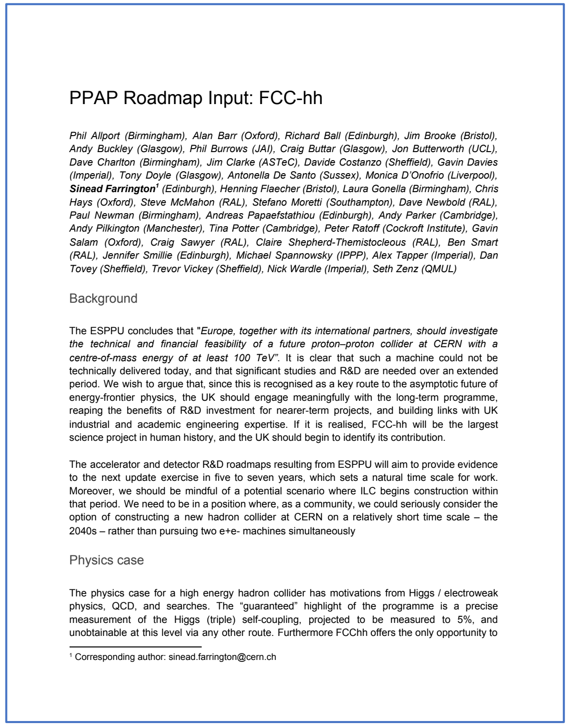
Future colliders - hadrons

Monica D'Onofrio
University of Liverpool

Submissions

- **F**uture **C**ircular **C**ollider is currently the (large-scale) hadron-collider option being considered beyond the LHC and its High-Lumi upgrade
  - Three submissions discussed today: **FCC-hh, FCC-eh, FCC-global**



PPAP Roadmap Input: FCC-hh

Phil Allport (Birmingham), Alan Barr (Oxford), Richard Ball (Edinburgh), Jim Brooke (Bristol), Andy Buckley (Glasgow), Phil Burrows (JAI), Craig Buttar (Glasgow), Jon Butterworth (UCL), Dave Charlton (Birmingham), Jim Clarke (ASTeC), Davide Costanzo (Sheffield), Gavin Davies (Imperial), Tony Doyle (Glasgow), Antonella De Santo (Sussex), Monica D'Onofrio (Liverpool), ***Sinead Farrington***[1] *(Edinburgh), Henning Flaecher (Bristol), Laura Gonella (Birmingham), Chris Hays (Oxford), Steve McMahon (RAL), Stefano Moretti (Southampton), Dave Newbold (RAL), Paul Newman (Birmingham), Andreas Papaefstathiou (Edinburgh), Andy Parker (Cambridge), Andy Pilkington (Manchester), Tina Potter (Cambridge), Peter Ratoff (Cockroft Institute), Gavin Salam (Oxford), Craig Sawyer (RAL), Claire Shepherd-Themistocleous (RAL), Ben Smart (RAL), Jennifer Smillie (Edinburgh), Michael Spannowsky (IPPP), Alex Tapper (Imperial), Dan Tovey (Sheffield), Trevor Vickey (Sheffield), Nick Wardle (Imperial), Seth Zenz (QMUL)*

Background

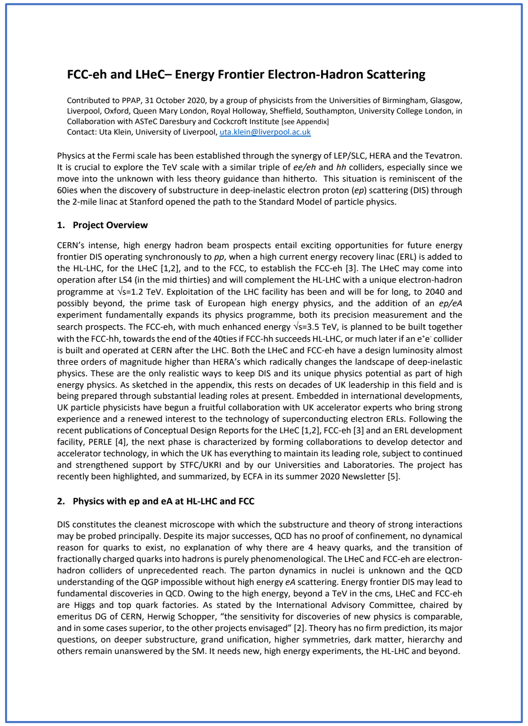
The ESPPU concludes that "*Europe, together with its international partners, should investigate the technical and financial feasibility of a future proton–proton collider at CERN with a centre-of-mass energy of at least 100 TeV*". It is clear that such a machine could not be technically delivered today, and that significant studies and R&D are needed over an extended period. We wish to argue that, since this is recognised as a key route to the asymptotic future of energy-frontier physics, the UK should engage meaningfully with the long-term programme, reaping the benefits of R&D investment for nearer-term projects, and building links with UK industrial and academic engineering expertise. If it is realised, FCC-hh will be the largest science project in human history, and the UK should begin to identify its contribution.

The accelerator and detector R&D roadmaps resulting from ESPPU will aim to provide evidence to the next update exercise in five to seven years, which sets a natural time scale for work. Moreover, we should be mindful of a potential scenario where ILC begins construction within that period. We need to be in a position where, as a community, we could seriously consider the option of constructing a new hadron collider at CERN on a relatively short time scale – the 2040s – rather than pursuing two e+e- machines simultaneously

Physics case

The physics case for a high energy hadron collider has motivations from Higgs / electroweak physics, QCD, and searches. The "guaranteed" highlight of the programme is a precise measurement of the Higgs (triple) self-coupling, projected to be measured to 5%, and unobtainable at this level via any other route. Furthermore FCChh offers the only opportunity to

[1] Corresponding author: sinead.farrington@cern.ch



FCC-eh and LHeC– Energy Frontier Electron-Hadron Scattering

Contributed to PPAP, 31 October 2020, by a group of physicists from the Universities of Birmingham, Glasgow, Liverpool, Oxford, Queen Mary London, Royal Holloway, Sheffield, Southampton, University College London, in Collaboration with ASTeC Daresbury and Cockcroft Institute [see Appendix]
Contact: Uta Klein, University of Liverpool, uta.klein@liverpool.ac.uk

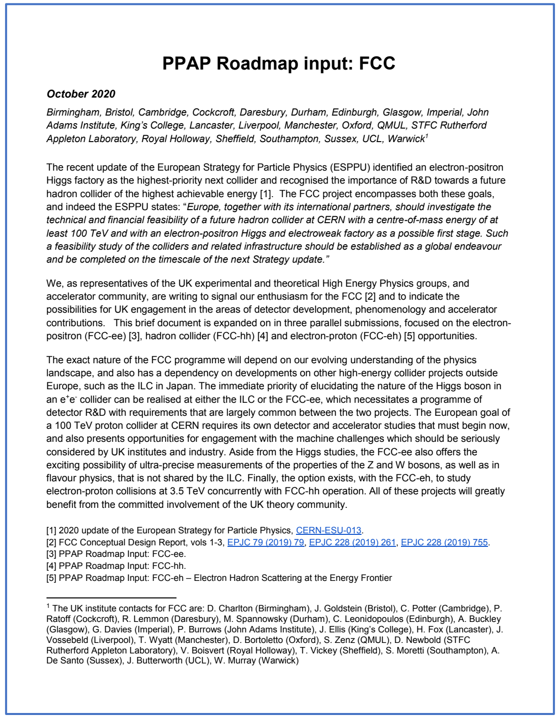
Physics at the Fermi scale has been established through the synergy of LEP/SLC, HERA and the Tevatron. It is crucial to explore the TeV scale with a similar triple of *ee/eh* and *hh* colliders, especially since we move into the unknown with less theory guidance than hitherto. This situation is reminiscent of the 60ies when the discovery of substructure in deep-inelastic electron proton (*ep*) scattering (DIS) through the 2-mile linac at Stanford opened the path to the Standard Model of particle physics.

1. Project Overview

CERN's intense, high energy hadron beam prospects entail exciting opportunities for future energy frontier DIS operating synchronously to *pp*, when a high current energy recovery linac (ERL) is added to the HL-LHC, for the LHeC [1,2], and to the FCC, to establish the FCC-eh [3]. The LHeC may come into operation after LS4 (in the mid thirties) and will complement the HL-LHC with a unique electron-hadron programme at $\sqrt{s}$=1.2 TeV. Exploitation of the LHC facility has been and will be for long, to 2040 and possibly beyond, the prime task of European high energy physics, and the addition of an *ep/eA* experiment fundamentally expands its physics programme, both its precision measurement and the search prospects. The FCC-eh, with much enhanced energy $\sqrt{s}$=3.5 TeV, is planned to be built together with the FCC-hh, towards the end of the 40ties if FCC-hh succeeds HL-LHC, or much later if an e^+e^- collider is built and operated at CERN after the LHC. Both the LHeC and FCC-eh have a design luminosity almost three orders of magnitude higher than HERA's which radically changes the landscape of deep-inelastic physics. These are the only realistic ways to keep DIS and its unique physics potential as part of high energy physics. As sketched in the appendix, this rests on decades of UK leadership in this field and is being prepared through substantial leading roles at present. Embedded in international developments, UK particle physicists have begun a fruitful collaboration with UK accelerator experts who bring strong experience and a renewed interest to the technology of superconducting electron ERLs. Following the recent publications of Conceptual Design Reports for the LHeC [1,2], FCC-eh [3] and an ERL development facility, PERLE [4], the next phase is characterized by forming collaborations to develop detector and accelerator technology, in which the UK has everything to maintain its leading role, subject to continued and strengthened support by STFC/UKRI and by our Universities and Laboratories. The project has recently been highlighted, and summarized, by ECFA in its summer 2020 Newsletter [5].

2. Physics with ep and eA at HL-LHC and FCC

DIS constitutes the cleanest microscope with which the substructure and theory of strong interactions may be probed principally. Despite its major successes, QCD has no proof of confinement, no dynamical reason for quarks to exist, no explanation of why there are 4 heavy quarks, and the transition of fractionally charged quarks into hadrons is purely phenomenological. The LHeC and FCC-eh are electron-hadron colliders of unprecedented reach. The parton dynamics in nuclei is unknown and the QCD understanding of the QGP impossible without high energy *eA* scattering. Energy frontier DIS may lead to fundamental discoveries in QCD. Owing to the high energy, beyond a TeV in the cms, LHeC and FCC-eh are Higgs and top quark factories. As stated by the International Advisory Committee, chaired by emeritus DG of CERN, Herwig Schopper, "the sensitivity for discoveries of new physics is comparable, and in some cases superior, to the other projects envisaged" [2]. Theory has no firm prediction, its major questions, on deeper substructure, grand unification, higher symmetries, dark matter, hierarchy and others remain unanswered by the SM. It needs new, high energy experiments, the HL-LHC and beyond.



PPAP Roadmap input: FCC

October 2020

Birmingham, Bristol, Cambridge, Cockcroft, Daresbury, Durham, Edinburgh, Glasgow, Imperial, John Adams Institute, King's College, Lancaster, Liverpool, Manchester, Oxford, QMUL, STFC Rutherford Appleton Laboratory, Royal Holloway, Sheffield, Southampton, Sussex, UCL, Warwick[1]

The recent update of the European Strategy for Particle Physics (ESPPU) identified an electron-positron Higgs factory as the highest-priority next collider and recognised the importance of R&D towards a future hadron collider of the highest achievable energy [1]. The FCC project encompasses both these goals, and indeed the ESPPU states: "*Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*"

We, as representatives of the UK experimental and theoretical High Energy Physics groups, and accelerator community, are writing to signal our enthusiasm for the FCC [2] and to indicate the possibilities for UK engagement in the areas of detector development, phenomenology and accelerator contributions. This brief document is expanded on in three parallel submissions, focused on the electron-positron (FCC-ee) [3], hadron collider (FCC-hh) [4] and electron-proton (FCC-eh) [5] opportunities.

The exact nature of the FCC programme will depend on our evolving understanding of the physics landscape, and also has a dependency on developments on other high-energy collider projects outside Europe, such as the ILC in Japan. The immediate priority of elucidating the nature of the Higgs boson in an e^+e^- collider can be realised at either the ILC or the FCC-ee, which necessitates a programme of detector R&D with requirements that are largely common between the two projects. The European goal of a 100 TeV proton collider at CERN requires its own detector and accelerator studies that must begin now, and also presents opportunities for engagement with the machine challenges which should be seriously considered by UK institutes and industry. Aside from the Higgs studies, the FCC-ee also offers the exciting possibility of ultra-precise measurements of the properties of the Z and W bosons, as well as in flavour physics, that is not shared by the ILC. Finally, the option exists, with the FCC-eh, to study electron-proton collisions at 3.5 TeV concurrently with FCC-hh operation. All of these projects will greatly benefit from the committed involvement of the UK theory community.

[1] 2020 update of the European Strategy for Particle Physics, CERN-ESU-013.
[2] FCC Conceptual Design Report, vols 1-3, EPJC 79 (2019) 79, EPJC 228 (2019) 261, EPJC 228 (2019) 755.
[3] PPAP Roadmap Input: FCC-ee.
[4] PPAP Roadmap Input: FCC-hh.
[5] PPAP Roadmap Input: FCC-eh – Electron Hadron Scattering at the Energy Frontier

[1] 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), D. Bortoletto (Oxford), S. Zenz (QMUL), D. Newbold (STFC Rutherford Appleton Laboratory), V. Boisvert (Royal Holloway), T. Vickey (Sheffield), S. Moretti (Southampton), A. De Santo (Sussex), J. Butterworth (UCL), W. Murray (Warwick)

- Submission focusing on interest and plans for the **Electron Ion Collider (EIC) -** from last night hence not yet reported here.

FCC-hh: outline

- **19** institutes represented
  - About **40 people** in the list

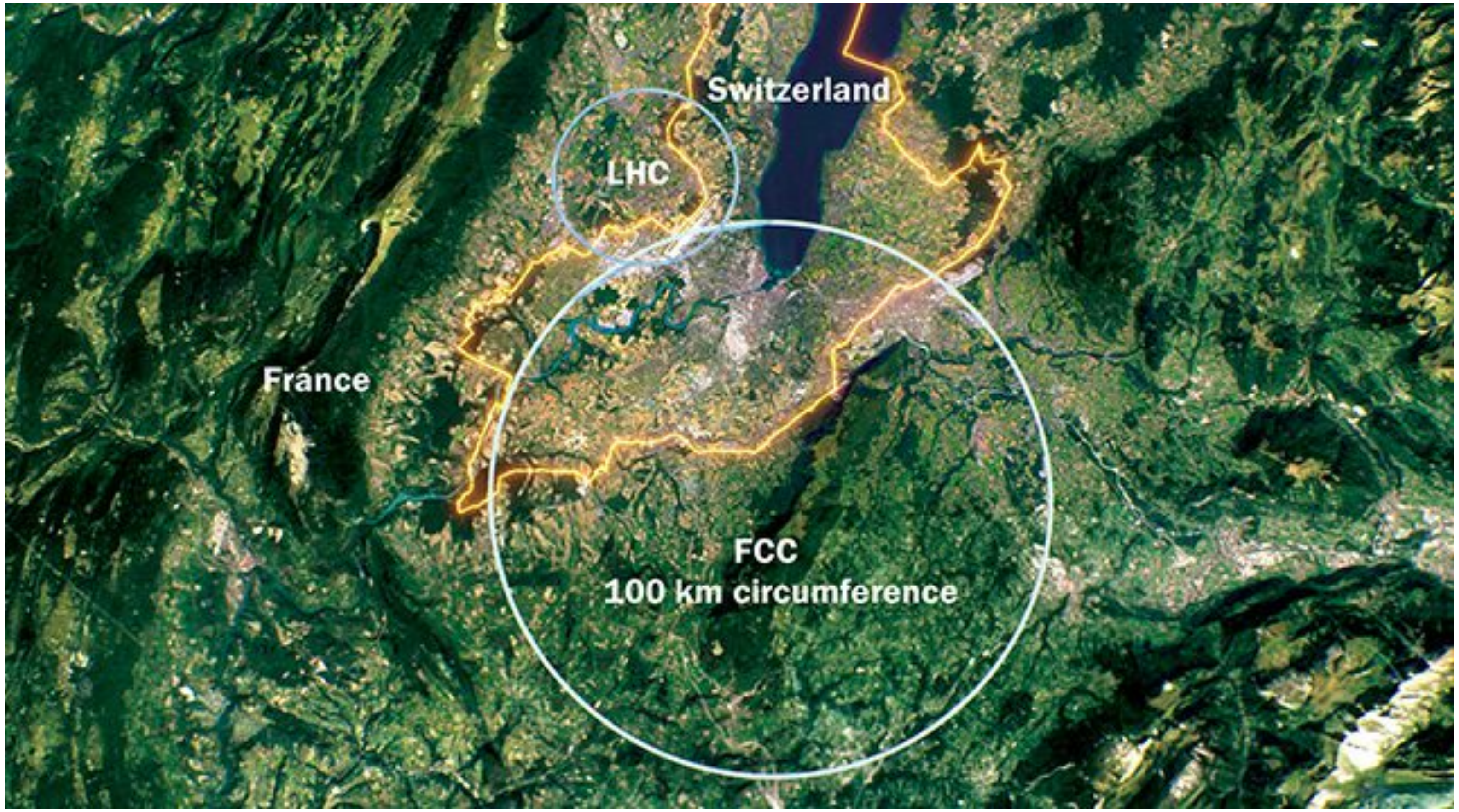
*Phil Allport (Birmingham), Alan Barr (Oxford), Richard Ball (Edinburgh), Jim Brooke (Bristol), Andy Buckley (Glasgow), Phil Burrows (JAI), Craig Buttar (Glasgow), Jon Butterworth (UCL), Dave Charlton (Birmingham), Jim Clarke (ASTeC), Davide Costanzo (Sheffield), Gavin Davies (Imperial), Tony Doyle (Glasgow), Antonella De Santo (Sussex), Monica D'Onofrio (Liverpool), **Sinead Farrington**[1] (Edinburgh), Henning Flaecher (Bristol), Laura Gonella (Birmingham), Chris Hays (Oxford), Steve McMahon (RAL), Stefano Moretti (Southampton), Dave Newbold (RAL), Paul Newman (Birmingham), Andreas Papaefstathiou (Edinburgh), Andy Parker (Cambridge), Andy Pilkington (Manchester), Tina Potter (Cambridge), Peter Ratoff (Cockroft Institute), Gavin Salam (Oxford), Craig Sawyer (RAL), Claire Shepherd-Themistocleous (RAL), Ben Smart (RAL), Jennifer Smillie (Edinburgh), Michael Spannowsky (IPPP), Alex Tapper (Imperial), Dan Tovey (Sheffield), Trevor Vickey (Sheffield), Nick Wardle (Imperial), Seth Zenz (QMUL)*

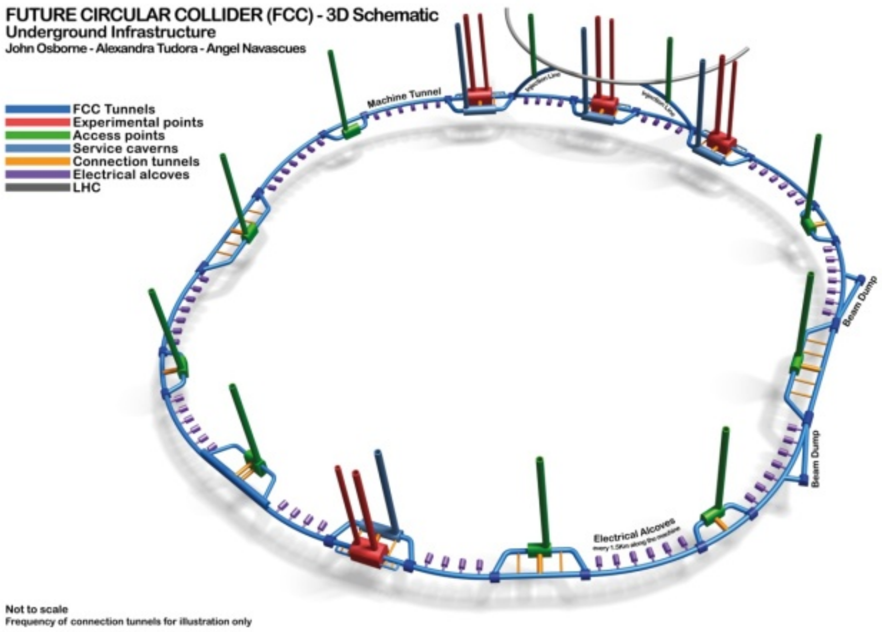
- Table of content includes:
  - ESPPU remarks and background
  - Physics case
  - Short term R&D and Impact
    - Detector
    - Accelerator
  - Timeframe and resources

The premises:
"*Europe, together with its international partners, should investigate the technical and financial feasibility of a future **proton–proton** collider at CERN with a centre-of-mass energy of at least 100 TeV*"

FCC-hh: project overview

- Proton-proton collider, 100 TeV, 30/ab lumi, up to 4 experimental sites

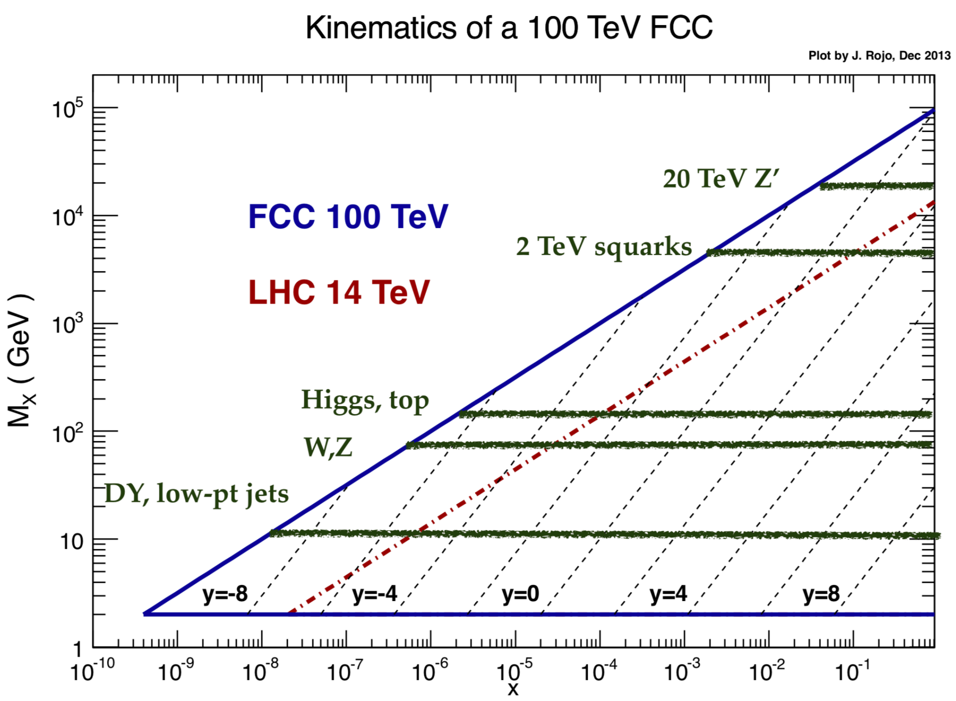




FCC-hh: physics case

Several unique targets:

- **Higgs / electroweak physics**: e.g. precise measurement of the Higgs (triple) self-coupling, projected to be measured to 5%; quartic Higgs self-coupling at any level.
- Direct **searches for NP**: compared to LHC, extended by an order of magnitude above the electroweak symmetry-breaking scale and towards the GUT scale.
- Searches for NP through **precision measurements**



FCC-hh: Short-term R&D and impact (1)

Premises: significant studies and R&D are needed over an extended period.

- **Physics case:**
  - extension of current preliminary physics studies are needed to inform on the needs for trigger, detector and reconstruction technologies
  - investment in phenomenological calculations should be made
    - can draw upon established expertise in the theory and experimental community
- **Detector:**
  - FCC-hh requires technology far beyond the current state-of-the-art
  - Examples of required technologies include highly integrated low-mass and radiation-tolerant detector systems; substantially increased on-detector data processing and intelligence; development of new thin superconducting magnet technologies; and entirely new methods of controlling, powering and gathering data from billions of detector channels.
    - Can draw directly on current HL-LHC work and expertise, representing a continuum of activity, in a similar way to the direct path from Tevatron to LHC to HL-LHC

FCC-hh: Short-term R&D and impact (2)

Premises: significant studies and R&D are needed over an extended period.

- **Accelerator:**
  - basic enabling technology is high-field superconducting magnets
  - Work should proceed first via an evaluation exercise, in engagement with the European R&D programme, and involving the efforts of national labs, the community, and experts in HTS technology from industry and academia.
    - Position the UK in this and re-engage in the grand challenge

Overall message: *FCC-hh is recognised as a key route to the asymptotic future of energy-frontier physics. The UK should engage meaningfully with the long-term programme, reaping the benefits of R&D investment for nearer-term projects, and building links with UK industrial and academic engineering expertise. If it is realised, FCC-hh will be the largest science project in human history, and the UK should begin to identify its contribution*

FCC-hh: Timeframe and resources

- The accelerator and detector R&D roadmaps resulting from ESPPU will aim to provide evidence to the next update exercise in five to seven years, which sets a natural time scale for work.
- The document presents a 'straw person' scenario based on a direct move to FCC-hh detailed design phase after the next ESPPU.

- 2021 – 2023: Evaluation studies of machine technology challenges and opportunities, first phase of an advanced detector R&D programme, preliminary physics studies (5FTE, £0.5M capital)
- 2024 – 2027: First phase of HTS magnet programme and machine studies, demonstrator phase of detector R&D programme, detailed physics studies in parallel with LHC LS3 (10FTE, £5M capital)
- 2027: Next update of ESPPU; 'go decision' on detailed design studies for FCC-hh
- 2028 – 2032: Detailed design studies for machine; HTS magnet demonstrator programme; detector design phase towards updated CDR (20FTE, £20M capital)
- 2033: Approval of FCC-hh construction
- 2033 – 2036: Civil construction; industrial magnet pre-series; final detector prototyping phase (50FTE, £20M capital plus direct machine contribution)
- 2036 – 2044: Machine and detector construction, (including software engineering); ramp-up of physics preparations post-LHC, including development of required theory codes and tools (60-80FTE; £100M capital plus direct machine contribution).
- 2044 – 2047: Commissioning
- 2048: Start of physics

The document presents also an overview of overall costs :
- total machine cost: **20GCHF**

An evaluation of the total bill to the UK over the period 2033 – 2044 which would be around £375M at 2020 rates, or **£35M** per year (+ additional costs up to the commissioning phase for R&D and detector work)

FCC-eh: outline

- **11** institutes represented
  - About **25 people** in the list

- Table of content includes:
  - Project overview
  - Physics with e-p and e-A
  - Intense High Energy Electrons from an Energy Recovery Linac and the PERLE Facility
  - Detector
  - Synergy in Technology
  - Physics Complementarity
  - Theory Developments
  - Relation to the EIC
  - Timeframe and resources

P.Allport[1], S.Belyaev[8], T. Berry[6], J.Bracinik[1], M.Campanelli[9], A. Cooper-Sarkar[4], M.D'Onofrio[3], T.Doyle[2], O.Fischer[3], C.Gwenlan[4], M.Klein[3], U.Klein[3], P.Kostka[3], J.Kretzschmar[3], K.Lohwasser[7], S.Moretti[8], P.Newman[1], E.Rizvi[5], J.Vossebeld[3]

The accelerator work is pursued in collaboration with ASTeC Daresbury (D. Angal-Kalinin, B. Militsyn, P.Williams et al.), the Cockcroft Institute (P. Ratoff et al.) and the University of Liverpool accelerator group (C. Welsch et al.). Contributions to the LHeC had also been made by the John Adams Institute.

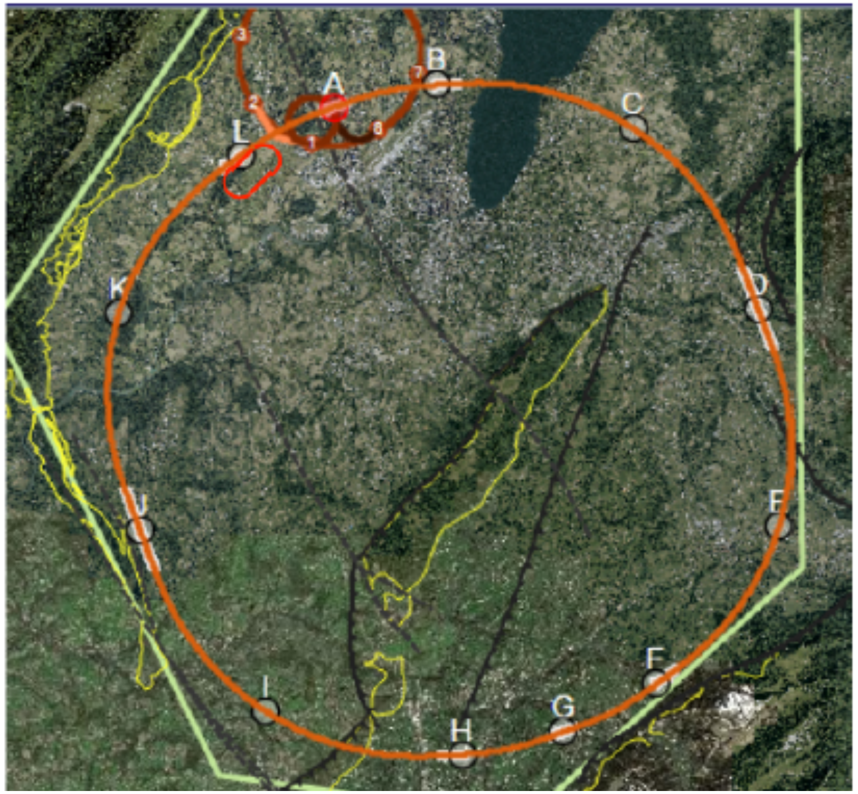
1 Birmingham
2 Glasgow
3 Liverpool
4 Oxford
5 Queen Mary London
6 Royal Holloway London
7 Sheffield
8 Southampton
9 University College London

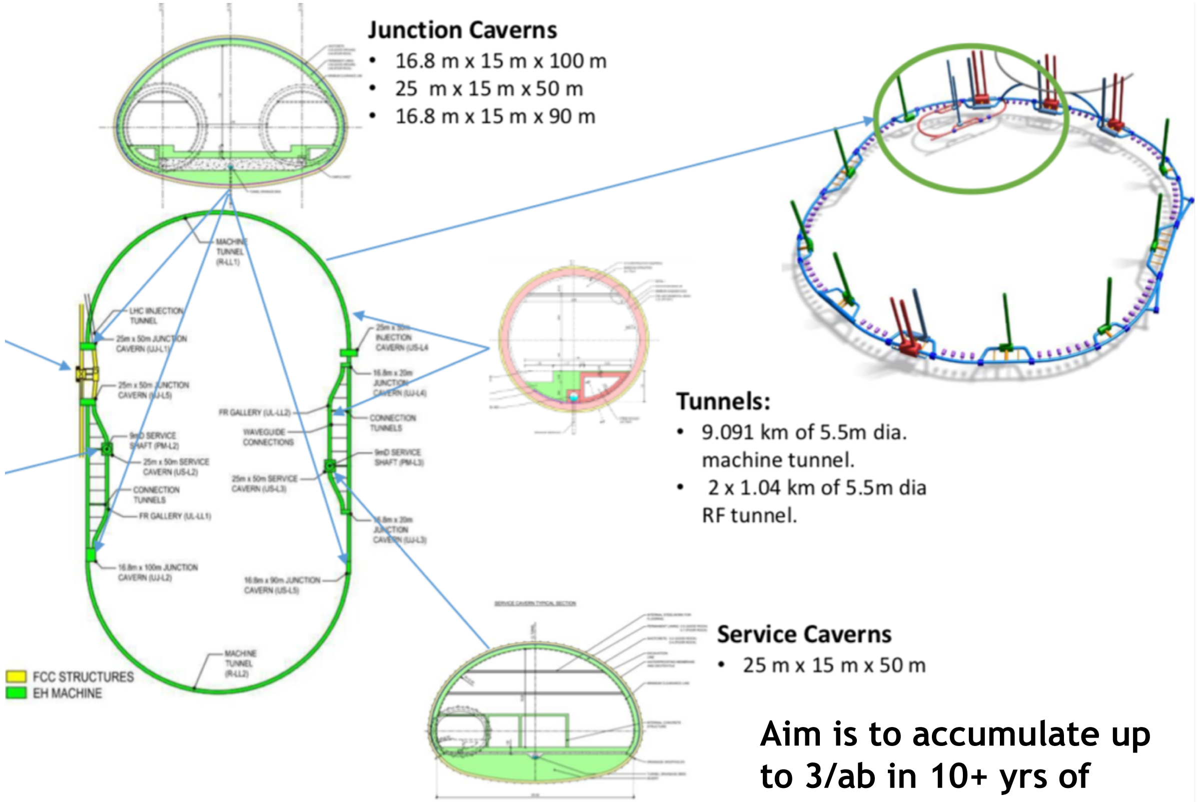
+ ASTeC Daresbury, Cockcroft Institute

The premises:
"Following the recent publications of Conceptual Design Reports for the LHeC, FCC-eh and an ERL development facility, PERLE, the next phase is characterized by forming collaborations to develop detector and accelerator technology […] the project has recently been highlighted, and summarized, by ECFA in its summer 2020 Newsletter. "

FCC-eh: project overview

- Electron-proton collider: E_e=60 GeV, E_p=50 TeV [*work as e-Ion as well*]
- Centre of mass energy 3.5 TeV
- planned to be built together with the FCC-hh, host one detector





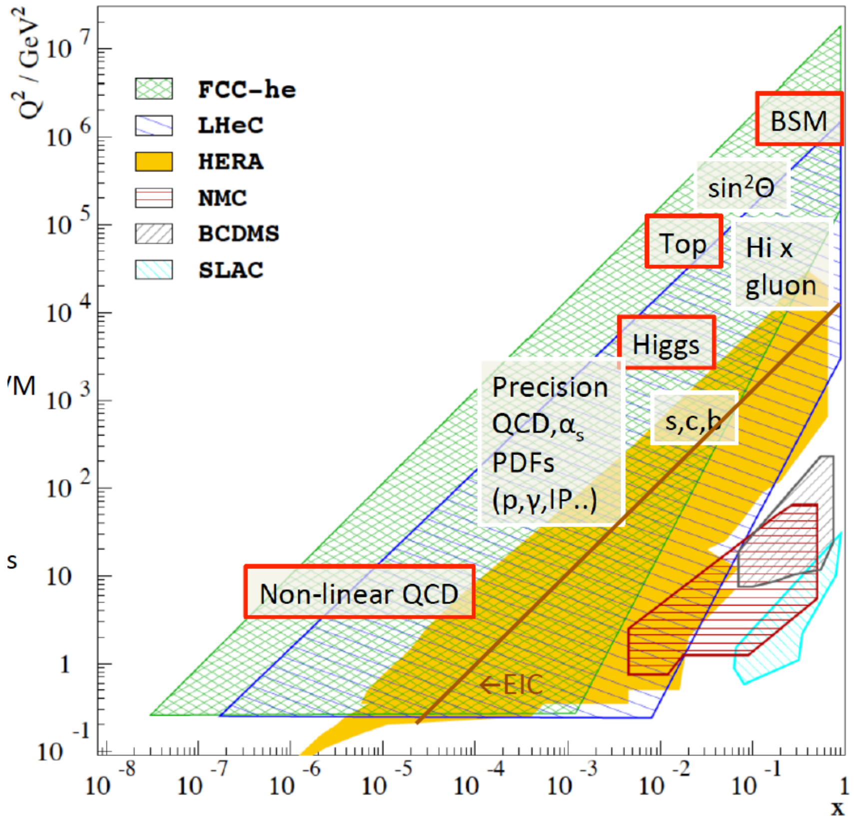
Aim is to accumulate up to 3/ab in 10+ yrs of operations

FCC-eh: physics case

e-p colliders as High-Resolution Microscope:

- QCD discovery (physics at high-x and low-x)
- Study of EW / VBF production and forward objects
- Higgs physics
- Beyond SM searches (e.g. long-lived particles, heavy neutrinos, dark sectors)

- Synergies with *hh* search programme:
  - direct (e.g. Higgs precision measurements, top studies);
  - indirect (e.g. PDF, EWK measurements)
- Theory developments include QCD to N^3LO (or N^4LO) precision calculations
- High energy and high-density measurements of heavy ion collisions
  - Nuclear DIS is extended by 3-4 orders of magnitude in x and Q^2.
  - Complementary coverage with respect to EIC (c.o.m.: 20 – 140 GeV) - highlighted in both submissions



FCC CDR Vol 1 and Vol 3, published in EPJ (2019)

FCC-eh: Short-term R&D and Impact

- Intense **High Energy electrons**:
  - Electron beam generated with two linacs → energy recovery linacs
    - **ERLs:** pioneering new high energy accelerator technologies, total power consumption of only 100 MW.
    - **PERLE Collaboration(*)** currently developing and building a 500 MeV machine
    - Several industrial applications (nuclear decommissioning, isotope production, lithography), and important possible step towards a UK FEL.
- **Detector** and **synergy** in technology:
  - detector design requires adjustment to technology developments, more thorough simulation, deeper technical inspection, studies on trigger and readout, and prototyping of critical items.
    - Low radiation level
    - Several aspects common with precision detectors for *e+e-* and *pp* (e.g. CMOS Si technology and Si-W calorimetry).

(*) ASTeC Daresbury, BINP Novosibirsk, CERN, Cockcroft Institute, Cornell University, Irene Joliot Curie Laboratory Orsay (host lab), Jefferson Laboratory, UoLiverpool

FCC-eh: Short-term R&D and Impact

- Overall programme until 2025 includes:
  - Detailed study of the relation of *ep* and *pp*, as well as *eA* with *AA* (*pA*), physics, as e.g. for BSM and Higgs, in close Collaboration with theorists;
  - Theory developments;
  - The realisation of the first phase of PERLE (injector) towards a 250 MeV electron beam at IJClab Orsay;
  - The formation of an international proto-detector Collaboration able to present the LHeC to the LHCC at CERN (*note: earlier option for e-p collider*) and to collaborate on detector technology R&D, with strong, leading UK contributions;
  - Layout of the machine-detector interface, including a mock-up of the first quadrupole, a plan for absorbers+masks, and a prototype solution of the elliptic beam pipe.

The project had been evaluated and this programme supported by the IAC (International Advisory Committee) of the LHeC/FCC-eh, see the brief IAC statement referred in document.

FCC-eh: Timeframe and resources

- Request for resources 2021-2025:

  - Support for a PhD program (6 PhD jointly supervised, with emphasis on detector development)
  - Detector development (2 FTE)
  - Physics Study (2 FTE)
  - £0.3M capital

  As outlined above, there is much synergy to be exploited with the other FCC (and HL-LHC) developments as well as in the collaboration of particle and accelerator physicists which is a remarkable advantage only few have worldwide. The accelerator development resources, especially for PERLE, are submitted independently.

The document presents also an overview of overall costs:

- Cost for the FCC-eh ERL tunnel, RF galleries and shaft cost: **300 MCHF** for a 9 km tunnel suitable for a 60 GeV beam. If the LHeC is built before the FCC, costs are lower (LHeC machine cost: 1.37 GCHF)
- **FCC-eh cost < 10% fraction of that of FCC-hh**

FCC-global: outline

- **23 institutes** – all of those in FCC-ee, hh and eh submissions, with several(most) of institutes interested in more than one option.

The recent update of the European Strategy for Particle Physics (ESPPU) identified an electron-positron Higgs factory as the highest-priority next collider and recognised the importance of R&D towards a future hadron collider of the highest achievable energy [1]. The FCC project encompasses both these goals, and indeed the ESPPU states: "*Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*"

We, as representatives of the UK experimental and theoretical High Energy Physics groups, and accelerator community, are writing to signal our enthusiasm for the FCC [2] and to indicate the possibilities for UK engagement in the areas of detector development, phenomenology and accelerator contributions. This brief document is expanded on in three parallel submissions, focused on the electron-positron (FCC-ee) [3], hadron collider (FCC-hh) [4] and electron-proton (FCC-eh) [5] opportunities.

FCC-global: overall message

- The exact nature of the FCC programme will depend on our evolving understanding of the physics landscape, and also has a dependency on developments on other high-energy collider projects outside Europe, such as the ILC in Japan.
- The immediate priority of elucidating the nature of the Higgs boson in an e+e- collider can be realised at either the ILC or the FCC-ee, which necessitates a programme of detector R&D with requirements that are largely common between the two projects. The European goal of a 100 TeV proton collider at CERN requires its own detector and accelerator studies that must begin now, and also presents opportunities for engagement with the machine challenges which should be seriously considered by UK institutes and industry. Aside from the Higgs studies, the FCC-ee also offers the exciting possibility of ultra-precise measurements of the properties of the Z and W bosons, as well as in flavour physics, that is not shared by the ILC. Finally, the option exists, with the FCC-eh, to study electron-proton collisions at 3.5 TeV concurrently with FCC-hh operation.
- All of these projects will greatly benefit from the committed involvement of the UK theory community.

References in documents

- FCC global (and hh)
  - 2020 update of the European Strategy for Particle Physics, CERN-ESU-013.
  - FCC Conceptual Design Report, vols 1-3, EPJC 79 (2019) 79, EPJC 228 (2019) 261, EPJC 228 (2019) 755.
- FCC-eh
  - CDR of LHeC: arXiv:1206.2913, published in J.Phys.G (2013)
  - LHeC at HL-LHC: arXiv:2007.14491, submitted to J.Phys.G (2020)
  - FCC CDR Vol 1 and Vol 3, see above
  - PERLE CDR: arXiv: 1705.08783, published in J.Phys.G (2018)
  - ECFA Newsletter Nr 5, 8/2020, https://cds.cern.ch/record/2729018/