ECFA
European Committee for Future Accelerators

8th Newsletter

Following the 109th Plenary ECFA meeting, 18 and 19 November 2021

https://indico.cern.ch/event/1085137/

Winter 2021

Since the previous Plenary ECFA meeting, at the end of July 2021, an important ECFA activity has been the finalisation of the Detector R&D Roadmap, which was unanimously approved at the Plenary ECFA meeting on 18 November. With this, an important milestone in the follow-up of the actions set out in the update of the European Strategy has been reached. The Roadmap outlines a list of important Detector R&D Themes and Detector Community Themes, which capture a number of the most pressing aspects of R&D requirements. In addition, General Strategic Recommendations have been issued. The major conclusions and recommendations have also been summarised in a synopsis document.

Finally, the Roadmap was presented to the CERN Scientific Policy Committee (SPC) and to the CERN Council in December. The Council took note of the Roadmap and synopsis documents as well as of the report by the SPC Chair indicating the Committee's support for the Roadmap recommendations and of the statements by Member and Associate Member State delegations voicing support and appreciation for the content of the documents. Although we have reached the end of our initial mandate, the work is not over, as the next important step is the development of an implementation plan, in which ECFA – together with the Large Particle Physics Laboratory Directors Group (LDG) – has been invited to play a leading role.

Much progress was also made on the ECFA activity to bring together all the e^+e^- Higgs factory efforts (ILC, CLIC, FCC-ee and CEPC) in order to share challenges and expertise, explore synergies and – wherever possible – develop common tools and methods. Following an important kick-off meeting in June 2021, the activities of two working groups got under way and are progressing well, with dedicated topical workshops and working groups. A first three-day workshop is planned for autumn 2022, and a call for bids to host it has been launched very recently.

A sixth expression of interest for a Joint ECFA−NuPECC−APPEC Activity, proposing to explore synergies between the Electron–Ion Collider (EIC, under construction in the USA) and the LHC, was received and endorsed by ECFA. From 3 to 6 May 2022, the second Joint ECFA–NuPECC–APPEC Seminar (JENAS) will be held in Madrid. In addition to discussing the joint activities, we will explore synergies in the challenging technology areas of detector development, data handling and computing. We will also hear reports from the common working groups on recognition (in large experiments) and on diversity and inclusion.

In this ECFA Newsletter, you find reports on the talks presented during the open Plenary ECFA meeting of 19 November at CERN. The session started with presentations of the final Accelerator and Detector R&D Roadmaps (for this, see also reports in the previous ECFA Newsletter), followed by an important talk addressing challenges in computing at the HL-LHC. These presentations were followed by reports from the two working groups on the ECFA studies towards a Higgs factory. The meeting continued with detailed presentations on CERN's activities and on the FCC Feasibility Study. In addition, short reports were given on the activities and plans of some of the major European laboratories (IJCLab, Nikhef, PSI and STFC). The meeting concluded with presentations on the status of possible future e^+e^- facilities (ILC, CLIC, FCC-ee and CEPC), covering updates on the layout of the accelerators, the status of possible detector designs and the physics capabilities.

Finally, we would like to take this opportunity to wish all of you a relaxing time over the upcoming holiday season and all the best for 2022.

Karl Jakobs
ECFA Chair

Patricia Conde Muíño
ECFA Scientific Secretary

Computing challenges and future directions

by S. Campana (CERN)

The time horizon for high-energy physics (HEP) software and computing challenges is around 10 years, during which the main contributor will be the High-Luminosity LHC, driven by ATLAS and CMS needs. The LHC resources are provided by the Worldwide LHC Computing Grid (WLCG) infrastructure. Other sciences use the same computing facilities as WLCG and will present comparable challenges by the end of the decade. The central processing unit (CPU) needs of ATLAS and CMS are driven by data reconstruction and Monte Carlo, detector simulation and event generation. For the latter two, common libraries such as Geant4 and various event generators serve the needs of both ATLAS and CMS, and any optimisation thereof could be beneficial for both experiments.

The roadmap towards HL-LHC in the computing area sets out a gradual and continuous evolution of the existing libraries to improve the physics description of the processes, efficiency and performance. In addition, several R&D projects exist to introduce disruptive changes such as the offloading of computations to graphics processing unit (GPU) accelerators or a broader use of machine-learning techniques. In particular, software portability and validation to non-X86 CPU architectures and the integration of GPUs will make it possible in the future to leverage more opportunistic computing capacity from facilities such as high-performance computing (HPC) centres.

The HL-LHC archive storage needs are dominated by the volume of raw data to be retained. The largest cost, however, comes from online media such as disk storage, and the need to serve reconstructed data for analysis. The main strategy for HL-LHC involves the deployment of reduced data formats that are more than one order of magnitude smaller than the more complete analysis formats but still contain enough information for most physics analyses. The adoption of those formats by the experiment analysis teams in the coming years will be key in addressing the storage challenge at HL-LHC. In addition, the experiments will be able to leverage archive media in a more dynamic model than in the past, with just-in-time staging of the data needed for organised productions, therefore avoiding the need to permanently retain large datasets on disk.

Reliable network infrastructure will be fundamental for the efficient use of computing and storage resources at the HL-LHC, and an incremental process to commission the network service towards the HL-LHC has been put in place. The first step of this process – the data challenges in preparation for Run 3 of the LHC – was completed successfully in 2021. The data analysis needs will be moderate in terms of resources at HL-LHC, and the efficiency of the analysis tools will be a major ingredient to improve the user experience. The ROOT team has implemented a new internal data format, RNtuple, that will enable fast adoption of modern technologies such as object stores. It is expected to bring much faster read efficiency and some storage saving.

The progress made by the experiments, the software communities and WLCG in preparation for the HL-LHC is being followed by the CERN LHCC through a series of reviews. In the last update in November 2021, the experiments highlighted the remaining gap between the resource needs and what will likely be available in WLCG. However, this gap has been regularly reducing as new improvements are introduced, and it has decreased by a factor three since the first projections made at ECFA in 2016. The experiments have also identified concrete R&D projects that, if successfully accomplished, would close that gap completely. For this to happen, more personpower needs to be identified. The most recent projections of ATLAS's needs for the HL-LHC are shown in figure 1. Similar projections exist for the CMS experiment.

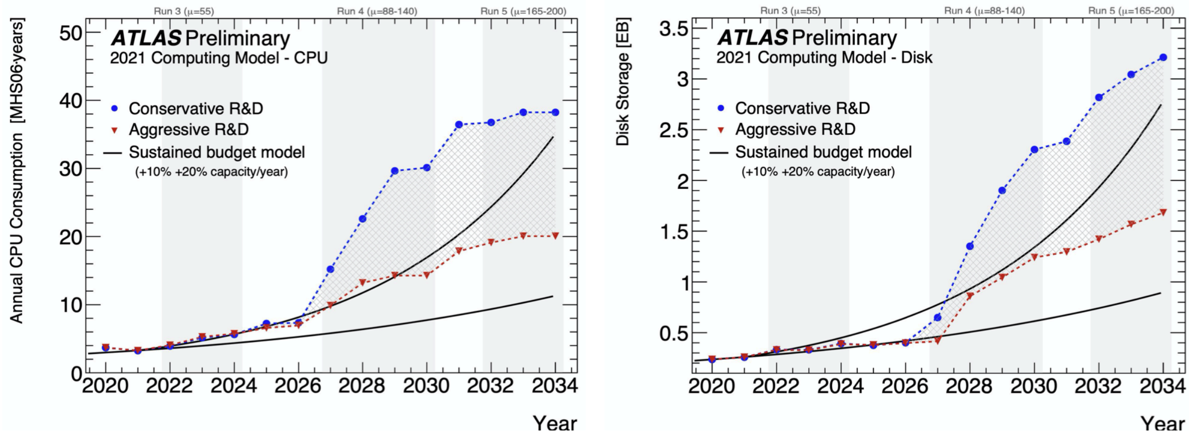

Figure 1: The most recent projections of the HL-LHC CPU and disk needs of the ATLAS experiment. Both an aggressive and a conservative R&D scenario are considered. The needs are compared with the expected available resources, based on a sustained budget model.

The HL-LHC computing challenge should not be seen as a pure resource issue. The aspect of infrastructure sustainability is at least as challenging: WLCG services have been providing the required functionality for the experiments for more than 15 years, and will need to support LHC computing for at least 15 more. The service technologies need to constantly evolve to take advantage of emerging technologies from open source communities, while providing a stable service for the experiments' operations.

In addition, many facilities in the WLCG infrastructure will serve the needs of other large HEP experiments and other sciences, such as astronomy and astroparticle projects. LHC computing is collaborating with those sciences towards a shared ecosystem of tools and services supporting future research needs, in line with the outcome of the European Strategy for Particle Physics (ESPP) update in 2020.

ECFA studies towards a Higgs/EW/top factory

by J. Alcaraz (CIEMAT) and P. Azzi (INFN-Padova)

The ESPP update has identified an electron–positron Higgs factory as the highest-priority next collider after the HL-LHC. Currently, several projects are being considered: linear colliders such as the ILC (Japan) and CLIC (CERN), or circular colliders, like the FCC-ee and CEPC.

The physics programmes of these projects extend far beyond performing precision measurements of the Higgs boson properties; they have great potential as electroweak and top factories as well. ECFA recognises the need for the experimental and theoretical communities involved in physics studies, experiment designs and detector technologies at future Higgs factories to gather together and become a reference to attract physicists from the LHC community to get involved in the studies for future lepton colliders.

ECFA is supporting a series of workshops to share challenges and expertise, to explore synergies among the various efforts, and to respond coherently to the priority set by the ESPP. This process would serve to not only extend physics studies with respect to those presented during the ESPP, but also better understand the interplay between the (HL-)LHC and the e+e- Higgs/EW/top factories. At the same time, it would encourage the development of common software tools and analysis methods in order to facilitate the process of exploiting synergies and discussing specific challenges.

To accomplish this ambitious goal and organise the vast spectrum of activities to be carried out during this process, a simple and effective structure has been defined: an International Advisory Committee, bringing together experts from the various lepton collider projects and the LHC, and two working groups, focusing on the physics measurements and their challenges and the tools needed to achieve them.

A kick-off meeting to present the plans for all these activities took place on 18 June 2021 [1].

Working Group 1 (WG1), called "Physics Potential", is led by Juan Alcaraz Maestre (CIEMAT-Madrid), Jenny List (DESY), Fabio Maltoni (UCL/University of Bologna) and James Wells (University of Michigan)[1]. Its central purpose is the creation of a forum to collect, compare and harmonise all the theoretical and experimental physics aspects of the work that is being done by the various future Higgs/top/electroweak factory projects and other ongoing parallel independent efforts. In this context, the Working Group is expected to identify areas requiring specific focus/development, with emphasis on those that are common/synergetic to the projects, and to propose new ideas, strategies or measurements where appropriate. The interplay with (HL)LHC physics is also part of the mandate.

Working Group 2 (WG2), called "Physics Analyses and Methods", is led by Patrizia Azzi (INFN/CERN), Fulvio Piccinini (INFN) and Dirk Zerwas (IJCLAB/DMLab). Its mandate covers all aspects that contribute to obtaining the final measurement result: Monte Carlo generators, simulation of detectors and machine effects, reconstruction of events and analysis algorithms and tools. All of these steps go together in the software ecosystem. For each of these components, some aspects need to be developed from scratch or improved to deal with the challenges at hand, be they common ones or specific to a project. Working in a common software ecosystem, irrespective of the actual Higgs factory chosen (linear or circular), will enable easy sharing and maintenance in the long term.

[1] Jorge de Blas (University of Granada) replaced James Wells in December 2021.

It should be stressed that participation in these working groups is open to all interested physicists. We are also open for cooperation with other ongoing studies, like e.g. the Snowmass process in the US.

WG1 status and plans

WG1 is in the process of identifying lead people to take forward five distinct fronts of activity. Up to five distinct fronts of activity have been defined, trying to cover all the focus points of WG1's mandate:

- WG1-PREC, covering precision calculations and theoretical, parametric and experimental systematic uncertainties;
- WG1-EFT, in charge of the global interpretations within (SM) effective field theory and ultraviolet complete models;
- WG1-HTE, focusing on Higgs, top and electroweak physics studies, with an emphasis on the interplay with LHC physics and the interpretation of results obtained at high Q^2;
- WG1-FLAV, exploring all specific aspects related with flavour physics;
- WG1-SRCH, studying the discovery potential at the scales that are directly accessible at Higgs/top/electroweak factories, with an emphasis on feebly interacting particle searches and comparisons with other experiments.

Two of the activities present in the WG1-PREC area overlap with WG2: "event generators" and "systematic uncertainties". While WG1 will concentrate its efforts on basic developments and strategies, WG2 will focus more on the development and deployment of methods and tools.

The division into several areas of activity should help build solid communities of the necessary critical size to address the expected challenges. Small topical workshops and/or seminars of specific interest will be organised on each area, and developments will be reported during parallel and plenary sessions at central ECFA workshops. The final results will be summarised in the corresponding chapters of a final report, to be delivered in 2024.

WG2 status and plans

Determining the feasibility of achieving a certain measurement precision or sensitivity relies on the availability of appropriate software packages and tools that are intertwined with physics models, machine conditions and detector concepts. The work of WG2 is the glue that connects the physics results and the software needed. Naturally, the first step is to take stock of the current development status of the various components, not only from the various lepton collider projects but also from the recent LHC experience. The next step is to evaluate the overall needs for the precision of the future measurements from e+e- colliders through discussion and exchange among the experts. It is important to underline that this is an opportunity to highlight the challenges that are common to the projects, as well as those that might be specific to a particular project or set-up. The forum provided by WG2 may trigger or follow up on the work required to overcome the obstacles. The outcome will be the development and deployment of new tools and knowledge in the common software ecosystem. The role of the chosen software ecosystem, Key4HEP (which is funded through AidaInnova), is crucial for WG2 activities and, for this reason, WG2 will be working closely with the experts in charge, Gerardo Ganis (CERN), Andre Sailer (CERN) and Frank Gaede

(DESY). Key4HEP integrates various software components to provide a ready-to-use fully fledged solution for data processing for HEP experiments. It naturally federates the needs of the FCC, ILC, CLIC, CEPC and other experiments, and is supported by international R&D efforts. If the discussion about physics processes already has a common language, the work of WG2 is to create connections to overcome existing technical boundaries between projects in the implementation of new software solutions. The modus operandi chosen to make progress with the overall plan is to organise a series of two-day "topical workshops" focused on well-defined subjects where the relevant experts can talk to each other in a format that allows open-ended discussion. The conveners prepare sets of questions beforehand on the main points of interest that need to be addressed, in such a way that the workshop brings a clear list of action items to drive the discussion or to be followed up later in shorter, focused meetings. The choice of topics follows a bottom-up approach, with the first workshop on generators (10 and 11 November 2021) [2] which is a common subject with WG1, as mentioned above, the second on simulation (1 and 2 February 2022) and the third on reconstruction (spring 2022). An example of the follow-up on specific issues identified in such meetings is the focus meeting on beamstrahlung that is scheduled for the afternoon of 12 January 2022.

Like for WG1, WG2 meetings are a forum bringing together all the lepton collider projects and LHC experts and beyond. While the majority of the actual work and development will happen inside the project's specific groups, an effort is being made to attract the interest of colleagues from the LHC who could share their expertise and get involved in specific tasks for the lepton colliders. Later on, once common software tools are available, it is expected that some cross-cutting efforts across projects could be put in place, such as for the definition of methods for systematic evaluations or validation of reconstruction and analysis tools.

The first steps of this ECFA initiative for future Higgs/EW/top factories have succeeded not only in bringing together experimental physicists already involved in the various lepton collider projects, but also in engaging colleagues from the LHC and other experiments along with representatives of the theory community at large.

The results of this process will appear in a final yellow report in 2024.

References:

[1] https://indico.cern.ch/event/1033941/

[2] https://indico.cern.ch/event/1078675/

FCC Feasibility Study

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

Following the ESPP update [1], the organisational structure and the major milestones and deliverables of the FCC Feasibility Study (FS) were approved by the CERN Council in June 2021 [2, 3]. The detailed motivation and scope of the FCC FS have been described previously (see e.g. ECFA Newsletter #7, summer 2021 [4]). The FCC FS will continue until the end of 2025. In the event that the project is approved before the end of the decade, tunnel construction could start at the beginning of the 2030s.

The main FCC FS activities concern the development and confirmation of a concrete implementation scenario in collaboration with the Host State authorities, accompanied by machine optimisation, physics studies and technology R&D, performed via global collaboration and supported by the European Commission's Horizon 2020 Design Study FCCIS [5], with the goal of demonstrating feasibility by 2025/26. The long-term goal is the creation of a world-leading high-energy physics infrastructure for the twenty-first century, to push the particle physics precision and energy frontiers far beyond present limits.

Ongoing high-field magnet R&D represents the first step towards a future hadron collider, FCChh. The main activities include research on materials, aiming at ~16 T for Nb_3Sn and at least ~20 T for HTS inserts, and on magnet technology with a focus on engineering, mechanical robustness, insulating materials and field quality. Production of models and prototypes will validate the material, design and engineering choices and address issues of industrialisation and costs. Infrastructure and test stations will be set up for tests up to ~ 20 T and 20–50 kA.

In September 2021, an optimised "lowest-risk" placement was defined to serve as the FS baseline. The corresponding machine layout is shown in figure 2. Compared with the CDR, for the FS baseline the number of surface sites has been reduced from 12 to 8, and the circumference decreased from 97.8 to 91.2 km. The FCC collider layout has now become fully super-periodic and can accommodate either two or four experiments.

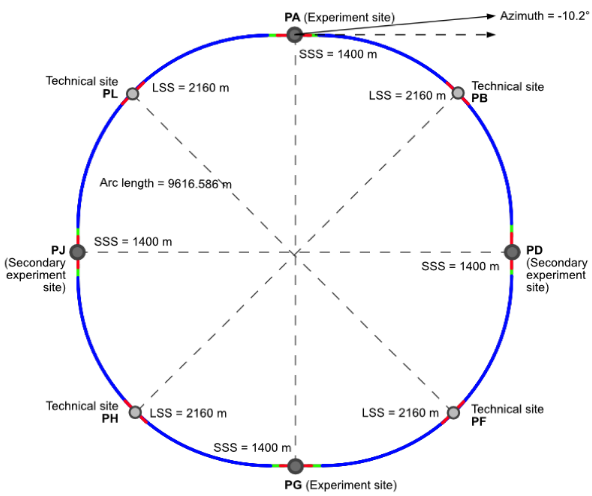

Figure 2: New layout of the FCC tunnel infrastructure.

An important component of the FCC FS is the high-risk-area site investigations. Overall, nine areas have been identified (see figure 3) with specific aspects to be investigated:

- Jura and Vuache (three areas): top of limestone; karstification and filling-in at the tunnel depth; water pressure
- Lake, Rhône, Arve and Usses Valley (four areas): top of the molasse; quaternary soft grounds; water bearing layers
- Mandallaz (one area): water pressure at the tunnel level; karstification
- Bornes (one area): high overburden molasse properties; thrust zones

The site investigations planned for the period from mid 2023 to mid 2025 will comprise

~40–50 drillings and cover 100 km of seismic lines.

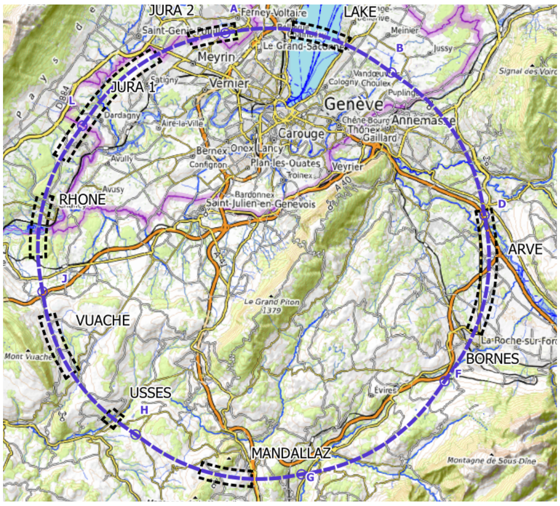

Figure 3: High-risk areas marked for priority site investigations (indicated by black-dashed boxes).

Figure 4 shows the organisational structure of the FCC FS. It reflects the classical structure common to many large CERN projects, with a supervisory layer consisting of Steering Committee, Collaboration Board and Scientific Advisory Committee.

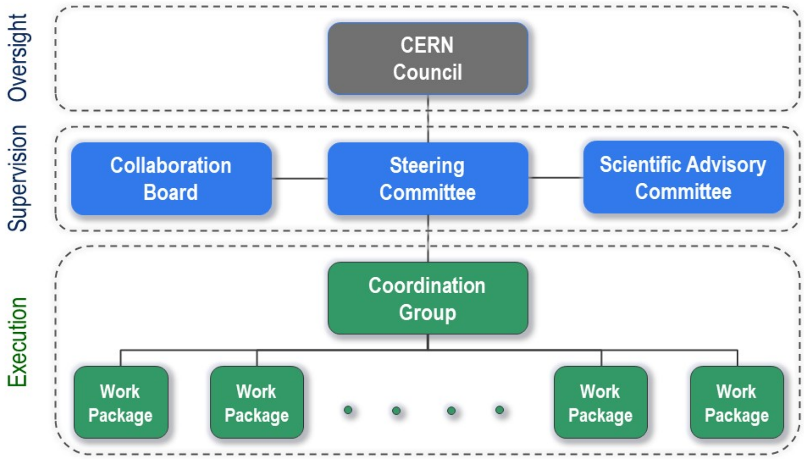

Figure 4: FCC FS organisational chart.

By 16 November 2021, 119 of the 147 former FCC collaboration members had confirmed their interest in continuing in the FCC FS, while the other 28 had not yet replied.

The new Memorandum of Understanding for the FCC Feasibility Study is available at:

https://twiki.cern.ch/twiki/bin/view/FCC/FCCMoU.

The FCC Collaboration Board (CB) met on 14 September and 12 October 2021. At these meetings, Professor P. Chomaz from CEA/IRFU (France) was elected as CB Chair for the entire Feasibility Study period (i.e. end 2025). A CB Executive Committee (CBEC) was established with two vice-chairs. For the role of vice-chair, Dr M. Boscolo from INFN-LNF (Italy) and Professor A. Lankford from UC Irvine (USA) were elected.

An FCC Physics Workshop will be held in Liverpool, United Kingdom, from 7 to 11 February 2022 [6]. The number of in-person participants is limited to ~160 (first come, first served). The meeting will also be broadcast on Zoom.

The FCC Week 2022 is expected to be held in Paris from 30 May to 3 June 2022 [7].

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] M. Benedikt and F. Zimmermann, *FCC Feasibility Study Update: Structure, Goals, Status and Plans*, ECFA Newsletter #7 (summer 2021), available at https://ecfa.web.cern.ch/ecfa-newsletters.
[5] 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.
[6] FCC Physics Workshop, Liverpool, United Kingdom, 7–11 February 2022, https://indico.cern.ch/event/1066234/.
[7] FCC Week 2022, Paris, 30 May–3 June 2022, https://indico.cern.ch/e/fccw2022.

Early-Career Researchers Panel

by the ECFA Early-Career Researchers Panel

As part of the 2020 ESPP update, an Early-Career Researcher (ECR) debate was organised, involving 200 participants from, or otherwise affiliated with, institutes and national laboratories around Europe, representing a broad range of HEP experiments and activities within theory and phenomenology. The invitees were encouraged to self-organise and provide key input to the consensus-gathering process. During this process, the benefits of establishing a permanent ECR Panel within ECFA were highlighted and, by the end of 2020, more than 70 ECRs had been appointed to this newly formed panel (mandate and details available here).

The ECR Panel held its inaugural meeting in January 2021 and had a busy year establishing its operational structure and participating in ECFA activities. In addition to its five members of PECFA (link) and one observer at RECFA (link), an organising committee of six members was selected to oversee day-to-day Panel activities and communication with the wider HEP community (contact email: ecfa-ecr-organisers@cern.ch; link).

The Panel quickly agreed on the importance of establishing working groups where ECRs could share ideas on specific topics and provide input to the broader community. A highlight of the Panel's activities in 2021 was the input provided by one such working group to the ECFA Detector R&D Roadmap. The Roadmap, discussed further in the previous ECFA Newsletter, followed the 2020 ESPP statement that "the community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels" and was developed to coordinate R&D activities in Europe, thereby maximising resources and ensuring that the technological demands of the detectors at the proposed future colliders can be met.

The ECR detector R&D working group was set up following an invitation for a representative of the Panel to make a presentation at the "Training in Instrumentation" symposium. The working group solicited a broad range of input from the wider ECR community by organising a town hall meeting and designing and analysing the results of a survey that received 473 responses despite short timescales. Following the symposium, the results of this process were published in a document endorsed by the ECR Panel and provided as input to the ECFA Roadmap.

This process highlighted that, while there is great enthusiasm within the ECR community for instrumentation work, there are barriers related to their impressions of the impact on career progression, and concerns about recognition and the (lack of) availability of networking opportunities for those working in instrumentation. To ensure that there is sufficient expertise for the success of future R&D projects, improved training is therefore only part of the solution. More details can be found in the presentation (link) and corresponding report (link).

The Panel hopes that this successful model will allow the ECR community to provide further valuable input to future consensus-gathering activities within ECFA. Recently, multiple working groups have been set up to address a diverse set of topics, including both physics and social/societal aspects of ECR work, as well as follow-up on the ECR detector R&D working group's recommendations. Further plans and activities will be discussed at the next Panel meeting, in January 2022.

Reports from European Labs

IJCLab – a new European Laboratory

by A. Stocchi (IJCLab , Universite Paris-Saclay, CNRS)

The *Laboratoire de Physique des 2 Infinis Irène Joliot-Curie* (Laboratory of the Physics of the two infinities Irène Joliot-Curie) or "IJCLab" was created on 1 January 2020. It is a joint research unit of CNRS (IN2P3), Université Paris-Saclay and Université de Paris, located on the Orsay campus some 30 kilometres south of Paris. It is the result of the merger of five laboratories (CSNSM, IMNC, IPNO, LAL and LPT) with common history and research interests. Among the 750 IJCLab members, there are about 230 researchers, 350 engineers and technicians and 120 PhD students.

IJCLab focuses on the "physics of the two infinities" (high-energy physics, nuclear physics, astrophysics and cosmology) and their applications (energy and the environment and the interface between life sciences and physics) and also has strong theoretical physics and accelerator R&D and construction departments. The technical R&D and support required for these research activities is provided by technical services with a high degree of expertise in electronics, IT and computing, instrumentation and detectors, mechanical engineering, RF and cryogenics. The presence of a large set of research and technological platforms (notably ALTO, Andromède, Laserix, SCALP and Supratech) is also an essential feature of IJCLab, with some of them essential to our leadership in accelerator physics.

The IJCLab physics programme illustrates the wide scope of research led by our teams.

We have a strong involvement (100 FTE) in many projects in accelerator-based particle physics. For instance, concerning the LHC upgrades at CERN, we strongly contribute to ATLAS (front-end calorimeter HGTD, ITK tracking system) and LHCb (calorimeter electronics and the new luminosity). We also make significant contributions to Belle II at KEK, and we participate in the design and development of new-generation detectors (CALICE, LHC/FCC). In hadronic physics, we have a visible presence in the JLab experiments (and, in future, EIC) and in ALICE at CERN.

As far as neutrino physics is concerned, we are involved in CUPID-Mo (cryogenic scintillation bolometers) for double beta search and we are starting to contribute to the DUNE experiment.

A strong component of our research in nuclear physics takes place at the national GANIL and ALTO facilities, but we are also present in other international sites such as RIKEN (exotic nuclei), Dubna and Argonne (super-heavy elements) and AGATA@Legnaro.

In astroparticle physics, we have been involved since the beginning of the Virgo/LIGO collaboration and its upgrade and we have started taking part in the design of future experiments (Einstein Telescope and LISA). IJCLab research activities also feature gamma-ray studies (CTA, AstroMeV) and cosmic-ray observation (Auger). In cosmology, our researches follow two main axes: CMB experiments with an increasing investment in LiteBird, and dark-energy experiments with LSST.

These activities benefit from the presence of a large theoretical physics department at IJCLab with recognised expertise in phenomenology and strong ties with experimentalists.

In accelerator physics, we are fully committed to the design and the construction of several experiments (100 FTE): the European Spallation Source (ESS), for which IJCLab has provided many cavities and cryomodules; the Myrrha project, which consists of a subcritical nuclear reactor driven by a high-power linear accelerator; and the on-site new-generation compact Compton Source ThomX, which is in commissioning. We also contribute to the PIP-II injector and to several activities on current and future colliders (LHC, SuperKeKB, FCC, ILC, etc.). Future IJCLab activities in accelerator physics are structured around two on-site projects with rapidly increasing personpower: the PALLAS experiment aimed at developing a 10 Hz laser-plasma accelerator test facility, and PERLE@Orsay, a high-current and multi-turn 10 MW ERL machine.

Finally, IJCLab is located in the heart of the internationally recognised scientific Paris-Saclay cluster and has strong links with two universities (Université Paris-Saclay and Université de Paris). This places IJCLab in an exceptionally favourable environment for teaching, training, knowledge transfer and popular science activities.

Activities at UK Laboratories

by D. Newbold (STFC Rutherford Appleton Laboratory)

STFC operates in the UK three national laboratories that contribute to the particle physics programme: Rutherford Appleton Laboratory (RAL) near Oxford; Daresbury Laboratory (DL) near Warrington; and Boulby Underground Laboratory in North-East England. Each site provides a range of multi-disciplinary facilities and capabilities, including those relevant to particle physics. The national laboratories support the entire UK HEP community in detector and accelerator design, construction and operation, with specialisms in accelerator systems at DL and low-background screening and detector assembly at Boulby. Via its Particle Physics Department (currently around 100FTE) RAL also plays a major role in maintenance and operation of particle detectors, in technology R&D, and in financial and administrative support for the field.

The current major activities for the laboratories include:

- Support of the LHC programme (ATLAS, CMS, LHCb and ALICE) as we approach the start of Run-3
- M&O activities for LZ and T2K
- Detector and accelerator design, construction, and project management for the HL-LHC, including the Phase-2 upgrades of ATLAS and CMS
- Detector and accelerator design and construction for DUNE, Hyper-K, and EIC
- Development of cold atom interferometers for GW and dark matter detection
- Engineering and detector studies for new large-scale underground neutrino and dark matter detectors at Boulby
- Data analysis activities related to each of the above projects
- Computing operational support including Tier-1 and Tier-2 centres
- Outreach and public engagement activities, including online masterclasses

Despite the impacts of the COVID pandemic, the lab has continued to operate continuously, and in the period preceding the ECFA meeting was able to sustain approximately 85% of normal staff numbers on site.

The future direction for the UK laboratories and the UK community is towards an increasing breadth and depth of R&D activities for both detectors and accelerators, in preparation for future generations of experiments. There is strong interest in both future colliders (FCC, ILC, MC) and future low-background experiments, with a ramp-up in activity planned in each area as deliverables for HL-LHC and the LBN programme are completed. In all cases, the need for sustainability in construction and operation of new facilities will be a major consideration.

Paul Scherrer Institute

by M. Seidel (PSI)

PSI is the largest research institute for natural and engineering sciences in Switzerland, conducting cutting-edge research in three main fields: matter and materials, energy and the environment and human health. Large research infrastructures, based on particle accelerators, are operated to conduct this research. The megawatt class high-intensity proton accelerator HIPA is used to generate high intensities of muons and neutrons serving 30 experiments and instruments at secondary beamlines. Science with photons is conducted using a 2.4 GeV electron synchrotron SLS, serving 20 beamlines. At present, a construction project is in preparation to upgrade the synchrotron with an entirely new magnet lattice that will result in a reduction of the emittance by a factor 35. The latest addition to the set of PSI infrastructures is an X-ray free electron laser, involving a 5.8 GeV high-brightness electron linear accelerator with two undulator beamlines. In addition, PSI operates a cancer therapy centre based on a 250 MeV proton accelerator with two gantries and a dedicated beamline for eye cancer treatment.

The particle physics programme at PSI utilises HIPA to perform precision tests of the Standard Model. A review of the physics programme was recently published [1]. One of the flagship experiments is the search for a neutron electric dipole moment using a high-intensity source of ultracold neutrons. The n2EDM experiment under construction aims to raise the already leading sensitivity by a factor 10. Exploiting the intense muon source, the MEGII experiment searches for the decay $\mu \rightarrow e\gamma$, improving on its predecessor MEG. Other activities include precision laser spectroscopy of light muonic atoms, and the search for the decay $\mu^+ \rightarrow e^+e^-e^+$ with Mu3e. PSI is also involved in the CMS experiment at the LHC and a centre for Si pixel detector development. The IMPACT project, an upgrade at HIPA, is planned for the period 2025–2028. It aims to install surface muon beamlines with record intensities of up to 10^{10} μ^+/s, as well as a new facility for the production of large quantities of medical isotopes.

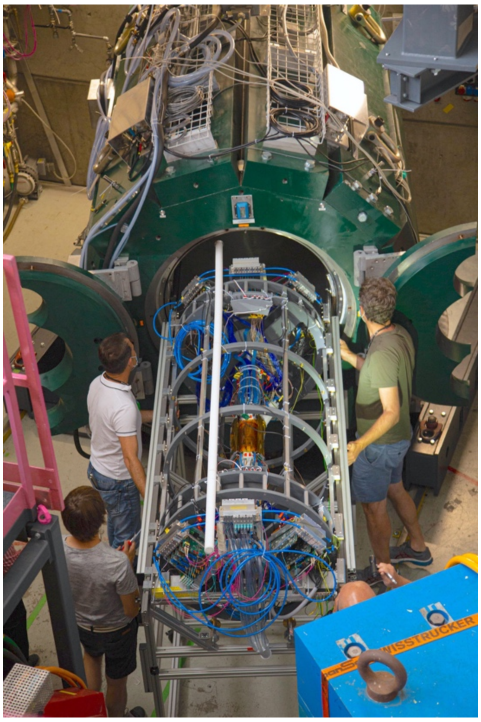

Figure 5: The prototype of the Mu3e being inserted into the 2T Mu3e magnet for the first integration run in June 2021

PSI is improving the sustainability of its operations by raising energy efficiency and reducing its overall carbon footprint. As a result of several technology choices, the upgraded synchrotron light source SLS2.0 will consume 30% less power than the present one. Other measures include heat recovery and building insulation, active management of business travel and the procurement of energy from sustainable sources.

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Mid-term reports

Mid-term report from Austria

by M. Jeitler (Austrian Academy of Sciences)

Particle physics research in Austria is pursued at several institutes in Vienna (some belonging to universities, others to the Academy of Sciences) and at university departments in the cities of Graz, Innsbruck and Linz. Being a small country, for accelerators and laboratory infrastructure Austria relies mostly on international collaboration with CERN (CMS, ATLAS, ALICE, ASACUSA and CLOUD), KEK (Belle II), Frascati (SIDDHARTA-II), LNGS Gran Sasso (CRESST-III, COSINUS and VIP-2) and the nuclear reactors at ILL Grenoble, FRM-2 in Munich, TRIGA Vienna and Chooz in France. A few years ago, however, the medical proton and hadron therapy facility MedAustron in Wiener Neustadt, not far from Vienna, went into operation. This facility also features a test beam for physics research (with protons up to 800 MeV and carbon ions up to 400 MeV/nucleon).

Hardware developments, in particular for silicon detectors for CMS (outer tracker and HGCal) and Belle II (silicon vertex detector), are carried out at the Institute of High Energy Physics in Vienna. Austrian physics interests include, among others, supersymmetry, beyond-the-Standard-Model physics, Standard Model precision tests, b-physics, heavy-ion physics and quark–gluon plasma, anti-matter physics, dark-matter and dark-energy searches, neutron beta decay experiments, quantum chromodynamics, formal theoretical aspects, cosmology, quantum gravity, holography and astroparticle physics. The wide range of physics topics is also reflected by a few new scientist positions.

A high-performance computing centre for joint use by biologists, physicists, mathematicians and other scientists has recently been put into successful operation. The usually very active outreach activities have suffered substantially as a result of the pandemic but are now slowly starting up again, and in-person conferences are planned for 2022.

Mid-term report from Romania

by A. M. Bragadireanu (Horia Hulubei National Institute of Physics and Nuclear Engineering, IFIN-HH)

Since March 2018, when the last RECFA visit to Romania took place, the funding of the CERNRO programme has improved. However, taking into account the evolution of the Romanian currency, the annual distribution of the CERN-RO budget in CHF is flat. The particle and nuclear physics communities are concentrated in IFIN-HH, which leads seven out of ten CERN-RO-funded projects. Romanian research teams are focused on key areas of particle physics with large discovery potential, precision measurements and searches for new physics. The CERN-RO upgrade programme for the LHC experiments is on track, with ALICE, ATLAS and LHCb teams successfully fulfilling their commitments. The NA62 team built a new calorimeter (HASC2), which was successfully commissioned at CERN in 2021. The ISOLDE team is actively participating in the IDS upgrade programme. The WLCG group continued to provide reliable computing services for the ALICE, ATLAS and LHCb experiments. The astroparticle physics community is involved in the Pierre Auger collaboration, which is contributing to the Auger radio upgrade, computing and remote shifts. Romania's industrial return for supplies contracts is "well balanced", with a score of 1.06, while for services contracts it is "poorly balanced". Regarding education and outreach, Romanian high-school students and teachers participated in two dedicated events at CERN in 2021, among other activities. Some of the issues raised in the 2018 RECFA recommendations letter remain to be followed up.

Mid-term report from the Slovak Republic

by P. Strizenec (Slovak Academy of Sciences)

The report presented an overview of the organisation, funding and activities of the particle physics community in the Slovak Republic. The typical level of annual funding for particle physics activities in the Slovak Republic is around 0.85 MEUR from the state budget for all activities (including running the WLCG Tier 2 centre), and the level is increasing only very slowly with time. Recently, 100 kEUR was added for the ATLAS Phase II upgrades. Only very few and very small additional grants were received from national grant agencies. The country has had well-balanced industrial return so far, with an index well above 1 for all past years.

The report included an overview of the diverse particle physics activities at universities and at the Academy of Sciences. CERN represents a major part of national particle physics activities, with participation in the ATLAS and ALICE experiments and their upgrades. A very agile, young group was formed around the ISOLDE activities at the Academy of Sciences, and the hope is that it will also succeed in obtaining additional financing. Small Slovak experiment groups are active at NA62 and in neutrino physics and nuclear structure physics. Outreach is also a permanent concern of the particle physics community, with some very successful contributions to various initiatives.

Status of possible future e^+e^- facilities

The status of the Compact Linear Collider

by S. Stapnes (CERN)

The Compact Linear Collider (CLIC) is a multi-TeV high-luminosity linear e+e− collider being developed by the CLIC accelerator collaboration. The accelerator has been optimised for three energy stages at centre-of-mass energies of 380 GeV, 1.5 TeV and 3 TeV [1].

Detailed studies of the physics potential of and the detector for CLIC, and R&D on detector technologies, have been carried out by the CLIC detector and physics (CLICdp) collaboration. CLIC provides excellent sensitivity to Beyond the Standard Model physics, through direct searches and a broad set of precision measurements of Standard Model processes, particularly in the Higgs and top-quark sectors.

The CLIC accelerator, detector studies and physics potential are documented in detail at: http://clic.cern/european-strategy. Information about the accelerator, physics and detector collaborations and the studies in general is available at: http://clic.cern.

CLIC layout

To reach multi-TeV collision energies with an acceptable site length and at an affordable cost, the main linacs use normal-conducting X-band accelerating structures to achieve a high accelerating gradient of 100 MV/m. For the first energy stage, a lower gradient of 72 MV/m is the optimum gradient to achieve the luminosity goal, which requires a larger beam current than at higher energies.

In order to provide the necessary high peak power, the novel drive-beam scheme uses low-frequency klystrons to efficiently generate long RF pulses and to store their energy in a long, high-current drive-beam pulse. The upgrade to higher energies will be implemented by lengthening the main linacs and increasing the RF capacity of the drive-beam complex. An alternative design for the 380 GeV stage has been studied, in which the accelerating structures of the main linac are directly powered by klystrons. The further stages would also be drive-beam based.

Technical maturity and performance overview

The CLIC accelerator studies are mature. Accelerating gradients of up to 145 MV/m have been reached with the two-beam concept at the CLIC Test Facility (CTF3). Breakdown rates of the accelerating structures well below the specifications are well documented. Substantial progress has been made towards realising the nanometre-sized beams required by CLIC for high luminosities, in the areas of beam-dynamics studies, technical developments and prototyping and testing of key components. In addition to good results from laboratory tests of components and from the experimental studies at ATF2 at KEK and light sources, the advanced beam-based alignment of the CLIC main linac has been successfully tested at FACET at SLAC and FERMI in Trieste. Recent developments, such as the advent of high-efficiency klystrons, have resulted in improved energy efficiency for the 380 GeV stage, as well as a lower estimated cost.

The baseline plan for CLIC operation results in an integrated annual luminosity equivalent to operating at full luminosity for 1.2×10^7 s [2]. Based on 8, 7 and 8 years of running at 380, 1500 and 3000 GeV respectively, and a luminosity ramp-up during the first years of each stage, integrated luminosities of 1.0, 2.5 and 5.0 ab^{-1} respectively would be reached for the three stages. CLIC provides ±80% longitudinal electron polarisation and proposes a sharing between the two polarisation states at each energy stage for optimal physics reach [3].

The CLIC beam energy can be adjusted to meet different physics requirements. In particular, a period of operation at around 350 GeV is planned in order to scan the top-quark pair-production threshold. Operation at much lower energies can also be considered. Running at the Z-pole results in an expected luminosity of about 2.3×10^{32} cm^{-2}s^{-1} for an unmodified collider. On the other hand, initial installation of just the linac needed for the Z-pole energy factory, and an appropriately adapted beam delivery system, would result in a luminosity of 0.36×10^{34} cm^{-2}s^{-1}. Furthermore, gamma-gamma collisions at up to ~315 GeV are possible with a luminosity spectrum interesting for physics [4].

Schedule, cost estimate and power consumption

The technology and construction-driven timeline for the CLIC programme comprises seven years of construction and commissioning, followed by 27 years of data taking covering the three energy stages. The running plan includes two intervals of two years between the stages to allow the extensions to be connected to the existing linacs.

The cost estimate for the initial stage is approximately 5.9 billion CHF. The energy upgrade to 1.5 TeV would cost approximately 5.1 billion CHF, including the upgrade of the drive-beam RF power system. The cost of the further energy upgrade to 3 TeV is estimated at approximately 7.3 billion CHF, including the construction of a second drive-beam complex.

The nominal power consumption for the 380GeV stage is approximately 170 MW, but it is expected that it can be reduced (see details below). Earlier estimates for the 1.5 TeV and 3 TeV stages are approximately 370 MW and 590 MW, respectively [5]. However, recent power savings applied to the 380 GeV design have not yet been implemented for these higher energy stages and new estimates are needed. Based on the current estimates, the annual energy consumption for nominal running at the initial energy stage would beat 0.8 TWh. By way of comparison, CERN's current energy consumption is approximately 1.2 TWh per year, about 90% of which is used by the accelerator complex.

Programme for 2021-25

The CLIC study collaboration will submit an updated project description for the next European Strategy update in 2026-27. The key changes will relate to the luminosity performance at 380 GeV, the power/energy efficiency and consumption at stage 1 and at multi-TeV energies, and further design-related, as well as technical and industrial developments, of the core-technologies, namely X-band systems, RF power systems and nano-beams and the associated hardware.

The development and dissemination of X-band core technology, capitalising on existing facilities (e.g. X-band test stands and the CLEAR beam facility at CERN), remain a primary focus. More broadly, the use of the CLIC core technologies - primarily X-band RF, associated components and nano-beams - in compact medical, industrial and research linacs has become an increasingly important test ground for CLIC, and is set to expand [6]. The adoption of CLIC technology for these applications is now providing a significant boost to CLIC-related R&D, involving extensive and increasing collaboration with laboratories and universities that use the technology and an expanding commercial supplier base.

On the design side, the parameters for running at multi-TeV energies with X-band or other RF technologies will be studied further, with the designs guided by energy efficiency in particular. Physics studies for the multi-TeV stages will remain important.

Other key development work will relate to luminosity performance. On the parameter and hardware side, these studies include alignment/stability studies, thermo-mechanical engineering of modules and support systems for critical beam elements, and studies of instrumentation, positron production, the damping ring and the final focus system. Recent studies have explored the margins and possibilities for increasing the luminosity [4]. The vertical emittance and, consequently, the luminosity, are to a large extent determined by imperfections in the accelerator complex. Significant margin has been added to the known effects to enhance the robustness of the design; without imperfections, a factor of three higher luminosity would be reached at 380 GeV [7]. In addition, at this energy the repetition rate of the facility, and consequently the luminosity, could be doubled from 50 Hz to 100 Hz without major changes and with relatively little increase in the overall power consumption and cost (around 30% and 5%, respectively). The physics impact of a higher initial-stage luminosity will be addressed in parallel.

Power and energy efficiency studies will continue, covering the accelerator structures themselves as well as - very importantly – the high-efficiency RF power system with optimal system designs using high efficiency klystrons and modulators, and it is expected that the power can be further reduced. Sustainability studies in general will be a priority, encompassing power/energy efficiency, the use of power predominantly in low-cost periods as is possible for a linear collider, and the use of renewable energy sources and energy/heat recovery where possible.

The planned CLIC studies overlap with other future collider studies in many areas, especially the R&D for high-gradient and high-efficiency RF systems. There are also challenges that are common to the development of linear collider beam-dynamics, drive beams, nanobeams, polarisation and alignment/stability solutions for novel accelerators, and to the development of muon cooling RF systems.

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ILC status

by S. Michizono (KEK), S. Asai (University of Tokyo)

The design study for an International Linear Collider (ILC) with a collision energy of 500 GeV was started in 2004, and the Technical Design Report (TDR) [1] was published by the international Global Design Effort (GDE) team in 2013. After the publication of the TDR, the R&D on linear colliders was organised by the Linear Collider collaboration (LCC). A 250 GeV ILC to serve as a Higgs factory was proposed and published in the ILC Machine Staging Report in 2017 [2]. In August 2020, the International Development Team (IDT) was established by the International Committee for Future Accelerators (ICFA). The IDT facilitates the transition to the ILC preparation phase. ILC-Japan, a new promotional body for the ILC project in Japan, was launched in the spring of 2021. Its main purpose was to broaden the community promoting the project by involving scientists from different projects and research fields, such as ATLAS, SuperKEKB and neutrino research, as well as theorists. Another important objective was to coordinate the supporters involved in the ILC project. Because the ILC is a very large project with an impact beyond science, many parties are involved, including funding agencies, politicians, industry, candidate sites and the international research community. As a representative of the Japanese community, ILC-Japan acts as a liaison with the relevant parties.

The ILC is an electron–positron collider, approximately 20 km long, with a collision energy of 250 GeV. It consists of polarised electron/positron sources (e-/e+ sources), damping rings (DRs) to minimise the emittance of the e-/e+ beam, main linacs (MLs) to accelerate the e-/e+ beam using superconducting RF (SRF) technology, and a beam delivery system (BDS) to focus and adjust the final beam to achieve the required brightness at the interaction points where the physics detectors are installed. The beam then travels towards the main beam dump. The AC power required to operate the accelerator is about 110 MW. Because the surface resistance of the accelerator structure (cavity) of the SRF is small, the AC plug power can be minimised. Further improvement in energy efficiency is expected as part of the "Green ILC" concept [3] for a sustainable laboratory.

The advantage of the linear collider is that its energy can be increased without the collider itself being affected (or limited) by synchrotron radiation ("energy upgradability"). The BDS and beam dump of the ILC can withstand collision energies of up to 1 TeV. Another upgrade scenario is a luminosity upgrade. By enhancing the high-power RF system, the luminosity can be doubled compared with the current scenario discussed in the TDR. It is also possible to accelerate and collide electrons and positrons, while maintaining their spin (polarised sources). This can significantly improve the physics potential and the measurement accuracy.

Two key accelerator technologies are being explored for the ILC. One is SRF technology: about 8,000 SRF cavities are installed in the MLs, operating at an average gradient of 31.5 MV/m. The other is nanobeam technology applied to the DR and BDS. Here, a 7.7 nm beam is focused vertically at the interaction point. The nanobeam technology was demonstrated at ATF2, a facility hosted at KEK as part of an international collaboration, and almost satisfied the requirements of the ILC. As for the SRF technology, the European X-ray Free-Electron Laser (European XFEL) at Hamburg has 800 superconducting cavities, one-tenth of the number of SRF cavities in the ILC, and the technology is maturing. Following this European XFEL, the LCLS-II at SLAC and SHINE in Shanghai are under construction. Efforts to improve the performance and reduce the cost of superconducting cavities are under way. New cavity surface treatments, such as nitrogen infusion and low-temperature baking, both developed at the Fermi National Accelerator Laboratory, improve the acceleration gradients and Q-values. These surface treatments are expected to reduce the length of the SRF linac, thus reducing the cryogenic capacity and cost. R&D projects focusing on niobium aim to reduce the cost of materials by optimizsng Nb ingot (raw material) production, disk/sheet production, including direct slicing, and tube formation processes. Based on the experience with the European XFEL, research is also being conducted to automate the cavity assembly process.

The IDT published a proposal for the ILC Pre-lab [4] in June 2021. This proposal outlines the organisational framework, implementation model and work plan for the Pre-lab and summarises the following items:

- Mission, governance model, organisational structure and Pre-lab start-up procedures
- Technical preparation of the ILC accelerator, preparation required for site construction and overall accelerator engineering design
- Strategy for preparation of the ILC physics programme.

Regarding the technical preparations, the items identified by the advisory panel of MEXT and the technical progress made after the TDR are described in the report on "Technical Preparation and Work Packages (WPs) during ILC Pre-lab" [5] and summarised in 18 work packages. The work packages are expected to be shared as in-kind contributions by participating laboratories worldwide during the Pre-lab period. The activities of the ILC Pre-lab will continue for about four years, and it is assumed that the construction of the ILC accelerator will take about ten years.

The ILC has the potential to be used for a variety of experiments other than Higgs boson production. At the ILCX2021 conference in October [6], the possibility of beam dump experiments, forward detectors near the collision site, far off-axis detectors, particle physics experiments using extracted beams and experiments in other scientific fields, including nuclear physics and condensed matter physics, was also discussed. These proposals will be discussed further in the future.

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FCC-ee status and plans

by A. Blondel (LPNHE, Paris) and P. Janot (CERN)

Until the beginning of the last decade, the odds were that LEP would be the last e^+e^- circular collider at the high-energy frontier, giving way to linear collider technology at higher energies (1). A unique alignment of stars at the beginning of the last decade decided otherwise: (i) the discovery of the 125 GeV Higgs boson led to the investigation of a rebuild of an e^+e^- collider in the LEP/LHC tunnel (2); (ii) the progress with B factories made it possible to envision operating such a collider with a luminosity in excess of 10^{34} $cm^{-2}s^{-1}$ at the ZH cross section maximum; (iii) the objective of increasing the hadron collider's energy to 100 TeV or more led to discussions of a new ring of 80–100 km, luckily optimal given the geography of the Geneva basin; and (iv) the happy coincidence that such a ring is required for an e^+e^- collider to reach and exceed the top-pair production threshold, made it ideally suited for a coherent electroweak precision physics programme.

This high-luminosity Higgs and electroweak factory (FCC-ee) offers just the right energy range to study all heavy particles of the Standard Model (Z, W, H, top and even b and tau) and is the most pragmatic, safe and effective way towards a 100 TeV pp collider (FCC-hh). The physics programmes of the two machines are both complementary and synergistic, and together offer a powerful long-term vision for high-energy physics (3). This vision was adopted by the 2020 ESPP, namely to prepare a Higgs factory followed by a future hadron collider with sensitivity to energy scales an order of magnitude higher than those of the LHC (4). The ESPP made the FCC technical and financial feasibility study the top priority (after the HL-LHC) for CERN and its international partners. At its June 2021 Session, the CERN Council approved the FCC Feasibility Study and its funding, with the focus on its first step, i.e. the tunnel and the first-stage FCC-ee machine (5). The R&D on FCC-hh high-field magnets is treated independently, with high priority and its own funding.

The FCC-ee will be implemented in stages as an electroweak, QCD, flavour, Higgs and top factory by spanning the energy range from the Z pole and the WW threshold to the maximum Higgs production rate, up to the top-pair threshold and beyond (6). In this energy range, the baseline design luminosity, summed of the two interaction points (IP), exceeds by large factors that of other e^+e^- collider proposals, as displayed in figure 6. During the envisioned 15-year experimental programme, $5 \cdot 10^{12}$ Z, $3 \cdot 10^{8}$ WW, 10^{6} ZH and 10^{6} $t\,\bar{t}$ events will be produced. The high luminosity at the Z pole (more than five orders of magnitude larger than at LEP) opens a unique domain for new particle searches. The option to run on the Higgs resonance, at $\sqrt{s} =$ 125 GeV, is under investigation. The possibility to operate four interaction points, enabled by the recently proposed ring layout with fourfold super-periodicity, would increase the luminosity at all energies (figure 6) and further enrich the physics programme.

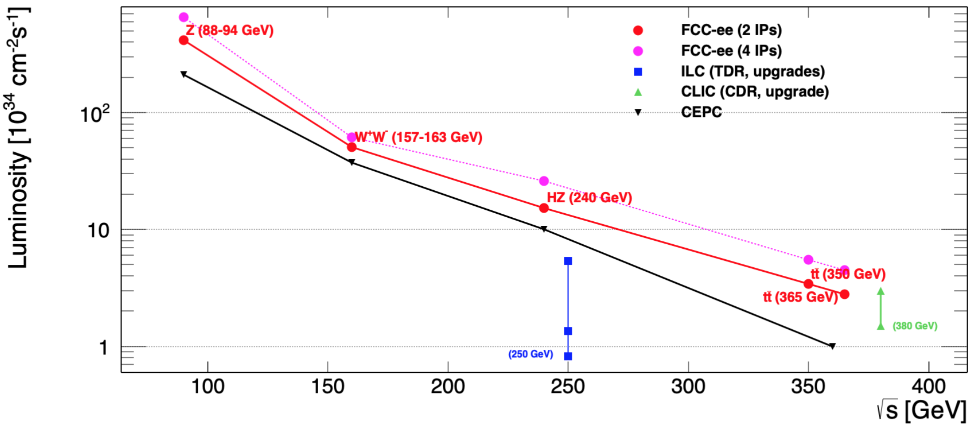

Figure 6: The FCC-ee baseline design luminosity summed over 2 IPs (red) as a function of the centre-of-mass energy, $\sqrt{s}$, in the range from the Z pole to the top-pair threshold, and the expected luminosity with 4 IPs (pink). Also indicated are the baseline luminosities – with possible upgrades – of other collider proposals, ILC (blue), CLIC (green) and CEPC (black), also presented at this Plenary ECFA meeting.

The unequalled statistical precision of the many measurements feasible at the FCC-ee will require careful preparation during the FCC Feasibility Study: coherent sets of detector requirements will be established from physics studies to match experimental systematic to statistical uncertainties, leading to innovative detector solutions, preliminary infrastructure requirements and cost estimates; in parallel, the potential scientific outcome of the promising opportunities and the discovery potential of precision measurements in various scenarios of new physics will be fully developed. The impact of these studies on the accelerator design, on the mode of operation and on theoretical developments required to match theoretical precision with statistical sensitivity will be evaluated. Some of the challenges created by these new opportunities have been the subject of a book of essays, soon to be published in a special issue of the *European Physics Journal* (7).

The original motivation for an e^+e^- circular collider was to build a high-luminosity Higgs factory, operating at 240 GeV to maximize the ZH production rate, for the measurement of the Higgs boson's properties. At the FCC-ee, this process is complemented at 365 GeV by WW fusion. Past linear collider studies set the scene in great detail, but the FCC-ee offers interesting bonuses. First, the FCC-ee delivers twice as many Higgs bosons five times quicker (at 240 GeV with two interaction points) than linear colliders, maximising the number of Higgs bosons produced per MW spent (8). The larger samples allow an accurate determination of the Higgs boson's mass to a couple of MeV (needed prior to the s-channel run at 125 GeV) and of the ZH cross section (instrumental for the first significant determination of the Higgs self-coupling) (9). The detector performance requirements are probably not drastically different but may need adapting to these additional challenges, as well as to the gentler beam conditions, the smaller beam pipe radius, the lower maximum operating energy and the continuous mode of operation. The s-channel Higgs production, which provides a unique opportunity to measure the electron Yukawa coupling (i.e. to prove that the Higgs boson gives mass to ordinary matter), also leads to demanding requirements on the centre-of-mass energy monochromatisation while keeping a high luminosity (10), and on the event selection to isolate Higgs decays from the overwhelming physics backgrounds (11).

Complementarity is key: the measurement of the Higgs boson's properties provides a very good reason for needing both e^+e^- and pp colliders. As soon as the Higgs coupling to the Z is known from the ZH total cross-section measurement, the HL-LHC or FCC-hh results for the relatively rare decays such as $H \rightarrow \mu\mu$, $\gamma\gamma$, or $Z\gamma$, become absolute measurements by normalising them to the $H \rightarrow ZZ^*$ decay. A similar comment applies to the top Yukawa coupling: it is determined with high statistical accuracy at a hadron collider but must be normalised to the ttZ process, which uses the FCC-ee measurement of the top electroweak couplings with $e^+e^- \rightarrow t\bar{t}$ production as a "standard candle". The precise and absolute top Yukawa coupling determination is in turn instrumental for an accurate measurement of the Higgs self-coupling at the FCC-hh. Not only does the FCC-ee provide new model-independent measurements, but it also renders more precise and model-independent those of the past and future hadron colliders. The FCC-ee / FCC-hh complementarity is outstanding (12).

The most stringent requirements on accelerator, experiments and theory will probably be set by the TeraZ run. The high luminosity and large event rate at the Z pole (over 100 kHz), to which simulated data needs to be added, turn into considerable challenges for data taking, storage and processing. The Z line shape determination, which is based on cross-section measurements as a function of the centre-of-mass energy for hadronic and leptonic Z decays, requires extremely accurate mechanical construction of the luminometer, as well as precise knowledge of the central detector (tracker and calorimeter) acceptance, for the di-lepton and di-photon events (and, to a lesser extent, for hadronic events). The point-to-point centre-of-mass-energy uncertainties of the resonance scan, which can be verified in particular by means of the muon pair invariant mass reconstruction, are most relevant for the Z width and the forward–backward asymmetries. This sets stringent constraints on the stability of the momentum reconstruction over time and scan points.

The expected statistical precision on the electroweak observables, e.g. m_Z (4 keV), Γ_Z (4 keV) or A_{FB} (down to a few 10^{-6}), is about 500 times smaller than that of the present world average (13). On the one hand, this calls for a ppm centre-of-mass energy calibration, achievable with the resonant depolarisation method (unique to circular colliders) and offering a number of serious challenges on its own (14; 15). On the other hand, the work that has started on the additional tools, calculations, observables and experimental inputs needed to compare experimental measurements to theoretical predictions at a level of precision similar or better than the statistical uncertainties must be pursued and planned. The situation is best illustrated in figure 7, which shows the projected uncertainties on the S and T parameters (used to parameterise virtual effects of new physics in the Z and W propagators) from a global fit of all electroweak precision observables, today, after the HL-LHC and after the complete FCC-ee programme with current estimates for future systematic experimental and theoretical uncertainties. The (much) smaller ellipse shows the stand-alone true sensitivity of the FCC-ee, should these uncertainties match the available statistics: there is a lot more potential to exploit with well-prepared experimental and theoretical set-ups than the present treatment suggests (13; 16). These aspects must be tackled at an early stage as they may affect the true discovery potential, the detector concepts and the run plan.

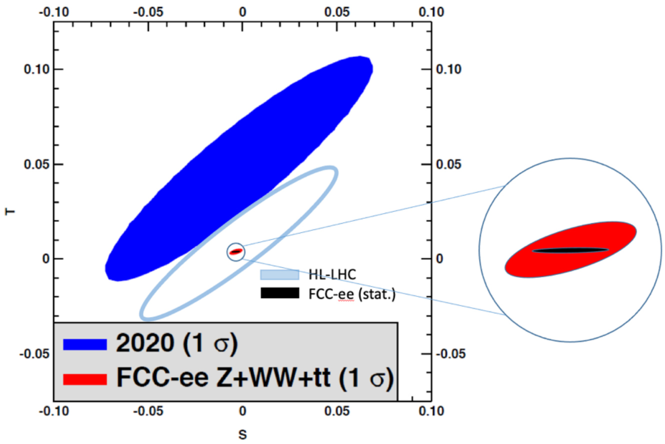

Figure 7: Contours of uncertainties for the S and T parameters from a global fit of all electroweak precision observables, today (dark blue); projections at the end of the HL-LHC (light blue); projections at the end of the FCC-ee, with the current (somewhat arbitrary) estimate of experimental and theoretical uncertainties (red); and with only statistical uncertainties (black). The HL-LHC and FCC-ee projections are centred around the Standard Model prediction for S and T. The insert represents the FCC-ee projected uncertainties expanded by a factor 10.

The TeraZ run offers four additional pillars to the FCC-ee physics programme: QCD, flavour physics, tau physics and direct search for rare/BSM processes, with real possibilities of discovery at the intensity frontier. Each of them would benefit from the enormous statistics of $5{\cdot}10^{12}$ Z (and more, if possible), and in turn provide specific and stringent detector requirements, including: a formidable vertexing ability for b, c and s tagging; superb electromagnetic energy resolution; hadron identification covering the whole momentum range expected at the Z resonance; precise knowledge of vertex detector dimensions; excellent momentum/energy and angular resolution for leptons and jets; tracker and calorimeter fine segmentation; e/μ/π separation; particle-flow reconstruction; extended detector volume and time-of-flight capability; etc. Specific case studies have begun to quantify the needs, and many more will be needed in the course of the Feasibility Study. The variety of detector requirements that will emerge from these studies may not be satisfied by one or even two detectors. Having four interaction points, in addition to offering an overall gain of luminosity for a given energy consumption, would allow a range of detector solutions to cover all FCC-ee opportunities, and would provide an attractive challenge for all skills in the field. Experience from LEP also taught us that different detector solutions are invaluable in uncovering hidden systematic biases and avoiding a conspiracy of errors.

To summarise, the FCC-ee offers great physics opportunities and is an ideal (the only possible) springboard to the FCC-hh, with its incomparably broad programme at the energy and luminosity frontiers. In addition to being the best Higgs factory that can be proposed today, FCC-ee is also a factory for Z, W, top, flavour, QCD and even (heavy) neutrino should they exist (10), with precise centre-of-mass energy measurement and a clean experimental environment. The FCC-ee challenges arise from the richness of the programme, to match experimental and theoretical systematic uncertainties to the statistical precision and to the detector configurations with the variety of channels and discovery cases. The physics, experiment and detector teams therefore clearly have their cut out with the FCC Feasibility Study in order to design the experimental set-up and prepare the theoretical tools to be able, demonstrably, to fully exploit (and communicate) the FCC-ee capabilities. Now that the FCC Feasibility Study has been approved by the CERN Council as the highest priority for CERN and Europe after the HL-LHC, the international community building and structuring deemed necessary for these goals to be met would greatly benefit from the explicit recognition and proactive support of ECFA for the FCC physics, experiment and detector studies. With the start of the FCC Feasibility Study, now is a great time to join and start participating in these studies, whose kick-off workshop will take place in Liverpool from 7 to 11 February 2022 (17).

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The Circular Electron–Positron Collider

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In light of the Higgs discovery at the LHC in 2012, an electron–positron collider with a circular structure became a feasible roadmap for a future Higgs factory. In September 2012, the Chinese high-energy physics community proposed the Circular Electron–Positron Collider (CEPC). In September 2013, a kick-off meeting took place at the Institute of High-Energy Physics (IHEP), Chinese Academy of Sciences. In the past few years, the CEPC study group has been making steady progress.

In November 2018, the CEPC CDR was released [1, 2]. In this conceptual design, CEPC is a 100-km-long double ring collider, with two interaction points. The preliminary plan is to start physics operation in the 2030s. Its ten-year operation plan includes seven years at the ZH production threshold ($\sqrt{s}\sim 240$ GeV), two years at the Z pole, and one year around the W+W- pair production threshold. It could be further upgraded to reach the $t\bar{t}$ production threshold ($\sqrt{s}\sim 360$ GeV). With future physics demands, the tunnel that houses CEPC could also be used for a $\sqrt{s}\sim 100$ TeV super proton–proton collider (SppC).

Since the release of the CDR, the CEPC study group has improved many aspects of the accelerator, including an S+C-band Linac with 20 GeV injection energy, a better tuned lattice, further optimised MDI, etc. The peak instantaneous luminosities have been increased to 5, 115, and 16 × 10^{34} $cm^{-2}s^{-1}$, for Higgs, Z-pole and W+W- operation modes, respectively. It will produce roughly 10^6 H, 10^{12} Z and 10^8 W bosons, providing opportunities for high-precision studies of the Higgs coupling, electroweak parameters, flavour physics and QCD, and probing physics beyond the Standard Model. The CEPC study group has published a Higgs physics white paper [3], and is working on white papers in the other four domains.

Significant progress has been made in research of key accelerator technologies. A 4500 m^2 superconducting laboratory was commissioned for superconducting RF (SCRF) cavity studies. SCRF cavities of 1.3 GHz 9-cell, 650 MHz 2-cell and 650 MHz 1-cell have been manufactured and tested. The performances exceed the CEPC specifications. The first prototype klystron achieved an efficiency of 62%. The second is undergoing tests and is expected to reach ~77%. These are crucial milestones towards completion of the accelerator TDR at the end of 2022.

The CEPC study group demonstrated two major conceptual detector designs in the CDR, including a baseline detector and the IDEA detector. The latter was also proposed for the FCCee. Various technologies are being studied. Prototype detectors have been constructed and tested. More studies are in progress. Recently, the group delivered a new conceptual design that includes: a drift chamber of maximally explored particle identification potential, a diagonal crystal bar electromagnetic calorimeter (ECAL) with better gamma/pi0 detection and compatibility with the particle flow algorithm (PFA), a PFA hadronic calorimeter (HCAL) that benefits from high-quality scintillation glass, and a thin low-mass high-temperature superconducting magnet that could be placed between the ECAL and the HCAL for cost reduction.

There are strong efforts from experts all over the world to make the CEPC a successful international facility. The International Advisory Committee (IAC) has met annually since 2015 to review progress and provide guidance. Two international R&D review committees started in 2019 for the accelerator and detector research. International workshops are organised regularly, with five successful events having been held in China, two in Europe and two in the US since 2017. International collaborative R&D is conducted through various channels, including well-established detector R&D collaborations such as CALICE and LCTPC. The CEPC team plans to form two international experiment collaborations around 2026, and to complete the detector TDRs in the subsequent two years or so.

CEPC has built strong ties with domestic industry. The CEPC Industrial Promotion Consortium (CIPC) was founded in 2017. More than 70 companies have joined to date. In the annual Chinese-edition CEPC workshops, the CIPC has a full programme to present their collaborative R&D work, in parallel with accelerator, detector and physics sessions. CEPC is looking into the possibility of extending the CIPC to international corporations.

Candidate CEPC sites have been proposed and investigated. A few key factors will be considered, including geology, an international-friendly environment, support from the local government and local community, etc. Recently, the government of Changsha city, one of the front-runner candidates, assembled a committee of experts from multiple disciplines. The committee evaluated the scientific potential of CEPC, the feasibility of a new science city utilising CEPC as a trigger, the impact on local development, etc. The committee's conclusion was very positive, and the Changsha government is interested in and very supportive of CEPC.

CEPC R&D projects have been supported domestically by the Ministry of Science and Technology, the National Science Foundation of China, the Chinese Academy of Sciences, institutes and local governments. Continuing R&D support is planned. In October 2021, the Institute of Science and Development, Chinese Academy of Sciences, started an independent social cost–benefit analysis of the CEPC project. The report will be available next August.

The CEPC group is working hard on various aspects in order to make R&D progress on key technologies and to gain support from various sources. It is hoped that, with the strong efforts of the group and the international HEP community, the CEPC project will be endorsed by the central government and eventually come to fruition.

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