EW measurements at FCC

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Acknowledgements: P. Azzurri, A. Blondel, M. Boscolo, D. Britzger, M. Dam, J. Gu, P. Janot, M. Klein, F. Piccinini
ee, $\ell p$, pp collisions and electroweak physics

Deep Inelastic scattering and discovery of neutral currents (1973)

proton antiproton collisions and discovery of Z, W bosons (1983)

LEP and high precision EW physics (1989-2000)

In this talk I will mostly discuss FCC-ee, with some perspectives for FCC-eh. FCC-hh \(\rightarrow\) talk of Andrea Wulzer
FCC-ee operation model assumed for the CDR

- Integrated luminosity goals for Z and W physics
  - 150 ab\(^{-1}\) around the Z pole (~25 ab\(^{-1}\) at 88 and 94 GeV, 100 ab\(^{-1}\) at 91 GeV)
  - 10 ab\(^{-1}\) around the WW threshold (161 GeV with ±few GeV scan)

<table>
<thead>
<tr>
<th>working point</th>
<th>luminosity/IP [10(^{34}) cm(^{-2})s(^{-1})]</th>
<th>total luminosity (2 IPs)/ yr</th>
<th>physics goal</th>
<th>run time [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z first 2 years</td>
<td>100</td>
<td>26 ab(^{-1})/year</td>
<td>150 ab(^{-1})</td>
<td>4</td>
</tr>
<tr>
<td>Z later</td>
<td>200</td>
<td>52 ab(^{-1})/year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>32</td>
<td>8.3 ab(^{-1})/year</td>
<td>10 ab(^{-1})</td>
<td>1</td>
</tr>
<tr>
<td>H</td>
<td>7.0</td>
<td>1.8 ab(^{-1})/year</td>
<td>5 ab(^{-1})</td>
<td>3</td>
</tr>
<tr>
<td>top (350 GeV)</td>
<td>0.8</td>
<td>0.2 ab(^{-1})/year</td>
<td>0.2 ab(^{-1})</td>
<td>1</td>
</tr>
<tr>
<td>top later (365 GeV)</td>
<td>1.5</td>
<td>0.38 ab(^{-1})/year</td>
<td>1.5 ab(^{-1})</td>
<td>4</td>
</tr>
<tr>
<td><strong>LEP (4 IPs)</strong></td>
<td><strong>0.6 fb(^{-1})</strong></td>
<td><strong>2.4 fb(^{-1})</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These are important, too, for WW physics!
**EW Physics observables at FCC-ee**

**TeraZ (5 X 10^{12} Z)**
From data collected in a lineshape energy scan:
- Z mass (key for jump in precision for ewk fits)
- Z width (jump in sensitivity to ewk rad corr)
- \( R_l = \frac{\text{hadronic/leptonic width}}{\text{lepton couplings}} \)
- peak cross section (invisible width, \( N_v \))
- \( A_{FB}(\mu\mu) \) (\( \sin^2\theta_{\text{eff}}, \alpha_{\text{QED}}(m_Z^2), \text{lepton couplings} \))
- Tau polarization (\( \sin^2\theta_{\text{eff}}, \text{lepton couplings, } \alpha_{\text{QED}}(m_Z^2) \))
- \( R_b, R_c, A_{FB}(bb), A_{FB}(cc) \) (quark couplings)

**OkuWW (10^8 WW)**
From data collected around and above the WW threshold:
- W mass (key for jump in precision for ewk fits)
- W width (first precise direct meas)
- \( R_W = \frac{\Gamma_{\text{had}}}{\Gamma_{\text{lept}}} \) (\( \alpha_s(m_Z^2) \))
- \( \Gamma_e, \Gamma_\mu, \Gamma_\tau \) (precise universality test)
- Triple and Quartic Gauge couplings (jump in precision, especially for charged couplings)
Determination of Z mass and width

- Uncertainty on $m_Z \approx 100$ KeV is dominated by the correlated uncertainty on the centre-of-mass energy at the two off peak points.

  At FCC-ee continuous $E_{CM}$ calibration (resonant depolarization) gives $\Delta E_{CM} \approx 10$ KeV (stat) + 100 KeV (syst).

- The off peak point-to-point anti-correlated uncertainty has a similar impact ($\approx 100$ KeV) on $\Gamma_Z$.

The exact choice of the off peak energies for $m_Z$, $\Gamma_Z$ is not very crucial at FCC-ee (differently from LEP) because of the high statistics. Instead the exact choice is crucial for $\alpha_{QED}(m_Z^2)$ which is driving the choice of $\sqrt{s_-} \approx 88$ GeV and $\sqrt{s_+} \approx 94$ GeV (slide 10).
Lineshape: radiator, $\gamma$-Z interference

- The lineshape is highly asymmetric (ISR), radiator function $H(s',s)$ used for de-convolution known at leading $O(\alpha^3)$ equivalent to $\approx 100$ KeV on mass and width (need higher orders for FCC-ee).

$$\sigma_{ff}(s) = \int_{4m_f^2}^{s} ds' H(s,s') \hat{\sigma}_{ff}(s')$$

- FCC-ee precision calls for a model independent fit of the lineshape (S-matrix) where $\gamma$-Z interference is measured independently.

A measurement of the $\gamma$-Z interference term for 100 keV precision for $m_Z, \Gamma_Z$ requires 100 fb$^{-1}$ collected at CM energy of $\approx 60-70$ GeV ... or use the 160 GeV run!
\[ \Gamma_z \text{ and beam energy spread} \]

- The beam energy spread affects the lineshape changing the cross section by

\[ \delta \sigma \approx 0.5 \frac{d^2 \sigma}{dE^2} \epsilon_{CMS}^2 \]

- The size of the energy spread (\( \approx 60 \text{ MeV} \)) and its impact on \( \Gamma_z (\approx 4 \text{ MeV}) \) is similar to LEP, but the approach to tackle the corresponding systematic uncertainty different because of FCC-ee beam crossing angle

- At LEP it was controlled at 1% level by measuring the longitudinal size of the beam spot, at FCC-ee can be measured with similar precision from the scattering angles of \( \mu^+\mu^- \) events
Control of energy spread with $\mu^+\mu^-$

- **FCC-ee**: Asymmetric optics with beam crossing angle $\alpha$ of 30 mrad
- $\alpha$ is measured in $e^+e^-\rightarrow\mu^+\mu^-(\gamma)$

$$\alpha = 2 \arcsin \left[ \frac{\sin (\varphi^- - \varphi^+) \sin \theta^+ \sin \theta^-}{\sin \varphi^- \sin \theta^- - \sin \varphi^+ \sin \theta^+} \right]$$

Together with $\gamma$ (ISR) energy, both distributions sensitive to energy spread.
- Energy spread measured at 0.1% with $10^6$ muons (4 min at FCC-ee)
- Current calculations of ISR emission spectrum sufficient
- Detector requirement on muon angular resolution 0.1 mrad

Can keep related systematic uncertainty on $\Gamma_2$ at less than 30 keV
Measurement of luminosity, $\sigma_{\text{had}}$, and neutrino families

- Goal on theoretical uncertainty from higher order for low angle Bhabha is 0.01%, corresponding to a **reduction of a factor 8 in uncertainty on number of light neutrino families** (we are already not far $\approx 0.02\%$)
  - Another goal is a point to point relative normalization of $5 \times 10^{-5}$ for $\Gamma_Z$

- To match this goal an accuracy on detector construction and boundaries of $\approx 2 \mu$m is required
  - clever acceptance algorithms, a la LEP, with independence on beam spot position should be extended to beam with crossing angle
  - luminometer fixed to central beam pipe

- Can potentially reach an uncertainty of 0.01% also with $e^+e^- \to \gamma\gamma$, statistically $1.4 \text{ ab}^{-1}$ are required (theory uncertainty already at this level, requires control of large angle Bhabha)

Mogens Dam, talk at Tuesday session
e.m. coupling: direct measurement of $\alpha_{\text{QED}}(m_Z^2)$

At LEP hadronic contributions to the vacuum polarization as external input (dispersion relations+ lower energy experiments) $\Delta_{\text{rel}} \approx 10^{-4}$

FCC-ee: direct measurement with better precision

$$A_{FB}^{\mu\mu} = \frac{N_F^{\mu\mu} - N_B^{\mu\mu}}{N_F^{\mu\mu} + N_B^{\mu\mu}} \approx f(\sin^2 \theta_W^\text{eff}) + \alpha_{\text{QED}}(s) \frac{s-m_Z^2}{2s} g(\sin^2 \theta_W^\text{eff})$$

<table>
<thead>
<tr>
<th>Type</th>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>$E_{\text{beam}}$ calibration</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>$E_{\text{beam}}$ spread</td>
<td>$&lt; 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>Acceptance and efficiency</td>
<td>negl.</td>
</tr>
<tr>
<td></td>
<td>Charge inversion</td>
<td>negl.</td>
</tr>
<tr>
<td></td>
<td>Backgrounds</td>
<td>negl.</td>
</tr>
<tr>
<td>Parametric</td>
<td>$m_Z$ and $\Gamma_Z$</td>
<td>$1 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>$\sin^2 \theta_W$</td>
<td>$5 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>$G_F$</td>
<td>$5 \times 10^{-7}$</td>
</tr>
<tr>
<td>Theoretical</td>
<td>QED (ISR, FSR)</td>
<td>$&lt; 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>Missing EW higher orders, QED(IFI)</td>
<td>few $10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>New physics in the running</td>
<td>0.0</td>
</tr>
<tr>
<td>Total</td>
<td>Systematics</td>
<td>$1.2 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>Statistics</td>
<td>$3 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Optimal centre-of-mass energies for a $3 \times 10^{-5}$ uncertainty on $\alpha_{\text{QED}}$, $\sqrt{s_-} = 87.9$ GeV and $\sqrt{s_+} = 94.3$ GeV

Work on EWK theoretical corrections required to reach $\approx 3 \times 10^{-5}$
FCC-ee strategy for neutral couplings and $\sin^2\theta_{\text{eff}}$

$$A_e = \frac{2g_{Ve}g_{Ae}}{(g_{Ve})^2 + (g_{Ae})^2} = \frac{2g_{Ve}/g_{Ae}}{1 + (g_{Ve}/g_{Ae})^2}$$

- Muon forward backward asymmetry at pole, $A_{FB}^{\mu\mu}$ ($m_Z$) gives $\sin^2\theta_{\text{eff}}$ with 5 $10^{-6}$ precision
  - uncertainty driven by knowledge on CM energy
  - assumes muon-electron universality

- Tau polarization can reach similar precision without universality assumption
  - tau pol measures $A_e$ and $A_\tau$, can input to $A_{FB}^{\mu\mu} = 3/4 A_e A_\mu$ to measure separately electron, muon and tau couplings, (together with $\Gamma_e, \Gamma_\mu, \Gamma_\tau$)

- Asymmetries $A_{FB}^{bb}, A_{FB}^{cc}$ provide input to quark couplings together with $\Gamma_b, \Gamma_c$

NOTE that LEP approach was different: all asymmetries were limited by statistics and primarily used to measure $\sin^2\theta_{\text{eff}}$
tau polarization plays a central role at FCC-ee

- Separate measurements of $A_e$ and $A_\tau$ from

\[ P_\tau(\cos \theta) = \frac{A_{pol}(1 + \cos^2 \theta) + \frac{8}{3} A_{pol}^{FB} \cos \theta}{(1 + \cos^2 \theta) + \frac{8}{3} A_{FB} \cos \theta} \]

At FCC-ee
- very high statistics: improved knowledge of tau parameters (e.g. branching fraction, tau decay modeling) with FCC-ee data
- use best decay channels (e.g. $\tau \rightarrow \rho \nu_\tau$ decay very clean), note that detector performance for photons / $\pi^0$ very relevant

$\rightarrow$ measure $\sin^2 \theta_{\text{eff}}$ with $6.6 \times 10^{-6}$ precision
**$A_{FB}^{bb}$ : from LEP to FCC-ee**

LEP combination dominated by statistics, projection for FCC-ee considers conservative reduction of various uncertainty components

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>$\Delta AFB(b)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>0.00156</td>
</tr>
<tr>
<td>Uncorrelated Systematic</td>
<td>0.00061</td>
</tr>
<tr>
<td>QCD Correction</td>
<td>0.00030</td>
</tr>
<tr>
<td>Light Quark Fragmentation</td>
<td>0.00013</td>
</tr>
<tr>
<td>Semileptonic Decays Modelling</td>
<td>0.00013</td>
</tr>
<tr>
<td>Charm Fragmentation</td>
<td>0.00006</td>
</tr>
<tr>
<td>Bottom Fragmentation</td>
<td>0.00003</td>
</tr>
<tr>
<td><strong>Total Systematic Error</strong></td>
<td><strong>0.00073</strong></td>
</tr>
</tbody>
</table>

- Most of this depends on stat.
- Can be reduced with improved calculations and proper choices of analysis methods (e.g. measure the asymmetry as a function of jet parameters, etc.)

Simple method to reduce QCD corrections for lepton analysis: raise cut on lepton momentum, as statistics is no longer dominant

Improved measurements also for the charm sector: $A_{FB}^{cc}$
Precisions on coupling ratio factors, $A_f$

$$A_e = \frac{2g_{Ve}g_{Ae}}{(g_{Ve})^2 + (g_{Ae})^2} = \frac{2g_{Ve}/g_{Ae}}{1 + (g_{Ve}/g_{Ae})^2}$$

<table>
<thead>
<tr>
<th>$A_e$</th>
<th>Statistical uncertainty</th>
<th>Systematic uncertainty</th>
<th>Improvement w.r.t. LEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\mu}$</td>
<td>$2.5 \times 10^{-5}$</td>
<td>$1.5 \times 10^{-4}$</td>
<td>30</td>
</tr>
<tr>
<td>$A_{\tau}$</td>
<td>$4. \times 10^{-5}$</td>
<td>$3. \times 10^{-4}$</td>
<td>15</td>
</tr>
<tr>
<td>$A_b$</td>
<td>$2 \times 10^{-4}$</td>
<td>$30 \times 10^{-4}$</td>
<td>5</td>
</tr>
<tr>
<td>$A_c$</td>
<td>$3 \times 10^{-4}$</td>
<td>$80 \times 10^{-4}$</td>
<td>4</td>
</tr>
</tbody>
</table>

$\sin^2 \theta_{W,eff}$ (from muon FB) & $10^{-7}$ & $5. \times 10^{-6}$ & 100 |

$\sin^2 \theta_{W,eff}$ (from tau pol) & $10^{-7}$ & $6.6 \times 10^{-6}$ & 75 |

Relative precisions, but for $\sin^2 \theta_{eff}$
Partial widths ratio ($R_l$)

- $R_l = \Gamma_l/\Gamma_{\text{had}} = \sigma_l/\sigma_{\text{had}}$ is a robust measurement, necessary input for a precise measurement of lepton couplings (and $\alpha_s(m_Z^2)$)

- Exploiting FCC-ee potential requires an accurate control of acceptance, particularly for the leptons
  - acceptance uncertainties were sub-dominant at LEP, but need to be reduced by a factor $\approx 5$ to match precision goal on $R_l$ of $5 \times 10^{-5}$
  - knowledge of boundaries, mechanical precisions: need to exploit 40 years of improvements in technology, need to use clever selections (at LEP was necessary only for luminosity)
  - fiducial acceptance is asymmetric in azimuth at FCC-ee because of 30 mrad cross angle→ boost in trasverse direction $\beta_x = \tan(\alpha/2) \approx 0.015$, however can measure $\phi^*$ and $\cos(\theta^*)$ event by event for dileptons!
Measurement of $R_b$ : double tagging

Divide event in two hemispheres according to thrust direction
• $F_1$ fraction of single tag
• $F_2$ fraction of double tag

\[
F_1 = R_b (\varepsilon_b - \varepsilon_{uds}) + R_c (\varepsilon_c - \varepsilon_{uds}) + \varepsilon_{uds}
\]
\[
F_2 = R_b (C_b \varepsilon_b^2 - \varepsilon_{uds}^2) + R_c (\varepsilon_c^2 - \varepsilon_{uds}^2) + \varepsilon_{uds}^2
\]

\[
R_b \approx \frac{C_b F_1^2}{F_2}
\]

\[
\varepsilon_b \approx \frac{F_2}{C_b F_1}
\]

LHC detectors and current taggers can reach three times $b$ tagging efficiency at same suppression of charm and uds, in a more harsh environment $\Rightarrow$ sizeable improvement possible at FCC-ee
• statistical uncertainty coming from double tag sample
• systematic uncertainty from hemisphere correlations becomes dominating

Efficient and pure secondary vertex finding will be important to study gluon splitting and nasty sources of correlations (e.g. momentum correlations) $\Rightarrow$ keep $b$-tag efficiency flat in momentum

FCC-ee projections conservatively consider reduction of uncertainty on hemisphere correlations from $\approx 0.1\%$ (LEP) to $\approx 0.03\%$

Improved measurements also for the charm sector: $R_c$
Precisions on normalized partial widths

\[ R_f = \frac{\sigma_f}{\sigma_{\text{had}}} \]

<table>
<thead>
<tr>
<th>( R_\mu ) (( R_\ell ))</th>
<th>Statistical uncertainty</th>
<th>Systematic uncertainty</th>
<th>Improvement w.r.t. LEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_\tau )</td>
<td>( 1.5 \times 10^{-6} )</td>
<td>( 10^{-4} )</td>
<td>20</td>
</tr>
<tr>
<td>( R_e )</td>
<td>( 1.5 \times 10^{-6} )</td>
<td>( 3 \times 10^{-4} )</td>
<td>20</td>
</tr>
<tr>
<td>( R_b )</td>
<td>( 5 \times 10^{-5} )</td>
<td>( 3 \times 10^{-4} )</td>
<td>10</td>
</tr>
<tr>
<td>( R_c )</td>
<td>( 1.5 \times 10^{-4} )</td>
<td>( 15 \times 10^{-4} )</td>
<td>10</td>
</tr>
</tbody>
</table>
Precisions on vector and axial neutral couplings

<table>
<thead>
<tr>
<th>fermion type</th>
<th>$g_a$</th>
<th>$g_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>$1.5 \times 10^{-4}$</td>
<td>$2.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$2.5 \times 10^{-5}$</td>
<td>$2.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$0.5 \times 10^{-4}$</td>
<td>$3.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>b</td>
<td>$1.5 \times 10^{-3}$</td>
<td>$1.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>c</td>
<td>$2.0 \times 10^{-3}$</td>
<td>$1.0 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Improvements 1 – 2 orders of magnitudes with respect to LEP, depending on the fermion (Still need to explore the potential for a measurement of the s quark coupling)

See talk of Jorge De Blas for impact on EFT operators
Electroweak physics at FCC-eh

**Electron ring**
- Energy recovery linac: $E_e = 60$ GeV
- Polarisation up to $P_e \sim 80\%$
- Similar concept for LHeC & FCC-eh

**Center-of-mass energies**
- LHeC: $\sqrt{s} \sim 1.3$ TeV
- FCC-eh: $\sqrt{s} \sim 3.5$ TeV
- Up to 1 ab$^{-1}$ integrated luminosity

**EW at FCC-eh in comparison to HERA**
- **CC** Large increase of kinematic range
- **CC** Largely improved experimental precision
- **NC** $\gamma/Z$-interference and ZZ effects will become important (higher $Q^2$)
Precise measurements of $u$, $d$ couplings at FCC-eh

Polarization of the electron beam, up to 80%, improves precision

**Weak neutral quark couplings**
- $u$- and $d$-quark couplings determined simultaneously
- Very precise measurements feasible

Daniel Britzger at 2nd FCC physics workshop
FCC-eh: measurement of the weak scale dependence

Can measure the scale dependence of the neutral coupling up to $\approx 1$ TeV

Note that the definition of $\sin^2 \theta_W$ here is

$$\sin^2 2\theta_W (m_Z)_{\overline{MS}} = \frac{4\pi\alpha}{\sqrt{2} G_F m_Z^2 [1 - \Delta f (m_t, m_h)]}$$

which is $\sin^2 \theta_W = e/g$ where $g$ is the SU(2) weak coupling
W mass and width from WW cross section

At LEP2 \( \sqrt{s}=161 \) GeV with 11/pb \( \Rightarrow m_W=80.40\pm0.21 \) GeV

Sensitivity to mass and width is different at different \( E_{\text{CM}} \): can optimize mass AND width by choosing carefully two energy points.

- Same concept can be used to minimize systematics (e.g. due to backgrounds)
- Centre-of-mass known by resonant depolarization (available at \( \approx 160 \) GeV)
- Luminosity from Bhabha, requirements similar to Z pole case

with \( E_1=157.1 \) GeV \( E_2=162.3 \) GeV \( f=0.4 \)
\( \Delta m_W=0.62 \) \( \Delta \Gamma_W=1.5 \) (MeV)

need syst control on:

- \( \Delta E(\text{beam})<0.35 \) MeV \( (4\times10^{-6}) \)
- \( \Delta \varepsilon/\varepsilon, \Delta L/L < 2 \times 10^{-4} \)
- \( \Delta \sigma_B<0.7 \) fb \( (2 \times 10^{-3}) \)
W mass from di-jet invariant mass (standard at LEP)

- Work in progress, started with the 4-quark channel, exploring resolution and kinematic fits (knowledge of beam energy crucial here, too!)
- Statistical uncertainty at the ≈ 1 MeV level
- Need to investigate how statistics can help in reducing LEP systematics (e.g. fragmentation, jet mass)
- Best result will be provided by the lvqq channel (no color reconnection)
**W decay Branching Fractions**

**W Leptonic Branching Ratios**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>W → eν 10.84 ± 0.09</th>
<th>W → μν 10.59 ± 0.15</th>
<th>W → τν 11.44 ± 0.22</th>
<th>W → lν 10.65 ± 0.17</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>10.78 ± 0.29</td>
<td>10.87 ± 0.26</td>
<td>11.25 ± 0.38</td>
<td>10.65 ± 0.27</td>
</tr>
<tr>
<td>DELPHI</td>
<td>10.55 ± 0.34</td>
<td>10.65 ± 0.27</td>
<td>11.46 ± 0.43</td>
<td>10.61 ± 0.35</td>
</tr>
<tr>
<td>L3</td>
<td>10.78 ± 0.32</td>
<td>10.03 ± 0.31</td>
<td>11.89 ± 0.45</td>
<td>10.61 ± 0.35</td>
</tr>
<tr>
<td>OPAL</td>
<td>10.40 ± 0.35</td>
<td>10.61 ± 0.35</td>
<td>11.18 ± 0.48</td>
<td>10.61 ± 0.35</td>
</tr>
</tbody>
</table>

**W Hadronic Branching Ratio**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>W → hadrons (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>67.13 ± 0.40</td>
</tr>
<tr>
<td>DELPHI</td>
<td>67.45 ± 0.48</td>
</tr>
<tr>
<td>L3</td>
<td>67.50 ± 0.52</td>
</tr>
<tr>
<td>OPAL</td>
<td>67.91 ± 0.61</td>
</tr>
</tbody>
</table>

**Flavor tagging**

- **lepton universality test at 2% level**
  - **tau BR 2.8 σ larger than e/μ**
  - **FCCee @ 4 × 10^{-4} level**

- **quark/lepton universality at 0.6%**
  - **FCCee @ 10^{-4} level**

- **8/ab@160GeV + 5/ab@240GeV**
  - **30M+ 80M W-pairs**

- **ΔBR(qq) (stat) = 10^{-4} (rel)**

- **Δα_S ≈ (9 π/2)ΔBR ≈ 2 × 10^{-4}**

- **ΔBR(e/μ/τν)(stat) = 10^{-4} (rel)**

**Flavor tagging → W coupling to c & b-quarks (V_{cs}, V_{cb} CKM elements)**

**χ^2/ndf = 6.3 / 9**

**χ^2/ndf = 15.4 / 11**

**μ**

**τ**

**τ → e,μ versus e,μ channels**
**FCC-eh**: measurement of W mass from NC/CC ratio

**W-boson mass from NC&CC DIS data**
- All other masses expected to be known
- HERA $\pm 63_{\text{exp}}^{29}_{\text{(PDF)}}$ MeV
- LHeC $\pm 14_{\text{exp}}^{10}_{\text{(PDF)}}$ MeV
- FCC $\pm 9_{\text{exp}}^{4}_{\text{(PDF)}}$ MeV

**High precision for W-boson mass**
- CC kinematics constraint by IS + FS measurements
  - no missing $E_T$ needed
  - IS photon tagging would be crucial
- PDF (QCD) uncertainties are small

---

**W-boson mass**

**expected uncertainties**

- HERA
- LHeC
- FCC
- LHeC & FCC
- PDG [2016] $\pm 15$ MeV


Inner errors: exp. only
Outer errors: exp. + PDF
FCC-ee: probing the TGCs at high precision

- Based on expected luminosity at 161, 240, 350 and 365 GeV
- Consider CP-even dimension 6 operators, SU(2)XU(1) symmetry leaves three independent anomalous couplings
- Include both total cross section and angles
- For the moment only statistical uncertainties
- One order of magnitude improvement with respect to LEP
Precision calculations for the FCC-ee

- From Workshop on EW precision calculations held in January.
- Next decade: complete 3 loop calculation, will provide the needed precision
- Need to invest adequate resources

Matches the demand in precision by the experiment!

Bottom line: YES we will be able to use EWPO with the precision provided by the experiments!
Conclusions

• The efforts of the past 2-3 years have shown that FCC for EW is not just a repetition of LEP with huge statistics: the considerable physics potential has required, and will require new strategies, new solutions and a lot of interesting work for experiment and theory.

• The prize is a gain of 1 – 2 orders of magnitude in precision for EWPO

• Writing of the CDR, describing what has been understood to date, is in progress