

Reconstruction of the W mass and width at and above WW threshold at FCC-ee

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In the Standard Model theory, the mass of the W boson is predicted with an uncertainty of $4 \text{ MeV}/c^2$ whereas the current experimental accuracy is of $12 \text{ MeV}/c^2$. The present uncertainty is currently limiting the sensitivity to possible effects of new physics through the global fit of the electroweak observables. With more than 2×10^8 W pairs produced at the W threshold energy and above, the FCC-ee collider will be a W boson factory allowing for W mass measurement with unparalleled precision. The W mass can be directly measured at and above the threshold from the kinematic reconstruction of the W-pair decay products. In addition, e^+e^- collisions offer the possibility to derive the W mass from the WW cross-section measured at the pair-production threshold. The precise measurement of the W mass and width, with both methods, is presented in the context of a future experiment at FCC-ee. A statistical uncertainty on the W mass below $1 \text{ MeV}/c^2$ is expected and the experimental and theoretical systematic uncertainties must be reduced to match such a level of precision.

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1. Introduction

With more than 2×10^8 W-pairs produced, FCC-ee will be a WW factory. All this statistics offers a lot of opportunities for the WW diboson physics, such as the accurate measurements of the W mass and width from direct reconstruction or from a threshold-scan but also the precise measurement of other observables linked to the W such as the partial widths, the strong coupling constant, the CKM matrix or the gauge self-couplings.

The precise relation between M_W , M_H and M_t is a crucial test of the internal consistency of the Standard Model (SM) and any failure might reveal new physics. However, there are currently no deviations between the mass measurements and their theoretical predictions within their uncertainties. The W mass which is now predicted with an uncertainty of about $4 \text{ MeV}/c^2$ whereas the experimental accuracy is $12 \text{ MeV}/c^2$, appears as fundamental parameter, which accuracy must be improved by a factor 10 for testing the consistency of SM.

2. W mass measurement at the WW threshold

The W-pair production threshold is around 160 GeV and the precise measurement of the W mass at threshold is achievable because of the rapid raise of the cross-section in this region. As shown on Figure 1, the variation of the W mass will introduce a shift on the cross-section, σ , while the variation of the width will change the slope of its lineshape. These sensitivities allow to measure only the W mass at a single point and to estimate simultaneously the mass and width with two or more data-taking points.

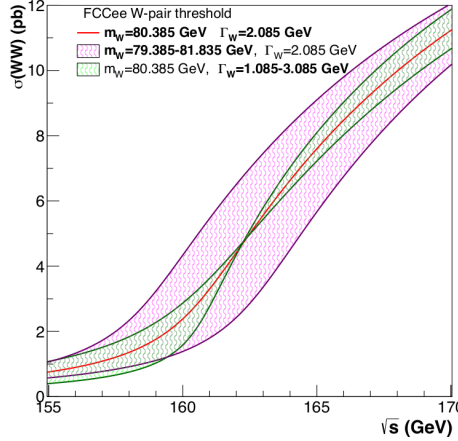


Figure 1: W-pair production cross-section variation with W mass and width as a function of the centre-of-mass energies [1].

The statistical uncertainty on the W mass is expressed as [1]:

$$\Delta M_{W,stat} = \left(\frac{d\sigma}{dM_W} \right)^{-1} \frac{\sqrt{\sigma}}{\sqrt{\mathcal{L}}} \frac{1}{\sqrt{\varepsilon p}} \oplus \left(\frac{d\sigma}{dM_W} \right)^{-1} \frac{\Delta\sigma_B}{\varepsilon} \oplus \left(\frac{d\sigma}{dM_W} \right)^{-1} \sigma \left(\frac{\Delta\varepsilon}{\varepsilon} \oplus \frac{\Delta\mathcal{L}}{\mathcal{L}} \right). \quad (2.1)$$

ε is the selection efficiency, \mathcal{L} the luminosity, p the purity defined as $\varepsilon\sigma/(\varepsilon\sigma + \sigma_B)$ and σ_B is the background cross-section. The two last terms of Equation 2.1 correspond to the systematic uncertainties propagation of these observables to the W mass. To determine the W mass with the highest

accuracy, the optimal data-taking point is chosen minimising the differential terms in Equation 2.1 as shown on Figure 2a. The optimal energy was found to be about $\sqrt{s} = 161.4$ GeV which gives a statistical uncertainty on the W mass equals to $0.23 \text{ MeV}/c^2$ ($\mathcal{L} = 12 \text{ ab}^{-1}$). At LEP2, the statistical uncertainty on the W mass with the threshold-scan strategy was $210 \text{ MeV}/c^2$ ($\mathcal{L} = 10 \text{ pb}^{-1}$). Such precision requires the control of systematic uncertainties and is achievable only if the background cross-section is estimated at 10^{-3} , the efficiency, luminosity and theoretical uncertainties with a 10^{-4} precision and the centre-of-mass energy is measured with a precision of 10^{-6} [1].

The same procedure can be used to determine simultaneously the mass and the width [1]. The optimal energies for the data-taking are found minimising the sensitivity of the cross-section to both the mass and the width as shown on Figure 2a and 2b. An optimal combination was evaluated to $E_1 = 157.1$ GeV, $E_2 = 162.3$ GeV and $f = 0.4$, where f is the fraction of integrated luminosity attributed to E_1 . With this scan optimisation, the uncertainties on the mass and width are $0.4 \text{ MeV}/c^2$ and $1.2 \text{ MeV}/c^2$ respectively.

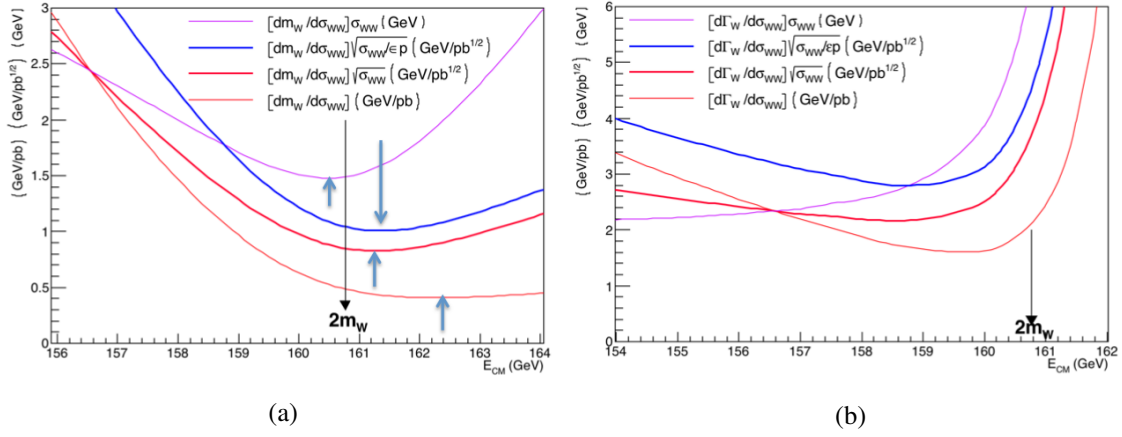


Figure 2: Sensitivity of the W-pair cross-section to the W mass (2a) and width (2b) as a function of \sqrt{s} [1]. These distributions were evaluated with $\epsilon = 0.75$, $\sigma_B = 0.3 \text{ pb}$ and $\mathcal{L} = 12 \text{ ab}^{-1}$ and using YFSWW3 1.18 [2].

In order to calibrate the beam energy by resonant depolarisation, the collider must operate at energies corresponding to half-integer spin tune. Then the beam energy will be given by $E_b = 0.4406486 (\nu + 0.5) \text{ GeV}$ [3]. The optimal combination is therefore shifted to $E_1 = 157.3$ GeV, $E_2 = 162.6$ GeV and $f = 0.4$, changing the statistical uncertainties to $0.45 \text{ MeV}/c^2$ and $1.3 \text{ MeV}/c^2$ for the W mass and width respectively [1].

In the threshold-scan measurement, the energy spread is an important parameter to consider because it might shift σ and introduce a systematic uncertainty on the W mass. The effect of the energy spread (σ_E) is [3]:

$$\delta\sigma_W \sim \frac{1}{2} \frac{d^2\sigma_W}{dE^2} \sigma_E^2 \quad (2.2)$$

At the FCC-ee, σ_E will be measured/monitored with $e^+e^- \rightarrow \mu^-\mu^+$ events with a relative precision of better than 0.2 %. It was shown that a relative precision of 1 % has a very small effect

on the cross-section, then it can be assumed that the energy spread has a negligible contribution on the W mass and width [3].

3. Direct reconstruction of M_W and Γ_W

3.1 Statistical uncertainties

The other method to measure the W mass and width is the direct reconstruction, where the invariant mass (raw mass) is directly determined from the measured four fermion-momenta. Thanks to the huge statistics expected, this method can be used at all FCC-ee energies. The study was done at 162.6 GeV, 240 GeV and 365 GeV.

The hadronic and semi-leptonic decays of the W pair were simulated with the PYTHIA8 [4] event generator and propagated through the CLIC-like detector (CLD) [5] with HEPPY [6], a fast simulation software implemented for the FCC-ee detectors study. The decay products were forced into four jets using the DURHAM [7] algorithm in the hadronic channel and into two jets and a lepton in the semi-leptonic channel. Only the muon decay of this channel has been studied ¹.

The raw mass was improved using the kinematic fit technique [1, 11]. The four-jets momenta were corrected imposing the energy-momentum conservation, corresponding to a four-constraint (4C) fit in the case of fully hadronic events and one-constraint (1C) fit in the case of semi-leptonic events. To further improve the invariant mass resolution, the mass equality of the two pair-produced bosons was required, for a five-constraint (5C) (two-constraint (2C)) fit for the hadronic (semi-leptonic) channel. At threshold, mass equality was not required because one of the two W masses is off-shell. In the hadronic decay channel, a jet four-momenta rescaling (4C rescaling) was used for a primary improvement of the invariant mass resolution, satisfying the total energy-momentum conservation while keeping jets angles and velocity fixed to their measured values. This method cannot be used in the semi-leptonic channel because the momentum of the neutrino is already computed from energy-momentum conservation. Figure 3 shows the smaller invariant (hadronic) and leptonic (semi-leptonic) mass distributions reconstructed with the different estimators at $\sqrt{s} = 240$ GeV. The same kind of distributions were obtained at the other energies [11].

The statistical uncertainties on the W mass and width were estimated independently with a binned maximum likelihood fit on the reconstructed W mass distributions, using templates with different nominal W mass and width values. Except for the 5C and 1C fits, where only one mass is reconstructed, the expected uncertainty was obtained by combination of the two statistical uncertainties. Figure 4 shows the W mass statistical uncertainty for the full FCC-ee luminosity obtained in both decay channels with the different estimators.

In both channels, the most constrained kinematic fit gives the best invariant mass reconstruction and the smallest uncertainty on the W mass with uncertainties around 1 MeV/c² or below in the hadronic decay and close to the 500 keV/c² level in the semi-leptonic decay. The same study

¹The track momentum for electrons that have not undergone bremsstrahlung is more precisely measured by the tracker. Assuming that the bremsstrahlung photon can be properly associated to the track, same performance may be expected in the electron and the muon channels. With this assumption, this study is done with muons only in order to simplify the issue.

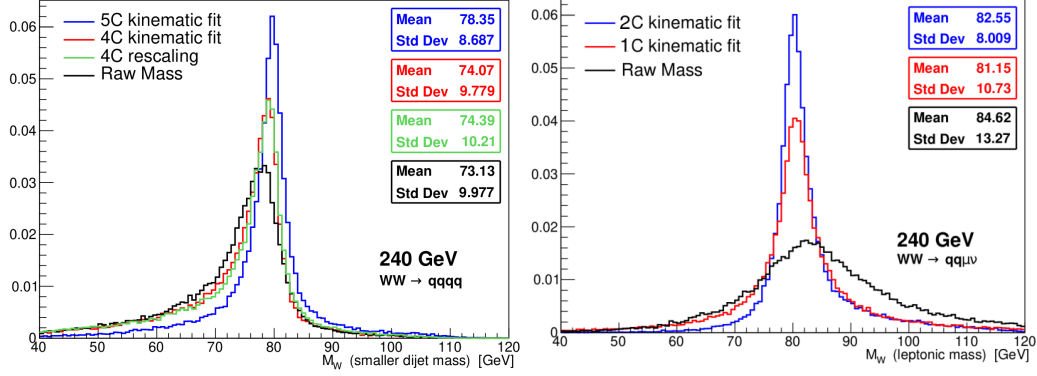


Figure 3: W invariant mass distributions in the hadronic (left) and semi-leptonic (right) channels reconstructed with different estimators at $\sqrt{s} = 240$ GeV.

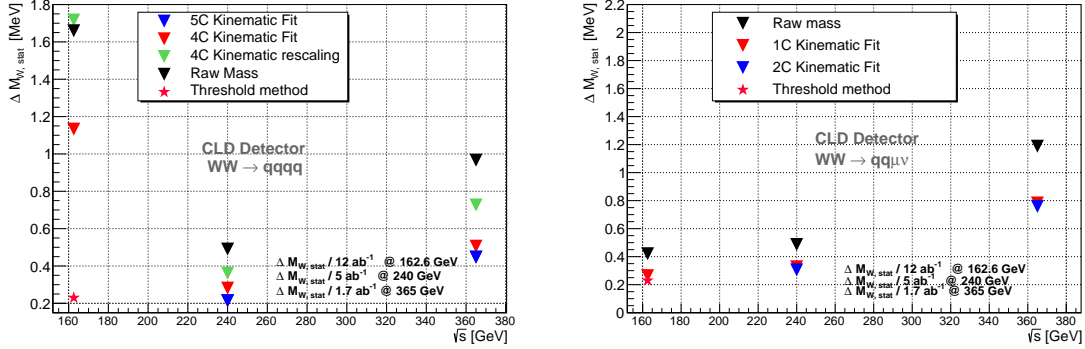


Figure 4: Estimated statistical uncertainties on the W mass in the hadronic (left) and semi-leptonic (right) channels reconstructed with different estimators at all centre-of-mass energies for the full FCC-ee luminosity.

\sqrt{s} [GeV]	hadronic	semi-leptonic
162.6	1.1	0.35
240	0.47	0.68
365	1.0	1.56

Table 1: Estimated statistical uncertainty on the width [MeV/c²] evaluated with the most constrained fit in hadronic and semi-leptonic decay channels at different centre-of-mass energies.

was done for the width, the statistical uncertainties evaluated with the most constrained kinematic fit in both decay channels and all energies are shown in Table 1.

3.2 Study of the systematic uncertainties

Among the main sources of systematic uncertainties on the W mass at LEP2, the largest was due to the Final State Interactions (FSI): the Colour Reconnection (CR) and Bose-Einstein Correlations (BEC) [8]. Thanks to the huge statistics, the other sources of systematic uncertainties are expected to be largely reduced at FCC-ee, therefore only the FSI effects were studied.

\sqrt{s} [GeV]	162.6		240		365	
δM_{FSI} [MeV/c ²]	standard	cone	standard	cone	standard	cone
SKI	14.6	7.5	23.9	11.5	32.2	17.5
SKII	7.9	3.8	12.1	6.0	14.7	8.3
BEC	3.1	1.8	5.9	2.1	9.9	5.5

Table 2: Estimated systematic uncertainties introduced in the W mass by the CR (SKI and SKII models) and BEC in hadronic decay channel for different centre-of-mass energies.

The FSI were simulated with PYTHIA8 and the CR was modelled using both the SKI and SKII models [9]. For the BEC study, one model, fitting all kinds of collisions, is implemented in PYTHIA [10]. To minimise the resulting shift of the W mass the ALEPH method was used: all particles outside a cone, directed around the jet axes and with an opening angle $R = 0.4$ rad, were rejected. This opening angle value was chosen for a preliminary study of the FSI systematic uncertainty on the W mass. A more complete adjustment must be performed to determine the optimal value of the opening angle, which might differ at higher energies.

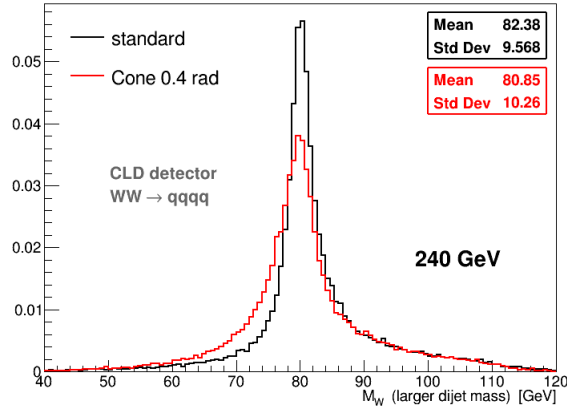


Figure 5: Invariant mass distribution in the hadronic channel (5C fit) with and without the cone at 240 GeV.

As shown on Figure 5, the loss of particle information because of the cone degrades the resolution. The degradations of the statistical uncertainties were estimated to be about a few percent at threshold, 10% at 240 GeV and 15% at 365 GeV [11]. Knowing that the cone should reduce the shift on the W mass by approximately 50% at all centre-of-mass energies (Table 2), the additional loss on the statistical uncertainties due to the cone is considered acceptable.

4. Conclusion

The amount of W-pairs at different centre-of-mass energies planned at FCC-ee presents a huge potential for the W physics measurements. This paper focuses on the W mass and width measurements with two different techniques. One of them relies on a threshold-scan strategy at the W-pair production threshold, where the mass and width can be accurately derived from the cross-section measurement. The other one is the direct reconstruction of the W-pair decay products at

threshold and above, yielding to a statistical precision below the MeV/c^2 level. The study of the systematic uncertainty introduced by the FSI shows that it could be reduced with the cone treatment which was already used at LEP2.

Such precision on the W mass offers the possibility to measure the centre-of-mass energy with a good accuracy ($2 \text{ MeV}/c^2$ at 365 GeV [3]) for energies above threshold, where the resonant depolarisation cannot be used. Ultimately, a simultaneous fit of WW, ZZ and $Z\gamma$ events could be performed to extract m_W/m_Z with a potential large cancellation of the systematic uncertainties.

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