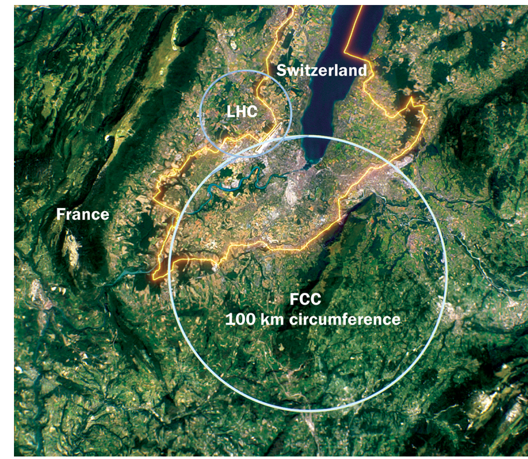
Towards a Future High-Energy Collider

- European Strategy Process on Particle Physics -



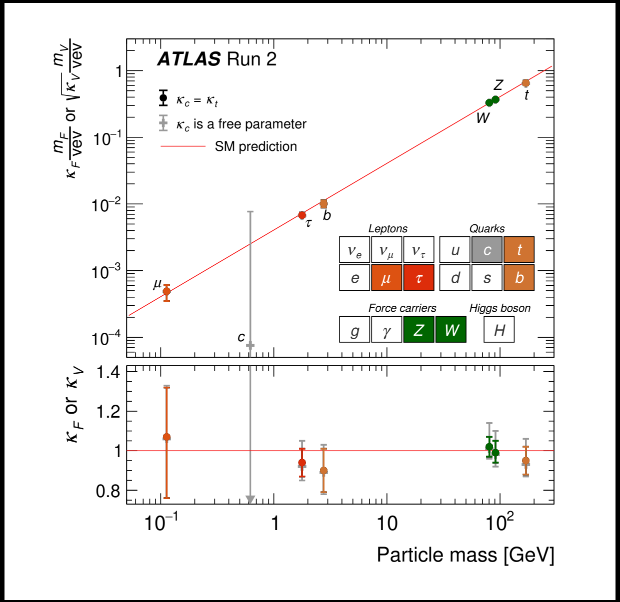
Karl Jakobs
University of Freiburg / Germany

Fermilab Colloquium
5th February 2025

Why do we need a new collider?
Where do we stand today?

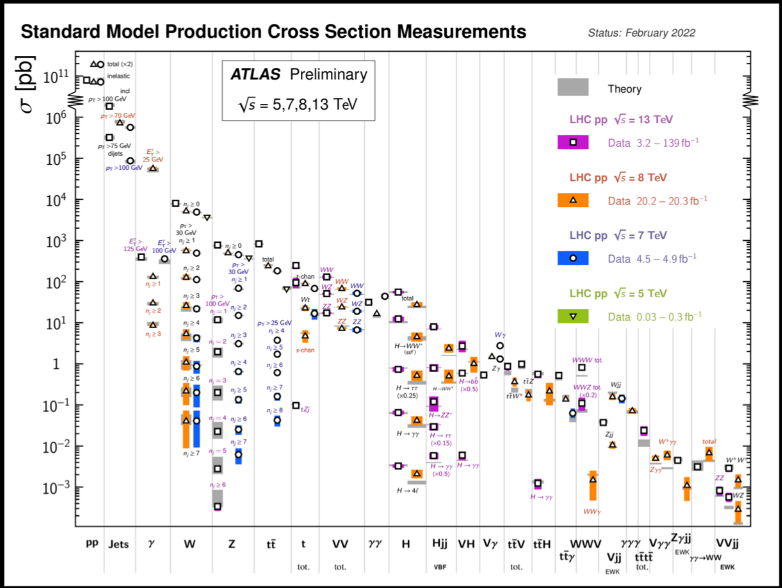
- The Higgs boson has been discovered

  → Last missing piece of the Standard Model

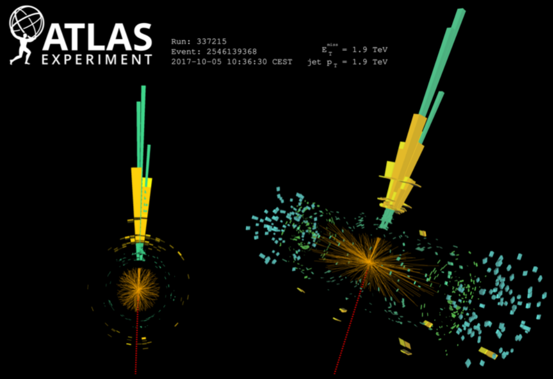


- Huge progress on exploring its properties over the past ~12 years (LHC Run 1 and Run 2)

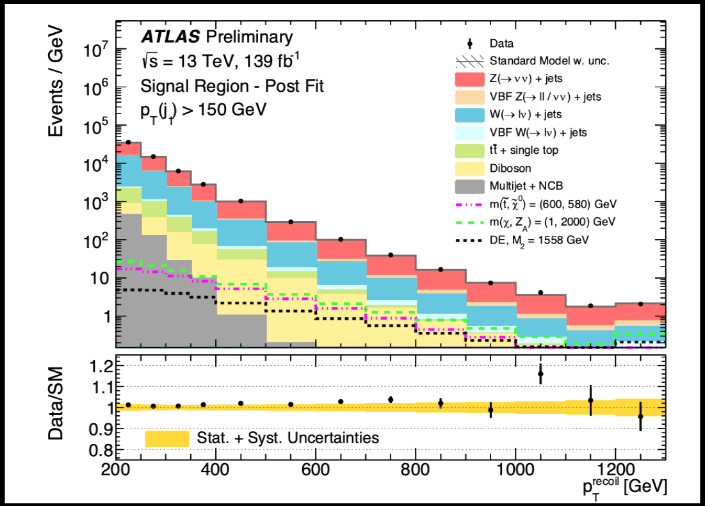
Standard Model predictions verified with high precision



Despite interesting events …



.. no indications of physics beyond the Standard Model



The Standard Model provides a successful description of the data

Triumph of experiment and theory

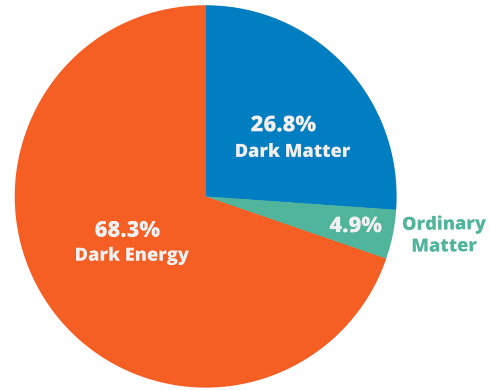
Huge progress as well on the theory side,
NNLO calculations (NNLO revolution!)

Important Open Questions

1. Mass

The Higgs boson exists!

- Does it have the predicted properties?
- Why is it so light? ("Hierarchy" or "naturalness" problem)
- Is it a fundamental particle or a composite scalar?

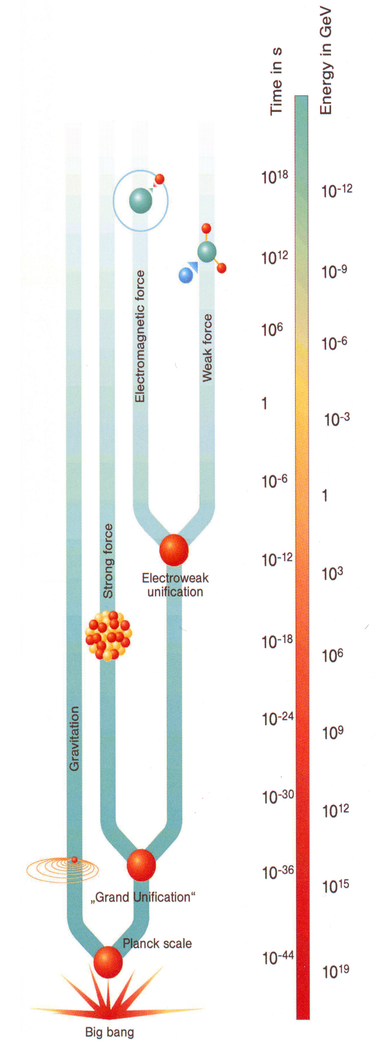


2. Unification

Can the different interactions be unified?
How can gravity be incorporated?
Why is gravity so weak?

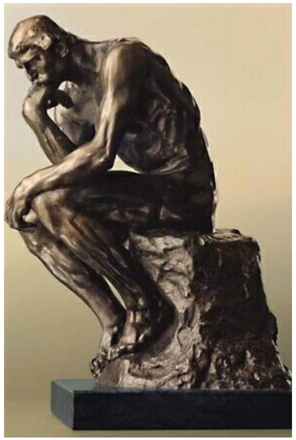
3. Structure and composition of matter

- Are there new forms of matter, e.g. supersymmetric particles?
- Are they responsible for the **Dark Matter in the Universe**?
- What is the origin of the **matter-antimatter asymmetry**?
- Why are there three families of fermions?
- What is the **origin of neutrino masses**?



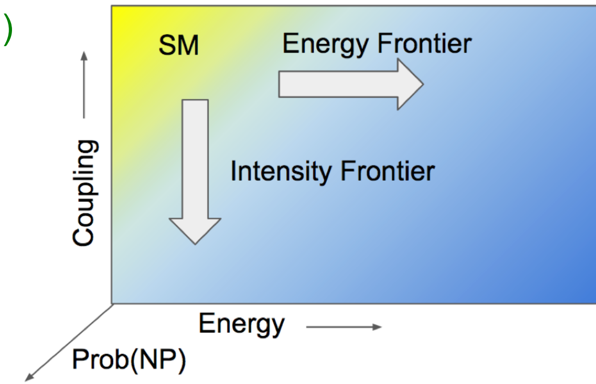
New physics required, but no clear indication of the energy scale

Towards the future



Energy Frontier → high-energy colliders remain essential;

In addition the **Intensity Frontier** needs to be explored
(e.g. search for Feebly Interacting Particles,
Neutral Heavy Leptons, Flavour anomalies,…)

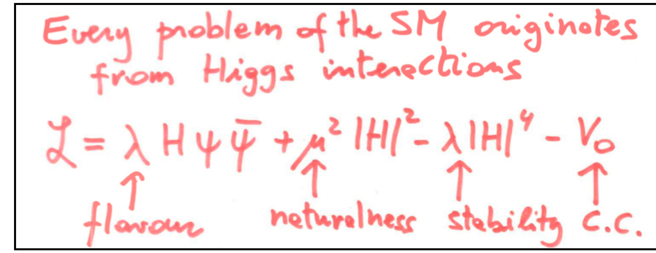


No strong guidance from theory

Experiments must show the way!

Understanding the **Higgs Sector** is vital:
the Higgs particle is not just "another particle"

- Profoundly different from all elementary particles discovered so far;
- The only spin-0 particle; carries a different type of "force";
- Related to the most obscure sector of the Standard Model
- Linked to some of the deepest structural questions
  (flavour, naturalness, vacuum, …)



G. Giudice, CERN

→ It provides a unique door into new physics,
… and calls for a very broad and challenging experimental programme

- Precision measurements of couplings (as many generations as possible, decays via loops, …)
- Higgs boson self coupling → Higgs potential
- Forbidden, rare and exotics decays, e.g. $H \to \tau \mu$ → flavour structure and source of fermion masses
- Other Higgs boson properties (CP admixture?)
- Probe of compositeness
- Search for additional Higgs bosons

The outstanding questions are compelling, difficult and interrelated

→ They can only be successfully addressed through a **variety of approaches**

- Particle colliders
- Dark matter direct and indirect searches
- Neutrino experiments
- Cosmic surveys
- Measurements of rare processes
- Dedicated searches (e.g. axions, dark-sector particles, feebly interacting particles, …)

Fabiola Gianotti, LHCP Conference 2021

	High-E colliders	Dedicated high-precision experiments	Neutrino experiments	Dedicated searches	Cosmic surveys
H, EWSB	x	x		x	
Neutrinos	x (ν_R)		x	x	x
Dark Matter	x			x	x
Flavour, CP, matter/antimatter	x	x	x	x	x
New particles, forces, symmetries	x	x		x	
Universe acceleration					x

High-energy accelerators are one of the best tools for exploration; unique in studying the Higgs boson

Needed: Precision + Energy

(1) Scientific diversity, and the **combination of complementary approaches**, are crucial to explore directly and indirectly the largest range of energy scales and couplings, and to properly interpret signs of new physics to reach the goal to build a coherent picture of the underlying theory

(2) Global coordination and optimisation of the particle physics programme is necessary to maximise the opportunities of the field, given the exciting physics questions, the cost and complexity of the projects

2020 Update of the European Strategy for Particle Physics

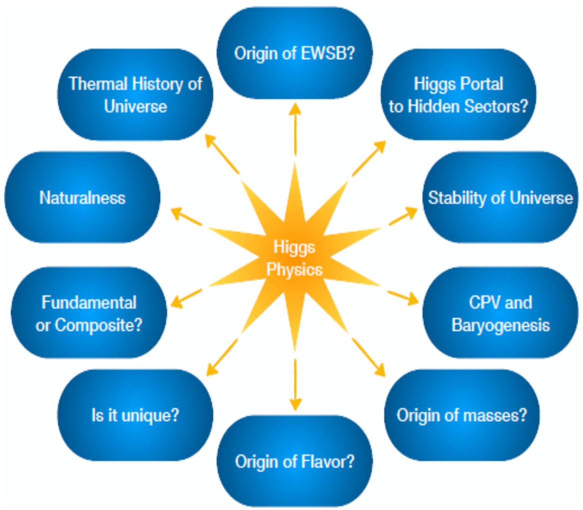
- *An **electron–positron Higgs factory is the highest-priority next collider**. For the **longer term**, the European particle physics community has the ambition to **operate a proton–proton collider at the highest achievable energy**.*

- *The particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that **for high-field superconducting magnets, including high-temperature superconductors.***

- *Europe, together with its international partners, should investigate the technical and financial **feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV** and with an electron–positron Higgs and electroweak factory as a possible first stage. Such a **feasibility study** of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

US Snowmass process (2022)

- **e⁺e⁻ Higgs factory as highest priority** next collider

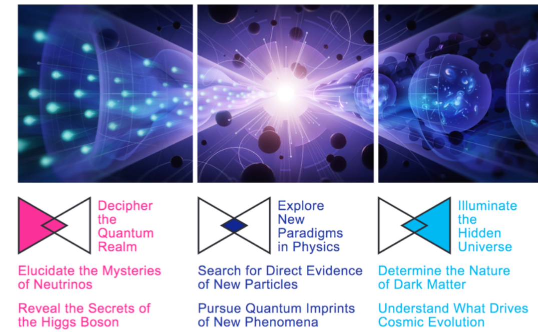


arXiv:2209.07510

- In addition: prioritisation of the **HL-LHC physics** exploitation programme and R&D towards a **TeV-scale Muon Collider**

Snowmass Summary Report

Conclusions of US P5 process (2023)



- *In the area of colliders, the panel **endorses an off-shore Higgs factory**, located in either Europe or Japan, to advance studies of the Higgs boson following the HL-LHC while maintaining a healthy on-shore particle physics program.*

- *The panel recommends dedicated R&D to explore a suite of promising future projects. One of the most ambitious is a future collider concept: a **10 TeV parton center-of-momentum (pCM) collider to search for direct evidence and quantum imprints of new physics at unprecedented energies.***

- *… we recommend **targeted collider R&D to establish the feasibility of a 10 TeV pCM muon collider**.*

European Strategy for Particle Physics: 2026 Update

Remit of the European Strategy Group (ESG)

- *In June 2024, the CERN Council established and approved the* ***remit of the European Strategy Group***

  "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 ESG should take into consideration:
  - The **input of the particle physics community;**
  - The **status of implementation of the 2020 Strategy update**;
  - The **accomplishments over recent years**, including the results from the LHC and other experiments and facilities worldwide, the progress in the construction of the High-Luminosity LHC, the outcome of the Future Circular Collider Feasibility Study, and recent technological developments in accelerator, detector and computing;
  - **The international landscape of 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.*

Expected input on baseline and alternative scenarios

- **FCC integrated programme:** Input via FCC Feasibility Study final report

  (technical feasibility, physics potential, environmental impact, …, update on the financial feasibility)
  In addition: reports from review committees will appear later in 2025

- **Lower-energy hadron collider:** Two important inputs are needed:

  (i) When will HFM magnets, e.g. accelerator magnets of 12 T or 14 T, become available?
  What technology? What price tag? Required R&D? To what extent can the timeline be accelerated?
  Input from → LDG + HFM Collaboration (Accelerator Roadmap) + international experts(?)

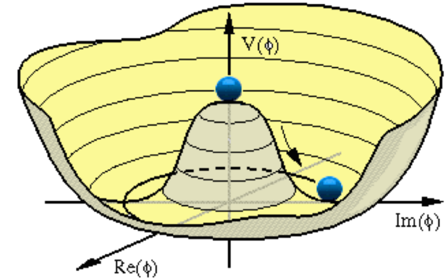
  (ii) Physics potential of a 91 km hadron collider with 12 or 14 T magnets (or lower);
  → plan to include it in FCC Feasibility Study report

- Linear Collider at CERN
- Muon Collider at CERN
- Extended LHC / LHeC physics programme

} Input will be prepared by respective communities

- Re-use of LEP/LHC ring for e^+e^- collisions
- ….

Guidelines for Input by large-scale projects



What do we know about the Higgs boson today?

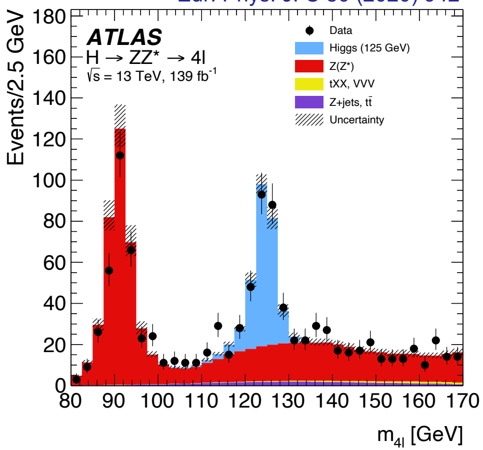
Where do we want to go?

and how?

LHC results on Higgs boson decays to bosons and fermions

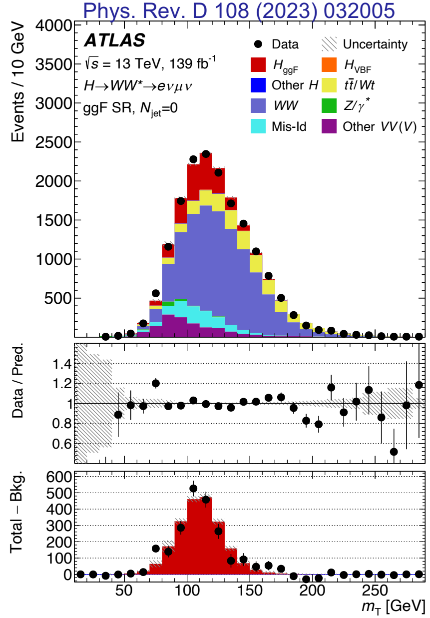
H → ZZ* → ℓℓ ℓℓ

Eur. Phys. J. C 80 (2020) 942

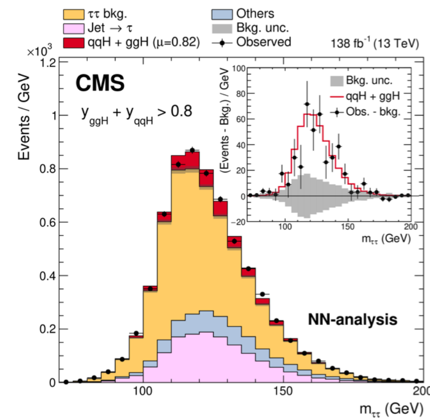


H → WW* → ℓν ℓν

Phys. Rev. D 108 (2023) 032005

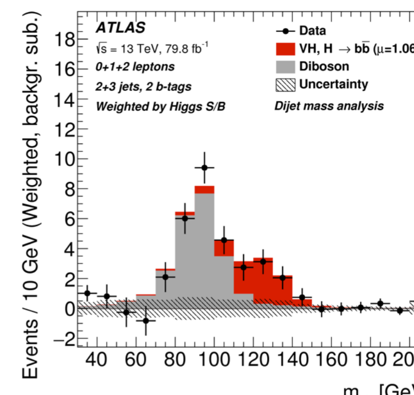


$H \rightarrow \tau\tau$



arXiv:2204.12957

$H \rightarrow b\bar{b}$



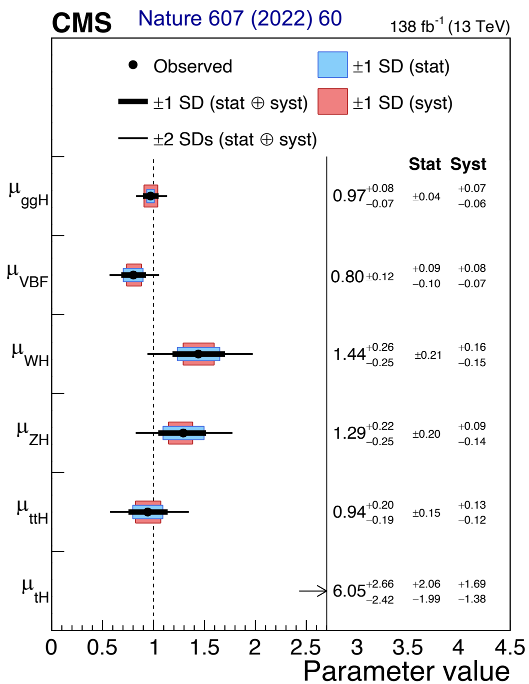
Phys. Lett. B786 (2018) 59

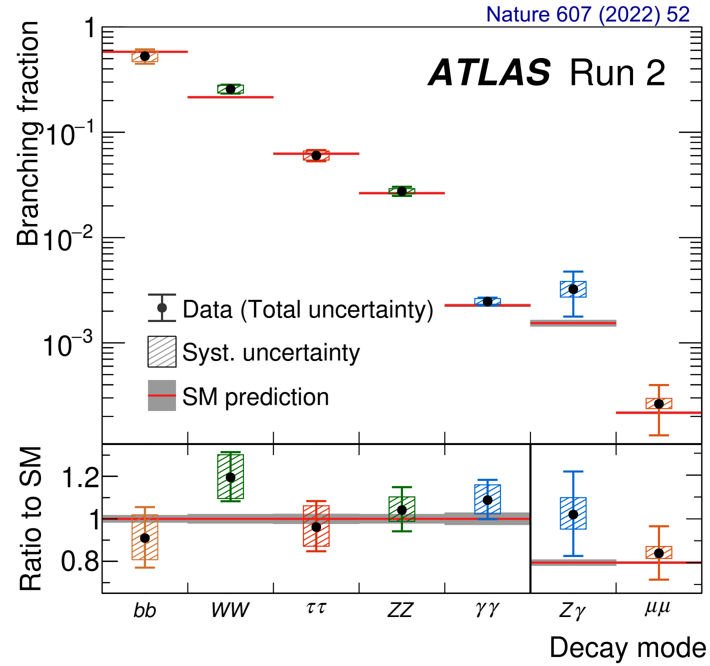
(i) Signal strengths for the different production channels

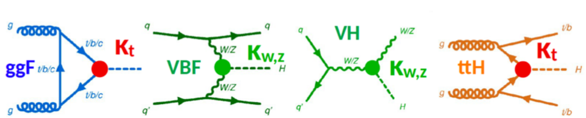
Yields (σ x BR), assuming SM branching ratios; (SM: μ = 1.0)

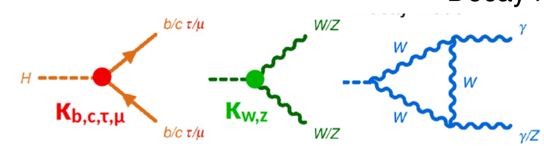
(ii) Branching fractions for the different decay modes

Assuming SM values for the production cross sections; (SM: μ = 1.0)





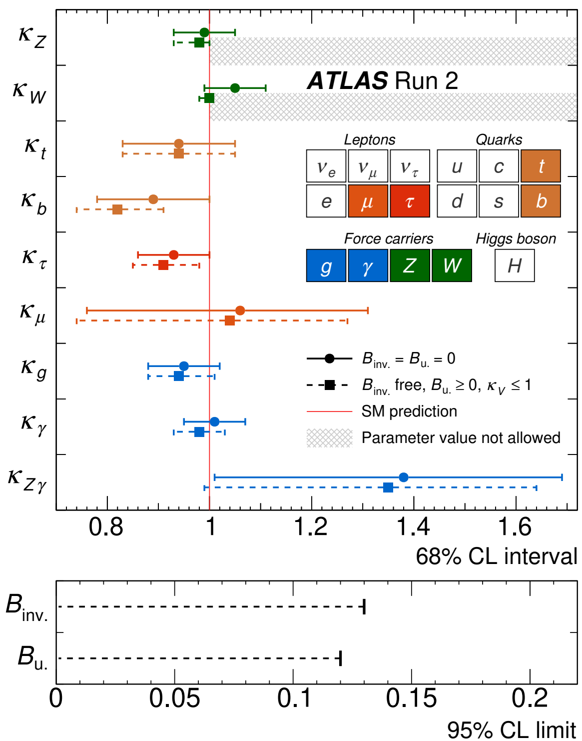




Excellent agreement of the SM predictions with the measurements of all production and decay processes in both experiments

(iii) Interpretation in the κ framework

*Introduce **coupling scale factors κ** for each particle, including effective photon and gluon couplings*



No BSM contributions
($B_{inv} = B_{undet} = 0$)

B_{inv} and B_{undet} added as free parameters with constraints $\kappa_W \leq 1$ and $\kappa_Z \leq 1$

Cross section times branching fraction of an individual channel σ(i → H → f) contributing to a measured signal yield:

$$\sigma_i \times B_f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma_f(\boldsymbol{\kappa})}{\Gamma_H}$$

Definition of coupling strength modifier: $\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}}$ or $\kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}$

Scale factor of Higgs boson width: $\kappa_H^2(\boldsymbol{\kappa}, B_{i.}, B_{u.}) = \frac{\sum_j B_j^{SM} \kappa_j^2}{(1 - B_{i.} - B_{u.})}$

Branching ratio of Higgs into invisible particles can also be constrained

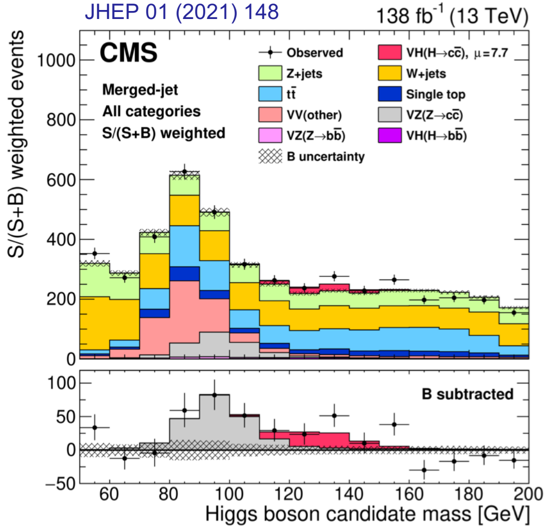
(VBF H → invisible, global fit)

Yukawa couplings of the 2nd generation?

$H \to c\bar{c}$?

- Even much more challenging! Search for associated production, with a leptonically decaying W/Z
- Novel charm jet identification and analysis methods using machine learning techniques
- Analysis is validated by searching for $Z \to c\bar{c}$ in VZ events (first observation, 5.7σ)

JHEP 01 (2021) 148



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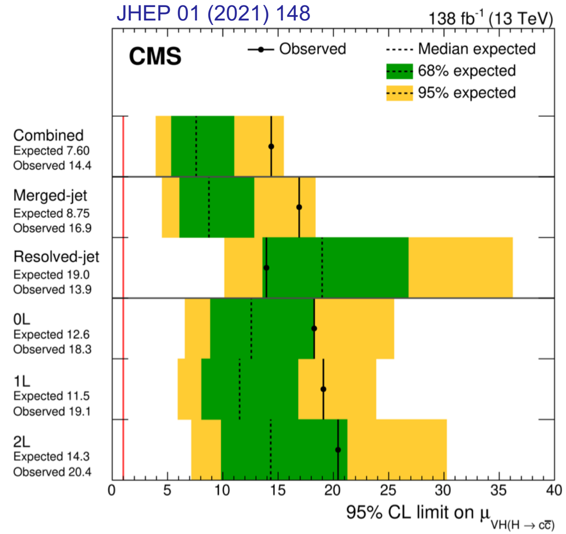


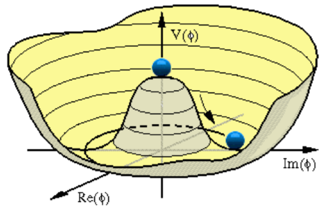
(strong contribution from "boosted" analysis, limit from combination)

Limit on signal strength: CMS: $\mu = \sigma_{obs} / \sigma_{SM}$ < 14 (expected 7.6)

ATLAS: $\mu = \sigma_{obs} / \sigma_{SM}$ < 11.5 (expected 10.6) [arXiv:2410.19611]

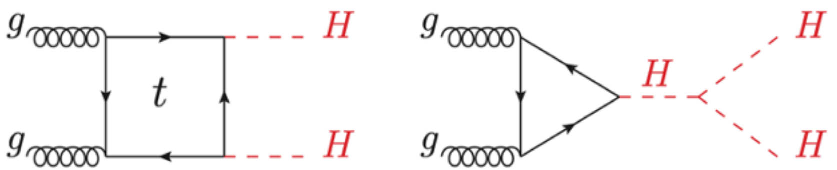
Run 3 and beyond essential to increase sensitivity

Higgs boson self coupling



- The missing piece!
  A key milestone for the High-Luminosity phase of the LHC (HL-LHC)

- Requires the measurement of di-Higgs boson production

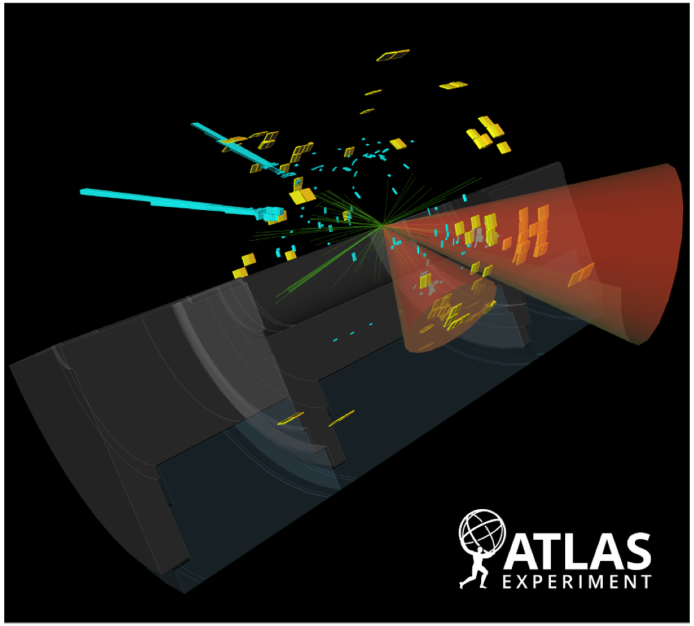


- Very small cross sections!
  - 1000 times smaller than for Higgs production
  - In addition, for self-coupling measurement, large di-Higgs continuum background!

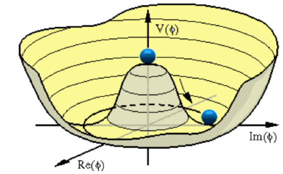
- Multiple channels investigated;

Promising: $HH \rightarrow b\bar{b}\,\tau\tau,\ \ b\bar{b}\,\gamma\gamma$

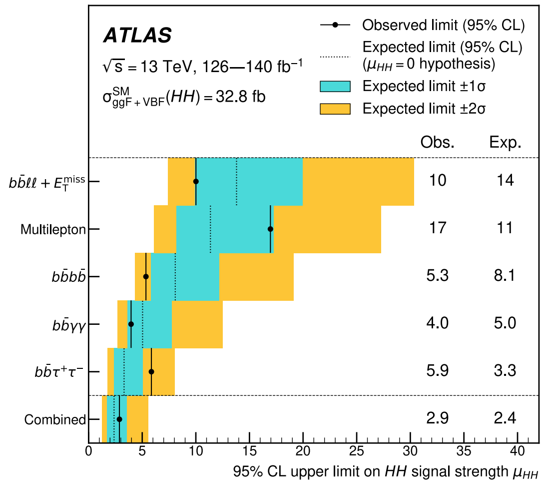
… already interesting constraints obtained with present data!

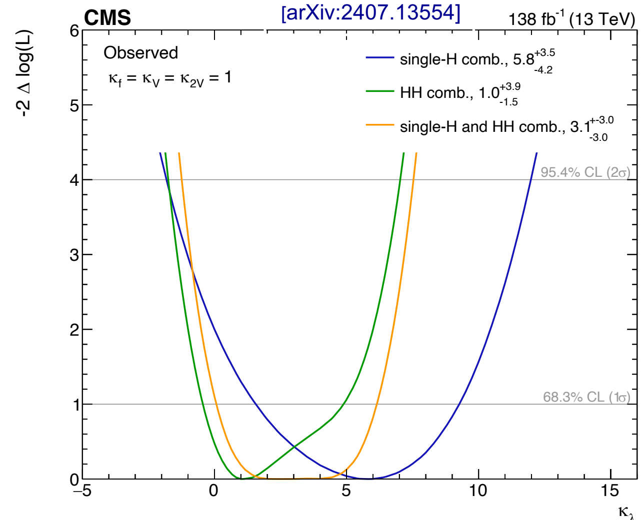


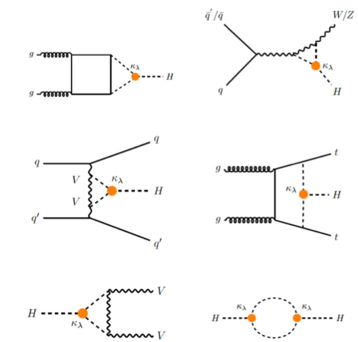
Higgs boson self coupling



Phys. Rev. Lett. 133 (2024) 101801 [arXiv:2406.09971]







κ_λ dependent NLO corrections to the main single Higgs production

- ATLAS and CMS combinations of various search channels
- Observed constraint on trilinear coupling: ATLAS: $-1.2 < \kappa_\lambda < 7.2$ (95% C.L.) (expected: $-1.6 < \kappa_\lambda < 7.2$)
  CMS: $-1.2 < \kappa_\lambda < 7.5$ (95% C.L.) (expected: $-2.0 < \kappa_\lambda < 7.7$)
  $-1.4 < \kappa_\lambda < 7.8$ (95% C.L.) (without SM assumption on other couplings)
- Major and exciting challenge for Run 3 (i.e. now), and for the HL-LHC
  (more data, two experiments to be combined, …)

The near future: High-Luminosity LHC

Recently changed schedule:

- Run 3 extended until June 2026
- Start of Run 4 in June 2030
- End of HL-LHC running remains at 2041

→ Increase of integrated luminosity by factor of ~ 20 (w.r.t. Run 2) (→ 3000 fb^{-1})

Major focus: - **Higgs boson**

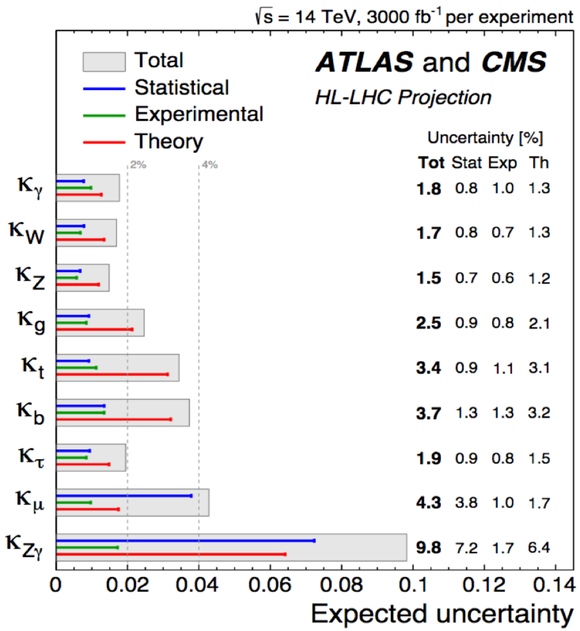
more precise measurements, rare decays, differential cross sections, EFT interpretations, Higgs self coupling, …)

- **Direct searches for new physics**

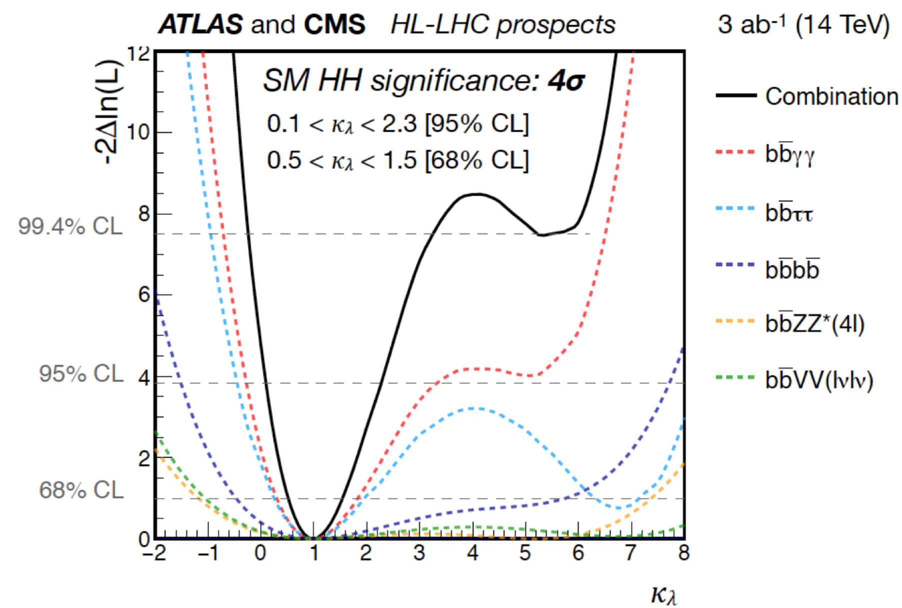
more exotic scenarios, e.g. long life times

Expected HL-LHC sensitivity: Higgs

Precision on Higgs coupling strength modifiers κ_i
(assuming no BSM particles in Higgs boson decays)



Higgs boson self-coupling?



HL-LHC:

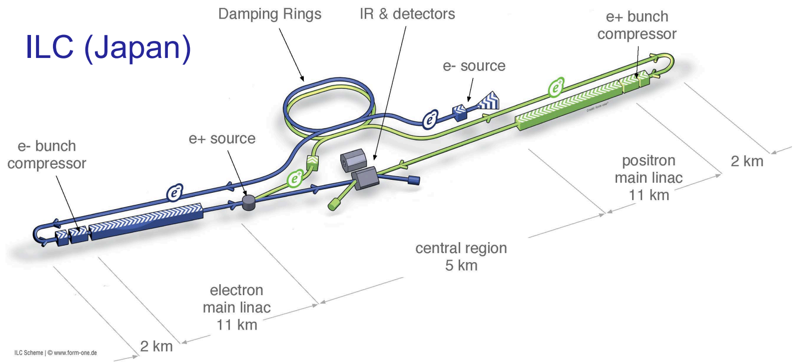
- Very significant improvement of the precision on the Higgs boson couplings (reach level of few %)
- First sensitivity on the Higgs boson self coupling (±50% uncertainty) *(conservative, will be updated based on present ATLAS and CMS performance)*

A future e^+e^- Higgs Factory

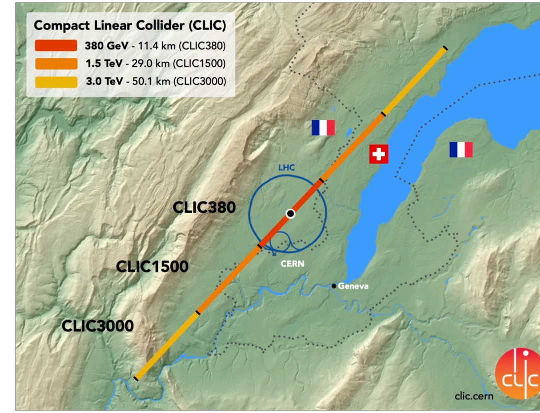
High-energy e$^+$e$^-$ collider projects

Linear Colliders

ILC (Japan)

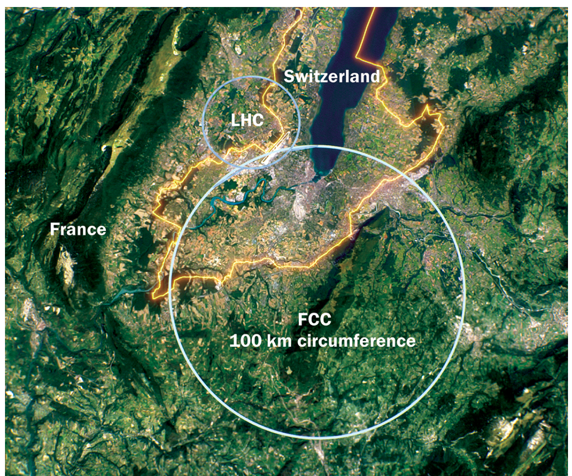


CLIC (CERN)

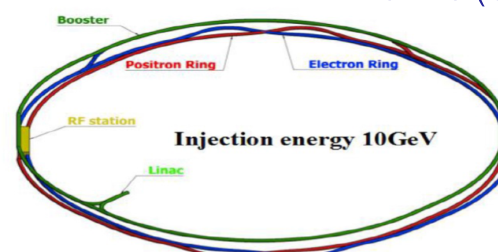


Circular Colliders

FCC (CERN)



CEPC (China)



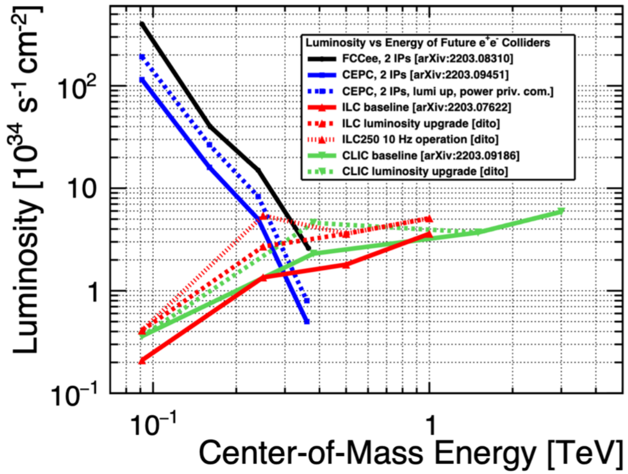
The same rings could be used in a second stage to host a ~100 TeV pp collider

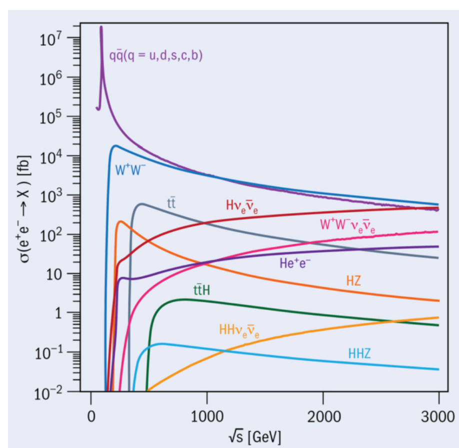
Circular or linear e^+e^- collider?

Circular e^+e^- colliders

- FCC-ee, CEPC
- Circumference: 90 - 100 km
- High luminosity & power efficiency at **low energies;**
  → huge rates at Z pole (table below)
- Less luminosity at higher E_{CM}
  (synchrotron radiation)
- Multiple interaction regions
- Very clean: little beamstrahlung

per detector in e^+e^-	# Z	# B	# τ	# charm	# WW
LEP	4 x 10^6	1 x 10^6	3 x 10^5	1 x 10^6	2 x 10^4
SuperKEKB	-	10^{11}	10^{11}	10^{11}	-
FCC-ee	2.5 x 10^{12}	7.5 x 10^{11}	2 x 10^{11}	6 x 10^{11}	1.5 x 10^8





Linear e^+e^- colliders

- ILC, CLIC
- Length
  ILC: 250 GeV – 1 TeV: 20.5 → 40 km
  CLIC: 380 GeV – 3 TeV: 11.4 → 50 km
- High luminosity & power efficiency at **high energies;**
- **Longitudinally spin-polarised beams**
- Long-term energy upgrades possible

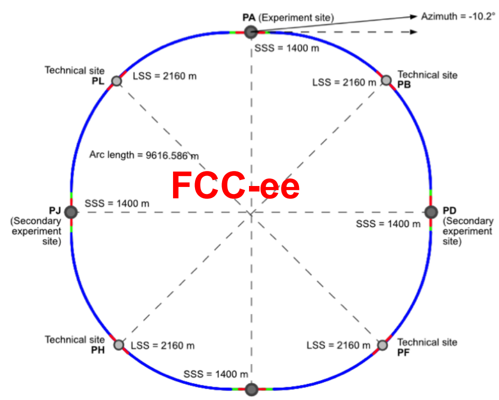
  - longer tunnel, same technology
    and/or
  - replacing accelerating structure with advanced technologies
    (RF cavities with higher gradients, plasma acceleration?)

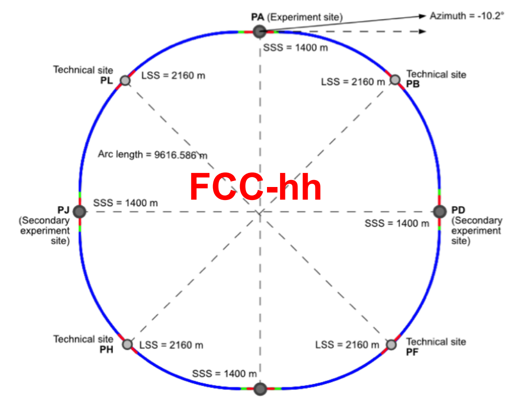
FCC integrated programme

Comprehensive long-term programme maximising physics opportunities:

- Stage 1: FCC-ee : e^+e^- Higgs, electroweak & top factory at highest luminosities [91 GeV → 365 GeV]
  Build on large progress made at circular e^+e^- colliders over the past decades → reach luminosities beyond 10^{34} cm^{-2} s^{-1}
- Stage 2: FCC-hh : 100 TeV pp collider, energy frontier machine (in addition: eh and ion options)

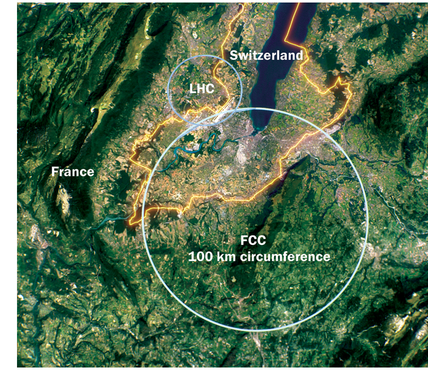
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC project start is coupled to HL-LHC programme → start operation of FCC-ee around 2048;
  can be accelerated if more resources available





2029 - 2041 | 2048 - 2063 | 2074 -

FCC Feasibility Study



- Demonstration of the **geological, technical, environmental and administrative feasibility** of the **tunnel and surface areas** and optimisation of the **placement and layout of the ring** and related infrastructure.

- Pursuit, together with the **Host States**, of the **preparatory administrative processes** required for a potential project approval.

- Optimisation of the **design of FCC-ee and FCC-hh colliders** and their injector chains, supported by **R&D to develop the needed key technologies**.

- Elaboration of a **sustainable operational model** for the colliders and experiments in terms of **human and financial resource** needs, as well as **environmental aspects** and **energy efficiency**.

- Development of a **consolidated cost estimate**, as well as the **funding and organisational models** needed to enable the project's technical design completion, implementation and operation.

- **Identification of substantial resources from outside CERN's Budget** for the implementation of the first stage of a possible future project (tunnel and FCC-ee).

- Consolidation of the **physics case** and **detector concepts** and technologies **for both colliders**.

Feasibility Study funded from CERN budget: 100 MCHF total over 5 years; in addition: ~ 20 MCHF/year for high-field magnet R&D;
Additional funding from the European Commission and collaborating institutes (e.g. CHART collaboration with Switzerland)

FCC Feasibility Study

Mid-term report presented at the end of 2023

- *The scientific and technical results have been reviewed by the* ***FCC Scientific Advisory Committee (A. Parker et al.)***

- *The cost and financial feasibility, which will focus on the first-stage project (tunnel, technical infrastructure, FCC-ee machine and injectors), has been reviewed by a* ***Cost Review Committee (N. Holtkamp et al.)*** *including external experts.*

See also CERN presentation on 13 Feb 2024: https://indico.cern.ch/event/1379648

Future Circular Collider
Midterm Report

February 2024

Edited by:
B. Auchmann, W. Bartmann, M. Benedikt, J.P. Burnet, P. Craievich, M. Giovannozzi, C. Grojean, J. Gutleber, K. Hanke, P. Janot, M. Mangano, J. Osborne, J. Poole, T. Raubenheimer, T. Watson, F. Zimmermann

This project has received funding under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.

This document has been produced by the organisations participating in the FCC feasibility study. The studies and technical concepts presented here do not represent an agreement or commitment of any of CERN's Member States or of the European Union for the construction and operation of an extension to CERN's existing research infrastructures.
The midterm report of the FCC Feasibility Study reflects work in progress and should therefore not be propagated to people who do not have direct access to this document.

→ Very successful, excellent progress on the technical side - no showstoppers identified for an FCC-ee as a first stage of an integrated FCC programme

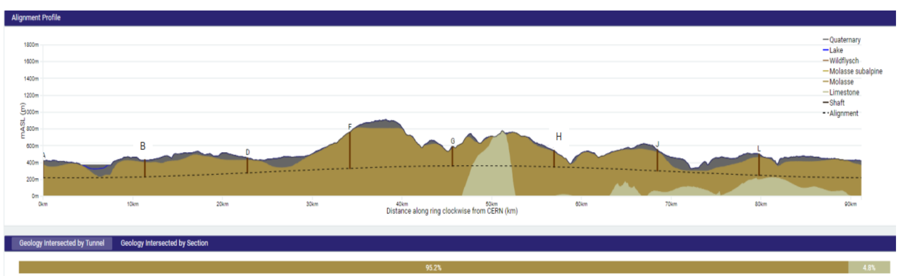
Optimised FCC layout (used for further feasibility studies)

- Layout converged on an optimised placement, chosen out of ~ 100 initial variants;

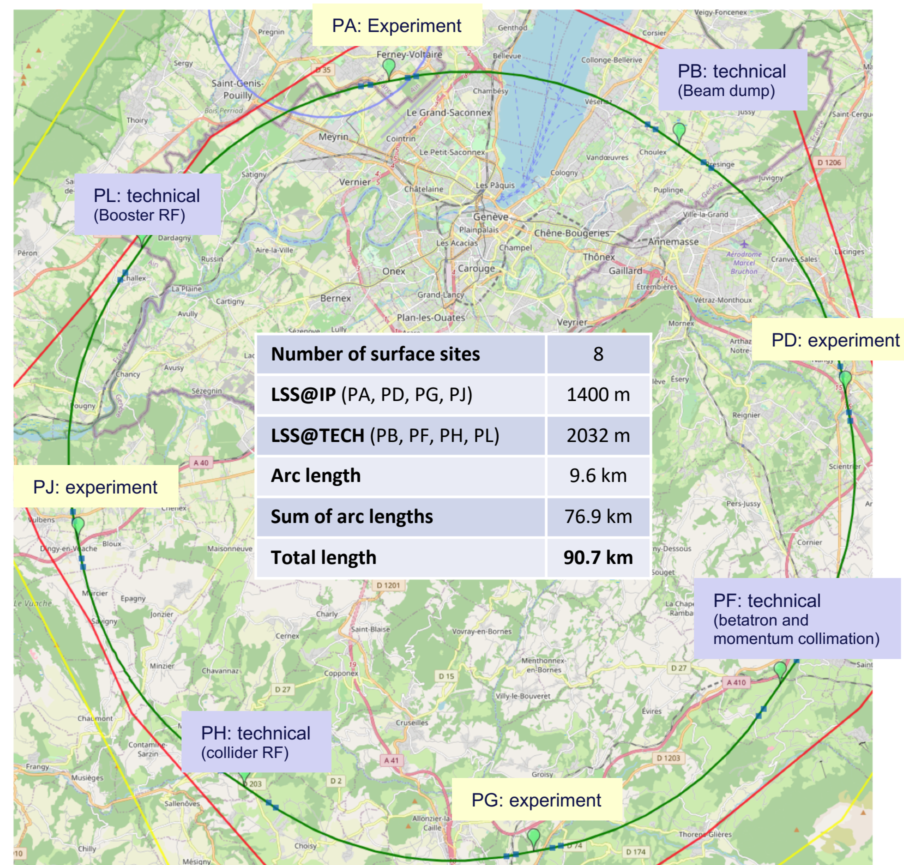
  (based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine perf.** etc.)

- 90.7 km ring, 4-fold symmetry
  8 surface points, 2 - 4 experiments

  Whole project now adapted to this placement



95% in molasse geology → minimising tunnel construction risk



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

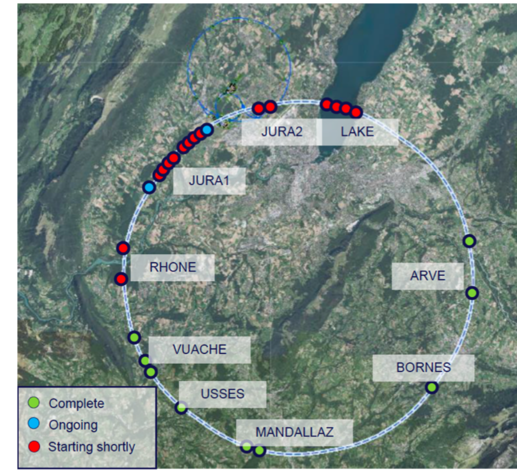
FCC Feasibility Study

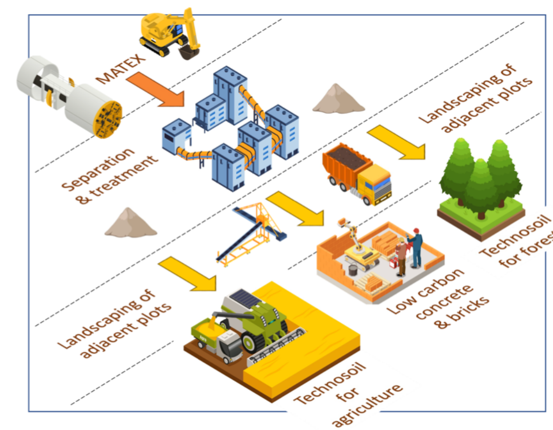
FUTURE CIRCULAR COLLIDER

Focus 2024 - 2025:

- Subsurface investigations, further optimization of implementation
- Design iteration (technical and cost optimisation)
- Reduction of cost uncertainties, development of risk register
- Further development of an affordable funding model and related governance implications (with Council)
- Environmental impact (civil engineering, excavated materials, sustainability); geological investigations

→ Completion of the FCC Feasibility Study in 2025 (submission to the European Strategy Update)

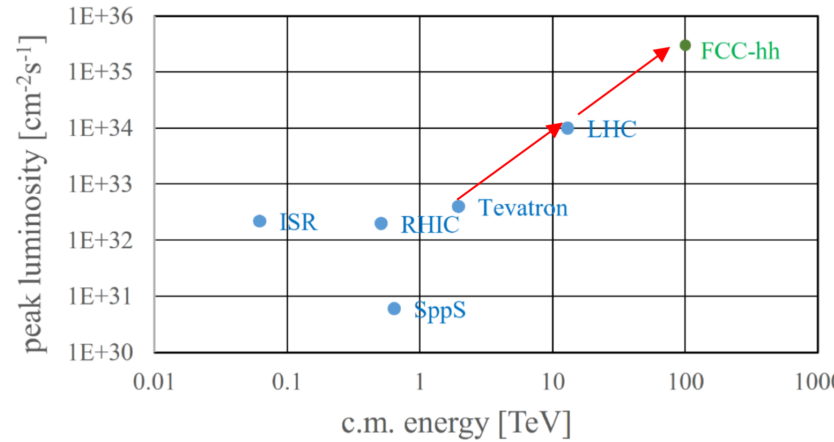




2024-2027: Develop and test an innovative process to transform sterile "molasse" into fertile soil for agricultural use and afforestation.

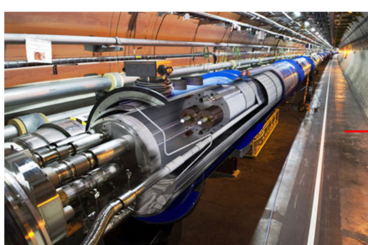
Stage 2: FCC-hh

- High energy frontier exploration machine, reaching **~100 TeV pp collisions**
- Performance increase by an order of magnitude in energy and luminosity w.r.t. LHC
- Planned to accumulate ~20 ab^{-1} per experiment, over 25 years



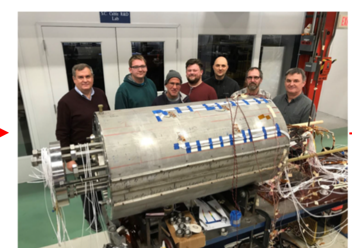
- Large challenges: - High bending power → high-field magnets with field strength of 16 – 20 T;
  - Costs (linked to magnets)

From LHC technology
8.3 T NbTi dipole



via HL-LHC technology
12 T Nb_3Sn quadrupole

via large R&D programme
(e.g. FNAL 14.5 T Nb_3Sn dipole demonstrator, 2019)



.. to high-field, high performance, industrially mass-produced FCC-hh dipole magnets

14 T (Nb_3Sn)?
16 – 20 T ?
High-field magnets, HTS technology?
(High Temperature Superconductors)

→ accelerator R&D roadmap

FCC-hh baseline for the Feasibility Study

- Parameter optimization towards "acceptable power consumption"
- Magnetic field considered realistic with today's technologies (Nb_3Sn, 14 T)
- Optimized accelerator optics design to increase arc dipole filling factor to maximise beam energy
- Increase cryo-magnet operation temperature

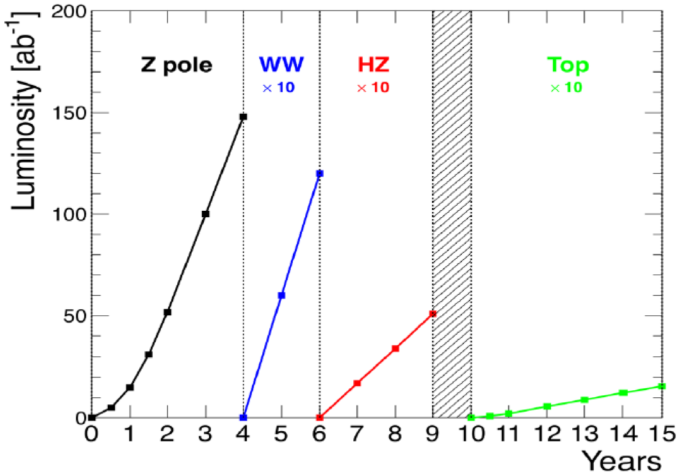
Parameter	Unit	FSR (2024)	CDR (2018)	(HL-)LHC
c.m. energy	**TeV**	**85**	**100**	14
dipole field	**T**	**14**	**16**	8.33
beam current	A	0.5	0.5	(1.12) 0.58
bunch population	10^{11}	1.0	1.0	(2.2) 1.15
bunches/beam		9500	10400	(2760) 2808
rf voltage	MV	35	20 - 48	(16) 16
longitudinal emit.	eVs	8.1	9.0	2.5
normalized transverse emittance	μm	2.2	2.2	(2.5) 3.75
IP beta*	m	0.3	0.3	(0.15) 0.55
initial σ*	μm	3.8	3.5	(7.1 min) 16.7
Initial luminosity	$nb^{-1}s^{-1}$	**170**	**200**	(50, lev'd) 10
initial pile up		590	690	(135) 27
ΔE / turn	MeV	2.4	4.7	0.0067
SR power/beam	**kW**	**1200**	**2400**	(7.3) 3.6

	FCC-hh 90.7km 14T	FCC-hh 90.7km 14T
Magnet temperature	**1.9 K**	4.5 K
Power consumption @ 85 TeV c.m.	**< 430 MW**	< 330 MW
Yearly electricity consumption	**< 2.8 TWh**	< 2.2 TWh

Physics Potential

- a few selected topics -

FCC-ee Running Scenarios and Physics Yield



Flexible operation scheme, HZ programme can be carried out earlier

arXiv:2203.06520

Working point	Z years 1-2	Z, later	WW	HZ	$t\bar{t}$		(s-channel H)
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340–350	365	m_H
Lumi/IP ($10^{34}\,cm^{-2}s^{-1}$)	115	230	28	8.5	0.95	1.55	(30)
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34	(7)
Physics goal (ab^{-1})	150		10	5	0.2	1.5	(20)
Run time (year)	2	2	2	3	1	4	(3)
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k WW $\rightarrow$ H	10^6 $t\bar{t}$ +200k HZ +50k WW $\rightarrow$ H		(6000)

Dedicated run to measure the **electron Yukawa coupling** via s-channel $e^+e^- \rightarrow H$ production

Under study!

Needs strong monochromatisation of the beams

- Huge potential at Z peak: $5 \cdot 10^{12}$ events (10^5 times LEP)
- WW and $t\bar{t}$ threshold scan (→ precision mass measurements of m_W and m_t)
- 10^6 HZ events (at 240 GeV) + 25.000 $H\nu\nu$ events (via W fusion)

- Precise mass scale; high precision of beam energy due to resonant depolarisation
  (δE (91 GeV) ~ 100 keV, δE (350 GeV) ~ 2 MeV)

Precision on Higgs boson couplings

Precision on Higgs coupling strength modifiers κ_i

(assuming no BSM particles in Higgs boson decays)

J. De Blas et al. JHEP 01 (2020) 139

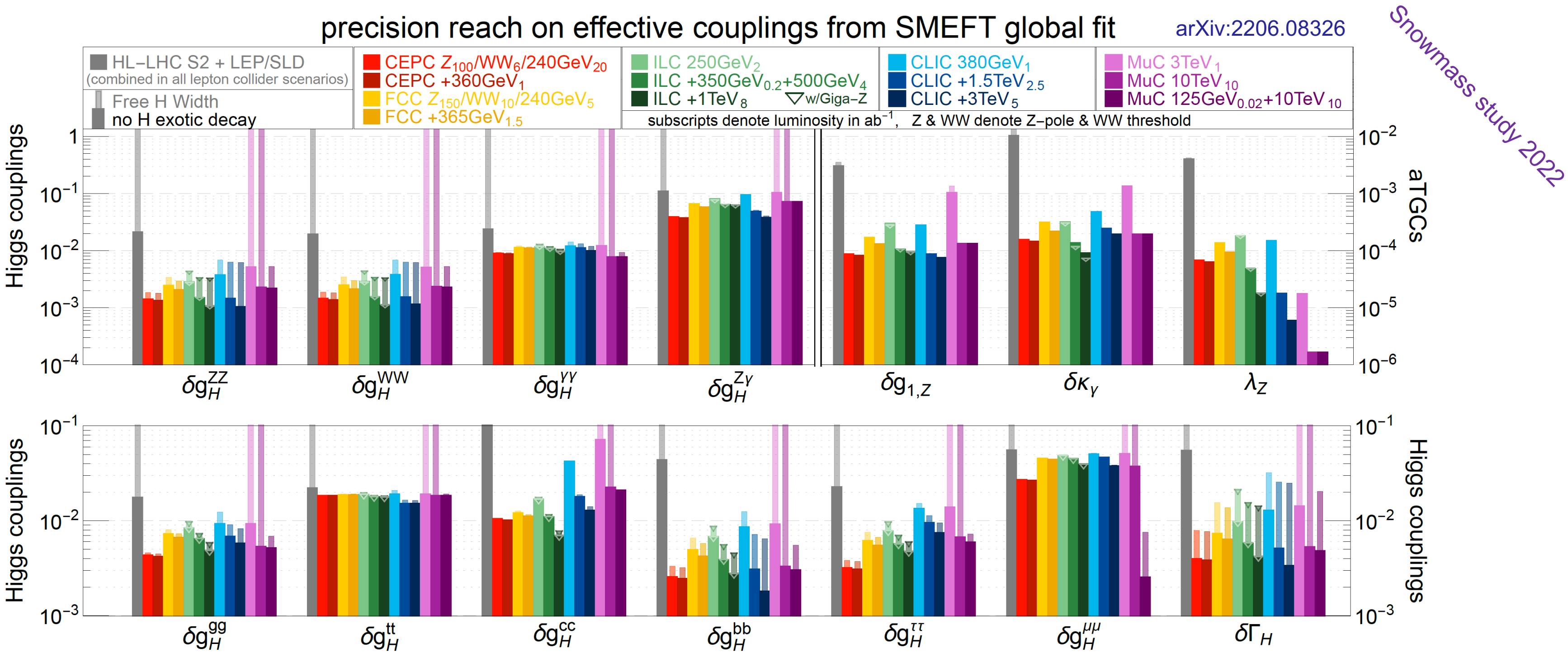
kappa-3 scenario	HL-LHC+									
	ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	FCC-ee_{240}	FCC-ee_{365}	FCC-ee/eh/hh
κ_W [%]	1.0	0.29	0.24	0.73	0.40	0.38	0.88	0.88	0.41	0.19
κ_Z[%]	0.29	0.22	0.23	0.44	0.40	0.39	0.18	0.20	0.17	0.16
κ_g[%]	1.4	0.85	0.63	1.5	1.1	0.86	1.	1.2	0.9	0.5
κ_γ [%]	1.4	1.2	1.1	1.4∗	1.3	1.2	1.3	1.3	1.3	0.31
* $\kappa_{Z\gamma}$ [%]	10.∗	10.∗	10.∗	10.∗	8.2	5.7	6.3	10.∗	10.∗	0.7
κ_c [%]	2.	1.2	0.9	4.1	1.9	1.4	2.	1.5	1.3	0.96
* κ_t [%]	3.1	2.8	1.4	3.2	2.1	2.1	3.1	3.1	3.1	0.96
κ_b [%]	1.1	0.56	0.47	1.2	0.61	0.53	0.92	1.	0.64	0.48
* κ_μ [%]	4.2	3.9	3.6	4.4∗	4.1	3.5	3.9	4.	3.9	0.43
κ_τ [%]	1.1	0.64	0.54	1.4	1.0	0.82	0.91	0.94	0.66	0.46
BR_{inv} (<%, 95% CL)	0.26	0.23	0.22	0.63	0.62	0.62	0.27	0.22	0.19	0.024
BR_{unt} (<%, 95% CL)	1.8	1.4	1.4	2.7	2.4	2.4	1.1	1.2	1.	1.

$$\sigma_{ZH} \times \mathcal{B}(H \to X\overline{X}) \propto \frac{g^2_{HZZ} \times g^2_{HX\overline{X}}}{\Gamma_H}$$

$$\sigma_{H\nu_e\overline{\nu}_e} \times \mathcal{B}(H \to X\overline{X}) \propto \frac{g^2_{HWW} \times g^2_{HX\overline{X}}}{\Gamma_H}$$

- Large improvement with future e^+e^- colliders (compared to (HL)-LHC)
- Powerful ability to measure Higgs boson production without any assumptions on its decay
- Higgs boson width within a few percent (via ZH cross section)
- **Comparable precision between different e^+e^- colliders at early stage**
- Complementarity to hadron collider * → ultimate precision (sub %) from FCC-hh

Higgs and anomalous couplings (SMEFT interpretation)



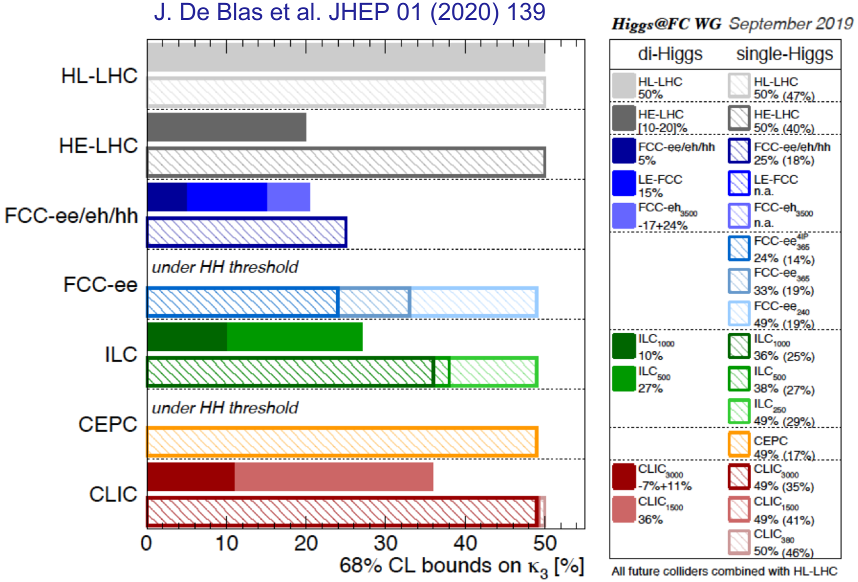
- All e^+e^- colliders show comparable performance (higher luminosities partly compensated by beam polarisation)
- Several couplings well below 1% level: Z, W, g, b, τ

  Others at ~ 1% level: γ, c

  No large improvements w.r.t. HL-LHC for: γ, t, μ

Precision on Higgs boson self coupling

J. De Blas et al. JHEP 01 (2020) 139

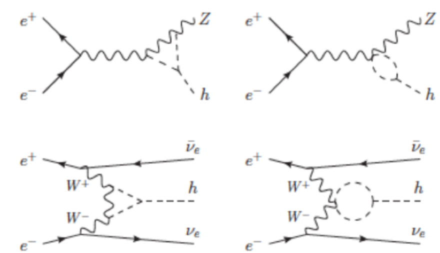


Precision on λ parameter:	
HL-LHC:	$\pm 50\%$
ILC (1 TeV):	$\pm 10\%$
CLIC (3 TeV):	$\pm(7-10)\%$
FCC-ee:	$\pm 35\%$
FCC-hh:	$\pm\ 5\%$

Results confirmed in Snowmass study arXiv:2211.11084

- At low-energy lepton colliders, no direct di-Higgs production possible

  → sensitivity via loop effects

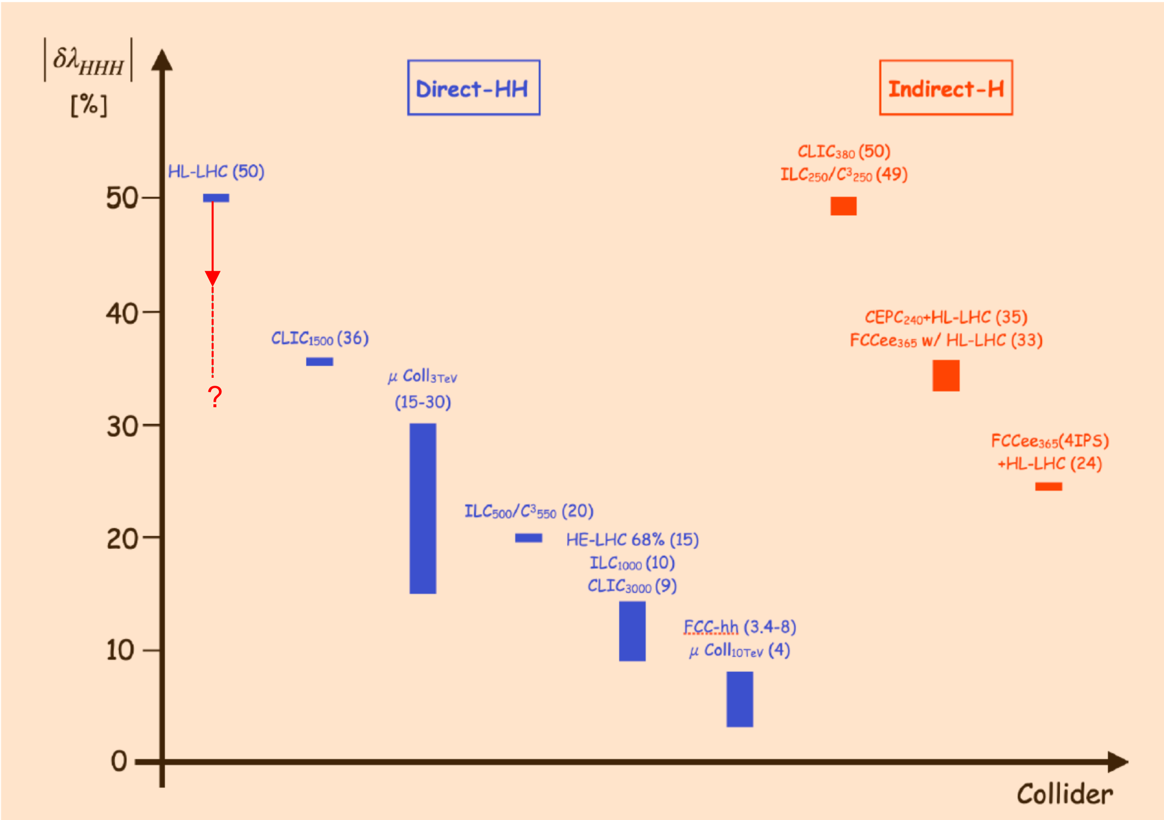


Precise cross section measurements required at more than one energy, e.g. at 240 and 360 GeV

- Higher sensitivity can be reached at high-energy lepton colliders (ILC, CLIC, Muon Collider)

need to be updated

Precision on trilinear Higgs self-coupling



M. M. Mühlleitner, German Strategy Meeting, DESY, 27 – 29 Nov 2024

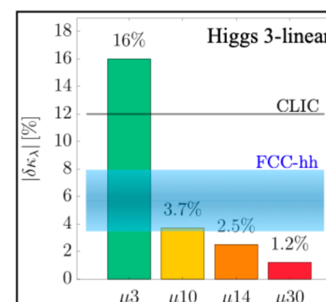
FCC-hh precision for different collider energies

100 TeV	s I	s II	s III
stat	3.0	4.1	5.6
syst	1.6	3.0	5.4
tot	**3.4**	**5.1**	**7.8**

80 TeV	s I	s II	s III
stat	3.5	4.7	6.4
syst	1.6	3.0	5.4
tot	**3.8**	**5.6**	**8.4**

M. Mangano, FCC-hh studies for the next Europ. Strategy, kickoff meeting 09/2024

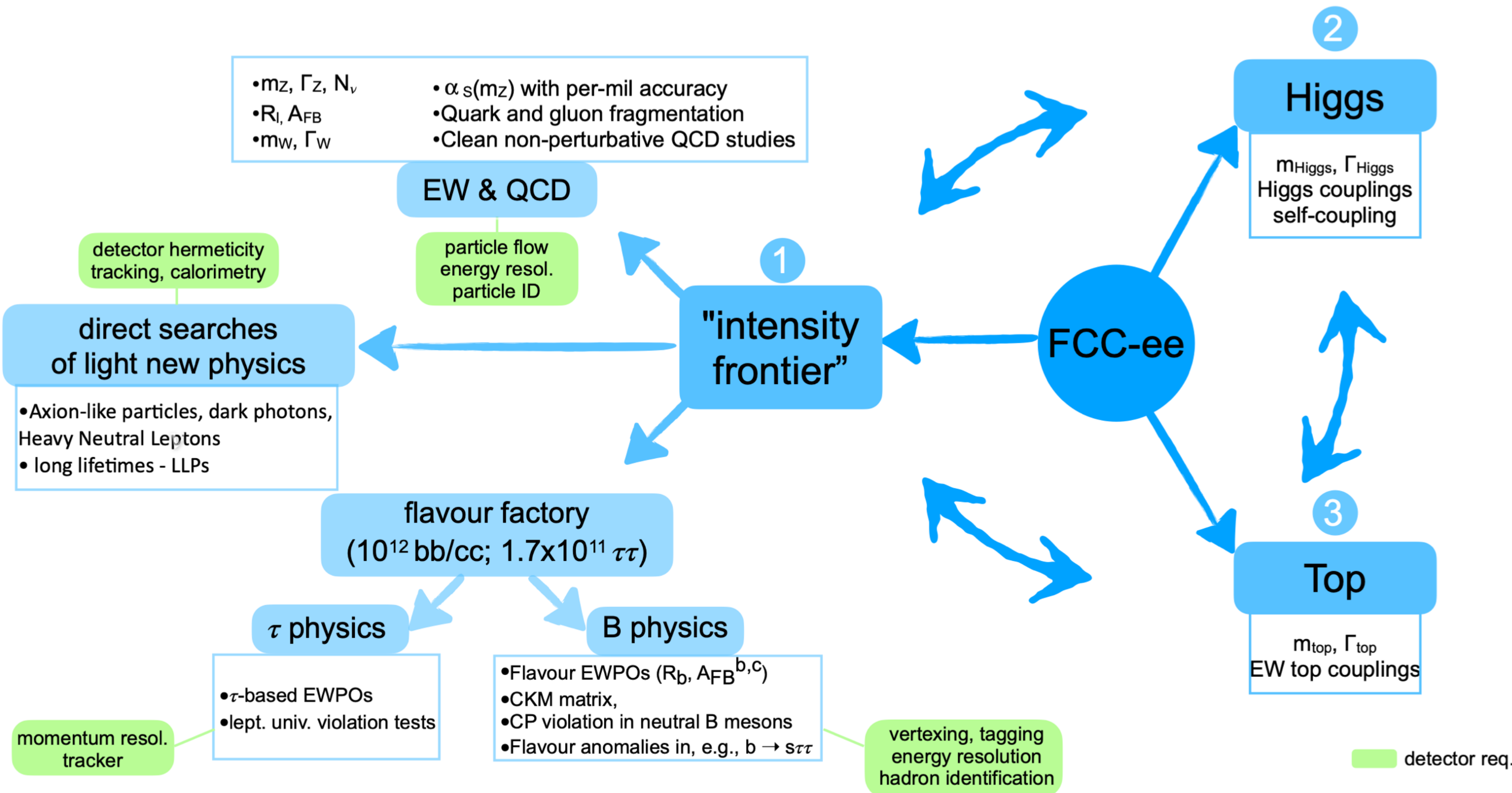
- Scenario I: Optimistic – target detector performance, similar to Run 2 LHC conditions.
- Scenario II: Realistic – intermediate detector performance.
- Scenario III: Conservative – pessimistic detector performance, assuming extrapolated HL-LHC performance using present-day algorithms.



Muon Collider sensitivity

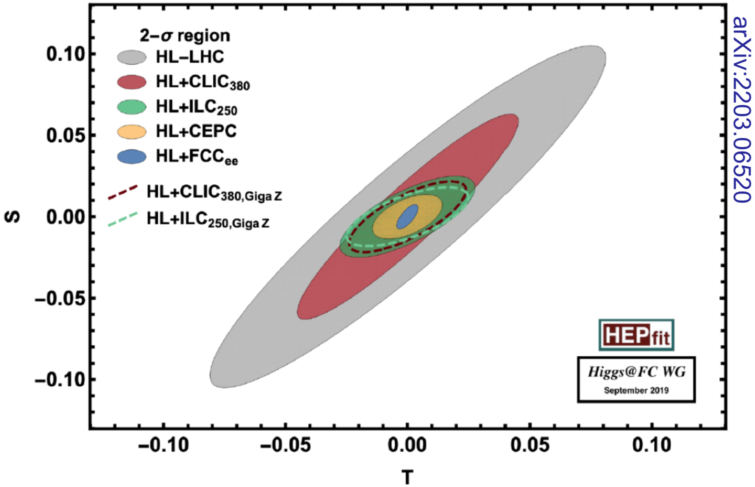
FCC-ee (and CEPC) Z-physics programme

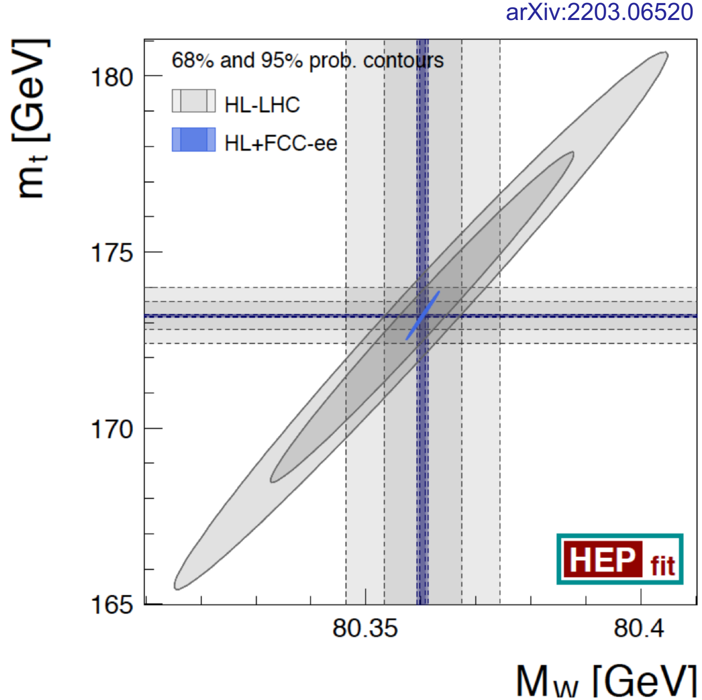
Christophe Grojean, FCC week 2022



Precision of electroweak observables

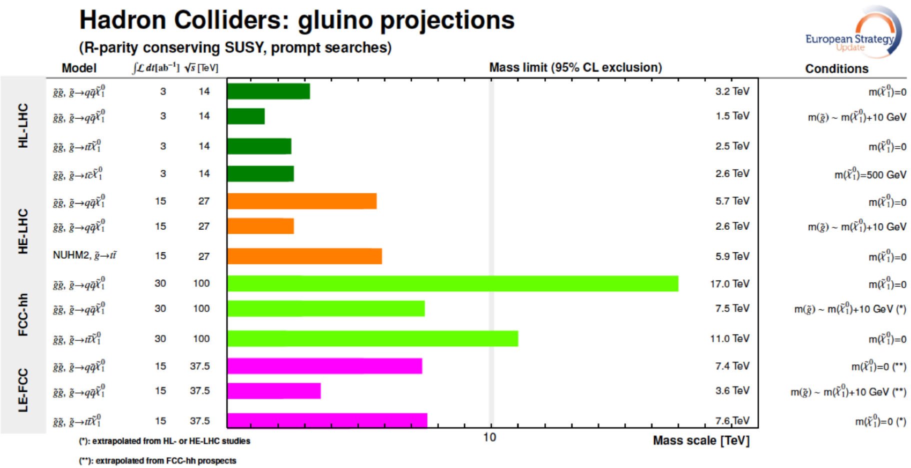
FCC-ee: Impressive precision on el.weak observables:
δm_Z ~ 100 keV, $\delta\Gamma_Z$ ~ 25 keV
δm_W < 500 keV (from WW threshold scan)
δm_t ~45 MeV (from $t\bar{t}$ threshold scan)

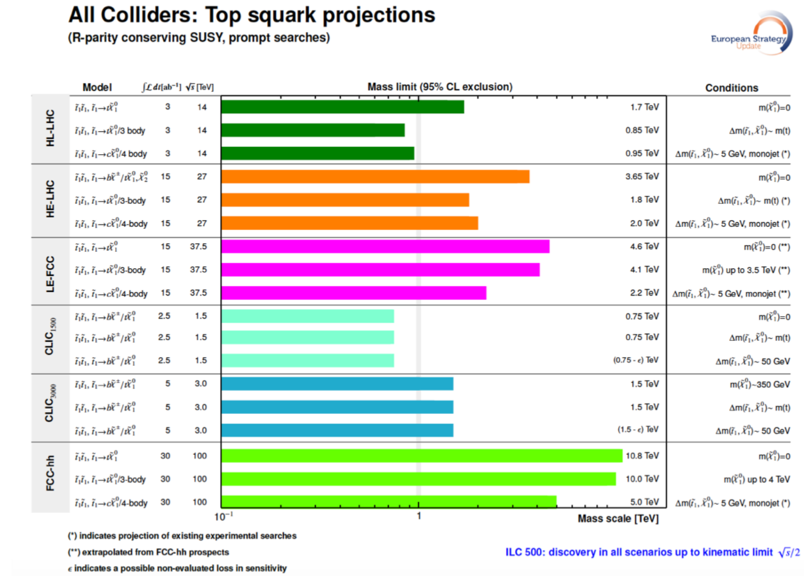




- Importance of el.weak precision:
  (i) Improve **sensitivity to new physics** (e.g: $\delta S \sim 10^{-2} \rightarrow M \sim 70$ TeV)
  (ii) **Reduce parametric uncertainties** for other measurements, global fits

Search for new Physics



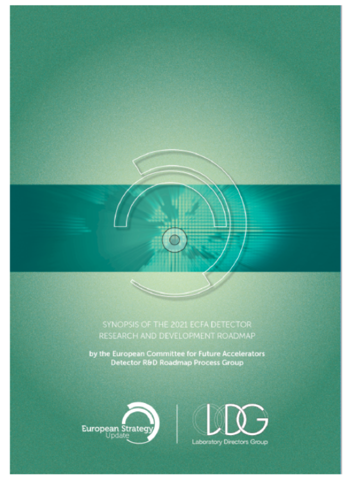


High-energy hadron colliders have the largest reach for strongly produced **gluinos, squarks**, in particular also **top-squarks**

Mass range > 10 TeV can be reached

Accelerator R&D Roadmap

"The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, … Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes."



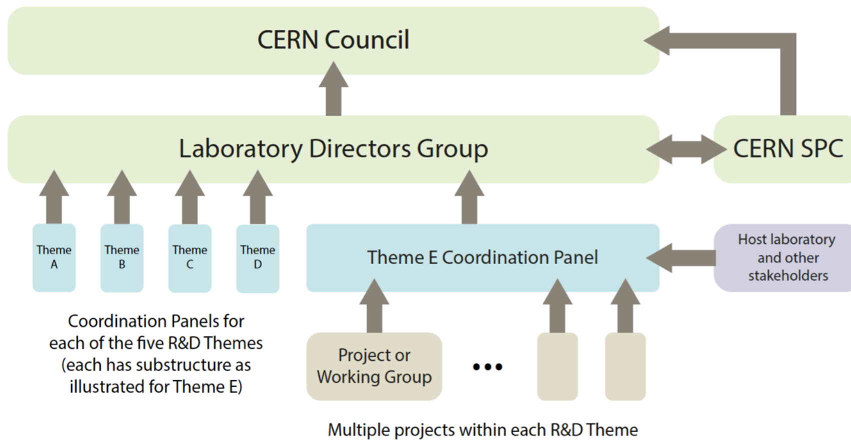
https://arxiv.org/abs/2201.07895

Key questions addressed:

- *What R&D remains to be done towards future facilities?*
- *What are the priorities?*
- *How long might it take? How much will it cost?*
- *What different options and trade-offs exist?*
- *What are the dependencies or conflicts between activities?*

Goal: provide the evidence allowing future decision-making by the field

Implementation: Coordination Structure of the Accelerator R&D



- Structure set up for cooperative, coordinated and focussed R&D towards future machines;

  Strong involvement of European National Laboratories and other institutes

- Coordination panels formed, work started

Coordination panel chairs

Magnets: M. Lamont (CERN), P. Vedrine (IRFU)
RF: G. Bisoffi (INFN-LNL), Peter McIntosch (RAL)
Plasma: W. Leemans (DESY), Rajeev Patahill (RAL)
ERL: J. D'Hondt (Brussels), M. Klein (Liverpool)
Muons: S. Stapnes (Oslo), D. Schulte (CERN)

Focus on five R&D Themes:

- High field magnets
- RF structures
- Plasma / Laser acceleration
- Energy-recovery Linacs
- Muon Beams

High-field Superconducting Magnets

- Key technology for future accelerators (hadron colliders, muon colliders, neutrino beams, …)

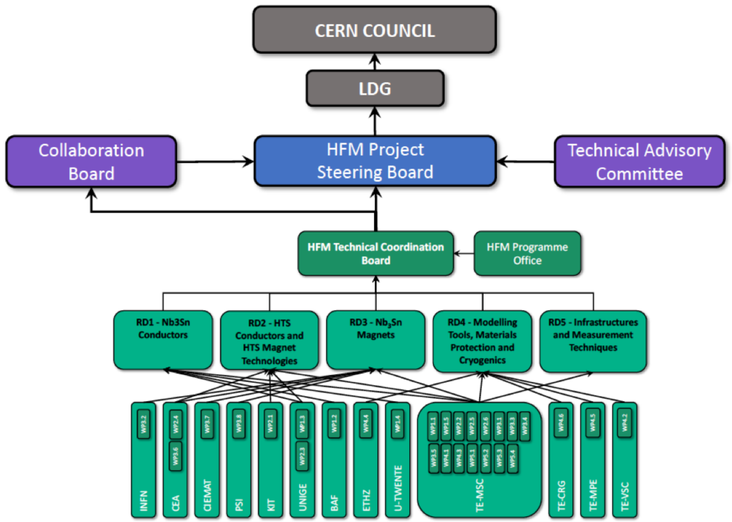
- To reach field strengths of 16 – 20 T for FCC-hh, new technologies have to be **established and brought into industrial production**
  (Present candidates: Nb_3Sn and High-Temperature Superconductors (HTS), …)

  Recent progress indicates that 14 T magnets can be realised with Nb_3Sn (timeline: 2050 – 2055)

Accelerator Roadmap:

- Encompass Nb_3Sn and HTS (REBCO, …) developments
  - Demonstrate **Nb_3Sn** magnet technology for large-scale deployment
  - Demonstrate the suitability of HTS for accelerator magnet applications

- “Vertically integrated” approach to R&D
  - Development of all aspects from conductors to cables to magnets to systems
  - Emphases: full system optimisation, fast turnaround for R&D



Other Accelerator R&D areas

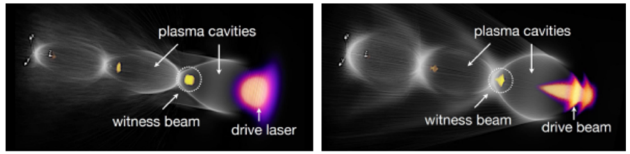
Plasma / Laser acceleration:

- Panel proposes a plasma and laser accelerator R&D roadmap that should be implemented and delivered in a three pillar approach

  By next strategy: A feasibility and pre-conceptual design report, i.e. evaluate the potential and performance reach for colliders

- *"The recently proposed HALHF concept may act as a spur to the improvement of specific plasma-acceleration techniques"*
  B. Foster et al. New J. Phys. 25 (2023) 093037, [arxiv:2303.10150]
  but: *"HALHF cannot be built tomorrow: many unsolved problems remain."*

  [DESY-D, INFN-I, STFC-UK, …]

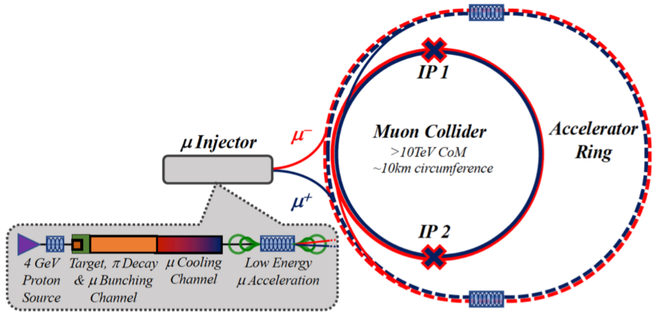


Muon Beams:

- Potentially interesting path to realise high-energy lepton colliders, however, the technology must overcome several significant challenges

- **Roadmap Objectives**: again focussed on the "plausibility case"
  → Examine the key technical barriers and cost drivers
  → Develop muon-collider concept (focus on 10 TeV, demonstrator around 2035) → input to 2026 Strategy process

  [CERN, INFN-I, STFC-UK, CEA-F, …]



European Strategy for Particle Physics: 2026 Update

The Strategy Secretariat and European Strategy Group (ESG)

Strategy Secretariat: Organising and running the ESPP process

Karl Jakobs (Strategy Secretary, Chair)
Hugh Montgomery (SPC Chair)
Mike Seidel (LDG Chair)) (→ has replaced Dave Newbold (STFC) as new LDG Chair on 1st Jan. 2025)
Paris Sphicas (ECFA Chair)

European Strategy Group (ESG) Preparation of the Strategy Document

- The Strategy Secretary (acting as Chair)
- **One representative appointed by each CERN Member State**
- **One representative appointed by each of the laboratories represented in the Large Particle Physics Laboratory Directors Group (LDG), including its Chair**
- **The CERN Director-General**
- **The CERN Director-General elect**
- The SPC Chair
- The ECFA Chair
- Invitees: President of CERN Council, one representative from each of the Associate Member and Observer States, one representative from the European Commission, the Chairs of APPEC, NuPECC and ESFRI, the members of the Physics Preparatory Group.

US representative: Mike Tuts (Columbia)

The Physics Preparatory Group (PPG)

Physics Preparatory Group collects input from the community, organizes the Open Symposium, prepares the Briefing Book

- Strategy Secretary (acting as Chair)
- **Four members appointed by Council on the recommendation of the SPC**
- **Four members appointed by Council on the recommendation of ECFA**
- **One representative appointed by CERN**
- **Two representatives from the Americas**
- **Two representatives from Asia**
- The SPC Chair
- The ECFA Chair
- The LDG Chair

US representative: Anadi Canepa (Fermilab)

PPG MEMBERS	
Strategy Secretariat	
Scientific Secretary (Chair)	Prof. Karl Jakobs (DE)
SPC Chair	Dr Hugh Montgomery (USA)
ECFA Chair	Prof. Pareskevas Sphicas(GR)
LDG Chair	Prof. Dave Newbold (UK)
SPC	
Prof. Pilar Hernandez (ES)	
Prof. Gino Isidori (CH)	
Prof. Fabio Maltoni (BE/IT)	
Prof. Jocelyn Monroe (UK	
ECFA	
Dr Tommaso Boccali (IT)	
Dr Thomas Bergauer (AT)	
Dr Cristinel Diaconu (FR)	
Prof. Monica Dunford (DE)	
CERN	
Dr Gianluigi Arduini (CERN)	
ASIA/AMERICAS	
Dr Anadi Canepa (USA)	
Prof. Xinchou Lou (China)	
Prof. Rogerio Rosenfeld (Brazil)	
Prof. Yuji Yamazaki (Japan)	

Organisation of the work in PPG

The Strategy Secretariat has set up **nine working groups** to cover the full range of physics topics as well as the technology areas of accelerators, detector technologies and computing.

Working Group			
	Co-convener (PPG member)	Co-convener	Scientific Secretary
Electroweak physics	Monica Dunford (DE, exp)	Jorge de Blas (ES, theory)	Emanuele Bagnaschi (IT)
Strong interaction	Cristinel Diaconu (FR, exp)	Andrea Dainese (IT, exp, HI)	Chiara Signorile-Signorile (DE)
Flavour physics	Gino Isidori (CH, theory)	Marie-Hélène Schune (FR, exp)	Maria Piscopo (NL)
BSM physics	Fabio Maltoni (BE/IT, theory)	Rebeca Gonzalez Suarez (SE, exp)	Benedikt Maier (UK)
Neutrino physics and cosmic messengers	Pilar Hernandez (ES, theory)	Sara Bolognesi (FR, exp)	Ivan Esteban (ES)
Dark matter and dark sector	Jocelyn Monroe (UK, exp)	Matthew McCullough (CERN, theory)	Yohei Ema (CERN)
Accelerator science and technology	Gianluigi Arduini (CERN, acc)	Phil Burrows (UK, exp, acc)	Jacqueline Keintzel (CERN)
Detector instrumentation	Thomas Bergauer (AT, exp)	Ulrich Husemann (DE, exp)	Dorothea vom Bruch (FR)
Computing	Tommaso Boccali (IT, exp, comp)	Borut Kersevan (SL, exp, comp)	Daniel Thomas Murnane (DK)

Physics Preparatory Group

- Each group has **two co-conveners** and one Early-Career Researcher (ECR) as **Scientific Secretary** to organise the work
- ECRs have been appointed by the co-conveners, in consultation with the Strategy Secretariat (partially based on nominations via ECFA)

Timeline for the update of the European Strategy for Particle Physics

End September 2024
Council appointment of the members of the **PPG** and decision on the venue for the **Open Symposium**

December 2024
Council decision on the venue for the **ESG Strategy Drafting Session**

31 March 2025
Deadline for the submission of main input from the community

26 May 2025
Deadline for the submission of additional national input in advance of the **Open Symposium**

23-27 June 2025
Open Symposium (in Venice)

End September 2025
Submission of the "Briefing Book" to the **ESG**

14 November 2025
Deadline for the submission of final national input in advance of the **ESG Strategy Drafting Session**

1-5 December 2025
ESG Strategy Drafting Session (in Ascona/ Switzerland)

End January 2026
Submission of the draft strategy document to the Council

March and June 2026
Discussion of the draft strategy document by the Council and **updating of the Strategy**

More details on ESPP web page: https://europeanstrategyupdate.web.cern.ch/

Community Involvement

Input and involvement of the community is important!
(… and explicitly asked for in the remit of the Strategy Process)

Goal must be to reach consensus in the community on the way forward for our field!

(i) Submission of input from the community by **31 March 2025**

Guidelines for documents to be submitted have been defined (see next slide)
→ **Comprehensive and self-contained summary of 10 pages (max)**

Additional information and details can be submitted in a **separate back-up document**, which can be consulted by the Physics Preparatory Group (PPG) if clarification on any aspects is required.
But the back-up document is not a mandatory component of the submission.

(ii) Input from **projects** (FCC, Linear Collider, …, Muon Collider, …, theory, …) is expected
Benchmarks for physics measurements / processes defined
In addition, input on technical data expected https://europeanstrategyupdate.web.cern.ch/call-input

(iii) Input from **national HEP communities** is a vital component of the Strategy Process
(ECFA guidelines for national HEP community input)

Work / topics covered and shared among PPG and ESG

PPG:
Physics + Technology working groups

- Electroweak physics (including Higgs physics)
- Strong interaction
- Flavour physics
- Beyond the Standard Model physics
- Neutrino physics and cosmic messengers
- Dark matter and dark sector
- Accelerator science and technology
- Detector instrumentation
- Computing

→ Physics Briefing Book

ESG: Overarching topics

- **National input / roadmaps (→ strategic)**
- **Projects (FCC, LC, LE-FCC-hh, MC, ..)**
  (timeline, costs, …. (physics → PPG))
- Comparisons across proposed projects
- Relations with other fields of physics
- …

→ *ESG working groups will be set up to cover thes topics*

Proposed ESG Working Groups

(1) National Input, Diversity in European Particle Physics

- Analyse and summarise the input that will be submitted by the national HEP communities.
- Discuss constraints imposed by a large accelerator project at CERN. What fraction of the CERN and European research budget should be put on a single flagship project?
- Discuss the level of European participation in projects outside Europe

(2) Project Comparison Group

(a) Project assessment (technical feasibility, timeline, risks, cost and human resources, environmental impact)
(b) Physics potential
(c) Development of international landscape of the field

(3) Implementation of the Strategy / Deliverability of larger projects

Main purpose: assess how European National Laboratories and institutes can best work together with CERN to deliver large scale accelerator and detector projects.

("Distributed delivery model" for CERN's next major infrastructure? New management practices and tools?
What lessons can be learnt from the recent major projects (e.g. ATLAS and CMS upgrades)?
What could be a model for international participation (beyond CERN Member and Associate Member States)?)

(4) Relations with other fields of physics (nuclear physics, astroparticle physics, …)
(5) Sustainability and environmental impact
(6) Public Engagement, Education, Communication
(7) Social and career aspects for the next generation
(8) Knowledge and Technology Transfer

Final Remarks on Strategy Process

- It is important to submit input by **31 March 2025 and at the later stages**

- Reaching a consensus on the next large collider project at CERN in this Strategy Update is vital!

  - Given the scale of the project, large timescales, …
    the decision cannot be postponed.

    → Get engaged (in discussions at the national level, projects, …)

    Attend the Open Symposium in Venice
    → discussion sessions!

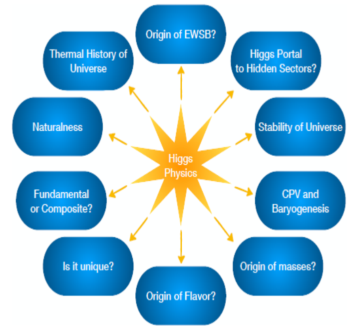
- Finally, it should be noted that the European Strategy for Particle Physics is not a project approval process. Projects are approved by the CERN Council through a separate decision process.

- Council decision on a future collider at CERN is expected to be taken in 2027-2028, in order to be able to begin construction in the early 2030s.

Conclusions

- High-energy future colliders will play a key role in the exploration of crucial fundamental questions of physics

- Despite the large progress at the (HL)-LHC, the further exploration of the Higgs sector is vital



Mature options for the realization of an e^+e^- Higgs factory exist:

ILC, FCC-ee, CEPC, CLIC

Long timescales → **approval process must converge soon!**

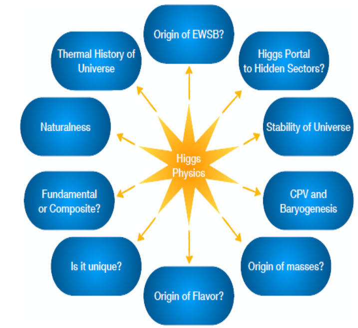
In 2025, key inputs for the decision will become available:

* FCC Feasibility Study (final results)
* Decision on CEPC in China; will the project be included in the next Five-Year Plan (2026 – 2030)?

Conclusions (cont.)

- Further R&D on accelerator technologies and development of innovative approaches must continue

  * High-field superconducting magnets, including a strong research line on high-temperature superconductors
  * Muon collider (US leadership + Europe)
  * Plasma/laser acceleration



- **Important for the realization of future colliders:**

  * Convince decision makers of the incredible physics case and of the vital role of high-energy colliders

  * Broad support within the HEP community is needed!
    In order to maximize the chances to get the next collider approved, we must reach consensus, and support the final plan, whatever it will turn out to be!

  * Continue optimization efforts on power reduction!