PPAP roadmap input: FCC-ee

Physics strengths and R&D opportunities for UK particle physics

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Introduction

This brief document follows the June 2020 European Particle Physics Strategy Update (EPPSU) [1] and the discussions that took place at the FCC-UK kick-off meeting [2] and PPAP Community meeting in September 2020. We hereby review the opportunities for UK engagement in detector development, phenomenology and accelerator contributions, and areas where the UK has key competitive advantages and can play a leading role in this international project. We also emphasise the great synergies that exist with the R&D required for other possible Higgs factories.

FCC-ee would be a state-of-the-art accelerator with a number of technical challenges to be overcome in order to maximise luminosity performance and minimise technical risk and/or cost. There are many overlaps with UK expertise on linear colliders and light sources, e.g. dynamics of intense low-emittance beams, beam instrumentation, feedback and control, vacuum systems, magnet technologies and RF systems, as well as design of the machine-detector interface. In all cases there is the opportunity for strong UK industrial engagement in design, development and supply of large-scale systems.

Physics opportunities

The UK has been leading many of the highest-profile physics areas at the current generation of colliders, so is ideally placed to continue with a strong involvement at future colliders.

Higgs Physics

The proposed operating strategy for FCC-ee is that it will run with large Higgs yields for seven years, of which three will be at a centre of mass energy of 240 GeV and four at 365 GeV. The

[1] FCC-UK (along with other FCC national groups from France, Italy, Spain, Poland, etc) report at the Future Circular Collider Physics & Experiments Steering Group about activities and planning at the national level. The UK institute contacts for FCC are: D. Charlton (Birmingham), J. Goldstein (Bristol), C. Potter (Cambridge), P. Ratoff (Cockcroft), R. Lemmon (Daresbury), M. Spannowsky (Durham), C. Leonidopoulos (Edinburgh), A. Buckley (Glasgow), G. Davies (Imperial), P. Burrows (John Adams Institute), J. Ellis (King's College), H. Fox (Lancaster), J. Vossebeld (Liverpool), T. Wyatt (Manchester), G. Wilkinson (Oxford), S. Zenz (QMUL), J. Dopke (STFC Rutherford Appleton Laboratory), V. Boisvert (Royal Holloway), T. Vickey (Sheffield), S. Moretti (Southampton), A. De Santo (Sussex), M. Campanelli (UCL), W. Murray (Warwick).

Higgs production at $\sqrt{s} \approx 240$ GeV is dominated by Higgsstrahlung ($e^+e^- \rightarrow HZ$) which allows for accurate tagging of Higgs events irrespective of the Higgs decay mode. The absolute measurement of the Higgs coupling to the Z boson is the starting point for the model-independent determination of its total width and its other couplings through branching-ratio measurements.

At the FCC-ee about 1 million ZH bosons pairs will be produced yielding a measurement of the Higgs coupling to the Z boson ($\delta g_{HZZ}/g_{HZZ}$) at the 0.2% level and extending the range of measurable Higgs boson properties by providing access to $H \rightarrow cc$ ($\delta g_{Hcc}/g_{Hcc}$=1.7%) and $H \rightarrow gg$ ($\delta g_{Hgg}/g_{Hgg}$=1.6%). The $H\,Z(\ell^+\ell^-)$ final state will set sensitive limits on invisible Higgs decays <0.3% at 95% C.L. The total Higgs boson width can be determined with a 2.7% uncertainty after the run at 240 GeV. The uncertainty will be reduced to 1.3% by including the run at 350 GeV, which is sensitive to vector-boson-fusion ($VV \rightarrow He^+e^-$, $\nu\nu$). The Higgs couplings to all gauge bosons and to the charged fermions of the second and third generations, except the strange-quark, will be known with a precision ranging from a few per mille to ~1%. The knowledge of the Higgs mass, m_H, to within a few MeV allows the FCC-ee to run at $\sqrt{s}=m_H$ this could set constraints on the otherwise inaccessible Higgs coupling to the electron in the s-channel mode $e^+e^- \rightarrow H$.

Electroweak/Flavour Physics

In three-to-four years of operation the FCC-ee detectors will accumulate 5 x 10^{12} *Z* decays, a factor 10^5 larger than LEP. This enormous increase in sample size presents a unique and highly attractive opportunity to improve greatly our knowledge of the so-called electroweak precision observables (EWPO), such as the *Z* width and the effective weak mixing angle, which are measurements that have great sensitivity to mass scales beyond the direct reach of any present or future collider. Taking advantage of this opportunity requires a corresponding advance in systematic control, a challenge that is already being confronted. For example, the machine is being designed with the capability of near-continuous resonant-depolarisation measurements of the beam energy, an innovation that will allow the dominant uncertainty in the LEP determination of the *Z* mass and width to be reduced by at least two orders of magnitude. The same attribute will allow the *W* mass to be measured with a precision far in excess of that possible at any other facility, which will be invaluable input for performing closure tests of the Standard Model. With suitably designed detectors, other measurements, such as the forward-backward di-muon asymmetry, or the determination of $\alpha_{QED}(m_Z^2)$, may end up remaining statistics limited. Searches for lepton-flavour violating *Z* decays and direct searches for heavy right-handed neutrinos will also be important components of the *Z* physics programme.

The FCC-ee will be a flavour factory. Operation at the *Z*-pole will deliver ~$10^{12} b\underline{b}$ pairs, a yield around 30 times larger than anticipated at Belle II, and in a similarly pristine environment. Many very important b-physics measurements can be made at FCC-ee that are impossible at LHCb or its upgrades, for example a detailed study of the modes $B^0 \rightarrow K^*\tau\tau$ or $B_c \rightarrow \tau\nu$. Many systematic effects that hinder LHCb measurements will be absent, or of a very different nature at FCC-ee, bringing great complementarity to the two projects. World-best measurements will also be achievable in tau physics, in particular of the tau lifetime and in searches for lepton-flavour violating modes. All of these studies will be vital inputs in searching for physics beyond the Standard Model.

The top quark mass and width will be measured from the rise in the $e^+e^- \to t\bar{t}$ cross section at the production threshold at a centre-of-mass energy around twice the top mass. With a luminosity of 25 fb^{-1} the top-quark mass and width can be determined with statistical precisions of ±17 MeV and ±45 MeV, respectively. The uncertainty on the mass improves to less than 10 MeV if the width is fixed to its SM value.

UK Interests in Detector R&D

UK experimental groups have long standing experience and an international reputation in both silicon tracking and vertex detectors, and calorimetry, as well as DAQ/trigger. These capabilities will allow us to take leading roles in the design of the critical detector elements that will be central to the physics output of FCC-ee. Currently a four interaction-point layout of the machine is under consideration. If pursued, this will greatly expand the phase space of detector layouts, the optimisation of which is a process that presents great opportunities for UK engagement. Moreover, there is much commonality in the requirements for such detectors at the FCC-ee, and those at other proposed Higgs factories (ILC, CLIC and CEPC), ensuring that any synergies on R&D activities over the coming years should be encouraged.

Tracking & vertexing detectors

The UK has a long-standing history developing and building silicon based tracking and vertex detectors. Some of the CMOS sensors that have been successfully used in international experiments have their origin in UK designs. The UK is currently contributing to several design efforts for future CMOS sensors as part of international collaborations, largely centred around CERN and as part of the ECFA process. This development is also required to fulfill the very demanding requirements on resolution and power consumption for the FCC. Some of these projects are pursued in collaboration with UK based industry. One of the other key requirements for a Higgs factory detector is ultra-low mass. Several R&D projects in the UK and with international collaborators are actively addressing this challenge from several angles: sensors, support structures, readout and cooling. The UK has invested significantly in research on these detectors and in facilities that enable large assemblies of silicon sensors for LHC detectors and also smaller scale experiments to be constructed. The knowledge, infrastructure and facilities resulting from this investment will be invaluable and exploited when building the large vertexing and tracking detectors for the FCC. CMOS sensors are also used in high resolution particle flow calorimetry and play a role in particle identification. R&D in one area will benefit the other area too.

Calorimeter detectors

The UK has long-standing leadership in development of calorimeter detectors for future colliders. Since its inception, the UK has been part of the CALICE collaboration with a strong presence in the R&D effort: test beams, performances, and Particle Flow algorithms of the SiW detector prototype. The UK has also continued with small scale development of alternative calorimeter sensors using MAPs technology. Within the CALICE collaboration, the UK has held various management positions (Physics Analysis coordinator, CB chair, PubCom Chair).

More recently, the UK has taken leading responsibilities in the development of the dual-readout calorimeter technology through participation in beam tests, simulation of the detector and development of the optical readout, aimed at characterising jets and their energy resolution. The UK has strong institutional expertise in rad-hard CMOS sensors for digital electromagnetic calorimetry, sensor R&D, optical SiPM readout systems, simulation and reconstruction techniques. We are also playing a leading role in high-granularity calorimetry for the HL-LHC programme.

Trigger/DAQ

Trigger/DAQ is another area of established UK expertise, which will be valuable in design and construction of the FCC-ee detectors. UK groups have held leading roles in the building and operation of readout, trigger and monitoring systems. For the FCC-ee experiments, the options being investigated are trigger-less (ie. software-based) designs and FPGA technologies for zero-suppression.

Particle ID

Any serious programme of flavour physics at the FCC-ee will necessitate high-quality particle-identification (PID), which will also enhance the flavour-tagging performance for jets. UK institutes have world class expertise in PID detectors, having taken leading responsibility for the LHCb RICH system, and been active in developing novel approaches for future application, such as the TORCH concept. We are therefore ideally equipped to explore solutions for adding PID capabilities to the FCC-ee experiments. The scope for involvement in such studies will grow if the machine design evolves to a four-interaction layout, presenting the opportunity to design an experiment optimised for flavour measurements

Machine/Accelerator opportunities

The main technologies for FCC-ee already exist today. The UK has a unique and very timely opportunity to develop a strong R&D program with industry to optimise the energy efficiency (efficient SFR, highly efficient RF power sources, energy-efficient magnets), maintainability, machine availability (modular design, early involvement of industry) and construction costs.

Theory opportunities

Interpreting the detailed and precise Higgs measurements offered by FCC-ee (and FCC-hh) will provide many theoretical opportunities including the improvement of Standard Model (SM) calculations and searches for signatures of new physics beyond the SM (BSM). The UK theory community has the interest and expertise to take a leading role in exploring these opportunities, with experience in many scenarios for electroweak symmetry breaking including fundamental and composite Higgs models, multi-Higgs models, and diverse supersymmetric models. Effective field theory (EFT) provides a powerful tool for the joint interpretation of Higgs and electroweak data, for which FCC-ee data will carry to a new level of precision. UK theorists have world-leading expertise in the formulation of the SM EFT and its use in data analysis and for indirect probes of new physics.

Prominent among motivations for BSM physics is the problem of dark matter, and FCC-ee and FCC-hh will both provide new opportunities for experimental probes of its composition. UK theorists are prominent in proposing dark matter candidates, and in understanding their possible signatures. The interpretation of FCC data will require precise understanding of QCD, and the UK theory community has world-leading expertise in higher-order perturbative calculations, the development and deployment of simulation tools and lattice calculations. The latter will underpin, in particular, the interpretation of the high-precision flavour data that will be provided by FCC. These UK theoretical strengths are complemented by expertise in phenomenological analyses made in conjunction with experiments as well as supporting phenomenological work.

Timeline & Resources

The next 5 years will be devoted to physics benchmark measurements and R&D studies by the international community in order to establish the feasibility of the FCC-ee project and lay out the detector requirements. The feasibility study will involve the possibility of construction of such a large infrastructure in the vicinity of CERN, the financial plan to complete the project, and the operational plan and governance in cooperation with international partners.

A provisional timeline of the next steps of the FCC-ee project is as follows:

- 2021 - 2025: Physics performance studies
- End of 2025: CDR/TDR (feasibility proof)
- 2025/6: FCC-ee proto collaborations and LoI
- 2026-27: Next ESPPU
- 2028: Project approval
- 2030: Start of tunnel construction
- 2035/36: Tunnel completion
- 2037: Start machine installation
- 2040: First e^+e^- collisions in FCC-ee

It is crucial that the UK HEP community has a very strong engagement in these studies in order to place ourselves in a position to claim central roles in detector building, civil construction, and optimise the "juste retour". This is particularly important given that starting with the project construction, the UK is expected to be contributing a large monetary amount, of the order of tens of £M per year for more than a decade.

The priority for the initial, 5-year period will be on Physics studies, software/computing development, phenomenological work for measurement projections, and detector/accelerator R&D. Aspects of this R&D work will require involvement with industry. We provisionally expect a ramping up from an initial 10 FTE to approximately 20 FTE by the time of the CDR/TDR submission.

A more detailed breakdown of requested resources will be prepared in the weeks ahead.

[1] June 2020 update of the European Strategy for Particle Physics
[2] FCC-UK community kick-off meeting, 11 September 2020