The Future Circular Collider

Uta Klein (Liverpool), Andy Pilkington (Manchester), Guy Wilkinson (Oxford)

PPAP meeting, Manchester, 22 September 2022

European Strategy: high priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- ***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/

Higgs physics at a future circular collider

$$\mathscr{L}_{\mathrm{SM}} = \cdots + |D_\mu \phi|^2 + \psi_i y_{ij} \psi_j \phi - V(\phi)$$

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
$g_{\mathrm{H}\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46	ee
$g_{\mathrm{H}\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43	pp
$g_{\mathrm{H}\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32	pp
$g_{\mathrm{HZ}\gamma}$ (%)	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
$\mathrm{BR}_{\mathrm{inv}}$ (%)	1.9	0.19	0.024	pp
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM (0.0)	1.1	1	ee

* g_{HWW} includes also ep

Factor 5-20 improvement in precision Higgs coupling measurements

Higgs physics at a future circular collider

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BR$_{\rm inv}$ (%)	1.9	0.19	0.024	pp
BR$_{\rm EXO}$ (%)	SM (0.0)	1.1	1	ee

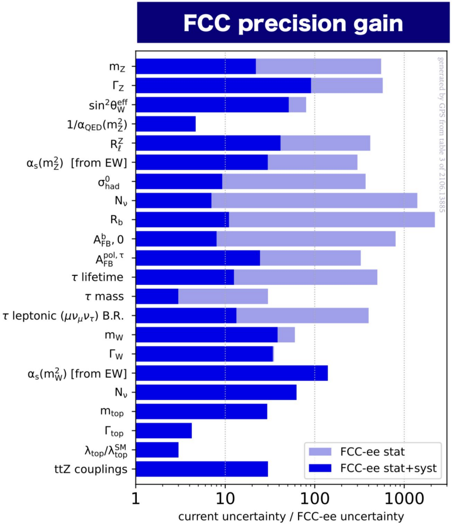
* $g_{\rm HWW}$ includes also ep

FCC-ee compared to FCC-eh

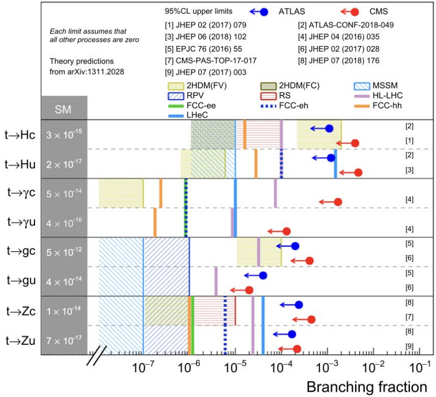
Collider	FCC-ee	FCC-eh
Luminosity (ab^{-1})	+1.5 @ 365 GeV	2
Years	3+4	20
$\delta\Gamma_{\rm H}/\Gamma_{\rm H}$ (%)	**1.3**	SM
$\delta g_{\rm HZZ}/g_{\rm HZZ}$ (%)	**0.17**	0.43
$\delta g_{\rm HWW}/g_{\rm HWW}$ (%)	**0.43**	0.26
$\delta g_{\rm Hbb}/g_{\rm Hbb}$ (%)	**0.61**	0.74
$\delta g_{\rm Hcc}/g_{\rm Hcc}$ (%)	**1.21**	1.35
$\delta g_{\rm Hgg}/g_{\rm Hgg}$ (%)	**1.01**	1.17
$\delta g_{\rm H\tau\tau}/g_{\rm H\tau\tau}$ (%)	**0.74**	1.10
$\delta g_{\rm H\mu\mu}/g_{\rm H\mu\mu}$ (%)	**9.0**	n.a.
$\delta g_{\rm H\gamma\gamma}/g_{\rm H\gamma\gamma}$ (%)	**3.9**	2.3
$\delta g_{\rm Htt}/g_{\rm Htt}$ (%)	—	1.7
BR$_{\rm EXO}$ (%)	$<$ **1.0**	n.a.

Factor 5-20 improvement in precision Higgs coupling measurements

Precision electroweak and top physics



Improvement in sensitivity to Top FCNC

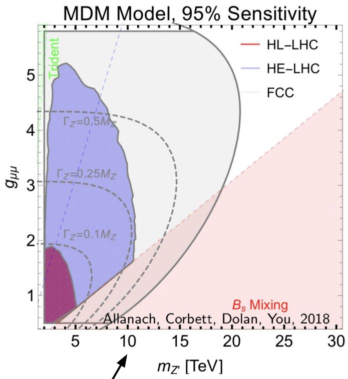


Orders of magnitude improvement in (i) precision and (ii) sensitivity to anomalous interactions

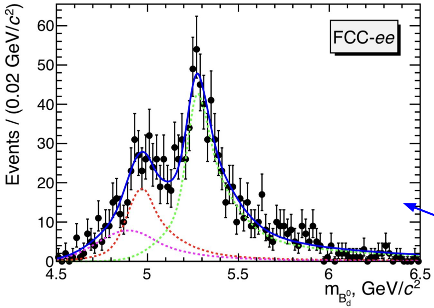
Flavour opportunities

15x more B-pairs at FCC-ee than at Belle-II
……..physics case obvious

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)



FCC-hh for the particles that would explain the current flavour anomalies



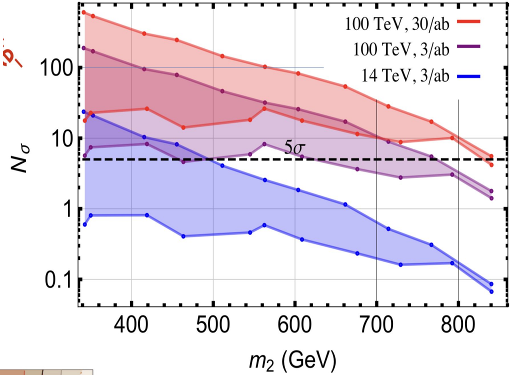
FCC-ee allows studies of new channels for the first time, i.e. B-> K* tau tau .

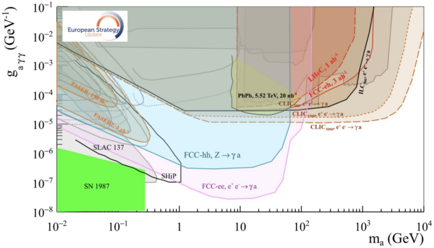
Searches for new particles

FCC is a discovery machine

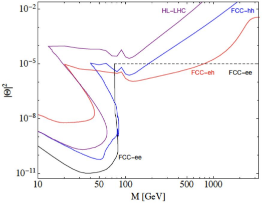
Improvement in sensitivity for general BSM models that have heavy particles (with $m_2 > 2m_1$).

Discovery potential greatly improved for a wide range of specific BSM models
- strengths across the ee, ep and pp programme





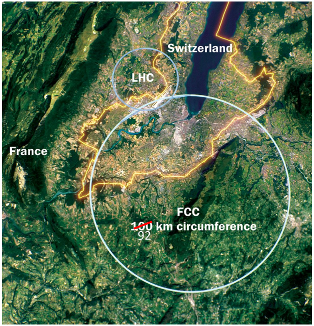
RH neutrinos

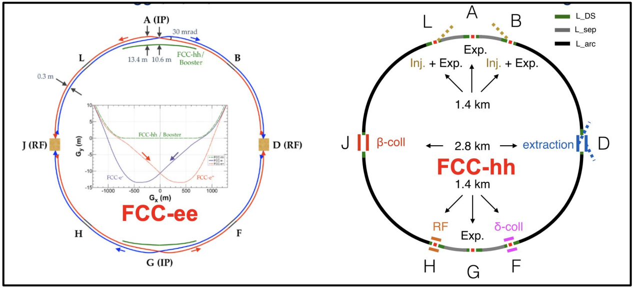


The FCC integrated programme

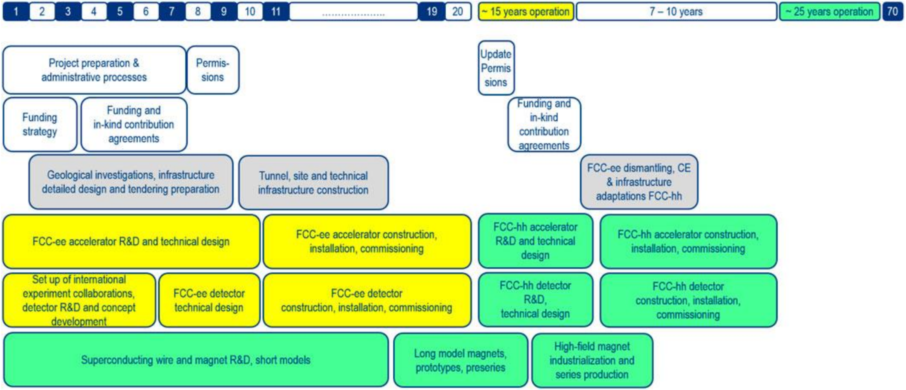
Based on the successful LEP-LHC programmes at CERN

- 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



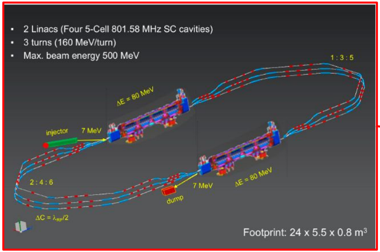


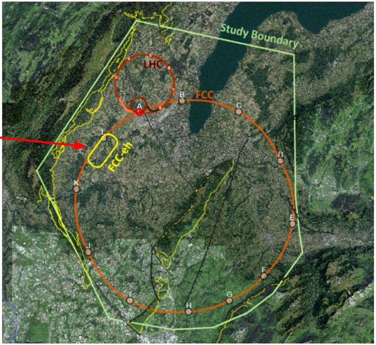
The FCC integrated programme (II)



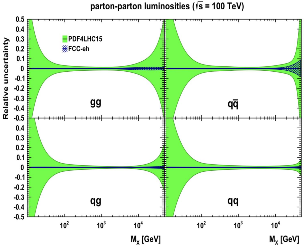
Integrated programme: https://www.frontiersin.org/articles/10.3389/fphy.2022.888078/full

The FCC integrated programme: what about eh mode?





FCC-eh:
- requires Energy Recovery Linac (ERL) to provide electron beam with E = 60GeV
- similar proposal to LHeC (higher COM)
- option included in original FCC-hh CDR and further expanded in a CDR update



Can run FCC-eh and FCC-hh concurrently.

The FCC Feasibility Study

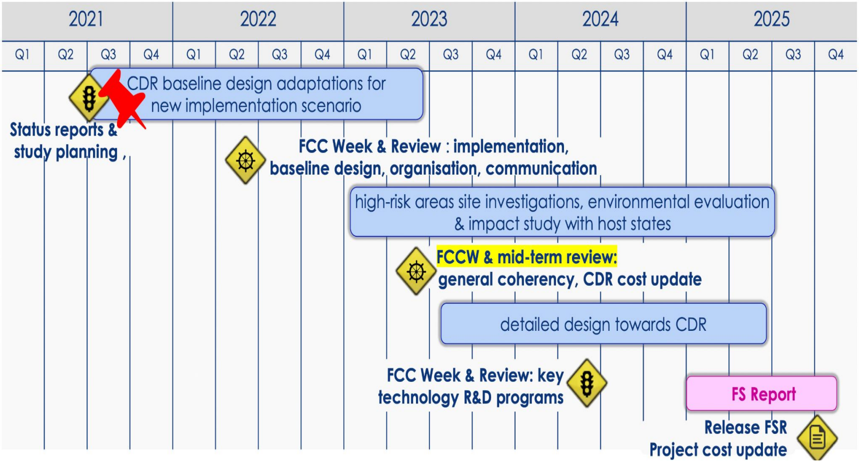
High-level objectives:

- tunnel feasibility (geological, technical, environmental)
- optimisation of ring layout and associated infrastructure
- optimise design of colliders, including R&D to develop key technologies
- develop sustainable operational model (inc human/financial resources and environmental considerations)
- develop consolidated cost estimate and future funding models
- identify resources from outside CERNs budget for first stage of future project
- consolidate physics case and detector concepts

Organisational Structure of the FCC Feasibility Study:
http://cds.cern.ch/record/2774006/files/English.pdf

***Main Deliverables and Timeline of the FCC Feasibility Study*:**
http://cds.cern.ch/record/2774007/files/English.pdf

The FCC Feasibility Study (II)



The FCC Feasibility Study: its impact

Statements of CERN DG in Paris FCC week (June ‘22)

“ • If project approved before end of decade → construction can start beginning of 2030s
• FCC-ee operation ~2045-2060
• FCC-hh operation ~2070-2090++ ”

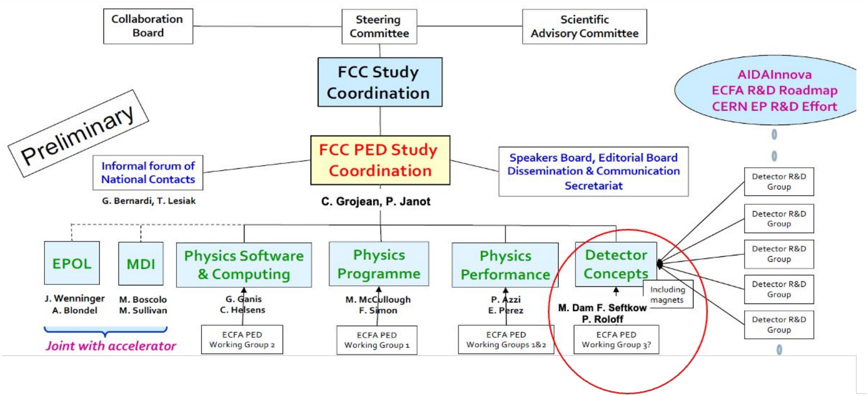
“ Substantial resources (~5 BCHF) needed from outside CERN’s budget… (contributions from non-Member States, special contributions from Host States and other Member States; ongoing discussion with European Commission; private funding?) → discussions started. ”

Cost category	[MCHF]	%
Civil engineering	5,400	50
Technical infrastructure	2,000	18
Accelerator	3,300	30
Detector (CERN contrib.)	200	2
Total cost (2018 prices)	10,900	100

Reminder of FCC-ee costs (Z, WW and HZ working points, and for two IP configuration)

FCC: physics and detector studies (a UK viewpoint)

Structure covers all FCC options, in principle…….
- strong focus thus far on FCC-ee
- implies opportunity for UK FCC-hh/eh aficionados to lead PED studies internationally

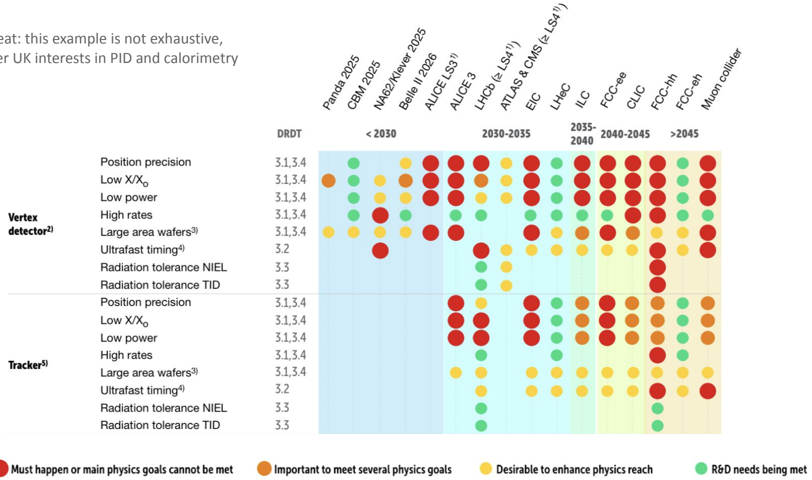


'Detector concepts' group, which will evaluate possible detector designs against benchmark physics processes, had a kick-off meeting 22-23 June.

UK community needs to engage in order to shape these designs !

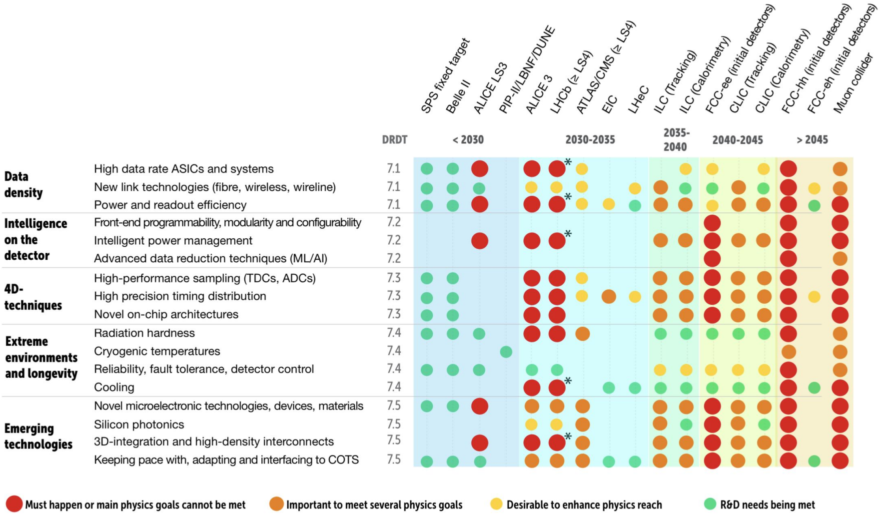
FCC: the detector challenges (e.g tracking and vertexing)

Caveat: this example is not exhaustive,
other UK interests in PID and calorimetry



UK expertise and leadership for HL-LHC in exactly these areas:
- but to lead these R&D for FCC requires new resources, such as the proposed Strategic R&D fund

FCC: the detector electronics & readout challenges



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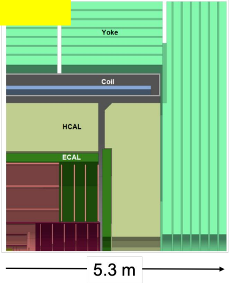
FCC-ee: detector concepts

CLD



- Well established design ('CLIC-like detector');
- Si vertex detector + tracker;
- CALICE-like calorimeter;
- Large coil outside calorimeters;
- Scope for optimisation, and for continuous beam operation;
- No significant PID capabilities, but possibilities under consideration (10 ps timing)

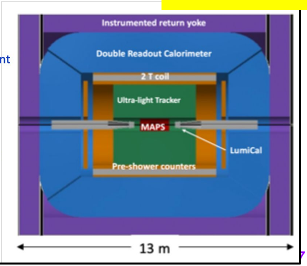
Three detector concepts for which simulations exist and ongoing detector R&D:
- far from set in stone, can easily change.
- Four IPs (instead of two in CDR) are under serious consideration.
- UK can play a major role in the R&D that enables the final designs.

IDEA

- (D)MAPS vertex detector (à la ALICE 3 ?);
- Drift chamber tracker;
- Silicon wrapper with time-of-flight (LGAD);
- Thin solenoid sharing ECAL cryostat;
- Scintillator + (return yoke) iron HCAL;
- Muon tagger.

LAr detector

- MAPS vertex detector;
- Ultra light drift chamber, intended to have significant PID capabilities through cluster counting;
- Compact coil;
- Dual readout calorimeter, possibly augmented by crystal ECAL within coil;
- Very active community, with prototype designs & test beams.



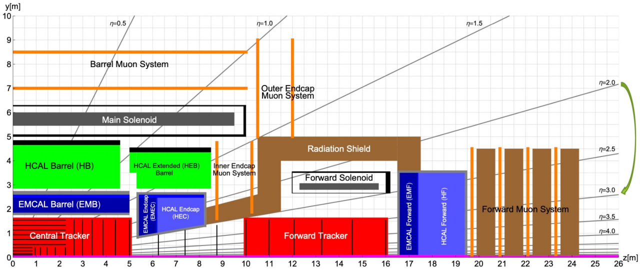
FCC-hh: experimental challenges

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)	$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	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)	$\mathrm{GHz\,cm}^{-2}$	0.1	0.7	2.7	8.4 (10)
1 MeV-neq fluence at 2.5 cm, est. (FLUKA)	$10^{16}\,\mathrm{cm}^{-2}$	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)
$\mathrm{d}E/\mathrm{d}\eta\|_{\eta=5}$ [340]	GeV	316	316	427	765
$\mathrm{d}P/\mathrm{d}\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0

Unprecedented particle flux and radiation levels

Detector concepts exist, but exact requirements for physics still under investigation.

- opportunity for UK to lead those studies
- interest declared at UK workshop in July: *https://indico.cern.ch/event/1147914/*



FCC-eh: the need for accelerator (ERL) R&D

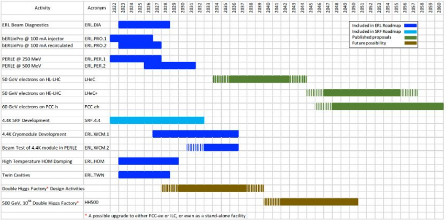


Fig. 6.12: Long-term vision for the ERL Roadmap showing how the activities in the next five to ten years lead to multiple options for future HEP Colliders.

5-10 years R&D needed for Energy Recovery Linac (ERL):
- see accelerator roadmap

UK interest and leadership of this internationally.

Series of workshops, the next one is 26th-28th October (register now!)

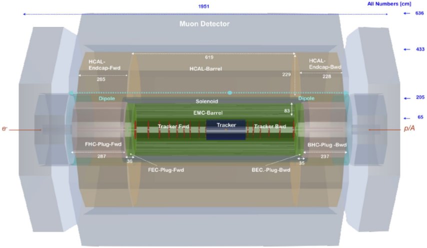
Detector concepts also developed.

Energy-recovery linacs

Panel members: M. Klein[i,∇] (Chair), A. Hutton[x] (Co-Chair), D. Angal-Kalinin[qq], K. Aulenbacher[rr], A. Bogacz[x], G. Hoffstaetter[ss,jj], E. Jensen[a], W. Kaabi[c], D. Kayran[jj], J. Knobloch[tt,uu], B. Kuske[uu], F. Marhauser[x], N. Pietralla[vv], O. Tanaka[y], C. Vaccarezza[f], N. Vinokurov[ww], P. Williams[qq], F. Zimmermann[a]

Associated members: M. Arnold[vv], M. Bruker[x], G. Burt[d], P. Evtushenko[xx], J. Kühn[uu], B. Militsyn[qq], A. Neumann[uu], B. Rimmer[x]

Sub-Panel on CERC and ERLC: A. Hutton[x] (Chair), C. Adolphsen[w], O. Brüning[a], R. Brinkmann[e], M. Klein[i], S. Nagaitsev[nn], P. Williams[qq], A. Yamamoto[y], K. Yokoya[y], F. Zimmermann[a]



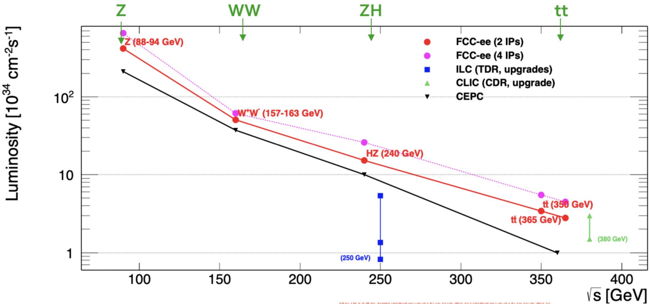
FCC-ee vs other e^+e^- colliders

The detector requirements of circular and linear e^+e^- projects have high degree of commonality

- work for both can be largely pursued in same R&D programme.
- Inevitably, some differences, *e.g.*:
  - Continuous beams at FCC-ee means power pulsing is not an option
  - Enormous sample sizes at FCC-ee TeraZ means challenges for detector/lumi, etc

Commonalities in detector R&D well appreciated by UK circular and linear communities.

- Discussions took place in FCC-ee UK meeting in July, and silicon meeting in September.
- Again: the community welcome the initiative for 'strategic R&D' !



14 year FCC-ee programme

150 ab^{-1} at Z pole

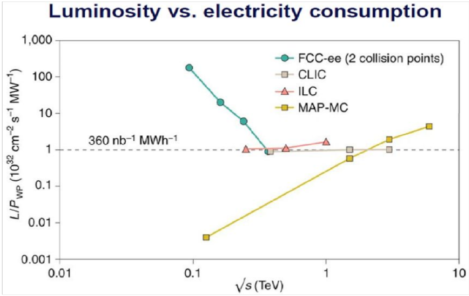
10 ab^{-1} at WW threshold

5 ab^{-1} at HZ threshold

0.2 ab^{-1} at top-antitop threshold

1.5 ab^{-1} at c.o.m of 365 GeV

FCC sustainability



Higgs factory	CLIC	ILC	C^3	CEPC	FCC-ee*
Running time as a Higgs factory (year)	8	11.5	11.5	10	3
Total number of Higgs bosons produced (10^6)	0.25	0.5	0.5	4	1
Energy consumption per Higgs boson (MWh)	14	17	18	4.1	**3.0**

* assumes 2 IPs; with 4 IPs consumption drops to 1.8 MWh / Higgs

[arXiv:2208.10466]

Summary

- The physics potential of the integrated FCC programme is enormous

- Over the next 3 years, the FCC feasibility study will take major steps towards establishing the FCC as a future project at CERN. A decision toward FCC could be taken by the end of the decade.

- Important detector R&D (and physics studies informing detector R&D) needs to be done now:
  - The UK should take a leading role in this
  - Strategic R&D funding is crucial in this regard

- You can get involved in UK activities for FCC by contacting:
  - Guy Wilkinson (FCC-ee)
  - Uta Klein (FCC-eh)
  - Andy Pilkington (FCC-hh)

Backup: the CEPC

Circular Electron Positron Collider (CEPC) is a Chinese project, whose main characteristics closely resemble those of FCC-ee. Indeed, over time, it has evolved closer & closer to FCC-ee design.

Operation mode		ZH	Z	W^+W^-	tt
$\sqrt{s}$ [GeV]		~240	~91.2	158-172	~360
L / IP [$\times 10^{34}$ $cm^{-2}s^{-1}$]	CDR (2018)	3	32	10	
	Latest	5.0	115	16	0.5

Accelerator TDR about to be complete, to be followed by two-year accelerator EDR phase.

Its best-case timeline places it ~10 years ahead of FCC-ee, with operation beginning in mid 2040s, but many uncertainties.

Watch closely ! Most activities directed at FCC-ee, equally valid for CEPC, although if timescales are indeed different (?), this would have implications for scope of R&D.

Already some significant UK interest.

Ideal Accelerator Roadmap

2016-2021	MOST phase-1 accelerator R&D
2018-2023	MOST phase-2 accelerator R&D
2023-2028	MOST phase-3 accelerator R&D
2022-2023	Accelerator TDR completion
2023-2025	Site selection, engineering design, prototyping and industrialization
2026-2034	Construction and Installation

Ideal Detector Roadmap

2016-2021	MOST phase-1 detector R&D
2018-2023	MOST phase-2 detector R&D
2023-2028	MOST phase-3 detector R&D
Now -2024	Seek collaboration, detector R&D
2025-2026	Prepare international collaborations
2027-2028	Detector TDR completed
2028-2034	Detector construction
2033-2034	Installation

For summary see Xinchou Lou presentation at FCC Week 2022, Paris.