Electroweak Physics at FCC-ee

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on behalf of the FCC-ee study group

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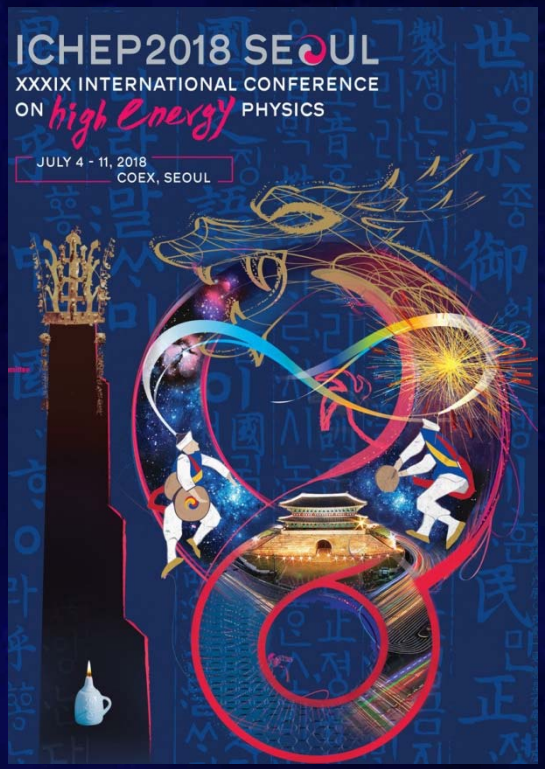


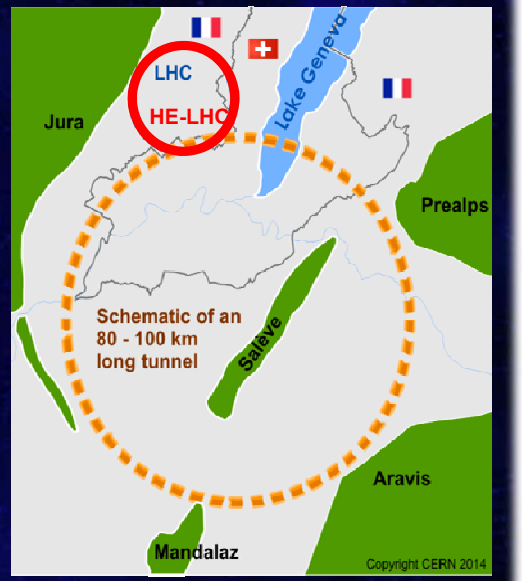
Outline

1. The Future Circular Collider Study
2. FCC-ee Electroweak Studies at the Z Pole
3. WW Physics at FCC-ee

FCC – Future Circular Collider

FCC - international collaboration hosted at CERN, goal: construction of ~100 km circumference tunnel infrastructure in Geveva area to host:

- ✓ **e^--e^+ collider:** FCC-ee – potential first step, preceding the FCC-pp
- ✓ **p-p collider:** FCC-hh – flagship, 100 TeV p-p, 16T magnets
- ✓ **e-p collider:** FCC-he – additional option of e-p collisions; e^- from ERL



fcc.web.cern.ch

- **124 institutes**
- **32 countries**
- **30 industrial partners**
- **EuroCirCol project**
- **EASITrain ITN**

„…the FCC offers a leap into completely uncharted territory, from delivering mind-boggling statistics of ~5 x 10^{12} Z decays (e^+e^-), all the way up to proton-proton collision at an energy of 100 TeV."

„CERN thinks bigger" , CERN Courier Magazine, June 2018

Short term goal: CDR and cost review by the end of 2018

to take part in discussion on European Strategy for Particle Physics 2020

FCC-ee Collider Parameters

- **FCC-ee:** two rings (separate for e^+ and e^-); four interaction points; flat beams with very strong focusing ($\beta^*_y \approx 1$mm); top-up injection, crab waist crossing, non-zero crossing angle

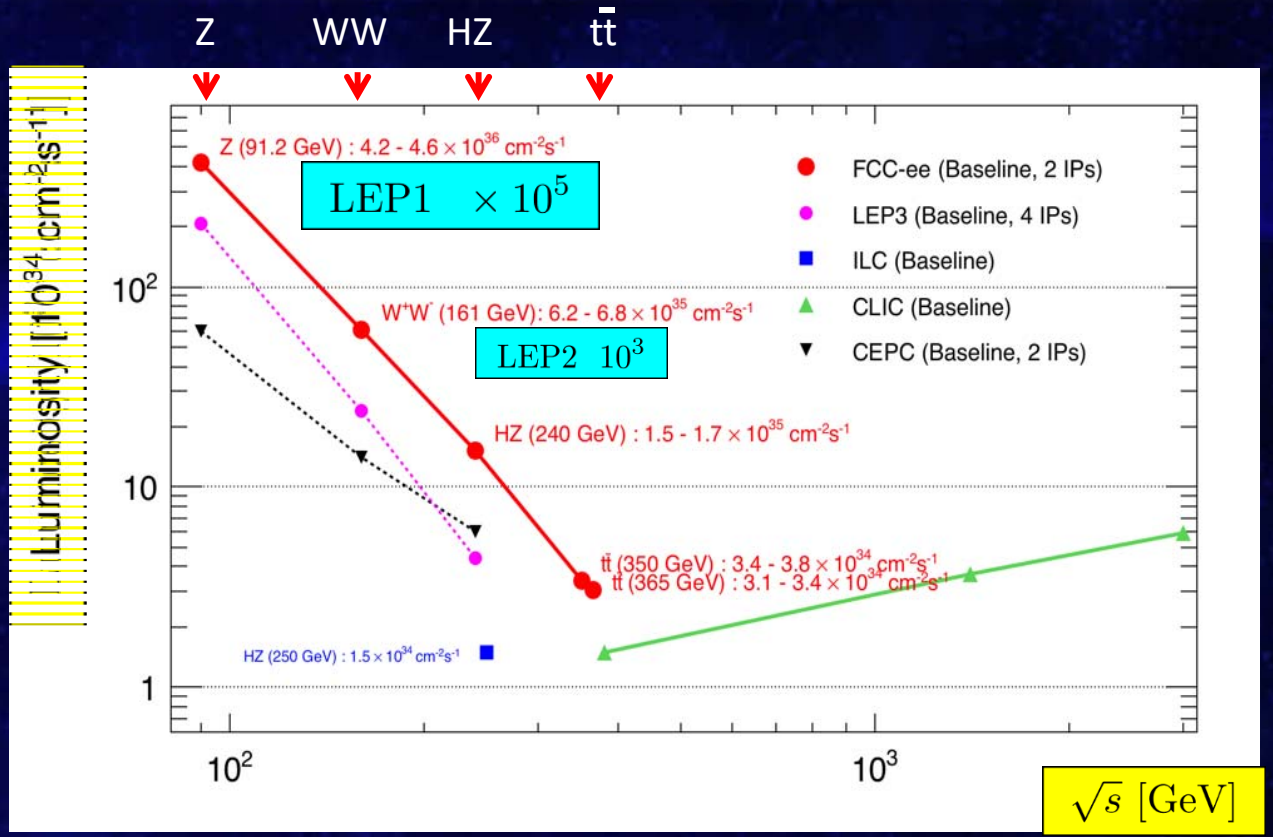
Four working points:

Parameter	$\sqrt{s} = M_Z$	$\sqrt{s} = M(WW)$	$\sqrt{s} = M(ZH)$	$\sqrt{s} = M(t\bar{t})$	LEP2
E_{beam} [GeV]	**45.6**	**80**	**120**	**182.5**	**104.5**
Beam current [mA]	1390	147	29	5.4	4
No. Bunches/beam	16 640	2 000	393	48	4
SR energy loss/turn [GeV]	0.036	0.34	1.72	9.21	3.34
SR power [MW]	100	100	100	100	22
RF Voltage [GV]	0.1	0.44	2.0	10.93	3.5
β^*_x [m]	0.15	0.2	0.3	1	1.5
β^*_y [mm]	0.8	1	1	1.6	50
ε_x [nm]	0.27	0.28	0.63	1.46	19.3
ε_y [pm]	1	1.7	1.3	2.9	230
L (10^{34} cm^{-2}s^{-1})/IP	**>200**	**>25**	**>7**	**>1.4**	**0.012**
Statistics (2expts)	5×10^{12} Z / 6yrs	3×10^{7} WW/2yr	10^6 ZH/5yrs	10^6 $t\bar{t}$ / 5yrs	

LEP1 : 2.1×10^{31} cm^{-2}s^{-1}

LEP2 : 3.6×10^{31} cm^{-2}s^{-1}

FCC-ee Collider Parameters

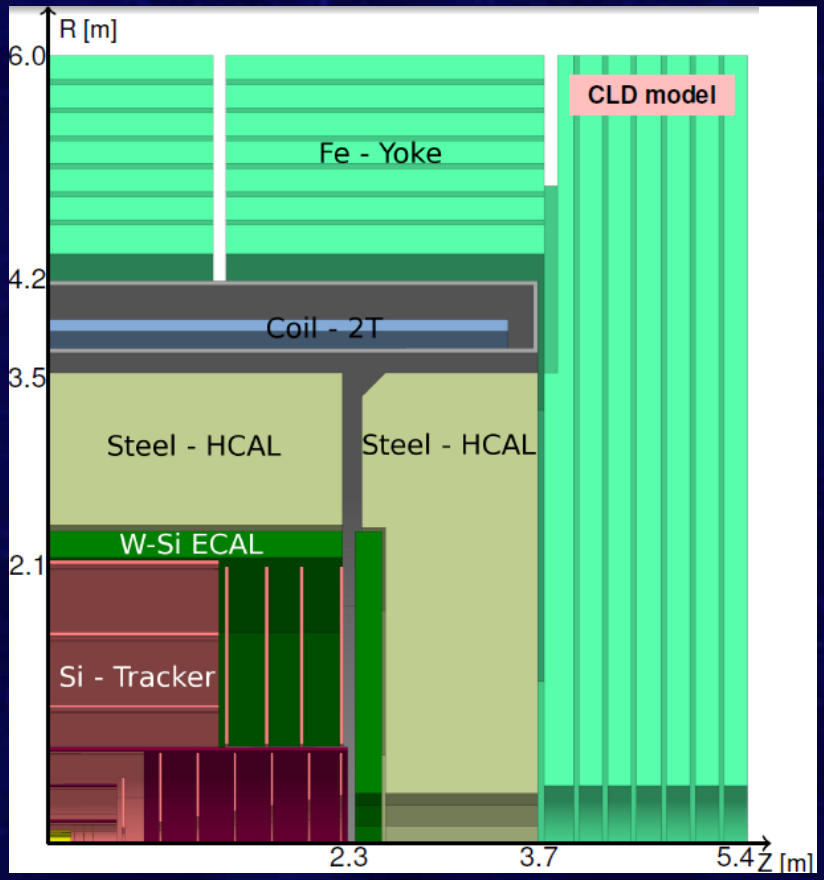


Event statistics :

					E_{CM} errors:
Z peak	**E_{cm} : 91 GeV**	**5 10^{12}**	**e+e- → Z**	**LEP x 10^5**	100 keV
WW threshold	**E_{cm} : 161 GeV**	**3 10^7**	**e+e- → WW**	**LEP x 10^3**	300 keV
ZH threshold	**E_{cm} : 240 GeV**	**10^6**	**e+e- → ZH**	**Never done**	5 MeV
$t\bar{t}$ threshold	**E_{cm} : 350 GeV**	**10^6**	**e+e- → $t\bar{t}$**	**Never done**	10 MeV

FCC-ee Detectors

CLD - **detector model for FCC-ee derived from CLICdp model and optimized for FCC-ee experimental conditions**



- Full silicon tracking system (≥12 hits/track)
- High granularity calorimeters optimized for particle flow reconstruction
- Superconducting coil (2T) located outside the calorimeters
- Steel return yoke containing muon chambers
- Forward region reserved for Machine-Detector Interface and LumiCal
- Tracking fully efficient from 700 MeV
- $\delta p_T \approx 4 \times 10^{-5}$ GeV^{-1} (for muons p=100 GeV)
- $\Delta E/E = (3\text{-}5)\%$ (barrel region)
- efficiency for electrons and gammas > 95%

IDEA - (International Detector Electron Accelerator) under development; drift chamber tracker

Electroweak Physics at the Z pole

LEP $N_Z = 1.7 \times 10^7$ → **FCC-ee** $N_Z \sim 5 \times 10^{12}$ → **Extreme precision of EW observables**

➢ Z mass and width (from Z pole scan):

The crucial factor: continuous E_{CM} calibration (resonant depolarization)

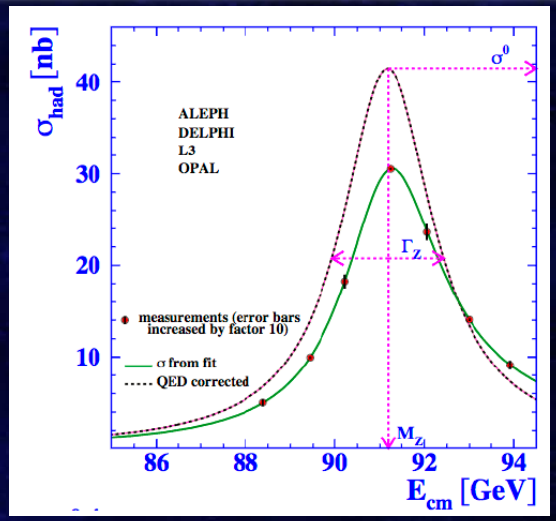
$$\Delta E_{\rm CM} \approx (10\ (\rm stat) + 100\ (\rm syst))\ \rm keV$$

	Δ_{rel} (LEP)	Improvement factor
Z mass	1×10^{-6}	20
Z width	5×10^{-5}	20

$(\sim 300\ (\rm stat)\ \oplus\ \sim 10\ (\rm syst))$

→ $2.1\ \rm MeV \rightarrow 100\ keV$

$2.3\ \rm MeV \rightarrow 100\ keV$



➢ Normalized partial widths:

$$R_l = \frac{\Gamma_{\rm had}}{\Gamma_{l\bar{l}}},\ l = e, \mu, \tau$$

$$R_q = \frac{\Gamma_{q\bar{q}}}{\Gamma_{\rm had}},\ q = b, c$$

$$\Gamma_{f\bar{f}} \propto (g_V^f)^2 + (g_A^f)^2$$

	PDG (LEP) value	PDG (LEP) rel. precision	FCC – ee Improvement factor
R_e	20.804 ± 0.050	2.4×10^{-3}	20
R_μ	20.785 ± 0.033	1.6×10^{-3}	20
R_τ	20.764 ± 0.045	2.2×10^{-3}	20
R_b	0.21629 ± 0.00066	3.1×10^{-3}	10
R_c	0.1721 ± 0.0030	1.7×10^{-2}	10

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

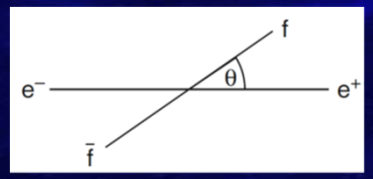
and $\alpha_S(m^2_Z)$ (from hadronic Z decays). FCC-ee precision: $\Delta_{\rm rel}\alpha_S(m_Z^2) = 2 \times 10^{-3}$ LEP: 2.5%

Electroweak Physics at the Z pole

➢ Z asymmetries:

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

$\mathcal{P}_e$ - polarization of the initial state e^-



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

The left-right asymmetry: $A^f_{LR} = \frac{\sigma_L-\sigma_R}{\sigma_L+\sigma_R} = \mathcal{A}_e$

$$\mathcal{A}_f = \frac{2g_V^f g_A^f}{(g_V^f)^2+(g_A^f)^2}$$

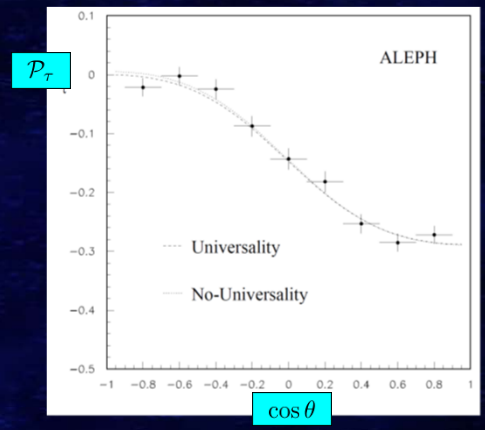
LEP & SLC: longstanding discrepancies between different asymmetry measurements; uncertainties dominated by statistics

tau lepton case:
the final state helicity can be measured

$$\mathcal{P}_\tau(\cos\theta) = \frac{d(\sigma_r-\sigma_l)}{d\cos\theta}\cdot\left(\frac{d(\sigma_r+\sigma_l)}{d\cos\theta}\right)^{-1}$$

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

$$A^\tau_{FB} = \frac{(\sigma_r-\sigma_l)_F-(\sigma_r-\sigma_l)_B}{(\sigma_r+\sigma_l)_F+(\sigma_r+\sigma_l)_B}$$



Experimentally accesible observables: $\langle\mathcal{P}_\tau\rangle = -\mathcal{A}_\tau$ $\quad A^\tau_{FB} = -\frac{3}{4}\mathcal{A}_e$

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

	$\Delta^{\rm stat}_{\rm rel}$ (FCC – ee)	$\Delta^{\rm syst}_{\rm rel}$ (FCC – ee)	Improvement factor w.r.t. LEP
$\mathcal{A}_e$	5.0×10^{-5}	1.0×10^{-4}	50
$\mathcal{A}_\mu$	2.5×10^{-5}	1.5×10^{-4}	30
$\mathcal{A}_\tau$	4.0×10^{-5}	3.0×10^{-4}	15
$\mathcal{A}_b$	2.0×10^{-4}	3.0×10^{-3}	5
$\mathcal{A}_c$	3.0×10^{-4}	8.0×10^{-3}	4

Systematic uncertainties dominate

Precision on vector and axial couplings from R_f and A_f :

Improvement w.r.t. LEP: 10-100

fermion	Δg_V	Δg_A
e	2.5×10^{-4}	1.5×10^{-4}
μ	2.0×10^{-4}	2.5×10^{-5}
τ	3.5×10^{-4}	0.5×10^{-4}
b	1.0×10^{-2}	1.5×10^{-3}
c	1.0×10^{-2}	2.0×10^{-3}

Electroweak Physics at the Z pole

$\sin^2\theta_{W,eff}$ (absolute) uncertainties:

	stat	syst	Improvement w.r.t. LEP
from muon FB	10^{-7}	5.0×10^{-6}	100
from tau pol	10^{-7}	6.6×10^{-6}	75

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

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

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 $\alpha_{QED}(0)$

- **The $A_{FB}^{\mu\mu}$ - self normalized quantity** $A_{FB}^{\mu\mu} = \frac{\sigma_{\mu\mu}^F - \sigma_{\mu\mu}^B}{\sigma_{\mu\mu}^F + \sigma_{\mu\mu}^B}$

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

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

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

2x 6 months of FCC-ee running:

Optimal CMS energies:

$\sqrt{s_-} = 87.9$ GeV

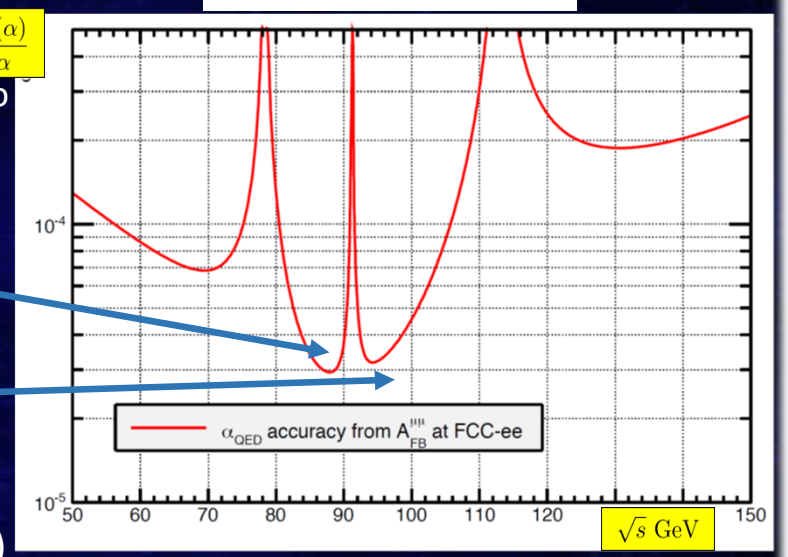
$\sqrt{s_+} = 94.3$ GeV

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

$\Delta\alpha_{QED}(m_Z^2) = 3 \times 10^{-5}$

(adequate for future precision EW fits)

P.Janot JHEP 02 (2016 053



The Z Invisible Width – Number of Light Neutrino Species

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

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

theory

all measured at the peak

$$N_\nu = 2.9840 \pm 0.0082$$

2σ below 3.0

A hint of non-unitarity of the PMNS matrix?

Only small room for improvements: precision limited mainly by the theoretical uncertainty on luminosity determination i.e. on small angle Bhabha cross section

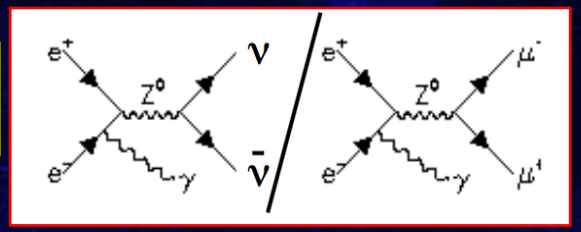
(LEP1: $\Delta L/L = 0.00061$, $\Delta N_\nu^{\rm lumi} = 0.0046$ ➔ $\Delta N_\nu^{\rm lumi} = 0.0001$ @FCC-ee).

$$\Delta N_\nu^{\rm FCC-ee} = 0.00008({\rm stat}) \pm 0.0001({\rm syst})$$

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

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

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



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

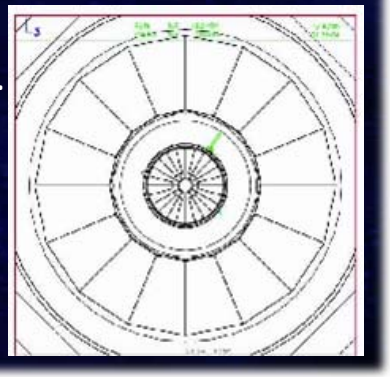
- Photon selection common for both final states ➔ cancellations of systematics.
- N_ν can be measured vs sqrt(s) ➔ sensitivity to NP at high energy scales.
- FCC-ee sensitivity:

$\sqrt{s}$ [GeV]	years of running	ΔN_ν (stat)
161	1	0.0011
240 & 340	5	0.0008
125	1	0.0004

$3 \times 10^7 \gamma Z({\rm inv})$ ev.

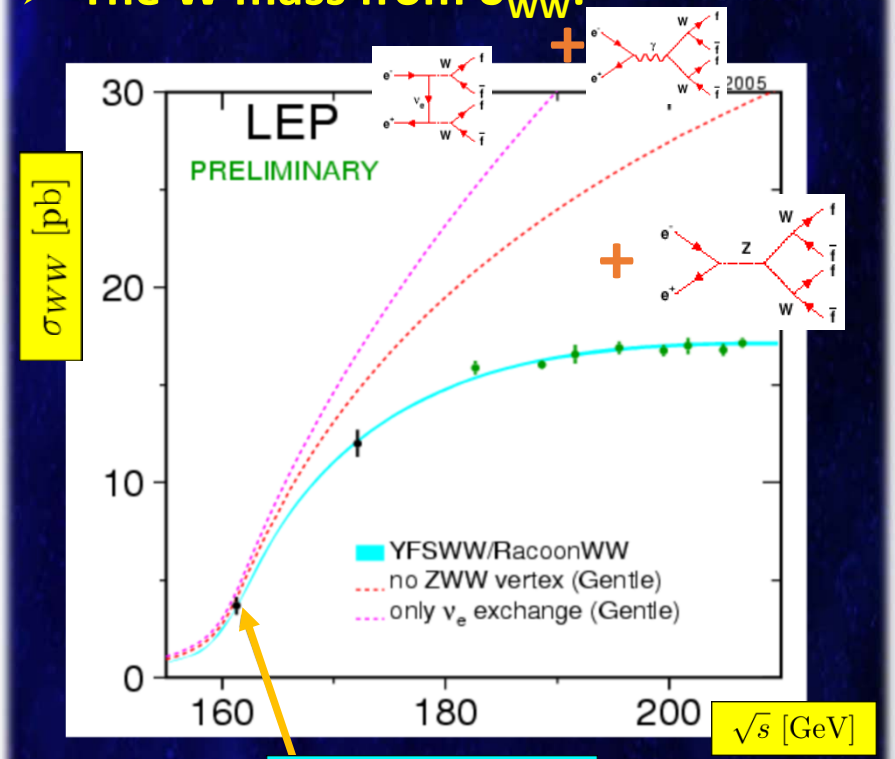
(running parasitically)

$$\Delta N_\nu \leq 4 \times 10^{-4}$$



WW Threshold Scan: the W Mass and Width

➢ The W mass from σ_{WW}:

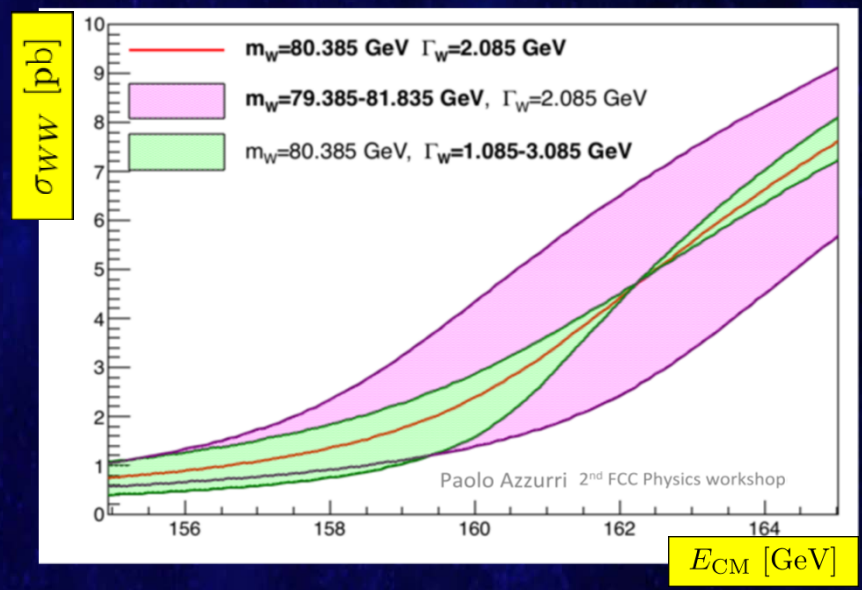


$$\Delta m_W = \left(\frac{d\sigma}{dm_W}\right)^{-1} \Delta\sigma$$

	LEP2 Stat./Prec.	FCC – ee stat (syst)
N_{WW}	4×10^4	3×10^7
M_W [MeV]	$80376 \pm 33 \pm 4$	$0.3\ (< \pm 1)$

$$\Delta m_W = 1 \text{ MeV}$$

➢ The W 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:

$E_1 = 157.1$ GeV | $E_1 = 162.3$ GeV | $f = 0.4$

➡ $\Delta\Gamma_W = 1.5$ MeV | $\Delta m_W^{stat} = 0.6$ MeV

W Physics: Branching Ratios, TGCs…

➢ WW samples (FCC-ee)

$\sqrt{s}$ [GeV]	161	240	350
$N_{WW}[\times 10^6]$	30	80	15

➢ W Branching ratios (%)

LEP2

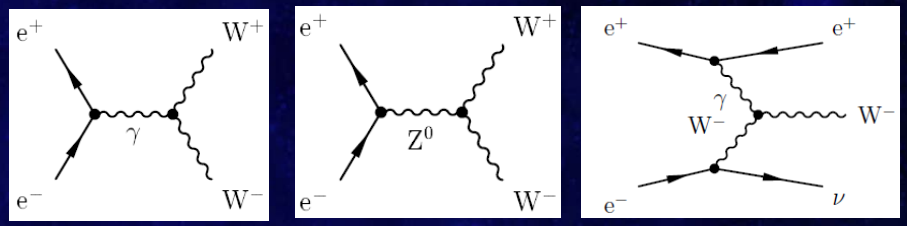
$BR(W \to e\nu)$	10.65 ± 0.17
$BR(W \to \mu\nu)$	10.59 ± 0.15
$BR(W \to \tau\nu)$	11.44 ± 0.22
$BR(W \to l\nu)$	10.84 ± 0.09
$BR(W \to \text{hadrons})$	67.48 ± 0.28

- Lepton universality tested at 2% level (2.7σ discrepancy between τand μ/e)
- Quark-lepton universality tested at 0.6%

FCC-ee

- Lepton universality test at 0.04% level
- Quark-lepton universality test at 0.01%
- Flavour tagging → Vcs Vcb…

➢ Triple Gauge Couplings



- Selected LEP limits (95% C.L.)

Δk_γ	$[-9.9, 6.6] \times 10^{-2}$
λ_γ	$[-5.9, 1.7] \times 10^{-2}$
Δk_Z	$[-7.4, 5.1] \times 10^{-2}$
λ_z	$[-5.9, 1.7] \times 10^{-2}$
Δg_1^Z	$[-5.4, 2.1] \times 10^{-2}$

- FCC-ee: overall improvements by a factor of 50 to compare with LEP

➢ The strong coupling constant:

- FCC-ee: $\Delta_{\rm rel}\alpha_S(m_W^2) = 3 \times 10^{-3}$ from hadronic W decays (Γ_W and $BR_{W,had}$)
- LEP2 precision: 37%

Summary

- ✓ **The FCC-ee offers unprecedented precision of electroweak studies !**

- ✓ **The expectations of precision for electroweak observables in the sector of Z pole and WW threshold have been discussed:**

$$\Delta M_Z = 100 \text{ keV} \qquad \Delta\Gamma_Z = 100 \text{ keV}$$

$$\Delta M_W = 1 \text{ MeV} \qquad \Delta\Gamma_W = 1.5 \text{ MeV}$$

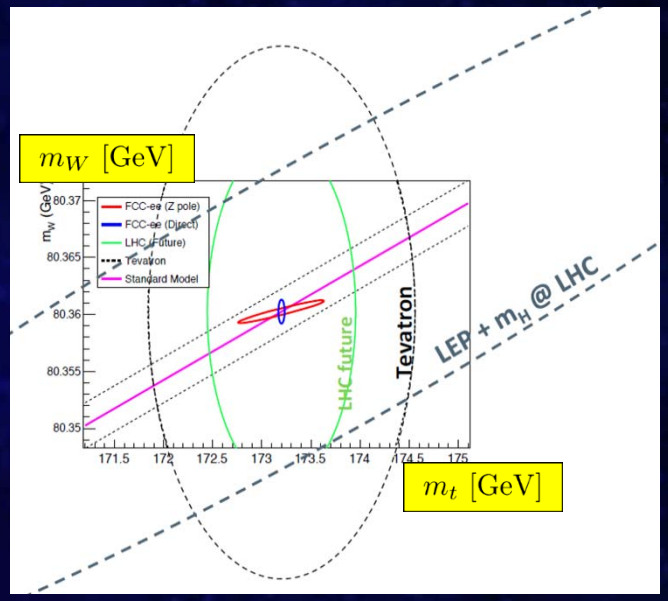
$$\Delta^{\text{stat}}_{\text{rel}} \sin^2\Theta_{W,\ \text{eff}} = 10^{-7}$$

- ✓ **Expectations for coupling constants:**

$$\Delta_{\text{rel}}\alpha_{\text{QED}}(m_Z^2) = 3\times 10^{-5}$$

$$\Delta_{\text{rel}}\alpha_S(m_Z^2) = 2\times 10^{-3} \qquad \Delta_{\text{rel}}\alpha_S(m_W^2) = 3\times 10^{-3}$$

- ✓ **The precision electroweak measurements have very strong sensitivity for New Physics searches**



The other talks about FCC-ee physics:

Physics at the FCC: a story of synergy and complementarity
Right-Handed neutrino searches at the FCC
Higgs measurements at the Future Circular Colliders
Top-quark physics at the Future Circular Colliders
QCD and gamma-gamma Physics at FCC-ee
Flavour Physics at FCC-ee (poster)