Update on integrated luminosity systematics at CEPC: beam energy spread

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Overview

- Introduction

- Determination of the beam energy spread
  - Method of the beam energy spread determination
  - Impact on integrated luminosity
  - Impact on precision of EW observables

- Summary

Introduction

- **Challenging control of luminosity systematics at 10^{-4} at 91.2 GeV and 10^{-3} at 240 GeV**

- **Most sources from mechanics and MDI have been studied** and documented in CEPC CDR and *JINST 17 P09014, 2022*

- In addition we discuss the possibility of experimental determination of the beam energy spread *(motivated by similar work at FCCee)*

- And its impact on luminosity systematics and precision EW observables at the Z-pole

- Only relevant design parameter is the luminometer aperture/fiducial volume, taken to be between 26 mrad and 105 mrad /53 mrad and 79 mrad

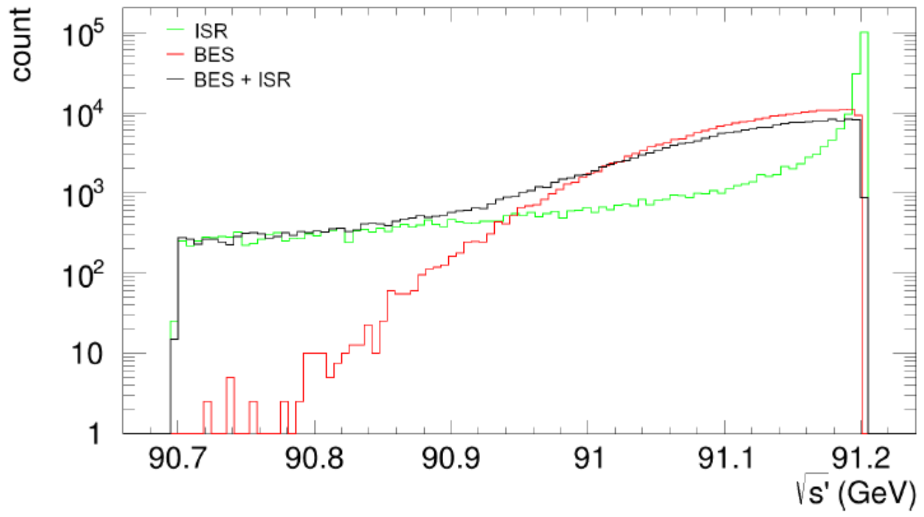
Beam energy spread determination

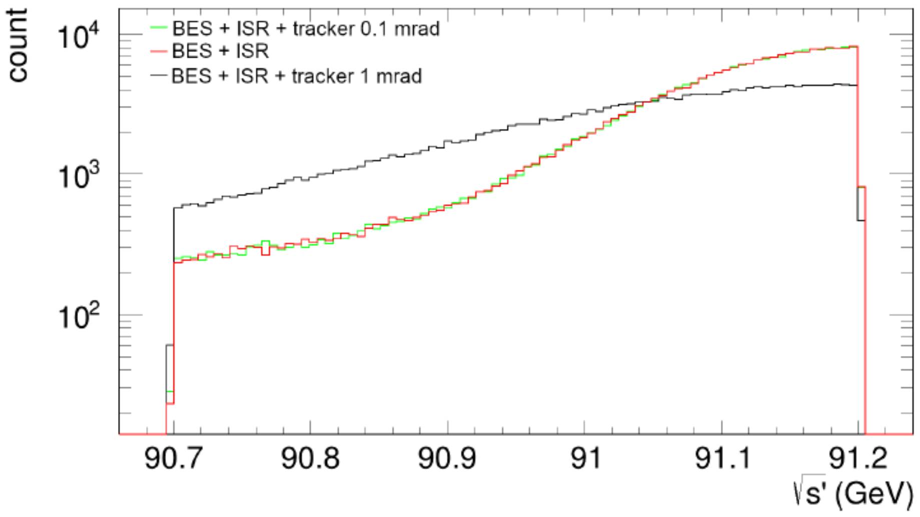
- High x-section, easy to identify, central process: $e^+e^- \rightarrow \mu^+\mu^-$ (~1.5 nb at Z-pole) to determine s'
- Several hundred thousand di-muon events at 91.2 GeV and 240 GeV CM energies using WHIZARD 2.6, in the central tracker acceptance from 8° to 172°
- Initial State Radiation (ISR) and detector angular resolution (Gaussan smearing), simulated individually to study their impact on the s'
- s' can be retrieved 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 BES leads to reduction of the number of di-muon events carrying near to maximal available energy
- Knowing this dependence from simulation enables determination of the effective BES (δ') once the count of di-muon events is known experimentally

Beam energy spread determination



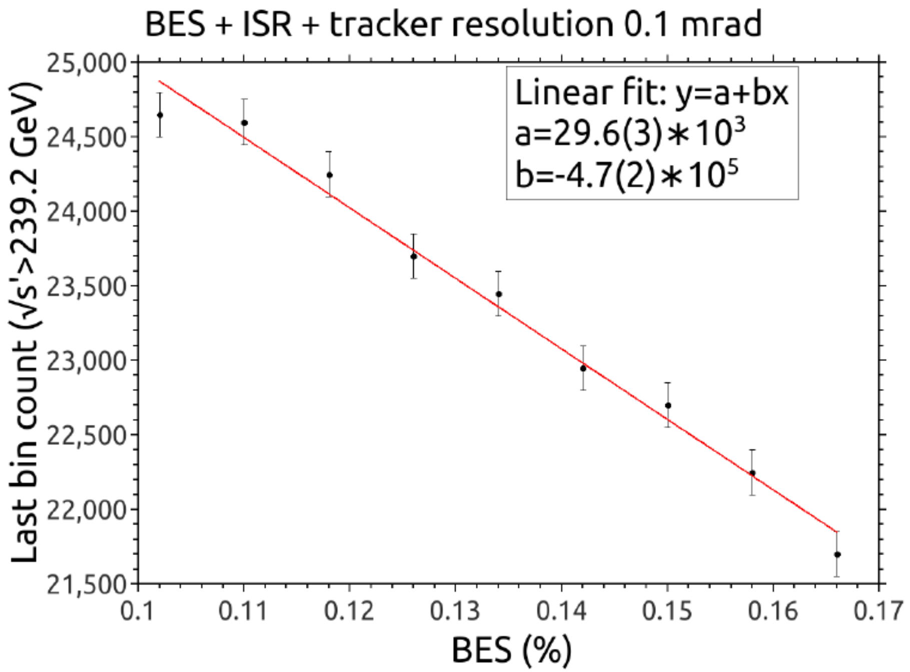


- BES dominates the *s'* shape at energies close to the nominal CM energy

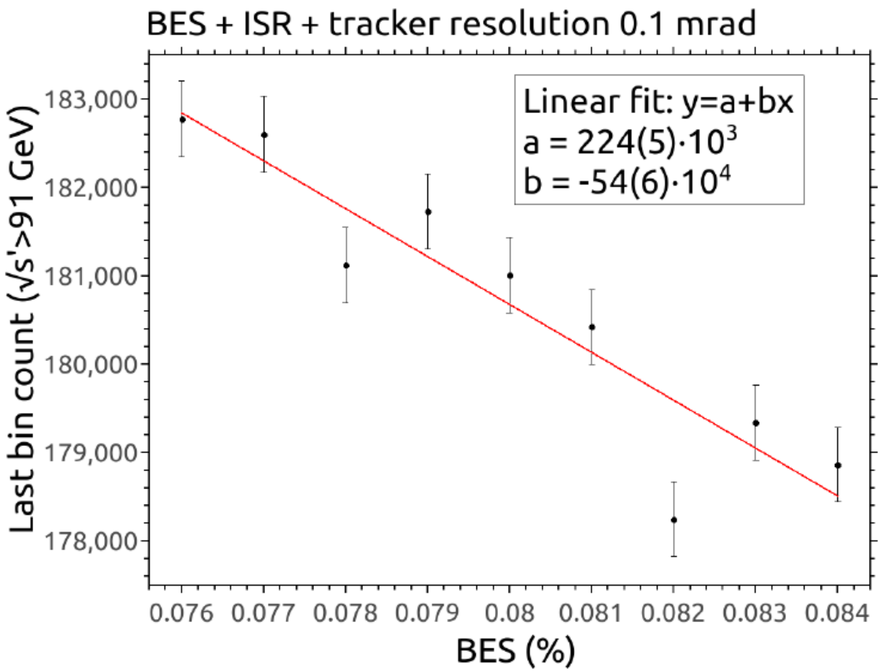
- Central tracker resolution in polar angle should not be larger than 0.5 mrad/500 μm

Beam energy spread determination

240 GeV



Z pole



- The effective beam-spread can be determined from the count of the top-part of the *s'* distribution

- Statistical uncertainty of di-muon count translates to the statistical uncertainty of the beam-spread, while uncertainty of the fit introduces systematic uncertainty of the measurement

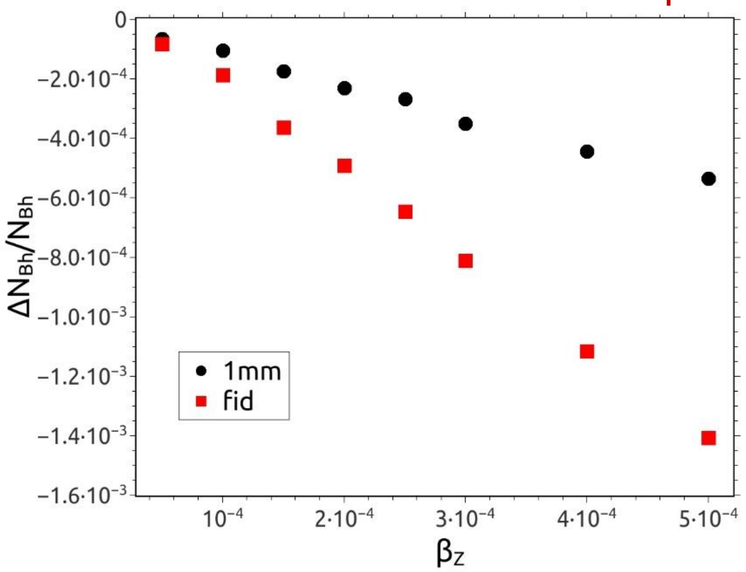
Beam energy spread determination

CEPC	$\mathcal{L}$ @ IP ($cm^{-2}s^{-1}$)	Nominal BES δ (%)	Number of events	Cross-section $e^+e^- \to \mu^+\mu^-$	Collecting time	Relative statistical uncertainty of BES	Total relative uncertainty of BES	ΔE_{BES} (MeV)
Z^0 pole	$1.02 \cdot 10^{36}$	0.080	$2.5 \cdot 10^5$	**1.5 nb**	**3 min**	**1.2%**	**25%**	**9**
240 GeV	$5.2 \cdot 10^{34}$	0.134	$1.0 \cdot 10^5$	**4.1 pb**	**5 days**	**2.3%**	**15%**	**24**

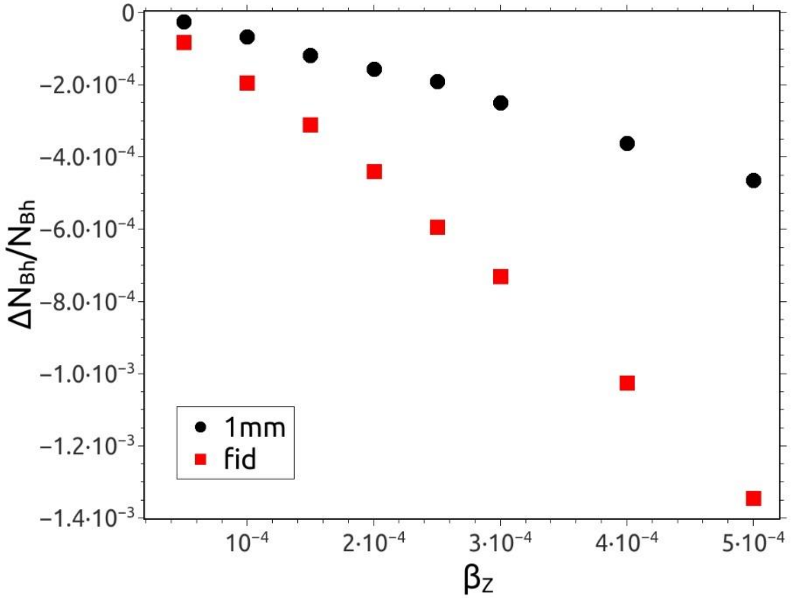
Impact on Bhabha count

- ΔE_{BES} translates into longitudinal boost $\beta_{BES}=2\cdot\Delta E_{BES}/\sqrt{s}$
- Impacting the Bhabha count due to a loss of coincidence

Z-pole

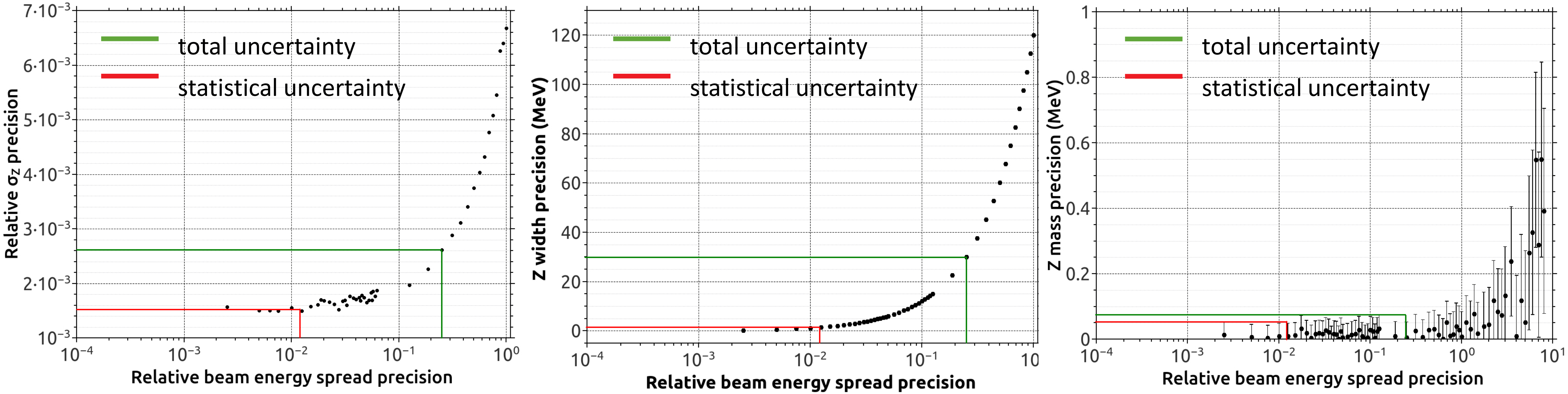


240 GeV



- Asymmetric counting is favored (for larger BES uncertainties)
- BES relative precision of $\sim 2\cdot 10^{-4}$ is not an issue; Contributes to $\Delta\mathscr{L}/\mathscr{L}=\Delta N/N$ as $\sim 5\cdot 10^{-4}$ even for the symmetric counting in the full FV

Impact on precision of EW observables



- EW observable precision is evaluated as the standard error of the mean (SEM), SEM=RMS/√N, where N=10^6 di-muon events, in order to minimize statistical effects of the samples' sizes
- Contribution of the total BES uncertainty at the Z^0 pole is found to be: $\delta(\sigma_Z)$~$2.6\cdot10^{-3}$, $\Delta\Gamma_Z$~30 MeV, Δm_Z<100 keV
- Uncertainties originated solely from the statistical uncertainty of the BES are significantly smaller: $\delta(\sigma_Z)$~$1.5\cdot10^{-3}$, $\Delta\Gamma_Z$~1 MeV, Δm_Z<50 keV

Summary

- A comprehensive list of the systematic uncertainties in integrated luminosity determination have been studied at the Z^0-pole and 240 GeV

- It is complemented with the estimate of the BES measurement precision using di-muon production

- 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 at the Z^0-pole

- The overall precision of the BES determination translates to the relative uncertainty of the integrated luminosity of $\sim 2\cdot 10^{-4}$ for the asymmetric counting

- And to the systematic uncertainty of the EW observables at the Z^0-pole: $\delta(\sigma_Z) \sim 2.6\cdot 10^{-3}$, $\Delta\Gamma_Z \sim 30$ MeV, $\Delta m_Z < 100$ keV

BACKUP

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

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
- 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)	240	9
ΔE (MeV)	120	5
Δx_{IP} (mm)	1.0	0.5
Δz_{IP} (mm)	10	2
τ (ps)	15	3