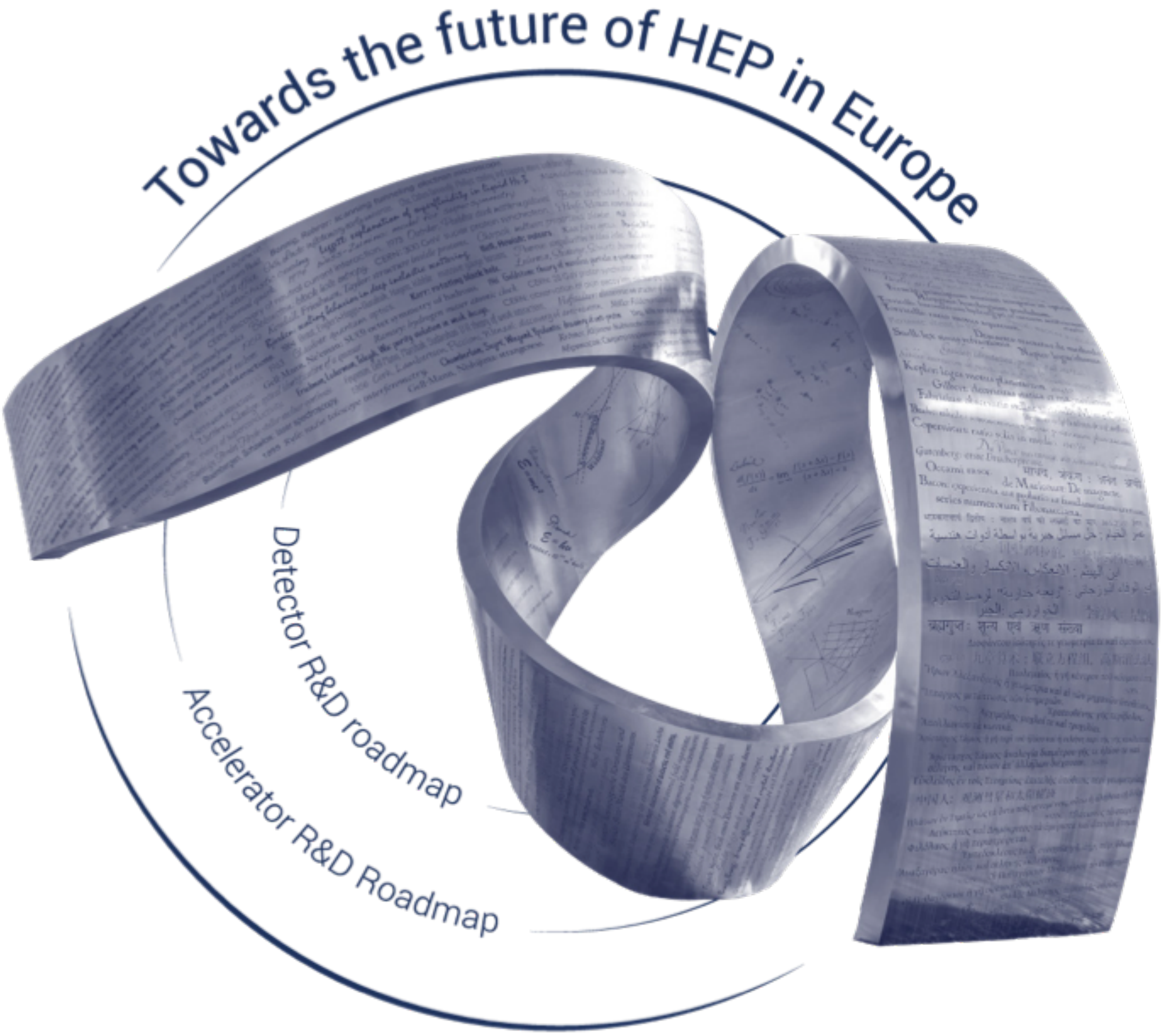
ECFA
European Committee for Future Accelerators

7th newsletter



Following the Plenary ECFA meeting, 23 and 30 July 2021

https://indico.cern.ch/event/1055738/

Summer 2021

During the first half of 2021, ECFA focused largely on addressing the major ECFA-related recommendations of the update of the European Strategy for Particle Physics (ESPP). The central activity was the development of a roadmap for Detector R&D to define the major research themes that should be addressed over the coming years with a view to successfully conducting future research programmes. Such a roadmap would identify and describe a diversified detector R&D portfolio to support proposals at the European and national levels. Progress with emerging technologies in adjacent fields should be taken into account. Already towards the end of last year, a Detector R&D Roadmap Panel was mandated to develop such a roadmap, taking community feedback into account. Routes for the community to shape the roadmap were through six technology task forces and three cross-cutting task forces. The task forces were composed of experts from the community covering the key sub-topics in the relevant technology areas. Another important opportunity for community input was the open symposia, organised between late March and early May 2021 and attended by more than 1300 registered participants. Following this important input and consultation phase, an intensive period of collating the input and drafting a first version of the roadmap document took place, resulting in the definition of major research themes for each task force as well as important general strategic recommendations.

In parallel, the European Laboratory Directors Group (LDG) took important steps towards accomplishing the mandate assigned to it by the ESPP, namely to develop a particle accelerator R&D roadmap. The roadmap would provide an agreed structure for a coordinated and intensified R&D programme towards future large-scale facilities, which should be coordinated across CERN and national laboratories. A series of concrete near-term deliverables would be defined in order to provide essential input to the next strategy update.

Both roadmaps are expected to be finalised during the second half of 2021, with presentations and endorsements planned for the CERN Council Session in December. During the Open Plenary ECFA meeting that took place in the ECFA-EPS session at the 2021 EPS conference, the status of these roadmaps was presented. Brief summaries are included in this newsletter.

In addition, significant progress was made in setting up the appropriate structure in preparation for ECFA workshops on physics studies, experiment designs and detector technologies for a future Higgs factory. Immediately after the strategy update was released and a Higgs factory was identified as the highest-priority project at the high-energy frontier, ECFA recognised the need to foster cooperation between the entire e+e- community. It was decided that a series of ECFA workshops should be held to share challenges and expertise between the various projects, explore synergies and respond coherently to this priority in the European Strategy. In several meetings at the beginning of 2021, an International Advisory Committee agreed that studies on the physics potential should be extended to areas that were not sufficiently covered during the ESPP process and that they should encompass the potential in the electroweak and top sectors. It was also stressed that the interplay between the (HL-)LHC and an e+e- Higgs/electroweak/top factory should be better understood. Although the development of common tools like software, fast and detailed simulations and common analysis tools was considered important, it was also stressed that synergies should be

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[1] Front-page picture thanks to C. Espirito Santo and S. Bruno.

exploited and challenges in the various projects should be discussed. Further, the requirements for theoretical accuracy and Monte Carlo generator improvements needed to be worked out. There was unanimous agreement that these objectives could only be reached if working groups were set up with conveners from both the experimental and theory sides. Three working groups were proposed, on (i) physics potential, (ii) physics analysis methods and (iii) detector R&D. While the first two groups have already started work, the third one is supposed to start after the Detector R&D Roadmap becomes available. Conveners for the first two groups have been assigned and an important kick-off meeting took place in June 2021. It should be stressed that these activities are open to the full worldwide community and that cooperation with other ongoing studies, e.g. the Snowmass studies, is encouraged.

As part of exploiting synergies between astroparticle, nuclear and particle physics, an important step was to establish Joint ECFA-NuPECC-APPEC Activities (JENAA). Following a call in autumn 2019, five expressions of interest (EoI) were endorsed by at least two of the three communities and important kick-off meetings were held. Some of these activities have held further meetings and work is progressing well. Short reports on the status and details of the planned activities are provided in this newsletter. Recently, a sixth EoI targeting synergies between the Electron–Ion Collider (EIC) and the LHC experiments has been submitted. It has the strong support of the NuPECC community and is at present under evaluation by APECC and ECFA. To intensify the discussions between the three communities and provide a forum for overarching discussions, including with representatives of funding agencies, a second Joint ECFA-NuPECC-APPEC Seminar (JENAS) is scheduled to take place from 3 to 6 May 2022 in Madrid.

APPEC, ECFA and NuPECC have recognised the importance of valuing and promoting diversity in order to boost productivity and innovation, fight prejudice and discrimination and contribute to improving social and economic standards within the three communities. The Diversity Working Group started by preparing a Diversity Charter, to be signed by research organisations, collaborations and conferences that operate in the fields of APPEC, ECFA and NuPECC and want to commit to supporting diversity and promoting equal opportunities at all levels. The signatories of the charter also agree to provide monitoring data concerning their diversity status, which can be done through a survey facilitated by the Diversity Working Group. After the charter and the first version of the surveys were sent out to large collaborations in summer 2020, the charter and survey were restructured and comments addressed. This summer, they were again sent out to large collaborations and conferences, and the first signatures have already been collected. A summary on the diversity status of the three communities is expected to be presented at the JENAS in Madrid next year.

Finally, we are happy to report that, after a call for nominations, 75 young researchers have been nominated to represent the young generation of the ECFA member states in the Early-Career Researcher (ECR) panel. They held their first meetings and nominated five ECFA and one RECFA observers, and the full panel and delegates were endorsed at the last two Plenary ECFA meetings. The ECR has already engaged with ongoing ECFA activities, such as by providing very valuable input to the Detector R&D Roadmap process, in particular on training and education aspects, on the long timescales of experiments and on tenured positions in detector R&D.

Due to the ongoing pandemic, scheduled country visits scheduled for the first half of 2021 had to be postponed again. To catch up and avoid further delays, the planned visits to France and Denmark have been moved to the second half of 2021 and five country visits, to Italy, Germany, Ukraine, Hungary and Israel, are planned for 2022.

Finally, we would like to take this opportunity to thank our predecessors, Professor Jorgen D'Hondt (Vrije Universiteit Brussels) as ECFA Chair and Dr Carlos Lacasta (IFIC Valencia) as ECFA Scientific Secretary, for their excellent work and commitment and for guiding and shaping ECFA's activities over the past three years.

Karl Jakobs ECFA Chair	Patricia Conde Muíño ECFA Scientific Secretary

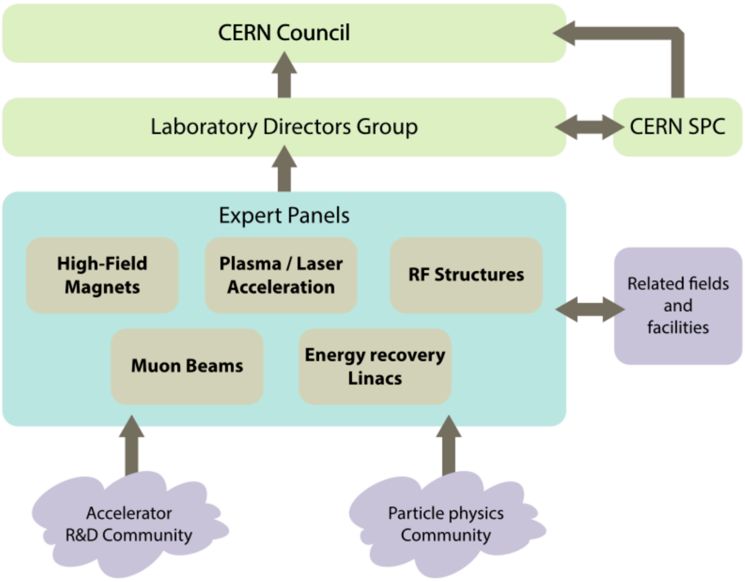
Accelerator R&D Roadmap

by D. Newbold (STFC Rutherford Appleton Laboratory)

The 2020 update of the ESPP identified and explored a range of potential future facilities for collider physics. These facilities will constitute the basic scientific infrastructure for the field in the era following the High-Luminosity LHC (HL-LHC). Any facility of this type requires a major international investment and a development programme over multiple decades, for the machine, the detectors and supporting computing infrastructure. The facilities identified include relatively near-term electron–positron colliders, further-future energy-frontier machines using hadrons and muons, and electron–hadron colliders. In some cases the necessary development is fairly mature, and in other cases it is just starting now.

As for previous generations of machines, each of these will require a substantial programme of R&D, ranging from basic acceleration and magnet technologies for far-future machines, to focused development of specific facilities for nearer-term ones. Most of these machines could not be built affordably using today's technology. The future of collider physics therefore depends on achieving significant cost-performance improvement through R&D, in terms of both construction and operational costs. As increasing attention is paid to questions of sustainability, the total environmental impact of any new facility will also be of primary importance. The ESPP update therefore recommended that "[t]he European particle physics community must intensify accelerator R&D and sustain it with adequate resources" and that "[d]eliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes".

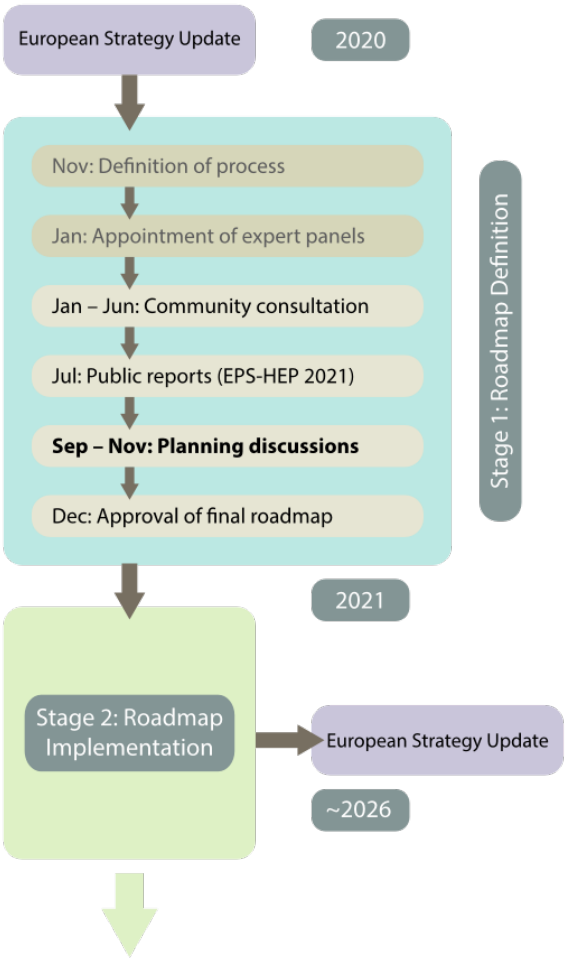
In November 2020, the Laboratory Directors Group (LDG), an advisory body to the CERN Council, developed the mandate for producing an Accelerator R&D Roadmap, complementing the Detector R&D Roadmap produced under the guidance of ECFA. The organisational structure of the process is shown in the figure below. The Roadmap, which will be presented



to the Council in December 2021 (see timeline in the figure) focuses on five key R&D areas where a significant improvement in coordination or the rate of development is necessary:

- Further development of high-field superconducting magnet technology
- Development and exploitation of laser / plasma acceleration techniques
- Development of advanced technologies for conventional RF structures
- Studies towards future bright muon beams and muon colliders
- Advancement and exploitation of energy-recovery linac technology

Although these are the focuses, clearly much other important work on accelerator R&D (e.g. towards specific future facilities) is ongoing and necessary.



Each of the five R&D areas has been considered by a panel of ten to twenty international experts representing the accelerator physics field as a whole. The process is steered by the LDG, which consists of senior representatives of the major particle physics laboratories in Europe. Each panel has spent several months gathering community input on R&D needs and challenges, through a series of meetings, workshops and formal consultations. On 9 July, an open symposium for the particle physics community attracted around 150 participants and, along with a presentation of each topic at the EPS-HEP conference later in the month, generated valuable feedback and further input. Each panel has now explicitly identified the key R&D challenges, their relationship to future facilities in collider physics, and the basic steps needed to address them. These findings are documented in an interim report that will be considered by CERN's Scientific Policy Committee (SPC) later in September, and will also be distributed to the community. The development of the Accelerator and Detector Roadmaps has been closely coordinated, for instance to ensure common assumptions on the rough timeline for future facilities, and on their parameters.

The process has now turned to the stage of detailed planning, where each panel has been charged with producing a prioritised concrete delivery plan, with a first estimate of the required human and financial resources. These plans should take into account existing commitments made by labs and institutes to current R&D programmes and near-future research infrastructure, but should also form a framework around which new funding requests can be built, and which makes clear the opportunities for new participants.

The plans will describe in detail a five-to-ten-year timeline, in the context of a longer complete development programme in each area, and will explicitly seek to address the following questions over the course of the next two ESPP updates:

- What R&D needs to be done towards future facilities? What are the priorities?
- How long might it take? What is the fastest technically limited schedule?
- How much will it cost?
- What different options and trade-offs exist?
- What are the linkages between activities?
- What science can be done using demonstrators, or intermediate-scale facilities?

Consideration is also being given to the organisation and governance of future R&D, where structures must be developed to allow proper approval, scrutiny and monitoring of proposed new developments, whilst maintaining freedom for individual institutes and collaborations to retain flexibility and undertake "blue-skies" exploration of new ideas.

Overall, care must be taken to maintain appropriate balance in investment across R&D areas, but also between "generic R&D" and planning of specific facilities. The delivery and commissioning of near-future facilities (including the HL-LHC and its detectors, and the LBNF facility in the USA) present a major load on the field at present, and, of course, many in the European machine-building community are also engaged in major new accelerator developments outside particle physics. Conversely an increased level of R&D cannot be postponed without risk of delaying subsequent progress towards new machines. The key challenge is to improve the speed, coordination and cost-effectiveness of both the R&D and the construction of the corresponding future facilities, such that our field is capable of maintaining the current momentum towards future scientific opportunities, and then delivering the necessary facilities in a timely way.

ECFA Detector R&D Roadmap for Particle Physics

by P. AllPort (University of Birmingham)

The ESPP update in 2020 [1] recommended that, "[o]rganised by ECFA, a roadmap should be developed by the community to balance the detector R&D efforts in Europe, taking into account progress with emerging technologies in adjacent fields". In response to this, ECFA set up the Detector R&D Roadmap Panel with the structure illustrated in figure 1, with the full membership of the Process Group including all the task force members listed at the Roadmap Panel web pages [2]. More details can also be found in the presentation made during the Plenary ECFA Session of the EPS Conference [3].

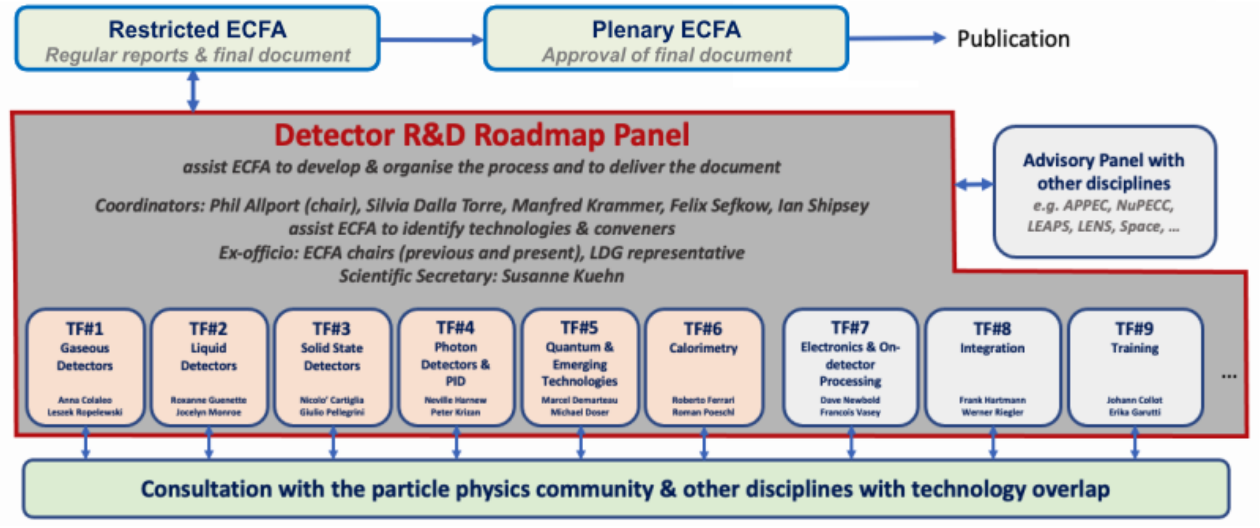


Figure 1: Organisation of the ECFA Detector Roadmap Process Group

Consultations with the community have taken place through a number of mechanisms, starting with presentations from key experts in the different future science programmes identified in the ESPP update in early 2021 to collect the main unmet detector R&D requirements. These were followed up by the task forces listed above by means of consultation through community questionnaires and surveys (with RECFA also naming additional national contacts for many countries who helped gather responses) and with the help of contacts appointed in each task-force area by the organisations representing neighbouring disciplines (APPEC, ESA, LEAPS, LENS and NuPECC). The consultation process culminated in nine full-day open symposia in spring 2021, for which 1359 members of the community were registered in total, with individual events attracting up to 500 online participants. The presentations, discussions and subsequent feedback were collated during a four-day intensive meeting of all those involved in the Roadmap Process into a first full draft of the final Roadmap document. This was then iterated with RECFA and the appointed national contact people in order to check the document's main messages and highlight concerns or propose corrections. Based on this feedback, the key findings were presented during the Plenary ECFA Session at the EPS Conference to the particle physics community, where further questions and feedback were received.

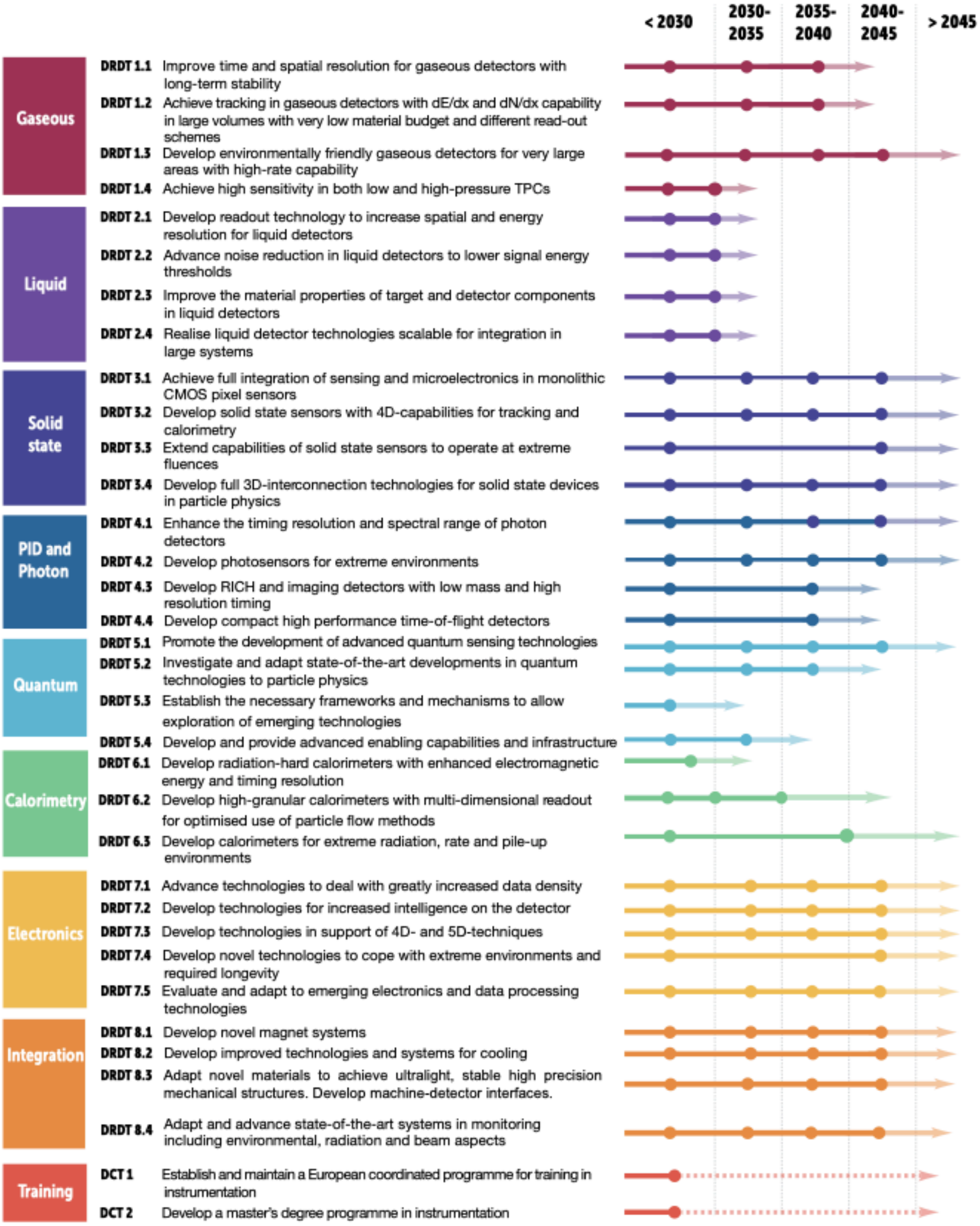
For detector developments, the focus of the Strategy is the need to build on the world-leading capabilities in Europe in technologies using gas- and liquid-based or solid-state sensors for particle detection, energy measurement and particle identification. Associated with this is the need for cutting-edge developments in bespoke microelectronics solutions, real-time data processing and advanced engineering. Resources for such technology developments are a necessary but hardly sufficient basis for future progress in experimental particle physics. Talented and committed people are also an absolutely core requirement. They need to be enthused, engaged, educated, empowered and employed. Key to the recommendations in the ECFA Detector R&D Roadmap report are proposals on how the scientists, engineers and technicians who will build the future facilities should be carefully nurtured and incentivised by appropriate and rewarding career opportunities.

Figure 2 illustrates the Detector R&D Themes (DRDTs) identified in the report, grouped by the areas addressed by the nine task forces of the ECFA Detector R&D Roadmap Process Group. The themes enumerated there have been identified as critical to achieving the science programme outlined in the European Strategy. They are derived from the technological requirements to match the scientific potential of the future facilities and projects listed in the Strategy, with the timing of the currently known farthest start-date experimental programme requiring each R&D activity illustrated by the ends of the arrows in the figure. The minimum duration of each programme is shown by the solid line, with allowance (represented by the fainter line) made for the time after R&D concludes for final engineering, prototyping, procurement, assembly, commissioning and installation.

In each case, care has been taken to ensure that, for the programmes identified in the European Strategy, detector readiness should not be the limiting factor for realising a future facility. In many cases, developments required for experiments are intermediate in time and can act as “stepping stones” (illustrated by the dots) towards achieving the final specifications.

The highest priority is placed in the European Strategy on a future Higgs factory to thoroughly explore the properties of this completely new type of particle, which is seen as key to a much deeper understanding of how the universe works. Until the discovery of the Higgs, every known particle was either a “matter” or a “force” particle, describing a world in terms of fundamental entities and their interactions without being able to accommodate the fact that particles also have mass. In the detector R&D strategy, the vision for the future facilities to explore this and many of the other deepest questions in physics is translated into a near- and mid-term focus on R&D in a similar way to that provided by the LHC and its upgrades in previous decades, whilst highlighting synergies with other projects on nearer timescales and showing how they are also embedded in the longer-term context.

DETECTOR RESEARCH AND DEVELOPMENT THEMES (DRDTs)



Gaseous	DRDT 1.1	Improve time and spatial resolution for gaseous detectors with long-term stability
	DRDT 1.2	Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
	DRDT 1.3	Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
	DRDT 1.4	Achieve high sensitivity in both low and high-pressure TPCs
Liquid	DRDT 2.1	Develop readout technology to increase spatial and energy resolution for liquid detectors
	DRDT 2.2	Advance noise reduction in liquid detectors to lower signal energy thresholds
	DRDT 2.3	Improve the material properties of target and detector components in liquid detectors
	DRDT 2.4	Realise liquid detector technologies scalable for integration in large systems
Solid state	DRDT 3.1	Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
	DRDT 3.2	Develop solid state sensors with 4D-capabilities for tracking and calorimetry
	DRDT 3.3	Extend capabilities of solid state sensors to operate at extreme fluences
	DRDT 3.4	Develop full 3D-interconnection technologies for solid state devices in particle physics
PID and Photon	DRDT 4.1	Enhance the timing resolution and spectral range of photon detectors
	DRDT 4.2	Develop photosensors for extreme environments
	DRDT 4.3	Develop RICH and imaging detectors with low mass and high resolution timing
	DRDT 4.4	Develop compact high performance time-of-flight detectors
Quantum	DRDT 5.1	Promote the development of advanced quantum sensing technologies
	DRDT 5.2	Investigate and adapt state-of-the-art developments in quantum technologies to particle physics
	DRDT 5.3	Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies
	DRDT 5.4	Develop and provide advanced enabling capabilities and infrastructure
Calorimetry	DRDT 6.1	Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
	DRDT 6.2	Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
	DRDT 6.3	Develop calorimeters for extreme radiation, rate and pile-up environments
Electronics	DRDT 7.1	Advance technologies to deal with greatly increased data density
	DRDT 7.2	Develop technologies for increased intelligence on the detector
	DRDT 7.3	Develop technologies in support of 4D- and 5D-techniques
	DRDT 7.4	Develop novel technologies to cope with extreme environments and required longevity
	DRDT 7.5	Evaluate and adapt to emerging electronics and data processing technologies
Integration	DRDT 8.1	Develop novel magnet systems
	DRDT 8.2	Develop improved technologies and systems for cooling
	DRDT 8.3	Adapt novel materials to achieve ultralight, stable high precision mechanical structures. Develop machine-detector interfaces.
	DRDT 8.4	Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects
Training	DCT 1	Establish and maintain a European coordinated programme for training in instrumentation
	DCT 2	Develop a master's degree programme in instrumentation

Figure : Detector R&D Themes (DRDT) and Detector Community Themes (DCT). Here, except in the DCT case, the final dot position represents the target date for completion of the R&D required by the latest known future facility/experiment for which an R&D programme would still be needed in that area. The time from that dot to the end of the arrow represents the further time to be anticipated for experiment-specific prototyping, procurement, construction, installation and commissioning. Earlier dots represent the time-frame of intermediate "stepping stone" projects where dates for the corresponding facilities/experiments are known. (Note that R&D for Liquid Detectors will be needed far into the future, however the DRDT lines for these end in the period 2030-35 because developments in that field are rapid and it is not possible today to reasonably estimate the dates for projects requiring longer-term R&D. Similarly, the dotted lines for the DCTs indicate that beyond the initial programmes, the activities will need to be sustained going forward in support of the instrumentation R&D activities).

In figure 2, the R&D priorities for the key detector types (based on gaseous, liquid or solid sensing materials) are outlined, along with the R&D required for sensing aspects specific to photon or particle identification (PID) or energy measurement (calorimetry). Additionally, the rapidly developing topic of quantum sensors offers radical new opportunities, and developments in this area will also benefit from their exploitation for the exacting requirements of particle physics. Across all of the detector types, the need for sophisticated read-out technologies are crucial and often the limiting factor when very large numbers of channels have to be instrumented with ever more demanding sensitivity and robustness for operation in the extreme environments of many particle physics experiments. Unique advanced engineering solutions are needed to complement these and, as for accelerators, the field drives many developments in magnet technology.

Given the vital importance of expertise in a wide range of cutting-edge technologies, the report also contains specific recommendations in terms of training (Detector Community Themes) that focus on the potential to achieve greater coordination between the many diverse training schemes available across Europe as well as to explore mechanisms to establish a core syllabus for a master's qualification in this area, pulling together the required resources from the many institutes where parts of what would be needed can already be found.

The above figure illustrates the long-term nature of the planning needed in the area of detector R&D for particle physics. In addition, the report concludes with ten key General Strategic Recommendations (GSRs). The aim of the GSRs is to propose mechanisms to achieve greater coherence across Europe in order to better streamline local and national activities and make them more effective while also giving the area greater visibility and voice at the European level in order to make the case for the additional resources needed for Europe to maintain a leading role in particle physics, with all the associated scientific and societal benefits.

The first two of these recommendations (GSR1 and GSR2) discuss the need to better coordinate support for the infrastructure required to undertake R&D on novel detectors. GSR1 focuses on facilities (accelerator beams, reactors, intense radiation sources) needed for both testing performance against the exacting specifications and long-term survival in extreme environments at experiments that must operate for up to decades. GSR2 reflects the increasing integration of functionality in detector systems in ways that require much greater access to advanced engineering design (mechanical, electrical and microelectronics) from the outset. A specific requirement for this and for innovation of all aspects of detector design is common access to all the latest simulation and design tools, including the support and updating of many packages in general use that were originally developed within the particle physics community (GSR3).

In some but not all areas of generic detector R&D, community-led collaborations provide a vital forum for exchanging ideas, pooling resources and reducing duplication of efforts. Springing from a CERN initiative around the challenges of detectors for the LHC, the ecosystem that has evolved over three decades has proved very effective and spawned a number of collaborations not linked to the original CERN structures. In GSR4, the proposal is made to significantly refresh the structures and processes for creation and peer reviewing of such R&D collaborations, encouraging CERN and the national laboratories to actively assist in catalysing this transformation.

A major concern for the future of several sensor R&D areas (particularly those linked to solid-state devices, microelectronics and on-detector data handling) is that R&D costs to exploit, adapt and further develop cutting-edge technologies far outstrip inflation. This is because niche specifications in what is, by commercial standards, a low-volume market, although providing an important vehicle for product development, can increasingly only be met through a significant pooling of resources, particularly given the growing complexity and degree of specialisation of those involved in the device design and the need to negotiate as a larger-scale organisation. GSR5 proposes that the required critical mass could be achieved through a network of national hubs that, while improving focus and cost-effectiveness, would still allow a vibrant research base in individual smaller institutes and university departments.

Linked to this and the decadal timescales for strategic R&D investments illustrated by figure 1 is the urgent need to augment the short-term funding mechanisms, suited for exploratory stages of the R&D cycle, with funding mechanisms better suited to long-term programmes, as outlined in GSR6. Continuity of adequate strategic investment is mandated by the scale of the technical challenges, the necessary planning horizons and the need to build serious relationships with industrial partners if they are also to commit matching resources.

The above is not to say, as GSR7 emphasises, that “blue-sky” R&D should be neglected, as transformational breakthroughs often result from pursuing more speculative concepts and can offer high returns on investment, albeit at higher risks, often historically delivering impacts that go way beyond particle physics. Examples of this include the development of the World Wide Web at CERN (to meet the demand for automated information-sharing between scientists around the world), capacitive touch screens (initially for the consoles controlling CERN’s accelerators) and numerous other applications, many bringing huge benefits, in particular for advanced healthcare.

GSR8 concentrates on the need to attract, nurture, recognise and sustain the careers of R&D experts with the recommendation that ECFA explore mechanisms to develop concrete proposals to both study the issue of better institutional recognition for those working on instrumentation R&D and help consolidate the route to an adequate number of sustained career positions in this area. Often those with internationally recognised key strategic skills are not sufficiently appreciated or rewarded within the organisations where they are directly employed.

GSR9 discusses the need to build stronger strategic links with industry (already touched on in GSR6), which requires a number of longer-term and resource-loaded cooperation schemes to be established, alongside a review of contractual and legal impediments to building closer partnerships with specific companies. One particularly delicate aspect is the commitment of the particle physics community to open science. Additionally, instrumentation journals do not always enjoy the same support for open access as journals publishing analysis of physics data. GSR10 encourages the appropriate bodies to look at routes to ensuring instrumentation results are as publicly available as any others in particle physics, so long as commercial confidentiality agreements can be respected.

The ECFA Roadmap for Detector R&D in Particle Physics also emphasises that synergies with adjacent research fields, knowledge institutions and industry are absolutely vital. The exciting vision for the next half-century of particle physics requires and deserves an equally exciting programme of instrumentation development. This will ensure that the proposed investments in ambitious new facilities deliver the maximum possible scientific returns while continuing to build new capabilities with the potential to further revolutionise technologies of benefit to society as a whole.

References

[1] https://europeanstrategy.cern/
[2] https://indico.cern.ch/e/ECFADetectorRDRoadmap.
[3] https://indico.desy.de/event/28202/sessions/10425/#20210730.

FCC Feasibility Study Update: Structure, Goals, Status and Plans

by M. Benedikt (CERN) and F. Zimmermann (CERN)

As reported previously (ECFA Newsletter Dec. 2020), the Future Circular Collider (FCC) Feasibility Study (FS) addresses a key recommendation of the 2020 ESPP update [1], which states that "Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron–positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

The FCC would search for answers to several fundamental physics questions. A growing amount of empirical evidence about our universe is not described by the Standard Model. For example, the latter does not explain the nature of dark matter, nor the asymmetry between matter and antimatter, nor the origin of the primordial density perturbations that led to the formations of galaxies and large-scale structures. Along with the body of experimental evidence, a number of theoretical motivations also point to the existence of new physics beyond the Standard Model, including the electroweak hierarchy problem, the strong CP problem and the mystery of flavour mixing patterns. The discovery of the Higgs boson is the start of a major research endeavour that could be pursued with the FCC, set to measure this particle's properties with the highest possible precision, including the full shape of its potential, and thus to test the validity of the Standard Model and to explore where new physics might be hiding.

Running at additional energies, e.g. as a Tera-Z and top factory, the FCC lepton collider, FCC-ee, would be the ultimate electroweak precision machine. The combination of FCC-ee and the FCC-hh hadron collider could allow us to discover not only that the Standard Model is incomplete, but also reveal the nature of new physics, e.g. through the possible discovery of sterile right-handed neutrinos at the FCC-ee Z factory, and through investigations of flavour anomalies. The FCC integrated programme would deliver physics events at unprecedented rates. Thanks to these, and to the exquisite beam energy calibration enabled by resonant depolarisation, the FCC-ee would be able to execute comprehensive and precise electroweak, flavour, top and Higgs precision measurements, with coupling measurements sensitive to new physics in the 10-100 TeV mass range, and would offer a 10- to 100-fold improvement on all experimental observables compared with the present state of the art.

The FCC-hh would rely on the "FCC-ee standard candles" to complement and extend the precise determination of the Higgs properties, notably improving the measurement of its coupling to muons and to the top quark, and of its self-coupling. The reach of FCC-hh for direct discovery of new particles extends up to 30-40 TeV, which would make it possible to unveil the nature of possible deviations exposed by FCC-ee precision measurements. The combination of high energy and large statistics, furthermore, would enable the FCC-hh to conclusively discover or rule out large classes of models proposed as dark matter candidates, and to explore the nature of the electroweak phase transition that, in the early universe, led to the current Higgs vacuum state. More generally, the FCC-hh would push by close to an order of magnitude the discovery reach of the LHC for a large multitude of models of new physics.

Following the 2020 ESPP update, preparations for the FCC FS began. The detailed scope, organisational structure and deliverables of the FCC FS were formulated and approved by the CERN Council in June 2021 [2,3]. The FS will be organised into five major work packages (WPs).

WP 1 covers "Physics, experiments and detectors". The deliverables and milestones include the consolidation of the physics case for the full FCC programme; the detailed requirements on theoretical calculations, Monte Carlo generators and other software; detector concepts for FCC-ee and FCC-hh (also based on experience with the HL-LHC upgrades); detector design and R&D (synergies with "R&D for future detectors" at CERN and the ECFA Detector Roadmap); and the requirements on accelerator performance, technical infrastructure, computing and integration.

WP2, "Accelerators", will advance and complete the design of FCC-ee and FCC-hh and their injectors; pursue the development of key technologies, including high-field superconducting magnets, superconducting radiofrequency (RF) systems, high-efficiency RF power production, and other sustainable and environment-friendly technologies; and develop the machine–detector interface for FCC-ee (final focus magnets and compensation solenoids).

WP3, "Technical infrastructures", will work out concepts for electricity supply and distribution; optimise electrical system efficiency and stability; design the cooling, ventilation and cryogenic systems; maximise energy efficiency via e.g. waste heat recovery; and develop concepts for safety, radiation protection, integration, logistics and transport.

WP4, "Organisation and funding", will develop organisational models for the design, implementation and operation of a possible future project; prepare a consolidated cost estimate; develop funding concepts and models for the construction and operation; prepare a procurement strategy/rules for the global project (with major contributions from non-Member States); and develop a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, environmental aspects and energy efficiency.

WP5, "Civil engineering and Host-State processes", will plan and manage site investigations in high-risk areas; pre-design tunnel and underground structures, including shafts and caverns; develop layout concepts for each of the surface sites, taking into account technical requirements and territorial constraints (buildings, streets, parking spaces, storage, integration of general services, etc.); provide preliminary concepts and requirements for access to each site; pre-design surface buildings; work out and deploy a communications plan for the local areas to support the site investigations; pursue the Host-State administrative processes needed for a possible construction start in the early 2030s; develop an integrated process for environmental evaluation in line with the regulations in both Host States, and the first part of the environmental evaluation process and impact study from 2023 onwards; and prepare roadmaps and plans for processes that will begin after the project's possible approval (e.g. acquisition of land plots for surface sites, public debates, an environmental impact study and compensation procedures).

The overall high-level FCC FS timeline is outlined in figure 3.

Increasing international collaboration is a prerequisite for success. So far, about 150 scientific institutes and 30 companies, from 34 countries, have joined the FCC collaboration. Among the participating institutes, 93 hail from CERN Member States, 16 from Associate Member States, 21 from non-Member States with Observer status, and 17 from other non-Member States. Strong links with science, R&D and high-tech industry will be essential to further advance the FCC. A first FCC FS collaboration board meeting is planned for mid-September 2021.

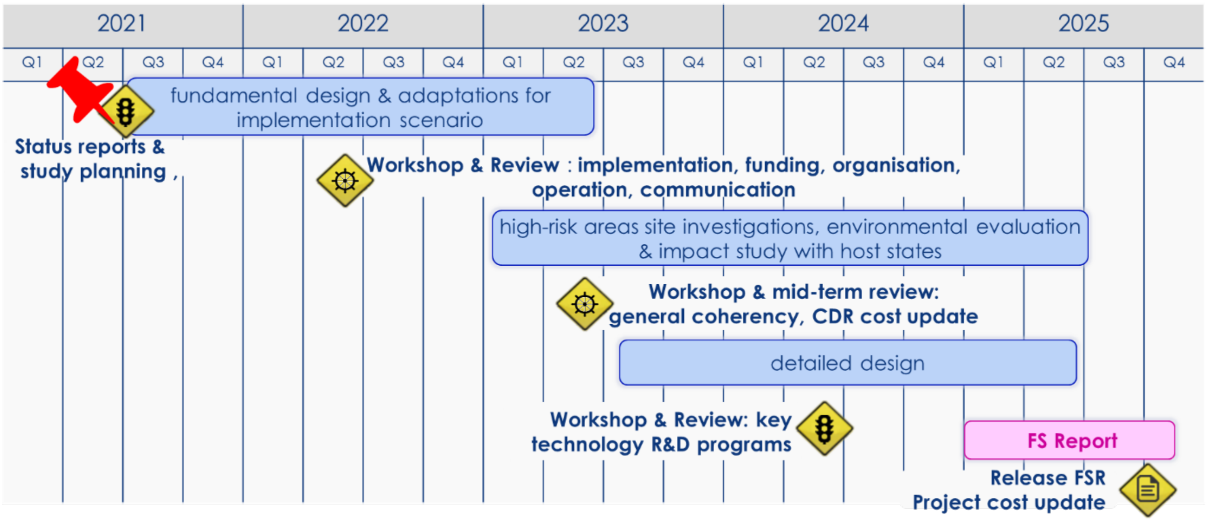


Figure 3: FCC FS timeline.

The EU co-funded FCC Innovation Study (FCCIS) [4], approved by the European Commission in 2020, forms an integral part of the FCC FS. FCCIS will not only support the optimisation of the FCC-ee lepton collider, in collaboration with important European and international partners, but also advance the construction planning, prepare the environmental evaluation, study the management of about 9 million cubic metres of excavation materials (e.g. through an international "Mining the Future" competition [5]), catalyse user-community building and public engagement and perform socio-economic impact analyses.

Recent FCC FS progress has been swift. In spring/summer 2021 three topical expert reviews were organised. The first review, of the FCC-ee injector complex, supported an optimised new layout (see figure 4; with simpler linac operation and higher electron energy for positron production than the layout presented in the FCC-ee Conceptual Design Report [6]), a conservative operation mode with few bunches per pulse, a positron target based on the SLC's, and a possible linac energy extension to eliminate the need for a pre-booster ring. To produce the main electron beam, low-energy, low-emittance electrons from an RF gun (source 1) are accelerated in LINAC1 to about 1.5 GeV and may then be fed into the damping ring (bottom right, with dimensions of 53 x 106 m) for emittance reduction and stabilisation, and, finally, further accelerated through LINAC2 to 6 GeV or higher. For positron production, more intense electron bunches from a thermionic gun (source 2) are accelerated through LINAC1 and LINAC2 and then hit the positron production target at a minimum energy of 6 GeV. The generated positrons are captured and then follow the same path as described earlier for the main electron bunches. The positron bunches must pass through the damping ring to acquire the required emittance. On the way to and from the damping ring, an energy spread compressor (EC) and bunch length compressors (BC) are indicated.

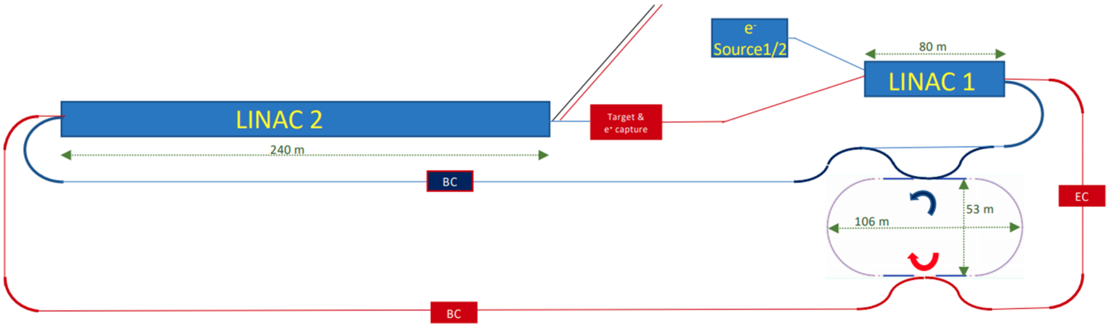


Figure 4: Optimised FCC-ee injector layout endorsed by a topical expert review in April and June 2021.

A second review, on FCC-ee superconducting RF systems, encouraged studies of a possible RF frequency of 600 or 650 MHz (possible synergies with EIC, JLEIC, PIP-II, CEPC) and the exploration of alternative cavity and RF staging concepts.

The third topical review focused on the FCC's placement. The placement optimisation must balance geological and territorial constraints against the machine requirements and the required physics performance. The review revealed that the most suitable scenarios are based on a 91-km circumference tunnel with eight surface sites, and a superperiodicity of four, which leaves open, for later, the possibility of choosing either two or four collision points and experiments.

Following the series of topical reviews, from 28 June to 2 July 2021, the annual FCC Week was held virtually [7]. Some 688 experts registered and participated online in 31 sessions, featuring 128 presentations and lively discussions. Figure 5 shows the geographical distribution of attendees.

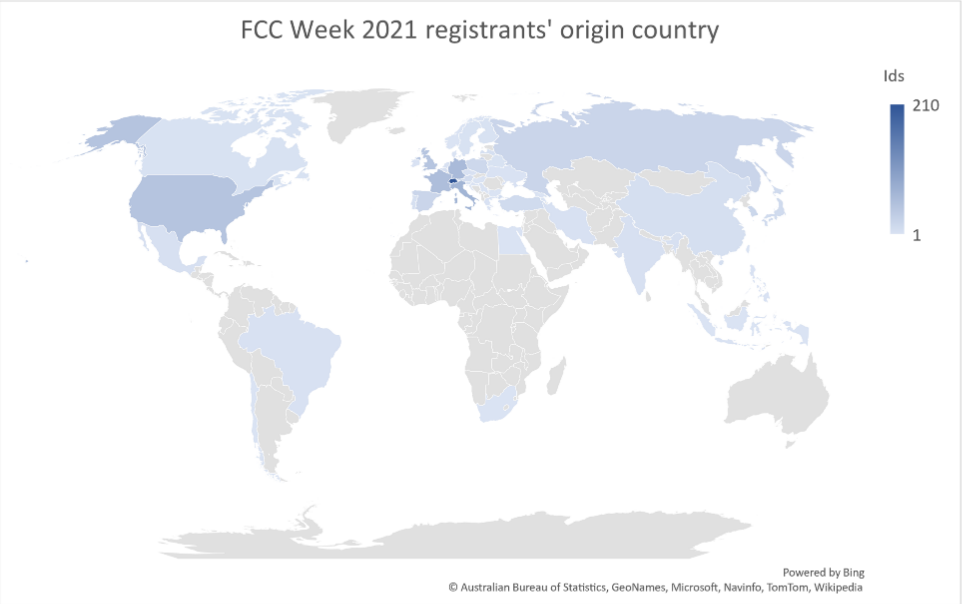


Figure 5: Countries of origin of FCC Week 2021 participants.

Another recent milestone has been the demonstration of several FCC-ee key concepts at SuperKEKB. Specifically, in June 2021 a new world record luminosity of 3.12×10^{34} cm^{-2} s^{-1} was achieved, based on a novel “virtual” crab waist optics, which was first developed for FCC-ee [8], and the minimum FCC-ee β_{γ}^{*} design value of 0.8 mm (envisaged for the FCC-ee Tera-Z factory) was established in both SuperKEKB rings.

In summary, the 2020 European Strategy update requested a comprehensive feasibility study of the FCC and suggested key technology R&D areas. The main activity of the FCC Feasibility Study is the development of a concrete local and regional implementation scenario in collaboration with the Host State authorities. This is accompanied by machine optimisation, physics studies and technology R&D, all of which are performed via global collaboration and supported by the FCCIS. The medium-term goal is to prove the FCC’s feasibility by 2025/2026. In parallel, a high-field magnet programme is being carried out with international partners, whose preliminary results will also be included in the FS report. The long-term goal is to establish world-leading HEP infrastructure for the twenty-first century that will push the particle-physics precision and energy frontiers far beyond present limits. The success of this endeavour relies on strong global participation and on the opportunities that we will create for the young generation.

References

[1] European Strategy Group, 2020 Update of the European Strategy for Particle Physics, CERN-ESU-013 (2020).
[2] Restricted Council, Future Circular Collider Feasibility Study – Proposed Organisational Structure, CERN/SPC/1155/Rev.2 CERN/3566/Rev.2, http://cds.cern.ch/record/2774006/files/English.pdf.
[3] Restricted Council, Future Circular Collider Feasibility Study – Main Deliverables and Milestones, CERN/SPC/1155/Rev.2 CERN/3566/Rev.2, http://cds.cern.ch/record/2774007/files/English.pdf.
[4] The FCC Innovation Study is an INFRADEV Research and Innovation Action project receiving funding from the European Union’s Horizon 2020 Framework Programme under grant agreement no. 951754; FCCIS Kick-off Workshop, 9-13 November 2020.
[5] FCCIS “Mining the Future” competition, http://miningthefuture.web.cern.ch/.
[6] M. Benedikt et al., FCC-ee: The Lepton Collider – Future Circular Collider Conceptual Design Report Volume 2, EPJ ST 228, 261-623 (2019) [open access].
[7] FCC Week 2021, https://indico.cern.ch/e/fccw2021.
[8] K. Oide et al., Design of beam optics for the future circular collider e+e- collider rings, Phys. Rev. Accel. Beams 19, 111005, https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.19.111005.

The Initiative for Dark Matter in Europe and Beyond

by M. Cirelli (LPTHE, CNRS & Sorbonne U.), C. Doglioni (Lund University) and F. Petricca (Max-Planck-Institut für Physik)

Understanding dark matter (DM), how it was produced in the early universe, its nature and where it is located in the cosmos is one of the fundamental physics problems of our century.

The community working on dark matter is active and diverse, including particle physics theorists and astrophysicists with a wide range of interests, as well as particle physics experimentalists focusing on collider, fixed-target, beam-dump, direct and indirect DM detection experiments, as well as dedicated axion/axion-like particle experiments. Given the diversity of the dark matter community, discovering or constraining dark matter requires broad discussions beyond the ongoing efforts for cross-collaboration within the different communities (e.g. the Dark Matter Working Group, the Physics Beyond Colliders study group and the long-lived particle community).

However, to date there has been no common permanent platform where all these communities can come together for discussion beyond ad hoc occasions like conferences and workshops.

The Initiative for Dark Matter in Europe and Beyond at JENAS

The need for an up-to-date collection of resources on dark matter that would facilitate more cross-talk beyond individual experimental efforts or models was identified and discussed during the first Joint ECFA-NuPECC-ApPEC Seminar (JENAS) [1], held in Orsay in autumn 2019. The JENAS call for expressions of interest for work across different communities was answered with a proposal to set up the Initiative for Dark Matter in Europe and Beyond (iDMEu), a common platform that would help identify cross-field and cross-experiment opportunities [2].

iDMEu is intended to be a permanent platform for dark matter discussions among different communities, facilitating the creation of new collaborations among dark matter researchers. It started its activities with a kick-off meeting in May 2021 [3]. It will continue its role as a distributed forum in the form of an online platform and regular town-hall meetings taking place in connection with dark matter conferences worldwide. iDMEu will also play a key role in communicating the breadth of the complementary set of experimental searches, cosmological observations and theoretical benchmarks by providing an online meta-repository of dark matter resources including for public outreach.

The iDMEu kick-off meeting and website

The starting event for iDMEu was an online kick-off meeting from 10 to 12 May 2021 [3]. The agenda of the iDMEu kick-off was planned with a view to creating conditions conducive for cross-talk and further collaboration: after getting to know the rest of the community, the iDMEu participants (including but not limited to the proponents) were invited to identify possible areas of collaboration/discussion. The first two days of the kick-off featured talks from a large number of dark matter communities with a concrete set of review questions to be addressed (e.g. brief report on status, challenges in comparisons of results and data sharing), including their expectations of how iDMEu could be useful to their community and proposals for common work. The outcomes were then developed in the breakout sessions on the second day and discussed in the conclusions, highlighting further concrete directions for collaboration from autumn 2021 onwards, e.g. kick-starting a concrete project to define standards for data sharing in direct detection experiments.

The third day of the kick-off saw a Q&A session with experimentalists and theorists: anonymous questions were sent to the iDMEu proponents, who then found an expert to answer in a brief talk. The questions submitted and answered were on the topics of cosmology and light dark matter. Also, a review of outreach activities on dark matter in different countries was organised, including a moderated panel discussion and a hands-on activity for the participants in order to enhance community building and engagement.

Many of the suggestions discussed in the breakout sessions and in the conclusions concerned a concrete focus for iDMEu: a website containing a meta-repository for dark matter resources, as well as an interactive discussion forum following the format of the Q&A in the kick-off meeting.

The iDMEu website has been under development during 2021 with the goal of creating an online platform containing:

1. A meta-repository with pointers to experiment and collaboration websites and basic descriptions, as well as to their data, analysis tools, results as made available by the individual collaborations and outreach material;
2. Links to the main scientific (workshop, conferences, seminars) and general public dark matter gatherings and events and their content;
3. A forum that facilitates the interactive exchange of information between members of the different dark matter communities and encourages them to discuss and start new projects.

The content of the iDMEu meta-repository is ambitious, given the breadth of the community and the fact that it needs to be sustainable on a 5-10 year timescale. The first stage of the work, available in a demonstration version of the website at idmeu.org, has been developed by undergraduate students associated with iDMEu, who wrote a review thesis and received a degree at their respective universities, under the supervision of the iDMEu organisers. The second stage will involve postdoctoral researchers associated with iDMEu interacting with ongoing community-wide initiatives and with the experiments themselves to create a two-way communication channel whereby the responsibility to keep the information up to date (and the credit for doing so) is shared.

Thanks to the support of JENAA, a professional company was commissioned to produce a more complete version of the iDMEu website, with the final structure and layout, including the discussion forum, delivered by autumn/winter 2021. Early-career researchers and the iDMEu organisers will also continue working on the content, seeking input from the various communities to make sure the information is up to date.

iDMEu in the context of the European Strategy update

Once the website is completed, the main work of the iDMEu organisers will be to keep encouraging cross-talk starting from this platform, with a follow-up iDMEu town-hall meeting in the lead-up to the next JENAA meeting in May 2022.

Overall, iDMEu is meant to achieve goals in line with the recommendations set out in the update of the European Strategy for Particle Physics [4]. It aims to identify cross-field and cross-experiment opportunities that will advance our understanding of dark matter while exploiting synergies between neighbouring fields, and to communicate the breadth of dark matter efforts to different stakeholders, from fellow scientists to students to the general public. Both of these objectives are necessary as part of advancing science, and require discussion across all communities.

To subscribe to the mailing list that will announce further iDMEu activities, follow this link (requires a CERN account). If you don't have a CERN account, you can email the organisers (currently: Marco Cirelli, Federica Petricca and Caterina Doglioni) to subscribe at iDMEu-jenaa-eoi-organizers@cern.ch.

References:

[1] First Joint ECFA-NuPECC-ApPEC Seminar (JENAS) https://jenas-2019.lal.in2p3.fr/.
[2] JENAA expression of interest for iDMEu https://indico.cern.ch/e/iDMEu.
[3] iDMEu kick-off meeting, with talks and recordings https://indico.cern.ch/e/iDMEuKickOff.
[4] European Strategy Deliberation Document https://cds.cern.ch/record/2720131?ln=en.

Gravitational Wave Probes of Fundamental Physics

by T. Galatyuk (GSI Helmholtzzentrum für Schwerionenforschung, Technical University Darmstadt) and P. Pani (Sapienza University of Rome)

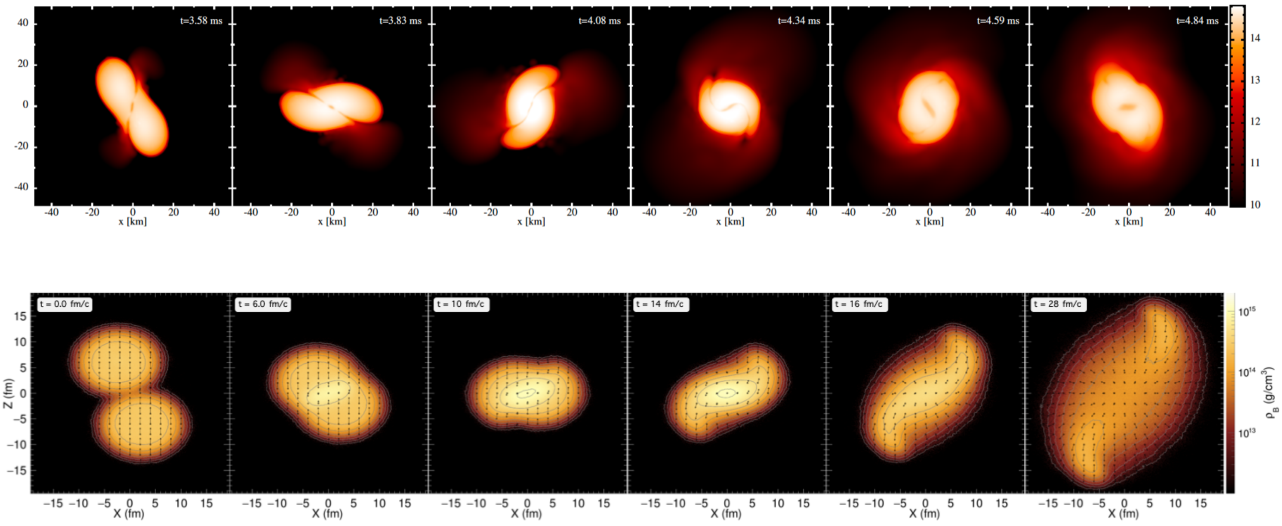


Figure 6: General relativity "meets" QCD matter equation of state. (Top panel, from Phys. Rev. X 11, 021053 (2021)) During an NS merger, the GW signal carries unique information about the matter content of the stellar interior. (Bottom panel, from Nature Phys. 15 (2019) 10, 1040-1045) Simulation of a heavy-ion collision at SIS18 energies.

With approximately 50 black-hole (BH) and a few neutron-star (NS) merger events detected by the LIGO and Virgo interferometers to date – and many more expected in the next few years – gravitational-wave (GW) science is now in full swing. In addition to their countless astrophysical applications, these discoveries open new cross-cutting avenues for exploring fundamental and high-energy physics. These synergies between previously disparate branches of physics pave the way for novel developments, which will be instrumental to exploit the huge scientific potential of future GW detectors. GW, electromagnetic (EM), neutrino and cosmic-ray observations of the same source provide a novel, global way to explore the cosmos and will shed light on the nature of merging BHs, the composition of NSs, the engine of relativistic jets and other high-energy phenomena, and the environments where these sources live. However, the unique opportunities offered by multi-messenger astronomy come with outstanding scientific challenges related to rapid, accurate detection and characterisation of GW signals for EM follow-up, the identification of the EM counterpart amongst a fog of other astrophysical transients and variables, and the complexity of astrophysical simulations given the multi-physics and multi-scale nature of violent EM sources and transients, as well as an integrated analysis and interpretation of the data in the context of astrophysics, nuclear and atomic physics, fundamental physics and cosmology.

The experimental, theoretical and community challenges associated with these big problems are enormous. From an experimental point of view, there is strong interest from funding agencies worldwide in groundbreaking experiments and space missions, such as the European third-generation Einstein Telescope interferometer and the ESA-led space mission LISA. From a theoretical point of view, current gravitational waveforms should be improved for reliable physical interpretation, given the high-precision data expected from future experiments. Last but not least, GW science means organising the effort of large and diverse communities and exploiting their synergies. This will also require GW physics training for the next generation of leaders in order to be able to communicate across a spectrum of sub-fields. Such an effort is instrumental to maximise the benefit from theoretical developments and from the current and future wealth of data from GW interferometers, radio and X-ray observatories, and particle accelerator facilities. These are the goals of "Gravitational Wave Probes of Fundamental Physics", an initiative endorsed by 600+ scientists from 25+ countries across the world and from different areas (astroparticle, atomic, nuclear, high-energy and gravitational physics, cosmology, and GW and multi-messenger astronomy) and supported by JENAA.

The initiative is organised around several outstanding themes:

i) Matter under extreme conditions – aimed at constraining strongly interacting matter at ultra-high density, temperature and isospin by combining current and future data from GW interferometers and relativistic heavy-ion collision experiments;

ii) Nuclear and atomic physics and their role in multi-messenger astronomy – aimed at interfacing nuclear and atomic physics with simulations of the complicated EM counterpart of an NS merger, in particular the "kilonova", to provide unparalleled constraints on the physics of neutron-rich nuclei, and to improve our understanding of the r-process in binary NS and BH–NS merger events as well as the accuracy of modelling accretion disks, jets and plasma physics around compact objects. This will also require efforts from atomic structure theory, in combination with laboratory benchmarking experiments, and with existing and upcoming x-ray satellite missions (e.g. NICER, GRAVITY, Athena, eXTP) and future GW data;

iii) Fundamental problems in high-energy and gravitational physics – aimed at unveiling the nature and phenomenology of dark matter with GWs in ways complementary to lab searches, testing the boundaries of classical general relativity in extreme gravitational sources, exploring potential signatures of quantum gravity near BHs, and exploiting the sophisticated technology built by the particle- and high-energy physics community to produce high-accuracy waveforms in order to reduce the modelling systematics and pave the way for precision GW physics;

iv) GWs and cosmology – aimed at using GW standard sirens to provide independent measurements of the expansion rate of the universe – shedding light on fundamental cosmological questions such as what is the nature of dark energy and whether gravity is modified at cosmological distances – and at exploring the primordial universe through the GW stochastic background from inflation and phase transitions and through the possible detection of primordial BH mergers.

The activities of the "Gravitational Wave Probes of Fundamental Physics" initiative are currently focused on fundraising to inaugurate this interdisciplinary community. A cross-cutting kick-off meeting is planned for 2022, hopefully in person.

Optimising the Design of Particle Detectors: the MODE Collaboration

by T. Dorigo (INFN, Padova) for MODE

The recent update of the European Strategy for Particle Physics [1] directs us to explore the feasibility of future ambitious projects, exploiting technological advancements as well as driving new ones. On the other hand, the world today faces huge global challenges (climate change, pandemics, overpopulation) that force us to direct a significant fraction of our resources to applied science solutions. In this situation, it is imperative to strive for maximum knowledge gains from any additional investment in fundamental research. This is true especially in high-energy physics, due to the unavoidably large construction costs of new endeavours and the public perception of the worth of the corresponding investments [2].

Building optimised particle detectors is a superhuman task, because when we design the sensors for a tracking device, choose the cell layout of a calorimeter or make budget decisions to partition resources, we are implicitly trying to find an optimal working point in an only loosely constrained parameter space with hundreds of dimensions. We solve the problem by targeting makeshift surrogates of our real objectives. For example, while we would desire "the highest precision on the Higgs boson self-coupling that our budget can achieve", we have no way of probing what exact compromises between the various design choices will produce that result. We therefore stick to robust notions from past experience and project the rich parameter space to very low dimensional surrogates for our objective, such as "maximum energy resolution for isolated photons". In contrast, a realignment of our design choices to our true objectives offers potentially huge gains in the final success metric.

MODE (an acronym of "Machine-Learning Optimised Design of Experiments" [3]) is a collaboration of physicists and computer scientists from 13 academic institutions in Europe and America. Its members recognise that the artificial intelligence tools available today allow us to tackle, for the first time, the challenging problem of the end-to-end optimisation of the design of instruments that operate by leveraging the interaction of radiation with matter.

Under the above umbrella definition, we can fit small- to large-scale particle detectors for high-energy physics, astrophysics, nuclear and neutrino physics studies, as well as a wide class of instruments for research and industrial applications. All those instruments share a few characteristic traits. They are typically very complex, employing cutting-edge technology, sensors and electronics; because they exploit subnuclear processes to function, their input data has an intrinsically stochastic component. Strictly speaking, this makes the information extraction reliant on simulation-based inference methods: an explicit form of the likelihood function of the observed data given the underlying parameters does not exist, hence variational methods cannot be applied to explore the parameter space. A thriving field of research nowadays addresses the above problem with local surrogates, generative adversarial networks, and variational autoencoders, and in general with approximations that allow the construction of differentiable models, crucial for such a high-dimensional optimisation problem.

The use of automatic differentiation [4] (available in e.g. TensorFlow and PyTorch [5]) allows us to encode the whole system – from the data generation processes to the inference extraction procedures – in a modular software pipeline that enables the seamless propagation of derivatives of the loss function with respect to design parameters through its connected elements. The multi-dimensional space of design choices may be automatically navigated with stochastic gradient descent, enabling the exploration of potentially groundbreaking solutions, as well as the determination of the most advantageous geometry, layout, quantity and quality specifications of the detection elements.

Key to the above plan is the careful specification of a multi-objective loss function that informs the software of the true goals of the instrument, along with existing boundary conditions (e.g. cost and geometrical constraints). Exploratory studies carried out by MODE members have shown the effectiveness of the above methodology, demonstrating that very large gains in performance [6,7] are potentially achievable from the study and optimisation of even very simple instruments; in addition, new solutions can in some cases be autonomously suggested by the models produced [8]. Of course, the solutions suggested by these software tools must be validated with full-scale simulations and in-field tests requiring the domain knowledge and insight of the physicists designing the apparatus, as would be the case with any new design idea.

MODE has the ambitious goal to show how the aforementioned techniques may be adapted to the complexity of modern and future particle detectors and experiments, while remaining applicable to a number of applications outside that domain. This will initially be achieved by considering simple applications, gradually building an arsenal of modular solutions that can be reused for different problems. In other words, we plan to acquire the expertise to successfully model particle detectors designed for simpler tasks, as we expect that ability to pay large dividends in future, more ambitious applications.

The studies currently in progress focus on the optimisation of detectors for muon tomography and imaging [9] and the optimisation of the electromagnetic calorimeter for the LHCb upgrade [10]. A first workshop on "Differentiable Programming for Experimental Design" [11] in Louvain-la-Neuve (6-8 September 2021), partially funded by JENAA [12], will make it possible to organise studies of other use cases of interest to the community.

MODE

1: University of Oxford
2: New York University
3: Treelogic
4: Université catholique de Louvain
5: HSE University
6: Université Clermont Auvergne, LPC, CNRS/IN2P3
7: INFN, Sezione di Padova
8: CERN
9: Università di Napoli "Federico II"
10: Université de Liège
11: Instituto de Física de Cantabria
12: Università di Padova
13: National University of Science and Technology MISIS

References

[1] The European Strategy Group, "2020 Update of the European Strategy for Particle Physics," CERN, Geneva, https://europeanstrategy.cern/, DOI: http://dx.doi.org/10.17181/ESU2020Deliberation, 2020.

[2] See, e.g., the *New York Times* op-ed by S. Hossenfelder at https://www.nytimes.com/2019/01/23/opinion/particle-physics-large-hadron-collider.html, 2019.

[3] MODE: Machine-learning Optimised Design of Experiments. Collaboration website: https://mode-collaboration.github.io/. The MODE research plan is the subject of an expression of interest supported by JENAA, see http://www.nupecc.org/jenaa/?display=eois.

[4] A. Güneş Baydin et al., "Automatic Differentiation in Machine Learning: a Survey", Journ. Mach. Learn. Res. 18.153 (2018) 1, http://jmlr.org/papers/v18/17-468.html.

[5] M. Abadi et al., "TensorFlow: Large-Scale Machine Learning on Heterogeneous Systems", arXiv:1603.04467 [cs.DC] (2016); Adam Paszke et al., PyTorch: An Imperative Style, High-Performance Deep Learning Library, arXiv:1912.01703 [cs.LG], Advances in Neural Information Processing Systems 32 (NeurIPS) (2019).

[6] S. Shirobokov et al., "Black-Box Optimization with Local Generative Surrogates", arXiv:2006.04632 [cs.LG], Advances in Neural Information Processing Systems 34 (NeurIPS) (2020).

[7] T. Dorigo, "Geometry optimization of a muon-electron scattering detector", Phys. Open 4 (2020) 100022, doi:https://doi.org/10.1016/j.physo.2020.100022.

[8] See, e.g., J. Kieseler, G. C. Strong, F. Chiandotto, T. Dorigo and L. Layer, "Calorimetric Measurement of Multi-TeV Muons via Deep Regression", arXiv:2107.02119v1 [physics.ins-det] (2021).

[9] L. Bonechi, R. D'Alessandro and A. Giammanco, "Atmospheric muons as an imaging tool", Rev. Phys. 5 (2020) 100038, doi:10.1016/j.revip.2020.100038.

[10] F. Ratnikov, "Using machine learning to speed up and improve calorimeter R&D", JINST 15 (2020) C05032, doi.org/10.1088/1748-0221/15/05/C05032.

[11] See https://indico.cern.ch/event/1022938/.

[12] See http://www.nupecc.org/jenaa/?display=eois.

Nuclear Physics at the Large Hadron Collider

by L. Fabbietti (Technical University Munich) and A. Kalweit (CERN)

In the high-energy physics community, the Large Hadron Collider is mostly known for its groundbreaking contributions to the most fundamental aspects of modern particle physics, ranging from the Higgs boson discovery and its properties, to flavour physics and the study of the quark–gluon plasma. However, as a versatile hadron collider, it also offers a unique possibility to study the interaction between the many particles that are produced in its collisions – ranging from those between ordinary protons and neutrons to more exotic particles like hyperons, antinuclei and charmed baryons. Quite remarkably, these studies have a wide breadth of possible applications to astrophysics and thus provide the ground for truly interdisciplinary studies. They provide the basis for a proposal that has been submitted to the JENAA initiative.

Antinuclei: from searches in space to laboratory measurements

Space-borne experiments like AMS or balloon experiments like GAPS look for antinuclei such as antideuterons or antihelium that are produced in the annihilation of dark matter particles or by other exotic sources. Collider measurements can contribute in several ways to understanding these antinuclei. Firstly, the formation probabilities of antinuclei based on coalescence models provide crucial input for signal and background rates. Secondly, the propagation of these particles through the galaxy is sensitive to the hadronic interaction cross section of antinuclei with proton and helium nuclei from interstellar matter. The ALICE experiment at the LHC, with its strong particle identification capabilities, is ideally suited to perform these investigations. In addition, the LHCb experiment is able to provide important measurements of antiprotons for the astrophysics community thanks to its coverage at forward rapidity and its ability to collect data in fixed-target mode. While there has not yet been a confirmed observation of antinuclei in space, their production is routinely studied at accelerator-based experiments like ALICE. The LHC itself can be considered an antimatter factory because particles and antiparticles are produced in equal abundance at midrapidity and, at the same time, many particles are produced per event. Currently, anti- and hypernuclei up to A=4 are in reach and several results on transverse momentum spectra and production yields have been obtained.

Figure 7 (below left) shows, by way of example, the cross section for the inelastic interaction of antideuterons recently measured by the ALICE collaboration. With this method, the cross section is obtained for the average material of the ALICE detector and can then be scaled to the relevant hydrogen and helium targets. In ongoing studies, these values are then fed into propagation codes like the GALPROP package in order to calculate the survival probability for reaching Earth.

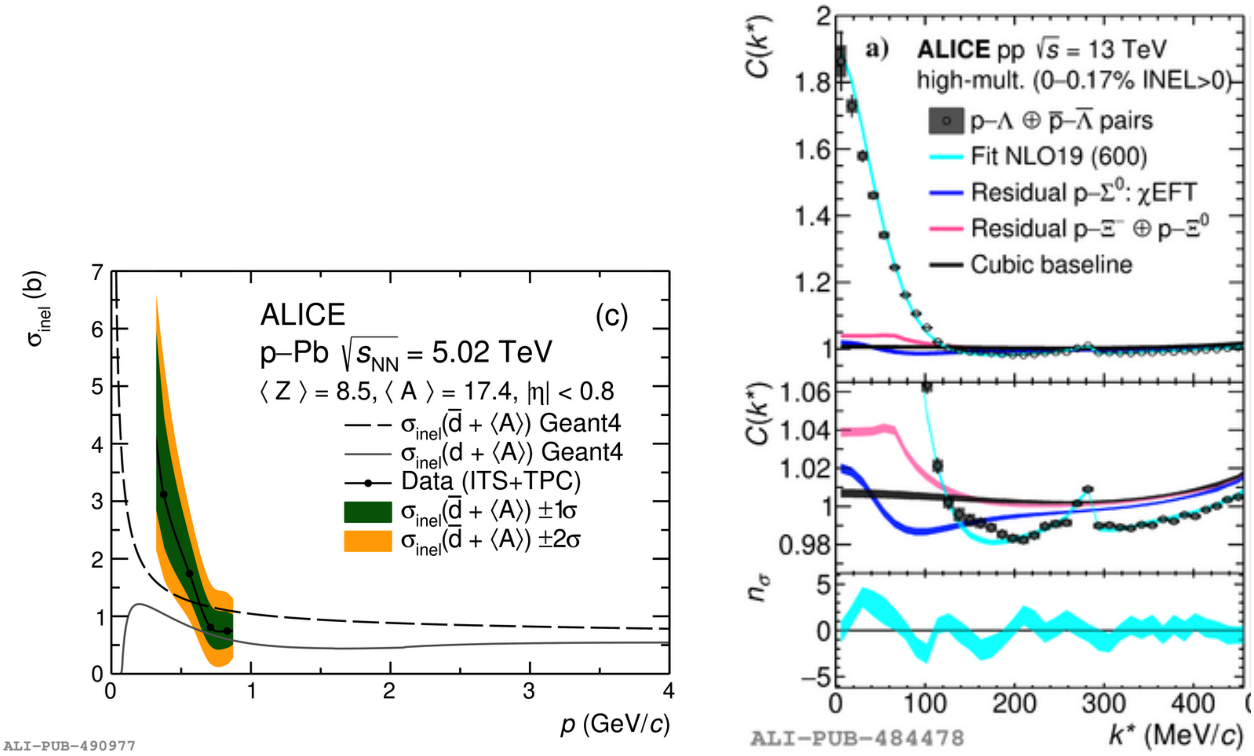


Figure 7: (Left panel) Inelastic cross section for antideuterons by ALICE. The figure is taken from [1]. (Right panel) Measured proton-Lambda correlation by the ALICE collaboration and comparison to theoretical predictions. The figure is taken from [2].

Hyperon–nucleon and nucleon–nucleon interactions

The second big subject in which LHC measurements can improve our astrophysical understanding is the equation of state of neutron stars – that is, the dependence of the system energy and pressure upon the density. The composition of an NS interior is not yet known, and one possible scenario is the appearance of hyperons via processes such as p+e- → Λ + νe, which could be energetically favoured due to the absence of Pauli blocking. In this scenario, the appearance of hyperons within a neutron-rich dense system introduces new degrees of freedom that soften the equation of state of the system.

A key element for a correct evaluation of the equation of state of dense neutron-rich systems that also contain hyperons is the precise knowledge of the hyperon–nucleon and hyperon–hyperon interactions. Scattering experiments with hyperon beams have provided some orientation for the two-body interaction and several measurements of single-Λ and double-Λ hypernuclei made it possible to establish the general attractive character of the Λ–N strong interaction. But it is only recently, thanks to the femtoscopy technique applied to pp and p–Pb collisions measured by ALICE, that the precision era for such measurements has begun. The femtoscopy technique involves measuring the correlation among particle pairs in the momentum space and relating this measurement to the space coordinates distribution of the particles of interest and their relative wave function and hence interaction. The right-hand panel of figure 7 shows the correlation function measured for p–Λ pairs produced by ALICE.

The fact that the correlation function is larger than one is related to the attractive nature of the measured interaction. The data is compared to theoretical calculations obtained within the χEFT framework. The p-Σ0 and p-Ξ- interactions have also been measured, for the first time ever, by the ALICE collaboration exploiting the same technique. This made a new computation of the equation of state for hyperon stars possible. Preliminary calculations anchored to these new interaction measurements lead to a stiffer equation of state.

A bright future ahead

The increased data samples expected in the future may enable studies to investigate three-body interactions including hyperons and nucleons. This could provide a unique tool to access the many body interactions in nuclear physics and perhaps solve the long-standing hyperon puzzle in neutron stars. In general, the upcoming LHC Runs in the 2020s (Runs 3 and 4) and 2030s (Run 5) will take these physics studies to the next level. For instance, the possible existence of light nuclei of charm baryons like the c-deuteron, a bound state of Λc and neutron, should be investigated. In addition, the proposed new large-acceptance experiment ALICE 3 for Run 5 and beyond with its fast readout capabilities and excellent performance for heavy flavour detection may open new directions for hadron-interaction studies including heavy flavour.

In space, future satellite missions are being considered, such as the AMS-100 proposal to position a fully instrumented particle detector in a translunar orbit. As the LHC is the only high-energy hadron collider experiment for many years to come, the LHC community has a duty to measure and understand antinuclei production as comprehensively as possible!

References for plots

[1] S. Acharya et al. (ALICE collaboration), “Measurement of the low-energy antideuteron inelastic cross section”, Phys. Rev. Lett. 125, 162001 (2020).

[2] S. Acharya et al. (ALICE collaboration), “Exploring the NΛ-NΣ coupled system with high precision correlation techniques at the LHC”, submitted to PRL, arXiv:2104.04427.

Electric Dipole Moment Measurements at Storage Rings

by C. Carli (CERN), P. Lenisa (University of Ferrara & INFN) and J. Pretz (FZ Jülich & RWTH Aachen University)

One of the biggest mysteries in particle physics and cosmology is the fate of antimatter. According to our present understanding, matter and antimatter were in balance in the early universe. Today, the visible universe is dominated by matter. Andrei Sakharov showed that CP violation is a necessary condition to explain the disappearance of antimatter. It turns out that the well-established CP violation of the Standard Model is orders of magnitude too small to explain today's dominance of matter.

Here, electric dipole moments (EDMs) enter the scene. Elementary particles can only have an EDM if parity (P) and time reversal symmetry (T) are violated. Assuming the validity of the CPT theorem, T violation implies CP violation. EDMs due to the CP violation of the Standard Model are orders of magnitude below current experimental sensitivities. On the other hand, many extensions of the Standard Model allow for additional CP violation and predict EDMs in reach of current experiments.

EDMs can be measured by observing their influence on the spin motion in electric fields. For neutral particles, this can be done in small volumes (e.g. particle traps). For charged particles, their acceleration requires larger volumes like storage rings. Figure 8 shows the principle of the experiment. With suitable combinations of electric and magnetic fields and particle momentum, spin precessions due to the magnetic moment relative to the momentum vector can be suppressed (frozen spin condition). The EDM causes a build-up of a vertical polarisation that can be observed using a polarimeter. In figure 8, various possible combinations of electric and magnetic fields for protons are shown. For particles with a positive G factor, e.g. protons, it is possible to use a pure electric ring. With a field strength of 8 MV/m, the bending radius of the ring is approximately 50 metres. The proton momentum has to be at its "magic" value of 700.7 MeV/c. A pure electric ring makes it possible to have simultaneously counter-rotating beams in the ring, which is very beneficial for systematic error cancellation. A second option is to construct a ring with a combination of magnetic and electric fields. One possibility, with an electric field of 7 MV/m and a magnetic field of 0.033 T,

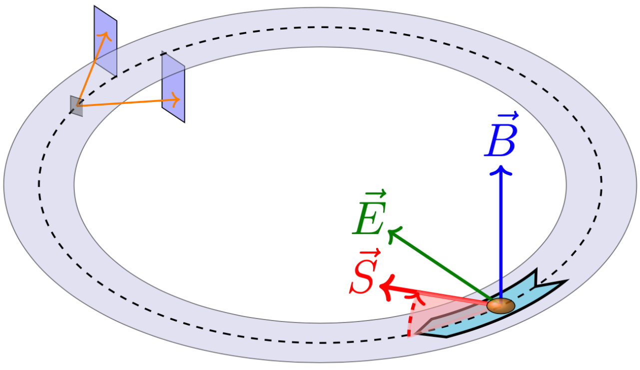


Figure 8: Principle of a storage ring EDM experiment: an EDM causes a vertical polarisation component of a beam initially polarised in plane. With a suitable combination of electric and magnetic fields and particle energy, spin motions due to the magnetic moment can be suppressed. The polarisation build-up can be observed via elastic scattering on a carbon target.

is shown in figure 9. In this case, the momentum amounts to about 300 MeV/c and the bending radius is only 9 metres.

Based on the work of the JEDI collaboration [1], which is performing a first measurement of the deuteron EDM at the storage ring COSY at *Forschungszentrum Jülich*, Germany, a new collaboration, CPEDM (Charged Particle Electric Dipole Moment) was formed. It emerged from a working group of the Physics Beyond Colliders initiative at CERN [2]. The aim is to construct a prototype ring (see Figure 9) before tackling the challenge of constructing a pure electric ring. With the prototype ring, many systematic studies and a first direct measurement of the proton EDM with a statistical precision significantly better than the neutron EDM ($\approx 10^{-26}$ cm) could be performed. Systematic limits are still under investigation. Another interesting aspect is that axion-like particles cause an oscillating EDM, which could also be measured with the same setup. Since we are looking at a resonance effect, the observable is less affected by systematic uncertainties.

The physics case has connections to astroparticle and particle physics, and the momentum range and the polarisation techniques are typical for hadron and nuclear physics. The core of the experimental setup is an accelerator. In this spirit, a JENAA expression of interest was submitted [3]. Earlier this year, a Heraeus Seminar “Towards Storage Ring Electric Dipole Moment Measurements” was held [4]. More details on the project can be found in the recent CERN yellow report [5] by the CPEDM collaboration.

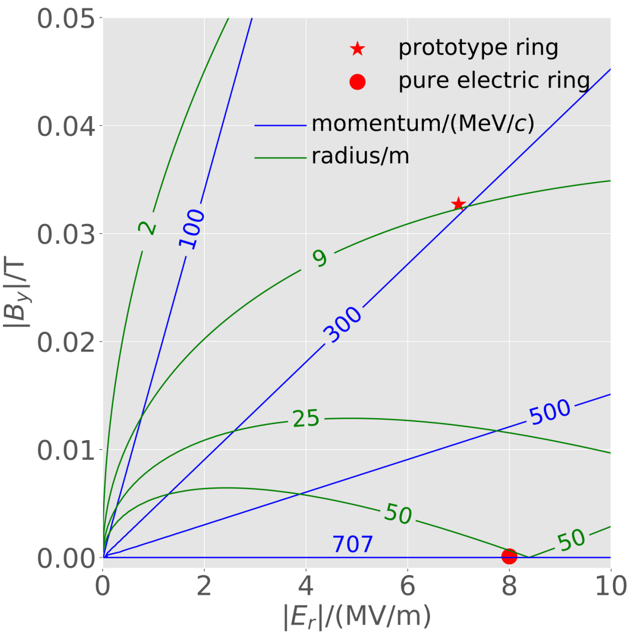


Figure 9: Bending radius and proton momentum for the frozen spin condition as a function of the magnetic and electric fields.

References

[1] JEDI, “JEDI collaboration,” http://collaborations.fz-juelich.de/ikp/jedi/, 2021. [Online]. Available: http://collaborations.fz-juelich.de/ikp/jedi/.
[2] J. Beacham, C. Burrage, D. Curtin, A. De Roeck, J. Evans, J. L. Feng, C. Gatto, S. Gninenko, A. Hartin, I. Irastorza and et al., “Physics beyond colliders at CERN: beyond the Standard Model working group report,” Journal of Physics G: Nuclear and Particle Physics, vol. 47, no. 1, p. 010501, Dec 2019. [Online]. Available: http://dx.doi.org/10.1088/1361-6471/ab4cd2.
[3] JENAA expression of interest: "Storage rings for the search of charged-particle electric dipole moments (EDM)", 2020. [Online]. Available: https://indico.ph.tum.de/event/4482/overview.
[4] 744. WE-Heraeus-Seminar, “Towards Storage Ring Electric Dipole Moment Measurements”. [Online]. Available: https://www.we-heraeus-stiftung.de/veranstaltungen/seminare/2021/towards-storage-ring-electric-dipole-moment-measurements/.
[5] Abusaif, F. et al, “Storage ring to search for electric dipole moments of charged particles: Feasibility study”, ser. CERN Yellow Reports: Monographs. Geneva. Geneva: CERN. CERN, 2021. [Online]. Available: https://doi.org/10.23731/CYRM-2021-003.