

Prospects of Particle Physics after the HL-LHC

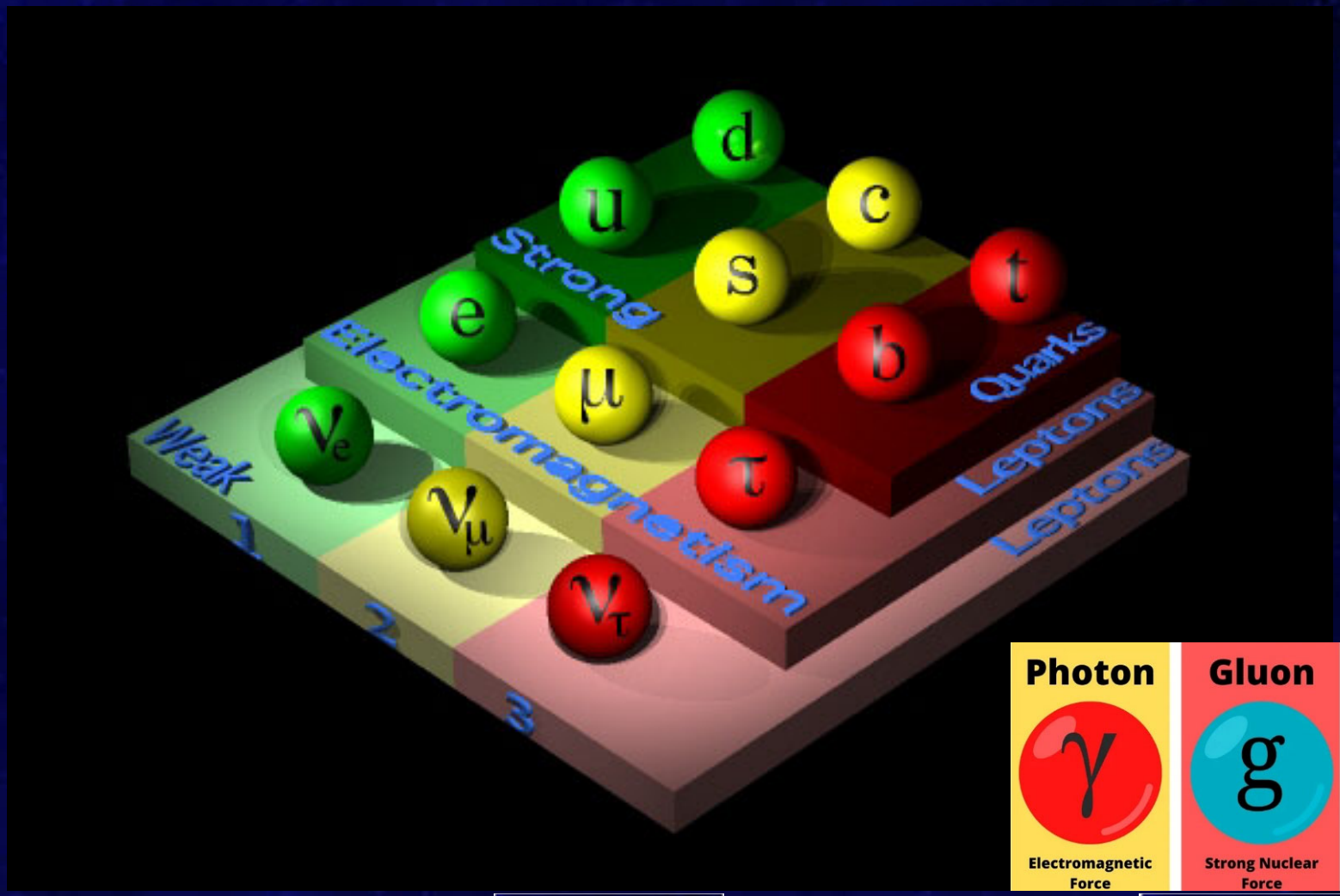
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1. **Particle physics: where do we stand?**
2. **The decision making process in particle physics**
3. **Prospects beyond HL-LHC: the Future Circular Collider project**

Particle Physics: where do we stand?

The Standard Model of particle physics



Source: QuarkNet

Space.com, image credit: Robert Lea

Shortcomings of the Standard Model



Source: Wikipedia



Source: dobrewiadomosci.net.pl

In particle physics research you will not complain about boredom

On the contrary, your hands will be full with studies of these enigmas

We are desperately searching for „New Physics (NP)”
or „Physics Beyond the Standard Model (BSM)”

Shortcomings of the Standard Model

With the observation of the Higgs boson, we have evidence for the complete set of particles predicted by the Standard Model

However, it is clear that the SM is not the ultimate theory of fundamental physics

It leaves us with many profound and fundamental questions:

- Why is the group structure of the SM so complicated? Do the three forces unify?
- Why are there so many types of particles, and in particular, why are there just three generations?
- Why are there so many free parameters (19 or 26 including massive neutrinos)?
- What is the nature of neutrinos (their masses, and whether they are Dirac or Majorana particles)?
- What is the origin of the matter – antimatter asymmetry (CP violation)?
- Why is strong CP violation unnaturally small?
- What is dark matter? The SM does not provide any natural candidate
- What is dark energy?

Shortcomings of the Standard Model

and some of the Higgs boson specific questions

- Why do the fermion masses exhibit so distinct pattern?
- Are there more Higgs bosons?
- Is the Higgs boson fundamental or composite?
- What stabilizes the Higgs mass?
- What is the nature of the Higgs potential

and the list is not yet fully exhaustive…

- How can we construct a quantum theory of gravity and unify it with the other three forces?
- Why are there three spatial dimensions? Are there additional dimensions?
- …

We have no clear or unequivocal indication of either the energy scale, at which a new theory of particles and fields must manifest itself, or of the coupling strengths of new particles to the SM components

→ Our research and tools should be as much versatile as possible…

→ In particular, we need more energy, more precision and greater sensitivity

The LHC has produced outstanding results

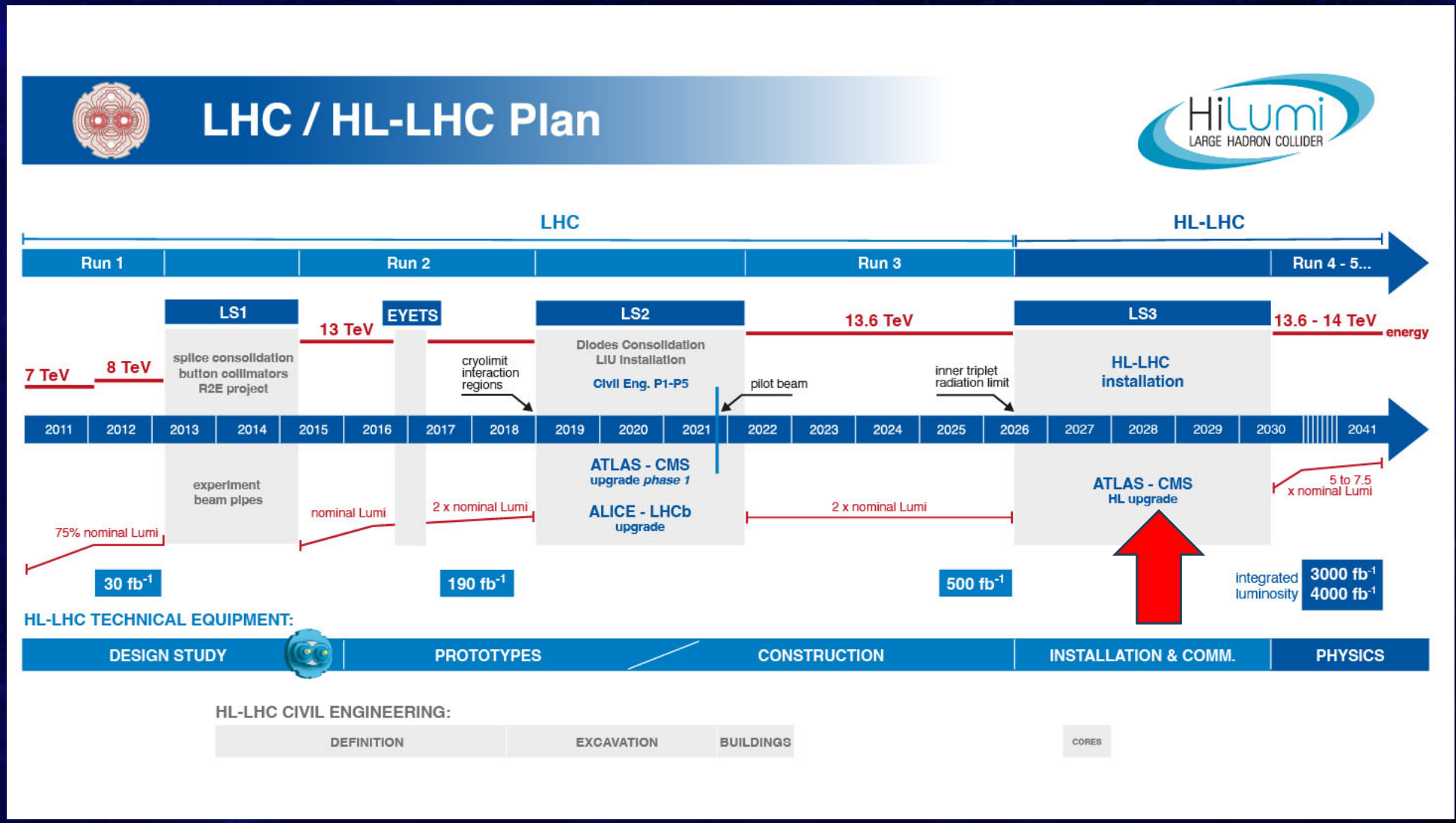
- **Discovery of the Higgs boson (2012)**
- Extensive follow up studies of the Higgs boson properties



Source: Erik Lindberg \ Nobel Foundation

- An extraordinary variety of measurements of SM observables
- Important studies of the properties of the top quark
- A very broad programme of searches for physics beyond the Standard Model
- Observation of a plethora of new hadron states (86 so far)
- A variety of results from ultra high-energy heavy ion collisions
- …

HL-LHC – the High-Luminosity Large Hadron Collider



The HL-LHC installation will be the largest project undertaken by CERN in approx. 20 years…

Highlights of the HL-LHC physics programme

- **A tenfold improvement in the data sample …**
  together with improved detector performance:

  - **Crucial improvements in our knowledge of the Higgs boson**
    (Higgs couplings to fermions and vector bosons, self-interactions, shape of the Higgs potential, search for new phenomena in the Higgs sector …)

  - **Qualitative improvements in the precision of electroweak parameters**

  - **Direct searches** – potential for discovery of new particles or exclusion of specific models (heavy resonances, supersymmetry, long-lived particles, dark matter…)

  - **Flavour physics:** CKM metrology, QCD spectroscopy, rare decays…

  - **Heavy ions:** precision studies of properties of QCD matter

  - …

The decision making process in particle physics

- **Major investments require extensive planning and decision making…**
- European particle physics: the CERN Council initiates and oversees the process of **updating the European Strategy of Particle Physics (ESPP)**, including with its final approval
- The latest edition: 2024-2026, with the following remit:

> *"The aim of the Strategy update should be to develop a **visionary and concrete plan** that greatly advances human knowledge in fundamental physics through the **realisation of the next flagship project at CERN**. This plan should attract and value **international collaboration** and should **allow Europe to continue to play a leading role in the field."***
>
> *"The Strategy update should include the **preferred option** for the next collider at CERN and **prioritised alternative options** to be pursued if the chosen preferred plan turns out not to be feasible or competitive."*
>
> *"The Strategy update should also **indicate areas of priority for exploration complementary to colliders** and for other experiments to be considered at CERN and at other laboratories in Europe, as well as for participation in projects outside Europe."*



All ESPP materials

The main conclusion from the recent ESPP:

FCC – Future Circular Collider; **FCC-ee** – FCC electron-positron; **FCC-hh** – FCC hadron-hadron

- The **FCC-ee** would deliver the world's **broadest high-precision particle physics programme**

  - Outstanding discovery potential through the Higgs, electroweak, flavour and top sectors, as well as advances in QCD
  - Its technical feasibility is demonstrated via the FCC feasibility study
  - Scope and costs are well defined, plausible funding models exist

European Strategy for Particle Physics — ESG Recommendations

- The FCC-ee would maintain **European leadership in high-energy particle physics,** also advancing technology and providing societal benefits

- **FCC-ee** would also **pave the way towards a hadron collider** reusing the tunnel and much of the infrastructure, providing a direct **discovery reach well beyond the 10 TeV parton energy scale**

→ Flagship project at CERN, which will allow Europe to play a leading role in the field

The CERN DG Mark Thomson:

The key points from the European Strategy Group (ESG) report regarding FCC:

- Overwhelmingly strong endorsement of the physics and strategic case for FCC-ee as the next flagship collider at CERN
  - Near consensus within the particle physics communities in CERN's Member States
- A descoped/staged FCC is preferred to other options as the alternative
- No explicit prioritization of LEP 3, LHeC, LCF, CLiC.

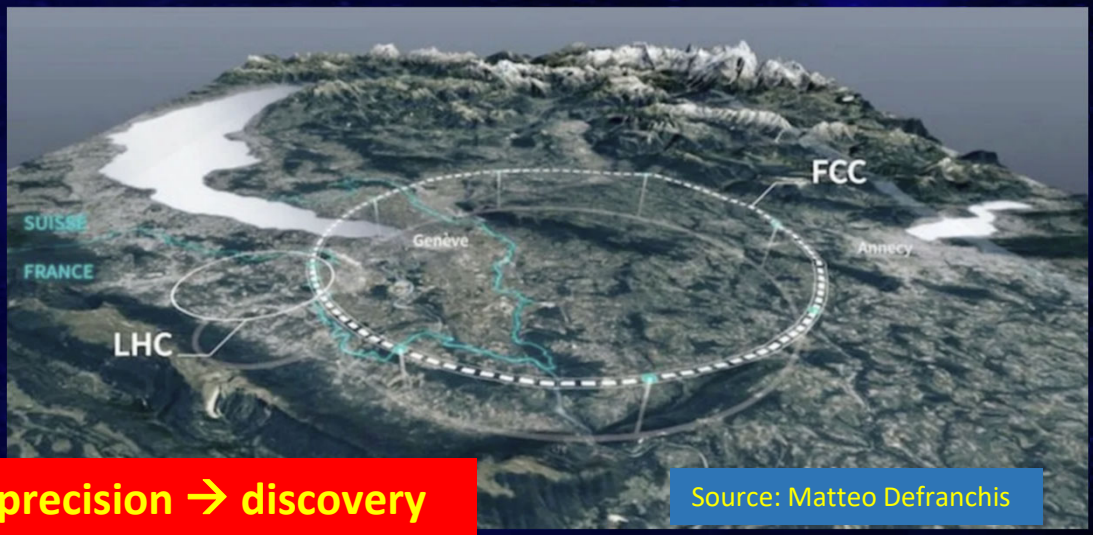
The FCC integrated programme

FUTURE CIRCULAR COLLIDER

FCC - a global international collaboration hosted at CERN

fcc.web.cern.ch | fcc-cdr.web.cern.ch

- ✓ **0th stage:** construction of ~91 km circumference tunnel infrastructure in Geneva area to host:
- ✓ **1st stage – FCC-ee:** electron positron collisions (90-360) GeV
- ✓ **2nd stage – FCC-hh:** proton-proton collisions at ~85 TeV



Source: Matteo Defranchis

A repetition of LEP & LHC success story: precision → discovery

Timeline:



FCC Feasibility Study Report:

Vol. 1

Vol. 2

Vol. 3

No apparent showstoppers identified

FCC: cost and socio-economic benefits

FCC-ee cost estimate (FSR 2025)

Capital cost (2024 CHF) for construction of the FCC-ee is summarised below. This cost includes construction of the entire new infrastructure and all equipment for operation at the Z, WW and ZH working points.

FCC-ee

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**

15.3

16.6

Note: Upgrade of SRF (800 MHz) & cryogenics for ttbar operation corresponds to additional cost of 1,260 MCHF

Cost summary table in 2024 MCHF for the construction of FCC-hh.

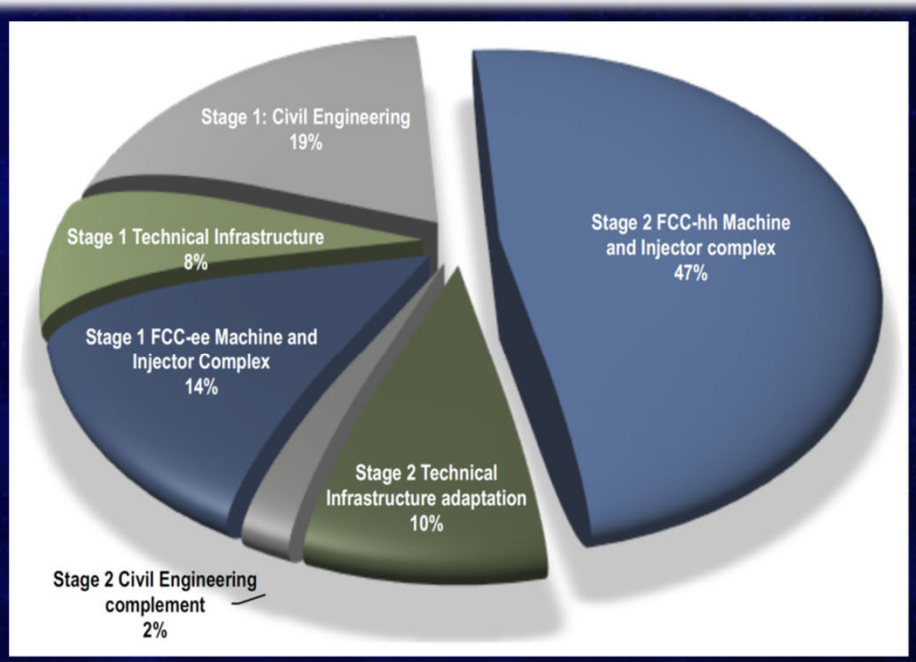
FCC-hh (after FCC-ee)

Domain	FCC-hh Cost [MCHF]
FCC-ee dismantling	200
Collider*	13400
Injectors and transfer linear	1000
Civil Engineering	520
Technical infrastructures	3960
Experiments	N/A
Total	**19080**

*target price of 2.0 MCHF per 14.3 m long magnet with 1.0 MCHF of conductor, 0.5 MCHF for assembly, and 0.5 MCHF for components

19.1

Source: FCC contrib. to the ESPP

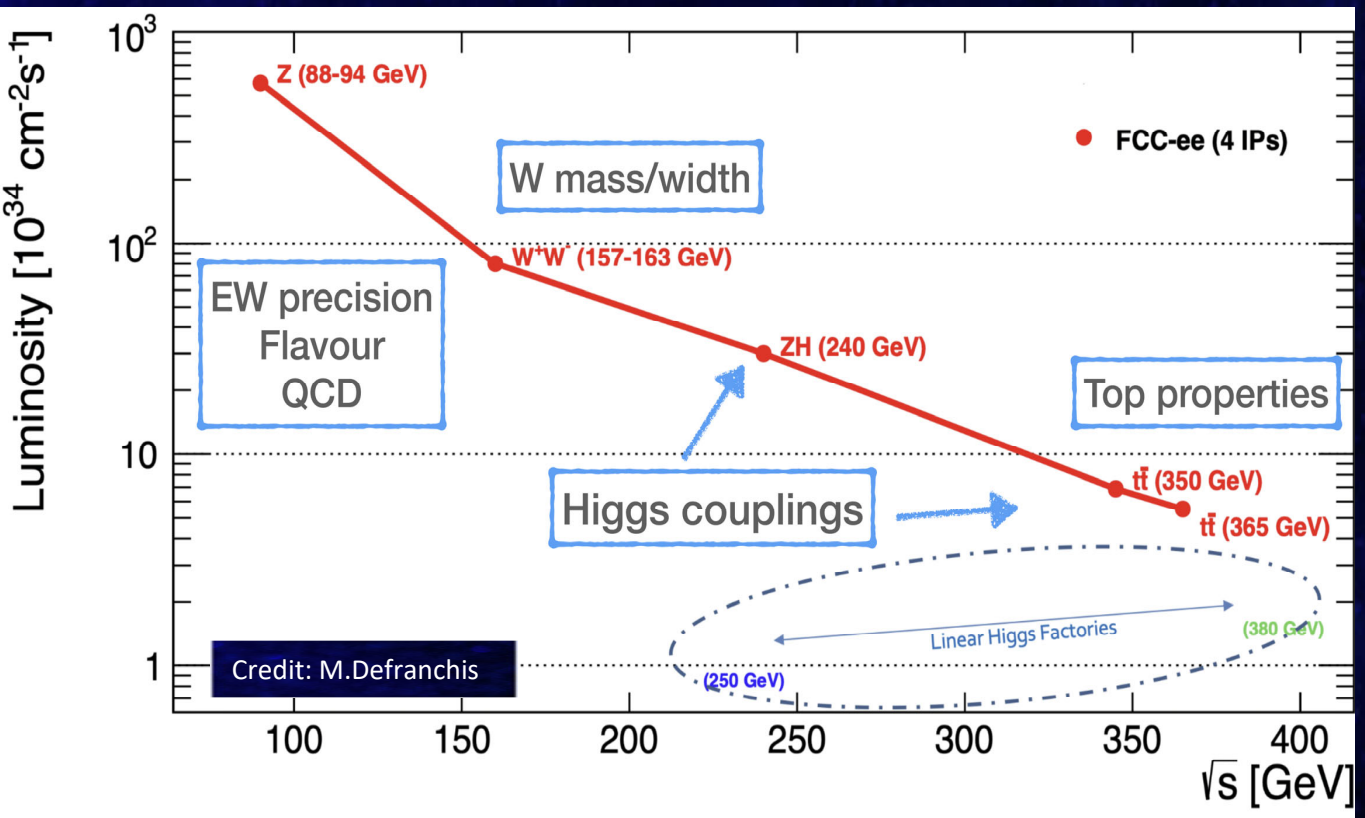


For FCC-ee it is expected that 1 EUR invested would generate 1.8 to 2 EUR for society

Source: FCC brochure



FCC-ee characteristics



Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^8 WW	2.2×10^6 ZH + 65k WW → H	2×10^6 $t\bar{t}$ + 370k ZH + 92k WW → H	

Huge data samples collected in a „clean” experimental environment:
x 10^5 (@Z),
x 10^4 (@WW)
of the luminosity of LEP

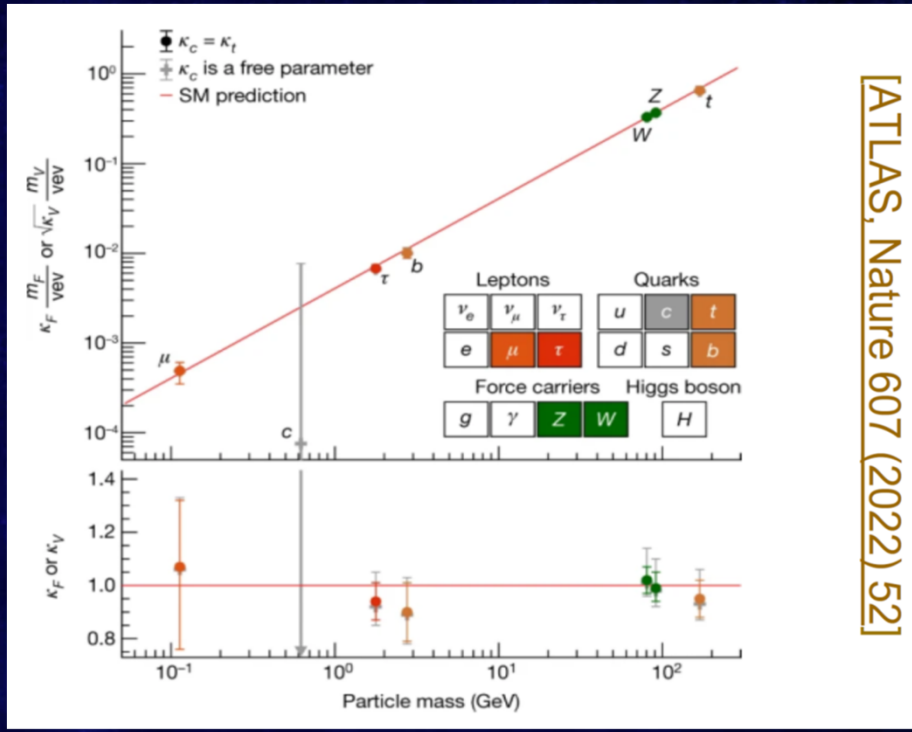
Four (+) energy points, explored in a compact 15-year programme

Higgs boson and top quark to be studied for the 1st time in e^+e^- collisions

Exciting options for extensions, e.g. Higgs-pole run

Higgs physics at the end of the HL-LHC

- The Higgs boson is a uniquely intriguing particle, connected to many of the open questions of the SM, and, possibly, also to cosmology
- Most likely the outcome of the extensive HL-LHC programme of ATLAS and CMS will be a Higgs boson that appear, at first sight, to behave as predicted by the SM



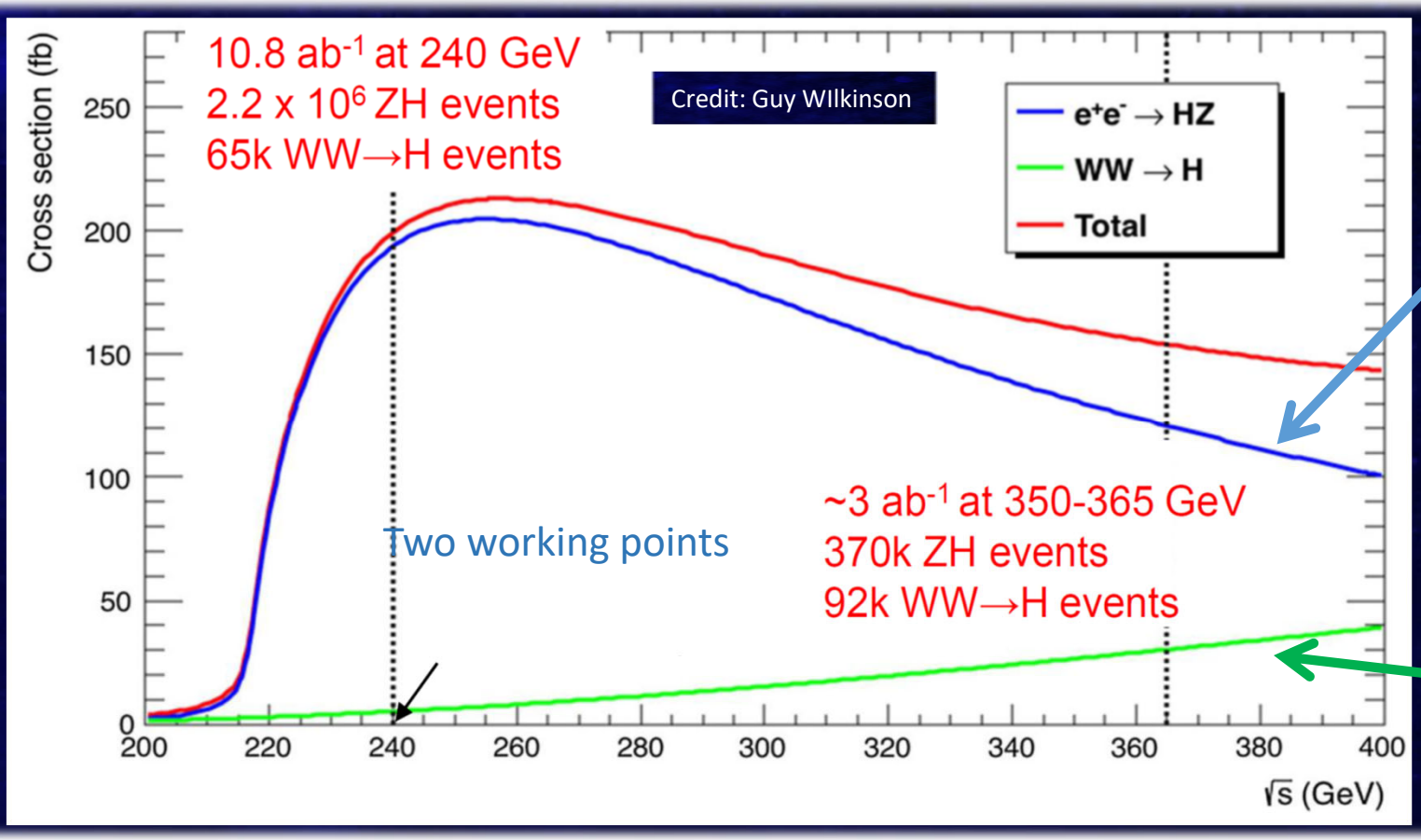
[ATLAS, Nature 607 (2022) 52]

The remaining limitations of Higgs physics at the end of the HL-LHC:

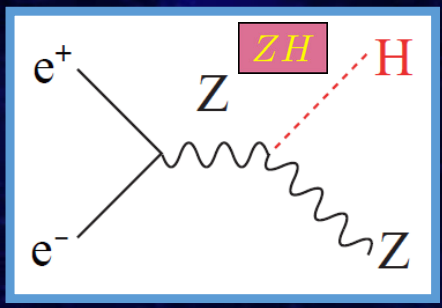
- Precision on couplings (5% in best case) is not sufficient to probe BSM physics
- Very limited information on second generation quarks
- Nothing is known about how Higgs couples to first generation („everyday") matter
- All results are model dependent because the Higgs width is poorly known
- Very limited knowledge of the Higgs coupling

The FCC-ee physics programme: Higgs boson

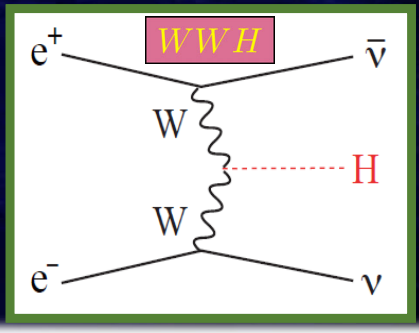
Overall goal: model independent measurement of the Higgs width and couplings with better than 1% precision



$e^+e^- \to ZH$



$e^+e^- \to \nu\bar{\nu}H$



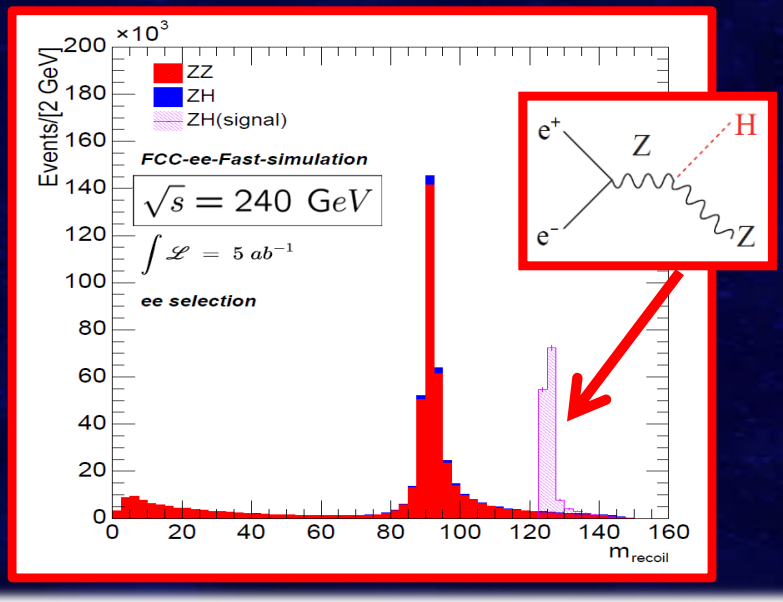
Model independence and absolute normalisation of Higgs width and couplings:
In e^+e^- →ZH, the presence of the Higgs boson can be inferred independently of its decay mode by reconstructing the recoiling Z boson

Higgs studies at FCC-ee

➢ **The recoil technique in e^+e^-→ ZH - unique to lepton colliders:**

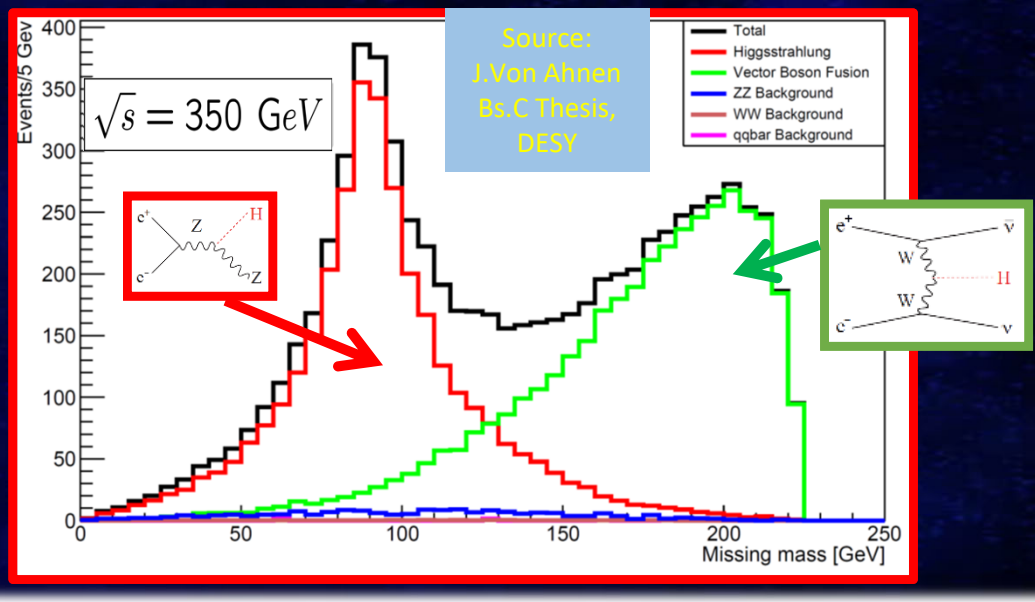
- Reconstruct only the Z and its decay products
- ZH events are tagged independently of Higgs decay mode (include invisible decay modes)
- Very clean determination of the Higgs mass: $\mathbf{m^2_{recoil} = (\sqrt{s} - E_Z)^2 - |p_Z|^2}$ $\Delta m_H \sim 2.5$ MeV
- Precise determination of the ZH cross-section: $\Delta\sigma(ZH)/\sigma(ZH) \sim 0.5\%$

$e^+e^- \to ZH$



Source: D.Boye ICHEP2026

$e^+e^- \to \nu\bar{\nu}H(\to b\bar{b})$



Higgs couplings at FCC-ee

➢ **Higgs couplings normalised to the SM predictions:**

$$k_f = \frac{g_{Hff}}{g^{SM}_{Hff}},\ f = b, c, \tau, \ldots$$

$$k_V = \frac{g_{HVV}}{g^{SM}_{HVV}},\ V = W, Z, \gamma, g$$

➢ **FCC-ee expectations:**

- **Precision of 0.1-0.5 % for many of the most interesting couplings**
- **Access to second-generation quarks for the first time**
- **Model independent results**
- **Results to be achieved within a compact eight-year programme**

Coupling	HL-LHC	FCC-ee
κ_Z (%)	1.3*	0.10
κ_W (%)	1.5*	0.29
κ_b (%)	2.5*	0.38 / 0.49
κ_g (%)	2*	0.49 / 0.54
κ_τ (%)	1.6*	0.46
κ_c (%)	–	0.70 / 0.87
κ_γ (%)	1.6*	1.1
$\kappa_{Z\gamma}$ (%)	10*	4.3
κ_t (%)	3.2*	3.1
κ_μ (%)	4.4*	3.3
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$
Γ_H (%)	–	0.78
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}

Source: Physics Briefing Book
arXiv: 2511.03883

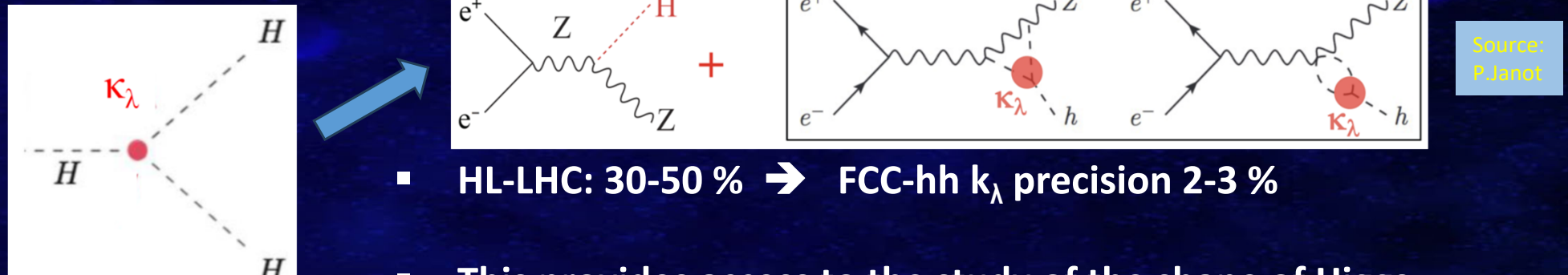
Any deviations → high sensitivity to New Physics

Higgs physics at FCC-hh

- The huge dataset of 20 billion Higgs bosons allows for sub-percent precision – a significant gain, particularly for rare H decays
- These results benefit from normalisation and model-independence provided by FCC-ee → great synergy and complementarity between FCC-ee and FCC-hh

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	–	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$	$^{+29}_{-67}$
Γ_H (%)	–	0.78	0.69
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}	6.7×10^{-3}

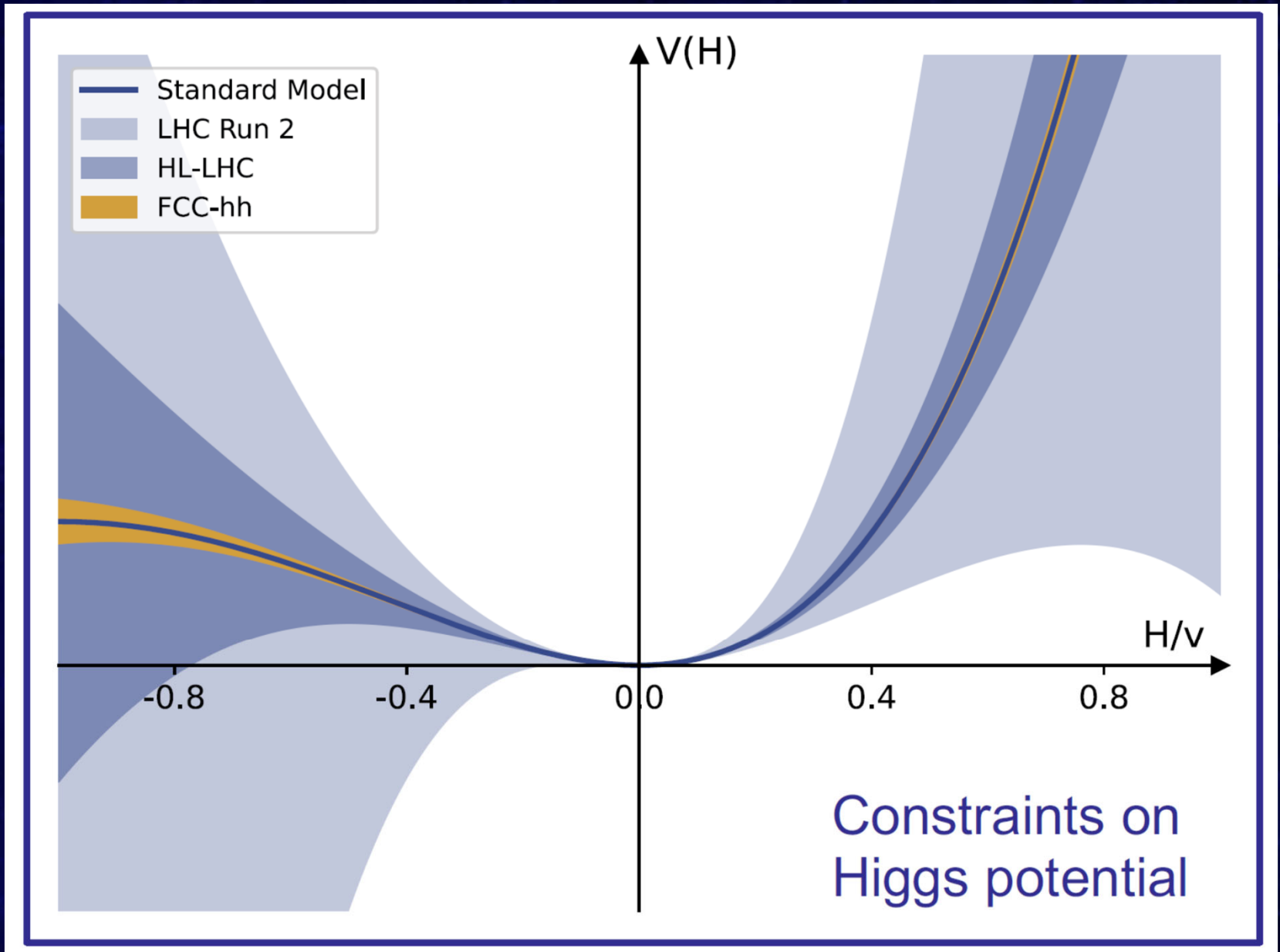
- FCC-hh also allows the Higgs self-coupling to be accessed through 30 million HH events:



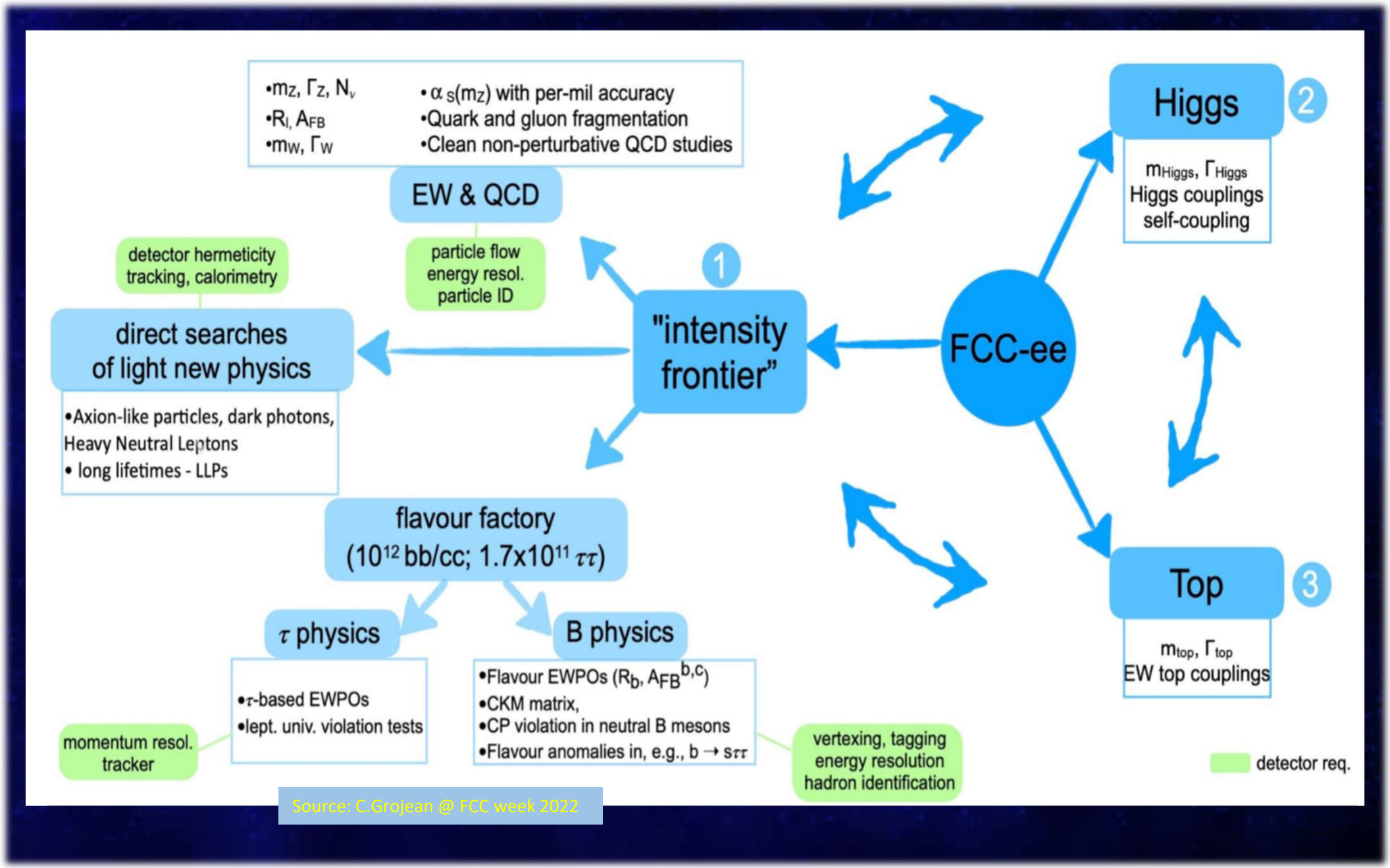
Source: P.Janot

- HL-LHC: 30-50 % → FCC-hh k_λ precision 2-3 %
- This provides access to the study of the shape of Higgs potential → critical information about the early Universe

Higgs studies at the LHC and FCC



The FCC-ee is much more than a Higgs factory…



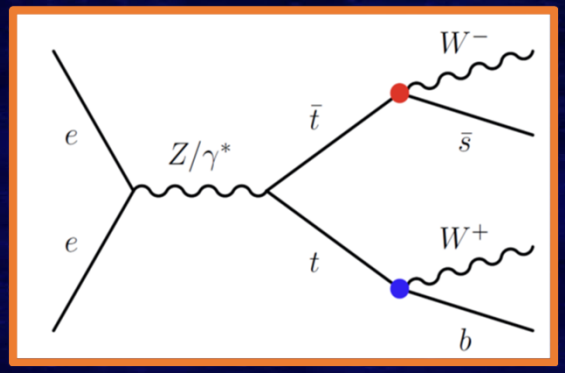
Source: C.Grojean @ FCC week 2022

Top quark studies at FCC-ee

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- **Any next gen. e^+e^- collider:**

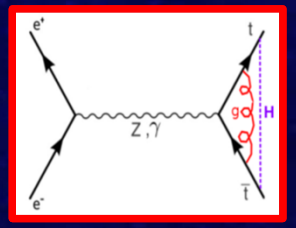
  for the 1st time the top quark can be studied using a precisely defined leptonic initial state

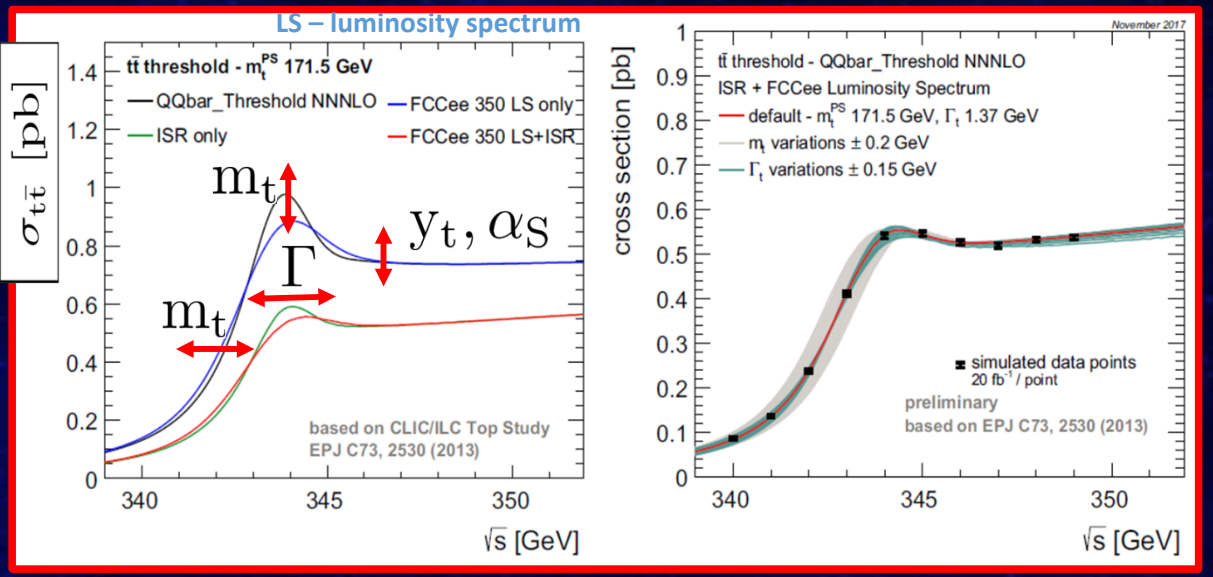


$$e^+e^- \to Z/\gamma \to t\bar{t} \to (bW^+)(\bar{b}W^-)$$

Final state	BR [%]	signature
Fully hadronic	46.2	6 jets
Semi leptonic	43.5	4 jets, 1 $l^{\pm}$, 1 ν
Fully leptonic	10.3	2 jets, 2 $l^{\pm}$, 2 ν

- **The shape of the $t\bar{t}$ production cross-section near the threshold is computable to high precision and depends on m_t, Γ_t, α_s, y_t (and the luminosity spectrum)**





Eur. Phys. J. C (2019) 79

arXiv:2203.06520

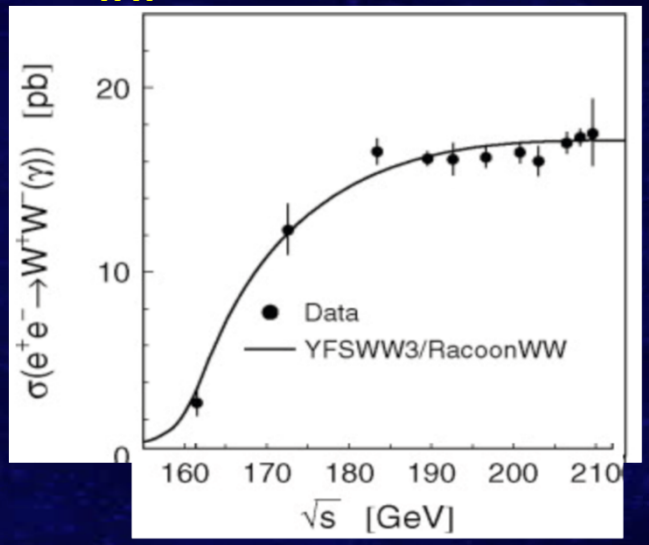
- **Measurement of the CKM matrix elements $|V_{tb}|$, $|V_{ts}|$, and $|V_{td}|$**

PDG : $\Delta m_t = 270$ MeV ➡ FCC-ee: $\Delta m_t \sim 7$ MeV

W boson studies at FCC-ee

➢ W mass measurement from σ_{WW} threshold scan:

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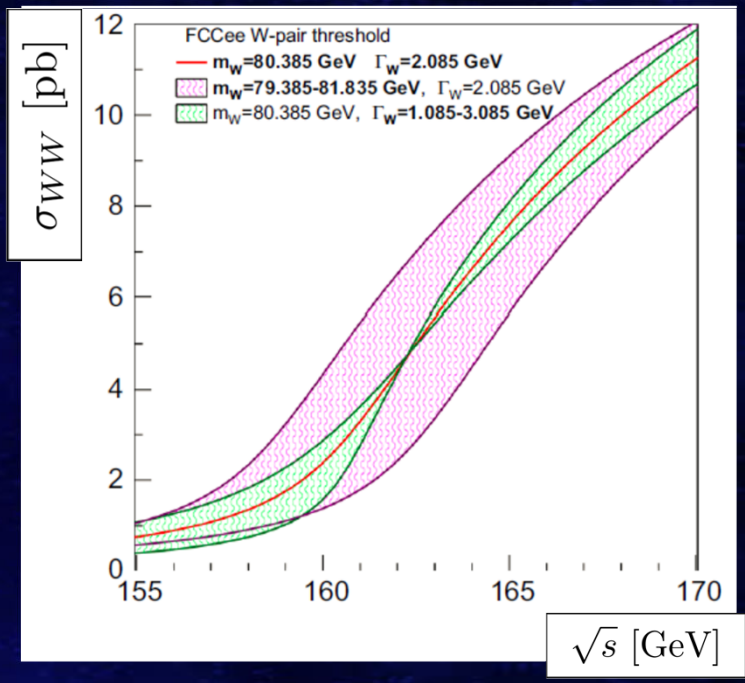


Measure σ_{WW} at two energy points E_1 and E_2, with luminosity fractions f and (1-f) ➔ evaluation of both m_W and Γ_W

$$\Delta\Gamma_W = 0.27 \text{ MeV}$$

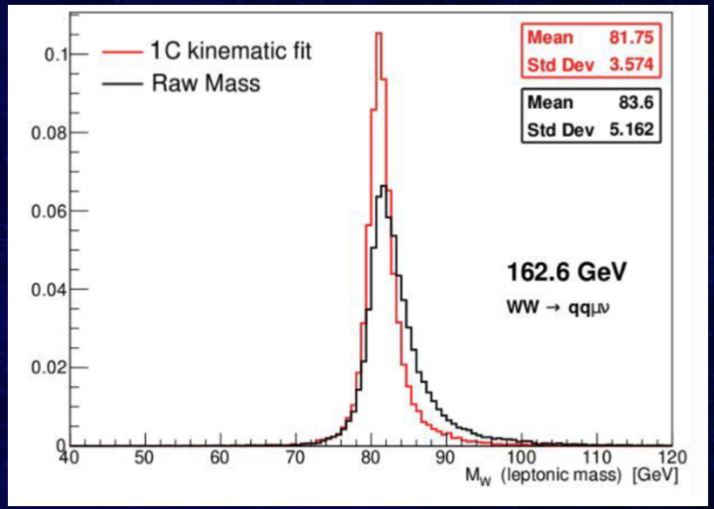
$$\Delta m_W = 0.18 \text{ MeV}$$

$$\text{LHC} : \Delta m_W = 10 \text{ MeV}$$



➢ Direct m_W measurements from decay products:

Source: M.Beguin thesis



➢ Other W topics:

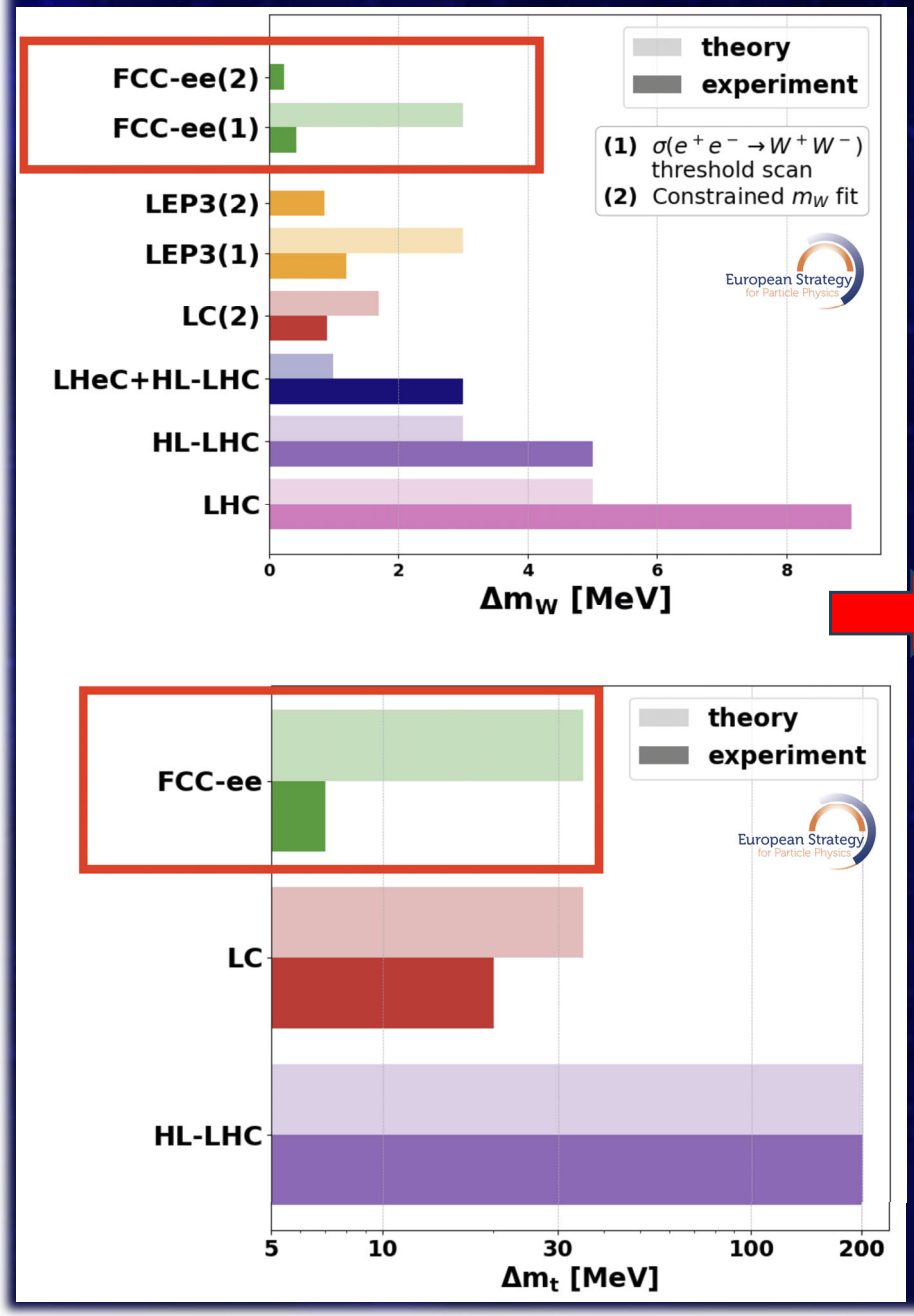
W branching ratios (lepton universality, lepton-quark universality), TGCs, $\alpha_s(m_W^2)$ …

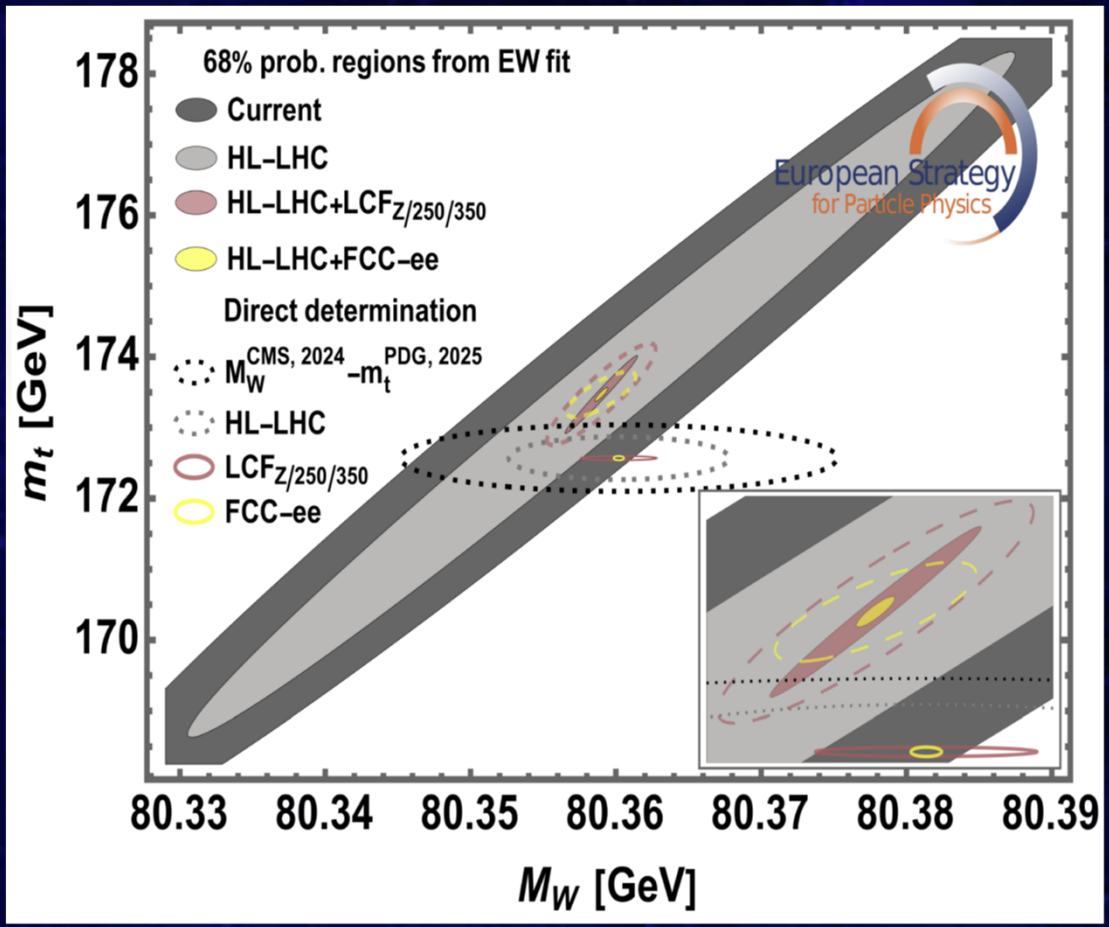
FCC-ee: summary of electroweak precision measurements

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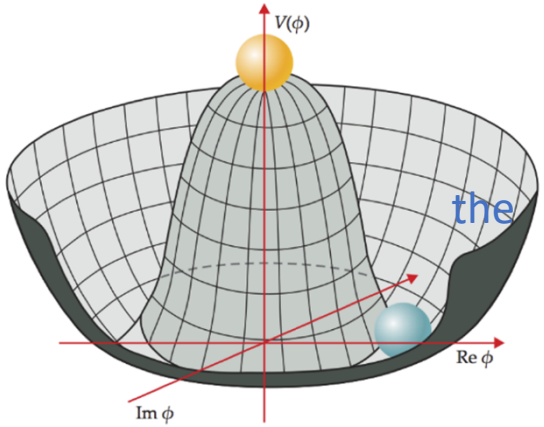
Observable	present value ± error	FCC-ee stat.	FCC-ee syst.	
m_Z (keV)	91186700±2200	5	100	×20
Γ_Z (keV)	2495200±2300	8	100	
R_l^Z (×10³)	20767±25	0.06	0.2-1.0	
α_s (m_Z) (×10⁴)	1196±30	0.1	0.4-1.6	
R_b (×10⁶)	216290±660	0.3	<60	
σ^0_{had} (×10³) (nb)	41541±37	0.1	4	
N_ν (×10³)	2991±7	0.005	1	
$\sin^2\theta^{eff}_W$ (×10⁶)	231480±160	3	2-5	×80
$1/\alpha_{QED}(m_Z)$ (×10³)	128952±14	4	Small	
$A^{b,0}_{FB}$ (×10⁴)	992±16	0.02	1-3	
$A^{pol,\tau}_{FB}$ (×10⁴)	1498±49	0.15	<2	
m_W (MeV)	80350±15	0.18	0.3	×80
Γ_W (MeV)	2085±42	0.27	0.3	
α_s (m_W) (×10⁴)	1170±420	3	Small	
N_ν (×10³)	2920±50	0.8	Small	
m_{top} (MeV)	172740±500	7	Small	×70
Γ_{top} (MeV)	1410±190	40	Small	

FCC-ee: summary of electroweak precision measurements





Are we living in a stable universe?

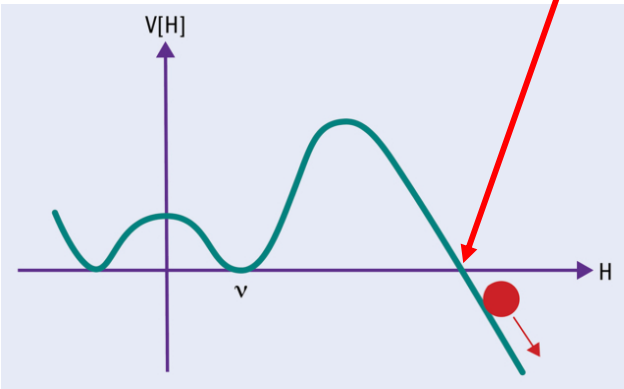


- It is usually supposed that the Higgs field has a constant value throughout the universe – at the bottom of the „Mexican hat" potential
- Hovewer, the shape of the Mexican hat is subjected to quantum effects that change its shape

- The quantum effects due to the Higgs's self-interactions „brim the hat upwards" and the interactions with the fundamental particles to which the Higgs field gives mass tend to „brim the hat downwards"
- In the latter case the most important of these is the heaviest matter particle: the top quark

- According to the current theoretical calculations and to the experimental knowledge about the top quark mass:

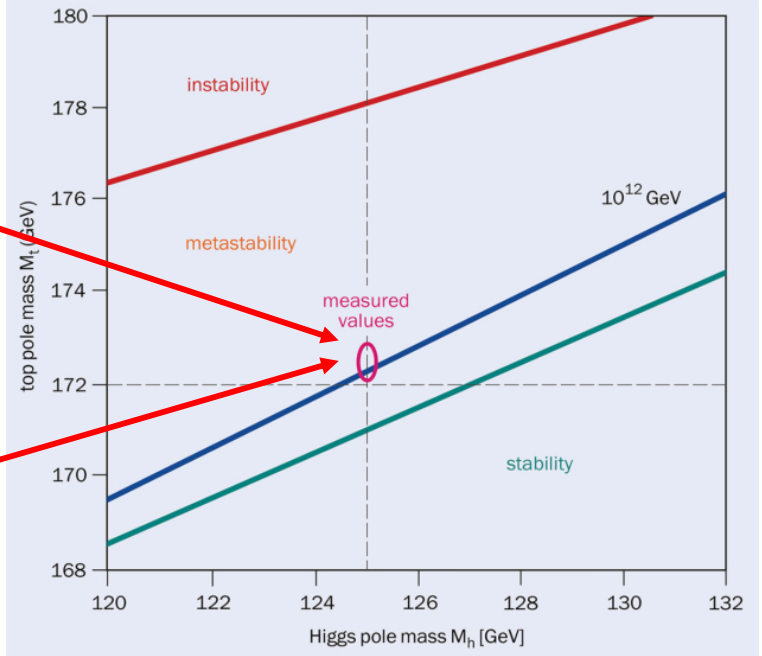
- **The brim of the Mexican hat turnes down at around 10^{12} GeV**



- **We live in a metastable universe**

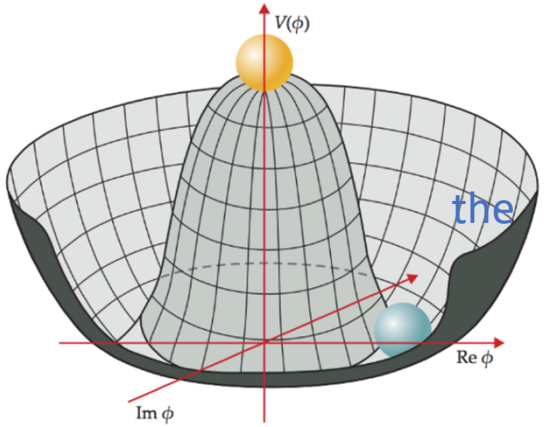
Source: CERN Courier

- **The FCC-ee can provide a qualitative shrinking of the uncertainty ellipsis**



- The FCC-ee results can also provide evidence for some NP which stabilises the vacuum that we live in

Are we living in a stable universe?

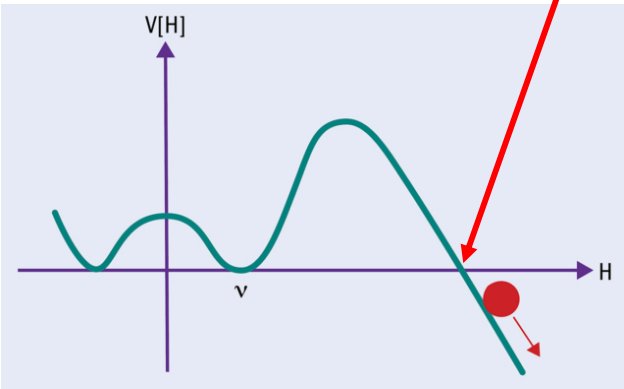


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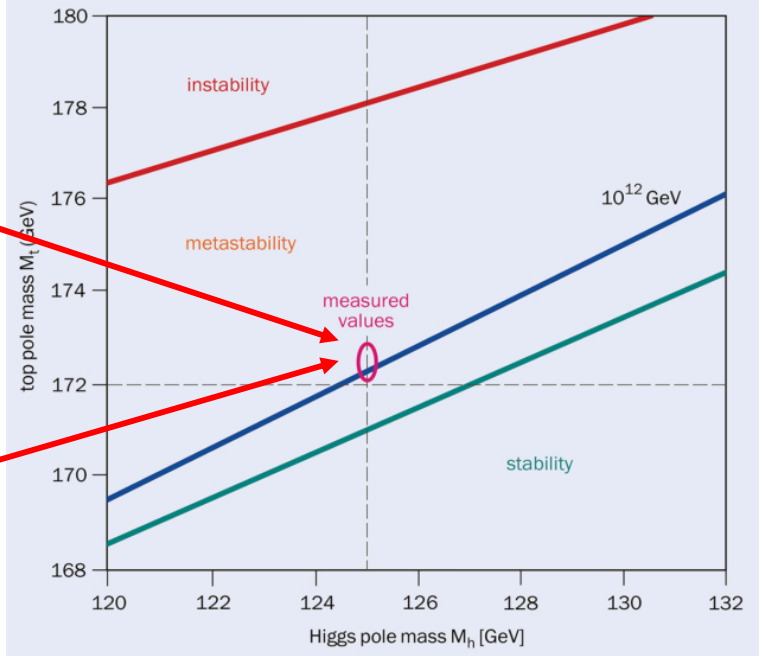
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The FCC integrated programme: FCC-hh as the second stage

2070 - 2100

parameter	FCC-hh	FCC-hh CDR	HL-LHC
collision energy cms [TeV]	85	100	14
dipole field [T]	14	16	8.33
circumference [km]	90.7	97.8	26.7
beam current [A]	0.5	0.5	1.1
synchr. rad. per ring [kW]	1200	2400	7.3
peak luminos. [10^{34} cm^{-2}s^{-1}]	30	30	5 (lev.)
integr. luminosity / IP [fb^{-1}]	20000	20000	3000

- Stored beam energy: 8 GJ/beam (0.4 GJ LHC) = 2 tons of TNT
  ➔ equivalent to an Airbus A380 (560 t) at full speed (850 km/h).



The parameters optimised to minimise electricity consumption (~ max. consumption of FCC-ee)

Magnetic field considered realistic with today's technologies (Nb_3Sn, ~ 14 T @ 1.9 K):

- For Nb_3Sn, @ 1.9 K consumption ~ 2.3 TWh / y)
- For Nb_3Sn, @ 4.5 K potential to reduce to ~ 1.8 TWh / y as FCC – ee)

The crucial ingredient is the success of **the High Field Magnets (HFM) programme**

The FCC integrated programme: High mass searches at FCC-hh

- **Two canonical goals of FCC-hh: Higgs studies and searches at energy-frontier**
  - The high parton-scale CM energies will allow for discoveries up to very high masses e.g. in searches for Higgs compositeness or supersymmetry
  - New Higgses could also be discovered in the 5-20 TeV range

BSM object (%)	84 TeV FSR baseline
$Z'_{SSM} \to \ell\ell$	37
$Z'_{SSM} \to \tau\tau$, tt	16
$Z'_{TC} \to$ tt	20
$G_{RS} \to$ WW	19
$Q^* \to$ jj	35
$\tilde{W}^0$	4.0
$\tilde{h}^0$	1.1

- Cross-sections for most interesting processes grow significantly from 14 TeV to 100 TeV
- **the overall physics programme of FCC-hh: (HL-)LHC on strong steroids: electroweak, QCD, flavour, heavy-ion physics, forward physics…**
- Enormous pile-up (~1000)
- At the scale of 100 TeV the SR radiation will NOT be negligible for the first time in pp collisions

ESPP: recommendations referring to accelerator technology

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

Accelerator Technology:

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

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

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

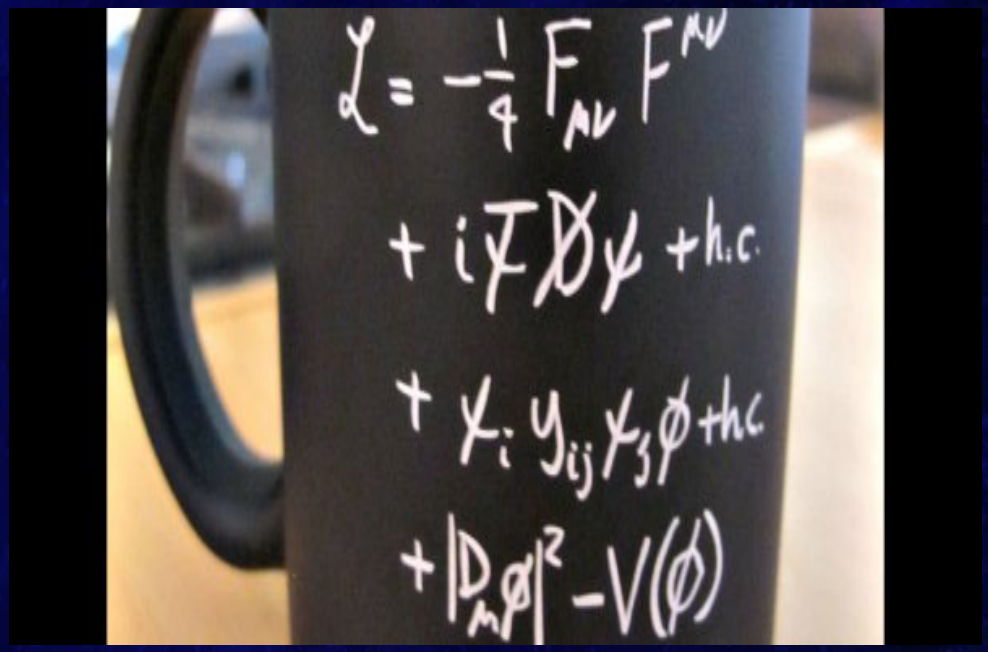
Instead of summary

Push forward the FCC integrated programme
OR
endanger the future of particle physics…

THANK YOU FOR YOUR LISTENING

Particle Physics: where do we stand?

The Standard Model (SM) Lagrangian



Source: Rain Rabbit / Flickr

$$\mathscr{L}^{(4)}_{SM} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \bar{\psi} i \not{D} \psi + (y_{ij} \bar{\psi}^i_L \phi \psi^j_R + \text{h.c.}) + |D_\mu \phi|^2 - V(\phi)$$

Symmetry and the Standard Model

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$\begin{aligned}
&1\ -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc} \partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4} g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
&\tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&2\ M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
&\tfrac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \\
&\tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \tfrac{2M^4}{g^2} \alpha_h - i g c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
&W^-_\nu \partial_\nu W^+_\mu)] - i g s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
&W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
&\tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
&g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\
&\tfrac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
&g M W^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2} i g [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
&W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \tfrac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \\
&\phi^+ \partial_\mu H)] + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + \\
&i g s_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - i g \tfrac{1 - 2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
&i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \tfrac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
&\tfrac{1}{4} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + \\
&W^-_\mu \phi^+) - \tfrac{1}{2} i g^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
&W^-_\mu \phi^+) + \tfrac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
&g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}^\lambda_j (\gamma \partial + m^\lambda_u) u^\lambda_j - \\
&3\ \bar{d}^\lambda_j (\gamma \partial + m^\lambda_d) d^\lambda_j + i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3} (\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3} (\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)] + \\
&\tfrac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3} s_w^2 - \\
&1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s_w^2 - \gamma^5) d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + \\
&(\bar{u}^\lambda_j \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \\
&\gamma^5) u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} \tfrac{m^\lambda_e}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
&4\ \tfrac{g}{2} \tfrac{m^\lambda_e}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \phi^+ [-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \gamma^5) d^\kappa_j) + \\
&m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1 + \gamma^5) d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}} \phi^- [m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 + \gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \\
&\gamma^5) u^\kappa_j] - \tfrac{g}{2} \tfrac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2} \tfrac{m^\lambda_d}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \\
&\tfrac{ig}{2} \tfrac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
&5\ \tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W^+_\mu (\partial_\mu \bar{Y} X^- - \\
&\partial_\mu \bar{X}^+ Y) + i g c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W^-_\mu (\partial_\mu \bar{X}^- Y - \\
&\partial_\mu \bar{Y} X^+) + i g c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
&\partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H] + \\
&\tfrac{1 - 2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \tfrac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
&i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \tfrac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}$$

Source: Symmetry Magazine

Shortcomings of the Standard Model



Source: Wikipedia



Source: dobrewiadomosci.net.pl

In particle physics research you will not complain about boredom

On the contrary, your hands will be full with studies of these enigmas

We are desperately searching for „New Physics (NP)”
or „Physics Beyond the Standard Model (BSM)”

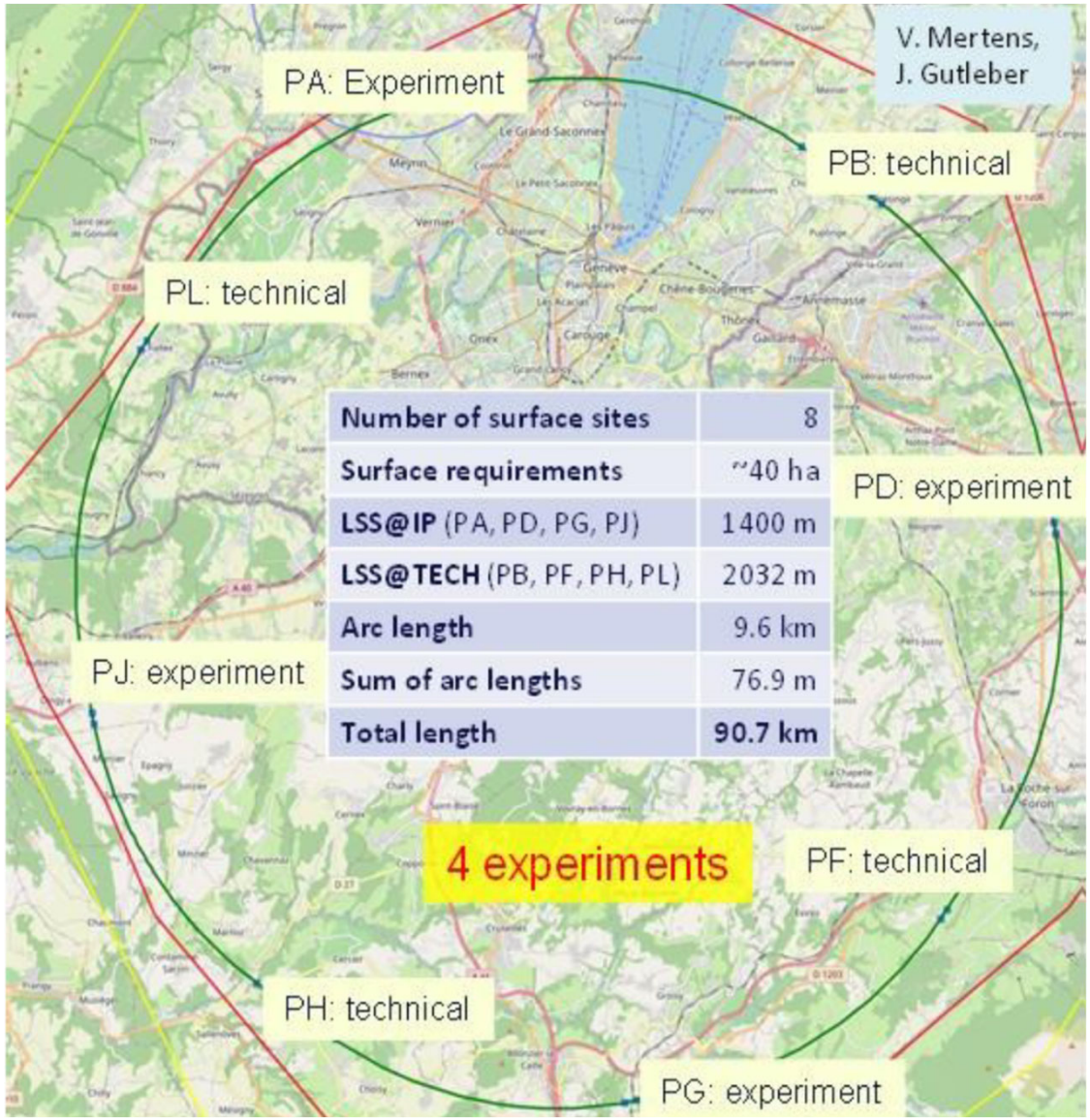
The FCC integrated programme: layout

Overall lowest-risk baseline:

- 90.7 km ring
- 8 surface points
- 4-fold symmetry

Layout chosen out of about 100 initial variants based on several criterias

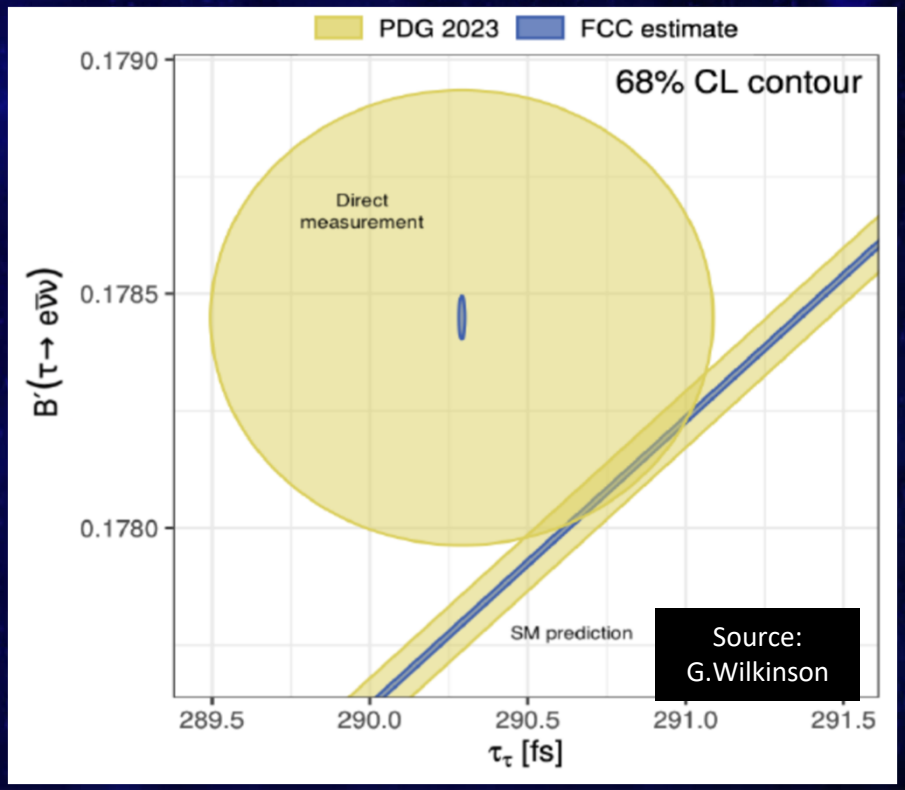
- **Geology**
- **Surface constraints** (land availability, urbanistic etc.)
- **Environment** (protected zones)
- **Infrastructure** (electricity, transport)
- **Accelerator performance**



Flavour physics studies at FCC-ee

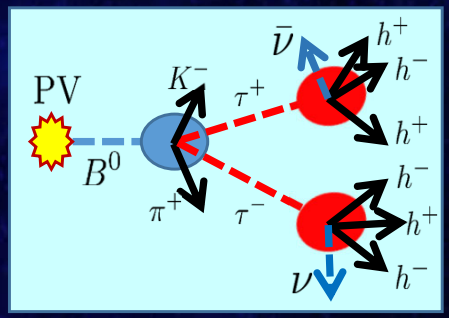
- Running at $E_{CM} = M_Z$ will produce huge numbers of beauty and charm hadrons and tau leptons in a very clean environment

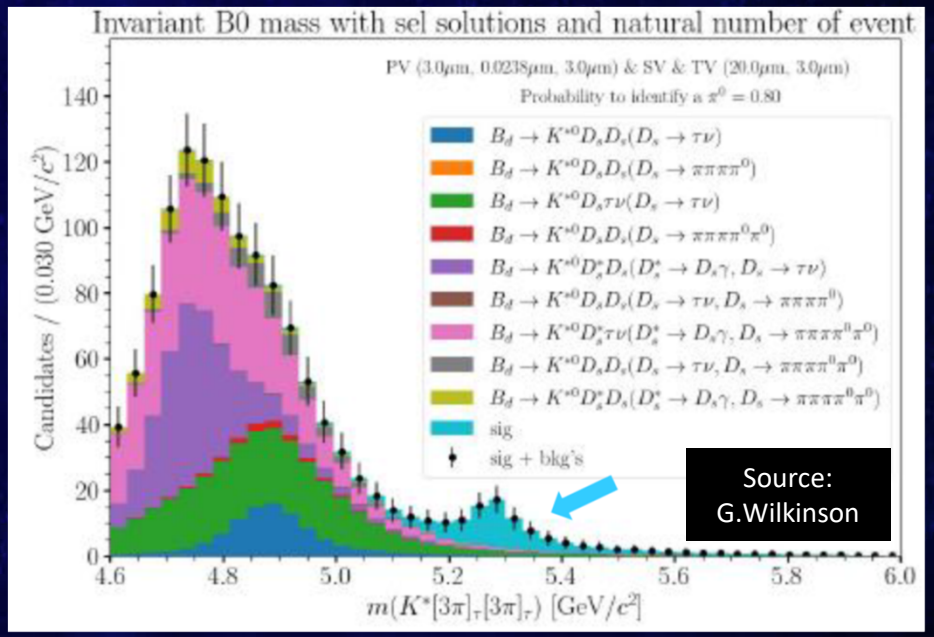
- Test of lepton universality with tau leptons



- B→K*(892)τ⁺τ⁻ decay: crucial for searches for New Physics

Only accessible at FCC-ee



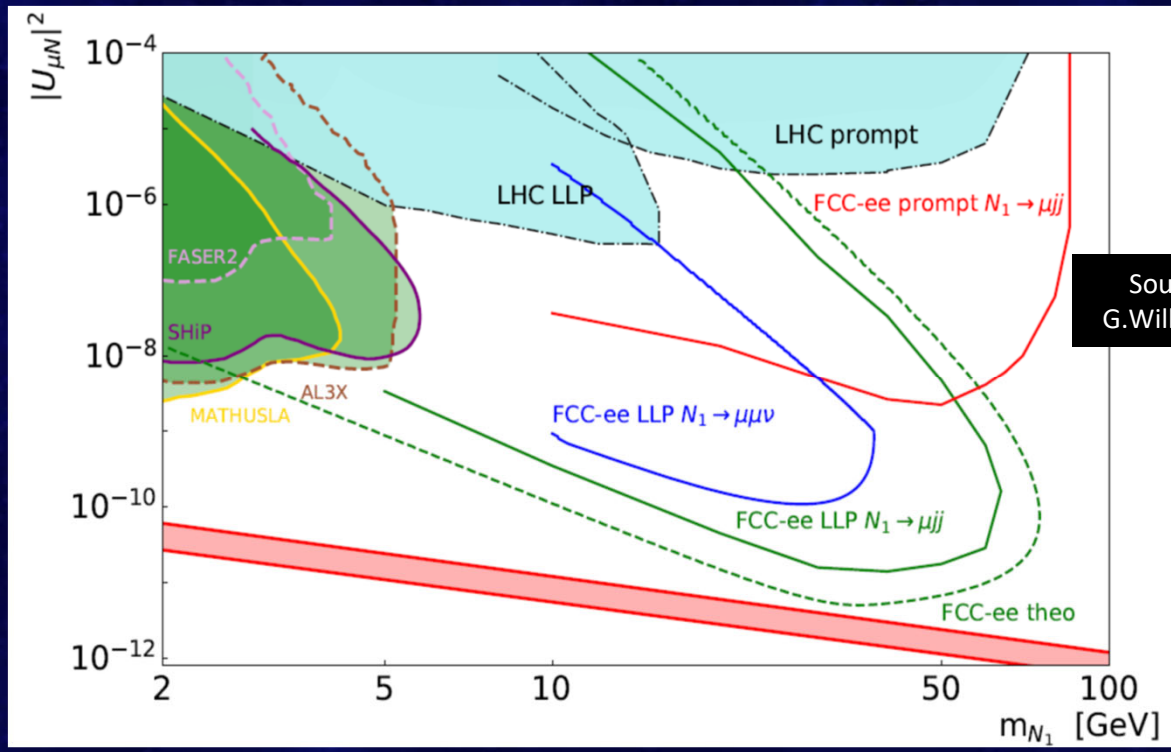


- Other complementary programms: Belle II, LHCb upgrade II

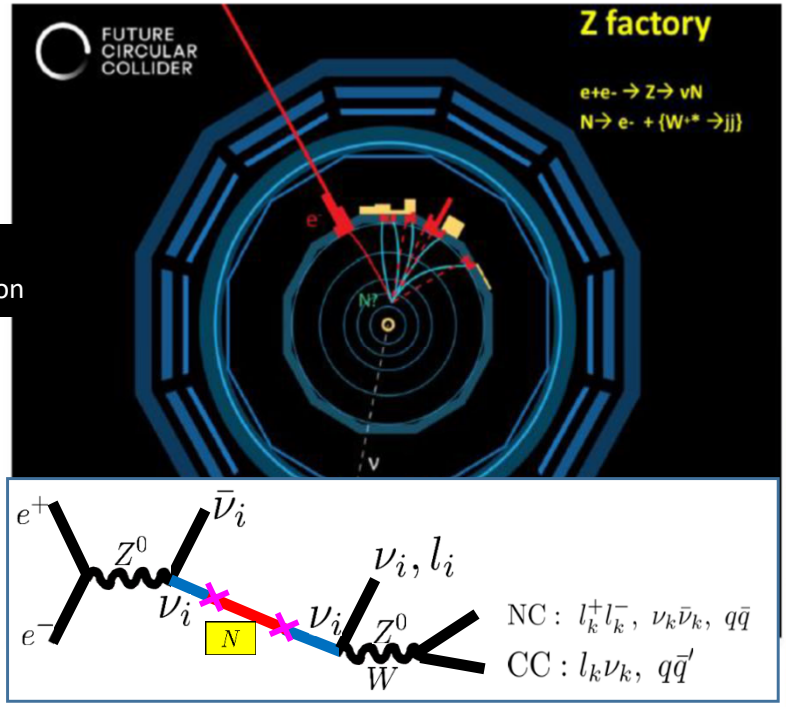
Direct searches for new particles at FCC-ee

- Huge data samples, mostly at $E_{CM} = M_Z$ → **vast potential for FCC-ee for searches for, in particular „low" mass, feebly coupling new particles, fully complementary to searches at energy frontier (FCC-hh)**

- Example: **searches for Heavy-Neutral Leptons** (HNLs, denoted by 'N')



Source: G.Wilkinson



- **High sensitivity for Axion-Like Particles** (ALPs, denotes by „a") from $e^+e^- \to a\gamma \to \gamma\gamma\gamma$ as well to many other exotic particles predicted by models of New Physics

The Standard Model Parameters

26 parameters of the Standard Model:	
6 quark masses	m_u, m_c, m_t, m_d, m_s and m_b
4 quark mixing angles	θ_{12}, θ_{23}, θ_{13} and δ
6 lepton masses	m_{ν_e}, m_{ν_μ}, m_{ν_τ}, m_e, m_μ and m_τ
4 lepton mixing angles	θ'_{12}, θ'_{23}, θ'_{13} and δ'
3 gauge couplings	$g_1(\alpha)$, $g_2(G_F)$ and g_3
1 Higgs vacuum expectation value	$v(M_Z)$
1 Higgs mass	m_H
1 strong CP violating phase	θ

Physics comparison: precision physics (II)

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

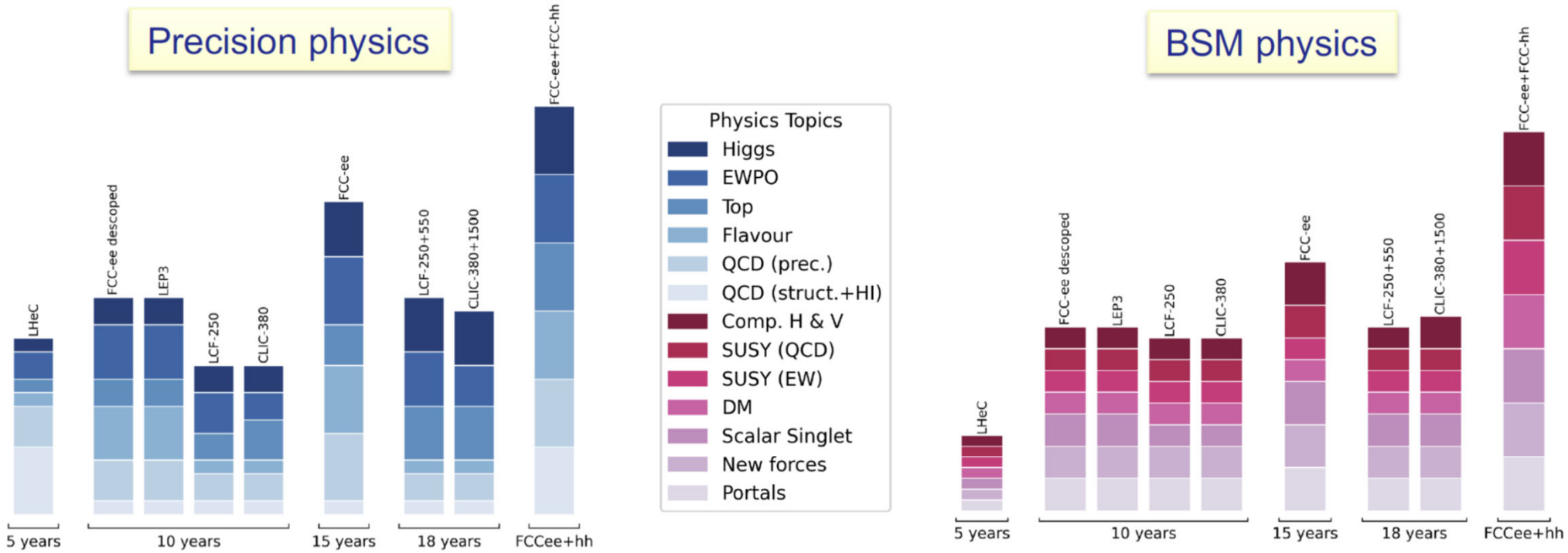
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Physics potential: BSM physics (II)

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

CERN-ESU-2026-006

Overall Physics Assessment

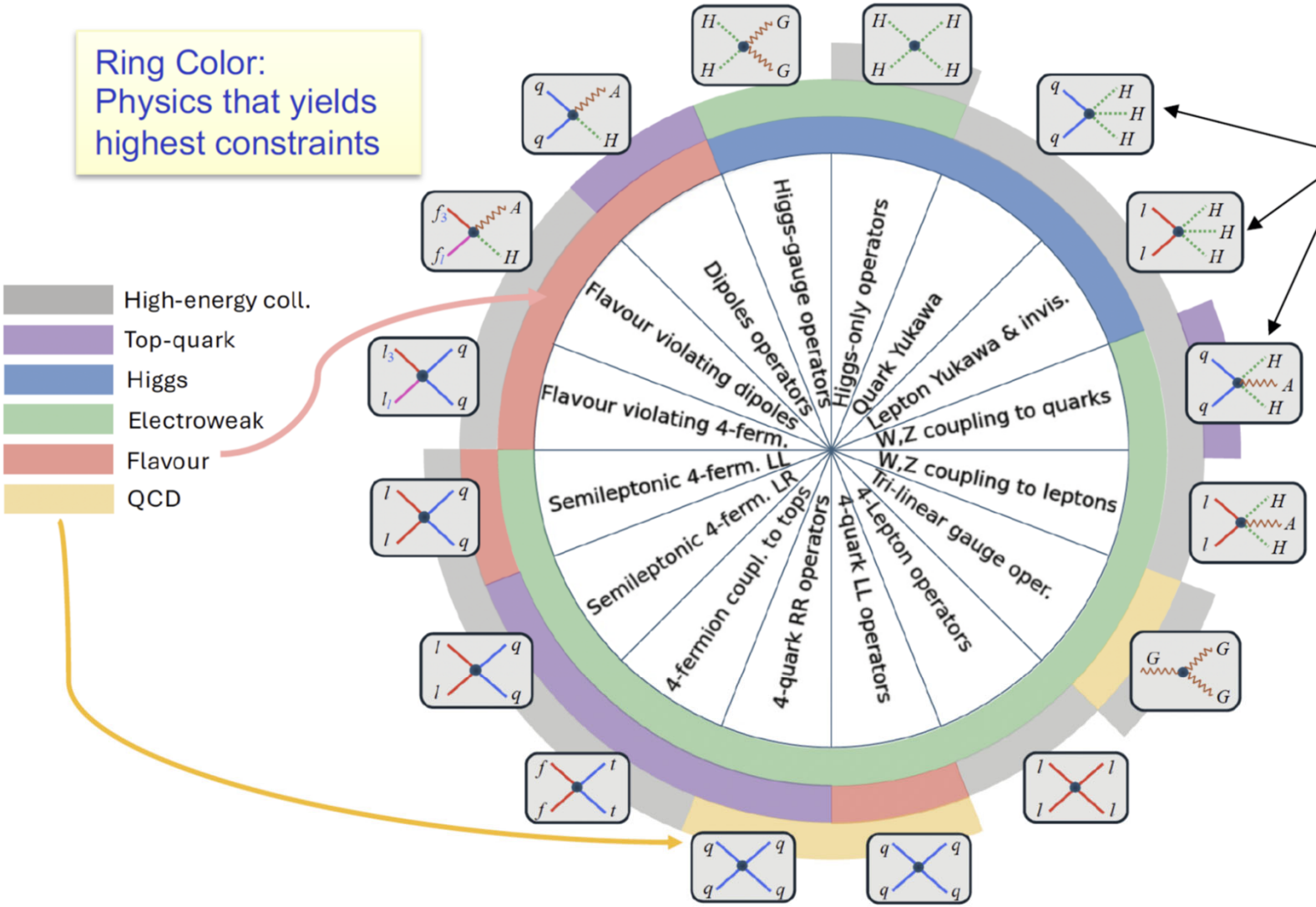


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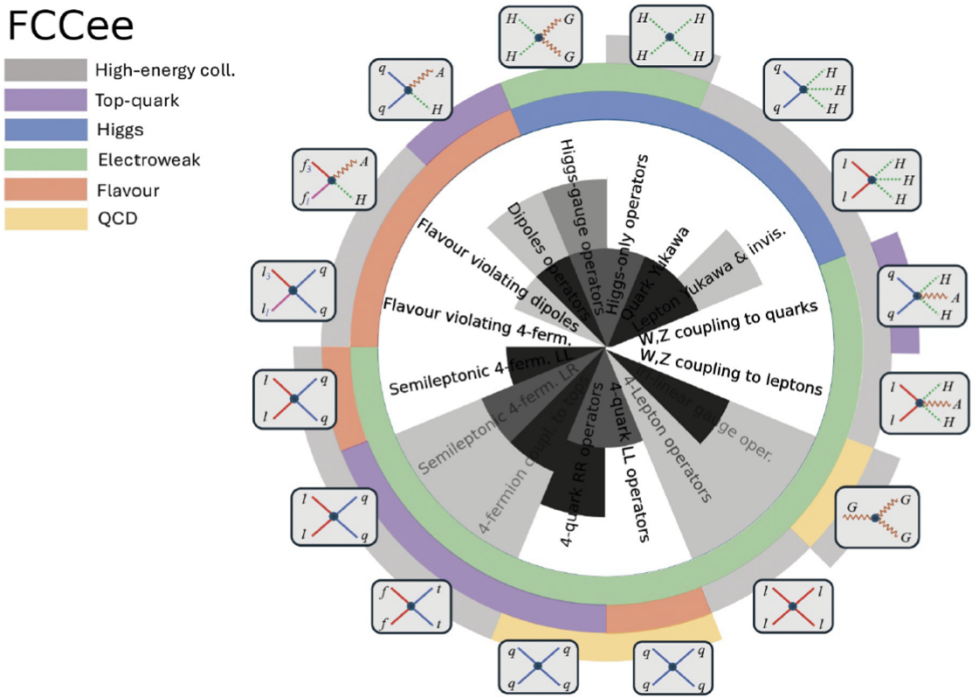
Coverage of the Physics Landscape

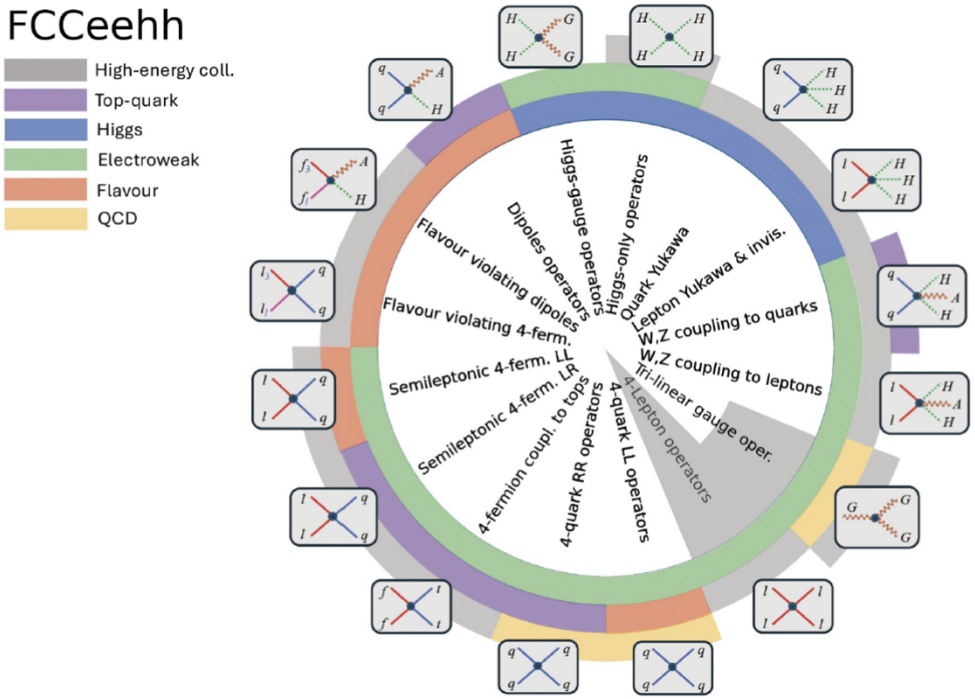
Ring Color:
Physics that yields highest constraints

Physics areas (SMEFT inspired):
16 sectors with possible BSM physics



Coverage of the FCC integrated programme





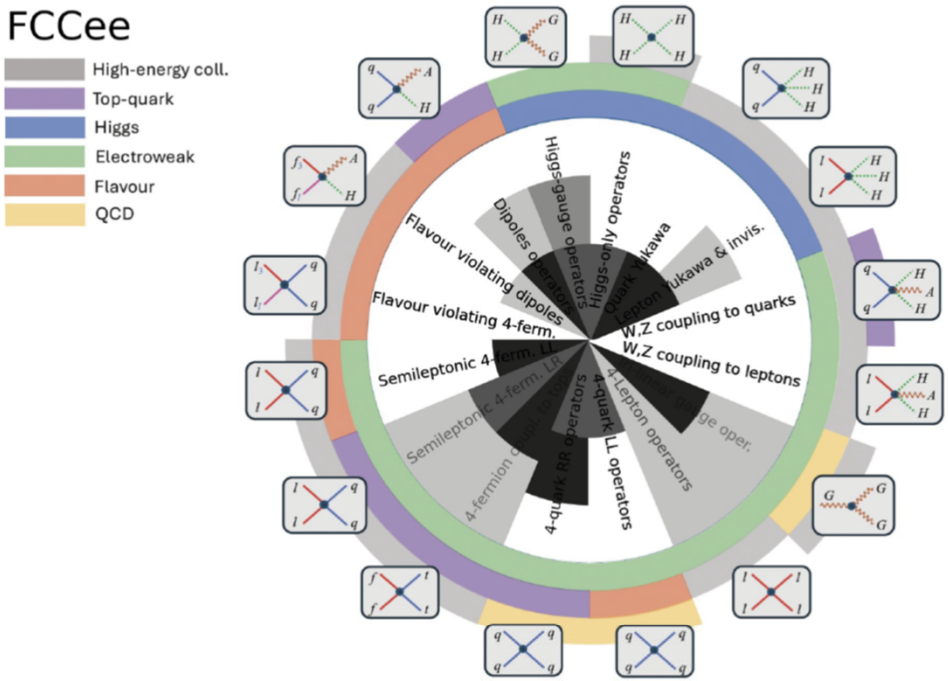
Improvement factors in precision w.r.t. HL-LHC are evaluated and mapped on a log-scale covering the range 1 to 5

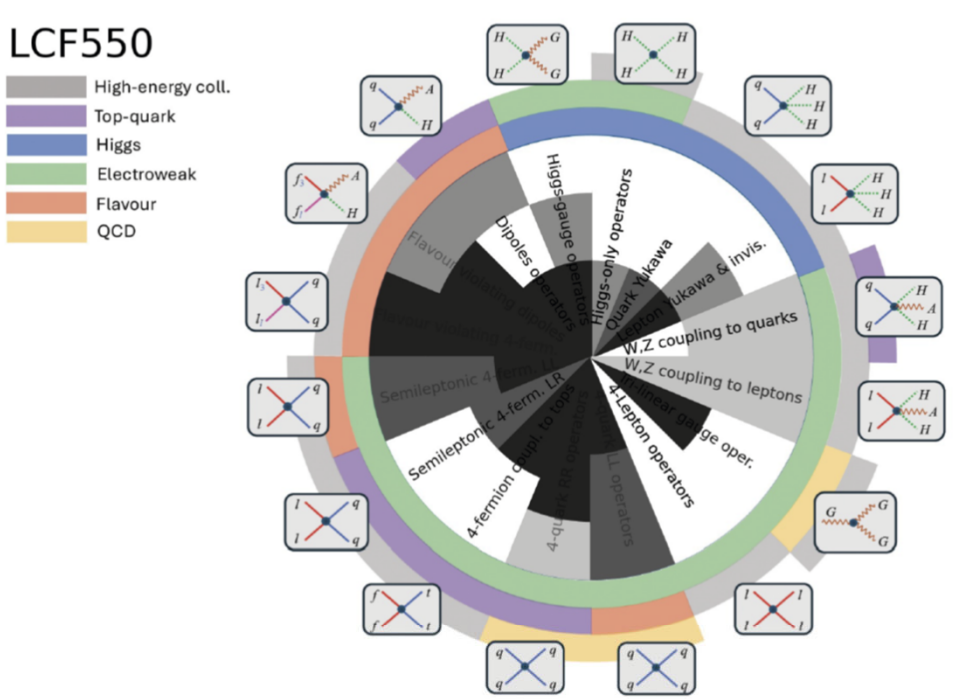
HL-LHC: 1 (gray scale 1 = black)

Best collider: 5 (gray scale 5 = white)

CERN-ESU-2026-006

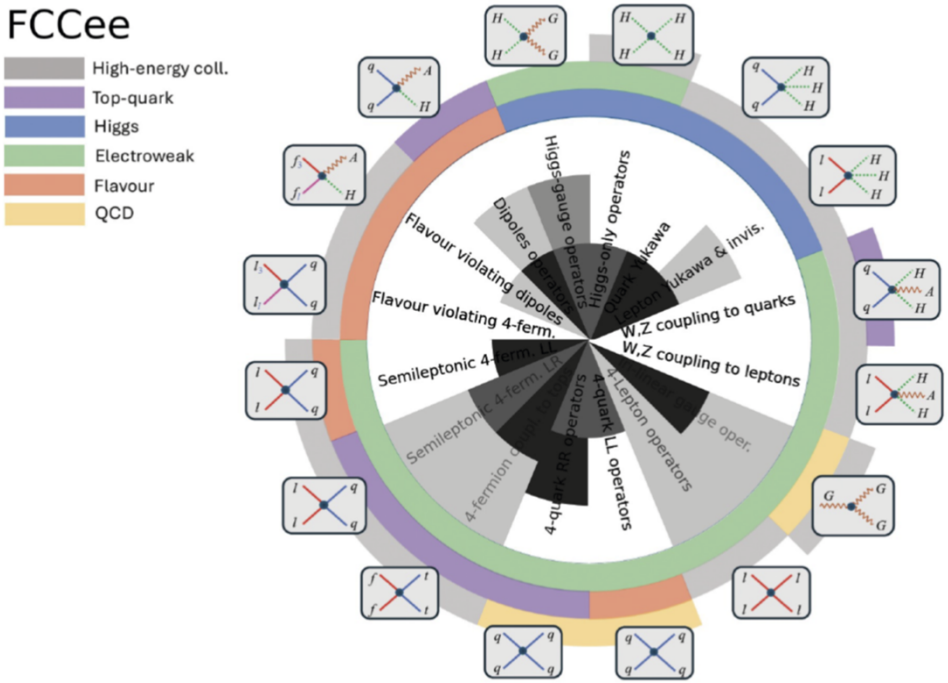
FCC-ee versus high-energy e^+e^- colliders (I)

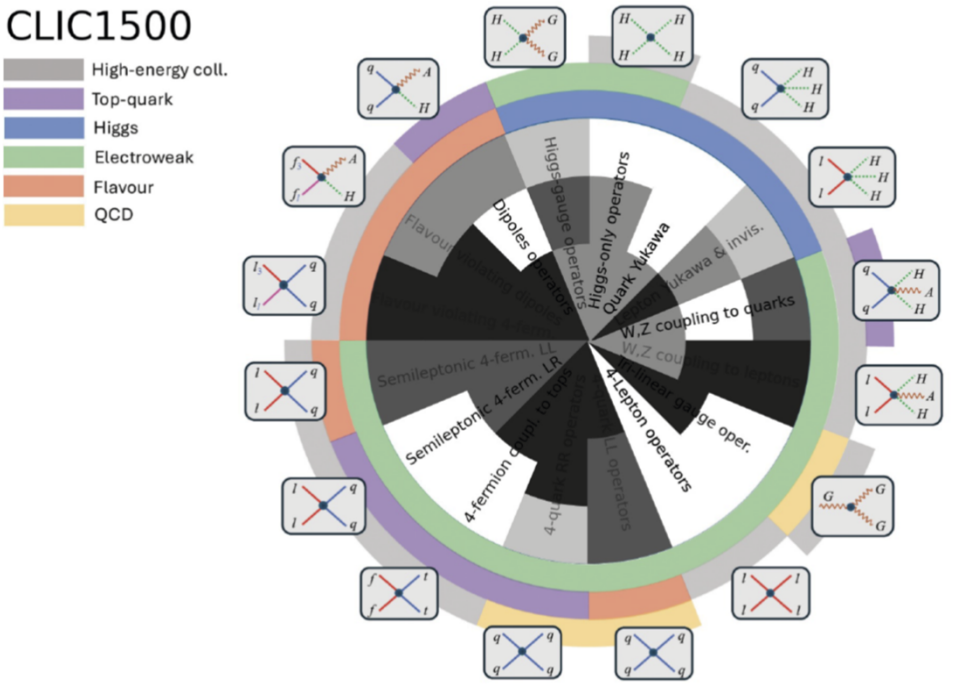




CERN-ESU-2026-006

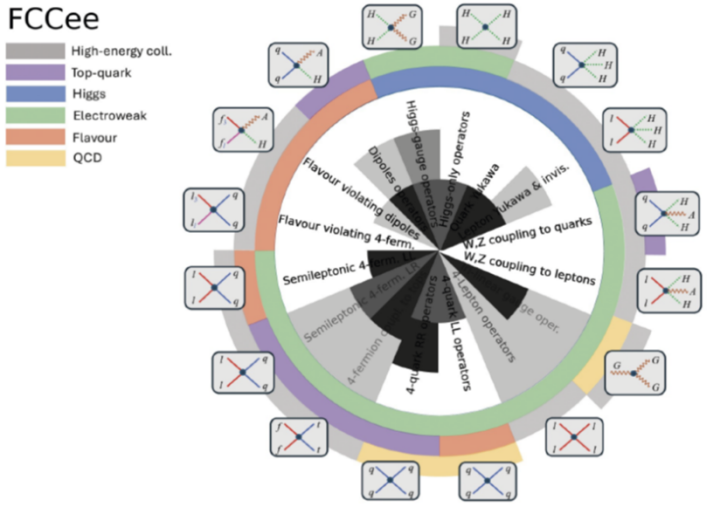
FCC-ee versus high-energy e^+e^- colliders (II)

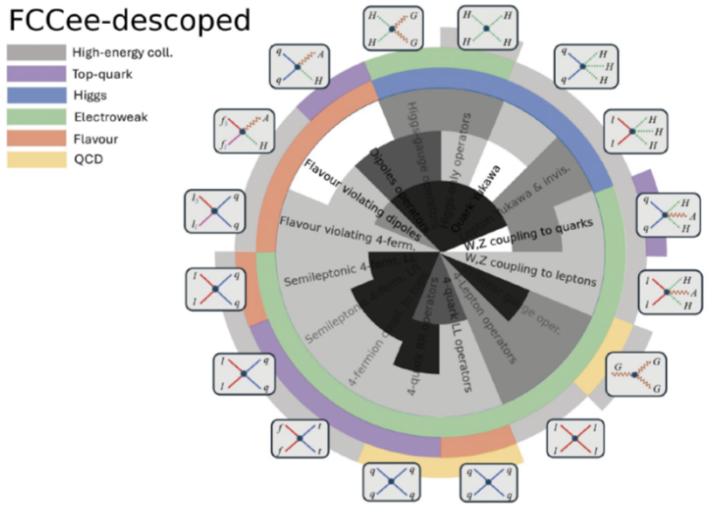


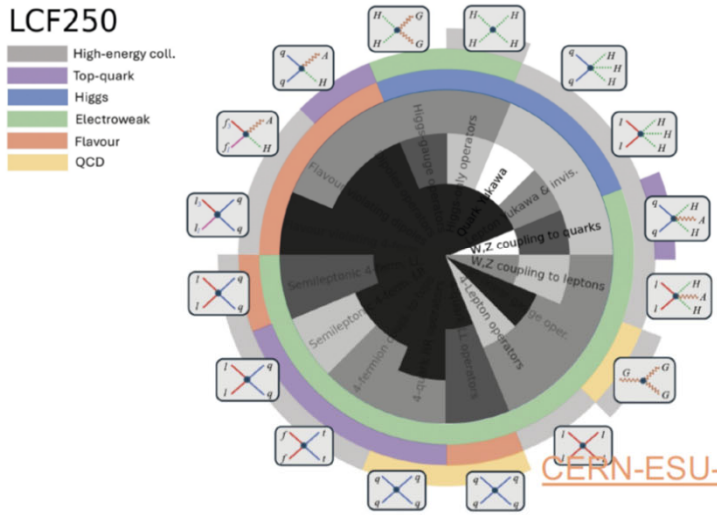


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FCC-ee versus descoped FCC-ee and LCF250

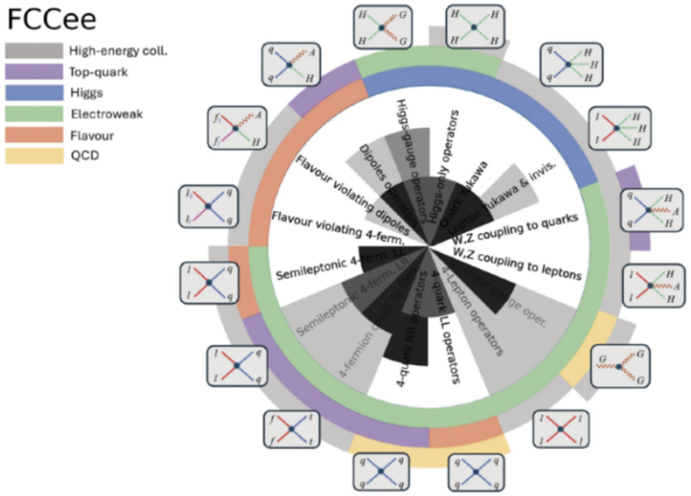


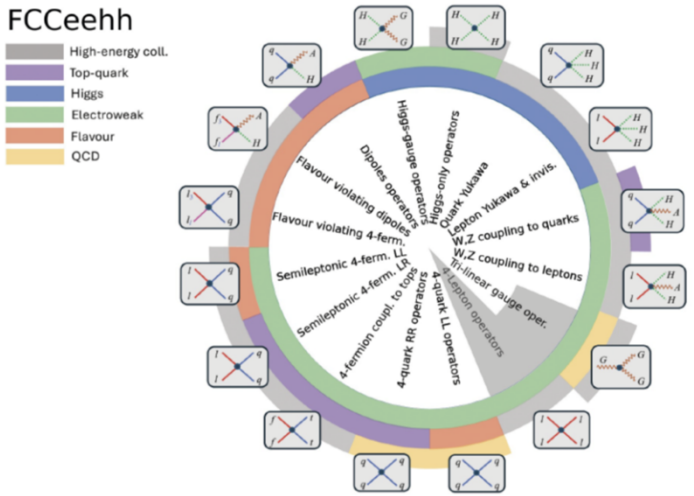


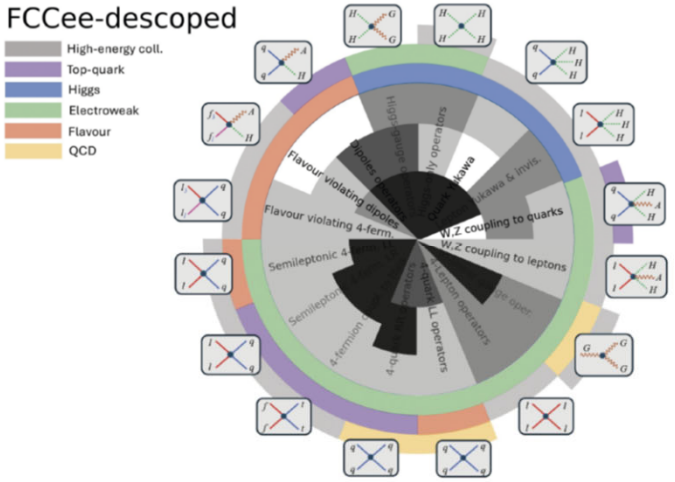


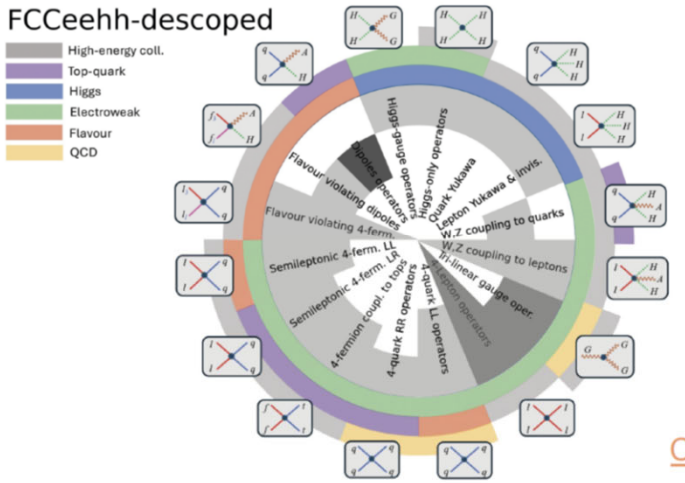
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FCCeehh versus FCC-ee-descoped + FCChh









CERN-ESU-2026-006

FCC: cost and socio-economic benefits

FCC-ee cost estimate (FSR 2025)

Capital cost (2024 CHF) for construction of the FCC-ee is summarised below. This cost includes construction of the entire new infrastructure and all equipment for operation at the Z, WW and ZH working points.

FCC-ee

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**

15.3

16.6

Note: Upgrade of SRF (800 MHz) & cryogenics for ttbar operation corresponds to additional cost of 1,260 MCHF

Cost summary table in 2024 MCHF for the construction of FCC-hh.

FCC-hh
(after FCC-ee)

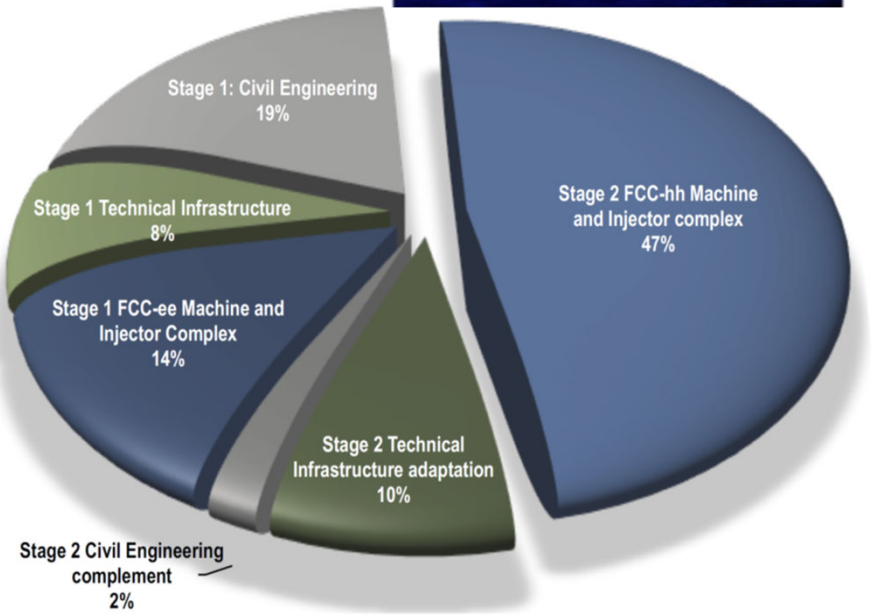
Domain	FCC-hh Cost [MCHF]
FCC-ee dismantling	200
Collider*	13400
Injectors and transfer linear	1000
Civil Engineering	520
Technical infrastructures	3960
Experiments	N/A
Total	**19080**

*target price of 2.0 MCHF per 14.3 m long magnet with 1.0 MCHF of conductor, 0.5 MCHF for assembly, and 0.5 MCHF for components

19.1

For FCC-ee it is expected that 1 EUR invested would generate 1.8 to 2 EUR for society

Source: FCC brochure



Source: FCC contrib. to the ESPP

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The FCC project - Paolo Giacomelli M.Benedikt 27

The FCC integrated programme at the popular level

188 Institutes

41 Countries + CERN



ACCELERATORS

PHYSICS

PLACEMENT STUDIES

INFRASTRUCTURES

EXPERIMENTS & DETECTORS

SOCIO-ECONOMIC IMPACT

2014 — FCC study kicks off

2021 - 2025 — FCC Feasibility Study

2026 - 2027 — Update of the European Strategy for Particle Physics

~2028 - 2029 — Deliberation with CERN's Council and its international partners

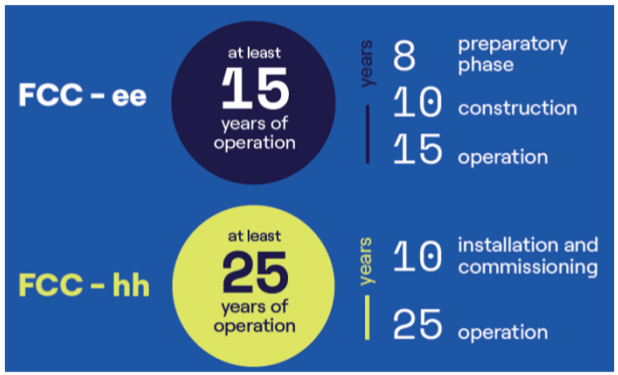
~2030 - 2045 — Civil engineering work and construction of FCC-ee (accelerator and experiments)

~2045 — Start of FCC-ee physics

~2060 - 2070 — Replacing FCC-ee with FCC-hh

~2070 — Start of FCC-hh physics

Source: FCC brochure



Higgs total width and couplings at FCC-ee

$\sqrt{s} = 240$ GeV

$$\sigma(HZ) \propto g^2_{HZZ}$$

→ g_{HZZ} measured (0.1%)

$\sqrt{s} = 240$ GeV

$\sqrt{s} = 365$ GeV

$$\frac{\sigma(e^+e^- \to H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})}{\sigma(e^+e^- \to HZ) \times BR(H \to b\bar{b})} \propto \frac{g^2_{HWW}}{g^2_{HZZ}}$$

→ g_{HWW} measured

$\sqrt{s} = 240$ GeV

$$\sigma(e^+e^- \to HZ) \times BR(H \to ZZ^*) \propto \frac{g^4_{HZZ}}{\Gamma_H}$$

→ Γ_H measured (1%)

Higgs couplings to $b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$, $\mu^+\mu^-$, gg, $\gamma\gamma$ …

can be determined through the tagging of the respective Higgs decay final states:

$\sqrt{s} = 240$ GeV

$$\sigma(e^+e^- \to HZ) \times \mathrm{BR}(H \to X\bar{X}) \propto \frac{g^2_{HZZ}g^2_{HXX}}{\Gamma_H}$$

$\sqrt{s} = 365$ GeV

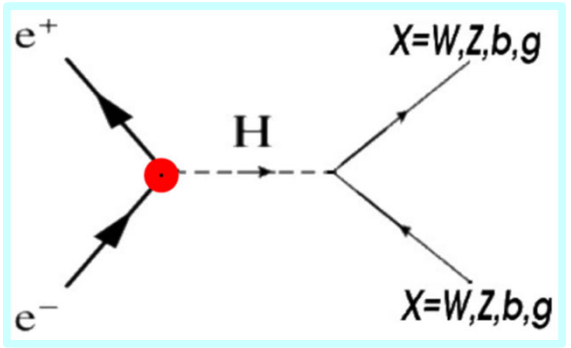
$$\sigma(e^+e^- \to \nu\bar{\nu}H) \times \mathrm{BR}(H \to X\bar{X}) \propto \frac{g^2_{HWW}g^2_{HXX}}{\Gamma_H}$$

→ g_{HXX} measured (X = b, c, τ, μ, g, γ,…)

Higgs studies at FCC: H → e⁺e⁻ - run at 125 G

- **FCC-ee: potential for direct measurement of the H-e-e Yukawa coupling**

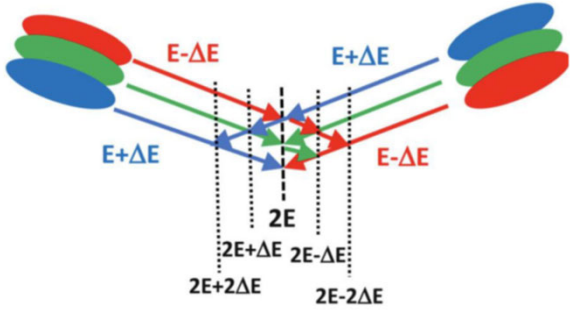
$$BR(H \to e^+e^-) \approx 5 \times 10^{-9}$$



- $\sigma(e^+e^- \to H) = 1.64$ fb - very small $(m_H = 125\ \text{GeV},\ \Gamma_H = 4.2\ \text{MeV})$
  (several (≈10) final states can be studied)

- The cross-section is tiny and, moreover, it is effectively decreased further through Initial State Radiation (ISR, see slide 50), and because Higgs width (about 4 MeV) is small compared to the E_{CM} spread

- The natural E_{CM} spread for colliding beams is about 100 MeV and thus must be reduced substantially (monochromatisation)

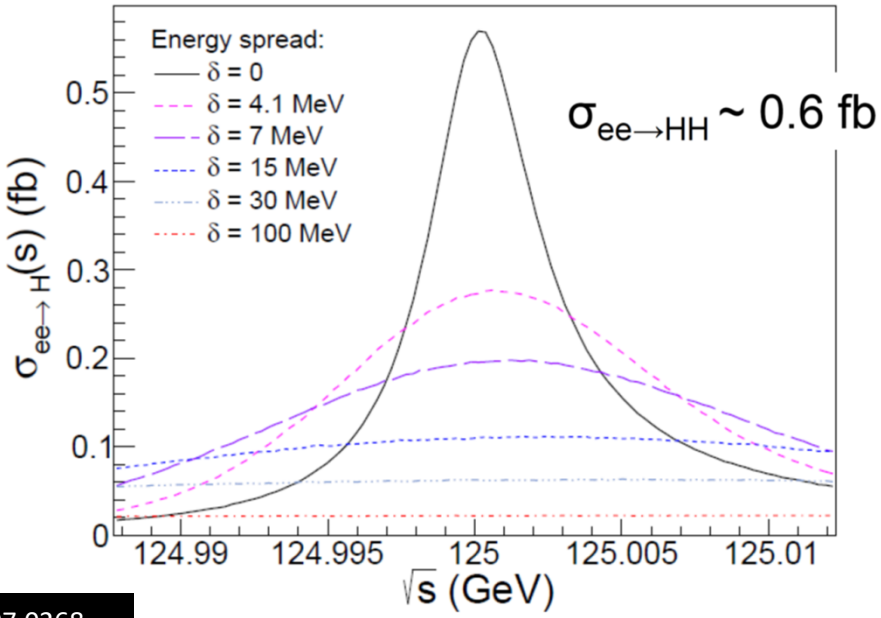


- Calls for a high-luminosity run precisely at

$$\sqrt{s} = M_H = 125\ \text{GeV}$$

- Requires a few years of running

- Not yet in the baseline of the FCC-ee project



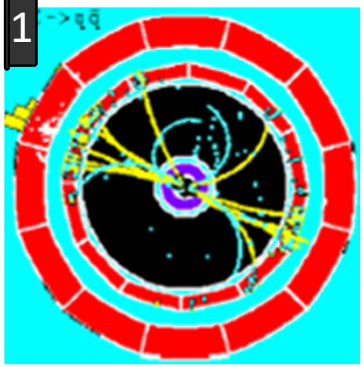
arXiv:2107.0268

Z boson studies at FCC-ee: electroweak (EW) obser

LEP $N_Z = 1.7 \times 10^7$ → **FCC-ee** $N_Z \sim 6 \times 10^{12}$ ⇒ **Extreme precision of EW observables**; **High indirect sensitivity to New Physics**

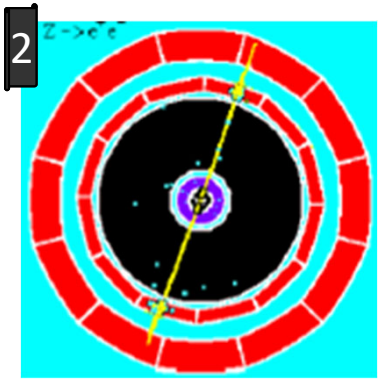
➢ **We measure cross-sections for these five categories of 'simple' final states:**

$Z^0 \to q\bar{q}$



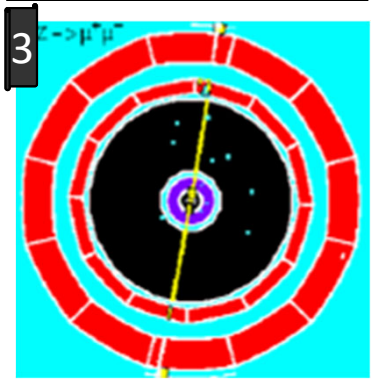
$q = u, d, s, c, b$

$Z^0 \to e^+e^-$



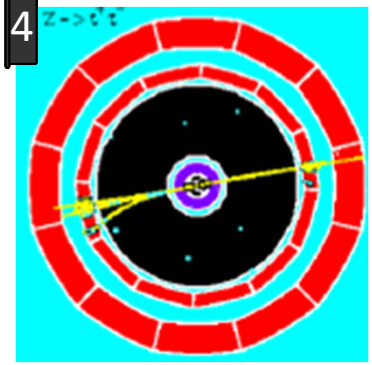
$x = e, \mu, \tau$

$Z^0 \to \mu^+\mu^-$

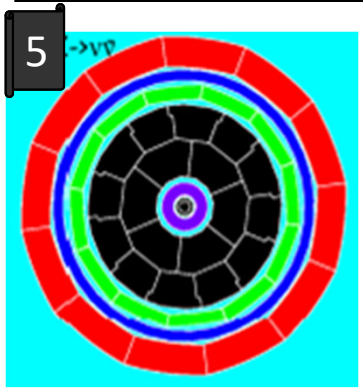


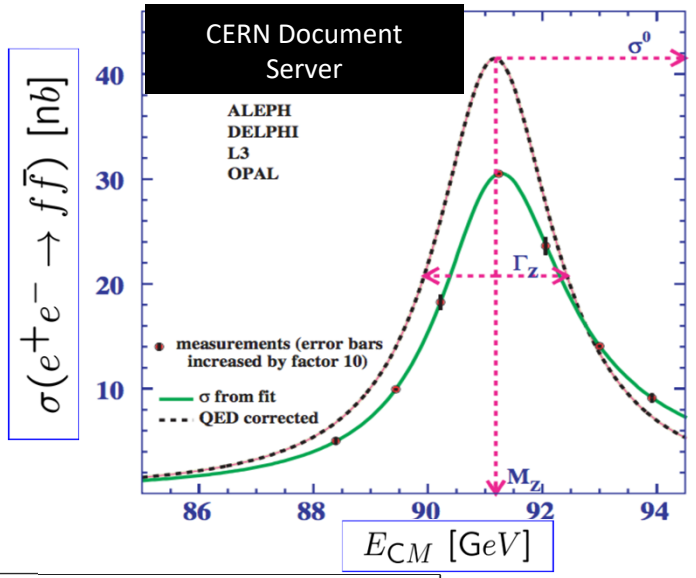
Source: G.Rolandi

$Z^0 \to \tau^+\tau^-$



$Z^0 \to \nu_x\bar{\nu}_x$





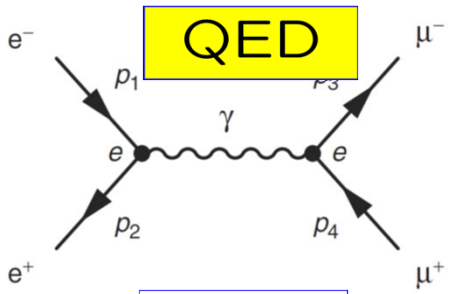
$$\sigma(\sqrt{s}) = \frac{N_{\text{signal}}}{\mathcal{L}} = \frac{N_{\text{selected}} - N_{\text{background}}}{\epsilon A \mathcal{L}}$$

Luminosity — Efficiency — Acceptance

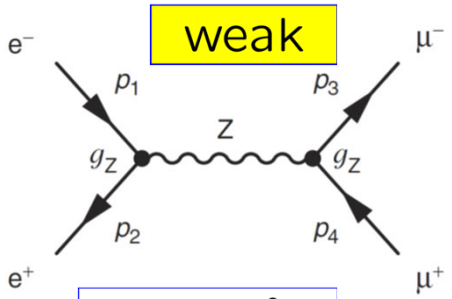
What can be extracted:

- Z mass (M_Z), Z width (Γ_Z)
- Hadronic peak cross-section($\sigma_{0,\text{hadr}}$)
- Ratio of leptons ($R_l = \frac{\Gamma_{\text{had}}}{\Gamma_{l\bar{l}}},\ l = e, \mu, \tau$)
- Number of light neutrinos…

- The two leading order Feynman diagrams (the final state $\mu^+\mu^-$ as an example):



$\mathcal{M}_\gamma \propto \frac{e^2}{q^2}$ +



$\mathcal{M}_Z \propto \frac{g_Z^2}{q^2 - m_Z^2}$ $\longrightarrow$

$q^2 = s = (p_1 + p_2)^2 = (p_3 + p_4)^2$

interference

$\sigma(e^+e^- \to f\bar{f}) \propto |M|^2 \propto |\mathcal{M}_\gamma + \mathcal{M}_Z|^2$

$\sqrt{s} < 40$ [GeV]

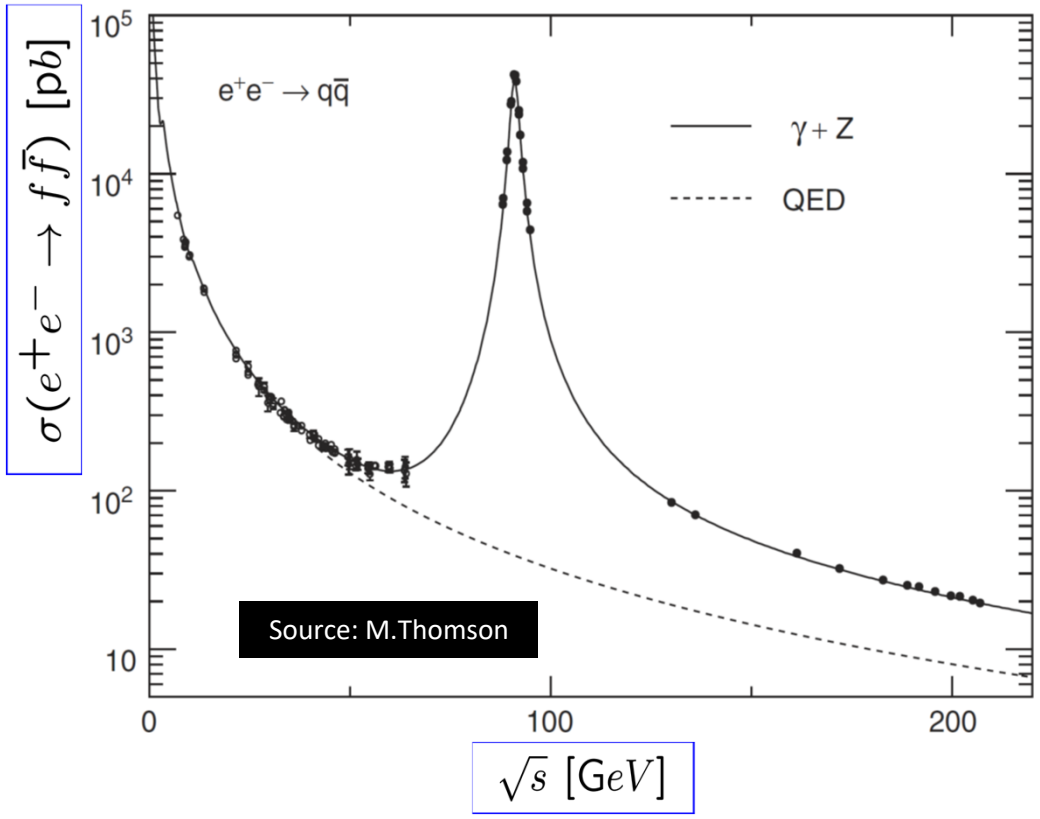
QED diagram dominates (photon exchange)

$\sqrt{s} = (50 - 120)$ [GeV]

Weak interaction dominates (Z exchange)

$\sqrt{s} \gg M_Z$ [GeV]

Both diagrams equally relevant



- **The total cross section (in terms of the partial decay widths)**

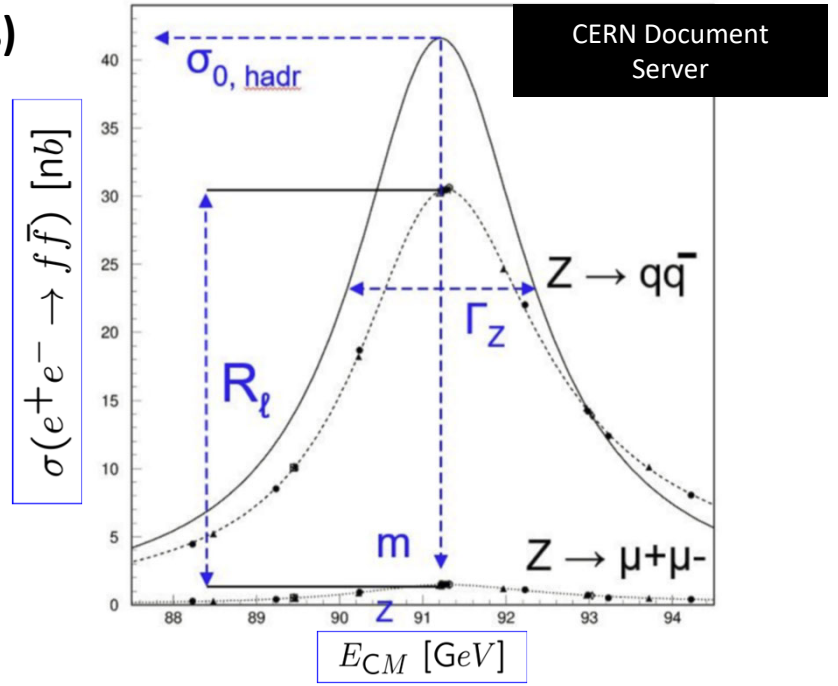
$$\sigma(e^+e^- \to Z \to f\bar{f}) = \frac{12\pi s}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}$$

$\Gamma_{f\bar{f}} = \Gamma(e^+e^- \to f\bar{f})$ $\quad f = e, \mu, \tau, q$ $\quad q = u, d, s, c, b$

- **The maximum value of the total cross section occurs at $\sqrt{s} = m_Z$**

$$\sigma^0_{f\bar{f}} = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$$

- The cross-section falls to half of its peak value at $\sqrt{s} = m_Z \pm \Gamma_Z/2$



The Γ_Z is not only the total Decay rate of the Z boson, but it is also the full-width-at-half-maximum (FWHM) of the cross-section as a function of centre-of-mass energy

The mass and total width of the Z boson can be determined directly from mearurements of the centre-of-mass energy of the cross section for $e^+e^- \to Z \to f\bar{f}$

Once Γ_Z and m_Z are known, the measured value of peak cross-section for a particular final-state fermion $\sigma^0_{f\bar{f}}$ can be related to the product of the partial decay widths:

$$\Gamma_{ee}\Gamma_{f\bar{f}} = \frac{\sigma^0_{f\bar{f}}\Gamma_Z^2 m_Z^2}{12\pi}$$

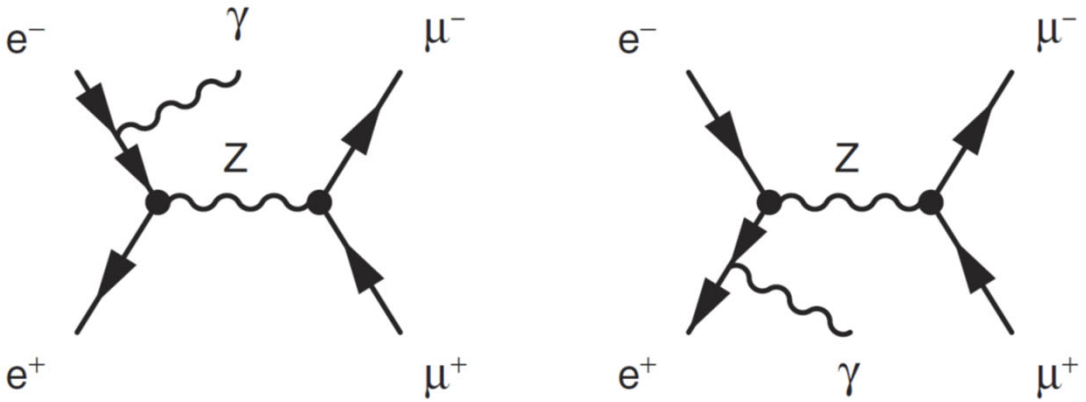
Using the σ^0_{ee} → Γ_{ee} determined

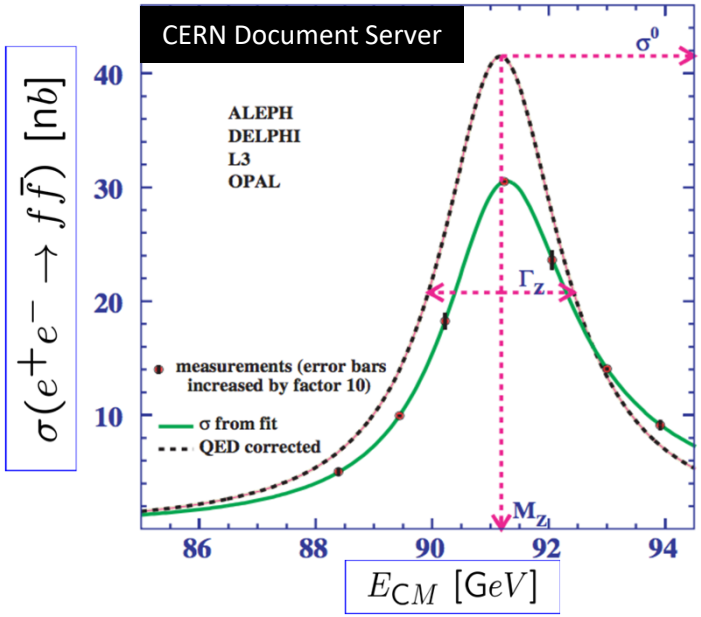
Using the $\sigma^0_{f\bar{f}}$ → $\Gamma_{f\bar{f}}$ determined $(f \neq e)$

- The cross section is described by the Breit-Wigner resonance curve with the maximum at $\sqrt{s} = m_Z$ and the FWHM Γ_Z

- BUT we have to take into account the effect of initial-state radiation (ISR) which distorts the shape of the Z resonance curve

- In addition to the lowest-order Feynman diagrams, there are two higher-order Feynman diagrams:





- The photon with energy E_γ is radiated from either the initial-state electron or positron;

- In the limit where the photon is emitted collinear w.r.t. the incoming electron:

$$p_1 = (E - E_\gamma, 0, 0, E - E_\gamma)$$

$$p_2 = (E, 0, 0, -E)$$

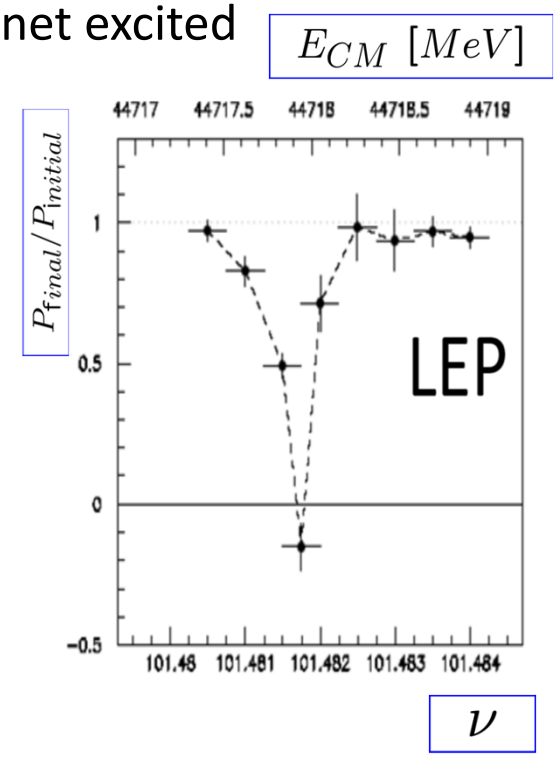
- Then the effective centre-of-mass energy squared at the e^+e^- annihillation vertex:

$$s' = (p_1 + p_2)^2 = (2E - E_\gamma)^2 - E_\gamma^2 = 4E^2\left(1 - \frac{E_\gamma}{E}\right) = s\left(1 - \frac{E_\gamma}{E}\right)$$

Z boson studies at FCC-ee

- The precise determination of the Z mass calls for an extreme accuracy in our knowledge about the average centre-of-mass energy of the e^+e^- collider: ΔE_{CM}
- In FCC-ee (and LEP) the e^+ and e^- beams polarize naturally along the magnetic field
- A visible depolarization can be realized with a transverse kicker magnet excited at a frequency (ν) in resonance with the spin precession frequency:
- The polarization is destroyed on this condition: $\nu = a_e\gamma = \frac{g_e-2}{2}\frac{E_{beam}}{m_ec^2} = \frac{E_{beam}}{0.4406486(1)}$

arXiv:1909.12245



- The precision at LEP: $\Delta E_{CM} = 2000\ keV$
- This achievement required a detailed understanding of a number of potential systematic biases:
  - Tidal effects due to the gravitational pull of the Moon (10 MeV)
  - Variations of the water level in the Geneva Lake (20 MeV)
  - Leakage currents from the TGV railway line (20 MeV)
- The expected precision at FCC-ee: $\Delta E_{CM}^{stat} = 5\ keV$ $\Delta E_{CM}^{syst} = 100\ keV$

- The total width of the Z boson:

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\text{hadrons}} + \Gamma_{\nu_e\nu_e} + \Gamma_{\nu_\mu\nu_\mu} + \Gamma_{\nu_\tau\nu_\tau}$$

- Assuming the lepton universality

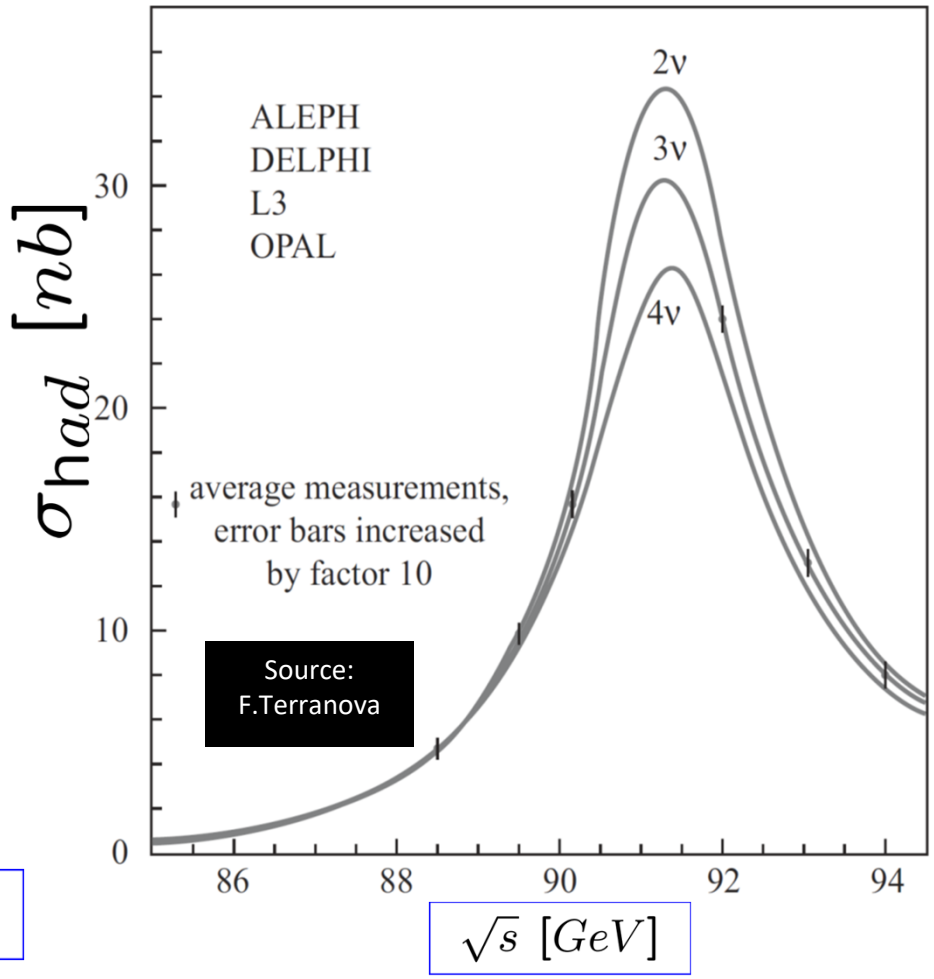
$$\Gamma_Z = 3\Gamma_{ll} + \Gamma_{\text{hadrons}} + 3\Gamma_{\nu\nu}$$

Let us replace $3 \rightarrow N_\nu$ - the number of light neutrino generations

$$N_\nu = \frac{\Gamma_Z - 3\Gamma_{ll} - \Gamma_{\text{hadrons}}}{\Gamma^{SM}_{\nu\nu}}$$

the Standard Model value

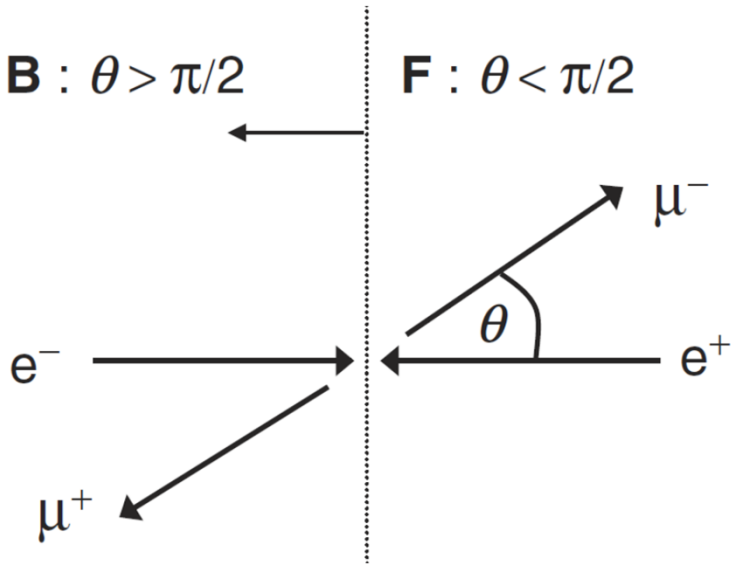
LEP & SLC: $N_\nu = 2.996 \pm 0.007$



- $\Delta\alpha_{\mathrm{QED}}(m_Z^2) = 10^{-4}$ **– the current precision is not sufficient for future precision SM tests**

  (the uncertainty dominated by the measurement at lower energy scale ($\alpha_{QED}(0)$)
  and the associated extrapolation)

- **Alternative:**
  the direct measurement of $\alpha_{QED}(m_Z^2)$ from the muon forward-backward (FB) asymmetry just below and just above the Z pole (as part of Z resonance scan)
  – no need of extrapolation from $\alpha_{QED}(0)$

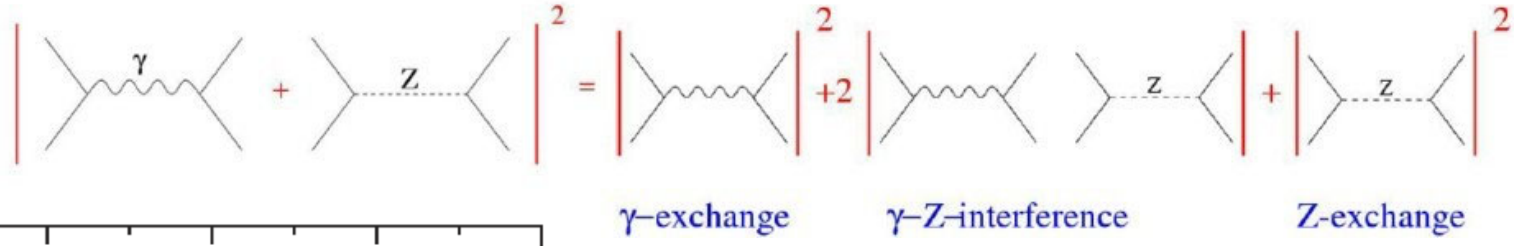


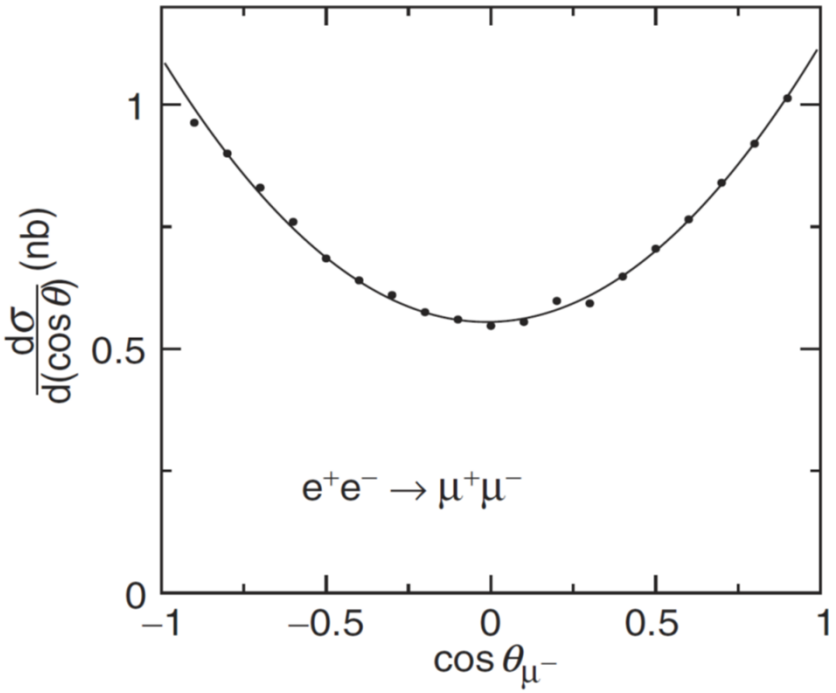
$$A_{FB}^{\mu\mu} = \frac{\sigma_{\mu\mu}^{F} - \sigma_{\mu\mu}^{B}}{\sigma_{\mu\mu}^{F} + \sigma_{\mu\mu}^{B}}$$

- **The $A_{FB}^{\mu\mu}$ - self normalized quantity**

  no need for measurement of integrated luminosity (L_{int}):
  most uncertainties (selection efficiency,
  det. accceptance) cancel in the ratio

Measurement of the fine-structure const



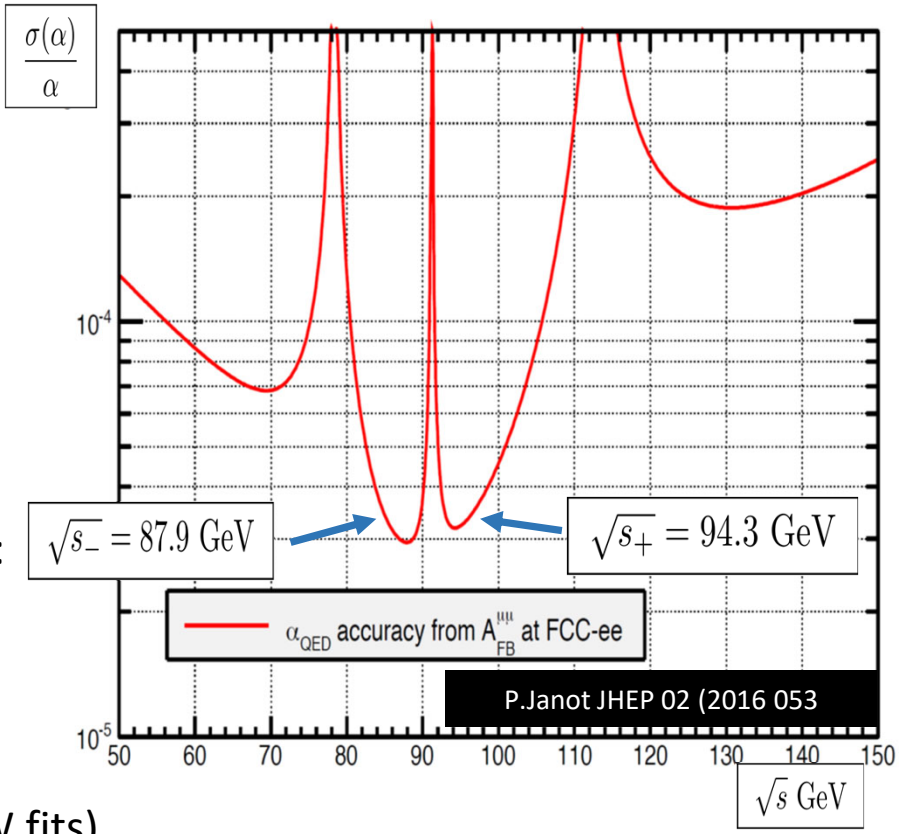


$$\frac{d\sigma}{d\Omega} \propto a(1+\cos^2\theta) + 2b\cos\theta$$

$$\frac{\Delta\alpha_{\rm QED}}{\alpha_{\rm QED}} \simeq \frac{\Delta A_{\rm FB}^{\mu\mu}}{A_{\rm FB}^{\mu\mu}} \times \frac{\mathcal{Z}+\mathcal{G}}{\mathcal{Z}-\mathcal{G}}$$

$\mathcal{Z}(\mathcal{G})$ - Z(photon)–exchange terms

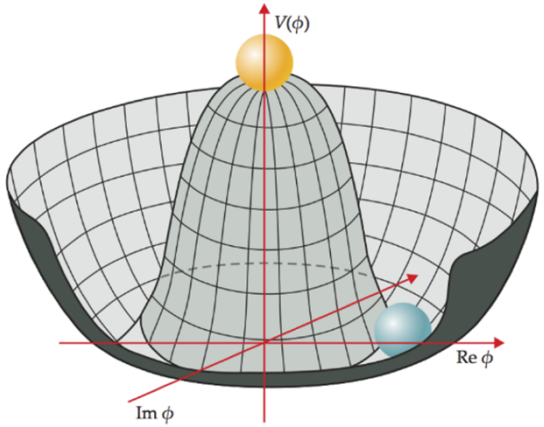
Optimal CMS energies:



2x 6 months of FCC-ee running:

$\Delta\alpha_{\rm QED}(m_Z^2) = 3\times10^{-5}$ (adequate for future precision EW fits)

Are we living in a stable universe?

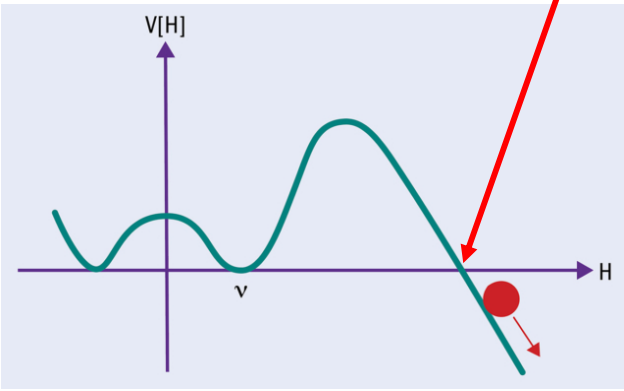


- It is usually supposed that the Higgs field has a constant value throughout the universe – at the bottom of the „Mexican hat" potential
- Hovewer, **the shape of the Mexican hat is subjected to quantum effects that change its shape**

- The quantum effects due to the Higgs's self-interactions „brim the hat upwards" and the interactions with the fundamental particles to which the Higgs field gives mass tend to „brim the hat downwards"
- In the latter case the most important of these is the heaviest matter particle: the top quark

- According to the current theoretical calculations and to the experimental knowledge about the top quark mass:

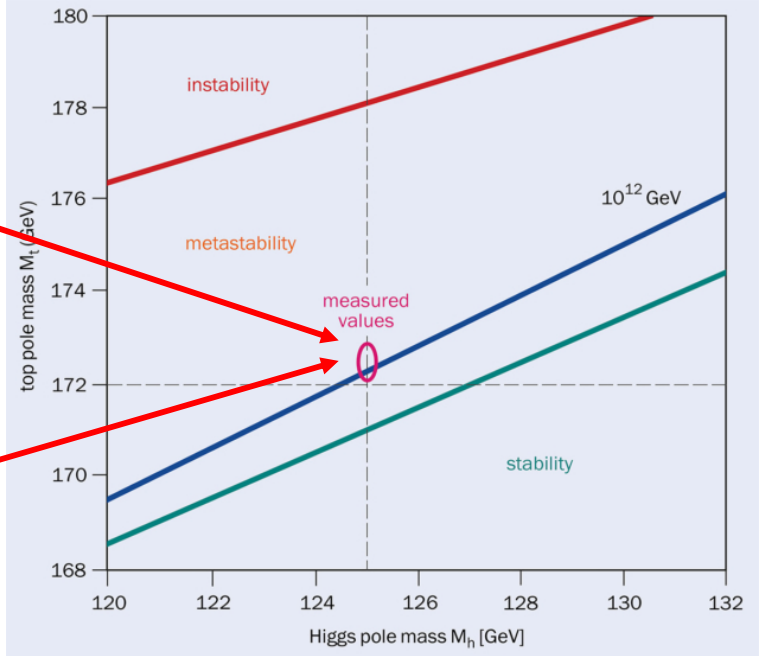
- **The brim of the Mexican hat turnes down at around 10^{12} GeV**



- **We live in a metastable universe**

Source: CERN Courier

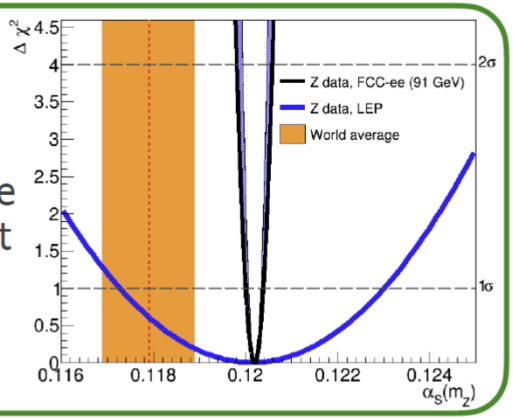
- **The FCC-ee can provide a qualitative shrinking of the uncertainty ellipsis**



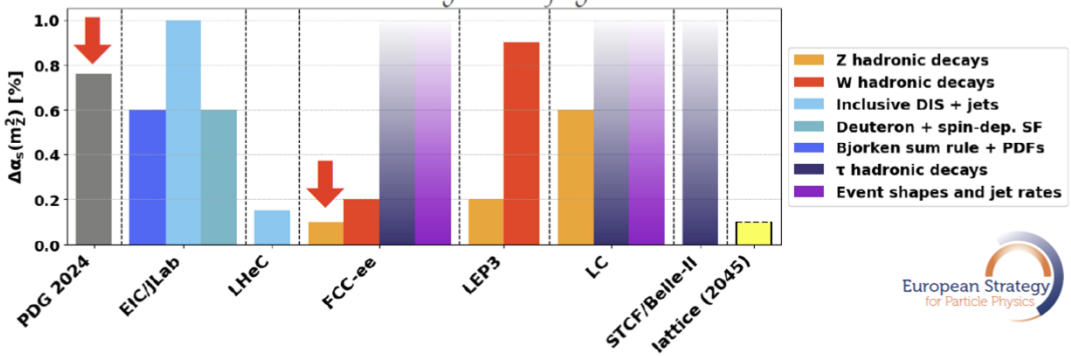
- The FCC-ee results can also provide evidence for some NP which stabilises the vacuum that we live in

FCCee as a QCD laboratory

Precise extractions of the strong coupling constant



From Physics Briefing Book 2511.03883

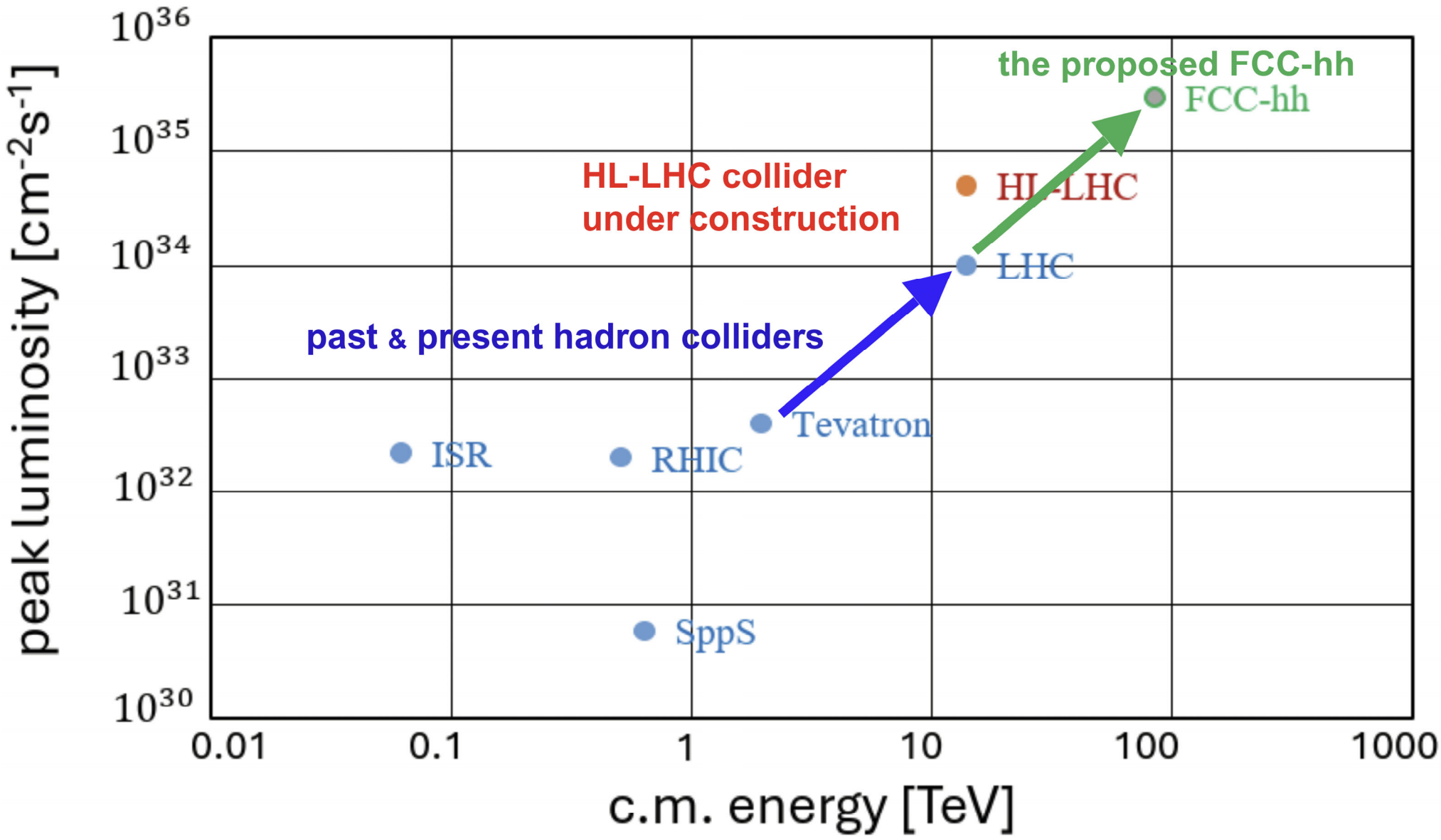


European Strategy for Particle Physics

Permille-level extraction from Z/W decays. Opportunity also to shed light, and possibly resolve outstanding puzzles in α_s determinations from τ decays and event shapes

24

Hadronic collider peak luminosity vs. c.m. energy



High Field Magnets (HFM) programme at CERN

- **High Field Magnets are among the key technologies that will enable future particle physics studies at the energy frontier ($p = 0.3RB$)**

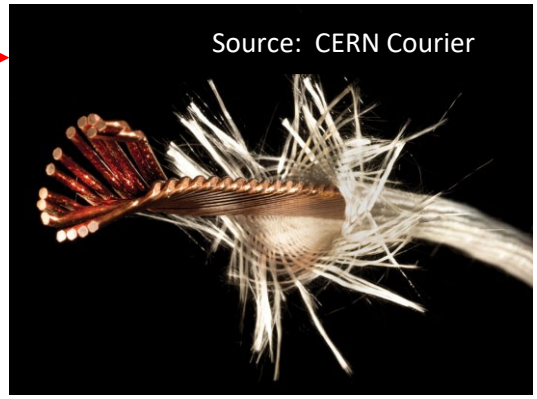
- **The FCC-hh programnne requires a new magnet technology able to achieve fields (14-20 T) beyond the reach of Nb-Ti and beyond the fields produced via Nb_3Sn in HL-LHC (12 T)**

Nb-Ti

Critical temp.:
$T_c = 9.2$ K

Critical field:
$B_c = 14.5$ T

Field@LHC:
$B = 8.33$ T



Nb_3Sn

$T_c = 18$ K $B_c = 30$ T

„twice better"
but very brittle

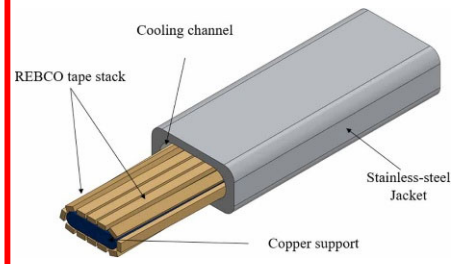
Field@HL-LHC:
$B = 12$ T

Max. Field: $B = 16$ T

Source: IOP Science

HTS (REBCO)

Rare-earth barium copper oxide



$T_c \approx 90$ K

$B_c \geq 100$ T

Field@future accelerator: $B \sim 20$ T

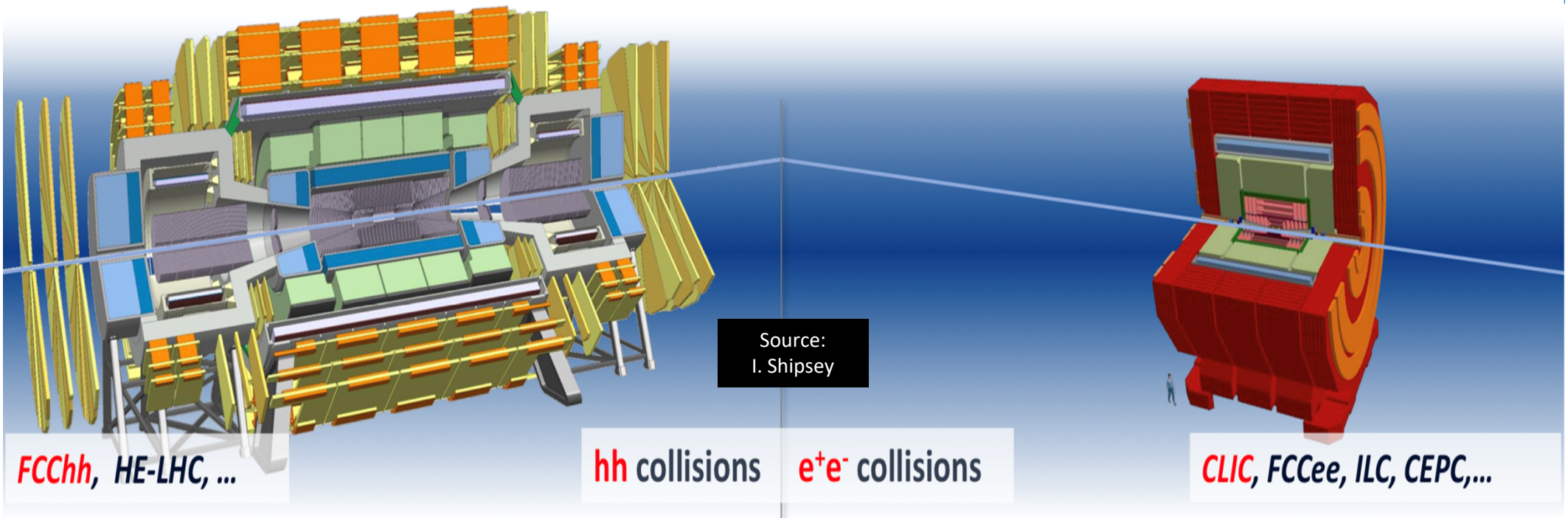
- **Goals of the High Field Magnets programme:**

- To demonstrate Nb_3Sn magnet technology for large-scale deployment (14 T)

- To demonstrate the suitability of high temperature superconductors (HTS), providing a proof-of-principle of HTS technology beyond the range of Nb_3Sn, with a target in excess of 20 T

Concepts → demonstrators → short & longer prototypes → full scale → mass production (30-40 years)

Spectrometers for FCC-ee and FCC-hh



FCChh, HE-LHC, … | **hh collisions** | **e^+e^- collisions** | **CLIC, FCCee, ILC, CEPC,…**

- **Large dimensions (50m)**
- **High radiation Level (up to 2.8 x10^{17}neq/cm2; 90MGy @10 year)**
- Central solenoid (10m) 4T, Forward solenoids 4T
- Silicon tracker **Tracker Radius 1.6m, Length 32m**
  radiation damage is a concern
- Barrel ECAL Lar/ Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr **2-4x better granularity than e.g. ATLAS**
  Silicon ECAL and ideas for digital ECAL with MAPS
- Muon system

➔ Detector R&D essential

- Standard dimensions
- Low radiation Level, Radiation level NIEL (<4×10^{10} neq cm^{-2}/yr); TID (<200Gy/yr)
- Magnet 4T, 2T
- Silicon tracker
  - **unprecedented spatial resolution (1-5 µm point resolution)**
  - **very low material budget (0.1X%)** Dissipated power (vertex) (<50mW/cm^2)
- Barrel fine grained calorimeter
- Compact Forward calorimeter

➔ Detector R&D essential

FUTURE CIRCULAR COLLIDER

FCC-ee Physics requirements

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Higgs Factory Programme

- At √s=240 and √s=365 GeV collect 2.6M HZ and 150k WW→ H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (~4 σ) via loop diagrams
- Unique possibility: s-channel $e^+e^- \rightarrow$ H at 125 GeV

→

- **Momentum resolution $\sigma(p_T)/p_T \simeq 10^{-3}$ @ $p_T \sim 50$ GeV**
  - σ(p)/p limited by multiple scattering → minimise material
- **Jet σ(E)/E ≃ 3-4% in multijet events for Z/W/H separation**
- **Superior impact parameter resolution for b, c tagging**
- **Hadron PID for s tagging**

Precision EW and QCD Programme

- 6×10^{12} Z and 2×10^8 WW events
- × 500 improvement of statistical precision on EWPO: m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W$, R_b, m_W, Γ_W, …
- 2×10^8 tt events: m_{top}, Γ_{top}, EW couplings
- Indirect sensitivity to new physics up to tens of TeV

→

- **Absolute normalisation of luminosity to 10^{-4}**
- **Relative normalisation to $\lesssim 10^{-5}$ (e.g. Γ_{had}/Γ_ℓ)**
  - Acceptance definition to $\mathcal{O}(10\ \mu m)$
- **Track angular resolution < 0.1 mrad**
- **Stability of B field to 10^{-6}**

Heavy Flavour Programme

- 10^{12} bb, cc, 2×10^{12} ττ (clean and boosted): 10 × Belle II
- CKM matrix, CP measurements
- rare decays, CLFV searches, lepton universality

→

- **Superior impact parameter resolution**
- **Precise identification and measurement of secondary vertices**
- **ECAL resolution at few %/√E**
- **Excellent π^0/γ separation for τ decay-mode identification**
- **PID: K/π separation over wide p range** → dN/dx, RICH, timing

Feebly coupled particles Beyond SM

- Opportunity to directly observe new feebly interacting particles with masses below m_Z
- Axion-like particles, dark photons, Heavy Neutral Leptons
- Long-lifetime LLPs

→

- **Sensitivity to (significantly) detached vertices (mm → m)**
  - tracking: more layers, "continous" tracking
  - calorimetry: granularity, tracking capabilities
- **Precise timing**
- **Hermeticity**

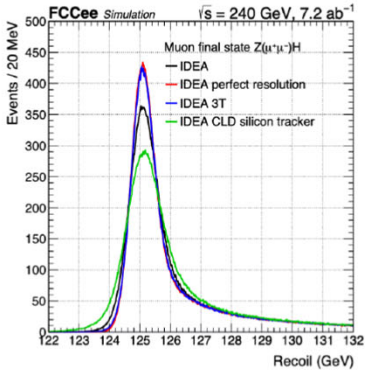
M. Dam

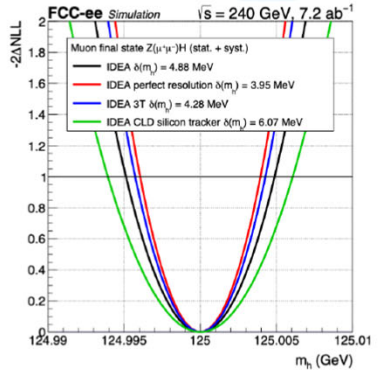
Physics requirements

In FCC-ee, **tracking crucial** for many physics cases eg. Higgs, Flavor physics, QCD-EWK, BSM

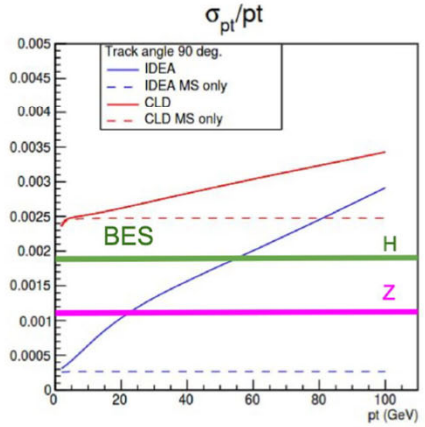
- **Excellent impact parameter resolution** needed for charm- and b-jet tagging → Radial distance of first tracking layer is key
- PID Capabilities (e.g. $H \to s\bar{s}$)
- High acceptance, high efficiency, hermeticity
- **Keep systematic uncertainties down to statistical errors**
- **Excellent momentum resolution** → at the level ~ $\mathcal{O}(50)\mathrm{GeV}$ $\sigma_{p_\mathrm{T}}/p_\mathrm{T}$~0.2%
  - Higgs mass measured at its intrinsic width (4 MeV)
  - Sensitivity driven by m_{recoil} for $Z(\mu^+\mu^-)H$ determined by BES (0.185%)
- **Transparency** of the tracker crucial

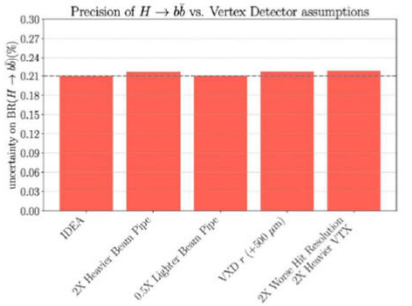






J. Eysermans, A. Li, G. Bernardi, FCC note: Higgs boson mass and model-independent ZH cross-section at FCC-ee in the di-electron and di-muon final states



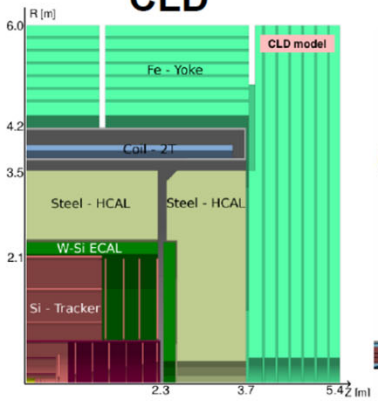


M. Selvaggi: Physics and Performance, Requirements on Tracking for future colliders

Detector concepts - Tracking systems

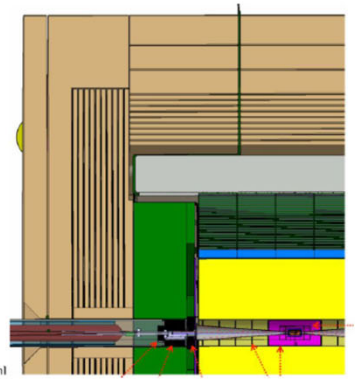
Legend: Inner Tracker, Outer Tracker, Wrappers

CLD



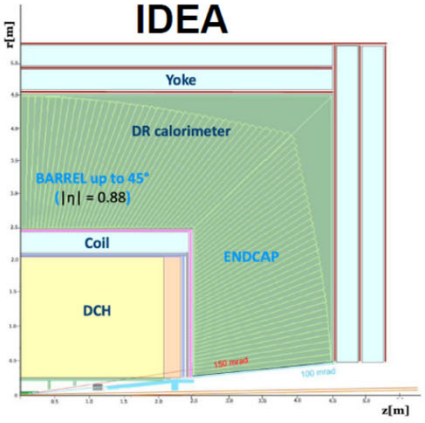
- Evolved from CLIC detector
- Silicon vertex with 25μm pixels
  - Geometry with ALICE ITS approximation → FCC-SEED
- Silicon tracker with 50μm strips
  - Sensors plus ASICs or monolithic structure or MAPS
- ARC (Array of RICH Cells) Lightweight with 20cm radial depth
  - Two radiators (gas + aerogel)

ILD



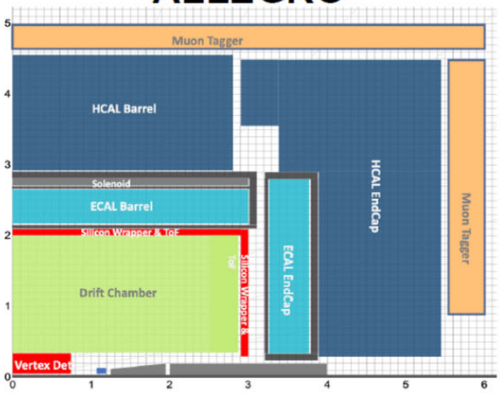
- Initial design for ILC
  - Significant changes for FCC-ee
- Silicon Vertex
  - Currently borrowed from CLD for simulations
- TPC as outer tracker
  - Studying different layouts varying the inner Radii
- Silicon External Tracker for ToF + momentum resolution

IDEA



- Conceived for FCC-ee
- Silicon vertex tracker
  - Outer based on ATLASPix3 with 50x150μm² pixels
  - Inner ARCADIA based 25x25 μm² pixels
- Outer tracker based on low mass Drift Chamber
  - 112 layers
  - 4m Long
  - R = 35-200cm
- Silicon wrapper
  - either with MAPS with with ~10^{11} channels!
  - or CMOS-LGADS ~40ps

ALLEGRO



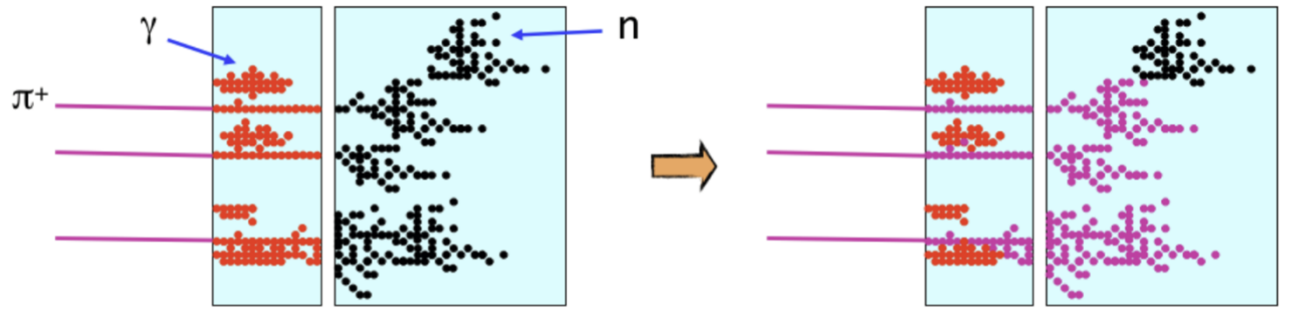
- Conceived for FCC-ee, started with a noble-liquid calorimeter
- Tracking system taken from IDEA
- Silicon Vertex with curved or straight sensors
- Outer tracker with
  - Extended Drift Chamber
  - Straw tubes
  - Scintillating Fiber Tracker (SciFi)
    - 5m Long
    - R = 35-200cm
- Silicon wrapper
  - Monolithic pixel or AC-LGADs

ALFA



- Newly Conceived project for FCC-ee
- MAPS tracker following ALICE ITS3 developments
  - Vertex curved MAPS 65 nm CMOS TPSCo 10x10 μm² pixels
  - Outer tracker Reticle-size MAPS,
    - 25x32 mm² to 50x128 mm² module
- ARC (Array of RICH Cells) Lightweight with 20cm radial depth
  - Two radiators (gas + aerogel)

Particle flow reconstruction



- Main goal
  - Minimize confusion term with optimized spatial resolution → high granularity
  - "Strips" of active material → pixel/tiles → embedded electronics
- Proof of concept
  - Within the CALICE and FCAL collaborations
  - Focus originally on linear colliders

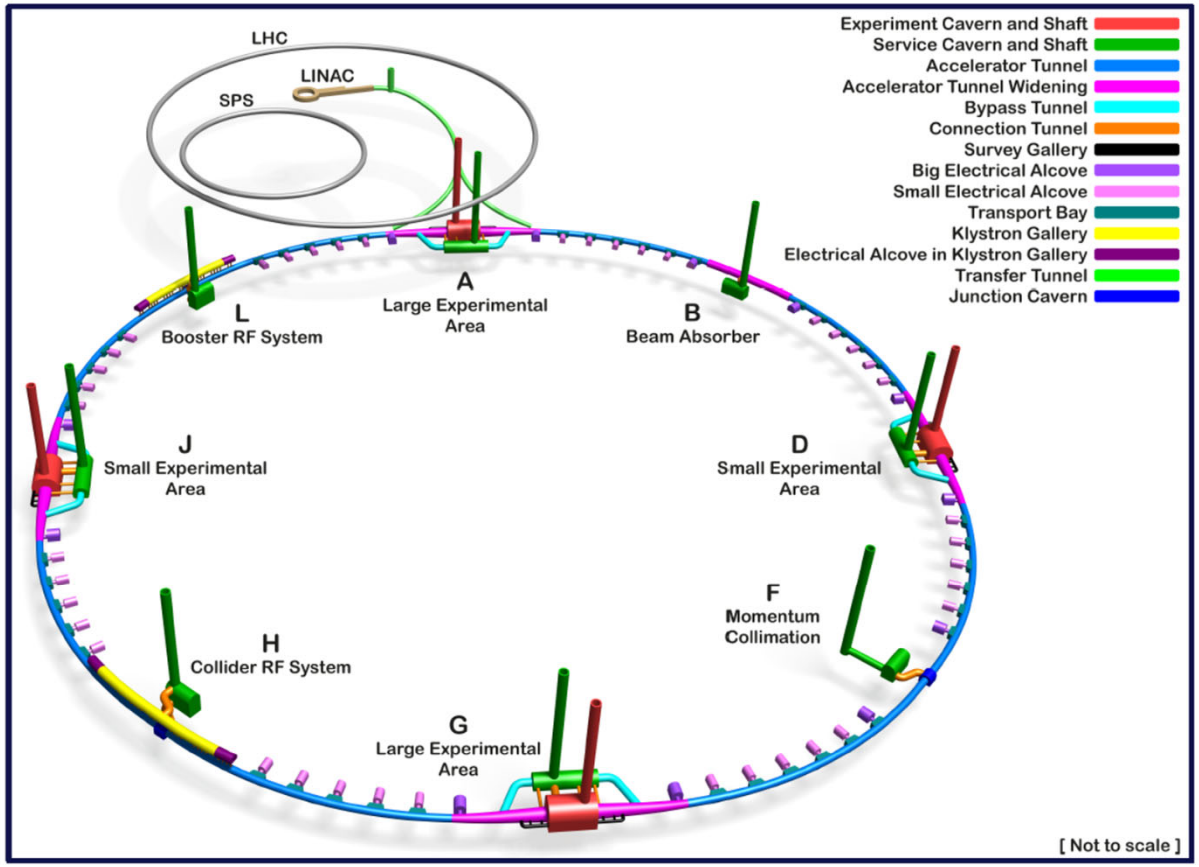

FCC-ee Proposed Detectors
Joshua Beirer
CERN
CLD
IDEA
ALLEGRO
ILD
ALFA
emerging
New!
AGORA
(CEPC ref. det.)

FUTURE CIRCULAR COLLIDER

Key features of the Underground Civil Engineering Baseline

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- Tunnel Circumference: 90.7 km
- Excavated vol: 6.25M m³ (*in-situ* volume)
- Access shafts: 12
- Construction shafts: 1
- Large experiment sites: 2
- Small experiment sites: 2
- Technical sites: 4
- Deepest shaft: 400m
- Average shaft depth: 243m
- Total concrete volume: 2 M m³

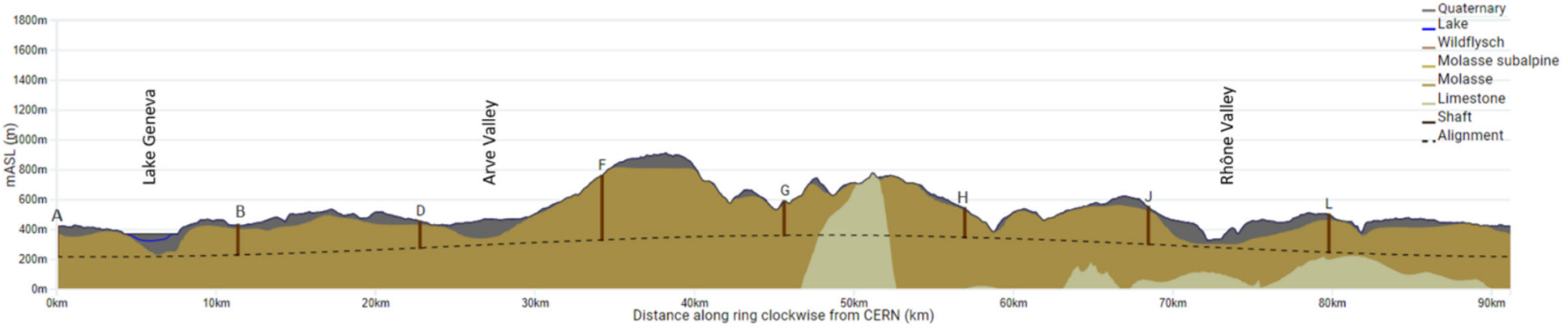


Schematic of FCC-ee Baseline Underground Civil Engineering

FUTURE CIRCULAR COLLIDER

Optimum placement of FCC tunnel and geology

INFN Istituto Nazionale di Fisica Nucleare



Tunnelling mainly in molasse layer (soft rock), well suited for fast, low-risk TBM construction.

6 million m^3 excavated volume → 8.5 million m^3 excavation material on surface

CE Designs of all underground structures developed

Average shaft depths ~240 m

To fix the vertical position of the tunnel, interfaces between geological layers have to be known

The FCC project - Paolo Giacomelli

M. Benedikt 17

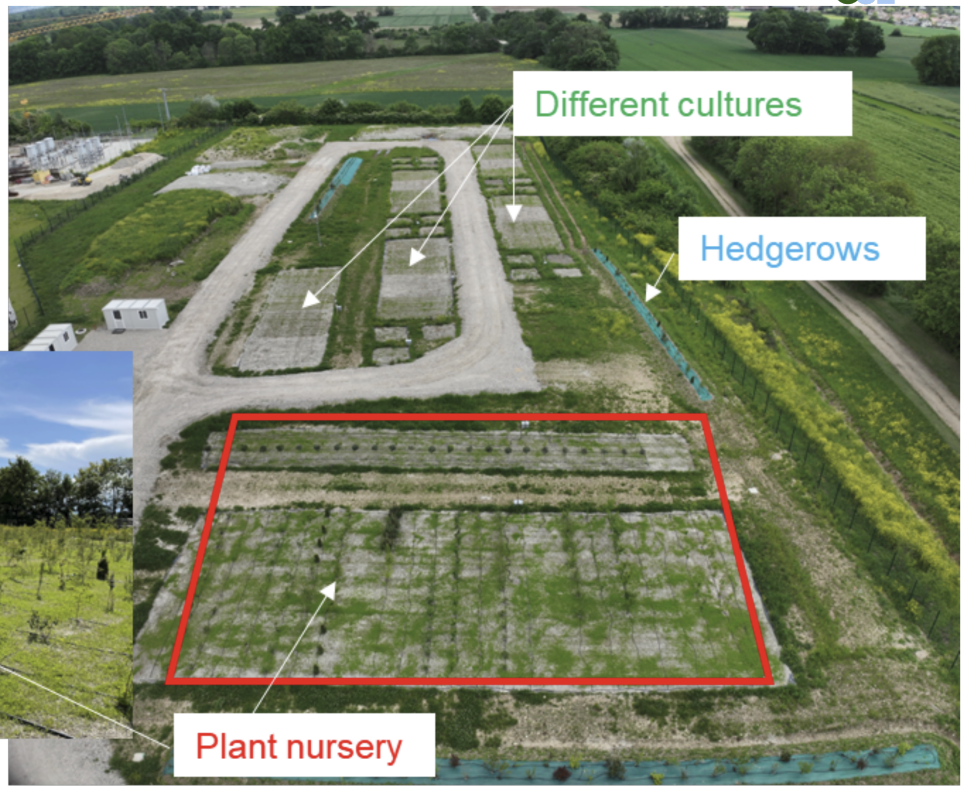
FUTURE CIRCULAR COLLIDER

Reuse of excavated materials: OpenSkyLab project

INFN Istituto Nazionale di Fisica Nucleare

OSL

- Develop a quality-managed process to transform excavated materials into fertile soil
- Permit reuse in renaturalisation, agriculture, etc.
- Additives as compost etc. in various mixtures
- Location: 1 ha field, LHC P5 CMS Cessy (FR)
- Applicable to entire alpine molasse region!



Estimate of reuse quantities:
40% refill of quarries (~ 7.5 Mt)
25% reconstituted soil (~ 4 Mt)
30% deposit (~ 5 Mt)
5% other reuse



hepia Haute école du paysage, d'ingénierie et d'architecture de Genève
brgm Géosciences pour une Terre durable
EDAPHOS ENGINEERING
BOKU UNIVERSITY
microhumus
MONTAN UNIVERSITÄT LEOBEN
BECC
wsp

The FCC project - Paolo Giacomelli

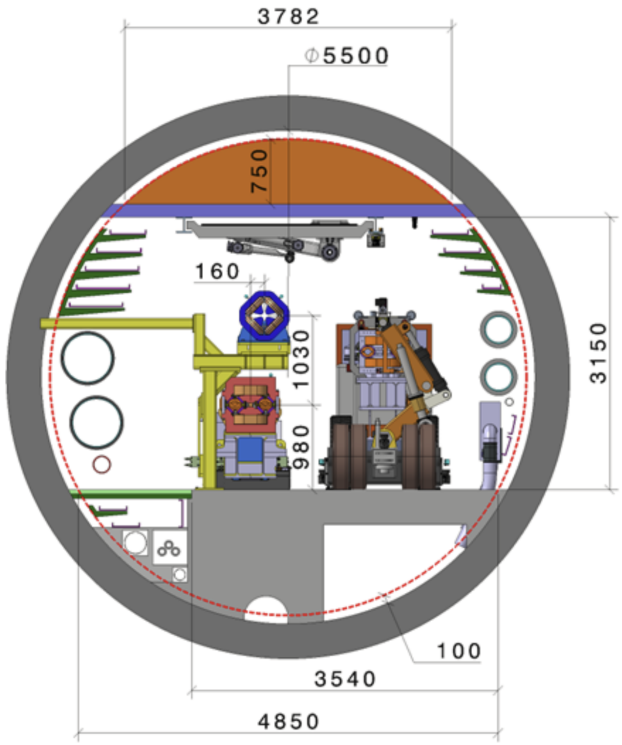
M. Benedikt 19

FUTURE CIRCULAR COLLIDER

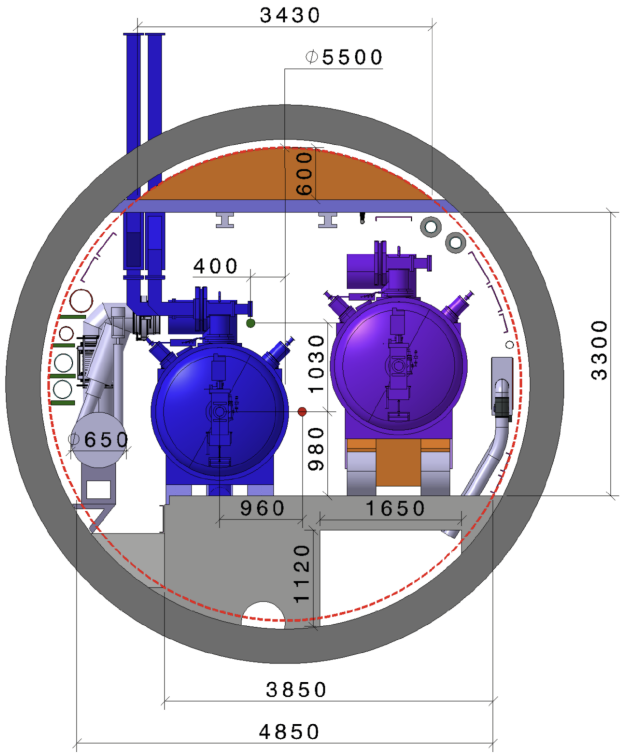
FCC – main tunnel integration – 5.5 m inner diameter

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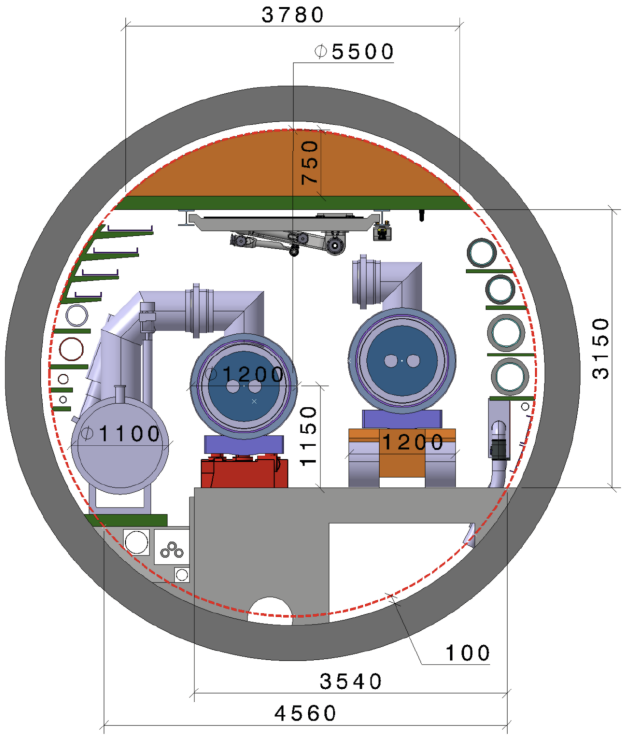
FCC-ee arc



FCC-ee 400 MHz RF section



FCC-hh arc



Integration & logistics studies for installation, safety concept reviewed, to confirm 5.5 m

FUTURE CIRCULAR COLLIDER

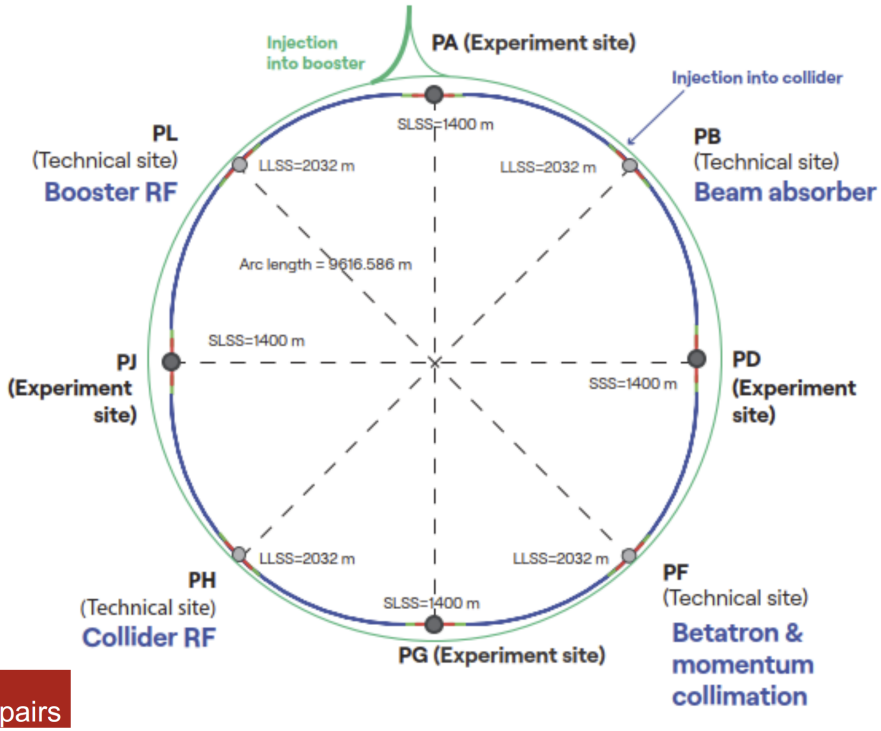
Stage 1: e^+e^- collider FCC-ee

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Consolidated main parameters

parameter	Z	WW	H (ZH)	
beam energy [GeV]	45.6	80	120	182.5
synchrotron radiation/beam [MW]	50	50	50	50
beam current [mA]	1294	135	26.8	5.1
number bunches / beam	11200	1852	300	64
total RF voltage 400/800 MHz [GV]	0.08 / 0	1.0 / 0	2.09 / 0	2.1 / 9.2
luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	145	20	7.5	1.4
total integrated luminosity / IP / year [ab^{-1} / yr]	17	2.4	0.9	0.17
electrical power operation [MW]	250	275	297	381
electrical energy per year [TWh]	1.17	1.32	1.41	1.85
	4 years 6 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years > 2x10^6 H	5 years 2 x 10^6 tt pairs

FCC-ee functional layout



10^4 (@WW) - 10^5 (@Z) x luminosity/energy of LEP → sustainable physics

The FCC project - Paolo Giacomelli

M. Benedikt - F. Zimmermann

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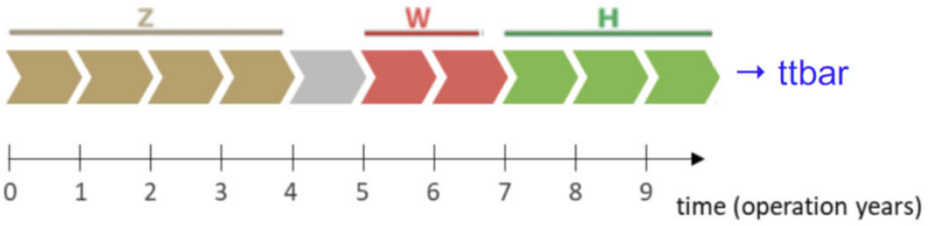
FUTURE CIRCULAR COLLIDER

Operation modes for RF

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- Physics at 4 different energy points:
  Z^0, W^+W^-, Higgs (ZH), t-tbar production
- Same SR power for all 4 modes

  P_{SR}= **50 MW** per beam



Lowest energy:
- Low RF voltage
- High beam current

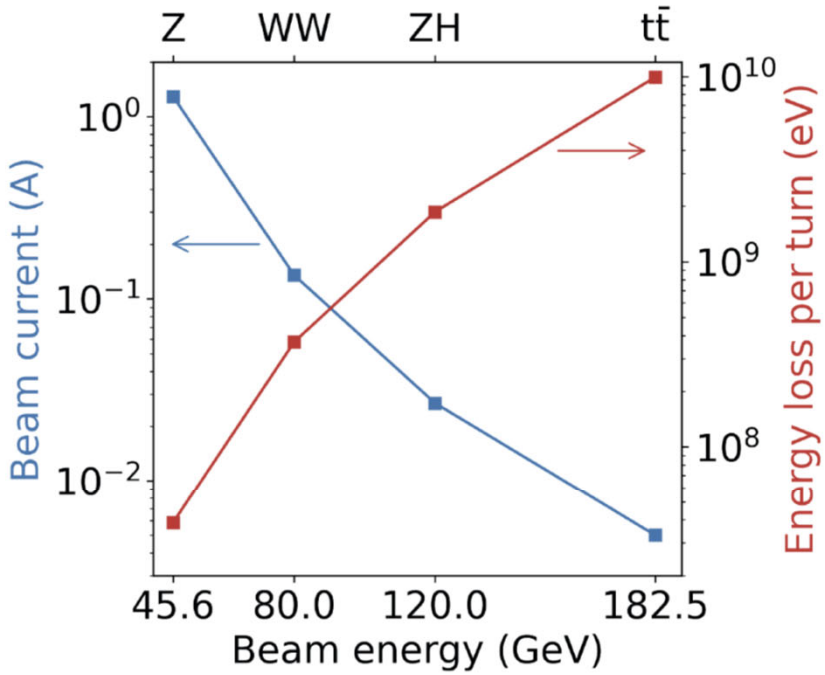
↓
- Few cavities
- Low voltage per cavity
- **High power** per cavity
- Significant HOM power
- Instabilities

↓
- 1- or 2-cell cavities at low RF frequency (400MHz)

Highest energy:
- High RF voltage
- Low beam current

↓
- Many cavities
- **High voltage** per cavity
- Low power per cavity
- Low HOM power
- High SR damping

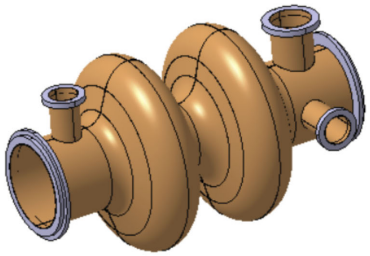
↓
- Multi-cell cavities at higher RF frequency (800MHz)



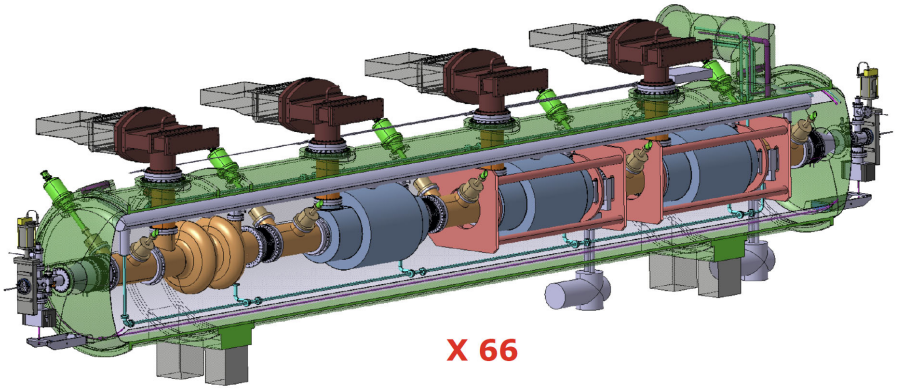
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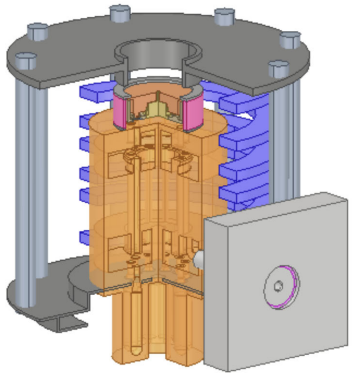
400 MHz system – collider Z, W, ZH



X 264



X 66



X 264

Superconducting elliptical cavity

- 400 MHz, 2-cell
- 1.5 m. long
- Electropolished and seamless RF surface
- Niobium thin film with HiPIMS

Cryomodule

- Segmented design, 4 cavities
- Vertical FPC, HOM damping and extraction
- Frequency tuning system
- Thermal and magnetic shielding

Multibeam Tristron

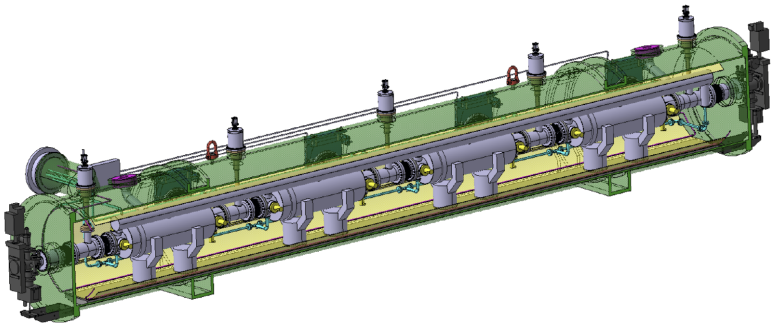
- **400 MHz**
- 46 kV
- 500 kW, CW
- ~ 90% efficiency

I. Syratchev

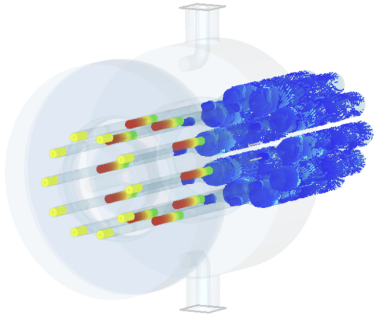
800 MHz system – $t\bar{t}$ (collider and booster)



X (408 + 448)



X (102 + 112)



Multibeam Tristron
- 800 MHz
- 250 kW, CW

X 408

Superconducting elliptical cavity
- 800 MHz, 6-cell
- Nb_3Sn if R&D is successful

Cryomodule
- Segmented design, 4 cavities, 2 K
- Operation at 4.5 K if R&D successful

Solid State Amplifier (SSA)
- 800 MHz
- 10-15 kW pulsed

X 448



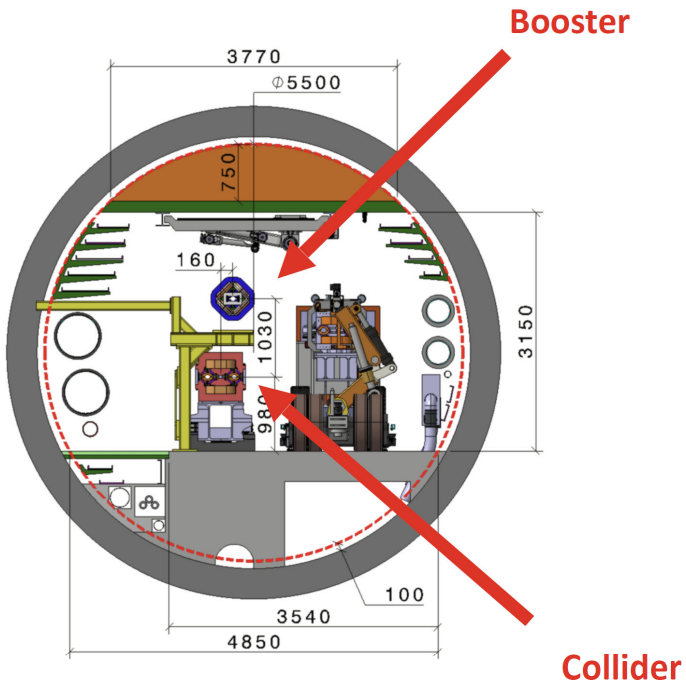
A. Butterworth

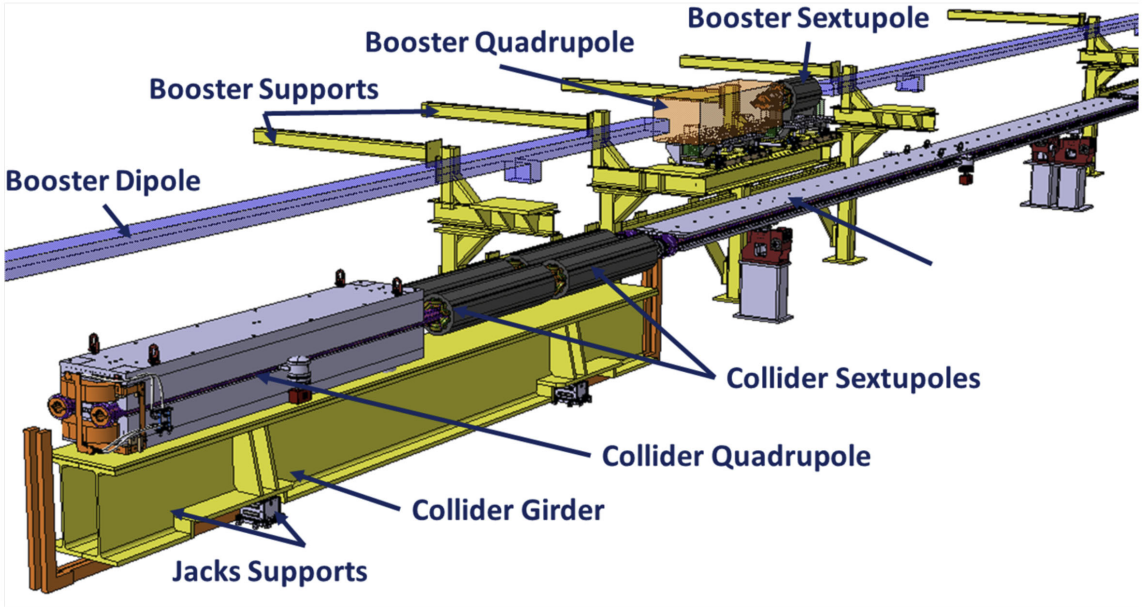
FUTURE CIRCULAR COLLIDER

FCC-ee booster

INFN Istituto Nazionale di Fisica Nucleare

full energy booster, ramping from 20 GeV to 46 GeV – 182.5 GeV; injection ~every minute to keep collider beam currents constant; booster intensity ~1% of collider; full RF voltage as in collider





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