High-energy e^+e^- colliders

- EPPSU 2020 outcome
- Considerations for arriving at a decision
- A (superficial) survey of the options
- How to get involved

Guy Wilkinson
UK EPPSU meeting
1/5/24

Outcome of 2020 EPPSU

[CERN-ESU-015]

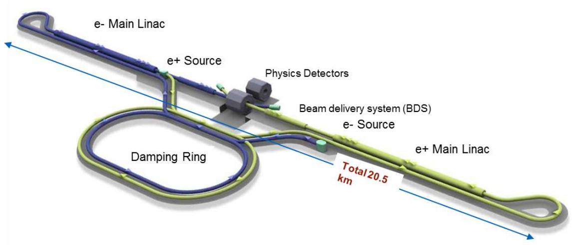
A. An electron-positron Higgs factory is the highest-priority next collider.

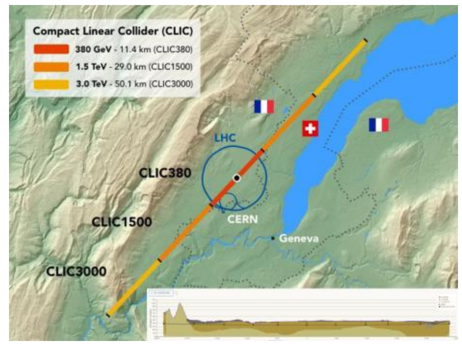
• ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility 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.***

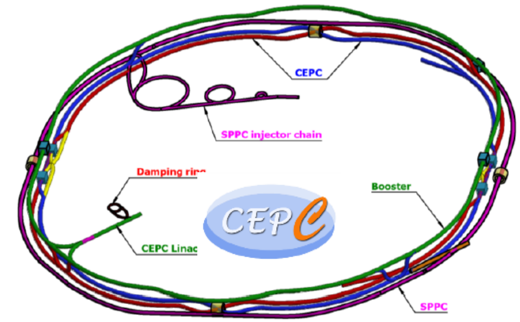
i.e. FCC

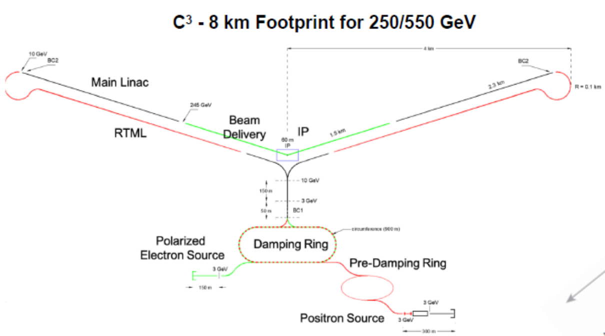
The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

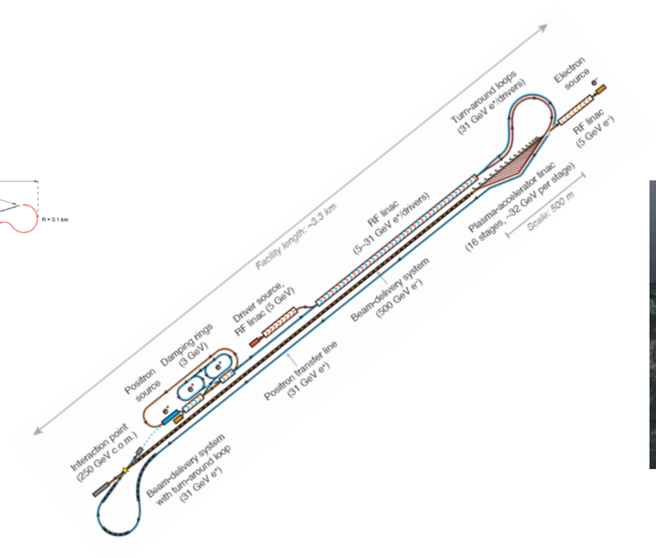
e^+e^- Higgs factories – a wealth of choice

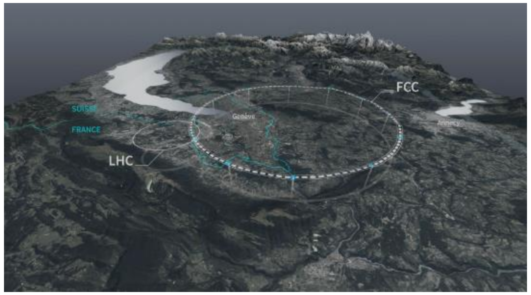




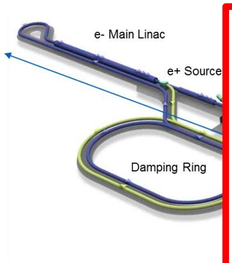


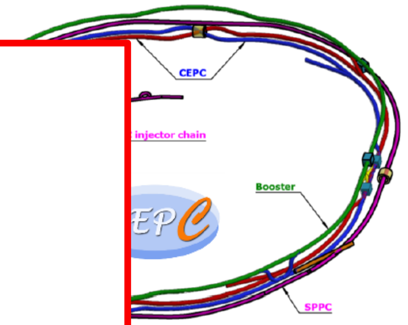






e^+e^- Higgs factories – a wealth of choice





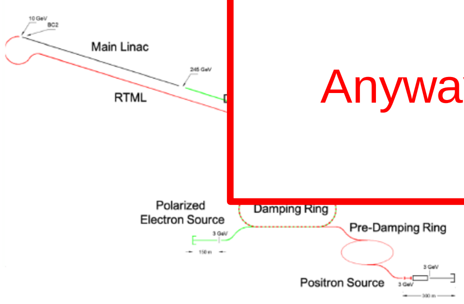
Is all this choice such a good thing ?

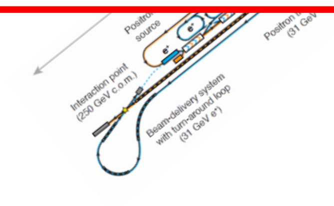
Recall Sheldon Stone on detector upgrades

> “Too many options are bad: 3 is a disaster,
> 2 is one too many, 1 is good.”

Does this apply to accelerator projects also ?

Anyway, a wealth of choice is what we have.





Considerations

No attempt today to provide ranking or comparison tables, but I suggest that the following considerations should inform our discussion up to the EPPSU.

- Circular vs linear
- Higgs physics capabilities
- Other physics capabilities
- Timescale and cost
- Technological readiness
- Prospects of international collaboration
- Cul de sac or open door to future projects ?
- Carbon footprint
- Any others ?

Considerations

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- Circular vs linear

Circular	Linear
Higher luminosities for Z, ZH and WW	Possible to operate at energies well above ttbar threshold
Transverse polarisation allows for precise beam-energy calibration	
Longitudinal polarisation more challenging (but in CEPC baseline, and will be considered by FCC)	Longitudinal polarisation generally available
Good track record of attaining design luminosity (but travails of SuperKEKb are a concern)	Options exist with much smaller footprint that circular machines

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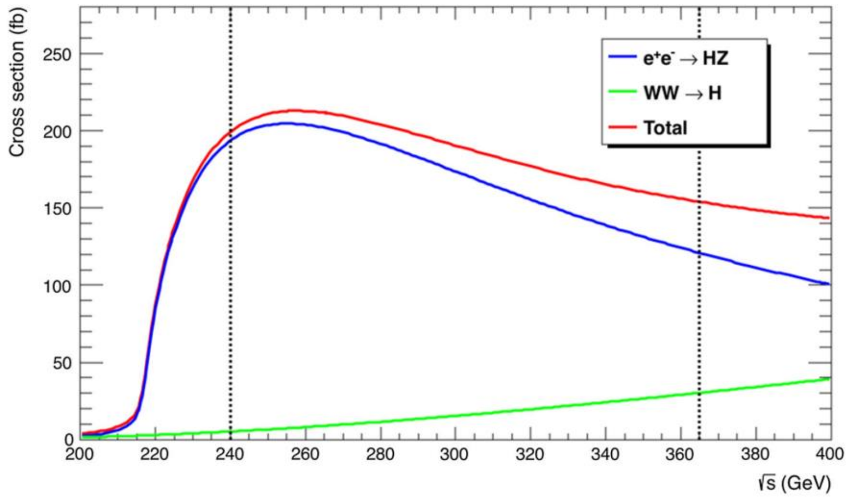
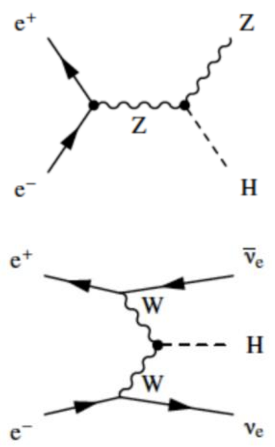
- Circular vs linear
- Higgs physics capabilities

Broadly similar at all machines, but takes a little longer at linear colliders.





FCC-ee/CEPC can also probe electron Yukawa, whereas linear colliders with high-energy upgrade can probe top Yukawa & Higgs self-coupling. But none of these options are in baseline plans.

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Very high luminosity at lower energies, and resonant depolarisation, give circular colliders remarkable opportunities in electroweak & flavour physics.

High-energy upgrades to linear colliders would access the TeV regime.

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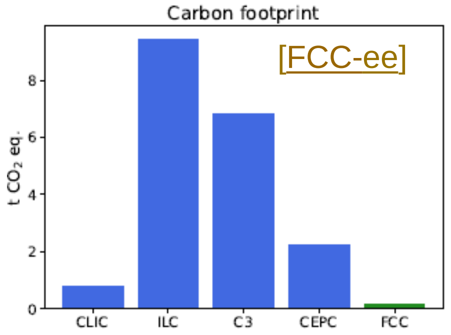
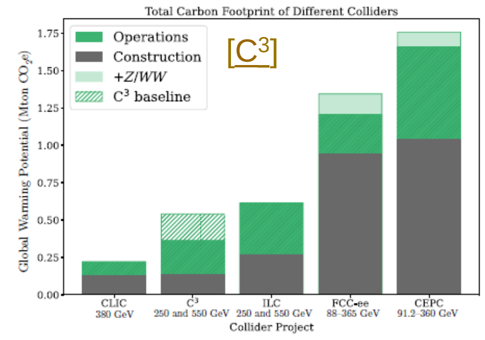
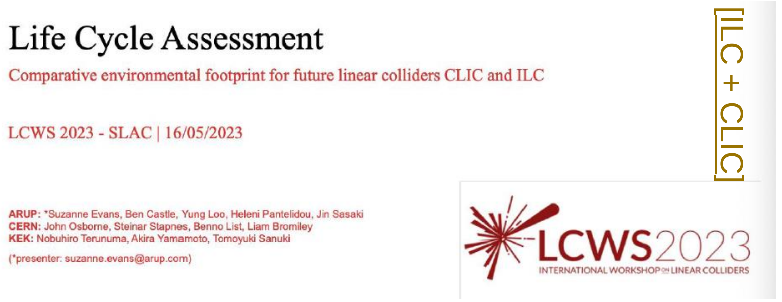






Being taken very seriously by all future projects:

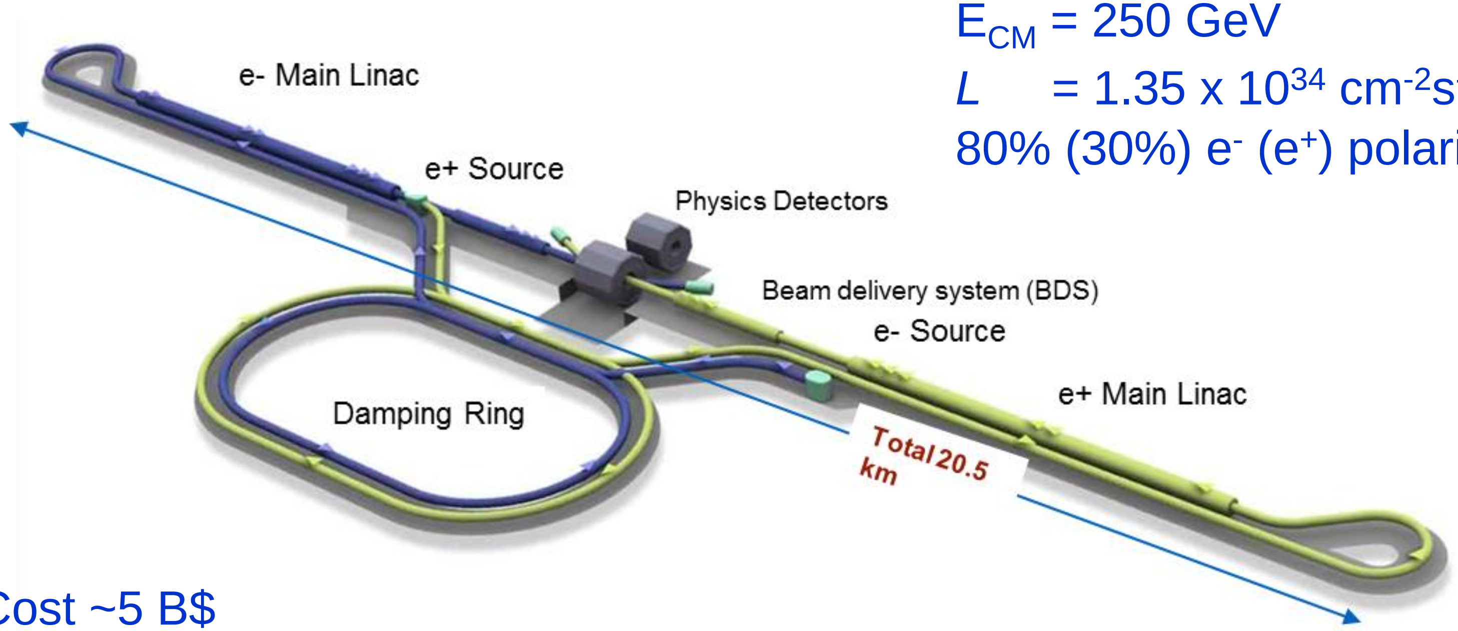
- wall-plug power X required running time;
- construction footprint and lifetime of facility;
- greenness of power supply.

No summary attempted today, but very important !

ILC – current baseline

Technologically mature project. Current baseline for first stage is descoped from 500 GeV machine proposed in 2013 TDR.

E_{CM} = 250 GeV
L = 1.35 x 10^{34} $cm^{-2}s^{-1}$
80% (30%) e^- (e^+) polarisation



Cost ~5 B$
Power ~110 MW

8,000 1.3 GHz
SRF cavities @ 2K

ILC – upgrade options

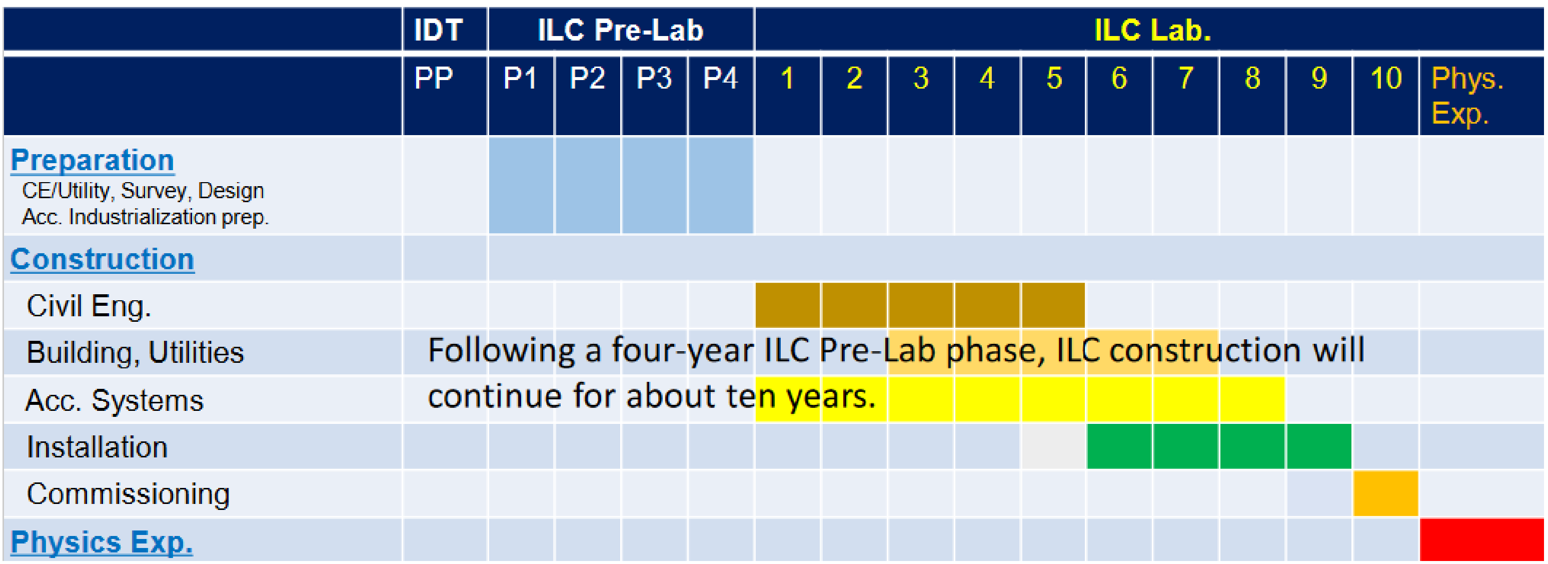
Extendable to higher luminosity, and higher energies (and also Z-pole operation).

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
Repetition frequency	f_{rep}	Hz	5	5	3.7	5	10	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312/2625	1312/2625	2625	2450
Bunch population	N_{e}	10^{10}	2	2	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	366	554/366	554/366	366	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	5.8/8.8	5.8/8.8	8.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727/961	727/961	961	897
Average beam power	P_{ave}	MW	5.3	10.5	1.42/2.84*)	10.5/21	21	27.2
RMS bunch length	σ^*_{z}	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35	35	30
RMS hor. beam size at IP	σ^*_{x}	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7	14.6	5.9	7.7	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	99 %	58.3 %	73 %	44.5 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %	0.16 %	4.5 %	2.6 %	10.5 %
Site AC power	P_{site}	MW	111	138	94/115	173/215	198	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

ILC – status

ILC conceived as 'global' project, where ownership is shared among the partners (as with ITER, or SKA), in contrast to 'international projects', which is initiated and hosted by a lab (*e.g.* LHC). Sounds good, but leads to chicken and egg problem.

→ Japanese government will not commit until other nations endorse project.

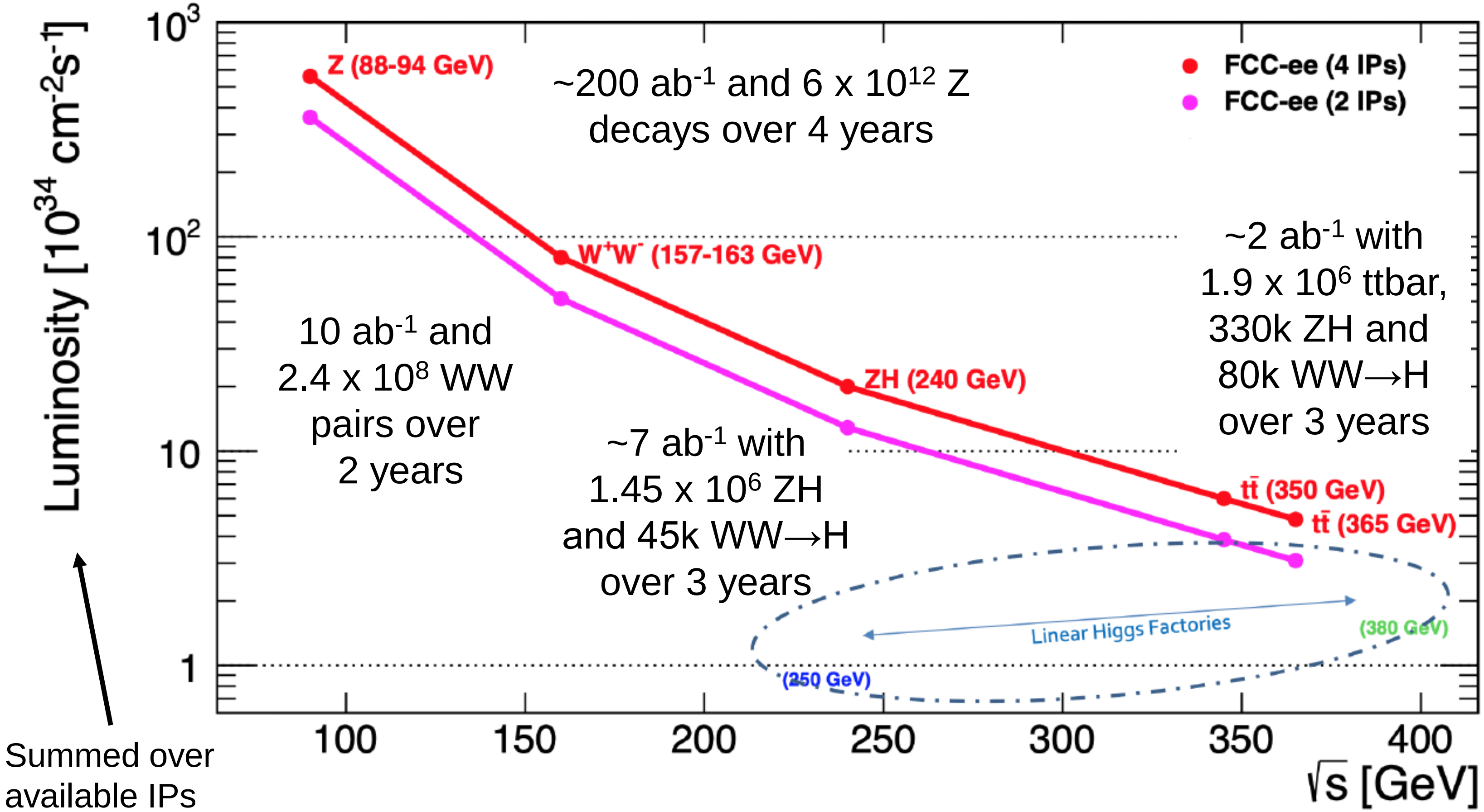


(IDT = International Development Team – established by ICFA in 2019)

Four year preparatory phase, followed by ~10 years of construction…
…but preparatory phase can not begin until chicken lays egg (or egg hatches).

FCC-ee: baseline run plan

FCC-ee will enable precision studies of all the heavy particles in the SM.



Five-year feasibility study
Four-and-a-bit

~700 page Midterm Report submitted late last year

Future Circular Collider
Midterm Report

February 2024 *

Edited by:
B. Auchmann, W. Bartmann, M. Benedikt, J.P. Burnet, P. Craievich, M. Giovannozzi, C. Grojean, J. Gutleber, K. Hanke, P. Janot, M. Mangano, J. Osborne, J. Poole, T. Raubenheimer, T. Watson, F. Zimmermann

This project has received funding under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.

This document has been produced by the organisations participating in the FCC feasibility study. The studies and technical concepts presented here do not represent an agreement or commitment of any of CERN's Member States or of the European Union for the construction and operation of an extension to CERN's existing research infrastructures.
The midterm report of the FCC Feasibility Study reflects work in progress and should therefore not be propagated to people who do not have direct access to this document.

https://doi.org/10.17181/mhas5-1f263

Reviewed by a Scientific Advisory Committee & a Cost Review Panel. Feedback very positive.

"The SPC would like to congratulate the FCC Feasibility Study team for successfully producing its Midterm Report, which substantially satisfies the designated deliverables specified by Council in 2022."

Hugh Montgomery, SPC Chair, Feb 2024

One immediate consequence: end-date of Feasibility Study brought forward, with Final Report now scheduled for early 2025...

...and the advancement of the EPPSU.

* Date of version released to CERN Users

Costs and timescale

Updated cost estimate in Midterm Report.

Accelerators (with Z, WW and ZH running)	3847 MCHF
Injectors and transfer lines	585 MCHF
Civil engineering (with 2 IPs)	5538 MCHF
Technical infrastructure (with Z, WW and ZH running)	2490 MCHF
Experiments (CERN contribution only, 2 IPs)	150 MCHF
Territorial development	191 MCHF
Total	12,801 MCHF
Total with 4 IPs	13,511 MCHF
Total with 4 IPs and running at 350 + 365 GeV	14,976 MCHF

Certainly, these costs cannot all be met from the CERN annual budget.

(NB the tunnel and much of infrastructure can be re-used for FCC-hh).

Costs and timescale

FCC is without doubt a long term project (delivering physics until the end of the century). The current plan is considered 'very realistic' based on CERN experience, and has the HL-LHC ending in 2041 and the FCC-ee starting in 2048.

It is stated that the project can be accelerated 'if additional resources are found'.

News from last week [link]

" Should the CERN Member States determine the FCC-ee is likely to be CERN's next world-leading research facility following the high-luminosity Large Hadron Collider, the United States intends to collaborate on its construction and physics exploitation, subject to appropriate domestic approvals."

Meanwhile in China…

CEPC is a 100 km synchrotron proposed in China, with very similar (but not identical) goals and capabilities to FCC-ee.

Accelerator and detector R&D at an advanced stage.

Ranked top in forthcoming 5-year plan for large science projects.

Proposal will be submitted for approval in 2025.

Construction could begin in 2027 and end in 2035 (even if this is ambitious, it is clear the project can have an earlier start date than the FCC).

Open questions: international collaboration ?

Cannot be ignored in EPPSU.

(More information available from website of recent Marseille workshop)

Compact Linear e^+e^- Collider (CLIC)

High energy e^+e^- at CERN
for post HL-LHC era, *i.e.*
an alternative (plan B) to FCC.

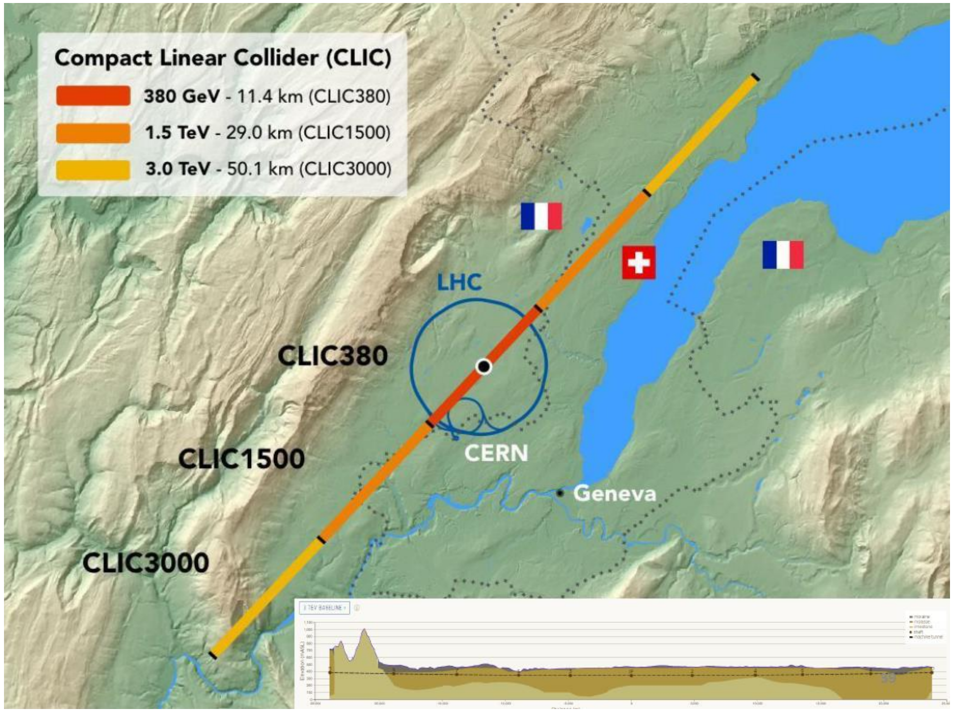
Novel and unique two-beam accelerating technique, based on high-gradient warm RF.

First stage:

- 380 GeV
- 11 km
- 20,500 cavities

- 4.9 BCHF
- 168 MW

Can be upgraded up to 3 TeV.

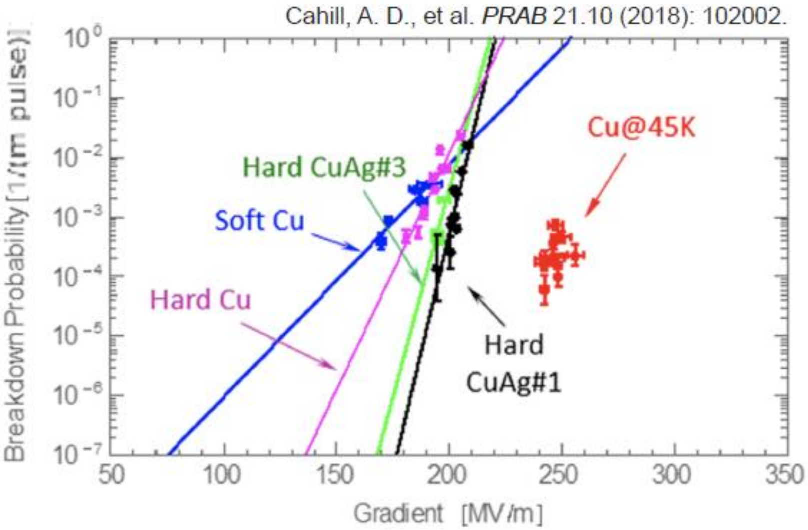


Extensively studied (CDR 2012), with substantial inputs to last EPPSU.

Cool Copper Collider (C^3)

[arXiv:2110.15800]

Driving concept: improvements in normal-conducting RF cavities since the adoption of SCRF as technology for ILC, a decision made ~20 years ago.



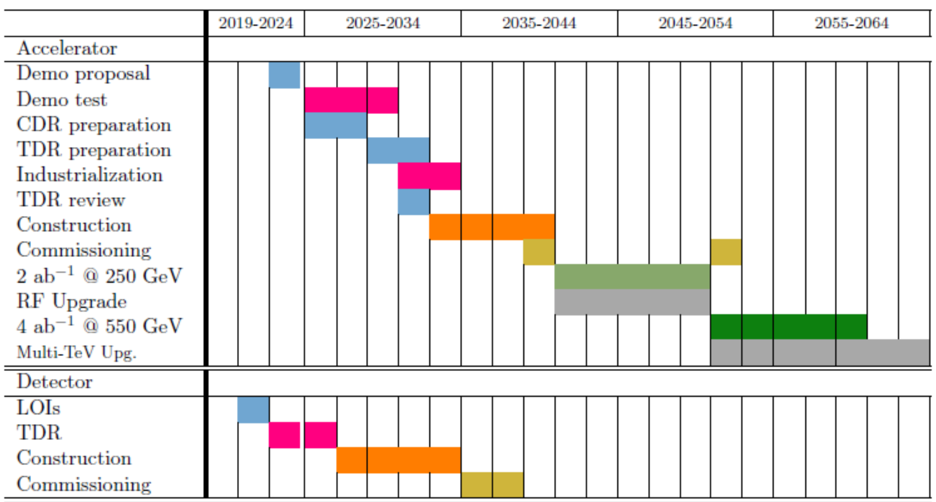
Big idea: cool copper to 80 K. Here the conductivity is higher, which reduces the resistive heating that cases defects, and allows for higher gradients (~100 MeV/m).

C^3 (continued)

C3 gradients offer the possibility of building a ‘short’ (8 km) collider for 250 GeV operation…

…and a clear path for upgrade to higher energies, which also could be deployed at *e.g.* second-stage ILC.

Collider	ILC[5]	C^3	C^3
CM Energy [GeV]	250 (500)	250	550
σ_z [μm]	300	100	100
β_x [mm]	8.0	12	12
β_y [mm]	0.41	0.12	0.12
ϵ_x [nm-rad]	500	900	900
ϵ_y [nm-rad]	35	20	20
Num. Bunches per Train	1312	133	75
Train Rep. Rate [Hz]	5	120	120
Bunch Spacing [ns]	369	5.26	3.5
Bunch Charge [nC]	3.2	1	1
Beam Power [MW]	2.63	2	2.45
Crossing Angle [rad]	0.014	0.014	0.014
Crab Angle	0.014/2	0.014/2	0.014/2
Luminosity [x10^{34}]	1.35	1.3	2.4
Gradient [MeV/m]	31.5	70	120
Effective Gradient [MeV/m]	21	63	108
Shunt Impedance [MΩ/m]		300	300
Effective Shunt Impedance [MΩ/m]		300	300
Site Power [MW]	125	~150	~175
Length [km]	20.5 (31)	8	8
L* [m]	4.1	4.3	4.3



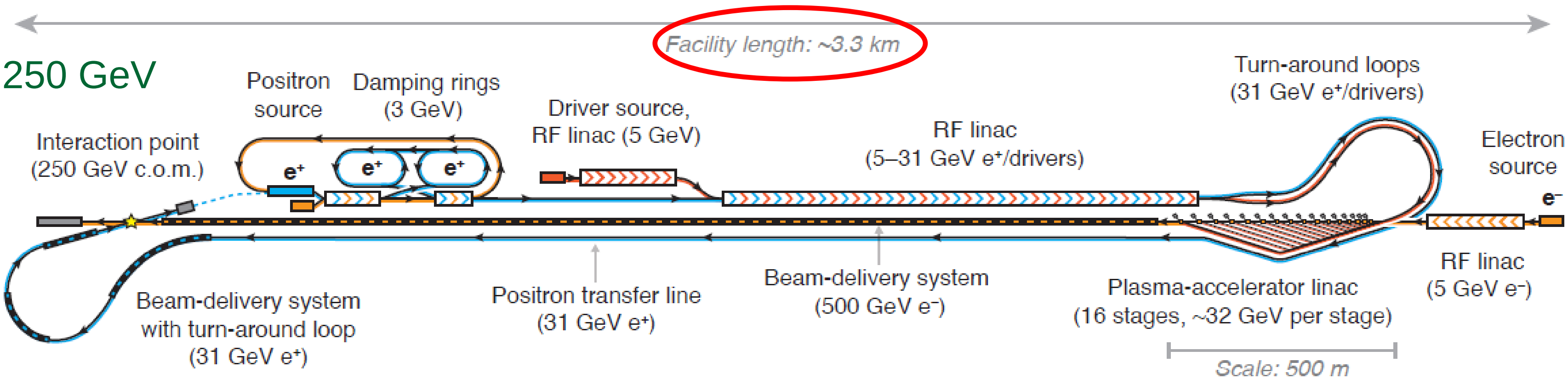
Bullish timeline

(warning: this not evaluated with the thoroughness of schedules for more mature projects, *e.g.* ILC or FCC)

Hybrid, asymmetric, linear Higgs factory (HALHF)

Plasma-wakefield acceleration (PWA) very promising technology for producing GV/m gradients, with high beam quality and power. However, this works much better for electrons than for positrons. So, why not build an asymmetric collider, with high-energy PWA-driven e^- beam, and conventional, lower energy e^+ beam ?

250 GeV



[Foster, D'Arcy and Lindstrøm. New J. Phys. 25 (2023) 093037, Lindstrøm, D'Arcy and Foster arXiv:2312.04975]

Machine parameters	*Unit*	*Value*
Centre-of-mass energy	GeV	250
Centre-of-mass boost		2.13
Bunches per train		100
Train repetition rate	Hz	100
Average collision rate	kHz	10
Luminosity	$cm^{-2}\ s^{-1}$	0.81×10^{34}
Luminosity fraction in top 1%		57%
Estimated total power usage	MW	100

Capital cost ~2 B$

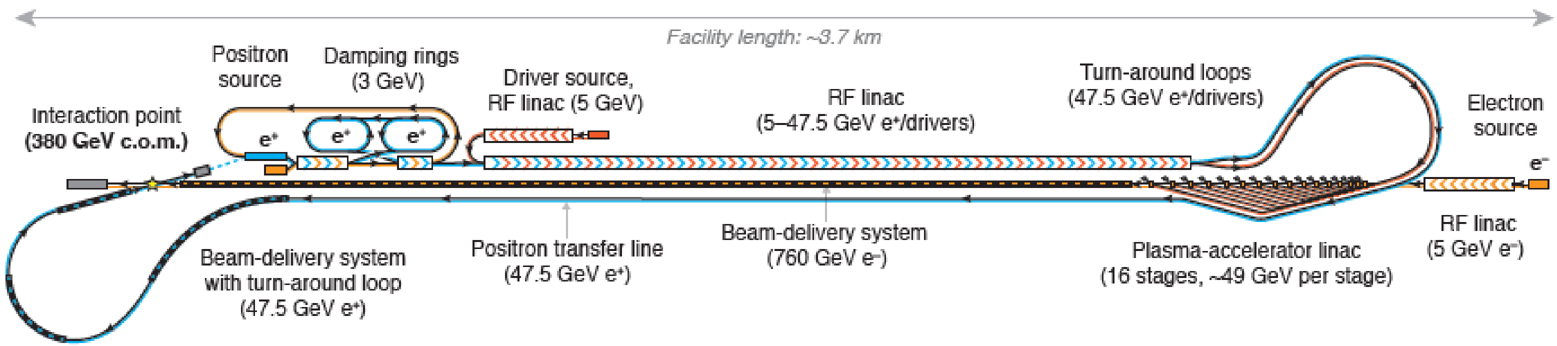
Cheaper than alternatives, and in same ballpark as EIC.

However, significant R&D required for PWA.

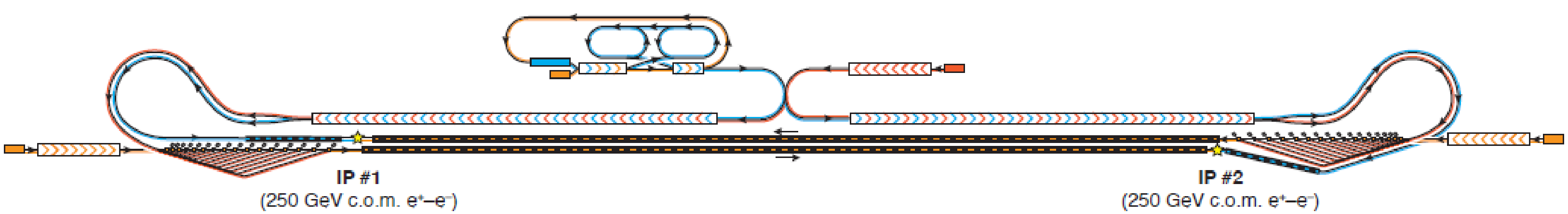
HALHF upgrade / alternatives

HALHF is a very recent concept, and baseline design is evolving fast. Higher-energy options, and two-IP options under consideration.

380 GeV (10% longer)



250 GeV with two IPs



Physics and detector studies towards the EPPSU

There is still opportunity to contribute to physics and detector studies that will inform the EPPSU. Suggestion: this is best done as part of a wider initiative, than as a standalone UK activity. Many UK physicists already actively engaged ! (no attempt to list names here).

Some examples:

- FCC Feasibility Study ongoing until end of year (and studies will continue beyond). Contact me if you need any pointers.
  Note also: FCC Week 2024, 10-14 June, San Francisco.

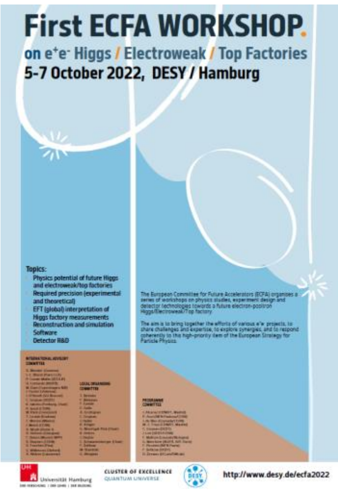
- Similarly, contact your favourite linear collider friend (Aidan Robson, Phil Burrows, Brian Foster…) if you need guidance here.
  Note also: LCWS2024, 8-11 July, Tokyo.

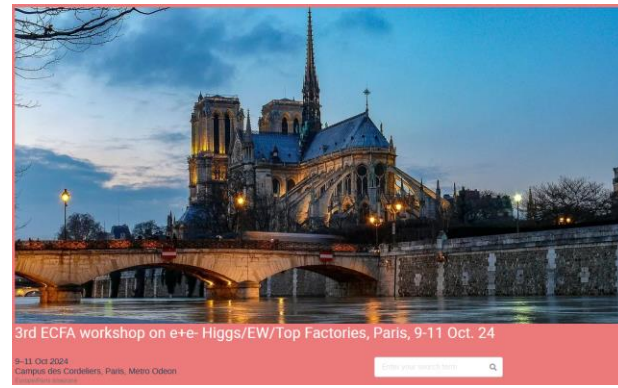
There is also the opportunity to contribute to non-machine-specific studies through the ECFA e^+e^- Higgs/EW./top initiative (see next slides).

ECFA e^+e^- Higgs/EW/top factory study

Ongoing study, with annual workshops, on physics potential, experiment design and detector technologies towards a future e^+e^- Higgs/EW/top factory [website].

DESY, Oct. 2022 | Paestum (Salerno), Oct. 2023 | Paris, 9-11 Oct. 2024





Registration to open this week !

Vibrant programme of regular meetings, *e.g.*:

WG1: Physics Performance
WG2: Physics Analysis Tools
WG3: Detector R&D

15 March: WG1-SRCH Exotic Scalars focus https://indico.cern.ch/event/1390299/
18 March: WG1-HTE ZH angular measurements https://indico.cern.ch/event/1393738/
22 March: WG1-PREC Two-fermion physics https://indico.cern.ch/event/1387393/
17 April: WG1-GLOB TTbar threshold https://indico.cern.ch/event/1404821/
17/18 April: WG1-FLAV mini-workshop https://indico.cern.ch/event/1401678/
29 April: WG1-SRCH LLPs https://indico.cern.ch/event/1392179/

Strong UK input through Aidan Robson and Christos Leonidopoulos.

ECFA e^+e^- Higgs/EW/top factory study

In order to harness efforts most efficiently, a set of 'focus topics' has been defined, which cover a characteristic set of measurements that could be made at such a future facility. Set is not comprehensive, but chosen to complete overall picture and to explore interplay of physics potential, analysis methods and detector performance.

List of topics, and other practical information, summarised in arXiv:2401.07564.

Topics not on this list can also be studied, and will be considered for final report.

1. **HtoSS** — $e^+e^- \to Zh$: $h \to s\bar{s}$ ($\sqrt{s} = 240/250$ GeV)
2. **ZHang** — Zh angular distributions and CP studies
3. **Hself** — Determination of the Higgs self-coupling
4. **Wmass** — Mass and width of the W boson from the pair-production threshold cross section lineshape and from decay kinematics
5. **WWdiff** — Full studies of WW and $e\nu W$
6. **TTthres** — Top threshold: Detector-level simulation studies of $e^+e^- \to t\bar{t}$ and threshold scan optimisation
7. **LUMI** — Precision luminosity measurement
8. **EXscalar** — New exotic scalars
9. **LLPs** — Long-lived particles
10. **EXtt** — Exotic top decays
11. **CKMWW** — CKM matrix elements from W decays
12. **BKtautau** — $B^0 \to K^{0*}\tau^+\tau^-$
13. **TwoF** — EW precision: 2-fermion final states ($\sqrt{s} = M_Z$ and beyond)
14. **BCfrag and Gsplit** — Heavy quark fragmentation and hadronisation, gluon splitting and quark-gluon separation

Timeline of study has had to be contracted, in light of earlier date of EPPSU, but there is still time to become involved ! A full draft of final report is foreseen before end of year, with any new results for inclusion to be shown in Paris in October.

Backups

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- Higgs physics capabilities
- Other physics capabilities
- Timescale and cost
- Technological readiness

Difficult to believe any project will deliver physics much before 2040,
But there is certainly a wide spread in when each machine can turn on.

CERN provides great advantages

– an international lab with established funding stream

but also challenges

– full exploitation of HL-LHC quite rightly remains a high priority.

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- Technological readiness
- Prospects of international collaboration

Easier for CERN, harder for China.

Even when the political climate is friendly, challenges can exist (*e.g.* ILC).

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- Cul de sac or open door to future projects ?

FCC-ee provides the tunnel and infrastructure for the FCC-hh…
…but also (arguably) closes-out other options prematurely.

Linear colliders can be upgraded to TeV energies.

HALHF road-tests an accelerator technology that has great future potential.