### 3.5.7 Systematics of integrated luminosity measurement

Systematic uncertainties arising from the detector mechanics and positioning, as well as the uncertainties related to the properties of beams, have been quantified through a simulation study of several tens of millions (~$10^7$) of small angle Bhabha scattering events generated with BHLUMI V4.04 [*S. Jadach et al., Comput.Phys.Commun. 102, 229–251 (1997)*] at the Z-pole and ant 240 GeV center of mass energy, documented in [*I. Smiljanic et al., Systematic uncertainties in integrated luminosity measurement at CEPC, JINST 17 P09014, 2022*] and [ *I. Smiljanic, I. Bozovic, and G. Kacarevic, Uncertainties from metrology in the integrated luminosity measurement with the updated design of a detector at CEPC, Progress of Theoretical and Experimental Physics, ptae141 (2024), arXiv:2404.18605 [hep-ex]*] respectively. The studies comprise following systematic effects:

1. Maximal uncertainty of the luminometer inner aperture ($\Delta r_{in}$),
2. RMS of the Gaussian dissipation of the radial shower position ($\sigma_r$) measured in the luminometer with respect to the exact position of the Bhabha hit, (measured i.e. by a tracker plane placed in front of the luminometer),
3. RMS of the Gaussian distribution of luminometer fluctuations with respect to the IP, in radial ($\sigma_{x_{IP}}$) and axial direction ($\sigma_{z_{IP}}$) , caused by vibrations and thermal stress,
4. Maximal absolute uncertainty ($\Delta l$) of the distance between left and right arms of the luminometer along the z-axis, where both halves are shifted equally for $\pm\Delta l$ with respect to the interaction point,
5. Maximal permanent bias ($\Delta E$) of a single beam energy with respect to the other beam, resulting in a longitudinal boost of the incoming $e^+e^-$ system with respect to the laboratory frame, and consequently, boost of the Bhabha center-of-mass system,
6. Maximal RMS of the Gaussian distribution of the beam energy spread ($\sigma_{E_{BS}}$ ), responsible for longitudinal boost on event-by-event basis, leading to the overall loss of Bhabha count order of $10^{-4}$,
7. Maximal radial ($\Delta x_{IP}^{BS}$) and axial ($\Delta z_{IP}^{SY}$) IP position displacements with respect to the luminometer arms, caused by the finite beam sizes (former) and beam synchronization (latter),
8. Maximal time shift in beam synchronization ($\Delta\tau$ ), derived from $\Delta z_{IP}^{SY}$.

| parameter | Z-pole | 240 GeV |
|---|---|---|
| $\Delta r_{in}$ ($\mu$m) | 1 | 10 |
| $\sigma_r$ ($\mu$m) | 350 | 700 |
| $\Delta l$ ($\mu$m) | 100 | 500 |
| $\sigma_{x_{IP}}$ ($\mu$m) | 250 | 1200 |
| $\sigma_{z_{IP}}$ (mm) | 10 | 12 |
| | | |
| $\Delta E$ (MeV) | 7 | 130 |
| $\sigma_{E_{BS}}$ (MeV) | 360 | 1000 |
| $\Delta x_{IP}^{BS}$ ($\mu$m) | 150 | 1250 |
| $\Delta z_{IP}^{SY}$ (mm) | 2 | 6 |
| $\Delta\tau$ (ps) | 7 | 20 |

Table 3.5.7_1 Limits of systematic effects contributing each to the integrated luminosity relative uncertainty as $10^{-4}$ at the Z-pole and $10^{-3}$ at 240 GeV center of mass energy.

As illustrated in Table 3.5.7_1, the most challenging issue is the luminometer inner aperture to be known at the micron level. The rest of the requirements are often significantly looser than the current technological capabilities to calibrate the beam energies (ΔE) or to monitor luminometer position in transverse ($\sigma_{x_{IP}}$) or longitudinal direction ($\sigma_{z_{IP}}$, Δl). Position resolution of Bhabha hits in the luminometer front plane can always be improved by placing a Si-tracker plane in front of the luminometer for $\sigma_r$ measurement with micrometer precision. It is also shown in [*I. Smiljanic et al., Systematic uncertainties in integrated luminosity measurement at CEPC, JINST 17 P09014, 2022*] that with the CEPC post-CDR instantaneous luminosity upgrade, beam energy spread can be determined with the accuracy corresponding to 9 MeV beam energy uncertainty in only 3 minutes of data-taking of di-muon events at the $Z$-pole. The accuracy is dominated by the systematic uncertainty of the method.

Other systematic effects have also been concerned in several simulation studies, including physics background from Landau-Lifshitz exchange of two virtual photons resulting in $e^+e^-f\bar{f}$ four-fermion final state [*I. Smiljanic et al., Systematic uncertainties in integrated luminosity measurement at CEPC, JINST 17 P09014, 2022*]. Figure 3.5.7_2 illustrates the presence of electron spectators in the luminometer fiducial volume at 240 GeV center of mass energy being less than $10^{-4}$ fraction of the signal. This type of background is even less pronounced at the Z-pole due to its cross section scaling with the squared center of mass energy as ~ln(s).

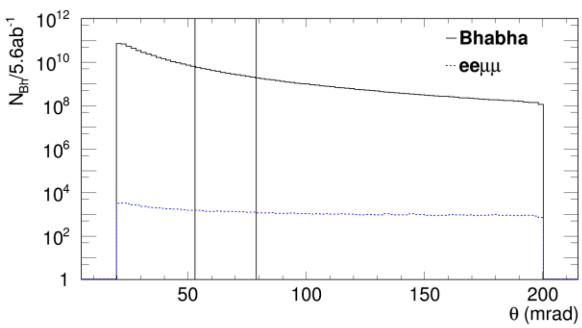


Figure 3.5.7_2 Contamination of the luminometer fiducial volumes with electron spectators from Landau-Lifshitz four-fermion final states at 240 GeV center of mass energy.

Electromagnetic interactions of incoming and outgoing beams (EMD1) as well as the interaction of incoming bunches with final state Bhabha electrons and positrons (EMD2 modify ) in general four-vectors of the Bhabha final states. There is ongoing study of EMD2, while EMD1 has been quantified in [*I. Bozovic Jelisavcic, I. Smiljanic, G. Kacarevic, Electromagnetic deflection of the initial state at the Z-pole at CEPC, EU Edition of the CEPC Workshop, University of Edinburgh, July 2023* ], resulting in effective reduction of the crossing angle for 140 μrad (70 μrad per beam) caused by the $p_x$ momentum kick of ~5.8 MeV the initial $e^+e^-$ system is receiving due to interaction of incoming and outgoing beams. This is illustrated in Figure 3.5.7_3. Relative Bhabha count in the fiducial volume of the detector would change as a few times $10^{-3}$ due to this effect, however it can be taken as a correction since the crossing angle can be precisely measured using di-muon production at CEPC. $10^6$ di-muon events can be collected in only 12 minutes of the CEPC run at the Z-pole, while the standard error scales as 260 μrad/$\sqrt{N_{\mu\mu}}$ resulting in crossing angle uncertainty below microradian.

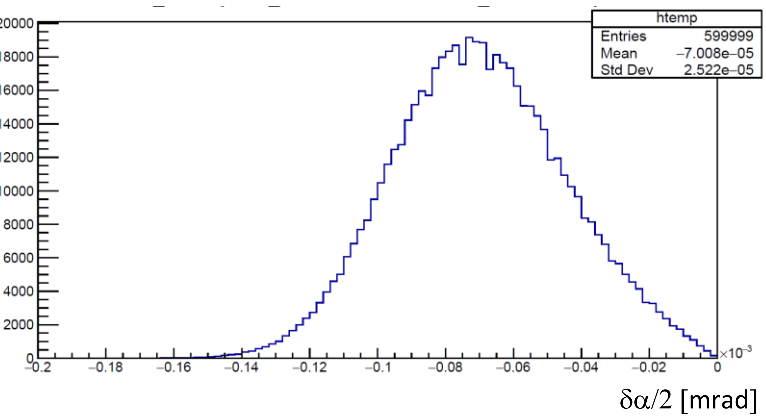


Figure 3.5.7_3 Absolute change of the initial state crossing angle per beam due to EM interaction between incoming and outgoing beams.

The comprehensive list of systematic effects in integrated luminosity measurement has been studied at CEPC, indicating that the foreseen relative precision of $10^{-3}$ ($10^{-4}$ at the Z-pole) is well within the achievable margins of contemporary laser-based systems for luminometer position monitoring. Also, beam properties and beam delivery to the interaction point seem to comply with the requirements. Remain challenge is the mechanical control of the luminometer aperture at the micron level, caused by the steep polar angle dependence of the Bhabha cross section ($\sim 1/\theta^3$), while some effects like EMD1 and uncertainty of the beam energy spread can be taken as corrections using additional central processes like di-muon production.