PROCEEDINGS OF SCIENCE

Electroweak Precision Physics at the FCC-ee

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The Future Circular Collider in its electron-positron stage (FCC-ee) will operate as a high-luminosity, multi-purpose collider at the intensity frontier. Its unique combination of centre-of-mass energy reach, absolute beam energy calibration via resonant depolarisation, and huge integrated luminosities will allow for electroweak precision measurements with unprecedented accuracy. The FCC-ee programme includes precise determinations of the Z- and W-boson properties, measurements of heavy-quark observables, tests of gauge couplings, and sensitivity to physics beyond the Standard Model (BSM) through global fits.

This contribution reviews the electroweak prospects at the FCC-ee, focusing on flagship measurements such as the Z lineshape, forward-backward asymmetries, R_b, and the W mass, together with recent feasibility studies and detector performance projections.

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1. FCC-ee as an electroweak laboratory

Precision measurements in the electroweak (EW) sector have played a central role in testing the Standard Model (SM) and constraining new physics. The LEP and SLC experiments provided the most stringent tests of the EW theory to date, including measurements of the Z-boson mass, width, asymmetries, and the W-boson mass [1]. With the discovery of the Higgs boson, the SM has become a complete renormalisable theory, but new physics is still expected at higher scales.

Indirect constraints via EW precision observables (EWPOs) are sensitive to heavy new states even beyond the direct reach of colliders. Reaching sub-permille precision on EWPOs requires both enormous statistics and exquisite control of systematic uncertainties. The FCC-ee [2], designed as a circular e^+e^- collider with four interaction points, can provide a unique platform for such measurements.

The FCC-ee is a proposed circular collider with a circumference of 91 km. Its key advantage over linear colliders is the enormous luminosity achievable, with four IPs and continuous beam energy calibration via resonant depolarisation of pilot bunches up to 160 GeV. In comparison, linear colliders achieve luminosities about three orders of magnitude smaller, albeit with the possibility of longitudinally polarised beams. The FCC-ee baseline programme foresees running at several centre-of-mass energies $\sqrt{s}$:

- **Z-boson pole** at $\sqrt{s} = 91.2$ GeV: 205 ab^{-1} in four years, corresponding to 6×10^{12} Z decays.
- **WW production threshold** at $\sqrt{s} \sim 160$ GeV: 19 ab^{-1} in two years, yielding 2.4×10^8 W pairs.
- **Higgs factory** at $\sqrt{s} = 240$–250 GeV: 11 ab^{-1} in three years.
- **$t\bar{t}$ production threshold** at $\sqrt{s} \sim 365$ GeV: 3 ab^{-1} in five years.

This staged programme allows a comprehensive exploration of the SM and provides indirect sensitivity to BSM physics across energy scales, from precision Z-pole measurements to top and Higgs physics.

2. Z Lineshape and electroweak observables

The Z-boson lineshape provides access to the mass, total width, hadronic cross section (Fig. 1), and ratios of partial widths such as R_ℓ and R_q. At LEP, the uncertainties were $\Delta m_Z \simeq 2$ MeV and $\Delta\Gamma_Z \simeq 2$ MeV. At the FCC-ee, the statistical precision will be at the few-keV level, while the dominant systematics are expected to come from the absolute beam energy calibration.

Resonant depolarisation provides point-to-point calibration with an accuracy of $O(100\text{ keV})$ in $\sqrt{s}$. This translates into projected uncertainties of $\Delta m_Z \sim 100$ keV and $\Delta\Gamma_Z \sim 12$ keV, two orders of magnitude better than at LEP [1].

Asymmetries such as A^ℓ_{FB} and A^q_{FB} probe effective weak mixing angles. In particular, the b-quark forward-backward asymmetry at the Z-pole, $A^{0,b}_{\text{FB}}$, is one of the most sensitive measurements of $\sin^2\theta^{\text{eff}}_W$, and LEP results showed a $> 2\sigma$ tension in the global EW fits [3]. FCC-ee statistics will essentially eliminate statistical uncertainties, making systematic control the limiting factor.

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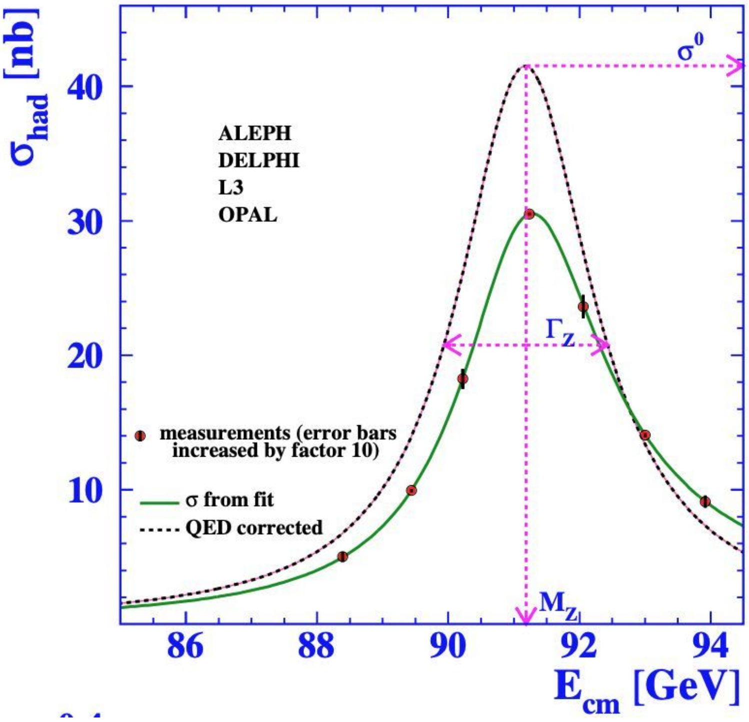

Figure 1: Measurement of the hadronic cross-section σ_{had} around the Z-boson pole in e^+e^- collisions at LEP [1]. This measurement provides input to the measurement of the Z-boson mass m_Z and width Γ_Z.

3. At the Z-pole

3.1 b-quark forward-backward asymmetry

Heavy-quark observables at the Z pole provide sensitivity to new physics affecting the third generation. The measurement of the b-quark forward-backward asymmetry, $A_{\text{FB}}^{0,b}$, requires charge identification of b versus $\bar{b}$ jets. Two main strategies, already investigated at LEP, are pursued, and each of them presents advantages and disadvantages:

- **Jet charge measurement**, using weighted sum of the charge of the tracks assigned to the b-jet. Alternatively, this information could be complemented by the secondary vertex charges. This method have relatively high efficiency, but presents a modest purity due to possible contamination by gluon splitting ($g \to b\bar{b}$) contribution.

- **Soft lepton tagging**, exploiting the information from a soft lepton, typically a muon, coming from semileptonic b-hadron decays. This offers better purity but is limited to a subset of decays and sensitive to decay modelling.

Machine learning approaches combining these inputs are being studied, showing potential for improved discrimination.

The analysis relies on an unfolding procedure (Fig. 2), to extract the $A_{\text{FB}}^{0,b}$ value from the parton-level differential angular distribution of $\cos\theta$. Systematic uncertainties from heavy-quark fragmentation, gluon radiation, and detector performance are the main challenge. Feasibility studies

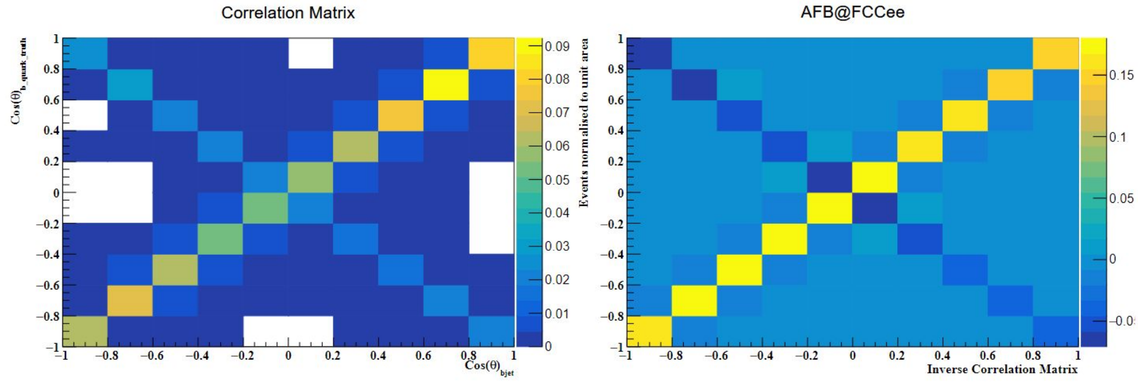

Figure 2: Correlation matrix (left) and its inverse, the unfolding matrix (right), for the A_{FB}^{b} extraction at the Z pole at the FCC-ee. The correlation matrix relates the $\cos\theta$ value at the jet reconstruction level (x-axis) to the one at the truth parton level (on the y-axis). The analysis relies on simulated events at $\sqrt{s} = m_Z = 91$ GeV using the IDEA detector concept.

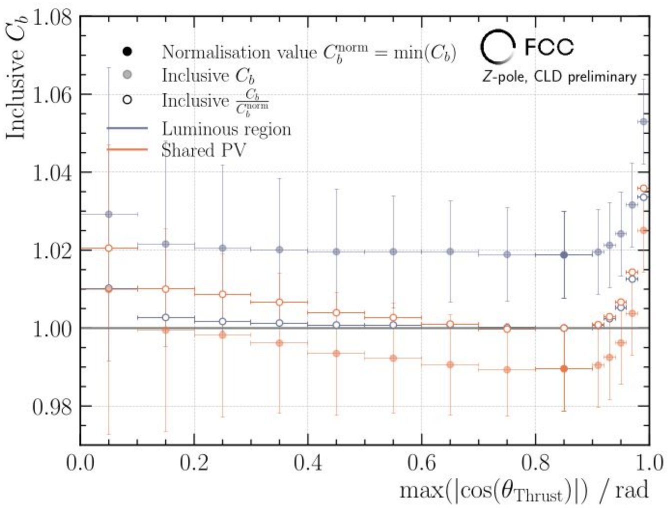

Figure 3: Measurement of the forward-backward hemisphere correlation C_b at the Z pole as a function of $\cos\theta$ with forced decays $Z \to [B^+ \to \bar{D}_0 pi^+]_{\bar{b}}[B^- \to D_0\pi^-]_b$. Analysis documented in [5].

using the Key4hep-FCCAnalyses framework with IDEA detector simulations show that unfolding methods can achieve sub-permille statistical precision [2, 4].

Similar strategies apply to another analysis which aims to measure $R_b = \Gamma_{b\bar{b}}/\Gamma_{\mathrm{had}}$, where exclusive b-hadron decays can be reconstructed with essentially pure samples, enabling systematic studies [5]. One of the observables measured in this analysis is forward-backward hemisphere correlation C_b, shown in Fig. 3.

4. At the WW threshold and above: the W boson mass and triple gauge couplings

The W-boson mass m_W is another key EW observable, which can be measured at the WW production threshold. At hadron colliders, the uncertainty on m_W remain at the 10 MeV level, *e.g.* $\Delta m_W = 9.9$ MeV from CMS [6] as shown in Fig. 4. At lepton colliders, threshold scans of the

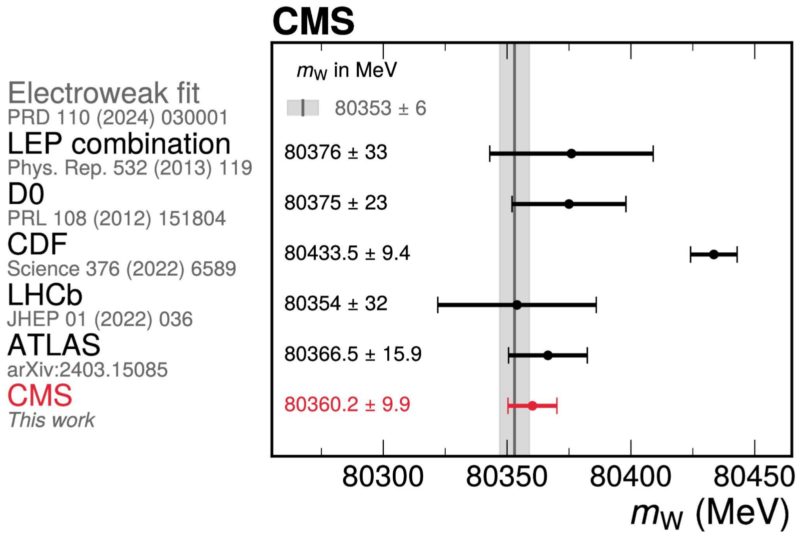

Figure 4: Measurement of the W-boson mass from LEP combination, D0 and CDF at Tevatron, and LHCb, ATLAS and CMS experiments at the LHC.

W^+W^- production cross section allow a direct and precise extraction of m_W and Γ_W [7], as shown in Fig. 5. At the FCC-ee, the projected uncertainty is $\Delta m_W \sim 150$ keV, driven by beam energy calibration, far beyond current precision.

Alternative methods include kinematic fits in direct reconstruction of W decays, particularly at higher energies (Fig. 6).

The huge W sample and large W production rate also allow precise determinations of leptonic branching ratios (BRs) and sensitivity to triple and quartic gauge couplings through angular analyses of WW production [2]. The absolute measurement of these W-boson couplings will be limited by luminosity ($\mathcal{L}$) determination. The projected relative uncertainty from $\gamma\gamma$/Bhabha scattering at FCC-ee is $\Delta\mathcal{L}/\mathcal{L} \sim 10^{-4}$.

5. Jet flavour tagging performance at the FCC-ee

Accurate jet flavour tagging is essential for many EW measurements. In this realm, a baseline b-tagging algorithm termed `ParticleNetIdea` has been tested [8] using fast-simulation studies. The IDEA detector concept foresees a drift chamber with excellent dE/dx resolution, a precision silicon vertex detector, and timing layers. Performance projections (Fig. 7) show that efficiencies and purities surpass those at LEP by large margins, enabling measurements such as A^b_{FB} and R_b to arrive at the following precision:

- R_b: [±1.2 (stat.) ±1.6 (syst.)] $\times 10^{-6}$
- A_{FB} (inclusive): [±7.8 (stat.) ±1.8 (syst.)] $\times 10^{-6}$,

down the 10^{-6} level [2]. Furthermore, the ability to tag s-quarks with $\sim$ 10% efficiency and 99% purity opens new avenues for precision studies. The long experience of ATLAS and CMS in developing advanced flavour-tagging algorithms, now based on graph neural networks and transformers, provides a strong foundation.

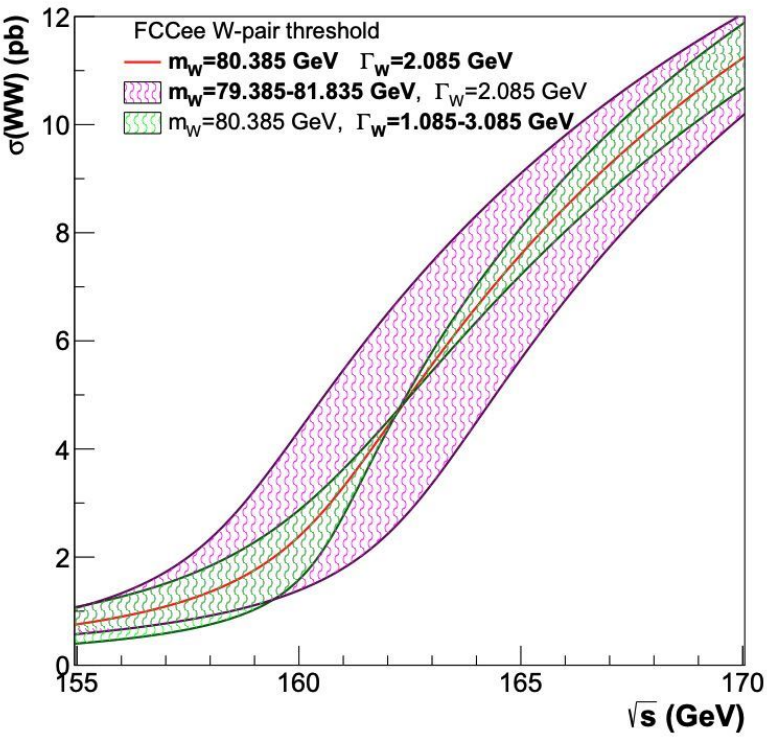

Figure 5: Cross-section of the W-pair production cross section as a function of the e^+e^- collision energy ECM as evaluated with the `YFSWW3 1.18` event generator [9]. The central curve corresponds to the predictions obtained with $m_W = 80.385$ GeV and $\Gamma_W = 2.085$ GeV. Purple and green bands show the cross section curves obtained varying the W mass and width by ±1 GeV. Taken from [7].

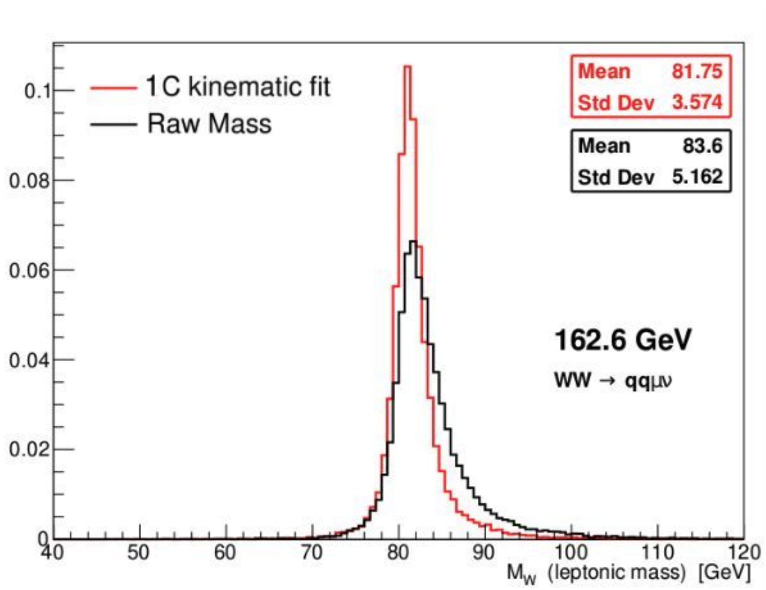

Figure 6: Reconstruction of the m_W mass at the FCC-ee in the $WW \to qq\mu\nu$ process via kinematic fit.

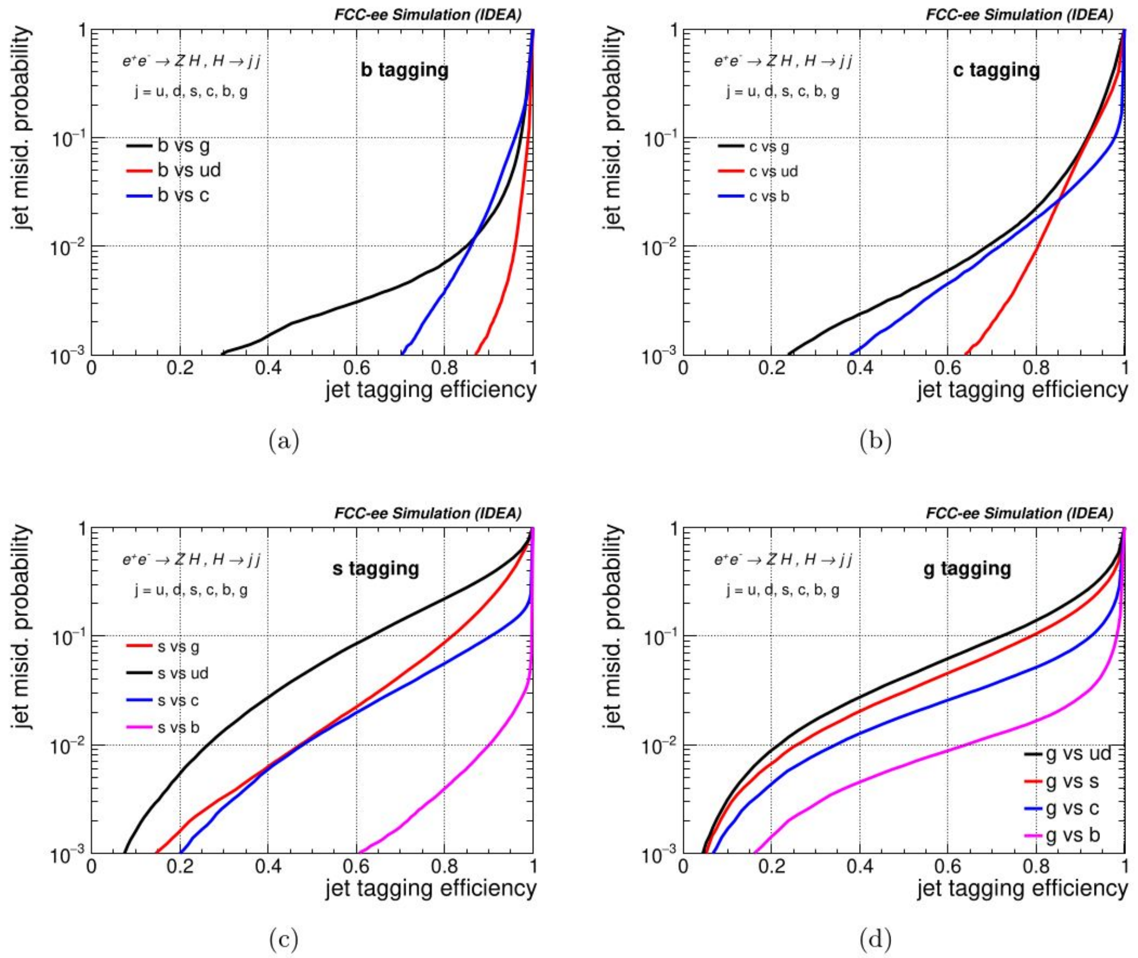

Figure 7: `ParticleNetIdea` performance in terms of a ROC curve for the identification of different: (a) b-quarks; (b) c-quarks; (c) s-quarks; (d) gluon-initiated jets. Taken from [8].

6. Conclusions

The FCC-ee, as part of the FCC integrated programme, offers an unrivalled opportunity for electroweak precision physics. With luminosities up to three orders of magnitude larger than previous facilities, and with absolute beam energy calibration, measurements such as m_Z, Γ_Z, A^b_{FB}, R_b, and m_W can be improved by factors of 10-100. Systematic uncertainties will play a dominant role, but ongoing work on flavour tagging, Monte Carlo generators, and analysis strategies shows that the ambitious goals are realistic. Together with Higgs and top-quark measurements, the FCC-ee will act as an electroweak laboratory, probing BSM physics at scales well beyond its direct kinematic reach. Its results will provide an essential complement to future linear colliders, muon colliders, and the FCC-hh.

References

[1] ALEPH, DELPHI, L3, OPAL, SLD, LEP Electroweak Working Group, SLD Electroweak Group, SLD Heavy Flavour Group, *Precision electroweak measurements on the Z resonance*, Phys. Rept. **427** (2006) 257.

[2] M. Benedikt, F. Zimmermann *et al.*, *FCC-ee Feasibility Study Report*, arXiv: 2505.00272.

[3] The Gfitter Group,J. Haller, A. Höcker, *et al.*, *Update of the global electroweak fit and constraints on two-Higgs-doublet models*, Eur. Phys. J. C **78**, 675 (2018).

[4] M. Cobal, G. Guerrieri, H. Khanpour, G. Panizzo, M. Pinamonti, L. Toffolin, *Bottom quark forward-backward asymmetry at the future electron-positron collider FCCee*, DOI: 10.17181/dpyb5-vnc32.

[5] L. Röhrig *et al.*, *FCC studies on exclusive R_b*, DOI: https://doi.org/10.17181/znj58-zvx36.

[6] CMS Collaboration, *High-precision measurement of the W boson mass with the CMS experiment at the LHC*, arXiv: 2412.13872.

[7] P. Azzurri, *The W mass and width measurement challenge at FCC-ee*, Eur. Phys. J. Plus **136** (2021) 12, 1203.

[8] F. Bedeschi, L. Gouskos, M. Selvaggi, *Jet Flavour Tagging for Future Colliders with Fast Simulation*, Eur. Phys. J. C **82**, 646 (2022).

[9] S. Jadach, W. Placzek, M. Skrzypek, B. F. L. Ward and Z. Was, *The Monte Carlo event generator YFSWW3 version 1.16 for W pair production and decay at LEP-2 / LC energies*, Comput. Phys. Commun. **140** (2001) 432–474.