Strategy for Particle Physics: Opportunities for South Africa

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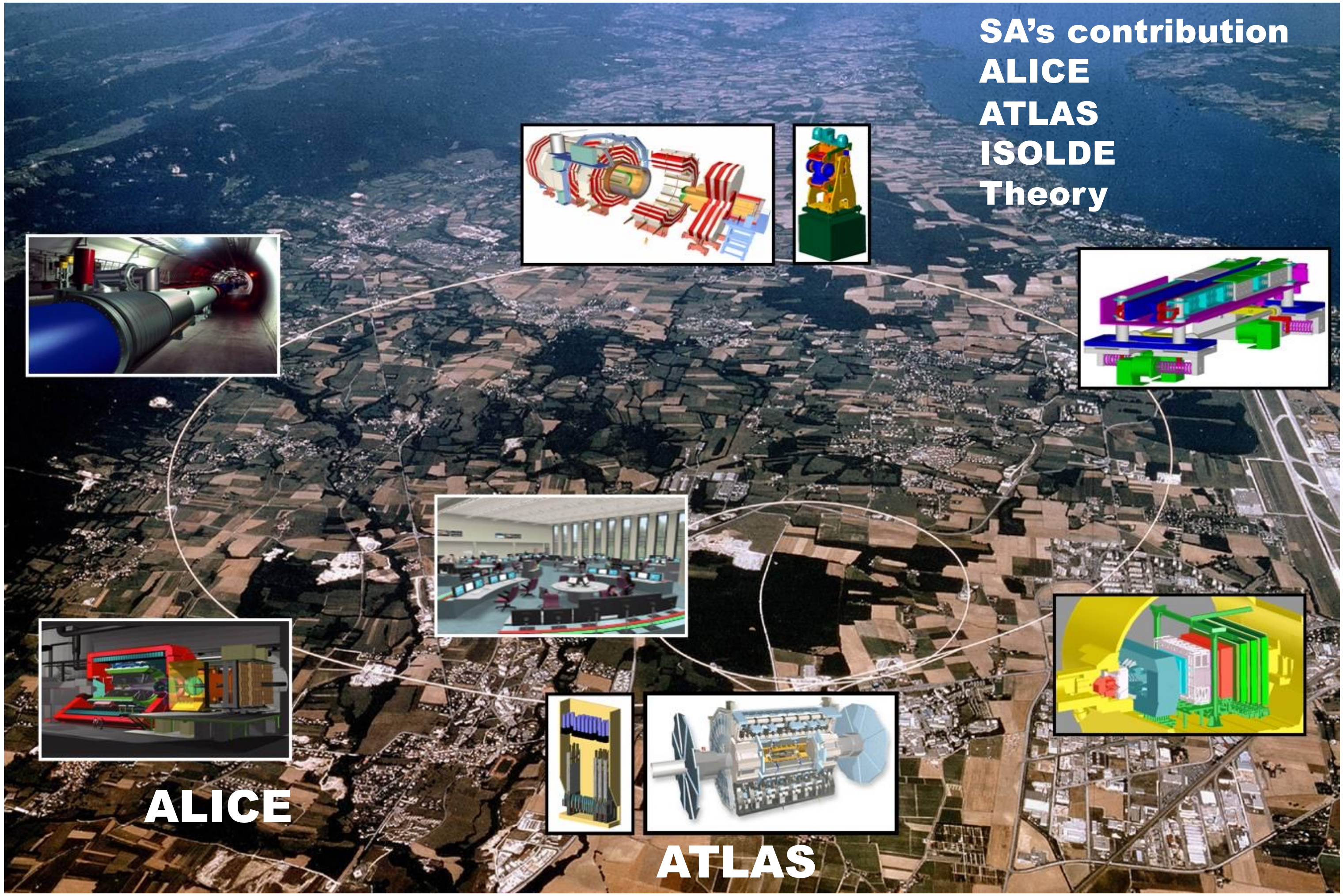
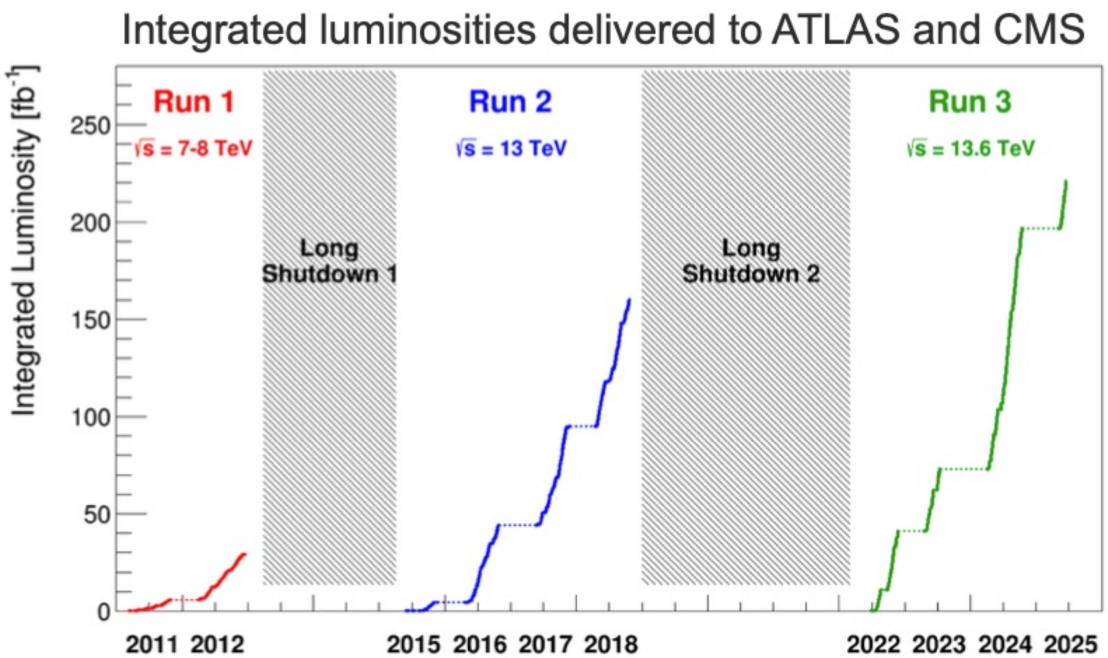
Outline

- ❑ The (High-Luminosity) LHC
  - ❑ Performance and timelines
- ❑ Electron-Positron Collider Options
  - ❑ The Physics Case
  - ❑ Luminosity expectations
  - ❑ Timelines
- ❑ Future Hadron Colliders
  - ❑ FCC-hh
  - ❑ SPPC
- ❑ "Bridge" Projects for CERN
  - ❑ LHeC, LEP3

The (High-Lumi) Large Hadron Collider

The Large Hadron Collider

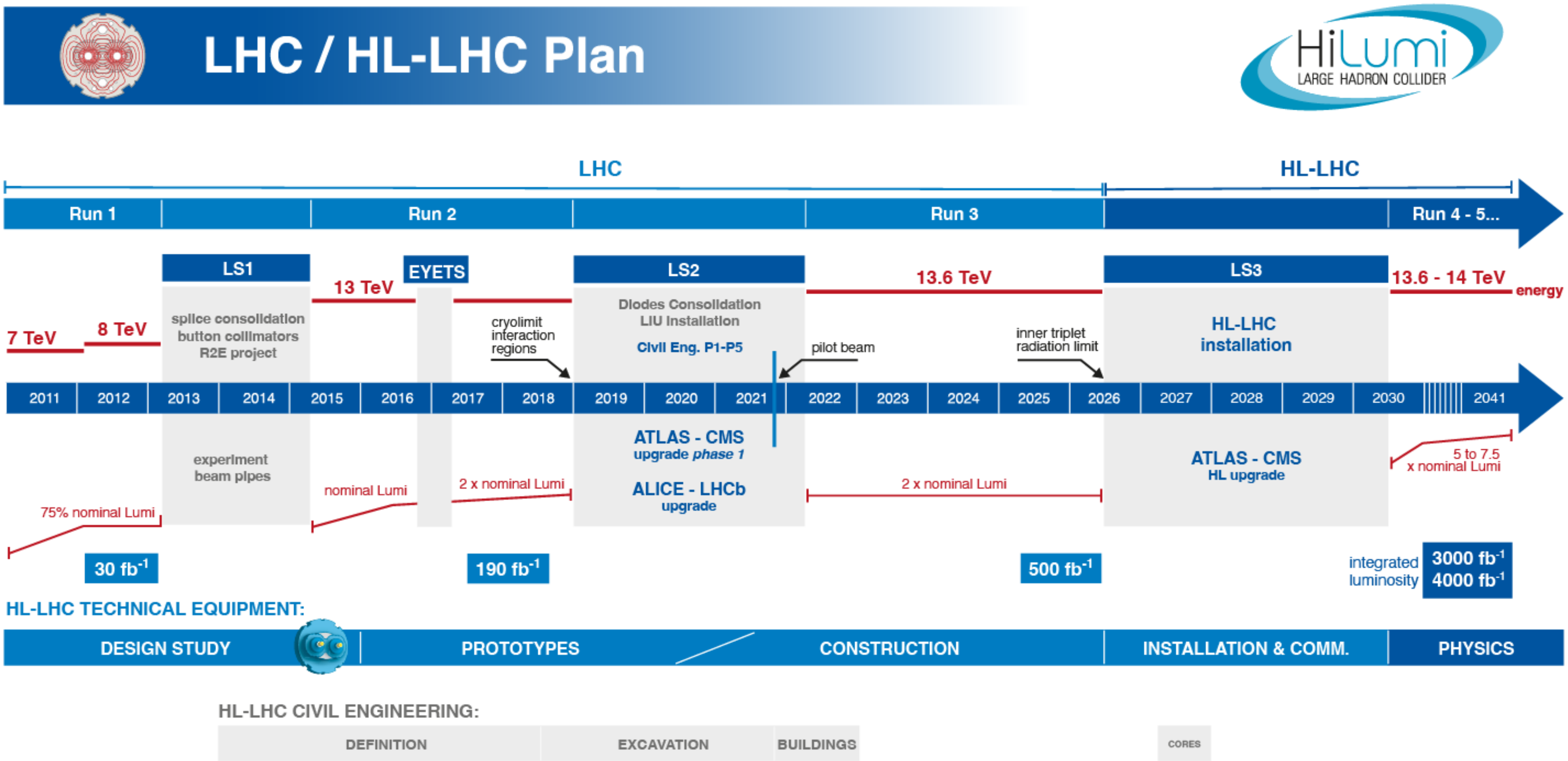


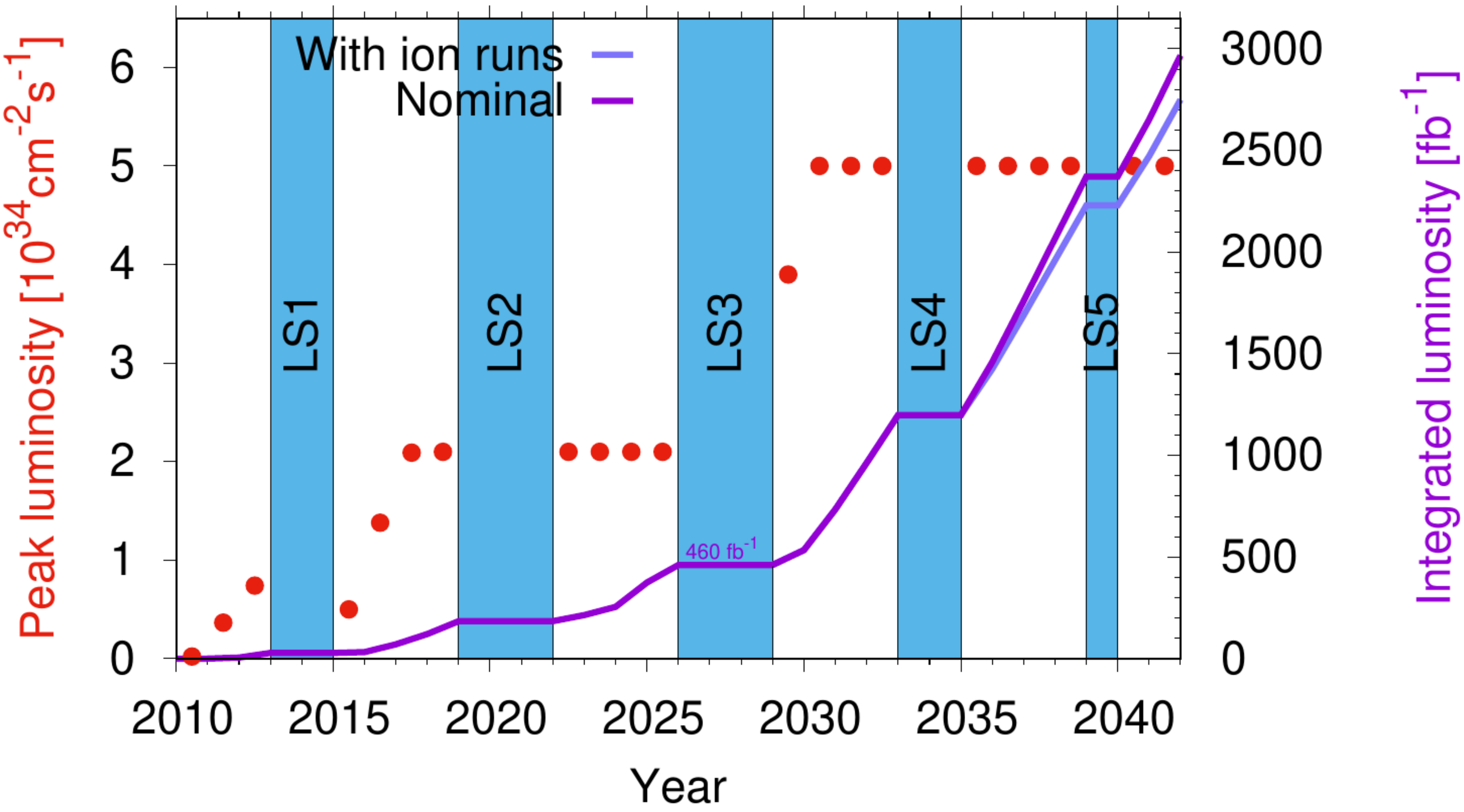


Total integrated luminosity to ATLAS and CMS since LHC start: **410 fb^{-1}**, of which **380 fb^{-1}** at $\sqrt{s} \geq 13$ TeV

Experiment	Fraction of delivered luminosity used for analysis (2024 pp data)
ALICE	76%
ATLAS	88%
CMS	89%
LHCb	86%

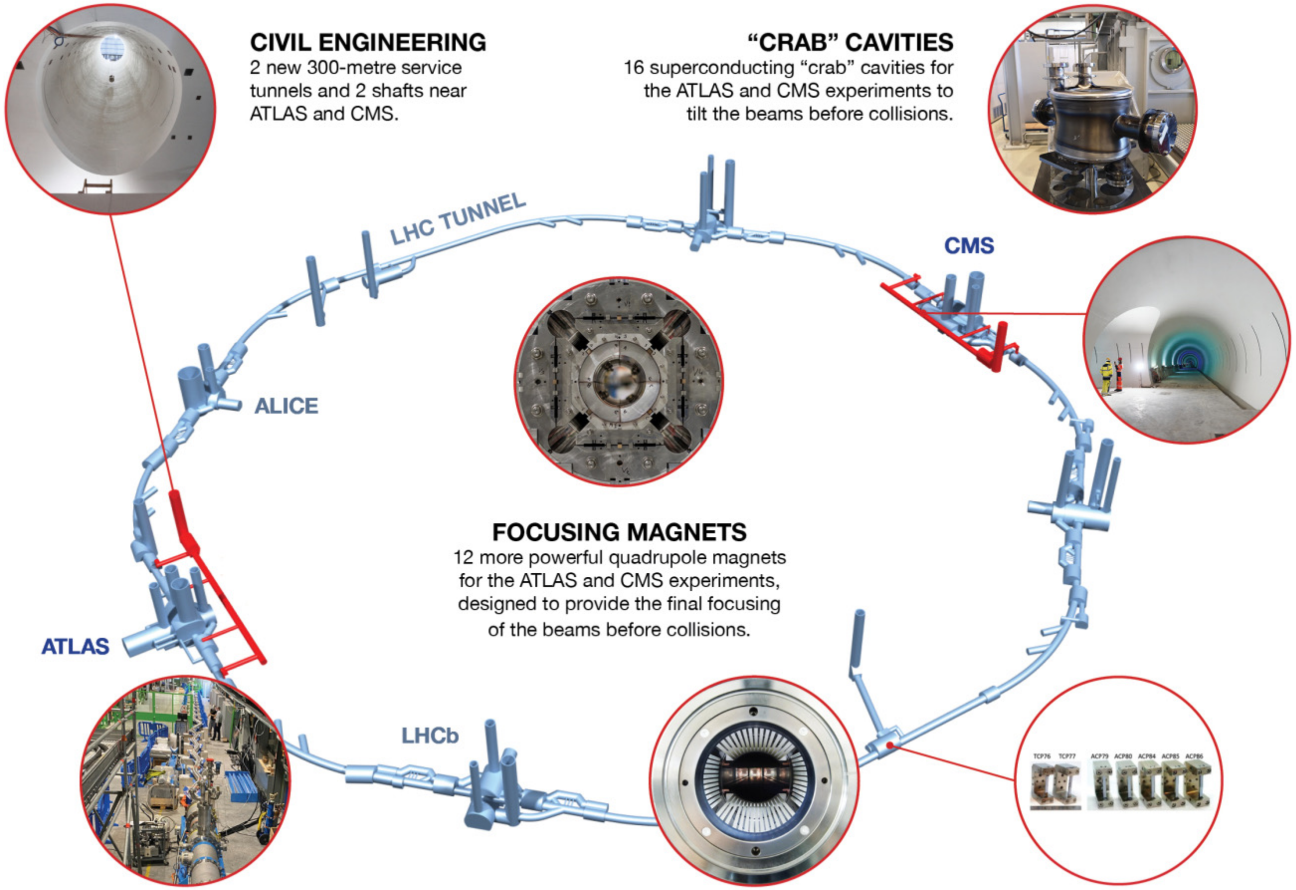
The High Luminosity LHC





With ion runs
Nominal
LS1
LS2
LS3
LS4
LS5
460 fb⁻¹
Peak luminosity [10³⁴cm⁻²s⁻¹]
Integrated luminosity [fb⁻¹]
Year
0
1
2
3
4
5
6
0
500
1000
1500
2000
2500
3000
2010
2015
2020
2025
2030
2035
2040

NEW TECHNOLOGIES FOR THE HIGH-LUMINOSITY LHC



CIVIL ENGINEERING

2 new 300-metre service tunnels and 2 shafts near ATLAS and CMS.

"CRAB" CAVITIES

16 superconducting "crab" cavities for the ATLAS and CMS experiments to tilt the beams before collisions.

FOCUSING MAGNETS

12 more powerful quadrupole magnets for the ATLAS and CMS experiments, designed to provide the final focusing of the beams before collisions.

SUPERCONDUCTING LINKS

Electrical transmission lines based on a high-temperature superconductor to carry the very high DC currents to the magnets from the powering systems installed in the new service tunnels near ATLAS and CMS.

COLLIMATORS

15 to 20 additional collimators and replacement of 60 collimators with improved performance to reinforce machine protection.

CRYSTAL COLLIMATORS

New crystal collimators in the IR7 cleaning insertion to improve cleaning efficiency during operation with ion beams.

Electron-Positron Collider Options

The Physics Case

h(125) couplings

Z Pole

152 GeV

95 GeV

The e^+e^- Collider

Discovery machine through precision and direct observation at the EW Scale

W Wass

Top Mass

Precision and Anomalies in Particle Physics are indicative of unique discovery opportunities at the EW for future e^+e^- accelerators

FCC integrated program – scope

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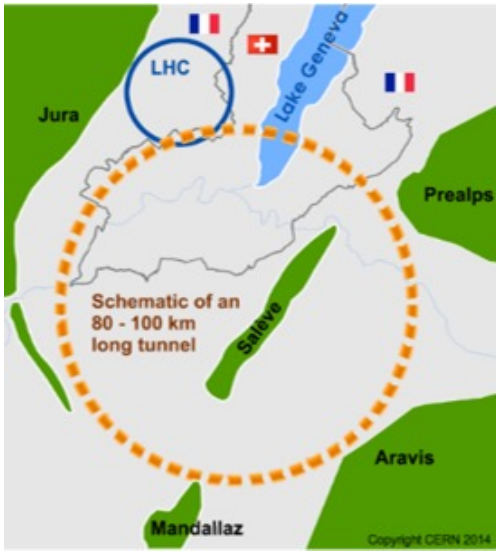
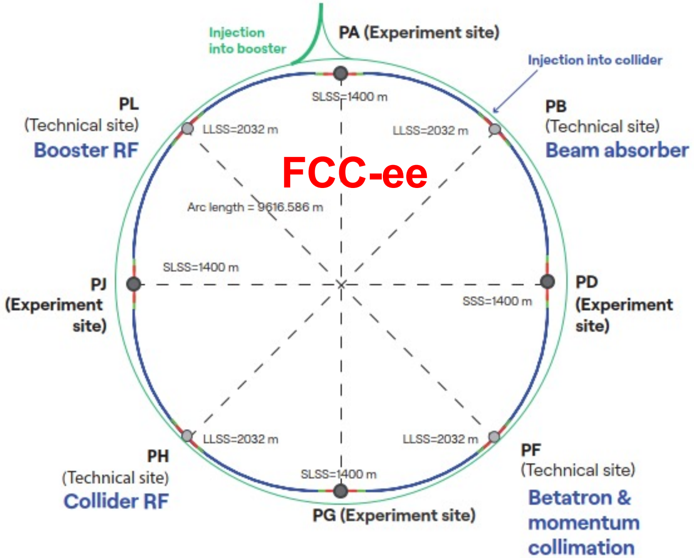
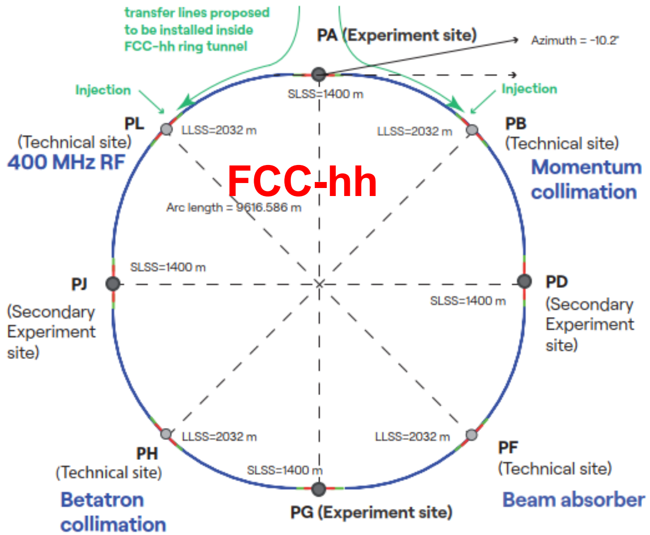
- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- **common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure**
- **FCC integrated project allows the start of a new, major facility at CERN within few years of the end of HL-LHC exploitation**







2020 - 2045 | **2046 - 2065** | **2070 - 2100**

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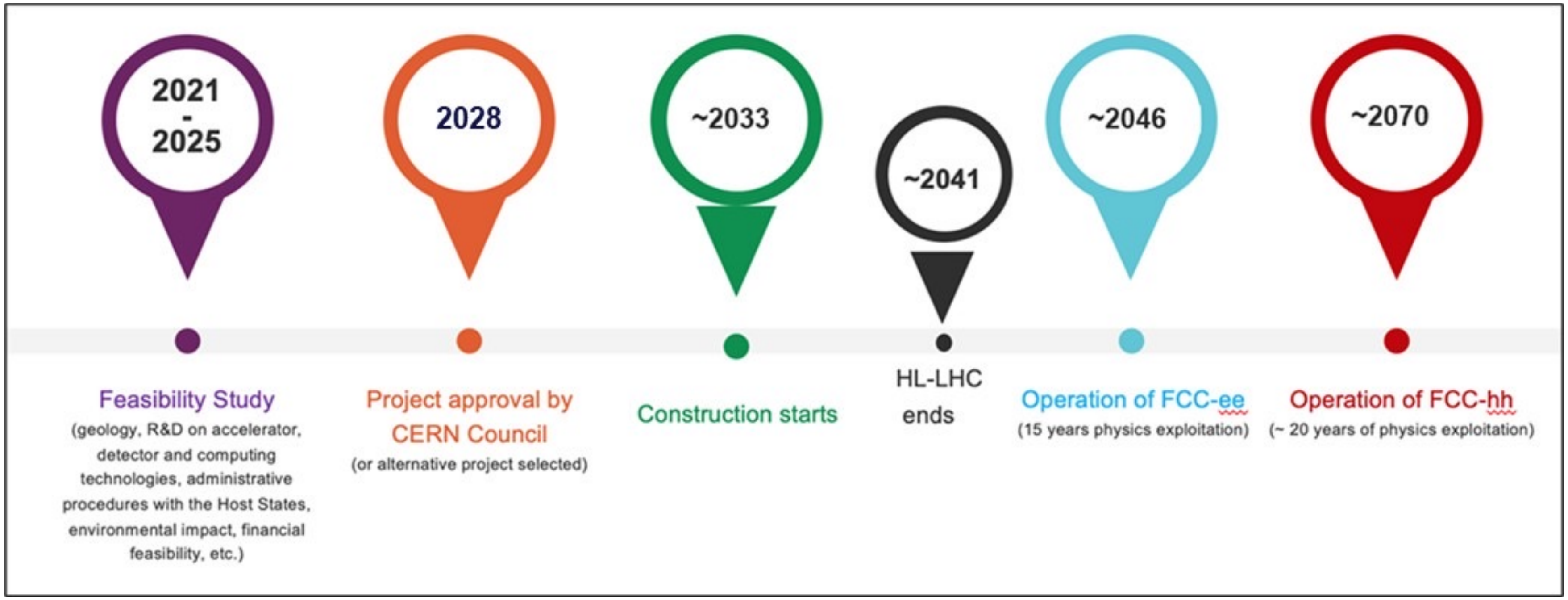
FCC integrated program - timeline



Ambitious schedule taking into account:

- past experience in building colliders at CERN
- approval timeline: ESPP, Council decision
- that HL-LHC will run until 2041
- **project preparatory phase with adequate resources immediately after Feasibility Study**

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FCC integrated program is fully documented in the three volumes of the Feasibility Study Report

- ***Vol. 1:*** *Physics, Experiments and Detectors*
- ***Vol. 2:*** *Accelerators, Technical Infrastructures, Safety Concepts*
- ***Vol. 3:*** *Civil Engineering, Implementation & Sustainability*

submitted for publication to EPJ (Springer-Nature)

Three FSR volumes & other FCC-related input to 2025/26 European Strategy Update posted at https://indico.cern.ch/event/1534205/

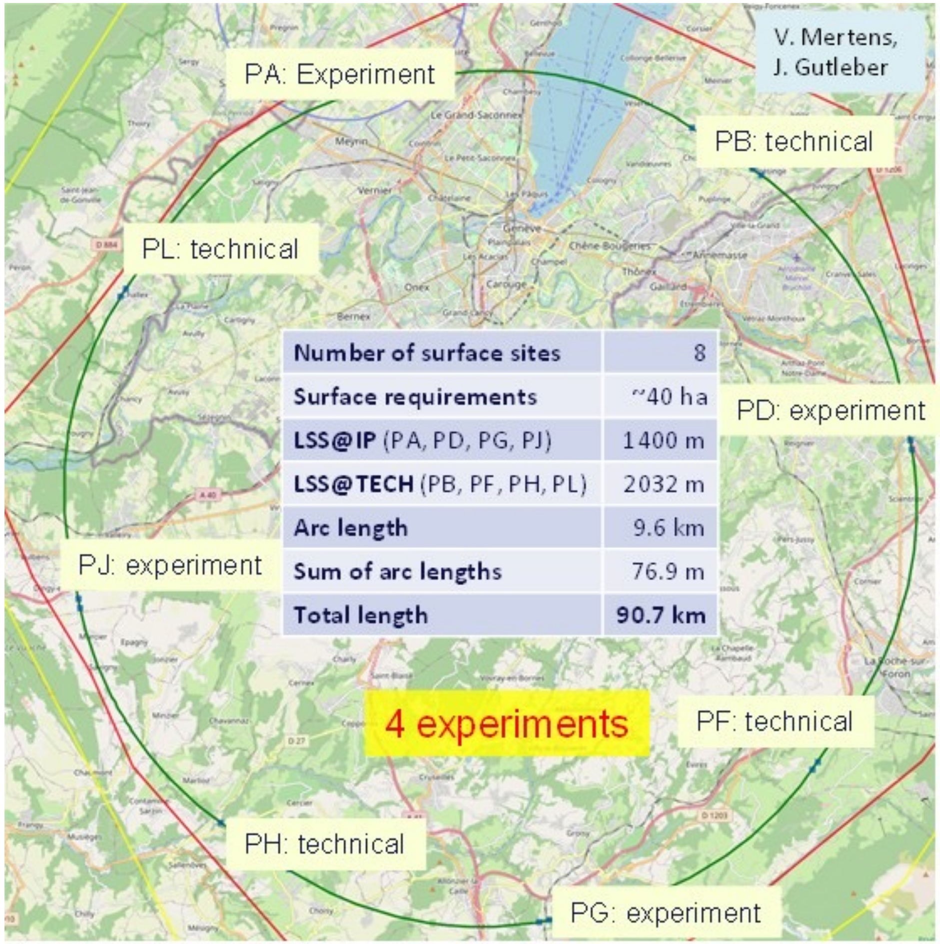
Reference layout and implementation: PA31 - 90.7 km

Layout chosen out of ~ 100 initial variants, based on several criterias:

- **geology,**
- **surface constraints** (land availability, urbanistic, etc.),
- **environment,** (protected zones),
- **infrastructure** (electricity, transport),
- **machine performance**

“Avoid-reduce-compensate” principle of EU and French regulations.

Overall lowest-risk baseline: 90.7 km ring, 8 surface points, 4-fold symmetry



Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	90.7 km

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Key Features of the Civil Engineering

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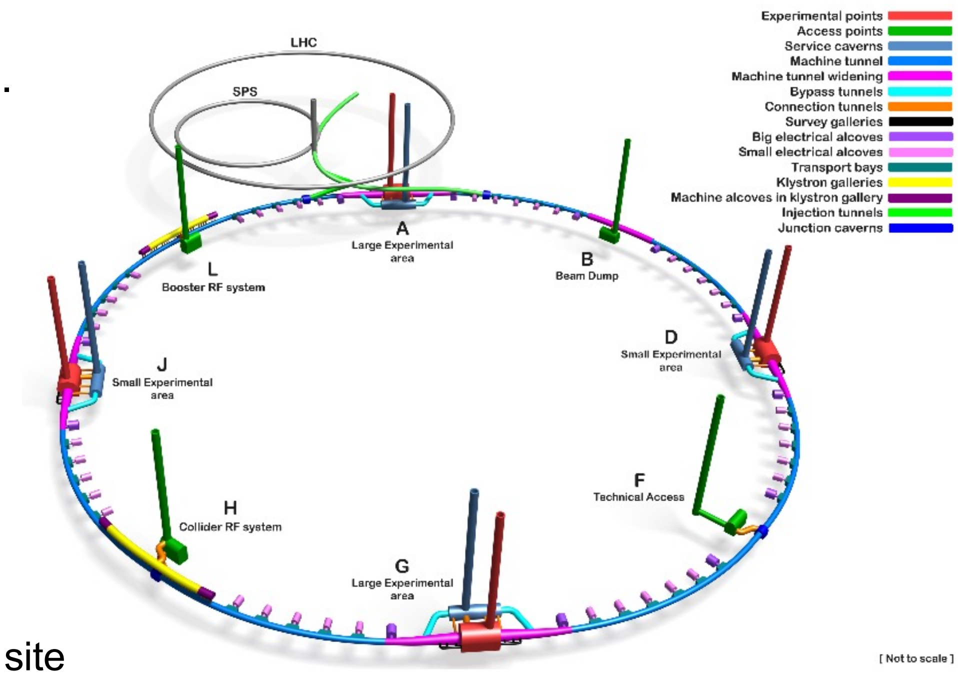
- 90.7 km main tunnel with an internal diameter of 5.5 m.
- Depth varies between 50m and 560m.
- 12 shafts up to 400 m deep and 18 m in diameter.
- 2 larger experiment caverns (35m span).
- 2 smaller experiment caverns (span 25m).
- >70 small caverns.
- 5 km transfer tunnel from the surface.
- 3 km of klystron gallery tunnels.
- Technical buildings on 8 surface sites
- Injector FCC-ee: high-energy linac at CERN Prevessin site

CE Construction carbon footprint estimate (A1 – A5):

Total CE: 530 000 - 1 184 000 tCO_2(eq)

Assessed according to European Norms, (EN 17472, EN15804+A2)



Schematic Layout of the FCC ee Underground Structures

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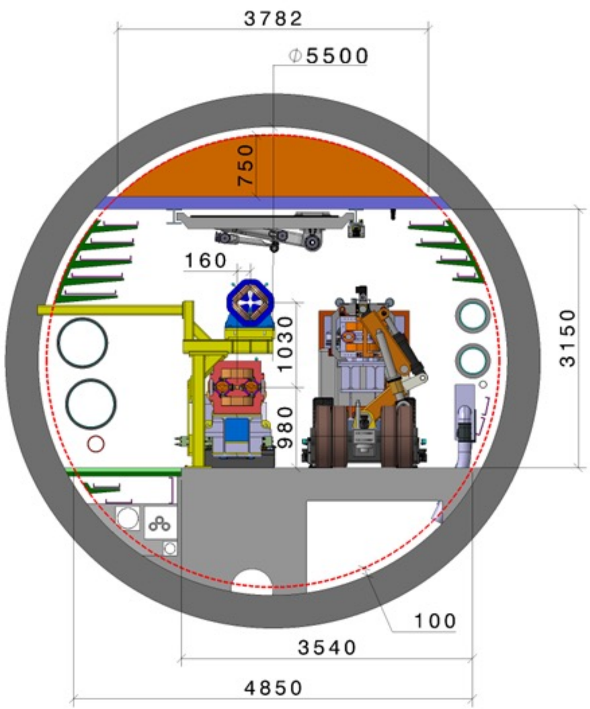
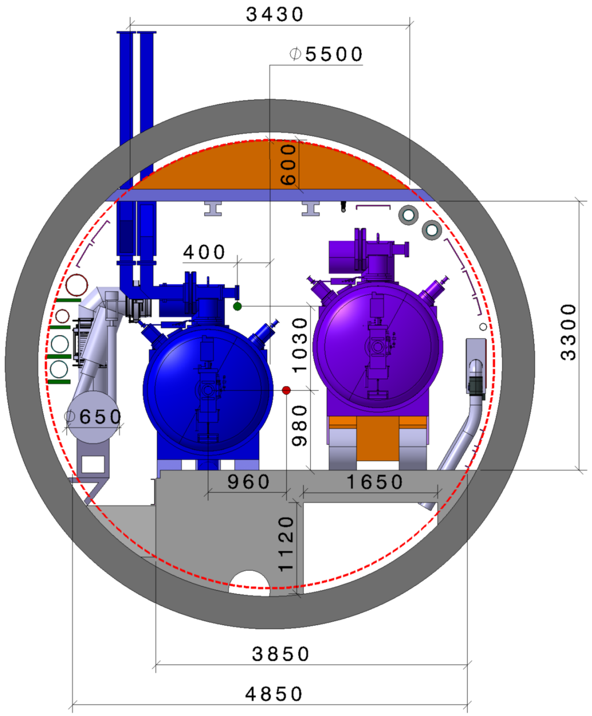
FCC – main tunnel integration – 5.5 m inner diameter

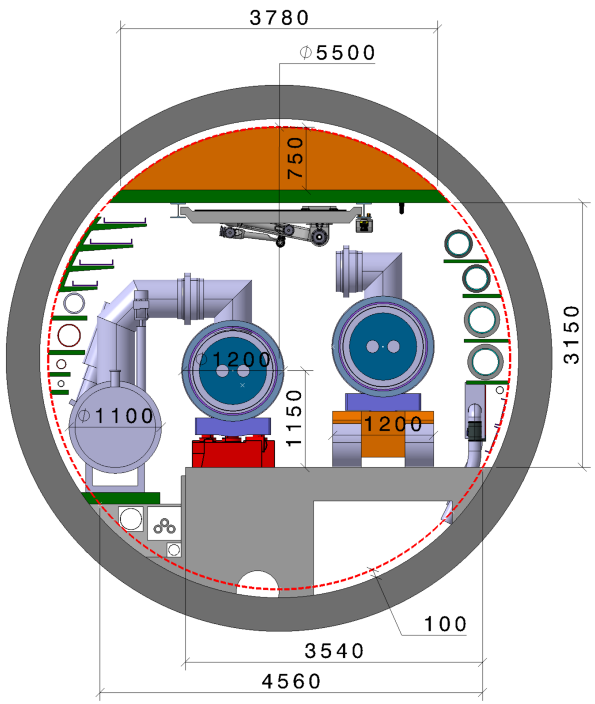
FCC-ee arc



FCC-ee 400 MHz RF section



FCC-hh arc



Optimum placement of FCC tunnel and geology

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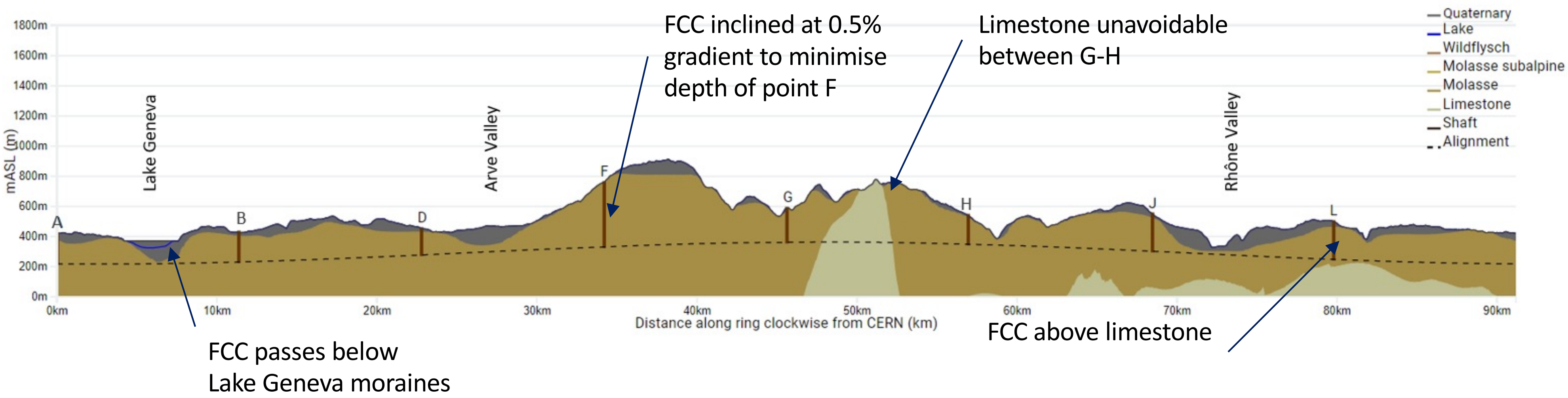

Tunneling mainly in molasse layer (soft rock), well suited for fast, low-risk TBM construction.

6 million m^3 excavated volume → 8.5 million m^3 excavation material on surface

CE Designs of all underground structures developed

Average shaft depths ~240 m

To fix the vertical position of the tunnel, interfaces between geological layers have to be known

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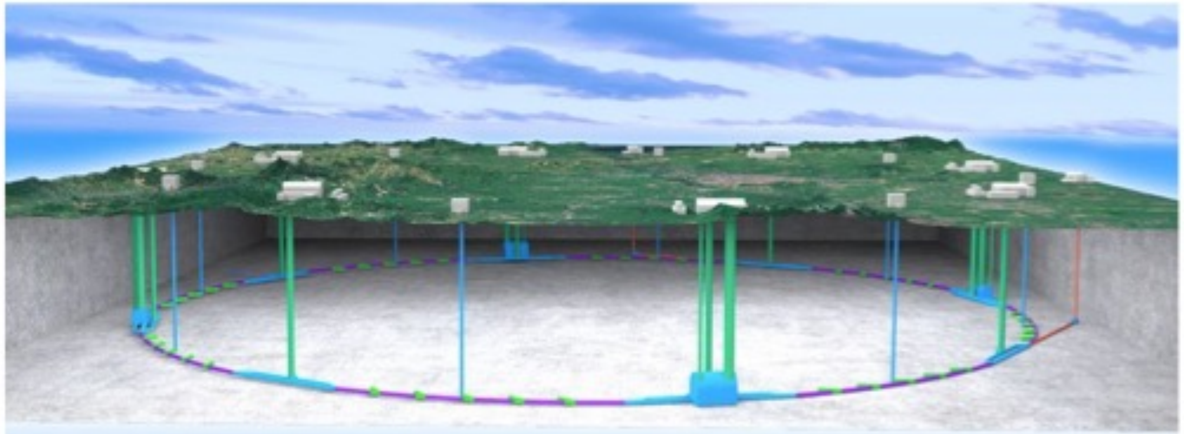
FCC-ee main parameters and operation plan

parameter	Z	WW	H (ZH)	$t\bar{t}$	
Collision energy $\sqrt{s}$ [GeV]	88, 91, 94	157, 163	240	340-350	365
synchrotron radiation/beam [MW]	50	50	50	50	50
beam current [mA]	1294	135	26.8	6.0	5.1
number bunches / beam	11200	1852	300	70	64
total RF voltage 400 / 800 MHz [GV]	0.08 / 0	1.0 / 0	2.1 / 0	2.1 / 7.4	2.1 / 9.2
luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	144	20	7.5	1.8	1.4
luminosity / year [ab^{-1}]	68	9.6	3.6	0.83	0.67
run time (including lumi ramp-up) [years]	4	2	3	1	4
total integrated luminosity [ab^{-1}]	205	19.2	10.8	0.4	2.7
total number of events	$6\ 10^{12}$ Z	$2.4\ 10^{8}$ WW (incl. WW at higher $\sqrt{s}$)	$2.2\ 10^{6}$ ZH 65k WW $\rightarrow$ H	$2\ 10^{6}$ $t\bar{t}$ + 370k ZH + 92k WW $\rightarrow$ H	

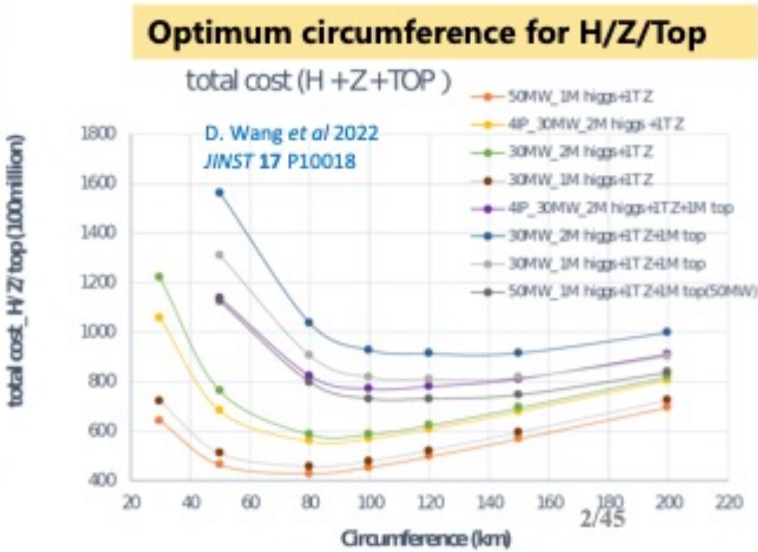
Circular Electron Positron Collider (CEPC)

Yifang Wang

- Since 2005, we were thinking about the next machine after BEPCII/BESIII
- After its discovery, we realized that Higgs is the best portal for new physics and for the future of HEP
- The idea of a Circular e+e- Collider(CEPC) followed by a possible Super proton-proton collider(SPPC) was firstly proposed in Sep. 2012, and reported at Fermilab during the workshop: “Higgs Factories 2012” in Oct. 2012
- It quickly gained momentum in China and in the world



Fermilab-Conf-13-037-APC
arXiv:1302.3318[physics.acc-ph]



CEPC Layout and Design

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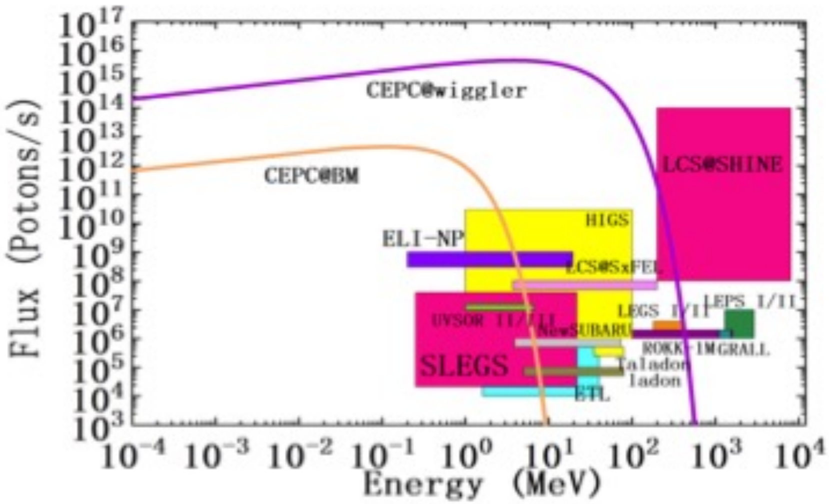
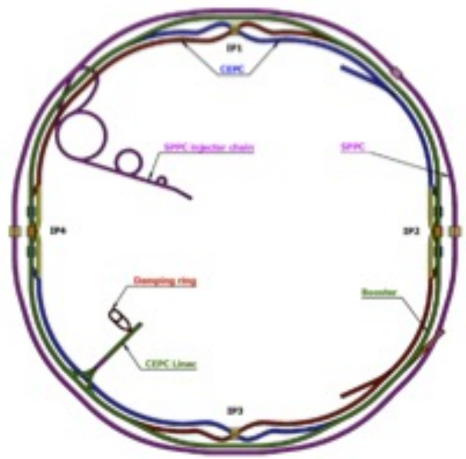
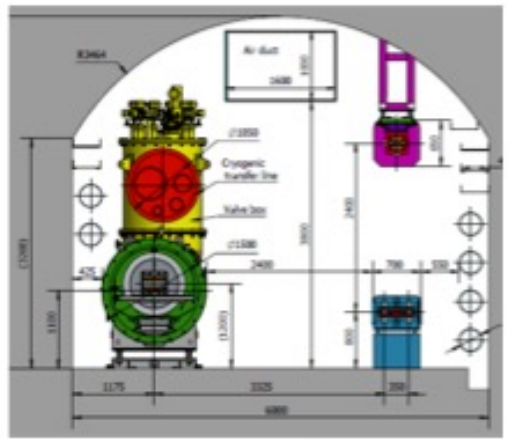
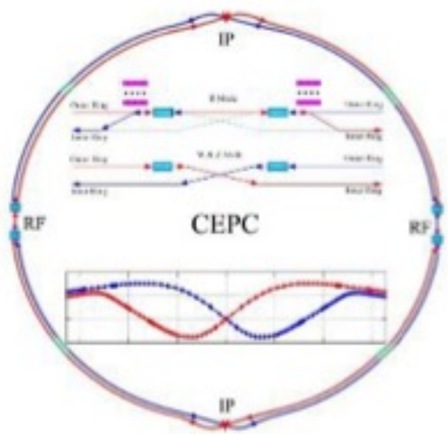
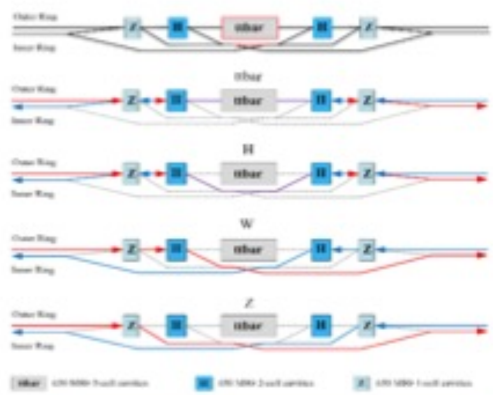
- 100km circumference
- Compatible tunnel for CEPC and SPPC
- Baseline: 100 km, 30 MW;
  Upgradeable to 50 MW, High Lumi Z, ttbar
- Switchable operation: Higgs, W/Z, top
- A very high energy Synchrotron radiation facility











H/W/Z/ttbar bypass scheme

CEPC Planning and Schedule

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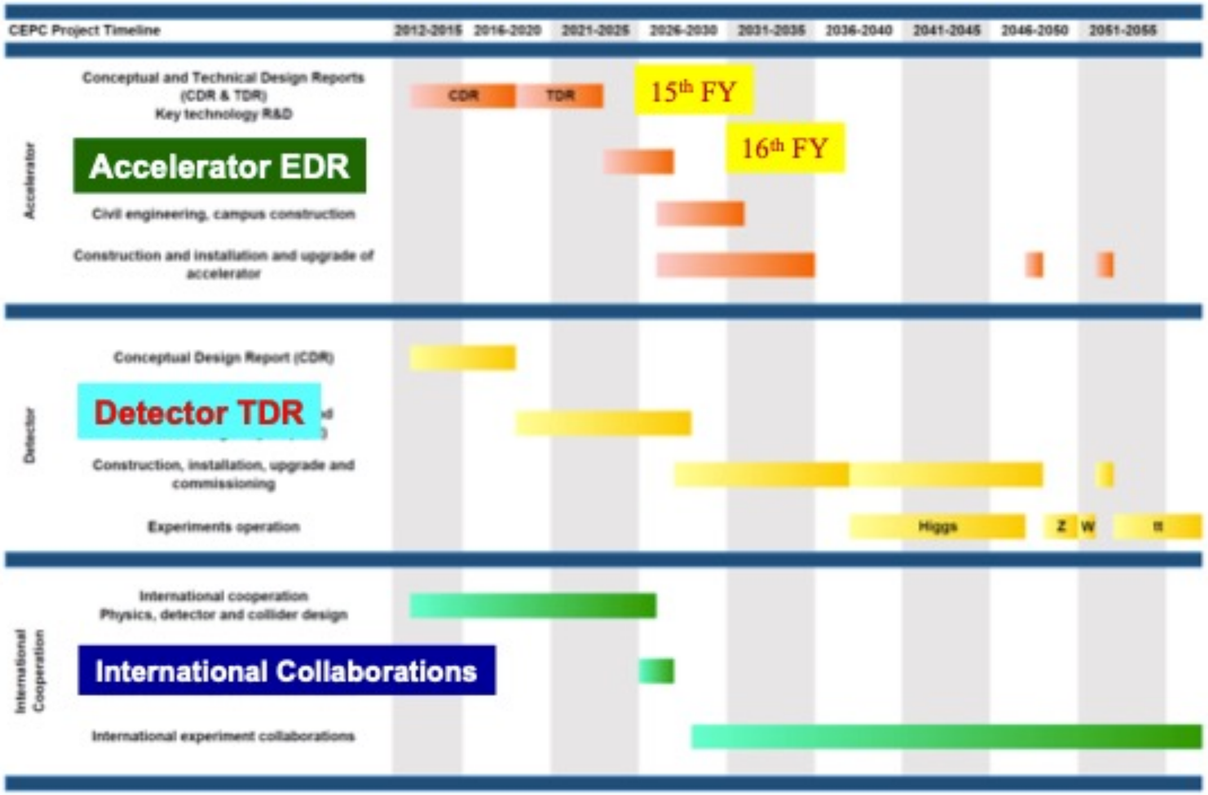
TDR (2023), EDR(2027), start of construction (~2027)



- ➢ CEPC plans to submit the proposal to the central government(NDRC) within the "15th five year plan"
- ➢ For this purpose, CAS organized studies and reviews
- ➢ CEPC was ranked by CAS as the No. 1 for HEP & NP, and No.2 for Basic Science
- ➢ We are waiting for the 2nd review by CAS later this year
- ➢ Waiting for the "call for proposals" by NDRC by the end of this year

NDRC: National Development and Reform commission

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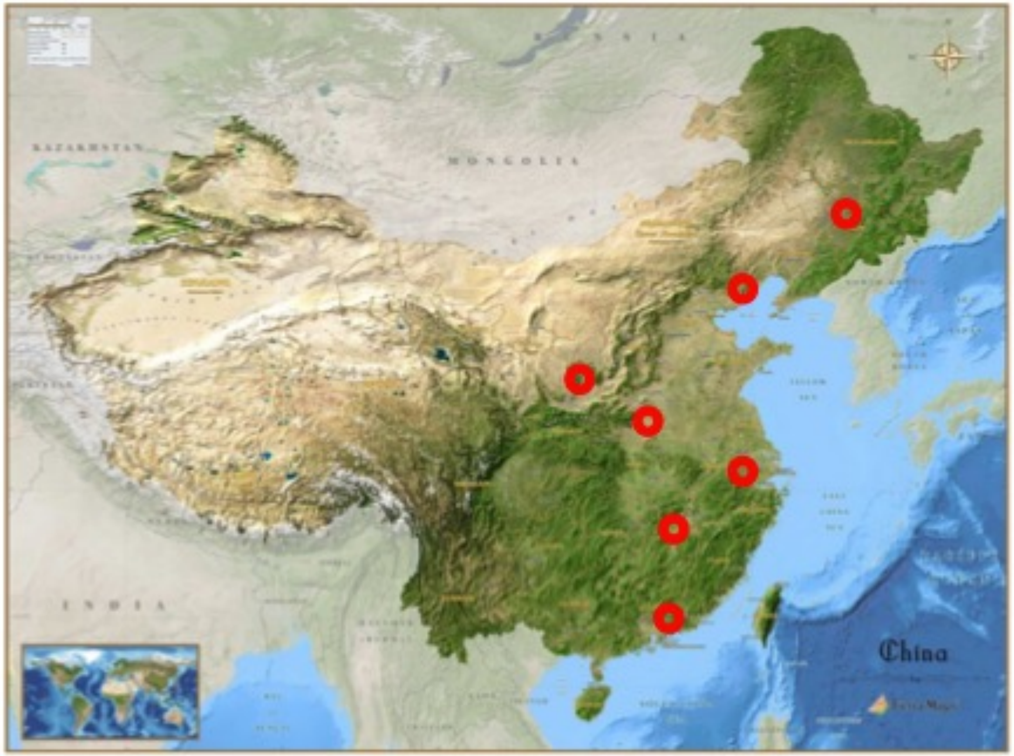
CEPC Site Selection



- All sites have been investigated: good geology, mostly granite
- Good living conditions, and local support

- Site selection will compare geology, electricity supply, transportation, environment for foreigners, local support & economy,…
- Final decision will depend on the negotiation between the central and local governments

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CEPC Operation Plan

Yifang Wang

* Higgs is the top priority. The CEPC will commence its operation with a focus on Higgs

Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. /IP ($10^{34}cm^{-2}s^{-1}$)	Integrated Lumi. /yr (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H*	240	10	50	8.3	2.2	21.6	4.3×10^6
			30****	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30****	115**	30	60	2.5×10^{12}
W	160	1	50	26.7	6.9	6.9	2.1×10^8
			30****	16	4.2	4.2	1.3×10^8
$t\bar{t}$	360	5	50	0.8	0.2	1.0	0.6×10^6
			30****	0.5	0.13	0.65	0.4×10^6

** Detector solenoid field is 2 Tesla during Z operation, 3Tesla for all other energies.

*** Calculated using 3,600 hours per year for data collection.

**** 30 MW leaves room for international in-kind contributions

Operating Scenario for a Linear Collider at CERN

arXiv:250319983

Stage 1: 250-380 GeV

precision Higgs mass and total σ(ZH)
precision Higgs couplings and total width to % level
resonance/compositeness search in ffbar, WW to 10's TeV
1-yr excursion to the Z pole - $\sin^2\theta_W$ to 3e-6

Stage 2: 550 GeV

precision Higgs couplings and total width to sub-% level
top quark Yukawa to 3%, Higgs self-coupling to 11%
top quark electroweak couplings to 0.1%
resonance/compositeness search in ffbar, WW to 50 TeV
1-yr excursion to the ttbar threshold - mt to 40 MeV

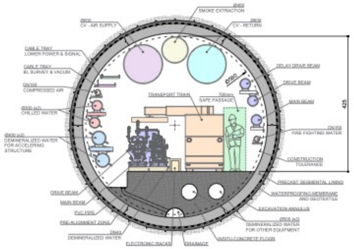
Higher energies: 1000 GeV or above

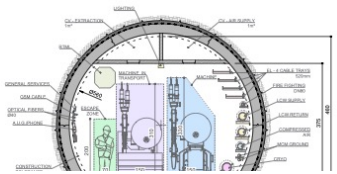
top quark Yukawa to 1%, Higgs self-coupling in WW fusion
Higgsino search to 500 GeV
follow up HL-LHC discoveries of new Higgs and electroweak states

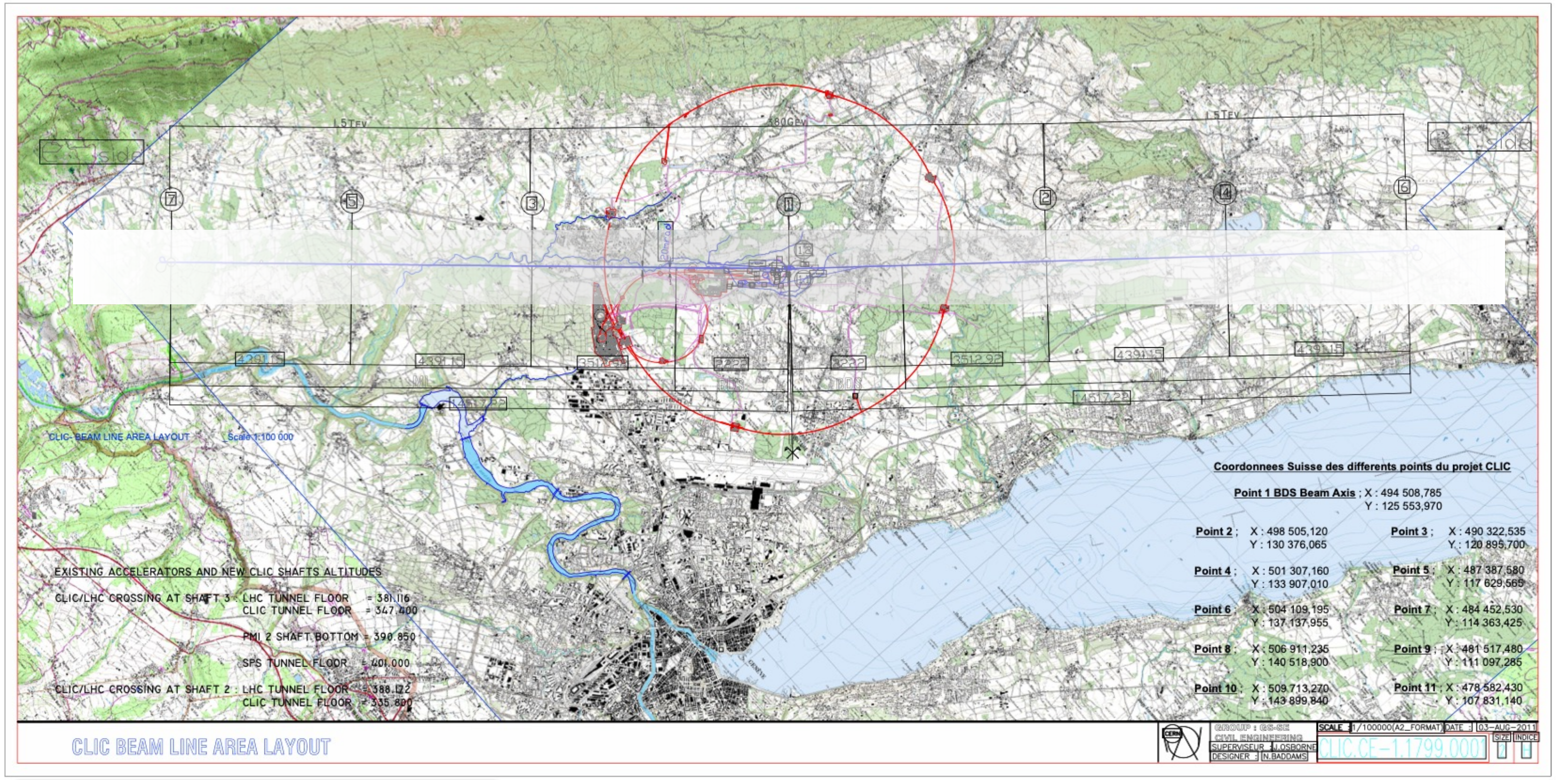
Fixed target program: dark sector, nonlinear QED

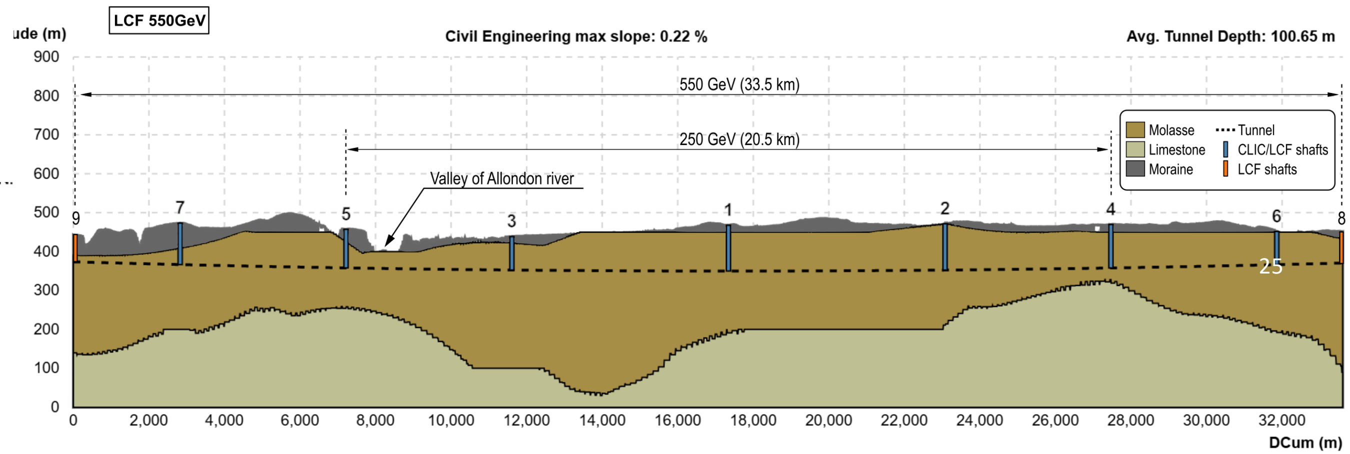
Linear Collider at CERN – Civil Engineering

Layout used for costing and drawings. Not final, can be translated, rotated and shafts can be moved.

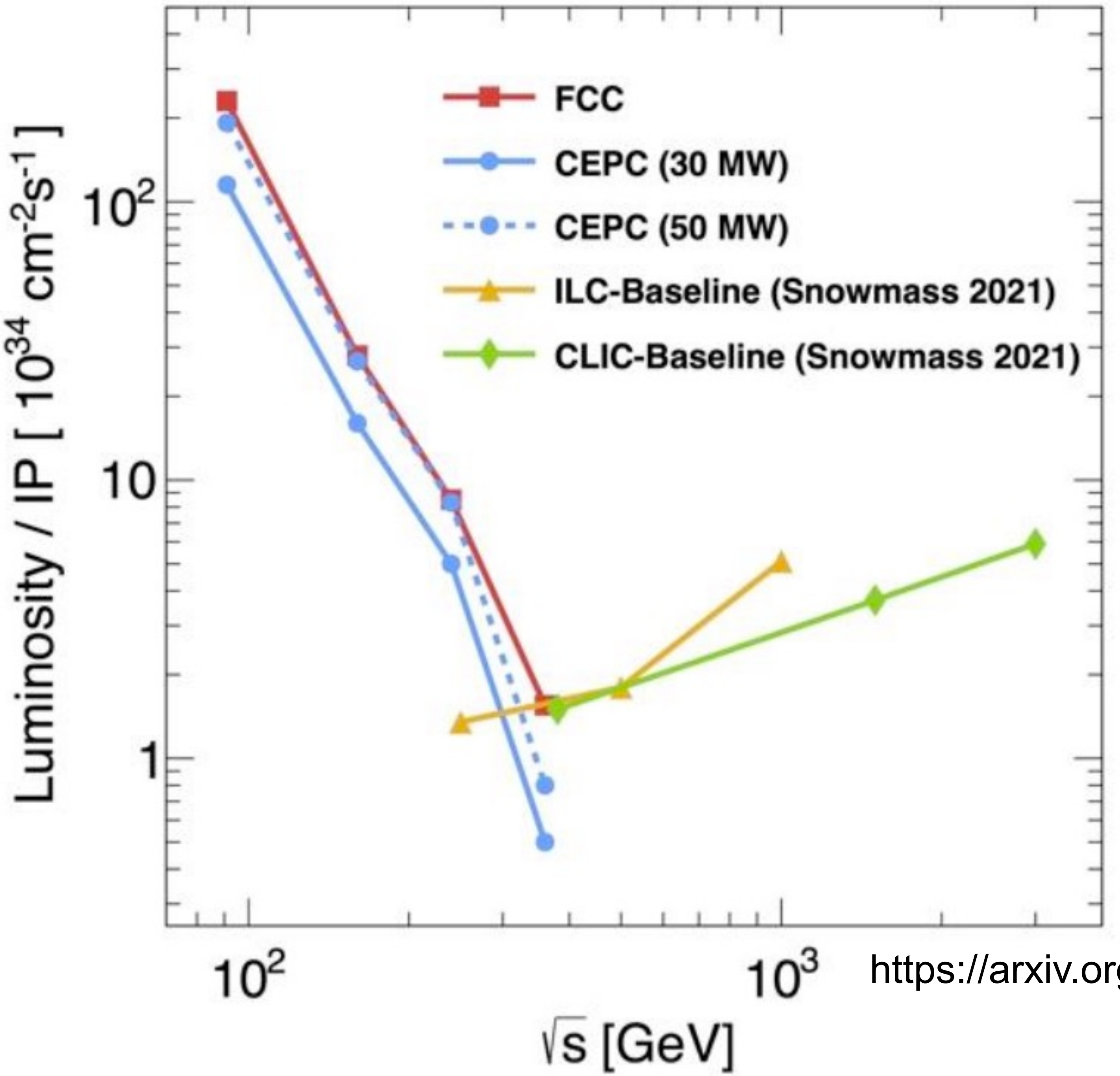








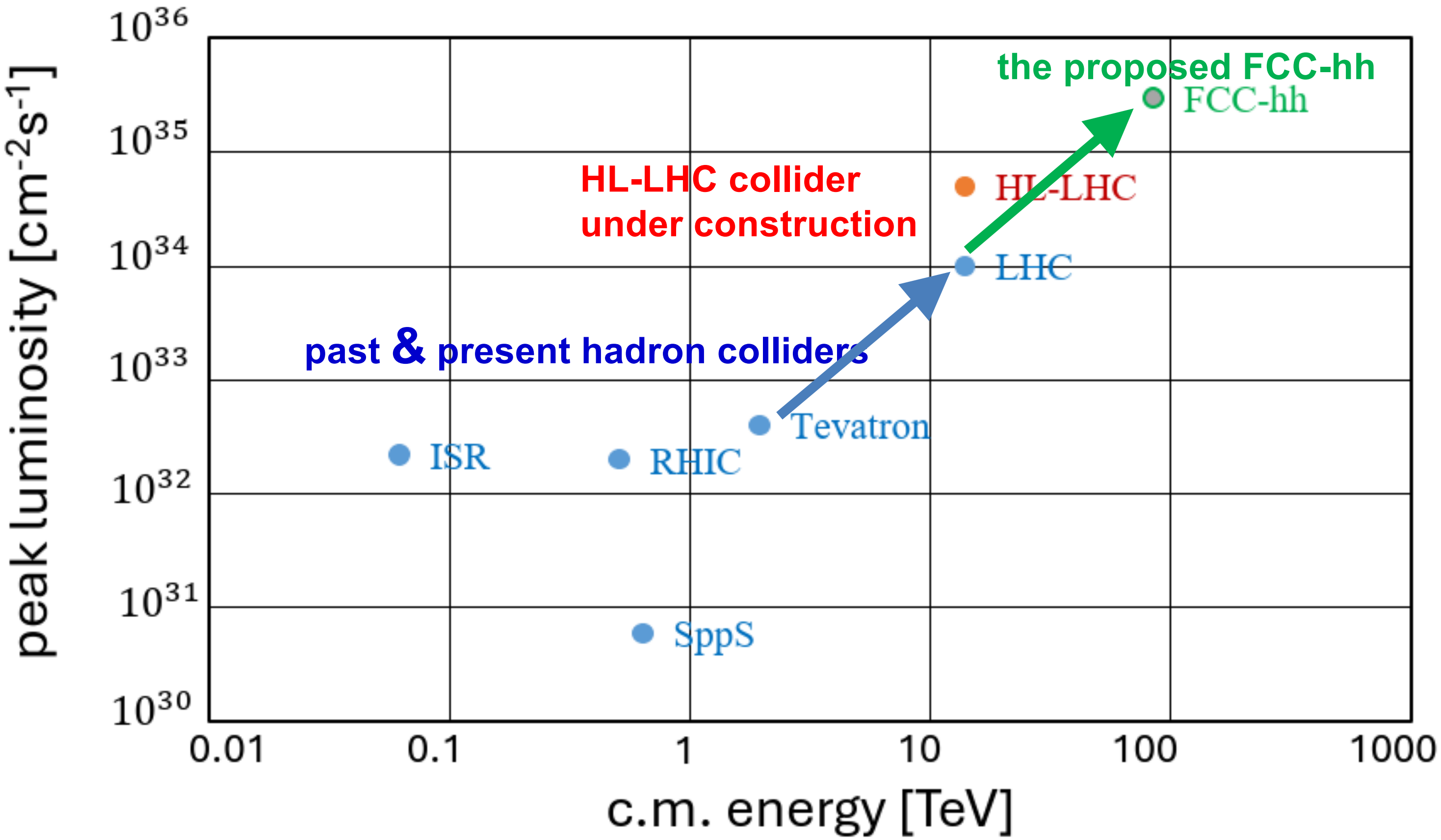
Instantaneous Luminosity for various e^+e^- collider options



https://arxiv.org/pdf/2312.1436

Future Hadron Colliders

hadron collider peak luminosity versus centre-of-mass energy



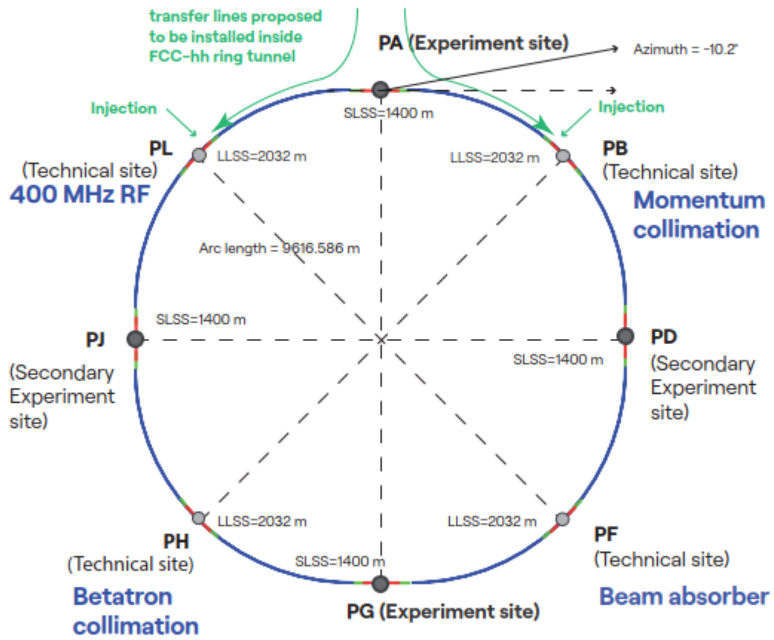
Future Circular Hadron Collider FCC-hh

- Parameter optimization to lower electricity consumption (~max. consumption of FCC-ee)
- Magnetic field considered realistic with today's technologies (Nb_3Sn, ~14T, 1.9 K)

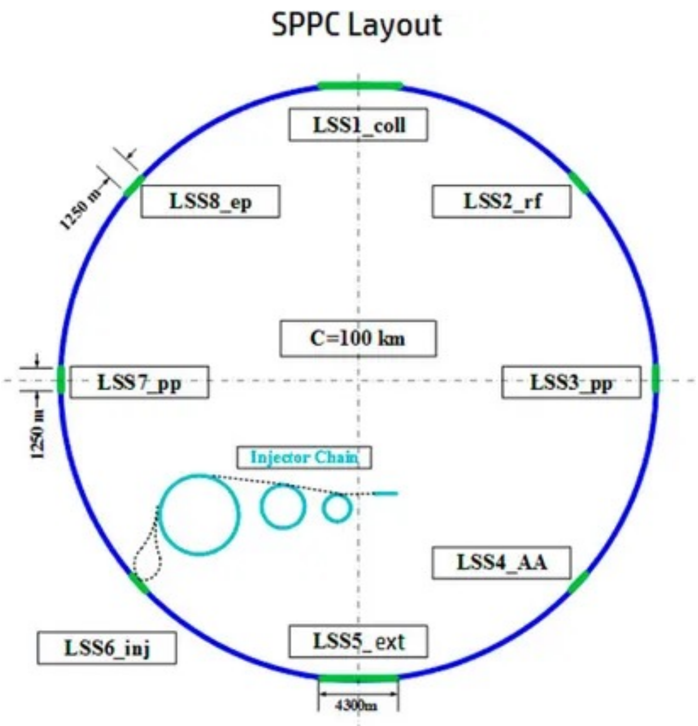
Main parameters FSR 2025

parameter	FCC-hh	FCC-hh CDR	HL-LHC
collision energy cms [TeV]	85	100	14
dipole field [T]	14	16	8.33
circumference [km]	90.7	97.8	26.7
beam current [A]	0.5	0.5	1.1
synchr. rad. per ring [kW]	1200	2400	7.3
peak luminos. [10^{34} $cm^{-2}s^{-1}$]	30	30	5 (lev.)
events/bunch crossing	1000	1000	132
stored energy/beam [GJ]	6.5	8.3	0.7
integr. luminosity / IP [fb^{-1}]	20000	20000	3000

FCC-hh functional layout



Design Concept for a Future Super Proton-Proton Collider



Parameter	Value		Unit
	Phase-I	Ultimate	
Center-of-mass energy	75	125–150	TeV
Nominal luminosity	1.0×10^{35}	—	$cm^{-2}s^{-1}$
Number of IPs	2	2	—
Circumference	100	100	km
Injection energy	2.1	4.2	TeV
Overall cycle time	9–14	—	hours
Dipole field	12	20–24	T

https://doi.org/10.3389/fphy.2022.828878

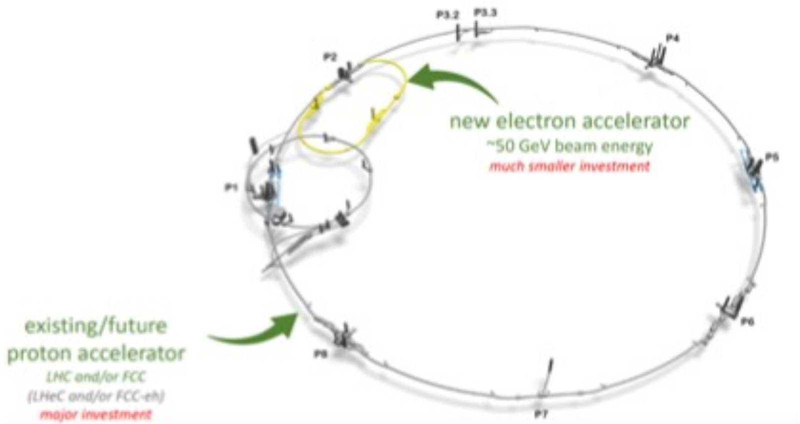
Parameter	Value	Unit
General design parameters		
Circumference	100	km
Beam energy	37.5	TeV
Lorentz gamma	39979	
Dipole field	12	T
Dipole curvature radius	10415.4	m
Arc filling factor	0.78	
Total dipole magnet length	65.442	km
Arc length	83.9	km
Number of long straight sections	8	
Total straight section length	16.1	km
Energy gain factor in collider rings	17.86	
Injection energy	2.1	TeV
Number of IPs	2	
Revolution frequency	3.00	kHz
Physics performance and beam parameters		
Nominal luminosity per IP	1.0×10^{35}	$cm^{-2}s^{-1}$
Beta function at collision	0.75	m
Circulating beam current	0.73	A
Nominal beam-beam tune shift limit per IP	0.0075	
Bunch separation	25	ns
Number of bunches	10080	
Bunch population	1.5×10^{11}	
Accumulated particles per beam	1.5×10^{15}	
Normalized rms transverse emittance	2.4	μm
Beam life time due to burn-off	14.2	h
Total inelastic cross section	147	mb
Reduction factor in luminosity	0.85	
Full crossing angle	110	μrad
rms bunch length	75.5	mm
rms IP spot size	6.8	μm
Beta at the first parasitic encounter	19.5	m
rms spot size at the first parasitic encounter	34.5	μm
Stored energy per beam	9.1	GJ
SR power per beam	1.1	MW
SR heat load at arc per aperture	12.8	W/m
Energy loss per turn	1.48	MeV

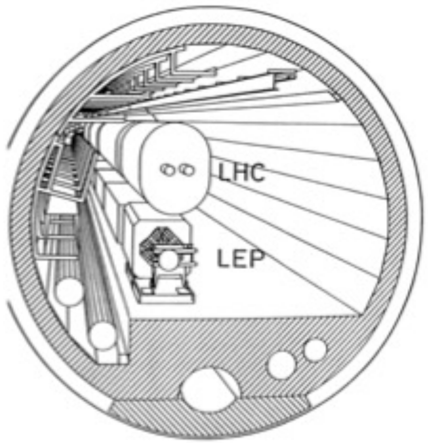
“Bridge” Projects

Karl Jakobs

"Bridge" Projects Towards the 10 TeV Scale

LHeC (> 50 GeV electron beam)
E_{CM} = 0.2 – 1.3 TeV (Q^2,x) range beyond HERA;
Bridge between HL-LHC and future large facility





Further exploitation of the LHC;
Addition of an eh-programme

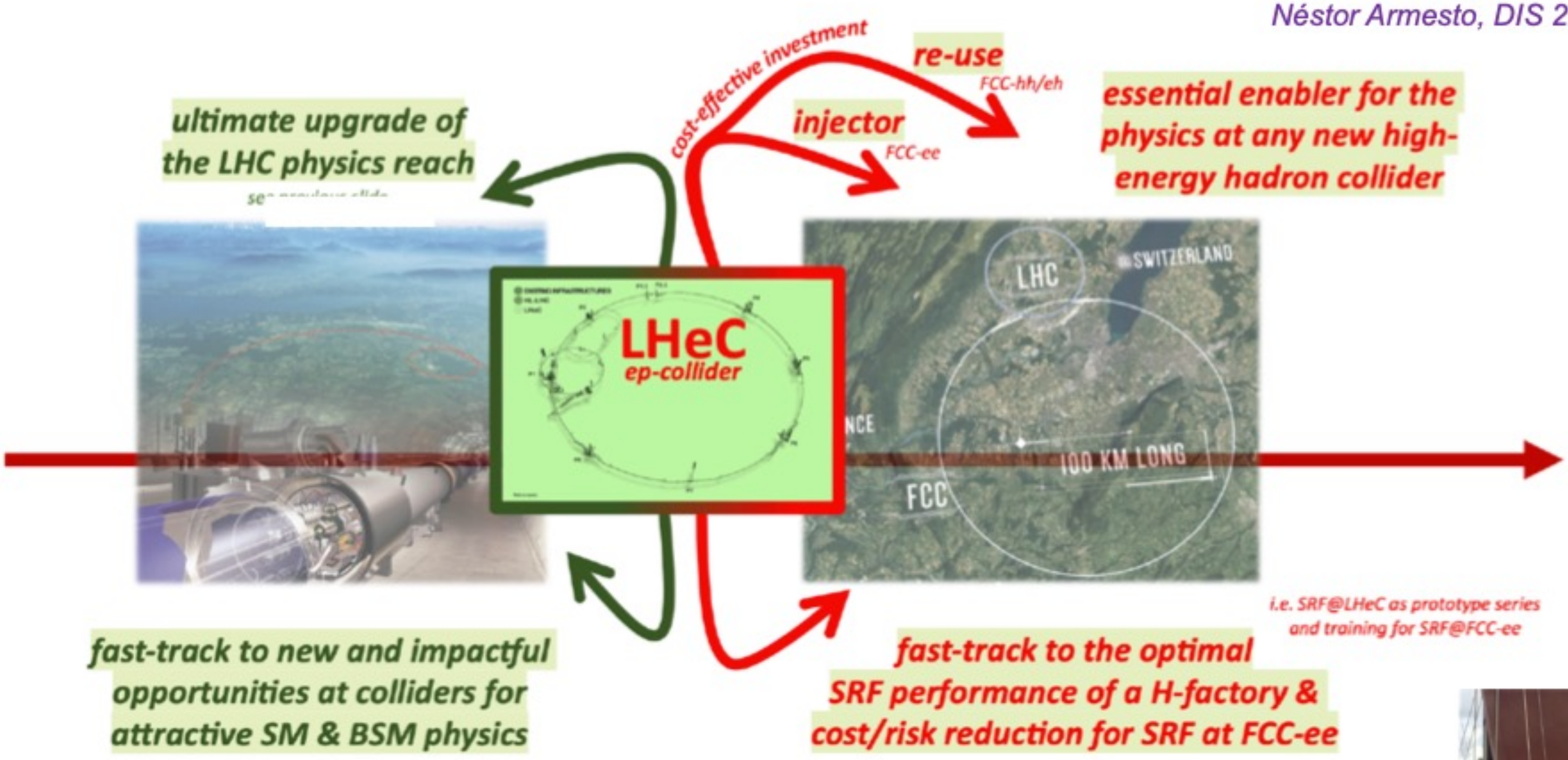
LEP3:
re-using the LEP/LHC tunnel for e^+e^- collisions at 230 GeV

Motivation:

- *Leave room (time, budget, resources) for further development of THE machine that can probe directly the energy frontier at a constituent √s ~ 10 times LHC*
- *Exploit interesting physics at CERN in the meantime*

The LHeC as a "Bridge" Project

Jorgen D'Hondt, ICHEP Prague, July 2024
Néstor Armesto, DIS 2025



ep option with HL-LHC
e.g. 6 years ep-only > 1 ab^{-1}

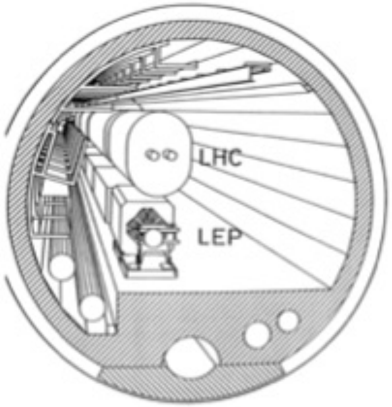

Max Klein (1951 – 2024)

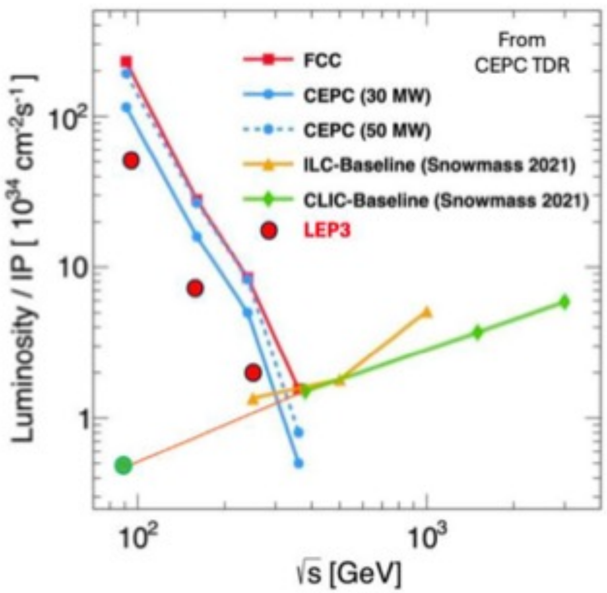
Karl Jakobs

LEP3 "Bridge" Project

Possible machine parameters:
(t.b.c, some technical details still need to be worked out)

- Luminosity: (2, 5.6, 32.5) · 10^{34} cm^{-2} s^{-1} at (ZH, WW, Z)-energies, respectively
- Number of interaction regions: 2
- Synchrotron radiation power loss: 50 MW
- ZH run at 230 GeV





LEP3 is not competitive with FCC-ee or CEPC, but still has an interesting Higgs and el.weak physics programme

Open Symposium on the European Strategy for Particle Physics, Venice 23rd - 27th 2025:

https://agenda.infn.it/event/44943/

European Strategy for Particle Physics – 2026 Update

https://europeanstrategyupdate.web.cern.ch/