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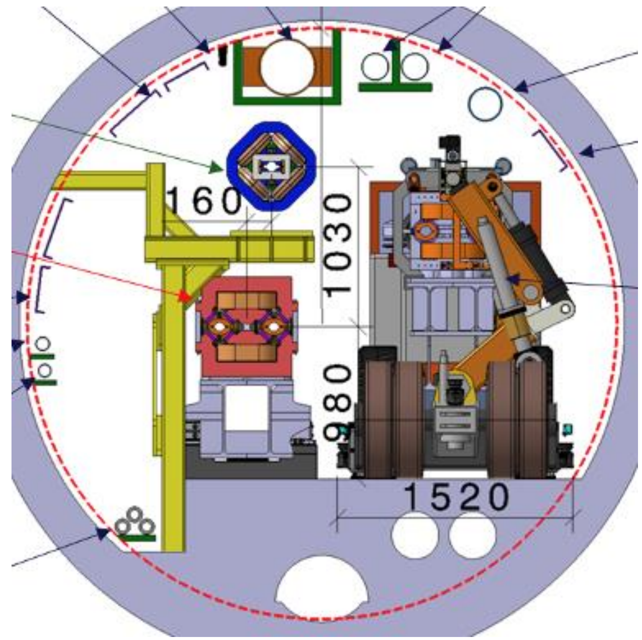
LEP3: A high luminosity electron-positron Higgs boson factory in the LHC tunnel

A possible back-up to the preferred option (FCC-ee and FCC-hh) for the next accelerator for CERN



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LEP3

Possibilities for PP's Future

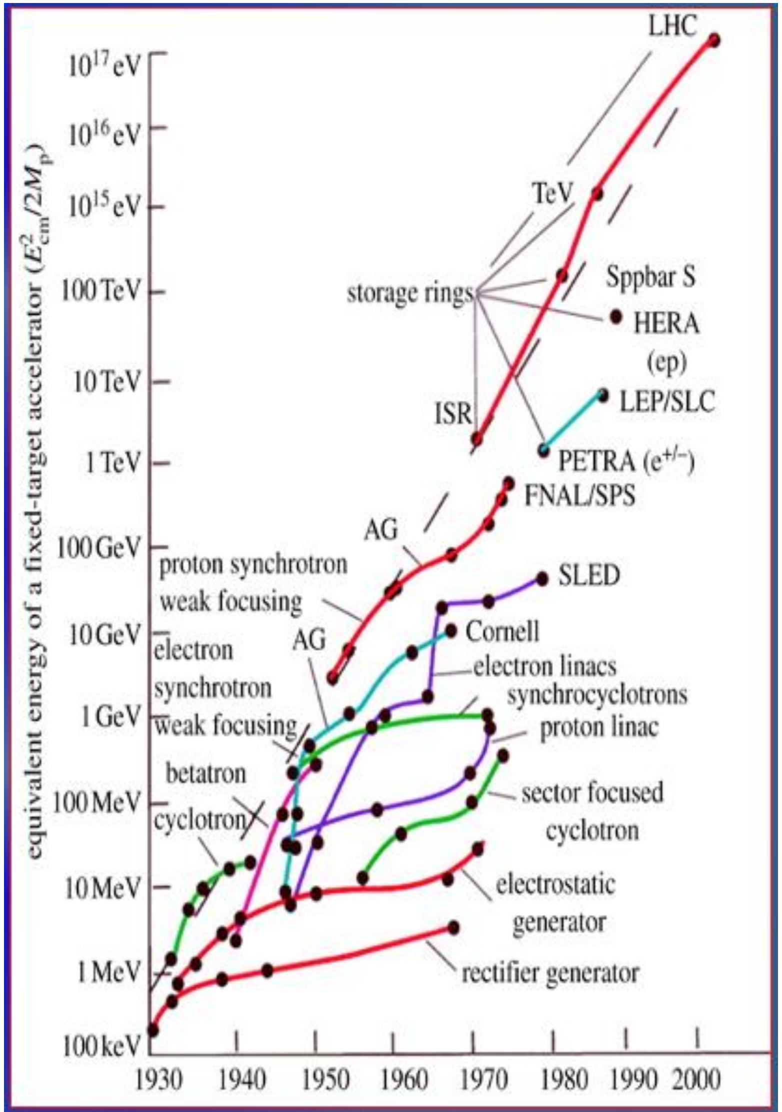
We support FCC-ee and FCC-hh as the preferred option for CERN's future

Longer-Term Aim: an accelerator with constituent √s ~10 times higher than LHC (1-2 TeV).

If FCC(ee) or CEPC is built then a **~100 TeV hadron collider** would be the obvious next step.

Muon colliders may provide alternative approach to reach constituent com energies of 10 TeV or higher.

(Programme could have milestones along the way that would deliver physics as the R&D progresses - muon driven neutrino beams for experiments such as nuSTORM or those on neutrino/antineutrino factories.)



Setting the Scene 1: 2019 ESPP

Recall Recommendations 2019 ESPP

a. The **successful completion of the HL-LHC**

b. Neutrino Platform

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

d. R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors

e. **investigate the technical and financial feasibility of a future hadron collider at CERN with $\sqrt{s}$ ~ 100 TeV and with an e^+e^- Higgs and electroweak factory as a possible first stage.**

Point e. clearly points to the FCC project, which has been extensively discussed.

Setting the Scene 2: Request for Alternatives

We support FCC-ee and FCC-hh as the preferred option for CERN's future, as it addresses both of ESPP2019 recommendations (c) and (e).

ESG Guidance

However, the ESG's remit explicitly states that "The Strategy update should include the preferred option for the next collider at CERN and prioritised alternative options to be pursued if the chosen preferred plan turns out not to be feasible or competitive".

It is imperative that the European HEP community should provide explicit feedback on both the preferred and alternative options for this "next collider at CERN", which will be the Laboratory's next flagship project, and an explanation of any specific prioritisation.

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ESPP 2025-2026: Timeline

- **In March 2024 CERN Council launched the new ESPP process: it will be completed in June 2026.**

Setting the Scene 3

It is desirable that any back-up to FCC should present fewer technical and/or financial difficulties than those associated with this preferred option, as well as have excellent physics potential.

To minimize the possibility of such difficulties, the LEP3 strategy is to re-use, as much as possible, the existing infrastructure of CERN, utilise maximally the R&D already carried out, and keep the required financing within the envelope of the current budget of CERN.

Corollary: Any other proposal, with a cost similar to the one for FCC, would have similar issues.

Several others have also discussed such a possibility in the past.

e.g. 2013 ESPP, a Higgs factory (LEP3) was proposed but not pursued any further. [https://cds.cern.ch/record/1471486].

LEP3: A High Luminosity e+ e- Collider in the LHC Tunnel to Study the Higgs Boson

A.P. Blondel (Geneva U.), F. Zimmermann (CERN), M. Koratzinos (CERN), M. Zanetti (MIT) (May, 2012)

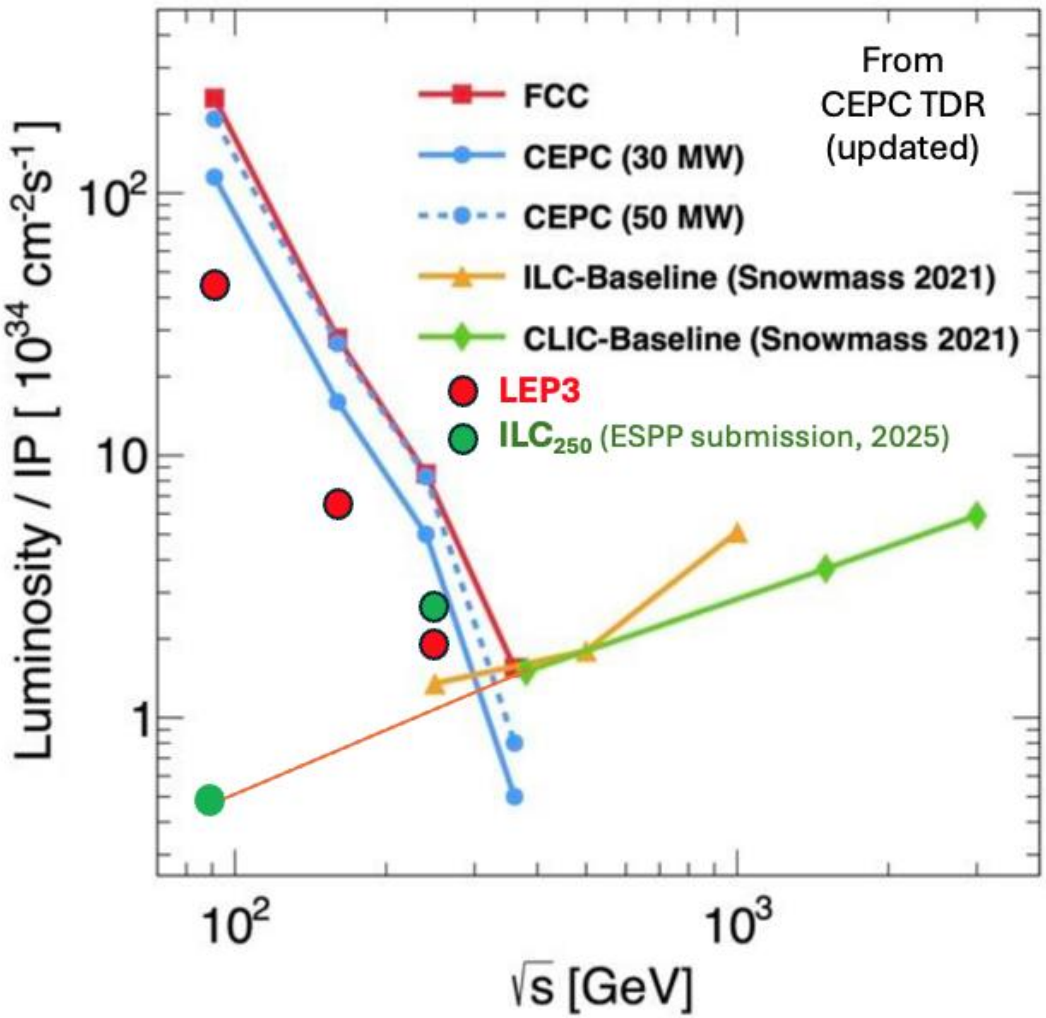
Contribution to: IPAC 2012

LEP3: A High Luminosity e^+e^- Collider to Study the Higgs Boson

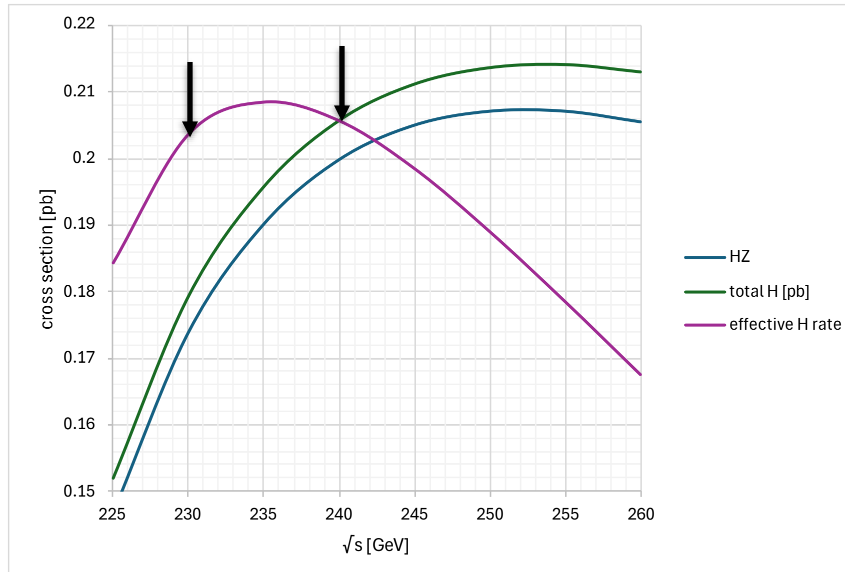
A. Blondel (Geneva U.), M. Koratzinos, R.W. Assmann (CERN), A. Butterworth (CERN), P. Janot (CERN) et al. (Aug, 2012)

e-Print: 1208.0504 [physics.acc-ph]

e^+e^- Colliders: Instantaneous Luminosity



In circular e+e- colliders, for the same synchrotron power loss, at a lower energy, more current can be put to increase luminosity.



LEP3: Run at √s =230 GeV

- Only 10% higher energy than LEP.
- 18% lower synchrotron power loss at √s=230 GeV compared with 240 GeV.

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LEP 3

LEP3 Principal Parameters

2017 Study with lattice proposed by K Oide

https://indico.cern.ch/event/687994/

LEP3 Parameters at 120 GeV with 4 IPs

parameter	old	new
beam energy [GeV]	120	
SR energy loss / turn [GeV]	7.44	6.92 → 5.83
beam current [mA]	6.7	7.2
longitudinal damping time [turns]	16.1	17.6
momentum compaction [10^{-5}]	2.43	2.434
horizontal emittance [nm]	4.6	4.2
vertical emittance [pm]	9.2	8.4
horizontal beta* [m]	1	
vertical beta* [mm]	2	
RF frequency [MHz]	800	
total RF voltage [GV]	8.0	
RF acceptance [%]	2.07	3.4
energy acceptance [%]	±1.5	±1.9
tunes, quarter-ring (x, y, s)	(0.53, 0.57, 0.0205)	(0.53, 0.57, 0.024)
bunch intensity [10^{11}]	2.3	2.7
number of bunches / beam	16	15
energy spread (SR / BS) [%]	0.2 / 0.208	0.197 / 0.217
bunch length (SR / BS) [mm]	2.53 / 2.65	2.13 / 2.36
Piwinski angle (SR / BS / BS+DB)	0.56 / 0.59 / 0.73	0.49 / 0.55 / 0.68
crab sextupoles	0.3	
length of interaction area [mm]	2.14	1.95
luminosity [10^{34} cm^{-2}s^{-1}]	0.74	1.11 → 1.5 2Xpts 230GeV
beam-beam tune shift ($\Delta\nu_x$ / $\Delta\nu_y$)	0.052 / 0.083	0.064 / 0.101
allowable asymmetry [%]	±3	
actual lifetime (w) by BS [min]	20	

Table from LEP3 submission
K. Oide & M. Koratzinos

	LEP3				LEP1
No. of IPs/Xpts	2				4
com energy √s (GeV). For final state(X)	230 (ZH)	163 (WW)	91.2 (Z)		91.20
…mference/Length [km]	26.606				26.659
Bending Radius (m)	2958				3026
Crossing Angle at IP [mrad]	30				0
SR Energy Loss/turn [GeV]	5.4	1.3	0.13		0.1
Total RF Voltage [GV]	6	1.5	0.18		0.2
SR Power /beam (MW)	50				0.33
Beam Current [mA]	9	39	371		3
Number of bunches/beam	18	200	4800		8
Bunch Intensity (10E11)	2.8	1.1	0.4		1.8
RF Frequency. [MHz]	800	800	400		352
Beam Lifetime (Bhabha+Brem) [min]	16	20	31		1390
Inst. Luminosity/IP [10^34 cm-2s-1]	1.8	6.4	44		0.002
Integrated L/IP [ab-1/yr]	0.216	0.8	5.28		0.0001
Years of Operation**	6	4	5		
No. Of Evts for 2 Xpts	4.7E+05	3.7E+07	1.7E+12		
rms bunch length (SR only). [mm]	2.4	2.5	2.8		2.3
rms bunch length (SR + BS). [mm]	2.7	3	4		2.3
horiz. Emittance εx. [nm]	3.8	1.8	0.6		45
vert. Emittance εx. [pm]	7.5	3.6	1.2		300
Longitudinal damping time [turns]	21	63	339		360
Horiz. β*(x) [m]	0.5	0.2	0.1		2
[illegible]	1	1	1		50
[illegible]	44	19	8		300
Vert. rms IP spot size [nm]	87	60	35		3873
Horiz. beam-beam parameter	0.09	0.03	0.01		0.02
Vert. beam-beam parameter	0.14	0.13	0.13		0.04

parameter	Z	HZ
beam energy [GeV]	45.6	120
SR energy loss / turn [GeV]	0.144	6.92
beam current [mA]	346	7.2
longitudinal damping time [turns]	316	17.6
momentum compaction [10^{-5}]	2.43	2.43
horizontal emittance [nm]	0.61	4.2
vertical emittance [pm]	1.4	8.4
horizontal beta* [m]	0.5	1
vertical beta* [mm]	1	2
RF frequency [MHz]	800	800
total RF voltage [GV]	0.2	8.0
RF acceptance [%]	1.5	3.4
energy acceptance [%]	±1.2	±1.9
tunes, quarter-ring (x, y, s)	(0.56, 0.59, 0.0072)	(0.53, 0.57, 0.024)
bunch intensity [10^{11}]	0.8	2.7
number of bunches / beam	2400	15
energy spread (SR / BS) [%]	0.075 / 0.099	0.197 / 0.217
bunch length (SR / BS) [mm]	2.67 / 3.58	2.13 / 2.36
Piwinski angle (SR / BS / BS+DB)	2.3 / 3.1 / 3.4	0.49 / 0.55 / 0.68
crab sextupoles	0.8	0.3
length of interaction area [mm]	1.0	1.95
luminosity [10^{34} $cm^{-2}s^{-1}$]	52	1.11
beam-beam tune shift ($\Delta\nu_x$ / $\Delta\nu_y$)	0.044 / 0.126	0.064 / 0.101
allowable asymmetry [%]	±5	±3
actual lifetime (w) by BS [min]	defined by vertical aperture	20

LEP3 Principal Parameters Abstracted

No. of IPs	2
Highest c.o.m. energy	230 GeV
SR power loss	Fix at 50 MW
SR energy loss/turn	~ 5.4 GeV
Total rf Voltage	~ 6 GV (800 MHz, 20MV/m SCRF cavities)
Inst Luminosity	~ 1.8, 6.4, 44 10^{34} $cm^{-2}s^{-1}$ at 230 GeV, WW threshold and Z-pole resp.
Crossing angle	30 mrad
Running Scenario	~ 20 years programme e.g. 6 yrs at 230 GeV, 4 years around WW, 5 years around Z
Est. total no. of Events	4.7×10^5 H, (cf. 6/22 $\times 10^5$H for ILC_{250}/FCC-ee) 3.7×10^7 WW at 163 GeV, 1.7×10^{12} Z at 91.2 GeV (cf. 0.001, 6 $\times 10^{12}$H for ILC_{250} and FCC-ee)

LEP3 can be competitive with alternatives wrt Higgs and E-W physics

Running time: 185 days of operation at 75% efficiency, with top-up running, giving 1.2 10^7 s/year of running

Physics Groups

PPG Working Groups: conveners, scientific secretaries (ECRs) and discussion leaders

Working Group	Conveners	Scientific Secretary	Discusion Leader
Electroweak incl. Higgs	Monica Dunford (DE, exp); Jorge de Blas (ES, theory)	Emanuele Bagnaschi (IT)	Florencia Canelli (CH)
Strong interactions	Cristinel Diaconu (FR, exp); Andrea Dainese (IT, exp, HI)	Chiara Signorile (DE)	Sven Moch (DE)
Flavour physics	Gino Isidori (CH, theory); Marie-Hélène Schune (FR, exp)	Maria Piscopo (NL)	Tim Gershon (UK)
BSM physics	Fabio Maltoni (BE/IT, theory); Rebeca Gonzalez-Suarez (SE, exp)	Benedikt Maier (UK)	Maurizio Pierini (CERN)
Neutrinos and cosmic messengers	Pilar Hernandez (ES, theory); Sara Bolognesi (FR, exp)	Iván Esteban (ES)	Mauro Mezzetto (IT)
Dark matter and dark sectors	Jocelyn Monroe (UK, exp); Matthew McCullough (CERN, theory)	Yohei Ema (CERN)	Caterina Doglioni (UK)
Accelerator technologies	Gianluigi Arduini (CERN, accelerators); Phil Burrows (UK, exp, accelerators)	Jacqueline Keintzel (CERN)	Tor Raubenheimer (US)
Detector instrumentation	Thomas Bergauer (AT, exp); Ulrich Husemann (DE, exp)	Dorothea vom Bruch (FR)	Daniela Bortoletto (UK)
Computing	Tommaso Boccali (IT, exp, comp); Borut Kersevan (SI, exp, comp)	Daniel Th. Nurnane (DK)	Stephane Jezequel (FR)

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LEP3

Higgs boson physics 2

Preliminary

To be checked and updated

	HL-LHC*	LEP3 **	LHeC	ILC 250***	Comment and leading err	FCCee	FCCee
C.o.m. energy		**230**	**e50+p7TeV**	**380**		240	LHC+240+365
No. of Experiments	**2**	**2**	**1**	1		4	4
Prog Integ. Lumi (ab-1)	3	2.5	1	2.7		10.8	
Years of Running	10	6	6	13		3	
Observable (σ, %) or as indicated		**σ.Br**	**κ*2**	**σ.Br**		**σ.Br**	κ (global fit)
δm(H) (MeV)	100	8.7		38	Sys: knowledge of Eb(ee)	4	
δΓ(H)/ΓH (%)	50			12			0.78
δσ(HZZ)/g(HZZ)	1.6	0.3	2.4	1.3		0.13	0.1
δσ(HWW)/g(HWW)	1.6	1.7	1.40	1.7		0.8	0.29
δσ(Hττ)/g(Hττ)	1.9	1.3	6.2	2.1		0.58	0.46
δσ(Hγγ)/g(Hγγ)	1.8	7.8	13.6	1.1		3.6	1.1
δσ(Hμμ)/g(Hμμ)	3	23.8		4		11	4.4
δσ(Hcc)/g(Hcc)	100	3.5	7.6	5	LHC from ~CMS/√2	1.6	0.87
δσ(Hbb)/g(Hbb)	3.6	0.5	3.8	0.29		0.21	0.49
δσ(Hgg)/g(Hgg)	2.4	1.7	7	2.1		0.8	0.54
δσ(Htt)/g(Htt)	3.4						3.1
δσ(HZγ)/g(HZγ)	6.8	25.5		9.1		11.8	3.3
BR (H>inv) (%) 95%CL	<2.5			0.2	LHC from CMS/√2		0.12
BR (H>EXO) (%) 95%CL	<4			1.6		<1.1	
δ(H self-cplg) (%) 95%CL	30 (SM)			50	HH from LHC, ZH from ee	40	20
		scale from FCC 240				Feasibility Study	

LEP3 can be competitive with other alternatives

LEP3 ~ 4.7×10^5 H bosons (6 yrs 2 expts) cf FCC(ee) ~2.2×10^6 (3 yrs 4 expts)

E-W physics 1

~1.7x10^{12} Z bosons (5 yrs at 91.2 GeV), and ~ 2.5×10^{7} WW pairs (2 eff yrs at √s=163 GeV)

cf FCC(ee) ~6 × 10^{12} and ~1.5 × 10^{8} resp.

Observable	LHC/Present		LEP3	ILC250	Comment and leading error	FCCee	FCCee
	value	± error	Stat+Sys	stat+Sys	Stat (M) and Sys (N) Errors scaled by √ratio (evt no)	Stat	Sys
No . of Experiments			2 Xpts	1 Xpt (eff)			
m(z) [keV]	91186700	± 2200	187.23		Sys - From Z line shape scan; beam energy calibration	4	100
Γ(z) [keV]	2495200	± 2300	23.66		Sys- From Z line shape scan; beam energy calibration	4	12
sin^2 θW^eff [10^6]	231480	± 160	3.17		From A(μμ)FB at Z peak, beam energy calibration	1.2	1.2
1/αQED (m2Z)(×10^3)	128952	± 14	7.40		Stat - From AμμFB off peak,QED & EW errors dominate	3.9	small
RZl (×10^3)	20767	± 25	0.13		Sys-Ratio of hadrons to leptons, acceptance for leptons	0.05	0.05
αs (m^2Z) [×10^4]	1196	± 30	1.88		Sys-From RZl., Gamma(tot),σo(had)	0.1	1
σ0had (×10^3) [nb]	41541	± 37	0.80		Sys-Peak hadronic x-section, luminosity measurement	0.03	0.8
Nν [×10^3]	2996	± 7	0.28		Sys-Z peak cross-sections, Luminosity measurement	0.09	0.12
Rb [10^6]	216290	± 660	0.73		Sys-Ratio of bb to hadrons, Stat extrap. from SLD	0.25	0.3
A(b)FB,0 [10^4]	992	± 16	0.08		Sys-b-quark asymmetry at Z pole, from jet charge	0.04	0.04
Apol,τFB [10^4]	1498	± 49	0.40		Sys-τ polarisation asymmetry, τ decay physics	0.07	0.2
τ lifetime [fs]	290.3	±0.12	0.01		Sys-radial alignment	0.001	0.005
τ mass [MeV]	1776.86	± 0.12	0.02		Sys-momentum scale	0.002	0.02
τ leptonic (μνμντ) BR [%]	17.38	± 0.04	0.006		Sys-e/μ/hadron separation	0.00007	0.003
m(W) [MeV]	80350	± 15	1.00	1.4	From WW threshold, beam energy calibration	0.18	0.16
Γ(W) [MeV]	2085	± 42	2.40		StatFrom WW threshold, beam energy calibration	0.27	0.2
αs (m^2W) [10^4]	1010	± 270	5.29		Stat-From RWl	2	2
Nν [10^3]	29292096	± 50	0.95		Stat-Ratio of invis. to leptonic in radiative Z returns	0.5	small
m(top) [MeV]*	172740	± 500	n/a		Stat-From ttt threshold scan, QCD errors dominate	4.2	4.9
Γ(top) [MeV]	1410	± 190	n/a		Stat-From ttt threshold scan, QCD errors dominate	10	6
λtop /λSM(top) **	1.2	± 0.05	n/a		Stat-From ttt threshold scan, QCD errors dominate	0.015	0.015
ttZ coupling [%]		± 3.4%	n/a		Stat-From √s=365 GeV run	0.5- 1.5	small
						FCC Feasilbility Study	

Preliminary

To be checked and updated

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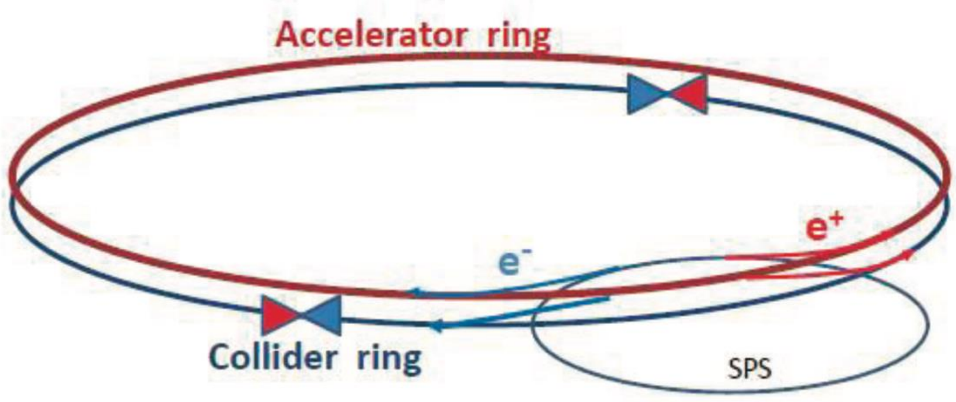
Follow ESPP2013 proposal & FCC(ee) Design

LEP3 installed in the existing LHC/LEP tunnel

Design of LEP3 could follow closely that outlined in FCC MTR and [ESPP 2013: https://cds.cern.ch/record/1471486].

- Separate full energy collider and accelerator (booster) rings, the latter for top-up injection. Electrons and positrons in the collider ring travel in separate beam pipes.
- With top-up - beam lifetime ~ 15 minutes (expected to be dominated by loss due radiative Bhabhas) top up ~ few 10^{10} electron/s

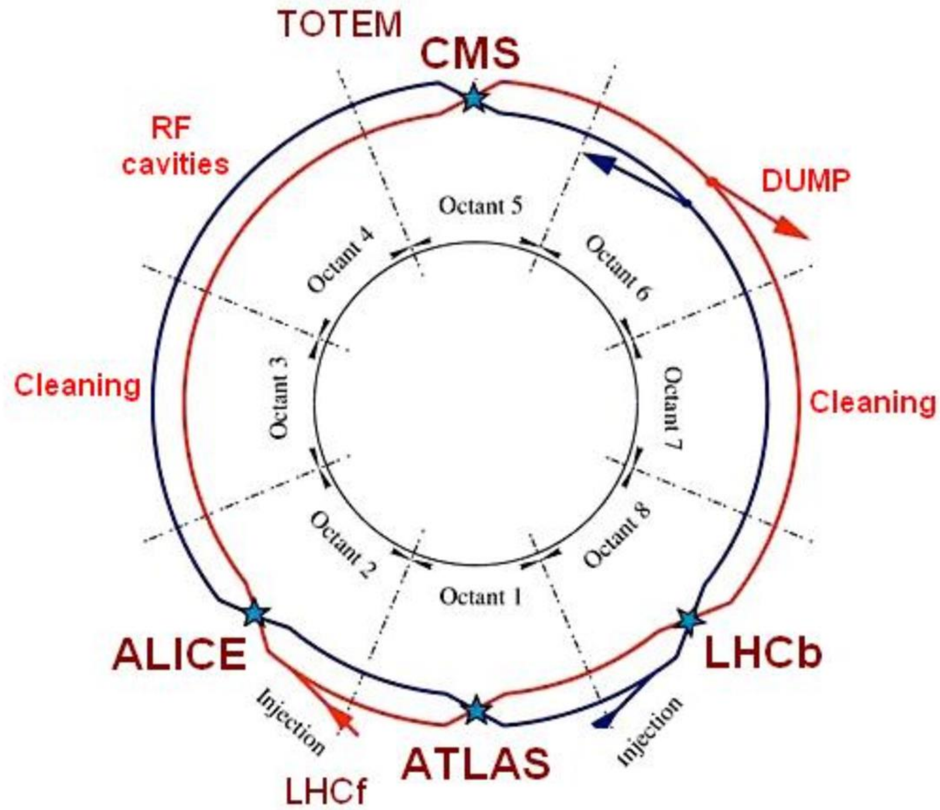
Earlier work (2013)



	LEP3	TLEP (LEP4)
circumference	26.7 km	80 km
max beam energy	120 GeV	175 GeV
max no. of IPs	4	4
luminosity at 350 GeV c.m.	-	0.7×10^{34} cm^{-2}s^{-1}
luminosity at 240 GeV c.m.	10^{34} cm^{-2}s^{-1}	5×10^{34} cm^{-2}s^{-1}
luminosity at 160 GeV c.m.	5×10^{34} cm^{-2}s^{-1}	2.5×10^{35} cm^{-2}s^{-1}
luminosity at 90 GeV c.m.	2×10^{35} cm^{-2}s^{-1}	10^{36} cm^{-2}s^{-1}

Note ratio of Lumi (1/5)

LEP3



The arcs are 2.45-km long, and the straight sections are 545-m long. The inner diameter of the tunnel varies between 3.8m in the arcs and ~ 4.4 m in the straight sections.

Either deploy two new experiment or use re-purposed ATLAS and CMS experiments

Choice of Components: Dipole Magnets & Injector

Follow FCC(ee) design

Instantaneous Luminosity [CEPC or FCC(ee) / LEP3] ~5; **~ 1.8×10^{34} cm^{-2}s^{-1} per IP**

2 Experiments; Coul reuse existing ATLAS and CMS experiments, suitably modified.

Use FCC designs for magnets

FCC Feasibility Study

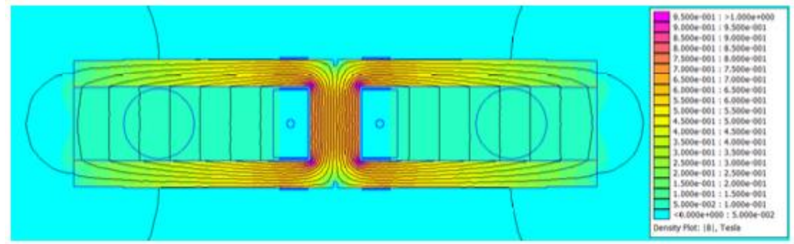
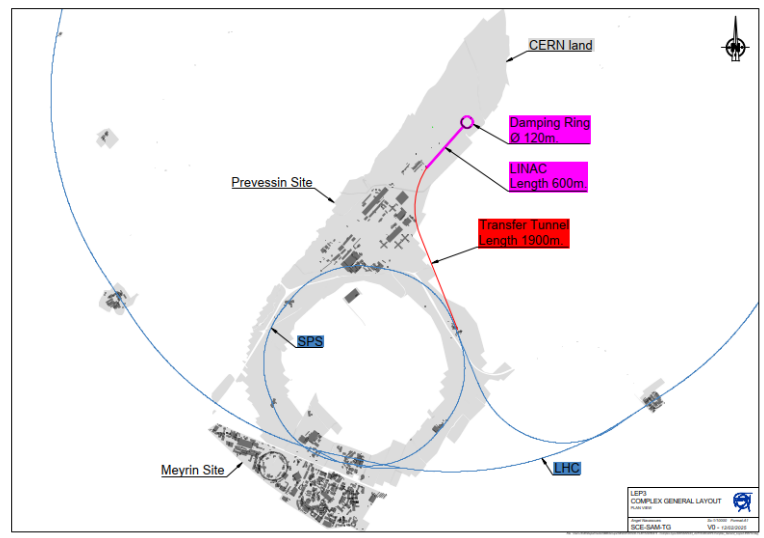


Fig. 3.1: Field map in the dipole cross-section at $t\bar{t}$ operation.

- **Dedicated linac injector** on Prevessin site;
- Injection energy lowered from 20 to 10 GeV. (Sensitive to field quality of bending magnets at injection.)

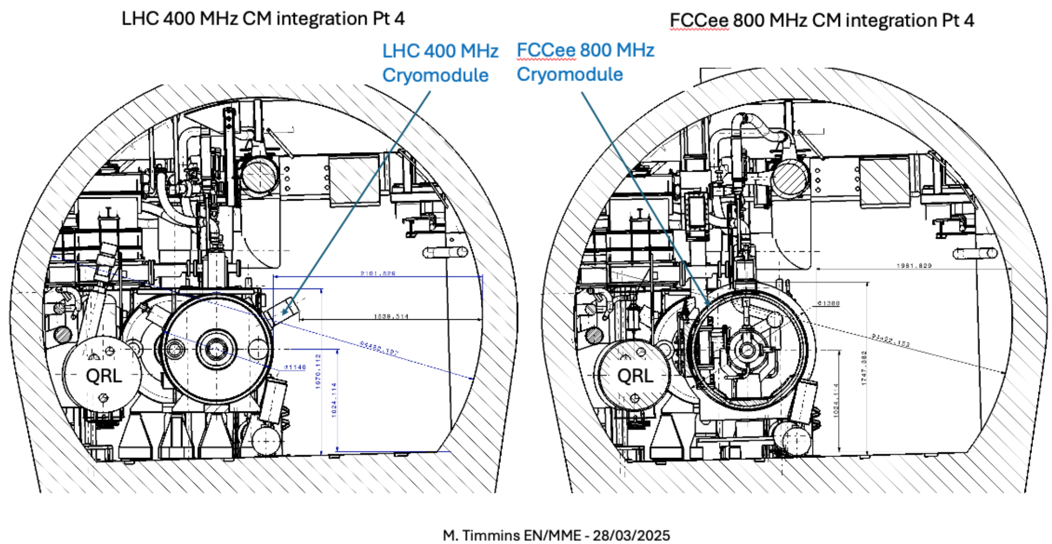


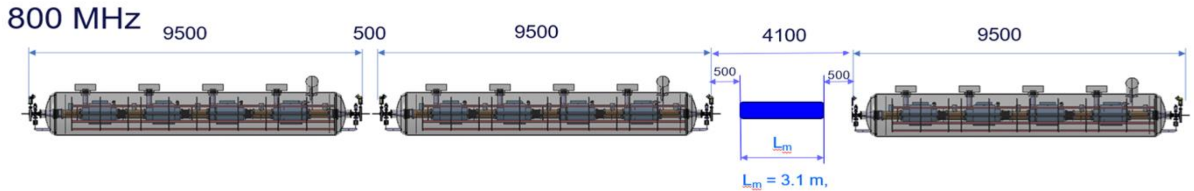
Choice of Components: RF System

RF: Energy loss/turn @ √s=230 GeV: 5.1 GeV.

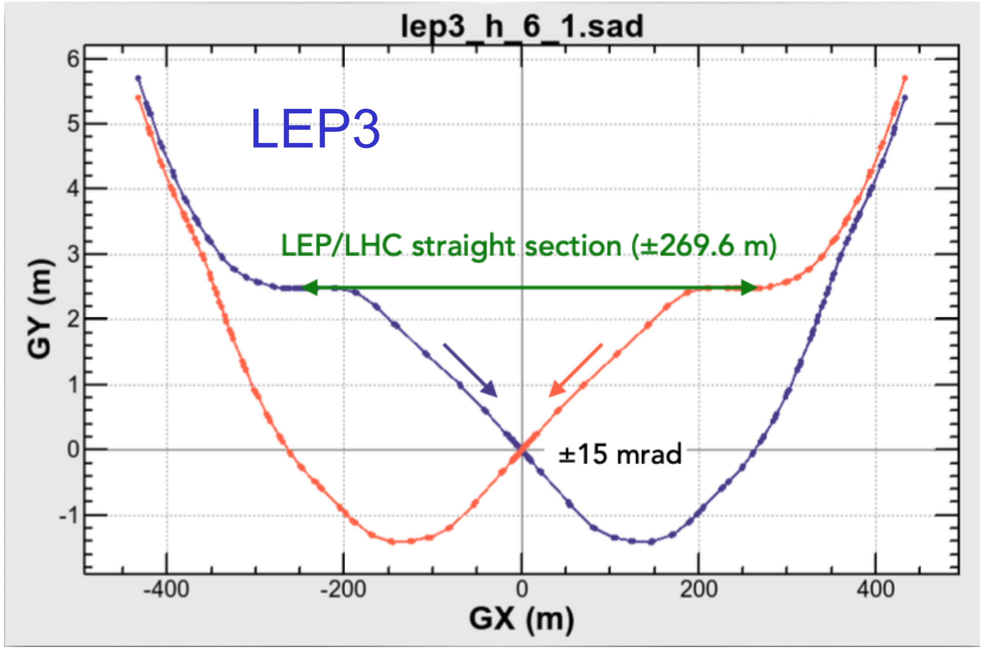
A total 6.0 GV to be installed, with the same margin as FCCee

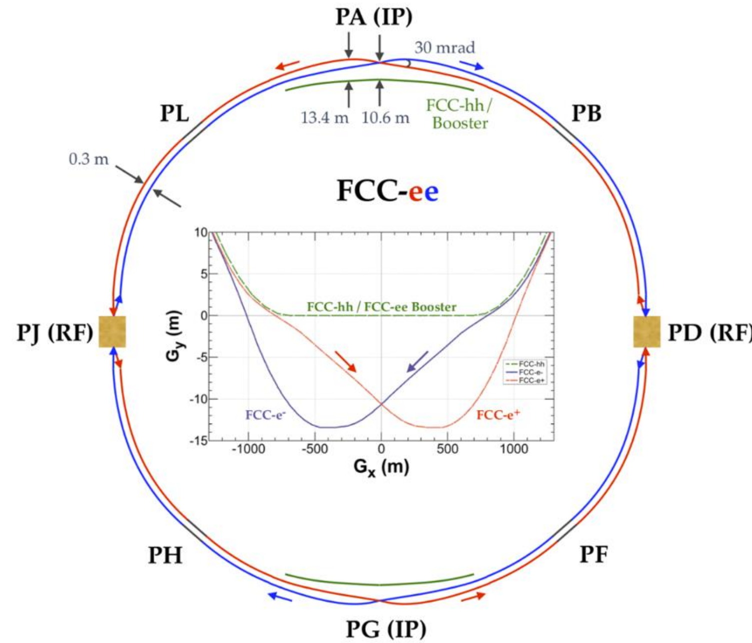
- **For Z running**: Investigating use of 400MHz 1-cell (0.9 MW) cavities/CRM. The beam current is too high to use 800 MHz cavities. Separate cavities for e- and e+
- **For WW and ZH running, and booster:** use 800 MHz 6-cell, 0.9 MW, 20 MV/m sc bulk niobium cavities run at 2K. One set for the accelerator and one set for the collider, each set in two LSS. The two colliding beams share RF. Still to check integration of booster RF.

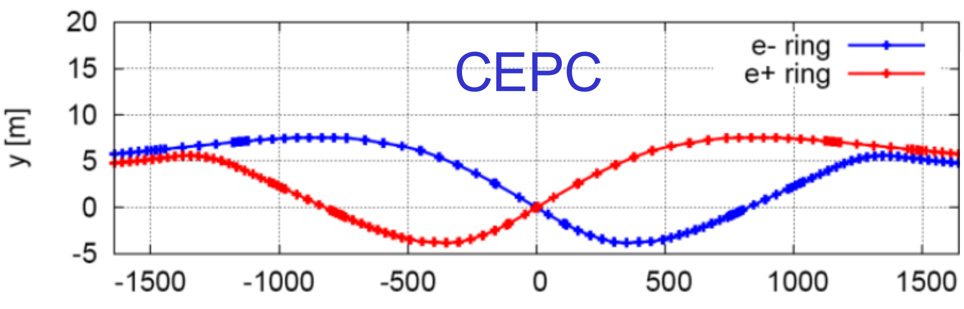


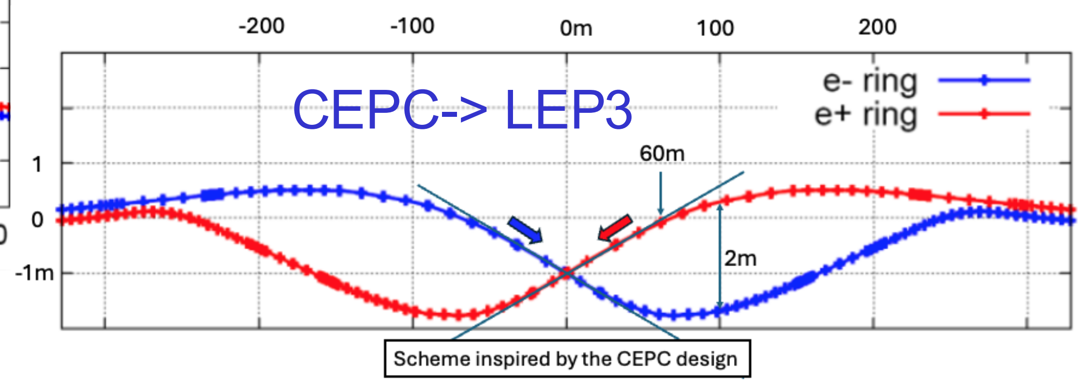


Crossing Angle





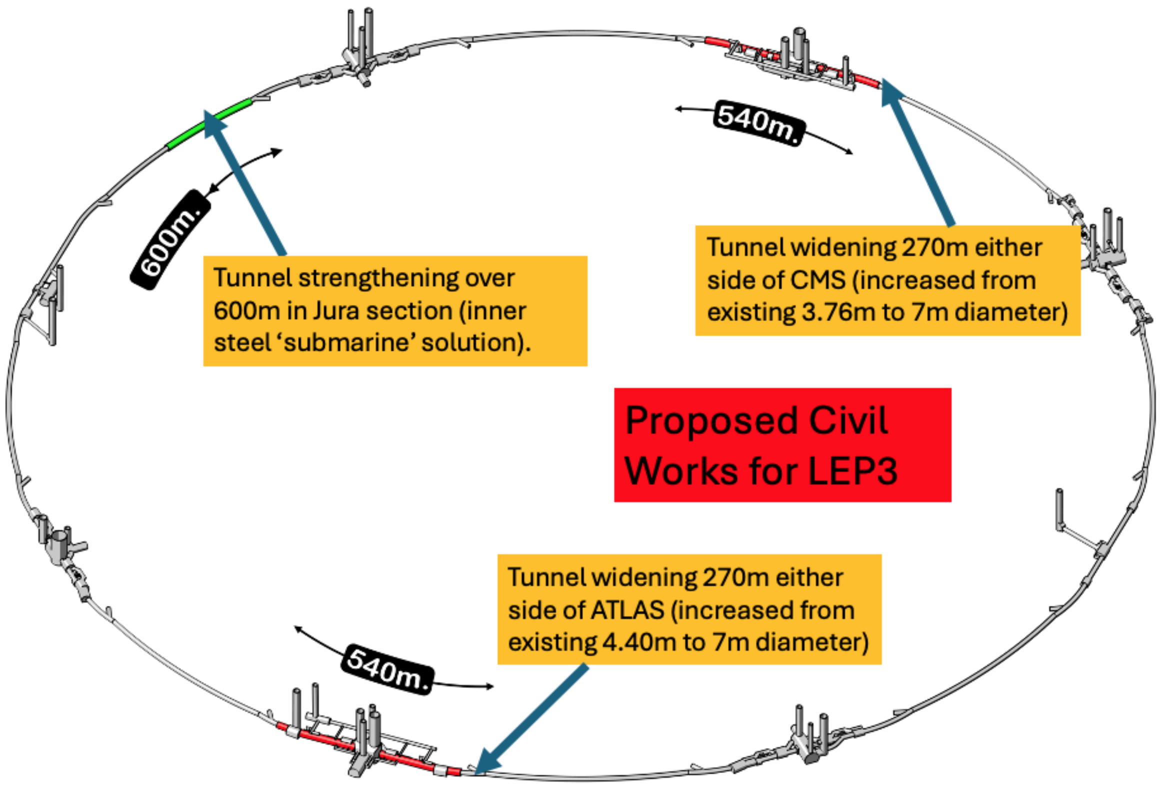




CEPC: No bending magnets placed in straight section within 70m of the collision points.

Cvil Engineering

- 40 years old infrastructure, some parts need maintainance
- High lumi acheived by crab-waist → large xing-angle → need to widen the LSS cross section on either side of the experiments
- possibly need of by-passes (avoidable possibly not needed)
- Overall civil engineering cost estimated: 165 MCHF



Experiments-Machine Detector Interface

Assume that the ATLAS and CMS experiments can be re-used with **suitable modifcation or rebuilding of the inner trackers and the integration of focusing quadrupoles** some 2m from the IP. Same magnets but at lower fields. Trackers costing around MCHF 100/per experiment are assumed. (Should save the community >1BCHF)

Exploit all R&D done for ILC, CLIC and FCC(ee) detectors as well as LHC upgrades.

Baseline: Accelerator(booster) beam passes through tracker. If too much of perturbation then need bypasses.

All of the above need detailed studies.

From FCC MTR:
Integration of IR optics.
Independent beam pipes ~ 1-2m from IP.

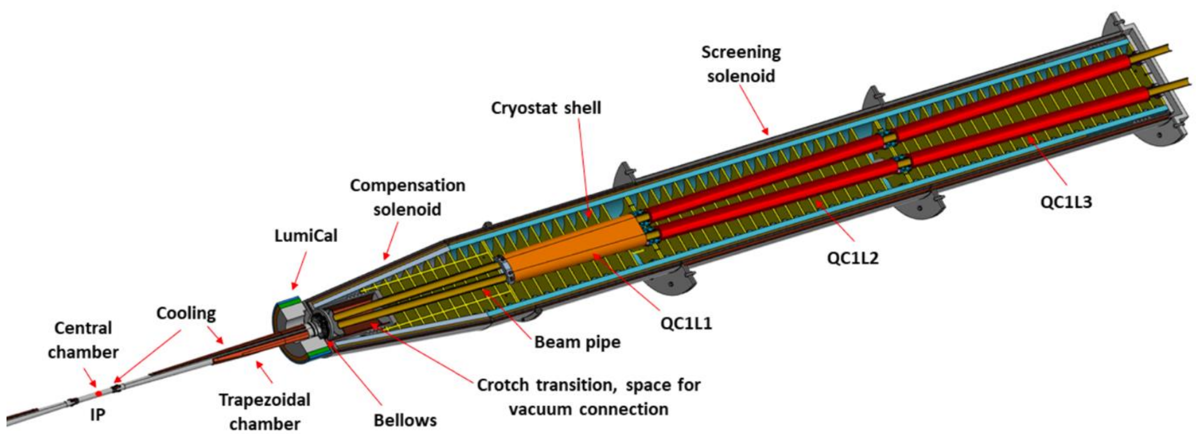


Fig. 217 Section view of the accelerator components from the IP to the end of the first final focus quadrupole (QC1), at about 8.4 m.

Cost

Use the FCCee costing methodology.
Costs scaled from FCC(ee) MTR costs: scaled according to numbers of components required

Two New Experiments

Cost Element	Cost to CERN	Cost to PP
Accelerator	2023	
Injectors and Transfer Lines	296	
Technical Infrastructures	433	
Experiments	128	900
Civil Engineering	165	
LHC Removal/LEP3 Installation	140	
Total (MCHF)	**3185**	**900**

Two Existing Experiments

Cost Element	Cost to CERN	Cost to PP
Accelerator	2023	
Injectors and Transfer Lines	296	
Technical Infrastructures	433	
Experiments	58	270
Civil Engineering	165	
LHC Removal/LEP3 Installation	140	
Total (MCHF)	**3115**	**270**

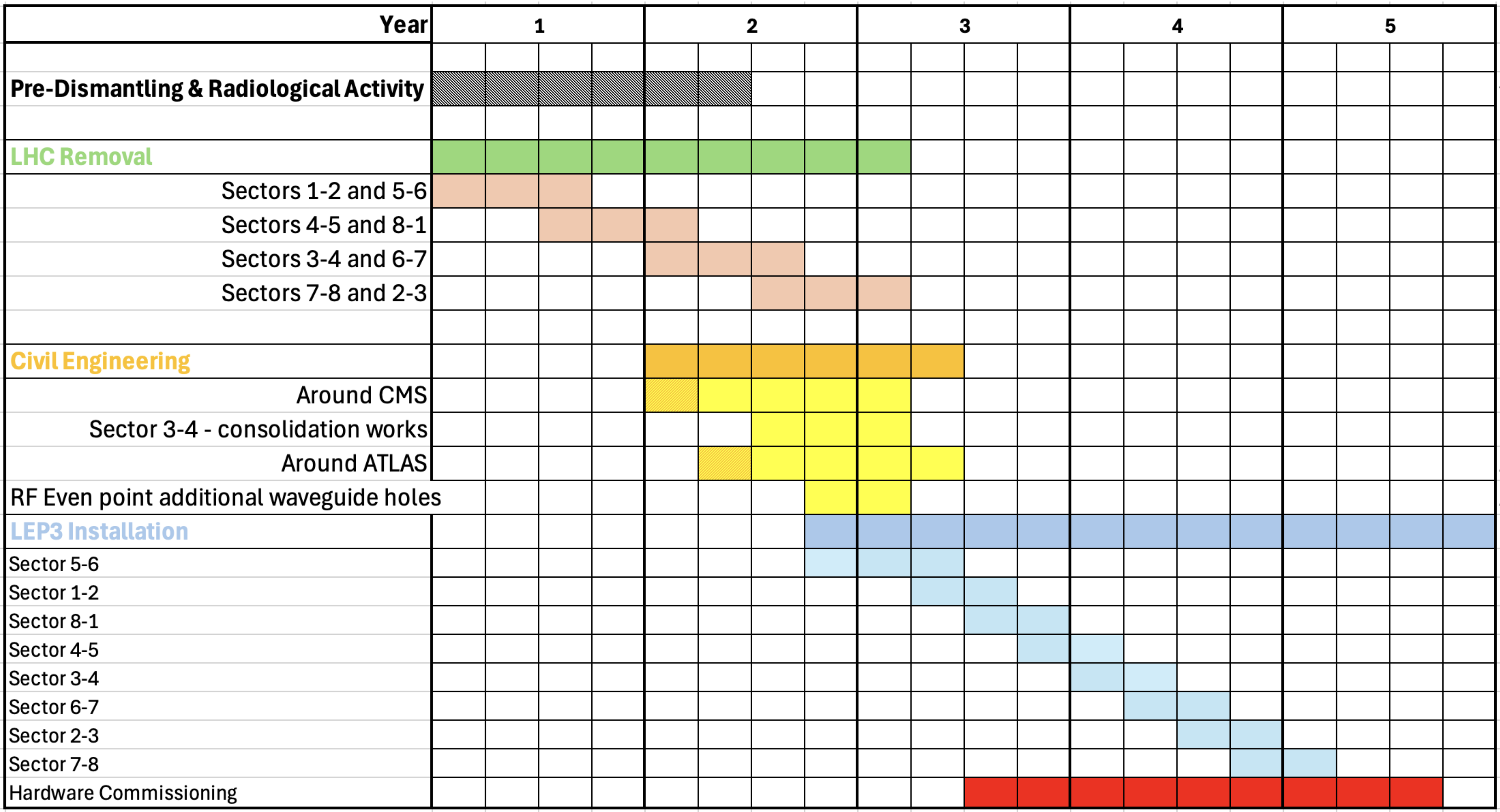
With assumed schedule (see next) LEP3 cost would be well within the standard CERN budget, allowing pursuit of other future-oriented initiatives [e.g. R&D on rf cavities (high gradient, low power), high-field magnets, muon collider demonstrator]

Cost: assumes careful removal of LHC machine in case it is needed later as an injector.

Funding assumes CBD paid off by 2035; 250 (350) MCHF saved/year when only running HL-LHC (when in shutdown).

Sustainability is an important issue: use ideas/proposals from the other projects

Example Shutdown Schedule: After LHC stops



Possibilities: The Future Beyond LEP3

Aim: an accelerator with constituent $\sqrt{s}$ ~10 times higher than LHC (1-2 TeV).

If FCC(ee) or CEPC is built then a ~100 TeV hadron collider would be the obvious next step. **R&D Goal: Develop high field magnets - followed by the setting up for industrial production to provide solid cost estimates.**

Muon colliders may provide alternative approach to reach constituent com energies of 10 TeV or higher. **R&D Goal: on muon colliders – programme could have milestones along the way that would deliver physics as the R&D progresses - muon driven neutrino beams for experiments such as nuSTORM or those on neutrino/antineutrino factories.**

If FCC-ee proceeds, then the required tunnel would already exist. However, if FCC-ee does not proceed, the FCC-hh tunnel could also be dug later, profiting from the site studies currently underway, and giving due time for magnet development and industrialization.

If it turns out that the muon collider is the preferred path, the required tunnel would be smaller than even the LEP/LHC tunnel, which could host an intermediate/injector ring.

After LEP3 (i.e. after around 30 years from today) perhaps via a worldwide strategy.

Additional R&D Goal: increase gradient and efficiency of rf cavities and bring down their cost

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Summary

We support (FCC-ee + FCC-hh) as the preferred option for CERN's future

ESPP requests an alternative/ backup option for the preferred one.
An e^+e^- collider in the LHC tunnel, referred to here as LEP3, is proposed as an a backup option

- Compared to the linear e^+e^- colliders proposed, LEP3 provides similar luminosity for ZH production, higher luminosity at lower energies and options for multiple experiments, all at much lower cost.
- LEP3 is a reasonable (perhaps the best) backup option
- Leaves room (time, budget, resources) for further development of THE machine that can probe directly the energy frontier at a constituent $\sqrt{s}$ ~ 10 times LHC.

No showstoppers have yet been identified, and we consider this proposal to be sufficiently interesting to deserve further study. We have identified important areas that would require deeper investigation before CERN could commit to LEP3.