Electroweak Precision Physics at the FCC-ee

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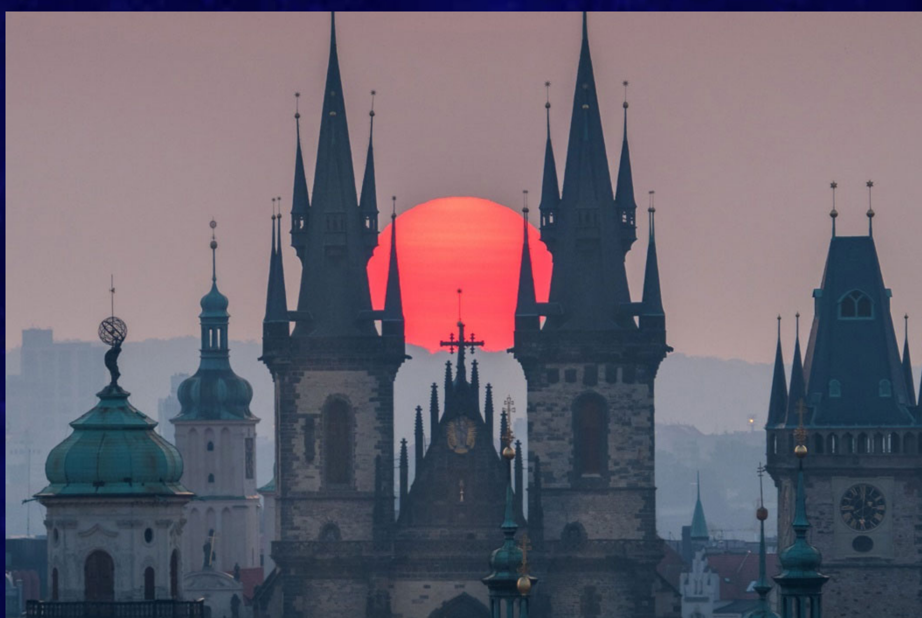
1. FCC project in a nutshell

2. FCC-ee Electroweak Physics Programme



See also the following FCC talks:

515 - „Flavour and tau physics at FCC-ee"
Aidan Wiederhold

504 - „High precision QCD physics at FCC-ee"
Stefan Kluth

489 – „ Higgs physics opportunities at the FCC"
Giovanni Marchiori

494 – BSM physics and Heavy Neutral Lepton searches at FCC-ee
Nicolo Valle

Future Circular Collider Project

FUTURE CIRCULAR COLLIDER

FCC - global international collaboration hosted at CERN

- ✓ **0th stage:** construction of ~91 km circumference tunnel infrastructure in Geveva area to host:
- ✓ **1st stage – FCC-ee: electron positron collisions (90-360) GeV**
- ✓ **2nd stage – FCC-hh: proton-proton collisions at ~100 TeV**
- ✓ **Options of AA and eh also envisioned**

fcc.web.cern.ch

fcc-cdr.web.cern.ch

FCC Feasibility Study mid-term review
https://cds.cern.ch/record/2887250

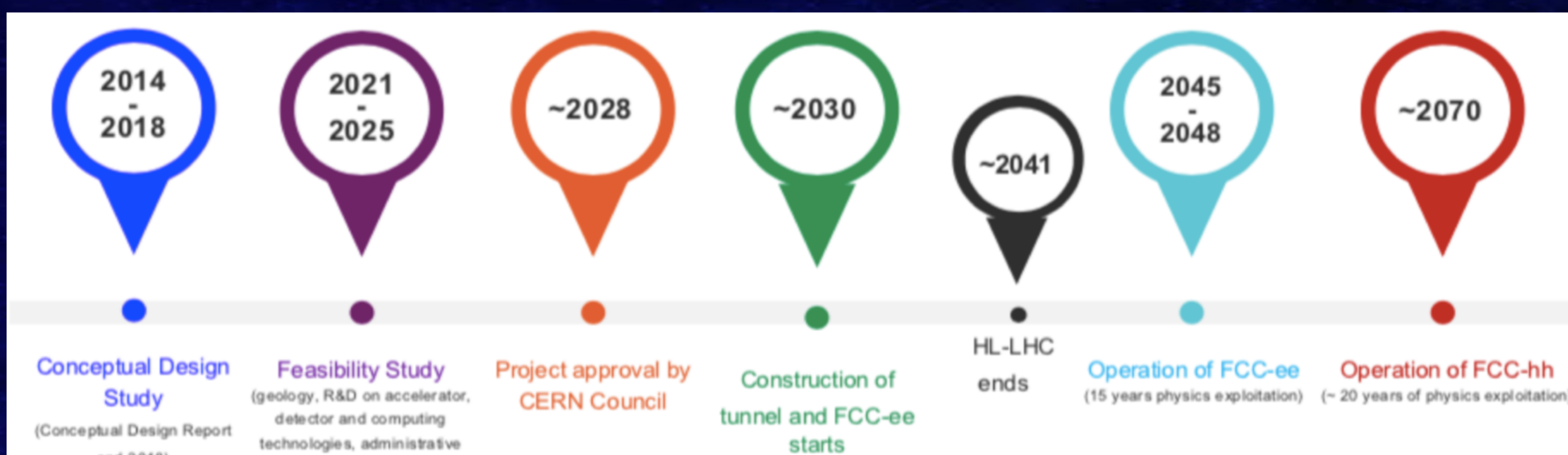
141 Institutes

32 Countries +CERN

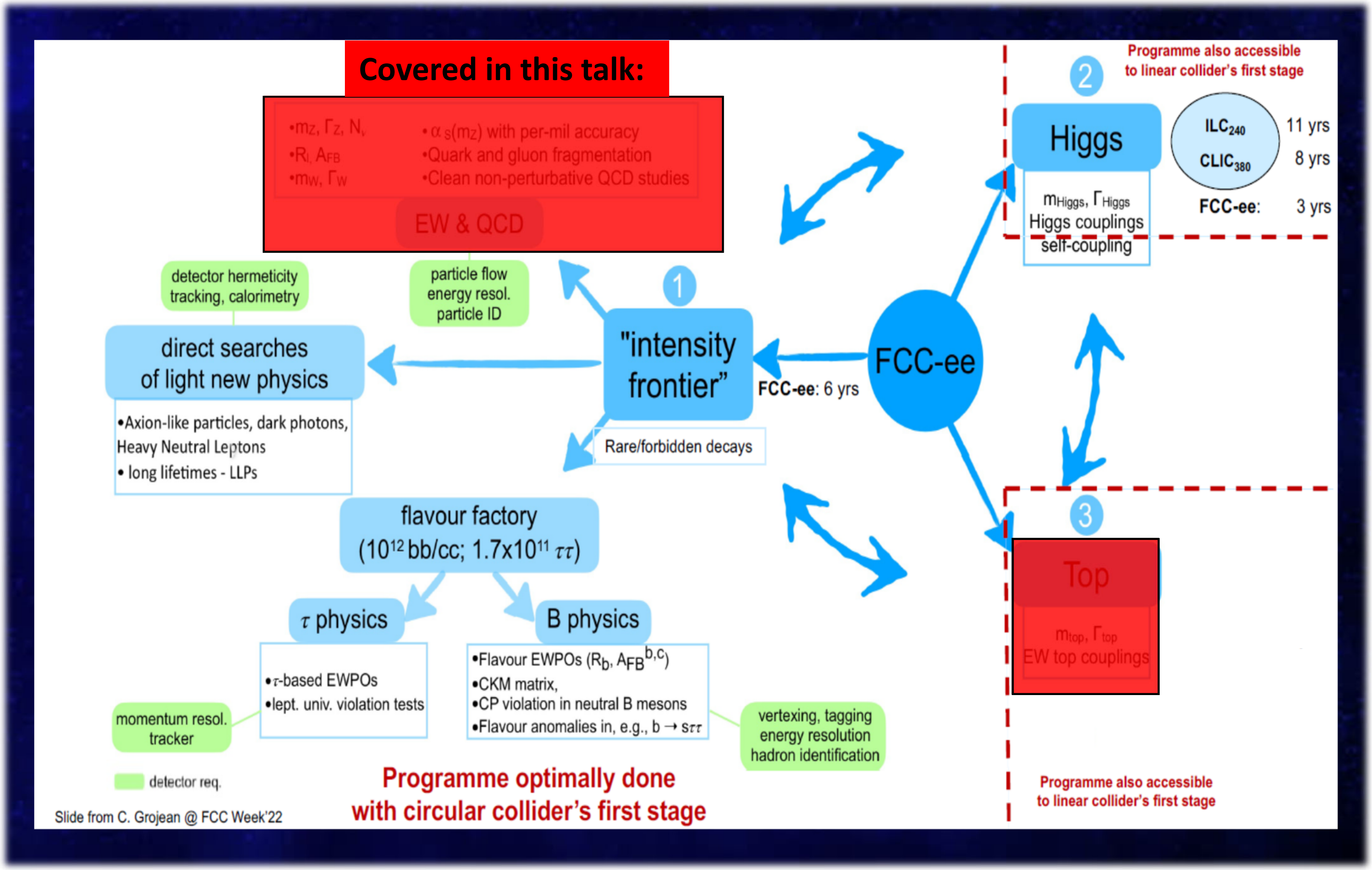
FCC Feasibility Study

EC H2020

Timeline

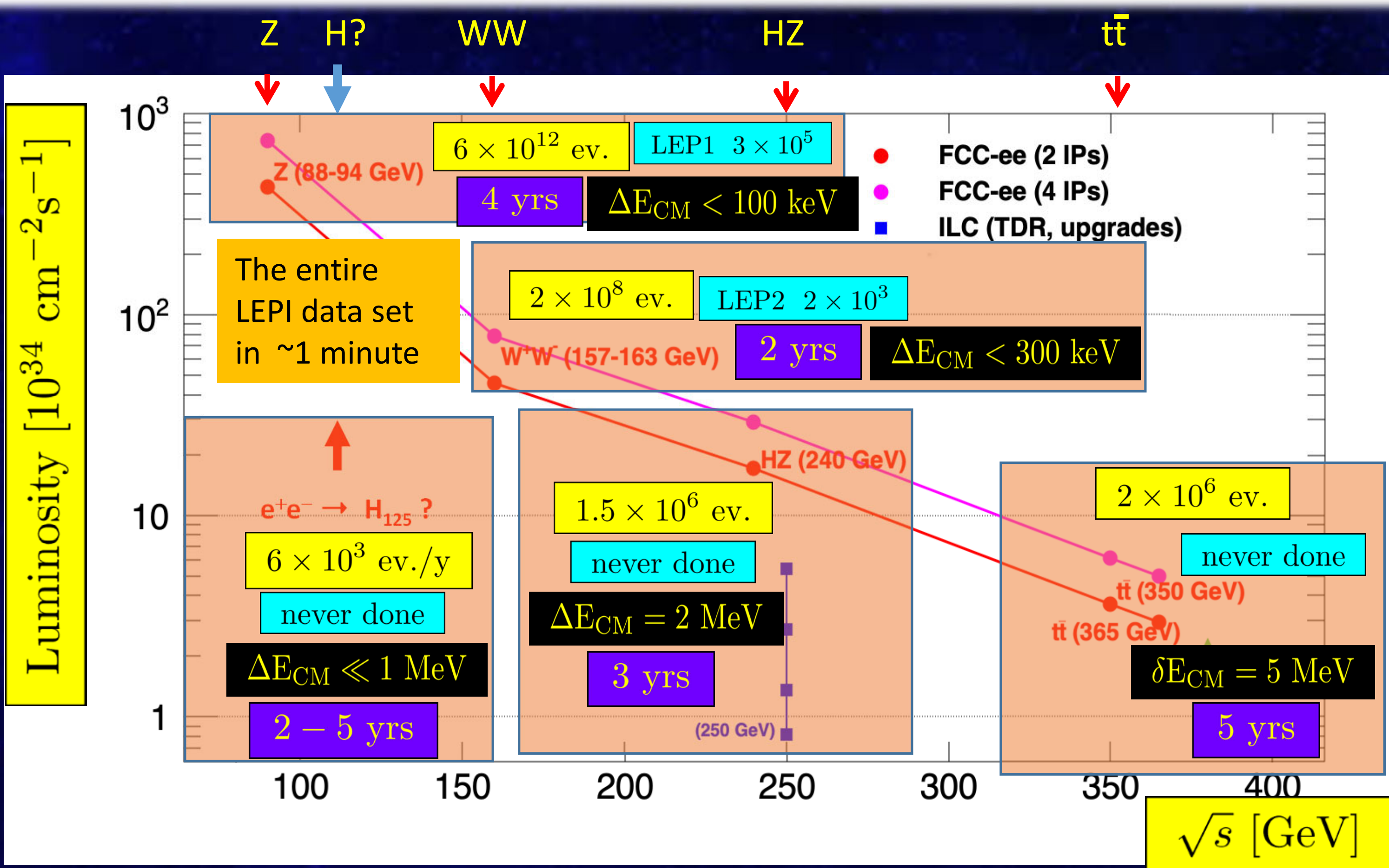


FCC-ee Physics Program



FCC-ee Working Points

FUTURE CIRCULAR COLLIDER



EW observables:

$m_Z,\ \Gamma_Z$

$N_\nu,\ \Gamma_{inv}$

$R_l,\ R_b,\ R_c$

$A^e_{FB},\ A^\mu_{FB}$

$A^b_{FB},\ A^c_{FB}$

$A^\tau_{FB},\ P_\tau$

$\sin^2\theta_W$

$\alpha_{QED}(m_Z^2)$

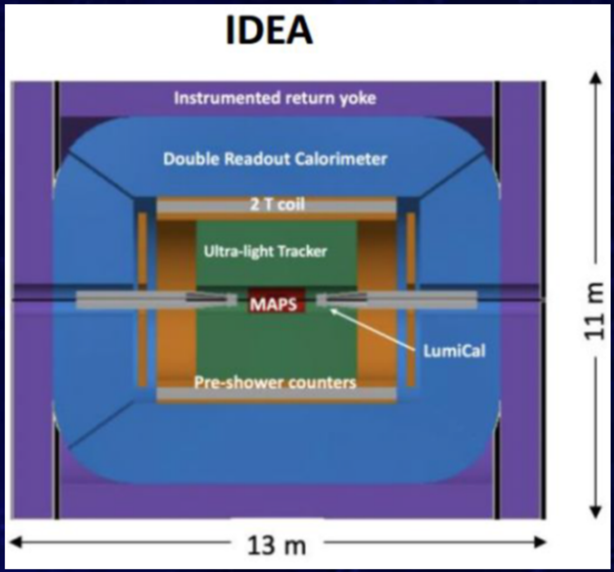
$m_W,\ \Gamma_W$

$m_t,\ \Gamma_t$

- **Optimal energy range for SM particles!**
- **HZ and ttbar thresholds never investigated at leptonic colliders !**
- **Circular colliders can serve up to 4 IPs → increase discovery potential and the community, better accelerator monitoring, robustness of systematic uncertainties, detector diversity, sustainability…**

FCC-ee Detectors

- **Detector design based on experience from LEP/ILC/CLIC/LHC & generic detector R&D , with the following requirements**
  - Matching systematic errors to the very small statistical uncertainties expected at the FCC-ee
  - Ability to withstand a large dynamic range in luminosity and energy
  - Si SVT: low material budget, cooling, MDI constraints (last focusing quadrupole +-2.2m from IP)
  - Tracker (Si, drift chamber, TPC): low material budget
  - Calorimeters: high granularity and identification capabilities (Particle Flow Algorithm PFA), power consumption, cooling
  - PID: dE/dx- gaseous detectors, compact RICH detectors
  - Hermeticity (forward region)
  - Precise luminosity detectors
  - Specific to the Z pole run: large collisions rates (~33 MHz), large event rates (~100 kHz), beamstrahlung
  - Cost: 300-400 MEUR
  - Three concepts: CLD, IDEA, ALLEGRO

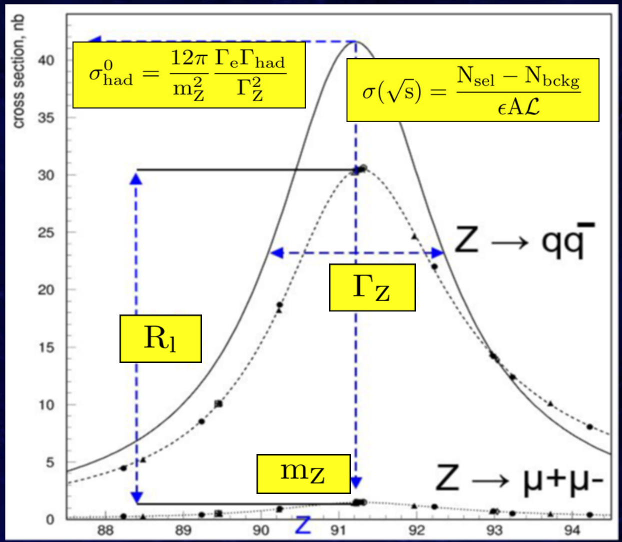


Junjie Zhu talk at the FCC weak (San Francisco, June 2024):
https://indico.cern.ch/event/1298458/contributions/5975666/attachments/2874286/5033190/DetectorRequirements_Zhu.pdf

The Z Lineshape Measurements

LEP $N_Z = 2 \times 10^7$ → FCC-ee $N_Z \sim 6 \times 10^{12}$ → extreme statistical precision of EW observables

- **Z mass and width (from Z pole scan):**
  - **The crucial factor limiting factor: uncertainty on the collision energy:** continuous E_{CM} calibration (resonant depolarization of the transversely polarized beams)
  - **Experimental (big) challenge:** match the detector capabilities to the statistical power
  - **Theoretical challenges:** improved precision on predictions used for lumi measurement, deconvolution of QED effects; EW/QCD corrections



Δ[keV]	LEP	FCC – ee		
		Total	stat	syst
Z mass	2100	100	10	100
Z width	2300	25	4	25

100 ab^{-1} at sqrt(s) = 91.2 GeV
50 ab^{-1} at sqrt(s) = 87.9 GeV, 50 ab^{-1} at 94.3 GeV

- **Normalized partial widths:** $R_q = \frac{\Gamma_{q\bar{q}}}{\Gamma_{\rm had}},\ q = b, c$ $\quad R_l = \frac{\Gamma_{\rm had}}{\Gamma_{l\bar{l}}},\ l = e, \mu, \tau$

$\Gamma_{f\bar{f}} \propto (g_V^f)^2 + (g_A^f)^2 \quad f = l,\ q$

$\times 10^{-6}$	PDG (LEP) rel. precision	FCC – ee Total	stat	syst
R_e	2400	10	3.6	10
R_μ	1600	10	2.6	10
R_τ	2200	10	3.1	10
R_b	3100	300	1.4	300
R_c	17000	1500	150	1500

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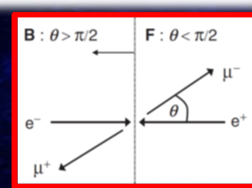
necessary input for a precise measurement of EW couplings (next slides)

and $\alpha_S(m^2_Z)$ (from hadronic Z decays). FCC-ee precision: $\Delta_{\rm rel}\alpha_S(m_Z^2) = (0.1 - 0.2)\%$ LEP: 2.5%

Electroweak Physics at the Z pole

- **Z asymmetries:** $$\frac{d\sigma_{f\bar{f}}}{d\cos\theta} = \frac{3}{8}\sigma^{\rm tot}_{f\bar{f}}\left[(1-\mathcal{P}_e\mathcal{A}_e)(1+\cos^2\theta)+2(\mathcal{A}_e-\mathcal{P}_e)\mathcal{A}_f\cos\theta\right]$$

$\mathcal{P}_e$ – longitudinal polar. of the initial state e^-



The forward-backward asymmetry: $$A^f_{FB} = \frac{\sigma_F-\sigma_B}{\sigma_F+\sigma_B} = \frac{3}{4}\mathcal{A}_f\frac{\mathcal{A}_e+\mathcal{P}_e}{1+\mathcal{P}_e\mathcal{A}_e}$$

The left-right asymmetry: $$A^f_{LR} = \frac{\sigma_L-\sigma_R}{\sigma_L+\sigma_R} = \mathcal{P}_e\mathcal{A}_e \qquad \mathcal{A}_f = \frac{2g^f_V g^f_A}{(g^f_V)^2+(g^f_A)^2}$$

Δ	PDG	FCC – ee $(\times 10^3)$ Total	stat	syst
A^e_{FB}	2.5	0.020	0.007	0.020
A^μ_{FB}	1.3	0.032	0.023	0.022
A^c_{FB}	3.5	0.250	0.200	0.150
A^b_{FB}	1.6	0.210	0.024	0.210

LEP & SLC: longstanding tensions between different asymmetry measurements; uncertainties dominated by statistics

tau lepton case: the final state helicity can be measured $$\mathcal{P}_\tau(\cos\theta) = \frac{d(\sigma_r-\sigma_l)}{d\cos\theta}\cdot\left(\frac{d(\sigma_r+\sigma_l)}{d\cos\theta}\right)^{-1}$$

Experimentally accessible observables:

$$A^\tau_{FB} = \frac{(\sigma_r-\sigma_l)_F-(\sigma_r-\sigma_l)_B}{(\sigma_r+\sigma_l)_F+(\sigma_r+\sigma_l)_B} \qquad A^\tau_{FB} = -\frac{3}{4}\mathcal{A}_e$$

$$\mathcal{P}_\tau(\cos\theta) = \frac{\mathcal{A}_\tau(1+\cos^2\theta)+2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta)+\mathcal{A}_e\mathcal{A}_\tau\cos\theta} \qquad \langle\mathcal{P}_\tau\rangle = -\mathcal{A}_\tau$$

Δ	LEP	FCC – ee $(\times 10^3)$ Total	stat	syst
$< P^\tau >$	1.3	0.20	0.005	0.20
A^τ_{FB}	4.9	0.020	0.015	0.20

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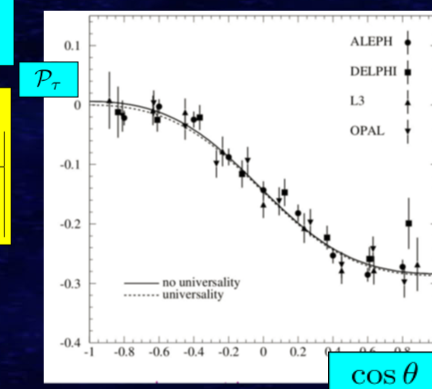

$\mathcal{A}_f$ **measured (f = e, μ, τ, b, c)** → $g_V^f\ g_A^f$ extracted → $$\sin^2\theta^f_{\rm W,eff} = \frac{1}{4}\left(1-\frac{g^f_V}{g^f_A}\right)$$

→ $\sin^2\theta_{\rm W,eff}$

$\Delta\sin^2\theta^f_{W,{\rm eff}}(\times 10^6)$	current	total	stat	syst
from muon FB	160	3.1	2.0	2.4

(absolute) uncertainties)

Task: further reduction of the systematic uncertainty

The Z Invisible Width – Number of Light Neutrino Species

1) N_ν determined at LEP1 from the Z line-shape scan:

$$N_\nu = 2.996 \pm 0.007$$

$$N_\nu \cdot \Gamma_\nu = \Gamma_Z - \Gamma_h - 3\Gamma_l$$

$$N_\nu = \left(\frac{\Gamma_l}{\Gamma_\nu}\right)_{\rm SM} \cdot \left(\sqrt{\frac{12\pi R_l}{M_Z^2 \sigma^0_{\rm had}}} - R_l - 3\right)$$

theory

all measured at the peak

Only small room for improvements:
limited mainly by precision in the measurement of the the luminosity
Theory: (more precise) evaluation of the small angle Bhabha cross section
(LEP1: $\Delta L/L = 0.00061$, $\Delta N_\nu^{\rm lumi} = 0.0046$ ➔ $\Delta N_\nu^{\rm lumi} = 0.001$ @FCC-ee).

room for improvement

$$\Delta N_\nu^{\rm FCC-ee} = 0.00005({\rm stat}) \pm 0.001({\rm syst})$$

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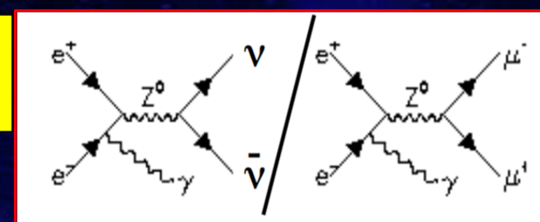
2) N_ν from the radiative return process $e^+e^- \to Z\gamma,\quad Z \to \nu\bar{\nu}$

from the higher masses than the Z resonance e.g. at the WW

Monophoton events (normalized to photon-lepton-lepton events):

$$N_\nu = \left(\frac{e^+e^- \to \gamma Z_{\rm inv}}{e^+e^- \to \gamma Z_{\rm lept}}\right)^{\rm meas} / \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{\rm lept}}\right)^{\rm SM}$$



- LEP1: $N_\nu = 2.92 \pm 0.05$ (statistics too scarse).

- Uncertainties associated with absolute luminosity cancel
- Photon selection common for both final states ➔ cancellations of systematics.

- N_ν can be measured vs sqrt(s) ➔ sensitivity to NP at high energy scales.

- FCC-ee sensitivity: $\Delta N_\nu^{\rm FCC-ee} = 0.0004$

Measurement of $\alpha_{QED}(m_Z^2)$

➢ $\alpha_{QED}(m_Z^2)$ - better precision necessary for future precision SM tests !

- **Current uncertainty:** $\Delta\alpha_{\rm QED}(m_Z^2) = 10^{-4}$ from running coupling constant formula: $\alpha_{\rm QED}(m_Z^2) = \frac{\alpha_{\rm QED}(0)}{1-\Delta\alpha_l(m_Z^2)-\Delta\alpha^{(5)}_{\rm had}(m_Z^2)}$

dominated by the experimental determination of the hadronic vacuum polarization, obtained from dispersion integral with expt. input from low energies (KLOE, Belle, BaBar, CLEO, BES CMD-2...)

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

- **The $A_{FB}^{\mu\mu}$ - self normalized quantity** $A_{FB}^{\mu\mu} = \frac{\sigma^F_{\mu\mu}-\sigma^B_{\mu\mu}}{\sigma^F_{\mu\mu}+\sigma^B_{\mu\mu}}$

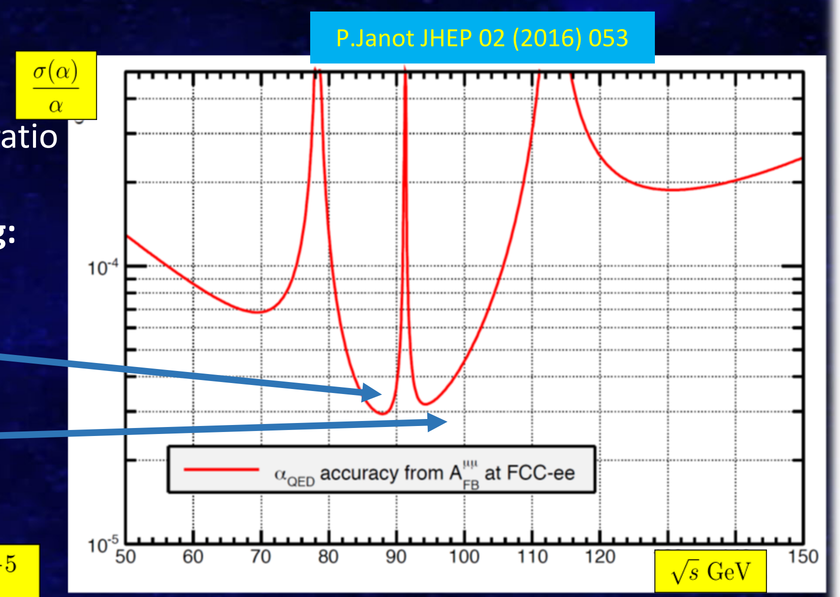
(no need for measurement of L_{int}; most uncertainties (sel. efficiency, det. accceptance) cancel in the ratio

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

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

2x 6 months of FCC-ee running:

Optimal CMS energies: $\sqrt{s_-} = 87.9$ GeV, $\sqrt{s_+} = 94.3$ GeV



$$\frac{1}{\alpha_{\rm QED}(m_Z^2)} = \frac{1}{\alpha_\pm} + \beta_{\rm QED}\log\frac{s_\pm}{m_Z^2}$$

⇨ $\Delta\alpha_{\rm QED}(m_Z^2) = 3\times10^{-5}$

(adequate for future precision EW fits)

WW Pair Production at Threshold

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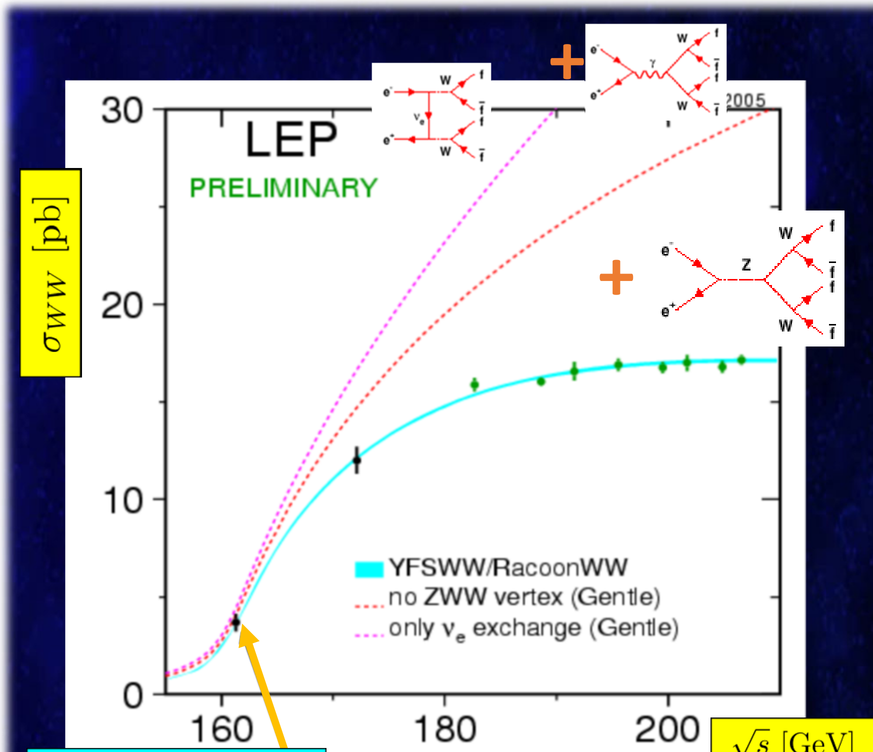

$$\Delta m_W = \left(\frac{d\sigma}{dm_W}\right)^{-1} \Delta\sigma$$

	LEP2 Stat./Prec.	FCC – ee stat (syst)
N_{WW}	4×10^4	2×10^8

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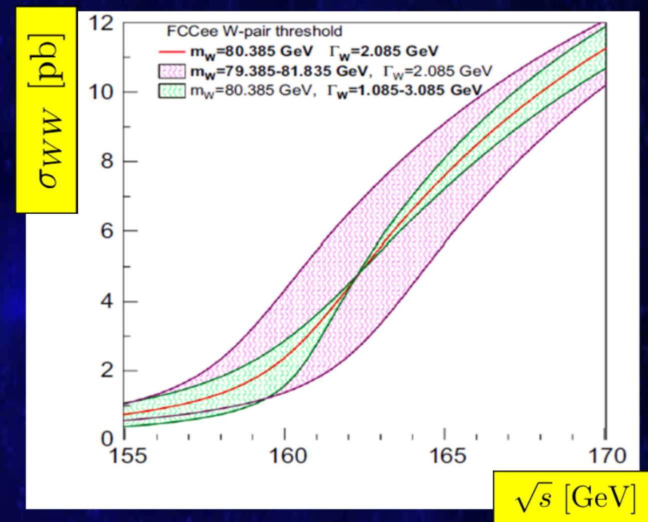
Other W topics:
W branching ratios (lepton universality, lapton-quark universality), TGCs, α_S (m_W^2) …

➢ The W mass and width from σ_{WW}:



- Measure σ_{WW} in two energy points E_1 and E_2, with the fractions of luminosity f and (1-f)
  ➔ evaluation of both m_W and Γ_W
- Choose the parameters E_1, E_2, and f in order to minimize the errors: $\Delta\Gamma_W$ an Δm_W:
  $E_1 = 157.5$ GeV $E_1 = 162.5$ GeV $f = 0.4$ 12 ab^{-1}
  ➔ $\Delta m_W = 0.5$ MeV $\Delta\Gamma_W = 1.2$ MeV
- **Exploiting also a direct reconstruction of the W at threshold:** $\Delta m_W = 0.25$ MeV

$t\bar{t}$ Pair Production at Threshold

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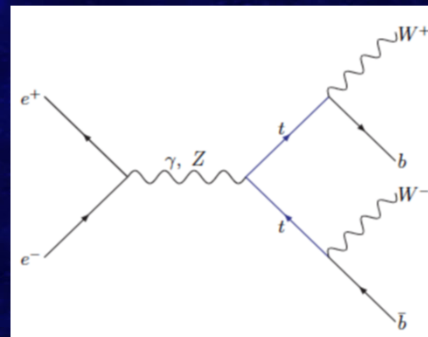
- **Any next e^+e^- collider:**

  for the 1st time the top quark to 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 at the threshold **is computable to high precision and depends on m_t, Γ_t, y_t, α_s (and luminosity** spectrum)

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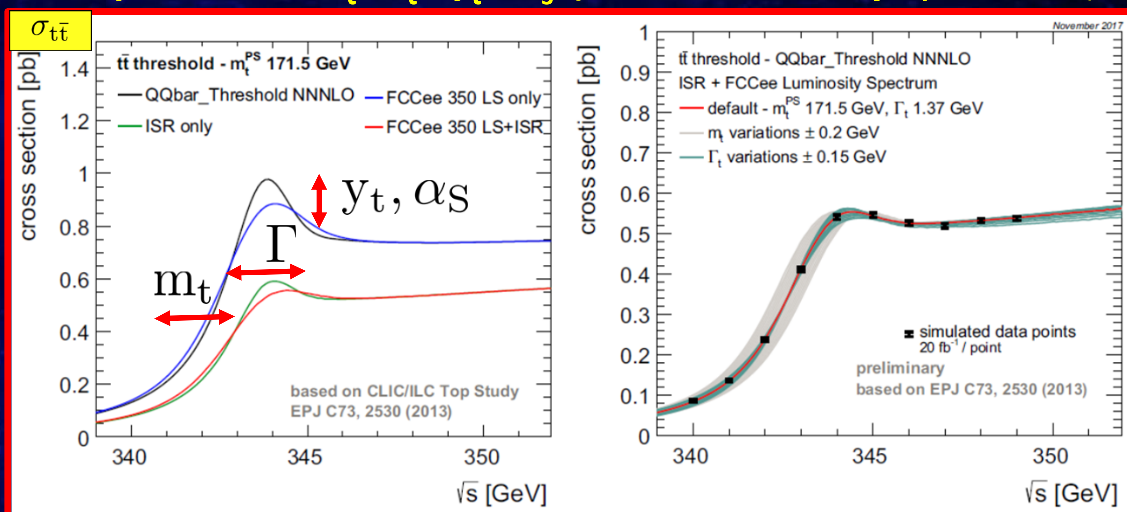
$25\ \mathrm{ab}^{-1}$

$E_1 = 340$ GeV
$E_2 = 341$ GeV
$E_3 = 341.5$ GeV
$E_4 = 342$ GeV
$E_5 = 343$ GeV
$E_6 = 343.5$ GeV
$E_7 = 344$ GeV
$E_8 = 345$ GeV



- **Other top topics:**

  Single top production, top quark FCNC, $e^+e^- \to t\bar{t}\gamma$, top-quark EW couplings …

PDG: $m_t = (172.69 \pm 0.30)$ GeV → FCC-ee

$\Delta m_t = 17$ MeV

$\Delta\Gamma_t = 45$ MeV

Electroweak Observables: Instead of Summary

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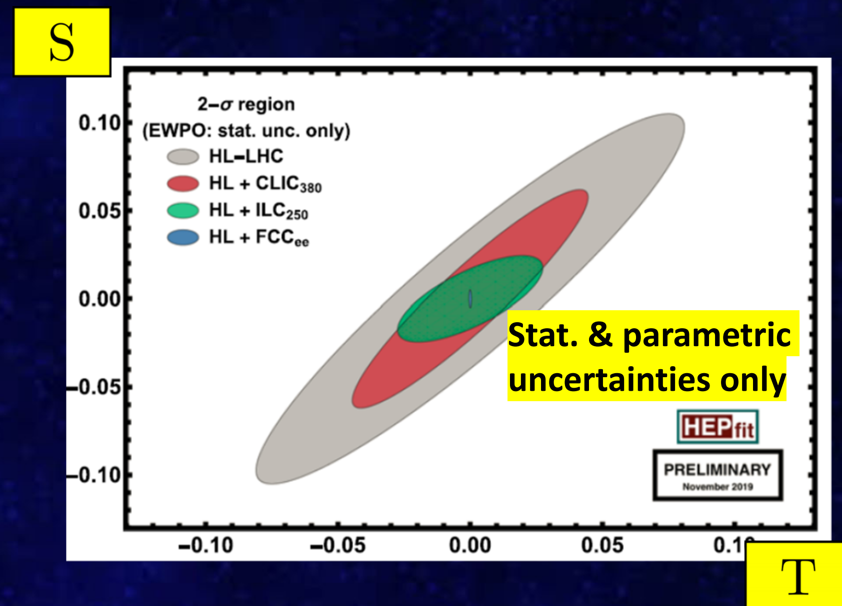
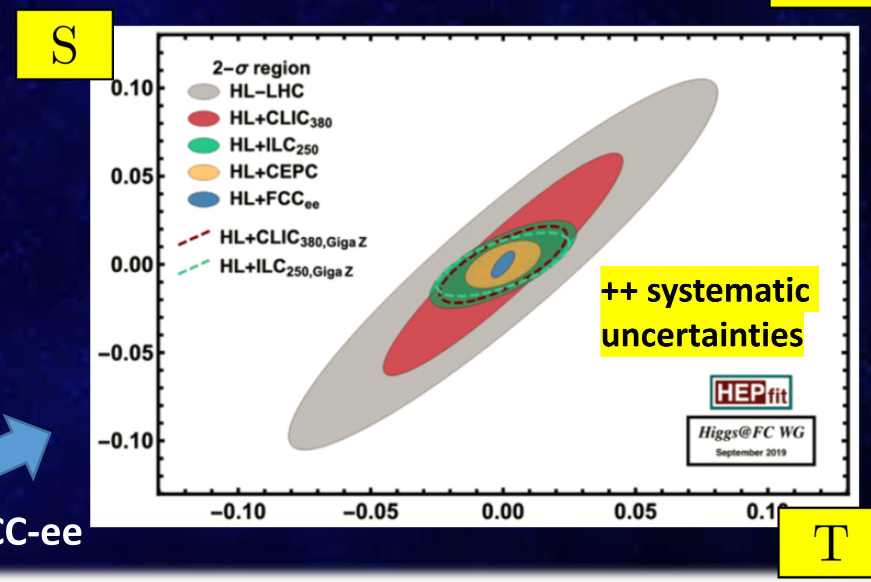
Observable	unit	Present value	± error	FCC-ee (stat.)	FCC-ee (syst.)
m_Z	[keV]	91 186 700	2 200	4	100
Γ_Z	[keV]	2 495 200	2 300	4	25
$\sin^2\theta_W^{\rm eff}$	[$\times10^6$]	231 480	160	2	2.4
$1/\alpha_{\rm QED}(m_Z^2)$	[$\times10^3$]	128 952	14	3	small
R_l^Z	[$\times10^3$]	20 767	25	0.06	0.2-1
$\alpha_S(m_Z^2)$	[$\times10^4$]	1 196	30	0.1	0.4-1.6
$\sigma^0_{\rm had}$	[$\times10^3$ nb]	41 541	37	0.1	4
N_ν	[$\times10^3$]	2 996	7	0.005	1
R_b	[$\times10^6$]	216 290	660	0.3	< 60
$A_{\rm FB}^{b,0}$	[$\times10^4$]	992	16	0.02	1-3
$A_{\rm FB}^{{\rm pol},\tau}$	[$\times10^4$]	1498	49	0.15	< 2
τ lifetime	[fs]	290.3	0.5	0.001	0.04
τ mass	[MeV]	1776.86	0.12	0.004	0.04
τ leptonic BR	[%]	17.38	0.04	0.0001	0.003
m_W	[MeV]	80 350	15	0.25	0.3
Γ_W	[MeV]	2 085	42	1.2	0.3
$\alpha_S(m_W^2)$	[$\times10^4$]	1 170	420	3	small
$m_{\rm top}$	[MeV]	172 740	500	17	small
$\Gamma_{\rm top}$	[MeV]	1 410	190	45	small





Important task and challenge:
matching the systematic and theoretical uncertainties to the statistical power of the FCC-ee

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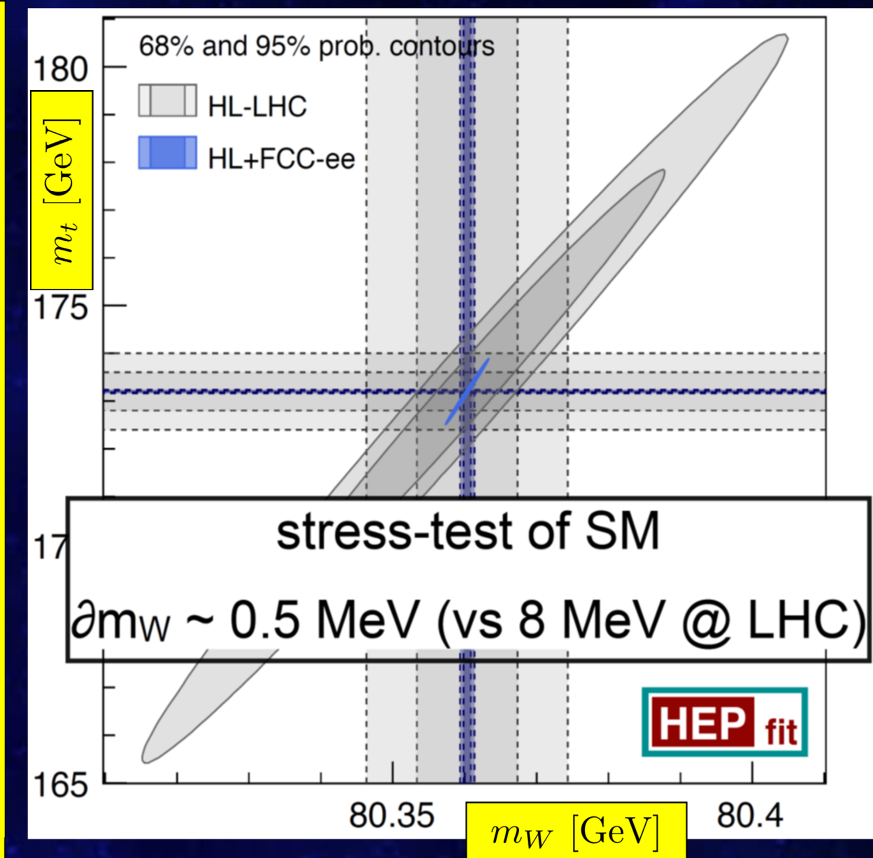

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Summary

- ✓ The FCC project offers a complete, coherent and exciting option for the particle physics for the next decades
- ✓ The process of decision about its appoval is gaining momentum in view of the update of European Strategy for Particle Physics
- ✓ FCC-ee studies of electroweak observables, would provide a qualitative leap in precision tests of the Standard Model, thus opening options for pinpointing new phenomena
- ✓ An extensive preparatory work is needed in order to fully exploit the expected statistical power of data, by optimising detector' designs and improving theoretical precision of observables