Future hadron-hadron colliders

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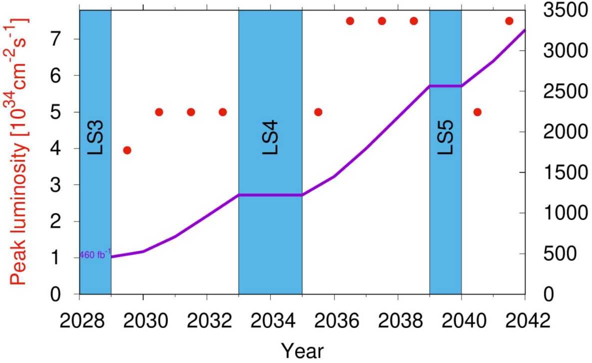
ECFA-UK European Strategy Initiative Kick-off Meeting, 1st May 2024

Recap of European Strategy 2020: HL-LHC priority



The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.

Recap of European Strategy 2020: future hadron colliders

• *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

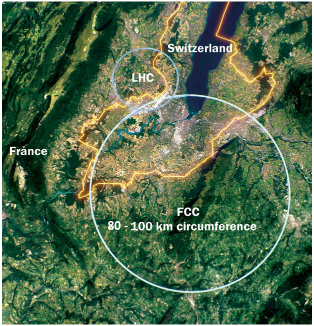
• *the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*

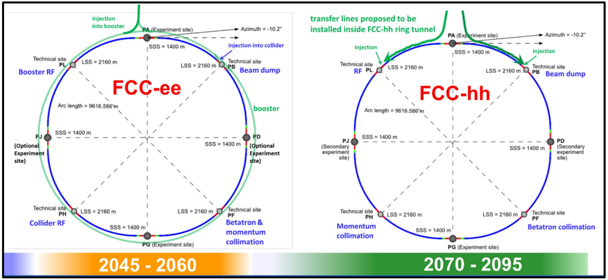
https://europeanstrategy.cern/european-strategy-for-particle-physics

The FCC integrated programme

Based on the successful LEP-LHC programmes at CERN

- complementary physics, common civil engineering and technical infrastructures
- building on, and reusing, CERN's existing infrastructure
- allows seamless continuation of collider-HEP after HL-LHC





A similar two-stage project (CEPC-SppS) is under study in China

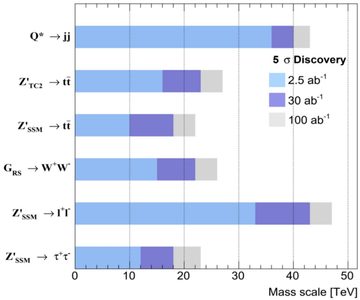
FCC-hh can run in parallel with FCC-eh (see talk by Uta)

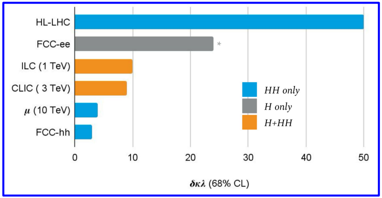
FCC FS mid-term review available here

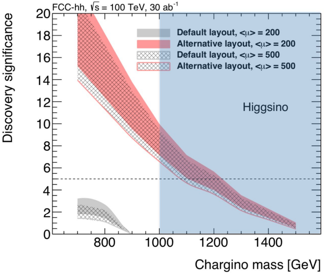
Physics motivation for 100 TeV: Higgs and search machine

Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-INT	
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30	
Years	10	3 + 1 + 4	25	
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16	ee
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19*	ee
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48	ee
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96	ee
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5	ee
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46	ee
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43	pp
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32	pp
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7	pp
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95	pp
g_{HHH} (%)	50.	44./33. 27./24.	3	pp
Γ_H (%)	SM	1.1	0.91	ee
BR_{inv} (%)	1.9	0.19	0.024	pp
BR_{EXO} (%)	SM (0.0)	1.1	1	ee

* g_{HWW} includes also ep

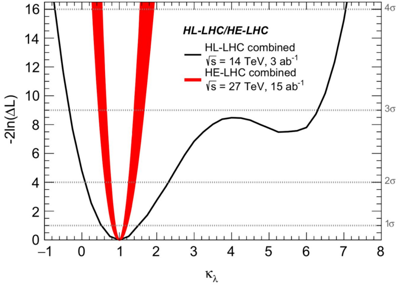






Aside: what about the HE-LHC?

- High-Energy LHC (HE-LHC) was a proposed 27 TeV proton-proton collider that re-uses the LHC tunnel and caverns.
- Extensively studied before the last ESPPU update, did not enter the recommendations.



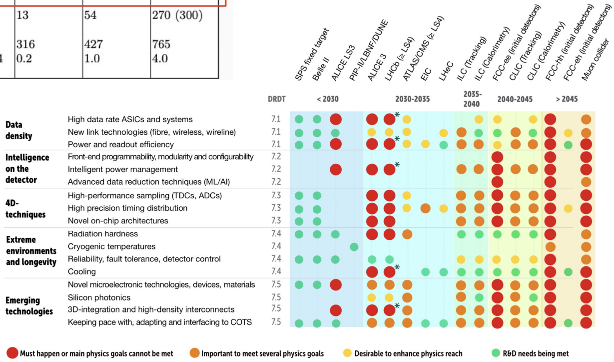
Process	HE-LHC (FCC-hh) 95%CL limit (TeV) 15 (30) ab^{-1}	5σ reach (Tev) 1 (2.5) ab^{-1}
$Z'_{SSM} \to e^+e^-/\mu^+\mu^-$	13 (40)	10 (33)
$Z'_{SSM} \to \tau^+\tau^-$	6 (14)	3 (12)
$Z'_{FA} \to \mu^+\mu^-$	4 (25)	– (10)
$Z'_{TC} \to t\bar{t}$	10 (28)	6 (16)
$G_{RS} \to WW$	8 (28)	5 (15)
$Q^* \to jj$	14 (43)	10 (36)

Experimental challenges for a 100TeV hadron collider

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\,cm^{-2}\,s^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10 600
Goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel} [340]	mb	80	80	86	103
σ_{tot} [340]	mb	108	108	120	150
BC rate	MHz	31.6	31.0	31.6	32.5
Peak pp collision rate	GHz	0.8	4	14	31
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950
Total number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm, est. (FLUKA)	$GHz\,cm^{-2}$	0.1	0.7	2.7	8.4 (10)
1 MeV-neq fluence at 2.5 cm, est. (FLUKA)	$10^{16}\,cm^{-2}$	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm, est. (FLUKA)	MGy	1.3	13	54	270 (300)
$dE/d\eta\|_{\eta=5}$ [340]	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0

Unprecedented particle flux and radiation levels = a technology driver

Detector concepts have existed for some time, but exact requirements for physics programme still being investigated.



UK physics analysis efforts for FCC-hh

The UKs ongoing studies for the FCC-hh physics include:

- Higgs self-coupling studies (Liverpool, UCL)
- CP violation in Higgs interactions (Manchester, Edinburgh, Glasgow, Cambridge)
- Boosted analysis techniques in ZH, H->bb (UCL)
- Flavour-tagging algorithms using GNN (UCL)
- Additional scalars in inert 2HDM models (Imperial)

It is widely recognised that the physics potential of FCC-hh still needs to be properly explored:

- Higgs physics: super-rare decays, first generation couplings
- interplay with (confirmation of) any anomalies uncovered at FCC-ee
- The role of precision EW measurements
- Opportunities with non-general-purpose experiments (flavour, BSM)

Excellent opportunities for UK involvement across all these areas in the coming years

Preparing UK input to the next ESPPU: hadron collider

Ongoing UK studies for FCC-hh will aim to be part of the input to the FCC feasibility study, which itself will be input to the ESPPU.

- studies need to be presented within FCC-PED over the summer period.
- need to be very advanced (nearly final) by September
- documented as an FCC Note by EoY

To inform the UK input to ESPPU, need:

- full review of Higgs, EW, QCD, BSM and flavour physics case for FCC-hh
- determine the interplay between FCC-hh and muon collider, i.e the pros and cons of each.
- contact me (for FCC-hh) if you want to help with this

Looking forward to the September meeting…..

From the 10pCM collider perspective, the UK will need to make statements on:

- The importance of the HL-LHC programme.
- The FCC integrated programme and the level of UK support for it.
- The CEPC-SppS version of the same integrated programme.
- UK priorities if another electron-positron machine (ILC, CEPC, CEPC-SppS) is fast-tracked elsewhere.
- The interplay/complementarity/competition between FCC-hh and a muon collider