Overview of the ESPPU strategy for Higgs and Electroweak physics
+intro to the discussion

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(based on summaries from Karl Jakobs, Monica Dunford, Jorge de Blas)

Open Symposium on the European Strategy for Particle Physics

	Monday	Tuesday	Wednesday	Thursday	Friday
09:00	**Opening Session**	**Large-scale accelerator projects at CERN, part I**	**Electroweak Physics** Talks (i), (ii) Discussion	**BSM** Talks (i), (ii) Discussion	**Overarching topics** (by ESG Working groups) e.g. National input and others
	Coffee break	Coffee break	Coffee break	Coffee break	Coffee break
11:15	**Parallel session I - IV**	**Large-scale accelerator projects at CERN, part II**	**Strong Interactions** Talks (i), (ii) Discussion	**Dark Matter / dark sector** Talks (i), (ii) Discussion	**Overarching topics (cont.)** (by ESG Working groups) **Closeout Session** Closeout talk, final discussion
13:00	Lunch Break	Lunch break	Lunch break	Lunch break	
14:00	**Parallel session I - IV**				
15:00		**Status in China, Japan, US**	**Flavour** Talks (i), (ii) Discussion	**Detector Technologies** status of DRDs, R&D needs, timeline, required resources	**ESG Meeting**
16:00	**Parallel sessions V - IX**	Coffee break	Coffee break	Coffee break	
	Coffee break	**Accelerator Technologies** Status of critical item, R&D needs timeline, required resources	**Neutrinos and Cosmic Messengers** Talks (i), (ii) Discussion	**Computing** Status of critical item, R&D needs timeline, required resources	
	Parallel sessions V - IX				
19:15					

9:00 - 10:45 Opening Session

Parallel Sessions I - IV
11:15 - 13:00 Parallel I - IV, part I
Lunch Break: 13:00 - 14:00

14:00 - 15:30 Parallel I - IV, part II
Very short break; 15:30 - 15:40 to change rooms
15:40 - 17:00 Parallel V - IX, part I
17:00 - 17:20 Coffee break
17:20 - 19:15 Parallel V-IX, part II

16:45 - 19:15 Accelerator Tech.

For each **Physics Block**:
(i) Status, open questions
(ii) How can they be addressed by the various projects
(iii) Discussion

11:15 - 12:30 ESG Session II
12:30 - 13:30 Closeout session

14:30 - 16:30 ESG Meeting

Photo Trevor Sherwin

Karl Jakobs: "Key messages from the Symposium"
Venice, Friday 27 June

Final Words

Over the past years very significant progress has been made towards the realisation of the next flagship project at CERN

- FCC: Successful completion of the Feasibility Study; No technical showstoppers identified
- Overwhelming support for the integrated FCC-ee/hh programme by the HEP communities in the CERN Member and Associate Member states and beyond;

  The strong support is largely based on the superb physics potential and the long-term prospects (FCC-ee /hh)

- Discussions on the financial feasibility are ongoing (CERN management and Council)

Photo Trevor Sherwin

Karl Jakobs: "Key messages from the Symposium"
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Final Words

Discussions on the prioritisation of alternative options are ongoing

- Linear colliders (LCF, CLIC) present as well mature options for a Higgs factory at CERN
- LEP3 and LHeC could be considered as "intermediate" collider projects
- The differences in the physics potential (→ Physics Briefing Book), review of the technical readiness and the final input from the national HEP communities (due by 14 Nov.) will be important ingredients in the final recommendations by the European Strategy Group

US National Academy Report (11-Jun-2025)

Host the World's Highest Energy Elementary Particle Collider

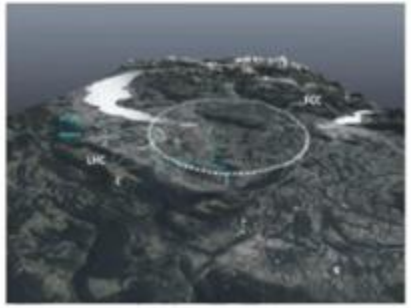
Recommendation 1: The United States should host the world's highest-energy elementary particle collider around the middle of the century. This requires the immediate creation of a national muon collider research and development program to enable the construction of a demonstrator of the key new technologies and their integration.

- Developing a US-hosted muon collider—an unprecedented machine requiring dedicated research, development, and a technology demonstrator followed by a feasibility study—would solidify U.S. leadership in particle physics and drive accelerator innovation.

  A collider with approximately 10 times the energy of the Large Hadron Collider is crucial to address the big questions of particle physics.

Participate in the Future Circular Collider

Recommendation 2: The United States should participate in the international Future Circular Collider Higgs factory currently under study at CERN to unravel the physics of the Higgs boson.



- Determining whether the Higgs is elementary or has substructure has huge ramifications for the future of particle physics.
- Active participation in a Higgs factory is crucial for the U.S. particle physics community.

	# of exp.	Z-pole (91.2 GeV)	WW (160 GeV)	Higgs (230-250 GeV)	Top (365 GeV)	Higher energy
FCC-ee	4	205 ab^{-1} (total, all IP) 4 years (of operation)	19 ab^{-1} 2 years	11 ab^{-1} 3 years	3 ab^{-1} 5 years	—
Linear collider	2	0.07 ab^{-1} 1 years	—	3 ab^{-1} 9years	CLIC: 4.4 ab^{-1} 10 years	550 GeV: 8 ab^{-1} 10 years
LEP3	2	53 ab^{-1} 5 years	5 ab^{-1} 4 years	2.5 ab^{-1} 6 years	—	—
FCC-hh	4	—	—	—	—	84.6 TeV 30 ab^{-1}
LHeC	1	—	—	—	—	1.2 TeV 1 ab^{-1} 6 years

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi} i \not{D} \psi + D_\mu \phi D^\mu \phi - V(\phi) - \left(Y_{ij}\bar{\psi}_L^i \phi \psi_R^j + \text{h.c.}\right)$$

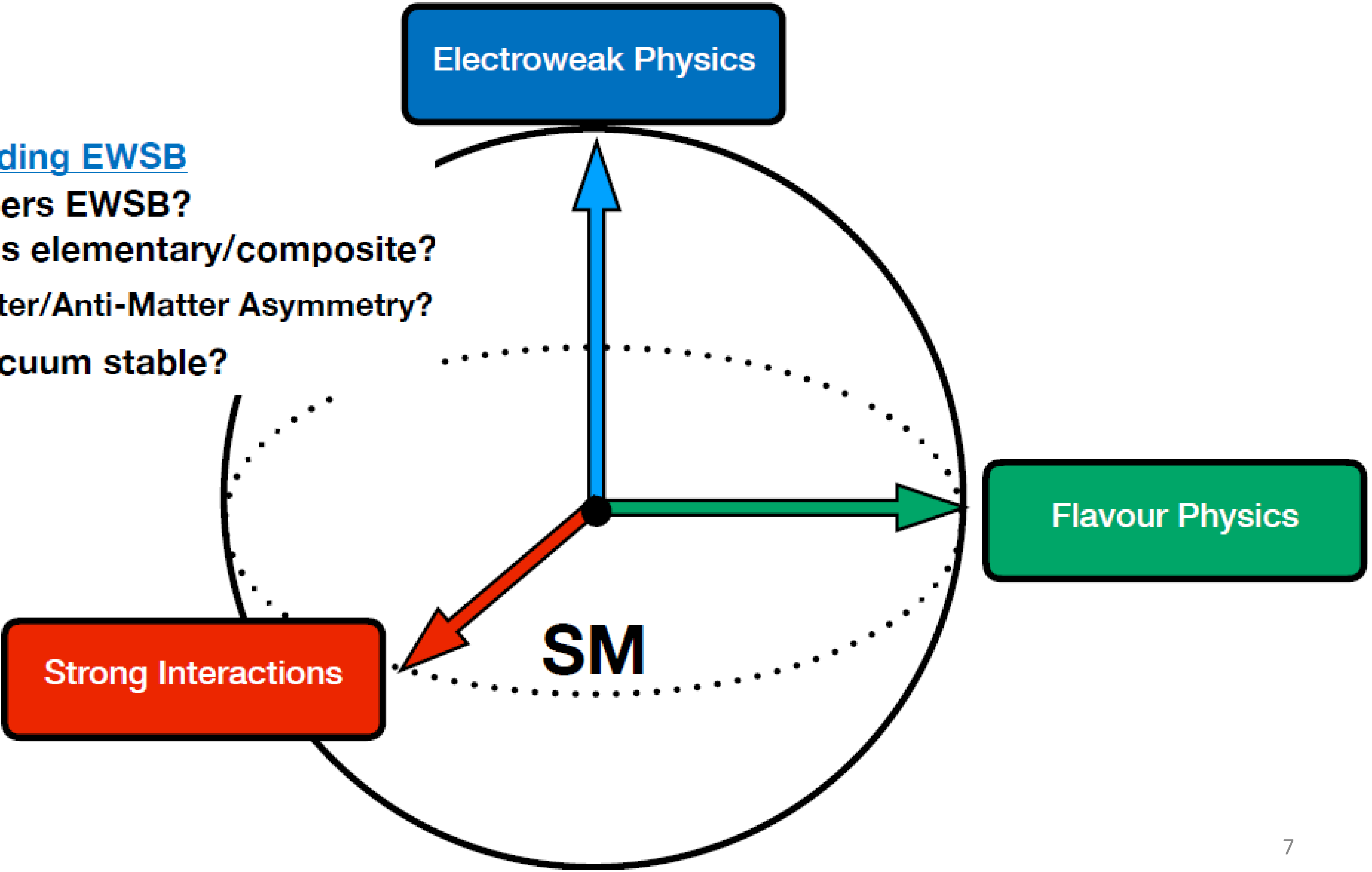
Understanding EWSB

What triggers EWSB?

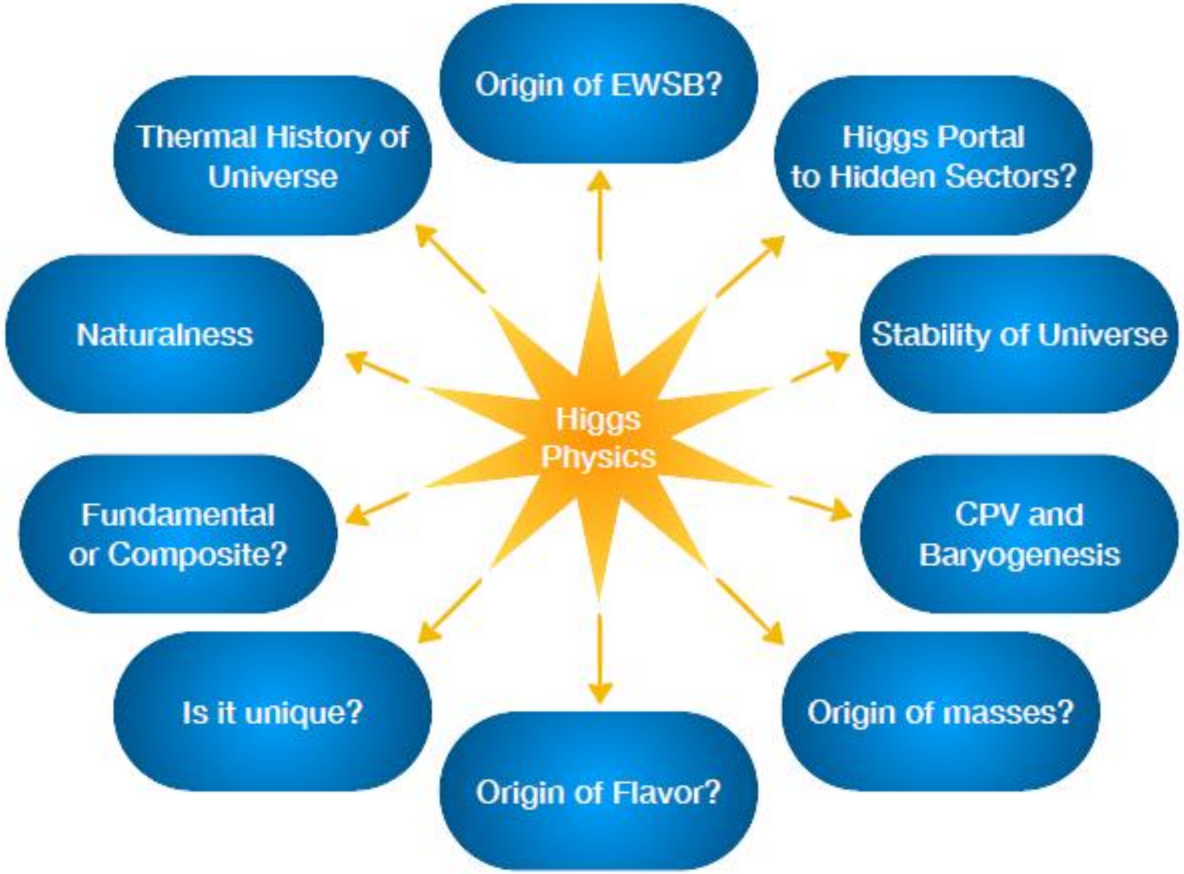
Naturalness? Is the Higgs elementary/composite?

Nature of the EWPT ↔ Matter/Anti-Matter Asymmetry?

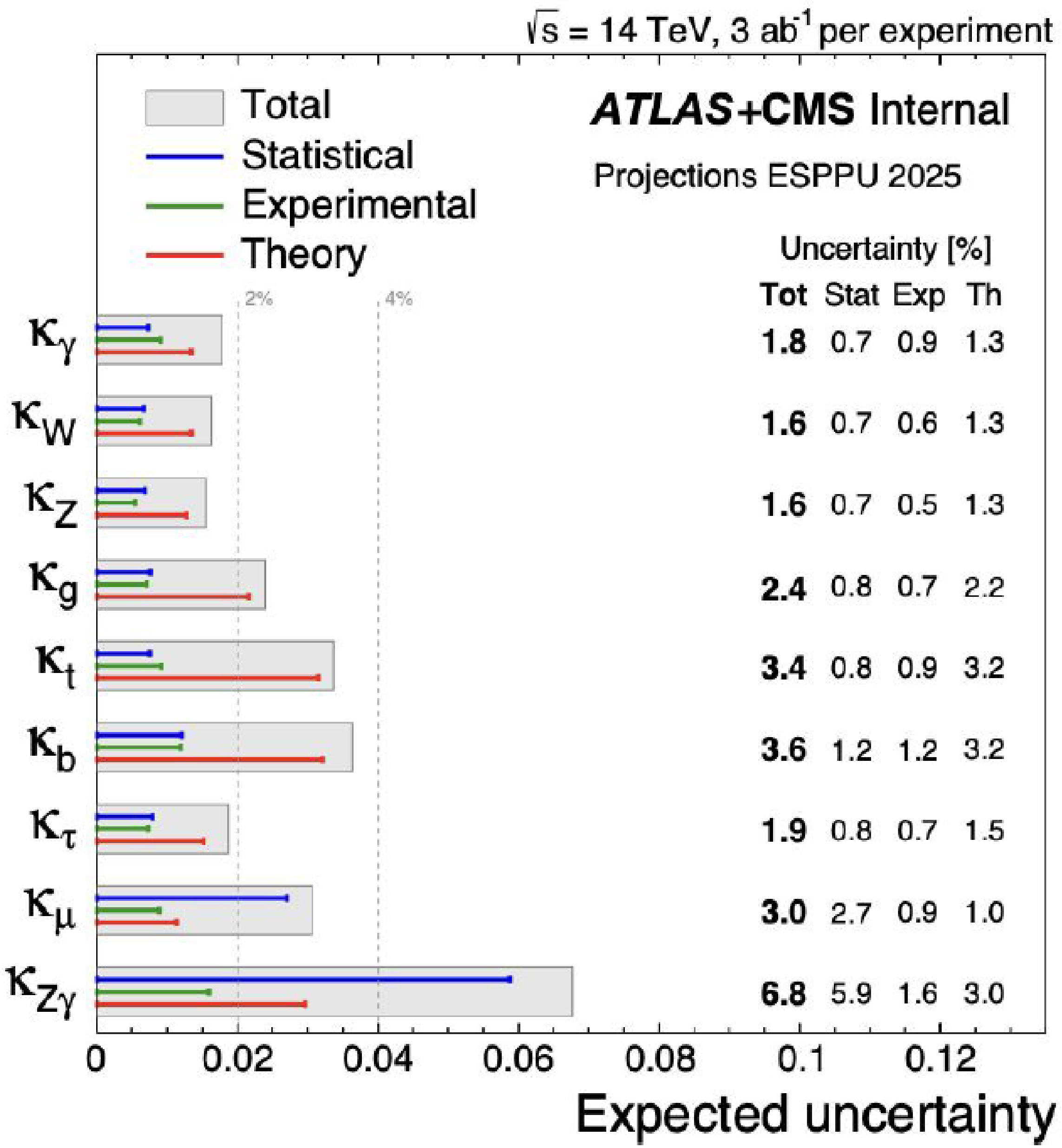
Is the EW vacuum stable?



BSM models typically modify Higgs properties⇒ Precision Higgs physics needed!

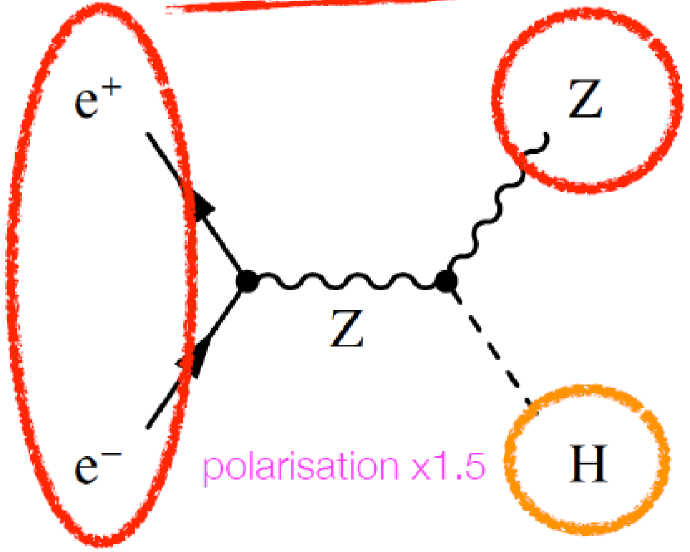


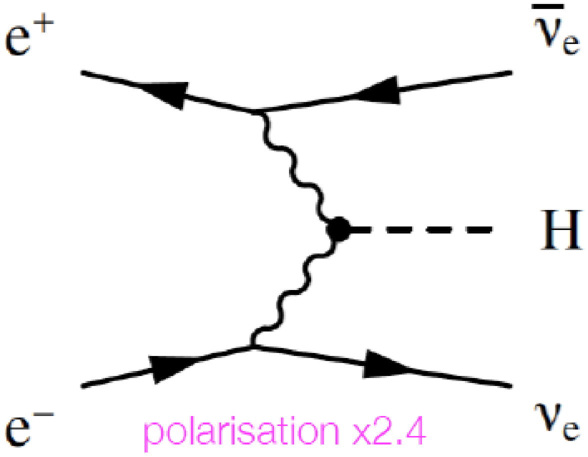
Precision Higgs Physics at the HL-LHC

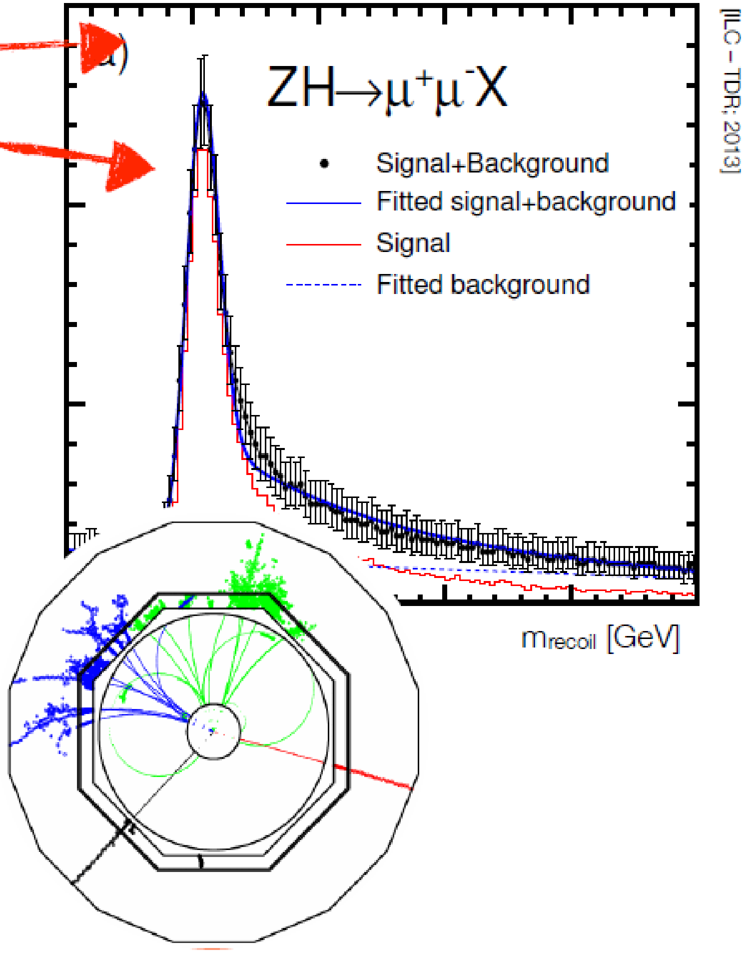


- HL-LHC precision on Higgs coupling modifier at the level of:
  - 2-4% for dominant decays
  - 3%-7% for rare decays
- Assumes progress on theory calculations
  - S2 scenario: TH systematics halved (where feasible)
    - ***Precision QCD needed*** for our understanding of the Higgs
    - ***PDF uncertainties*** also significantly impact Higgs observables

Higgs Production: electron-positron colliders







Total Cross Section:
[from recoil mass]

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

Exclusive Production:
[from individual H-decays]

$$\sigma(ee \to HZ) \times BR(H \to XX) \propto g^2_{\mathrm{HZZ}} \cdot \frac{g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$

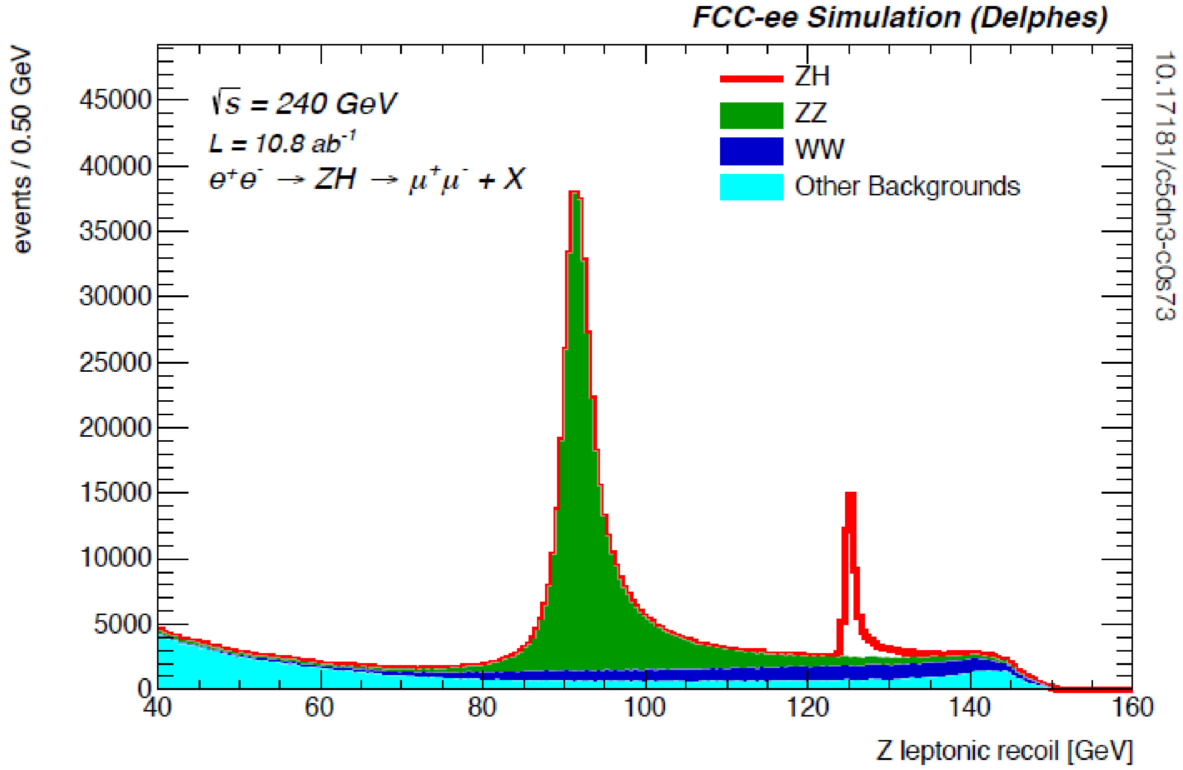
Total Width:
[from individual H-decays]

$$\Gamma_H \propto \frac{(\sigma_{e^+e^-\to ZH} \times BR_{H\to ZZ^*})^2}{\sigma_{e^+e^-\to ZH}}$$

With the width (Γ_{H}), everything follows…

Higgs total cross section and width

Precision on total xsect:
0.3% FCC, 0.8% LC, 0.6% LEP3

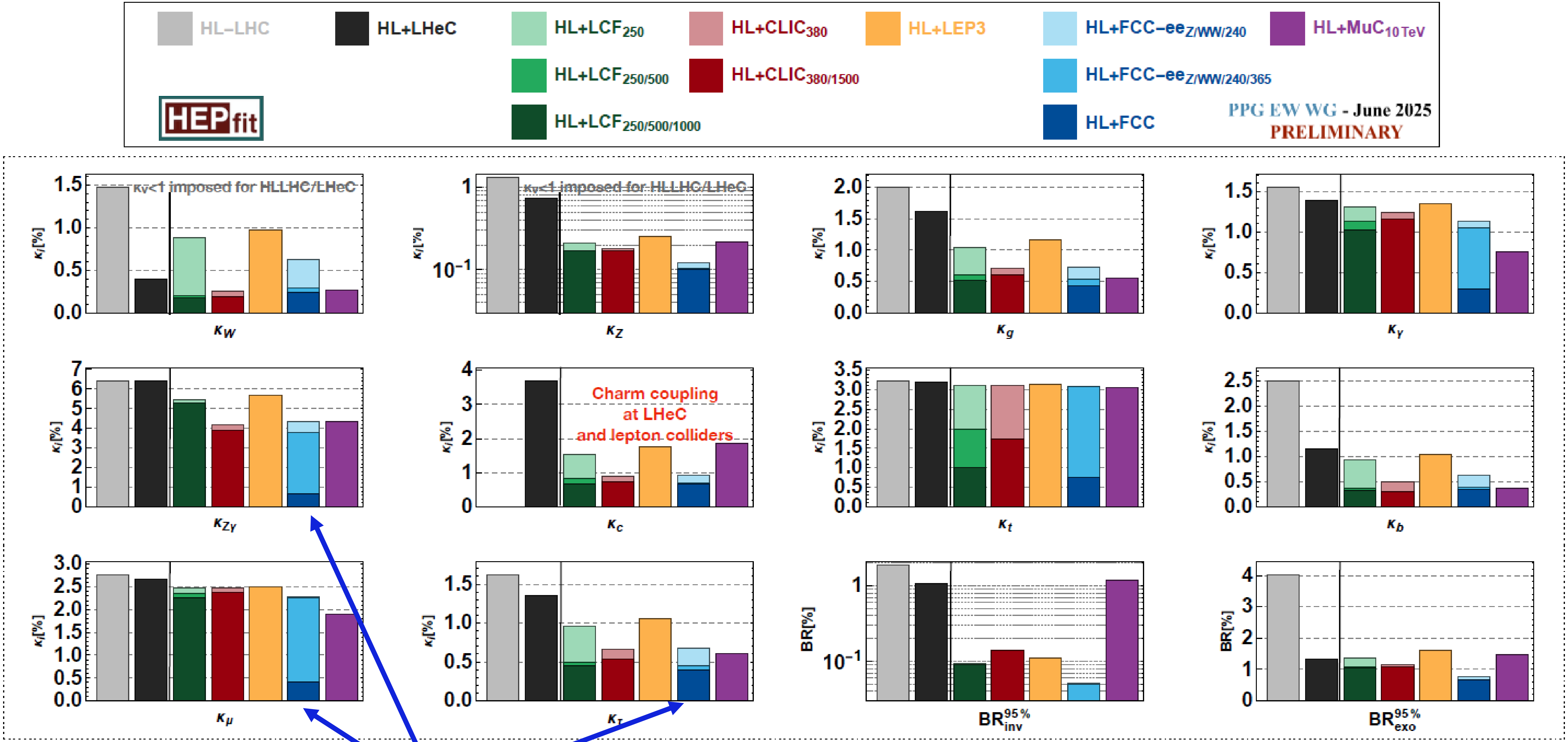


- Assumes that
  - Statistical uncertainties dominate
  - Backgrounds controlled to better than 1% (and large control samples available to constrain them)
  - All experimental and luminosity uncertainties are smaller than statistical uncertainties
  - Theory uncertainties from missing higher orders - extensions of existing methods likely sufficient to make them subdominant

Higgs precision can be nicely summarized in term of the Kappa-framework

$$(\sigma \cdot \mathrm{BR})(i \to H \to f) = \kappa_i^2 \sigma^{\mathrm{SM}}(i \to H) \frac{\kappa_f^2 \Gamma^{\mathrm{SM}}(H \to f)}{\Gamma_H}$$

Kappa framework results



FCC-INT always provide the best precision

Higgs at electron-positron machines

HL-LHC: 21 MeV
FCC-ee: 3 MeV
Linear collider: 12 MeV
LEP3: 15 MeV

Higgs mass estimates

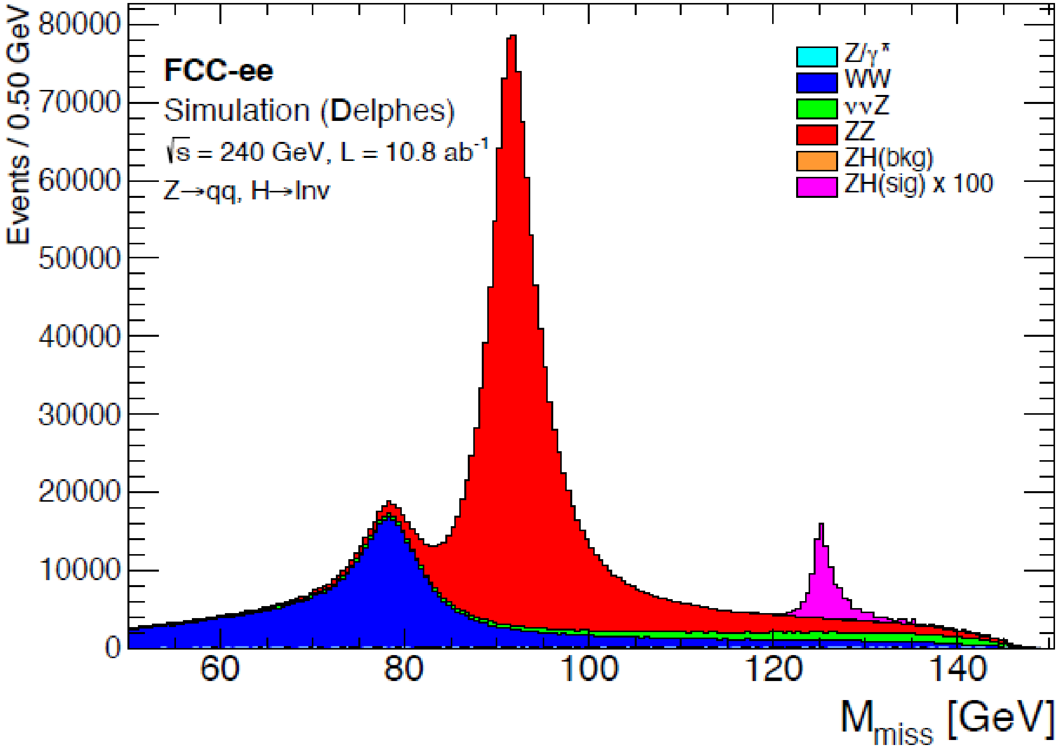
'Stats dominated' sets the design requirements on detector performance: momentum resolution, jet energy resolution, impact parameter resolution etc

- Impact parameter resolution of 3μm, momentum resolution of 0.1%, particle flow jet energy resolution of 2-3 GeV

Invisible, 1st/2nd generations, rare couplings

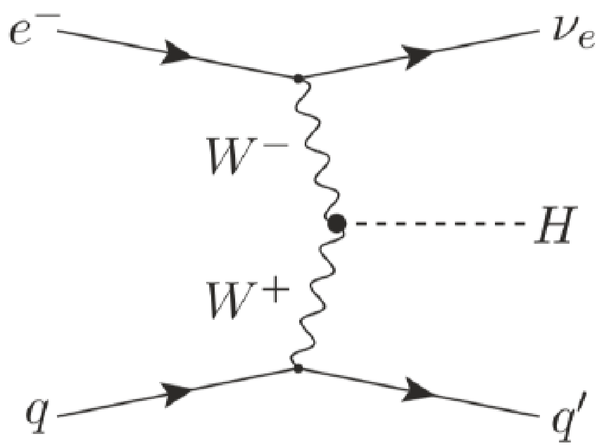
- Higgs to invisible limit of 0.05%
- Excellent b/c-tagging performance yields 1.5 (2.5)% FCCee (LC) precision for Hcc
- Some rare decays (like H→μμ) don't improve compared to HL-LHC
- FCCee: Potential access first generation
  - Needs 4 MeV precision on Higgs mass, reduce beam spread, 5 years of running

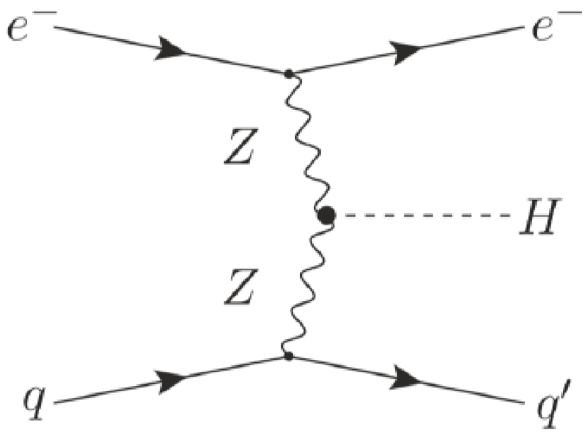
10.17181/7hbn8-3d233



Higgs to invisible example

Higgs couplings: electron-hadron





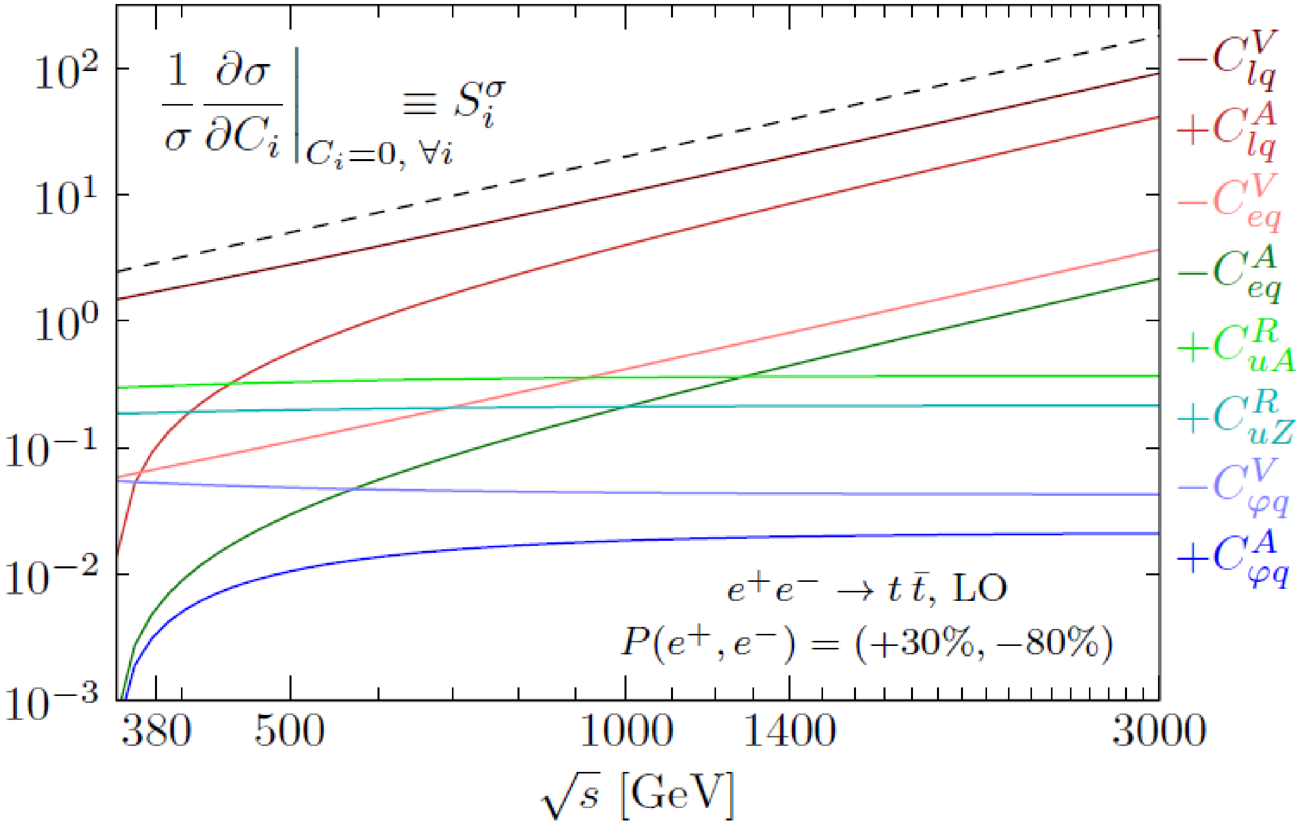
Use electron to distinguish the NC process

- Up to 50% improvement to HL-LHC Higgs couplings via better PDFs
- Strong near-term sensitivity to some Higgs coupling
  - HWW: 0.7% LHeC, 0.8% (0.3%) at FCCee 250 GeV (w/365 GeV)
  - First measurement of Hcc at 3%

Top physics at threshold and beyond

- Lepton colliders vs. hadron colliders have complementary sensitivity to top operators
  - i.e. 2-lepton+2-quark operators vs. 4-quark operators
- A large energy lever arm (i.e. LC at 550 GeV and beyond) breaks degeneracies between operators
- Runs with two beam polarization effectively doubles the number of observables and further breaks degeneracies

Durieux, Perello, Vos, Zhang, JHEP 10 (2018) 168

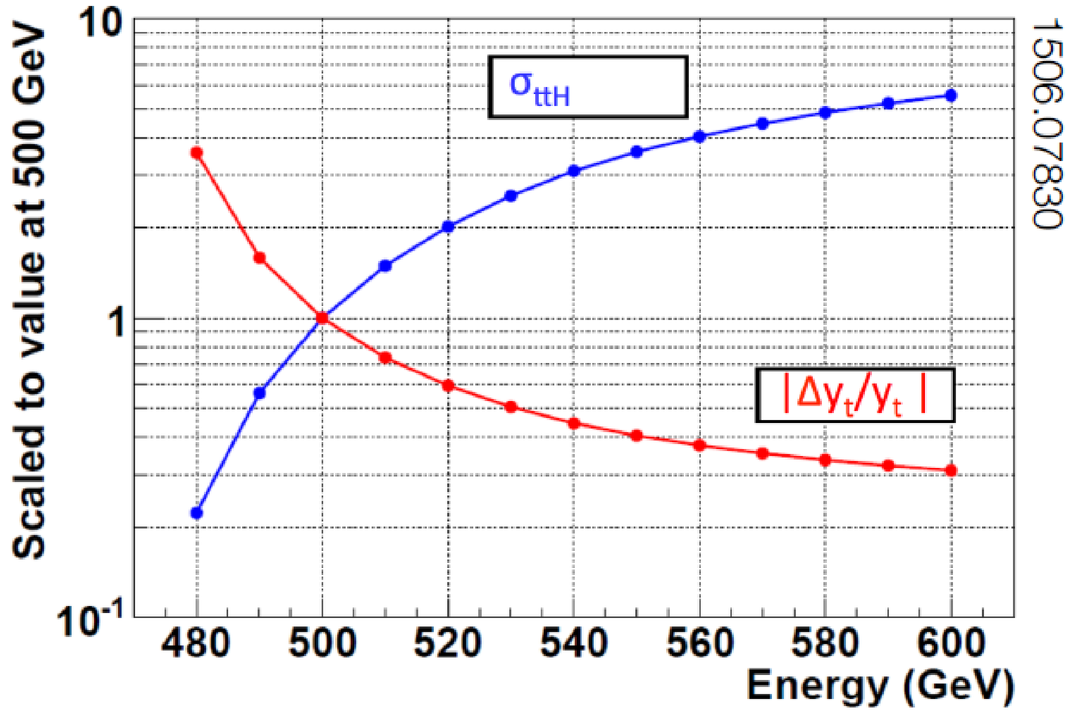


e+e- scans around the top threshold yield excellent mass/width precision

- HL-LHC: 200 MeV, FCC-ee: 6 MeV, Linear collider: 20-40 MeV

Top physics at threshold and beyond

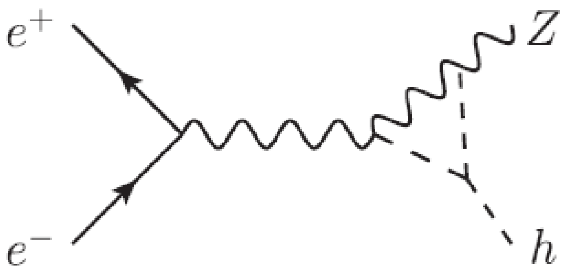
- Top Yukawa
  - At lepton colliders, ttH production opens at energies above 480 GeV
  - At hadron machines, ratios like ttH and ttZ cancel theory uncertainties, assumes ttZ coupling known to 1% from FCCee (top run)
- LHeC: can provide a series of top precision measurements, i.e. Wtb coupling



- Electron/positron collider: stats limited. Implies small selection and reconstruction biases, small background uncertainties, etc. Selection efficiency close to 10%
- More fundamental advancements in theory techniques and tools needed

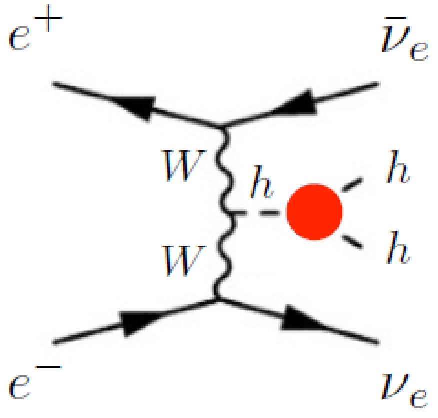
Probing Higgs Self Coupling

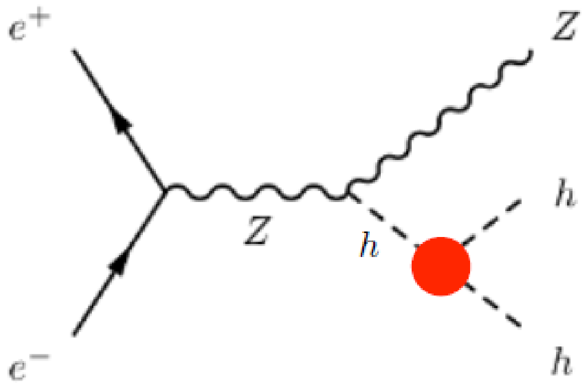
Below Higgs pair threshold
via single Higgs



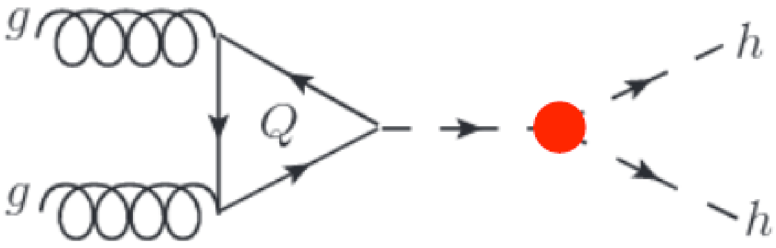
FCCee, LC at 250 GeV

Above Higgs pair threshold via HH





LC at 550 GeV+



HL-LHC, FCChh

Higgs Self Coupling: electron-positron colliders

Uncertainty on λ at the SM value	HL-LHC: 27% FCCee+HL-LHC: ~15% LC (at 550 GeV): 11-18%

Challenges below threshold

- Size of the modification goes like

$$\sigma_{ZH}^{\rm NLO} \approx \sigma_{ZH}^{\rm NLO,SM}(1 + 0.014\,\delta\kappa_3)$$

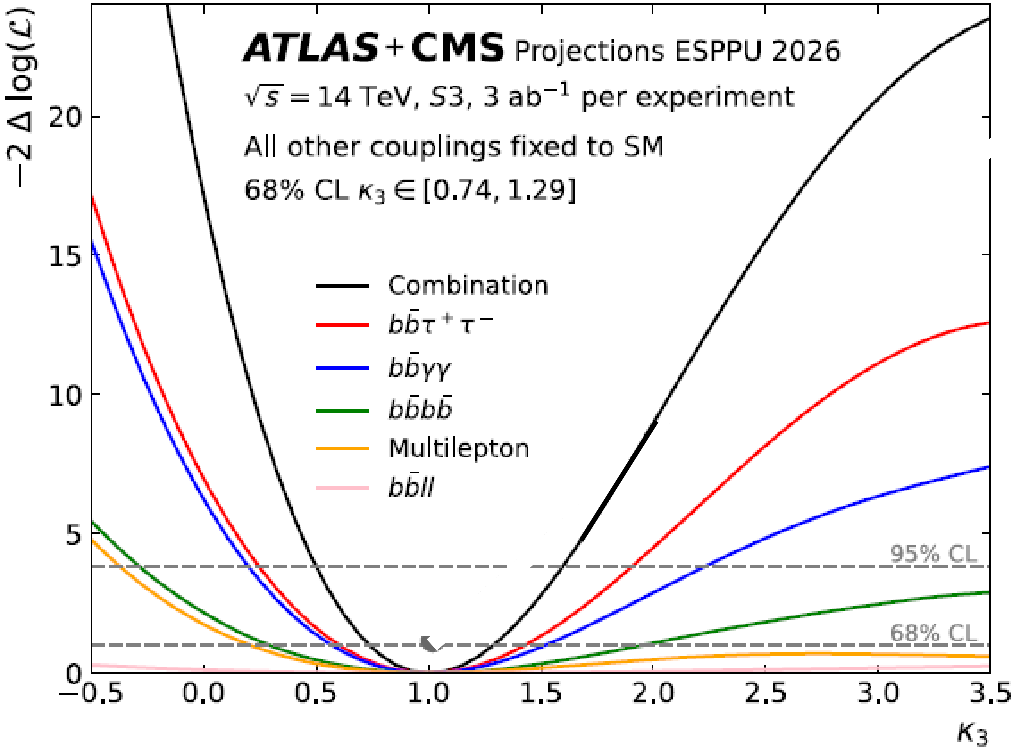
- To be competitive, ZH cross section needs to be measured with an accuracy below 1%
- Need to disentangle deviations from other possible contributions. Different center-of-mass energies helps

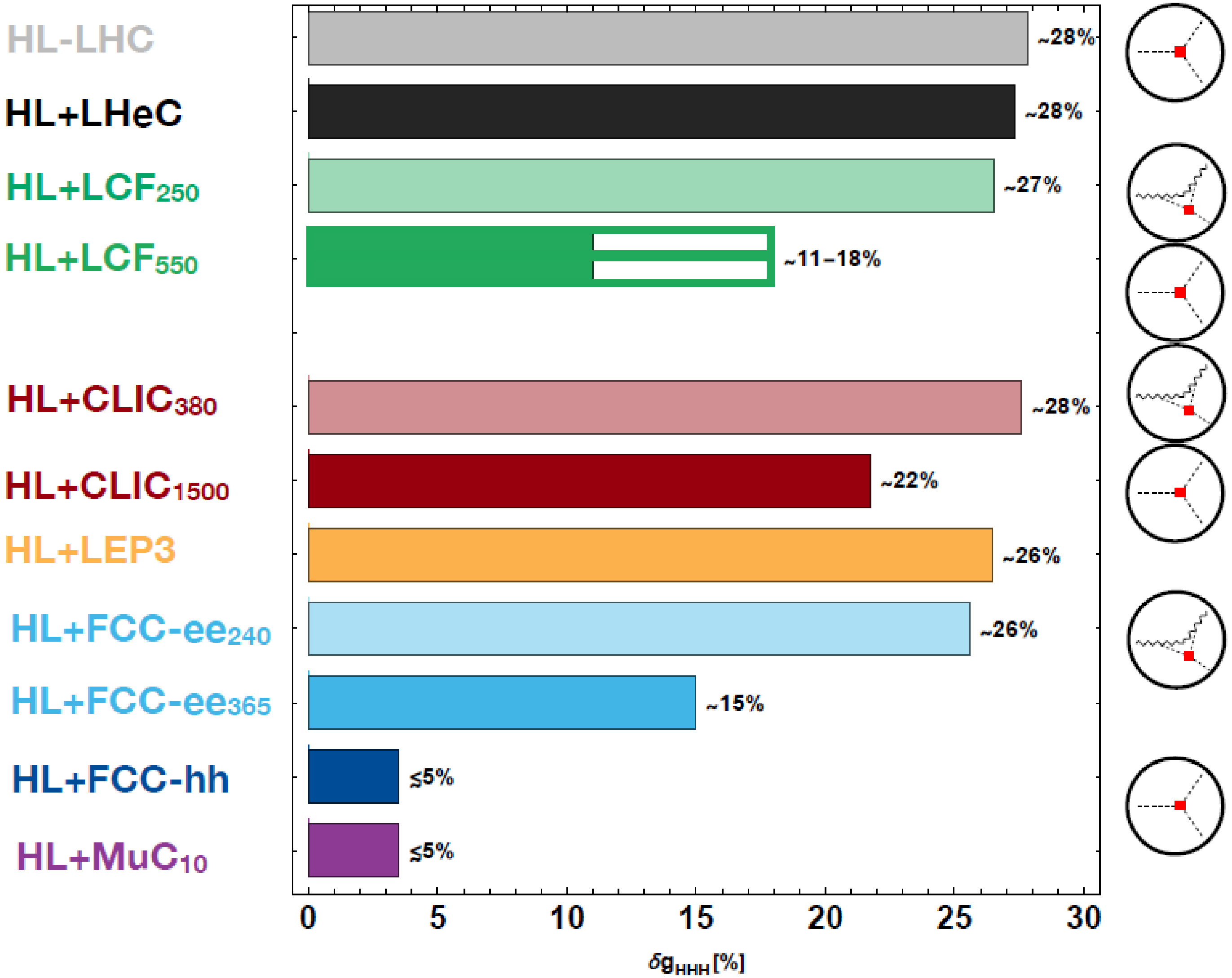
Challenges above threshold

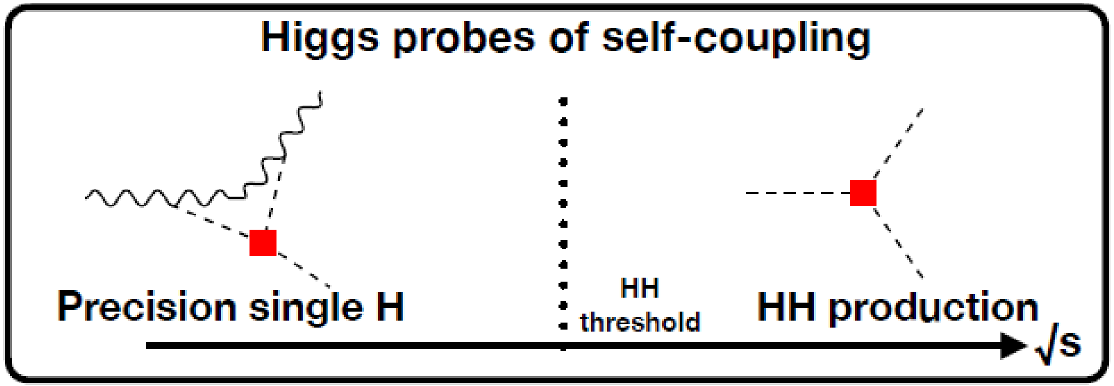
- Major challenges are jet assignment, jet energy resolution and flavour tagging
- HH total production xsec sensitive to BSM besides the triple coupling. More observables are needed to disentangle
- Expected uncertainty on σ(ννHH) ≈ 22 % CLIC 1.5 TeV. Note: these have not been updated to include modern taggers, etc.

The Higgs self-coupling at Future Colliders

On the Higgs self-coupling (Higgs potential)







EW Precision measurements: electron-positron colliders

- At Z-pole
  - Z mass, width, alpha (circular only), sigma_had
  - Leptonic/hadronic asymmetries
  - Partial widths and universality tests
- At WW threshold or above:
  - W mass, width, branching ratios

Left-right asymmetry for LCs (beam polarisation)

$$A_{LR} = \frac{1}{P_{\text{eff}}} \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \approx \mathcal{A}_e$$

- Direct sensitivity to Zee chiral coupling asymmetry. Chiral observables (asymmetries) are measured better at LCs by P/A_e ~ 6 for a given luminosity
- Polarisation via tau decays can also be used by both

Available to circular and linear

$$A_{FB}^f = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

Dominant uncertainties

- For the most part, systematics dominated
- Most of the systematics are limited by the statistics of the calibrations samples
  - i.e. sample size used to determine the luminosity
- More fundamental advancements in theory techniques and tools needed

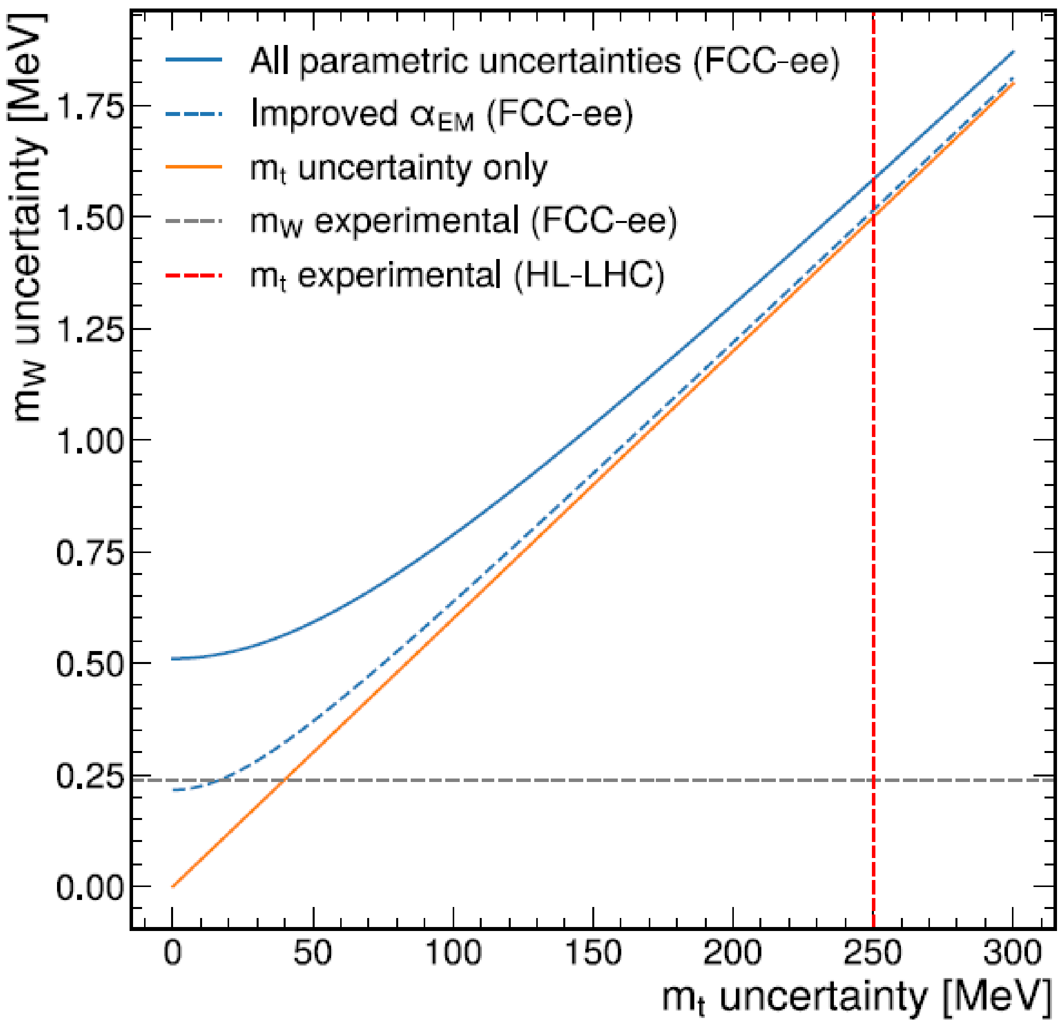
Observable	present value	±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate
R_ℓ^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
σ_{had}^0 ($\times 10^3$) (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement
N_ν($\times 10^3$)	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
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics
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_ν ($\times 10^3$)	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
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.015**	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
ttZ couplings		±	30%	**0.5–1.5 %**	small	From $\sqrt{s} = 365$ GeV run

The W mass (and the Top mass)

- W mass analysis methodology varies depending on the data sample

HL-LHC: 3-5 MeV
FCC-ee: 0.2 MeV
Linear collider: 1.5 MeV
LEP3: 1 MeV
LHeC+HL-LHC: 2-3 MeV

Defranchis, de Blas, Mehta, Selvaggi, Vos
https://arxiv.org/pdf/2503.18713

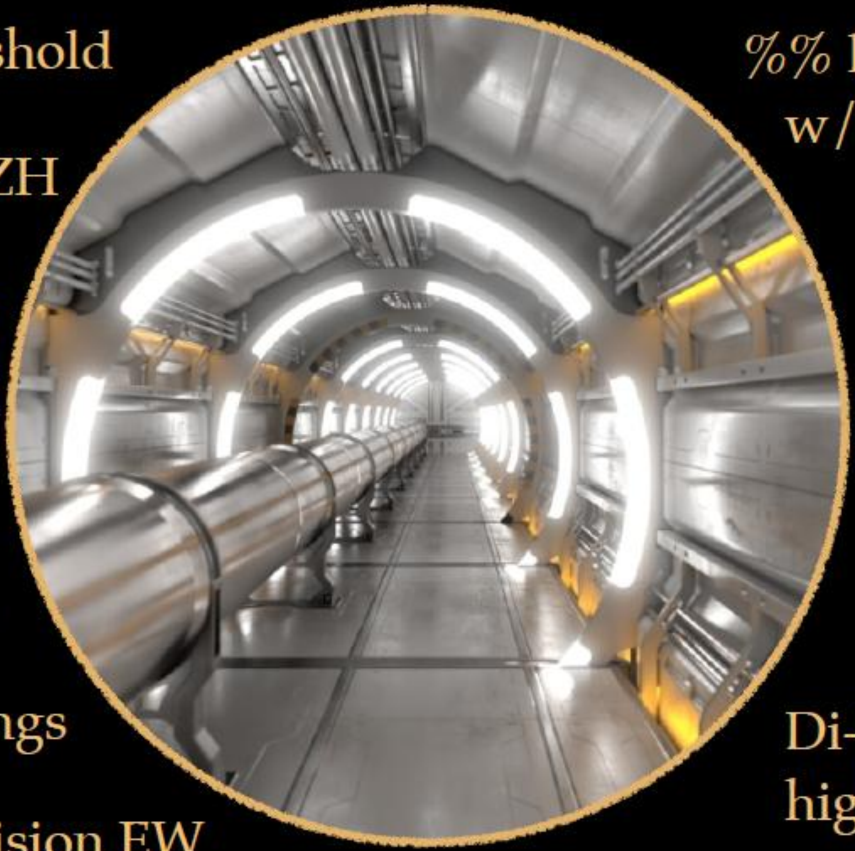


FCC came out clearly as the main option

FCCee

FCChh

High luminosity



Energies up to top threshold

Easy transition between Z, WW, ZH

% to %% level precision on Higgs couplings (except top), stats limited

Best precision on Higgs couplings of all e+e- options

Possible 1st generation couplings

TeraZ run for precision EW

%% level precision on Higgs w/FCCee, ttH production

% level precision on Higgs self-coupling

Access to rare decays and high pT distributions with strong BSM potential

Di-boson measurements at high energy

Combined precision top results

What would be option B ? If A could not be financed?
If CEPC would be built rapidly?

LC 250 GeV, CLIC 380 GeV

- x4 ZH (x1000 Z-pole) less luminosity
- "only" two detectors
- Polarisation enhances sensitivity in some channels
- Less precision on Higgs couplings
- Less precision on EW observables
- No access to top, OK with CLIC 380 GeV
- No reach to 1st generation couplings

+ LC 550 GeV and 1+ TeV

- Di-boson measurements at high energy
- Access to direct HH and ttH production
- Excellent top program with large energy span and polarisation
- No hadron option

LHeC

- Improved PDFs and strong coupling
- Excellent Higgs coupling on Hcc, Hbb, HWW
- Interesting top physics (i.e. via single top production)
- Competitive near-term W mass determination
- No clear following projects

LEP 3

- x4 less luminosity compared to FCCee
- Short-term energy changes w/reduced lumi
- Precision Higgs couplings, worse w.r.t. FCCee
- Systematics increase for EW measurements
- No high energy run
- Impacts Higgs width via lack of VBF H
- No top program

FCChh - direct

- Large luminosities and energy reach
- Excellent self-coupling sensitivity
- Excellent sensitivity to low BR Higgs couplings, if…
- Sensitivity to top operators, differential distributions
- Search for di-bosons, large BSM potential
- Reduced or no e+e- could affect Higgs results
- More studies needed to compare its full sensitivity