Electroweak physics at the Z and W experimental capabilities

Paolo Azzurri – INFN Pisa
FCC week Berlin
May 30th 2017
EWK CDR content

R.Tenchini, F.Piccinini work in progress

• 1. Electroweak physics at the Z pole
  1.a Experimental categorisation of Z decays
  1.b The Z lineshape
  1.c Measurement of the number of neutrino species
  1.d Measurement of Rb and Rc
  1.e Measurement of forward-backward asymmetries

• 2. Electroweak physics at the WW production threshold and above
  2.a Measurement of the W mass and width at threshold
  2.b Measurement of W decay branching fractions
  2.c Direct measurement of W mass and width
  2.d Single and double boson cross sections
  2.e Constraints on gauge couplings
  2.f Radiative Z events
the Tera Z pole precision

\[ L \sim 2 \times 10^{36} \Rightarrow \sim 4 \times 10^{12} \text{ Z decays} \]

Continuous \( E_{\text{CM}} \) calibration (resonant depolarization)

Z mass and width: 10 KeV (stat) + 100 KeV (syst)

Radiation function calculated up to \( O(\alpha^3) : 10^{-4} \) precision

Relative precisions [JHEP01(2014)164]

- \( R_l \) hadronic/leptonic width: \( 5 \times 10^{-5} \)
- \( R_b \) Zbb partial width: \( 5 \times 10^{-5} \)
- Invisible width: \( 10^{-3} \) \( N_\nu \) (Z\( \gamma \))

\[
\Delta_{\text{rel}} \alpha_s(m_Z^2) : 2 \times 10^{-3}
\]

\[
\Delta_{\text{rel}} \alpha_{\text{QED}}(m_Z^2) : 3 \times 10^{-5}
\]
Z pole acceptance

- @LEP acceptance effects at $10^{-4}$ OK for cross sections at $10^{-3}$ level. Main effects were due to track losses, angle mis-measurements and knowledge of boundaries.
- @FCCee exploit a statistical uncertainty at $10^{-5}$ !

Example from ALEPH, EPJC 14 (2000) 1

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta\sigma/\sigma$ (%)</th>
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</thead>
<tbody>
<tr>
<td>Acceptance</td>
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</tr>
<tr>
<td>Momentum calibration</td>
<td>0.006 (0.009)</td>
</tr>
<tr>
<td>Momentum resolution</td>
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</tr>
<tr>
<td>Photon energy</td>
<td>0.05</td>
</tr>
<tr>
<td>Radiative events</td>
<td>0.05</td>
</tr>
<tr>
<td>Muon identification</td>
<td>$\approx 0.001 (0.02)$</td>
</tr>
<tr>
<td>Monte Carlo statistics</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.10 (0.11)</strong></td>
</tr>
</tbody>
</table>

@LEP detectors inner edge (relevant boundary) was known at the level of up to 20 μm
The beam displacement (vertical and horizontal) becomes ineffective by choosing two fiducial regions (loose and tight) and alternating them in the two sides

@FCCee can use similar methods for cross sections measurements (e.g. different and alternating forward and backward fiducial regions), but still need to identify and know well the relevant boundaries (~1μm level)
couplings and $R_b$

couplings measurements require asymmetry and width ratios

$$A_{FB}(b) = \frac{\sigma_F - \sigma_B}{\sigma_{tot}} = \frac{3}{4} A_e A_b \ (LEP) \quad \rightarrow \quad \frac{g_{Vf}}{g_{Af}}$$

$$R_b = \frac{\Gamma(Z \rightarrow b\bar{b})}{\Gamma_{had}} \quad A_b = A_{FB}^{pol}(b) = 0.921 \pm 0.021 \ (SLC) \quad \rightarrow \quad (g_{Af})^2 + (g_{Vf})^2$$

- $R_b$ Very sensitive to rad. vertex corrections due to new particles
- Important to sort out LEP b-couplings issue
- Measurement exploits the presence of two b hadrons and b-tagging.
- **Independent** from b-tagging efficiency, but not from hemisphere correlations
- Higher b-tagging performance (vertex detectors) helps in reducing the correlation
- Correlations sources should be identified and studied with data (done at LEP)

$$\Delta R_b \approx 1 \ (5-20) \ 10^{-5} \ stat \ (syst) \quad \Delta R_c \approx 3 \ (50) \ 10^{-5} \ stat \ (syst)$$
Z asymmetries

- Z boson decay to ff : 3 observables from the direction and decay of the outgoing fermion

\[
A_f = \frac{2g_{Vf}g_{Af}}{(g_{Vf})^2 + (g_{Af})^2} \\
\sin^2 \theta_{eff} \equiv \frac{1}{4} \left( 1 - \frac{g_{Vl}}{g_{Al}} \right)
\]

\[
A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_{tot}} = \frac{3}{4} A_e A_f \quad \text{Can measure for } e, \mu, \tau, c, b
\]

\[
A_{pol} = \frac{\sigma_{F,R} + \sigma_{B,R} - \sigma_{F,L} - \sigma_{B,L}}{\sigma_{tot}} = -A_f \quad \text{Can measure with } \tau' \text{'s}
\]

\[
A_{pol}^{FB} = \frac{\sigma_{F,R} - \sigma_{B,R} - \sigma_{F,L} + \sigma_{B,L}}{\sigma_{tot}} = -\frac{3}{4} A_e
\]

- Additional asymmetries with polarization of initial state:

\[
A_{LR} = \frac{\sigma_l - \sigma_r}{\sigma_{tot}} = A_e
\]

\[
A_{FB}^{pol} = \frac{\sigma_{F,l} - \sigma_{B,l} - \sigma_{F,r} + \sigma_{B,r}}{\sigma_{tot}} = \frac{3}{4} A_f
\]
Z asymmetries

FCCee will sizably improve $b$ asymmetry
  • use semileptonic $b$ decays
  • use weighted charge of particles in the hemisphere
  • different systematic effects [QCD corrections to be improved]

$\Delta A_b \approx 2 (40) \times 10^{-5}$ stat (syst) $\Delta A_c \approx 3 (40) \times 10^{-5}$ stat (syst)

tau polarization $A$
Polarization vs the production angle allows $A_e$ to be separated from $A_\tau$:
Universality test and $\sin^2 \theta_W$

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

$A_{FB}(\mu^+\mu^-)$ and $A_{FB}(\tau^+\tau^-)$ can also be considerably improved. $A_{FB}(e^+e^-)$ more difficult because of t-channel.

$\Delta A_\tau \approx 4 (30) \times 10^{-5}$ stat (syst) $\Delta A_e \approx 5 (10) \times 10^{-5}$ stat (syst)

$\Delta_{rel} \sin^2 \theta_{eff} \approx 2 \times 10^{-5}$ (syst)

S-matrix approach is desirable: trade statistical power for reduced theoretical assumptions
# Z pole summary

from A. Blondel

<table>
<thead>
<tr>
<th>$X$</th>
<th>Physics</th>
<th>Present precision</th>
<th>TLEP stat Syst Precision</th>
<th>TLEP key</th>
<th>Challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_Z$ MeV</td>
<td>Input</td>
<td>91187.5 ±2.1</td>
<td>Z Line shape scan</td>
<td>0.005 MeV &lt;±0.1 MeV</td>
<td>$E_{CM}$</td>
</tr>
<tr>
<td>$\Gamma_Z$ MeV</td>
<td>$\Delta\rho \ (T) \ (\text{no } \Delta\alpha !)$</td>
<td>2495.2 ±2.3</td>
<td>Z Line shape scan</td>
<td>0.008 MeV &lt;±0.1 MeV</td>
<td>$E_{CM}$</td>
</tr>
<tr>
<td>$R_l$</td>
<td>$\alpha_s, \delta_b$</td>
<td>20.767 ±0.025</td>
<td>Z Peak</td>
<td>0.00001 ± 0.002</td>
<td>Statistics</td>
</tr>
<tr>
<td>$N_{\nu}$</td>
<td>Unitarity of PMNS, sterile $\nu$'s</td>
<td>2.984 ±0.008</td>
<td>Z Peak</td>
<td>0.000008 ±0.004 0.001</td>
<td>$\rightarrow$lumi</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$\delta_b$</td>
<td>0.21629 ±0.00066</td>
<td>Z Peak</td>
<td>0.000003 ±0.000020 - 60</td>
<td>Statistics, small IP</td>
</tr>
<tr>
<td>$A_{FB}$</td>
<td>$\Delta\rho, \varepsilon_3, \Delta\alpha \ (T, S)$</td>
<td>0.0171 ±0.0010</td>
<td>Z peak</td>
<td>0.0000003 ±0.00001</td>
<td></td>
</tr>
</tbody>
</table>
Direct measurement of $\alpha_{\text{QED}}(m_Z^2)$

Patrick Janot: arXiv:1512:05544, JHEP 2016(2) 1

High precision of FCCee will require higher order perturbative calculations: a bottleneck will be represented by the hadronic contributions to the vacuum polarization

Rely of a self-normalizing quantity, the forward-backward asymmetry

$$A_{\mu\mu}^{FB} = A_{FB,0}^{\mu\mu} + \frac{3}{4} \frac{a^2}{v^2} \frac{Z}{G+Z}.$$  

$$\sigma(A_{FB}^{\mu\mu}) = \sqrt{1 - \frac{A_{FB,0}^{\mu\mu}}{G} \frac{Z+G}{Z-G}}.$$  

$$\frac{\Delta\alpha}{\alpha} = \frac{\Delta A_{FB}^{\mu\mu}}{A_{FB}^{\mu\mu} - A_{FB,0}^{\mu\mu}} \times \frac{Z+G}{Z-G} \approx \frac{\Delta A_{FB}^{\mu\mu}}{A_{FB}^{\mu\mu}} \times \frac{Z+G}{Z-G}.$$  

$\sigma(\alpha)/\alpha$ plot, for a year of running at any $\sqrt{s}$

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

Two measurements:

$$\alpha_- \equiv \alpha_{\text{QED}}(s_-) \text{ and } \alpha_+ \equiv \alpha_{\text{QED}}(s_+)$$

Solve for $\alpha_0 = \alpha_{\text{QED}}(m_Z^2)$

$$\frac{\Delta \alpha_0}{\alpha_0} \approx 0.528 \frac{\Delta A_{FB}}{A_{FB}}(s_-) + 0.563 \frac{\Delta A_{FB}}{A_{FB}}(s_+)$$

<table>
<thead>
<tr>
<th>Type</th>
<th>Source</th>
<th>Uncertainty</th>
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<tbody>
<tr>
<td>Experimental</td>
<td>$E_{\text{beam}}$ calibration</td>
<td>$1 \times 10^{-5}$</td>
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<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, IFI)</td>
<td>$&lt; 10^{-6}$</td>
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<tr>
<td></td>
<td>Missing EW higher orders</td>
<td>few 10</td>
</tr>
<tr>
<td></td>
<td>New physics in the running</td>
<td>0.0</td>
</tr>
<tr>
<td>Total (except missing EW higher orders)</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>

IFI at better than 1% to reach the required precision on $\alpha_{\text{QED}}(m_Z^2)$: work in progress

Box + Vertex EW correction
the OkuW

$\sqrt{s}=161 : L \sim 4 \times 10^{35} \text{ collect } 8/\text{ab }$

$30 \times 10^6 \text{ WW decays}$

$\sqrt{s}=240 : L \sim 0.9 \times 10^{35} \text{ collect } 5/\text{ab }$

$80 \times 10^6 \text{ WW decays}$
**WW threshold**

**Graph 1:**
- 68% and 95% CL contours
- fit w/o $M_W$ and $m_t$ measurements
- fit w/o $M_W$, $m_t$, and $M_H$ measurements
- direct $M_W$ and $m_t$ measurements

**Graph 2:**
- LEP PRELIMINARY
- $\Delta m_W = \frac{d\sigma}{dm_W} \Delta\sigma$

**Notes:**
- At LEP2 $\sqrt{s}=161$ GeV $\sigma=4$pb
- $\epsilon=0.75$, $\sigma_B=300$ fb
- $\rho=0.9 : \epsilon\rho \approx 0.68$ (@161)
- $m_W = 80.40 \pm 0.21$ GeV
- with $11$/pb @ $E_{CM}=161$ GeV
$m_W$ from $\sigma_{WW}$: sensitivity vs $E_{CM}$

$\sigma_{WW}$ with YFSWW3 $1.18$

$m_W=80.385$ GeV

**Max stat sensitivity at $\sqrt{s}\sim 2m_W + 600$ MeV**

- $\sqrt{\epsilon}p$ with fixed: $\epsilon=0.75$ and $\sigma_B=0.3$ pb

**statistical precision**

- with $L = 11$/pb $\Rightarrow \Delta m_W \approx 350$ MeV
- with $L = 8$/ab $\Rightarrow \Delta m_W \approx 0.40$ MeV

**need syst control on:**

- $\Delta E(\text{beam}) < 0.40$ MeV ($5 \times 10^{-6}$)
- $\Delta \epsilon/\epsilon$, $\Delta L/L < 10^{-4}$
- $\Delta \sigma_B < 0.7$ fb ($2 \times 10^{-3}$)
**Γ_w from σ_{WW}**

Measure σ_{ww} in two energy points E_1, E_2 with a fraction f of lumi in E_1

→ determine both m_W & Γ_w

Determine f, E_1, E_2 such to minimize (ΔΓ_w, Δm_W) with some target

Evaluate loss of Δm_w precision in the single parameter (m_W) determination wrt scenario of running only at an optimal E_0=161 point

\[ \frac{dσ_{WW}}{dΓ_w} = 0 \]

at \( E_{CM} \sim 162.3 \) GeV

\( \sim 2m_W + 1.5 \) GeV
$m_W$ & $\Gamma_W$ from $\sigma_{WW}$

$m_W = 80.385$ GeV  \hspace{0.2cm} $\Gamma_W = 2.085$ GeV

$\Delta m_W$, $\Delta \Gamma_W$: error on W mass and width from fitting both

$\Delta m_W$: error on W mass from fitting only $m_W$

with $E_1 = 157.1$ GeV \hspace{0.2cm} $E_2 = 162.3$ GeV \hspace{0.2cm} $f = 0.4$

$\Delta m_W = 0.62$ \hspace{0.2cm} $\Delta \Gamma_W = 1.5$ \hspace{0.2cm} $\Delta m_W = 0.56$ (MeV)

$\Rightarrow \Delta \alpha_S \approx (3\pi/2)\Delta \Gamma/\Gamma \approx 0.003$
acceptance

how do we control acceptance at the $10^{-4}$ level (0.01%) ?

aim for the highest possible acceptance and efficiency WP

• lepton tracking reco efficiency (was controlled at the $10^{-3}$ level at LEP2)
• lepton identification performances
  • @LEP2 $10^{-3}$ level: (T&P with Z): effects on total $\Delta \sigma$ mitigated down to the 2-3 $10^{-4}$ level thanks to $\tau \rightarrow e, u$ channel migrations recoveries
  • would need lepton-id at $10^{-4}$ level for max BR precision
• jet reconstruction and energy calibration
  • @LEP2 1-2% level $\Rightarrow$ 0.1% on $\Delta \varepsilon$:
  • FCCee would need calibration at 0.1% level (10x better) with control data ; best possible jet energy resolution helps
• missing momentum scale/resolution : similar to jet energy for qqlv
• lepton isolation
  • @LEP2 control at the $\Delta \varepsilon \sim 2 \times 10^{-3}$ level: need to do 10x better
• jet modeling (signal & bkg)
  • was important syst on $\sigma_{WW}@LEP2$ (at the 2 $10^{-3}$ level)

impact of theoretical uncertainties will hopefully not be limiting but work is needed to reach the target $0.5 \times 10^{-3}$ precision level
background control

<table>
<thead>
<tr>
<th>decay</th>
<th>efficiency</th>
<th>purity</th>
<th>bkg</th>
<th>[LEP1996]</th>
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</thead>
<tbody>
<tr>
<td>lνlν</td>
<td>70-80%</td>
<td>80-90%</td>
<td>50fb (ττ,γγ→ττ,Zγ*→ννll)</td>
<td></td>
</tr>
<tr>
<td>eνqq</td>
<td>85%</td>
<td>~90%</td>
<td>30fb (qq, Zee, Zγ*)</td>
<td>-10fb (Wev)</td>
</tr>
<tr>
<td>μνqq</td>
<td>90%</td>
<td>~95%</td>
<td>10fb (Zγ*,qq)</td>
<td></td>
</tr>
<tr>
<td>τνqq</td>
<td>50%</td>
<td>80-85%</td>
<td>50fb (qq, Zγ*)</td>
<td></td>
</tr>
<tr>
<td>qqqq</td>
<td>90%</td>
<td>~90%</td>
<td>~200fb (qq (qqqq,qqgg))</td>
<td></td>
</tr>
</tbody>
</table>

some 4f bkg is identical to the signal final state \( \rightarrow \) CC03-4f interferences

measure directly the **backgrounds** with very different S/B levels **at different** \( E_{cm} \) **points**

measure forward electrons (\( θ ≥ 0.1 \) rad) for Zee Wev : determine forward pole \( dσ/dθ \) and WW interference effects

acceptance down to \( θ = 0.1 \) [\( \cosθ = 0.995 \)] would also cover forward jets

limiting **correlated** syts can cancel out taking data at more \( E_{cm} \) points where

\[
\left( \frac{dσ}{dΓ_W} \right)^{-1} \quad \left( \frac{dσ}{dm_W} \right)^{-1} \quad \left( \frac{dσ}{dm_W} \right)^{-1} \quad \left( \frac{dσ}{dm_W} \right)^{-1} \quad \left( \frac{dσ}{dΓ_W} \right)^{-1} \quad \sigma
\]

differential factors are equal
W BR

Winter 2005 - LEP Preliminary

**W Leptonic Branching Ratios**

- **ALEPH**
  - $W \rightarrow e\nu$: 10.78 ± 0.29
  - $W \rightarrow \mu\nu$: 10.87 ± 0.26
  - $W \rightarrow \tau\nu$: 11.44 ± 0.22

- **DELPHI**
  - $W \rightarrow e\nu$: 10.55 ± 0.34
  - $W \rightarrow \mu\nu$: 10.65 ± 0.27
  - $W \rightarrow \tau\nu$: 11.46 ± 0.43

- **L3**
  - $W \rightarrow e\nu$: 10.78 ± 0.32
  - $W \rightarrow \mu\nu$: 10.03 ± 0.31
  - $W \rightarrow \tau\nu$: 11.89 ± 0.45

- **OPAL**
  - $W \rightarrow e\nu$: 10.40 ± 0.35
  - $W \rightarrow \mu\nu$: 10.61 ± 0.35
  - $W \rightarrow \tau\nu$: 11.18 ± 0.48

**ALEPH**

23/02/2005

2005 - LEP Preliminary

**W Hadronic Branching Ratio**

- **ALEPH**
  - $W \rightarrow e\nu$: 67.13 ± 0.40

- **DELPHI**
  - $W \rightarrow e\nu$: 67.45 ± 0.48

- **L3**
  - $W \rightarrow e\nu$: 67.50 ± 0.52

- **OPAL**
  - $W \rightarrow e\nu$: 67.91 ± 0.61

**ALEPH**

23/02/2005

8/ab@160GeV + 5/ab@240GeV

⇒ 30M+ 80M W-pairs

⇒ $\Delta BR(qq) \text{ (stat)} = [1] \times 10^{-4} \text{ (rel)}$

⇒ $\Delta \alpha_S \approx (9 \pi/2) \Delta BR \approx 10^{-3}$

⇒ $\Delta BR(e/\mu/\tau\nu) \text{(stat)} = [4] \times 10^{-4} \text{ (rel)}$

$q/ \ell$ universality at 0.6%

⇒ FCCee @ $10^{-4}$ level

Lept universality test at 2% level
tau BR ~2.7 σ larger than $e/\mu$
⇒ FCCee @ $4 \times 10^{-4}$ level

will need much better control of lepton id
i.e. cross contaminations in signal channels
( $\tau \rightarrow e,\mu$ in the $e,\mu$ channels and v.v.)

Flavor tagging would also allow to measure coupling to c & b-quarks (Vcs, Vcb,..)

FCC week Berlin 30/05/17
P. Azzurri -- FCee experimental EW Z and W capabilities
18
reco mass of the W boson

full $m_W$ reco with kinematic fit. main ingredients:
$E_{CM}$ – jet/lepton angles – (jet boost)

$M_Z^2 = s \frac{\beta_1 \sin \theta_1 + \beta_2 \sin \theta_2 - \beta_1 \beta_2 | \sin (\theta_1 + \theta_2) |}{\beta_1 \sin \theta_1 + \beta_2 \sin \theta_2 + \beta_1 \beta_2 | \sin (\theta_1 + \theta_2) |}$


ignoring low energy particles in the qqqq channel

$m_W = 80440 \pm 43(\text{stat.}) \pm 24(\text{syst.}) \pm 9(\text{FSI}) \pm 9(\text{LEP})$ MeV

$\Gamma_W = 2140 \pm 90(\text{stat.}) \pm 45(\text{syst.}) \pm 46(\text{FSI}) \pm 7(\text{LEP})$ MeV
reco mass of the W boson

8/ab@160GeV + 5/ab@240GeV ➔ 30M+80M W-pairs ➔ Δm_W (stat)= 0.5 MeV

Is ΔE_{beam}<1MeV at E_{CM}=240 GeV possible? With Zγ events?

Δm_W (syst) ≤ 1 MeV?

Table 9: Summary of the systematic errors on m_W and Γ_W in the standard analysis averaged over 183-209 GeV for all semileptonic channels. The column labelled ℓνq̅ lists the uncertainties in m_W used in combining the semileptonic channels.

<table>
<thead>
<tr>
<th>Source</th>
<th>Δm_W (MeV/c²)</th>
<th>ΔΓ_W (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>eνq̅</td>
<td>μνq̅</td>
</tr>
<tr>
<td>e+µ momentum</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>e+µ momentum resoln</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Jet energy scale/linearity</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Jet energy resoln</td>
<td>4</td>
<td>2</td>
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<tr>
<td>Jet angle</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Jet angle resoln</td>
<td>3</td>
<td>2</td>
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<tr>
<td>Jet boost</td>
<td>17</td>
<td>17</td>
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<tr>
<td>Fragmentation</td>
<td>10</td>
<td>10</td>
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<tr>
<td>Radiative corrections</td>
<td>3</td>
<td>2</td>
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<tr>
<td>LEP energy</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Calibration (eνq̅ only)</td>
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<td>-</td>
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<tr>
<td>Ref MC Statistics</td>
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<td>3</td>
</tr>
<tr>
<td>Bkgnd contamination</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>
TGCs (also at threshold)

\(SU(2) \otimes U(1)\) Gauge Cancellations

\[
\begin{align*}
|\text{We}_V + \gamma WW + ZWW|^2 \\
|eV + \gamma WW|^2 \ (\text{no } ZWW) \\
|eV|^2 \ (\text{no TGCs}) \\
|\gamma WW|^2 \\
|ZWW|^2
\end{align*}
\]

without TGCs

\[
\sigma_{WW} + 40\% @ 157\text{GeV} \ + 25\% @ 162\text{GeV}
\]

while \(\Delta \sigma/\sigma \approx 0.5 \times 10^{-3}\)

LEP2 limits: \(\kappa, \lambda < 2 - 6 \times 10^{-2}\)
Conclusions

• FCC ee is a total game-changer for EW W/Z physics measurements
• No “a priori” walls on the road map to achieve the FCC goals for EW precision measurements but a lot of work, firstly on the theoretical calculations side
• At the Z, off peak data will play an important role (more than at LEP times)
  – can deliver $a_{\text{QED}}(m_Z^2)$ to $3 \times 10^{-5}$
• The WW threshold lineshape is a great opportunity to measure both $m_W$ and $\Gamma_W$
  – optimal points to take data are $\sqrt{s}=2m_w+1.5$ GeV (Γ-insensitive) and $\sqrt{s}=2m_w-2$-3 GeV (-Γoff shell)
• Huge potential for other W physics measurements including higher energy data still need to be explored with attention
  – direct $m_W$, W BRs, TGCs
• Work from experimentalist needed to evaluate with care limiting systematics, study ways to overcome them, and reflect on the detector design consequences: opportunities to contribute
• The potential of FCCee data for EW Z/W measurements needs to be fully unraveled