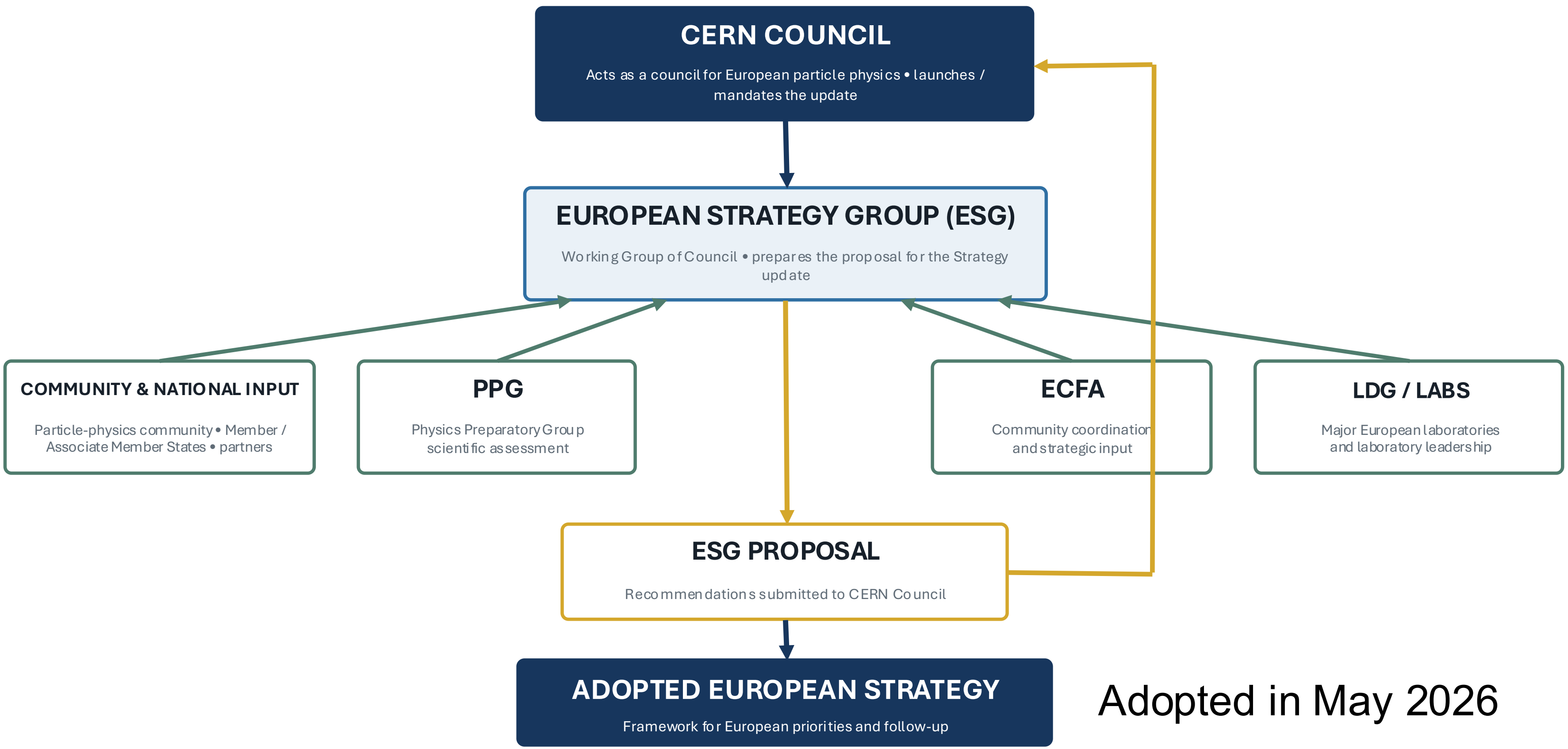
ESPP: The selection of the preferred and alternative next collider for CERN

Karl Jakobs (Strategy Secretariat Chair) for the European Strategy Group
ECFA Plenary Meeting, Nikhef Amsterdam, 10th July 2026

adapted by Marko Mikuž for F9 Strategic Meeting, Krvavec, September 28

European Strategy for Particle Physics (ESPP) in a Nutshell

CERN Council owns the formal process: it launches the update, establishes the ESG and adopts the Strategy



Adopted in May 2026

The ESG is a Working Group of Council and ceases to exist after Council adopts the new Strategy.

The European Strategy Group (ESG)

MEMBERS

CERN Member States representatives
Professor Jochen Schieck (Austria)
Professor Pierre Van Mechelen (Belgium)
Professor Venelin Kozhuharov (Bulgaria)
Professor Rupert Leitner (Czech Republic)
Professor Jens-Jørgen Gaardhøje (Denmark)
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Professor Eric Laenen (Netherlands)
Professor Heidi Sandaker (Norway)
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Professor Borut Paul Kerševan (Slovenia)
Professor Maria Jose Costa (Spain)
Professor Richard Brenner (Sweden)
Professor Ben Kilminster (Switzerland)
Professor Mark Lancaster (United Kingdom)

CERN Director-General
Dr Fabiola Gianotti until 31 December 2025
Professor Mark Thomson as of 1 January 2026
(attended in 2025 as Director-General Designate)

Major European National Laboratories
Professor Nicanor Colino (CIEMAT)
Professor Ulrich Husemann (DESY)
Professor Achille Stocchi (IJCLab)
Professor Franck Sabatié (IRFU)
Dr Sandra Malvezzi (LNF)
Professor Ezio Previtali (LNGS)
Professor Jergen D'Hondt (NIKHEF)
Professor Klaus Kirch (PSI)
Professor Sinead Farrington (STFC-RAL)
Professor Jim Clarke (STFC-Daresbury Lab.)

Strategy Secretariat Members
Professor Karl Jakobs (Strategy Secretary, ESG Chair)
Dr Hugh Montgomery (SPC Chair until 31 December 2025; *thereafter, ad personam*)
Professor Philip Burrows (SPC Chair as of 1 January 2026)
Professor Mike Seidel (LDG Chair)
Professor Paraskevas Sphicas (ECFA Chair)

ESG INVITEES
President of the CERN Council
Professor Costas Fountas

ESG Working Group 2a Co-convener
Professor Philip Burrows

Associate Member States in the pre-stage to Membership
Professor Panos Razis (Cyprus)

Associate Member States
Professor Leandro Salazar de Paula (Brazil)
Dr Budimir Kliček (Croatia)
Ms Antra Gaile (Latvia)
Dr Andrius Juodagalvis (Lithuania)
Dr Masood Iqbal/Dr Zafar Yasin (Pakistan)
Professor Suat Özkorucuklu (Türkiye)
Professor Borys Grynyov (Ukraine)

Observer States
Dr Kazunori Hanagaki (Japan)
Professor Michael Tuts (United States of America)

Organisations with Observer status
Ms Patricia Postigo McLaughlin
(European Commission)

Other invitees
Dr Carlos Peña Garay (Chair APPEC)
Professor Eberhard Widmann (Chair NuPECC)
Professor José Luis Martinez (Chair ESFRI)
Other members of the PPG *(in addition to the Strategy Secretariat)*

ESG Recommendations on CERN's Next Collider

I. The *next CERN flagship collider project*

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

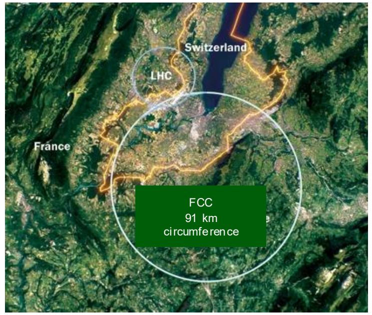
ii. A descoped FCC-ee is the preferred alternative option for the next flagship collider at CERN

At this stage, without knowing the reasons for which the FCC-ee would not be feasible, other alternative options are not ranked.

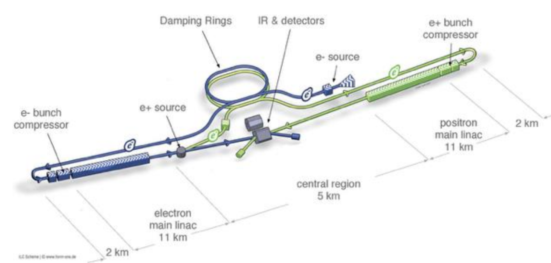
Proposed large-scale projects at CERN, ~ 2045

e^+e^- colliders
("Higgs factories")

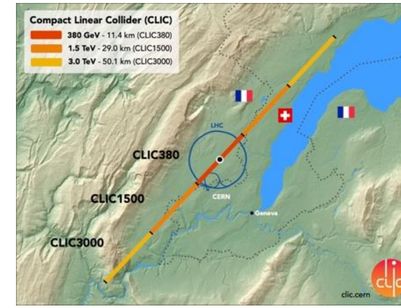
FCC-ee (e^+e^-, circular, 91 – 365 GeV)



LCF (e^+e^-, linear, 91 – 240, 550 GeV)



CLIC (e^+e^-, linear, 380 GeV, 1.5 TeV)

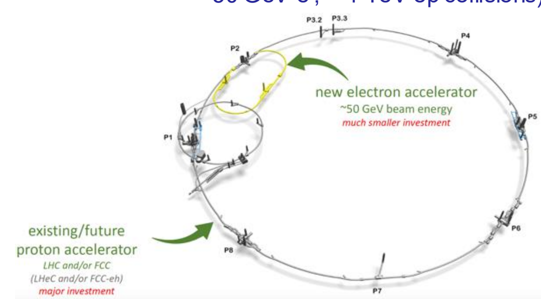


Intermediate projects

(Leave room (time, budget, resources) for further development of THE machine that can probe directly the energy frontier at the 10 TeV parton scale)

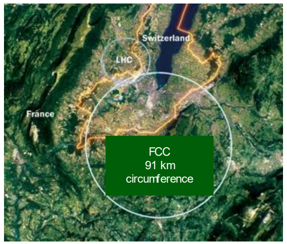
LEP3 (e^+e^-, circular, 91 – 230 GeV)

LHeC (ep, circular, electron ERL, 50 GeV e^-, > 1 TeV ep collisions)



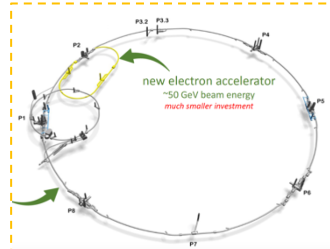
Potential for development: future 10 TeV parton-scale collider options

FCC-ee



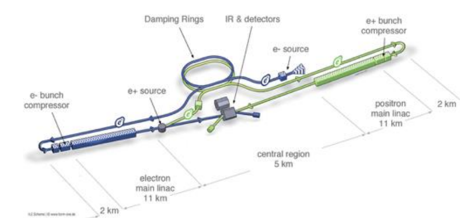
LEP3

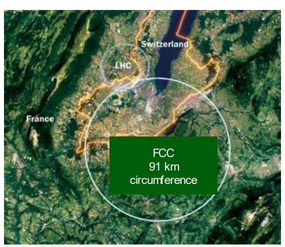
LHeC



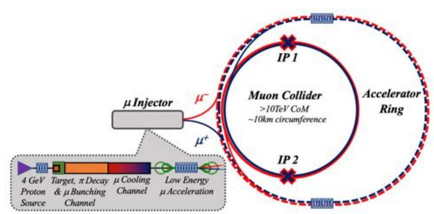
PERLE

LCF, CLIC





FCC-hh,
baseline 85 TeV (→ 120 TeV)
+ possibility for HI collisions



Muon Collider (3, 10 TeV)

R&D

e^+e^- with improved acceleration technologies
LCF, C^3 (→ 1 TeV), CLIC (1.5 TeV), HALHF, …
→ plasma acceleration for higher energies
(can $\mathcal{O}(10)$ TeV be reached? on what timescale?)

A descoped FCC-ee

A descoped FCC-ee (to improve the financial feasibility)

- Descoping scenarios include:
  - removing the top-quark run -1.26 BCHF
  - constructing two rather than four interaction regions and experiments - 0.80 BCHF
  - decreasing the RF system power (50 MW → 30 MW) - 0.35 BCHF
- These measures would reduce the construction cost by approximately 15%
- *The luminosity for the descoped FCC-ee would be (M. Benedikt, F. Zimmermann):*

$$\mathcal{L}\,(\text{FCC-ee})_{\text{descoped}} = \mathcal{L}\,(\text{FCC-ee}) \times 3/5 \times 2/4 \times 1.2 = \mathcal{L}\,(\text{FCC-ee}) \times 0.36$$

- Should additional resources become available, these descoping scenarios would be reversible

Important input for the decision on the next CERN flagship project

(i) Physics Potential

Physics Briefing Book (→ 30 Sept. 2025)

→ Assessment of overall Physics Potential
ESG Working group 2b report

(ii) Project assessment

Technical feasibility, required R&D, risks, timeline, costs and human resources (including estimates for the associated detectors), environmental impact
ESG Working Group 2a report

(iii) Final input by the National HEP communities

ESG Working Group 1 report

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 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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Theoretical Overview: Eric Laenen[19,83,85]
Reviewers: Anadi Canepa[49], Xinchou Lou[58], Rogerio Rosenfeld[72], Yuji Yamazaki[73]
Editors: Roger Forty[7], Karl Jakobs[74], Hugh Montgomery[75], Mike Seidel[28,76], Paris Sphicas[7,77]

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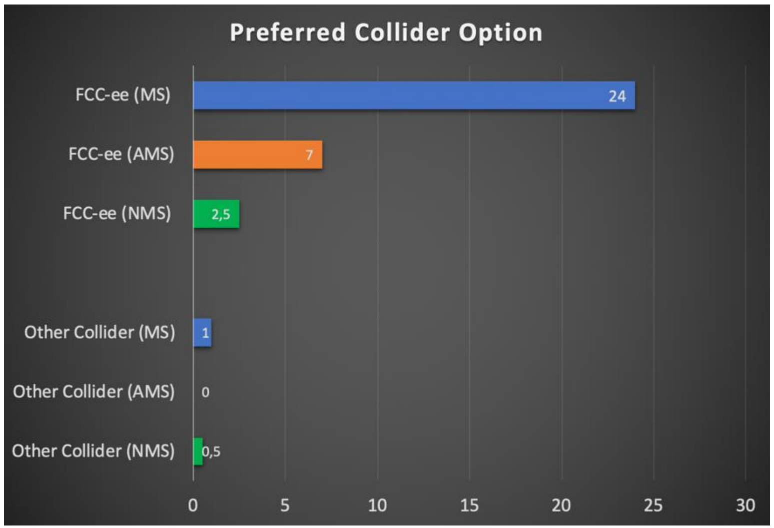
https://arxiv.org/abs/2511.03883

CERN Yellow Report

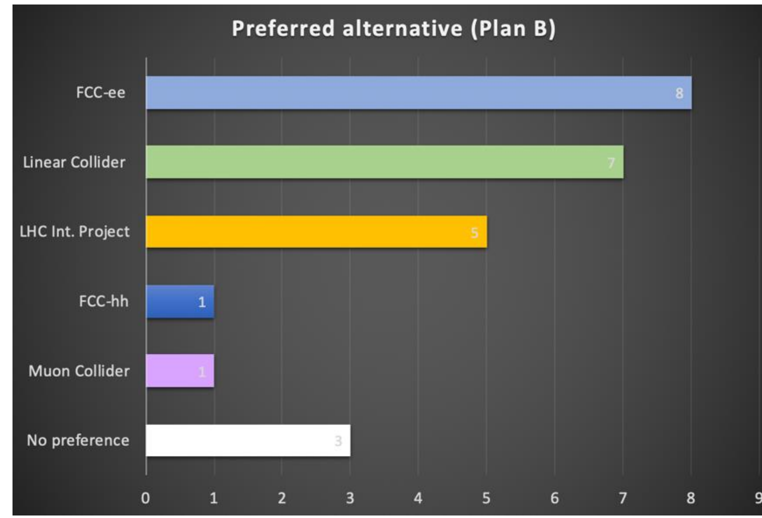
Final input from the national HEP communities (Nov. 2025)

What is the preferred large-scale post-LHC accelerator at CERN?



- Overwhelming support (24/25 CERN Member States HEP communities) in favour of the FCC-ee programme
- Support as well from Associate Member States (AMS) and Non-Member States (NMS)

What is the preferred alternative if the preferred option would not be feasible?



No consensus; **three main axes:**

- FCC (stretched in time, descoped, …)
- Linear Collider
- Intermediate project in LHC tunnel as bridge towards FCC-hh (10++ TeV scale)

Evaluation by the European Strategy Group

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

31 October 2025

G. Arduini[1,a] (convener), F. Bordry[1] (co-opted accelerator expert), R. Brinkmann[2] (co-opted accelerator expert), P. Burrows[3,b] (convener), K. Desch[4], S. Farrington[5,6], F. Gianotti[1], K. Hanagaki[7], N. Holtkamp[8,9] (co-opted accelerator expert), J. Keintzel[1,c] (scientific secretary), B. Kilminster[10], T. Lesiak[11], L. Rivkin[12,13] (co-opted accelerator expert), F. Sabatié[14], M. Tuts[15], A. Zoccoli[16].

Project	Scope	TRL	R&D	Test facilities	Performance uncertainty	Site preparation	Schedule uncertainty	Cost uncertainty	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							

Evaluation by the European Strategy Group

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FCC-hh - SA 85 TeV		4 - 7 (Nb_3Sn) / 5					Nb_3Sn		
LCF 250 - 550 GeV		5 - 7 / 5.5							
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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							

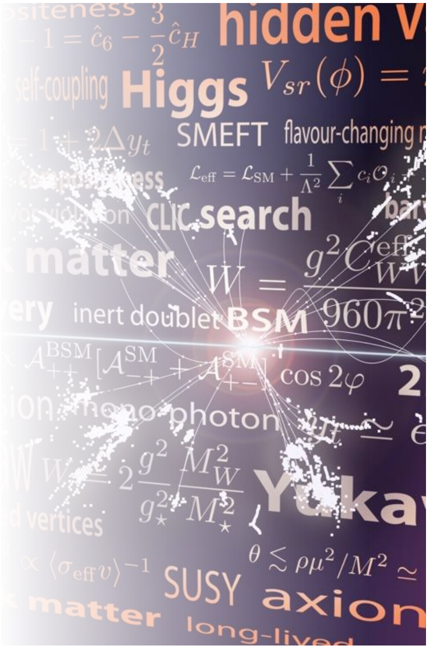
- Muon Collider: The technologies underpinning the MC design are in the early phases of exploration;
  Comprehensive R&D programme defined (300 MCHF, 1800 FTEy);
  Demonstrator need to be built.

- FCC-hh: Further R&D and industrialisation of high-field magnets (Nb_3Sn 15 - 20 y);
  Costs of HFM, further developments of high-temperature superconducting (HTS) magnets

- LEP3: Absence of a detailed lattice design and full-scale simulation → uncertainties on projected luminosity;
  Proposed baseline HTS nested quadrupoles/sextupoles represent the lowest TRL (luminosity, power)

- LHeC: Performance critically depends on a very high-current Energy-Recovery Linac (ERL);
  Uncertainty on luminosity of an order of magnitude;
  Successful demonstration of the PERLE programme at IJCLab is vital

Physics Potential



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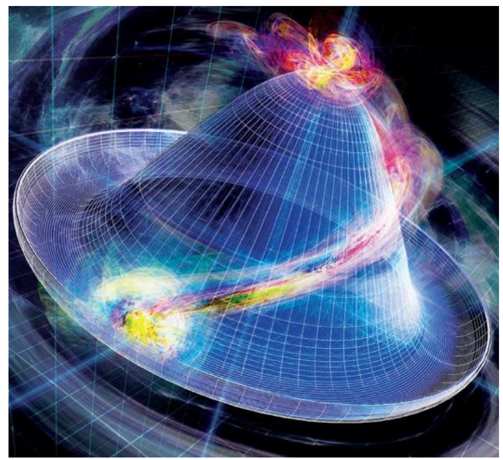
[CERN Yellow Report]



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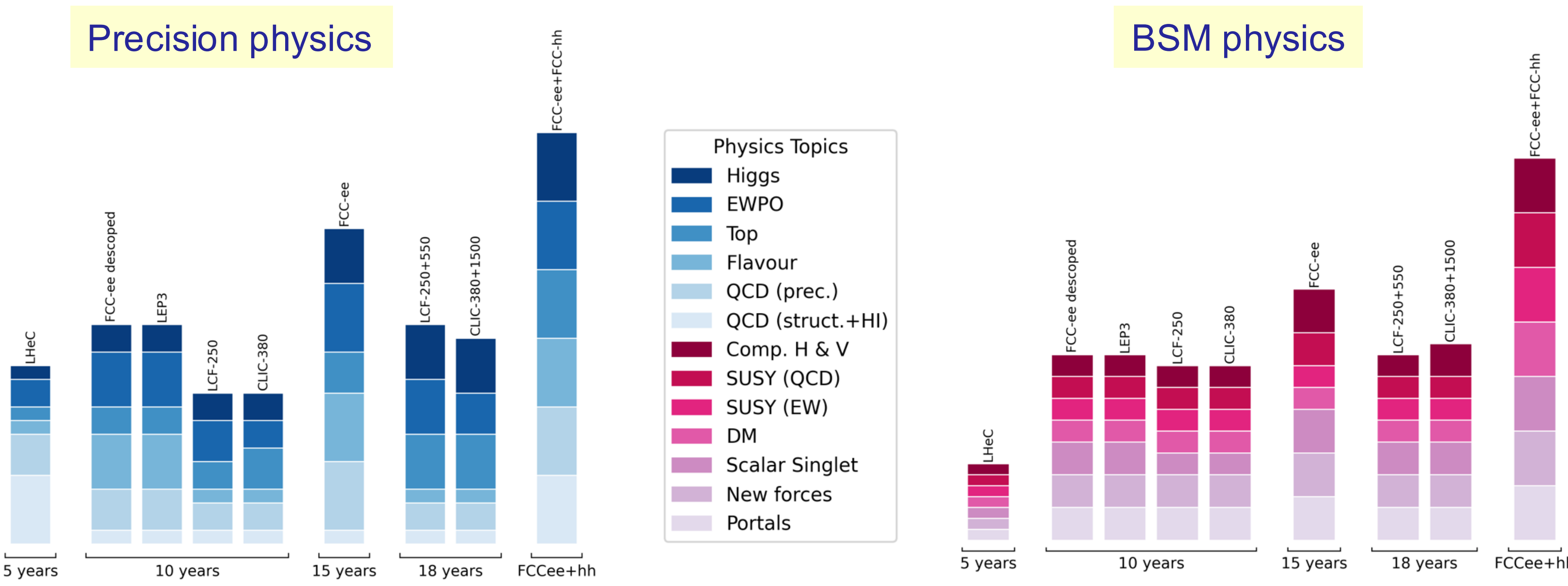
*Beyond the **Technical Readiness**, the **physics potential** and the **long-term prospects** of reaching the 10++ TeV energy scale are the driving arguments for the choice of the next collider;*

Overall Physics Assessment



CERN-ESU-2026-006

What is lost, if an alternative collider, other than the FCC, would be chosen?

What is lost, if an alternative collider, other than the FCC, would be chosen?

Aim of the Strategy Process, as defined in the remit by the CERN Council:

"The aim of the Strategy update should be to develop a ***visionary and concrete plan*** *that greatly advances human knowledge in fundamental physics through the* ***realisation of the next flagship project at CERN****. This plan should attract and value* ***international collaboration*** *and should* ***allow Europe to continue to play a leading role in the field."***

"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."*

What is lost, if an alternative collider, other than the FCC, would be chosen?

In addition:

- *New physics is needed!*
- *No guidance from theory*

→ the ***coverage of a new flagship collider has to be as broad as possible***

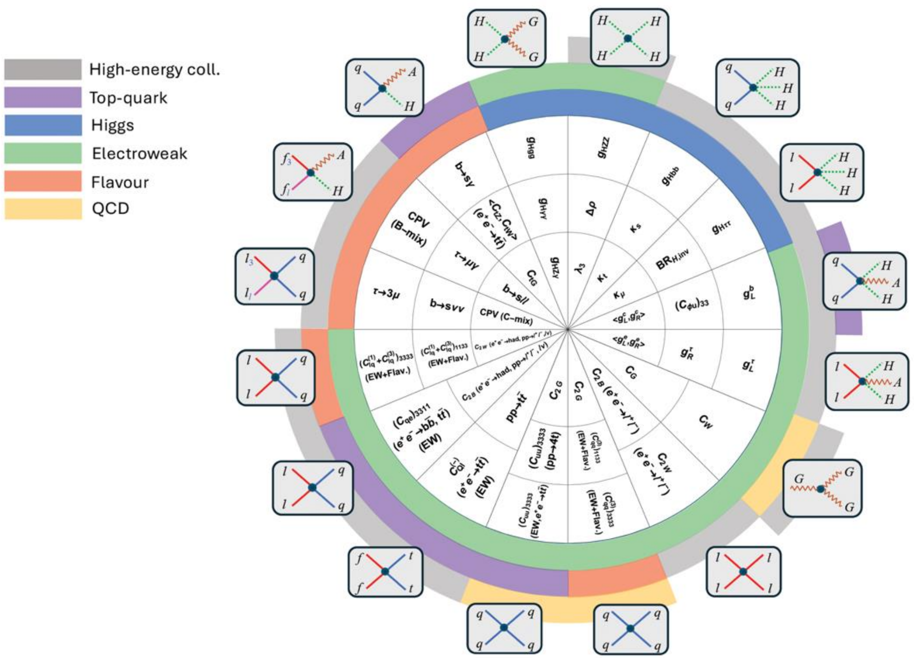
Venice Strategy Symposium:

1. *Precision and energy*
2. Synergies of **Higgs, electroweak, top and flavour** physics programmes are essential to maximise the **indirect discovery potential**

Coverage of the Physics Landscape

(i) Methodology*

effective interactions



*Thanks to Jorge de Blas, Monica Dunford and Gino Isidori (ESG WG 2b)

- Slice physics landscape in 16 different sectors (adequate representation of the effective interactions among SM fields where new physics can show up)
- Sensitive to: Higgs, el.weak, top, flavour, QCD, high-energy observables

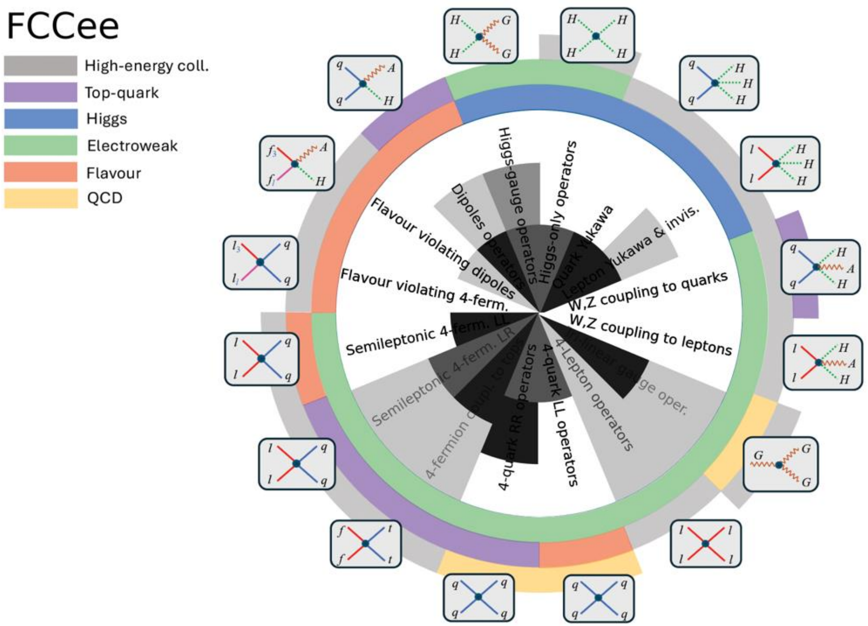
  examples (details on the next slide):
  - Higgs-only operators $(HZZ, \Delta\rho, \lambda_3)$
  - Quark Yukawa (Y_b, Y_s, Y_t)

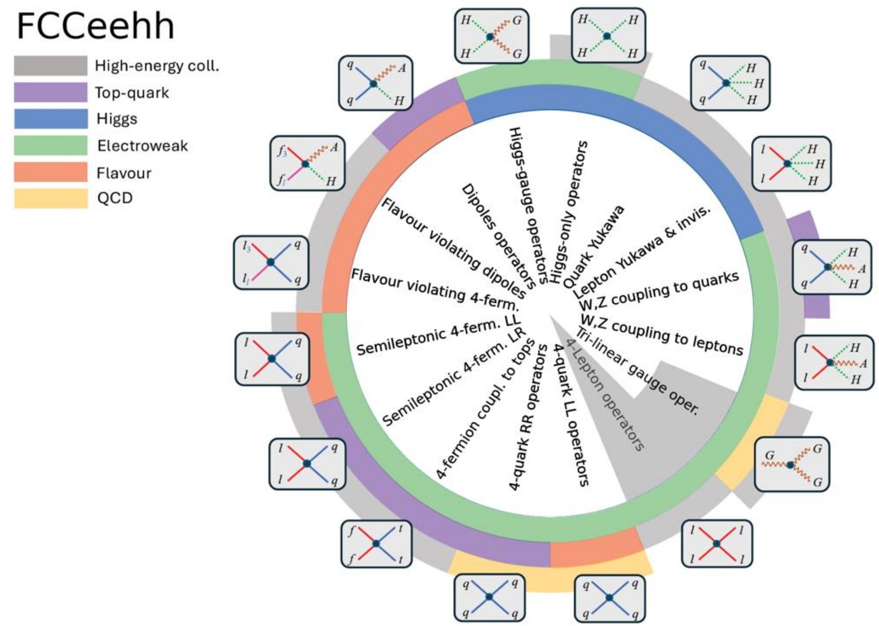
  - Tri-linear gauge operators (el.weak, GGG)
  - 4-lepton ops. (W parameter, Y parameter)

  → each sector is subdivided in 2 or 3 rings with increasing measurement challenges
- Compare potential of each collider for all sectors/rings
- HL-LHC performance is used as reference
- **Improvement factors** in precision w.r.t. HL-LHC are evaluated and mapped on a log-scale covering the range 1 to 5

  HL-LHC: 1 (gray scale 1 = black)
  Best collider: 5 (gray scale 5 = white)

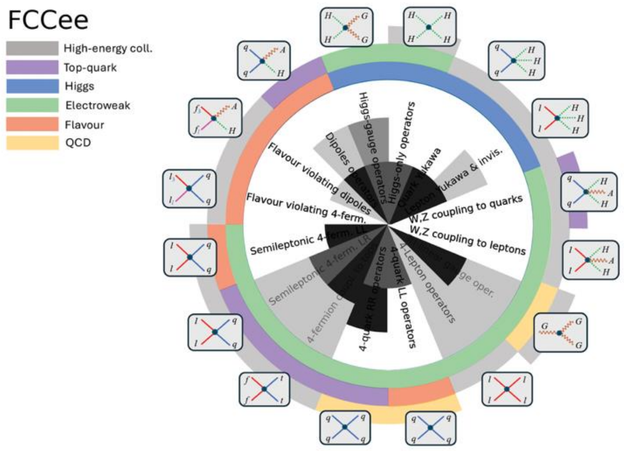
Coverage of the FCC-ee and FCC-eehh

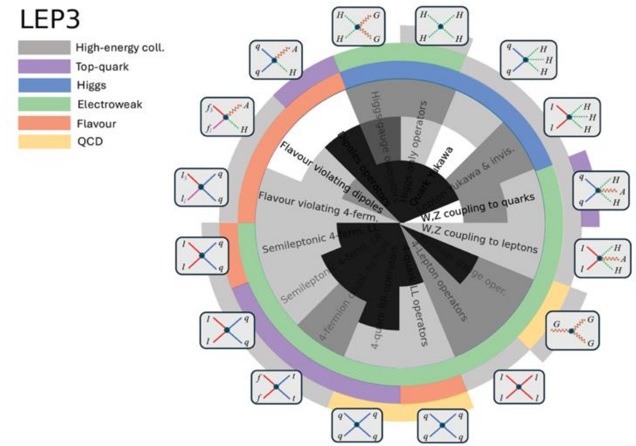


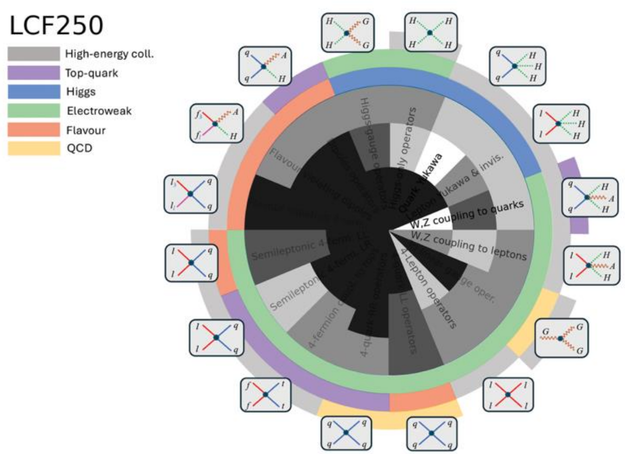


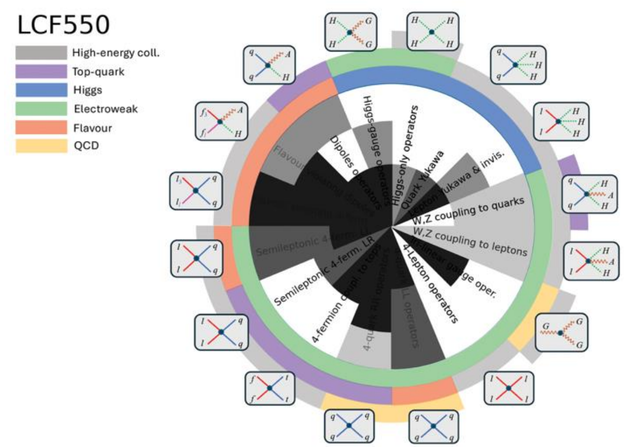
CERN-ESU-2026-006

Coverage of first-stage e^+e^- colliders









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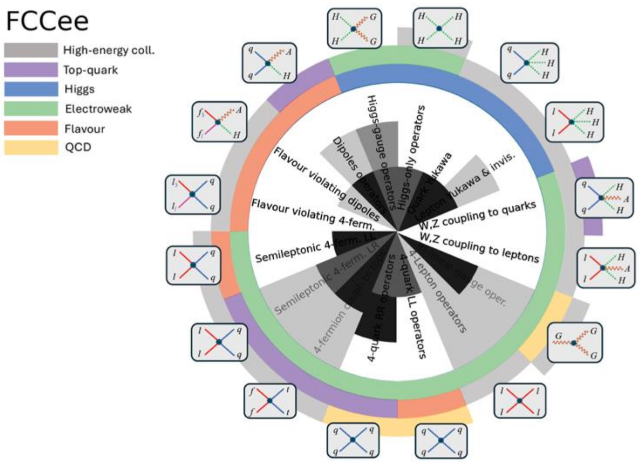
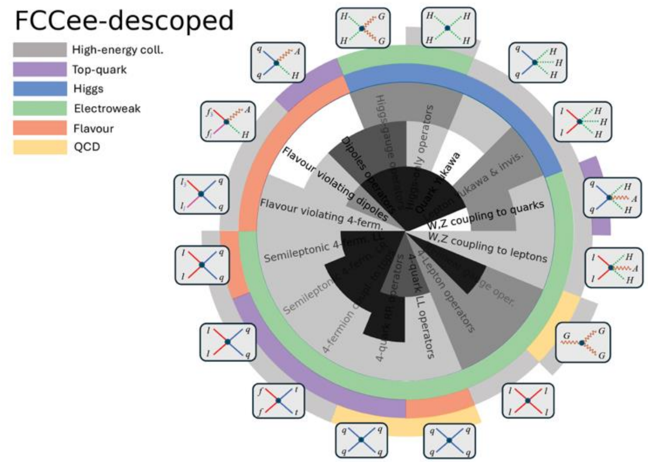
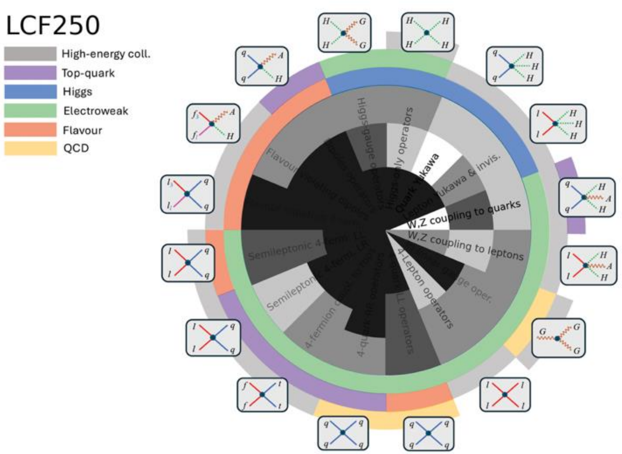
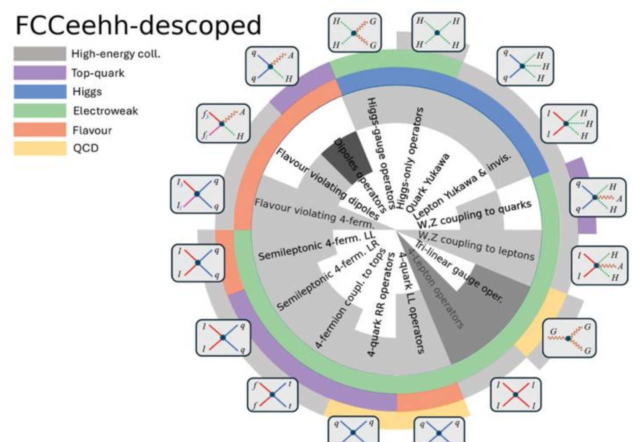
FCC-ee versus descoped FCC-ee and LCF250









CERN-ESU-2026-006

Overall Summary

Machine	Precision Physics	BSM physics	Physics vs CEPC	Technical readiness	Constr. cost (BCHF)	Time scale	Path to ≥10 TeV
FCC-ee	22	23			15.3	2046-2060	
Descoped FCC-ee	15	17			12.9	2046-2055	
LCF550	15	17			14.8	2045-2065	
CLIC1500	14	18			14.6	2045-2066	
LCF250	10	16			9.4	2045-2053	
CLIC380	10	16			7.5	2045-2054	
LEP3	15	17			4.1	2047-2062	
LHeC	8	7			2.1	2044-2051	

Physics: from WG2b: sum of precision/BSM physics

Phys vs CEPC: competitiveness, assuming CEPC is running in parallel

Tech readiness: from WG2a

Construction cost: from proponents + exp. (CERN part)

What will happen if the FCC-ee will not be feasible?

While the FCC-ee has been demonstrated to be technically feasible, its implementation remains subject to uncertainties related to:

(i) **Financial viability**

and

(ii) The potential **emergence of unforeseen challenges**, notably those associated with **tunnel construction** (acceptance by the population/political)

Alternative Collider Options?

(i) Possible alternatives if FCC-ee and the descoped FCC-ee are **financially not feasible**?

- LCF250, CLIC380 as low-energy e^+e^- colliders:
  cost: 9.4 , 7.5 BCHF
  - no satisfactory physics programme
  - not competitive with an FCC-ee-like collider
  - no demonstrated path to 10 TeV

- LCF250 + 550:
  cost: 14.8 BCHF (comparable to FCC-ee)
  - reduced physics potential
  - not competitive with an FCC-ee-like collider
  - no demonstrated path to 10 TeV

- CLIC380 + 550:
  cost: 9.5 BCHF
  - reduced physics potential
  - not competitive with an FCC-ee-like collider
  - extended test facility needed (closer to full CLIC linac section, full CLIC parameters)
  - no demonstrated path to 10 TeV

- LEP3:
  cost: 4.1 BCHF
  - reduced physics potential
  - path to 10 TeV: needs a tunnel (91 km, FCC-hh) at a later stage

- LHeC:
  cost: 2.1 BCHF
  - significantly reduced physics potential
  - path to 10 TeV: needs a tunnel (91 km, FCC-hh) at a later stage

Alternative Collider Options?

(ii) Possible alternatives if a 91 km **tunnel cannot be realised**?

- LCF250 + 550, CLIC 380 + 1500: require 33 km long tunnel

  Can such a tunnel be realised, if a 91 km FCC tunnel cannot?

  - No information about this at present;

  - FCC-ee realisation studies over the next years may provide some guidance on this

- LEP3 / LHeC: - reduced / significantly reduced physics potential

  - if 91 km FCC tunnel not possible, no 2nd stage FCC-hh

  → other scenarios for high-energy machines need to be considered

→ Given these large uncertainties, at this stage, without knowing the reasons for which the FCC-ee would not be feasible, other alternative options are not ranked.

Conclusions: main messages from the European Strategy Process

1. *FCC-ee: stands out as the unique option that offers both a concrete plan (outstanding physics programme) and a clear vision for the long-term future of the field (paving the way towards the 10++ TeV scale, re-using the tunnel for a pp collider)*

   → It would maintain European leadership in particle physics

   Large consensus has been reached in the European Particle Physics Community and beyond

2. *There is no convincing alternative collider concept as "plan B" (physics, competitiveness, path to 10 TeV)*

   In case FCC-ee should financially not be feasible, a descoped FCC-ee is the preferred alternative option for the next flagship collider at CERN

   → All possible efforts should be made by the CERN Council and CERN management to explore if FCC-ee or a descoped FCC-ee can be realised over the next years (until 2028)

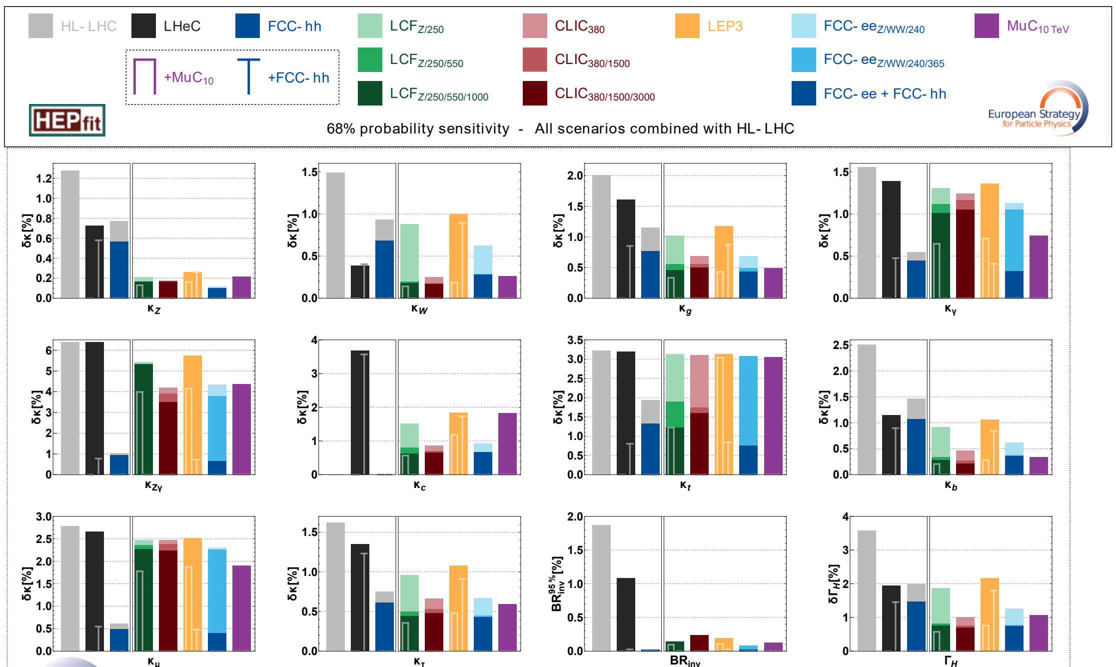
3. *Should this fail (finances, tunnel construction, …), the CERN Council should consider to launch a new **"light-weight" strategy process** in 2028 to define a new plan*

   (ESPP is a cornerstone of Europe's decision-making process for the long-term future of the field, well established, important to involve the full community in the decision on the large-scale, long-term facility for the entire field)

Backup Slides

Higgs Boson Physics: Coupling measurements - κ modifiers

- e^+e^- machines can make **model-independent measurements** of the Higgs boson couplings
- **Sub-percent precision in several channels**; significant improvement w.r.t. HL-LHC
  - 240 GeV: performance of different e^+e^- colliders comparable; FCC-ee has highest precision (large luminosity)
  - 550 GeV or above: $t\bar{t}H,\ ZHH$ and $\nu\bar{\nu}HH$ accessible → significant improvements ($\kappa_W,\ \kappa_t,..$)
- For rare processes ($\mathrm{H} \to \mu\mu,\ H \to Z\gamma$) HL-LHC prevails, strong improvement at FCC-hh

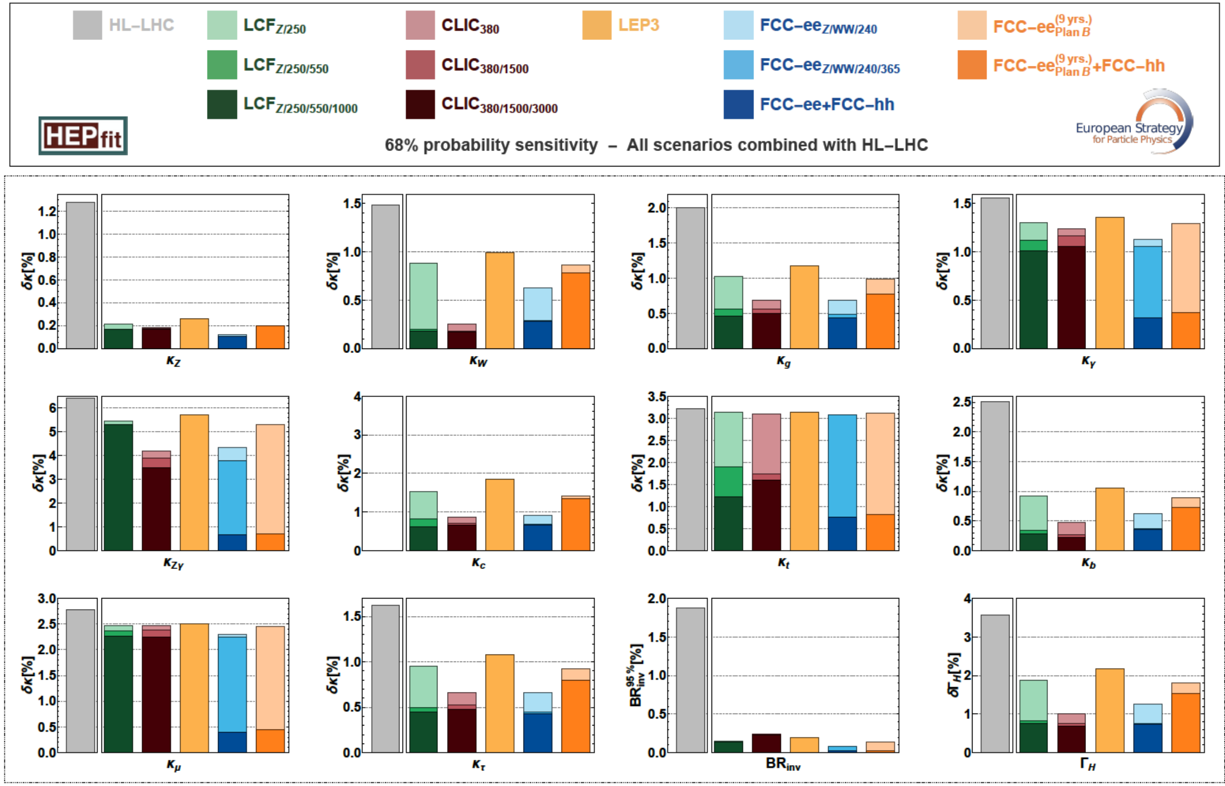


2nd generation couplings at e^+e^- colliders:
- $c\bar{c}$: good precision (+ LHeC)
- $s\bar{s}$: constrained: FCC-ee: $|\kappa_s| \in [0.4, 1.3]$
  LCF (LEP3): $|\kappa_s| < 1.2\ (1.3)$

Higgs boson width:
- Best precision FCC-ee .or. low-energy e^+e^- combined with a high-energy machine

Invisible width:
- Best precision at FCC-hh (0.02%)

Impact of de-scoped FCC-ee on Higgs boson couplings

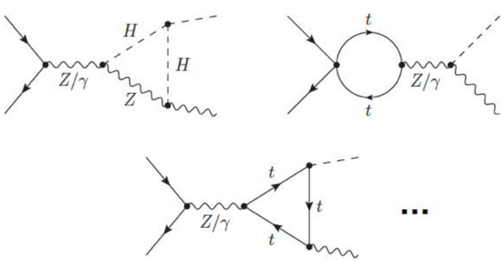


Higgs Boson Physics: Self-coupling

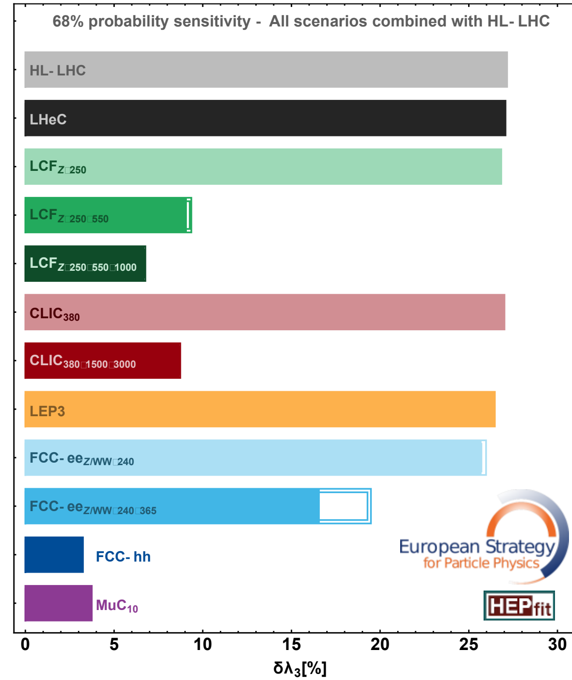
(i) Determination via di-Higgs production
HL-LHC estimate: $\pm$27%

(ii) Determination from single Higgs boson production
(sensitivity via loop effects)

- Two e^+e^- energies
- Constraining other contributions in the loops
  (sizeable contributions from top operators)



→ FCC-ee (240, 365 GeV) ($\pm$17-20%)
→ LCF-550 GeV ($\pm$10%)
→ FCC-hh, MC ($\pm$3-4%)



EFT analysis, single + di-Higgs, combination with HL-LHC

Absolute precision depends on λ_3

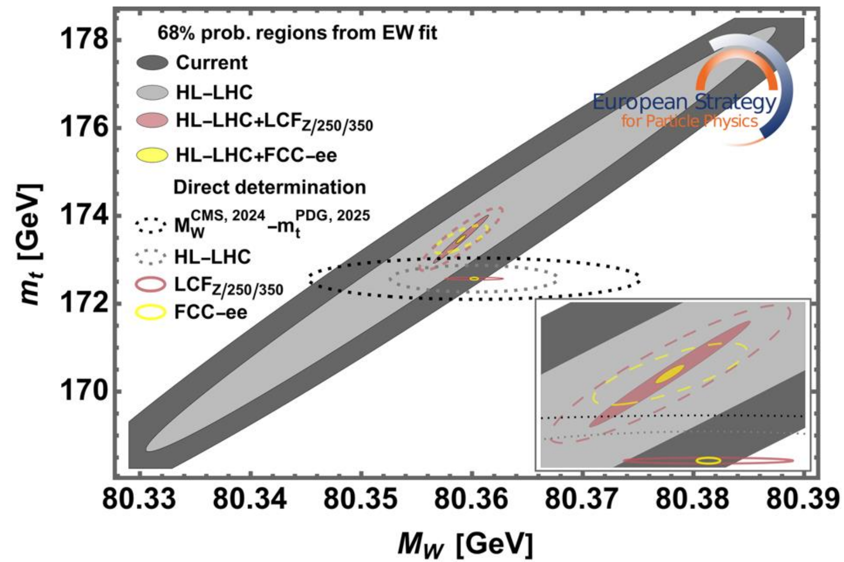
LCF550: uncertainty remains roughly constant, due to combination of ZHH and $\nu\nu HH$ processes

Electroweak precision observables (EWPO)

- Impressive precision in circular colliders due to large Z samples ($6{\cdot}10^{12}$ ($2{\cdot}10^{12}$) Z at FCC-ee (LEP3) per interaction region))
- High-energy linear colliders: partly compensate (polarised beams, enhanced sensitivity via vector-boson scattering)

Observable	Current	FCC-ee	LCF	LEP3
Δm_Z (keV)	2000	4 (100)	200	7.5 (100)
$\Delta\Gamma_Z$ (keV)	2300	4 (12)	125	7.5 (23)
δR_μ $(\times 10^{-6})$ $R_\mu \equiv \frac{\Gamma_{\rm had}}{\Gamma_\mu}$	1600	2.4 (2.3)	90 (90)	4.5 (2.3)
δR_b $(\times 10^{-6})$ $R_b \equiv \frac{\Gamma_b}{\Gamma_{\rm had}}$	3300	1.2 (1.6)	70 (60)	2.2 (3.0)
$\Delta\sin^2\theta_W$ $(\times 10^6)$	130	0.4 (0.5)	2.7 (2.3)	0.75 (0.95)
$\Delta\alpha(m_Z)^{-1}$ $(\times 10^3)$	14	0.8, 3.8	–	1.4, 7.3
Δm_W (keV)	9900	180 (160)	500 (1600)	430 (700)
$\Delta\Gamma_W$ (keV)	42000	270 (200)	2000	650 (500)

Current and projected uncertainties of EWPOs at various colliders;
stat. uncertainty quoted, exp. syst. in parentheses (single number → total uncertainty)

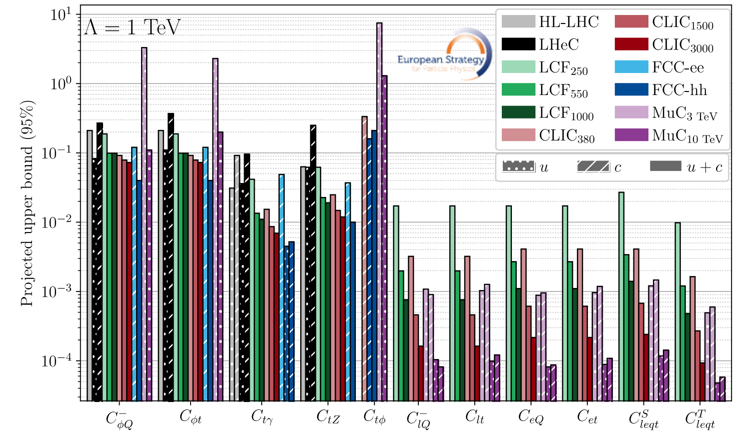


- Reaching these uncertainties places strong requirements on the detector design
- Unprecedented precision for the EWPO at the FCC-ee
- Theory uncertainties could be as well be a limiting factor in realising the full potential → significant and sustained investment in theory work is needed

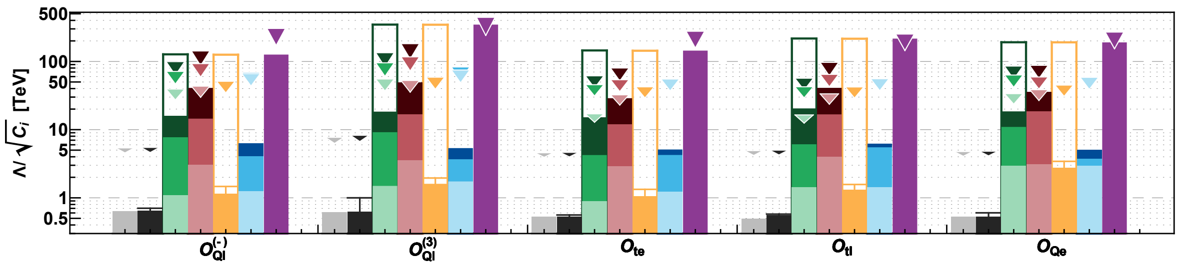
Top-Quark Physics

- Linear Colliders at higher energies significantly improve the sensitivity to EFT operators in the top-physics area;
- 550 GeV opens up sensitivity to energy-dependent operators

  → stronger bounds on ($e^+e^-t\bar{t}$) interactions
- Highest sensitivity: 10 TeV muon collider,
  followed by 3 TeV (CLIC), 1 TeV LCF
- Hadron colliders complementary
  ($q\bar{q}\ t\bar{t}$, best measurement of the top-Yukawa coupling)



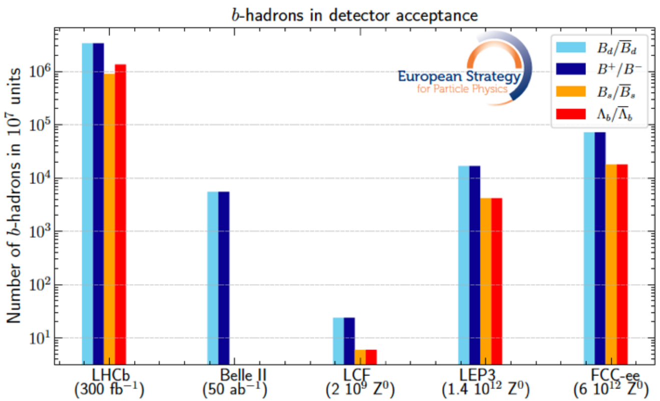
Sensitivity of SMEFT operators to FCNC in the top-quark sector



Sensitivity to ($l^+l^-t\bar{t}$) four-fermion operators

Flavour physics

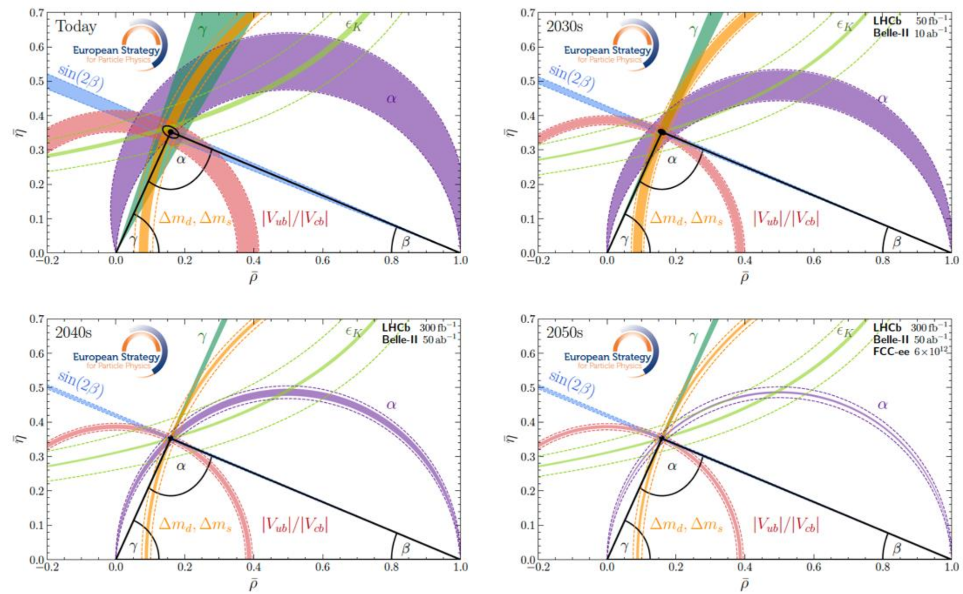
- Large progress will be made by LHCb and Belle-II over the next decade (until 2040)



2030s
Belle II 10 ab^{-1}
LHCb 50 fb^{-1}

2040s
Belle II 50 ab^{-1}
LHCb 300 fb^{-1}

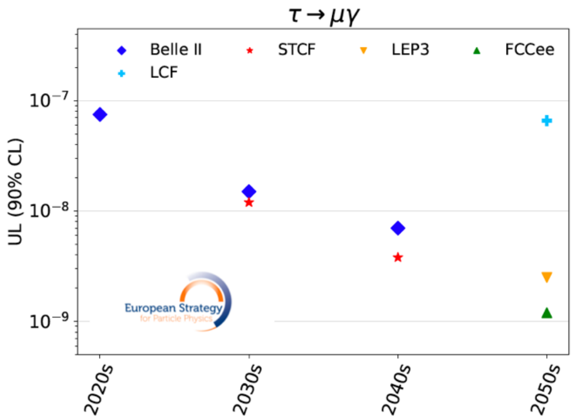
2050s
LCF 2 10^9 Z^0
LEP3 1.4 10^{12} Z^0
FCC-ee 6 10^{12} Z^0

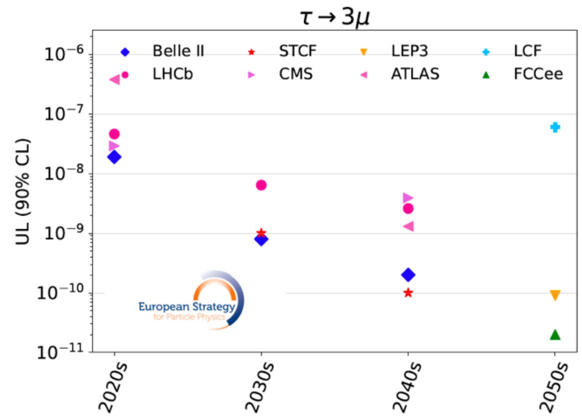


- For some b-decays and also for τ–physics, Tera-Z production at a future FCC-ee would provide a step forward (beyond the LHCb and Belle II reach)

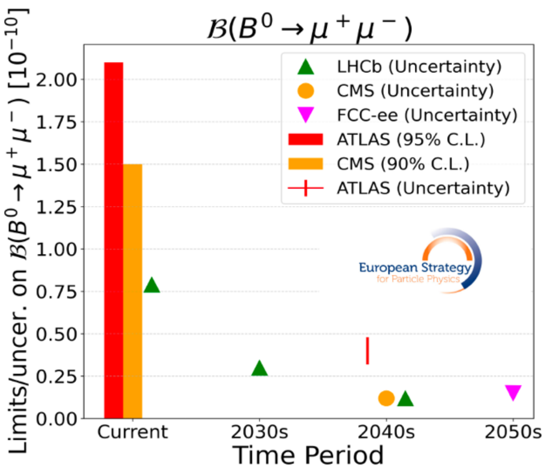
- Giga-Z has strongly reduced potential for flavour physics

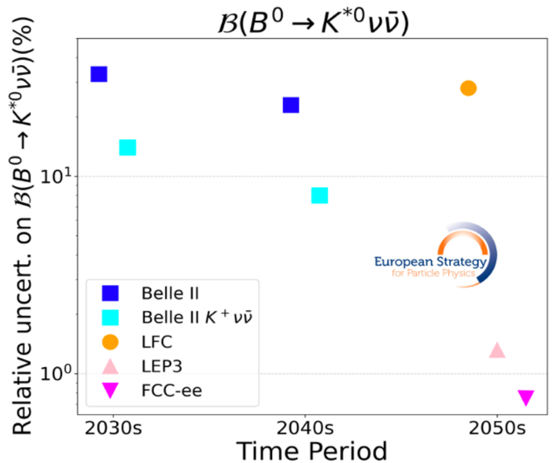
Flavour Physics





Expected upper limits at 90% CL on BR ($\tau \to \mu\gamma$) and BR ($\tau \to \mu\mu\mu$)





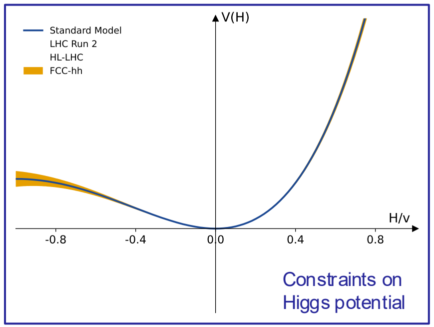
Left: current and expected uncertainties on BR ($B^0 \to \mu\mu$);

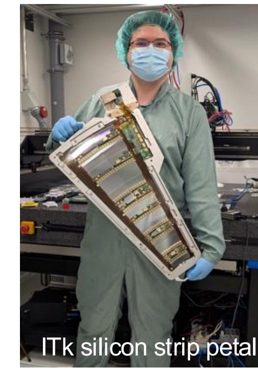
Right: expected relative uncertainty on BR ($B^0 \to K^{*0}\nu\bar{\nu}$)

Other Recommendations

General Recommendations

i. *The **full exploitation of the physics potential of the LHC and the HL-LHC and the completion of the high-luminosity upgrade remain the highest priorities** of European particle physics.*
Every effort must be made to complete the HL-LHC upgrade within the current schedule.





ii. *The unique ecosystem of particle physics research centres and universities in Europe should be further strengthened in order to address the objectives set out in this Strategy.*

iii. *The implementation of the Strategy should be pursued in strong collaboration with global partners and neighbouring fields.*

iv. *The relationship between the particle physics community and the European Commission should be further strengthened, exploring funding opportunities for the realisation of infrastructure projects and R&D programmes in cooperation with other fields of science and industry.*

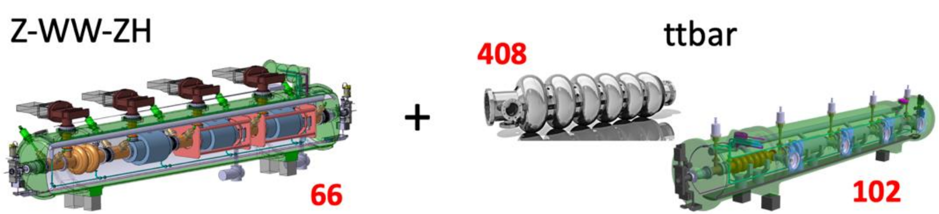
Technologies

To ensure that Europe remains at the forefront of technologies for particle physics, R&D in collaboration with international partners and industry must continue to be supported with high priority, thereby enhancing sustainability and societal impact.

Accelerator science and technology:

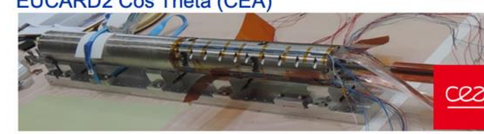
*i. In order to realise the visionary plan presented, the **highest priority** must be the **development and industrialisation of key technologies**: **advanced superconducting and normal-conducting RF structures, efficient RF power sources** and **accelerator-quality magnets in the 14 - 20 T range**, including those based on **high-temperature superconductors**.*

FCCee Collider RF system (400 MHz and 800 MHz)



EUCARD2 Feather M2 (CERN)

EUCARD2 Cos Theta (CEA)



ReBCO Racetracks, CERN

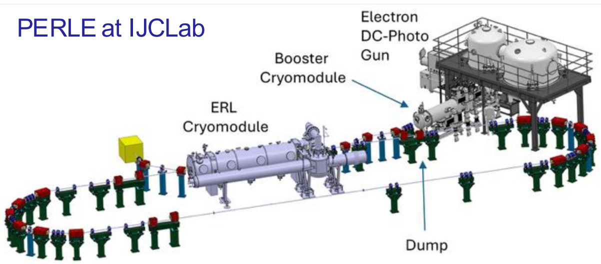
Technologies (cont.)

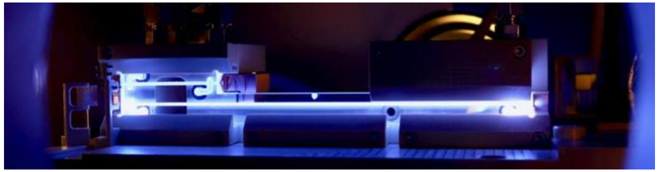
Accelerator science and technology (cont.):

*ii. Demonstration of **high-current multi-turn energy recovery** in linacs constitutes an important step towards power-efficient lepton accelerators for a broad range of applications and should be pursued.*

*iii. The **longer-term** development of advanced technologies, such as **high-gradient wakefield acceleration and those underpinning bright muon beams**, should be supported at an appropriate level.*
Synergies with the US initiative on muon collider R&D should be exploited.

PERLE at IJCLab





Plasma acceleration

Preliminary design of a muon cooling cell → Demonstrator

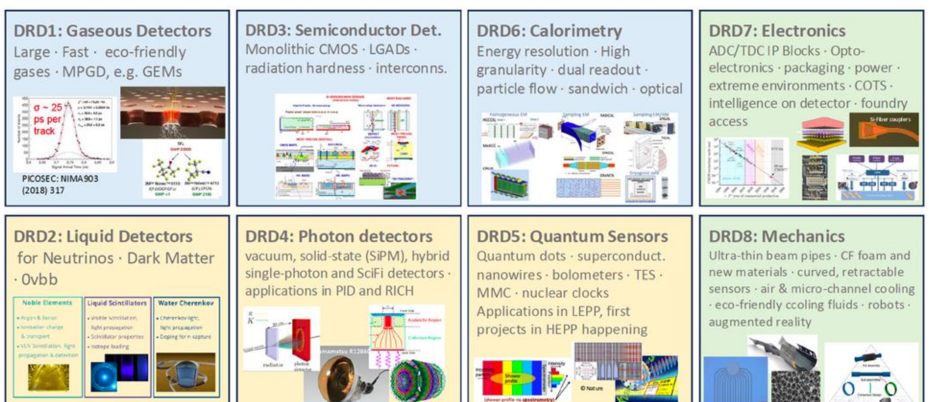
Technologies (cont.)

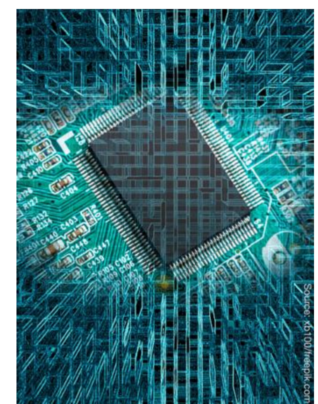
Detector development:

i. *For the **DRD collaborations** to address the requirements of future flagship projects, they **must receive adequate funding**. New R&D topics and initiatives should be integrated in the DRD scheme. The General Strategic Recommendations in the roadmap must be fully addressed by dedicated initiatives coordinated across the DRD collaborations.*

ii. *A coherent, strategic approach and sufficient resources to support **close cooperation with industry are required to address the rising costs and growing complexity in engineering, particularly in microelectronics.***

iii. *To enhance efficiency and align developments with global technology trends in other fields, standardised, off-the-shelf solutions should be prioritised over custom designs, where applicable.*





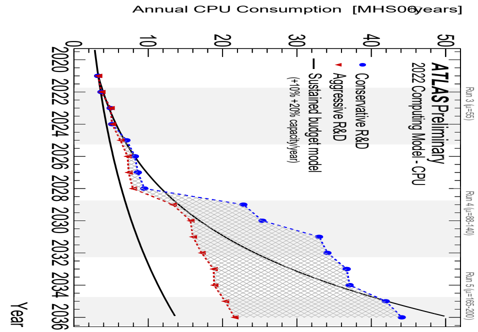
Technologies (cont.)

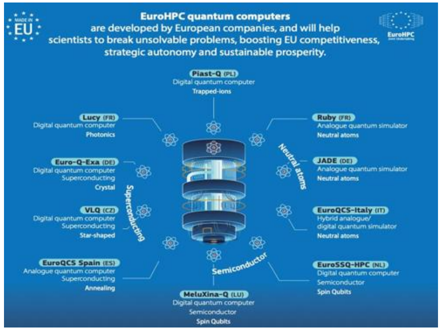
Computing:

i. ***Adequate and sustained support for and coordination of software and computing*** *must be provided to achieve the goals of future particle physics projects, starting with the HL-LHC.* ***Planning of future projects should include software and computing from the outset****, addressing energy efficiency and sustainability.*

ii. *In order to address theoretical and experimental needs, such as in lattice QCD, data-intensive workflows through WLCG and long-term data preservation and reinterpretation, the particle physics community should further engage with and* ***help shape the evolution of EuroHPC, AI factories and other global initiatives.***

iii. *The European particle physics community must further* ***intensify its activities in AI*** *and sustain them with adequate resources. A* ***roadmap****, coordinated among CERN and national laboratories, institutes and universities, should be developed* ***to prioritise AI activities*** *taking into account synergies with international partners and other communities.*





Technologies (cont.)

Knowledge and Technology Transfer (KTT):

*i. The European particle physics community should **reinforce KTT** as a pillar of basic research that enables its impact on society. Concepts and implementations for **bidirectional KTT should be an integral part of all particle physics projects**, including R&D collaborations.*

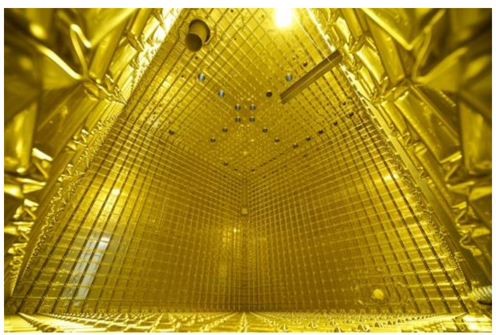
ESG Working Group 7 report

Other research directions in particle physics

i. ***European contributions to both accelerator-based and non-accelerator neutrino and dark matter experiments are essential and should be supported.***

ii. *CERN should continue to provide support to the global long-baseline neutrino programme via the Neutrino Platform. The collaboration between CERN and non-accelerator-based experiments on technologies of mutual benefit should be continued.*

iii. *The ecosystem of European particle physics laboratories should continue to support a broad, diverse spectrum of key precision experiments in particle physics.*



Large TPC, CERN Neutrino Platform

DM Xenon experiment
at Gran Sasso

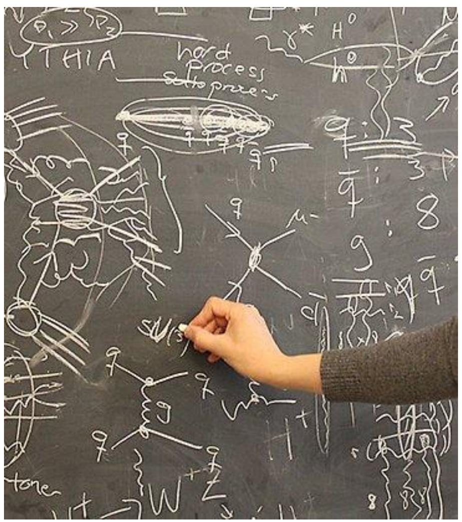
Mu3e integration run at PSI

ALPS experiment at DESY

Theory

i. ***Europe should maintain a strong and diverse particle theory landscape****, from formal to phenomenological aspects, while further strengthening and leveraging connections to neighbouring fields.*

ii. *Collaborative efforts to improve the precision of theoretical predictions should be recognised and supported. Europe is world-leading in these areas and should strive to remain so by attracting, fostering and retaining early-career global talent. CERN should continue to be an integral part of all these efforts.*



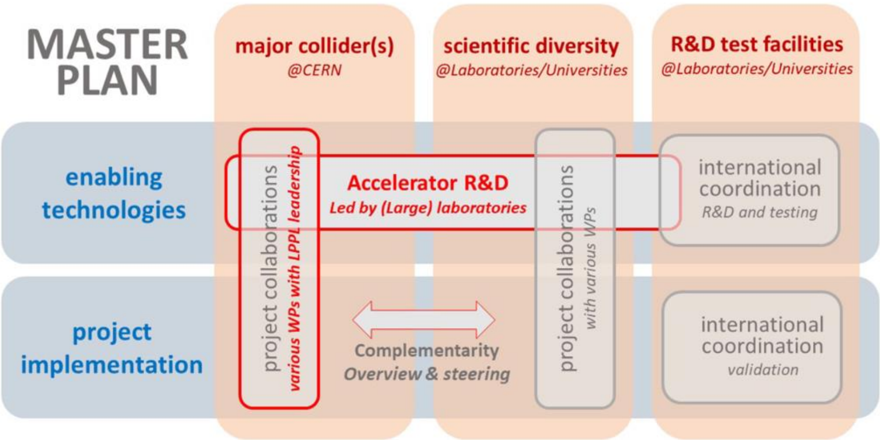
Project Implementation, cooperation with large Particle Physics Laboratories (PPLs) in Europe

i. *The next flagship collider at CERN should be developed under CERN's leadership, with coordinated in-kind contributions from the PPLs.* ***Collaboration between CERN and PPLs should be strengthened for strategic technology developments.***

ii. *The Large Particle Physics* ***Laboratory Directors Group (LDG) should explore the possibility for a new initiative to enable and strengthen the implementation and promotion of scientific diversity in particle physics with a shared European vision.***

iii. *The LDG must continue the coordination of the Accelerator R&D Roadmap by integrating strategic priorities, enhancing collaboration across PPLs and CERN, and by optimising usage of laboratory resources. In addition, R&D efforts to enhance the sustainability and energy efficiency of accelerators from design to operation and decommissioning should be supported.*

ESG Working Group 3 report

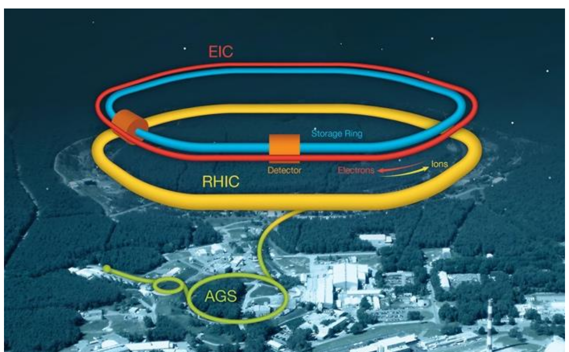


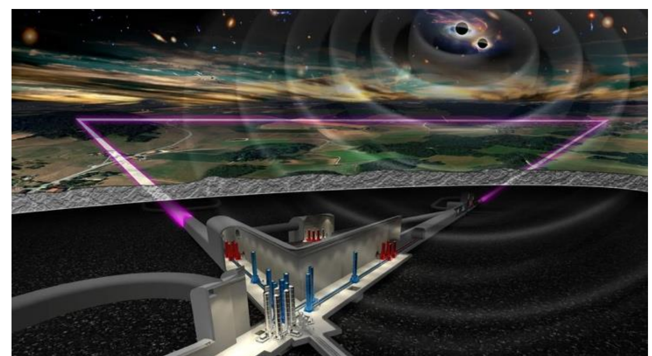
Synergies with neighbouring fields

i. *The European particle physics community, in coordination with APPEC and NuPECC, should maintain its scientific diversity via strong collaboration with nuclear and astroparticle laboratories and research infrastructures in Europe and beyond, including the Einstein Telescope in Europe and the Electron-Ion Collider in the US.*

ii. *CERN should continue its involvement in experimental nuclear physics and astroparticle physics at the current level. Consideration of additional experimental activities outside of CERN's accelerator-based particle physics programmes should be subject to adequate resources being available for CERN's primary mission.*

[ESG Working Group 4 report]





Sustainability and environmental impact

i. *For new proposed projects, a detailed life cycle assessment should be carried out at each stage, from concept to design and implementation, in order to quantify and minimise environmental impact.*

ii. *The particle physics community should continue and intensify its efforts to develop and adopt sustainable solutions.*

iii. *An effective balance between in-person and online meetings should be considered in order to mitigate the environmental impact of carbon-intensive travel.*

ESG Working Group 5 report

Domain	Value in reference year (2018)	Current status	Target for 2030
Scope 1 emissions (tCO_2e)	192 100	170 100 (2023)	➢ Reduce by 50% w.r.t. 2018
Electricity consumption (GWh)	1252	1142 (2023) 1290 (estimation 2024)	➢ Max 1500 ➢ 10% renewable
Gas consumption (GWh)	61 (average 2016-2018)	39 (2024)	➢ Reduce by 60% w.r.t. 2018

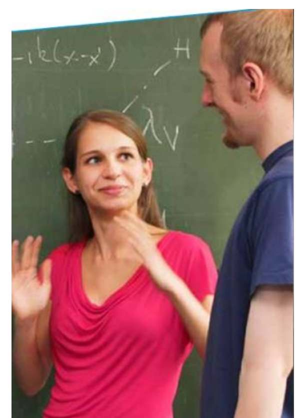
Public engagement, education, communication, social and career aspects

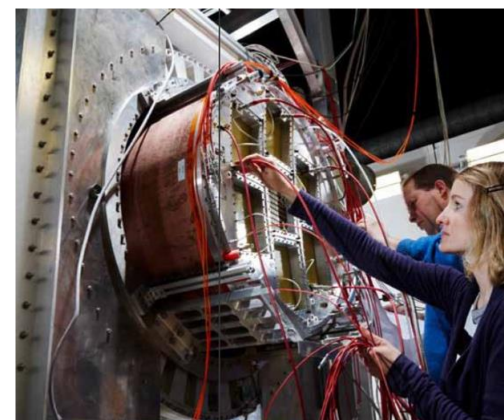
i. *Education, communication and engagement in particle physics should target a broad range of stakeholders, with a dedicated effort to reach diverse and underrepresented audiences.*

ii. *The many education, communication and outreach initiatives in the various European national communities, EPPCN, IPPOG and the Teacher and Student Forum should be further encouraged, integrated and supported by European institutions and CERN.*

iii. ***Dedicated European training programmes*** *in* ***accelerator science, computing and detector instrumentation,*** *including sustainability aspects as well as first-hand exposure to the latest technologies, should be further developed at the master and doctoral levels. The existing international schools in these areas should be strengthened to offer an expanded, coherent training programme.*

ESG Working Group 6 report





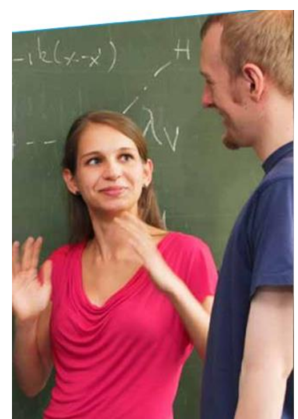
Public engagement, education, communication, social and career aspects

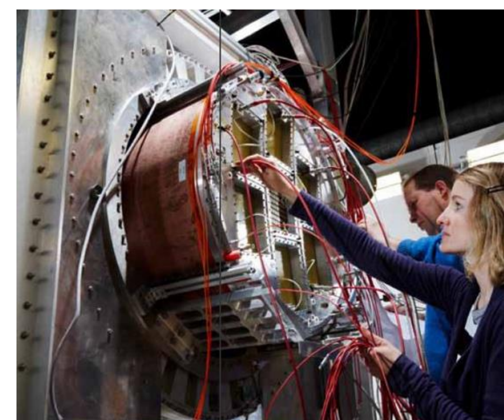
iv. *The community should actively promote the creation of **long-term positions for engineers and technicians**, as well as **physicists with technological expertise** in accelerators, detectors and computing. Two-way transfer of knowledge via mobility between industry and academia should also be encouraged.*

v. *The particle physics community should continue its unwavering commitment to place the principles of Equity, Diversity, and Inclusion (EDI) at the heart of all its activities.*

vi. *Current efforts for mentoring, easing mobility across institutions and promoting well-being of early-career researchers should be reinforced. In addition to scientific achievements, career evaluation should also consider technological, outreach and knowledge transfer activities.*

ESG Working Group 6 report





Overall Physics Assessment (Precision Physics)

Project	Higgs	EWPO	Top	Flavour	QCD (precision)	QCD (PDF + HIs)
HL-LHC	**State-of-the-art starting point at the end of HL-LHC**					
Lepton and *ep* Colliders						
FCC-ee	4	5	3	5	5	1
FCC-ee no-top	2	4	2	5	4	1
FCC-ee descoped	2	4	2	4	3	1
LEP3	2	4	2	4	3	1
LCF-250	2	3	2	1	2	1
CLIC-380	2	2*	3	1	2	1
LHeC	1	2	1	1	3	5
Mid-Energy Lepton Colliders						
LCF-550	4	4	4	1	2	1
LCF-1000	4	4	4	1	2	1
CLIC-1500	4	3*	4	1	2	1
CLIC-3000	4	3*	4	1	2	1
Energy frontier						
FCC-hh	3	No information		3	2	5
muC	4	3	5	3	1	2
Precision w/ energy						
LHeC + FCC-hh	3	2	2	3	4	5
LEP3 + FCC-hh	4	4	3	4	3	5
LEP3 + muC	4	5	5	4	3	2
LCF-1000 + muC	4	5	5	3	3	2
FCC-ee descoped + FCC-hh	4	4	3	4	4	5
FCC-ee + FCC-hh	5	5	5	5	5	5

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For CLIC, operations at the Z-pole are possible but not considered in the Briefing Book studies; such operations would strengthen its EWPO programme, as noted by the "" in the table, bringing its rank to the same level as the LCF project.*

Overall Physics Assessment (BSM Physics)

Project	Comp. H & V	SUSY (QCD)	SUSY (EW)	DM	Scalar Singlet	New forces	Portals
HL-LHC	**State-of-the-art starting point at the end of HL-LHC**						
Lepton and *ep* Colliders							
FCC-ee	4	3	2	2	4	4	4
FCC-ee no-top	3	3	2	2	3	4	4
FCC-ee descoped	2	2	2	2	3	3	3
LEP3	2	2	2	2	3	3	3
LCF-250	2	2	2	2	2	3	3
CLIC-380	2	2	2	2	2	3	3
LHeC	1	1	1	1	1	1	1
Mid-Energy Lepton colliders							
LCF-550	2	2	2	2	3	3	3
CLIC-1500	3	2	2	2	3	3	3
LCF-1000	3	2	2	2	3	4	3
CLIC-3000	4	3	3	3	4	4	3
Energy frontier							
FCC-hh	5	5	5	5	4	5	4
muC	5	4	5	5	5	5	4
Precision w/ energy							
LHeC+ FCC-hh	5	5	5	5	4	5	4
LEP3 + FCC-hh	5	5	5	5	4	5	4
LEP3 + muC	5	4	5	5	5	5	4
LCF + muC	5	4	5	5	5	5	4
FCC-ee descoped + FCC–hh	5	5	5	5	4	5	4
FCC-ee + FCC-hh	5	5	5	5	5	5	5

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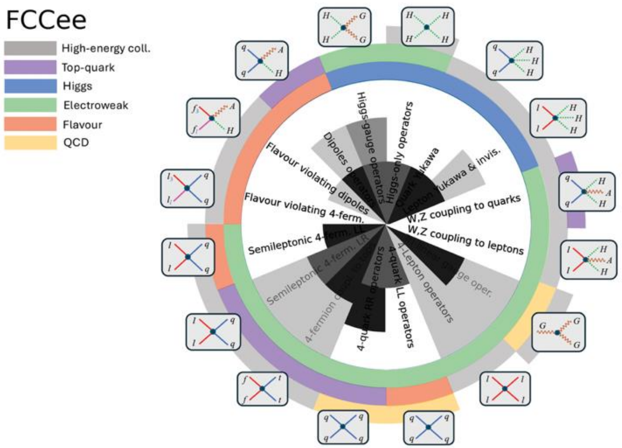
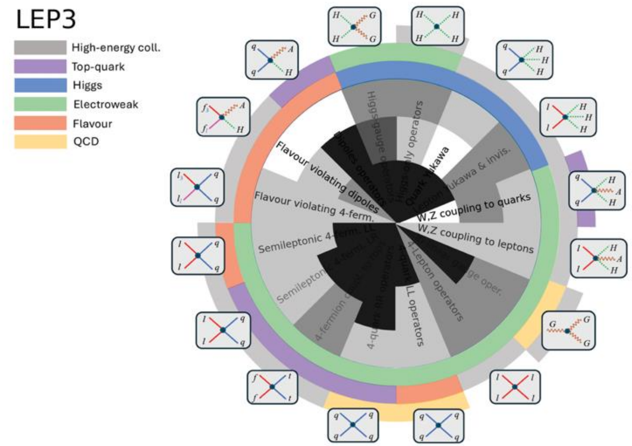
Coverage of first-stage e^+e^- colliders

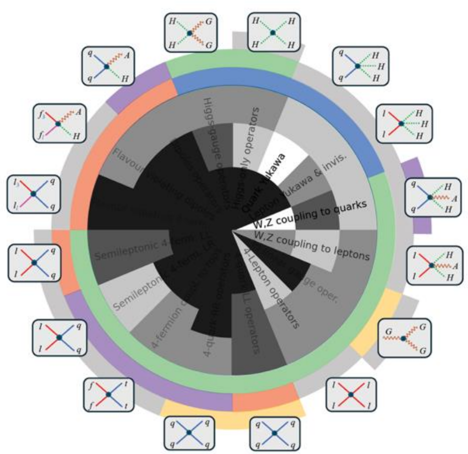
FCCee



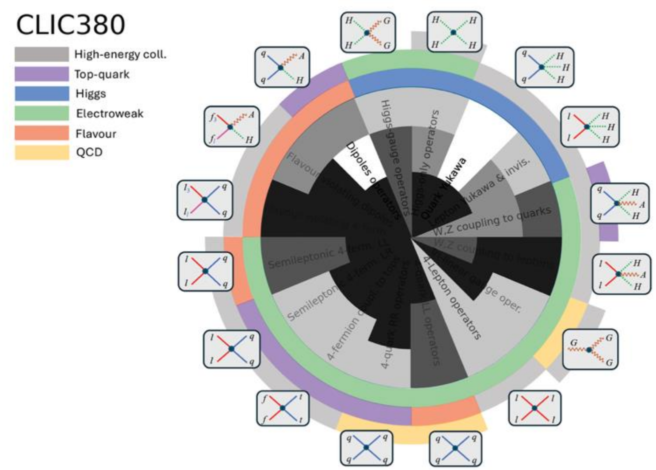
LEP3



LCF250



CLIC380



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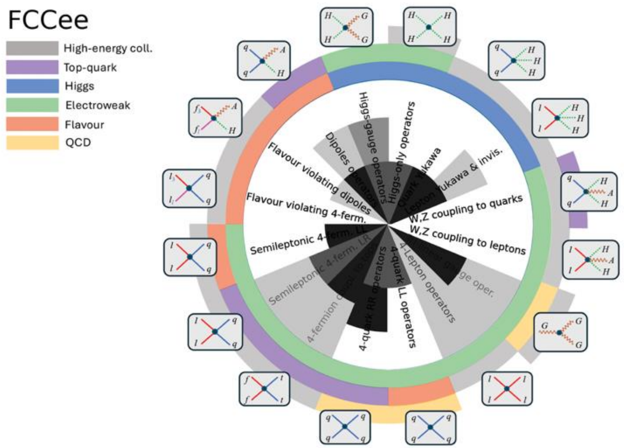
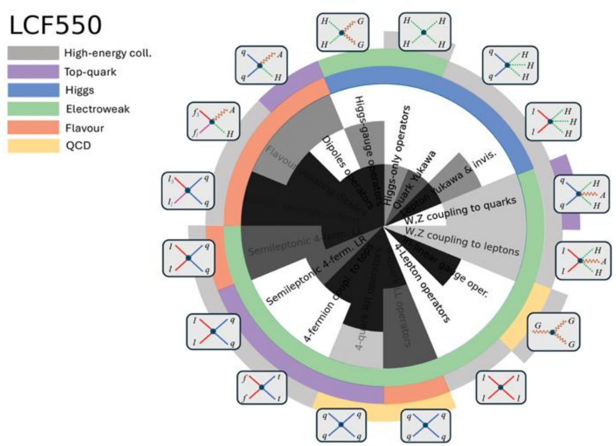
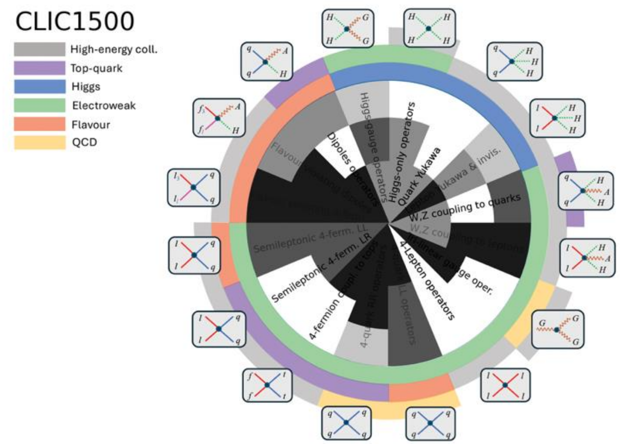
FCC-ee versus high-energy e^+e^- colliders







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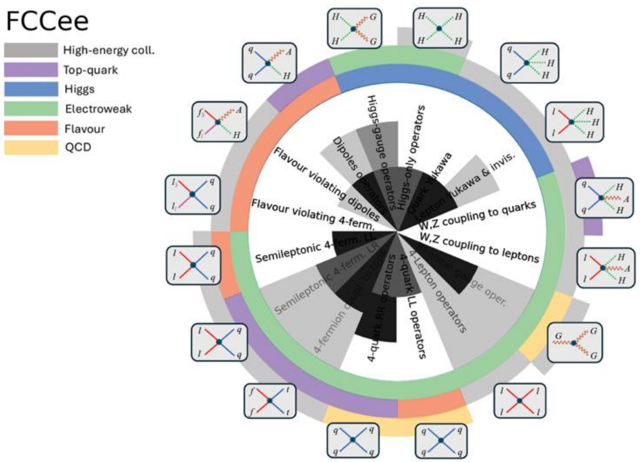
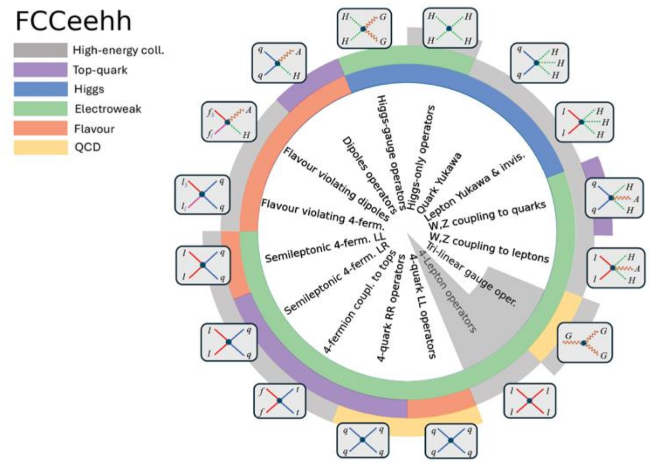
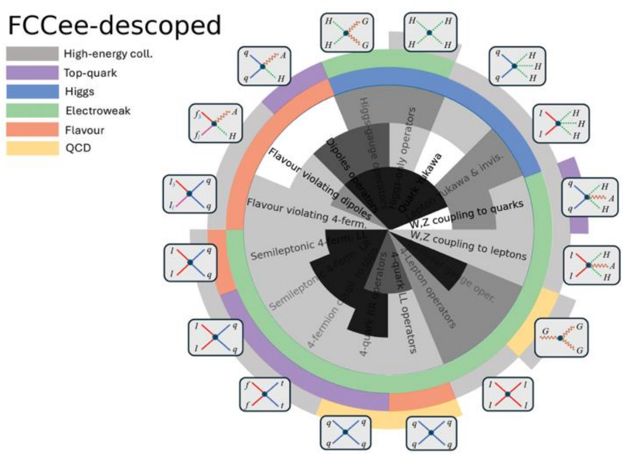
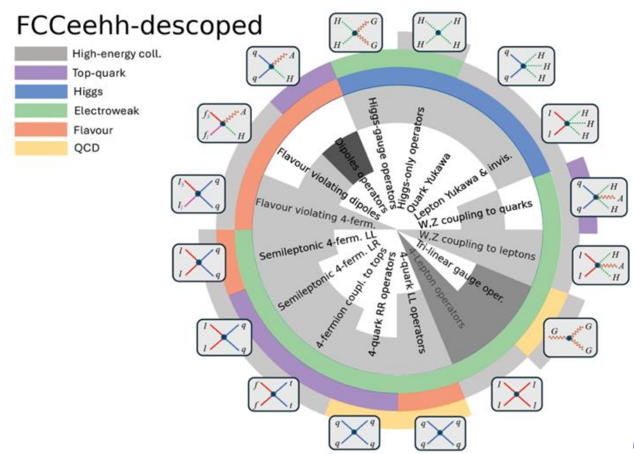
FCCeehh versus FCC-ee-descoped + FCChh









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