Overview of proposed Higgs factories

Summary of ECFA Higgs, Top & ElectroWeak Factory Workshop (Oct. 2024)

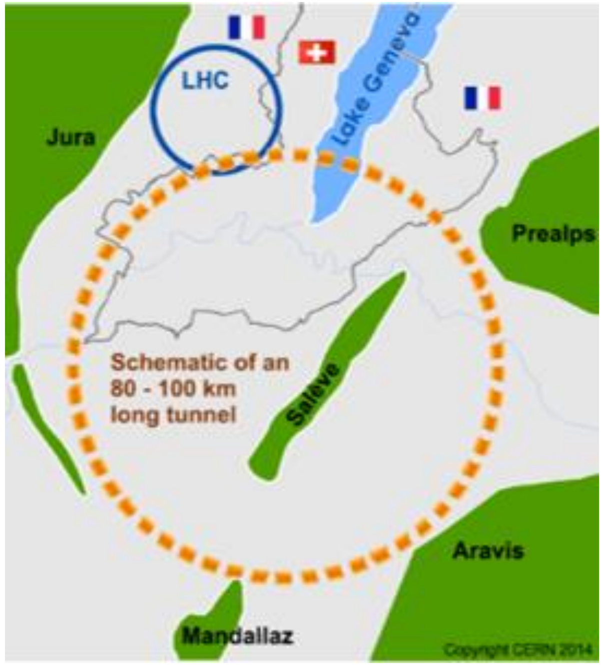
Thomas Bergauer

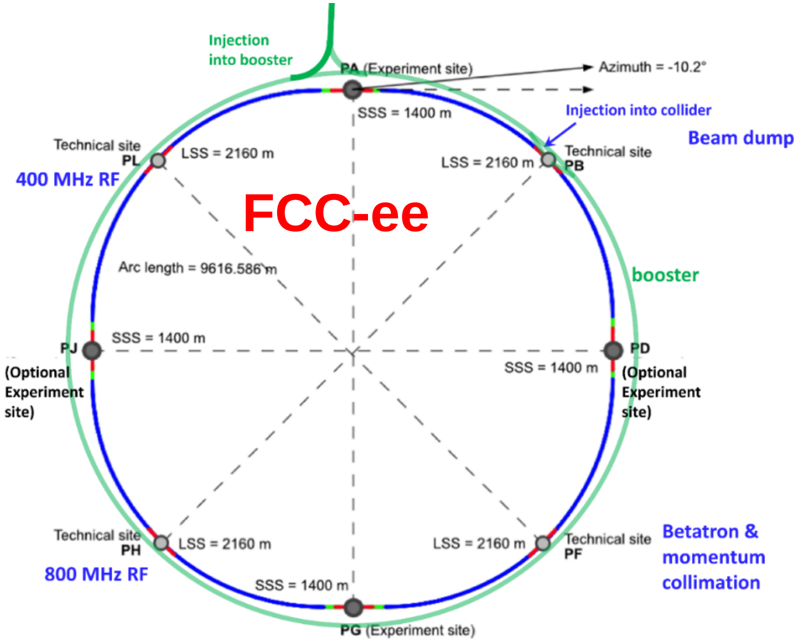
11 Oct 2024

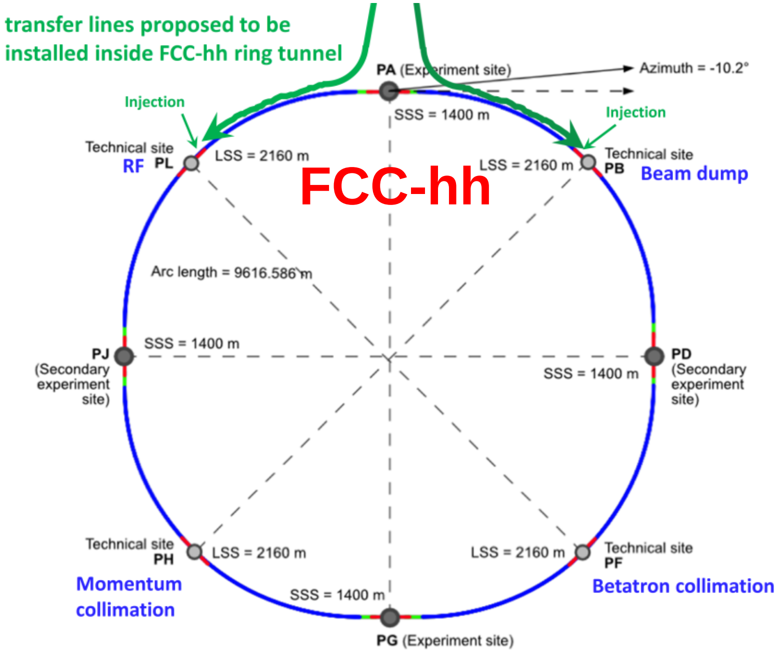
FCC

comprehensive long-term programme maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**







2020 - 2045 | **2045 - 2065** | **2070 -**

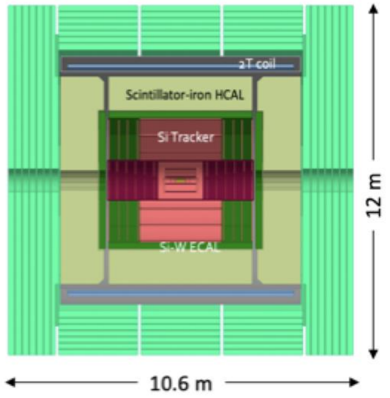
FCC-ee

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
	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

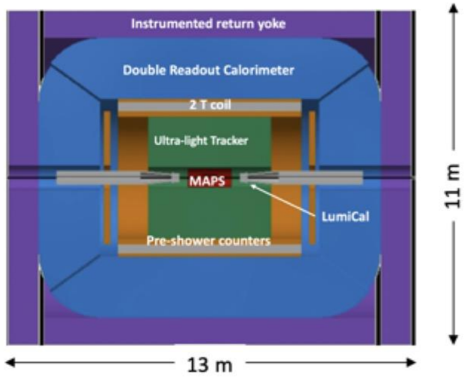
F. Gianotti

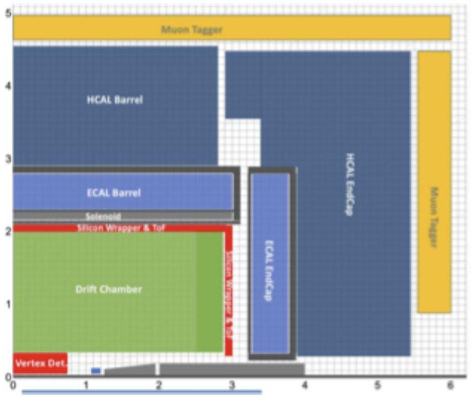
FCC Detector Concepts

CLD	IDEA	Noble Liquid ECAL based



CDR





new

CLD

- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker; CALICE-like calorimetry; large coil, muon system
- Engineering and R&D needed for
  - reduction of tracker material budget
  - operation with continous beam (no power pulsing: cooling of Si sensors for tracking + calorimetry)
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: timing and/or RICH?

IDEA

- Less established design
  - But still ~15y history: ILC 4th Concept
- Si vtx detector; ultra light drift chamber w powerfull PID; compact, light coil; monolitic dual readout calorimeter; muon system
  - Possibly augmented by crystal ECAL
- Active community
  - Prototype designs, test beam campains, …

Noble Liquid ECAL based

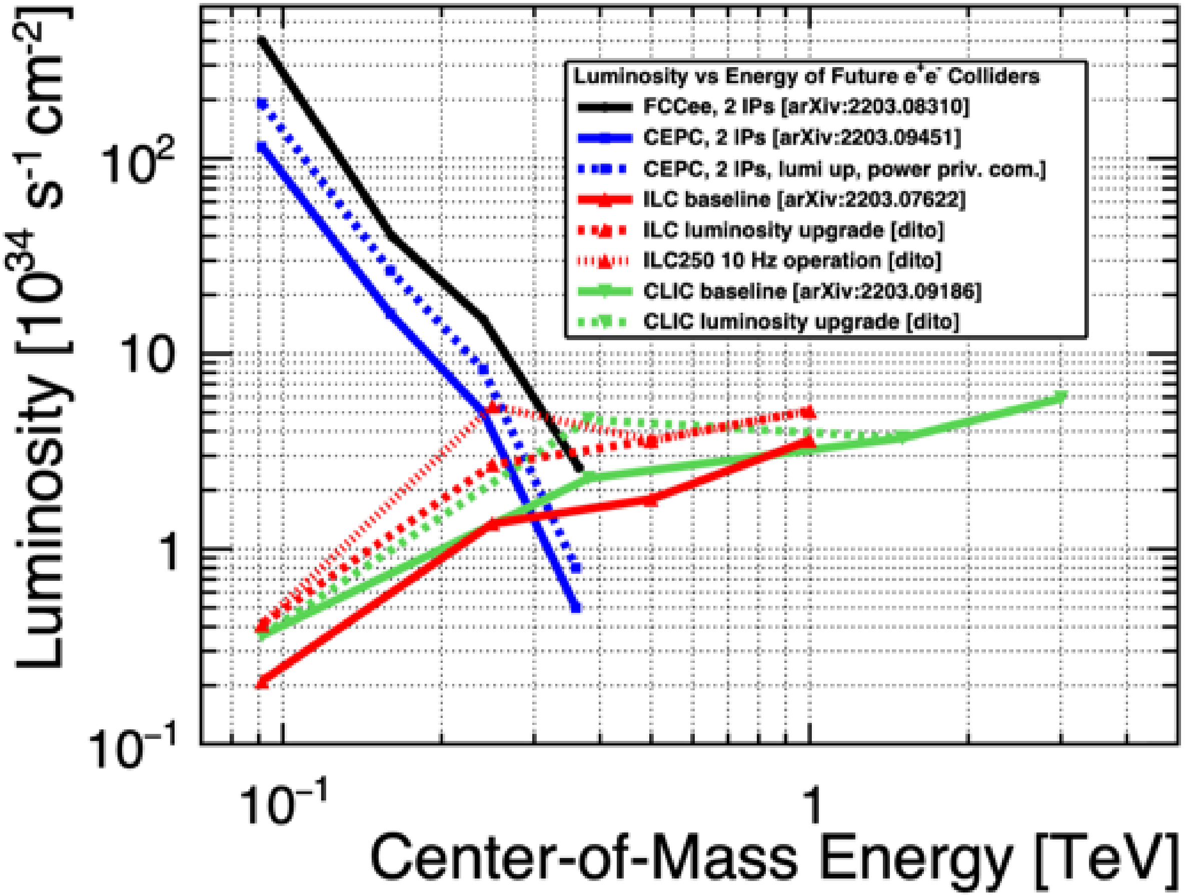
- A design in its infancy
- High granularity Noble Liquid ECAL is core
  - Pb+LAr (or denser W+LCr)
- Drift chamber; CALICE-like HCAL; muon system.
- Coil inside same cryostat as LAr, possibly outside ECAL
- Active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

Linear Colliders

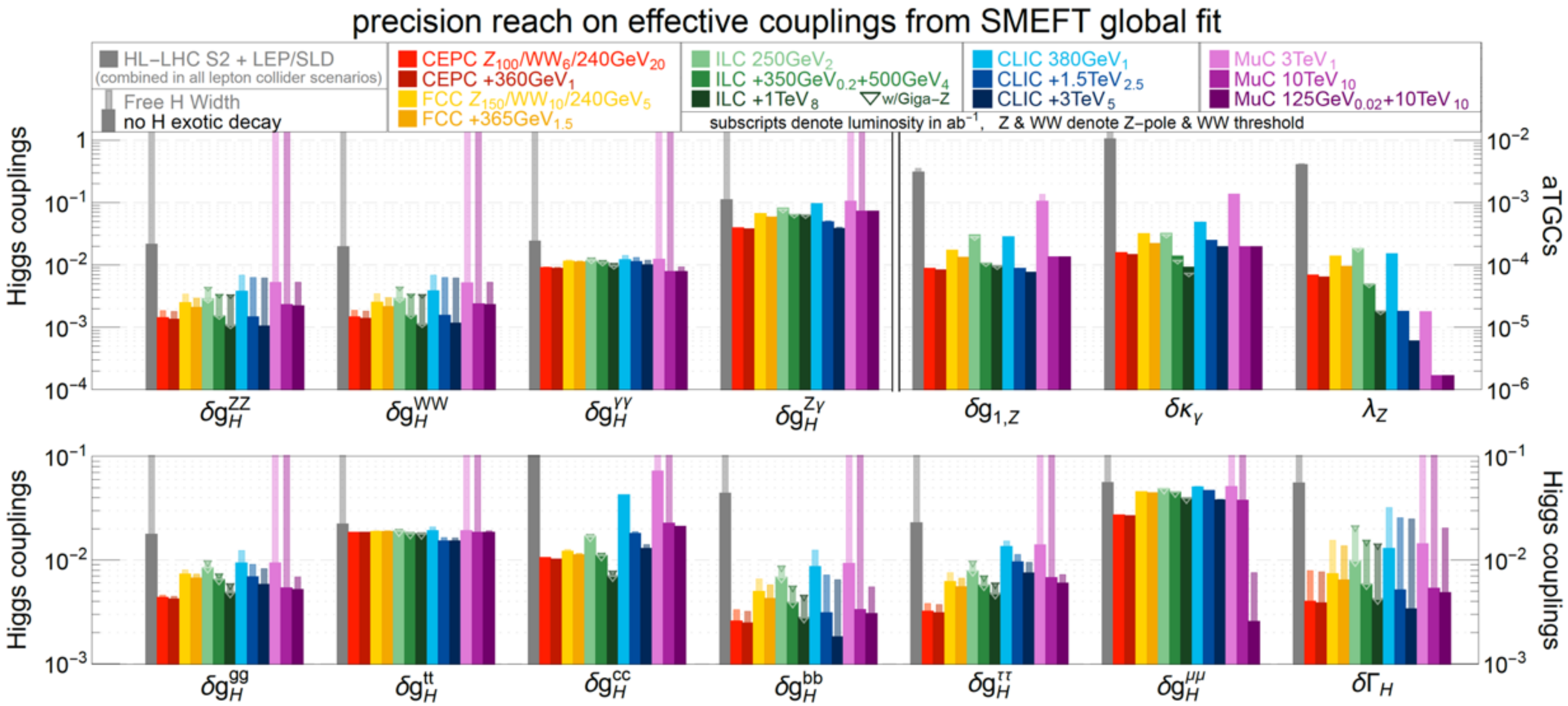
Increased luminosity with energy,
e.g. 1-3 x 10^{34} $cm^{-2}s^{-1}$ for Higgs factories at 250 GeV, 6 x 10^{34} at 3 TeV

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



LC Physics Performance



e+e- colliders show very comparable performance for standard Higgs program, despite quite different assumed integrated luminosities (beam polarization)

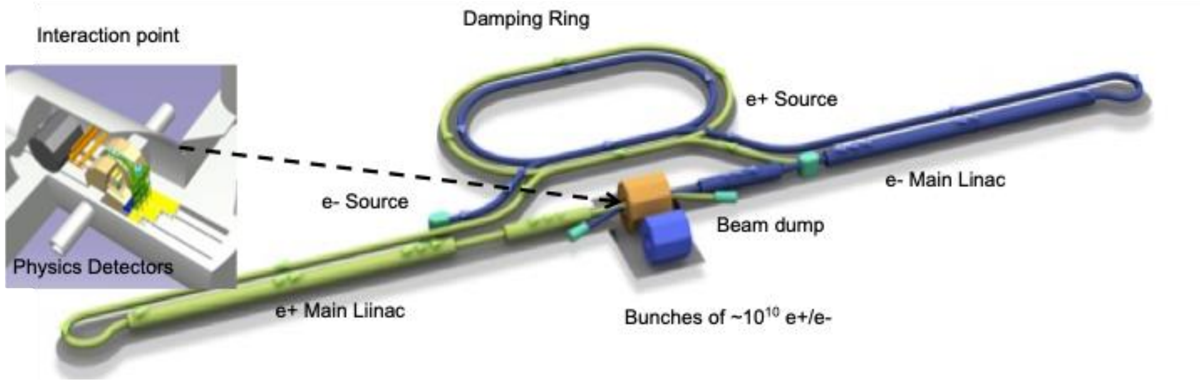
- several couplings at few-0.1% level: Z, W, g, b, τ
- some more at ~1%: γ, c

Arxiv: 2206.08326

ILC

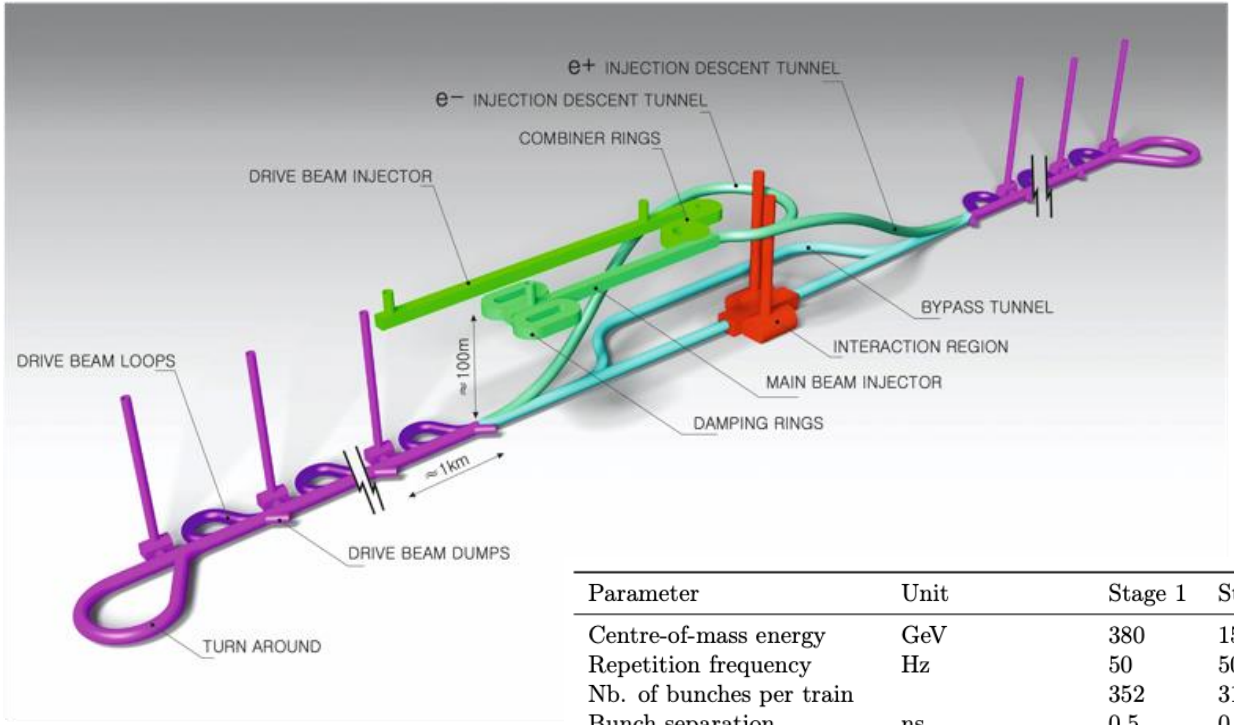
- **250 GeV, ~2ab-1:**
  - precision Higgs mass and total ZH cross-section
  - Higgs -> invisible (Dark Sector portal)
  - basic ffbar and WW program
  - optional: WW threshold scan
- **Z pole, few billion Z's: EWPOs 10-100x better than today**
- **350 GeV, 200 fb-1:**
  - precision top mass from threshold scan
- **500…600 GeV, 4 ab-1:**
  - Higgs self-coupling in ZHH
  - top quark ew couplings
  - top Yukawa coupling incl CP structure
  - improved Higgs, WW and ffbar
  - probe Higgsinos up to ~300 GeV
  - probe Heavy Neutral Leptons up to ~600 GeV
- **800…1000 GeV, 8 ab-1:**
  - Higgs self-coupling in VBF
  - further improvements in tt, ff, WW, ….
  - probe Higgsinos up to ~500 GeV
  - probe Heavy Neutral Leptons up to ~1000 GeV
  - searches, searches, searches, …

ILC @ Japan:

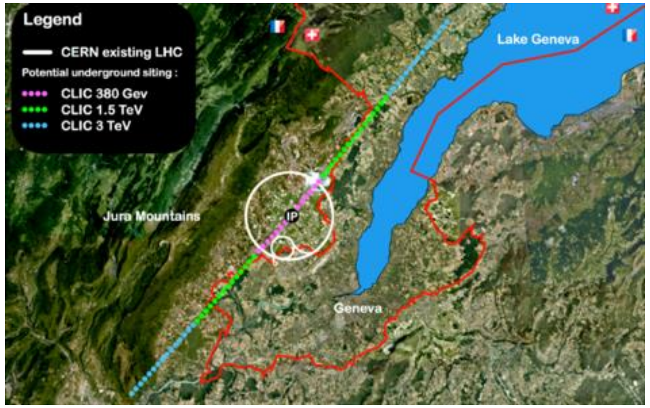


Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade
Centre of mass energy	$\sqrt{s}$	GeV	250	250
Luminosity	$\mathcal{L}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	1.35	2.7
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)
Repetition frequency	f_{rep}	Hz	5	5
Bunches per pulse	n_{bunch}	1	1312	2625
Bunch population	N_e	10^{10}	2	2
Linac bunch interval	Δt_b	ns	554	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8
Beam pulse duration	t_{pulse}	μs	727	961
Average beam power	P_{ave}	MW	5.3	10.5
RMS bunch length	σ_z^*	mm	0.3	0.3
Norm. hor. emitt. at IP	$\gamma\epsilon_x$	μm	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	nm	35	35
RMS hor. beam size at IP	σ_x^*	nm	516	516
RMS vert. beam size at IP	σ_y^*	nm	7.7	7.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %
Site AC power	P_{site}	MW	111	128
Site length	L_{site}	km	20.5	20.5

CLIC



Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	1×10^{9}	5.2	3.7	3.7
Bunch length	µm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20



- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 structures at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier) presented in previous ESPP updates
- CDR in 2012 with focus on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs and top.

P5 recommendation (US)

https://www.usparticlephysics.org/2023-p5-report/full-list-of-recommendations

- Recommendation 1: As the highest priority […] complete construction projects and support operations of […] HL-LHC […] Belle-II
- Recommendation 2: Plan and start the following major initiatives in order of priority from highest to lowest:
  - CMB-S4 telescopes both the South Pole and Chile
  - A re-envisioned second phase of DUNE
  - An **offshore Higgs factory**, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. **The current designs of FCC-ee and ILC meet our scientific requirements**.

P5 Recommendations

We recommend the following:

1. As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science. This includes High-Luminosity LHC, the first phase of Deep Underground Neutrino Experiment (DUNE) and Proton Improvement Plan II, the Rubin Observatory to carry out the Legacy Survey of Space and Time (LSST).

2. Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

a. **CMB-S4**, which looks back at the earliest moments of the universe,

b. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam and a third far detector as the definitive long-baseline neutrino oscillation experiment,

c. **Offshore Higgs factory, realized in collaboration with international partners**, in order to reveal the secrets of the Higgs boson,

d. **Ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog,

e. **IceCube-Gen2** for the study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter.

3. Create an improved balance between small-, medium-, and large-scale projects to open new scientific opportunities and maximize their results, enhance workforce development, promote creativity, and compete on the world stage. The proposed portfolio includes implementing the recommended program, Advancing Science and Technology using Agile Experiments (ASTAE).

4. Support a comprehensive effort to develop the resources—theoretical, computational and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV parton center-of-momentum (pCM) collider. In particular, the muon collider option builds on Fermilab strengths and capabilities and supports our aspiration to host a major collider facility in the US.

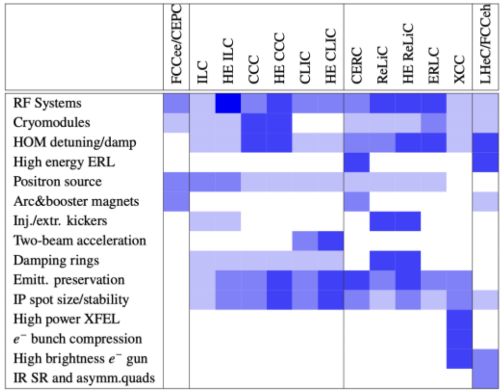
5. Invest in initiatives aimed at developing the workforce, broadening engagement, and supporting ethical conduct in the field. This commitment nurtures an advanced technological workforce not only for particle physics, but for the nation as a whole.

Snowmass Report 2021

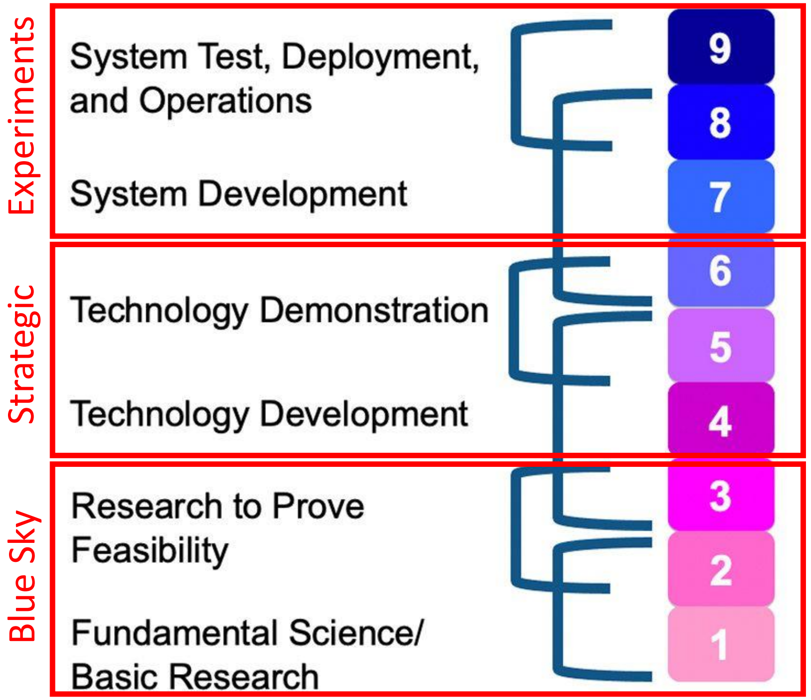
https://arxiv.org/abs/2208.06030

Proposal Name (c.m.e. in TeV)	Collider Design Status	Lowest TRL Category	Technical Validation Requirement	Cost Reduction Scope	Performance Achievability	Overall Risk Tier
FCCee-0.24	II					1
CEPC-0.24	II					1
ILC-0.25	I					1
CCC-0.25	III					2
CLIC-0.38	II					1
CERC-0.24	III					2
ReLiC-0.24	V					2
ERLC-0.24	V					2
XCC-0.125	IV					2
MC-0.13	III					3
ILC-3	IV					2
CCC-3	IV					2
CLIC-3	II					1
ReLiC-3	IV					3
MC-3	III					3
LWFA-LC 1-3	IV					4
PWFA-LC 1-3	IV					4
SWFA-LC 1-3	IV					4
MC 10-14	IV					3
LWFA-LC-15	V					4
PWFA-LC-15	V					4
SWFA-LC-15	V					4
FCChh-100	II					3
SPPC-125	III					3
Coll.Sea-500	V					4

Technical Risk Factor	Color Code
TRL = 1,2	
TRL = 3,4	
TRL = 5,6	
TRL = 7,8	

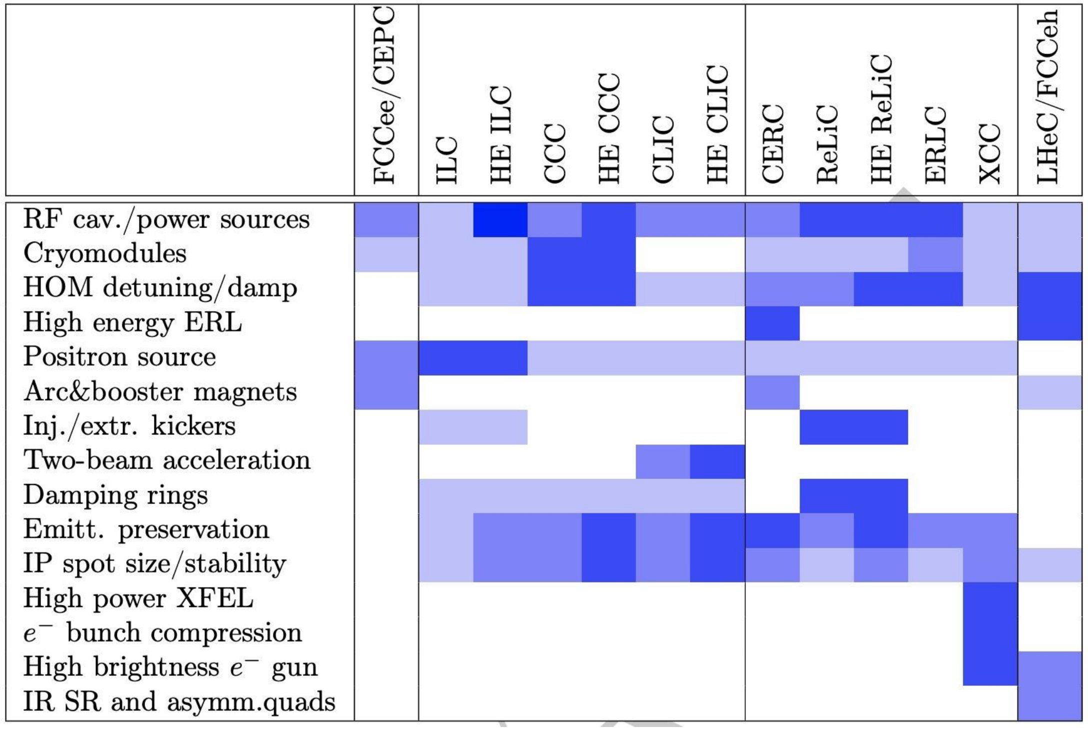


Technology Readiness Levels (TRLs) 1-9:
Method for estimating the maturity of technologies



Snowmass Report 2021

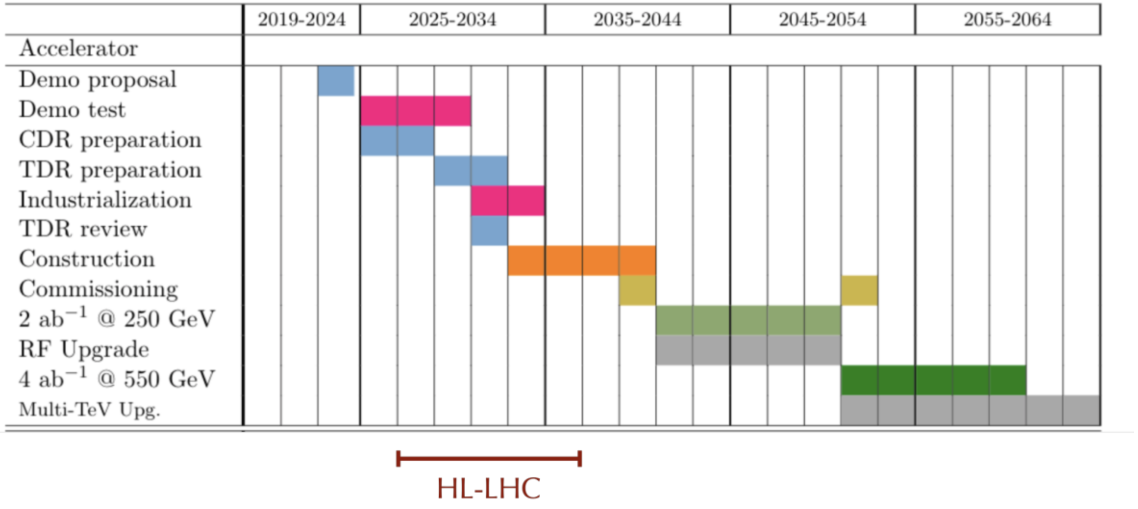
Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
FCC-ee (0.24 TeV)	280	91 km	I	I
CEPC (0.24 TeV)	340	100 km	I	I
ILC (0.25 TeV)	140	14 km	I	I
CLIC (0.38 TeV)	170	13.4 km	II	I
CCC (0.25 TeV)	150	3.7 km	I	I
CERC (0.24 TeV)	90	100 km	II	I
ReLiC (0.24 TeV)	370	20 km	II	I
ERLC (0.24 TeV)	250	60 km	II	I
XCC (0.125 TeV)	90	1.4 km	II	I
MC (0.13 TeV)	200	3 km	I	II
ILC (3 TeV)	~400	59 km	II	II
CLIC (3 TeV)	~550	42 km	III	II
CCC (3 TeV)	~700	26.8 km	II	II
ReLiC (3 TeV)	~780	360 km	III	I
MC (3 TeV)	~230	10-20 km	II	III
LWFA (3 TeV)	~340	1.3 km	II	I
PWFA (3 TeV)	~230	14 km	II	II
SWFA (3 TeV)	~170	18 km	II	II
MC (14 TeV)	~300	27 km	III	III
LWFA $\gamma\gamma$ (15 TeV)	~210	6.6 km	III	I
PWFA $\gamma\gamma$ (15 TeV)	~120	14 km	III	II
SWFA $\gamma\gamma$ (15 TeV)	~90	90 km	III	II
FCC-hh (100 TeV)	~560	91 km	II	III
SPPC (125 TeV)	~400	110 km	II	III

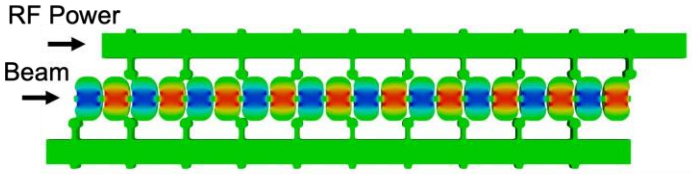


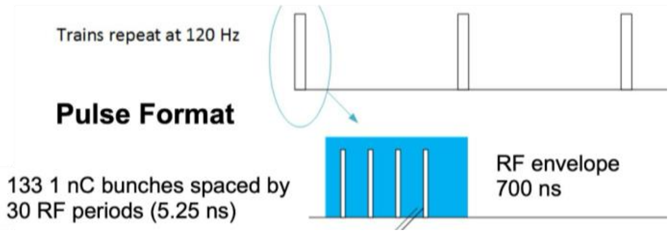
Other Proposals: CCC C^3

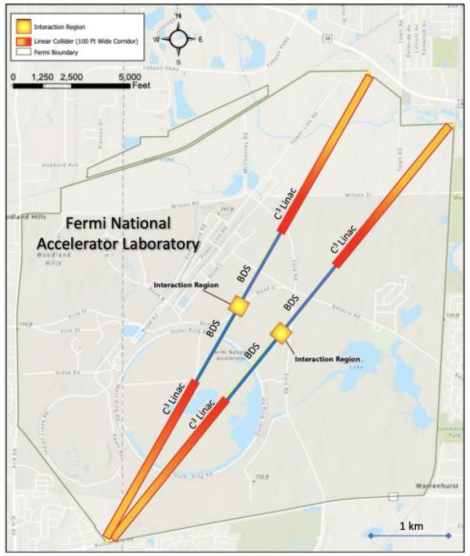
DOI 10.1088/1748-0221/18/07/P07053
and this talk

- **Cool Copper Collider** is based on a new rf technology
  - Distributed power to each cavity from a common RF manifold
  - Operation at cryogenic temperatures (LN_2 ~80K)
  - High gradient: 120 MeV/m
- Evaluating both underground and surface sites
  - Surface – lower cost and faster to first physics
  - "Fermilab Filler" concept

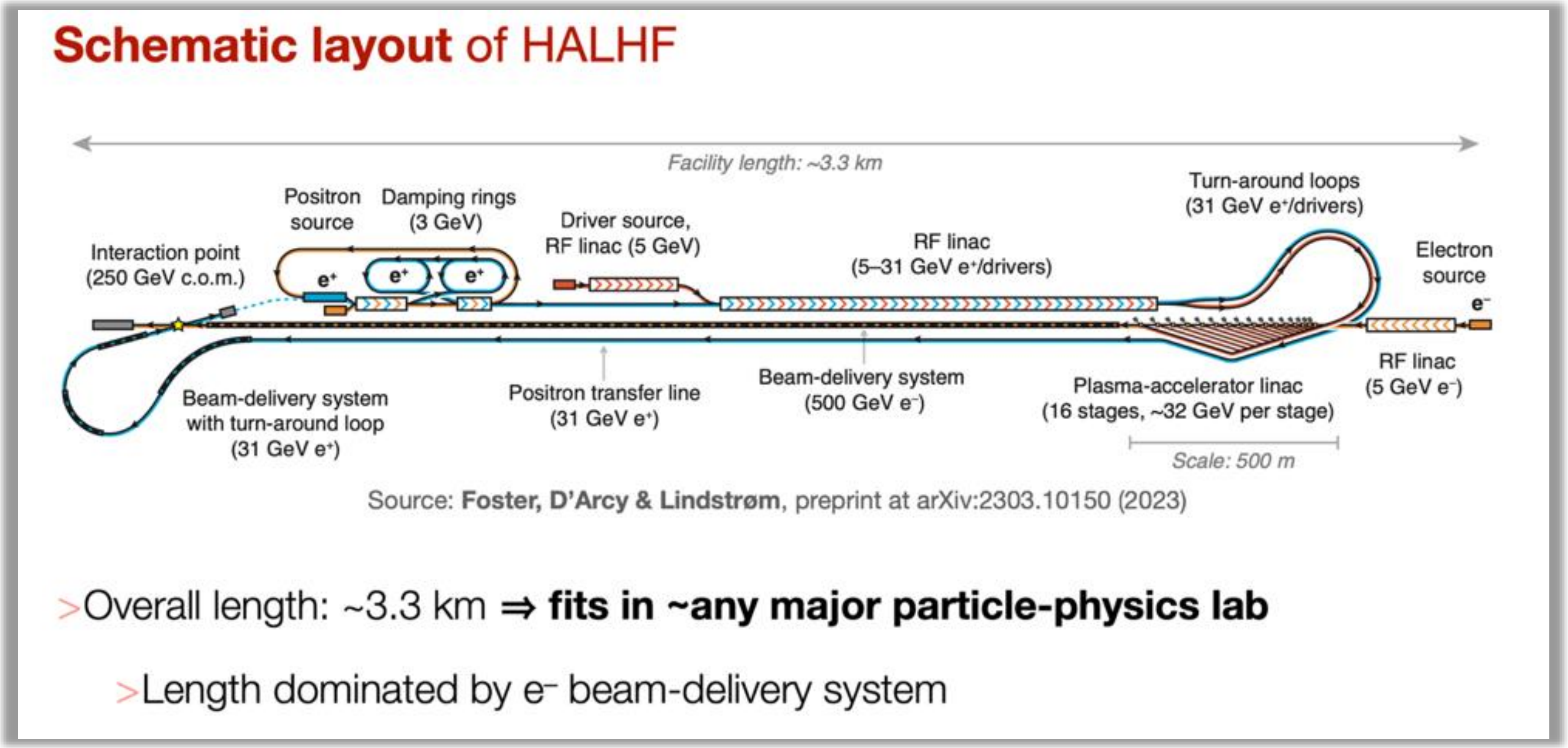






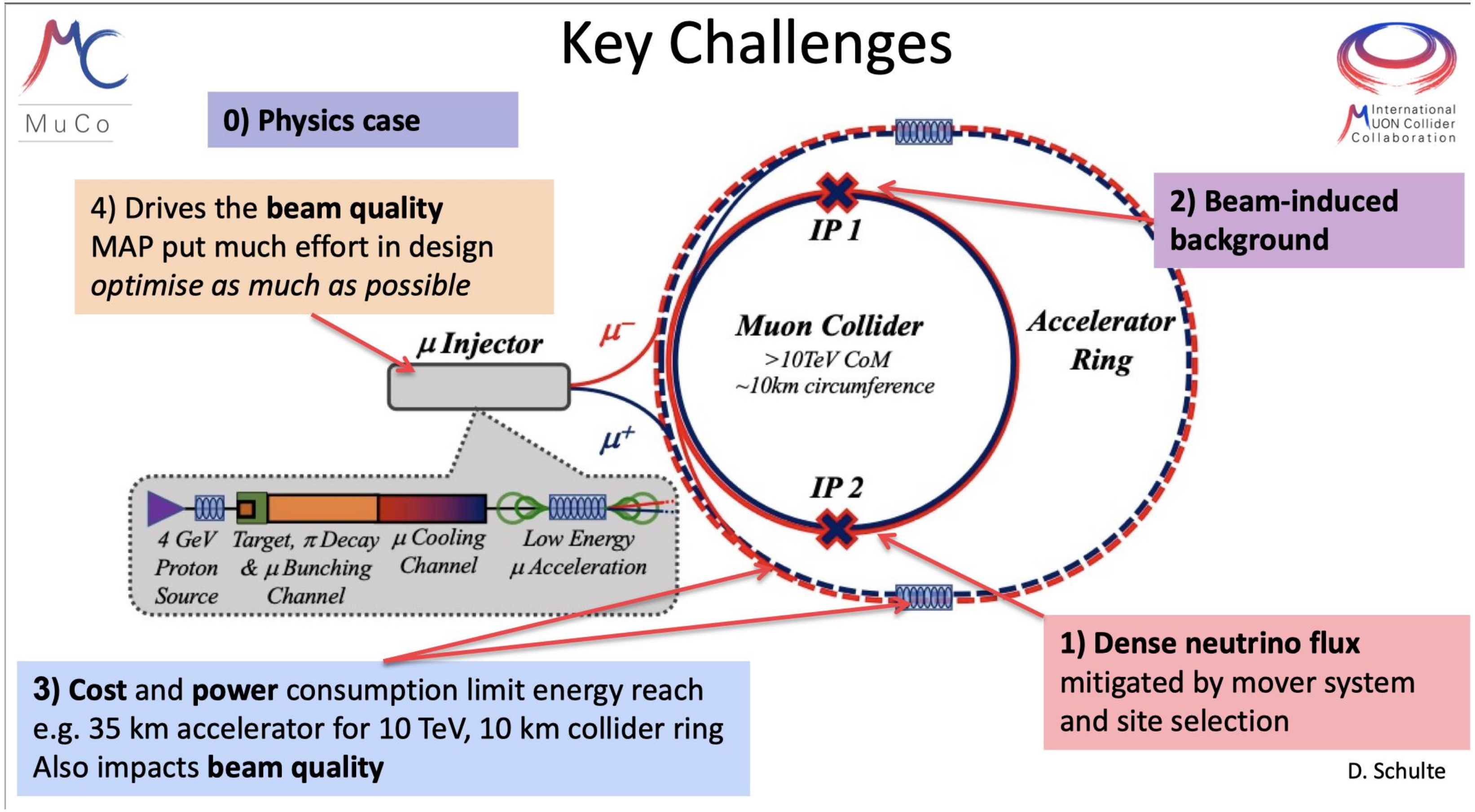


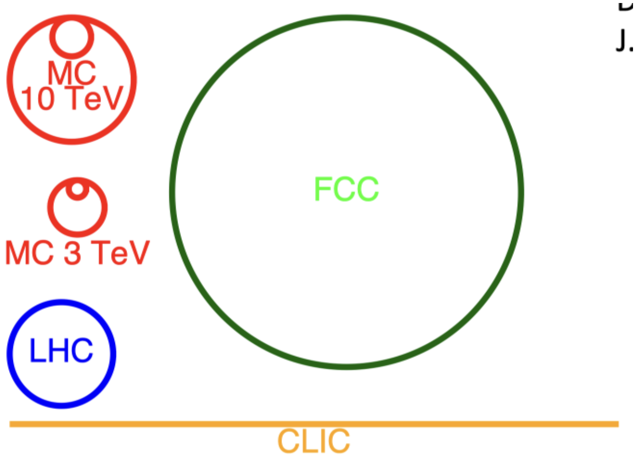
Hybrid Asymmetric Linear Higgs Factory Project - HALHF



- **New concept**, aiming for pre-CDR (LINK)
- 500 GeV for electrons with plasma acceleration
- 31 GeV positrons with RF based linac, used also to provide electron drivebeam for the plasma wakefield acceleration
- Reach 250 GeV collision energy, luminosity 10^{34}
- Asymmetric technologies, energies and bunch charges

Muon Collider





EU Design Study:
https://mucol.web.cern.ch

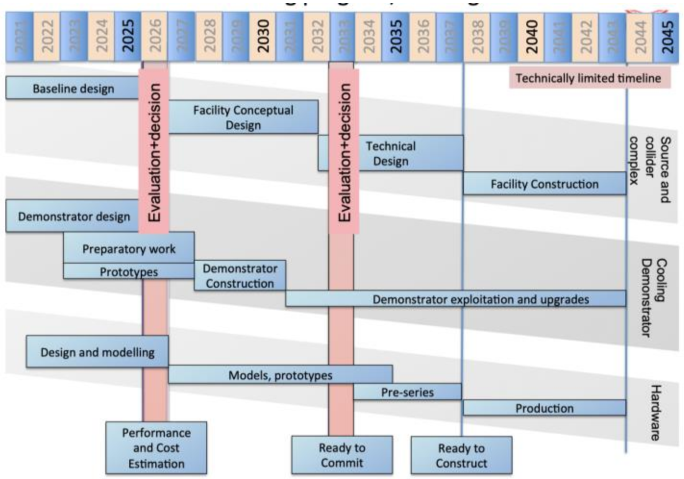


Table 3 Radiation levels per year at a $\sqrt{s} = 1.5$ TeV muon collider and HL-LHC.

	muon collider	HL-LHC
maximum dose at $R = 2.2$ cm	10 Mrad	100 Mrad
maximum dose at $R = 150$ cm	0.1 Mrad	0.1 Mrad
maximum fluence at $R = 2.2$ cm	10^{15} 1 MeV-neq/cm^2	10^{15} 1 MeV-neq/cm^2
maximum fluence at $R = 150$ cm	10^{14} 1 MeV-neq/cm^2	10^{13} 1 MeV-neq/cm^2

Experiments at Muon collider
(Arxiv 2311.03280)

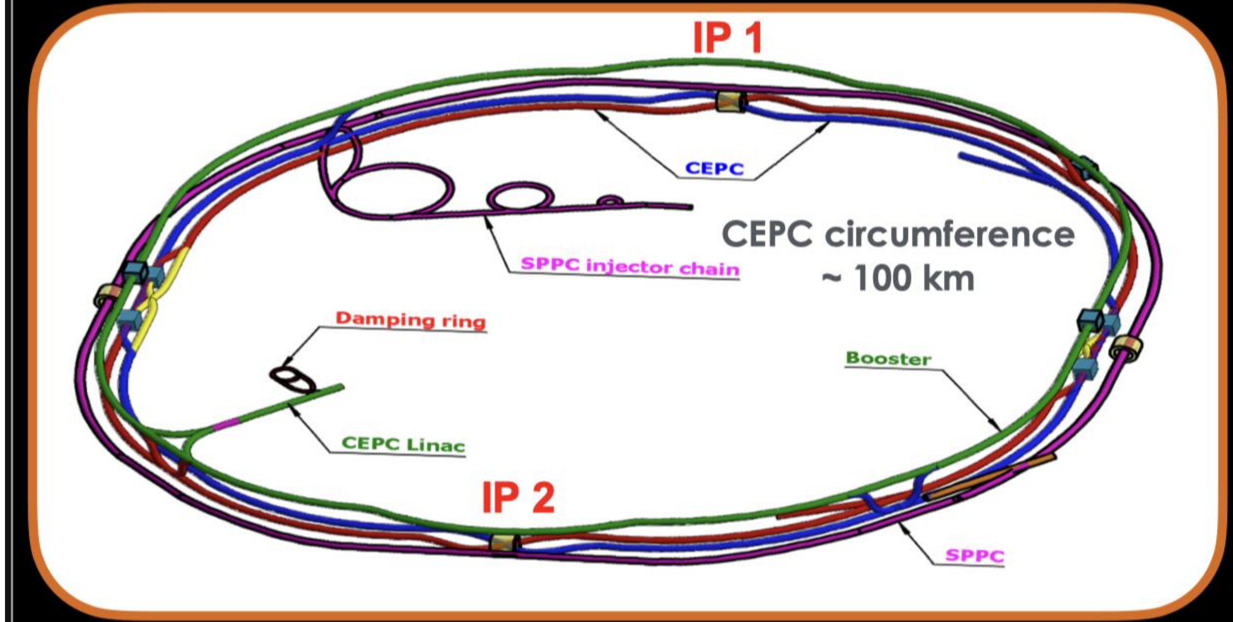
Muon Collider Challenges

- Muon Production: 4GeV Protons on target → Pions → Muons
  - Muon Cooling: Muons generated from pion decay have a broad range of momenta and directions
- Acceleration (max time 2.2μs): rapid-cycling synchrotrons or linear accelerators
  - High-field superconducting magnets capable of high radiation tolerance.
  - Although muons radiate less synchrotron energy, radiation is generated by decaying muons.

- Decay Products Management: Muons decay into electrons and neutrinos, producing a large flux of secondary radiation.
  - Detectors need to withstand the intense radiation environment from muon decay
  - Neutrino Radiation: The decay of muons results in high-energy, long-range neutrinos

CEPC in China as FCC-ee competitor

- CEPC accelerator TDR has been completed and formally released in Dec. 2023 (arXiv: 2312.14363)
  - Price tag: 5B€



Mode	√s (GeV)	Events
WH	240	>1 million
WW	160	
Z	90	Tera-Z

Upgrade path

1. Higher power: 30 MW → 50 MW
2. Higher energy → top quark pair production
3. Super pp Collider (SppC) at ~100 TeV

CEPC to start construction in ~2027/8 and deliver Higgs data in the 2030s

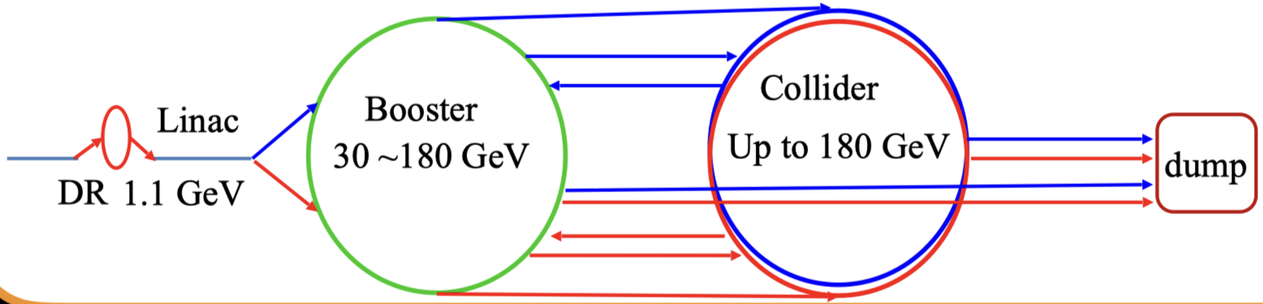
CEPC Parameters

Booster

		Higgs		*W*	*Z*		*tt*
		Off axis injection	On axis injection	Off axis injection	Off axis injection		Off axis injection
Circumference	km	100					
Injection energy	GeV	30					
Extraction energy	GeV	120		80	45.5		180
Bunch number		268	261+7	1297	3978	5967	35
Maximum bunch charge	nC	0.7	20.3	0.73	0.8	0.81	0.99
Beam current	mA	0.94	0.98	2.85	9.5	14.4	0.11
SR power	MW	0.94	1.66	0.94	0.323	0.49	0.93
Emittance	nm	1.26		0.56	0.19		2.83
RF frequency	GHz	1.3					
RF voltage	GV	2.17		0.87	0.46		9.7
Full injection from empty	h	0.14	0.16	0.27	1.8	0.8	0.1

Baseline Collider

	Higgs	Z	W	tt
Number of IPs	2			
Circumference (km)	100			
SR power per beam (MW)	30			
Energy (GeV)	120	45.5	80	180
Bunch number	268	11934	1297	35
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Beam size at IP σ_x/σ_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
RF frequency (MHz)	650			
Luminosity per IP (10^{34} cm^{-2} s^{-1})	5.0	115	16	0.5



Running scenarios:
- Higgs 10 years
- Z 3 years
- W 1 year
- ttbar 5 years

8

CEPC Site Evaluation

Civil construction cost was evaluated by 3 experienced companies:

Yellow River Engineering Consulting Co., Ltd
HUADONG Engineering Corporation Limited,
ZHONGNAN Engineering Corporation Limited

Three sites were considered: Changsha, Huzhou and Qinhuangdao

International Panel has reviewed the cost evaluation given by the 3 companies

All sites can satisfy requirements for CEPC construction. The main geological problems encountered can be solved by engineering measures.

Advance the civil engineering design as soon as possible.

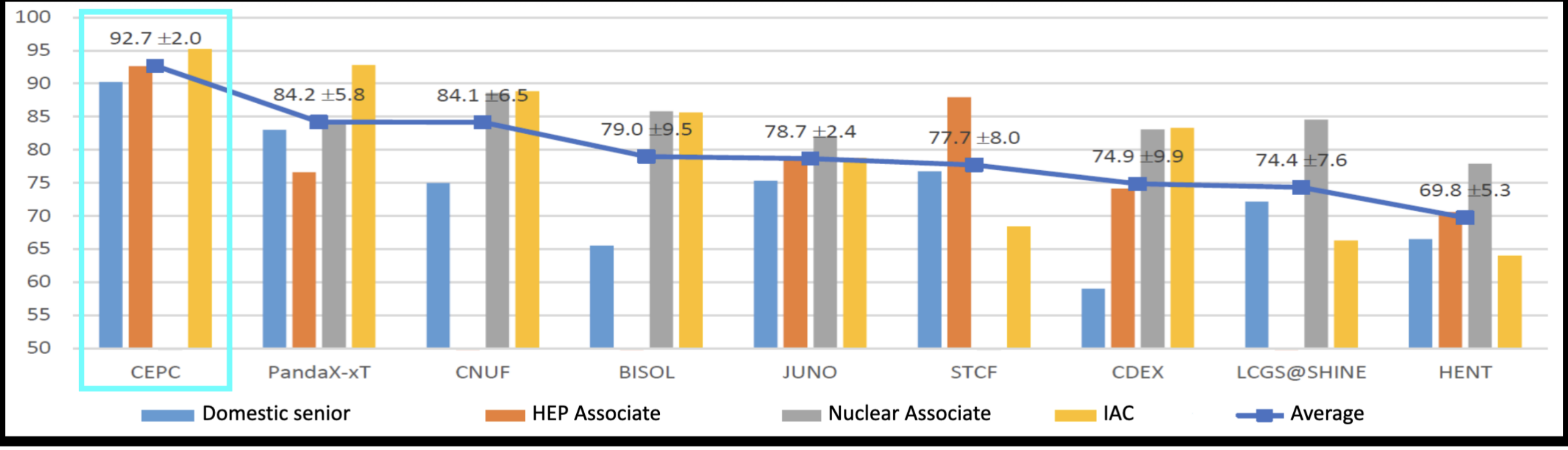
Decide the site
Complete the project proposal, feasibility study, preliminary design, and tender design before construction

14

CEPC Approval

CEPC Plan: 15th Five Year Plan — Chinese Academy of Sciences

- CAS planning for the 15th 5-years plan for large science projects
  - A steering committee has been established, chaired by the president of CAS
- High energy physics, as one of the 8 groups, accomplished the following:
  - Set up rules and selection standards (based on scientific and technological merits, strategic value and feasibility, R&D status, team and capabilities, etc.); established domestic and international advisory committees
  - 9 proposal selected (from 15 submitted)
  - Evaluations and ranking by committees after oral presentations by each project
- CEPC was ranked No. 1, with the smallest uncertainties, by every committee
- A final report was submitted to CAS for consideration



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ECFA Questions and CEPC

- Should CERN/Europe proceed with the preferred option set out in 3a) or should alternative options be considered:
  - if Japan proceeds with the ILC, China proceeds with the CEPC or if the US proceeds with a muon collider?
  - if there are major new (unexpected) results from the HL-LHC or other HEP experiments?

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ECFA Questions

- 3) Questions to be considered by countries/regions when forming and submitting their "national input" to the ESPP:
  - 3a) Which is the preferred next major/flagship collider project for CERN?
  - 3b) What are the most important elements in the response to 3a)?
    - Physics potential, Long-term perspective , Financial and human resources: requirements and effect on other projects, Timing, Careers and training , Sustainability

- 4) What other areas of physics should be pursued, and with what relative priority? (preferred prioritisation for non-collider projects)
  - To what extent should CERN participate in nuclear physics, astroparticle physics or other areas of science, while keeping in mind and adhering to the CERN Convention? Please use the current level and form of activity as the baseline for comparisons.

Summary

- Last Strategy update recommended Higgs factory as the highest priority to follow the LHC, while pursuing a technical and financial feasibility study for a next-generation hadron collider in parallel, in preparation for the long-term
- **Now its about deciding on a facility.**
  - Strategy update is about 6-7 years
  - Only a realistic machine should be proposed, if start of construction is considered "now"
  - If we "sit and wait" also other options can be considered
- Other input proposals expected: LHeC, extend HL-LHC runtime

- Biggest elephant in the room is the Chinese decision to include CEPC in 5-years plan in 2025 → then Europe is only 2nd and the question for alternative concepts arises