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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Birth of the high-energy network

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

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. We will be very happy to welcome you back to CERN again!
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 successful replacement of 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 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.
measurements of an antineutrino energy in South Korea, which generates a high from the 2.8 GW Hanbit nuclear power plant scintillator located just 24 m from the core far inconclusive.

three standard neutrino flavours. An early hint by altering the rate of oscillation between the interactions, are predicted by extensions of the under the electromagnetic, strong and weak additional neutrinos if they are “sterile”. Such excess of three, it is still possible to have properties of such a particle. Even 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

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 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”

Outlier curves for 3 + 1 neutrino oscillations in the sin22 41 ranging from 0.2–2.3 eV2 at 90% C.L. are shown as the blue shaded area. The excess is consistent with anomalies seen at longer-baseline neutrino experiments. With no strong evidence for “3 + 1”

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 manipulate proton beams, the first time that a crab cavity has ever been used for manipulating 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.

At AMTIMATTER GBAR falls into place

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.
Light Transport Systems

A major challenge in radiation-intensive environments is the signal transfer from the source to the often expensive and not radiation-hard detection system. Lens-based light transport systems suffer from aberrations, misalignment and radiation damage. D-Beam offers optical fibre based light transport systems that can replace conventional lens-based systems.

Amongst others, we are experienced in the development, optimisation and experimental exploitation of synchrotron radiation-based profile monitors, novel mini mirror arm-based beam halo monitors for the measurements with high dynamic range, and advanced sensor technologies, such as silicon photomultipliers.

Beam Loss Monitors (BLM) Based on Fibres

D-Beam offers BLMs based on fibres with unique features compared to the commonly used BLMs. The fibre-based BLM gathers the information from the entire beam line you are interested in, and not only one point.

Due to the large number of monitors necessary to cover all beam modules in latest generation large scale accelerators, it is desirable to find a solution which minimises also the overall costs of the system. The use of optical fibres in different configurations allows covering larger segments of the machines. This allows to find new sources or losses and to protect the equipment.

Our systems provide a resolution of around 10 cm, which gives an accurate determination of the loss position. Due to their intrinsic design advantages our systems are completely insensitive to magnetic fields and neutron radiation.

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D-Beam offers easy-to-use and user friendly diagnostics for charged particle beams. This includes custom-build diagnostics for your specific needs. We have a wide range of numerical and analytical tools for modelling and optimising our products for even the most challenging projects. We have established a collaborative network with universities, research centres and industry partners from all over the world.

Further information can be found at www.d-beam.co.uk

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CMS inches to the top of the Higgs-coupling mountain

The discovery of the Higgs boson in 2012, a fundamentally new type of 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 their 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 (gaugetop production) 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 looks 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 on 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 allowing one to identify the pattern of secondary vertices produced by decays proceeding close to the LHC beam pipe, yielding sensitivity to non-prime decay or SUSY events 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 full swing, with many more signatures being investigated to close in on models of electroweak-scale supersymmetry.

Further reading
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.

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 $P_{v_2}$ 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 percent most central collisions, that the third-order coefficients $v_{3P}$ are larger than the second-order coefficients, $v_{2P}$.

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 presence of flow using measurements of differential transverse-momentum correlators, $P_{v_n}$. 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, the magnitude and 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 gives rise to 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. The presence of other sources of particle correlation, generally called non-flow, are expected to break this simple scaling, however. ALICE has now found that the scaling relation between $P_{v_2}$ 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 percent most central collisions, that the third-order coefficients $v_{3P}$ are larger than the second-order coefficients, $v_{2P}$.

Further reading

Further reading
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.

Come and visit us at the Spanish Pavilion (#137)

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**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 × 10^10 bytes of information including a full computer operating system, a short French film from 1895, a $50 Amazon gift card, and 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 × 10^9 retrievals. The results indicate that perfect data storage and retrieval is feasible at a density of 215 petabytes per gram of DNA, improving previous work by an order of magnitude.

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**Supersolid firms up**

A supersolid is a bizarre quantum state that is rigid like a solid, yet can flow like a zero-visibility 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. Juan-Rui 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 an atomic superfluid, but placed it in an optical cavity and excited the atoms with photons 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 research that is rigid like a solid, yet can flow like a superfluid. The two elements formed a compound (Na2He). 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.

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**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 Tuboada 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, the frogs make their own light. The fluorescent molecules are unlike those in any other animals, being derived from dihydroisoquinoline.

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**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 two elements formed a compound (Na2He), 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.

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**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 sucrose-solution reward. 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.
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 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 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
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 FPS 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 ESPIRE to serve as a multipurpose fast spectrum irradiation facility for various fields of research.

The subcortical core of the MYRRHA reactor (~100 MWth) 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 FPs. 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 multiparticle 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 subcortical 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 competes 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

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 dark-matter (ΛCDM) 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 decoupled 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 opposite). 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 complementary to the upcoming Euclid observations. Euclid will observe the universe at a redshift of z ~ 2, about 500 million light years away, thereby enabling surveys of the mature universe. It will use the leading edge in science and technology to conduct unique surveys of the universe to be planned in the framework of the Euclid 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 ΛCDM universe at three different epochs (left-to-right above), corresponding to redshifts 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.)

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 overlay). 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 its measured redshift, the geometry of the universe can be obtained.

Hydrodynamical cosmological simulations of a ΛCDM universe at three different epochs (left-to-right above), corresponding to redshifts 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.)

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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 to 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, 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

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 μm. To avoid additional image distortions, it has no imaging optics of its own and is equipped with a camera made up of 36 4k × 4k pixel CCDs with a pixel scale of 0.1 arc second that must be aligned to a precision better than 15 μm 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 μm and has a silt-less spectroscopy mode equipped with three identical grisms (grating prisms) covering the wavelength range 1.25–1.85 μm. 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 NSFP focal plane is equipped with 16 near infrared HgCdTe detector arrays of 2k × 2k 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 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 organised 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


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’histoire de l’expansion de l’Univers prédite 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-IPMC/14 and CE/A/RU, on behalf of the Euclid Consortium, and Giuseppe Racca and Rene Laureijs, ESA.
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.”

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.

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.)
Dark-matter history

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

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 Einn 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 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 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

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<th>Cyclotron</th>
<th>Energy (MeV)</th>
<th>Isotopes Produced</th>
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<td>F, Rn, Ni, Cd, Bi, Po, Te, Br, I, At, Po</td>
</tr>
<tr>
<td>Best 20/25</td>
<td>20-15, 25-15</td>
<td>Best 15 + F, Rn, Ni, Cd, Bi, Po, Te, Br, I, At, Po</td>
</tr>
<tr>
<td>Best 28u (Upgradeable)</td>
<td>25-15</td>
<td>Best 15 + F, Rn, Ni, Cd, Bi, Po, Te, Br, I, At, Po</td>
</tr>
<tr>
<td>Best 35</td>
<td>35-15</td>
<td>Production of Best 15, 20/25 isotopes plus Ti, H, He, Kr</td>
</tr>
<tr>
<td>Best 70</td>
<td>70-35</td>
<td>Sr, Rb, Tm, I, Sr, Cu, Kr + research</td>
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**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.

**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 pointed out 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”.

**Fig. 1. Flat rotation curves for galaxies, which indicate they are rotating 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 Bosma and Shostak in 1972, where the bars under the galaxy names indicate their average radial diameter and Rg corresponds to the radius containing 80% of the observed hydrogen.”

**Specifications within are subject to change.**
Dark-matter history

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

The triumph of particle dark matter

In the early 1980s there was still nothing resembling a consensus about what 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 = m/a, in the limit of very low velocities (a << a0 ~ 1.2 × 10^{-10} m/s²), then it would be possible to account for the observed motions of stars 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 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 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 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

Résumé
Comment la matière noire est devenue une particule
La matière noire, prédite 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.
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 experiments 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+e– linear collider called CLIC. With an energy up to 3 TeV, CLIC would combine the precision of an e+e– 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+e– 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 unmatched 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 underway 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...
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 apply 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 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 10^9 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– → HZ, the mass recoiling against the Z has a sharp peak that allows a unique and absolute determination of the Higgs decay width (the Higgs width is not measurable directly at LEP). 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 more.
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 10^10 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 simulation 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 θ 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 even 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.

Unpredictable discoveries such as quark substructure might also arise. Uniquely, in electron–proton collisions new particles can be created 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 experiments 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.

Un collisionneur de 100 km de circonférence, tel qu’imaginé par CERN, pourrait 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 electron-proton permettrait de mesurer la sous-structure du proton avec une précision inégalée.

Michangelo Mangano, CERN, Patricia Azzi, INFN Sezione di Padova, Monica D’Onofrio, University of Liverpool, and Matthew Mccullough, CERN.

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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. 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 evidence that there exists an additional form of invisible matter that explains additional gravitating energy. The second of these debates is that different parts of space–time are glued together via quantum entanglement. This is due to van Raamsdonk and has been extended and popularised by Maldacena and Susskind with the slogan “EPR = ER”, where EPR is a reference to Einstein–Podolsky–Rosen and ER refers to the Einstein–Rosen bridge: a “wormhole” that connects the two parts of the black-hole geometry on opposite sides of the horizon. These ideas are being developed by many theorists, in particular in the context of the Anti-de Sitter/Conformal Field Theory (AdS/CFT) correspondence. The goal is then to derive the Einstein equations from this microscopic–quantum perspective. The first step in this programme was already made before my work, but until now most results were derived for AdS space, which describes a universe with a negative cosmological constant and therefore differs from our own. In my recent paper (arXiv:1611.02269) I extended these ideas to de Sitter space, which contains a positive dark energy and has a cosmological horizon. My insight has been that, due to the...
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**Embracing Gravity from Entanglement**

Matthew Chalmers, CERN

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**Interview: Erik Verlinde**

Matthew Chalmers, CERN May 2017

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**CERN COURIER**

Volume 57 Number 4 May 2017

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

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

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**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. This proposed a new regime that makes 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 2001 paper [arXiv:001.0785] 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.

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

I submitted my work that goes against a widely supported theory. As is often the case in science, this requires some courage, and the fact that I have already demonstrated 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.

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**How did the paper change the field?**

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

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

CERN communications make the grade

The Czech Republic’s Academy 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.

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Hidden Figures premiered

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 Beaurecorse and Anne-Marie Magnain from CMS, and Andy Rakotosaindrabe 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.

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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 in Nanyang University in Singapore on 23–26 January. The event gathering leading experts in the foundations of quantum mechanics, quantum cosmology, quantum field theory, quantum condensed matter, quantum optics, quantum information and technology, and quantum chemistry. A highlight 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.

CLIC looks to the future

The annual Compact Linear Collider (CLIC) workshop took place at CERN on 6–10 March, attracting 220 collaborators from 20 countries and highlighting 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 p28). 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 process such as double Higgs production, which is sensitive to the important Higgs self-coupling.

The RICH detector at CERN’s NA62 experiment, which searches for extremely rare kaon decay using highly intense beams.

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 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 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 linear 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.

The annual Compact Linear Collider (CLIC) workshop took place at CERN on 6–10 March, attracting 220 collaborators from 20 countries and highlighting 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.
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 200 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+ 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 and promote collaborative projects including a free electron laser, two-electron–positron colliders (VEPP 2000 and VEPP4M) and facilities for radiopharmaceutical research.

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 advancing 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.

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Making photons count
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 introduced actions of nonlinear partial differential equations – solitons, and he believed that they would reduce the number of fields in Lagrangians.

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 and profound humility who was always ready to discuss new ideas. We will miss him very much.

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
Heinrich Leutz 1928–2017

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 proposing 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 met at CERN, friends and former colleagues recall the great times they spent with Heinrich Leutz.

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Challenges and Goals for Accelerators in the XXI Century
By Oliver Beer and Stephen Myers (eds)
World Scientific

Also available at the CERN bookshop
www.worldscientific.com/worldsdeclubs/10.1142/9789814563546

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: A) in Frascati, VEP3 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 an innovative approach to electron–positron collisions.

The next section is devoted to beginnings, starting from the time of the Brookhaven Cosmotron and Berkeley Bevatrons. 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) – are then discussed. The ISR’s breakthroughs were numerous, including the discovery of the Z particle, the demonstration of stochastic cooling and absolute luminosity measurements by van der Meer scans. Even more remarkable was the harvest of the SPS proton–antiproton collider, culminating with the Nobel prize awarded to Carlo Rubbia and Simon van der Meer. The necessary Antiproton Accumulator and Collector are described in a separate chapter, which ends with an amusing recollection: “December 1982 saw the collider arriving at an integrated luminosity of 28 inverse nanobarns and Rubbia offering a ‘champagne-only’ party with 28 champagne bottles!” Antiproton production methods are covered in detail, including a description of the manoeuvres needed to manipulate antiproton bunches and of the production of cold antihydrogen atoms. This subject is continued in a later chapter dedicated to CERN’s new ELENA antiproton facility.

The Fermilab proton–antiproton collider started later than the SPS, but eventually led to the discovery of the top quark by the CDF and D0 collaborations. The Fermilab antiproton recycler and main ring are described, followed by a chapter dedicated to the Tevatron, which was the first superconducting collider. The first author remarks that, over the years, some 100 antiprotons were accumulated at Fermilab, corresponding to about 17 nanograms and more than 90% of the world’s total man-made quantity of nuclear antimatter.

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 LHCC. 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.

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Big Data, Storage, Sharing, and Security
By Fei Hu
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 and analyse 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 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. 

- David Llazar Garcia, CBRC.

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 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 particles 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 Daniel Lanza Garcia
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 recollected in the volume are widely used in molecular, liquid and solid-state physics, as well as in spin-dependent electronics (spintronics).

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–phonon 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.
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. Could there be such perfection? It would obviously be rather strange if we needed to explain their behaviour. As we classified the particles in groups, mathematically treating them as rather exotic entities, something new was discovered. The “building blocks” [quarks].

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 80-inch Betatron. 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

Our changing view of the nature of matter 1954–1974

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 electrons emerging from the beta decay of cobalt 60. They were spinning clockwise and, to preserve the angular momentum balance, emerging neutrinos (which could not be detected) must always be spinning anticlockwise. By now we know that there are only left-hand spinning neutrinos; right-hand spinning neutrinos do not exist.

This was a profound philosophical change in our view of Nature. We believed that Nature was symmetric and “right” and “left” were human conventions to help us find our way through intermediary mesons, pions. But perhaps gravitation is deeply involved with the electric properties of matter but so far no firm framework has been found for it.

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^{-20} 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 it.

The strong force

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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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