since delicate information could be extracted. The topic is addressed in several chapters from different points of view, from looking at outsourced data to accountability and integrity. Special attention is also given to cloud environments, since they are not as controlled



astrophysical objects at different stages of their evolution as well as in plasma, condensed-matter and nuclear physics. It is also of great interest for the physics of high-energy concentrations that are either already attained or can be reached in the near future under controlled terrestrial conditions.

Ultra-extreme astrophysical and nuclear-physical applications are also analysed. Here, the thermodynamics of matter is affected substantially by relativity, high-power gravitational and magnetic fields, thermal radiation, the transformation of nuclear particles, nucleon neutronisation, and quark deconfinement.

The book is intended for a wide range of specialists who study the EOS of matter and high-energy-density physics, as well as for senior students and postgraduates.

### Theory of Quantum Transport at Nanoscale: An Introduction

By Dmitry A Ryndyk

Springer

This book provides an introduction to the theory of quantum transport at the nanoscale – a rapidly developing field that studies charge, spin and heat transport in nanostructures and nanostructured materials. The theoretical models and methods recollect in the volume are widely used in nano-, molecular- and bio-electronics, as well as in spin-dependent electronics (spintronics).

The book begins by introducing the basic concepts of quantum transport, including the Landauer–Büttiker method; the matrix Green function formalism for coherent transport; tunnelling (transfer) Hamiltonian and master equation methods for tunnelling; Coulomb blockade; and vibrons and polaron.

In the second part of the book, the author gives a general introduction to the non-equilibrium Green function theory, describing first the approach based on the equation-of-motion technique, and then a more sophisticated one based on the Dyson–Keldysh diagrammatic technique. The book focuses in particular on the theoretical methods able to describe the non-equilibrium (at finite voltage) electron transport through interacting nanosystems, specifically the correlation effects due to electron–electron and electron–vibron interactions.

The book would be useful for both masters and PhD students and for researchers or professionals already working in the field of quantum transport theory and nanoscience.

as those "in house". Cloud environments may require data to be securely transmitted, stored and analysed to avoid access by unauthorised sources. Proposed approaches to apply security include encryption, authorisation and authentication methods.

The book is a good introduction to many of the aspects that readers might face or want to improve in their big-data environment.

• Daniel Lanza García, CERN.

### Books received

#### Thermodynamics and Equations of State for Matter: From Ideal Gas to Quark–Gluon Plasma

By Vladimir Fortov  
World Scientific

This monograph presents a comparative analysis of different thermodynamic models of the equation of state (EOS). The author aims to present in a unified way both the theoretical methods and experimental material relating to the field.

Particular attention is given to the description of extreme states reached at high pressure and temperature. As a substance advances along the scale of pressure and temperature, its composition, structure and properties undergo radical changes, from the ideal state of non-interacting neutral particles described by the classical statistical Boltzmann function to the exotic forms of baryon and quark–gluon matter.

Studying the EOS of matter under extreme conditions is important for the study of

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# CERN Courier Archive: 1974

A LOOK BACK TO CERN COURIER VOL. 14, MAY 1974, COMPILED BY PEGGIE RIMMER

## Our changing view of the nature of matter 1954–1974

### The electromagnetic force

In quantum electrodynamics (QED) intermediary photons removed the enigma of “action at a distance” between charged particles. However, when trying to calculate physical quantities we finished up with infinite values. A charged particle sets up its photon cloud which changes the properties of the charged particle which changes the properties of the cloud and so on. In the late 1940s, R P Feynman, J Schwinger and S Tomonaga noticed that behind the infinities lie apparent infinities of particle mass and charge. When they “renormalized” the theory by feeding in physically observed values of mass and charge, finite values emerged for electromagnetic phenomena.

But why do we have to plug in the observed mass and charge for the calculations to work with such perfection? It would obviously be philosophically more satisfying if they emerged naturally from the theory itself.

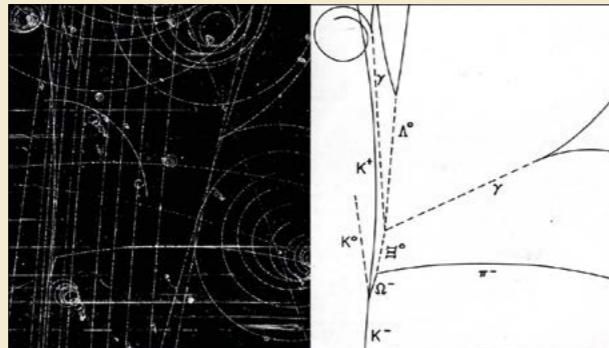
Perhaps the electron is a black hole! One can plausibly argue that its Schwarzschild radius of about  $10^{-55}$  cm would give it enough size to get rid of the QED infinities and give the correct electron mass. So perhaps gravitation is deeply involved with the electric properties of matter but so far no firm framework has been found for these ideas.

### The strong force

In 1954 the picture was of protons and neutrons [baryons] bound in the nucleus through intermediary mesons, pions. But trouble was brewing. A heavier meson, the kaon, had been spotted in nuclear emulsion photographs of cosmic rays, and heavier baryons (such as the lambda and sigma) had been seen.

The floodgates really opened when the large bubble chambers of L Alvarez came into operation at the Berkeley 6 GeV Bevatron. A whole host of new mesons and baryons were identified and the list has grown to include over 200 distinct particles. Initially thought of as rather exotic entities, something new was needed to explain their behaviour.

The most important advance came in 1961 from Y Ne'eman and M Gell-Mann using SU(3), a simple 19th century unitary group of transformations in three complex dimensions for studying sets of three objects. They classified the particles in groups, multiplets, mathematically treating them as if in reality they were built up of three basic



*Perhaps the most famous bubble chamber picture in history – the detection of the omega minus particle predicted by the classification scheme of unitary symmetry – taken in the 80-inch chamber at Brookhaven.*

“building blocks” [quarks].

The most spectacular prediction was of the existence of the omega minus. Playing with their three mathematical blocks, they grouped baryons of spin 3/2 in a group of ten and by 1961 nine of these had been identified. During the CERN conference of 1962, Gell-Mann wrote on the blackboard the mass (1680 MeV), charge (-1) and strangeness (-3) of the missing tenth member. At the beginning of 1964, the omega minus, with precisely these properties, was seen for the first time at Brookhaven.

### The weak force

The first big change in our view of the weak force came in 1956. T D Lee and C N Yang, attempting to explain some puzzling observations on kaon decay into two and three mesons, made the revolutionary suggestion that in weak interactions Nature might be particular about the direction in which things happen, violating parity. Immediately after, C S Wu looked at

• Compiled from texts on pp156–166.

### Compiler's Note



Point-like black holes are still a matter of conjecture but big ones made headline news recently. In 2015, on 14 September and again on 26 December, jubilant teams at the LIGO observatory in the US watched the Earth being shaken by gravitational waves created when pairs of huge black holes collided, 1.3 and 1.4 billion years ago, respectively. Closer to home, the composite Event Horizon Telescope (EHT), located at nine sites, is zooming in on a picture of Sagittarius A\*, the black hole at the centre of the Milky Way, a mere 26,000 light-years away.

As for traffic islands, with the number of potentially Earth-like exoplanets discovered by astronomers steadily increasing, so does the chance of finding aliens out there smart enough to appreciate the

properties of terrestrial traffic islands, although it would be tricky to explain why the polarity flips from place to place across our planet!



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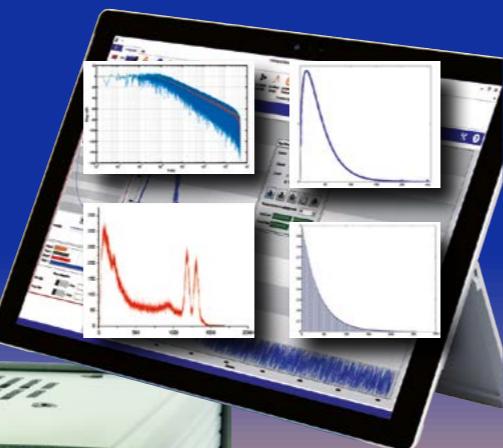


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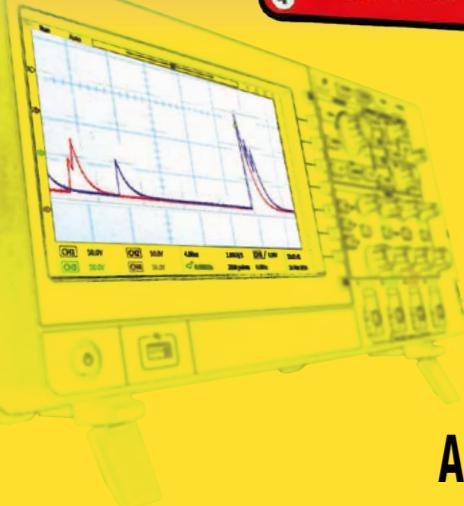
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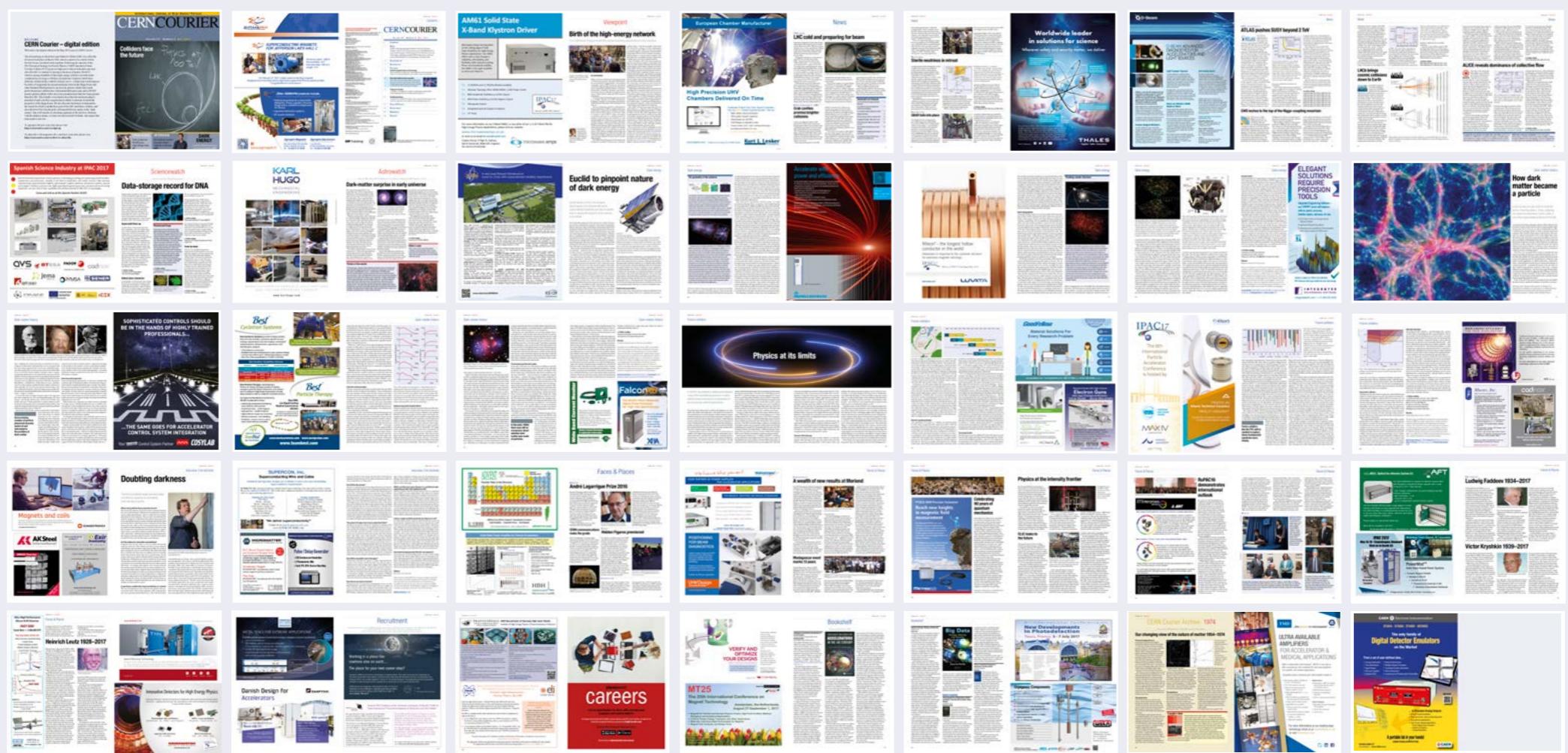


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VOLUME 57 NUMBER 4 MAY 2017

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