Measurement of the Z lineshape at FCC-ee

Letter of Interest submitted to Snowmass 2021

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Abstract

The FCC-ee is a frontier Higgs, Top, Electroweak, and Flavour factory. It will be operated in a 100 km circular tunnel built in the CERN area, and will serve as the first step of the FCC integrated programme towards $\geq$ 100 TeV proton-proton collisions in the same infrastructure [1]. In addition to an essential and unique Higgs program, it offers powerful opportunities for direct or indirect evidence for BSM physics, via a combination of high precision measurements and searches for forbidden and rare processes and feebly coupled particles.

A key element of the FCC-ee physics program is the measurement of the Z lineshape with a total of 5×10^{12} Z bosons produced, and with unique ppm beam-energy calibration. The defining parameters $(\mathrm{m_Z}, \Gamma_\mathrm{Z}, \alpha_\mathrm{s}(\mathrm{m_Z^2}), \mathrm{N}_\nu, \sin^2\theta_\mathrm{W}^\mathrm{eff}, \alpha_\mathrm{QED}(\mathrm{m_Z^2}))$ can be extracted with a leap in accuracy of up to two orders of magnitude. The ultimate goal, that experimental and theory systematic errors match the statistical accuracy, leads to highly demanding requirements on detector design and on theoretical calculations. This letter of interest describes some of the many challenges presented by these benchmark measurements.

Thematic Areas:

☐ (EF01) EW Physics: Higgs Boson properties and couplings
☐ (EF02) EW Physics: Higgs Boson as a portal to new physics
☐ (EF03) EW Physics: Heavy flavor and top quark physics
■ (EF04) EW Physics: EW Precision Physics and constraining new physics
■ (EF05) QCD and strong interactions: Precision QCD
☐ (EF06) QCD and strong interactions:Hadronic structure and forward QCD
☐ (EF07) QCD and strong interactions: Heavy Ions
☐ (EF08) BSM: Model specific explorations
☐ (EF09) BSM: More general explorations
☐ (EF10) BSM: Dark Matter at colliders

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One of the main physics goals of FCC-ee, when operated at and around the Z pole, is a set of electroweak precision observable (EWPO) measurements with statistical precision improved by more than two orders of magnitude with respect to the state-of-the-art. A sample of these measurements and an initial estimate of the statistical and systematic uncertainties, with $100\,\mathrm{ab}^{-1}$ at $\sqrt{s} = 91.2\,\mathrm{GeV}$, and $50\,\mathrm{ab}^{-1}$ equally shared between $\sqrt{s} = 88$ and $94\,\mathrm{GeV}$, is presented in Table 1 [2]. The great FCC-ee experimental challenge will be to reach systematic uncertainties at the same level or smaller than the statistical ones.

Table 1: Measurement of selected EWPOs at FCC-ee operated at and around the Z pole, compared with present precision. The systematic uncertainties are initial estimates: the aim is to improve down to the statistical uncertainties expected from 3.5×10^{12} hadronic Z decays and 1.5×10^{11} leptonic decays in each lepton flavour.

Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
$\mathrm{m_Z}$ (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\mathrm{R}_\ell^\mathrm{Z}$ ($\times 10^3$)	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_\mathrm{s}(\mathrm{m}_\mathrm{Z}^2)$ ($\times 10^4$)	1196 ± 30	**0.1**	0.4-1.6	from $\mathrm{R}_\ell^\mathrm{Z}$ above
σ^0_had ($\times 10^3$) (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
N_ν($\times 10^3$)	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_\mathrm{W}^\mathrm{eff}$($\times 10^6$)	231480 ± 160	**2**	2.4	from $\mathrm{A}_\mathrm{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_\mathrm{QED}(\mathrm{m}_\mathrm{Z}^2)$($\times 10^3$)	128952 ± 14	**3**	1	from $\mathrm{A}_\mathrm{FB}^{\mu\mu}$ off peak QED&EW errors dominate

With this large leap in precision on all electroweak observables, the discovery of tiny deviations with respect to the standard model predictions will be sensitive to large coupling new physics up to scales from 10 to 70 TeV in a description with dimension-six operators, and possibly much higher in specific new physics (non-decoupling) models. Moreover, these essential inputs used as "fixed candles" will enhance and maximise the physics reach of FCC-hh at the precision and the energy frontiers, taking advantage of the multiple complementarities and synergies of FCC-ee and FCC-hh [3].

The ratio $\boldsymbol{R_\ell}$ of the number of Z hadronic decays to the number of Z leptonic decays can be potentially measured at FCC-ee with a relative statistical precision of $\mathcal{O}(3 \times 10^{-6})$ for each lepton type. It is a key quantity [4] that serves – in conjunction with the total Z decay width and the peak hadronic cross section – as input to several fundamental quantities: *(i)* the measurement of the leptonic Z partial width $\Gamma_{\ell\ell}$, a very clean electroweak observable whose relation to the Z mass is the ρ (or T) parameter, and unaffected by $\alpha_\mathrm{QED}(m_\mathrm{Z}^2)$, with a 10^{-5} relative precision; and *(ii)* the measurement of the strong coupling constant $\alpha_\mathrm{S}(m_\mathrm{Z}^2)$ with an absolute experimental uncertainty below 0.0001. Experience from LEP showed that a limiting systematic uncertainty comes from the knowledge of the geometrical acceptance for lepton pairs. The requirements on the detector design to match the statistical precision will be studied in the full context of the constraints from the interaction region layout. As a by-product, the determination of the geometrical acceptance for the $\mathrm{e^+e^-} \to \gamma\gamma$ process, which may be used for the measurement of the absolute luminosity, potentially with a statistical precision of a few 10^{-5}, will be investigated. The knowledge, at the same level of precision, of the acceptance for the more abundant hadronic Z decays, a much easier problem at LEP, will need to be verified.

The Z total decay width $\boldsymbol{\Gamma_\mathrm{Z}}$ can be measured at FCC-ee with sample of 3.5×10^{12} $\mathrm{Z} \to$ hadrons events produced around the Z pole at $\sqrt{s} \approx 87.8$, 91.2, and 93.9 GeV, with a statistical precision of 4 keV [2]. Experience from LEP showed that a limiting systematic uncertainty comes from the uncorrelated point-to-point error on the centre-of-mass energies of the three resonance scan points. At FCC-ee, this error can possibly be controlled in situ with the invariant mass distributions obtained from large dimuon event samples [2]. The requirements of the detector design (muon momentum and angular resolution and scale stability) to match the statistical precision will be studied in the context of the constraints from the full interaction region layout (beam crossing angle, beam energy spread, magnetic field). As a by-product, the possible improvements brought about by a five-point scan of the Z resonance will be investigated.

The Z peak cross section $\boldsymbol{\sigma^0_{\mathrm{had}}}$ can be measured at FCC-ee with hadronic and dimuon events produced at $\sqrt{s} = 91.2\,\mathrm{GeV}$, with a potential relative statistical precision of $\mathcal{O}(10^{-6})$. Together with the ratio R_ℓ, this quantity allows the determination of the number of light neutrino types with a precision of 0.0004. A limiting systematic uncertainty comes from the absolute determination of the integrated luminosity. A determination with low-angle Bhabha scattering is likely to be limited by a relative theoretical precision of $\mathcal{O}(10^{-4})$ [5], but that might not be the case for large angle diphoton production, $\mathrm{e^+e^-} \to \gamma\gamma$ (to be checked with actual full two-loop calculations [6]). The requirements on the detector design to measure the absolute luminosity with diphoton events, and in particular to separate these events from the large angle Bhabha background, will be studied, in synergy with the lepton acceptance studies required for $\boldsymbol{R_\ell}$.

Finally, the measurement of **the muon-pair forward-backward asymmetry $\boldsymbol{A^{\mu\mu}_{\mathrm{FB}}}$** at the Z pole ($\sqrt{s} = 91.2\,\mathrm{GeV}$) will allow the determination of the effective weak mixing angle $\boldsymbol{\sin^2\theta^{\mathrm{eff}}_{\mathrm{W}}}$ with an absolute statistical precision of 3×10^{-6} [2]. A 3×10^{-5} relative statistical precision on $A^{\mu\mu}_{\mathrm{FB}}$ just below ($\sqrt{s} \sim 88\,\mathrm{GeV}$) and just above ($\sqrt{s} \sim 94\,\mathrm{GeV}$) the Z pole also gives access to a direct determination of the QED coupling constant $\boldsymbol{\alpha_{\mathrm{QED}}(m^2_{\mathrm{Z}})}$ with a similar statistical accuracy, and with experimental uncertainties that can be kept well below this value [7]. Such an accuracy is an essential input to the new physics interpretation of precision electroweak data. A limiting systematic uncertainty comes from QED corrections to the $\mathrm{e^+e^-} \to \mu^+\mu^-$ process, and in particular from the interference between initial- and final-state radiation (IFI) [8], which modifies very substantially (by a few %) the value of $A^{\mu\mu}_{\mathrm{FB}}$. Experimental and phenomenological ways to minimize the effect of IFI on $\alpha_{\mathrm{QED}}(m^2_{\mathrm{Z}})$ and $\sin^2\theta^\ell_{\mathrm{W}}$ will be developed and studied, and control of IFI with independent data will be investigated, in order to estimate the requirements on the theoretical precision with which QED corrections need to be computed.

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