FCC-hh: 100 TeV pp collider

Andy Pilkington (Manchester) *on behalf of the FCC-hh UK community*

European Strategy: reminder of previous strategy update

• 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.

**European Strategy for Particle Physics Update (2020):* https://cds.cern.ch/record/2721370/

This has been largely realised with the proposed FCC integrated programme:

- electron-positron collider (FCC-ee) followed by proton-proton collider (FCC-hh)
- mid term reports of the feasibility study available to CERN users here.
- Progress made on civil engineering, technical infrastructure, R&D plans for magnets, FCC-hh layout and injection lines.

Looking forward:

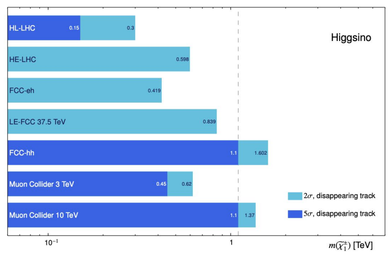
- FCC collaboration will submit FCC-ee and FCC-hh documents to the next ESPPU.
- Final report of FCC feasibility study in 2025.

Physics case for a 100 TeV pp collider

A 100 TeV pp collider will be **both a discovery and precision machine**:

- **Precision rare Higgs couplings** (*HZγ, Htt, Hγγ, Hμμ*) all measured to **factor 5-10 better** than HL-LHC or electron-positron collider; **exploration of Higgs interactions at high p_T**.
- Unique probe of the EW phase transition: (i) **Higgs self coupling measured to 3%** accuracy, (ii) access the scale of EW baryogenesis (9TeV).
- Direct search for new particles: **mass reach an order of magnitude above HL-LHC** and accessing scales indicated by indirect evidence at HL-LHC or electron-positron collider.
- Capability to reach predicted masses for WIMP **dark matter thermal relics**
- **Indirect search for new physics** via precision differential cross section measurements across a **multitude of final states** (multi-boson, multi-top, etc), at high Q^2 and far above the electroweak scale.

Collider	HL-LHC	FCC-INT
Lumi (ab^{-1})	3	30
Years	10	25
$g_{H\mu\mu}$ (%)	4.4	0.43/0.43
$g_{H\gamma\gamma}$ (%)	1.8	0.32/0.32
$g_{HZ\gamma}$ (%)	11.	0.71/0.7
g_{Htt} (%)	3.4	1.0/0.95
g_{HHH} (%)	50.	3
BR_{inv} (%)	1.9	0.024



Facilities and technological requirements

Extension of existing CERN infrastructure:

- New 91km tunnel to house FCC-hh with existing LHC/SpS acting as injectors.
- Excavation of caverns for experiments
- New roads/buildings needed for access
- All of this extensively studied for FCC-ee and detailed in the mid-term report

FCC-hh requires advances in all areas of technology: this is good, FCC-hh is a technology driver

- Accelerator requires 16 T magnets
- Extensive R&D needed for all detector systems to cope with expected rates.

“Upgrade” potential:

- High Temperature Superconductors could (i) produce 20 T magnets for (ii) higher collision energies and (ii) lower power consumption. This is low-TRL and needs longer time for R&D.
- FCC-eh: electron-proton collisions using an electron beam in energy recovery linac

Datasets, running conditions and timelines

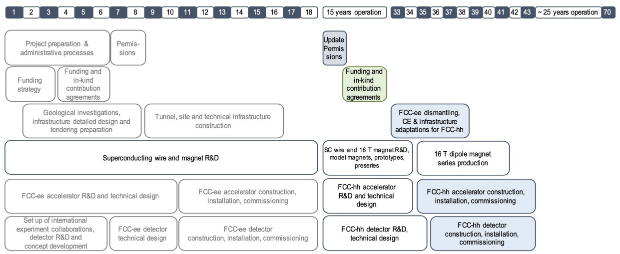
Machine target performance:

- $\sqrt{s}$ = 100 TeV (requires 16T magnets)
- L_{int} = 30/ab
- 4 interactions points (2 GPDs)
- 25 years operations, including technical stops for upgrades
- Wall power of 550-580 MW, which equates to 4 TWh/yr (c.f. HL-LHC 1.4 TWh/yr)

FCC integrated programme foresees **a timeline to first FCC-hh collisions** of 43 years.

- 10 year gap between end of FCC-ee and start of FCC-hh
- 18 years of magnet R&D (=HTS?)

Standalone FCC-hh project (see here) foresees a timeline of 23 years to first FCC-hh collisions.



Costs: financial and environmental

Financial costs, not updated from 2018 CDR (see here):

- 24 BCHF for standalone FCC-hh, 17 BCHF if reusing infrastructure from FCC-ee.
- 180 MCHF in electricity per annum (2015 electricity prices)

Environmental costs:

- Civil engineering (tunnels, shafts, caverns, surface sites): 1.17 $MtCO_2$ (eq)
- Significant efforts to reduce environmental impact studied in FCC feasibility study, i.e. reduce carbon footprint by 50%,; supply 300-400GWh/yr of generated heat to local homes; use excavated molasse for agriculture [see slides by Guy Wilkinson for FCC-ee)
- All environmental costs shared with FCC-ee if tunnel used for two colliders.

Domain	**Cost (MCHF)**	**Cost (MCHF)**
Collider and injector complex	13 600	13 600
Technical infrastructure	4400	2800
Civil engineering	6000	600
Total cost	24 000	17 000

Scenario planning: are 16T magnets a potential showstopper?

Current magnet technology:

- 8 T magnets used in LHC
- 11-12 T demonstrators already produced for HL-LHC using Nb_3Sn. These are short models
- recent Nb_3Sn setups produced with 14.5 T fields, but far from operational

What is 'feasible' post-LHC?

- 8 T magnets translate to a CoM energy of 50 TeV; 12 T translates to 72 TeV
- This means that $\sqrt{s}$ = 70 TeV is (effectively) already achievable (see these slides).
- Important note: the cost and industrial scalability of any magnet system is something that needs careful consideration. Review is ongoing in this area.

Note that physics potential largely unaffected if FCC-hh operates at $\sqrt{s}$ = 80 TeV (see e.g. here).

drafting day discussion: a fast-tracked FCC-hh might be a compelling next collider at CERN if CEPC is funded.

Dipole field [T]	c.m. energy	Comment
12	72	not far above peak field of HL-LHC Nb_3Sn quadrupoles
14	84	Nb_3Sn or HTS
17	102	HTS
20	120	HTS