Update on W mass measurement studies at FCC-ee

Marina Béguin
On behalf of the WG2 working group

June 25, 2019
$\sqrt{s} = 160 \text{ GeV}, L = 12 \text{ ab}^{-1}$
$\rightarrow 60 \cdot 10^6 \text{ WW}$

$\sqrt{s} = 240 \text{ GeV}, L = 5 \text{ ab}^{-1}$
$\rightarrow 80 \cdot 10^6 \text{ WW}$

$\sqrt{s} = 365 \text{ GeV}, L = 1.7 \text{ ab}^{-1}$
$\rightarrow 20 \cdot 10^6 \text{ WW}$
WW diboson physics at FCC-ee

- Measurements of the W mass and width directly and with threshold scan;
- W partial branching ratios;
- Strong coupling constant;
- CKM matrix;
- Gauge self-couplings ...

... with unprecedented accuracy
Precise relation between $M_W$, $M_H$, $M_t$ is a crucial test of the internal consistency of SM and failure might reveal new physics.

Methods

- At WW threshold;
- Direct determination
\( \Delta M_{W, \text{stat}} = \left( \frac{d\sigma}{dM_W} \right)^{-1} \Delta \sigma \)
\[ \Delta M_{W, \text{stat}} = \left( \frac{d\sigma}{dM_W} \right)^{-1} \frac{\sqrt{\sigma}}{\sqrt{\mathcal{L}}} \frac{1}{\sqrt{\epsilon p}} \]

with 
\[ p = \frac{\epsilon \sigma}{\epsilon \sigma + \sigma_B} \]
\[ \Delta M_{W,\text{stat}} = \left( \frac{d\sigma}{dM_W} \right)^{-1} \frac{\Delta \sigma}{\sqrt{\mathcal{L}}} \frac{1}{\sqrt{\frac{\sqrt{\mathcal{L}}}{\sqrt{\epsilon p}}} \right) \\
\oplus \left( \frac{d\sigma}{dM_W} \right)^{-1} \frac{\Delta \sigma_B}{\epsilon} \\\n\oplus \left( \frac{d\sigma}{dM_W} \right)^{-1} \sigma \left( \frac{\Delta \epsilon}{\epsilon} \oplus \frac{\Delta \mathcal{L}}{\mathcal{L}} \right) \]
$M_W$ at WW threshold

**Optimal energy**: $E = 161.4$ GeV

$\Delta M_W = 0.23$ MeV

**LEP**: $\Delta M_W = 210$ MeV

$L = 10$ pb$^{-1}$

LEP : $\Delta M_W = 210$ MeV

$L = 12$ ab$^{-1}$

$\epsilon = 0.75$

$\sigma_B = 0.3$ pb
$M_W$ at WW threshold

Optimal energy : $E = 161.4$ GeV
$\Delta M_W = 0.23$ MeV

LEP : $\Delta M_W = 210$ MeV
$L = 10$ pb$^{-1}$

\[
\Delta M_{W,stat} = \left( \frac{d\sigma}{dM_W} \right)^{-1} \sqrt{\frac{\sigma}{\sqrt{L}} \frac{1}{\epsilon p}}
\]
\[
\oplus \left( \frac{d\sigma}{dM_W} \right)^{-1} \frac{\Delta\sigma_B}{\epsilon}
\]
\[
\oplus \left( \frac{d\sigma}{dM_W} \right)^{-1} \sigma \left( \frac{\Delta\epsilon}{\epsilon} \oplus \frac{\Delta L}{L} \right)
\]

Need systematic controls on:
- $\Delta\sigma_B < 0.6$ fb ($2 \cdot 10^{-3}$)
- $\left( \frac{\Delta\epsilon}{\epsilon} \oplus \frac{\Delta L}{L} \right) < 2 \cdot 10^{-4}$
- $\Delta\sigma_{theory} < 0.8$ fb ($2 \cdot 10^{-4}$)
- $\Delta E_{CM} < 0.2$ MeV ($2 \cdot 10^{-6}$)
$M_W$ and $\Gamma_W$ at WW threshold

Optimal combination:

$E_1 = 157.1$ GeV, $E_2 = 162.3$ GeV, $f = 0.4$

$\Delta M_W = 0.4$ MeV and $\Delta \Gamma_W = 1.2$ MeV

With resonant depolarisation, $E_b = 0.4406486(\nu + 0.5)$ GeV

$E_1 = 157.3$ GeV, $E_2 = 162.6$ GeV, $f = 0.4$

$\Delta M_W = 0.45$ MeV and $\Delta \Gamma_W = 1.3$ MeV
Effect of the energy spread ($\sigma_E$):

$$\delta \sigma_W \sim \frac{1}{2} \frac{d^2 \sigma_W}{dE^2} \sigma_E^2$$

$$\frac{\sigma_E}{E} = a$$

$\sigma_E$ measured/monitored with $e^+e^- \rightarrow \mu^+\mu^-$ events.

At FCCee the energy spread will be measured with a relative precision of better than 0.2% →**Negligible** contribution on $\Delta M_W$ and $\Delta \Gamma_W$. 
Direct reconstruction of $M_W$ and $\Gamma_W$

Hadronic decay channel

*Study at 162.6 GeV, 240 GeV and 365 GeV*

- PYTHIA simulation
- Reconstruction with Heppy (CLD detector, Durham algorithm)

$W$ mass estimators:

- **Raw mass**
- **4C jets momenta rescaling**
- **Kinematic fit** with energy-momentum conservation (4C) and $W$ masses equality (5C)
Direct reconstruction of $M_W$ and $\Gamma_W$ Hadronic decay channel

Statistical uncertainty estimated with a **binned maximum likelihood fit** on the reconstructed $M_W$ distributions, using **templates** with different nominal $W$ mass(width) values.

- @162.6 GeV
  $\Delta \Gamma_W(4C) = 1.11$ MeV
- @240 GeV
  $\Delta \Gamma_W(5C) = 0.48$ MeV
- @365 GeV
  $\Delta \Gamma_W(5C) = 1$ MeV

Full FCCee luminosity
Direct reconstruction of $M_W$ and $\Gamma_W$
Semi-leptonic decay channel

Study at 162.6 GeV, 240 GeV and 365 GeV

Only the muon decay

\[ \nu \mu qq \rightarrow WW \]

5C kinematic fit
4C kinematic fit
Raw Mass

\[ @162.6 \text{ GeV} \quad \Delta \Gamma_W(1C) = 0.35 \text{ MeV} \]
\[ @240 \text{ GeV} \quad \Delta \Gamma_W(2C) = 0.68 \text{ MeV} \]
\[ @365 \text{ GeV} \quad \Delta \Gamma_W(2C) = 1.56 \text{ MeV} \]

\[ \Delta M_{W, \text{stat}} / 12 \text{ ab}^{-1} @ 162.6 \text{ GeV} \]
\[ \Delta M_{W, \text{stat}} / 5 \text{ ab}^{-1} @ 240 \text{ GeV} \]
\[ \Delta M_{W, \text{stat}} / 1.7 \text{ ab}^{-1} @ 365 \text{ GeV} \]

Full FCCee luminosity
### Systematic uncertainties

**Main sources of systematic uncertainties at LEP2:**

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic Uncertainty in MeV on $m_W$</th>
<th>Systematic Uncertainty in MeV on $\Gamma_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$q\bar{q}\nu\bar{\nu}$</td>
<td>$q\bar{q}q\bar{q}$</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Hadronisation</td>
<td>13</td>
<td>19</td>
</tr>
<tr>
<td>Detector effects</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>LEP energy</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Colour reconnection</td>
<td>–</td>
<td>35</td>
</tr>
<tr>
<td>Bose-Einstein Correlations</td>
<td>–</td>
<td>7</td>
</tr>
<tr>
<td>Other</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Total systematic</td>
<td>21</td>
<td>44</td>
</tr>
<tr>
<td>Statistical</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Statistical in absence of systematics</td>
<td>30</td>
<td>31</td>
</tr>
<tr>
<td>Total</td>
<td>36</td>
<td>59</td>
</tr>
</tbody>
</table>

**\(\sqrt{s} \) [GeV]**

<table>
<thead>
<tr>
<th>(\delta M_{FSI} ) [MeV]</th>
<th>162.6 standard</th>
<th>240 standard</th>
<th>365 standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKI</td>
<td>14.6</td>
<td>24.1</td>
<td>32.2</td>
</tr>
<tr>
<td>SKII</td>
<td>8</td>
<td>12.5</td>
<td>15.1</td>
</tr>
<tr>
<td>BEC</td>
<td>3.3</td>
<td>5.9</td>
<td>10.2</td>
</tr>
</tbody>
</table>

**\(\Delta M_{W,stat} \)** is degraded with the cone by a few percents at threshold and 10-15% above.

**FSI simulated with Pythia (SKI/SKII).**

\(\delta M_{W,FSI} \) reduced using a cone (0.4 rad) on jets.

![Graph showing CLD detector WW → qqqq with and without FSI](image)

- **Mean (162.6 GeV):** 82.38 ± 9.568
- **Mean (240 GeV):** 80.85 ± 10.26

**W study at FCC-ee**

June 25, 2019
Other opportunities with W physics at FCC-ee
Probing the TGCs

Marina Béguin

W study at FCC-ee

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LEP: TGCs constrained at few % level

\[ \mathcal{L}_{SM} \xrightarrow{BSM} \mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i \quad i = 1, 6 \]

Focus on CP-even dimension 6 operators

\[ \mathcal{L}_{TGC} = f(\delta g_{1,z}, \delta \kappa_z, \delta \kappa_\gamma, \lambda_Z, \lambda_\gamma) \]

Gauge inv. \( \rightarrow \delta \kappa_z = \delta g_{1,z} - \tan^2(\theta_W) \delta \kappa_\gamma \)

\[ \lambda_\gamma = \lambda_Z \]

In the semi-leptonic channel

\[ d\sigma_{WW} = f(\theta_W, \theta_1^*, \Phi_1^*, \theta_2^*, \Phi_2^*) \]
\[ \frac{B_q}{1 - B_q} = 3 \left(1 + \frac{\alpha_s(m_W^2)}{\pi}\right) \sum_{i=u,c;j=d,s,b} |V_{ij}|^2 \]

\[ \Delta B r_q / B r_q = 10^{-4} \]

\[ \rightarrow \Delta \alpha_s \sim 9 \pi / 2 \Delta B r_q \sim 2 \cdot 10^{-4} \]

assuming CKM unitarity.

\[ \text{With } B_q \text{ and } \alpha_s \text{ precisely measured} \]

CKM unitarity tested at \(10^{-4}\).

Flavour tagging

\[ \rightarrow W \text{ coupling to } b \& c \text{ quarks} \]

\(V_{cs}, V_{cb}\)

\(B r_\tau > B r_e, B r_\mu(2.8\sigma)\)

LEP : test at 2\% level (lept. universality)

FCCee test at \(4 \cdot 10^{-4}\)

\(q/l\) universality at 0.6\%

\[ \text{Requires excellent control of jet reconstruction and lepton identification i.e. cross-contamination and correlation between channels (} \tau \rightarrow e, \mu) \]
Conclusion

The amount of $W$-pairs at different centre-of-mass energies presents a huge potential for the $W$ physics measurements.

- Measurement of $M_W$ and $\Gamma_W$ simultaneously at the $W$-pair production threshold with high precision ($\Delta M_W = 0.45$ MeV).
- Direct $M_W$ and $\Gamma_W$ measurements at threshold and above. Best statistical uncertainty expected at higher energies ($\Delta M_W = 0.28$ MeV at 240 GeV and $\Delta M_W = 0.46$ MeV at 365 GeV in the hadronic decay channel).
- Other $W$ physics measurements: improvements of the gauge couplings sensitivity, $W$ decay couplings at $10^{-4}$ level ($\alpha_s(M_W^2)$ and CKM matrix).
BACK-UP
Color Reconnection (CR) : interaction between partons of the two Ws

\[ e^+ e^- \rightarrow WW \rightarrow q_1 \bar{q}_2 q_3 \bar{q}_4 \]

Because WW separation in phase-space is smaller than the typical distance scale of hadronisation: \((q_1 \bar{q}_4)\) and \((q_3 \bar{q}_2)\)

Models in Pythia for \(e^+e^-\) collisions are based on string hadronisation.

- SK1 : string = cylindrical bag. Colour reconnection probability proportional to the integrated overlap between cylinders.
- SK2 : string = vortex line. Colour reconnection if the cores are crossing.
W mass distributions - Hadronic channel

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W study at FCC-ee
June 25, 2019
W mass distributions - Semi leptonic channel

40 50 60 70 80 90 100 110 120 (hadronic mass) \[GeV\]

**Mean** 81.52
**Std Dev** 3.868

**Mean** 81.9
**Std Dev** 4.03

162.6 GeV

**Mean** 82.55
**Std Dev** 6.001

**Mean** 82.15
**Std Dev** 10.73

**Mean** 84.62
**Std Dev** 13.27

240 GeV

**Mean** 82.55
**Std Dev** 6.009

**Mean** 81.15
**Std Dev** 10.73

**Mean** 84.62
**Std Dev** 13.27

365 GeV

**Mean** 82.94
**Std Dev** 9.855

**Mean** 82.28
**Std Dev** 10.06

**Mean** 80.58
**Std Dev** 13.23

**Mean** 85.39
**Std Dev** 18.8

4C kinematic fit

5C kinematic fit

Raw Mass

\[\nu \mu qq \rightarrow WW\]

4C kinematic fit

5C kinematic fit

Raw Mass
**W mass and width statistical uncertainties**

**Table: Hadronic decay**

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [GeV/c$^2$]</th>
<th>$\sigma_{M_W}$ [MeV/c$^2$]</th>
<th>$\sigma_{\Gamma_W}$ [MeV/c$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>162.6 240 365</td>
<td>162.6 240 365</td>
</tr>
<tr>
<td>Luminosity ($ab^{-1}$)</td>
<td>12 5 1.7</td>
<td>12 5 1.7</td>
</tr>
<tr>
<td>Raw Mass</td>
<td>1.66 0.49 0.97</td>
<td>1.44 1.10 1.71</td>
</tr>
<tr>
<td>4C rescaling</td>
<td>1.72 0.36 0.73</td>
<td>1.53 0.77 1.48</td>
</tr>
<tr>
<td>4C fit</td>
<td>1.14 0.28 0.51</td>
<td>1.1 0.58 0.95</td>
</tr>
<tr>
<td>5C fit</td>
<td>0.22 0.45</td>
<td>0.47 1.02</td>
</tr>
</tbody>
</table>

With threshold method $\sigma_{M_W} = 0.23$ GeV

**Table: Semi-leptonic decay**

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<thead>
<tr>
<th>$\sqrt{s}$ [GeV/c$^2$]</th>
<th>$\sigma_{M_W}$ [MeV/c$^2$]</th>
<th>$\sigma_{\Gamma_W}$ [MeV/c$^2$]</th>
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<td></td>
<td>162.6 240 365</td>
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</tr>
<tr>
<td>Luminosity ($ab^{-1}$)</td>
<td>12 5 1.7</td>
<td>12 5 1.7</td>
</tr>
<tr>
<td>Raw Mass</td>
<td>0.42 0.49 1.19</td>
<td>0.39 0.87 1.94</td>
</tr>
<tr>
<td>1C fit</td>
<td>0.26 0.33 0.78</td>
<td>0.35 0.59 1.36</td>
</tr>
<tr>
<td>2C fit</td>
<td>0.31 0.75</td>
<td>0.68 1.56</td>
</tr>
</tbody>
</table>
The loss of particle information degrades the resolution by 2.9% at 162.6 GeV, 6.7% at 240 GeV and 16.9% at 365 GeV.
Cone effect on $\Delta M_{W,\text{stat}}$

Full FCCee luminosity

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [GeV]</th>
<th>162.6</th>
<th>240</th>
<th>365</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta M_{W,\text{stat}}$ [MeV]</td>
<td>standard</td>
<td>cone</td>
<td>standard</td>
</tr>
<tr>
<td>woFSI</td>
<td>1.14</td>
<td>1.18</td>
<td>0.215</td>
</tr>
<tr>
<td>SKI</td>
<td>1.18</td>
<td>1.21</td>
<td>0.225</td>
</tr>
<tr>
<td>SKII</td>
<td>1.17</td>
<td>1.19</td>
<td>0.218</td>
</tr>
<tr>
<td>BEC</td>
<td>1.17</td>
<td>1.18</td>
<td>0.224</td>
</tr>
</tbody>
</table>

$\Delta M_{W,\text{stat}}$ is degraded with the cone by few percent at threshold and 10-15% above.
f with 0.05 steps; $E_1$ and $E_2$ with 10 MeV

Data taking configuration that minimise arbitrary combination of the expected mass and width statistical uncertainties $F(\Delta M, \Delta \Gamma)$.

Here $F(\Delta M, \Delta \Gamma) = \Delta M_W + \Delta \Gamma_W$
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 $\tau \rightarrow e, \mu$ channel migrations recoveries
  - would need lepton-id at $10^{-4}$ level for max BR precision
- jet reconstruction and **energy calibration**
  - @LEP2 1-2% level ⇒ 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 qq\(\nu\)
- **lepton isolation**
  - @LEP2 control at the $\Delta \varepsilon \sim 2 \ 10^{-3}$ 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 0.2 $10^{-3}$ precision level
background control

2-fermion : \(\tau\tau\), qq
4-fermion : \(\gamma\gamma \rightarrow \tau\tau, ll\nu\nu\), Zee, Wev

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

<table>
<thead>
<tr>
<th>decay</th>
<th>efficiency</th>
<th>purity</th>
<th>bkg</th>
<th>[LEP1996]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(l\nu l\nu)</td>
<td>70-80%</td>
<td>80-90%</td>
<td>50 fb</td>
<td>(\tau\tau, \gamma\gamma \rightarrow \tau\tau, Z\gamma^* \rightarrow \nu\nu l\nu)</td>
</tr>
<tr>
<td>evqq</td>
<td>85%</td>
<td>(\sim)90%</td>
<td>30 fb</td>
<td>(qq, Zee, Z\gamma^*) -10 fb (\text{Wev})</td>
</tr>
<tr>
<td>(\mu\nu qq)</td>
<td>90%</td>
<td>(\sim)95%</td>
<td>10 fb</td>
<td>(Z\gamma^*, qq)</td>
</tr>
<tr>
<td>(\tau\nu qq)</td>
<td>50%</td>
<td>80-85%</td>
<td>50 fb</td>
<td>(qq, Z\gamma^*)</td>
</tr>
<tr>
<td>qqqq</td>
<td>90%</td>
<td>(\sim)90%</td>
<td>(\sim)200 fb</td>
<td>(qq (qqqq, qqgg))</td>
</tr>
</tbody>
</table>

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

measure forward electrons (\(\theta \geq 0.1\) rad) for Zee Wev : determine forward pole \(d\sigma/d\theta\) and WW interference effects

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

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

\[
\left(\frac{d\sigma}{d\Gamma_w}\right)^{-1} \quad \left(\frac{d\sigma}{dm_w}\right)^{-1} \quad \left(\frac{d\sigma}{d\Gamma_w}\right)^{-1} \quad \sigma \quad \left(\frac{d\sigma}{d\Gamma_w}\right)^{-1} \quad \sigma
\]
differential factors are equal