Systematic uncertainties in integrated luminosity measurement at CEPC

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Overview

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  - Uncertainties from mechanics and positioning
  - MDI related uncertainties
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  - Method of the beam energy spread determination
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Introduction

- CEPC physics program requires **relative uncertainty of the integrated luminosity** measurement to be of order of **10^{-4} at 91.2 GeV** and of order of **10^{-3} at 240 GeV**
- Precision reconstruction of position and energy of electromagnetic showers calls for finely segmented and compact luminometer
- Usual method of integrated luminosity measurement is counting of Bhabha scattering events - a well described QED process ($\delta\sigma_{Bh} \sim 10^{-4}$)
- However, there is an extensive list of systematic effects to be known with the same accuracy as the luminosity

- Results presented here are accepted for publication at JINST and can be found at arXiv: arXiv:2010.15061 [physics.ins-det]

Integrated luminosity measurement and systematic uncertainties

1. Uncertainties from mechanics and positioning

2. MDI related uncertainties

3. Physics interactions

4. Impact of the uncertainty of a beam energy spread (BES)

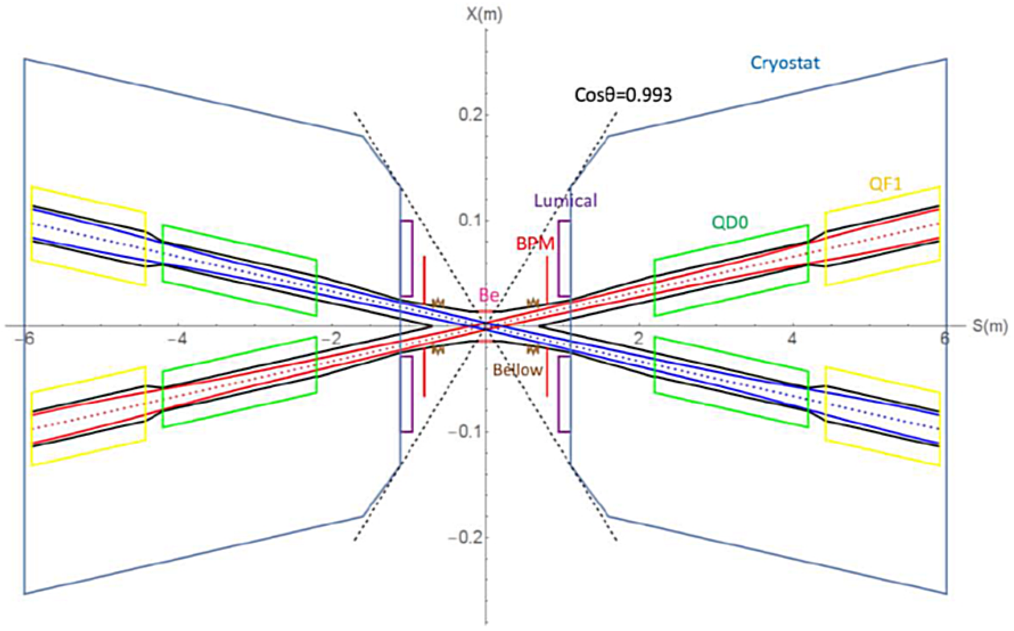
5. Impact of beam-beam interaction

6. Off-momentum particles

Uncertainties from mechanics and positioning

- **Simulation:**
- 10^7 Bhabha scattering events generated using BHLUMI Bhabha event generator, at two CEPC center-of-mass energies: 240 GeV and Z^0 production threshold
- The effective Bhabha cross-section in the luminometer's fiducial volume (between 53 mrad and 79 mrad) is of order of a few nb
- Final state particles are generated in the polar angle range from 45 mrad to 85 mrad (slightly wider than the fiducial volume), to allow events with non-collinear FSR to contribute
- We assumed that the shower leakage from the luminometer is negligible

- **Event selection:**
- asymmetric in polar angle acceptance on the left and right arm of the detector (like at OPAL) - at one side we consider the full fiducial volume, while at the other side we shrink the radial acceptance for Δr; this has been done subsequently to the left (L) and right (R) side of the luminometer, event by event, leading to cancellation of L-R asymmetries



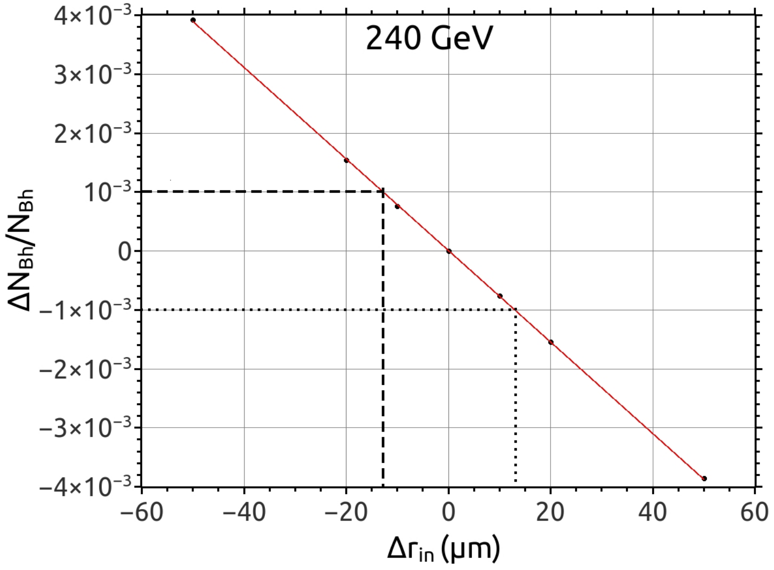
Uncertainties from mechanics and positioning

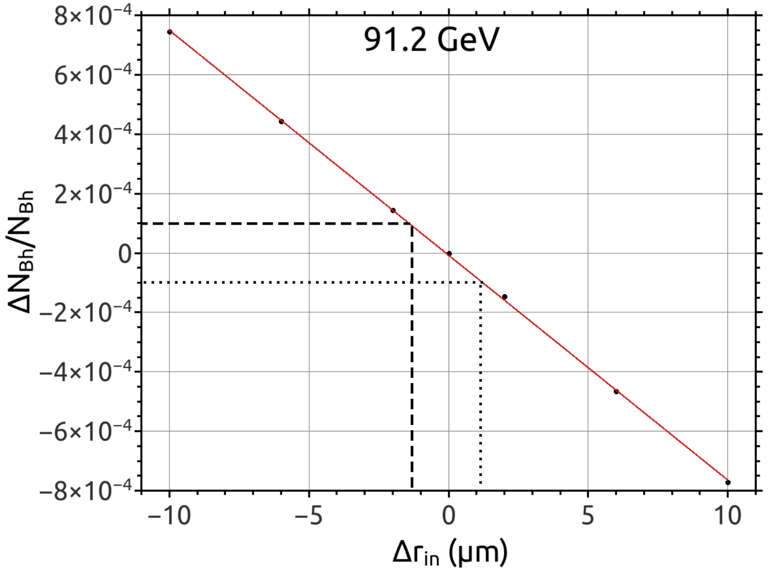
Considered detector-related uncertainties arising from manufacturing, positioning and alignment, basically affecting acceptance:

- uncertainty of the luminometer inner radius (Δr_{in}),
- spread of the measured radial shower position w.r.t. to the true impact position on the luminometer front plane (σ_r),
- uncertainty of the longitudinal distance between left and right halves of the luminometer (Δl),
- mechanical fluctuations of the luminometer position with respect to the IP caused by vibrations and thermal stress, radial and axial (σ_{xIP}, σ_{zIP})
- twist of the calorimeters corresponding to different rotations of the left and right detector axis with respect to the outgoing beam ($\Delta\varphi$)

Parameter	Precision @240 GeV	Precision @91 GeV
Δr_{in} (μm)	10	1
σ_r (mm)	1.00	0.20
Δl (mm)	1.00	0.08
σ_{xIP} (mm)	1.0	0.5
σ_{zIP} (mm)	10	7
$\Delta\varphi$ (mrad)	6.0	0.8

Uncertainties from mechanics and positioning





Δr_{in}~10 μm corresponds to 10^{-3} relative uncertainty of Bhabha count at 240 GeV

Δr_{in}~1 μm corresponds to 10^{-4} relative uncertainty of Bhabha count at 91.2 GeV

It is clear that due to the σ_{Bh} ~$1/\theta^3$ dependence, inner aperture of the luminometer is one of the most demanding mechanical parameters to control (1 μm @ Z-pole).

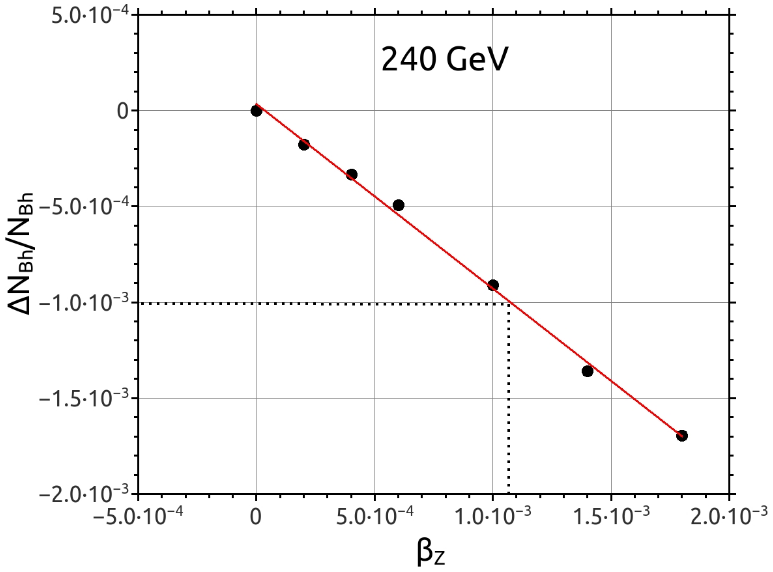
MDI related uncertainties

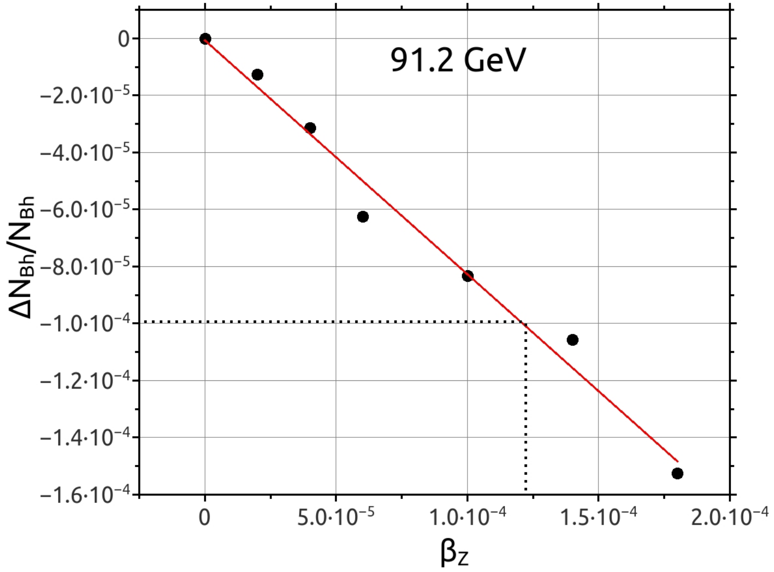
Considered MDI related effects:

- uncertainty of the average net center-of-mass energy (ΔE_{CM}) – cross-section calculation
- asymmetry in energy of the e^+ and e^- beams, given as the maximal deviation (ΔE) of the individual beam energy from its nominal value – longitudinal boost w.r.t. the lab frame – loss of coincidence
- IP position displacements with respect to the luminometer, radial and axial (Δx_{IP}, Δz_{IP}), caused by the finite beam transverse sizes and beam synchronization, respectively – affecting acceptance
- time shift in beam synchronization (τ) leading to IP longitudinal displacement Δz_{IP} – affecting acceptance

Parameter	Precision @240 GeV	Precision @91 GeV
ΔE_{CM} (MeV)	120	5
ΔE (MeV)	130	6
Δx_{IP} (mm)	1.0	0.5
Δz_{IP} (mm)	10	2
τ (ps)	15	3

MDI related uncertainties

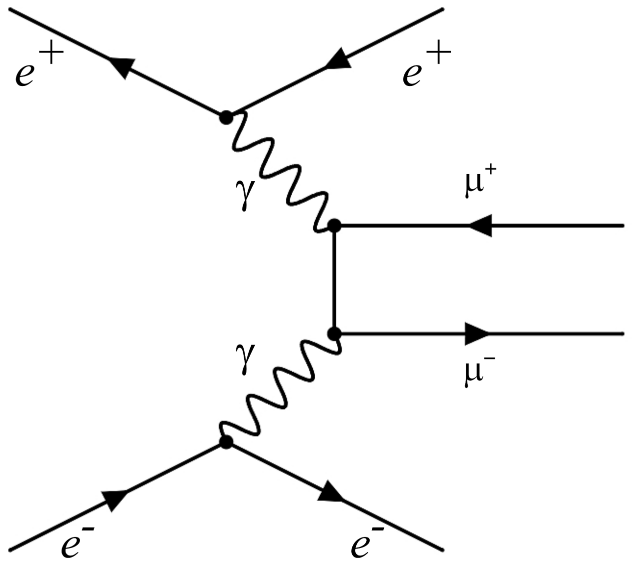


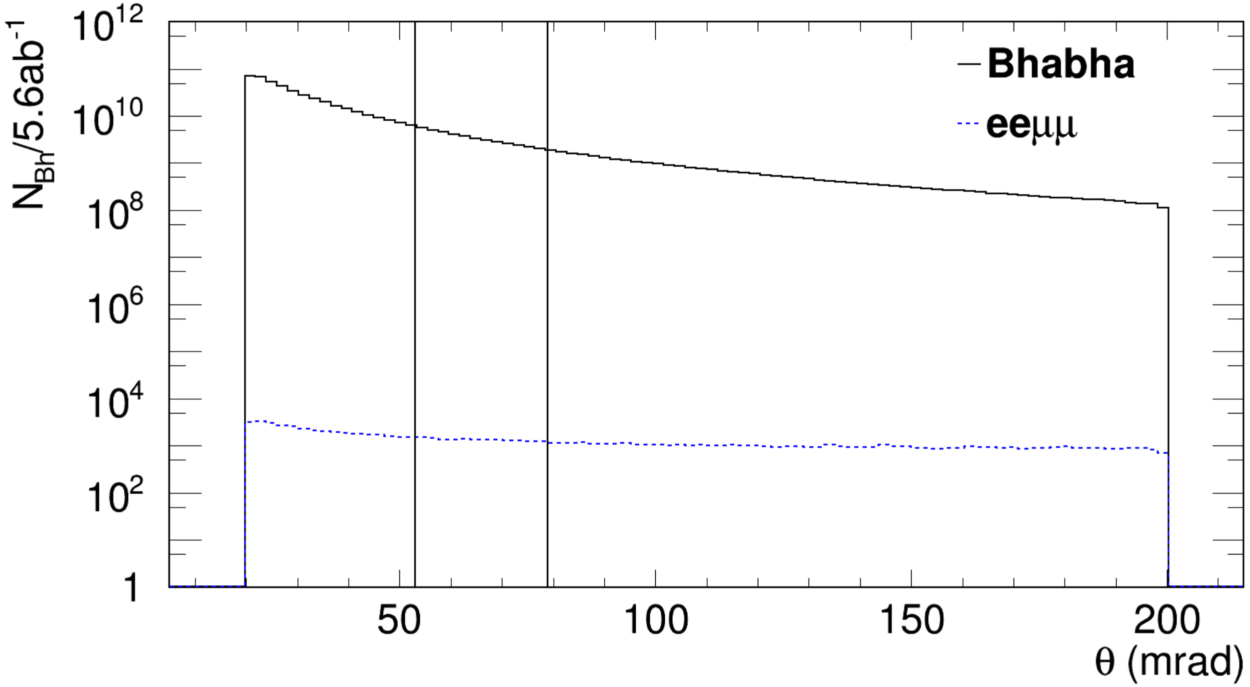


Loss of the Bhabha count in the luminometer due to the longitudinal boost of the CM frame β_z, where $\beta_z = 2\cdot\Delta E/E_{CM}$. Dotted line indicates 10^{-3} (10^{-4}) relative uncertainty of the Bhabha count required at 240 GeV (Z^0 pole) CEPC run.

- Individual beam energy need to be controlled at the level of 10^{-4} w.r.t. the nominal beam energy at the Z^0 pole
- The corresponding uncertainty of the beam energy of ~6 MeV required at the Z^0 pole is several times smaller than the nominal BES (0.08% or ~36.5 MeV)
- The current value of the BES at the Z^0 pole will contribute to δL as ~$8\cdot10^{-4}$ as the cause of asymmetry in beam energies (giving rise to longitudinal boost β_z)

Two-photon processes as a background





- Multiperipheral process ~nb x-section
- High energy e- spectators can fake the signal
- We simulated 10^5 $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ events at 240 GeV using WHIZARD 2.8
- Most of spectators go below luminometer acceptance
- There is additional effect of radiative Bhabha events to be considered. Here we assumed that the separation can be achieved with the tracking plane placed in front the luminometer.

Beam energy spread determination

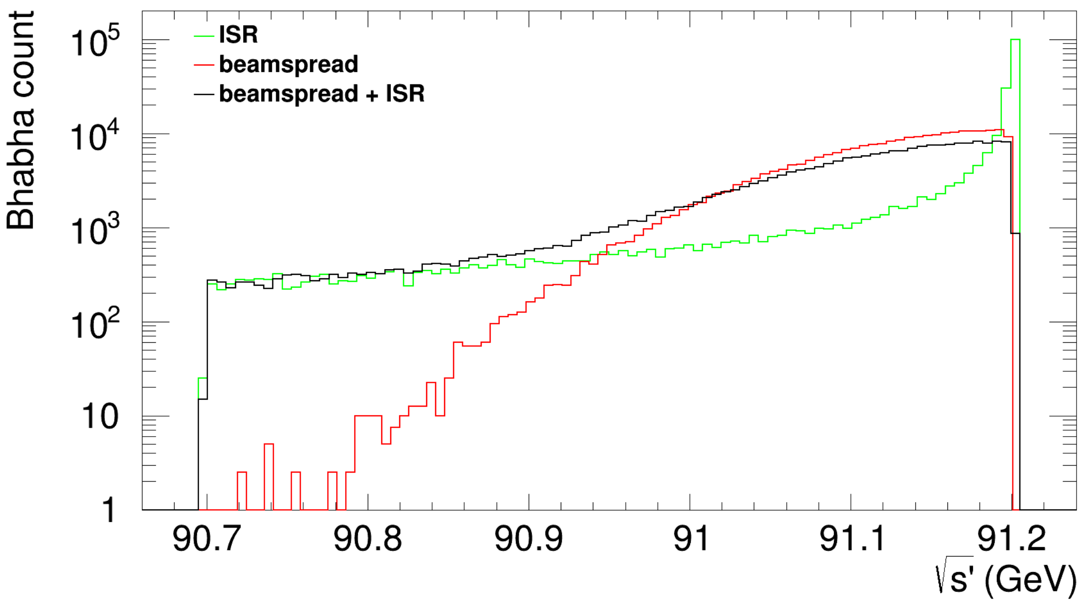
Can the precision of the beam spread influence Bhabha count?
Yes, by providing the longitudinal boost of the colliding system due to asymmetry in beam energies.

- Motivated by the similar work done by FCCee, we looked into **high x-section, easy to identify, central process**: $e^+e^- \rightarrow \mu^+\mu^-$ (x-section is ~1.5 nb at Z-pole) in order to determine the precision to measure BES at CEPC.
- **Rely on the excellent performance of the central tracker** for muon reconstruction (0.1 mrad mean corresponding to 100 µm position resolution)
- We generated several hundred thousand $e^+e^- \rightarrow \mu^+\mu^-$ events at 91.2 GeV and 240 GeV CM energies using WHIZARD 2.6, in the central tracker acceptance from 8^o to 172^o
- Events are generated simulating individually effects of the Initial State Radiation (ISR) and detector angular resolution (Gaussan smearing), to study their impact on the effective CM energy s' as competitive effects to BES
- s' can be calculated from the reconstructed muons' polar angles:

$$\frac{s'}{s} = \frac{sin\theta^+ + sin\theta^- - |sin(\theta^+ + \theta^-)|}{sin\theta^+ + sin\theta^- + |sin(\theta^+ + \theta^-)|}$$

- Larger beam-spread leads to the corresponding reduction of the number of di-muon events carrying near to maximal available energy from the collision
- Knowing this dependence from simulation enables determination of the effective beam-spread (δ') once the count of di-muon events is known experimentally

Beam energy spread determination



Count of Bhabha events versus the effective CM energy (top part of the spectrum) at the Z^0 pole. BES is the dominant effect to reduce the number of events at the maximal CM energy.

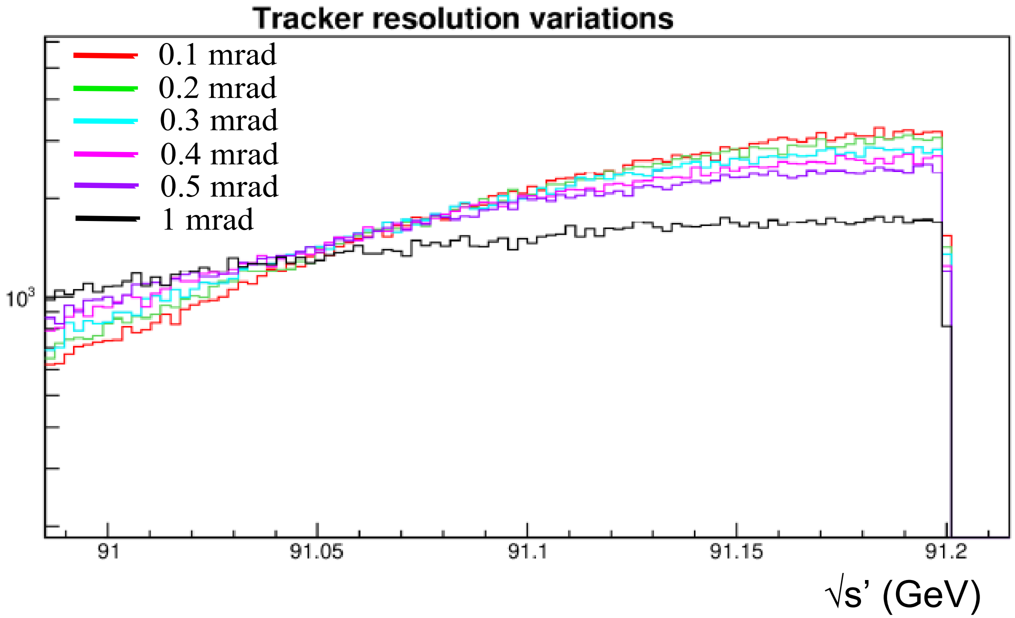
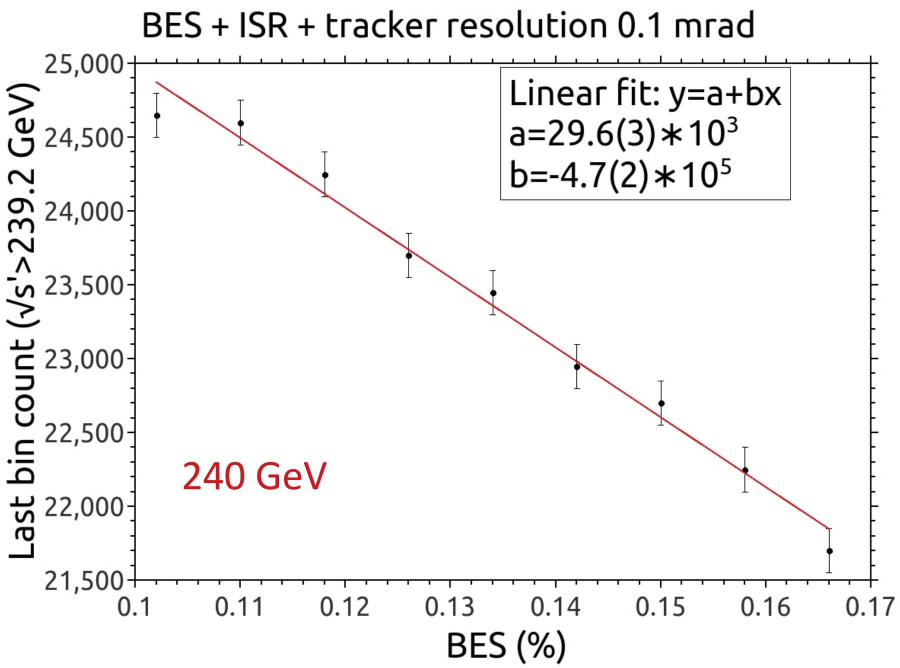
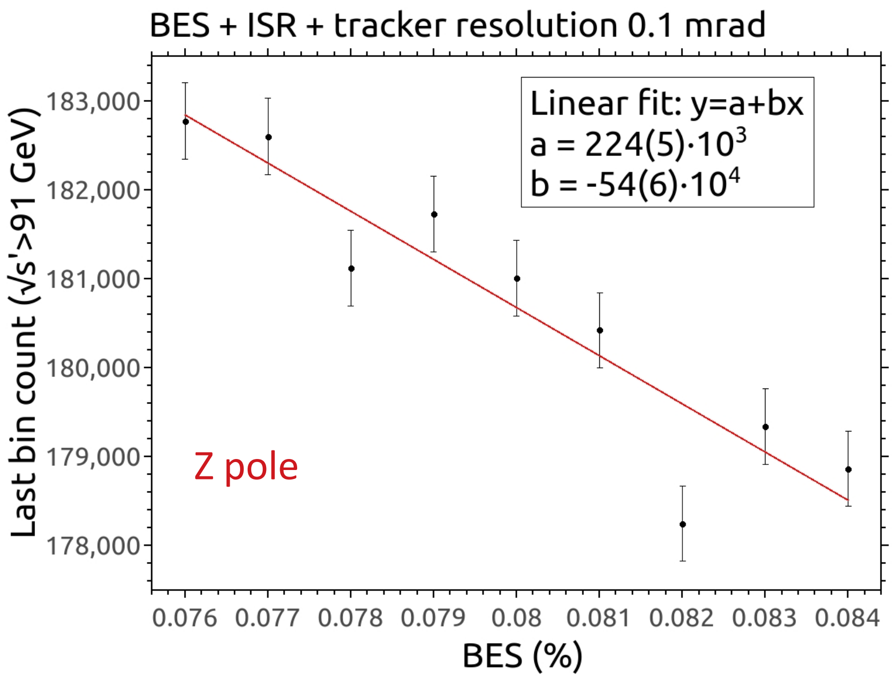


Illustration of the impact of the central tracker resolution in polar angle.

- **Central tracker resolution in polar angle should not be larger than 0.5 mrad/500 μm**

Beam energy spread determination



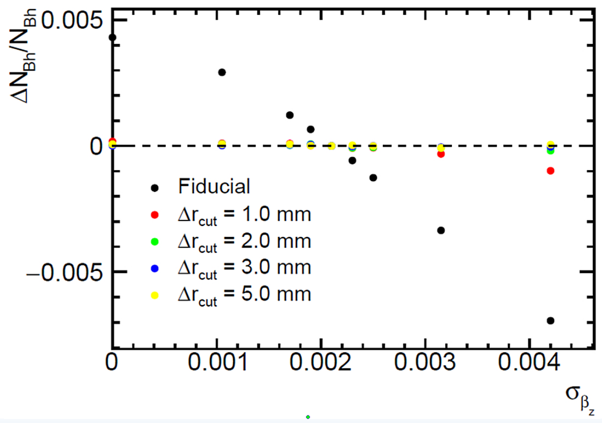


- To exploit *s′* **peak count sensitivity** to the BES values, BES is varied around the nominal value
- Dependence can be fitted using a simple linear fit where the statistical uncertainty of the **muon count translates to the statistical uncertainty of the beam-spread**, while **uncertainty of the fit introduces systematic uncertainty of the BES measurement**

Beam energy spread determination

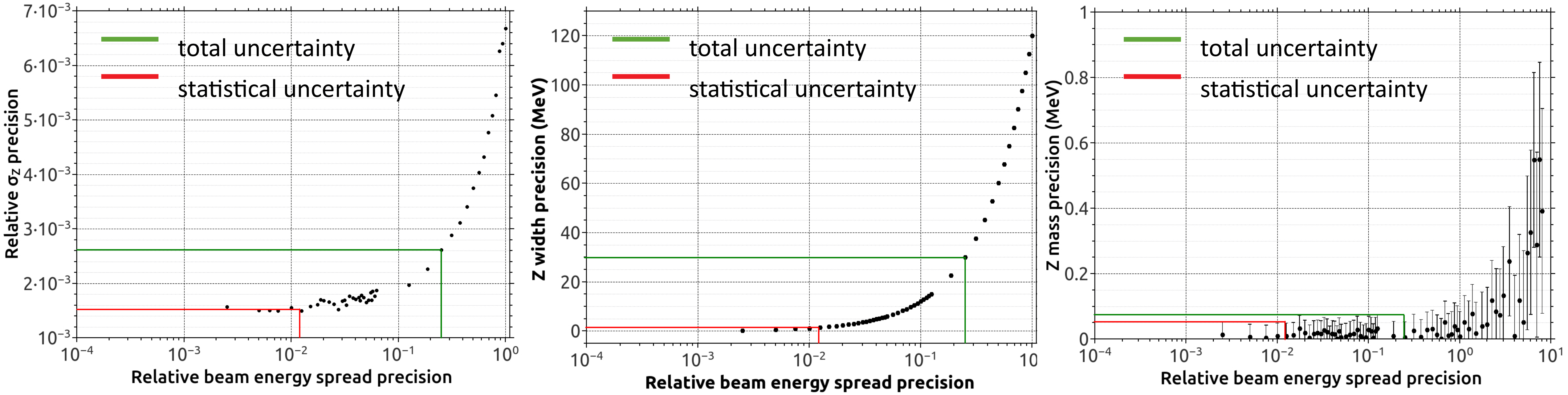
CEPC	L@ IP (cm^{-2} s^{-1})	Nominal BES (%)	Number of events	Cross-section $e^+e^- \to \mu^+\mu^-$	Collecting time	Relative stat. uncertainty BES	Relative total uncertainty BES	Uncertainty ΔE_{BES} (MeV)
Z - pole	$1.02\cdot10^{36}$	0.080	$2.5\cdot10^{5}$	1.5 nb	3 min	1.2%	25%	9
240 GeV	$5.2\cdot10^{34}$	0.134	$1.0\cdot10^{5}$	4.1 pb	5 days	2.3%	15%	24

- At the Z pole, relative variations of the BES can be measured with 25% total relative uncertainty, where the systematic uncertainty comes from the calibration curve; 1.2% relative statistical uncertainty for only 3 minutes of data taking with $1.02\cdot10^{36}$ cm^{-2}s^{-1} instantaneous luminosity
- Contribution to the beam energy uncertainty from BES determination is 9 MeV (24 MeV) at the Z-pole (240 GeV)



- The above translates to $4\cdot10^{-3}$ uncertainty of the Bhabha count at the Z^0 pole, if events are counted symmetrically
- For the asymmetric counting the effect is negligible → luminometer should be placed at the outgoing beam

Impact on precision of EW observables



- For each EW observable precision is evaluated as the standard error of the mean (SEM), SEM=RMS/√N, where 1 million di-muon events are simulated in order to minimize statistical effects of the samples' sizes (uncertainty on the y-axis)
- Contribution of the total BES uncertainty at the Z^0 pole is found to be: $\delta(\sigma_Z)\sim2.6\cdot10^{-3}$, $\Delta\Gamma_Z\sim30$ MeV, $\Delta m_Z<100$ keV
- Uncertainties originated solely from the statistical uncertainty of the BES are significantly smaller: $\delta(\sigma_Z)\sim1.5\cdot10^{-3}$, $\Delta\Gamma_Z\sim1$ MeV, $\Delta m_Z<50$ keV

Conclusion

- A comprehensive list of the systematic uncertainties in integrated luminosity determination have been studied at CEPC (Z^0 pole and 240 GeV)
- **Inner radius** of the luminometer should be controlled at the micron level (or better if we go below θ_{min}~30 mrad or change L^*)
- Uncertainty of energy of individual beams (caused by beam-beam interactions, ISR, BES) should not exceed 6 MeV at the Z^0 pole
- BES at the Z^0 pole (36.5 MeV) already contributes to $\delta L/L$ as $8 \cdot 10^{-4}$
- With the CEPC post-CDR design, BES can be determined with the total **relative** accuracy of 25% corresponding to 9 MeV beam energy uncertainty in only 3 minutes of data-taking of di-muon events at the Z^0 pole
- Impact of the BES uncertainty on integrated luminosity can be annulled with asymmetric Bhabha counting
- However, it impacts precision EW observables (at the Z^0 pole), translating to the relative uncertainty of the Z^0 production cross-section of $2.6 \cdot 10^{-3}$ and absolute precisions of the Z^0 mass and width below 100 keV and 30 MeV respectively

Thanks for your attention!