# Future Colliders: Possibilities and Challenges
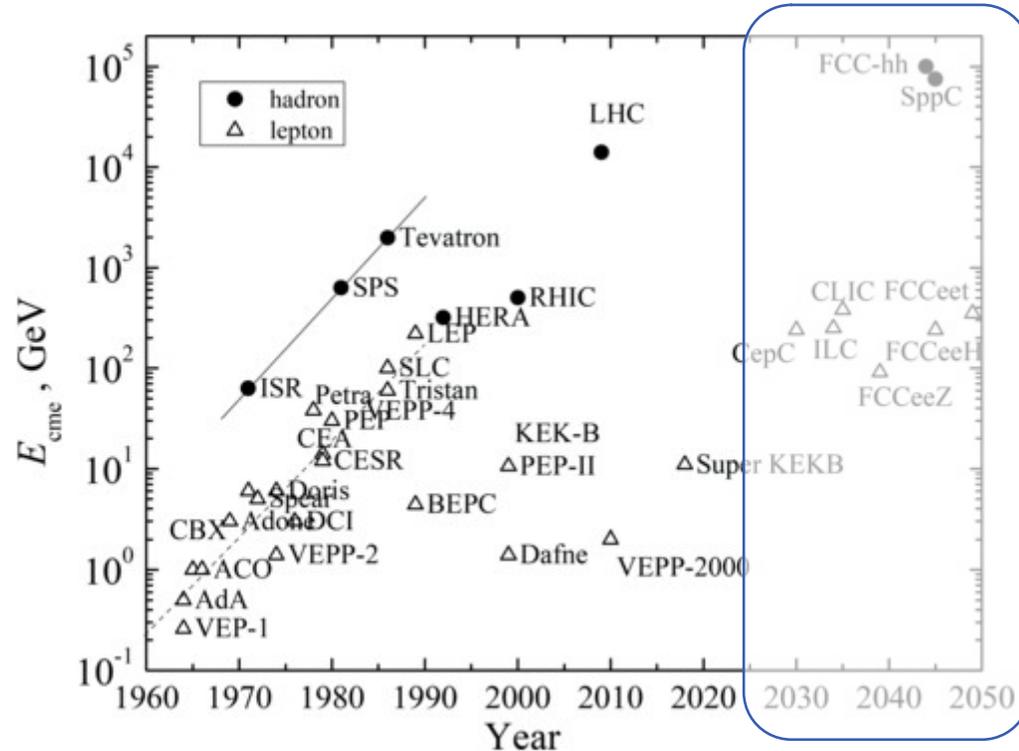
Jacqueline Keintzel

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TH Colloquium
CERN, Switzerland
12 November 2025

# Collider history

◦ Collider physics started in the 1960s with the first ones being electron-positron colliders
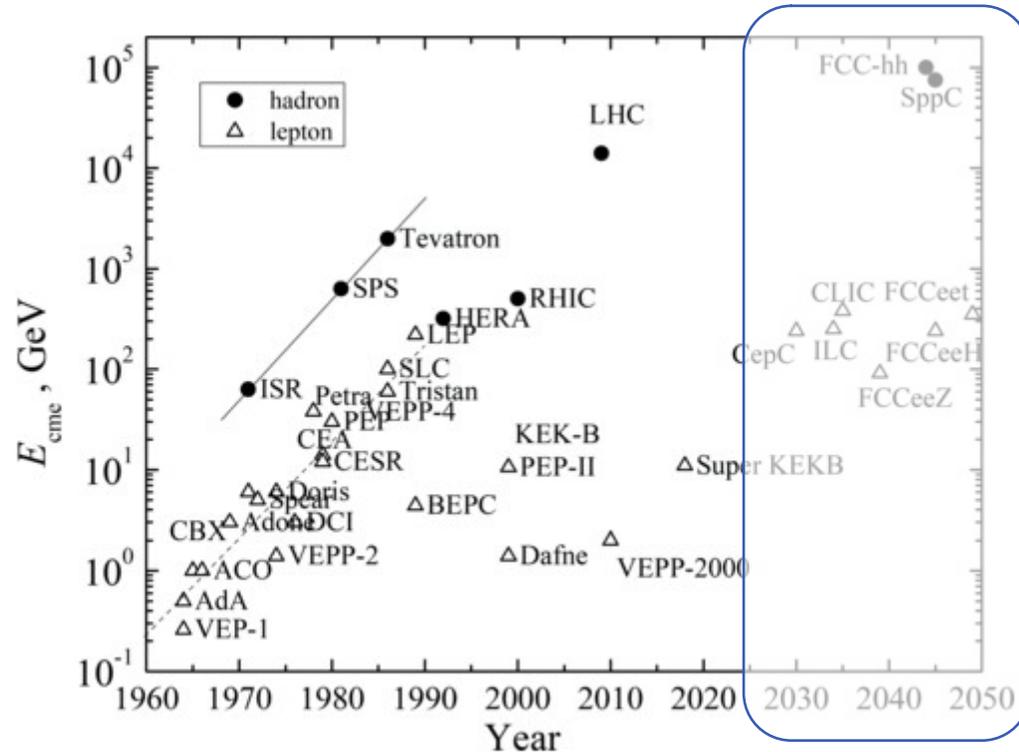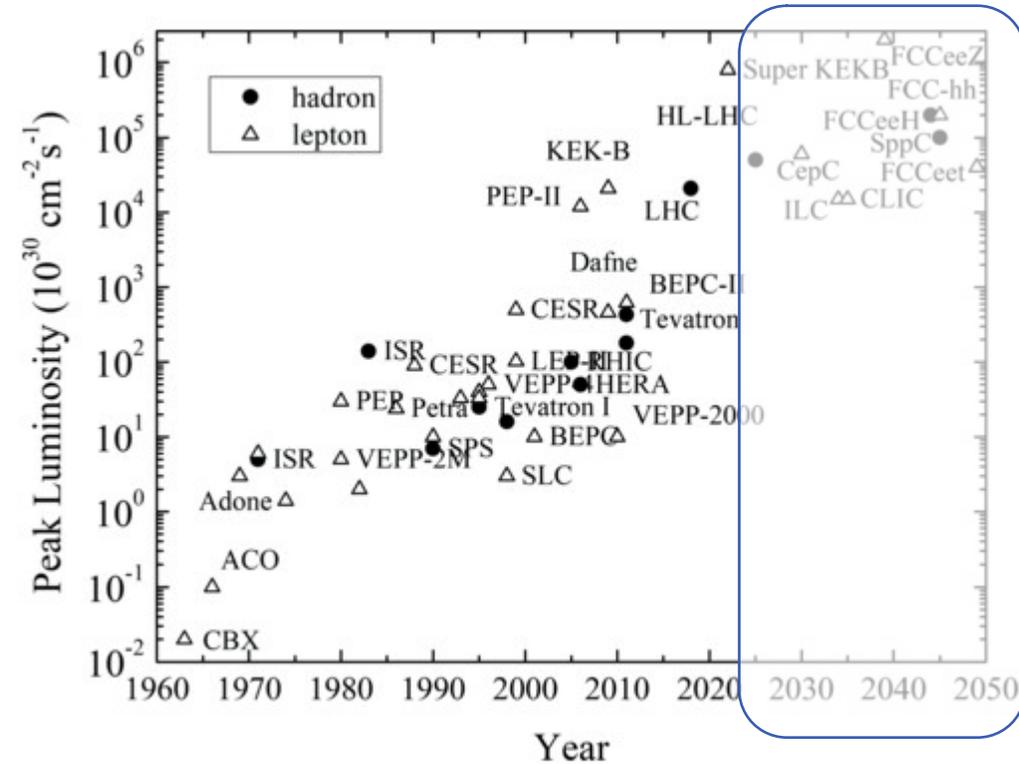


Too optimistic

Ref: V. Shiltsev and F. Zimmermann, Rev. Mod. Phys. 93, 015006, 2021.

# Collider history

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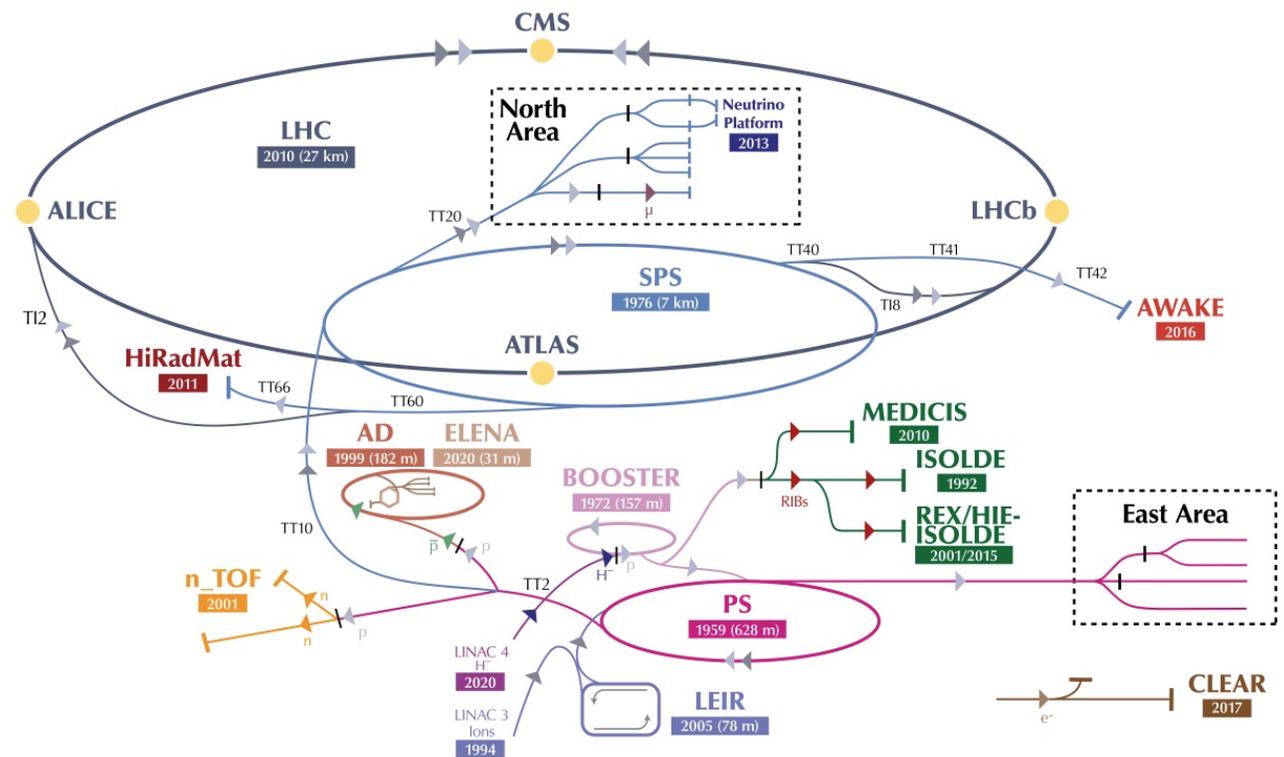


Too optimistic

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Ref: V. Shiltsev and F. Zimmermann, Rev. Mod. Phys. 93, 015006, 2021.

# The biggest e+e- collider so far

○ Large Electron Positron Collider (LEP) with 27 km circumference

○ Predecessor of the Large Hadron Collider (LHC) → same tunnel for 2 different colliders

○ In operation from 1989 to 2000

○ Up to 209.2 GeV center-of-mass energy

# Particle physics status

○ Standard Model (SM) confirmed to high accuracy up to several TeV

○ Higgs-boson discovered

  ○ At the mass predicted within the SM by LEP

    precision electro-weak measurements

○ Absence of new physics at the TeV scale

Need for a new, broad and ambitious program
→ more precision
→ more energy
→ for more sensitivity for new physics



https://forumias.com/blog/the-standard-model-of-particle-physics-gets-a-jolt/#gsc.tab=0

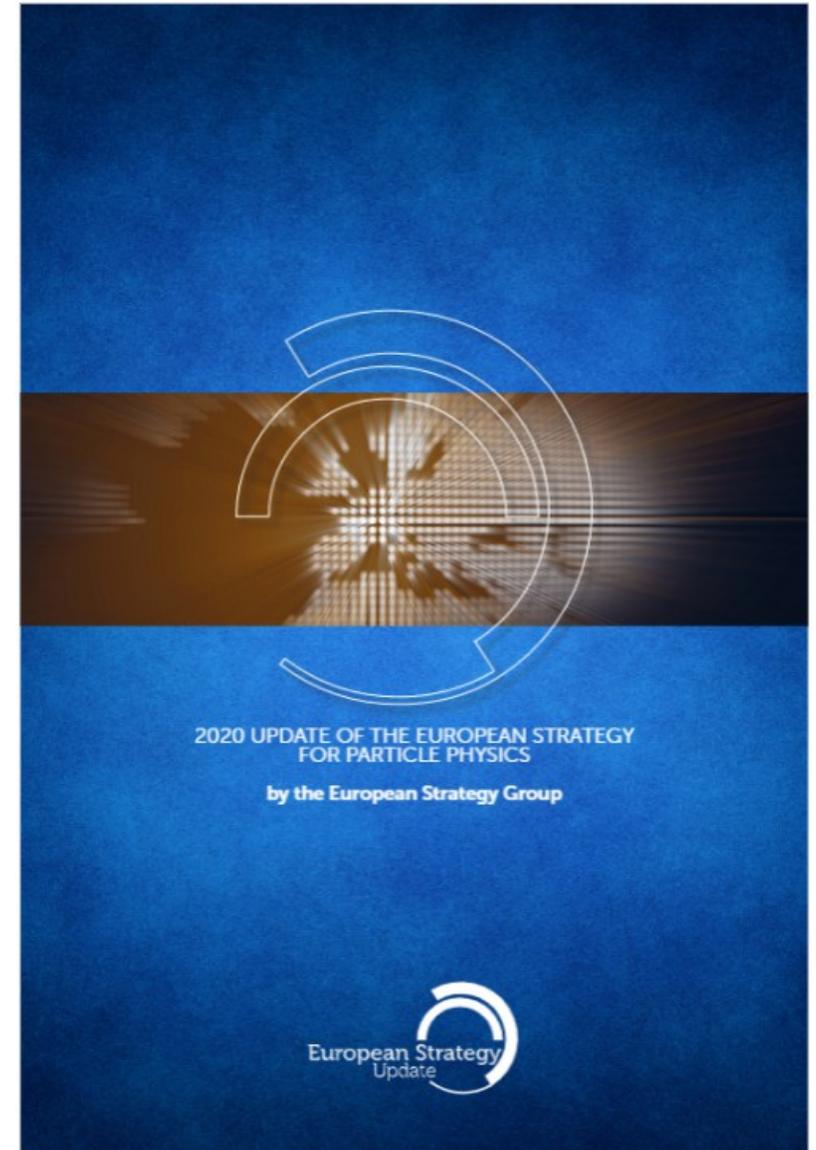# Particle physics future 2020

- In 2020 the European Strategy of Particle Physics Update (ESPPU) expressed the long-term plan for particle colliders:

  - 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 center-of-mass energy of at least 100 TeV and with an **electron-positron Higgs and electroweak factory as a possible first stage**.

- Particle Physics Project Prioritization Panel (P5) published recommendations in 2023, high priority projects:

  - Exploitation of LHC and HL-LHC

  - **Oversea Higgs and electroweak factory**

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy Update

# Considerations

◦ What?

| Hadrons | Leptons |
|---|---|
| ◦ Mix of quarks and gluons | ◦ Elementary particles colliding |
| ◦ Discoveries at physics frontier | ◦ High-precision measurements |
| ◦ Typically high collision energy | ◦ Well-defined center-of-mass energy |
| ◦ Main limitation: dipole field and ring size | ◦ Main limitation: synchrotron radiation (SR); RF |

# Considerations

◦ How?

Linear collider

◦ Single-pass

◦ Few magnets, many RF-cavities

◦ Main limitation: collider length and RF

Circular collider

◦ Multi-pass

◦ More magnets, fewer RF-cavities

◦ Main limitation: circumference, magnet field and SR

# Considerations

- When?

- Order
  - What is the next logical step?

- Technological readiness
  - Completeness of proposals
  - Maturity of technology

- Resources
  - How many large-scale machines can be build and operate simultaneously?

# What we want is obvious

20 GeV to 150 TeV

First physics tomorrow

Cost effective
and low
consumption

Electrons, positrons,
hadrons and muons

# What we want is obvious



20 GeV to 150 TeV

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# What we want is obvious



20 GeV to 150 TeV

First physics tomorrow

Cost effective and low consumption

Electrons, positrons, hadrons and muons

Let's talk about accelerators...

# Classical optics in a nutshell



**Focusing structure (F)**
Converging lens

**Defocusing structure (D)**
Diverging lens

**Focusing structure (F)**
Converging lens

○ Optical lenses focus and defocus light



W. Demtröder, Experimentalphysik 2

# Beam optics in a nutshell

Focusing structure (F)
Focusing quadrupole

Defocusing structure (D)
Defocusing quadrupole

Focusing structure (F)
Focusing quadrupole

○ Optical lenses focus and defocus light

○ Magnetic lenses focus charged particle beams

   ○ Dipoles for circular path

   ○ Quadrupoles for focusing

   ○ Many higher order magnets

Vertical plane
Y-plane

X-plane + Y-plane =
2 transverse planes

Horizontal plane
X-plane

Beam in longitudinal
direction s

Wordsun.com

# Tune

○ Transverse focusing and defocusing leads to betatron oscillations

○ Tune $Q_x$, $Q_y$: Number of betatron oscillations per turn

○ Longitudinal focusing with RF-cavities leads to synchrotron oscillations

○ Synchrotron tune $Q_s$: Number of synchrotron oscillations per turn



Off-momentum (chromatic) particles (blue and green) oscillate around the nominal energy (red)

Reports on Progress in Physics, 68 Vol. 9, p. 1997-2265

# Chromatic effects

Off-momentum particles have different beam optics

○ Dispersion

  ○ Generates a shift of transverse position for off-momentum particles

  ○ Stems from dipoles and quadrupoles

○ Chromaticity

  ○ Generates a betatron tune shift for off-momentum particles

  ○ Change in focusing for different momenta



W. Demtröder, Experimentalphysik 2

Classical optics: path length depends on wavelength

Classical optics: focal length depends on wavelength

# Options for Future Colliders

○ This talk: focuses mostly on proposals submitted to the ESPP for future colliders at CERN

○ Aims to highlight technology challenges and R&D directions

○ Linear e+e- c.
  ○ CLIC
  ○ LCF

○ Circular e+e- c.
  ○ FCC-ee
  ○ LEP3

○ Circular hadron c.
  ○ FCC-hh

○ Lepton-hadron c.
  ○ LHeC

○ Muon c.

○ + Plasma wakefield acceleration

# Linear e+e- collider

○ Single pass for each bunch, followed by beam dump → must withstand high power beams continuously

○ Each bunch can only collide in one detector once (push-pull or dual beam delivery system)

Damping ring

Damping ring

Beam delivery system

LINAC

LINAC

e- source

Detector

e+ source

# CLIC – Compact Linear Collider

- Based on two-beam acceleration concept

  - Power extracted from lower energy high intensity beam

- Normal conducting X-bend 12 GHz RF with 72 to 100 MV/m

  - In 2031: 1 GeV X-band RF linac at EuPRAXIA

- Novel accelerator concept tested at CLIC Test Facility CTF

  - TBA tested on short scale ~ 20 m (880 m required for CLIC)

- Polarized e- beams

| | CLIC | | |
|---|---|---|---|
| Particles colliding [-] | $e^+/e^-$ | | |
| C.o.m. energy [GeV] | 380 | 550 | 1500 |
| Length [km] | 12.1 | 15 | 29.6 |
| #IPs [-] | 2 | 2 | 1 |
| Peak inst. lumi/IP [$10^{34}$cm$^{-2}$s$^{-1}$] | 2.2 | 3.2 | 3.7 |
| Peak power consumption [MW] | 166 | 210 | 287 |
| Cost [BCHF][a] | 7.2 | +30%[b] | +7.1 |

Higher energy excluded,
very high power consumption

# Two beam acceleration



**Drive Beam Accelerator**

**Delay Loop** x 2
gap creation, pulse compression & frequency multiplication

■ RF Transverse Deflectors

**Combiner Ring** x 3
pulse compression & frequency multiplication

**Combiner Ring 4**
pulse compression & frequency multiplication

**Drive Beam Decelerator Sector**
Power Extraction

# Normal-conducting RF

*Technology challenge*

◦ Relevant for: CLIC, FCC-ee injectors, MC cooling

- For CLIC very high gradients (up to 100 MV/m) required for CLIC
- Very low break-down rate
- Prototypes done, but further development for mass production



- 20 GeV beams required at FCC-ee injectors
- Compared to 6 GeV at SwissFEL
- 21 MV/m

# LCF – Linear Collider Facility

- 1.3 GHz SC bulk-Nb RF with 31.5 MV/m gradient with quality factor ($Q_0$) of $2 \times 10^{10}$ (double wrt ILC)

  - At EU-XFEL: 640 SRF modules operated at 27 MV/m

- 2 IPs, repetition rate of 5 or 10 Hz

- In addition to polarized e-, also polarized e+ source

  - Higher beam current than CLIC

- Challenging final focus (magnetic lattice around the IP)

  - Extremely small beam sizes to compensate for rep. rate

  - Accelerator test facility (ATF)

| | LCF | | | |
|---|---|---|---|---|
| | LP | FP | | |
| Particles colliding [-] | $e^+/e^-$ | | | |
| C.o.m. energy [GeV] | 250 | 91.2 | 250 | 550 |
| Length [km] | 33.5 | | | |
| #IPs [-] | 2 | | | |
| Peak inst. lumi/IP [$10^{34}$cm$^{-2}$s$^{-1}$] | 1.35 | 0.28 | 2.7 | 3.85 |
| Peak power consumption [MW] | 143 | 123 | 182 | 322 |
| Cost [BCHF][a] | 8.3 | +0.8 | | +5.5 |

# Super-conducting RF

◦ Relevant for: LCF, FCC, MC acceleration, LEP3, LHeC



- 9 cell, 1.3 GHz bulk Nb cavity for ILC
- 8/14 cavities achieved 31.5 MV/m
- Higher Q0 required for LCF
- High performance target

- 2 cell, 400MHz Nb/Cu thin film cavity for FCC-ee
- Demonstration required by 2031
- High performance target



- 5 cell 800 MHz cavity relevant for LHeC
- High sustainability target

# Circular colliders

- Multi pass for each bunch

- Periodicity interrupted by dedicated insertions

  - Interaction regions with IPs

  - Collimation

  - RF-section

  - Injection and dump

- **Proposed lepton colliders:** top-up injection at nominal energy

# FCC-ee – Future Circular e+e- Collider

○ 8 long straight sections with 4 IPs

○ Normal conducting dipoles, quadrupoles and sextupoles

○ Circular machine leads to strong SR losses each turn

   ○ Limit of SR losses determines maximum beam current

   ○ → determines luminosity

○ SRF to compensate for strong SR losses

   ○ Flexible energy range up to 240 GeV

|  |  | FCC-ee |  |  |
| --- | --- | --- | --- | --- |
| Particles colliding [-] | $e^+/e^-$ | | | |
| C.o.m. energy [GeV] | 91.2 | 160 | 240 | 365 |
| Length [km] | 90.7 | | | |
| #IPs [-] | 4 | | | |
| Peak inst. lumi/IP [$10^{34}cm^{-2}s^{-1}$] | 140 | 20 | 7.5 | 1.4 |
| Peak power consumption [MW] | 251 | 276 | 297 | 381 |
| Cost [BCHF][a] | 15 | | | |

# Synchrotron radiation

○ Electrons/Positrons about 2000 times lighter than protons → $10^{13}$ greater radiation losses

$$P_\gamma = \frac{2}{3} r_0 E_0 c \frac{\gamma_{\text{rel}}^4 \beta_{\text{rel}}^4}{\rho^2}$$

○ Naturally damps emittance over time

$$\varepsilon(\,t\,) = e^{-2\,t/\tau_{\text{SR}}} \qquad \tau_{\text{SR}} = \frac{T_0 E}{j_{x,y} U}$$

No damping

With damping

Synchronous particle

# Quantum fluctuation

- Photons emitted in discrete quanta following a random Poisson process

- Sudden loss leads to an instantaneous jump of the particle if emitted in dispersive region

- Introduced noise leads to emittance growth towards equilibrium

$$\epsilon_0 = C_q \gamma_0^2 \frac{I_5}{j_x I_2}$$

Cq... quantum radiation constant
$I_2/I_5$ ... radiation integrals
jx ... partition number



Blue: only synchrotron radiation;     Orange: with quantum excitation

# RF with reversed phase operation



- Same two-cell RF cavities for Z, WW and ZH-operation

- Constant cavitiy coupling thanks to reversed phase operation at Z

- Experimentally verified  at KEKB

- Baseline solution for the EIC



400 MHz 2-cell cavity
Niobium thin film on Copper,
Operation at 4.5 Kelvin
Max. accel. gradient $E_{acc}$  = 13 MV/m
Quality factor $Q_0$ = 3.3 × $10^9$

# RF with reversed phase operation



- Same two-cell RF cavities for Z, WW and ZH-operation

- Constant cavitiy coupling thanks to reversed phase operation at Z

- Experimentally verified  at KEKB

- Baseline solution for the EIC

- Quasi instantaneous switching from 45.6 to 120 GeV

  - Electrostatic separators and magnetic field to limit SR towards RF

  - Extra year of operation

# LEP3 – Large e+e- collider 3

○ Normal conducting dipoles and high temperature superconductor (HTS) nested quadrupoles and sextupoles

   ○ With NC magnets power consumption would increase and/or performance decrease

○ Circular machine leads to strong SR losses each turn

   ○ Limit of SR losses determines maximum beam current

   ○ Smaller circumference leads to higher losses at same energy

   ○ → lower luminosity than FCC-ee

○ Currently only a pre-conceptual design available

| | LEP3 | | |
|---|---|---|---|
| Particles colliding [-] | $e^+/e^-$ | | |
| C.o.m. energy [GeV] | 91.2 | 160 | 230 |
| Length [km] | 27.6 | | |
| #IPs [-] | 2 | | |
| Peak inst. lumi/IP [$10^{34}cm^{-2}s^{-1}$] | 40 | 6.2 | 1.6 |
| Peak power consumption [MW] | 200 | 226 | 250 |
| Cost [BCHF][a] | 3.9 | | |

# High Temperature Superconductors

○ Relevant for: LEP3, alternative options for FCC-ee, FCC-hh, MC

○ Higher field reach with less power consumption

○ 4 to 20 K operating temperature

CEA MI
Racetrack

6 T insert coils by IHEP

Selection of cable and
insulation technology.
Partial demonstration
of accelerator specs.

*FEASIBILITY*
Reproducibility
and first scaling
in length

*SCOPING*
Short model
≥ 14 T

*PROTOTYPING*

*PRE-SERIES*

*CANAVASSING*
Demonstrators to
select cable
and coil design

Proof of short model
with all requirements

Proof of reproducibility
and first long magnets

*INDUSTRIALIZATION*

| `25 | `26 | `27 | `28 | `29 | `30 | `31 | `32 | `33 | `34 | `35 | `36 | `37 | `38 | `39 | `40 | `41 | `42 | `43 | `44 | `45 | `46 | `47 | `48 | `49 | `50 | `51 | `52 | `53 | `54 |

RunIII

HL-LHC RunIV

HL-LHC RunV

# Circular colliders

◦ Multi pass for each bunch

◦ Periodicity interrupted by dedicated insertions

  ◦ Interaction regions with IPs

  ◦ Collimation

  ◦ RF-section

  ◦ Injection and dump

◦ Proposed lepton colliders: top-up injection at nominal energy

◦ **Proposed hadron collider:** ramping to nominal energy

# FCC-hh – Future Circular hadron Collider

○ Superconducting machine to achieve high energy thanks to high fields (nominal 8.3 T at HL-LHC, 14 T for FCC-hh)

  ○ For higher energy hadron machines: larger circumference and/or higher dipole field

  ○ 11 T for HL-LHC (peak at new quadrupoles)

○ Baseline $Nb_3Sn$ low temperature superconducting magnets

  ○ Industrialization design requires 10-20 years

○ Technological readiness as stand-alone ~2055 and later with HTS

|  | FCC-hh |
|---|---|
| Particles colliding [-] | p/p |
| C.o.m. energy [GeV] | 84600 |
| Length [km] | 90.7 |
| #IPs [-] | 4 |
| Peak inst. lumi/IP [$10^{34}cm^{-2}s^{-1}$] | 30 |
| Peak power consumption [MW] | 355 |
| Cost [BCHF][a] | +19[c] |

*Technology challenge*

# Low Temperature Superconductors

- Relevant for: FCC-hh, LEP3 as possible back-up, MC

- Until 2035 HTS and LTS development in parallel

- 1.9 K baseline operating temperature (4.5 K or 12 T for improving costs)



First selection of design

Short model program on two selected designs (>5 each type)

5-m-long prototypes (>5 each type)

Industrialization (pre-series magnets)

Feedback HL-LHC operation

15 m long prototypes (>5)

Production and test

Ongoing 12 T and 14 T short models

Selection of final design to start long magnets

Tender for the series

Installation and commissioning

| `25 | `26 | `27 | `28 | `29 | `30 | `31 | `32 | `33 | `34 | `35 | `36 | `37 | `38 | `39 | `40 | `41 | `42 | `43 | `44 | `45 | `46 | `47 | `48 | `49 | `50 | `51 | `52 | `53 | `54 |

RunIII

HL-LHC RunIV

HL-LHC RunV

$Nb_3Sn$ timeline for FCC-hh [January 2024, E. Todesco, et al.]

# Large Hadron electron Collider

○ Special dedicated IP for electron-hadron collisions

○ New electron accelerator for one 50 GeV beam with 50 mA

  ○ 2.5 GW beam power (3 orders of magnitude more than shown)

○ Foresees energy recovery linac principle with 1/3 LHC length

  ○ Completely new regime for collider physics

  ○ If not performance or power consumption could suffer

| | LHeC |
|---|---|
| Particles colliding [-] | e⁻/p |
| C.o.m. energy [GeV] | 1180 |
| Length [km] | 9.2/27.6 |
| #IPs [-] | 1 |
| Peak inst. lumi/IP [$10^{34}$cm$^{-2}$s$^{-1}$] | 2.3 |
| Peak power consumption [MW] | 220 |
| Cost [BCHF][a] | 2 |



Linac 1 (1008m

Matching/splitter

Injector

Matching/combiner (31m)

Arc 1,3,5

Bypass (230m)

Linac 2 (1008m

# Energy recovery linacs

○ Relevant for: LheC

○ Could drastically improve sustainability if feasibility demonstrated

○ PERLE: Powerful Energy Recovery Linac for Experiments at IJCLab, Orsay

- Clear demonstrator for energy recovery

- Beam quality after collision cannot be studied



**PERLE will proceed in phases**
➤ Phase 1: injection line installation (2027)
➤ Phase 2: ERL single turn (2028-2029)
➤ Phase 3: ERL 3-turn 250 MeV (2030)

# Muon Collider

○ μ are elementary particles but heavier than electrons → less synchrotron radiation

○ 10 to 14 TeV μ collission comparable to 100 to 200 TeV protons

○ Not yet at maturity compared to other collider proposals

○ Green-field proposal up to 10 TeV



| | MC | |
|---|---|---|
| Particles colliding [-] | μ⁺/μ⁻ | |
| C.o.m. energy [GeV] | 3200 | 7600 |
| Length [km] | 11/4.8 | 11/8.7 |
| #IPs [-] | 2 | |
| Peak inst. lumi/IP [$10^{34}$cm$^{-2}$s$^{-1}$] | 0.9/2 | 7.9/10.1 |
| Peak power consumption [MW] | 117 | 182 |
| Cost [BCHF][a] | 12 | 17 |

# Muon Collider – some challenges

- 6D cooling

  - High field solenoids, high RF gradients and repetition rate



- 2 μs lifetime → very challenging acceleration chain

  - Fast ramping NC magnets in the collider ring 4200 T/s

  - High RF demands (90 GV and 3000 cavities)

- M are not stable particles → decay

  - High intensity neutrino flux to be "controlled"



- Test facility required before decision on collider

# Plasma wake-field acceleration

◦ Drive beam (laser or charged particle beam) excites plasma wave and wake

◦ Due to space charge electrons from plasma are expelled and rush back on axis

◦ Conversion of the transverse electric field of a drive bunch into a longitudinal electric field in the plasma

◦ Witness bunch accelerated with gradients of ~ GV/m (e.g. at AWAKE at CERN)

# Analogy and Challenges

◦ Very efficient, interesting and novel way to accelerate beams, however some challenges ahead:

  ◦ Positron acceleration

  ◦ Multi-staging for high energy

  ◦ Repetition rate

# Detour: Linear proton accelerators

○ Not sufficient energy reach for frontier physics, but used for e.g. nuclear applications

○ Myrrha designed with 400 m proton linac to achieve 600 GeV beam energy for 4 mA current

## The world's 1ST large scale Accelerator Driven System

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is the world's first large scale Accelerator Driven System (ADS) that consists of a subcritical nuclear reactor driven by a high power linear accelerator. With the subcritical concentration of fission material, the nuclear reaction is sustained by the particle accelerator only. Turning off the proton beam results in an immediate and safe halt of the nuclear reactions.



https://www.myrrha.be/

# Options for Future Colliders

○ Sustainability and power consumption plays an important role for any future collider



Fig. 10.1: Nominal yearly integrated luminosity over all experiments divided by the corresponding electricity consumption for future $e^+e^-$ colliders (excluding off-line computing) as reported in Tables 10.1 and 10.2. For LCs the total luminosity (including that below 99% of the nominal c.o.m. energy) is considered. LEP and LEP2 data are derived from Refs. [790, 861, 862] (Courtesy N. Mounet - CERN).

# And now? → ESPPU 2026



Council appointment of the members of the **PPG** and decision on the venue for the **Open Symposium**

**End September 2024**

**Deadline** for the submission of main input from the community

**31 March 2025**

**Open Symposium**

**23-27 June 2025**

**Deadline** for the submission of final national input in advance of the **ESG Strategy Drafting Session**

**14 November 2025**

Submission of the draft strategy document to the Council

**End January 2026**

**December 2024**

Council decision on the venue for the **ESG Strategy Drafting Session**

**26 May 2025**

**Deadline** for the submission of additional national input in advance of the **Open Symposium**

**End September 2025**

Submission of the "Briefing Book" to the **ESG**

**1-5 December 2025**

**ESG Strategy Drafting Session**

**March and June 2026**

Discussion of the draft strategy document by the Council and **updating of the Strategy**

We are here

# ESPPU 2026

- 266 submissions in total for the ESPPU

  - https://indico.cern.ch/event/1439855/contributions/

- Physics Preparatory Groups (PPGs) digested input and summarized input to write the Physics Briefing Book

  - https://cds.cern.ch/record/2944678

**Physics Briefing Book**

*Input for the 2026 update of the European Strategy for Particle Physics*

**Electroweak Physics:** Jorge de Blas[1], Monica Dunford[2] (*Conveners*), Emanuele Bagnaschi[3] (*Scientific Secretary*), Ayres Freitas[4], Pier Paolo Giardino[5], Christian Grefe[6], Michele Selvaggi[7], Angela Taliercio[8] (*Contributors*)

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**Beyond the Standard Model Physics:** Fabio Maltoni[8,31], Rebeca Gonzalez Suarez[32] (*Conveners*), Benedikt Maier[33] (*Scientific Secretary*), Timothy Cohen[7,28,78,*], Annapaola de Cosa[34,*], Nathaniel Craig[35], Roberto Franceschini[36], Loukas Gouskos[37], Aurelio Juste[38], Sophie Renner[14], Lesya Shchutska[28] (*Contributors*)

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**Editors:** Roger Forty[7], Karl Jakobs[74], Hugh Montgomery[75], Mike Seidel[28,76], Paris Sphicas[7,77]

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# ESPPU 2026

- 266 submissions in total for the ESPPU
  - https://indico.cern.ch/event/1439855/contributions/

- Physics Preparatory Groups (PPGs) digested input and summarized input to write the Physics Briefing Book
  - https://cds.cern.ch/record/2944678

- 7 ESG working groups for overarching topics
  - Including project and physics comparison:
  - https://cds.cern.ch/record/2947728

**Assessment of large-scale accelerator projects at CERN
Report of ESG WG2a**

31 October 2025

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1

# WG2a - Summary

| Project | Scope | TRL | R&D | Test facilities | Performance | Site preparation | Schedule | Cost | Risk |
|---|---|---|---|---|---|---|---|---|---|
| CLIC 380 GeV, 1.5 TeV | | 4 - 6 / 5.2 | | | | | | | |
| FCC-ee 91-365 GeV | | 4 - 7 / 6.0 | | | | | | | |
| FCC-hh 85 TeV | | 4 - 7 ($Nb_3Sn$) / 4.3 | | | | | | | |
| | | 2 - 7 (HTS) / 3.2 | | | | | | | |
| FCC-hh - SA 85 TeV | | 4 - 7 ($Nb_3Sn$) / 5 | | | | | $Nb_3Sn$ | | |
| LCF 250 - 550 GeV | | 5 - 7 / 5.5 | | | | | | | |
| LEP3 91 - 230 GeV | | 3 - 6 / 4.0 | | | | | | | |
| LHeC: HL-LHC + 50 GeV ERL | | 3 - 6 / 4.5 | | | | | | | |
| MC 3.2 TeV, 7.6 TeV | | 3.2 TeV: 3 - 5 / 7.6 TeV: 2 - 5 | | | | | | | |

**Table 16:** Summary table schematically representing the key findings of the WG according to the assessment criteria and based on the present status of the large-scale collider project proposals as submitted to the ESPP2026. Scope=Scope level-of-definition; TDR=Technical Readiness Level score - the range of values and the cost-weighted average for the baseline scenarios are listed; the colour code is selected based on on the cost-weighted average TRL score (TRL≥ 6 - green, 4≤TRL<6 - yellow, TRL<4 - red); R&D=R&D requirements, R&D plan level-of-definition, R&D funding status; Test facilities=need of test facilities or demonstrators and (if needed) level-of-definition of their scope; Performance=Performance uncertainty; Site preparation=Site preparation status; Schedule=Schedule uncertainty; Cost=Cost uncertainty; Risk=Risk level-of-definition. The cost-weighted average TRL score could not be estimated for the MC project as there is no detailed cost breakdown by sub-system. The colour code for the various criteria is defined according to the summary assessment in the Tables A.1 to A.8.

# Why FCC?

### Physics



- Immense physics potential for lepton and hadron colliders
- Luminosity frontier: Precision physics experimements
- Energy frontier: Discovery potential thanks to 84 TeV $E_{cm}$ for FCC-hh

### Timeline



- FCC-ee technology is mature; collisions could start few years after HL-LHC
- Integrated FCC project allows for ~20 more years magnet R&D
- Optimized overall investment

### Community



- 4 collision points for high-energy physics experiments
- Many other possibilities (fixed-target, use of beam dump, ..)
- Only facility to commensuate the size of the CERN community

# Thank you!

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12 November 2025

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# High level parameters

| | CLIC | | | FCC-ee | | | | FCC-hh | LCF LP | LCF FP | | | LEP3 | | | LHeC | MC | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Particles colliding [-] | e+/e- | | | e+/e- | | | | p/p | e+/e- | | | | e+/e- | | | e-/p | μ+/μ- | |
| C.o.m. energy [GeV] | 380 | 550 | 1500 | 91.2 | 160 | 240 | 365 | 84600 | 250 | 91.2 | 250 | 550 | 91.2 | 160 | 230 | 1180 | 3200 | 7600 |
| Length [km] | 12.1 | 15 | 29.6 | 90.7 | | | | 90.7 | 33.5 | | | | 27.6 | | | 9.2/27.6 | 11/4.8 | 11/8.7 |
| #IPs [-] | 2 | 2 | 1 | 4 | | | | 4 | 2 | | | | 2 | | | 1 | 2 | |
| Peak inst. lumi/IP [$10^{34}$cm$^{-2}$s$^{-1}$] | 2.2 | 3.2 | 3.7 | 140 | 20 | 7.5 | 1.4 | 30 | 1.35 | 0.28 | 2.7 | 3.85 | 40 | 6.2 | 1.6 | 2.3 | 0.9/2 | 7.9/10.1 |
| Peak power consumption [MW] | 166 | 210 | 287 | 251 | 276 | 297 | 381 | 355 | 143 | 123 | 182 | 322 | 200 | 226 | 250 | 220 | 117 | 182 |
| Cost [BCHF][a] | 7.2 | +30%[b] | +7.1 | 15 | | | | +19[c] | 8.3 | +0.8 | | +5.5 | 3.9 | | | 2 | 12 | 17 |

# High level parameters

| | CLIC | | | FCC-ee | | | | LCF LP | LCF FP | | | LEP3 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| c.o.m. energy [GeV] | 380 | 550 | 1500 | 91.2 | 160 | 240 | 365 | 250 | 91.2 | 250 | 550 | 91.2 | 160 | 230 |
| Circumference/length collider tunnel [km] | 12.1 | 15 | 29.6 | 90.7 | | | | 33.5 | | | | 27.6 | | |
| Number of experiments (IPs) | 2 | 2 | 1 | 4 | | | | 2 | | | | 2 | | |
| SR power/beam [MW] | — | | | 50 | | | | — | | | | 50 | | |
| Longitudinal polarisation ($e^-$ / $e^+$) [%] | ±80 / 0 | | | 0 / 0[a] | | | | ±80 / ±30 | | | ±80 / ±60 | 0 / 0[a] | | |
| Number of years of operation (total) | 10 | N/A | 10 | 4 | 2 | 3 | 5 | 5 | 1 | 3 | 10 | 5 | 4 | 6 |
| Nominal years of operation (equivalent)[b] | 8 | N/A | 9 | 3 | 2 | 3 | 4.5 | 3 | 1 | 3 | 9 | 5 | 4 | 6 |
| Instantaneous luminosity per IP above 0.99 $\sqrt{s}$ (total) [$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$] | 1.3 (2.2) | 1.6 (3.2) | 1.4 (3.7) | 140 | 20 | 7.5 | 1.4 | 1 (1.35) | 0.28 (0.28) | 2 (2.7) | 2.25 (3.85) | 40 | 6.2 | 1.6 |
| Integrated luminosity above 0.99 $\sqrt{s}$ (total) over all IPs over each phase [$\mathrm{ab}^{-1}$] | 2.56 (4.4) | N/A | 1.51 (3.96) | 205 | 19.2 | 10.8 | 3.1 | 0.72 (0.97) | 0.067 (0.067) | 1.44 (1.94) | 4.85 (8.32) | 48 | 6.0 | 2.3 |
| Peak power consumption [MW] | 166 | 210 | 287 | 251 | 276 | 297 | 381 | 143 | 123 | 182 | 322 | 200 | 226 | 250 |
| Electricity consumption per year of nominal operation [TW h/y][c] | 0.82 | 1.1 | 1.4 | 1.2 | 1.3 | 1.4 | 1.9 | 0.8 | 0.7 | 1.0 | 1.8 | 0.94 | 1.1 | 1.2 |
| Cost [BCHF][d] | 7.24 | +30%[e] | +7.1[e] | 13.73 | | | +1.26 | 8.29 | +0.77 | | +5.46 | 3.74 | | |

[a] Vertical polarisation of at least a few percent for ~200 non-colliding pilot bunches, enabling precise quasi-continuous measurement of the beam energy. No longitudinal polarisation in the baseline. Residual longitudinal polarisation of colliding bunches should be controlled at the $10^{-5}$ level.

[b] This row lists the equivalent number of years of operation at nominal instantaneous luminosity, hence taking into account the luminosity ramp up.

[c] Computed from the peak power consumption and the assumptions on the operational year (see Table A.1 in Ref. [ID281])

[d] Total installation and construction cost quoted by the proponents of the projects in 2024 prices. The additional cost of each individual upgrade is indicated. It includes the cost of the technical components, materials, contracts, services, civil construction and conventional systems and associated implicit labour such as that provided by a company to produce components. It does not include labour provided by the host institution and the collaborating laboratories, contingency, any potential future inflation, the costs prior to project approval (construction and R&D), off-line computing, spares, maintenance, beam commissioning. The cost of the experiments is not included. The cost of land acquisition, site activation (e.g. external roads, water supplies, power lines) and spoil removal are not included for CLIC and LCF though they are expected to represent a minor contribution to the total cost (at the percent level). The additional cost of each individual upgrade is indicated.

[e] Cost of the upgrade from 380 GeV.

# CLIC - Parameters

| Parameter | Unit | **380 GeV** | **1.5 TeV** | 250 GeV | 550 GeV |
|---|---|---|---|---|---|
| Centre-of-mass energy | GeV | 380 | 1500 | 250 | 550 |
| Repetition frequency | Hz | 100 | 50 | 100 | 100 |
| Nb. of bunches per train | | 352 | 312 | 352 | 352 |
| Bunch separation | ns | 0.5 | 0.5 | 0.5 | 0.5 |
| Pulse length | ns | 244 | 244 | 244 | 244 |
| Accelerating gradient | MV/m | 72 | 72/100 | 72 | 72 |
| Total luminosity | $10^{34}$ cm$^{-2}$ s$^{-1}$ | 4.5 | 3.7* | ~3.0 | ~6.5 |
| Lum. above 99% of $\sqrt{s}$ | $10^{34}$ cm$^{-2}$ s$^{-1}$ | 2.7 | 1.4 | ~2.1 | ~3.2 |
| Total int. lum. per year | fb$^{-1}$ | 540 | 444 | ~350 | ~780 |
| Power consumption | MW | 166 | 287 | ~130 | ~210 |
| Main linac tunnel length | km | 12.1 | 29.0 | 12.1 | ~15 |
| Nb. of particles per bunch | $10^9$ | 5.2 | 3.7 | 5.2 | 5.2 |
| Bunch length | μm | 70 | 44 | 70 | 70 |
| IP beam size | nm | 149/2.0 | 60/1.5 | ~184/2.5 | ~124/1.7 |

# FCC-ee Parameters

| Running mode | Z | WW | ZH | $t\bar{t}$ |
|---|---|---|---|---|
| Number of IPs | 4 | 4 | 4 | 4 |
| Beam energy (GeV) | 45.6 | 80 | 120 | 182.5 |
| Bunches/beam | 11200 | 1856 | 300 | 60 |
| Beam current [mA] | 1292 | 135 | 26.8 | 5.1 |
| Luminosity/IP [$10^{34}$ cm$^{-2}$ s$^{-1}$] | 144 | 20 | 7.5 | 1.45 |
| Energy loss / turn [GeV] | 0.039 | 0.369 | 1.86 | 9.94 |
| Synchrotron Radiation Power [MW] | 100 | 100 | 100 | 100 |
| RF Voltage 400/800 MHz [GV] | 0.09/0 | 1.0/0 | 2.1/0 | 2.1/9.2 |
| Rms bunch length (SR) [mm] | 5.15 | 3.46 | 3.26 | 1.91 |
| Rms bunch length (+BS) [mm] | 15.2 | 5.28 | 5.59 | 2.33 |
| Rms relative momentum spread (SR) [%] | 0.039 | 0.069 | 0.102 | 0.152 |
| Rms relative momentum spread (+BS) [%] | 0.115 | 0.105 | 0.176 | 0.186 |
| Rms horizontal emittance $\varepsilon_x$ [nm] | 0.71 | 2.16 | 0.66 | 1.65 |
| Rms vertical emittance $\varepsilon_y$ [pm] | 2.1 | 2.0 | 1.0 | 1.32 |
| Longitudinal damping time [turns] | 1171 | 218 | 65.4 | 19.6 |
| Horizontal IP beta $\beta_x^*$ [mm] | 110 | 220 | 240 | 900 |
| Vertical IP beta $\beta_y^*$ [mm] | 0.7 | 1.0 | 1.0 | 1.4 |
| Hor. IP beam size $\sigma_x^*$ [μm] | 9 | 22 | 13 | 37 |
| Vert. IP beam size $\sigma_y^*$ [nm] | 40 | 45 | 32 | 44 |
| Beam lifetime (q+BS+lattice) [min.] | 87 | 75 | 100 | 105 |
| Beam lifetime (lum.) [min.] | 22 | 16 | 10 | 11 |
| Total beam lifetime [min.] | 18 | 13 | 9 | 10 |
| Total int. annual luminosity [ab$^{-1}$/yr] | 68[†] | 9.6 | 3.6 | 0.67[‡] |

# FCC-hh Parameters

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

# LCF - Parameters

| Quantity Name | Symbol | Unit LCF | Initial-250 250 LP | Upgrades 250 FP | Upgrades 550 FP | Initial-550 550 LP | Upgrade 550 FP |
|---|---|---|---|---|---|---|---|
| Centre-of-mass energy | $\sqrt{s}$ | GeV | 250 | 250 | 550 | 550 | 550 |
| Inst. luminosity | $\mathscr{L}$ ($10^{34} cm^{-2} s^{-1}$) | | 2.7 | 5.4 | 7.7 | 3.9 | 7.7 |
| Polarisation | $|P(e^-)|/|P(e^+)|$ (%) | | 80 / 30 | 80 / 30 | 80 / 60 | 80 / 30 | 80 / 60 |
| Repetition frequency | $f_{rep}$ | Hz | 10 | 10 | 10 | 10 | 10 |
| Bunches per pulse | $n_{bunch}$ | 1 | 1312 | 2625 | 2625 | 1312 | 2625 |
| Bunch population | $N_e$ | $10^{10}$ | 2 | 2 | 2 | 2 | 2 |
| Linac bunch interval | $\Delta t_b$ | ns | 554 | 366 | 366 | 554 | 366 |
| Beam current in pulse | $I_{pulse}$ | mA | 5.8 | 8.8 | 8.8 | 5.8 | 8.8 |
| Beam pulse duration | $t_{pulse}$ | $\mu s$ | 727 | 897 | 897 | 727 | 897 |
| Average beam power | $P_{ave}$ | MW | 10.5 | 21 | 46 | 23 | 46 |
| Norm. hor. emitt. at IP | $\gamma \varepsilon_x$ | $\mu m$ | 5 | 5 | 10 | 10 | 10 |
| Norm. vert. emitt. at IP | $\gamma \varepsilon_y$ | nm | 35 | 35 | 35 | 35 | 35 |
| RMS hor. beam size at IP | $\sigma_x^*$ | nm | 516 | 516 | 452 | 452 | 452 |
| RMS vert. beam size at IP | $\sigma_y^*$ | nm | 7.7 | 7.7 | 5.6 | 5.6 | 5.6 |
| Lumi frac. in top 1 % | $\mathscr{L}_{0.01}/\mathscr{L}$ | % | 73 | 73 | 58 | 58 | 58 |
| Lumi in top 1 % | $\mathscr{L}_{0.01}$ ($10^{34} cm^{-2} s^{-1}$) | | 2.0 | 4.0 | 4.5 | 2.2 | 4.5 |
| Site AC power | $P_{site}$ | MW | 143 | 182 | 322 | 250 | 322 |
| Annual energy consumption | | TWh | 0.8 | 1.0 | 1.8 | 1.4 | 1.8 |
| Site length | $L_{site}$ | km | 33.5 | 33.5 | 33.5 | 33.5 | 33.5 |
| Average gradient | $g$ | MV/m | 31.5 | 31.5 | 31.5 | 31.5 | 31.5 |
| Quality factor | $Q_0$ | $10^{10}$ | 2 | 2 | 2 | 2 | 2 |

# LEP3 Parameters

| | LEP3 | | |
|---|---|---|---|
| No. of IPs/Xpts | 2 | | |
| com energy √s (GeV). For final state( X) | 230 (ZH) | 160 (WW) | 91.2 (Z) |
| Circumference/Length [km] | 26.659 | | |
| Bending Radius (m) | 2958 | | |
| Crossing Angle at IP [mrad] | 30 | | |
| SR Energy Loss/turn [GeV] | 5.4 | 1.3 | 0.13 |
| Total RF Voltage  [GV] | 6 | 1.5 | 0.5 |
| SR Power /beam (MW) | 50 | | |
| Beam Current   [mA] | 9 | 39 | 371 |
| Number of bunches/beam | 20 | 220 | 800 |
| Bunch Intensity (10E11) | 2.5 | 1 | 2.6 |
| RF frequency. [MHz] | 800 | | |
| Beam Lifetime  (Bhabha+Brem) [min] | 17 | 19 | 28 |
| Inst. Luminosity/IP [10^34 cm-2s-1] | 1.6 | 6.2 | 40 |
| Integrated L/IP  [ab-1/yr] | 0.192 | 0.7 | 4.8 |
| Years of Operation** | 6 | 4 | 5 |

# LHeC Parameters

| | LHeC | |
|---|---|---|
| | **p** | **e⁻** |
| Beam Energy [GeV] | 7000 | 50 |
| Luminosity [$10^{34}$cm$^{-2}$s$^{-1}$] | 2.3 | |
| Normalized emittance $\gamma\varepsilon_{x,y}$ [μm] | 2.5 | 20 |
| | 0.07 | 0.1 |
| Beta Function $\beta^*_{x,y}$ [m] | 4 | 4 |
| rms Beam size $\sigma^*_{x,y}$ [μm] | 1100 | 50 |
| Beam Current @ IP [mA] | 25 | 25 |
| Bunch Spacing @ IP [ns] | 2.2 | 0.078 |
| Bunch Population [$10^{11}$] | 35 | 1.24 |
| Bunch charge [nC] | | |

# MC Parameters

| CERN-specific muon collider parameters | | | | | | |
|---|---|---|---|---|---|---|
| Parameter | Symbol | unit | Scenario 1 | | Scenario 2 | |
| | | | Stage 1 | Stage 2 | Stage 1 | Stage 2 |
| Centre-of-mass energy | $E_{cm}$ | TeV | 3.2 | 7.6 | 3.2 | 7.6 |
| Target integrated luminosity | $\int \mathcal{L}_{target}$ | $ab^{-1}$ | 1 | 10 | 1 | 10 |
| Estimated luminosity | $\mathcal{L}_{estimated}$ | $10^{34} cm^{-2} s^{-1}$ | 0.9 | 7.9 | 2.0 | 10.1 |
| Collider circumference | $C_{coll}$ | km | 11 | 11 | 4.8 | 8.7 |
| Collider arc peak field | $B_{arc}$ | T | 4.8 | 11 | 11 | 14 |
| Collider dipole technology | | | NbTi | $Nb_3Sn$ or HTS | $Nb_3Sn$ | HTS |