



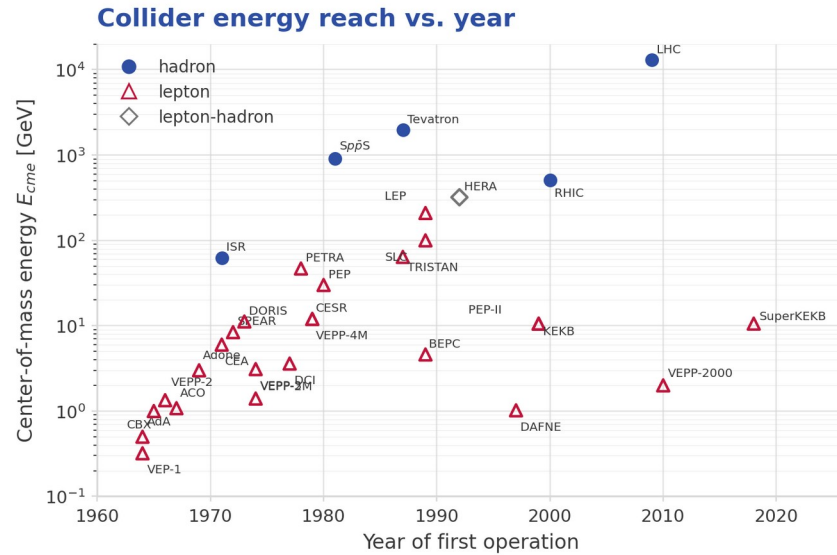
Future Colliders: Possibilities and Challenges

Jacqueline Keintzel

NSTAR 2026
Seville, Spain
11 September 2026

Collider history

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

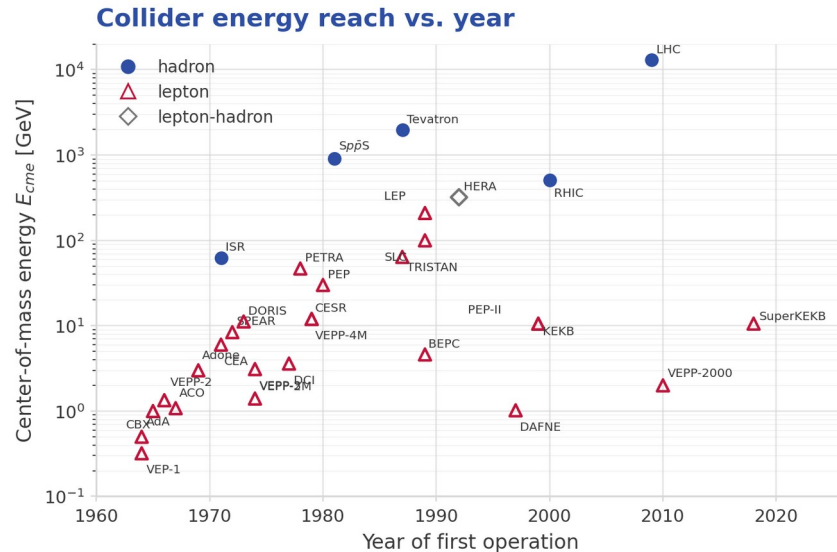


Data: Shiltsev & Zimmermann, Rev. Mod. Phys. 93, 015006 (2021), Table I; SuperKEKB updated to latest achieved value.

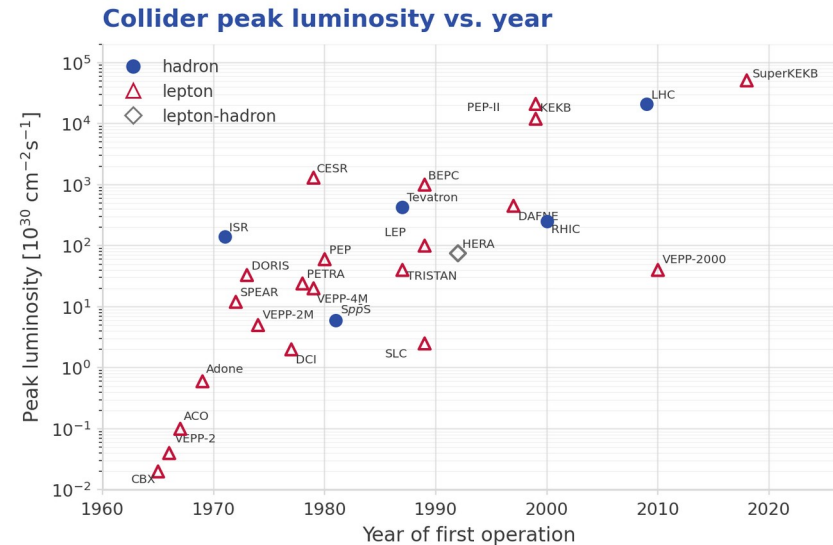
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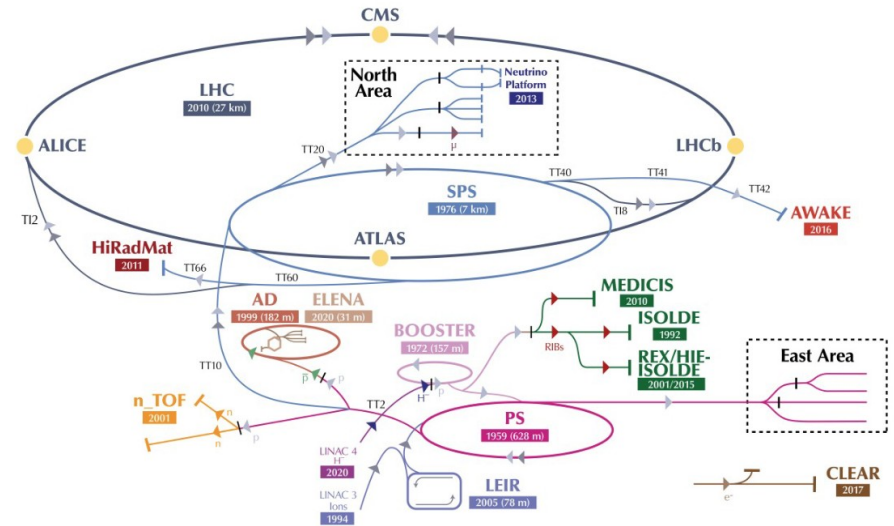


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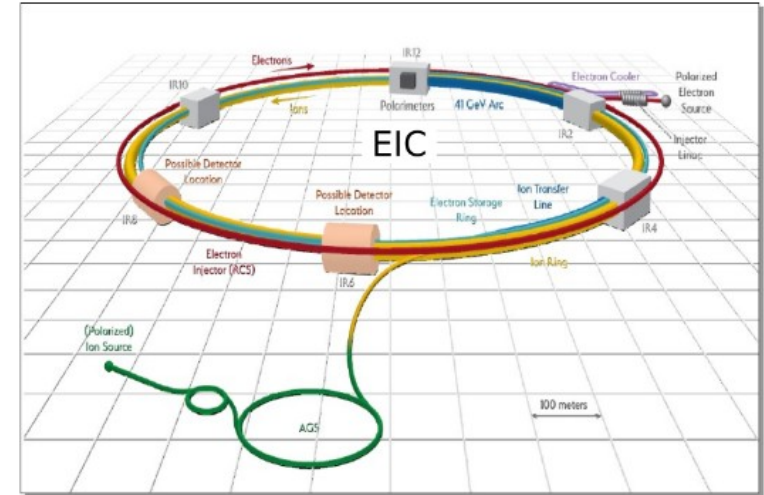
The biggest collider so far

- 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



EIC – Electron Ion Collider

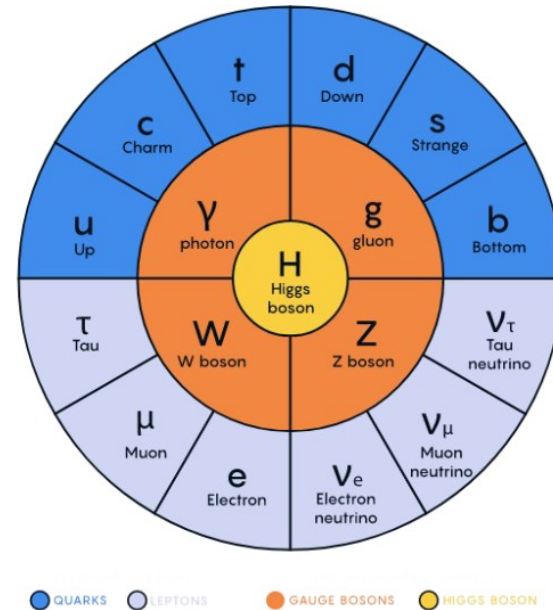
- Approved collider in near future, at Brookhaven National Laboratory (BNL)
- Not a high-energy physics collider, but a nuclear physics collider
- Nuclear physics scattering experiments
- Collective and single-particle effects in strong interaction
- Aims to answer 3 fundamental nuclear physics questions:
 - How does nuclear mass arise?
 - How does nuclear spin arise?
 - What are emergent properties of dense gluon systems?



Particle physics status

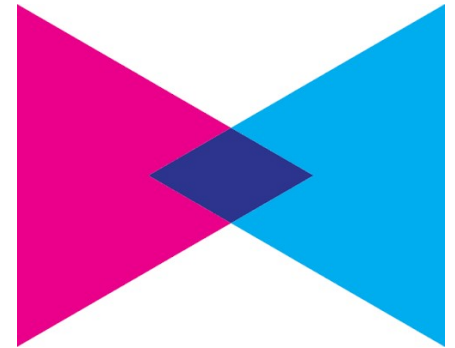
- Standard Model (SM) confirmed to high accuracy up to several TeV
- Higgs-boson discovered
- At the mass predicted within the SM by LEP precision electro-weak measurements
- Absence of new physics at the TeV scale

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



The strategy so far

- 2020 European Strategy for Particle Physics Update (ESPPU):
 - An electron-positron Higgs factory is the highest-priority next collider
 - Europe should investigate a future hadron collider at CERN with ≥ 100 TeV, with an e^+e^- Higgs/EW factory as a possible first stage
- 2023 US Particle Physics Project Prioritization Panel (P5):
 - High priority: exploitation of LHC and HL-LHC
 - High priority: support for an offshore Higgs and electroweak factory



Considerations: what, and how?

What collides?

- Hadrons
 - → Mix of quarks/gluons, high collision energy, discoveries at the physics frontier
 - → Limited by dipole field & ring size
- Leptons
 - → Elementary particles, high-precision, well-defined center-of-mass energy
 - → Limited by synchrotron radiation and RF

How to accelerate?

- Linear
 - → single pass, few magnets, many RF cavities
 - → Limited by collider length & RF
- Circular
 - → multi pass, more magnets, fewer RF cavities
 - → Limited by circumference, magnet field & synchrotron radiation

Also matters: when (what's the logical next step?), technological readiness, and how many large-scale machines can realistically be built and operated at once.

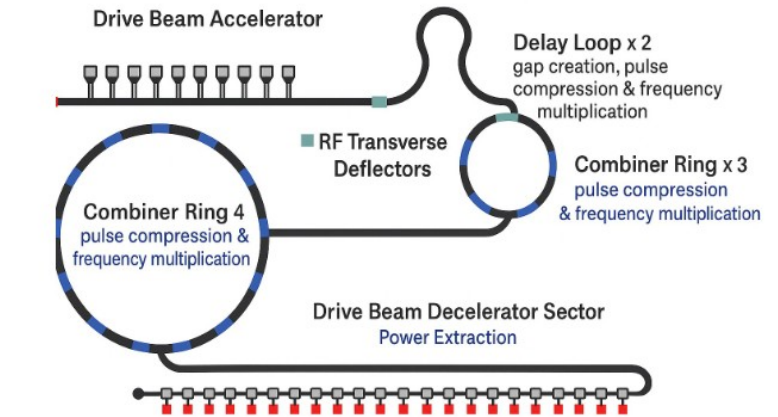
Options for future colliders

- 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 collider: single pass per bunch, then beam dump; luminosity depends entirely on how tightly the once-used beam can be focused
 - Circular collider: multi-pass for each bunch,
-
- | | | | | |
|----------------------|------------------------|--------------------------|------------------------|------------------------|
| ◦ Linear e+e- | ◦ Circular e+e- | ◦ Circular hadron | ◦ Lepton-hadron | ◦ Muon collider |
| ◦ CLIC | ◦ FCC-ee | ◦ FCC-hh | ◦ LHCeC | |
| ◦ LCF | ◦ LEP3 | | | |

+ Plasma wakefield acceleration – a longer term technology

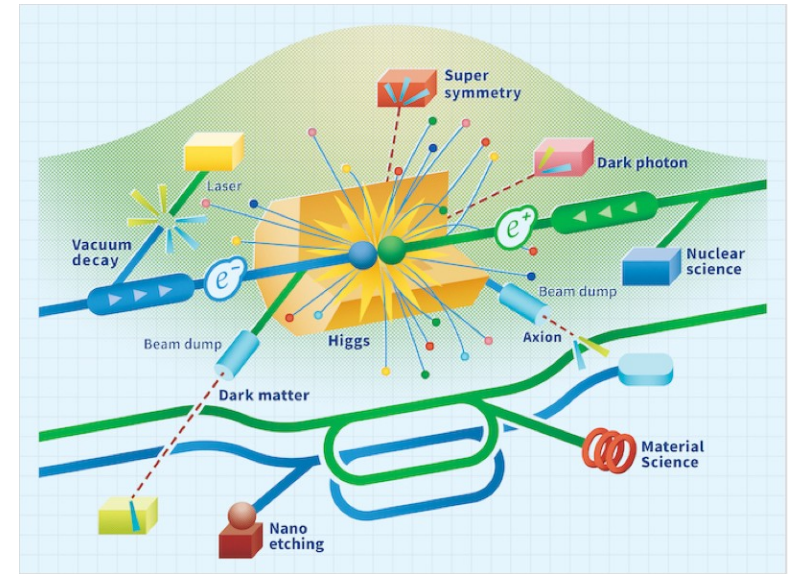
CLIC – Compact Linear Collider

- 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



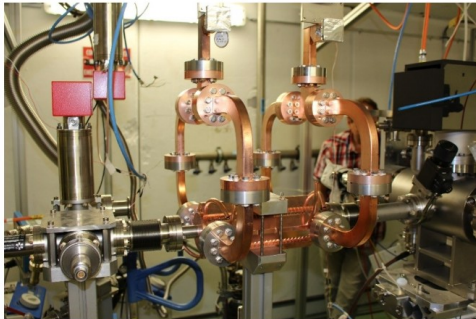
LCF – Linear Collider Facility

- 1.3 GHz SC bulk-Nb RF with 31.5 MV/m gradient
 - At EU-XFEL: 640 SRF modules operated at 27 MV/m
- Up to 2 IPs, repetition rate of 5 or 10 Hz
- In addition to polarized e^- , also polarized e^+ source
- Challenging final focus (magnetic lattice around the IP)
 - Extremely small beam sizes to compensate for rep. rate
 - Accelerator test facility (ATF)



RF Technology

- Normal conducting RF
- Relevant for: CLIC, FCC-ee injectors, MC cooling
- Example: For CLIC very high gradients (up to 100 MV/m) required with very low break-down rate. Prototypes done, but further development for mass production

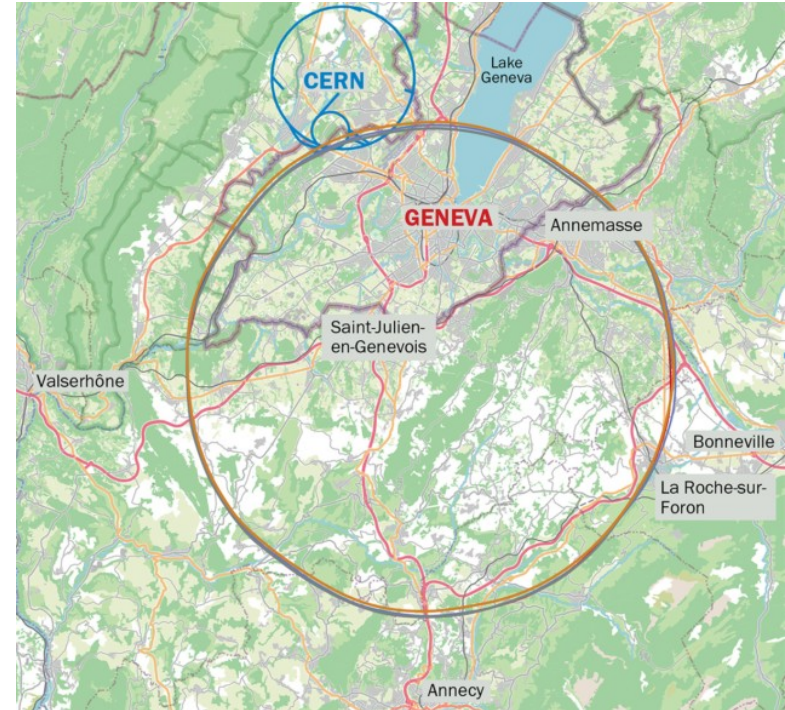


- Super conducting RF
- Relevant for: LCF, FCC, MC acceleration, LEP3, LheC
- Example: 9 cell, 1.3 GHz bulk Nb cavity for ILC (International Linear Collider). Some cavities achieved 31.5 MV/m. Higher quality factor required for e.g. LCF



FCC-ee – Future Circular Collider e+e-

- 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 – Parameter table

	Z	WW	ZH	ttbar
Beam energy [GeV]	45.6	80	120	182.5
SR power/beam [MW]	50			
SR losses/turn [GeV]	0.0394	0.374	1.89	10.42
Beam current [mA]	1270	137	26.7	4.9
Bunches/beam [-]	11200	1780	440	60
Bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
RF voltage 400/800MHz [GV]	0.08/0	1.0/0	2.1/0	2.1/9.4
Horizontal β -function at IP [mm]	110	200	240	1000
Vertical β -function at IP [mm]	0.7	1.0	1.0	1.6
Horizontal emittance [nm]	0.71	2.17	0.71	1.59
Vertical emittance [pm]	1.9	2.2	1.4	1.6
Luminosity/IP [$10^{34}\text{cm}^{-2}\text{s}^{-1}$]	141	20	5	1.25
Integrated luminosity/IP/year [ab^{-1}]	15	12	12	11

Design and parameters dominated by choice to allow for 50 MW synchrotron radiation power per beam

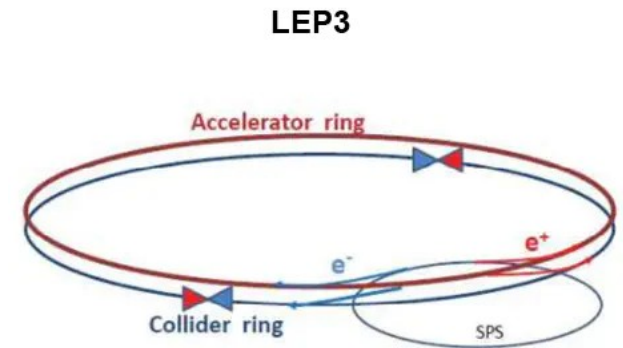
Defines
 → RF system
 → Beam parameters

FCC-hh – Future hadron Circular 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 Nb₃Sn low temperature superconducting magnets
 - Industrialization design requires 10-20 years
- Technological readiness as stand-alone ~2055 and later with HTS

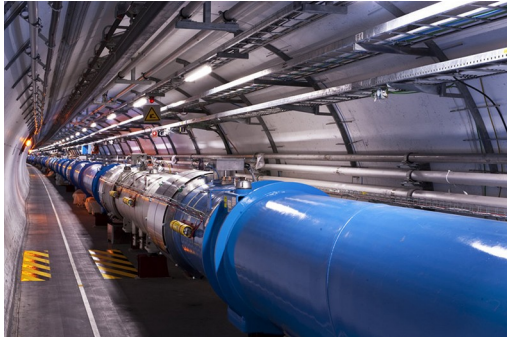
LEP3 – Large Electron Positron Collider 3

- Normal conducting dipoles and 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



Magnet technology

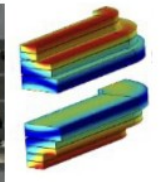
- Low temperature superconductors (LTS)
- Relevant for: FCC-hh, LEP3 as possible back-up, MC
- Until 2035 HTS and LTS development in parallel
- 1.9 K baseline operating temperature (4.5 K or 12 T for improving costs)



- High temperature superconductors (HTS)
- Relevant for: LEP3, alternative options for FCC-ee, FCC-hh, MC
- Higher field reach with less power consumption
- 4 to 20 K operating temperature

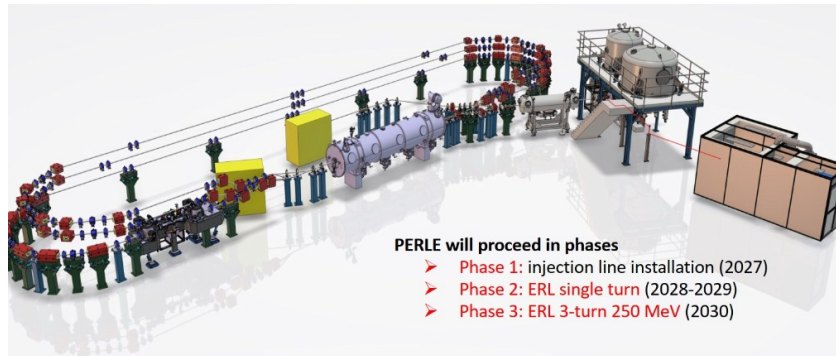
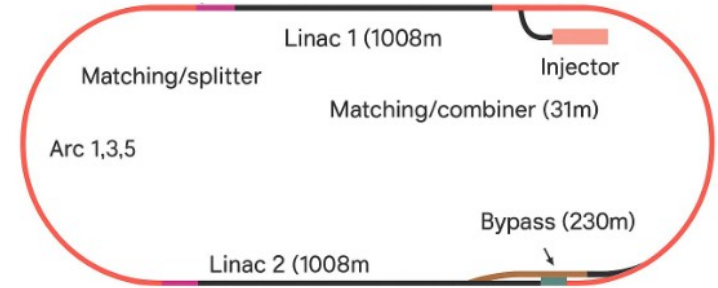


CEA MI
Racetrack



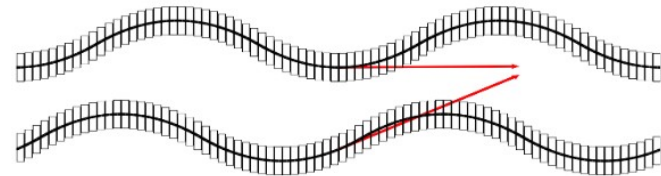
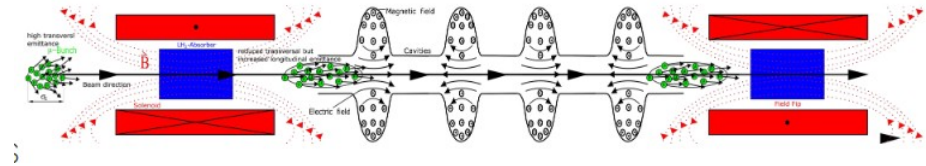
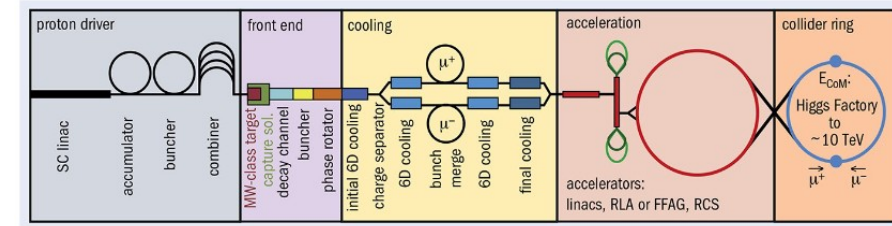
LHeC – Large Hadron electron collider

- Special dedicated IP for electron-hadron collisions
- New electron accelerator for one 50 GeV beam with 50 mA
- Foresees energy recovery linac (ERL) principle with 1/3 LHC length
 - ERL demonstrator: PERLE (Powerful Energy Recovery Linac for Experiments at IJCLab, Orsay)



MC – Muon Collider

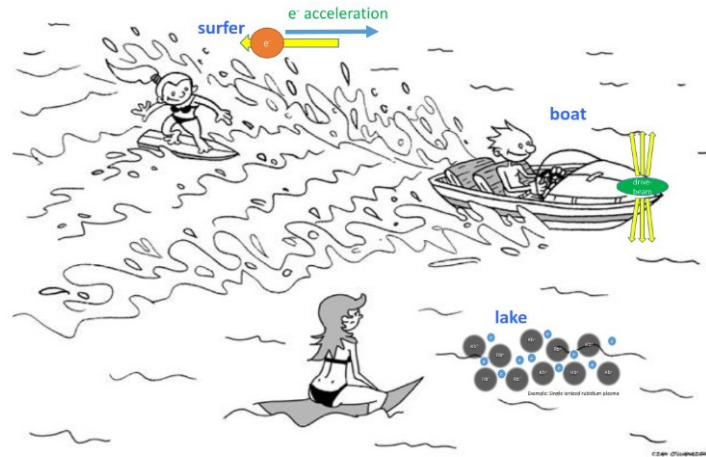
- μ are elementary particles but heavier than electrons
- 10 to 14 TeV μ collision comparable to 100 to 200 TeV protons
- 6D cooling
 - High field solenoids, high RF gradients and repetition rate
- 2 μ s lifetime $\rightarrow$ very challenging acceleration chain
- Fast ramping NC magnets in the collider ring 4200 T/s
- High RF demands (90 GV and 3000 cavities)
- μ are not stable particles $\rightarrow$ decay
 - High intensity neutrino flux to be “controlled”
- Very interesting, but many challenges



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
- Witness bunch accelerated with gradients of $\sim$ GV/m

- Very efficient, interesting and novel way to accelerate beams
- Some challenges ahead:
 - Positron acceleration
 - Multi-staging for high energy
 - Repetition rate



Analogy:
lake $\rightarrow$ plasma

Boat $\rightarrow$ particle beam
(drive beam)

Surfer $\rightarrow$ accelerated
particle beam (witness
beam)

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.



Luminosity and collision energy

- In addition: sustainability and power consumption plays an important role for any future collider

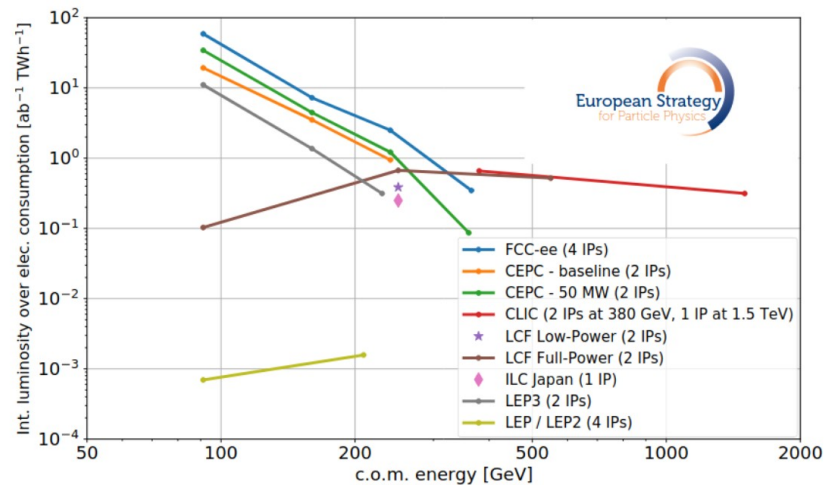


Fig. 10.1: Nominal yearly integrated luminosity over all experiments divided by the corresponding electricity consumption for future e^+e^- colliders (excluding off-line computing) as reported in Tables 10.1 and 10.2. For LCs the total luminosity (including that below 99% of the nominal c.o.m. energy)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

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>

CERN-ESU-2025-001
30 September 2025

Physics Briefing Book

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

Electroweak Physics: Jorge de Blas¹, Monica Dunford² (*Conveners*), Emanuele Bagnaschi³ (*Scientific Secretary*), Ayres Freitas⁴, Pier Paolo Giardinò⁵, Christian Grefe⁶, Michele Selvaggi⁷, Angela Taliercio⁸ (*Contributors*)

Strong Interaction Physics: Andrea Dainese⁹, Cristinel Diaconu¹⁰ (*Conveners*), Chiara Signorile-Signorile¹¹ (*Scientific Secretary*), Néstor Armento¹², Roberta Amaldi¹³, Andy Buckley¹⁴, David d'Enterria¹⁵, Antoine Gérardin¹⁵, Valentina Mantovani Sarti¹⁶, Sven-Olaf Moch¹⁷, Marco Pappagallo¹⁸, Raimond Snellings^{19,83}, Urs Achim Wiedemann⁷ (*Contributors*)

Flavour Physics: Gino Isidori²⁰, Marie-Hélène Schune²¹ (*Conveners*), Maria Laura Piscopo⁸³ (*Scientific Secretary*), Marta Calvi²⁴, Yuval Grossman²³, Thibaud Humair²⁴, Andreas Jüttner²⁵, Jernej F. Kamenik^{26,65}, Matthew Kenzie²⁷, Patrick Koppenburg²⁸, Radoslav Marchevski²⁹, Angela Papa²⁹, Guillaume Pignol³⁰, Justine Serrano³¹ (*Contributors*)

Neutrino Physics & Cosmic Messengers: Pilar Hernandez³², Sara Bolognesi⁴⁰ (*Conveners*), Ivan Esteban⁴¹ (*Scientific Secretary*), Stephen Dolan⁴², Valerie Domicke⁴³, Joseph Formaggio⁴², M. C. Gonzalez-Garcia^{44,81,82}, Aart Heijboer¹⁹, Aldo Ianni⁴⁴, Joachim Kopp^{7,79}, Elisa Resconi⁴⁵, Mark Scott⁴⁶, Viola Sordini⁴⁷ (*Contributors*)

Beyond the Standard Model Physics: Fabio Maltoni^{8,31}, Rebecca Gonzalez Suarez³² (*Conveners*), Benedikt Maier³³ (*Scientific Secretary*), Timothy Cohen^{7,28,78,*}, Annapaola de Cosa^{34,*}, Nathaniel Craig³⁵, Roberto Franceschini¹⁶, Loukas Gouskos³⁷, Aurelio Juste³⁸, Sophie Renner³⁴, Lesya Shchutska²⁸ (*Contributors*)

Dark Matter and Dark Sector: Jocelyn Monroe^{54,46}, Matthew McCullough⁷ (*Conveners*), Yohei Ema^{7,7} (*Scientific Secretary*), Paolo Agnes³, Francesca Calore⁴⁸, Emanuele Castorina²², Aaron Chou⁴⁹, Monica D'Onofrio⁵⁰, Maksym Ovchinnikov⁵¹, Tina Pollmann¹⁹, Josef Pradler^{29,206}, Yotam Soreq⁵², Julia Katharina Vogel⁵³ (*Contributors*)

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Editors: Roger Forty⁷, Karl Jakobs³⁴, Hugh Montgomery⁷⁵, Mike Seidel^{28,76}, Paris Sphicas^{7,77}

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- 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

G. Arduini^{1,2} (convener), F. Bordry¹ (co-opted accelerator expert), R. Brinkmann² (co-opted accelerator expert), P. Burrows^{3,4} (convener), K. Desch⁵, S. Farrington^{5,6}, F. Gianotti¹, K. Hanagaki⁷, N. Holtkamp^{8,9} (co-opted accelerator expert), J. Keintzel^{1,10} (scientific secretary), B. Kilminster¹⁰, T. Lesiak¹¹, L. Rivkin^{12,13} (co-opted accelerator expert), F. Sabatié¹⁴, M. Tuts¹⁵, A. Zoccoli¹⁶.

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Recommendation 2026

- Huge effort within our community to update European Strategy for Particle Physics
- Drafting session beginning of December with recommendations released in 2026
- Goal: be ready for a go/no-go decision on FCC-ee by 2028

I. The next CERN flagship collider project

- The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN.*
- A descoped FCC-ee is the preferred alternative option for the next flagship collider at CERN*



Thank you !

Jacqueline Keintzel

NSTAR 2026
Seville, Spain
11 September 2026

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 ₃ Sn) / 4.3							
		2 - 7 (HTS) / 3.2							
FCC-hh - SA 85 TeV		4 - 7 (Nb ₃ Sn) / 5					Nb ₃ Sn		
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 the cost-weighted average TRL score (TRL $\geq$ 6 - green, 4 $\leq$ 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.

High level parameters

	CLIC			FCC-ee				FCC-hh	LCF				LEP3			LHeC	MC	
									LP	FP								
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				LP	LCF				LEP3		
									FP						
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^+) [%]	$\pm 80 / 0$			$0 / 0^a$				$\pm 80 / \pm 30$				$\pm 80 / \pm 60$	$0 / 0^a$		
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) [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	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 [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 [TWh/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.

EIC parameters

- Hadron storage ring: 40 – 275 GeV (existing)
 - 1160 bunches, 1 A beam current
 - Small vertical emittance
 - Strong cooling
- Electron storage ring: 2.5 – 18 GeV (new)
 - Up to 1160 polarized bunches
 - Large beam current of 2.5 A $\rightarrow$ 9 MW SR power
 - Superconducting RF
- Rapid cycling synchrotron (RCS): 0.4 – 18 GeV (new)
- High luminosity interaction regions: (new)

