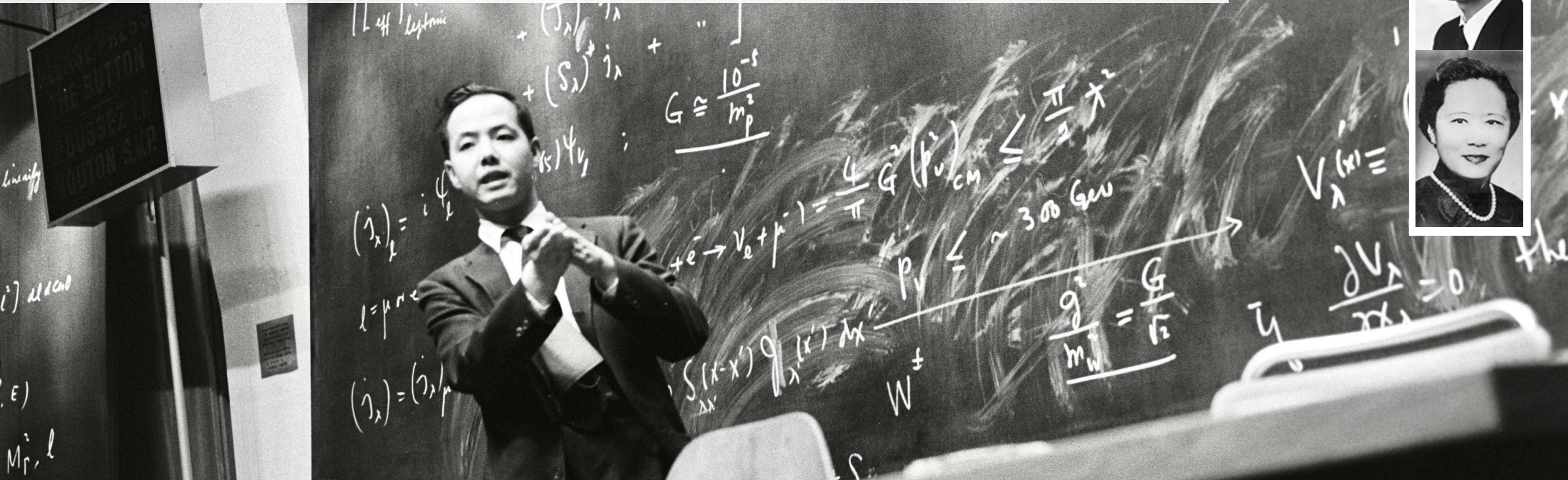


(Precision) probes of fundamental interactions at high-energy colliders

Andreas Hoecker (CERN)

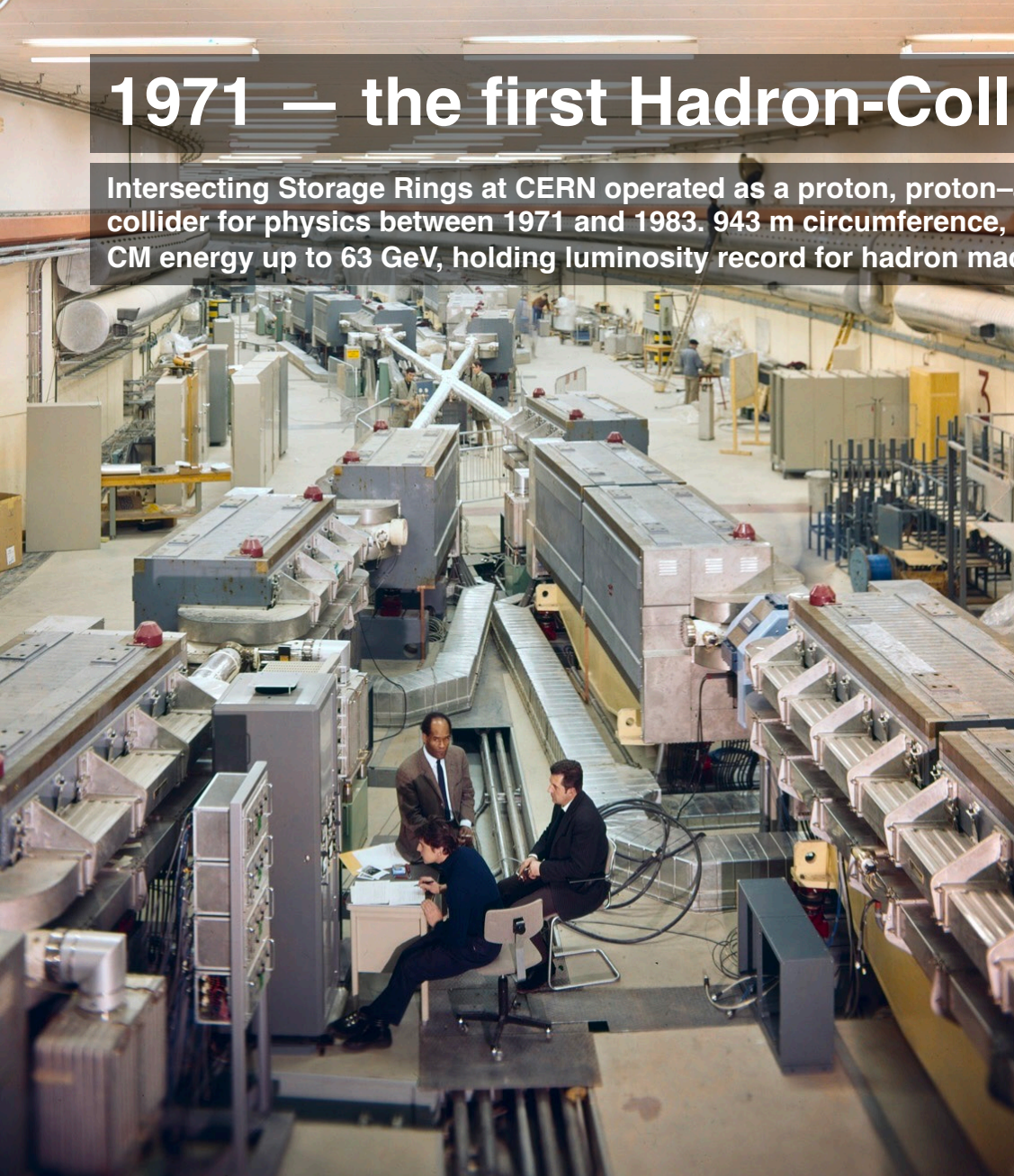
Shanghai Symposium on Particle Physics and Cosmology: 70th Anniversary of the Discovery of Parity Nonconservation and Prospects in Frontier Physics, 23 June 2026



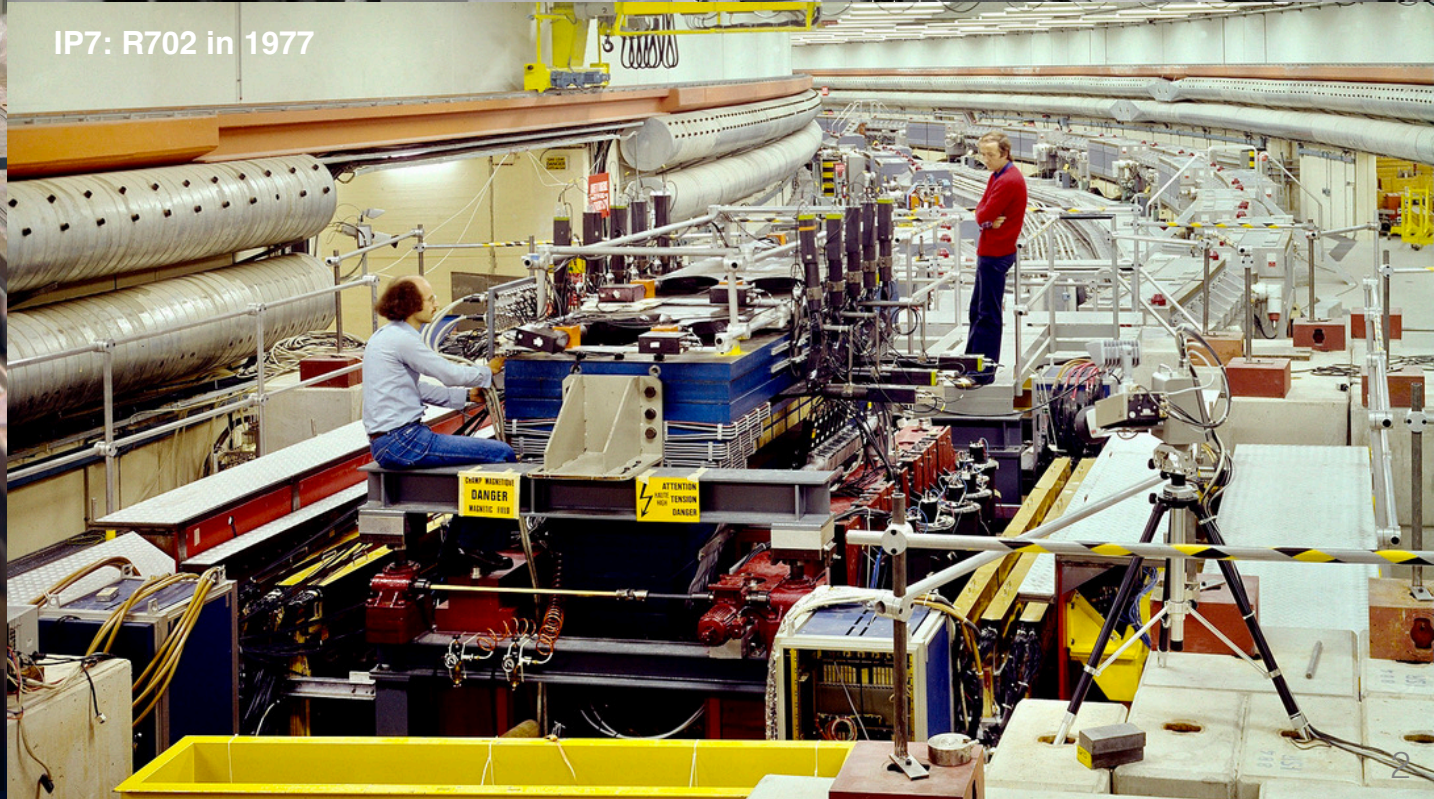
T. D. Lee speaking about weak interactions at a neutrino conference at CERN in 1965 [Ref]

1971 — the first Hadron-Collider

Intersecting Storage Rings at CERN operated as a proton, proton-antiproton and ion collider for physics between 1971 and 1983. 943 m circumference, 1.3 T dipole field, CM energy up to 63 GeV, holding luminosity record for hadron machines until 2004



IP7: R702 in 1977



Huge advantage over fixed target; for protons: $E_{\text{CM}} = 1.4\sqrt{\text{GeV}}\sqrt{E_{\text{beam}}}$

→ $E_{\text{CM}} = 14 \text{ TeV}$ would require a $104,000 \text{ TeV} = 104 \text{ PeV}$ beam

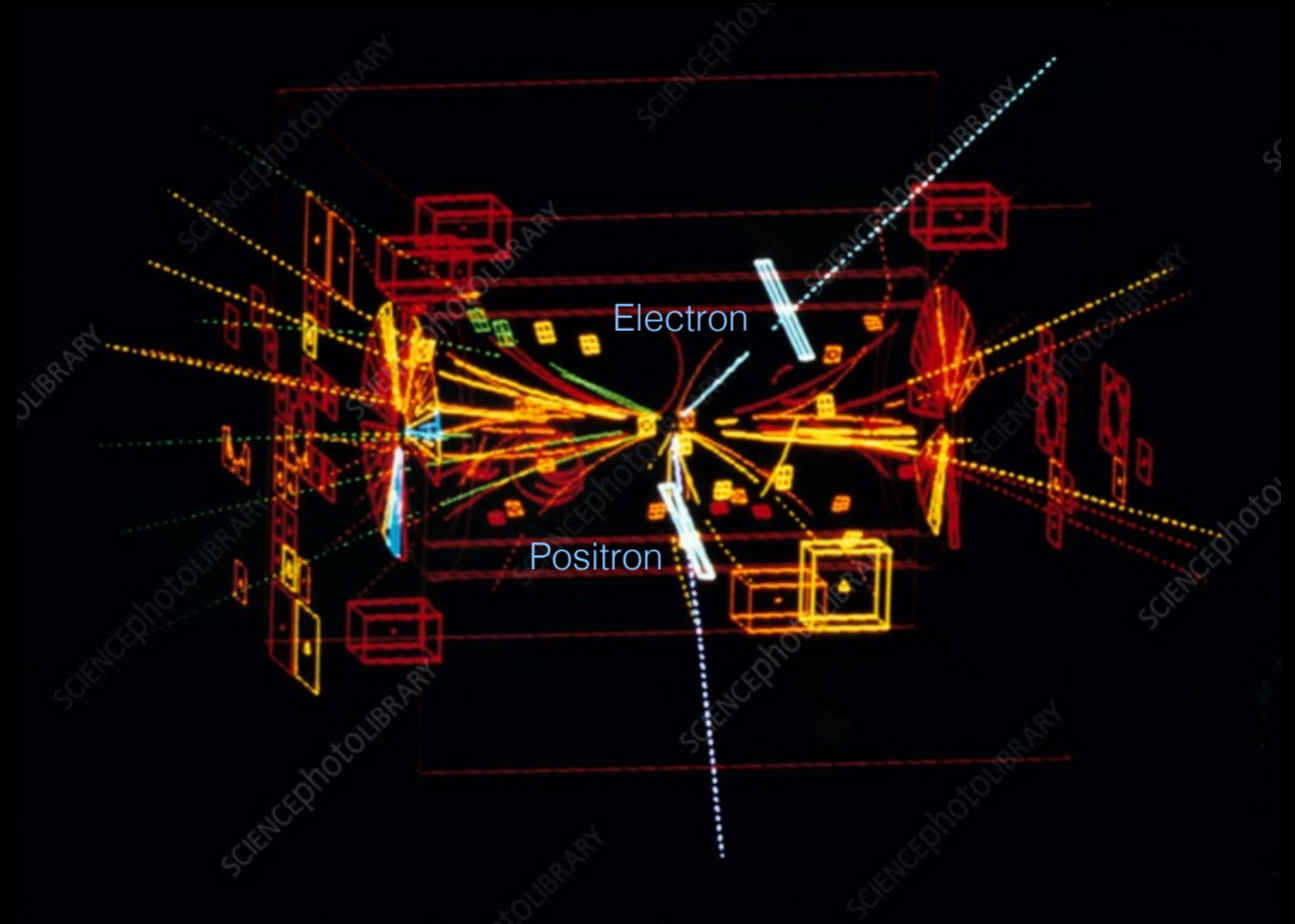
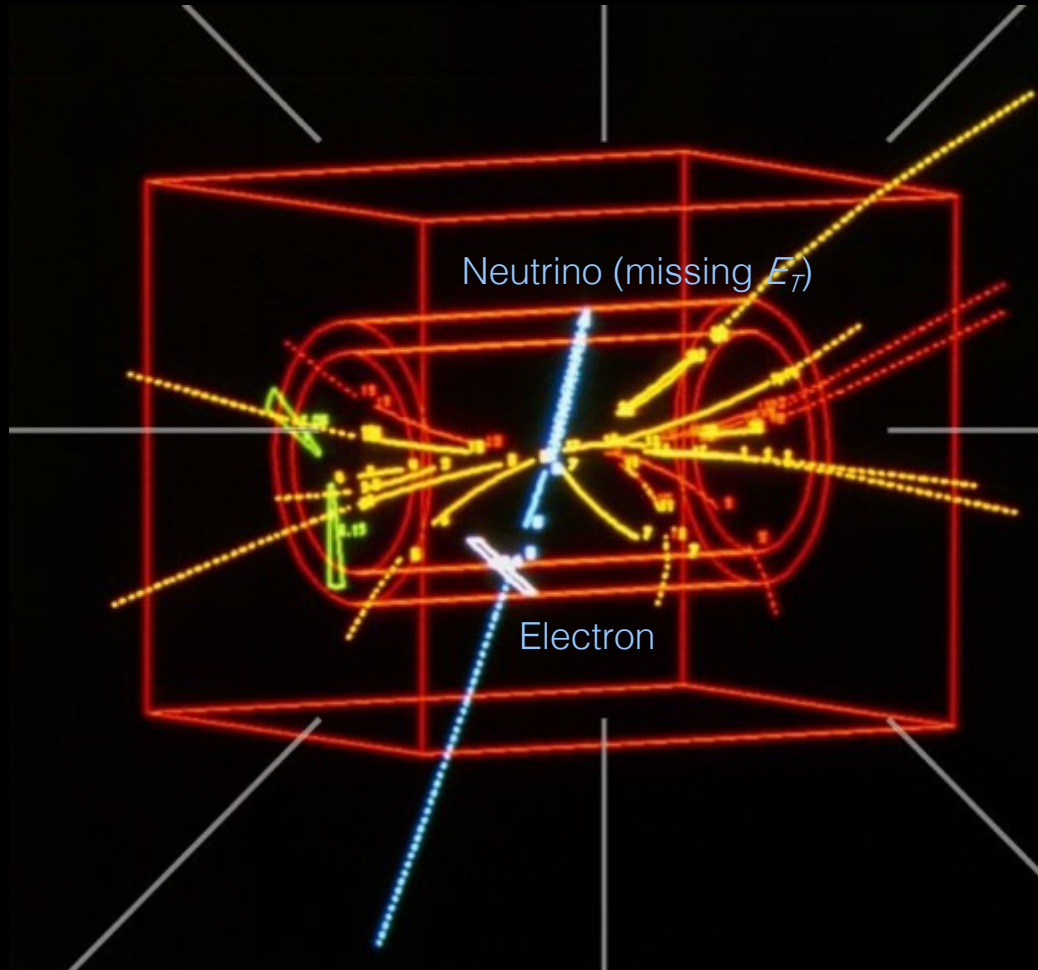
ISR Control Room (early 70s)





SPS: 6.9-km proton synchrotron and ppbar collider, (900 GeV) with UA1 and UA2 detectors
Both experiments were approved in 1978, first data taking in 1981

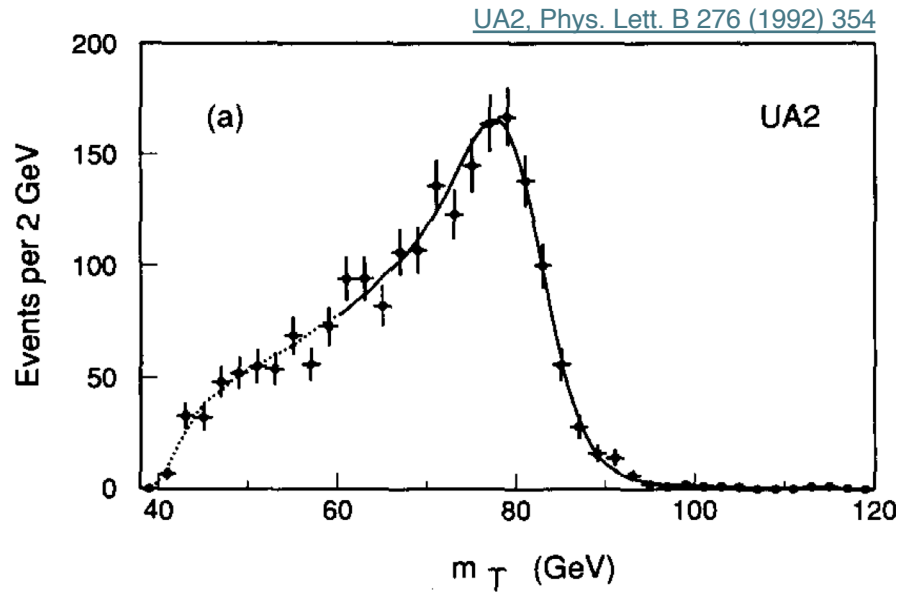
**Discovery of the W and Z bosons by UA1 and UA2 at CERN's SPS collider in 1983:
the charged and neutral weak currents at the origin of parity violation**



Displays show W (left) and Z (right) boson candidates from proton–antiproton collisions measured in the UA1 detector (1982/83)

Nobel Prize 1984 to Carlo Rubbia and Simon van der Meer *for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction* [[Link](#)]

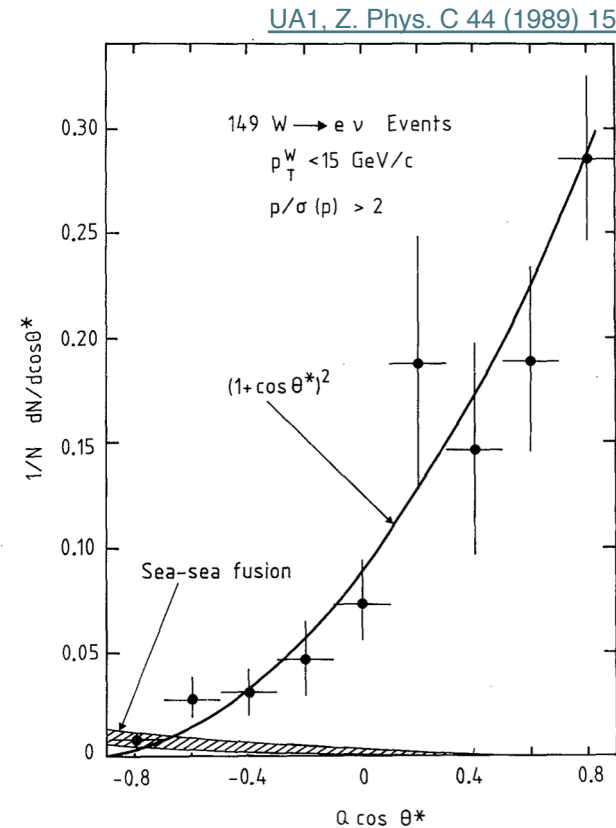
Discovery of the W and Z bosons by UA1 and UA2 at CERN's SPS collider in 1983: the charged and neutral weak currents at the origin of parity violation



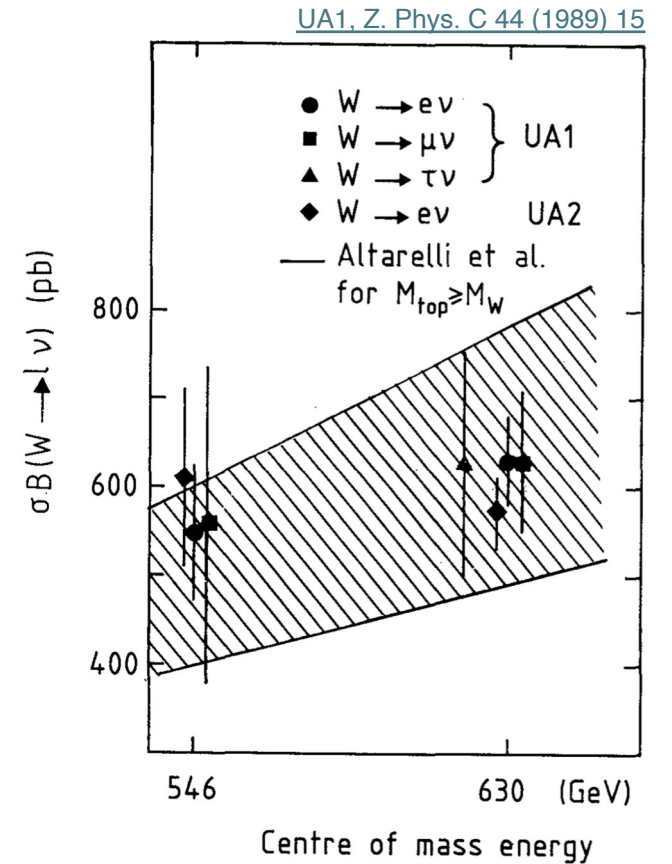
Transverse mass with full UA2 dataset (1992):
 $m_W = 80.84 \pm 0.22 \pm 0.81$ (calibration) GeV

Together with Z-mass measurement allowed to
determine the weak mixing angle and to test the
custodial symmetry relation:

$$\rho \equiv m_W^2 / (m_Z^2 \cdot \cos^2 \theta_W) \approx 1$$



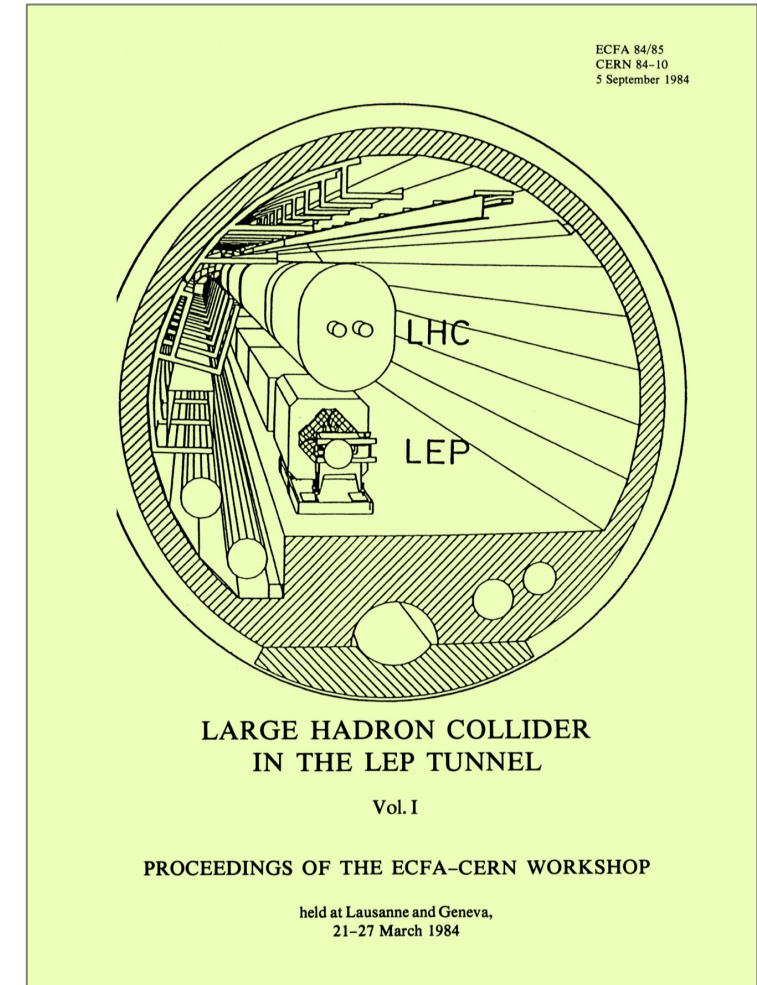
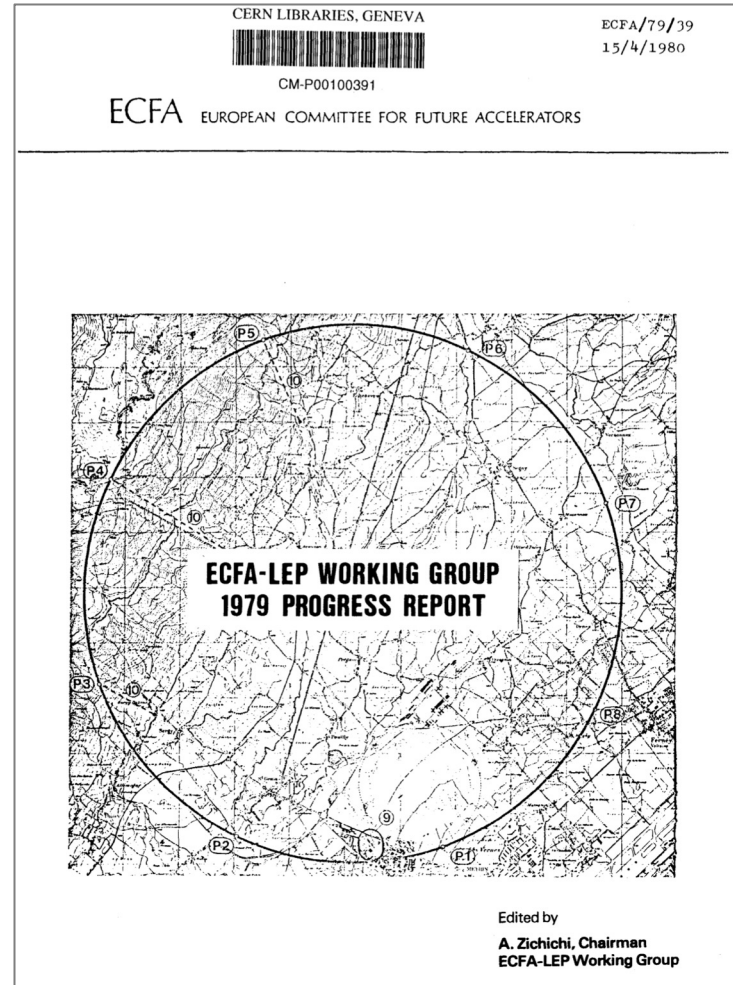
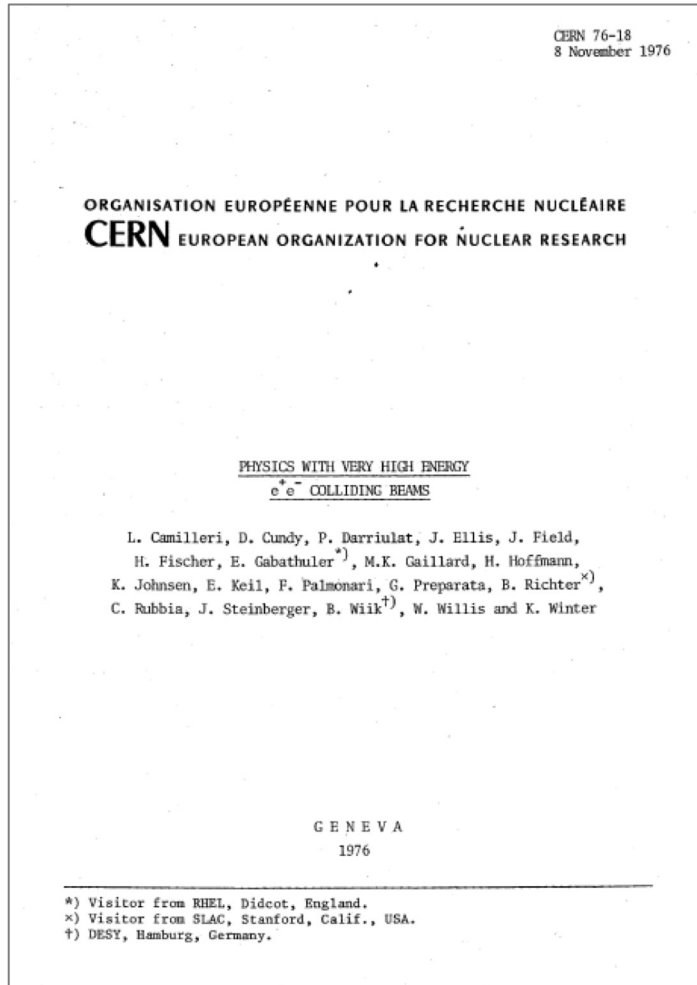
Charge asymmetry in the $W \rightarrow e\nu$
decay: W production polarised along
anti-p beam due to V-A coupling



Universality of weak currents: flavour-
independent parity violation

A new Circular Collider at CERN

The birth of LEP and the LHC: a 26.7 km tunnel facility

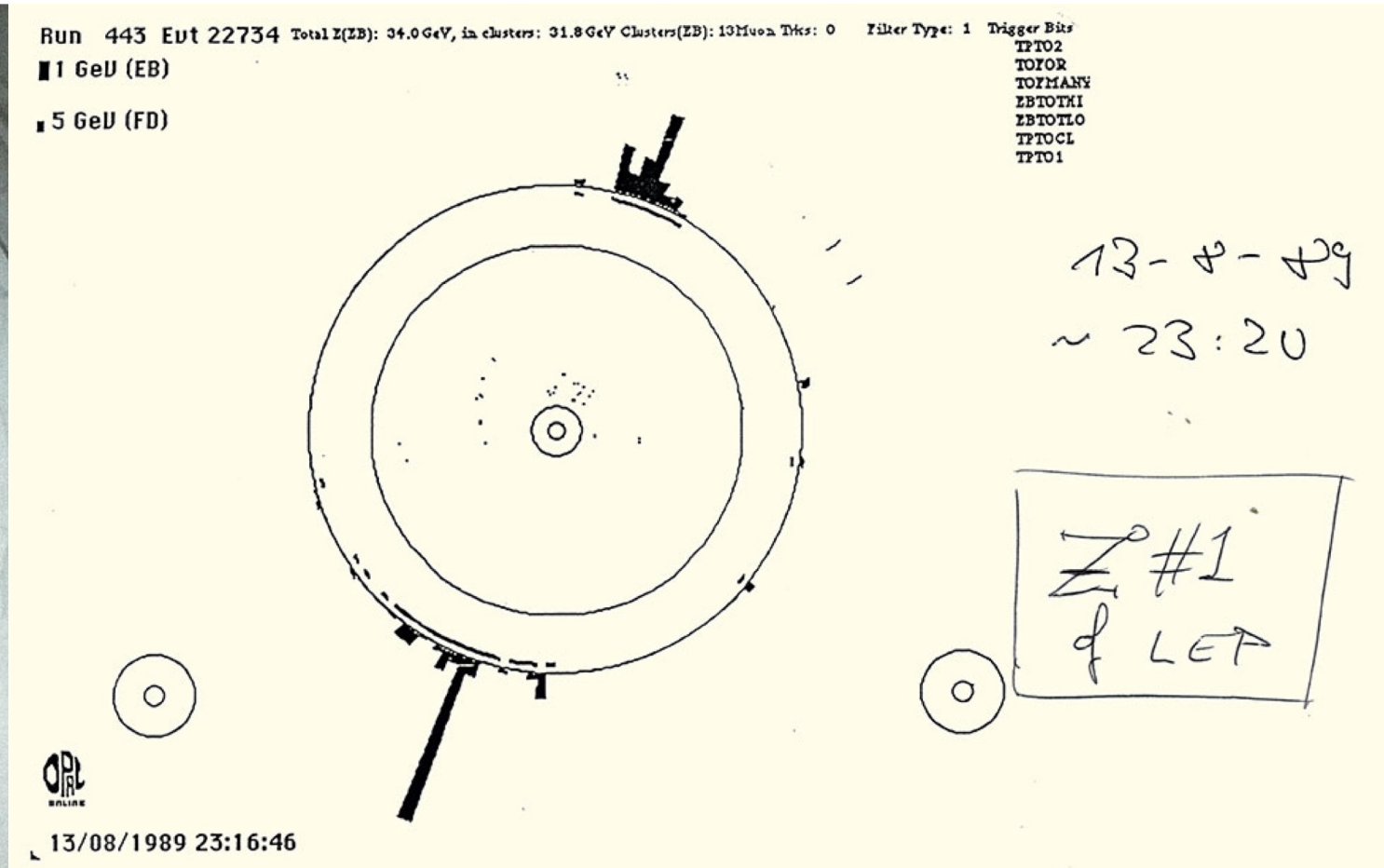


The Large Electron–Positron Collider

LEP was formally approved in 1981, tunnel construction 1983–1988, first beam on 14 July 1989



LEP tunnel before installation of bending magnets

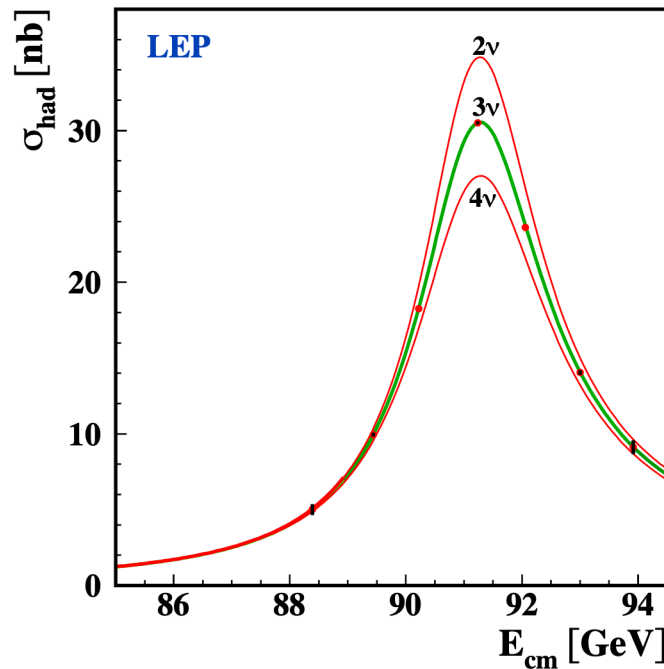


OPAL logbook entry on 13 Aug 1989 with the first Z-boson candidate

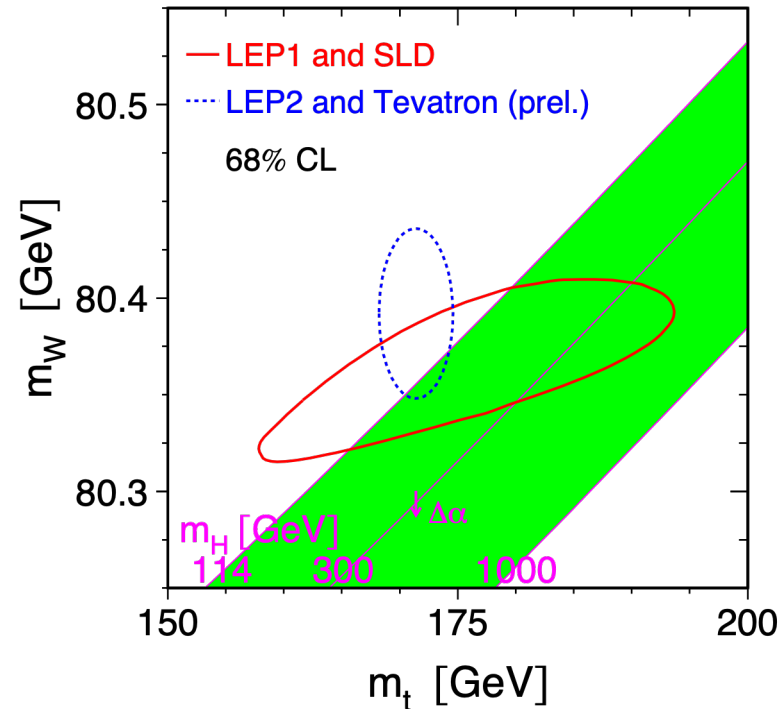
With LEP and SLC, the Standard Model entered the precision era

Huge amount of experimental and theoretical developments during LEP and SLC (SLAC) years, pioneering era of high-precision physics in HEP, **constraints on yet unseen heavy particles through quantum loops**

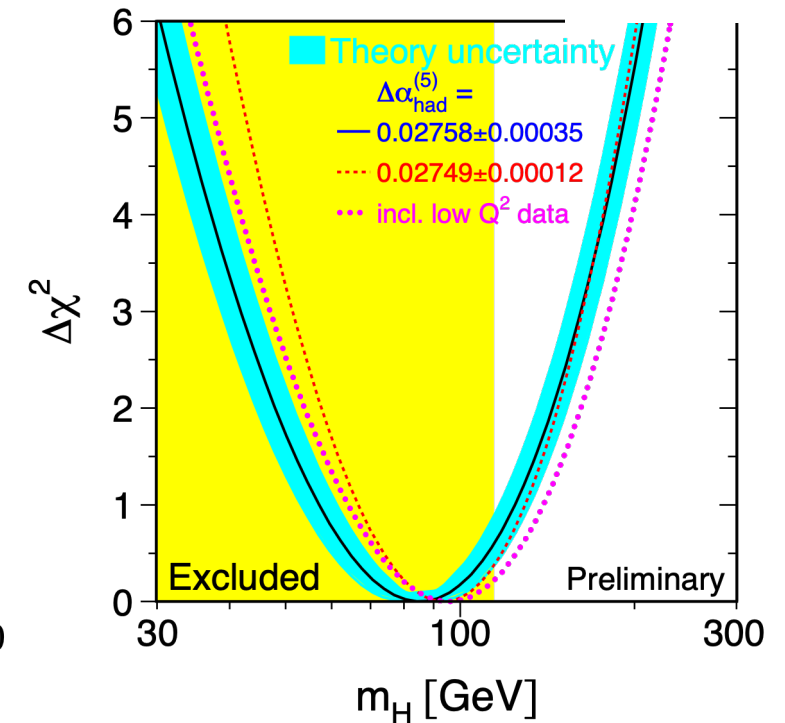
There are 3 light neutrino families



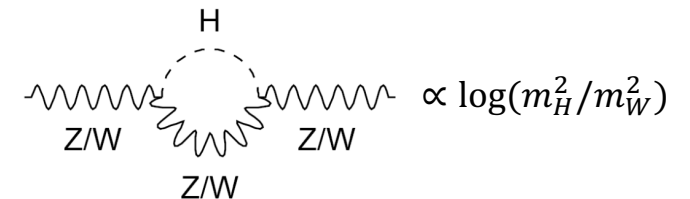
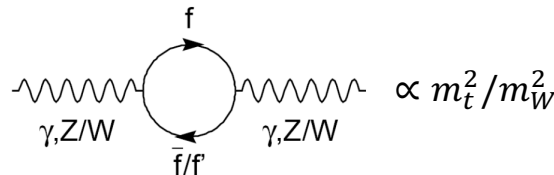
The top quark is heavy



The Higgs boson is light, but $> m_Z$

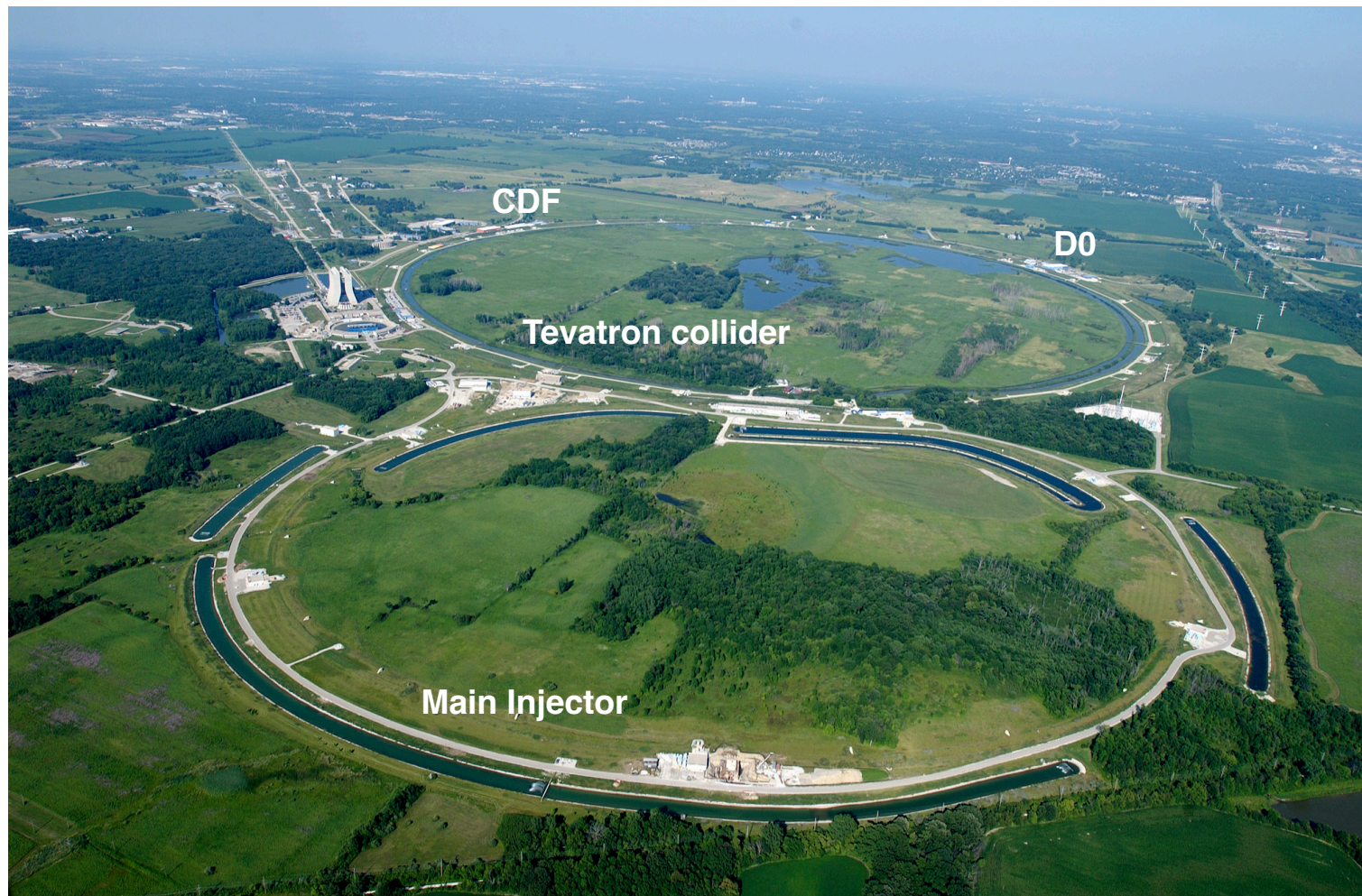


- m_Z measured to 2.1 MeV (0.0023%) precision via beam-energy calibration
- Per-mil tests of lepton universality, QCD, and tau-lepton properties



Late 1980s: the Tevatron at Fermilab climbed at the energy frontier

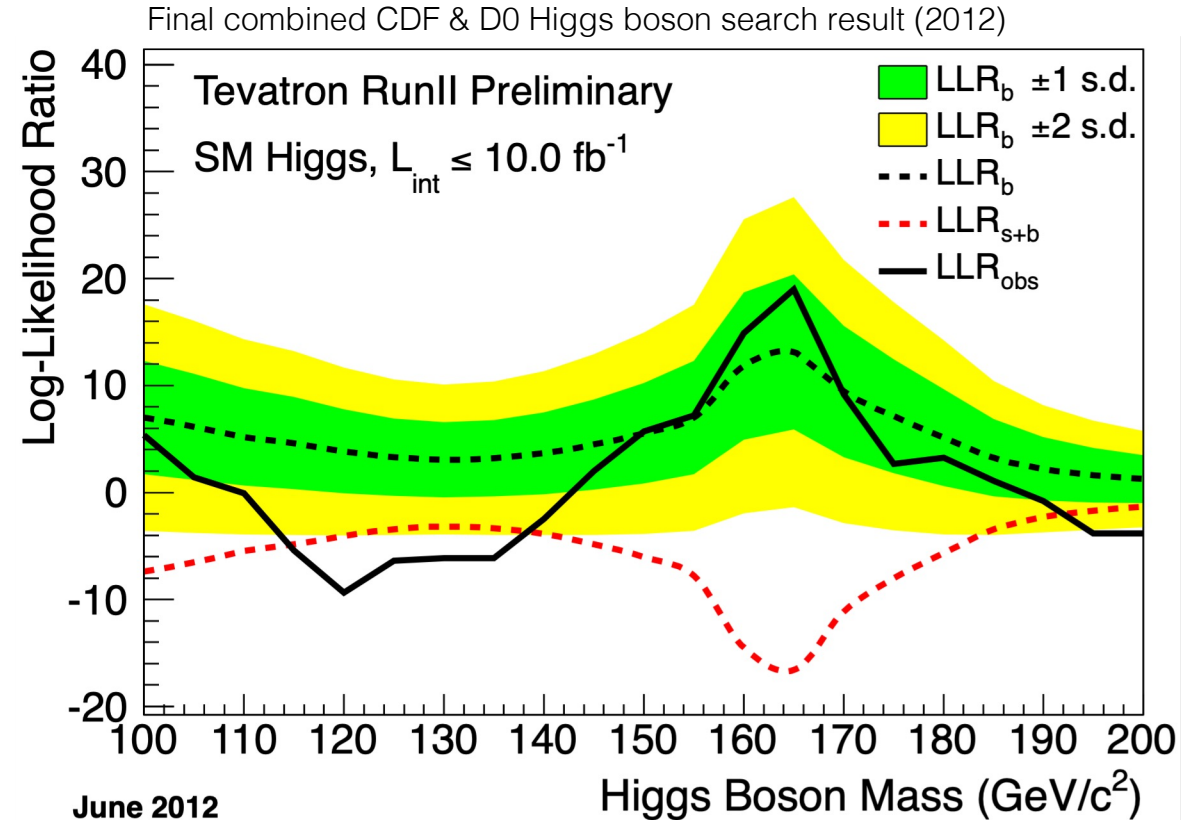
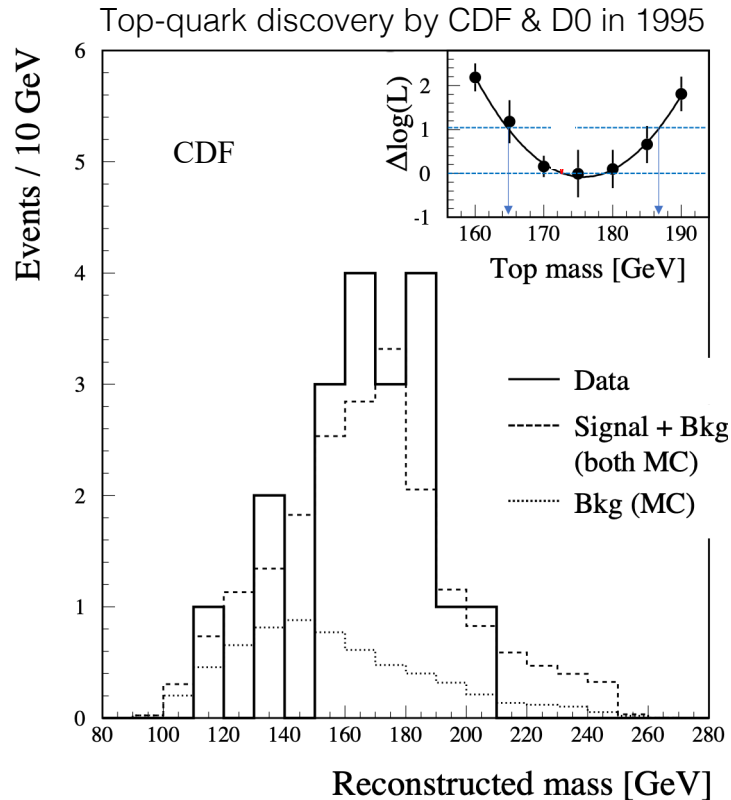
Thanks to 4.4 T superconducting dipole magnets, the 6.3-km circumference Tevatron reached 1.8 TeV proton–antiproton collision energy (later up to 1.98 TeV) and quickly overtook the SppS after physics operation started in 1987 (the antiproton cooling was based on Gersh Budker’s electron cooling method during Run 2) and ended in 2011



Aerial view of Fermilab's proton--antiproton accelerator and collider complex in 2011. The Main Injector and Recycler ring is seen in front and the 6.3-kilometre circumference Tevatron collider ring in the background. On the left the iconic Wilson Hall, Fermilab's central laboratory building. Close-by are the proton source and the Booster. Tevatron's main detectors CDF and D0 are placed to the left and right along the ring, respectively.

Late 1980s: the Tevatron at Fermilab climbed at the energy frontier

Among the Tevatron legacies:



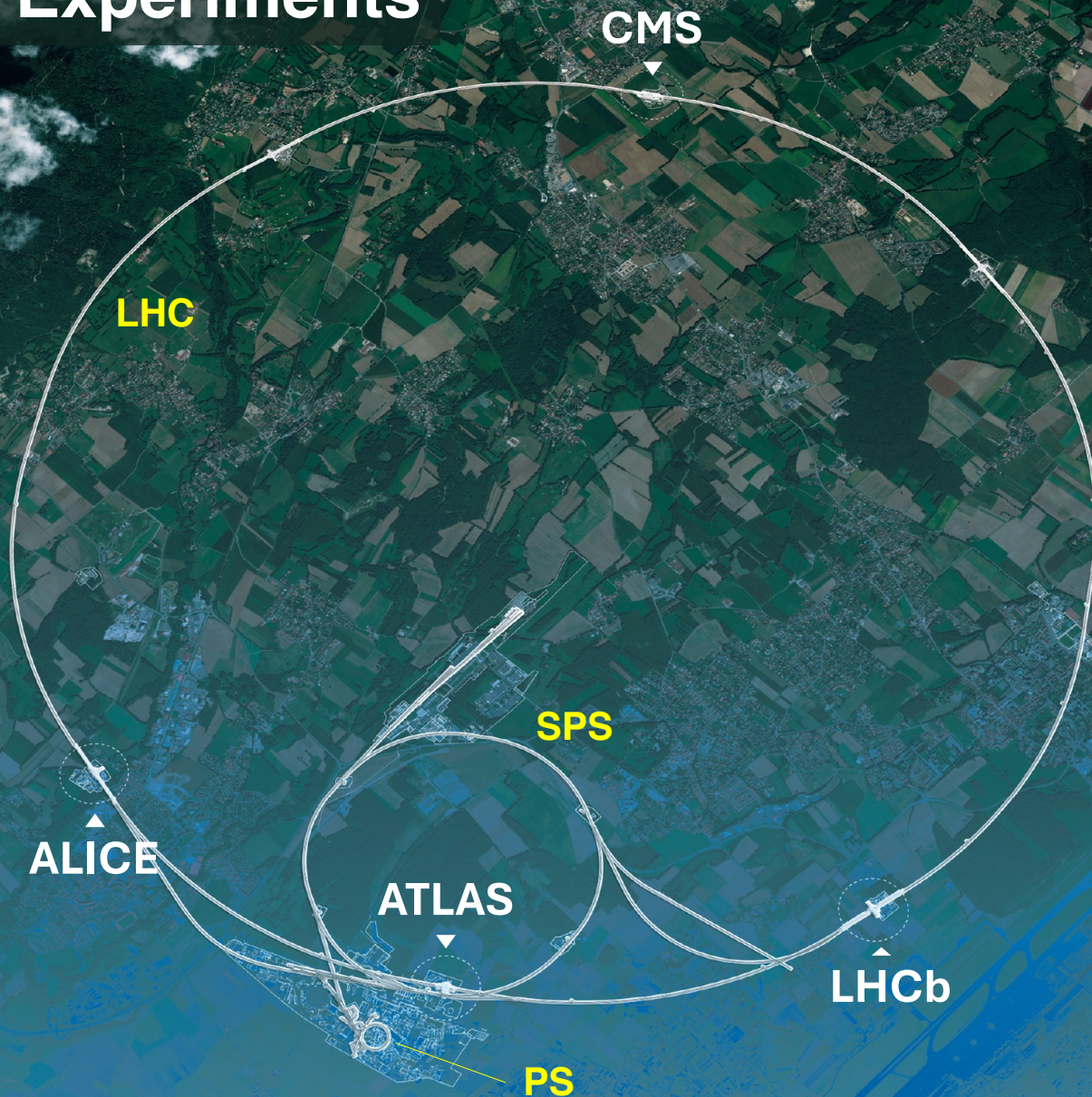
- High-precision top and W mass measurements, $\sigma(m_{\text{top}}) = 0.65 \text{ GeV}$ (0.4%), $\sigma(m_W) = 16 \text{ MeV}$ (0.02%)
- Also: first observation of neutral B_s oscillation by CDF in 2006

Large Hadron Collider (LHC) at CERN: the world's largest accelerator reaching unprecedented energy and intensity



- 26.7 km underground accelerator and collider
- Superconducting magnets ($1.9\text{ K} = -271.3\text{ }^{\circ}\text{C}$) steer the particles around the ring
- Proton and ions are accelerated to multi-TeV scale energies before they collide

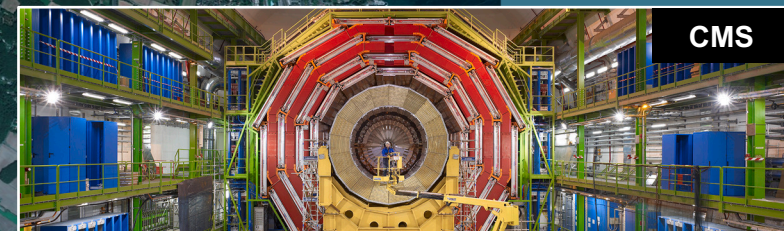
LHC and Experiments



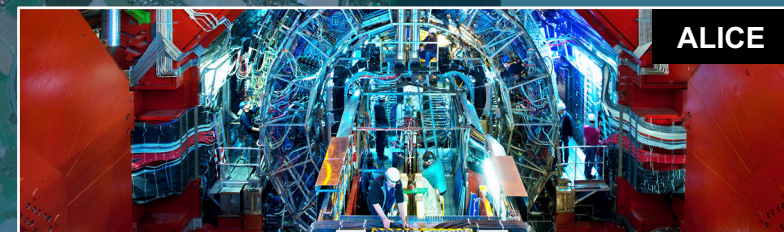
Aerial view



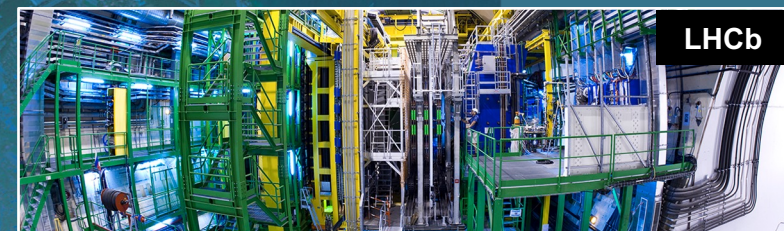
ATLAS



CMS



ALICE



LHCb

Huge, ultra-sophisticated detectors
Built and operated by global collaborations

LHC and Experiments

LHC

CMS
▼ MilliQan

SPS

ALICE

ATLAS

▼ LHCf

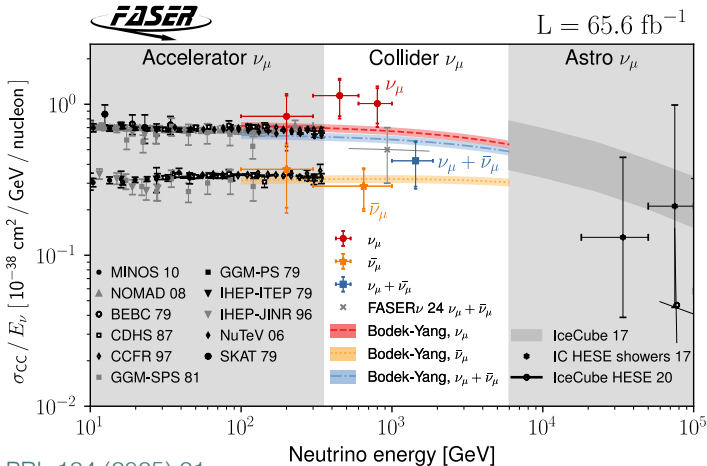
FASER

PS

LHCb
MoEDAL

FASER

SND@LHC



PRL 134 (2025) 21

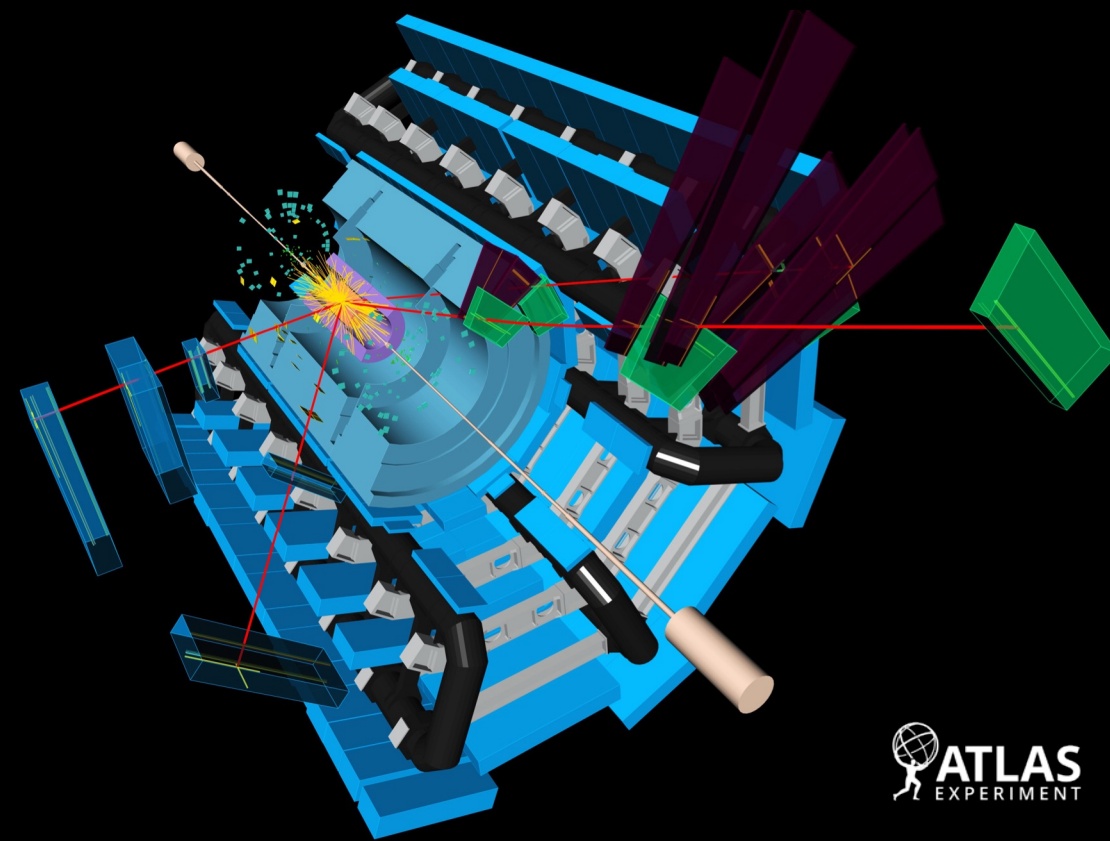
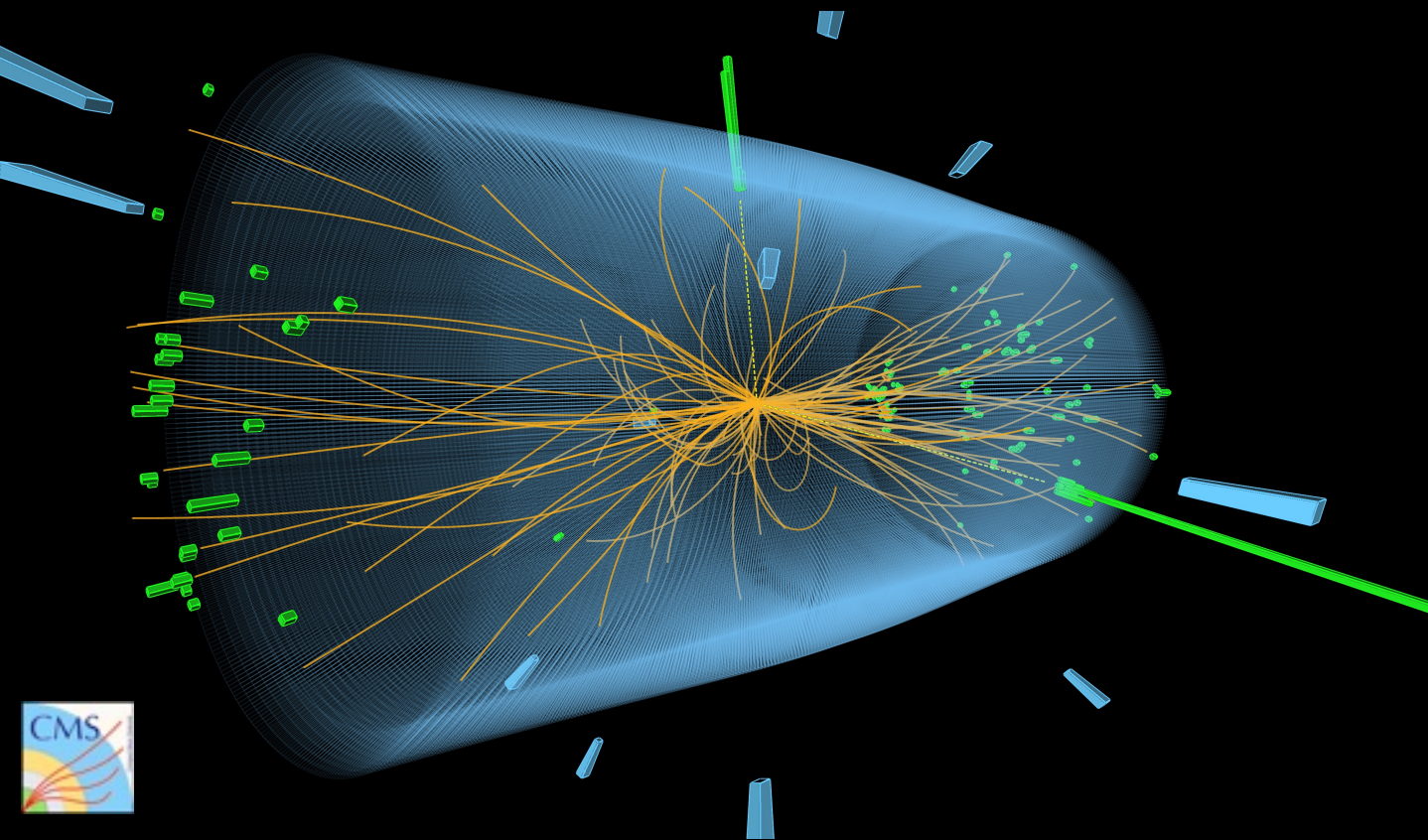
Aerial view

A monumental discovery



Presentation of Higgs boson discovery by ATLAS and CMS at CERN on 4 July 2012

A monumental discovery

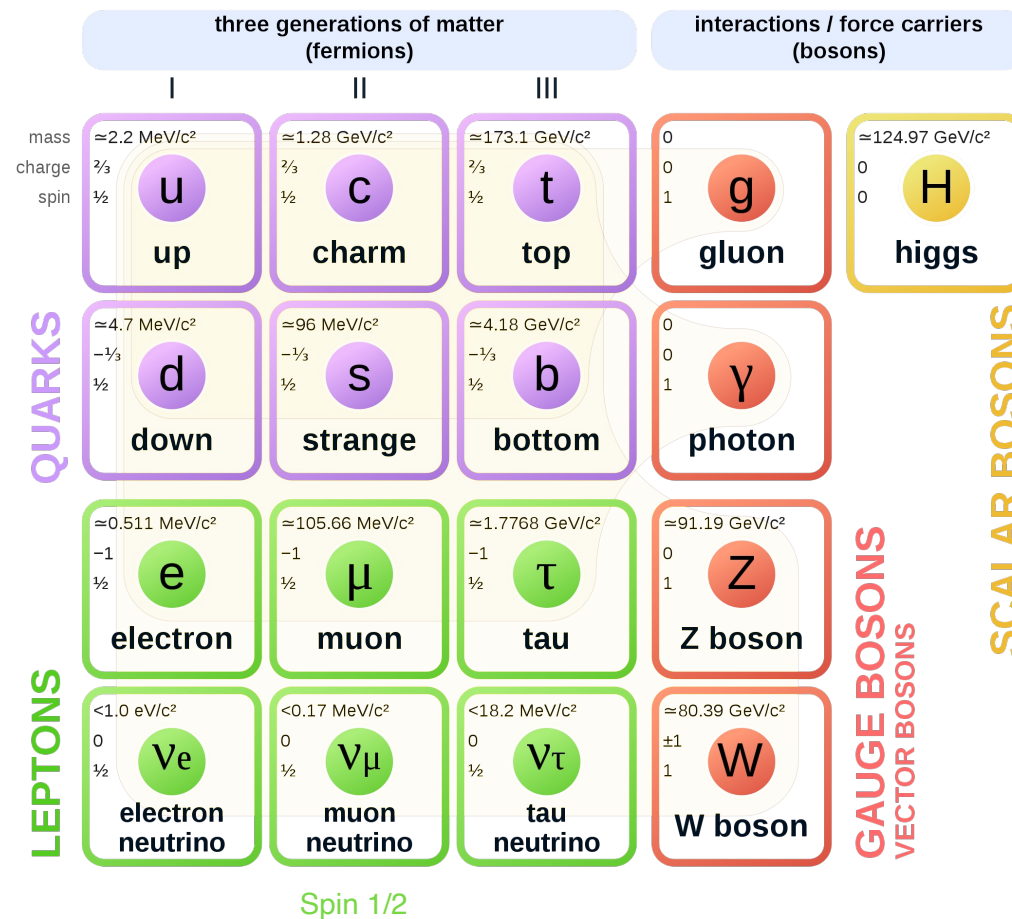


Presentation of Higgs boson discovery by ATLAS and CMS at CERN on 4 July 2012

The fundamental universe is profoundly strange

The sub-atomic structure of matter and its interactions is described by the [Standard Model \(SM\)](#)

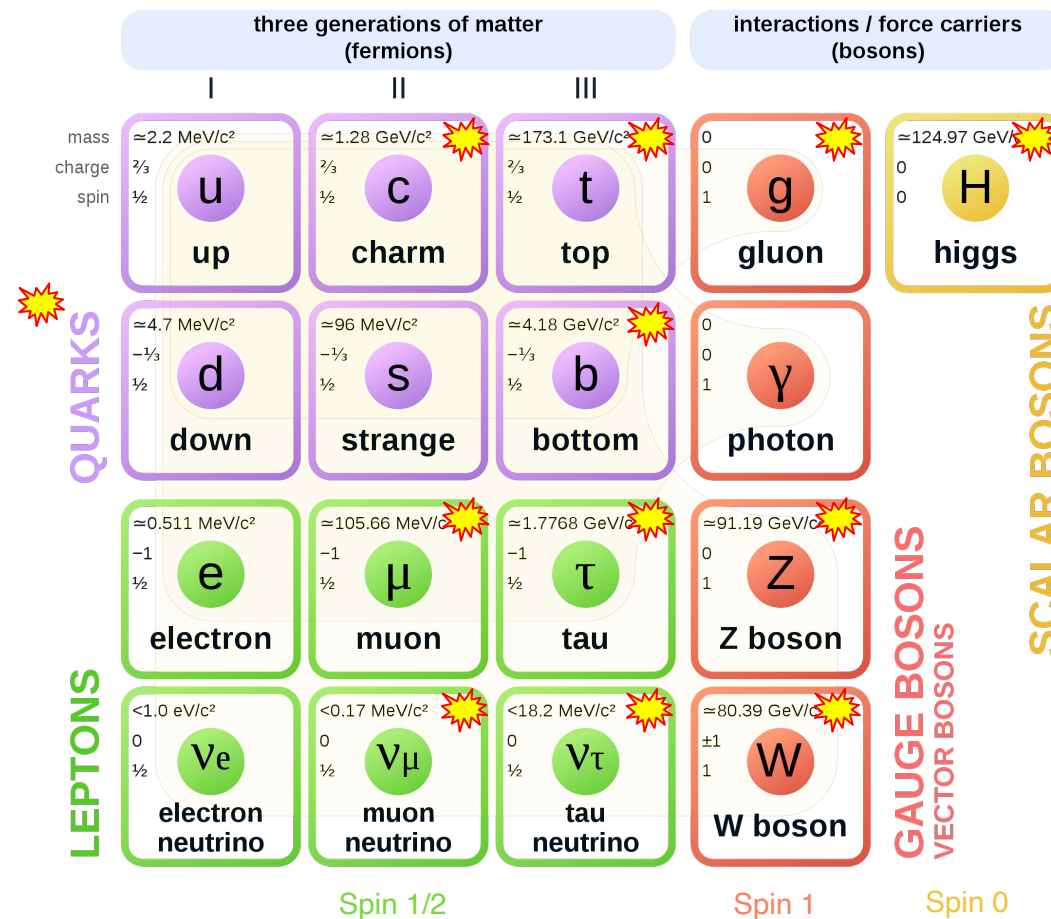
Standard Model of Elementary Particles



The fundamental universe is profoundly strange

The sub-atomic structure of matter and its interactions is described by the **Standard Model (SM)**

Standard Model of Elementary Particles



☀ Particles discovered through decades of **international, high-technology accelerator-based** research

The fundamental universe is profoundly strange

The sub-atomic structure of matter and its interactions is described by the **Standard Model (SM)**

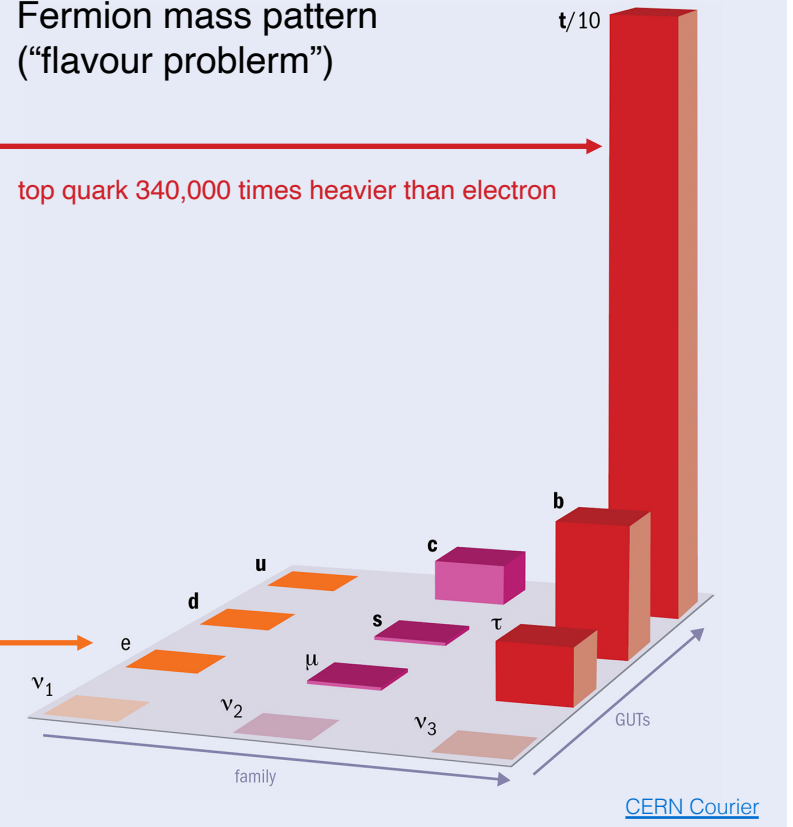
Standard Model of Elementary Particles

three generations of matter (fermions)			
	I	II	III
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
QUARKS	u up	c charm	t top
	$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$\approx 96 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom
	$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ e electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ μ muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 $\frac{1}{2}$ τ tau
LEPTONS	$< 1.0 \text{ eV}/c^2$ 0 $\frac{1}{2}$ ν_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_μ muon neutrino	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_τ tau neutrino

Spin 1/2

Fermion mass pattern
("flavour problem")

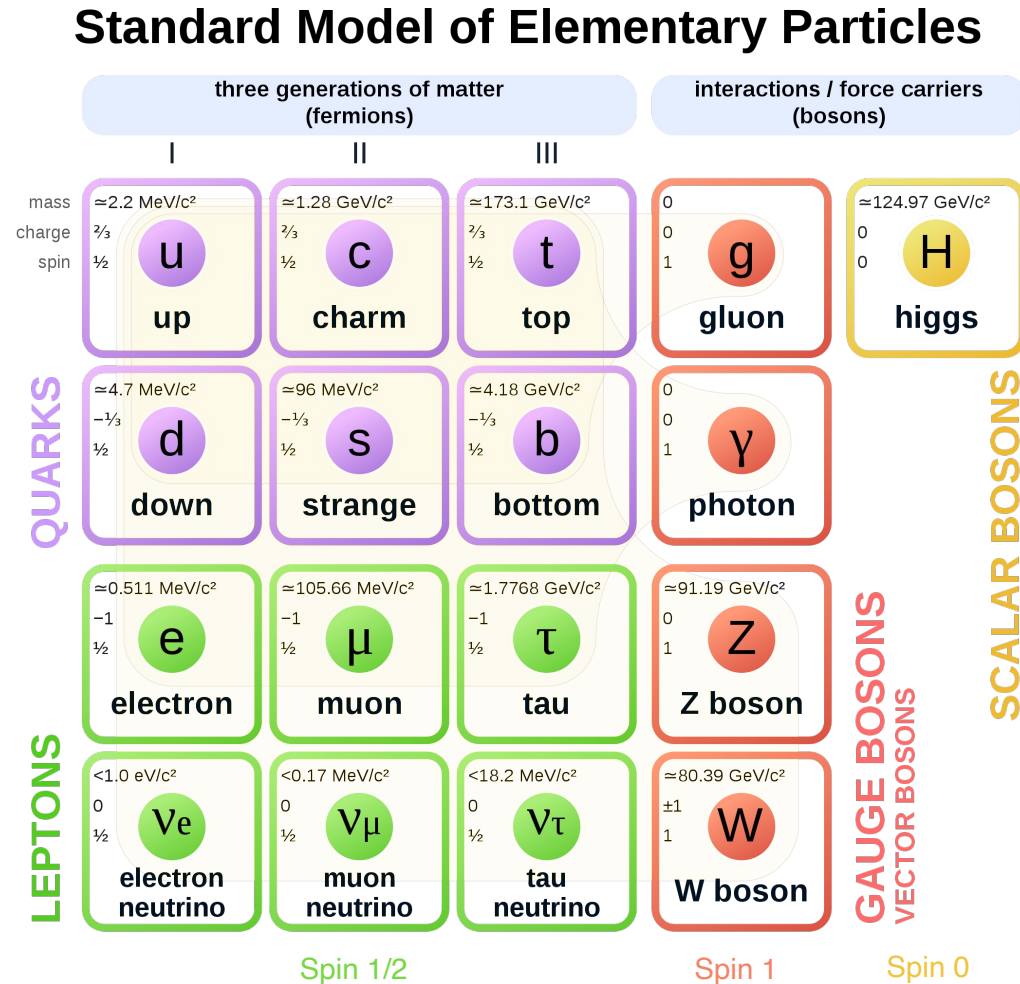
top quark 340,000 times heavier than electron



CERN Courier

The fundamental universe is profoundly strange

The sub-atomic structure of matter and its interactions is described by the **Standard Model (SM)**



New kind of interactions, unlike any known force

A manifestation of a vacuum field that gives elementary particles mass according to their coupling strength

The core conceptual challenges of the SM are tied to the Higgs sector (unstable mass)

The Higgs may also hold clues to dark matter, matter–antimatter asymmetry, and physics beyond the SM

Is the Brout-Englert-Higgs mechanism real?

Discovery of Higgs boson enables the direct study of electroweak symmetry breaking and the process of mass generation

The image features a black mug with the following handwritten text:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \text{h.c.} + \chi_i y_{ij} \chi_j \phi + \text{h.c.} + |D_\mu \phi|^2 - V(\phi) + \dots$$

Below the equations, it says: "Unpleasant scalar sector (23 parameters) — key to many mysteries".

Four callout boxes show Feynman diagrams for Higgs couplings:

- Top-left:** A dashed line labeled H enters a vertex from the left. Two solid lines labeled f exit the vertex to the right. The vertex is labeled κ_f . The coupling is proportional to $\frac{m_f}{v}$.
- Top-right:** A dashed line labeled H enters a vertex from the left. Two dashed lines labeled H exit the vertex to the right. The vertex is labeled κ_λ . The coupling is proportional to $\frac{3m_H^2}{v}$.
- Bottom-left:** A dashed line labeled H enters a vertex from the left. Two wavy lines labeled W/Z exit the vertex to the right. The vertex is labeled $\kappa_{W/Z}$. The coupling is proportional to $\frac{2m_{W/Z}^2}{v}$.
- Bottom-right:** A dashed line labeled H enters a vertex from the left. Two solid lines labeled f exit the vertex to the right. The vertex is labeled κ_f . The coupling is proportional to $\frac{m_f}{v}$.

Coupling strength modifiers: $\kappa_i = \kappa_i^{\text{obs}} / \kappa_i^{\text{SM}}$

The Brout-Englert-Higgs mechanism is real !

Discovery of Higgs boson enables the direct study of electroweak symmetry breaking and the process of mass generation

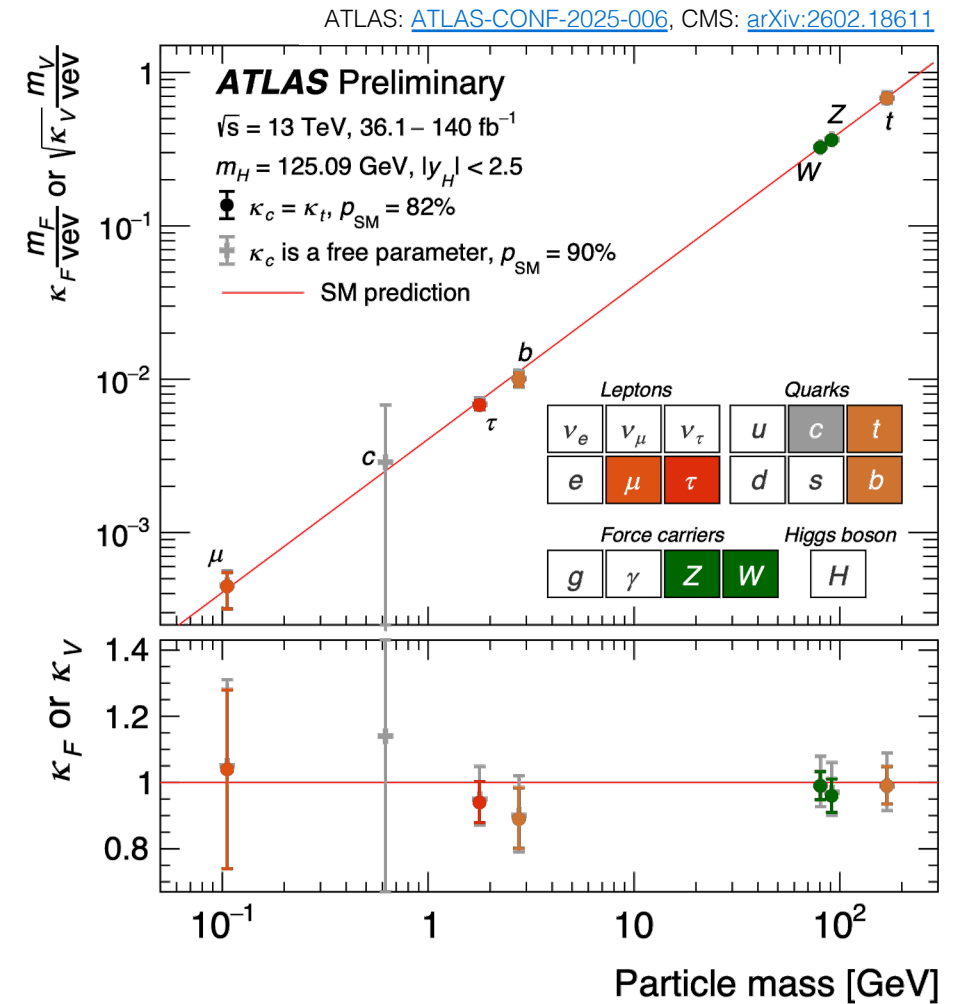
BREAKTHROUGH PRIZE
2013, 2025

Coupling strength modifiers: $\kappa_i = \kappa_i^{\text{obs}} / \kappa_i^{\text{SM}}$

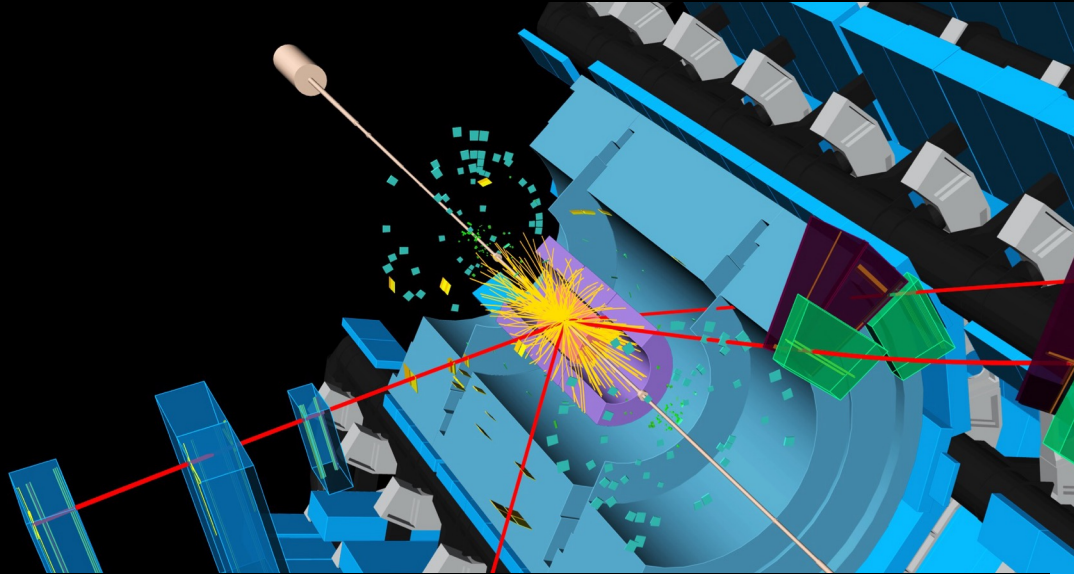
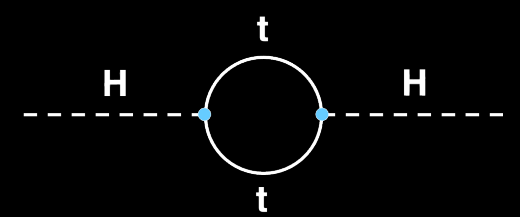
Diagram 1: Higgs boson decay into two fermions (f). The coupling is $\kappa_f \propto \frac{m_f}{v}$.

Diagram 2: Higgs boson decay into two Higgs bosons (H). The coupling is $\kappa_\lambda \propto \frac{3m_H^2}{v}$.

Diagram 3: Higgs boson decay into two W/Z bosons. The coupling is $\kappa_{W/Z} \propto \frac{2m_{W/Z}^2}{v}$.



The Brout-Englert-Higgs mechanism is real



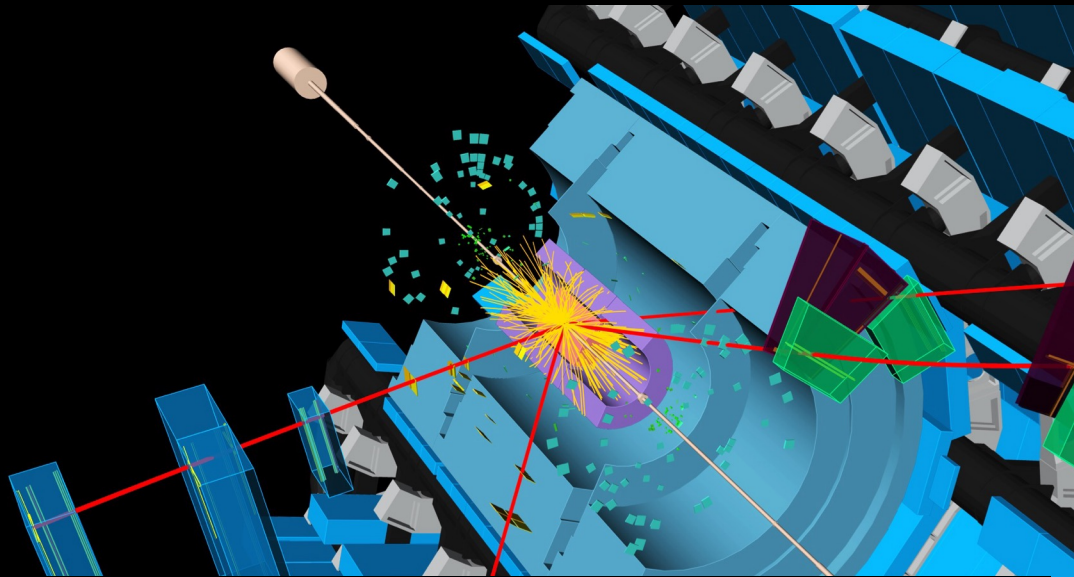
The new Higgs sector opens up a range of possibilities and raises a number of important questions

The Higgs boson and open questions in particle physics and cosmology

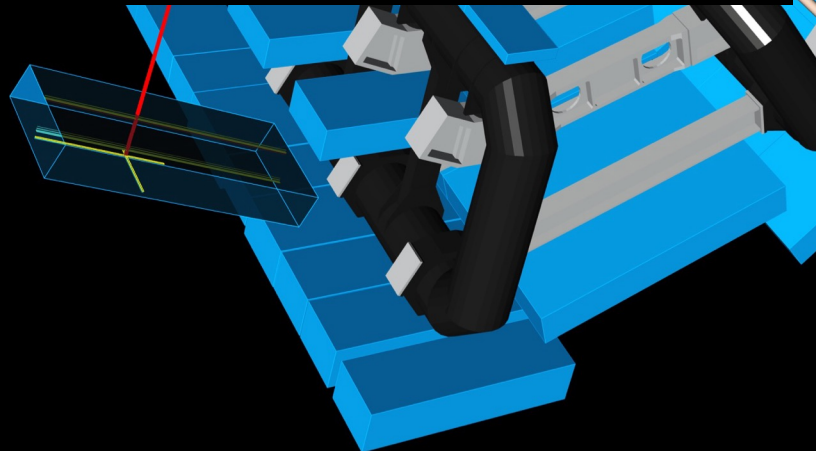
- Why is the Higgs boson so light?
- Is the Higgs boson elementary or composite ?
- Do Higgs interactions violate matter-antimatter symmetry?
- Is the Higgs boson unique?
- Does the Higgs boson couple to dark matter?
- What is the origin of the large mass hierarchy of the fermions in the Standard Model?
- What is the form of the Higgs energy potential; is the vacuum metastable?
- Is the Higgs field connected with cosmic inflation?
- Why is the dark energy in the universe so much smaller than the Higgs vacuum energy?

See, eg: [Salam, Wang, Zanderighi: Nature 607, 41 \(2022\)](#)

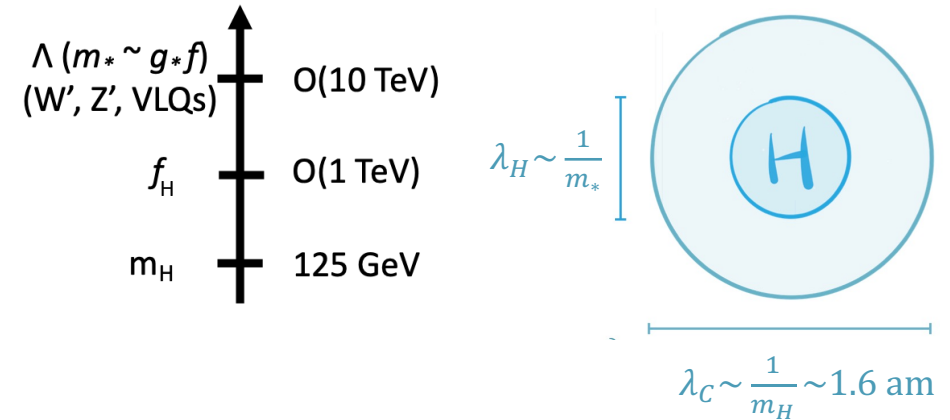
Is the Higgs boson elementary?



Higgs doublet might emerge as a composite bound state of a global symmetry that is spontaneously broken by new strong dynamics



Potential spectrum of putative new strong dynamics



In strongly interacting light Higgs (SILH) models, strong dynamics modifies the Higgs kinetic term, leading to a universal rescaling of all Higgs couplings

$$\kappa_i \rightarrow \kappa_i \left(1 - \frac{c_H v^2}{f_H^2} \right) = \kappa_i (1 - c_H \xi)$$

The **best measured coupling probes compositeness** of the Higgs boson!

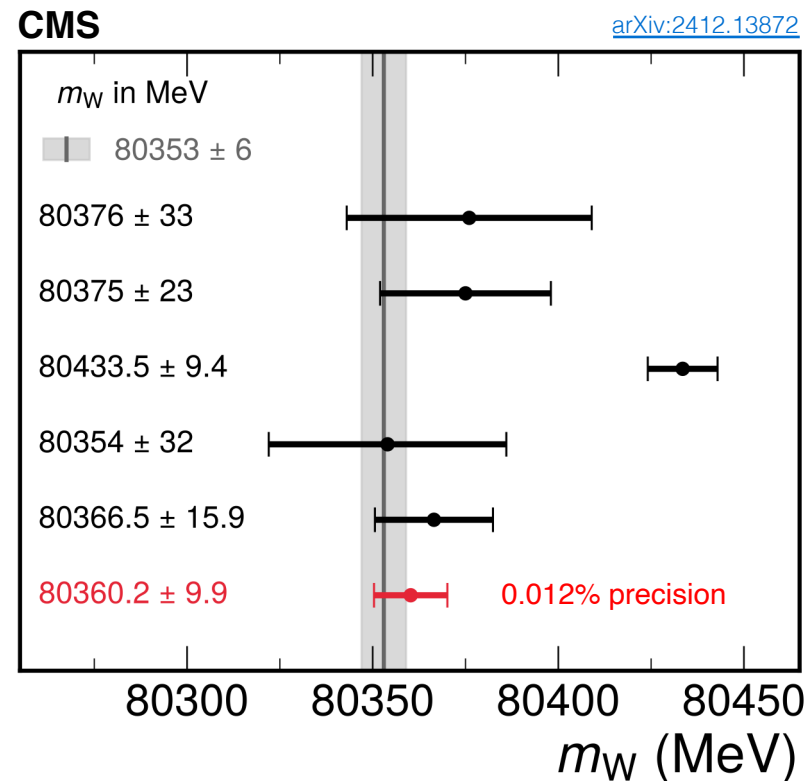
5.0 (0.1)% precision on κ_i probes $f_H \sim 1.1$ (7.8) TeV

The LHC delivers precision physics

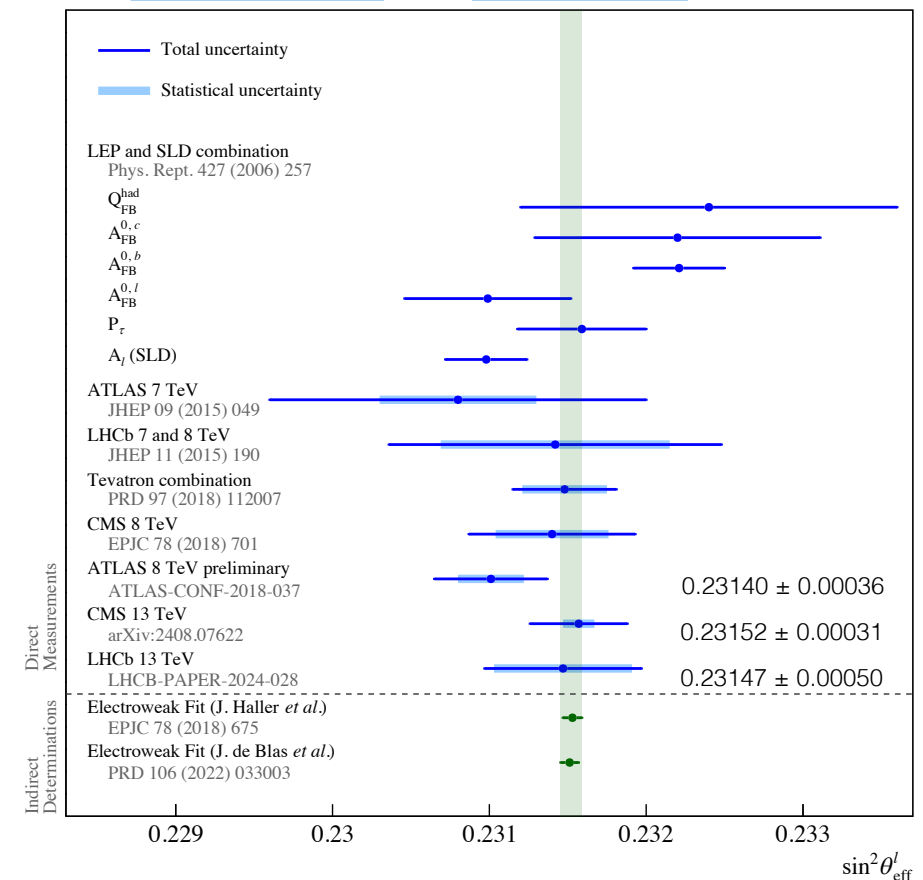
Hadron colliders are discovery *and* precision machines

- $m_H = 125.11 \pm 0.11$ GeV [0.09%, ATLAS, $4\ell + \gamma\gamma$ | [PRL 131 \(2023\) 251802](#)], 125.07 ± 0.13 GeV [CMS, $\gamma\gamma$ | [CMS-PAS-HIG-24-007](#)]
- $m_{\text{top}} = 172.52 \pm 0.33$ GeV [0.2%, LHC combination | [PRL 132 \(2024\) 261902](#)]
- W mass (bottom)
- Weak mixing angle (right)

Electroweak fit
PRD 110 (2024) 030001
LEP combination
Phys. Rep. 532 (2013) 119
D0
PRL 108 (2012) 151804
CDF
Science 376 (2022) 6589
LHCb
JHEP 01 (2022) 036
ATLAS
arXiv:2403.15085
CMS
This work

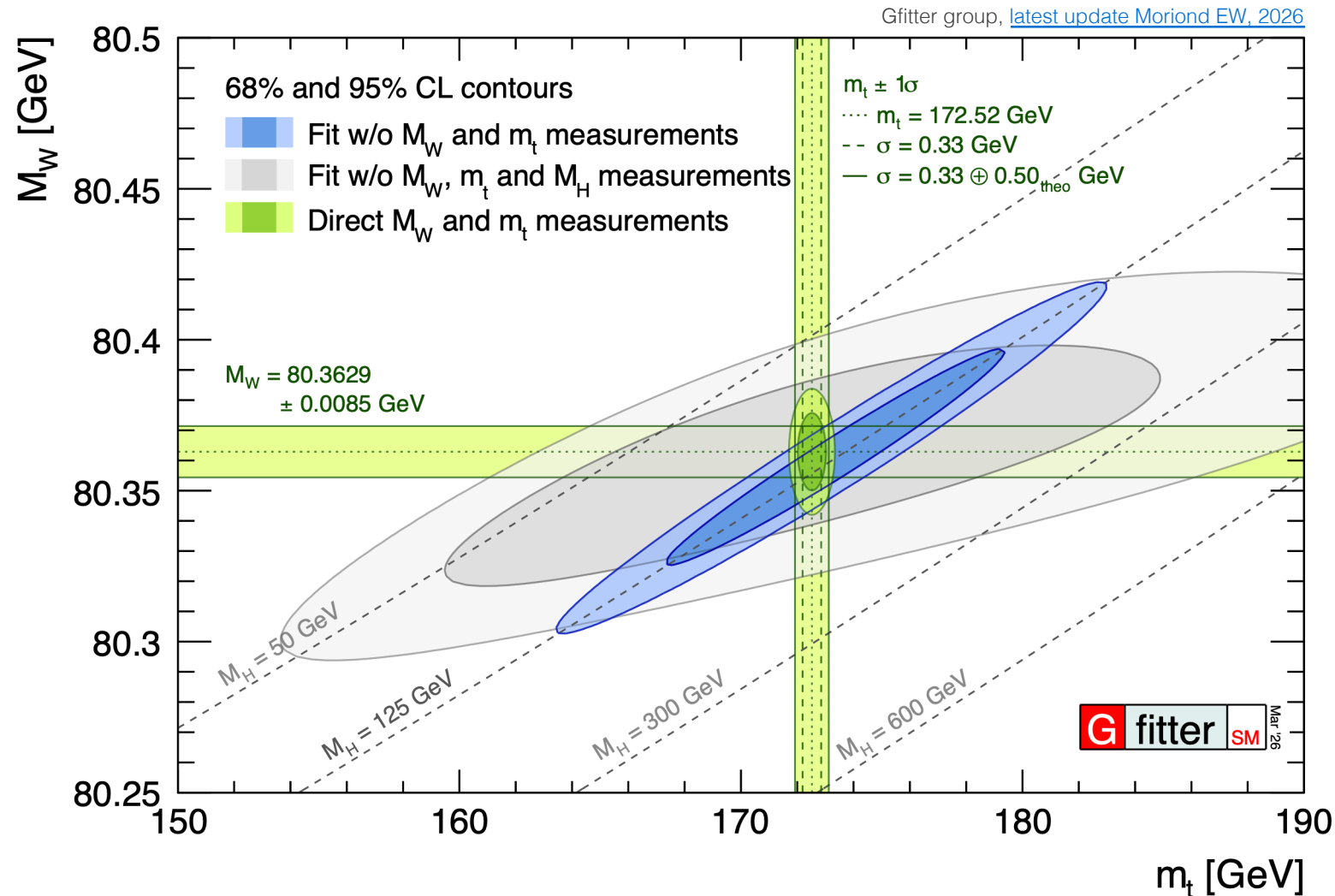


CMS: [PLB 866 \(2025\) 139526](#), LHCb: [JHEP 12 \(2024\) 026](#)



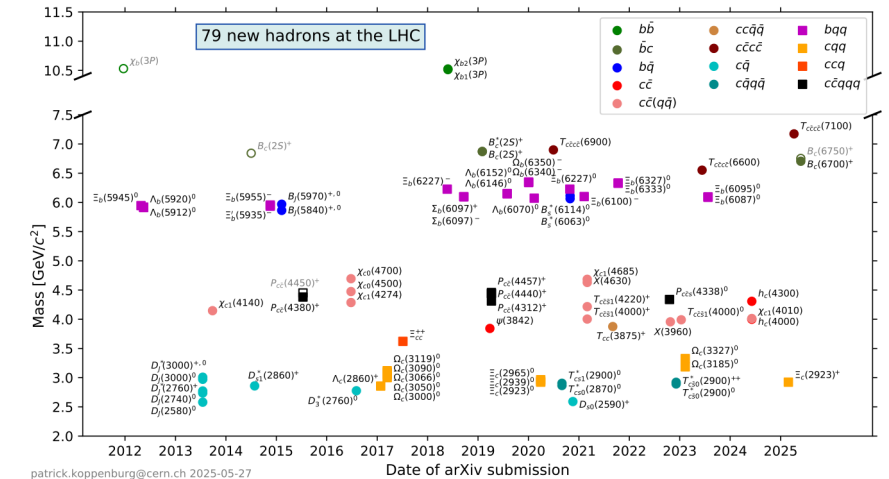
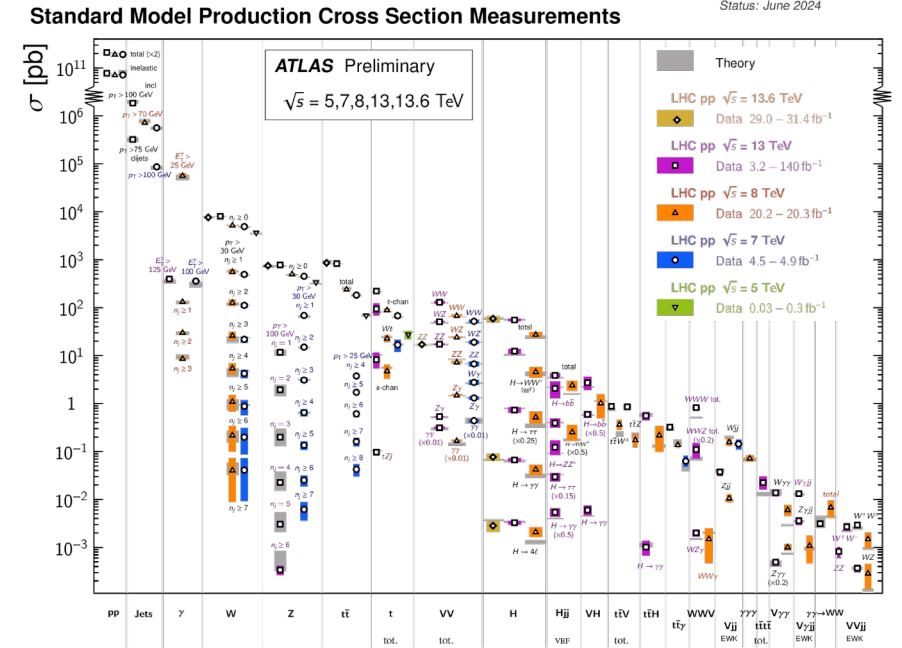
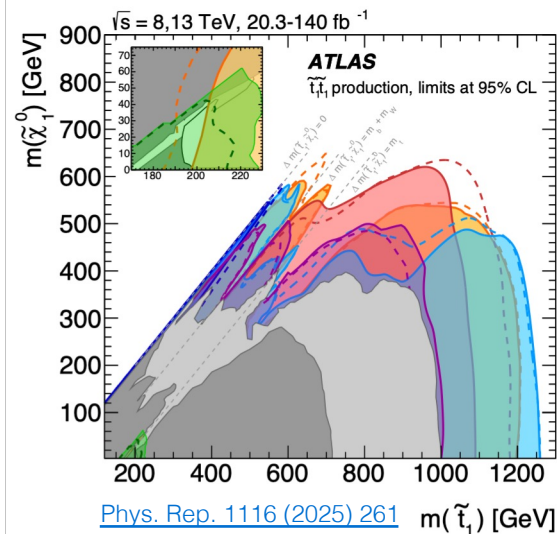
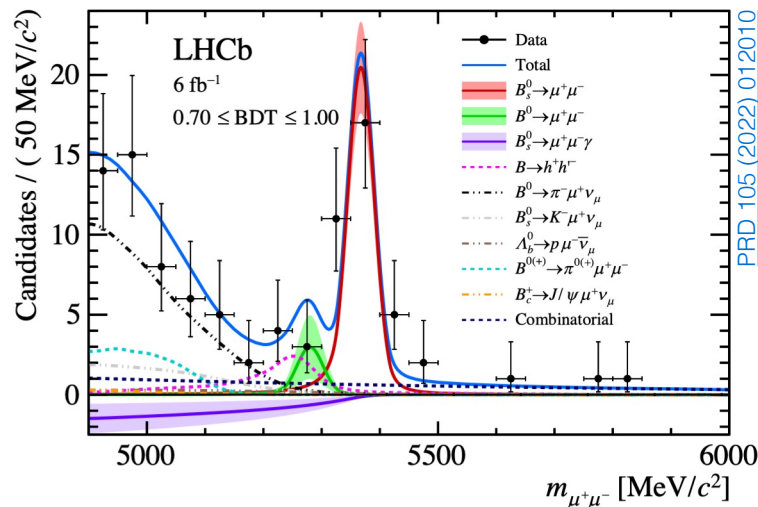
The LHC delivers precision physics

Global Electroweak Fit — Testing the Standard Model



We have learned so much more at the LHC ...

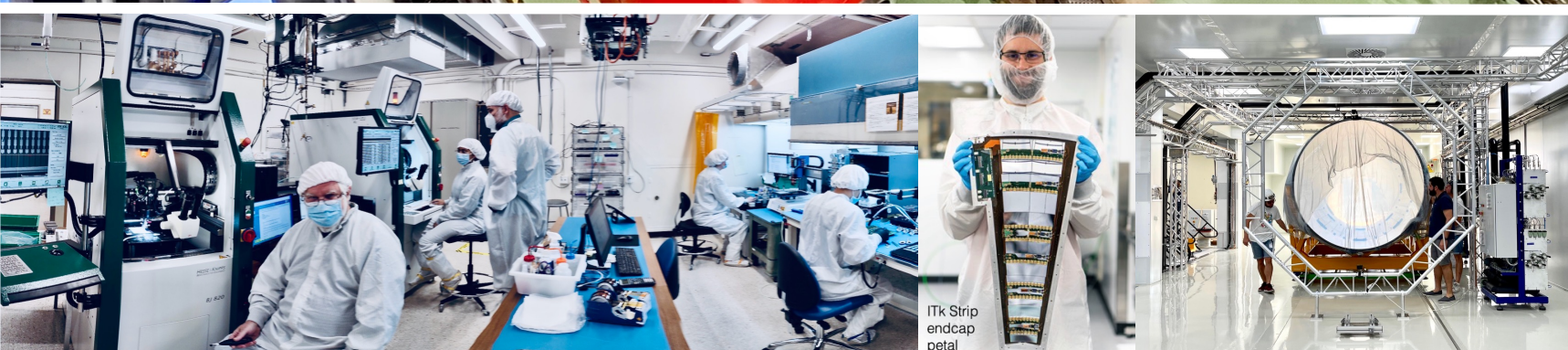
- A plethora of measurements, some involving extremely rare and sensitive processes, confirm the predictive power of the SM and deepen our understanding
- 82 new hadronic bound states discovered so far (most by LHCb), 28 of which exotic, the heaviest being toponium
- Heavy-ion collisions enabled unprecedented insights into the quark-gluon plasma
- Searches for new phenomena have set tight constraints on some of the most popular SM extensions, thus completely changing the field of beyond the SM physics





Upgrade to the High-Luminosity LHC is under way

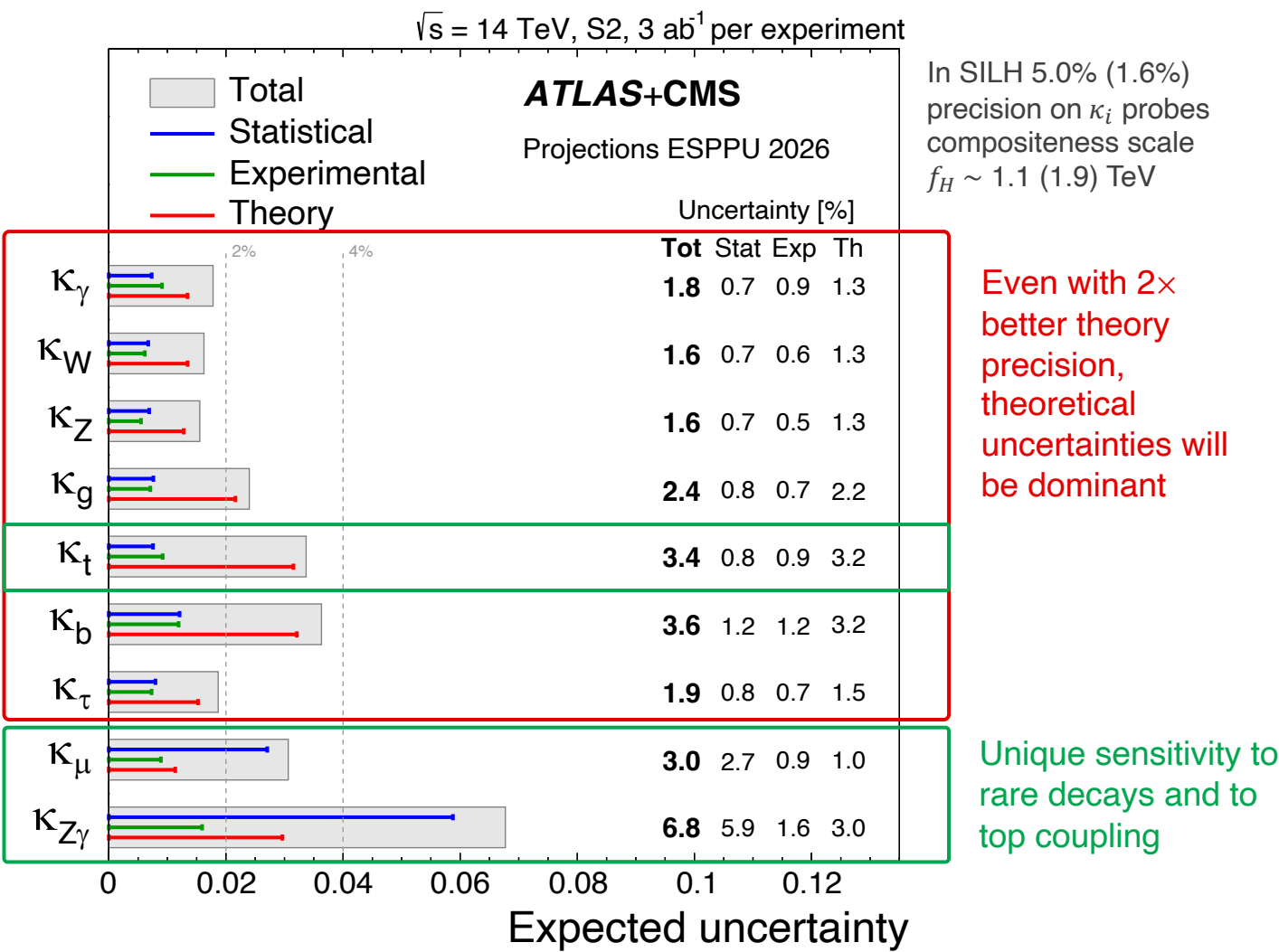
- The HL-LHC will use new technologies to provide 6 times more collisions than the LHC
- Intensities require large-scale detector upgrades
- It will start operating in 2030 and run until 2041, delivering 3000 fb^{-1}
- **Complementary in many ways to the FCC-ee / CEPC**



ITk Strip
endcap
petal

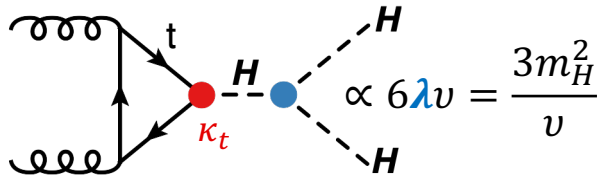
HL-LHC Physics prospects — Higgs

Higgs coupling prospects | Coupling strength modifiers ($\kappa_i^2 \equiv \sigma_i/\sigma_i^{SM}$, assuming SM Γ_H)



Cornering the Higgs potential through Higgs self-coupling

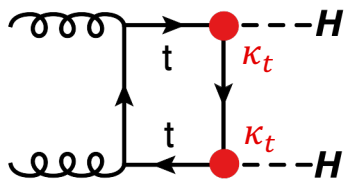
Higgs self-coupling via Higgs pair production: complex final states, eldorado for ML enthusiasts, strongest channels: $HH \rightarrow b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$. Best sensitivity to λ at low $m(HH)$



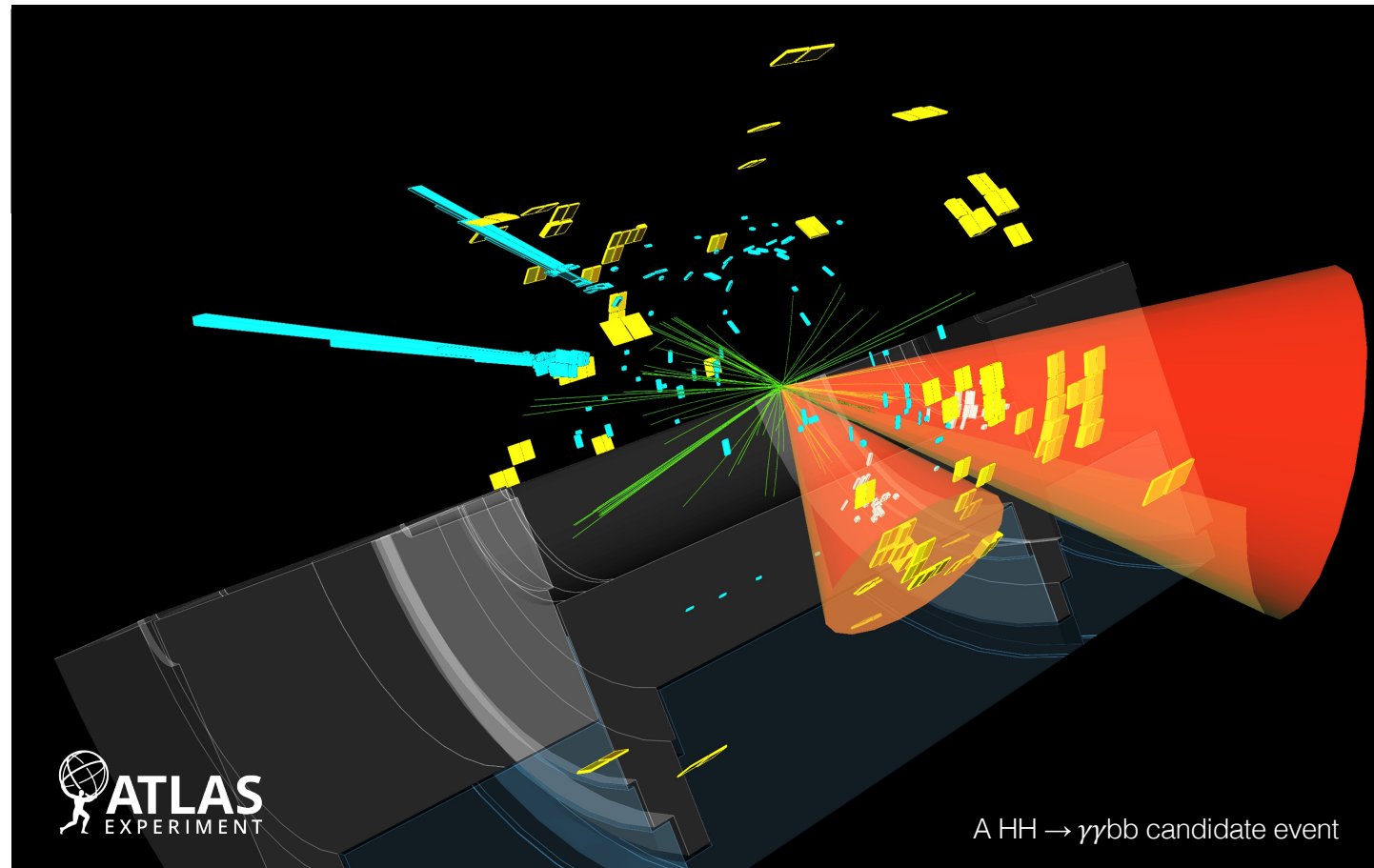
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

$$\kappa_\lambda \equiv \lambda^{\text{obs}}/\lambda^{\text{SM}}$$

Destructive interferes with box diagram:

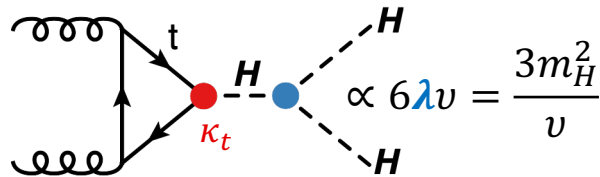


Very small HH SM cross section of 36 fb at 13.6 TeV, dominated by gluon fusion



Cornering the Higgs potential through Higgs self-coupling

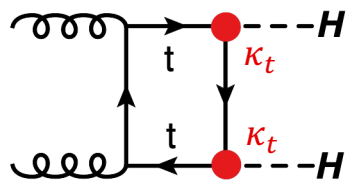
Higgs self-coupling via Higgs pair production: complex final states, eldorado for ML enthusiasts, strongest channels: $HH \rightarrow b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $bbbb$. Best sensitivity to λ at low $m(HH)$



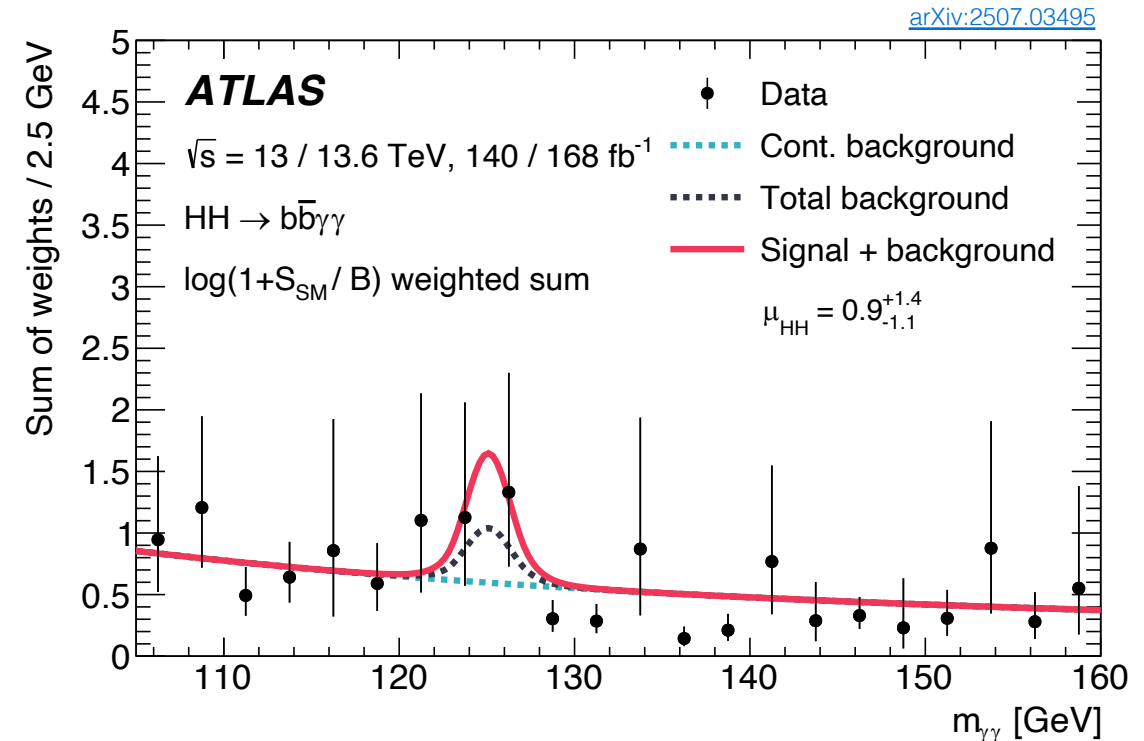
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

$$\kappa_\lambda \equiv \lambda^{\text{obs}}/\lambda^{\text{SM}}$$

Destructive interferes with box diagram:



Very small HH SM cross section of 36 fb at 13.6 TeV, dominated by gluon fusion



First Run-2+3 result on $HH \rightarrow b\bar{b}\gamma\gamma$:

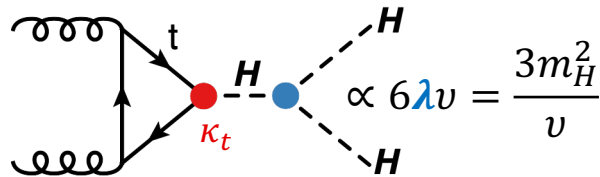
- Signal strength: $0.9^{+1.4}_{-1.1}$
- $\kappa_\lambda = 1.3^{+3.8}_{-1.8}$

ATLAS & CMS Run-2 combination:

- Signal strength: $0.8^{+0.9}_{-0.7}$
- $\kappa_\lambda = 1.8^{+2.8}_{-1.4}$ [arXiv:2602.23991](https://arxiv.org/abs/2602.23991)

Cornering the Higgs potential through Higgs self-coupling

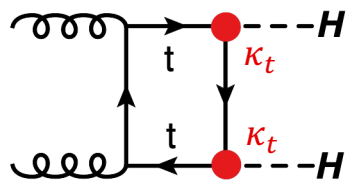
Higgs self-coupling via Higgs pair production: complex final states, eldorado for ML enthusiasts, strongest channels: $HH \rightarrow b\bar{b}\gamma\gamma, b\bar{b}\tau^+\tau^-, b\bar{b}b\bar{b}$. Best sensitivity to λ at low $m(HH)$



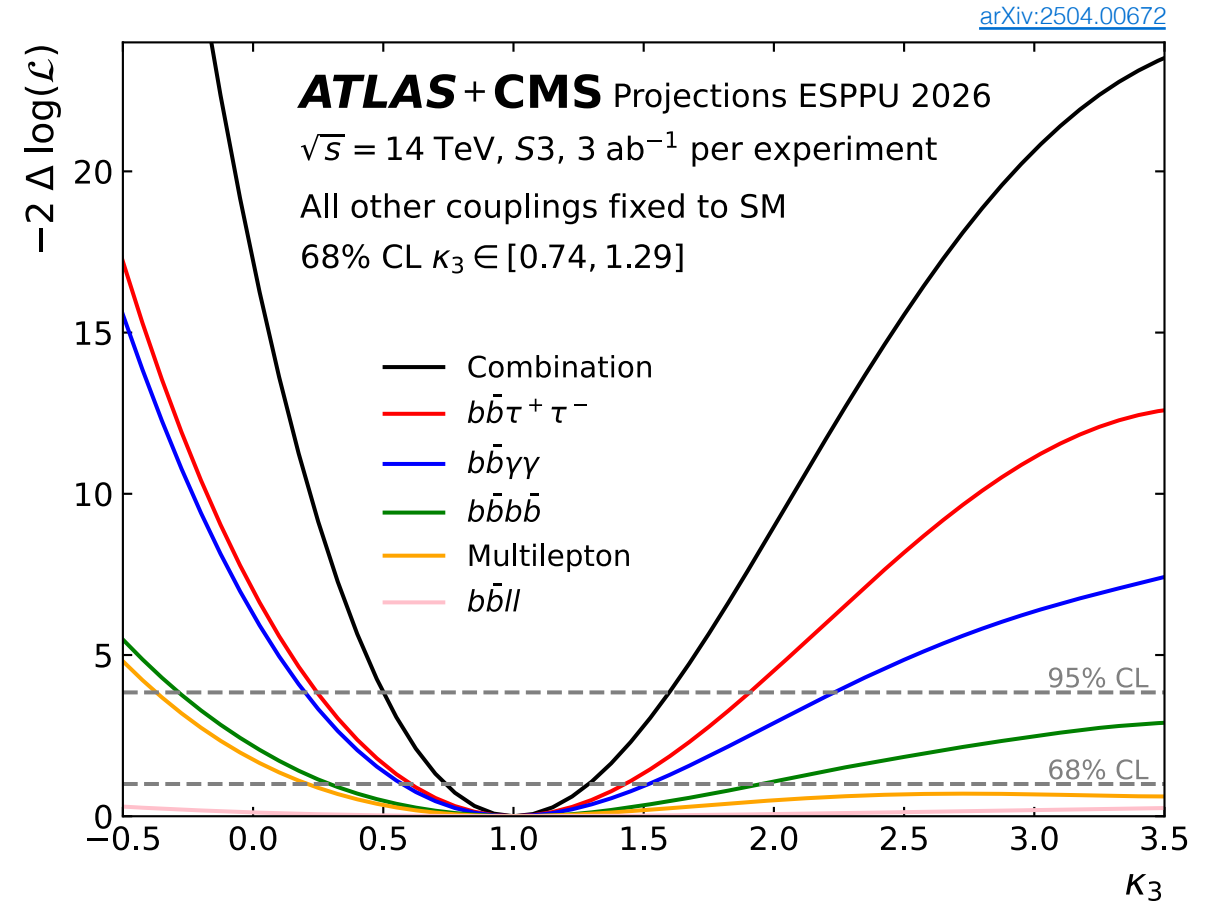
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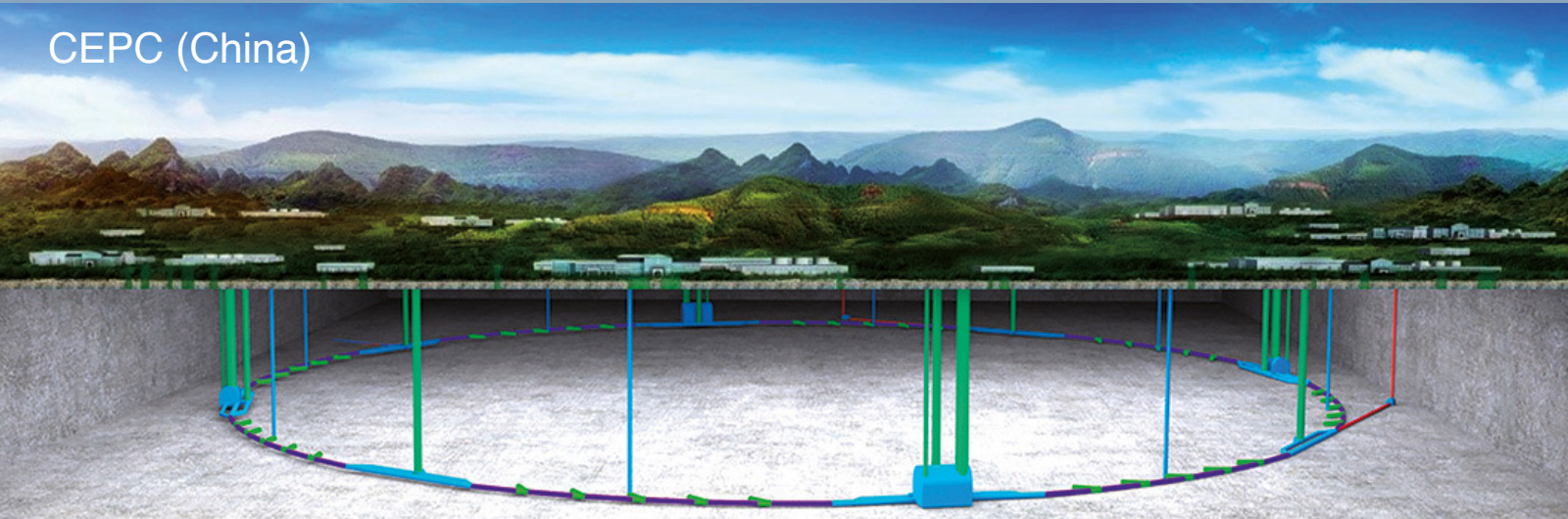


For SM at HL-LHC: expect HH observed $> 7\sigma$, and λ precision $< 30\%$

New facilities to explore the high-precision and high-energy frontiers

90–100 km circumference tunnels to host an e^+e^- and a hadron collider

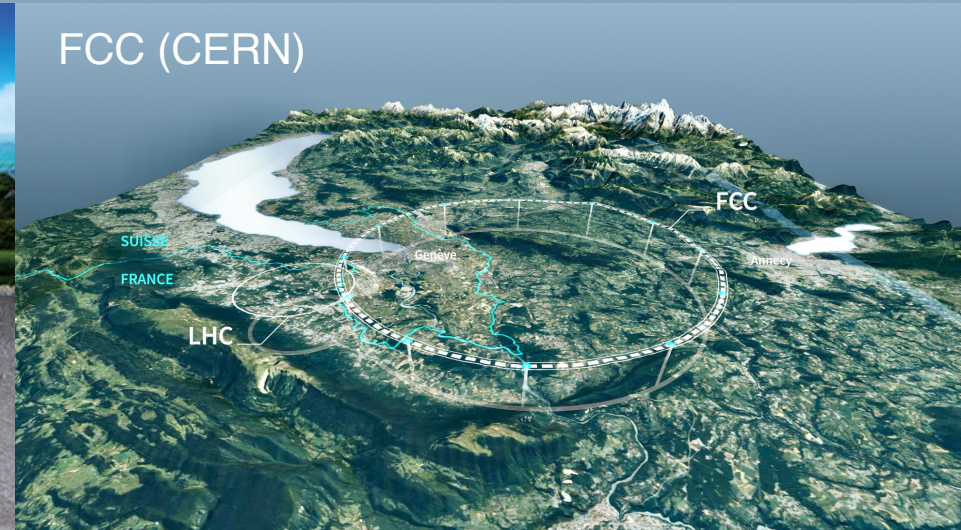
CEPC (China)



CEPC TDR: [arXiv:2312.14363](https://arxiv.org/abs/2312.14363)
Detector TDR: [arXiv:2510.05260](https://arxiv.org/abs/2510.05260)

CEPC proposal was submitted in 2025 to Chinese Academy of Science for inclusion in 15th 5-year plan, but not retained. R&D continues, increased collaboration with FCC-ee, and resubmission in 2030 if FCC-ee does not go ahead

FCC (CERN)

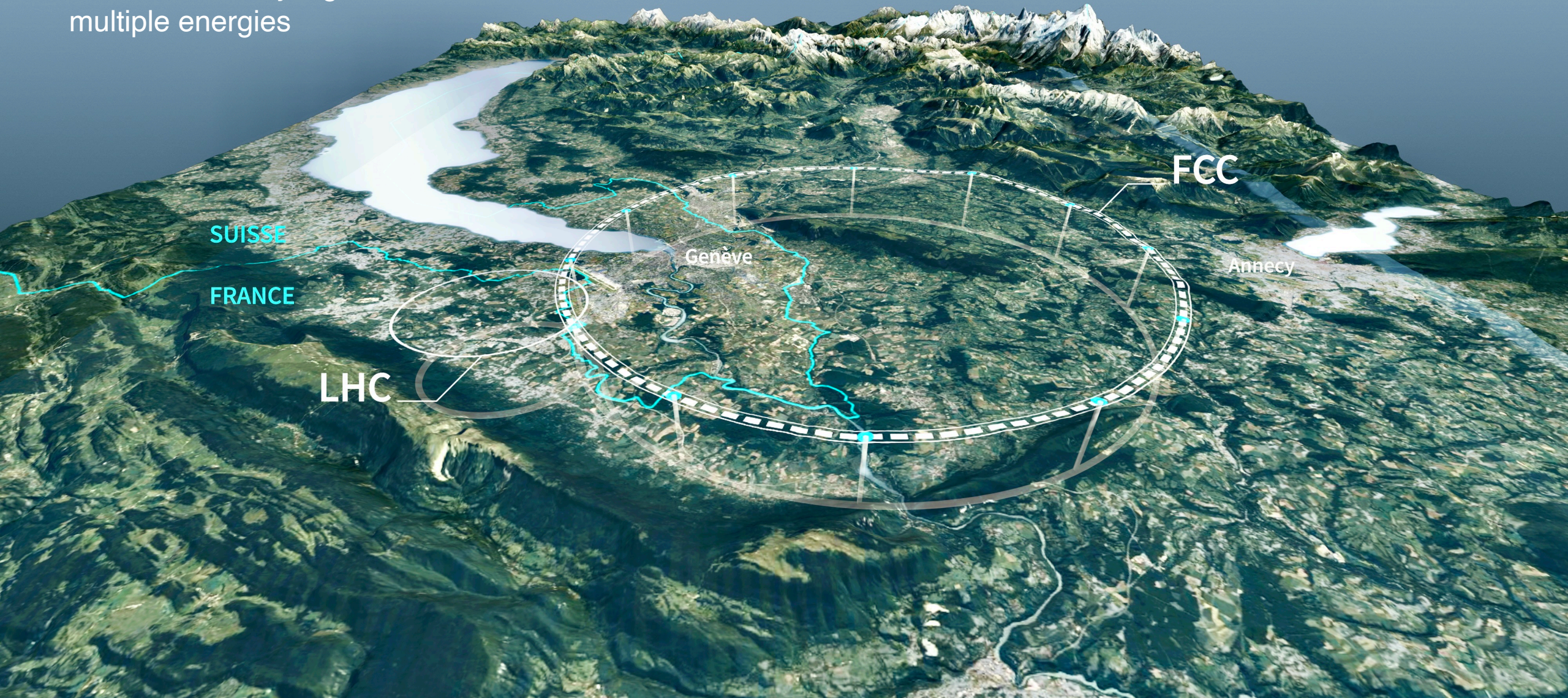


Feasibility study: 3 volumes (physics & experiments, accelerator, civil engineering & sustainability) (March 2025), [All documents](#)

FCC-ee is proposed as CERN's next flagship collider in the 2026 European Strategy for Particle Physics update [[Link to recommendations](#) / [CERN Council resolution](#)]. Aiming at go / no-go decision by CERN Council in 2028

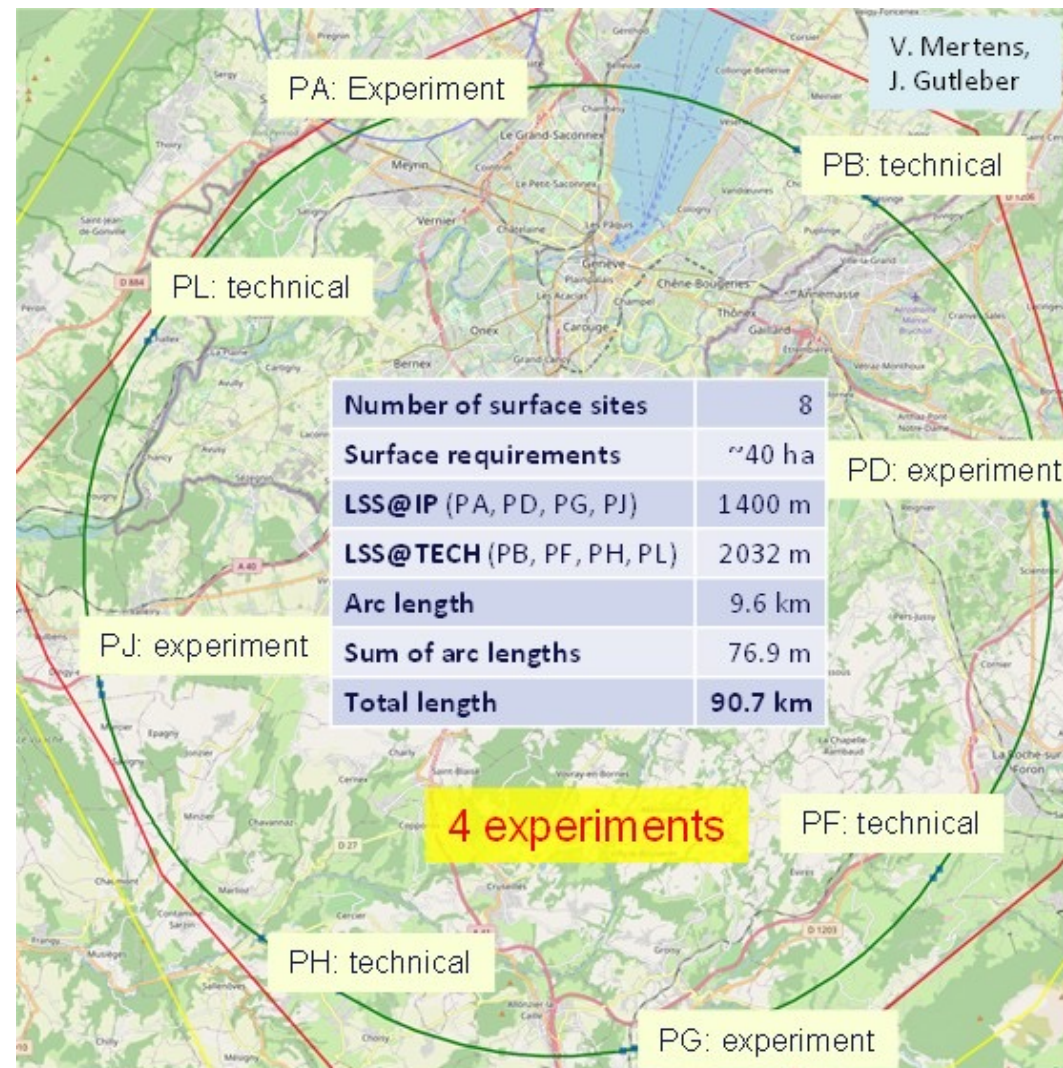
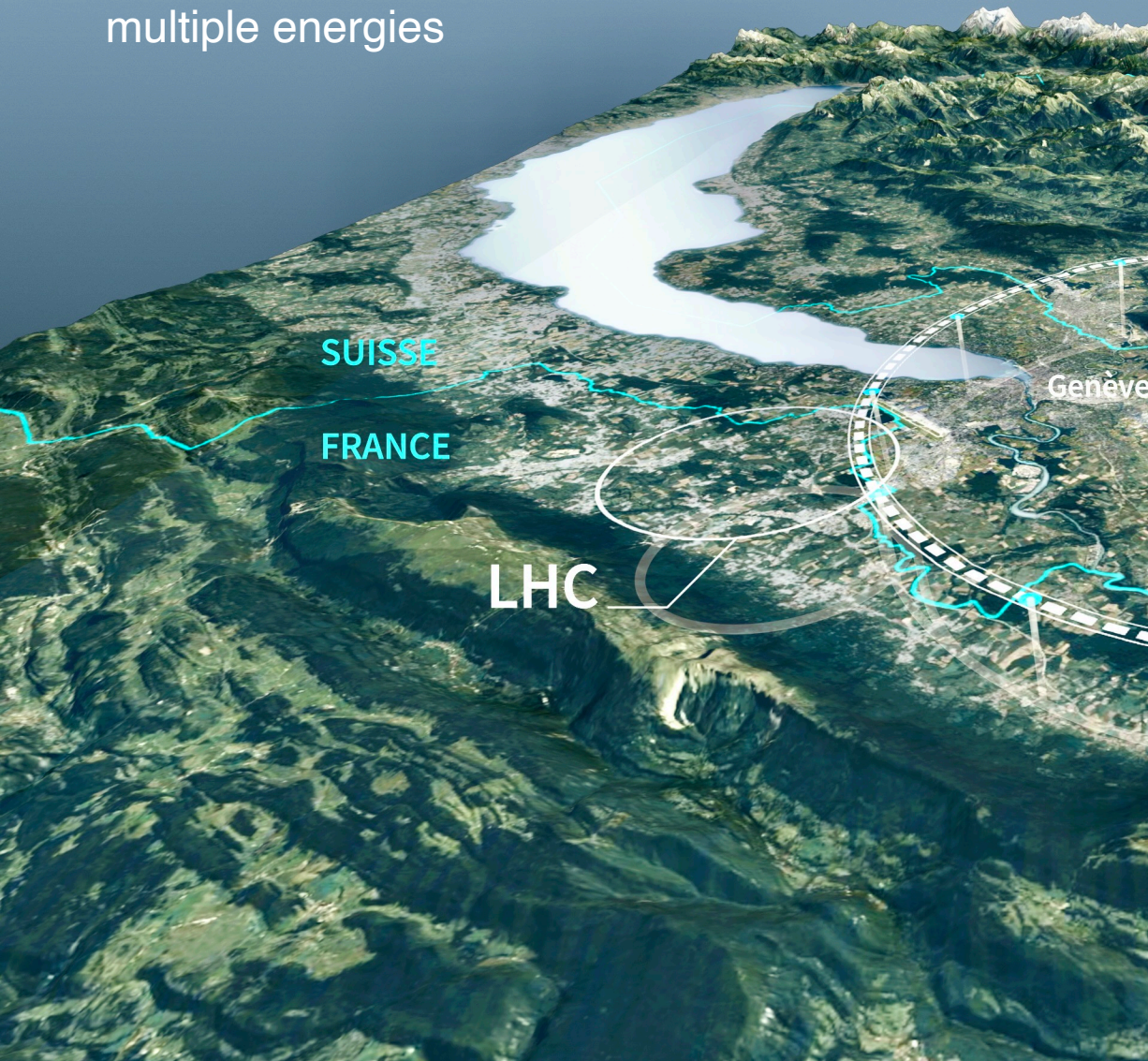
FCC-ee

Next-generation circular e^+e^- collider to deliver extremely high luminosities across multiple energies



FCC-ee

Next-generation circular e^+e^- collider to deliver extremely high luminosities across multiple energies

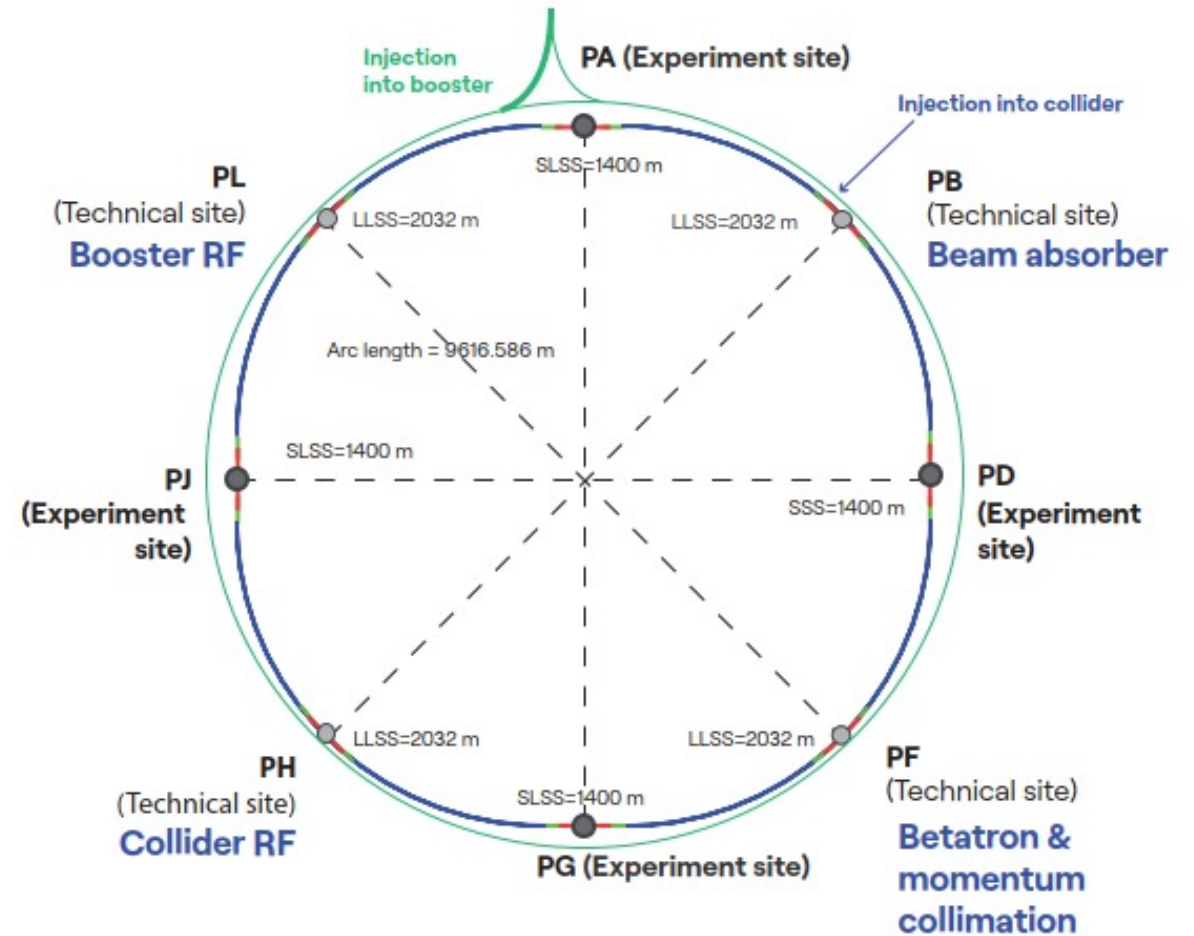
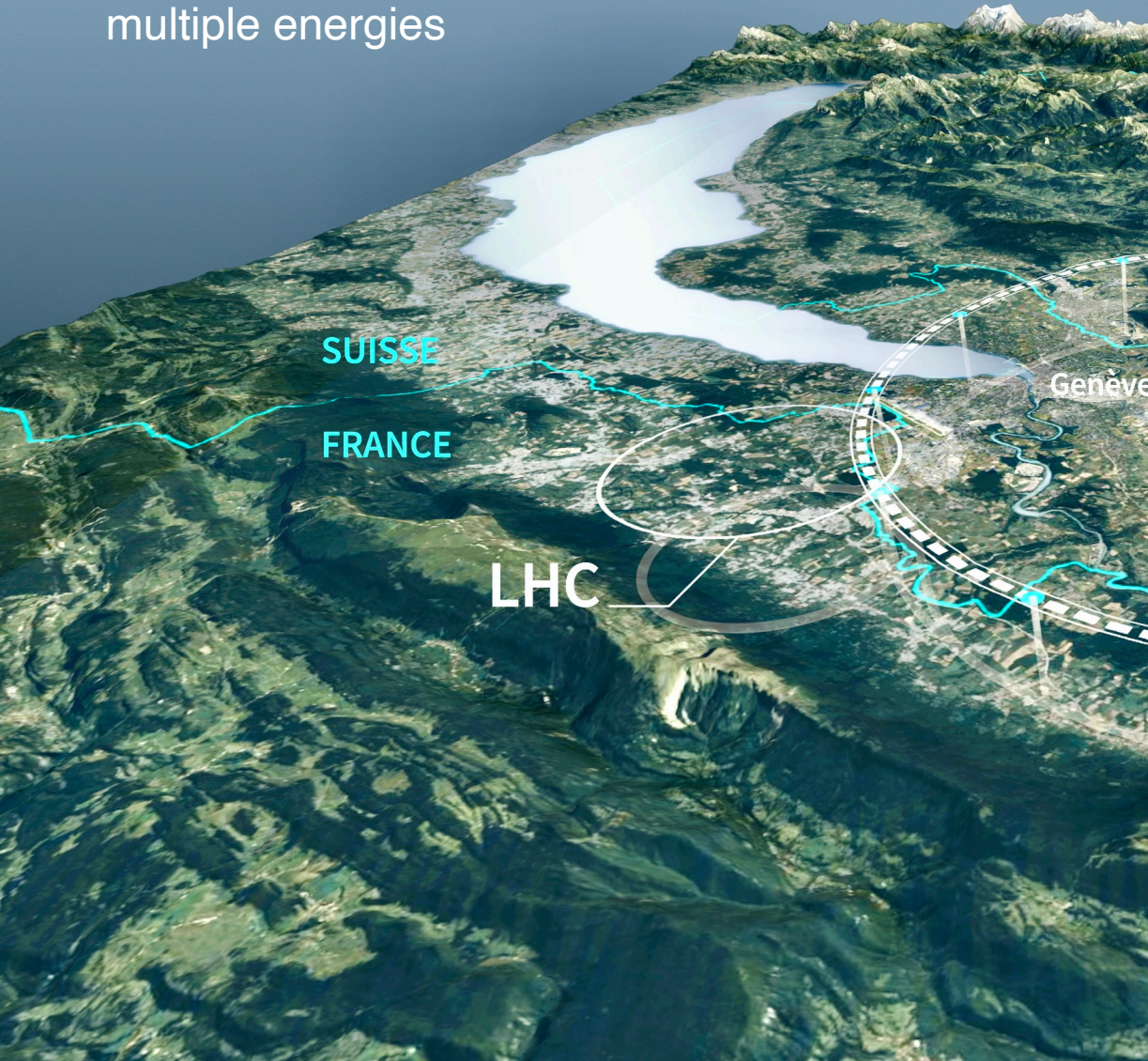


Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	90.7 km

Detailed feasibility study: layout selected from ~100 variants following the EU “Avoid–Reduce–Compensate” principle — 90.7 km ring, 8 surface sites (7 FR, 1 CH), 5.5 m tunnel diameter, 50–560 m depth

FCC-ee

Next-generation circular e^+e^- collider to deliver extremely high luminosities across multiple energies



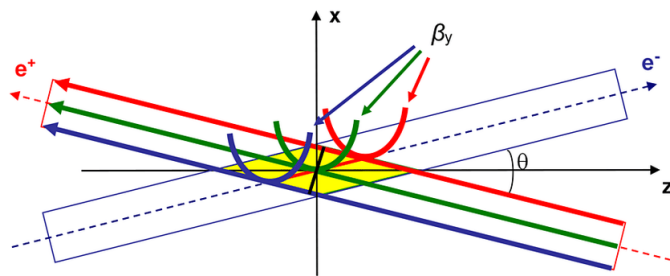
Ring structure: 4 experiments, 1 RF-section / beam, 1 collimation section, 1 section for injection and dump

Booster is single-beam synchrotron which cycles within a few seconds between accelerating and top-up injecting e^+ and e^-

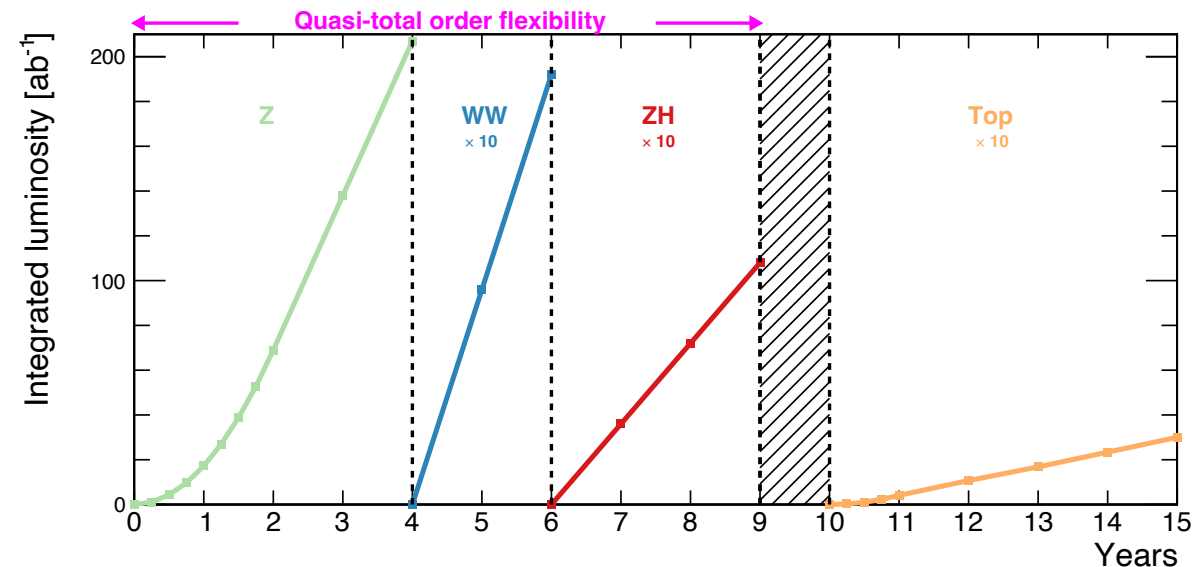
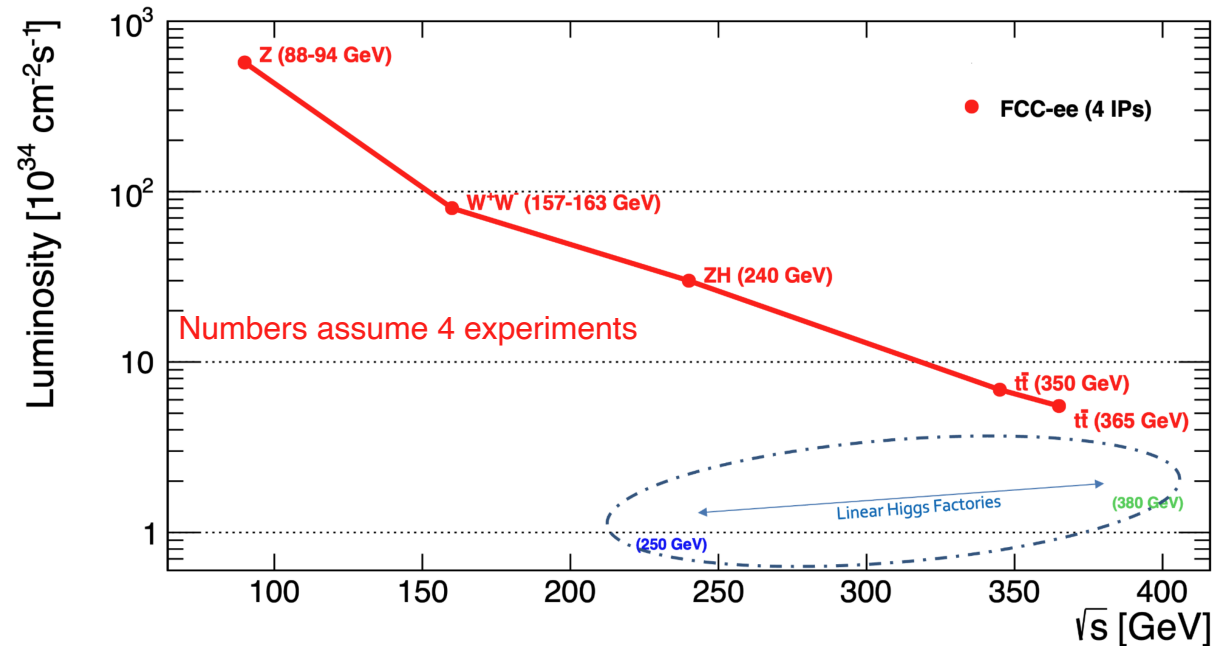
FCC-ee — maximum luminosity

FCC-ee collider concept for maximum luminosity

- **Double ring collider:** many bunches, high current, like LHC and B factories, different from LEP (CERN)
- **Top-up injection (booster) during collisions:** needed due to short luminosity lifetime ($\sim 10\text{--}20$ min, radiative Bhabhas), standard at light sources and used at PEP-II, KEKB, BEPCII. Booster intensity $\sim 1\%$ of collider; full RF voltage as in collider
- **Superconducting RF:** LEP-proven Nb/Cu 400 MHz cavities; bulk Nb 800 MHz cavities as in ESS/EuXFEL; efficient RF sources and simplified energy-switching scheme
- **Crab-waist collisions:** successfully demonstrated at DAΦNE and SuperKEKB



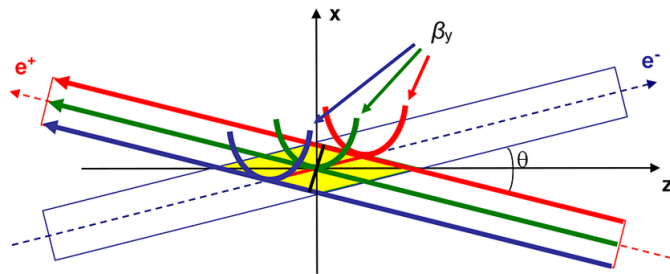
Crab waist scheme: sextupoles near IP rotate vertical waist along the opposing beam's path (and suppresses beam-beam resonances)



FCC-ee — maximum luminosity

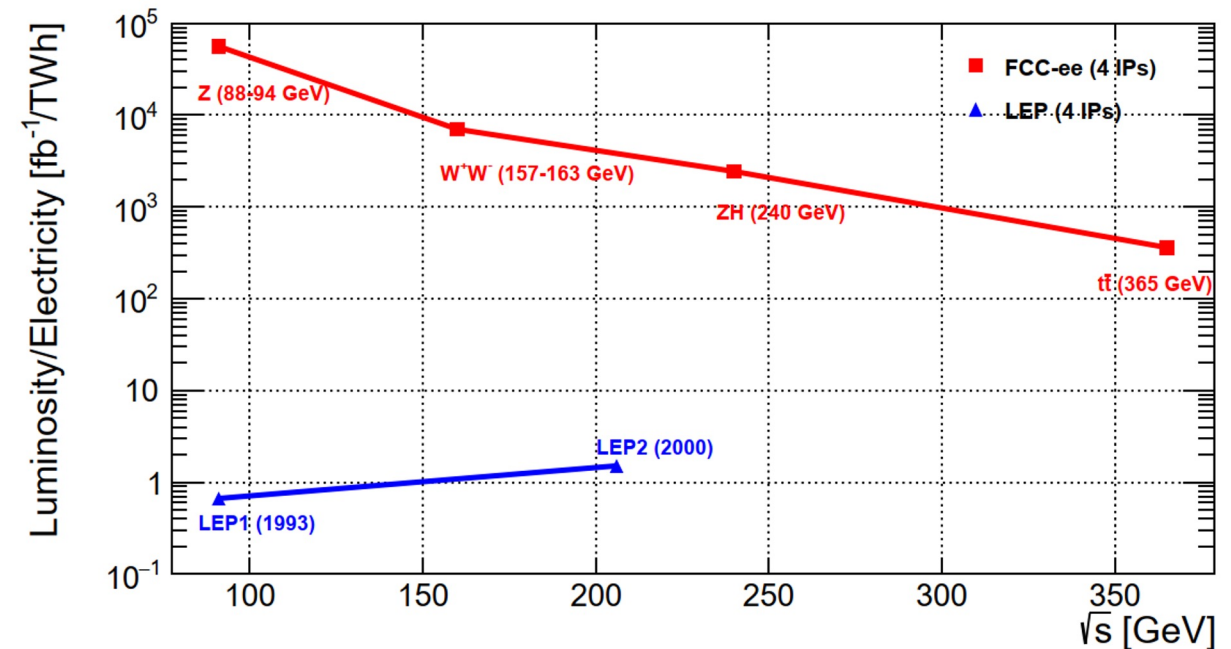
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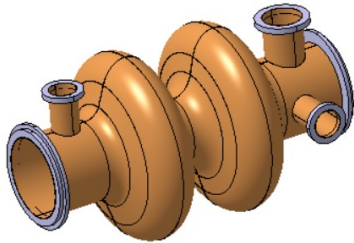
Combining all these concepts results in a giant efficiency step: $10^4 - 10^5 \times$ luminosity / electrical power of LEP



$$*\eta = \frac{P_{\text{RF out}}}{P_{\text{beam}}}$$

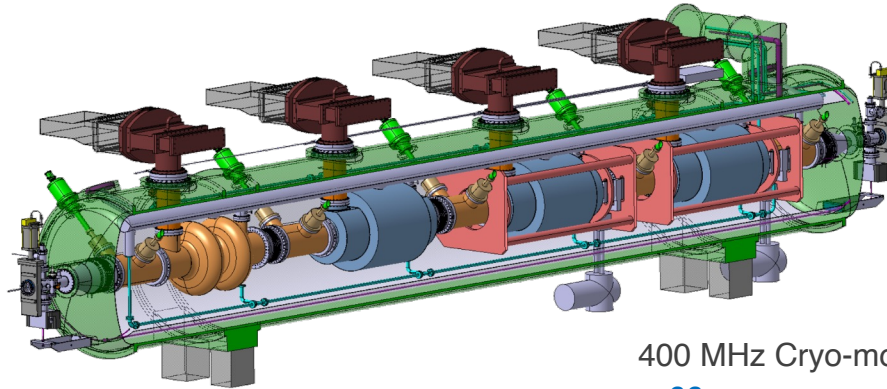
Superconducting RF system — key technology

- 2-cell* 400 MHz SRF system for Z, W and ZH



400 MHz superconducting cavity (6~10 MV/m), copper Nb coated, 1.5 m long

× 264



400 MHz Cryo-module

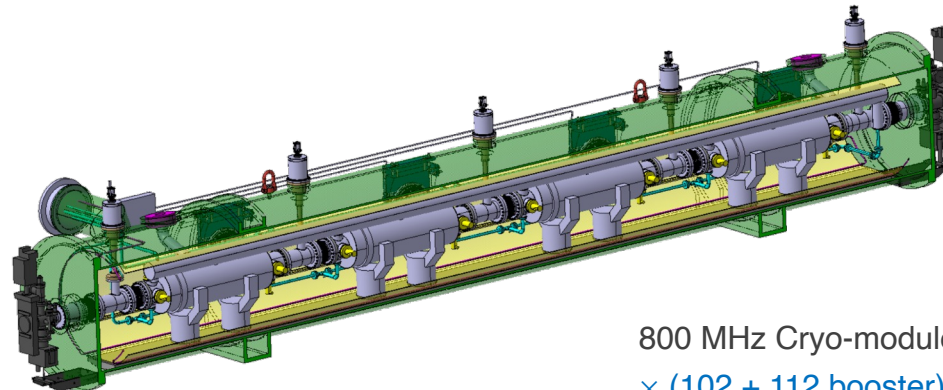
× 66

- Higher gradient 6-cell 800 MHz SRF system for tt collider operation and booster at all energies



Compact 800 MHz cavity (~20 MV/m), 6-cell, bulk Nb, Nb₃Sn if R&D is successful

× (408 + 448 booster)

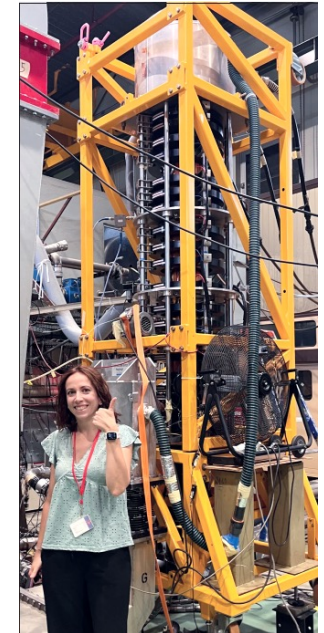


800 MHz Cryo-module

× (102 + 112 booster)

Power source: 380 kW Klystron prototype built (HL-LHC) $\eta^* = 70\%$
 → two-stage Klystrons $\eta = 86\%$
 → multibeam Tristrons $\eta > 90\%$ (R&D)

× 264



Klystron prototype

× 204 Tristons +
 448 × 10 kW SSA booster

FCC-ee — parameters

$$\Delta E_{\text{SR-loss}} \propto E_{\text{beam}}^4 / (m_e^4 \cdot \varrho), \quad P_{\text{SR}} = U_0 I, U_0 \propto E^4$$

FCC-ee main parameters (assuming 4 IPs / experiments)

Ref: [arXiv:2505.00274](https://arxiv.org/abs/2505.00274)

Parameter	Z	WW	H (ZH)	t $\bar{t}$	
Collision energy $\sqrt{s}$ [GeV]	88, 91, 94	157, 163	240	340–350	365
SR energy loss / turn [GeV]	0.036	0.08	1.7	7.8	9.2
Total RF voltage 400 / 800 MHz [GV]	0.08 / 0	1.0 / 0	2.1 / 0	2.1 / 7.4	2.1 / 9.2
Synchrotron radiation/beam [MW]	50	50	50	50	50
Number bunches / beam	11200	1852	300	70	64
Luminosity / IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	144	20	7.5	1.8	1.4
Luminosity / year [ab^{-1}]	68	9.6	3.6	0.83	0.67
Run time (including lumi ramp-up) [years]	4	2	3	1	4
Total integrated luminosity [ab^{-1}]	205	19.2	10.8	0.4	2.7
Total number of events	$6 \cdot 10^{12} \text{ Z}$	$2.4 \cdot 10^8 \text{ WW}$ (incl. WW at higher $\sqrt{s}$)	$2.2 \cdot 10^6 \text{ ZH}$ 65k WW $\rightarrow$ H	$2 \cdot 10^6 \text{ t}\bar{\text{t}} + 370\text{k ZH}$ + 92k WW $\rightarrow$ H	

$\sim 350,000 \times \text{LEP-1}$ (~6 years)

$\sim 5,000 \times \text{LEP-2}$
(~5 years)

FCC-ee — detectors

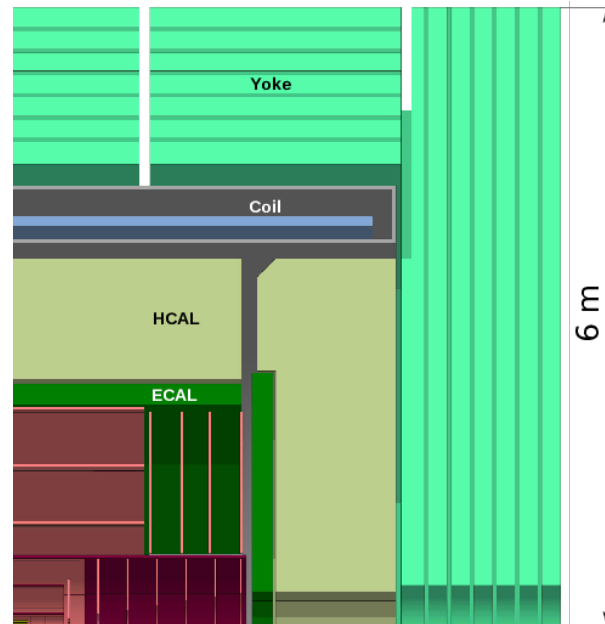
*A too-strong detector solenoid (≥ 4 T) would distort the beam trajectories, induce transverse coupling, and blow up the vertical emittance — drastically reducing luminosity

Event rates and radiation are modest compared to HL-LHC, but Tera-Z precision demands unprecedented stability, resolution, luminosity control and acceptance knowledge; most measurements will ultimately be systematics- and theory-limited

Detector concepts use high-granularity particle-flow calorimetry, close-to-beam MAPS* vertex detectors, low-material central trackers, PID, a 2~3 T solenoids, and muon tagging. **CEPC also has an innovative and ambitious reference detector design** [Ref]



ALLEGRO detector concept around noble-liquid EM calorimeter [Ref]



CLD detector concept silicon-tungsten EM calorimeter and tracker [Ref]

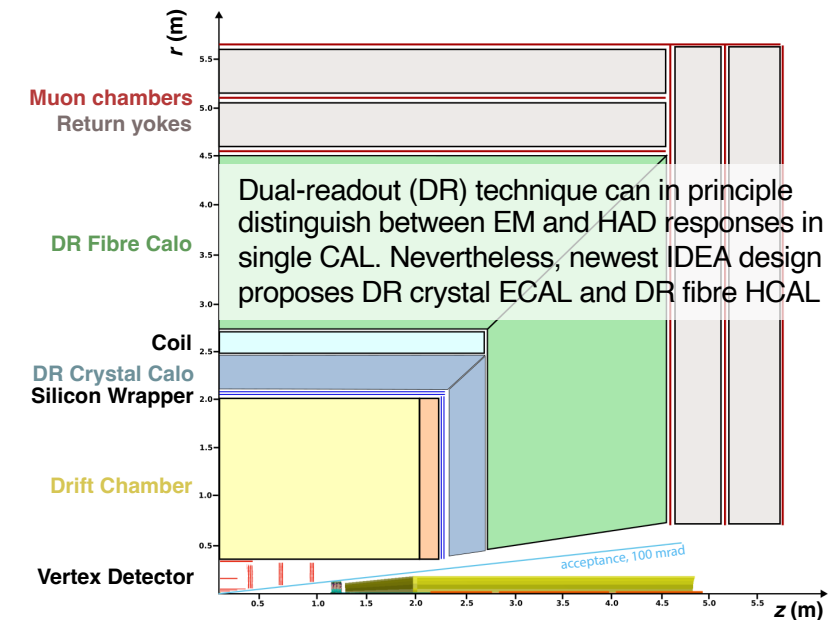


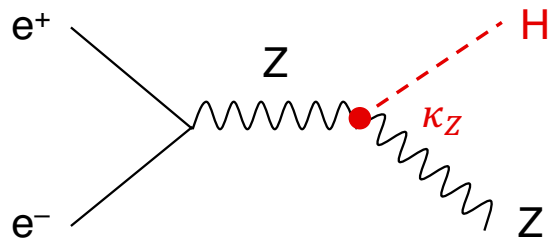
Figure 3: Overview of the IDEA detector layout.

IDEA detector concept around dual-readout (scintillation (all) & Cherenkov (relativistic – e/γ) light) fiber/Cu calorimeters [Ref]

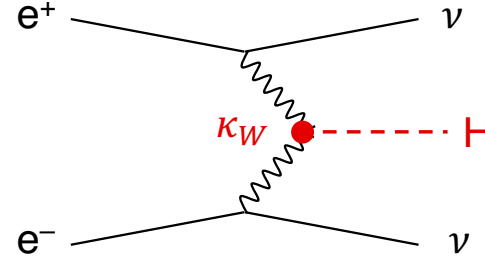
*MAPS = Monolithic Active Pixel Sensors

FCC-ee — Higgs Factory

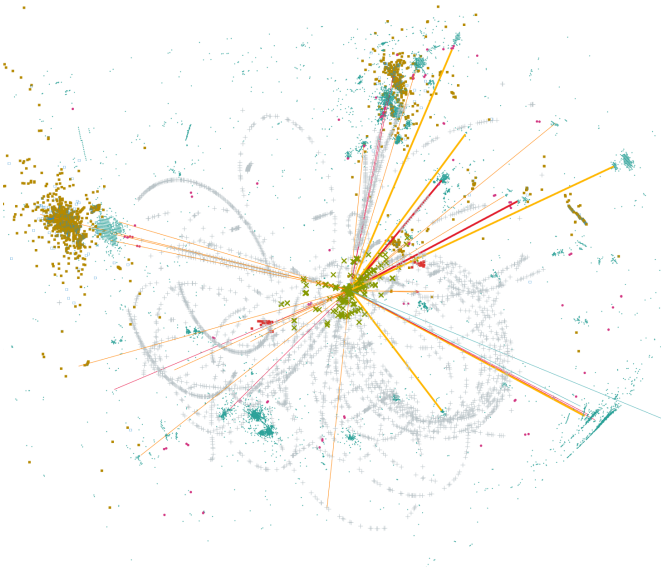
Primary goal: Higgs precision measurements



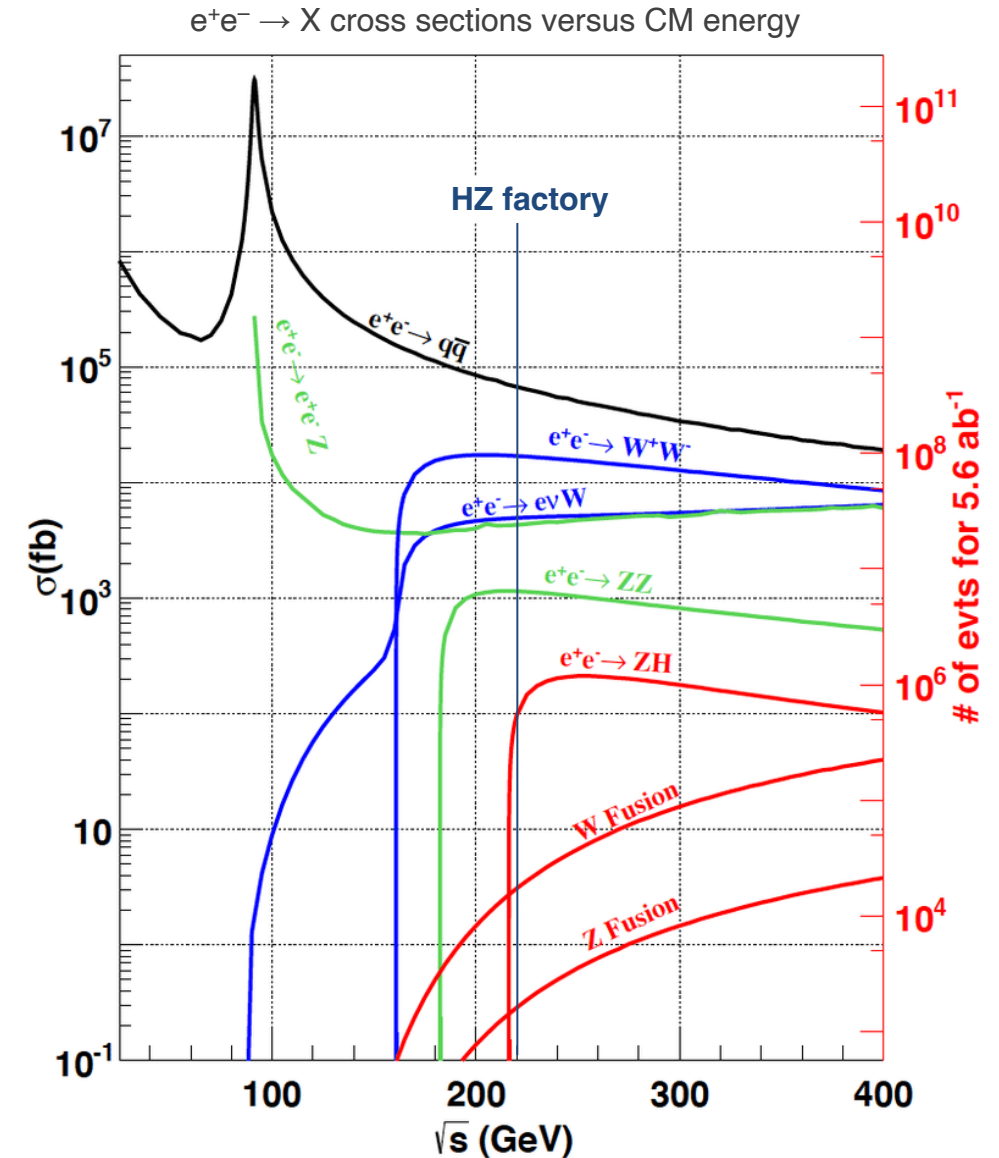
Higgsstrahlung ($\sigma = 232 \text{ fb}$ at $\sqrt{s} = 240 \text{ GeV}$)
 s-channel: $\sigma \propto 1/s$ — falling off a resonance



W-boson fusion (6.7 fb)
 (Z-boson fusion 0.63 fb)
 WBF: $\sigma \propto \ln^2(s/m_W^2)$ — e^+/e^- radiate
 W/Z, which increases with energy

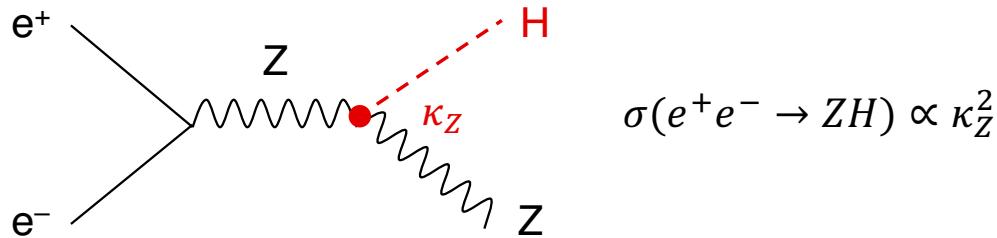


Simulated $e^+e^- \rightarrow ZH$ event at
 $\sqrt{s} = 240 \text{ GeV}$ in IDEA detector



FCC-ee — Higgs Factory

Absolute coupling strengths — difficult at LHC due to weak constraint on Γ_H (current precision $\sim 50\%$, HL-LHC $< 25\%$)

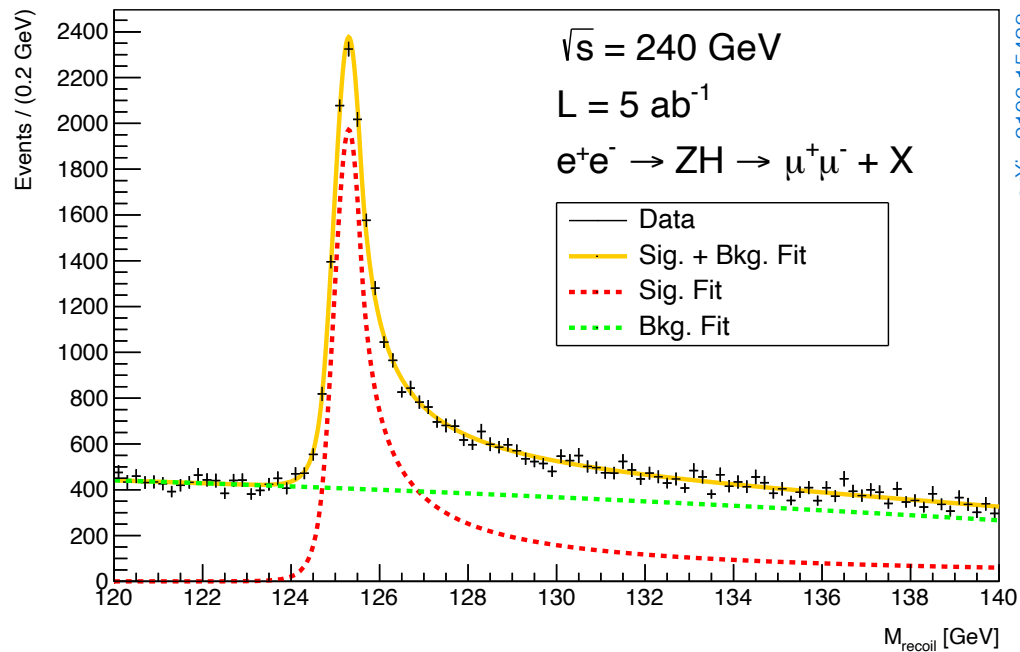


Can measure total HZ cross section and hence κ_Z (0.1% precision) independently of Higgs decays via recoil mass (M_{recoil}) by counting events with an identified $Z \rightarrow \ell\ell$

$$M_{\text{recoil}}^2 = (\sqrt{s} - E_{\ell^+} - E_{\ell^-})^2 - |\mathbf{p}_{\ell^+} + \mathbf{p}_{\ell^-}|^2$$

Standard reference to be used by all other Higgs coupling measurements

Higgsstrahlung ($\sigma = 232 \text{ fb}$ at $\sqrt{s} = 240 \text{ GeV}$)



Combination with measurement of $\sigma(e^+e^- \rightarrow ZH(\rightarrow ZZ^*)) \propto \frac{\kappa_Z^4}{\Gamma_H}$ allows to determine Γ_H to 0.8% precision ($30 \times \text{HL-LHC}$)

FCC-ee – the Higgs factory

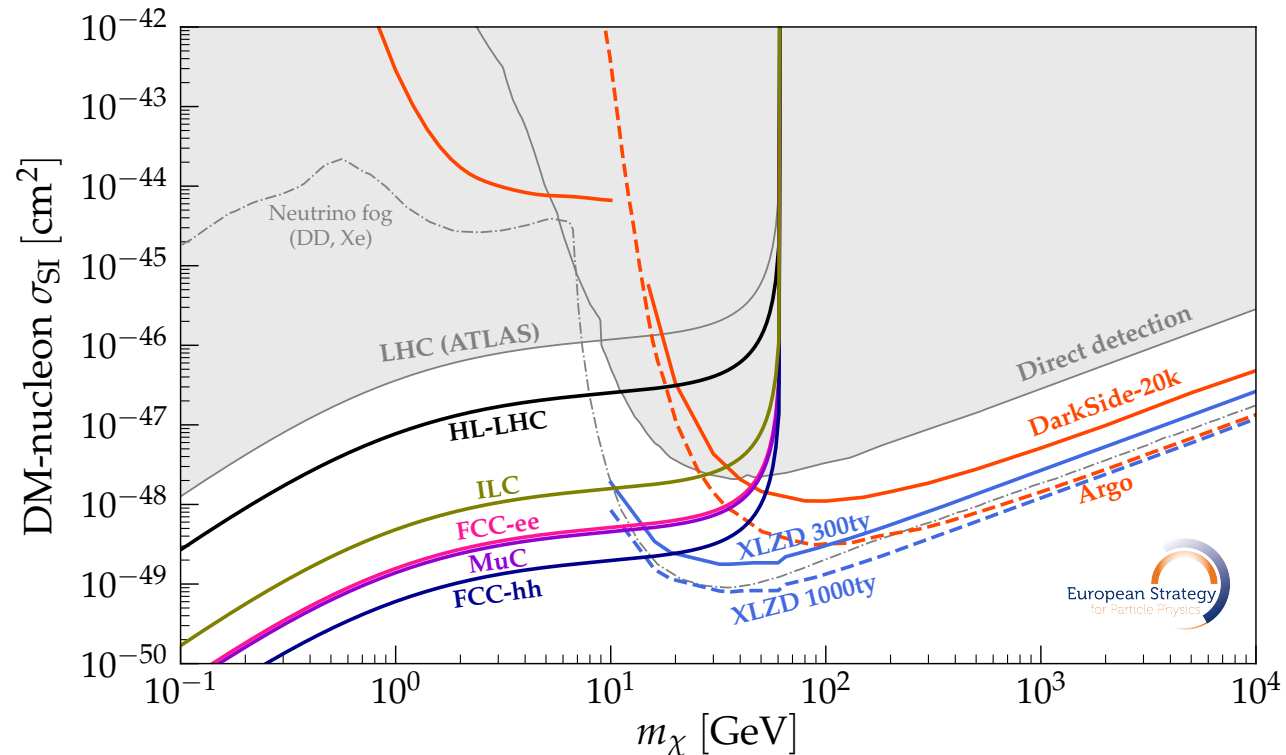
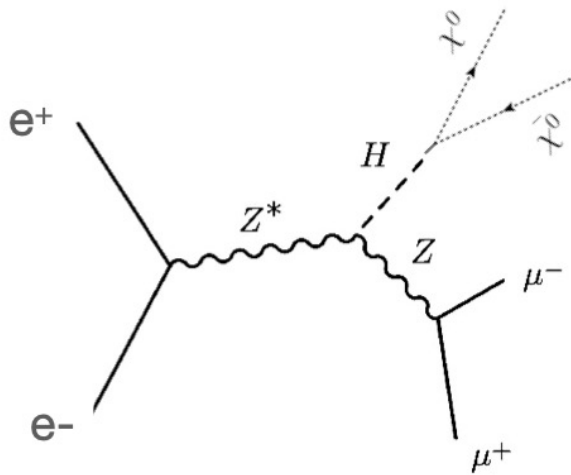
Why “factory”? 2.2M Higgs (FCC-ee) vs 350M (HL-LHC), production through Higgsstrahlung rather than s-channel
→ **e^+e^- collisions offer exceptionally clean Higgs reconstruction, unmatched precision on decays with large branching ratios**

FCC-ee feasibility study (Vol 1): [arXiv:2505.00272](https://arxiv.org/abs/2505.00272)

		Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh	Uncertainty HL-LHC / FCC-ee	
*Incl. SM parametric uncertainties		κ_Z (%)	1.6	0.10	0.10	16	Most precise coupling, probes $f_H \sim 8$ TeV
		κ_W (%)	1.6	0.29	0.25	5.5	
		κ_b (%)	3.6	0.38 / 0.49*	0.33 / 0.45	7.3	Particularly large improvement over HL-LHC
		κ_g (%)	2.4	0.49 / 0.54	0.41 / 0.44	4.4	
		κ_τ (%)	1.9	0.46	0.40	4.1	
Note: current uncertainties on Higgs branching fraction predictions O(1.5%)		κ_c (%)	~ 40	0.70 / 0.87	0.68 / 0.85	~ 44	
		κ_γ (%)	1.8	1.1	0.30	1.6	
		$\kappa_{Z\gamma}$ (%)	6.8	4.3	0.67	1.6	
		κ_t (%)	3.4	3.1	0.75	1.1	
		κ_μ (%)	3.0	3.3	0.42	0.9	
		$ \kappa_s $ (%)	—	$^{+29}_{-67}$	$^{+29}_{-67}$	—	BR($H \rightarrow 4\nu$) = $10.6 \cdot 10^{-4}$
		Γ_H (%)	< 25	0.78	0.69	~ 30	
		$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	0.025	5×10^{-4}	2.3×10^{-4}	50	
		$\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$	0.04	6.8×10^{-3}	6.7×10^{-3}	5.9	

FCC-ee – the Higgs factory

Why “factory”? 2.2M Higgs (FCC-ee) vs 350M (HL-LHC), production through Higgsstrahlung rather than s-channel
 → e^+e^- collisions offer exceptionally clean Higgs reconstruction, unmatched precision on decays with large BR



Collider limits overlaid onto direct detection (Higgs portal assuming Majorana DM)

$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	0.025	5×10^{-4}	2.3×10^{-4}	50
	HL-LHC	FCC-ee	FCC-ee + FCC-hh	

$\text{BR}(H \rightarrow 4\nu) = 10.6 \cdot 10^{-4}$

FCC-ee – also a Tera-Z, W and top factory

Extreme luminosity on Z pole: $140 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ / IP, 205 ab^{-1} & $6 \cdot 10^{12} \text{ Z}$ (4 IPs) — ultimate EW precision data

[arXiv:2505.00272](https://arxiv.org/abs/2505.00272)

Observable	value	present ±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	4	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	4	12	From Z line shape scan Beam energy calibration
$\sin^2 \theta_W^{\text{eff}} (\times 10^6)$	231,480	±	160	1.2	1.2	From $A_{\text{FB}}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\text{QED}}(m_Z^2) (\times 10^3)$	128 952	±	14	3.9 0.8	small tbc	From $A_{\text{FB}}^{\mu\mu}$ off peak From $A_{\text{FB}}^{\mu\mu}$ on peak QED&EW uncert. dominate
$R_\ell^Z (\times 10^3)$	20 767	±	25	0.05	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2) (\times 10^4)$	1 196	±	30	0.1	1	Combined R_ℓ^Z , Γ_{tot}^Z , σ_{had}^0 fit
$\sigma_{\text{had}}^0 (\times 10^3) \text{ (nb)}$	41 480.2	±	32.5	0.03	0.8	Peak hadronic cross section Luminosity measurement
$N_\nu (\times 10^3)$	2 996.3	±	7.4	0.09	0.12	Z peak cross sections Luminosity measurement
$R_b (\times 10^6)$	216 290	±	660	0.25	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{\text{FB}}^{b,0} (\times 10^4)$	992	±	16	0.04	0.04	b-quark asymmetry at Z pole From jet charge
$A_{\text{FB}}^{\text{pol},\tau} (\times 10^4)$	1 498	±	49	0.07	0.2	τ polarisation asymmetry τ decay physics

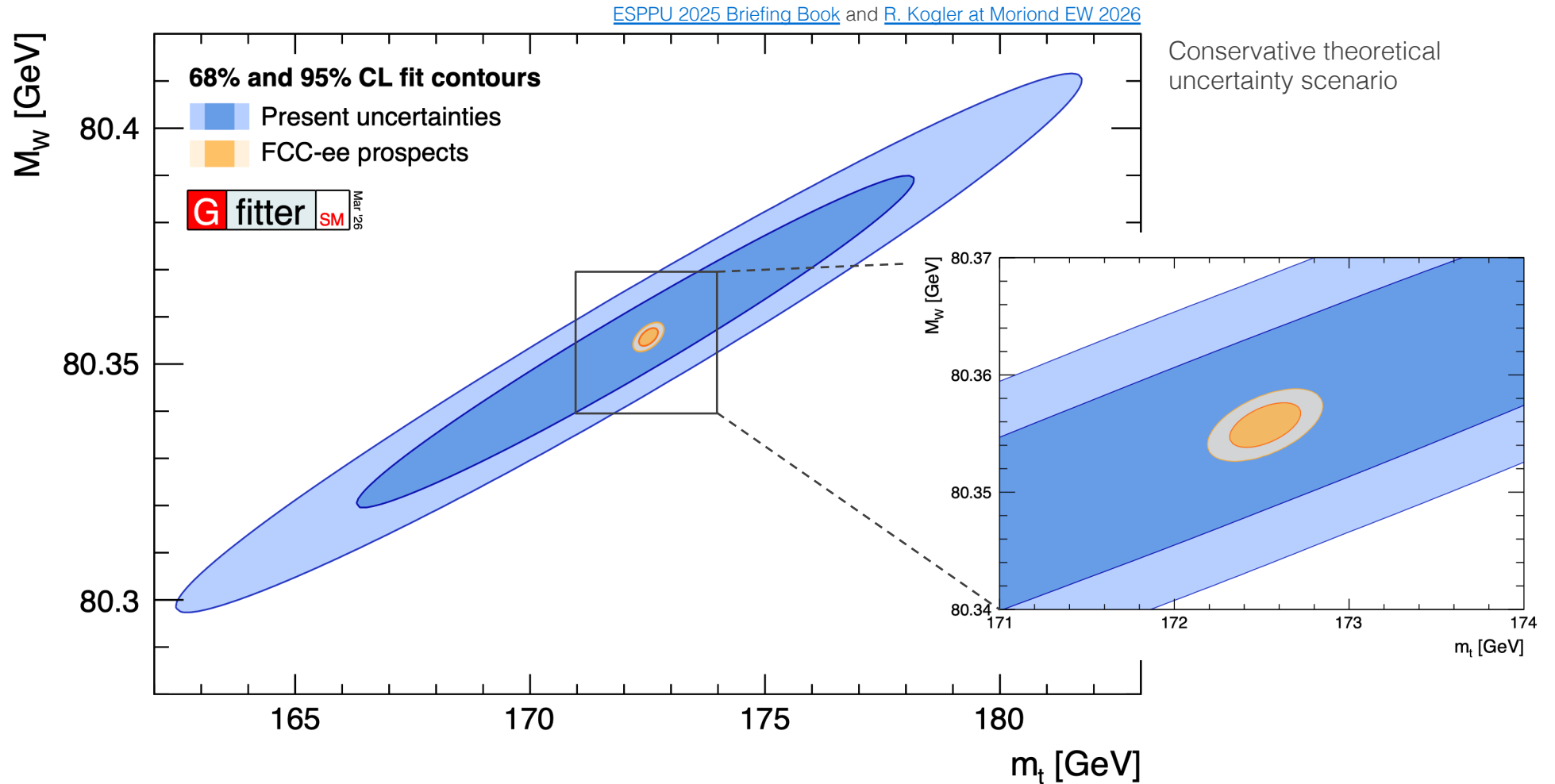
Observable	value	present ±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
τ lifetime (fs)	290.3	±	0.5	0.001	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	±	0.09	0.002	0.02	estimator bias, ISR, FSR
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	±	0.04	0.00007	0.003	PID, π^0 efficiency
m_W (MeV)	80 360.2	±	9.9	0.18	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	0.27	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2) (\times 10^4)$	1 010	±	270	2	2	Combined R_ℓ^W , Γ_{tot}^W fit
$N_\nu (\times 10^3)$	2 920	±	50	0.5	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172 570	±	290	4.2	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	±	190	10	6	From $t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	1.2	±	0.3	0.015	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
$t\bar{t}Z$ couplings		±	30%	0.5–1.5 %	small	From $\sqrt{s} = 365 \text{ GeV}$ run

Improvements up to $\times 300$ over current knowledge

Input to global electroweak fit: **requires significant improvements in theoretical predictions**

FCC-ee – also a Tera-Z, W and top factory

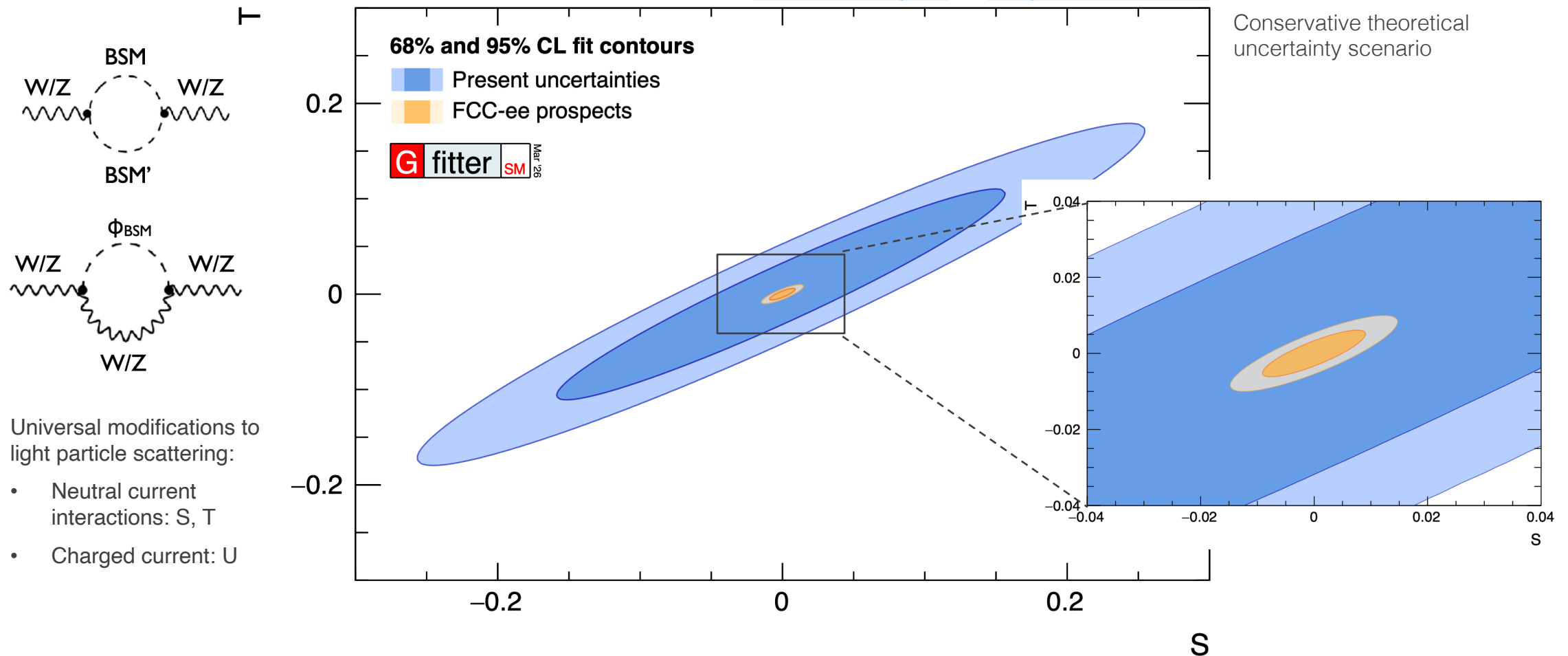
Global electroweak fit expressed on top versus W mass



FCC-ee – also a Tera-Z, W and top factory

Constraint heavy BSM physics to vacuum polarisation diagrams: “oblique parameters” S, T, U

[ESPPU 2025 Briefing Book](#) and [R. Kogler at Moriond EW 2026](#)



FCC-ee – also a flavour factory (on Z pole)

BR(Z → bb / cc) = 15% / 12%

$\Gamma(Z \rightarrow q\bar{q}) \propto (g_V^2 + g_A^2)$

Large c and b-hadron statistics — combines strengths of Belle-II ($e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$) and LHCb ($pp \rightarrow b\bar{b} + X$)

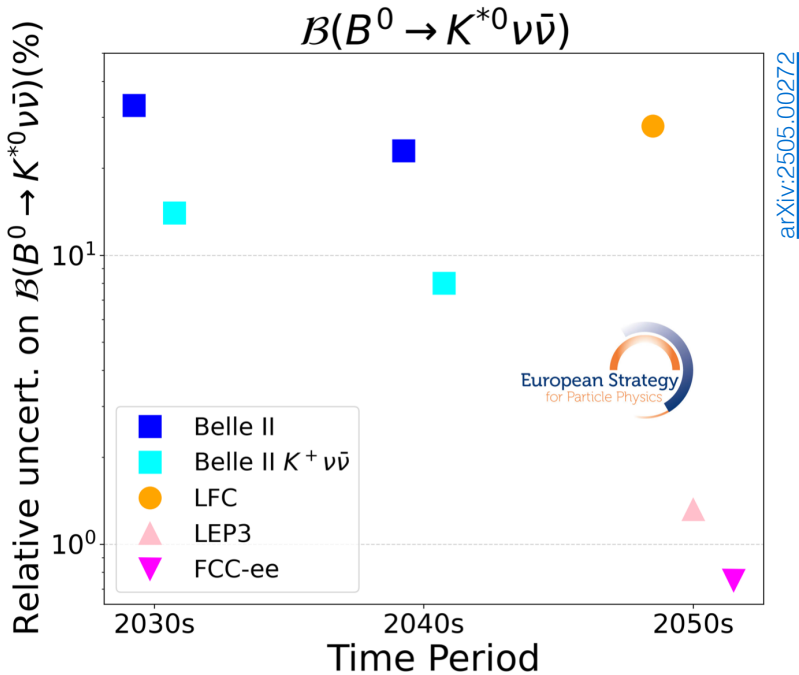
Attribute	$\Upsilon(4S)$	pp	Z
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
High geometrical acceptance	✓		✓
Low backgrounds	✓		✓
Flavour-tagging power	✓		✓
Initial-energy constraint	✓		(✓)

Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
FCC-ee ($\times 10^9$)	370	370	90	80	2	720	200
Belle-II ($\times 10^9$)	28	28	—	—	—	33	46

Yields for $6 \cdot 10^{12}$ Z

Yields for 50 ab^{-1}

The larger yield of B mesons than Belle II allows unmatched precision on B decays with neutrinos



Clean reconstruction due to boost and flavour tagging ($> \text{LHCb}$), excellent charm / τ separation (challenging at $\Upsilon(4S)$)

Ultimate CKM angle precision (similar to LHCb)

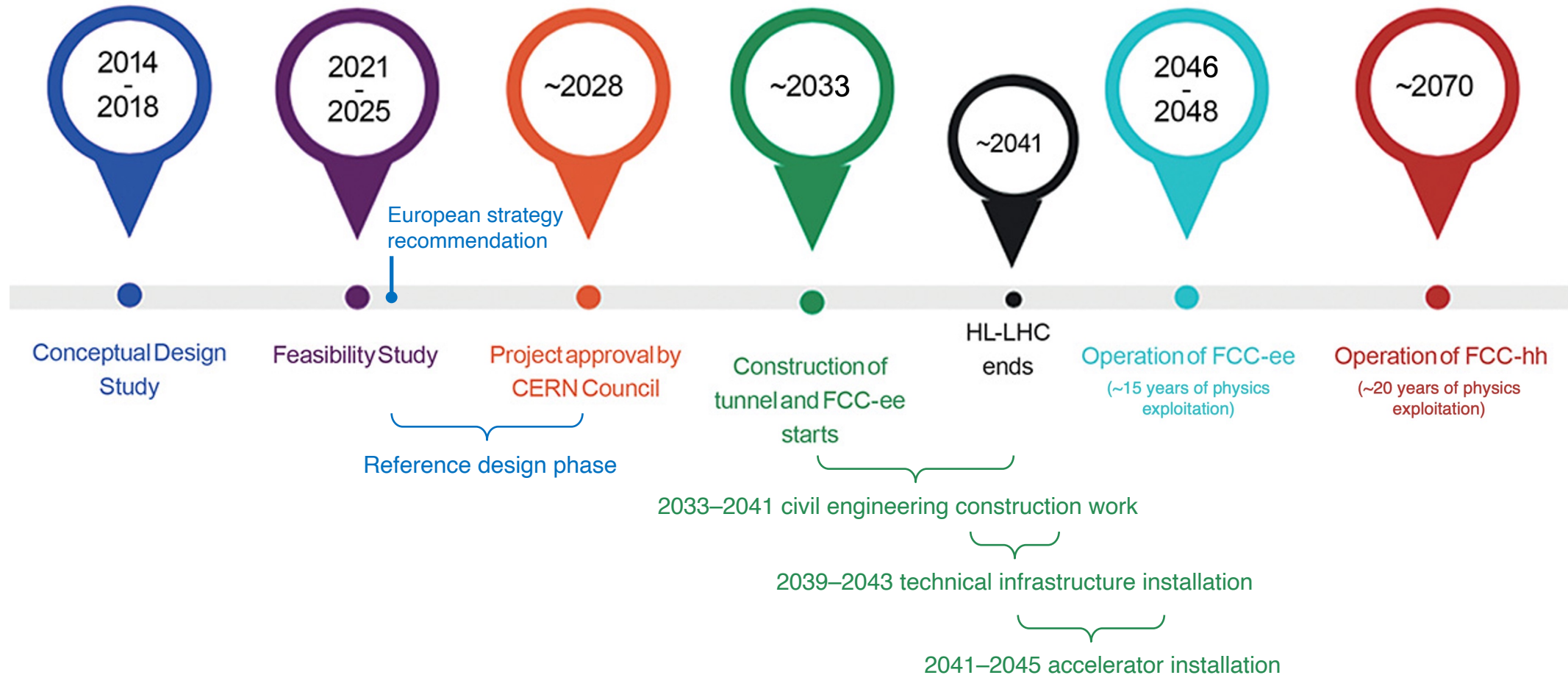
Ultimate τ factory

$B \rightarrow \tau \nu$ allows 1% measurement of $|V_{ub}|$ and running above WW threshold allows *on-shell* measurement of $|V_{cb}|$ to $\sim 1\%$

Current precision $3.5_{V_{ub}} / 1.1_{V_{cb}}\%$, but discrepancies between exclusive and inclusive results of $17_{V_{ub}} / 5_{V_{cb}}\%$, respectively

FCC — timeline of integrated programme

FCC-ee followed by FCC-hh



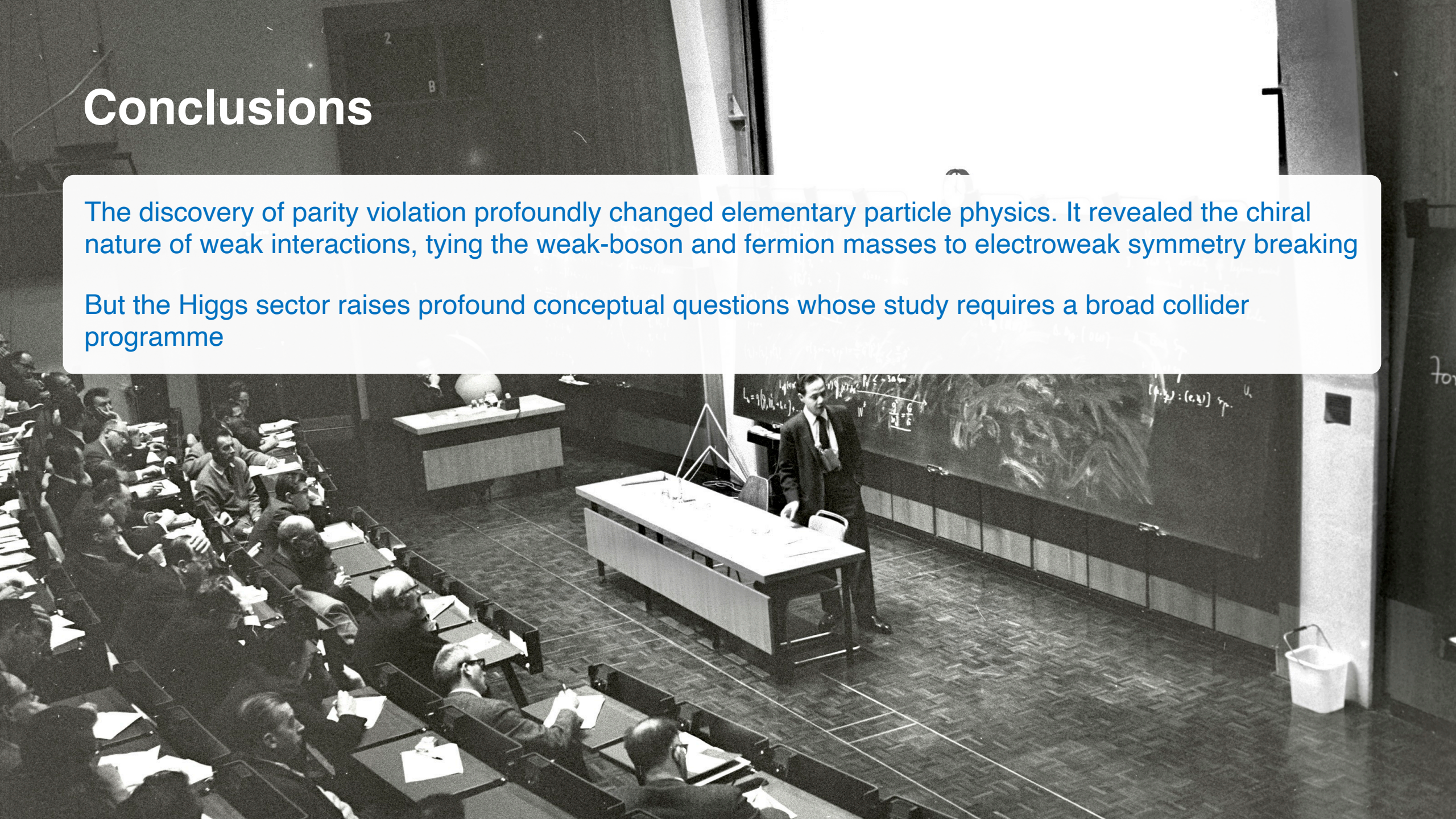
Conclusions



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The discovery of parity violation profoundly changed elementary particle physics. It revealed the chiral nature of weak interactions, tying the weak-boson and fermion masses to electroweak symmetry breaking

But the Higgs sector raises profound conceptual questions whose study requires a broad collider programme



Conclusions

The discovery of parity violation profoundly changed elementary particle physics. It revealed the chiral nature of weak interactions, tying the weak-boson and fermion masses to electroweak symmetry breaking

But the Higgs sector raises profound conceptual questions, whose study requires a broad collider programme

LHC Run 3 and the HL-LHC will deliver 95% of the full LHC dataset, opening major opportunities complementary to a future e^+e^- collider, amidst a surge of innovation through AI/ML

FCC-ee is Europe's priority for CERN's next flagship collider. FCC-ee and CEPC are transformative precision instruments, deeply probing the quantum structure of Higgs and electroweak interactions

FCC-ee and CEPC also lay the foundation for a future hadron collider in the same infrastructure, creating a highly synergistic programme with maximal long-term physics reach

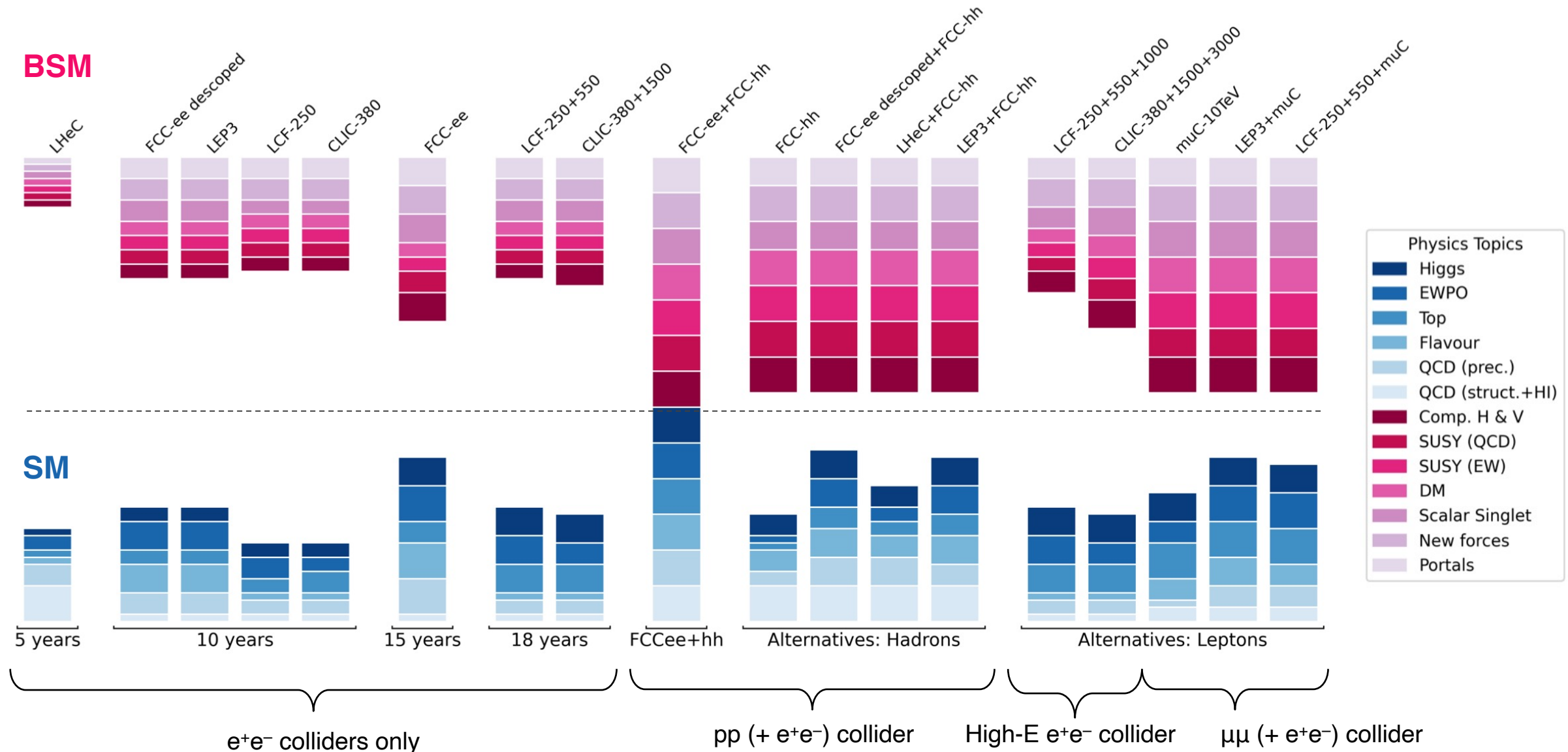
Extra slides ...

Doodle pad by T.D. Lee during talks with C.N. Yang at BNL in summer 1956 [\[Link\]](#)



Assessment of physics reach

[\[Link to ESG WG2b report\]](#)



LEP3 — a Higgs and EW factory in the LHC tunnel

Backup if (preferred) FCC-ee cannot be realised with long-term goal of an energy-frontier hadron or muon collider:
similar to FCC-ee with booster and collider rings, 2 beampipes, 50 MW / beam, 2 IPs

LEP3	Parameter	Z	WW	H (ZH)		t $\bar{t}$	Construction:
	Inst. luminosity / IP [10^{34} cm $^{-2}$ s $^{-1}$]	40	6.2 (160 GeV)	1.6 (230 GeV)		—	Total cost 3.7B CHF ESPPU input: arXiv:2504.00541
	SR energy loss / turn [GeV]	0.13	1.3	5.4		(~25 GeV)	
	Integrated luminosity / year / IP [ab $^{-1}$]	4.8	0.7	0.19		—	
	Run time [years]	5	4	6		—	
	Total integrated luminosity [ab $^{-1}$, 2 IPs]	48	6.0	2.3		—	
	Total number of events [2 IPs]	$1.4 \cdot 10^{12}$	$0.36 \cdot 10^8$	$0.42 \cdot 10^6$		—	
FCC-ee	Inst. luminosity / IP [10^{34} cm $^{-2}$ s $^{-1}$]	144	20 (157, 163 GeV)	7.5 (240 GeV)	1.8 (~350 GeV)	1.4 (365 GeV)	Total cost 13.7B + 1.3B $_{t\bar{t}}$ CHF
	SR energy loss / turn [GeV]	0.036	0.08	1.7	7.8	9.2	
	Integrated luminosity / year / IP [ab $^{-1}$]	17	2.4	0.9	0.21	0.17	
	Run time (including lumi ramp-up) [years]	4	2	3	1	4	FCC-ee SR loss reference
	Total integrated luminosity [ab $^{-1}$, 4 IPs]	205	19.2	10.8	0.4	2.7	
	Total number of events [4 IPs]	$6 \cdot 10^{12}$	$2.4 \cdot 10^8$	$2.2 \cdot 10^6$	$2 \cdot 10^6$		

Challenges for LEP3 include design of IRs, large E-loss, need 6.0 GV RF power installed in 4 long straight sections (2 booster, 2 collider), crab-waist scheme requires large crossing angle and widening tunnel on either side of the experiments from ~4m to 7m diameter along 270 m

Linear Collider Facility (LCF) at CERN

Very similar to ILC: baseline is 33.5 km tunnel, SRF cavities with an accelerating gradient of 31.5 MV m^{-1} , $\sqrt{s} = 250 \text{ GeV}$ upgradable to 550 GeV, longitudinal polarisation ($\pm 80/30\%$ for e^-/e^+ , $\sim 20\%$ higher $\sigma(\text{ZH})$), 2 IPs (sharing luminosity)

LCF	Parameter	Z	WW	H (ZH)	above $t\bar{t}$	
	Inst. luminosity / IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	0.28	—	$1.4_{\text{LP}} / 2.7_{\text{FP}}$ (250 GeV)	3.9 (550 GeV)	
	Integrated luminosity / year / IP [ab^{-1}]	30	—	$0.19_{\text{LP}} + 0.64_{\text{FP}}$	2.3	
	Run time [years]	1	—	$5_{\text{LP}} + 3_{\text{FP}}$	10	
	Total integrated luminosity [ab^{-1} , 2 IPs*]	0.07	—	$1.0_{\text{LP}} + 1.9_{\text{FP}}$	8.3	
	Total number of events [2 IPs*]	$0.002 \cdot 10^{12}$	—	$0.8 \cdot 10^6$	$\sim 1.6 \text{ (H)} / 3.9 \text{ (tt)} \cdot 10^6$	
FCC-ee	Inst. luminosity / IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	144	20 (157, 163 GeV)	7.5 (240 GeV)	1.8 ($\sim 350 \text{ GeV}$)	1.4 (365 GeV)
	Integrated luminosity / year / IP [ab^{-1}]	17	2.4	0.9	0.21	0.17
	Run time (including lumi ramp-up) [years]	4	2	3	1	4
	Total integrated luminosity [ab^{-1} , 4 IPs]	205	19.2	10.8	0.4	2.7
	Total number of events [4 IPs]	$6 \cdot 10^{12}$	$2.4 \cdot 10^8$	$2.2 \cdot 10^6$	$2 \cdot 10^6$	

Construction:

Total cost:

- 8.5B CHF (250 GeV, LP)
- 9.3B CHF (250 GeV, FP)
- 14.8B CHF (550 GeV)

ESPPU input: [arXiv:2503.19983](https://arxiv.org/abs/2503.19983)

Total cost 15.3B CHF

*LCF proposes to share luminosity among two interaction regions, ie, same integrated luminosity as for single IP

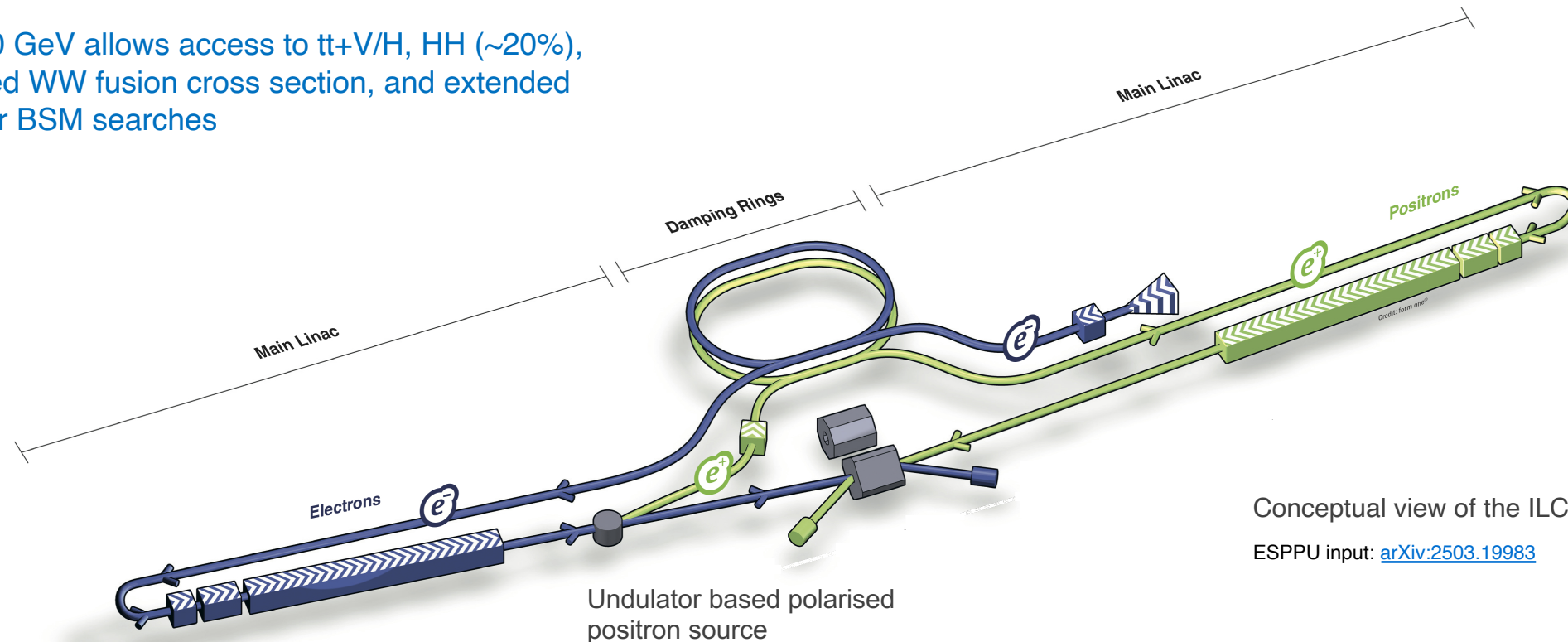
Challenges for for LCF include the positron source, final focus and nano-beam stability ($\sigma_y^* \sim 6\text{--}8 \text{ nm}$, FCC-ee: 40 nm)

Options to increase energy beyond 550 GeV with development and installation of higher gradient accelerating technologies (see [here](#) for a discussion of options)

Linear Collider Facility (LCF) at CERN

Very similar to ILC: baseline is 33.5 km tunnel, 1.3 GHz niobium SRF cavities with an accelerating gradient of 31.5 MV/m, $\sqrt{s} = 250$ GeV upgradable to 550 GeV, 10 Hz repetition frequency, low/full-power (LP/FP) 1312/2625 bunches per pulse, power usage of 140–320 MW at 250–550 GeV, longitudinal polarisation ($\pm 80/30\%$ for e^-/e^+ , $\sim 20\%$ higher $\sigma(ZH)$), 2 IPs (sharing luminosity)

$\sqrt{s} = 550$ GeV allows access to $t\bar{t}+V/H$, HH ($\sim 20\%$), increased WW fusion cross section, and extended reach for BSM searches



Conceptual view of the ILC / LCF

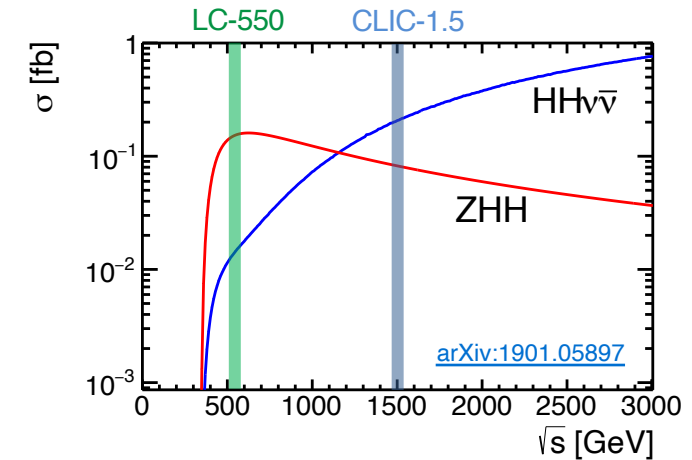
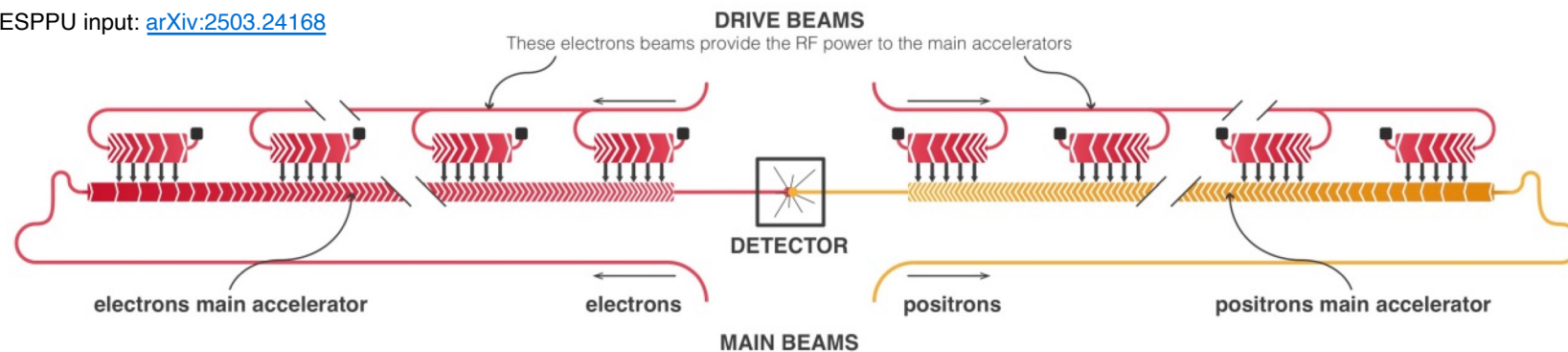
ESPPU input: [arXiv:2503.19983](https://arxiv.org/abs/2503.19983)

Other collider options for CERN

Compact Linear e^+e^- Collider (CLIC): $\sqrt{s} = 380 \text{ GeV} - 1.5 \text{ TeV}$, two-beam acceleration with high-current 12 GHz drive beam to reach up to 100 MV/m gradient in main-beam X-band cavities, 100 Hz repetition rate, 0.5 ns bunch separation, 1.5–2 nm IP

- Multiple test facilities were built at CERN, the latest, CTF3, demonstrated the drive-beam concept, but a larger-scale demonstrator is needed to fully validate the concept under realistic operating conditions → requires more R&D
- Running at 1.5 TeV allows direct access to κ_λ via ZHH and $\nu\nu\text{HH}$ ($\kappa_\lambda = 1^{+0.11}_{-0.08}$, $\mathcal{L} = 2.5 \text{ ab}^{-1}$ in 6 yr)

ESPPU input: [arXiv:2503.24168](https://arxiv.org/abs/2503.24168)

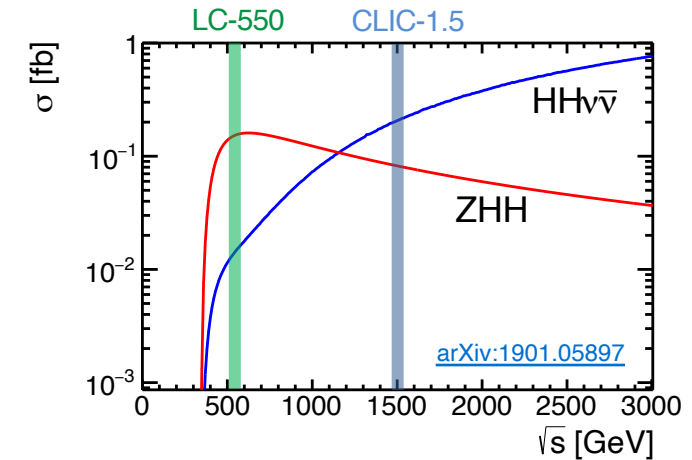
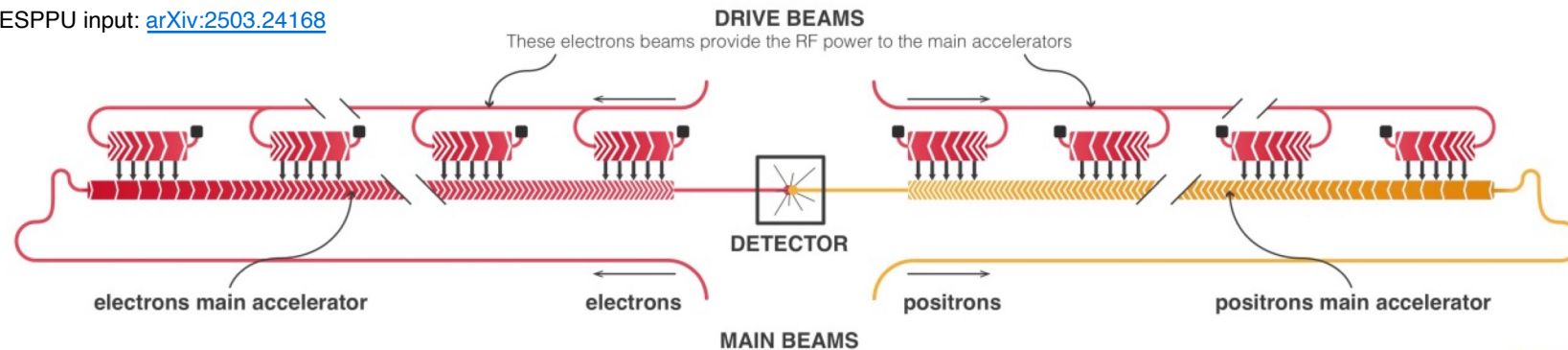


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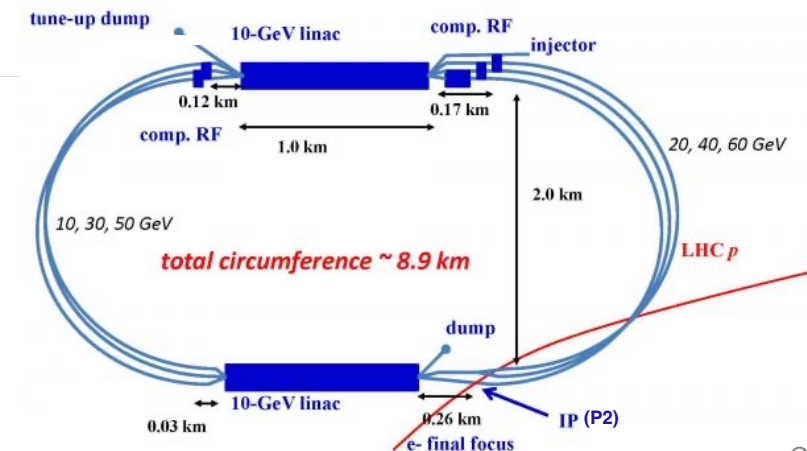
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ESPPU input: [arXiv:2503.24168](https://arxiv.org/abs/2503.24168)



LHeC electron–proton/ion collider: 50 GeV e^- -beam ($\sqrt{s} = 1.2 \text{ TeV}$) with 1 GW power from innovative multi-pass energy recovery linac (ERL), up to 1 ab^{-1} in 6 years (HERA: $\sqrt{s} = 320 \text{ GeV}$, $2 \times 0.5 \text{ fb}^{-1}$) [ESPPU input: [arXiv:2503.17727](https://arxiv.org/abs/2503.17727), see also [this nice talk](#)]

- ERL test facility PERLE under construction at IJCLab (start 2029), success of LHeC relies on ERL concept to work as planned
- Excellent PDF and QCD precision, 200k H allow precise measurements of κ_c , κ_b , κ_W , κ_Z (but Higgs yield strongly dependent on achieved e^- -beam power)

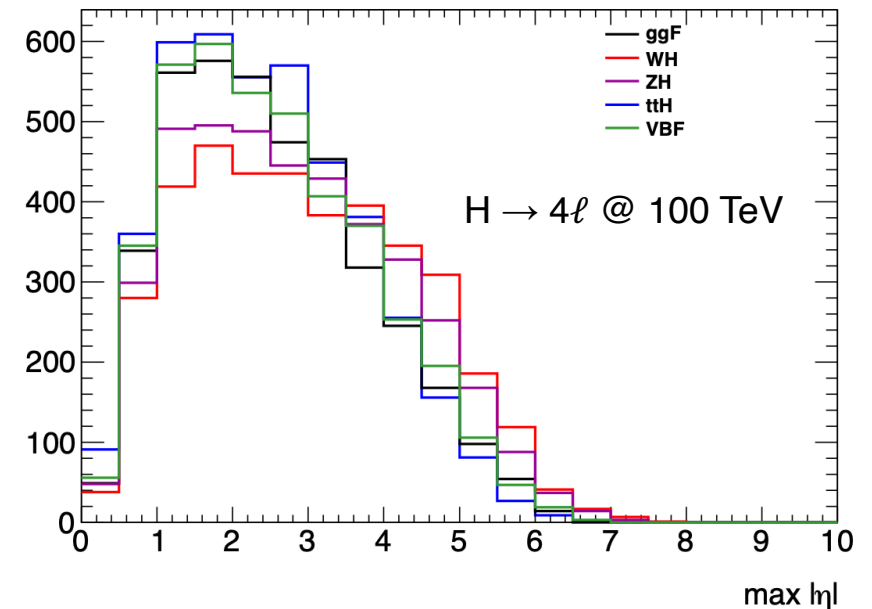
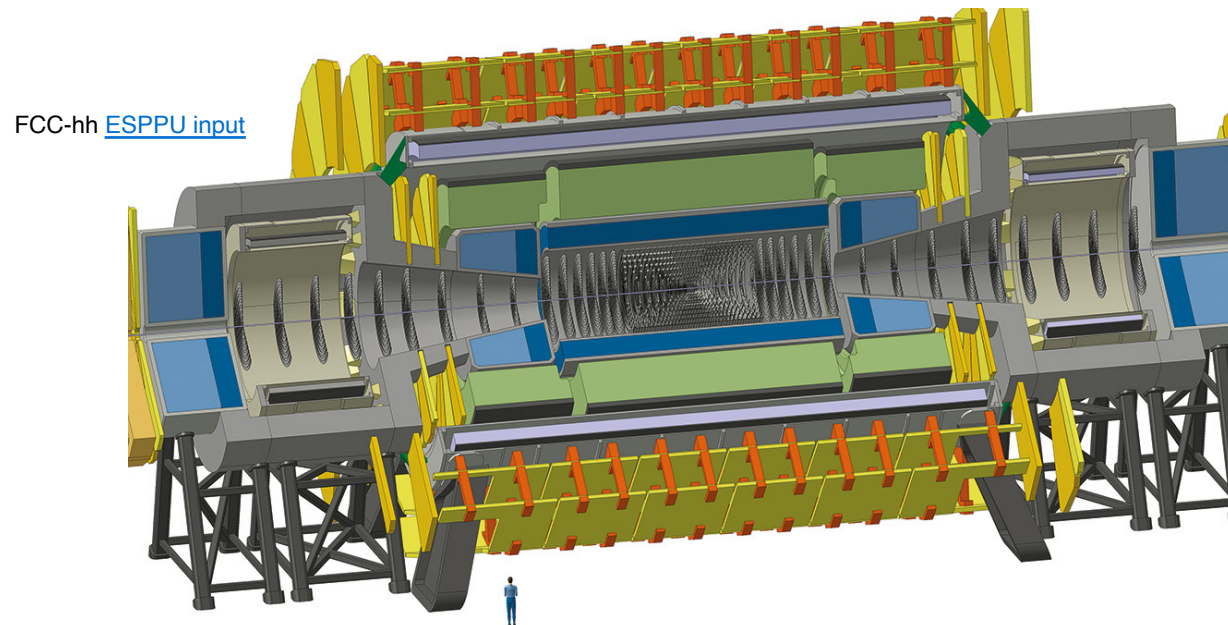


High-energy frontier, longer term R&D projects

Significantly expanding the reach for new physics requires a new energy frontier, which are long-term R&D projects

FCC-hh: current baseline is 85 TeV based on 14 T Nb₃Sn high-field magnet technology, $L = 30 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, pileup 1000, 20 ab⁻¹ / IP in 20 years of operation

- Challenges: industrial production & cost control of magnets, beam screens (1200 kW synchrotron radiation vs 7.3 kW at HL-LHC), safety: 10 × stored energy of HL-LHC (6.5 vs 0.7 GJ), power consumption: 1.9 or 4.5 K helium cooling (2.5 vs 2.0 TWh annual)
- Detector design: much of the SM physics (low Bjorken-x) peaks forward (Higgs produced up to rapidity of ~ 6.5 (0.3 deg) (up to 2.5 (9 deg) at LHC), Detector granularity will be critical: decay product of a Z at 10 TeV separated by $\Delta R \sim 0.01$
- Superb BSM physics reach, Higgs & SM programme, incl. few % on κ_λ



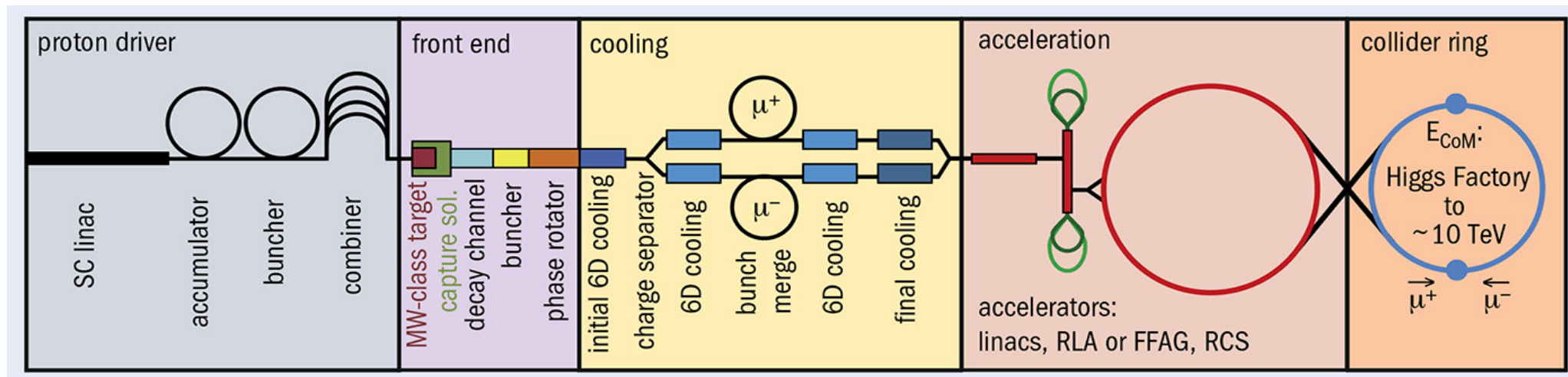
High-energy frontier, longer term R&D projects

Significantly expanding the reach for new physics requires a new energy frontier, which are long-term R&D projects

Muon collider: best of all worlds? High energies (3–10 TeV), high luminosities with excellent luminosity per MW ratio, (relatively) clean lepton collision events

- Challenges: muon production (MW-scale proton drivers, robust targets, ~20 T capture solenoids), ionisation cooling (longitudinal & transverse (6D) emittance reduction via absorbers + RF in strong B-fields), acceleration by series of high-energy rapid-cycling synchrotrons with fast rising magnets, collision — all within ~0.1 s, detector backgrounds, high neutrino flux (>3 TeV)
- Demonstrator facility needed before full realisation
- Superb BSM physics reach, Higgs & SM programme

Muon Collider [ESPPU input](#)



Conceptual layout of a muon collider

The big picture: next-generation collider projects for CERN

Project	Construction start	First beams	Peak lumi at Z per IP [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	Peak lumi at HZ per IP [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	Years of operation	Construction cost* [BCHF]	Next stage collider	Start of operation	Total construction cost* [BCHF]
FCC-ee	2033	2046	144	7.5	14	15.3	FCC-hh	2079	34.7
LEP3	2037	2047	40	1.6	15	4.1	FCC-hh	2074	32.5
LCF 250 → 550 GeV	2035	2045	0.28	1.4 – 2.7	19	9.4 + 5.4 = 14.8	> 1 TeV collider?	–	–
CLIC 380 → 1500 GeV	2035	2045	–	1.2 _{380 GeV}	20	7.5 + 7.1 = 14.6	3 TeV collider?	–	–
LHeC	2037	2044	–	2.3	7	2.1	FCC-hh	2064	30.5

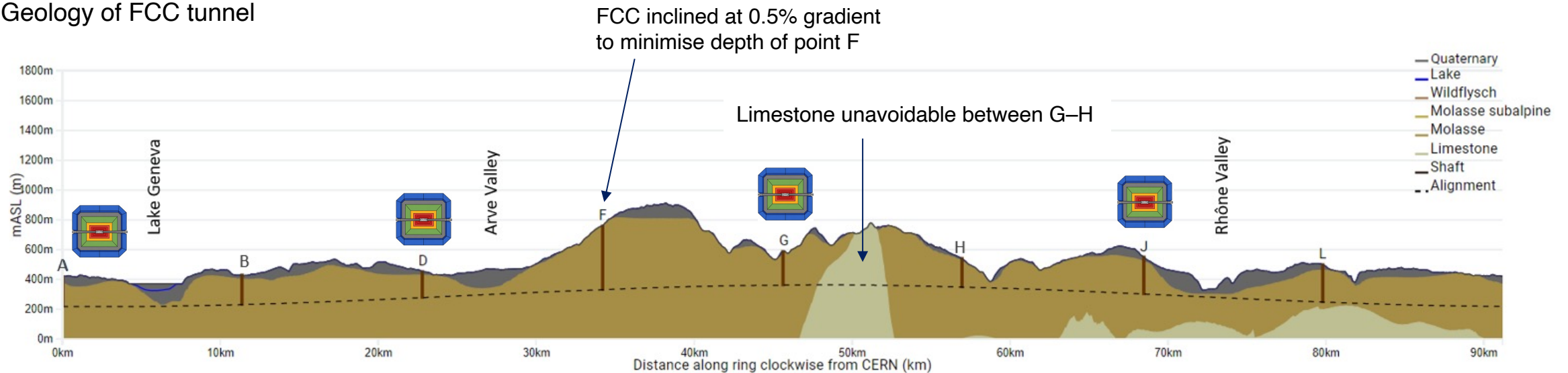
Similar start dates driven by HL-LHC running until 2041

*Construction costs include experiments

FCC-ee

Next-generation circular e^+e^- collider to deliver extremely high luminosities across multiple energies

Geology of FCC tunnel



Tunneling mainly in molasse layer (soft rock), well suited for fast, low-risk construction, 6 million m^3 excavated volume
→ 8.5 million m^3 excavation material on surface (OpenSkyLab R&D project to study reuse), average shaft depths ~240 m

265'000 m^3 concrete/year over 8 years (0.075% of annual EU production), use of low-carbon concrete under study

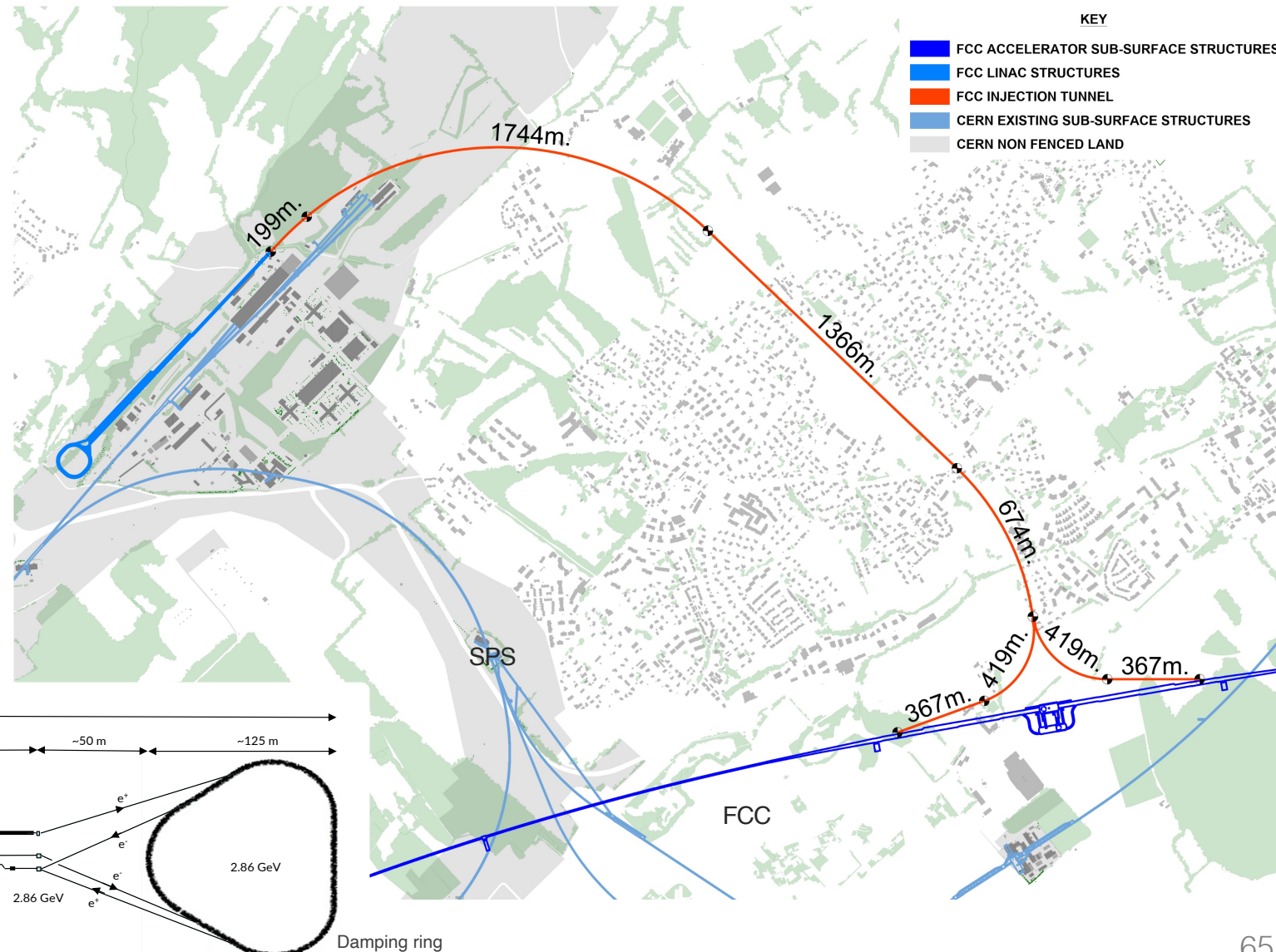
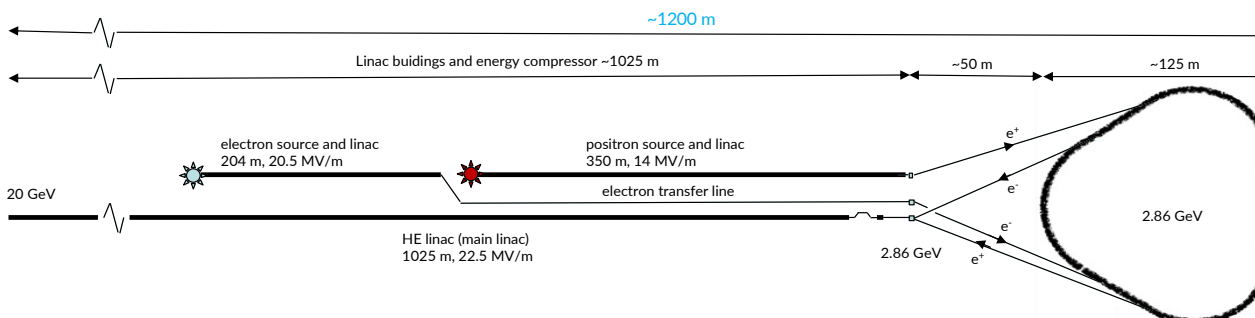
Total civil engineering construction carbon footprint estimate: 530,000 – 1,184,000 $\text{tCO}_2(\text{eq})$ = 1.5 – 3.4 × CERN with LHC operation per year

Assessed according to European Norms (EN 17472, EN15804+A2)

FCC-ee – Injector

FCC-ee injector with high-energy linac

- Located on CERN Préveessin site
- Transfer line to FCC PA (LHC P8, LHCb), “cut and cover” construction
- Conventional positron source using tungsten target + capture linac, need: $1.1 \times 10^{13} \text{ e}^+/\text{s}$ (SLC: $\sim 6 \times 10^{12} \text{ e}^+/\text{s}$)
- 2.9 GeV damping ring with wigglers (small synchrotron to reduce transverse and longitudinal beam emittance)
- Main linac $\sim 1 \text{ km}$ with 22.5 MV/m to accelerate e^+ and e^- to 20 GeV for injection into booster
- Total length about 1.2 km



FCC-ee — parameters

Parameter	Z	WW	H (ZH)	t $\bar{t}$	
Collision energy $\sqrt{s}$ [GeV]	88, 91, 94	157, 163	240	340–350	365
SR energy loss / turn [GeV]	0.036	0.08	1.7	7.8	9.2
Total RF voltage 400 / 800 MHz [GV]	0.08 / 0	1.0 / 0	2.1 / 0	2.1 / 7.4	2.1 / 9.2
Synchrotron radiation/beam [MW]	50	50	50	50	50

Despite the constant synchrotron power ($U_0 \propto E^4/\rho$, $P_{SR} = U_0 I$), due to the larger RF voltage and system size (increased cryogenic system), RF efficiency losses, and other increasing accelerator demands, the electrical power consumption increases with CM energy:

FCC-ee electrical energy consumption	Z	W	H	top	
Beam energy [GeV]	45.6	80	120	182.5	
Peak power during beam operation [MW]	250	275	297	381	LHC + injectors: ~ 200 MW peak power
Total FCC-ee yearly consumption [TWh]	1.2	1.3	1.4	1.85	Today with LHC operating: ~1.3 TWh

Various R&D towards further reduction of electrical energy consumption

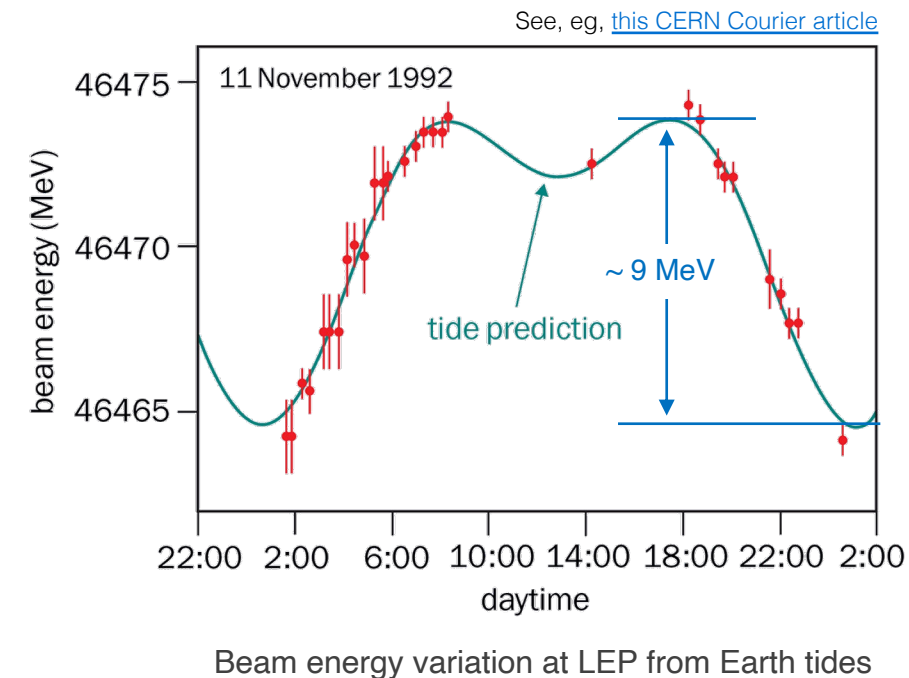
FCC-ee — beam energy

Precise knowledge of beam energy at Z pole crucial, meticulous work done at LEP to achieve

	m_Z	Γ_Z
LEP E_{CM} related syst. uncertainty:	1.7 MeV (1.9×10^{-5})	1.2 MeV
FCC-ee statistical uncertainty:	4 keV ($\ll 10^{-6}$)	4 keV

Precise beam energy calibration ($\Delta E/E < 10^{-6}$) through resonant depolarisation (RDP) as previously done at VEPP-2M (Novosibirsk) and LEP

- Due to synchrotron radiation, $e^\pm$ in storage ring become transversely polarised with a spin tune (number of spin precessions per turn in the bending field): $\nu_e = a_e \gamma = a_e E_e / m_e$. By applying an external RF field tuned to ν_e , which depolarises the beam, E_e can be measured with extraordinary precision
- At LEP, RDP could only be performed in a few fills, before or after collisions. E_{CM} knowledge limited by modelling of time evolution between measurements. E_{CM} calibration must be a central consideration in FCC-ee design & operational strategy: quasi-continuous RDP using non-colliding (unpaired) bunches
- Expect that E_{CM} systematics can be limited to 100 keV on m_Z and 25 keV on Γ_Z



FCC-ee – the Higgs factory

Extremely challenging — cornering the electron Yukawa coupling: $g_e = \sqrt{2}m_e/v \approx 2.9 \cdot 10^{-6}$

Can we measure the decay? (recall: $\Gamma_H = 4.1$ MeV)

$$\text{BR}(H \rightarrow e^+e^-) \simeq \frac{1}{\Gamma_H} \cdot \frac{G_F m_H m_e^2}{4\pi\sqrt{2}} \approx 5.2 \cdot 10^{-9}$$

The entire HL-LHC may produce 2 such events!

At the FCC-ee, BW s-channel resonance:

$$\sigma(e^+e^- \rightarrow H) \simeq \frac{4\pi\Gamma_H\Gamma(H \rightarrow e^+e^-)}{(s - m_H^2)^2 + m_H^2\Gamma_H^2} \xrightarrow{s=m_H^2} \frac{4\pi}{m_H^2} \text{BR}(H \rightarrow e^+e^-) \approx 1.6 \text{ fb}$$

but ISR and $\sqrt{s}$ spread will lead to smearing of BW peak, so that effective cross section is 0.3 fb (remember: $\mathcal{L}_{\text{ZH}} = 10.8 \text{ ab}^{-1}$). **Can it be done?**

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
mass $\approx 2.2 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ u up	 mass $\approx 1.28 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ c charm	 mass $\approx 173.1 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ t top	 mass 0 charge 0 spin 1 g gluon	 mass $\approx 124.97 \text{ GeV}$ charge 0 spin 0 H higgs
 d down	 mass $\approx 96 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ s strange	 mass $\approx 4.18 \text{ GeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ b bottom	 mass 0 charge 0 spin 1 γ photon	
 e electron	 mass $\approx 105.66 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ μ muon	 mass $\approx 1.7768 \text{ GeV}/c^2$ charge -1 spin $\frac{1}{2}$ τ tau	 mass $\approx 91.19 \text{ GeV}/c^2$ charge 0 spin 1 Z Z boson	
 ν_e electron neutrino	 mass $< 1.0 \text{ eV}/c^2$ charge 0 spin $\frac{1}{2}$ ν_μ muon neutrino	 mass $< 18.2 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$ ν_τ tau neutrino	 mass $\approx 80.39 \text{ GeV}/c^2$ charge ± 1 spin 1 W W boson	

QUARKS

LEPTONS

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

Almost all Higgs couplings to SM particles will have been measured at HL-LHC & FCC-ee

FCC-ee – the Higgs factory

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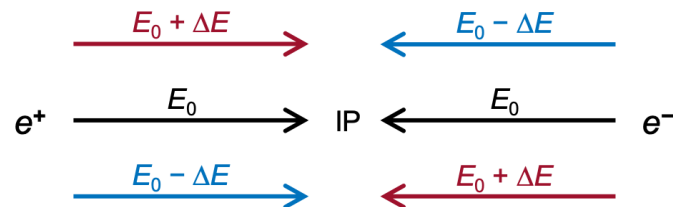
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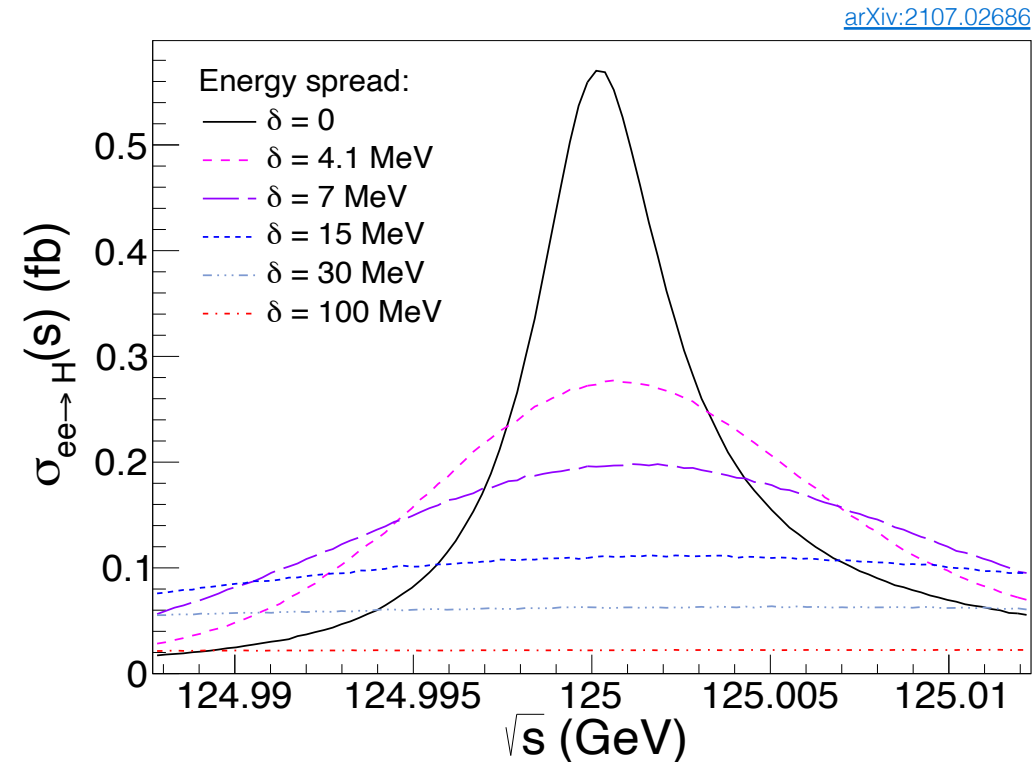
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but ISR and $\sqrt{s}$ spread will lead to smearing of BW peak, so that effective cross section is 0.3 fb (remember: $\mathcal{L}_{ZH} = 10.8 \text{ ab}^{-1}$). **Can it be done?**

- Requires precise knowledge of Higgs mass to few MeV
- Beam must be monochromatized to match narrow Γ_H [arXiv: 2411.04210]



Correlate energy and transverse position so high-energy particles collide with low-energy ones (opposite beam dispersions at IP) — requires dedicated instruments: proposed for many e^+e^- colliders, but never implemented



Possible sensitivity to g_e of $\sim 0.5\sigma$ per year and IP

FCC-ee — projected construction cost

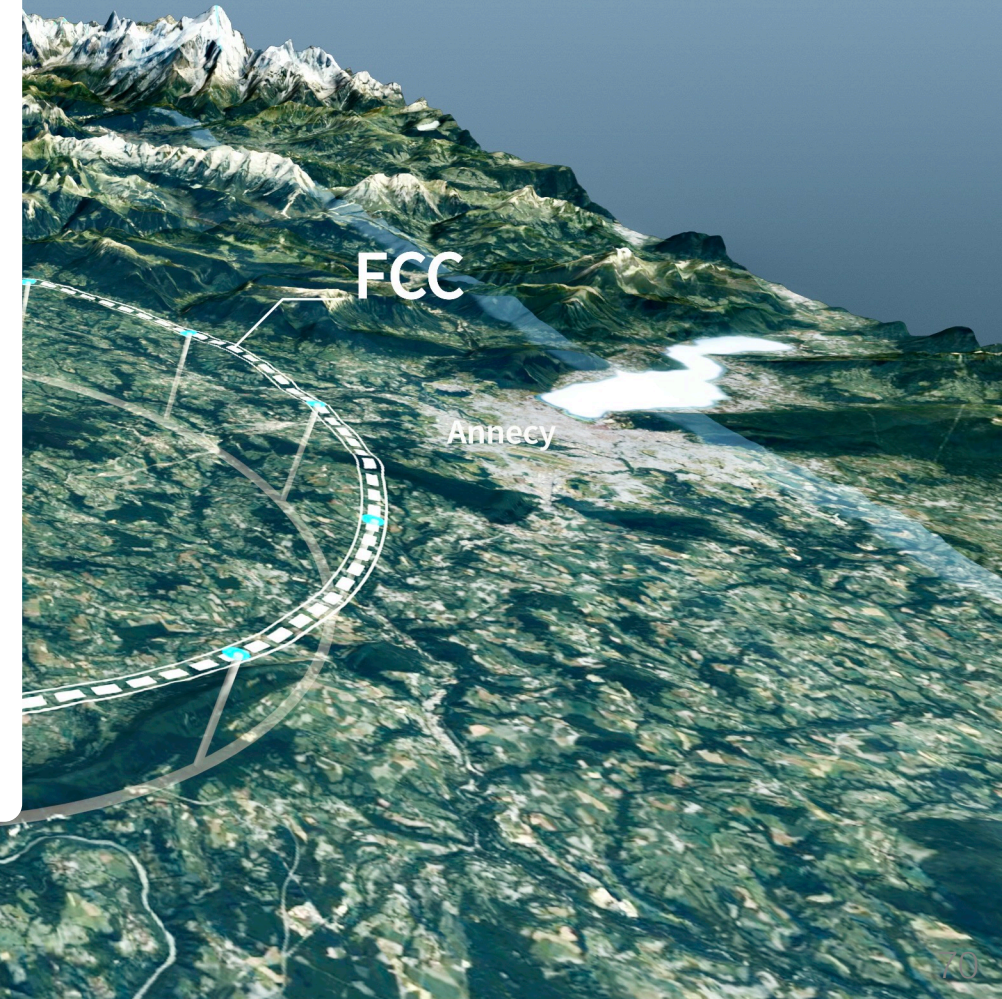
First stage incl. Z, WW and ZH working points. Upgrade to ttbar adds 1,260 MCHF

Domain	Cost [MCHF]
Civil engineering	6,160
Technical infrastructures	2,840
Injectors and transfer lines	590
Booster and collider	4,140
CERN contribution to four experiments	290
FCC-ee total	14,020
+ four experiments (non-CERN part)	1,300
FCC-ee total incl. four experiments	15,320

Note: First FCC-ee stage (up to ZH)

Over a period of 15 years

- Human resources for construction estimated to 15,000 FTE-years



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Socio-economic impact analysis (incl. investment, personnel, external effects, dismantling, ...) estimates benefit–cost factor of 1.2 (net: 4.1 MCHF)

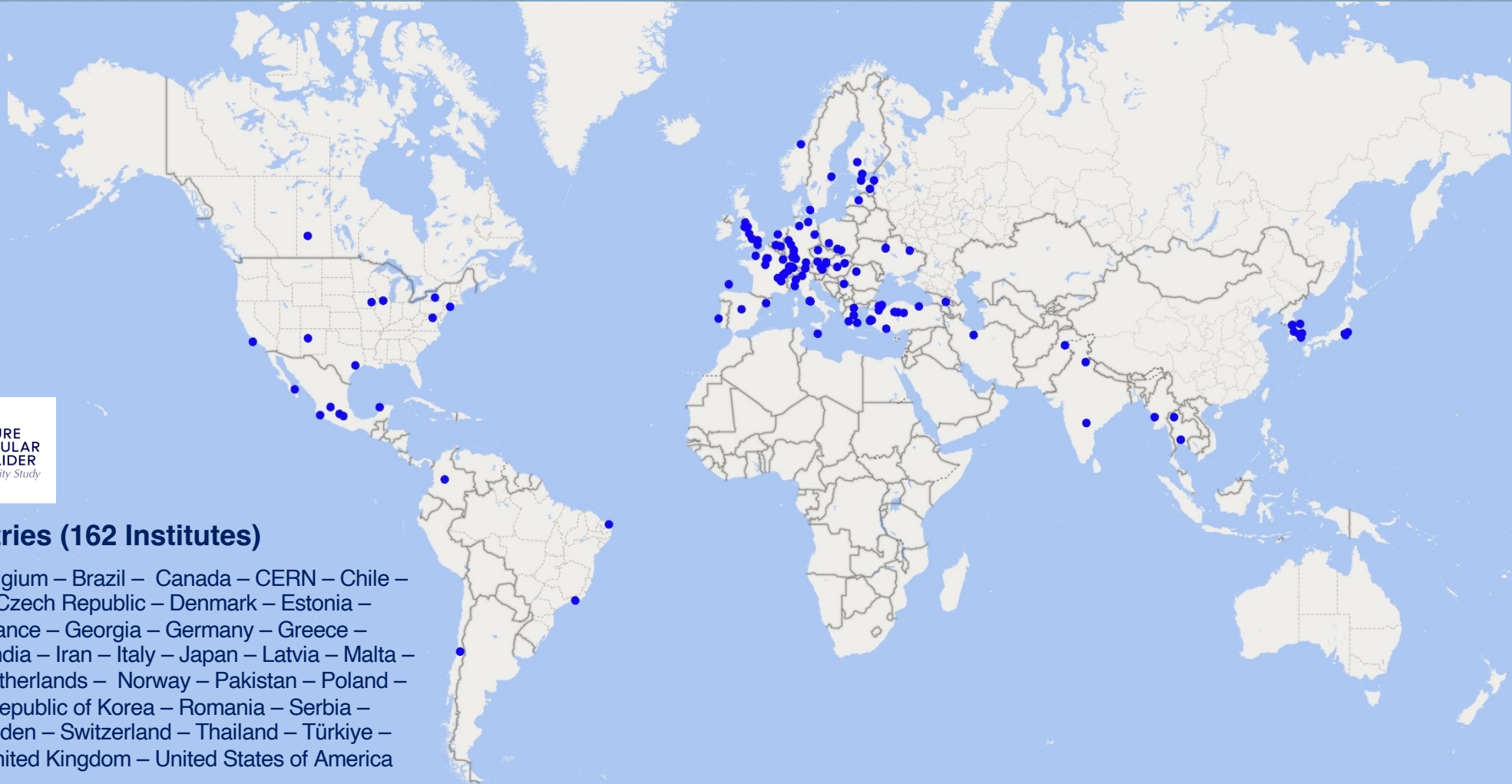
TOTAL COSTS (MCHF) 20,020		TOTAL BENEFITS 24,092	
INVESTMENTS (CAPEX)	10,8%	SCIENTIFIC PRODUCTIO	11,7%
OPERATION COSTS	9,42%	EARLY CAREER TRAINING	20,7%
Personnel	7,544	INDUSTRIAL BENEFITS (SUPPLIERS)	39,7%
Other Ops	1,879	OPEN SOFTWARE	18,2%
NEGATIVE EXTERNALITIES	1,7%	CULTURAL BENEFITS	9,7%
Shadow Cost of Carbon	341	Onsite Visitors	2,242
Other (Radiation, Noise, Air Pollution, etc.)	13	Online Visitors	102
DECOMMISSIONING	72		
NET PRESENT VALUE 4,071 MCHF		BENEFIT–COST RATIO 1.20	

90% CL lower limit

<https://doi.org/10.5281/zenodo.10653395>

FCC-ee — global collaboration

Increasing international collaboration is a prerequisite for success. Links with science, R&D, and high-tech industry will be essential to further advance and prepare the implementation of the FCC



38 Countries (162 Institutes)

Austria – Belgium – Brazil – Canada – CERN – Chile – Colombia – Czech Republic – Denmark – Estonia – Finland – France – Georgia – Germany – Greece – Hungary – India – Iran – Italy – Japan – Latvia – Malta – Mexico – Netherlands – Norway – Pakistan – Poland – Portugal – Republic of Korea – Romania – Serbia – Spain – Sweden – Switzerland – Thailand – Türkiye – Ukraine – United Kingdom – United States of America

European Commission — moonshots

Recognition by the European Commission highlights the strategic value of the FCC, not only for fundamental research but also as a project fostering high-level collaboration in Europe

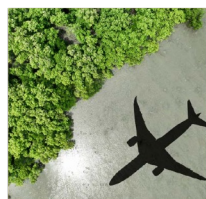
[Link to document](#)



Future Circular Collider

What: Sustain Europe's leadership in particle physics by investing in CERN's next-generation collider.

How: Co-invest with other CERN countries, leveraging Horizon Europe funding.



Clean Aviation

What: Lead the world in developing the next generation of CO₂-free aircraft.

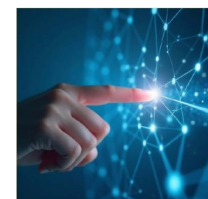
How: Bring together industry and scientific capacities to achieve breakthroughs in clean aviation.



Quantum Computing

What: Make Europe the first continent with fully integrated quantum computing in daily life.

How: Develop applications from medicine to climate, solving previously impossible problems for 450 million citizens.



Next Generation AI

What: Model the new AI on the laws of nature and grounded in physics and biology.

How: AI developed by, with, and for European scientists and industry, drawing to Europe the world's best minds.



Data Sovereignty

What: Make Europe the global leader and safest hub for critical research data.

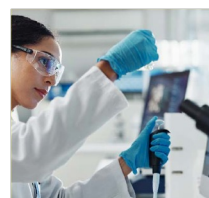
How: Provide access to critical data for researchers, universities and companies, offering competitive advantage in tackling global challenges.



Automated Transport and Mobility

What: Advance safe, inclusive, and emission-reducing automated transport and mobility in Europe.

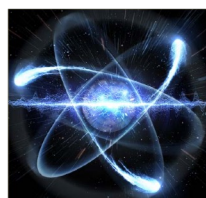
How: Invest in smart transport systems to improve traffic, reduce emissions, and enhance access.



Regenerative Therapies

What: Deliver breakthrough therapies to improve people's health and lives.

How: Harness Europe's scientific strengths to treat incurable diseases and personalise medicine.



Fusion Energy

What: The first commercial nuclear fusion power plant, generating safe, consistent, and reliable electricity.

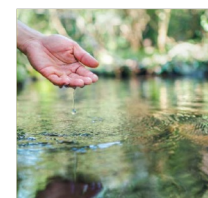
How: Overcome the scientific and technological challenges necessary to put fusion on the grid in Europe by 2034.



Space Economy

What: Make Europe the leader in the space economy.

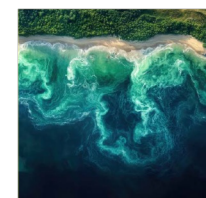
How: Develop the next generation launch vehicles such as reusable rockets, able to deploy massive cargo by 2040.



Zero Water Pollution

What: Move towards zero pollution of water in the EU.

How: Stimulate innovation to build a true water-smart economy which secures sufficient, clean and affordable water and sanitation to all at all times.



Ocean Observation

What: Achieving strategic autonomy in ocean observation infrastructure, data and information services.

How: Developing, connecting, governing and securing the next generation of European ocean observing technologies

The European Strategy for Particle Physics

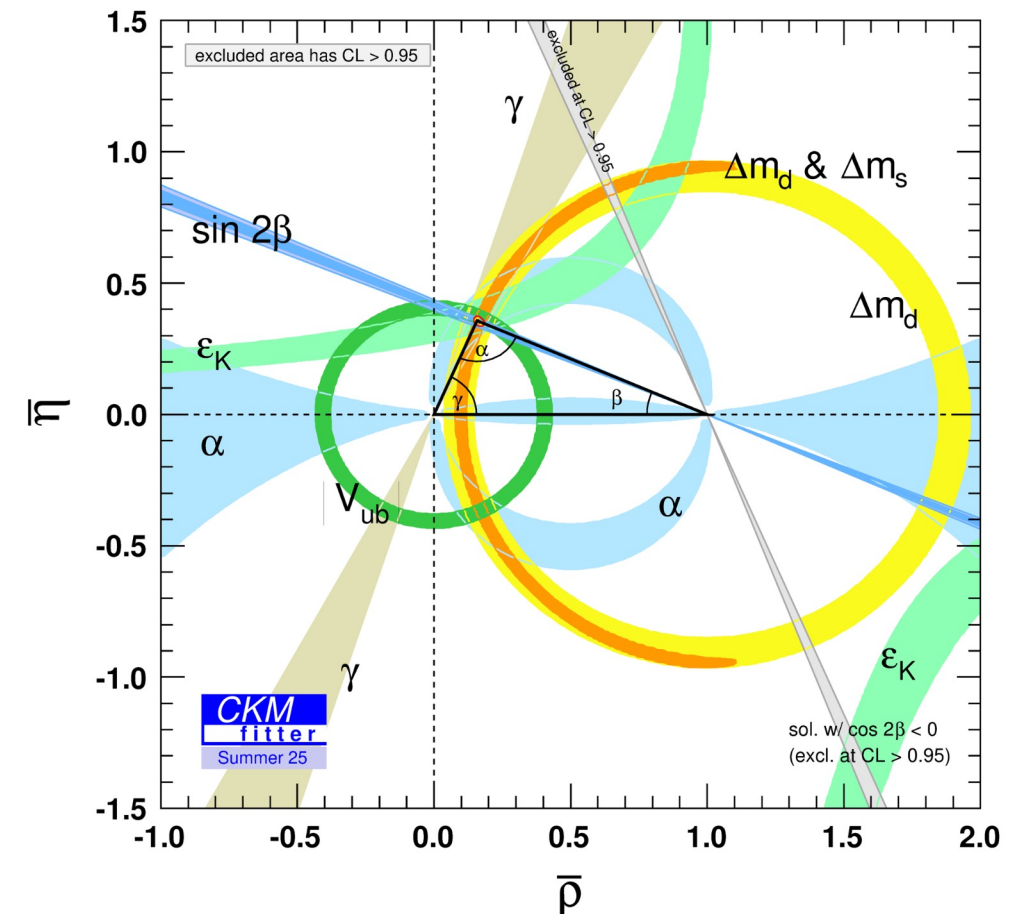
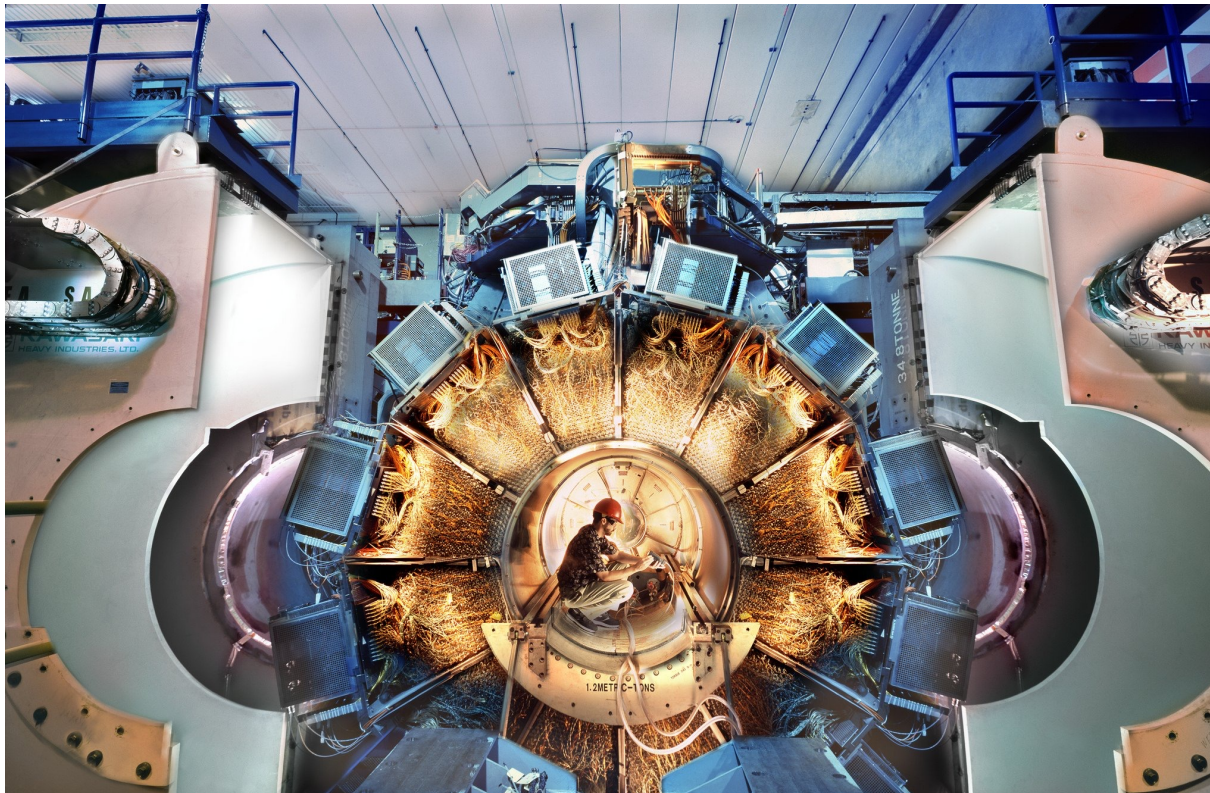
Main recommendations of the 2026 strategy update

- **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
- **The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN**
- A descoped FCC-ee* is the preferred alternative option for the next flagship collider at CERN
*No $t\bar{t}$ run: –1.26 BCHF, drop 2 / 4 experiments: –0.80 BCHF, decrease RF power from 50 → 30 MW (–0.35 BCHF)
- **The particle physics community should continue and intensify its efforts to develop and adopt sustainable solutions**
- ...

Links: [CERN Council resolution](#), [Recommendations](#), [Briefing book](#), [All documents](#), [More information](#), [CERN Colloquium by Karl Jakobs](#)

Beyond the energy frontier

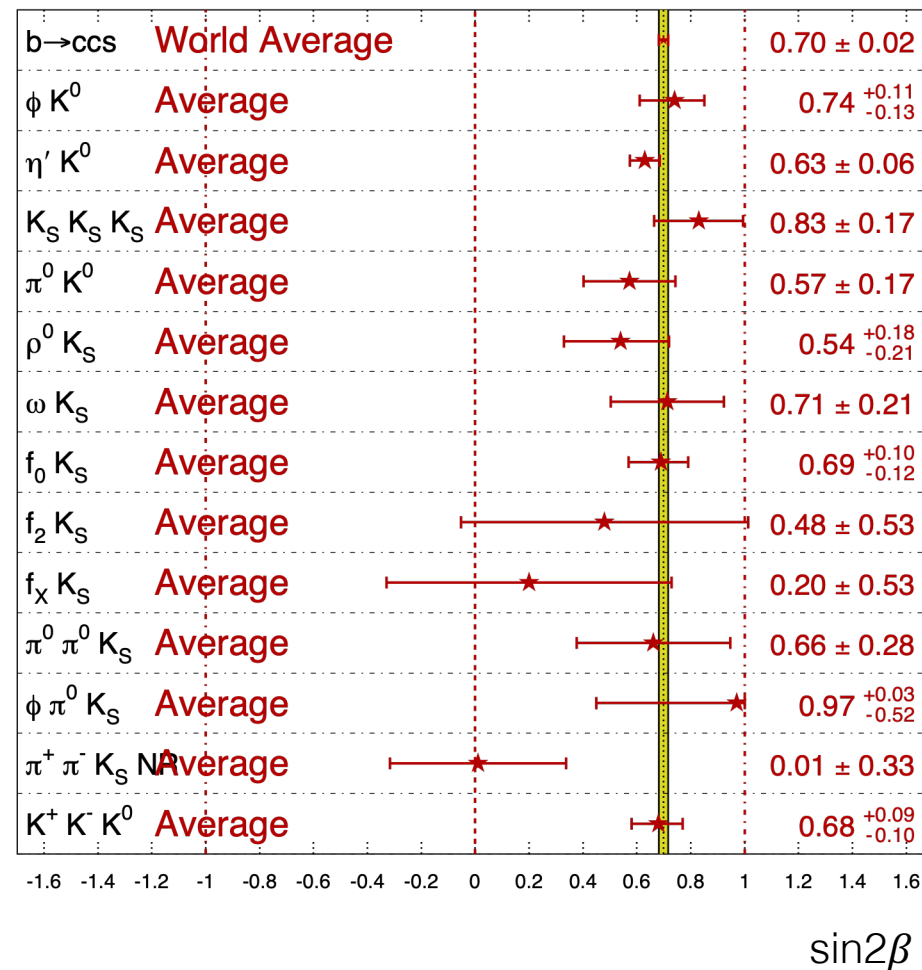
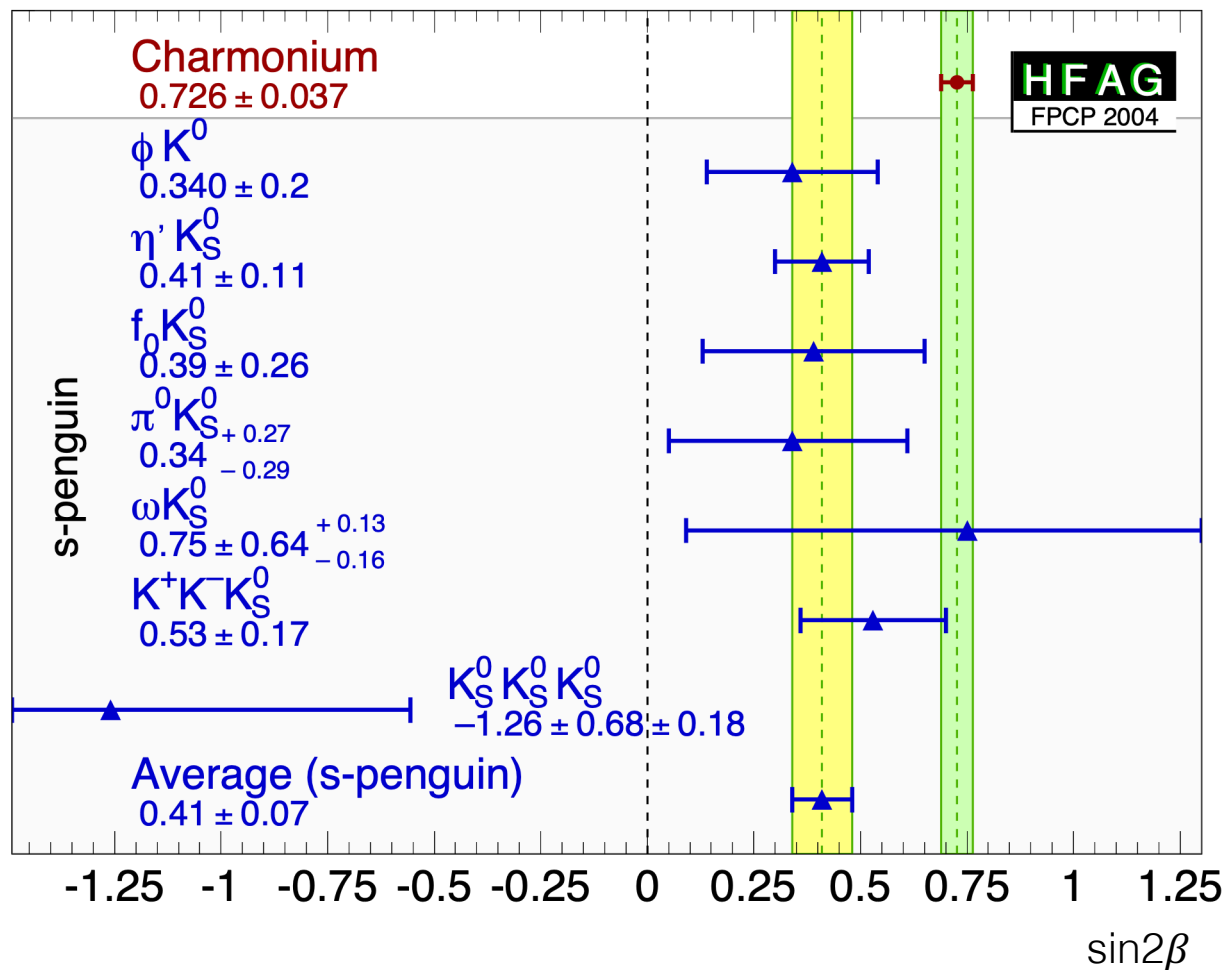
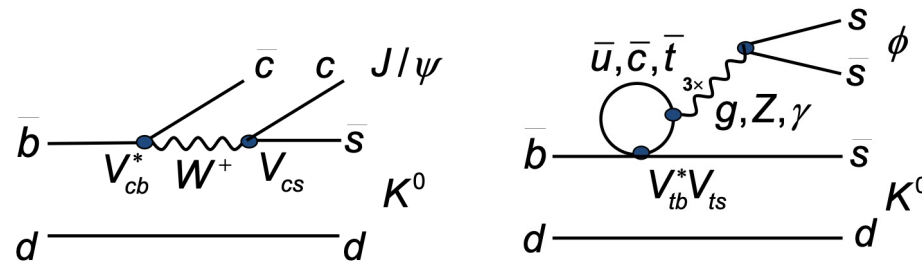
Asymmetric B-factories began data taking at KEK and SLAC in 1998 and observed CP violation in the B sector, a highly successful programme which continues at KEK with the SuperKEKB / Belle-II project



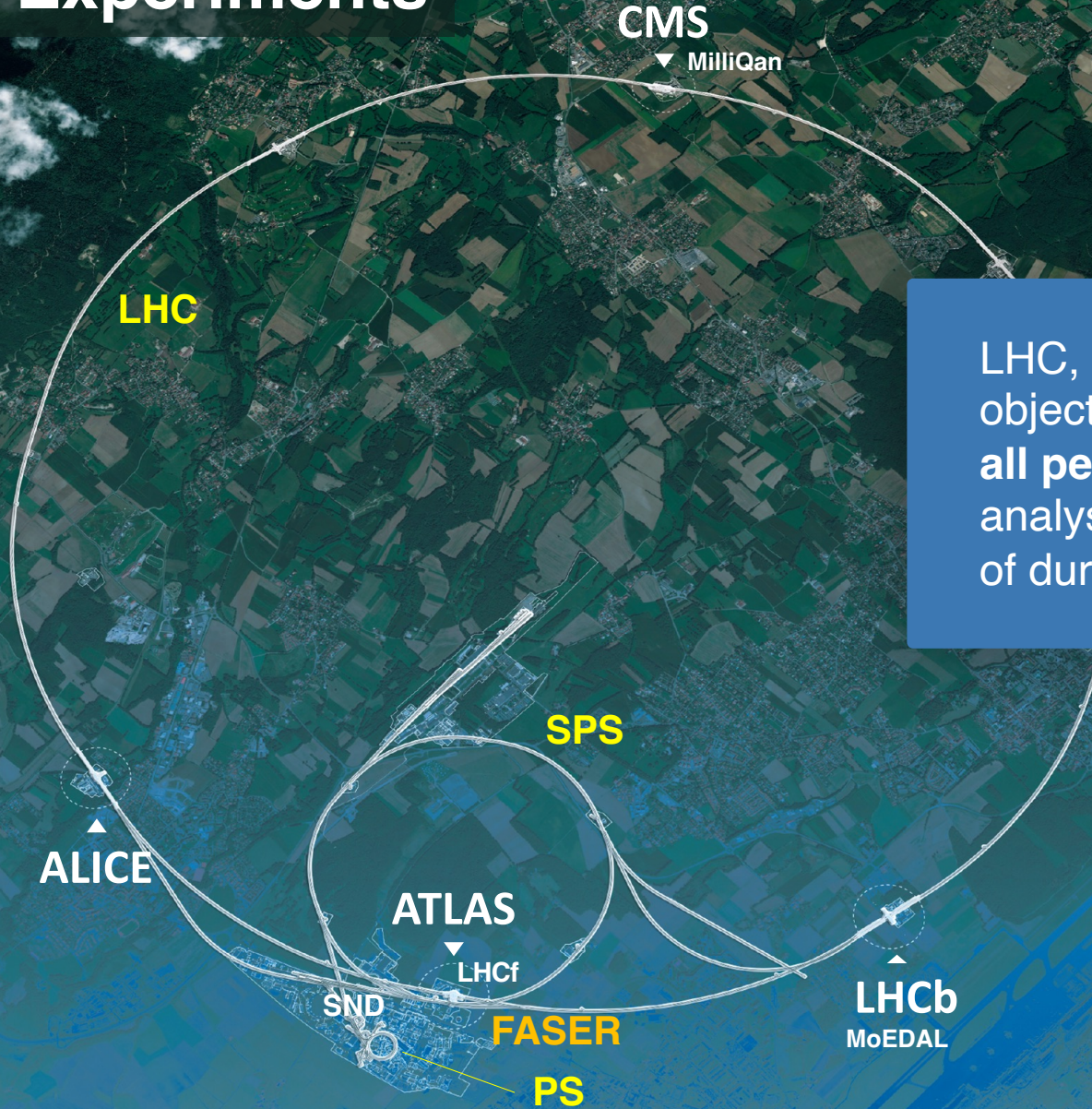
Left: DIRC — novel particle ID detector at the BABAR experiment
Right: legacy of the B factories (2012) — the Standard Model holds

Beyond the energy frontier

A lesson on penguins



LHC and Experiments



LHC, experiments, software & computing, object reconstruction and physics analysis — **all perform beyond design**. Many new analyses ideas emerged that were not thought of during the design phase. ML now ubiquitous

Aerial view