FCC-ee detector requirements: geometric acceptance requirements for dilepton and diphoton events at Z pole energies

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Abstract

The FCC-ee run plan foresees a scan of the Z line shape featuring a delivery of 45 ab^{-1} per experimental interaction point on top of the resonance. This provides more than 1.4×10^{12} hadronic Z decays and a total of 2.0×10^{11} leptonic Z decays, for each experiment, leading to an unprecedented statistical precision of $\mathcal{O}(6\ \mathrm{keV})$ on the Z mass and width, as well as a few ppm statistical accuracy on the leptonic and hadronic partial widths and their ratios. The cross-section normalization can be, as is traditional, based on the low-angle t-channel Bhabha process, but for the first time the diphoton process $\mathrm{e}^+\mathrm{e}^- \to \gamma\gamma$ is statistically competitive, providing an independent and possibly systematically and theoretically safer determination of the luminosity. For all these measurements, the definition of the fiducial volume is an inescapable source of systematic uncertainty; we calculate at zeroth order the sensitivity of the total cross-section measurement to a low angle acceptance cut uncertainty for the dilepton processes $\mathrm{e}^+\mathrm{e}^- \to \ell^+\ell^-$ and diphoton process $\mathrm{e}^+\mathrm{e}^- \to \gamma\gamma$. A range of geometrical tolerances at the level of 5–10 microradians on a polar angle cut at low angles (10–20 degrees) in the end-cap regions are defined. The exact value of the cut and how it is implemented remain to be decided for each detector setup after deeper analysis, in particular of the separation of the $\mathrm{e}^+\mathrm{e}^-$ and $\gamma\gamma$ processes. Remarkably, the required accuracy is similar for the two processes.

1 Motivation

The discovery of the Higgs boson marks the beginning of a new era of exploration.

1. The Standard Model, as it is defined in [1], with the known interactions and particle content, including mass-less neutrinos, is complete; certainly many open questions remain, among which the nature and origin of neutrino masses, of dark matter and of the matter-antimatter asymmetry of the Universe.
2. As a model however, it is prescriptive, extremely successful at the level of precision at which it has been tested, and now that the Higgs boson mass is known, all relevant parameters have been measured. The SM predictions are well defined, up to parametric and calculation uncertainties.
3. We know that new physics exists but we do not know what is its nature, mass-scale or couplings to SM particles; however any significant deviation from the SM predictions will constitute a discovery.
4. The precision measurements at the Z pole and WW threshold are particularly important tools of search for the effect of new physics via loops or mixing.
5. FCC-ee as a Z factory offers the prospects of an improvement by a factor 500 in statistical precision (sometimes more), on a broad number of observables, offering unprecedented opportunities for discovery. Whichever the result, the many precision measurements will constitute an important net of constraints on the properties of the new physics.

Making full use of this remarkable increase of sensitivity requires a concerted and proactive effort of reduction of systematic errors by a similarly large factor on many fronts: on the accelerator design and operation and center of mass energy calibration; on the experimental techniques; and on theoretical calculations and simulations.

Physics at the Z pole is described in detail in [1] to which we refer for formulae and references. The observables that are of interest in the present study are as follows.

1. The peak hadronic cross-section $\sigma_{\mathrm{had}}^{\mathrm{peak}}$, is the most sensitive observable for the determination of the invisible partial width, which is directly sensitive to a mixing of the active neutrinos to heavy right-handed partners [2]. The selection of hadronic events is, of experience at LEP, extremely efficient, and systematic uncertainties can be effectively controlled. The total cross-section determination, however depends critically on the luminosity measurement. The cross-section normalization can be, as is traditional, based on the low angle t-channel Bhabha process for which the luminosity monitor and its detector requirements have been described elsewhere [3]. For the first time the diphoton process $\mathrm{e}^+\mathrm{e}^- \to \gamma\gamma$ is statistically competitive, and offers prospects of a systematically safer determination of the luminosity [4].
2. More generally the cross-section as function of centre of mass energy on the Z resonance is critical for the determination of the Z mass and width.
3. The ratio of leptonic to hadronic cross-sections, $\mathrm{R}_\ell \simeq \Gamma_{\mathrm{lepton}}/\Gamma_{\mathrm{hadron}}$ is a key observable for the determination of the strong coupling constant, $\alpha_{\mathrm{s}}(\mathrm{m}_{\mathrm{Z}}^2)$, with an expected precision of 10^{-4} or better. If another measurement of $\alpha_{\mathrm{s}}(\mathrm{m}_{\mathrm{Z}}^2)$ were available, this would constitute a very powerful test of lepton-hadron universality. Given that the Z hadronic branching fraction is 0.7 while that for each lepton

flavour is 0.033, the statistical precision is dominated by the number of leptonic events. Surprisingly, the systematic uncertainties were also, at LEP, dominated by the determination of acceptance for leptons; at the time the origin of this difficulty was traced to the fact that the end-cap region was not specifically designed with this measurement in mind.

2 Event selection cuts

In the following we concentrate on the particular requirements on end-cap design that are required to make full use of the available statistics of dilepton, $e^+e^- \to \ell^+\ell^-$, or diphoton, $e^+e^- \to \gamma\gamma$, events.

An unavoidable feature of the selection of these events is a polar angle cut. It is assumed in the following that a generic analysis will be similar to the low-angle Bhabha selection used in the LEP experiments to measure luminosity [5–7]. The analysis alternatively (or randomly) applied a tight fiducial cut on one side (forward or backward scattering w.r.t. the electron) of the event and a looser cut on the other. In this way the systematic errors due to the alignment of the beam spot in space, or its length or size, canceled at first order, provided the misalignments were small compared to the difference between the tight and loose cuts. The unavoidable and limiting systematic uncertainty could then be expressed as stemming from an equivalent systematic uncertainty on the (tight) lower angle cut that would be applied on an event by event basis on one side or the other of the events.

The LEP luminosity analyses were largely based on the calorimeters; a cut was applied on the energy deposited within a fiducial area in the plane perpendicular to the beam axis at a suitable depth in the calorimeter. The fiducial area was often defined by the limits between readout pads where the radial position resolution is optimal, for the purpose of minimizing the systematic uncertainties due to event migrations; this feature is specific to particular detector construction and might be revisited. These techniques would be applicable to diphoton and dielectron e^+e^- final states. For dimuons this technique might work in the calorimeter, but it might work better in the tracker – although this would create a sensitivity to final state radiation which is reduced in the calorimeters where all energy is counted. For dielectrons it might be possible to use both calorimetry and tracking, thus providing a cross-calibration of the cut.

Whether these fiducial uncertainties are correlated between the two side of one event and between the four experiments running at FCC-ee will be a matter of discussion. A priori, they are not. Depending on the details of the alignment procedures, they are likely to be largely correlated between all the two-particle final states.

2.1 Dilepton events

Hadronic and leptonic cross-sections at the top of the Z resonance are 31.4 nb for hadron final state and 1.5 nb for muon or tau pairs (4.5 nb for the *s*-channel Z decay in the three leptons combined). For one experiment and an exposure of 45 ab^{-1} at the Z pole, this corresponds to a total sample of 1.4×10^{12} hadronic Z decays and 6.7×10^{10}

for each of the lepton channels, 2.0×10^{11} for the three lepton families combined. i.e. for each experiment, a statistical precision of 2.2×10^{-6} on R_ℓ.

Integrating over the lepton charge, the angular distribution of $\mathrm{e^+e^-} \to \ell^+\ell^-$ as function of polar angle is as follows

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = \frac{3}{8}\sigma_{\mathrm{tot}}\left(1+\cos^2\theta\right).$$

The dependence of the acceptance upon the value of the angular cut is shown in Fig. 1. The uncertainty is driven by the number of events which are lost. The resulting systematic uncertainty resulting from a 1 mrad uncertainty on that cut is shown in Fig. 2. It is evident that the ability to place the cut at a low angle reduces the resulting systematic uncertainty.

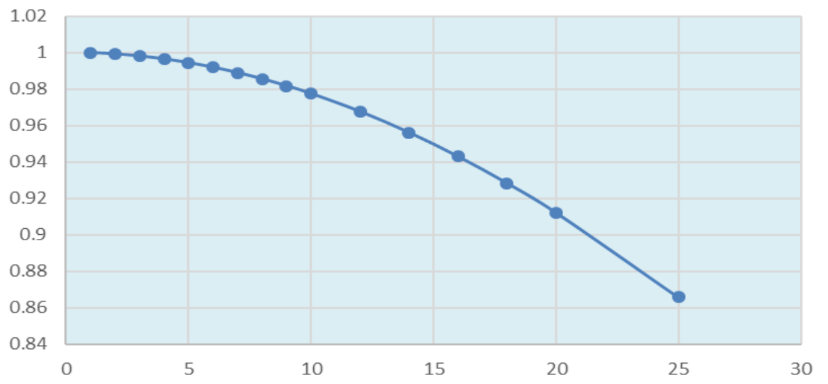

Fig. 1 Geometrical acceptance for the s-channel dilepton process $\mathrm{e^+e^-} \to \mathrm{Z} \to \ell^+\ell^-$ as a function of the polar angle cut in degree.

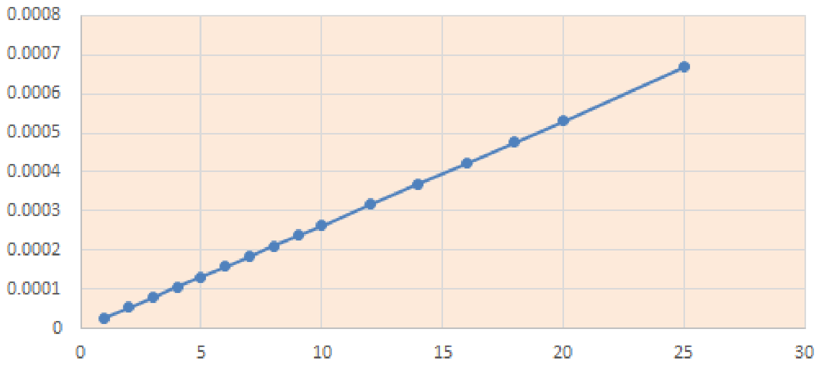

Fig. 2 Dilepton relative acceptance uncertainty stemming from the 1 mrad uncertainty on the polar angle cut, as a function of the polar angle cut in degree.

It is then straightforward to determine the tolerance on the accuracy of the cut angle that would ensure a systematic precision of 2.2×10^{-6}. This tolerance is plotted on Fig. 3 and Fig. 4, expressed as a position measurement accuracy for an end-cap detector situated at 2.5 m from the IP. The harder requirement (in blue) corresponds to the statistical uncertainty for a measurement of the total leptonic partial width, for which all lepton species are considered, when also the acceptance systematic uncertainty for the two end-caps are considered to be fully correlated. Also indicated, in red, in Fig. 4 is the most relaxed target, corresponding to the case of the comparison between two lepton species (alternatively the case where one would chose to measure precisely only one species of leptons), and in the case where the acceptances for the two sides of the event are assumed to be uncorrelated. The acceptance cut uncertainties between all experiments are always assumed to be uncorrelated.

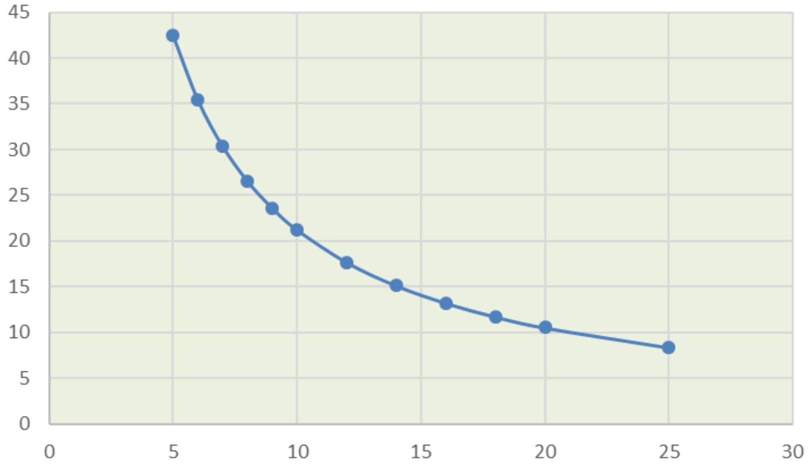

Fig. 3 Tolerance on the accuracy of the cut angle on dilepton events that would ensure a systematic precision of 2.2×10^{-6}, expressed as a position measurement accuracy for a detector situated at 2.5 m from the IP, as a function of the polar angle cut in degree

It is important to stress that these required accuracies are not the event by event angular resolution, nor the required position accuracy over the whole solid angle of the detector. They express the systematic accuracy on the cut, or the limit on a possible systematic shift of the actual cut with respect to its nominal setting.

2.2 Diphoton events

The differential cross-section for diphoton events as function of polar angle

$$\frac{\mathrm{d}\,\sigma}{\mathrm{d}\cos\theta} = \frac{2\pi\alpha^2}{s}\frac{1+\cos^2\theta}{1-\cos^2\theta}$$

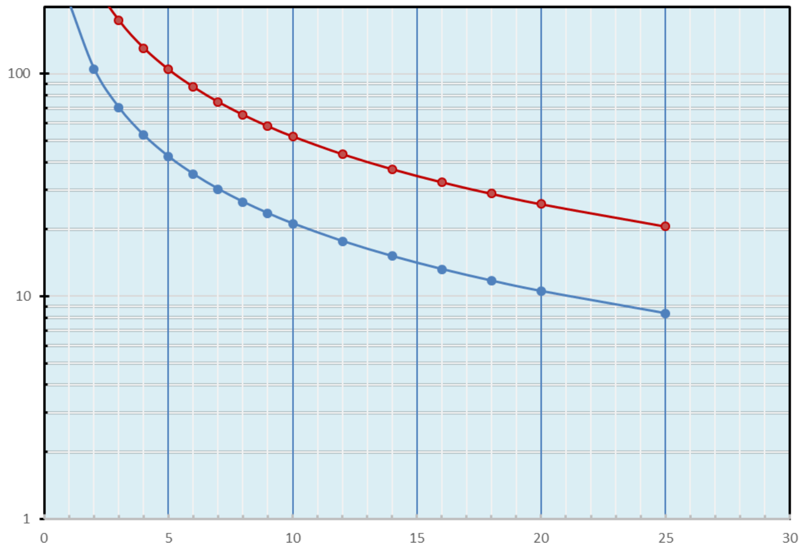

Fig. 4 Same as Fig. 3, but in logarithmic scale. The harder requirement (in blue) corresponds to the statistical uncertainty for a measurement of the total leptonic partial width, for which all leptons are considered, when also the acceptance systematic uncertainty for the two endcaps are considered to be fully correlated. Also indicated, in red, is the most relaxed target, corresponding to the case of the comparison between two lepton species, and with the acceptances for the two sides of the event assumed to be uncorrelated.

results in a integrated cross section of the form

$$\sigma(\mathrm{e}^+\mathrm{e}^- \to \gamma\gamma) = \frac{2\pi\alpha^2}{s}\left\{\ln\frac{1+\cos\theta_{\min}}{1-\cos\theta_{\min}} - \cos\theta_{\min}\right\},$$

where $\theta_{\min}$ defines the minimum polar angle of acceptance. The cross section is peaked at small angles as shown in Fig 5.

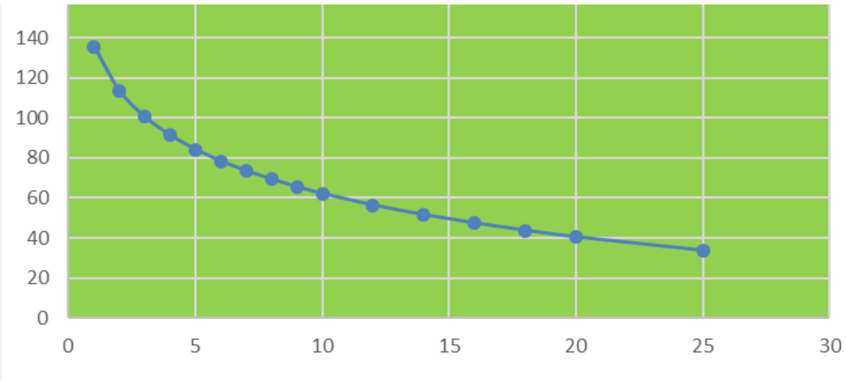

Fig. 5 Diphoton integrated cross-section vs. angular cut

The total cross-section at the Z pole energy is 40 pb for an angular cut of $\theta_{\mathrm{min}} = 20$ degrees. For an exposure of 45 ab^{-1} this yields a total number of events of 1.8×10^9, or a statistical precision of 2.3×10^{-5}. This is particularly interesting since prospects for theoretical precision are better than for the low angle Bhabha scattering process. The tolerance can be calculated in the same way as before, expressed as a radial cut accuracy required for a systematic precision of 2.3×10^{-5}. Alternatively the accuracy needed to match the statistical precision as a function of polar angle cut can be calculated. The two graphs are shown on Fig. 6. Remarkably the tolerance is in the same ballpark to that stated above for dileptons – albeit for cross-section precisions that differ by a factor ten.

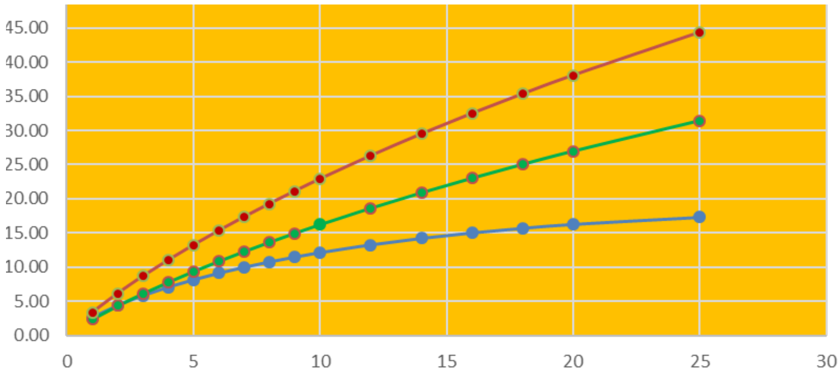

Fig. 6 Tolerance, for diphotons, on the accuracy of the cut angle that would ensure a systematic precision of 1.5×10^{-5} (in blue). Also indicated the requirement such that the uncertainty equals the statistical precision expressed as a position measurement accuracy for a detector situated at 2.5 m from the IP, as a function of the polar angle cut in degree – in green assuming fully correlated systematics between the two endcaps, in red assuming uncorrelated systematics.

3 Discussion

It is remarkable that the requirement for dileptons and diphotons is similar, of the order of 10–25 microns accuracy for a detector situated 2.5 meters from the interaction point, on a 10–20 degrees angular acceptance cut. The final choice of the cut should preferably be made before freezing the design of the detector. A direct measurement and monitoring capability of the distance between the endcap detectors should be foreseen, with a precision of better than about five times the radial accuracy, i.e. ∼75 microns. For reference, the LEP luminosity monitors of second generation all had their low radius region constructed in such a way as to ensure a precision on the radial cut at the level of O(10 microns). This is true in particular for the OPAL detector which had achieved a 5 microns precision [5].

The possibility of measuring the diphoton process with high precision is a new feature of FCC-ee, which will have important consequences on the physics output. Setting the value of the fiducial cut is not the only design feature. It must be ensured

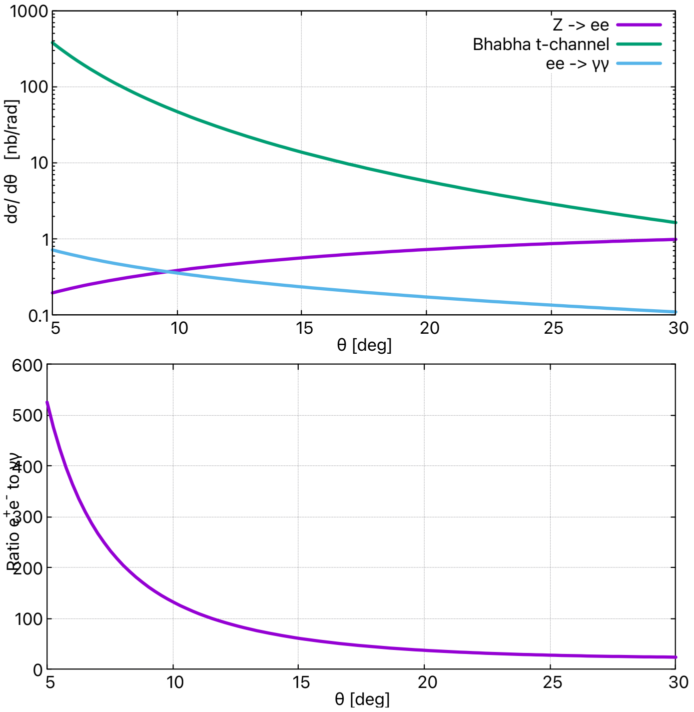

Fig. 7 Top: Differential cross-sections for s-channel and t-channel Bhabha and diphoton processes, as a function of the polar scattering angle θ in degrees. Bottom: ratio of e^+e^- to $\gamma\gamma$ cross sections.

that diphoton events are observed with a near-perfect ($\simeq$100%) and perfectly understood efficiency over the full fiducial volume; special attention is to be paid to the traditionally delicate transition region between the forward and barrel ECAL sections. The separation, or confusion, between the diphoton and dielectron final state, which at these small angles is much more abundant, is a serious concern. To illustrate the difficulty we have plotted in Fig. 7 the differential cross-section for s-channel and t-channel Bhabha, and diphoton processes, as well as the ratio between dielectron and diphoton cross sections. In the vicinity of $\theta = 10°$, the cross-section ratio is above 100. A good separation of the two channels will undoubtedly lead to design requirements:

1. It is essential to place a tracker in front of the calorimeter in order to separate electrons from photons;
2. the critical number is *"how many 45 GeV electrons give no track in front of the tracker"* (catastrophic bremsstrahlung);
3. the material between the interaction point and the first sensitive element should be minimized in order to reduce radiation;
4. and of course an analysis based on presence of two sides per event (single tag/double tag) will be of great help.

The precise design, simulation and benchmarking of detectors in view of the diphoton luminosity measurement will be an endeavour of undoubtedly several years by the experimental collaborations. Most importantly, in view of detector construction, is to understand the separation between electrons and photons in the low angle region. This will require studies involving both generation of higher order processes, especially those where the final state is an electron and a photon, and the understanding of the correlation of the electron/photon separation between the two hemispheres.

The LEP experiments performed, for their luminosity measurements, systematic studies of the residual impact of beam parameters or detector misalignments that should be repeated. Methods to determine internally the required parameters using directly the various distributions and asymmetries of the signal events were employed, with a gain of a considerable improvement in precision. The applicability, generalization, or improvements on these methods should be studied, given the new accelerator diagnostics; the fact that beams cross at an angle; and the possibility to design ahead of time a set for internal monitoring of the detector alignment.

Understanding of the possibility to cross-calibrate the dielectron, diphoton and dimuon acceptances will require simulations and benchmarking in test-beam. The requirements on the test beam setups should be delineated soon enough in the game.

4 Conclusions

The ultra-precise measurements made feasible by the huge statistics of FCC-ee in the diphoton and dilepton processes will constitute the basis of constraints on possible new physics for a very long time, and are well worth preparing with the best possible accuracy.

This first look at detector requirements for these processes have been considered with emphasis, in a first step, on the accuracy of the low angle cut. This study should be seen as encouragement for more detailed study, especially considering the issue of the separation of the e^+e^- and $\gamma\gamma$ processes, aimed at fixing the value of the cut in view of a detailed design of the detector.

The required accuracy on the cut becomes more and more severe for dilepton events when the cut value increases to larger angles. This emphasizes the great advantage of instrumenting effectively the low angle region of the detector. For the diphoton process, the trend is opposite, larger angles allow to relax the cut, at the rapid expense of the available statistical precision. The requirement from the dileptons is almost always more severe, and there is every interest to synergise the two.

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