Electroweak Precision Physics at FCC-ee

Jan Eysermans (Massachusetts Institute of Technology)

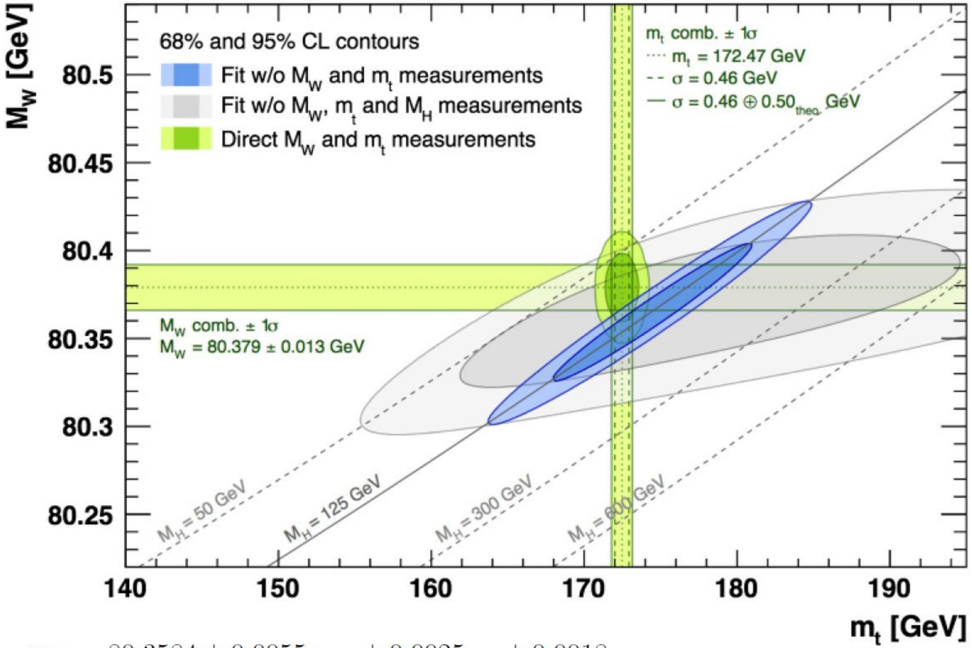
EPS-HEP2021 conference – July 26 2021

EWK measurements overview

Contour fits of EWK measurements with experimental data available to date

Higher precision on EWK parameters enable further constraints and test SM closure tests:

- Direct sensitive to new physics
- Parameters entangled: m_W, m_{top}, α_S, ...
- Also theory improvements necessary

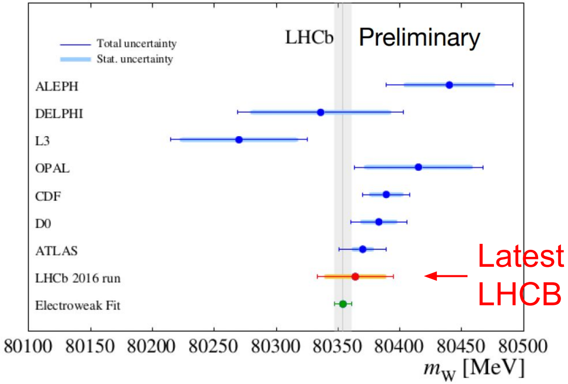


$$m_W = 80.3584 \pm 0.0055_{m_{top}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{QED}} \pm 0.0020_{\alpha_S} \pm 0.0001_{m_H} \pm 0.0040_{theory} \text{ GeV} = 80.358 \pm 0.008_{total} \text{ GeV},$$

Data PDG
80.379± 0.012 GeV

$$\sin^2\theta_W^{eff} = 0.231488 \pm 0.000029_{m_{top}} \pm 0.000015_{m_Z} \pm 0.000035_{\alpha_{QED}} \pm 0.000010_{\alpha_S} \pm 0.000001_{m_H} \pm 0.000047_{theory} = 0.23149 \pm 0.00007_{total},$$

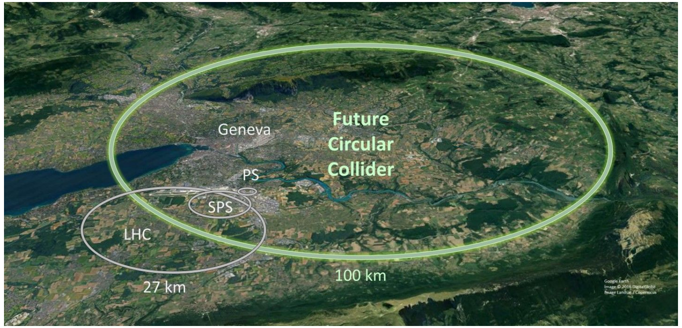
Data PDG
0.23121 ± 0.00004

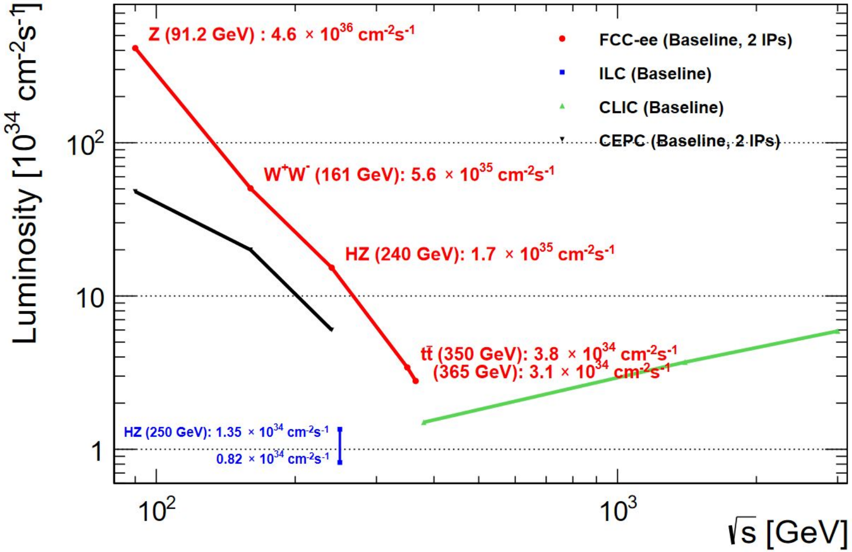


← Latest result from LHCB (2021)

FCCee overview

- Circular e+/e- collider with ~ 100 km in circumference
- Colliding at 2 interaction points (4 IPs under discussion)
- Facility to host hh collider at later stage (cfr. LEP–LHC)
- Foreseen timeline: construction 2030–40, operation 40–55 (15y)

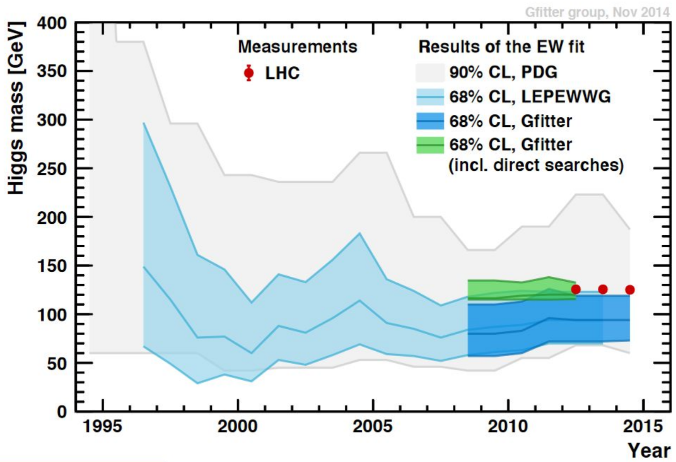




Multiple energy points exploiting large range of physics			
Threshold	Center-of-mass	Luminosity	Events
Z-pole	91 GeV	150	5x10^{6}M Z
WW-pole	161 GeV	12	50M WW
H-pole	240 GeV	5	1M ZH
tt-pole	365 GeV	1.5	1M tt

FCCee physics potential

"FCCee = TeraZ or Higgs factory": true, but also a discovery machine!



Rich physics programme including (EWK) precision measurements:

- Mass, width, cross section of W, Z, top and Higgs
- Strong and electromagnetic coupling constants at various √s
- Neutrino species/Z-invisible
- Flavor physics
- Direct searches for new physics
- …

Put large constraints on SM EWK parameter space, narrowing down closure tests hence sensitive to new physics

Ref.: "Future Circular Collider Study. Volume 1: Physics Opportunities. Conceptual Design Report, preprint edited by M. Mangano et al. CERN accelerator reports, CERN-ACC-2018-0056, Geneva, December 2018. Published in Eur. Phys. J. C"

To further increase and optimize the physics potential, a detailed feasibility study is needed:

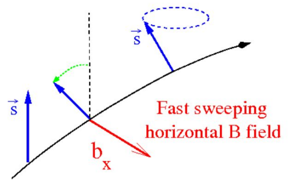
- Baseline of machine parameters and detector concepts
- Assess impact on systematic uncertainties with direct feedback to machine/detector R&D
- Assess shortcomings on theory

FCCee key elements

Key elements of FCCee for order-of-magnitude(s) improvement of EWK precision measurements

1) High statistics (e.g. 10^7 times more Zs than LEP1)

2) Dedicated energy points for precision measurements and combinations → unique programme!



3) In-situ beam energy calibration (arXiv:1909.12245):

   - Center-of-mass uncertainty dominant for many EWK precision (mass) measurements
   - Z/WW: resonant depolarisation measurements on a continuous basis → 10^{-6} relative accuracy achievable
     100(300) keV unc. at Z(WW)
   - Higher energies: cannot use RDP, usage of Z-γ radiative return events (~ 2 MeV at 240 GeV)

4) Online luminosity meter:

   - Precise knowledge of luminosity important for cross-section and branching fraction measurements
   - Using Bhabha-scattering events with dedicated forward detector → dL/L ~ 10^{-4} accuracy achievable
     Point-to-point ~ 10^{-5}

5) Detectors: high granularity, improved impact parameter → better reconstruction and resolutions

6) Very clean environment (cfr. LEP)

Z lineshape – $\alpha_{QED}(m_Z^2)$

Z → μμ forward/backward asymmetry sensitive to $\alpha_{QED}(m_Z^2)$ due to Z-γ interference:

$$A_{\mathrm{FB}}^{\mu\mu}(s) \simeq \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_{\mu} \times \left[1 + \frac{8\pi\sqrt{2}\alpha_{\mathrm{QED}}(s)}{m_{\mathrm{Z}}^2 G_{\mathrm{F}}\left(1 - 4\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}}\right)^2}\frac{s - m_{\mathrm{Z}}^2}{2s}\right]$$

→ strongly depends on √s

→ **direct** measurement of $\alpha_{QED}(s)$ at √s != m_Z

→ measure $\sin^2\theta_W$ to high precision (later)

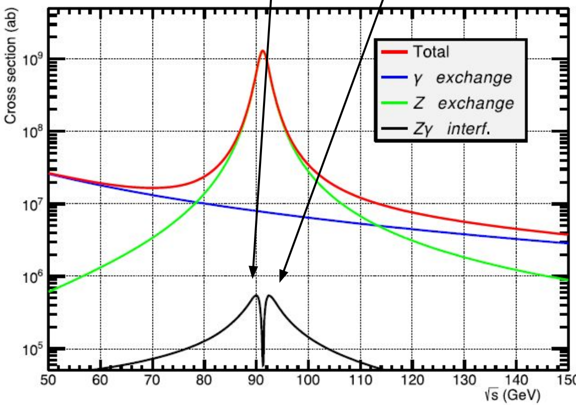
Perform line-scan around Z-pole to maximise Z-γ interference and measure A_{FB}:

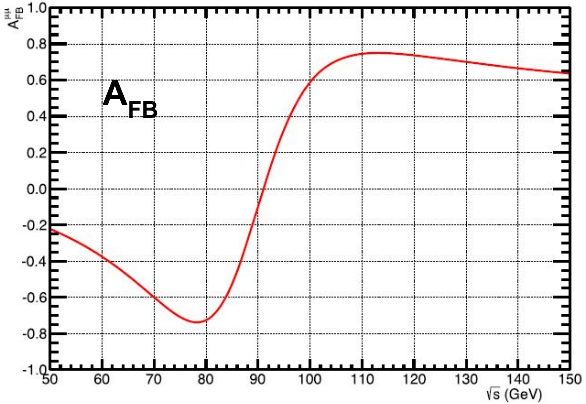
- Nominal 91.2 GeV, 80 /ab
- Off-peak: 87.7 and 93.9 GeV, each 40 /ab

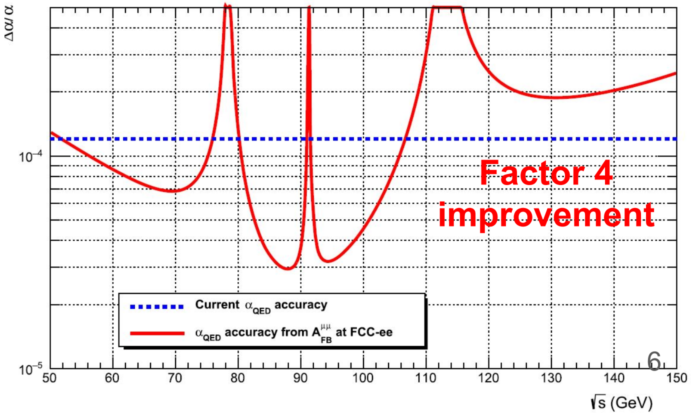
→ Measure $\alpha_{QED}(m_Z^2)$ to 3×10^{-5} rel. precision (currently 1.1×10^{-4})

→ Stat. dominated; syst. uncertainties < 10^{-5} (dominated by √s calib)

→ Theoretical uncertainties ~ 10^{-4}, higher order calcs needed







Z peak – $\sin^2\theta_W$

Z → μμ forward/backward asymmetry also used to measure ewk mixing angle $\sin^2\theta_W$ at Z-pole = 91.2 GeV:

$$A_{FB}^{\mu\mu}(s) \simeq \frac{3}{4}\mathcal{A}_e\mathcal{A}_\mu \longrightarrow \mathcal{A}_e = \frac{g_{L,e}{}^2 - g_{R,e}{}^2}{g_{L,e}{}^2 + g_{R,e}{}^2} = \frac{2v_e/a_e}{1+(v_e/a_e)^2}, \text{with} \quad v_e/a_e \equiv 1 - 4\sin^2\theta_W^{eff}$$

$\Delta A_{FB}^{\mu\mu}(s) \sim 3\times10^{-6}$ (stat) + 4×10^{-6} (syst)

→ Measure $\sin^2\theta_W$ to 3×10^{-6} abs. precision (currently 1.6×10^{-4})

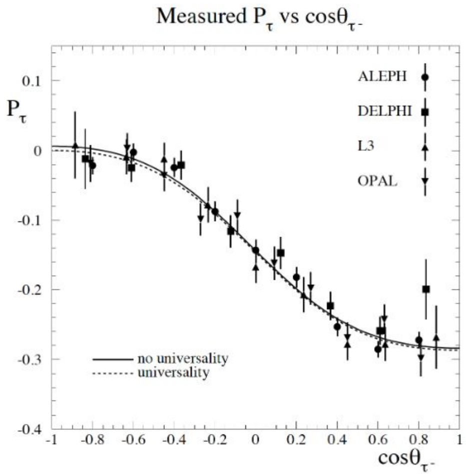
→ *Assumes lepton universality*: $A_e = A_\mu$

→ Mainly dominated by energy calibration (point-to-point)

Tau polarization used to constrain the mixing angle to a similar precision

- *No assumption on lepton universality* (direct separation A_e from A_τ)
- A_e from P_τ: benefit from high statistics and very robust measurement

$$P_\tau(\cos\theta) = \frac{A_{pol}(1+\cos^2\theta) + \frac{8}{3}A_{pol}^{FB}\cos\theta}{(1+\cos^2\theta) + \frac{8}{3}A_{FB}\cos\theta} \Longrightarrow P_\tau \equiv \frac{\sigma(\tau_R) - \sigma(\tau_L)}{\sigma(\tau_R) + \sigma(\tau_L)} \simeq -2(1 - 4\sin^2\theta_W)$$



Z lineshape – mass, width and σ^0_{had}

→ Mass ± 4 keV (stat) ± 100 keV (syst) [LEP 2.1 MeV]

- Systematics limited due to beam calibration uncertainties (RDP ~ 100 keV)

→ Width ± 4 keV (stat) ± 25 keV (syst) [LEP 2.3 MeV]

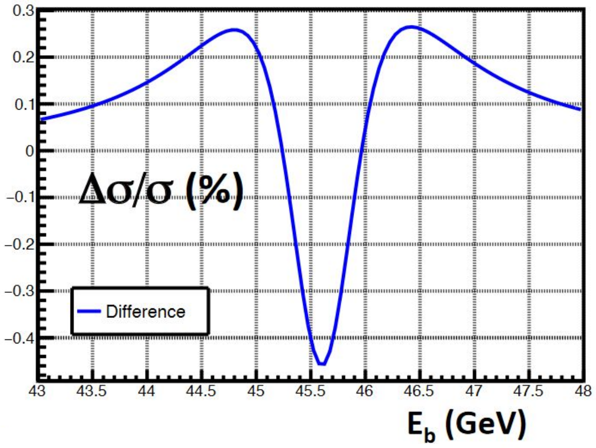
- Systematics dominated by:
  - Relative (point-to-point) uncertainty on the √s ~ 22 keV
  - Impact on beam-energy spread uncertainty ~ 10 keV
    - Absolute uncertainty on BES ~ 84 MeV
    - Constrained using $e^+e^- \to \mu^+\mu^-(\gamma)$ events:

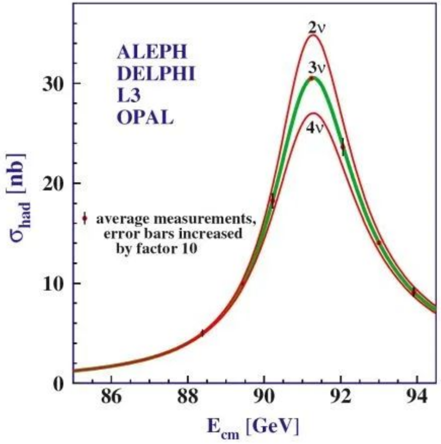
      → Constrain BES uncertainty to per-mille level
      → Taking into account asymmetric beam optics (x-angle α 30 mrad) and γ-ISR
      → Muon angular resolution ~ 0.1 mrad required

→ Hadronic cross-section σ^0_{had}: ± 4 pb [LEP 37 pb]
→ Number of neutrino families: 1×10^{-3} (abs) [LEP 7×10^{-3}]

- Dominated by luminosity uncertainty

Lineshape cross-section





Z peak – couplings and $\alpha_S(m_Z^2)$

Couplings measured from ratio of hadronic and leptonic partial widths

→ need control on detector acceptances: detector precision ~ 10 μm

	Statistical uncertainty	Systematic uncertainty
R_μ (R_ℓ)	10^{-6}	5×10^{-5}
R_τ	1.5×10^{-6}	10^{-4}
R_e	1.5×10^{-6}	3×10^{-4}
R_b	5×10^{-5}	3×10^{-4}
R_c	1.5×10^{-4}	15×10^{-4}

Relative stat. and syst. Unc. (similar)

→

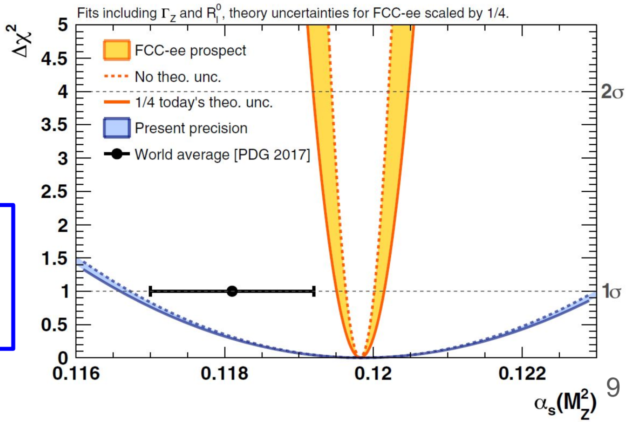
fermion type	g_a	g_v
e	1.5×10^{-4}	2.5×10^{-4}
μ	2.5×10^{-5}	$2. \times 10^{-4}$
τ	0.5×10^{-4}	3.5×10^{-4}
b	1.5×10^{-3}	1×10
c	2×10^{-3}	1×10

Relative unc. on couplings

1-2 orders of magnitude Improvement w.r.t. LEP

Extract strong coupling constant $\alpha_S(m_Z^2)$ using leptonic/hadronic width ratio: $R_l = \Gamma_{had}/\Gamma_{lep}$

→ $\Delta\alpha_S(m_Z)$ ~ $1\text{x}10^{-5}$ (stat) + $1.5\text{x}10^{-4}$ (syst) abs. (current value $\Delta\alpha_S$ $30\text{x}10^{-4}$)
→ Systematically dominated (acceptance)



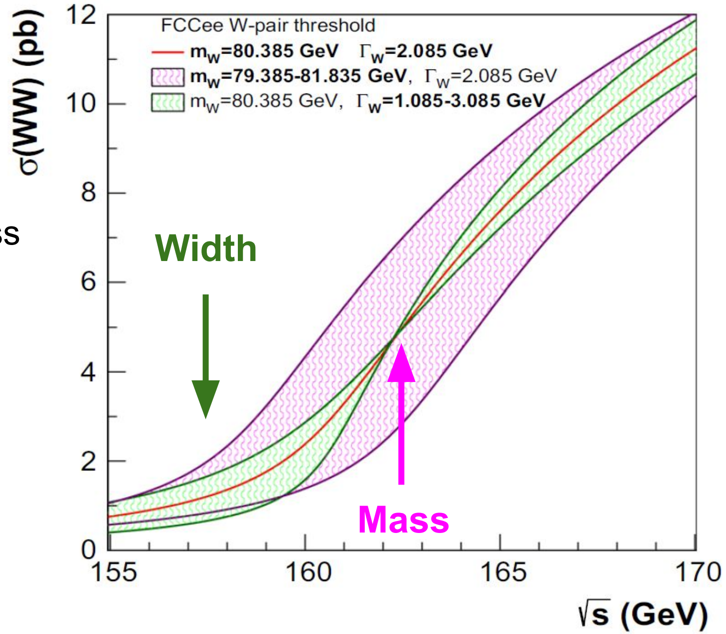
WW threshold

W mass and width extracted from line-scans using WW xsec

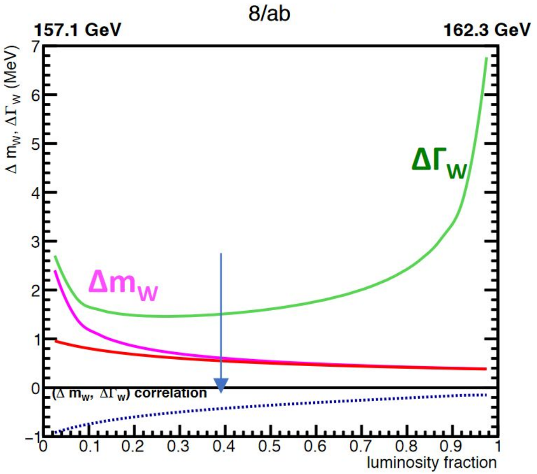
Energy points determined from Δm_W and $\Delta\Gamma_W$ sensitivities on WW xsec:

→ **157.1 GeV width measurement:** maximum sensitivity on width

→ **162.5 GeV mass measurement:** minimal impact on width, max. on mass



Luminosity ($<10^{-4}$) and center-of-mass (< 0.5 MeV) uncertainties to be controlled, but weaker constraints than on Z pole



Combined fit with optimized lumi fraction (f=0.4: 5 /ab at 157.1, 7 /ab at 162.5)

→ precision m_W to 250 (stat) + 300 (syst) keV (present 15 MeV)

→ precision Γ_W to 1.2 (stat) + 0.3 (syst) MeV (present 42 MeV)

W kinematic reconstruction

Independent analysis on W mass and width using kinematic reconstruction techniques in WW → qqlv events

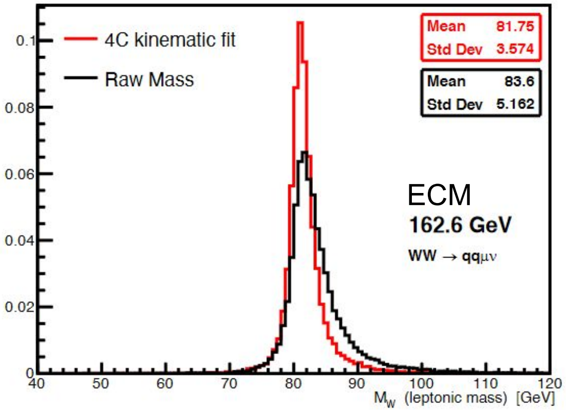
- Profit from precise angle and velocity measurements
- Run at all kinematically accessible energy points (WW, ZH and tt)

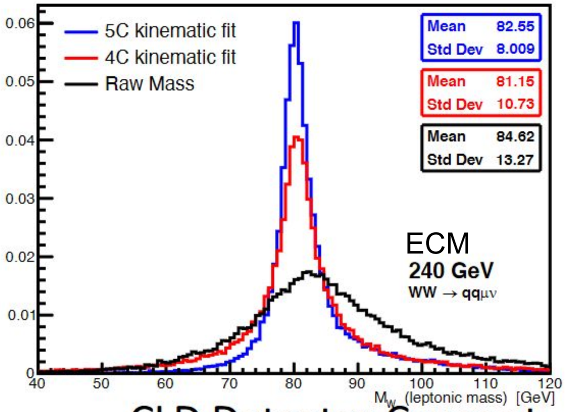
Source	Δm_W (MeV/c^2)				$\Delta\Gamma_W$ (MeV)			
	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu q\bar{q}$
e+μ momentum	3	8	-	4	5	4	-	4
e+μ momentum resoln	7	4	-	4	65	55	-	50
Jet energy scale/linearity	5	5	9	6	4	4	16	6
Jet energy resoln	4	2	8	4	20	18	36	22
Jet angle	5	5	4	5	2	2	3	2
Jet angle resoln	3	2	3	3	6	7	8	7
Jet boost	17	17	20	17	3	3	3	3
Fragmentation	10	10	15	11	22	23	37	25
Radiative corrections	3	2	3	3	3	2	2	2
LEP energy	9	9	10	9	7	7	10	8
Calibration ($e\nu q\bar{q}$ only)	10	-	-	4	20	-	-	9
Ref MC Statistics	3	3	5	2	7	7	10	5
Bkgnd contamination	3	1	6	2	5	4	19	7

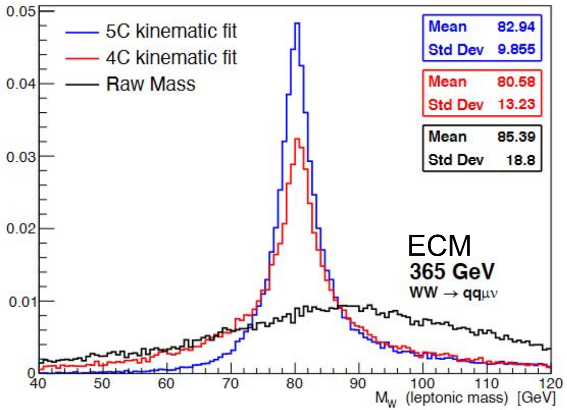
Δm_W (stat) ~ 250 keV → similar as xsec measurement

$\Delta\Gamma_W$ (stat) ~ 350 keV → reduction factor 2-3

Limited by systematics (beam energy, resolution, fragmentation) → constrain







CLD Detector Concept

M. Béguin, PhD thesis, 2019 https://cds.cern.ch/record/2710098 M. Béguin, E.Locc, iPoSEPS-HEP2019(2020) https://doi.org/10.22323/1.364.0653

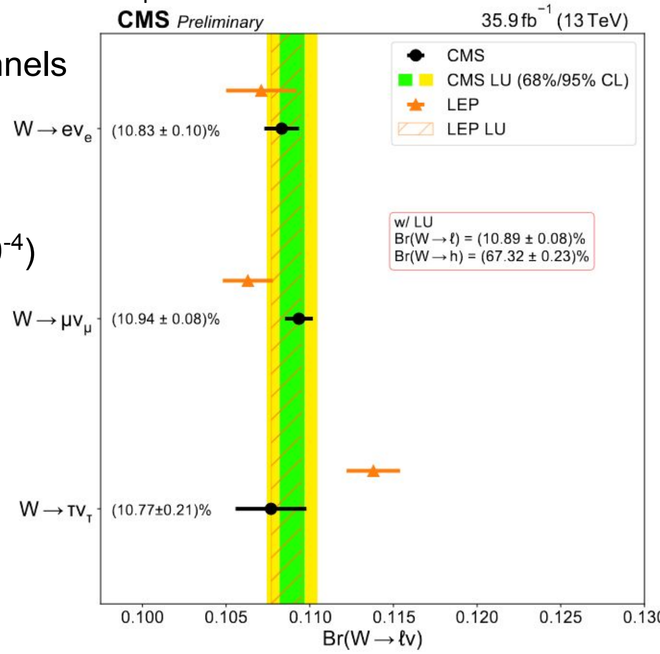
W decay branching ratios

Precise measurement of W decays

- Precise control of lepton ID to avoid cross contamination in signal channels (e.g. $\tau \to e,\mu$ vs. e,μ channels)
- Precision of 10^{-4} achievable (rel.)
- Simultaneously probe lepton and q/l universality to high precision (~ 10^{-4})

Decay mode relative precision	$B(W \to e\nu)$	$B(W \to \mu\nu)$	$B(W \to \tau\nu)$	$B(W \to qq)$
LEP2	1.5%	1.4%	1.8%	0.4%
FCC-ee	$3 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$4 \cdot 10^{-4}$	$1 \cdot 10^{-4}$

CMS-PAS-SMP-18-011
http://cds.cern.ch/record/2758905



Flavor tagging

- Allows precise measurement CKM matrix elements V_{cs}, V_{ub}, V_{cb}
- Extract strong coupling constant at WW-threshold

$$R_W = \frac{B_q}{1 - B_q} = \left(1 + \frac{\alpha_S(m_W^2)}{\pi}\right) \sum_{i=u,c;j=d,s,b} |V_{ij}|^2$$

→ $\Delta\alpha_S(m_W)$ ~ $3\text{x}10^{-4}$ (abs)
→ Statistically dominated

Top mass and width measurement

Top mass and width measurements similar as WW line-shape

Though more energy points needed:

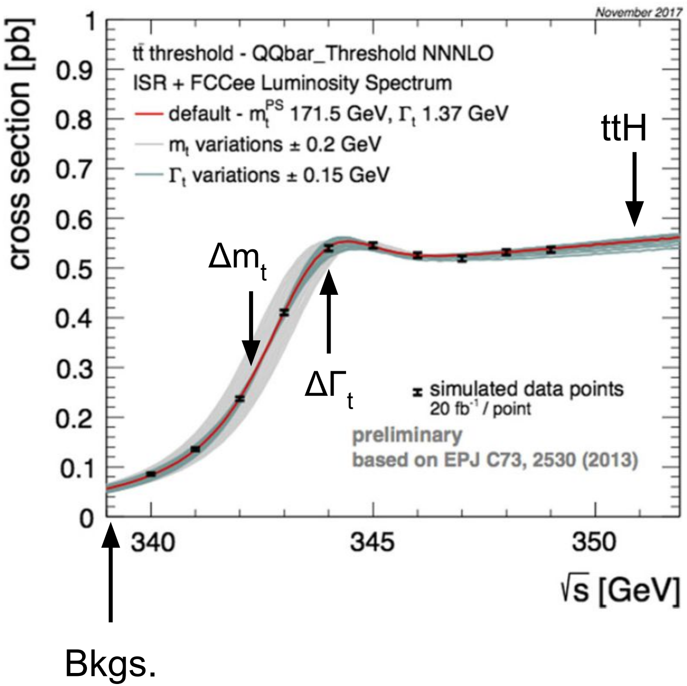
- Relative large uncertainty on top mass (+/- 0.5 GeV)
- Need to constrain shape in optimal way
- Possible to constrain backgrounds (below) and ttH (above)

→ Multipoint scan in 5 GeV window [340, 345], each ~ 25 /fb

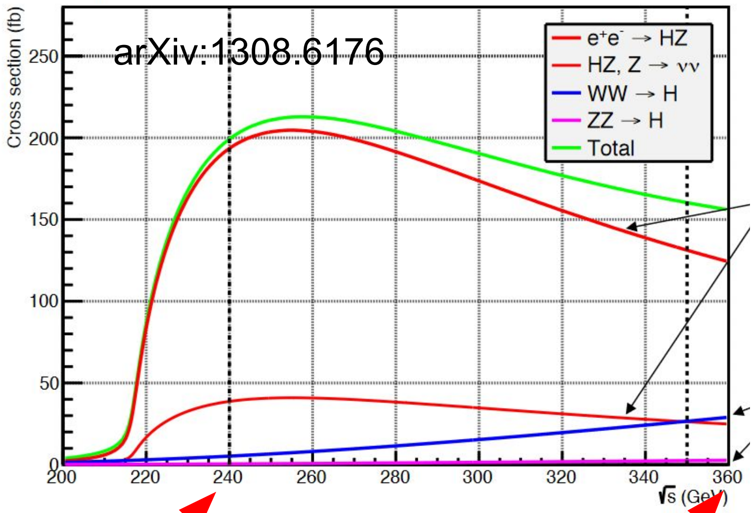
→ Δm_t (stat) ~ 17 MeV

→ $\Delta\Gamma_t$ (stat) ~ 45 MeV

To date: theoretical QCD errors order of 40 MeV for mass and width

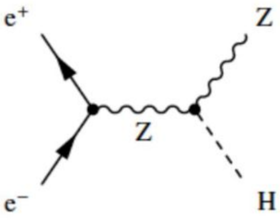


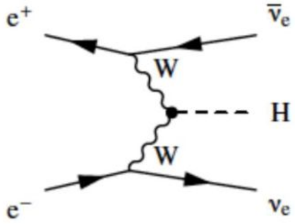
Higgs physics at FCCee



240 GeV, 5 /ab
10^6 ZH events
25k WWH events

365 GeV, 1.5 /ab
200k ZH events
50k WWH events





Higgs-pole at 240 GeV

- Higgs–strahlung dominant: $e^+e^- \rightarrow ZH$
- Precise Higgs **mass measurement** up to ~ 5 MeV
- Measurement of **decay-mode-independent xsec** up to % level, sensitive to new physics H → invisible
- Higgs width extracted from H → ZZ at % level

Top threshold at 365 GeV

- Opens significance for WW fusion: $e^+e^- \rightarrow WW\nu\nu \rightarrow H\nu\nu$
- Significant reduction in couplings and width

Combined performance at both energy points

- Higgs coupling precision < % level
- In particular, exotic Higgs decays constraint to < 1 %
- Probing CP violation using H → ττ phase

→ See dedicated talk Thursday by S. Braibant

Summary

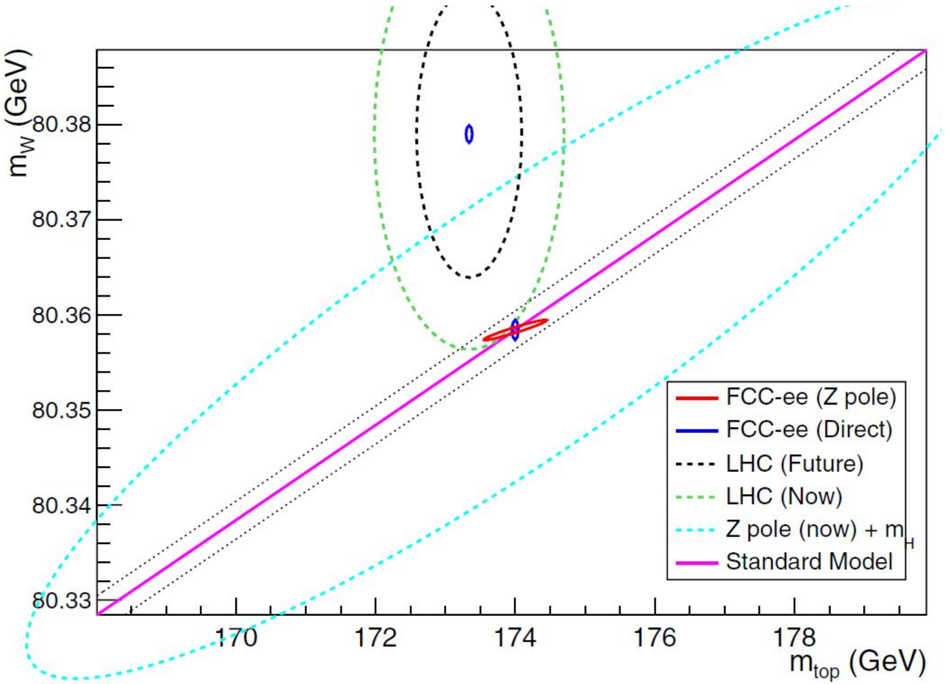
Rich physics programme at Z-threshold and higher energies

- FCC delivers excellent precision on various EWK parameters with improvements of 1-2 orders of magnitude
- Combined results at all energy thresholds provides unique closure tests for SM

→ Ongoing efforts with several analyses to evaluate physics potential

→ Feedback towards detector and machine R&D for systematic uncertainty reduction on key measurements

→ Work on theoretical side needed to cope with experimental level of accuracy



Backup

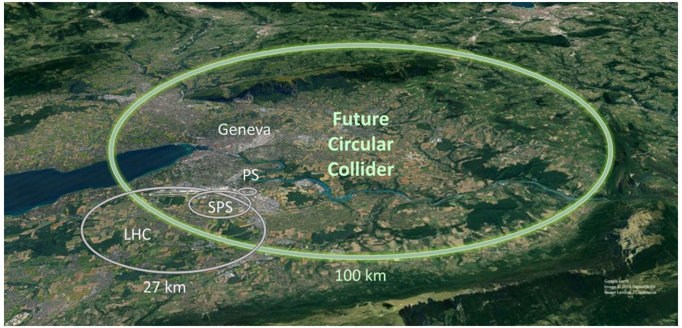
FCCee Physics Performance overview

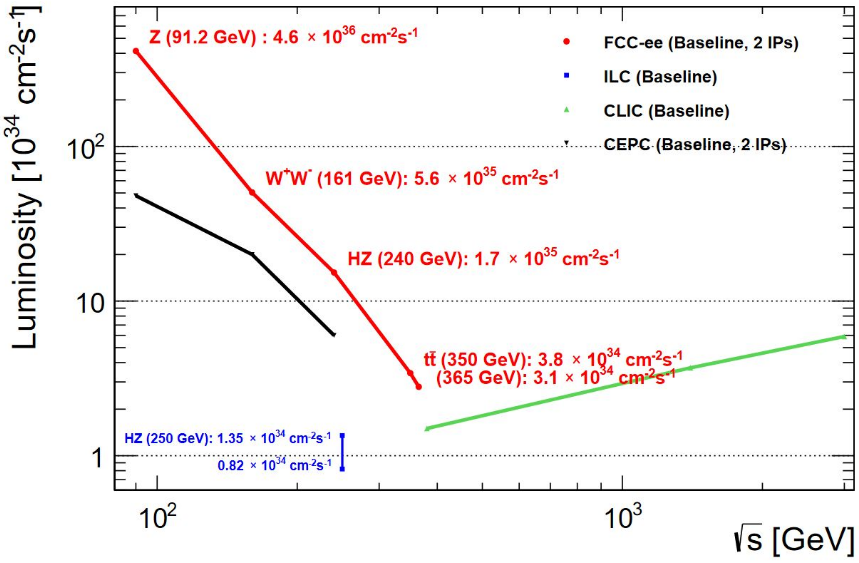
Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	4	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run

ArXiv 2106.13885

FCCee overview

- Circular e+/e- collider with ~ 100 km in circumference
- Colliding at 2 interaction points (4 IPs under discussion)
- Facility to host hh collider at later stage (cfr. LEP-LHC)
- Foreseen timeline: construction 2030–40, operation 40–55 (15y)





Multiple energy points exploiting large range of physics

- **Z-pole** 91.2 GeV ~ 150 /ab → 5□10^{12} Z
- **WW-pole** 161 GeV ~ 12 /ab → 5□10^{7} WW
- **H-pole** 240 GeV ~ 5 /ab → 1□10^{6} ZH
- **tt-pole** 365 GeV ~ 1.5 /ab → 1□10^{6} tt