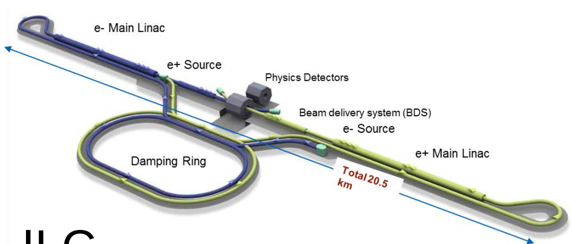
High-energy e^+e^- colliders

A reminder of options on the table, differences in main parameters and how this influences physics opportunities…

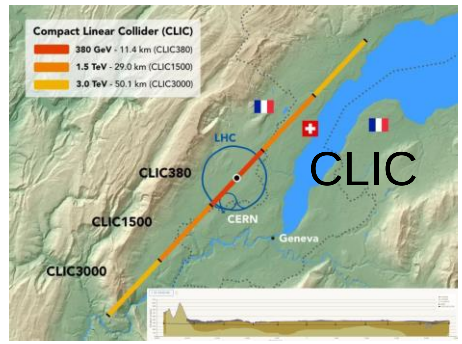
…intentionally, there is no mention of cost, timescale, sustainability *etc.*
This meeting is focused on physics opportunities, not project choice !

Guy Wilkinson
UK EPPSU meeting, Durham
23/5/24

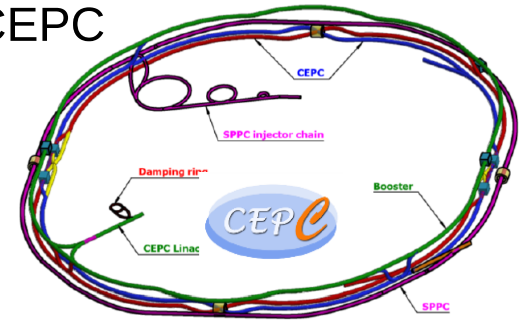
e^+e^- Higgs factories – a wealth of choice



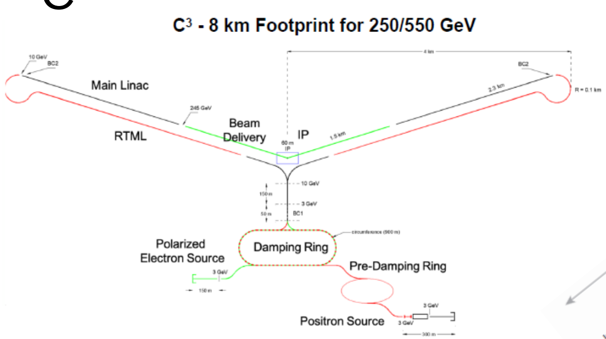
ILC

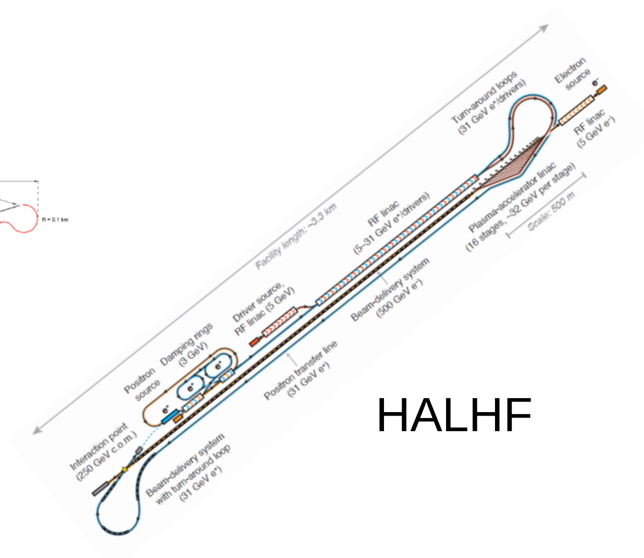


CEPC



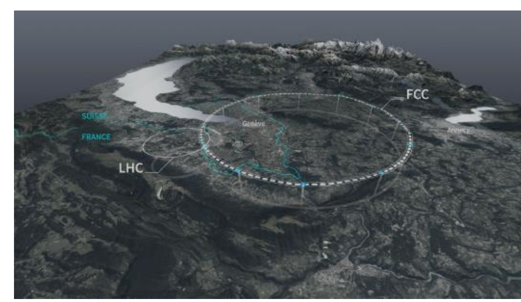
C^3





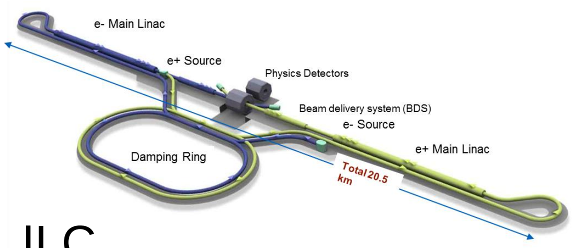
HALHF

FCC-ee

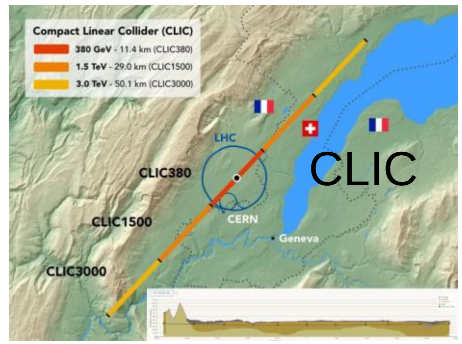


e^+e^- Higgs factories – a wealth of choice

Technologically mature projects, with well-understood physics capabilities

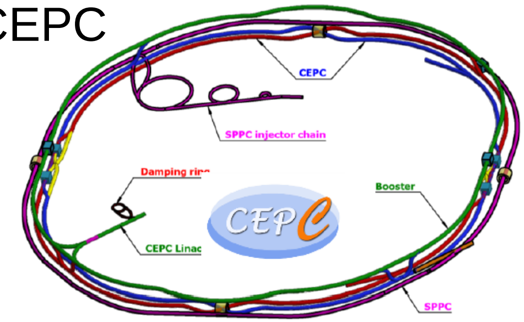


ILC

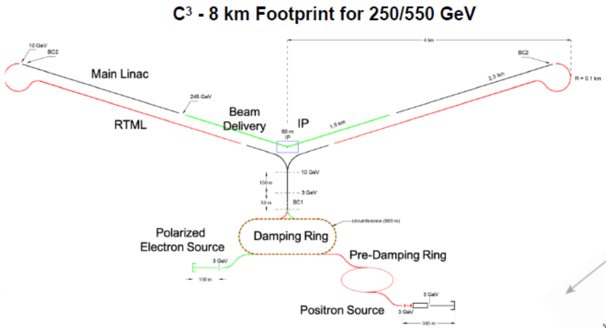


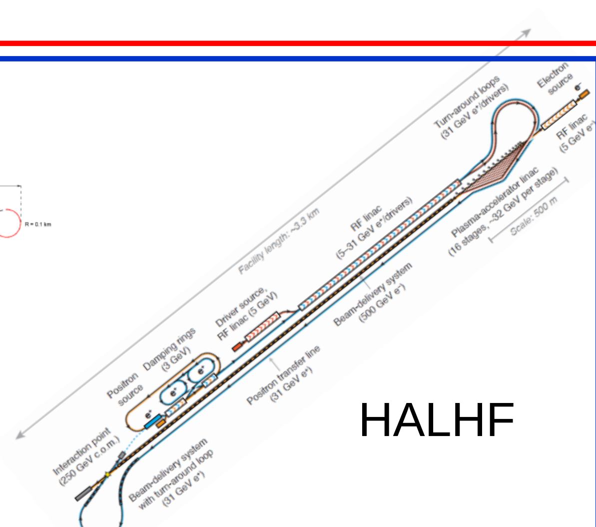
CLIC

CEPC



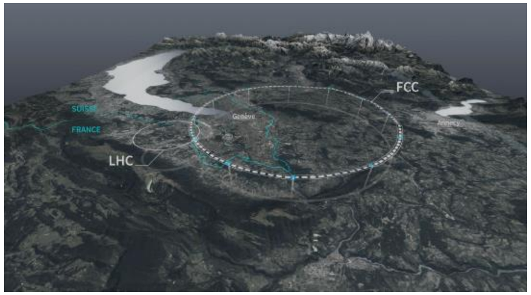
C³





HALHF

FCC-ee



More recent proposals needing further study

Physics considerations

What differences exist between physics opportunities at circular & linear machines?

- Circular vs linear

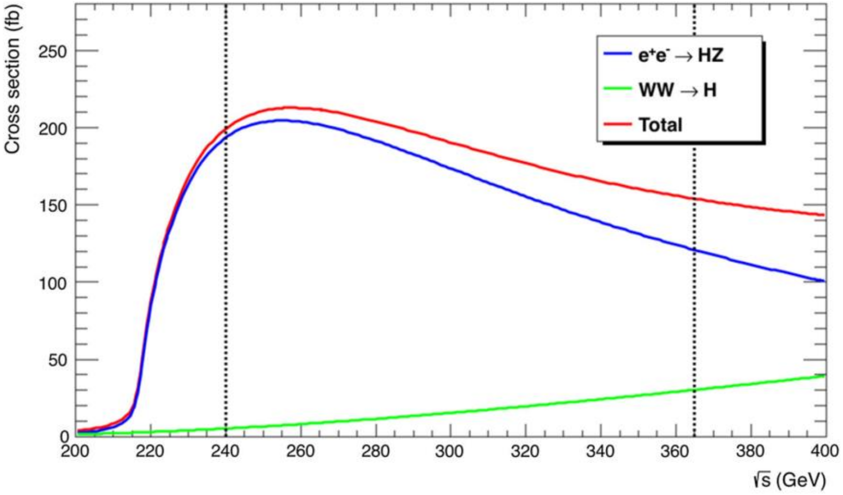
Circular	Linear
Higher luminosities for Z, WW and ZH. No operation above ttbar	Possible to operate at energies well above ttbar threshold
Transverse polarisation allows for precise beam-energy calibration (important for Z and W EW physics)	Longitudinal polarisation generally available (useful for Z and Higgs physics)
Longitudinal polarisation more challenging (but in CEPC baseline, and will be considered by FCC)	Options exist with much smaller footprint that circular machines

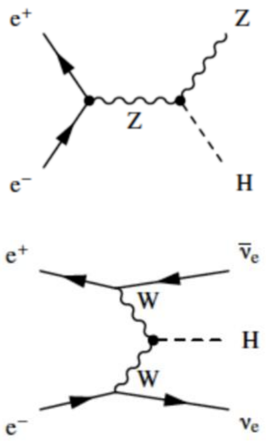
Physics considerations

What differences exist between physics opportunities at circular & linear machines?

- Circular vs linear
- Higgs physics capabilities

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





FCC-ee 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.

Physics considerations

What differences exist between physics opportunities at circular & linear machines?

- Circular vs linear
- Higgs physics capabilities
- Other physics capabilities

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

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

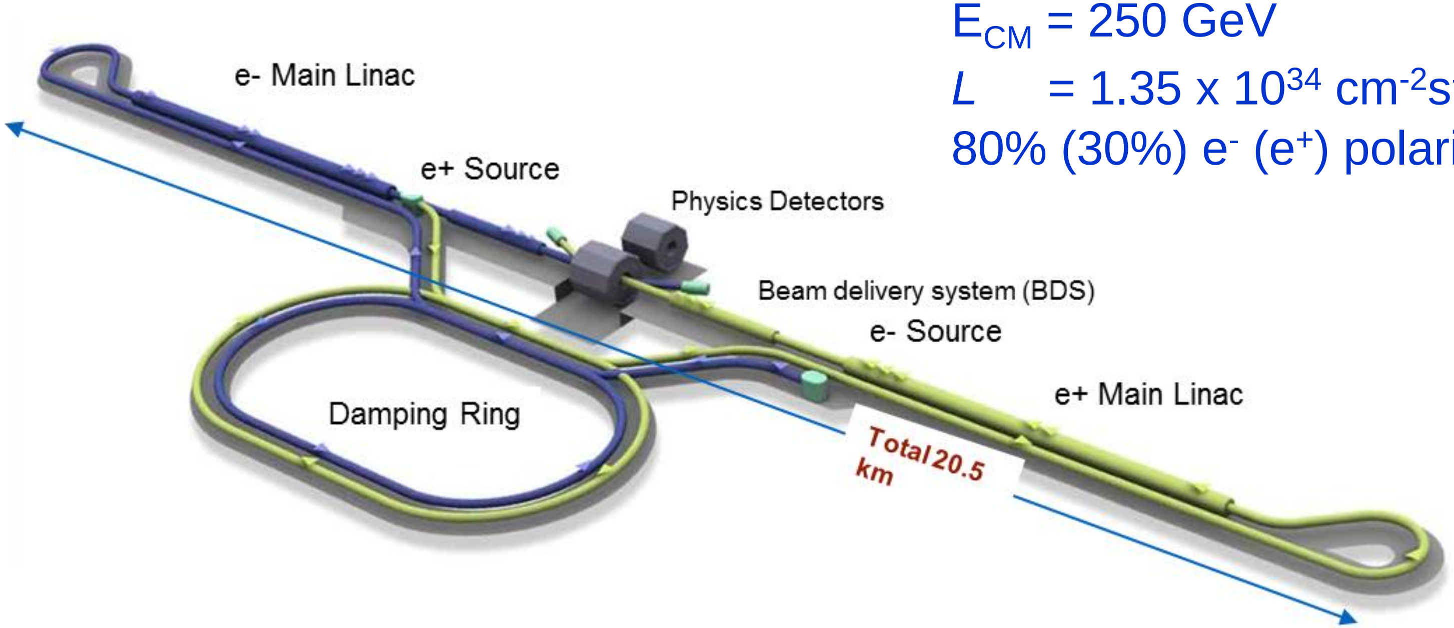
ILC – current baseline

Well-established and mature project. Current baseline for first stage is descoped from 500 GeV machine proposed in 2013 TDR.

E_{CM} = 250 GeV

L = $1.35 \times 10^{34}\ cm^{-2}s^{-1}$

80% (30%) e^- (e^+) polarisation



8,000 1.3 GHz
SRF cavities @ 2K

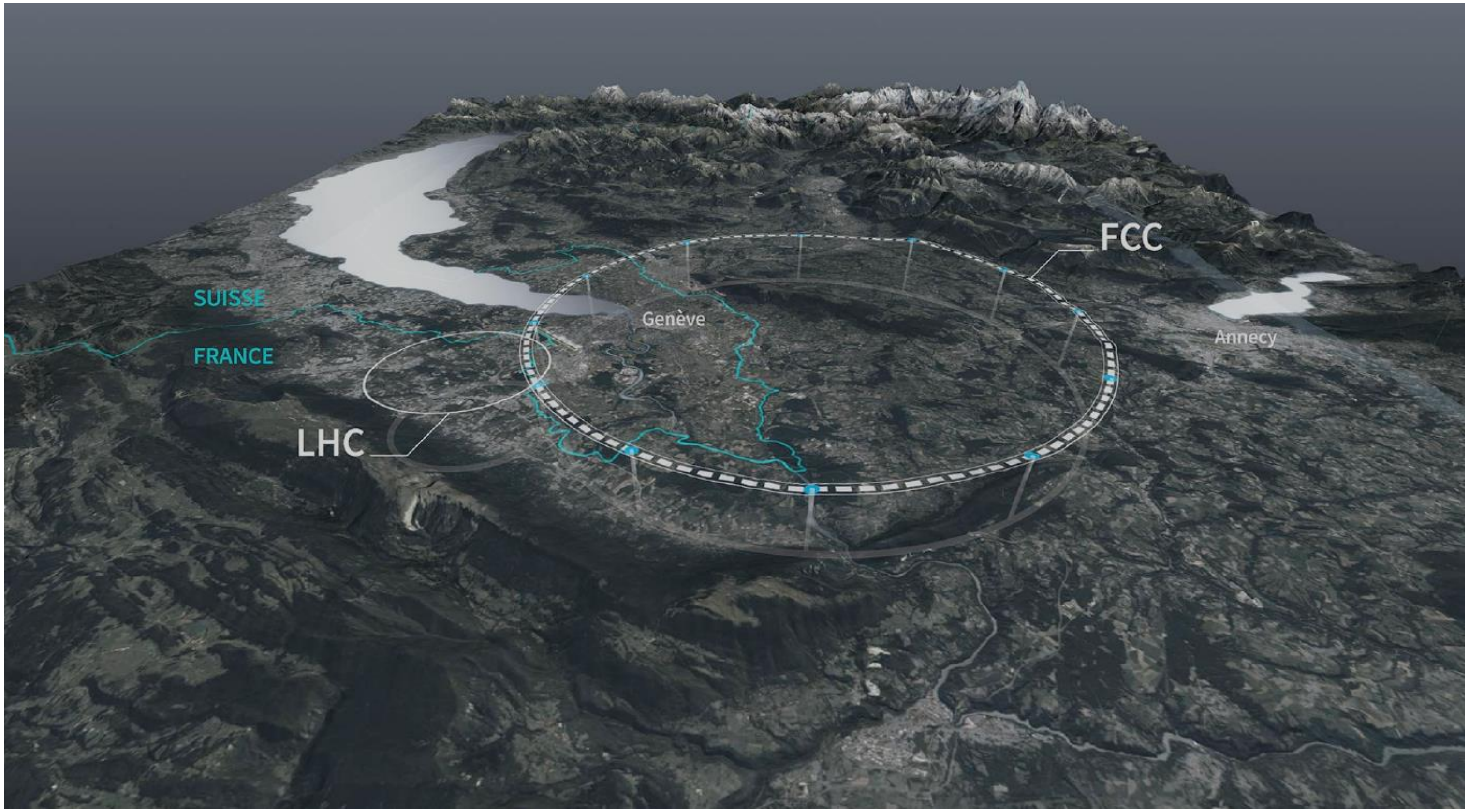
ILC – upgrade options

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	$\mathcal{L}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	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	$\gamma\epsilon_x$	μm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	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

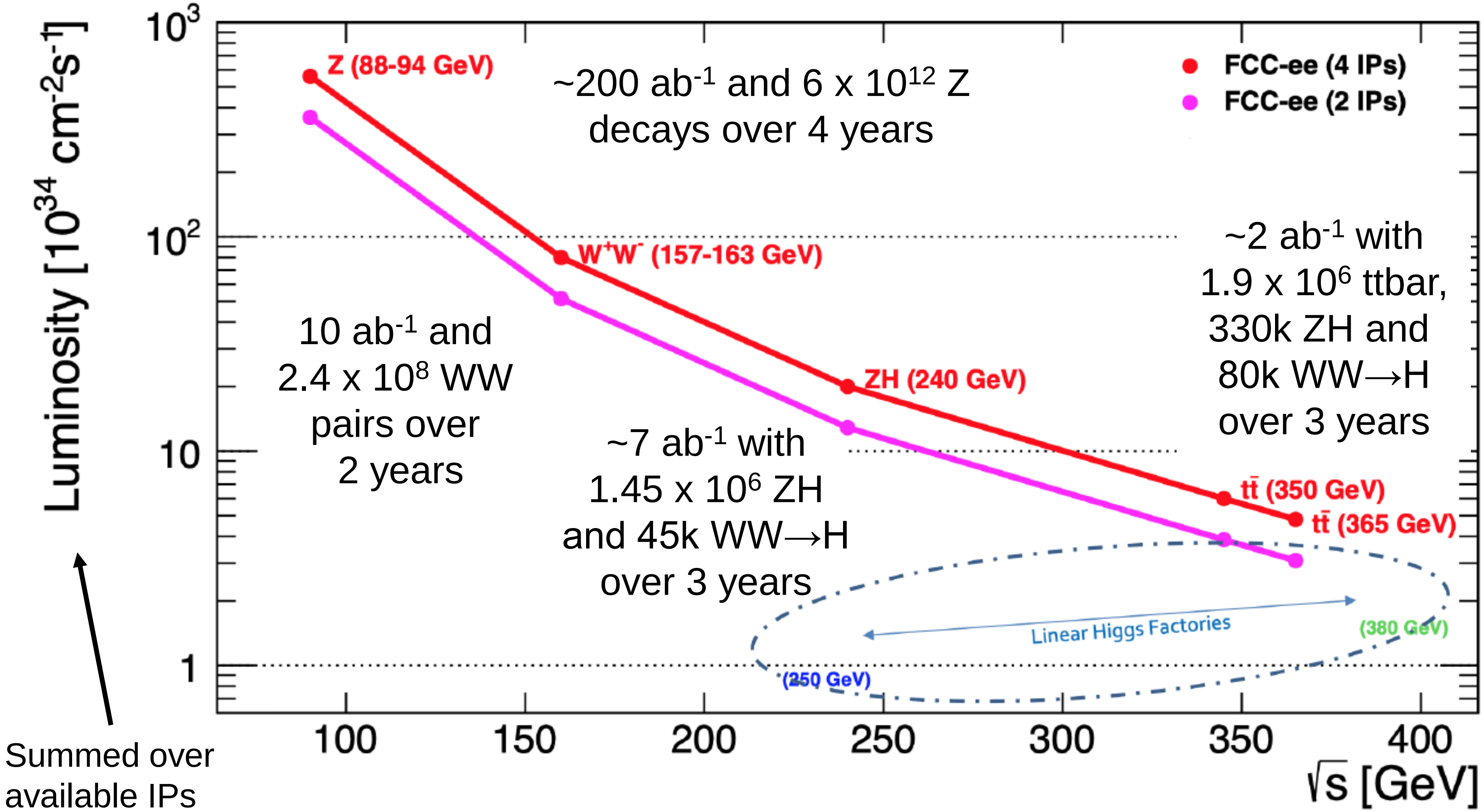
FCC-ee

91 km tunnel, four IPs, E_{CM} running points from Z pole to 365 GeV.



FCC-ee: baseline run plan

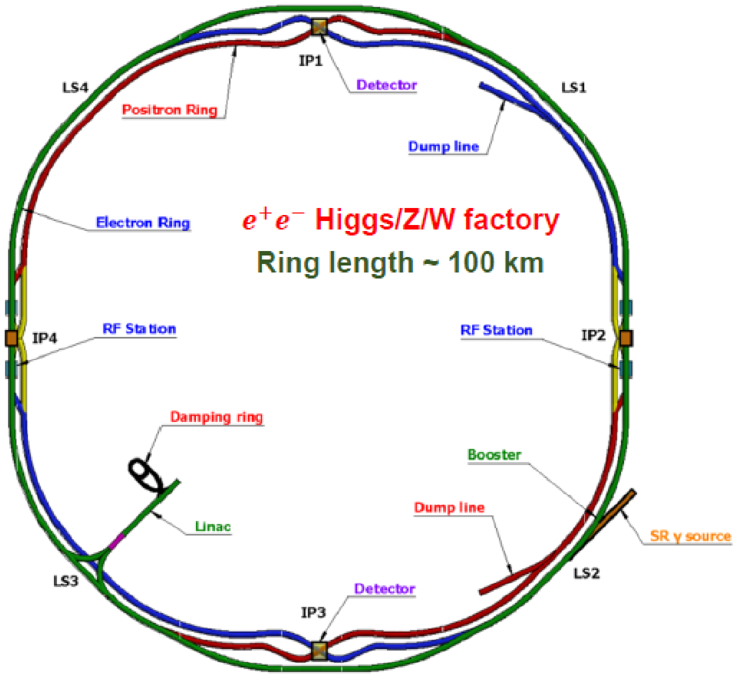
FCC-ee will enable precision studies of all the heavy particles in the SM.

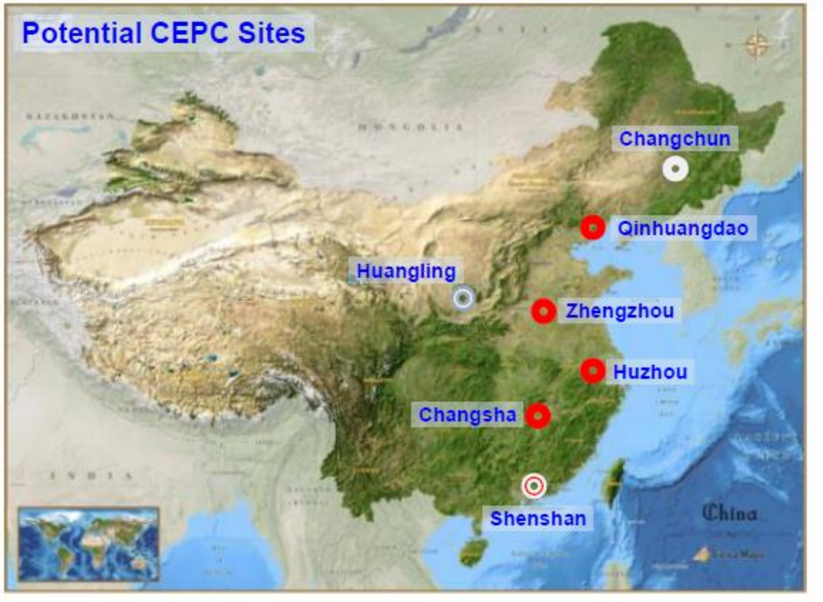


Other running points, *e.g.* 125 GeV for electron Yukawa measurement, under study.

Meanwhile in China…

CEPC is a broadly similar project to FCC-ee (albeit with interesting differences).





(More information available from
website of recent Marseille workshop)

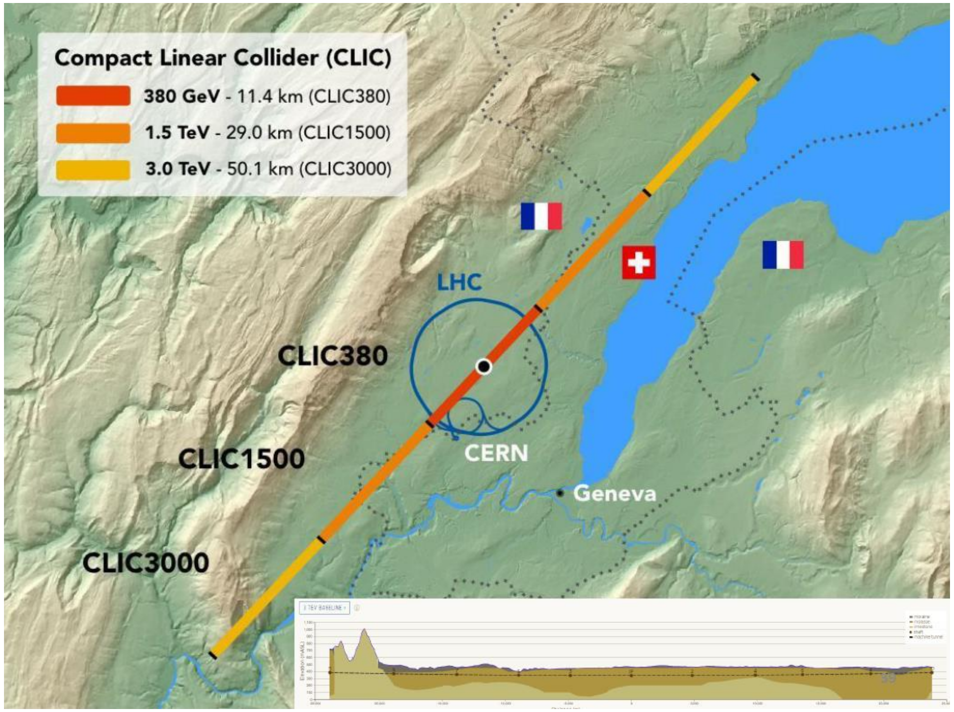
Compact Linear e^+e^- Collider (CLIC)

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

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

First stage:
- 380 GeV
- 11 km
- 20,500 cavities

Can be upgraded up to 1.5, 3 TeV.

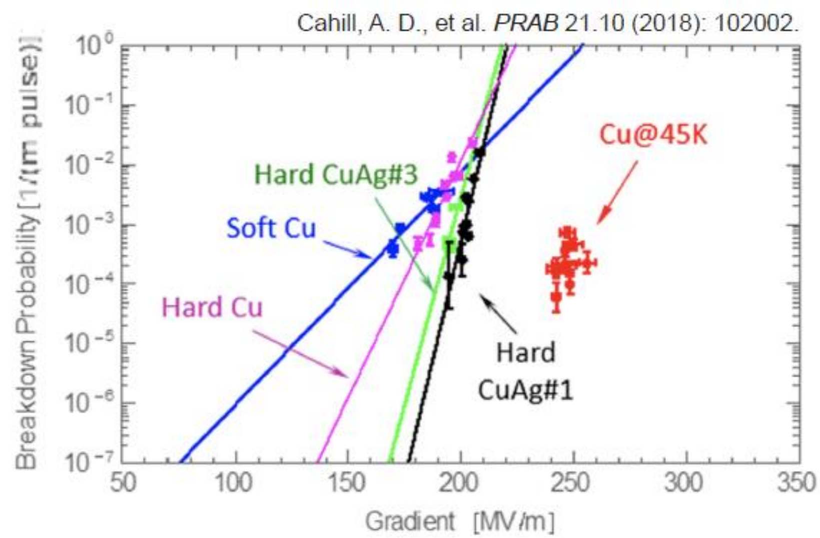


Extensively studied (CDR 2012), with substantial inputs to last EPPSU.

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.

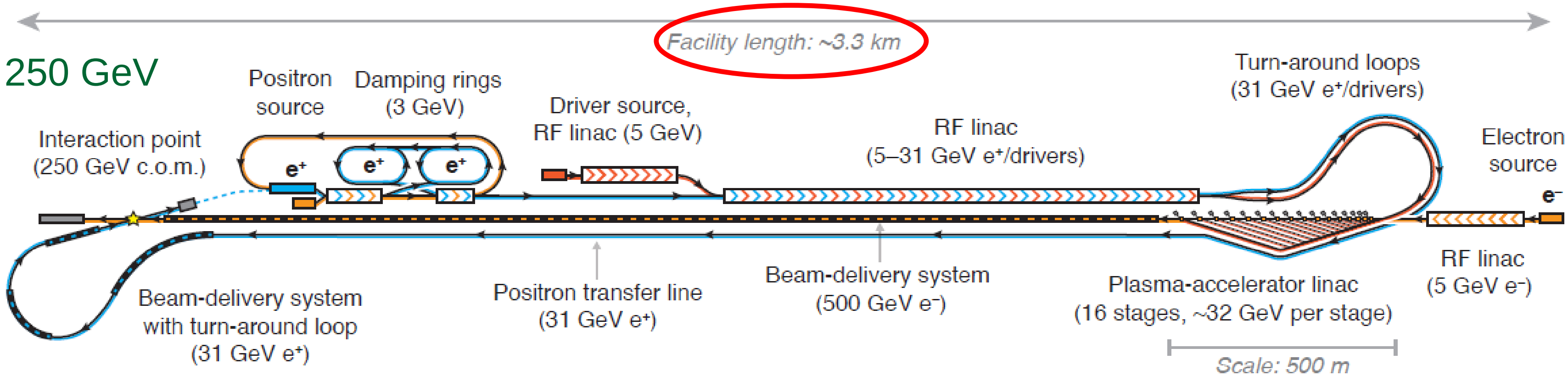


Big idea: cool copper to 80 K. Here the conductivity is higher, which reduces the resistive heating that cases defects, and allows for higher gradients (~100 MeV/m).

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

Significant R&D required for PWA.