Input from KTH+SU on questions 3a-3f

C. Clément (SU) on behalf of

particle physics at SU and KTH

European Strategy for Particle Physics - Swedish Town Hall Meeting - January 9th 2025

3) Questions to be considered by countries/regions when forming and submitting their "national input" to the ESPP:

a) Which is the preferred next major/flagship collider project for CERN?

Answer: FCC integrated programme (FCC-ee + FCC-hh (and FCC-eh?))

Pros:

- Technical feasibility for ee-state already established for FCC-ee
- Higher long-term potential
- Higher luminosity than linear colliders
- More experiments
- hh-stage drives accelerator development
- HH measurements at FCC-hh

Cons: ee-stage expensive

3) Questions to be considered by countries/regions when forming and submitting their “national input” to the ESPP:

a) Which is the preferred next major/flagship collider project for CERN?

Answer: FCC integrated programme (FCC-ee + FCC-hh (and FCC-eh?))

What about CLIC then?

- Seems cheaper
- Similar physics reach to FCC-ee
- Drives accelerator development
- More technical risk? leading to schedule and cost risks.
- What do we do after? no long-term program?

3b) What are the most important elements in the response to 3a)?

i) **Physics potential**

ii) **Long-term perspective**

iii) Financial and human resources: requirements and effect on other projects

iv) **Timing (but less so than the other two)**

v) Careers and training

vi) Sustainability

3c) Should CERN/Europe proceed with the preferred option set out in 3a) or should alternative options be considered:

i) if Japan proceeds with the ILC in a timely way?

In this scenario we would recommend an update to the ESPP depending on the physics reach of ILC (which CoM energy etc). CERN could push directly for FCC-hh.

ii) if China proceeds with the CEPC on the announced timescale?

Yes CERN should proceed with FCC-ee anyway.

iii) if the US proceeds with a muon collider?

Yes proceed with FCC-ee. However in the unlikely scenario that the muon collider can be built on the same timescale as FCC-ee, revist the ESPP

iv) if there are major new (unexpected) results from the HL-LHC or other HEP experiments?

Would then need to update the ESPP to make sure we choose the best follow-up machine given the observed new physics (select beam type + Ecom).

3d) Beyond the preferred option in 3a), what other accelerator R&D topics (e.g. highfield magnets, RF technology, alternative accelerators/colliders) should be pursued in parallel?

Answer: plasma-wakefield acceleration (but of course also crucial that CERN keep a general accelerator R&D program). We also think detector R&D should be a high priority part of the program.

3e) What is the prioritised list of alternative options if the preferred option set out in 3a) is not feasible (due to cost, timing, international developments, or for other reasons)?

Answer: FCC integrated programme (3a) > CLIC > HE-LHC

3f) What are the most important elements in the response to 3e)? (The set of considerations in 3b should be used).

Answer: The field needs a Higgs factory and we prefer it to be at CERN. Not so many options except for FCC and CLIC.

Project [Refs]	Approval date	Start constction	Cost	Run	Operations	Operation/lumi	Int Luminosity	Comments (1)
FCC-ee [FCC1]	Proj. 2027/28	2032	17 BCHF over 15 years	Z-pole	2045-2060 ~4 years	$5\ 10^{12}\ Z^0$	17 ab^{-1} /IP/y	Now considering 4 expts. - 90km
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CLIC 380 [CLIC1,CLIC2, CLIC3]	Proj. 2028	~2030 [CLIC1]	6 BCHF		2037-45(??)	8 years	1.5 ab^{-1}	11km 2 push/pull expts
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CLIC 3TeV (?)			+7 BCHF (tot18)		2056-64	8 years	5 ab^{-1}	50km
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CEPC [CEPC1]	Gov ~2025 EDR ~2027	2028	5 B$	H(240)	2036-45 (45) ~10(7) years	O(10^6)		2 experiments one reserved fro chinese institutions (construction 2026-2035 bbly shifted by 2 years compare [CEPC1] and [CEPC2])
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				tt(360)	2050-54 ~5y	"upgradable"		
SPPC	R&D till 2035	2045-50			2050? 10-15y		30 ab^{-1}	B=20T E=125TeV [CEPC2]

FCC integrated programme –ee & -hh

According to [FCC1] a **Feasibility Study Report to be released by March 2025**

FCC-ee dataset

- Run at $\sqrt{s} = 91.2$ GeV — 5 10^{12} Z^0
- Run at $\sqrt{s} \sim 240$ GeV — 10^6 Higgs bosons
- Run at $\sqrt{s} = 160$ GeV — 10^8 WW pairs
- Run at $\sqrt{s} = 350 - 365$ GeV — 10^6 ttbar pairs

Improvement accuracy of their interactions over LHC by at least one order of magnitude.
Sensitivity to rare processes at low mass by several order of magnitudes.
Sensitivity to ALP, Dark Matter...

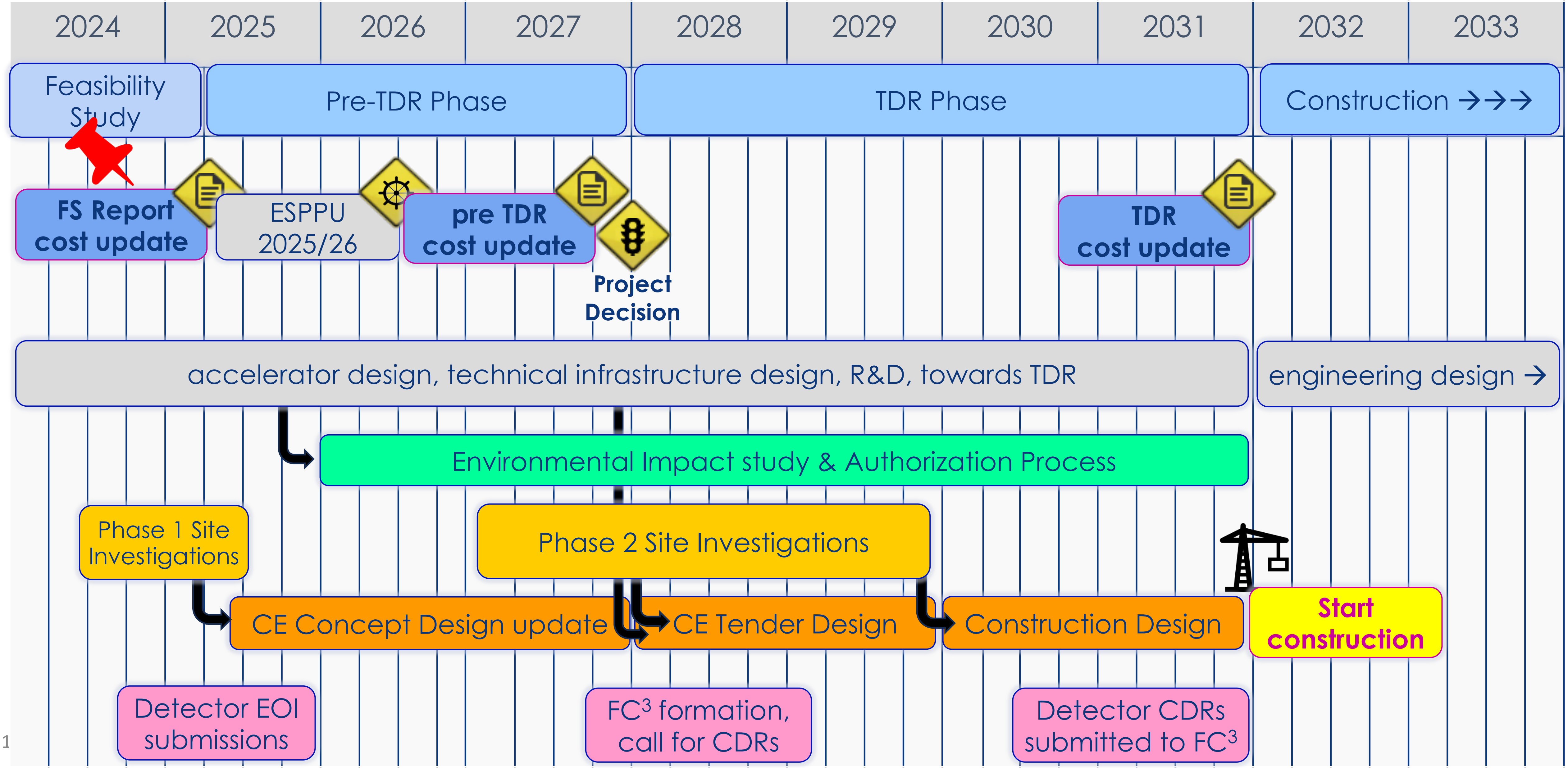
FCC-hh dataset

pp at $\sqrt{s} \sim 100$ TeV L=20 ab^{-1} in 15 years
PbPb at $\sqrt{s_{NN}} \sim 39$ TeV
ep $\sqrt{s_{ep}} \sim 3.5$ TeV

Hadron colliders are typically the discovery machines.

FCC Expected time line till start of construction

Source [FCC1]
=> Start construction **2032**.



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CLIC Timescales

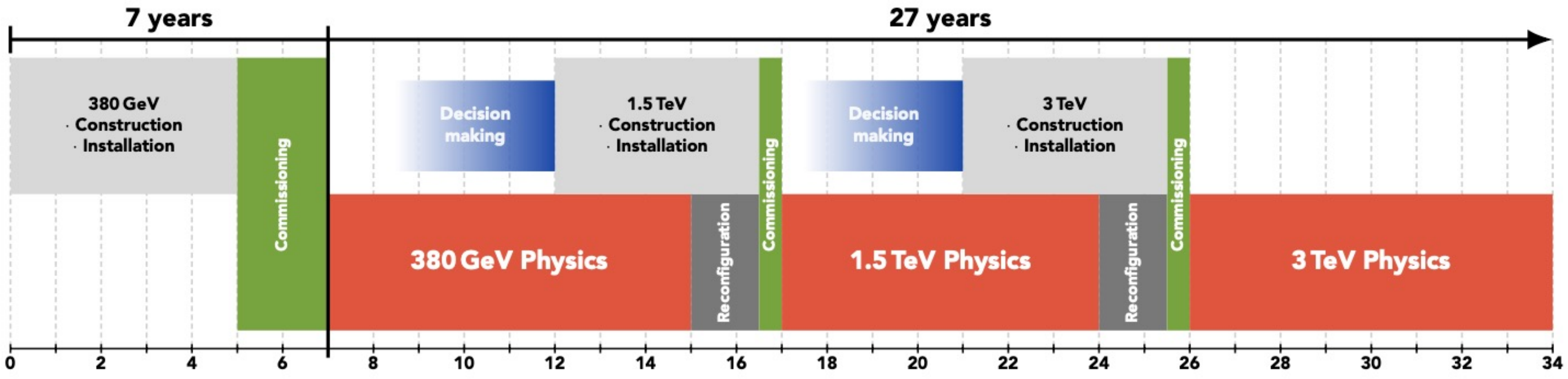
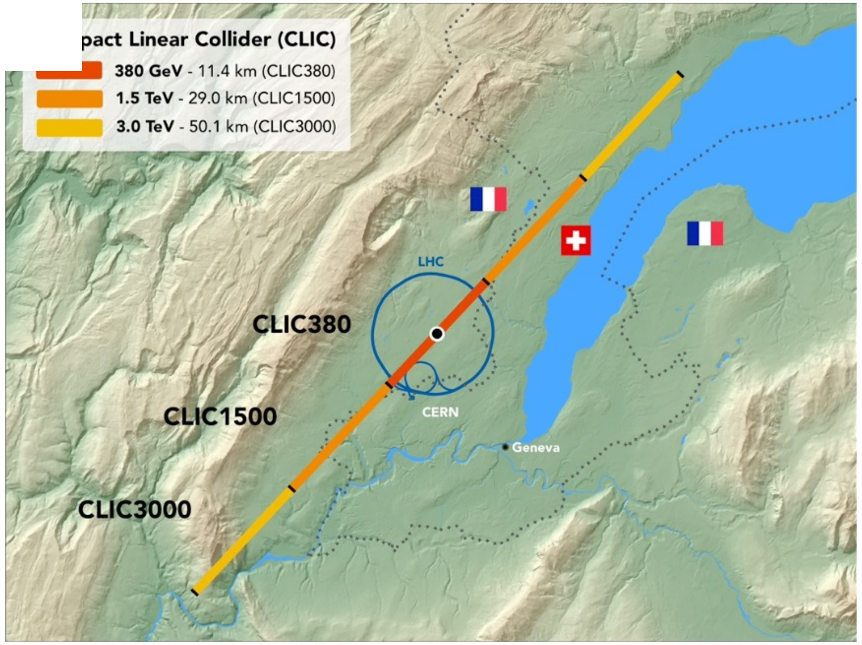


Fig. 4.6: Technology-driven CLIC schedule, showing the construction and commissioning period and the three stages for data taking. The time needed for reconfiguration (connection, hardware commissioning) between the stages is also indicated. (image credit: CLIC)

[CLIC3]O. Brunner et al. *The CLIC project Snowmass 21*
https://arxiv.org/abs/2203.09186

[CLIC1]
" Project (tunnel) construction can start in ~ 2030. "



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CLIC cost estimates

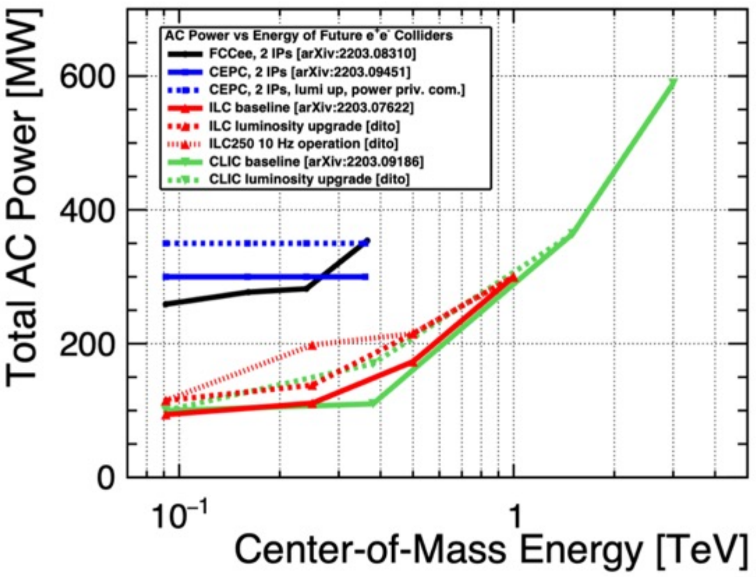
[CLIC2] Steinar Stapnes – Talk presented at **International Workshop on Future Linear Colliders, LCWS2024, Tokyo July 2024**
https://agenda.linearcollider.org/event/10134/timetable/?view=lcc#25-clic-status

CLIC 380 GeV (5.9/7.3)±1.7 BCH (Drivebeam vs Klystron design)
CLIC 1.5 TeV +5.1 BCH
CLIC 3 TeV +7.3 BCH
Site length ranging from 11 to 50 km.

Increased luminosity with energy, e.g. 1-3 x 10^{34} $cm^{-2}s^{-1}$ for Higgs factories at 250 GeV, 6 x 10^{34} at 3 TeV

Higher energies "natural" – 3 TeV studied (for CLIC), but many TeVs challenging:

- Power proportional to luminosity
- Reach up to 50km
- Higher energy means smaller beams and increasingly important beam-beam effects



A. Blondel, C. Grojean, P. Janot, G. Wilkinson
[arXiv:2412.13130v1 [hep-ph]](arXiv:2412.13130v1 [hep-ph])

"For the same reason [energy consumption] as the third CLIC stage [3 TeV] was recently abandoned"

and the paper quotes [CLIC1]
however not really clear from reading that reference.

[CLIC1] S. Stapnes. Linear colliders, towards the ESPP update. Presentation at the 3rd ECFA workshop on Higgs, top and Electroweak factories, Paris, 9–11 Oct 2024,
https://indico.in2p3.fr/event/32629/timetable/?view=standard#21-linear-colliders-recent-upd

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Old estimates!

[ILC1] The ILC TDR Vol1 (2013) linearcollider.org/files/images/pdf/Executive%20Summary.pdf

[ILC2] **The International Linear Collider Machine Staging Report 2017** **https://arxiv.org/abs/1711.00568**

[ILC3] 5 September 2024 - IDT-EB-2024-001 ILC Cost-update - External Review - ILC International Development Team Executive Board

+ studies for ILC at CERN

ILC Runs

[ILC4]

	91 GeV	250 GeV	350 GeV	500 GeV	1000 GeV
$\int \mathcal{L}$ (ab^{-1})	0.1	2	0.2	4	8
duration (yr)	1.5	11	0.75	9	10
beam polarization (e^-/e^+; %)	80/30	80/30	80/30	80/30	80/20
(−, -+, +-, ++) (%)	(10,40,40,10)	(5,45,45,5)	(5,68,22,5)	(10,40,40,10)	(10,40,40,10)
δ_{ISR} (%)	10.8	11.7	12.0	12.4	13.0
δ_{BS} (%)	0.16	2.6	1.9	4.5	10.5

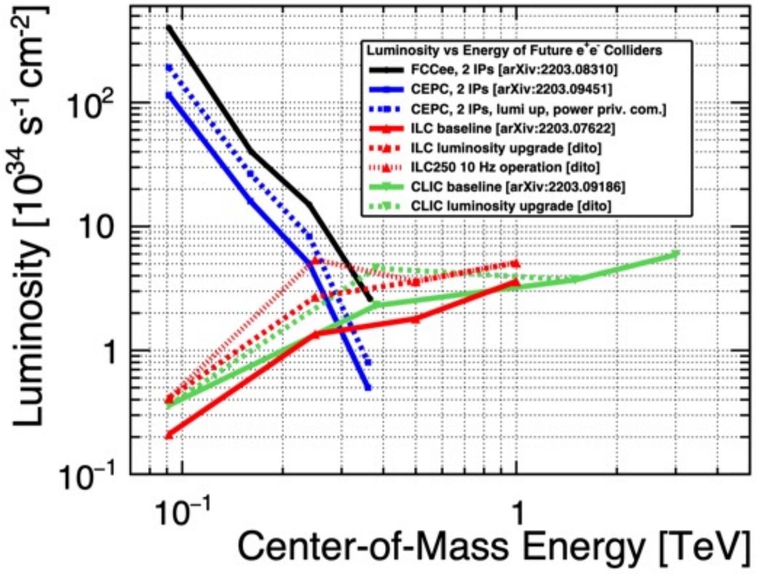
Table 5.1: Parameters of the ILC stages most relevant for physics studies. The values given here are those actually used for the results to be quoted in this report. The fourth line gives the fraction of the total running time spent in each of the four possible beam polarization orientations. The fifth and sixth lines give the average energy loss in the electron or positron energy spectrum due to initial state radiation and beamstrahlung, respectively.

Compare sensitivity in the Higgs sector [Phys1]

Table 2: Precision reach (in percentage) on effective couplings from a SMEFT global fit of the Higgs measurements in the first stage of FCC-ee (3 years), CLIC (8 years) and ILC (15 years). The results from the free-Γ_H fit, scaled from Ref. [11], are shown.

Precision (%) on Higgs coupling to	$FCC\text{-}ee_{240}$	$CLIC_{380}$	ILC_{250}
b	0.45	0.90	0.83
c	0.95	3.51	1.8
τ	0.46	1.14	0.87
Z	0.21	0.46	0.37
W	0.21	0.46	0.37

(another picture stolen from S. Stapnes)



FCC-ee achieves higher precision in a much shorter time (driven by the luminosity).

Table 5: Precision reach (in percentage) on effective couplings from a SMEFT global fit of the Higgs measurements after the planned second stages of FCC-ee (365 GeV), CLIC (1.5 TeV) and ILC (500 GeV), i.e., after 8, 15 and 28 years of operation, respectively. The results from the free-Γ_H fit, scaled from Ref. [11], are shown.

Precision (%) on coupling to	$\text{FCC-ee}_{240+365}$	$\text{CLIC}_{380+1500}$	$\text{ILC}_{250+500}$
b	0.40	0.56	0.56
c	0.89	1.81	1.2
τ	0.42	0.89	0.63
Z	0.17	0.36	0.26
W	0.17	0.37	0.26

Ealier studies from 2020
(J. De Blas et al. JHEP 01 (2020) 139
shows more similar performance
New here: 4 IP at FCC-ee
do not consider the CLIC3000

These studies indicate that *when considered as pure Higgs factories,* FCC-ee overperforms CLIC and ILC.

"For the precise measurement of the many Higgs boson couplings that require the production of billions of Higgs bosons (such as Hγγ, HZγ, Hμμ, or HHH), the combination of FCC-ee and FCC-hh is order of magnitude better than what linear colliders can ever do"

Higgs-self coupling

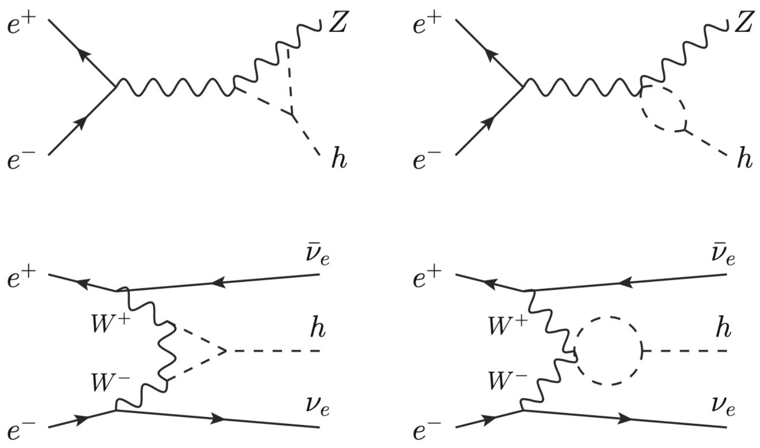
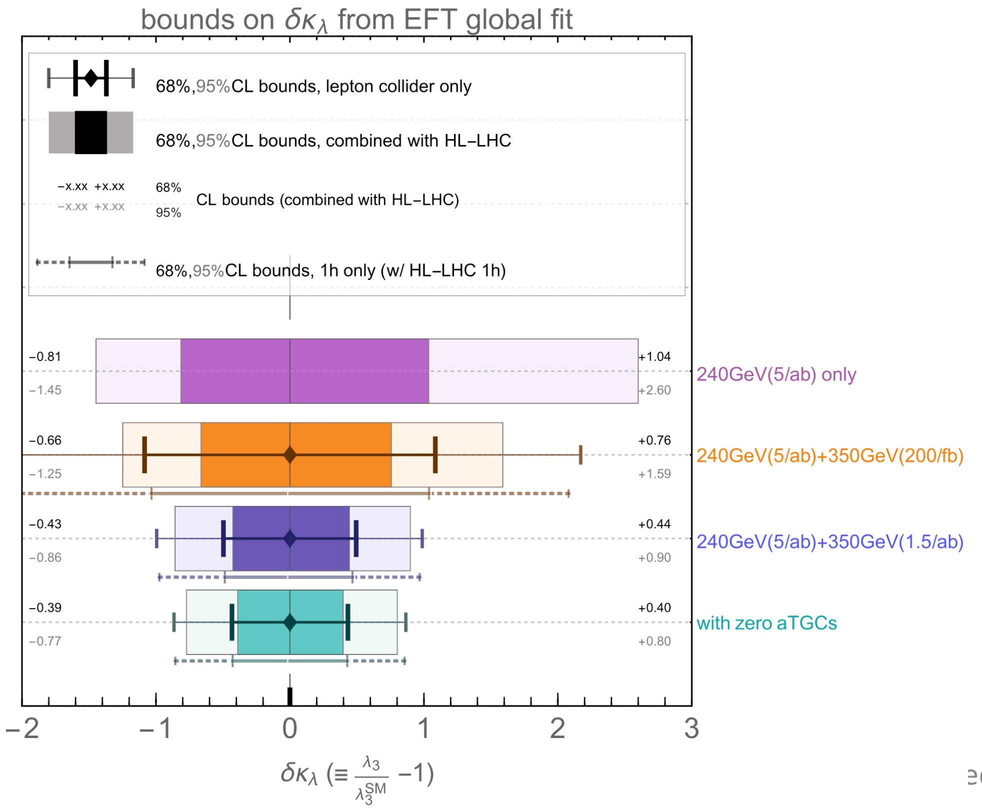


Fig. 10.2 From Ref. [288], sample Feynman diagrams illustrating the effects of the Higgs trilinear self-coupling on single Higgs process at next-to-leading order

Fig. 10.3 Indirect measurements of the Higgs self-coupling at FCC-ee combining runs at different energies



Better sensitivity at higher energy ILC 1TeV CLIC 3 TeV due to ability to produce HH directly

Snowmass21

Precision on λ parameter:

HL-LHC:	$\pm 50\%$
ILC (1 TeV):	$\pm 10\%$
CLIC (3 TeV):	$\pm(7-10)\%$
FCC-ee:	$\pm 35\%$
FCC-hh:	**± 5%**

https://arxiv.org/abs/2211.11084

Sustainability considerations: Carbon footprint

Eur. Phys. J. Plus **137**, 1122 (2022). https://doi.org/10.1140/epjp/s13360-022-03319-w

Table 1: For each of the Higgs factory projects (1st row): Centre-of-mass energy (2nd row); Instantaneous wall-plug power [13] (3rd row); Assumed annual operational time and operational efficiency [17–21] (4th and 5th rows); Inferred annual energy consumption in operation (last row).

Higgs factory $\sqrt{s}$ (GeV)	CLIC 380	ILC 250	C^3 250	CEPC 240	FCC-ee 240
Instantaneous power P (MW)	110	140	150	340	290
Annual collision time T (10^7 s)	1.20	1.60	1.60	1.30	1.08
Operational efficiency ϵ (%)	75	75	75	60	75
Annual energy consumption E (TWh)	0.4	0.7	0.8	1.6	1.0

Table 2: For each of the Higgs factory projects (1st row): Running time in the current operation model (2nd row); Total number of Higgs boson produced with the baseline values for the centre-of-mass energy, beam longitudinal polarisation and integrated luminosity (3rd row); Energy consumption per Higgs boson (4th row).

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**

Table 3: For each of the Higgs factory projects (1st row): Assumed collider location (2nd row); Carbon intensity of electricity production in 2021 at each location, except for China where the carbon intensity is averaged over the whole 2021 (3rd row); Corresponding carbon footprint of each Higgs boson produced (last row).

Higgs factory Operated from	CLIC CERN	ILC KEK	C^3 FNAL	CEPC China	FCC-ee CERN
Carbon intensity (kg CO_2 eq. / MWh)	56	565	381	546	56
Carbon footprint per Higgs boson (t CO_2 eq.)	0.8	9.4	6.8	2.2	**0.17**

In short, and as illustrated in Fig. 2, FCC-ee is – by very large factors – the least disruptive in terms of environmental impact during operation, among the e^+e^- candidate Higgs factories aimed at operating by the end of HL-LHC.

Project [Refs]	Approval date	Start constction	Cost	Run	Operations	Operation/lumi	Int Luminosity	Comments (1)
FCC-ee [FCC1]	Proj. 2027/28	2032	17 BCHF over 15 years	Z-pole	2045-2060 ~4 years	5 10^{12} Z^0	17 ab^{-1} /IP/y	Now considering 4 expts. - 90km
				WW	~2 years	10^8 WW	2.4 ab^{-1} /IP/y	
				H(ZH)	~3 years	2 10^6 H	0.6 ab^{-1} /IP/y	
				ttbar	~5 years	2 10^6 tt	0.15 ab^{-1} /IP/y	
CLIC 380 [CLIC1,CLIC2, CLIC3]	Proj. 2028	~2030 [CLIC1]	6 BCHF		2037-45(??)	8 years	1.5 ab^{-1}	11km 2 push/pull expts
CLIC 1.5TeV			+5 BCHF (tot11)		2047-54	7 years	2.5 ab^{-1}	~30km
CLIC 3TeV (?)			+7 BCHF (tot18)		2056-64	8 years	5 ab^{-1}	50km
ILC 250			~5-10B$ (2018est) [ILC2]		11 years [ILC4]		2 ab^{-1}	~20km
ILC 500			~8B$ (2013est) [ILC1]		9 years [ILC4]		4 ab^{-1}	~30km new cost 25 [ILC3]
ILC 1000			?		10 years [ILC4]		8 ab^{-1}	~50km [ILC4]

By mid ~2060 the cost will have been in both FCC-ee and CLIC close to 20BCH, with better physics performance in the Higgs sector with FCC-ee than with CLIC. However CLIC could be well suited to study additional resonance found at LHC/HL-LHC. ILC cost less clear, wait for the cost update expected this year.

From sustainability perspective "normalised" to physics goals FCC-ee seems to be superior.

Circular Electron-Positron Collider – CEPC schedule

CEPC-SPPC Preliminary Conceptual Design Report. 1. Physics and Detector
IHEP-CEPC-DR-2015-01, IHEP-TH-2015-01, IHEP-EP-2015-01
https://inspirehep.net/literature/1395734

Recent ECFA talk shows start of construction 27/28

Super-Proton-Proton-Collider - SPPC
70–100 TeV [48] accumulating 3 ab^{-1}.

SRF engineering schedule found in [CEPC1] shows 8 years for construction.

	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034-2035	2036-2045	2046-2047	2048	2049-2053
EDR																
Civil construction																
Acc. construction & installation																
Commission & operation													H	Z	W	ttbar
SRF system engineering design	Layout, cost, module, beam-cavity, LLRF, interfaces ...															
650 MHz test module (2x2-cell)	Beam operation, replace with high Q cav & variable coupler															
650 MHz H module (6x2-cell)	Design	pCM fabrication		pCM test	Prepare	Production of 32 CM / 192 2-cell CAV for 30 MW H				Installation, Commissioning			Op & +24 CM	Operation		
1.3 GHz H module	High Q module	Mass production of modules with SCM and BPM			pCM fab	pCM test	Production of 12 CM / 96 9-cell CAV			Installation, Commissioning			Operation			
1.3 GHz Z module (high current)		Design and R&D			pCM fabrication		pCM test		Production of 4 CM / 32 9-cell CAV		Installation, Commissioning		Operation			
650 MHz HL-Z module	Conceptual design. 500 MHz high current module production.				Design and R&D							Produce and Install 60+40 1-cell CM		Op		
ttbar cavity and module	Design and R&D of high gradient high Q and new material (Nb3Sn etc.) 650 MHz and 1.3 GHz cavities and module for ttbar								pCM fabrication and test				Production and Installation of 48 CM / 192 650 MHz 5-cell CAV 32 CM / 256 1.3 GHz 9-cell CAV			Op

Project [Refs]	Approval date	Start constction	Cost	Run	Operations	Operation/lumi	Int Luminosity	Comments (1)
FCC-ee [FCC1]	Proj. 2027/28	2032	17 BCHF over 15 years	Z-pole	2045-2060 ~4 years	$5\ 10^{12}\ Z^0$	17 ab^{-1} /IP/y	Now considering 4 expts. - 90km
				WW	~2 years	10^8 WW	2.4 ab^{-1} /IP/y	
				H(ZH)	~3 years	$2\ 10^6$ H	0.6 ab^{-1} /IP/y	
				ttbar	~5 years	$2\ 10^6$ tt	0.15 ab^{-1} /IP/y	
FCC-hh			+~17 BCHF (?) [FCC2]		~2070 - 25 years	15 years at 100 TeV?		
CLIC 380 [CLIC1,CLIC2, CLIC3]	Proj. 2028	~2030 [CLIC1]	6 BCHF		2037-45(??)	8 years	1.5 ab^{-1}	11km 2 push/pull expts
CLIC 1.5TeV			+5 BCHF (tot11)			ars	2.5 ab^{-1}	~30km
CLIC 3TeV (?)			+7 BCHF (tot18)			ars	5 ab^{-1}	50km
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ILC 1000			?		10 years [ILC4]		8 ab^{-1}	~50km [ILC4]
CEPC [CEPC1]	Gov ~2025 EDR ~2027	2028	5 B$	H(240)	2036-45 ~10 years	O(10^6)		2 experiments one reserved fro chinese institutions (construction 2026-2035 bbly shifted by 2 years compare [CEPC1] and [CEPC2])
				Z(91)	2046-48 ~3 years	O(10^{12})		
				WW(160)	2049 ~1y	$20\ 10^6$		
				tt(360)	2050-54 ~5y	"upgradable"		
SPPC	R&D till 2035	2045-50			2050? 10-15y		30 ab^{-1}	B=20T E=125TeV [CEPC2]

Discuss the completion dates of the H(ZH) datasets from FCC-ee and CEPC

Revisited answers to the ESPP questions

3) Questions to be considered by countries/regions when forming and submitting their "national input" to the ESPP:

a) Which is the preferred next major/flagship collider project for CERN?

Answer: FCC integrated programme (FCC-ee + FCC-hh (and FCC-eh?))

Pros:

- Technical feasibility for ee-state already established for FCC-ee
- Higher long-term potential
- Higher luminosity than linear colliders
- More experiments
- hh-stage drives accelerator development
- HH measurements at FCC-hh

Cons: ee-stage expensive

Complementary observations

+ Better physics potential in terms of Higgs(?)

+ Best energy efficiency (sustainability)

(benefits of higher luminosity of FCC-ee compared to linear colliders)

FCC-ee and CLIC in its entirety may have similar total cost O(20BCH)

3) Questions to be considered by countries/regions when forming and submitting their "national input" to the ESPP:

a) Which is the preferred next major/flagship collider project for CERN?

Answer: FCC integrated programme (FCC-ee + FCC-hh (and FCC-eh?))

What about CLIC then?

- Seems cheaper
- Similar physics reach to FCC-ee
- Drives accelerator development
- More technical risk, leading to schedule and cost risks.
- What do we do after? no long-term program?

Complementary observations on CLIC

- Less performant for single Higgs production(?)

+ More performance for Higgs self-coupling.

- Could be important if a high mass resonance is observed at LHC.

+ There is also a long-term perspective with linear collider (see S.Stapnes ECFA talk): reuse the tunnel with more performant technologies eg. C^3 Accelerator concept.
See Snowmass paper

3b) What are the most important elements in the response to 3a)?

i) **Physics potential**

ii) **Long-term perspective**

iii) Financial and human resources: requirements and effect on other projects

iv) **Timing (but less so than the other two)**

v) Careers and training

vi) Sustainability

Complementary observations

Physics potential & sustainability perhaps somewhat in favour of FCC

Thre is potentially a long-term perspective with a linear collider.

3c) Should CERN/Europe proceed with the preferred option set out in 3a) or should alternative options be considered:

i) if Japan proceeds with the ILC in a timely way?

In this scenario we would recommend an update to the ESPP depending on the physics reach of ILC (which CoM energy etc). CERN push directly for FCC-hh.

Complementary observations

FCC-ee could also go directly to the 380 GeV run + TeraZ runs

ii) if China proceeds with the CEPC on the announced timescale?

Yes CERN should proceed with FCC-ee anyway.

Complementary observations

Can the H(ZH) run of FCC-ee be moved ealier?

iii) if the US proceeds with a muon collider?

Yes proceed with FCC-ee. However in the unlikely scenario that the muon collider can be built on the same timescale as FCC-ee, revist the ESPP

iv) if there are major new (unexpected) results from the HL-LHC or other HEP experiments?

Would then need to update the ESPP to make sure we choose the best follow-up machine given the observed new physics (select beam type + Ecom).

3d) Beyond the preferred option in 3a), what other accelerator R&D topics (e.g. highfield magnets, RF technology, alternative accelerators/colliders) should be pursued in parallel?

Answer: plasma-wakefield acceleration (but of course also crucial that CERN keep a general accelerator R&D program). We also think detector R&D should be a high priority part of the program.

Additional comment:

Mention the C^3 Accelerator concept?

3e) What is the prioritised list of alternative options if the preferred option set out in 3a) is not feasible (due to cost, timing, international developments, or for other reasons)?

Answer: FCC integrated programme (3a) > CLIC (> HE-LHC?)

3f) What are the most important elements in the response to 3e)? (The set of considerations in 3b should be used).

Answer: The field needs a Higgs factory and we prefer it to be at CERN. Not so many options except for FCC and CLIC.

Additional observation comment:

Physics potential

Long-term perspective

R&D also relates to a CLIC scenario, ie. R&D so that on the timescale 2050 we could have some options to reuse the linear tunnel with higher accelerating power/m

BACKUP

- FCC physics
- FCC-ee main machine parameters
- FCC-hh main machine parameters
- Higgs production cross section vs sqrt(s)
- Luminosity vs sqrt(s) for various acceleators

[FCC1] F. Zimmermann *FCC: recent updates and goals/plans for contribution to ESPPU,* 3rd ECFA workshop on e+e- Higgs/EW/Top Factories, Paris, 9-11 Oct. 24
https://indico.in2p3.fr/event/32629/timetable/?view=standard#20-fcc-recent-updates-and-goal
[FCC2] P. Collier, *Status and Plans for CERN Accelerator Complex*, PoS XXIX International Symposium on Lepton Photon Interactions at High Energies - LeptonPhoton2019, 2019, Toronto, Canada
[FCC3] *FCC CDR Physics Opportunities* Eur. Phys. J. C (2019) 79 :474 https://link.springer.com/article/10.1140/epjc/s10052-019-6904-3
[CLIC1] S. Stapnes, *Linear colliders, towards the ESPP update*. Presentation at the 3rd ECFA workshop on Higgs, top and Electroweak factories, Paris, 9–11 Oct 2024, https://indico.in2p3.fr/event/32629/timetable/?view=standard#21-linear-colliders-recent-upd
[CLIC2] S. Stapnes, *CLIC Status,* Talk presented at International Workshop on Future Linear Colliders, LCWS2024, Tokyo July 2024
https://agenda.linearcollider.org/event/10134/timetable/?view=lcc#25-clic-status
[CLIC3] O. Brunner et al. *The CLIC project* https://arxiv.org/abs/2203.09186
[ILC1] The ILC TDR Vol1 (2013) linearcollider.org/files/images/pdf/Executive%20Summary.pdf
[ILC2] *The International Linear Collider Machine Staging Report 2017* **https://arxiv.org/abs/1711.00568**
[ILC3] 5 September 2024 - IDT-EB-2024-001 *ILC Cost-update - External Review* - ILC International Development Team Executive Board
[ILC4] *The International Linear Collider: Report to Snowmass 2021* https://arxiv.org/abs/2203.07622
[CEPC1] J. Guimaraes da Costa, Talk given at **3rd ECFA workshop on e+e- Higgs/EW/Top Factories, Paris, 9-11 Oct. 24**
https://indico.in2p3.fr/event/32629/timetable/?view=standard#23-cepc-status-of-the-proposal
[CEPC2] CEPC Accelerator Study Group *Snowmass2021 White Paper AF3-CEPC* https://arxiv.org/abs/2203.09451
[LHeC1] Max Klein: *(16–20 April 2018). The case for LHeC (PDF). XXVI International Workshop on Deep-Inelastic Scattering and Related Subjects. Kobe.*
[Phys1] A. Blondel et al. *Higgs factory options for CERN, A comparative study,* arXiv:2412.13130v1 [hep-ph] 17 Dec 2024
[Sust1] P. Janot, A. Blondel, **The carbon footprint of proposed e+e− Higgs factories.** *Eur. Phys. J. Plus* **137**, 1122 (2022). https://doi.org/10.1140/epjp/s13360-022-03319-w

Table S.1 Precisions determined in the κ framework on the Higgs boson couplings and total decay width, as expected from the FCC-ee data, and compared to those from HL-LHC. All numbers indicate 68% C.L. sensitivities, except for the last line which gives the 95% C.L. sensitivity on the "exotic" branching fraction, accounting for final states that cannot be tagged as SM decays. The fit to the HL-LHC projections alone (first column) requires assumptions: here, the branching ratios into $c\bar{c}$ and into exotic particles (and those not indicated in the table) are set to their SM values. The FCC-ee accuracies are subdivided in three categories: the first sub-column gives the results of the fit expected with 5 ab^{-1} at 240 GeV, the second sub-column in bold includes the additional 1.5 ab^{-1} at $\sqrt{s} = 365$ GeV, and the last sub-column shows the result of the combined fit with HL-LHC. Similar to the HL-LHC, the fit to the FCC-eh projections alone requires an assumption to be made: here the total width is set to its SM value, but in practice will be taken to be the value measured by the FCC-ee

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	FCC-ee			FCC-eh
Luminosity (ab^{-1})	3	2	0.5	5 @ 240 GeV	+ 1.5 @ 365 GeV	+ HL-LHC	2
Years	25	15	8	3	+ 4	–	20
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	2.7	**1.3**	1.1	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.30	0.60	0.2	**0.17**	0.16	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.3	**0.43**	0.40	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.3	**0.61**	0.56	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	1.7	**1.21**	1.18	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	1.6	**1.01**	0.90	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.4	**0.74**	0.67	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	10.1	**9.0**	3.8	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	4.8	**3.9**	1.3	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	3.1	1.7
BR_{EXO} (%)	SM	< 1.8	< 3.0	< 1.2	$<$ **1.0**	< 1.0	n.a.

From [FCC3]

Table S.3 Measurement of selected electroweak quantities at the FCC-ee, compared with the present precision. The systematic uncertainties are present estimates and might improve with further examination. This set of measurements, together with those of the Higgs properties, achieves indirect sensitivity to new physics up to a scale Λ of 70 TeV in a description with dim 6 operators, and possibly much higher in some specific new physics models

[FCC3]

Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.	Comment and dominant exp. error
m_Z (keV/c^2)	91,186,700 ± 2200	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2,495,200 ± 2300	8	100	From Z line shape scan beam energy calibration
R_ℓ^Z ($\times 10^3$)	20,767 ± 25	0.06	0.2–1	Ratio of hadrons to leptons acceptance for leptons
α_s (m_Z) ($\times 10^4$)	1196 ± 30	0.1	0.4–1.6	From R_ℓ^Z above
R_b ($\times 10^6$)	216,290 ± 660	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
σ_{had}^0 ($\times 10^3$) (nb)	41,541 ± 37	0.1	4	Peak hadronic cross-section luminosity measurement
N_ν ($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	231,480 ± 160	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}$ (m_Z) ($\times 10^3$)	128,952 ± 14	4	Small	From $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1–3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	< 2	τ Polarisation and charge asymmetry τ decay physics
m_W (MeV/c^2)	80,350 ± 15	0.5	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan beam energy calibration
α_s (m_W) ($\times 10^4$)	1170 ± 420	3	Small	From R_ℓ^W
N_ν ($\times 10^3$)	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172,740 ± 500	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5–1.5%	Small	From E_{CM} = 365 GeV run

EW phase transition

"The FCC should conclusively probe new states required by a strong 1st order EW phase transition." [FCC3]

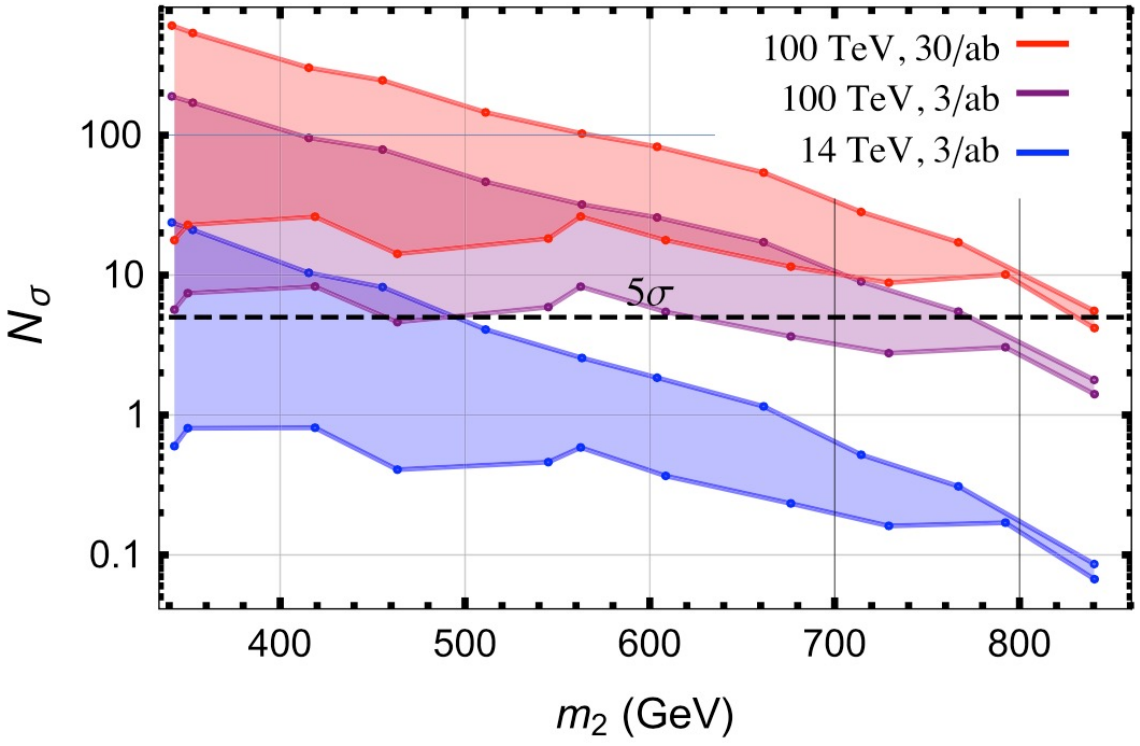


Fig. S.3 Manifestations of models with a singlet-induced strong first order EWPT. Left: discovery potential at HL-LHC and FCC-hh, for the resonant di-Higgs production, as a function of the singlet-like scalar mass m_2. 4τ and $b\bar{b}\gamma\gamma$ final states are combined.

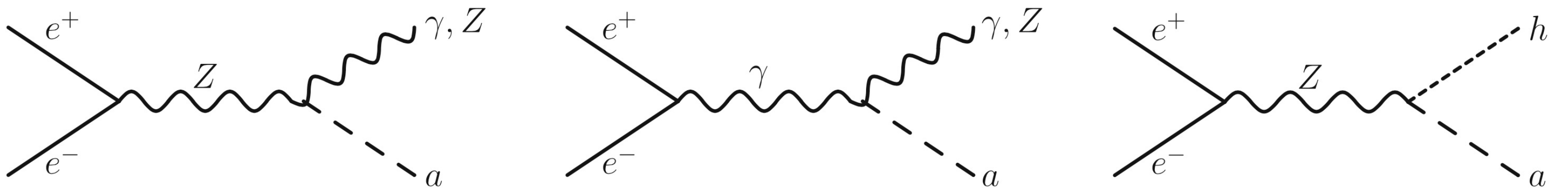


Fig. 1 Tree-level Feynman diagrams for the processes $e^+e^- \to Xa$ with $X = \gamma, Z, h$

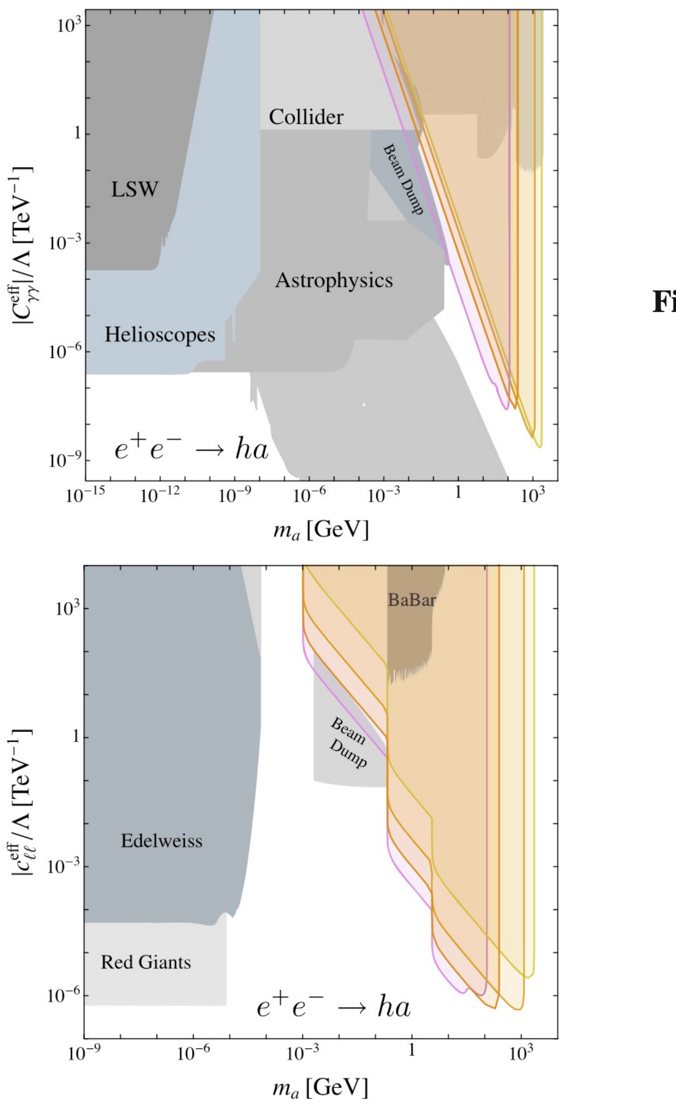


Fig. 7 Left: projected sensitivity regions for searches for $e^+e^- \to ha \to b\bar{b}\gamma\gamma$ (upper panels) and $e^+e^- \to ha \to b\bar{b}\ell^+\ell^-$ (lower panels) for future e^+e^- colliders, assuming that $|C_{Zh}^{\rm eff}| = 0.72\,\Lambda/\rm TeV$ and $\mathrm{Br}(a \to \gamma\gamma) = 1$ (upper panels) and $\mathrm{Br}(a \to \ell^+\ell^-) = 1$ (lower panels). Right: sensitivity regions for the example of the FCC-

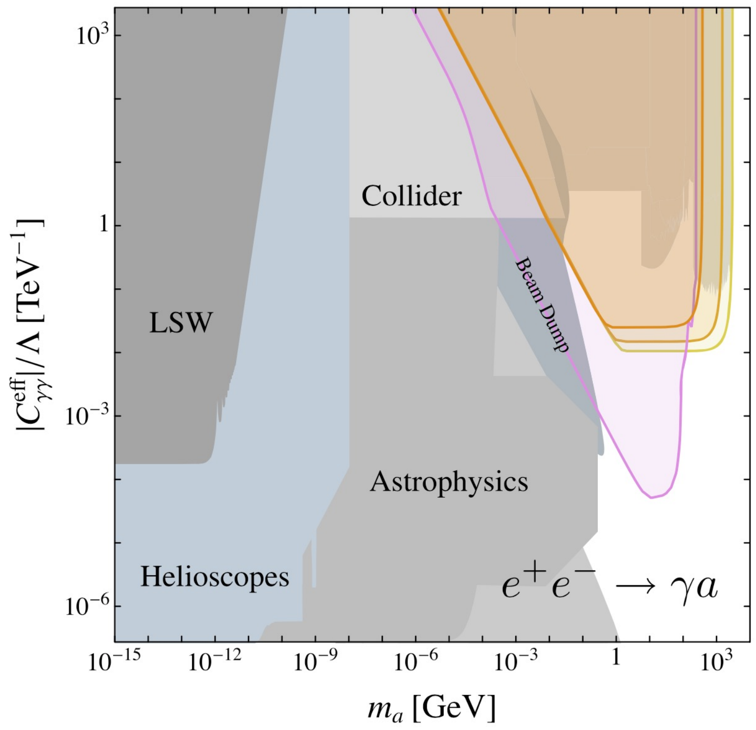


Fig. 6 Projected sensitivity regions for searches for $e^+e^- \to \gamma a \to 3\gamma$

M. Bauer, M. Heiles, M. Neubert, A. Thamm
Eur. Phys. J. C (2019) 79:74
https://doi.org/10.1140/epjc/s10052-019-6587-9

From [FCC1] October 2024

FCC-ee main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter x_x / x_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	140	20	≥5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

F. Gianotti

Design and parameters to maximise luminosity at all working points:

- allow for 50 MW synchrotron radiation per beam
- Independent vacuum systems for electrons and positrons
- full energy booster ring with top-up injection, collider permanent in collision mode

Improvements:

- x10-50 on all EW observables
- up to x 10 on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points

→ robustness, statistics, possibility of specialised detectors to maximise physics

FCC-hh main machine parameters

From [FCC1] October 2024

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	84 - 120	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1100 - 4570	7.3	3.6
SR power / length [W/m/ap.]	14 - 58	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.3 – 9.2	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

With FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies

Formidable challenges:

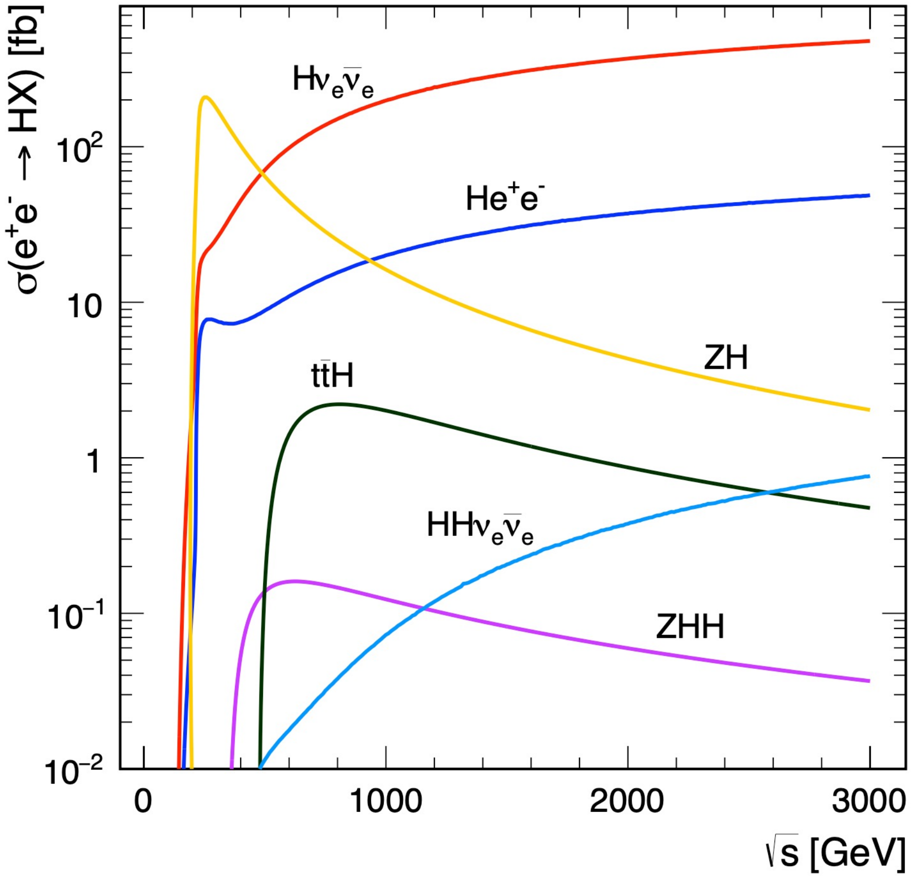
- ❑ high-field superconducting magnets: 14 - 20 T
- ❑ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ❑ stored beam energy: ~ 9 GJ → machine protection
- ❑ pile-up in the detectors: ~1000 events/xing
- ❑ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:

- ❑ Direct discovery potential up to ~ 40 TeV
- ❑ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ❑ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, μμ)
- ❑ Final word about WIMP dark matter

F. Gianotti

Higgs production cross section at e^+e^- colliders



CLIC YR 2016

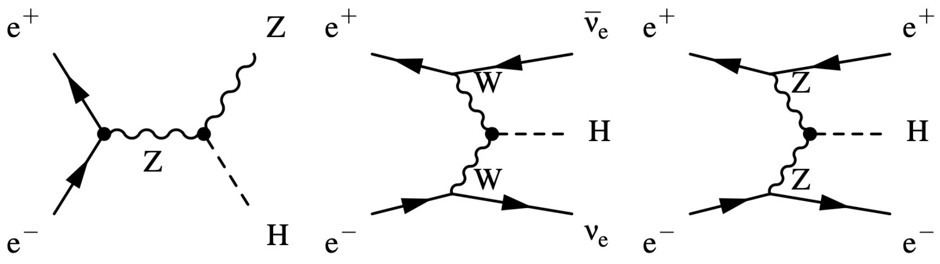


Figure 2: The three highest cross section Higgs production processes at CLIC.

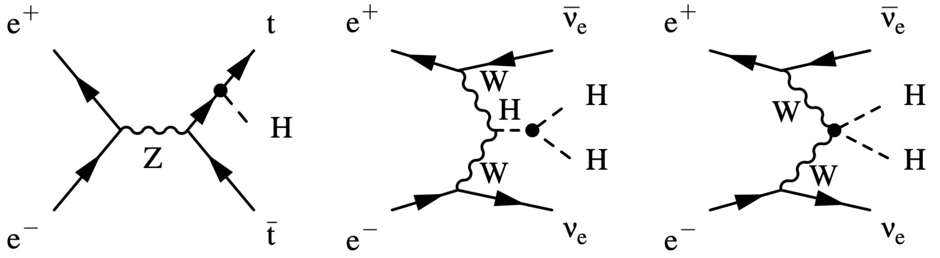
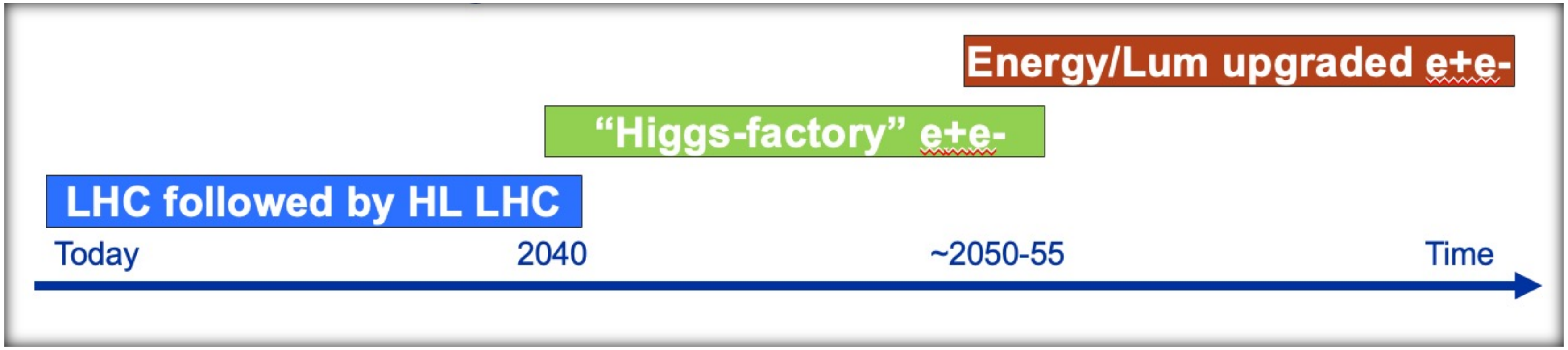


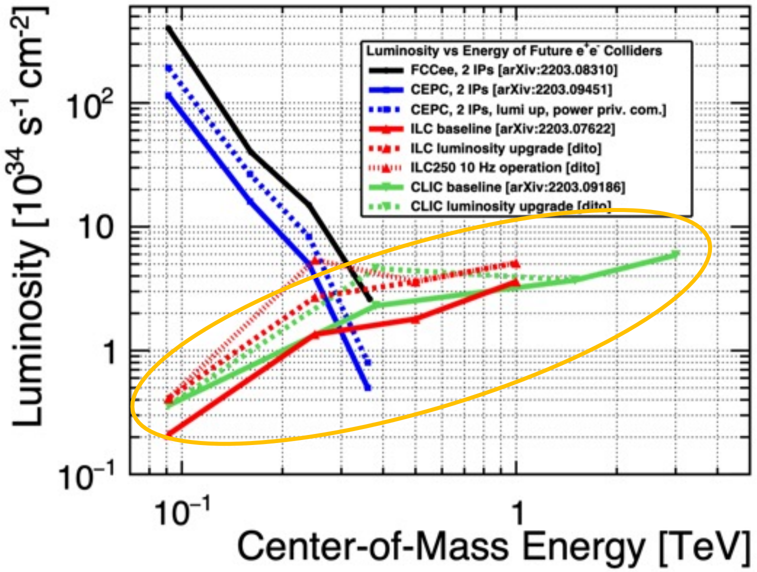
Figure 3: The main processes at CLIC involving the top Yukawa coupling g_{Htt}, the Higgs boson trilinear self-coupling λ and the quartic coupling g_{HHWW}.

From:
S. Stapnes ECFA Oct. 2024

LC general considerations - reminder



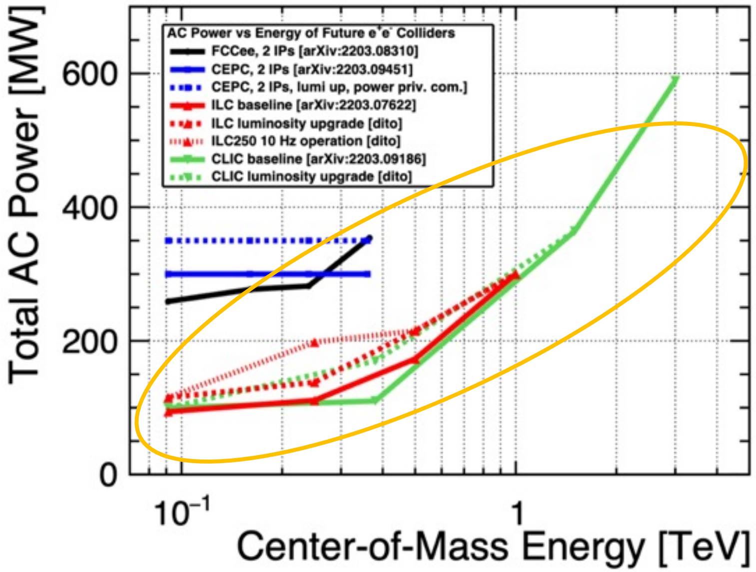
Start with mature technology, can expand in length and/or technology



Increased luminosity with energy, e.g. 1-3 x 10^{34} $cm^{-2}s^{-1}$ for Higgs factories at 250 GeV, 6 x 10^{34} at 3 TeV

Higher energies "natural" – 3 TeV studied (for CLIC), but many TeVs challenging:

- Power proportional to luminosity
- Reach up to 50km
- Higher energy means smaller beams and increasingly important beam-beam effects



The Cool Copper Collider (C3)

C^3: A "Cool" Route to the Higgs Boson and Beyond
https://arxiv.org/abs/2110.15800

See also S. Stapnes ECFA Oct. 24. [CLIC1]

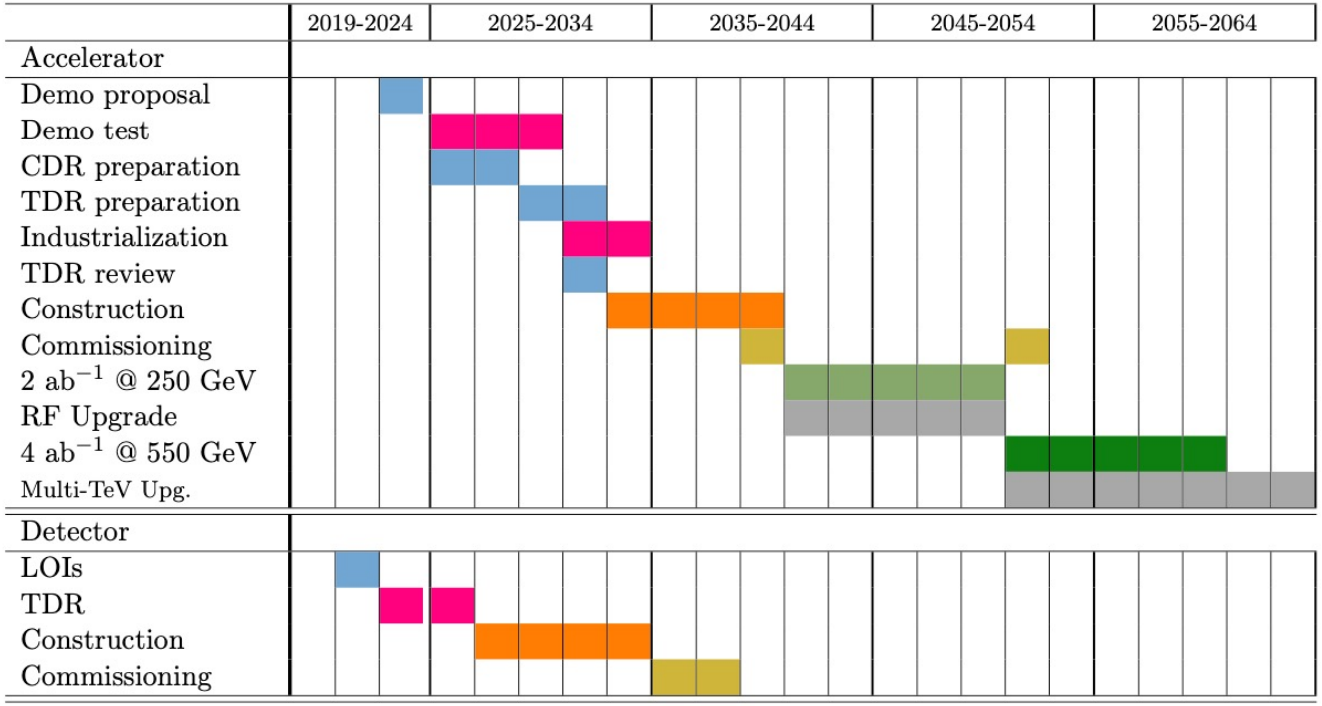
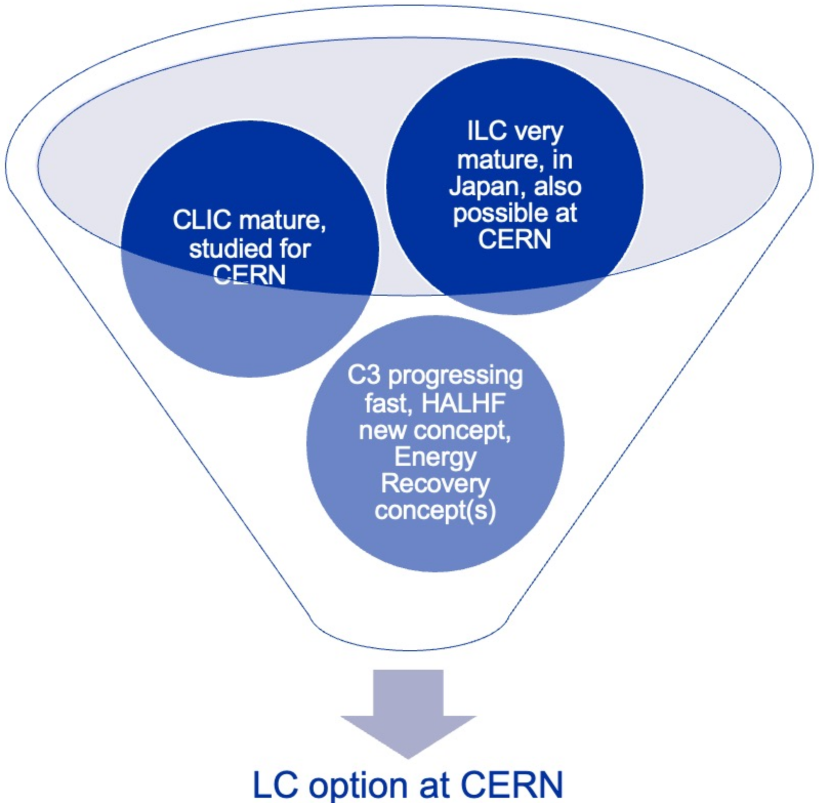


Table 1: Timeline and Milestones for the proposed C^3 development

The challenge for the EPSS update:



S. Stapnes ECFA Oct. 24.