Measurements in the forward region: integrated luminosity and beam energy spread

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Overview

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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

- In addition we discuss the possibility of experimental determination of the beam energy spread
- …. and its impact on precision EW observables measurement at the Z-pole

- Results presented here can be found at [arXiv:2010.15061 [physics.ins-det]](arXiv:2010.15061) and are submitted to JINST

Integrated luminosity measurement and systematic uncertainties

1. Uncertainties from mechanics and positioning:

- uncertainty of the luminometer inner radius (Δr_{in})
- spread of the measured radial shower position with respect to the true impact position in 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 ($\Delta\varphi$)

2. MDI related uncertainties:

- uncertainty of the average net center-of-mass energy (ΔE_{CM})
- uncertainty of the asymmetry in energy of the e^+ and e^- beams, given as the maximal deviation (ΔE) of the individual beam energy from its nominal value
- 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
- time shift in beam synchronization (τ) leading to IP longitudinal displacement Δz_{IP}

3. Physics interactions:

- Two-photon processes as a background

It is worth noting that the only relevant design parameter is the luminometer aperture / fiducial volume, taken to be between 26 mrad and 105 mrad /53 mrad and 79 mrad

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 te fiducial volume 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 cancelation of L-R assymetries

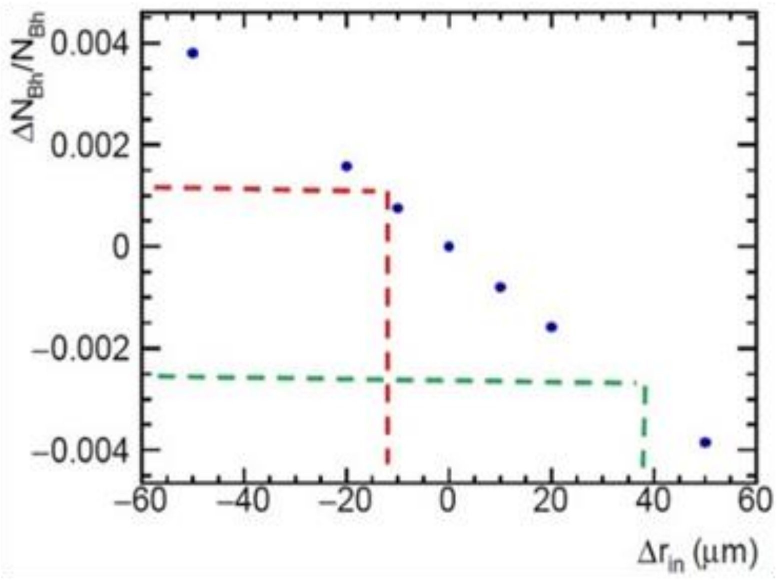
Uncertainties from mechanics and positioning

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



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 (1µm @ Z-pole).

Shrinking of r_{in} for 13 µm corresponds to 10^{-3} relative uncertainty of Bhabha count (red). On the other hand, enlargement of 40 μm results in the same uncertainty of the Bhabha count (green). All @240 GeV.

MDI related uncertainties

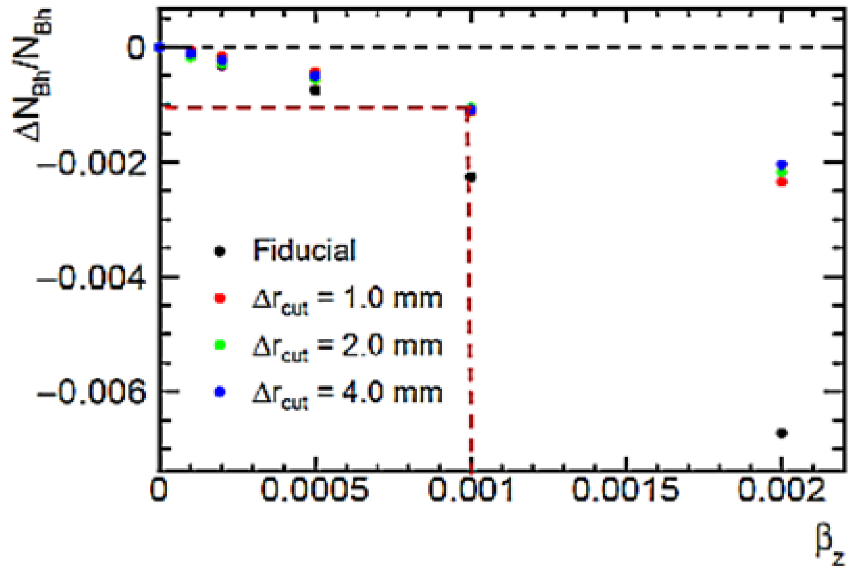
Considered MDI related effects:

- uncertainty of the average net center-of-mass energy (ΔE_{CM}) – cross-section calculation
- uncertainty of the 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

MDI related uncertainties

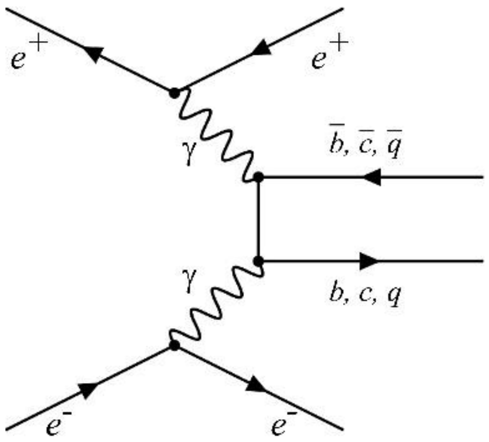
- Individual beam energy/effective CM energy need to be controlled at the level of 10^{-5} w.r.t. the nominal beam/CM energy at the Z^0 pole
- The corresponding uncertainty of the beam energy of ~5 MeV required at the Z^0 pole is several times larger than the BES (~36.5 MeV)
- The current value of the BES at the Z^0 pole will contribute to $\delta\mathcal{L}$ as $\sim 8 \cdot 10^{-4}$, due to the uncertainty of the effective CM energy ΔE_{CM} (for the Bhabha cross-section calculation) and the asymmetry in beam energies (giving rise to longitudinal boost β_Z)

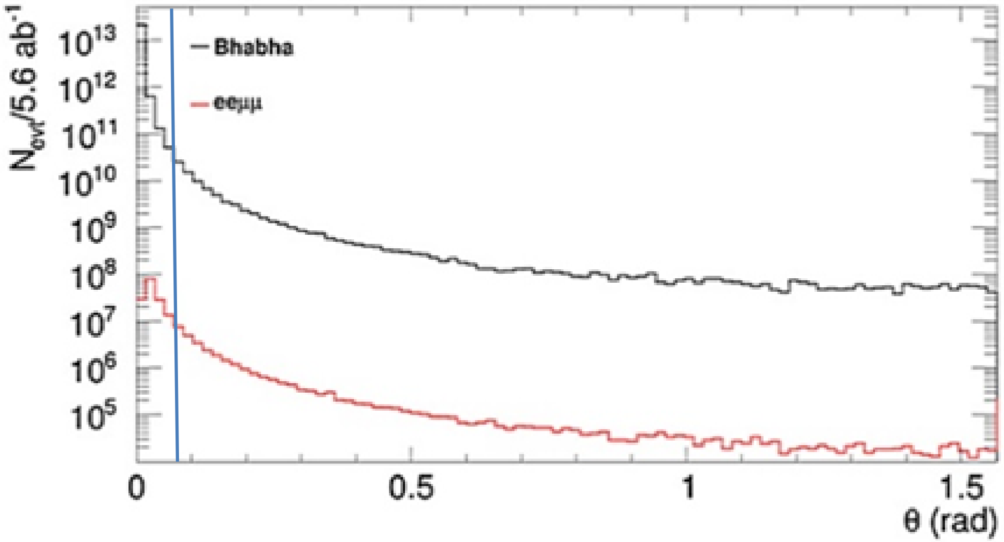


Loss of the Bhabha count in the luminometer due to the longitudinal boost of the CM frame β_z, where $\beta_z = 2 \cdot \Delta E/E_{CM}$, at 240 GeV

Two-photon processes as a background

- Multiperipheral process ~nb x-section
- High energy e- spectators can fake the signal
- We simulated 10^5 $e^+e^- \to e^+e^-\mu^+\mu^-$ events at 240 GeV using WHIZARD
- Most of spectators go below luminometer acceptance
- Initial contamination (without any selection) of the detector volume is ~10^{-4} w.r.t. the signal at 240 GeV CEPC
- Even smaller at the Z^0-pole since 2-photon x-section is scaling like ~$\ln^2(s)$
- With the cut on relative energy $(E_1+E_2)/2E_{beam}=E_{rel}>0.8$, B/S ratio is ~$8\cdot10^{-5}$
- Further refinements are possible (if needed) with the coplanarity request between left and right detector arms, $|\varphi_{e+}-\varphi_{e-}|$ (also reducing off-momentum paticles)





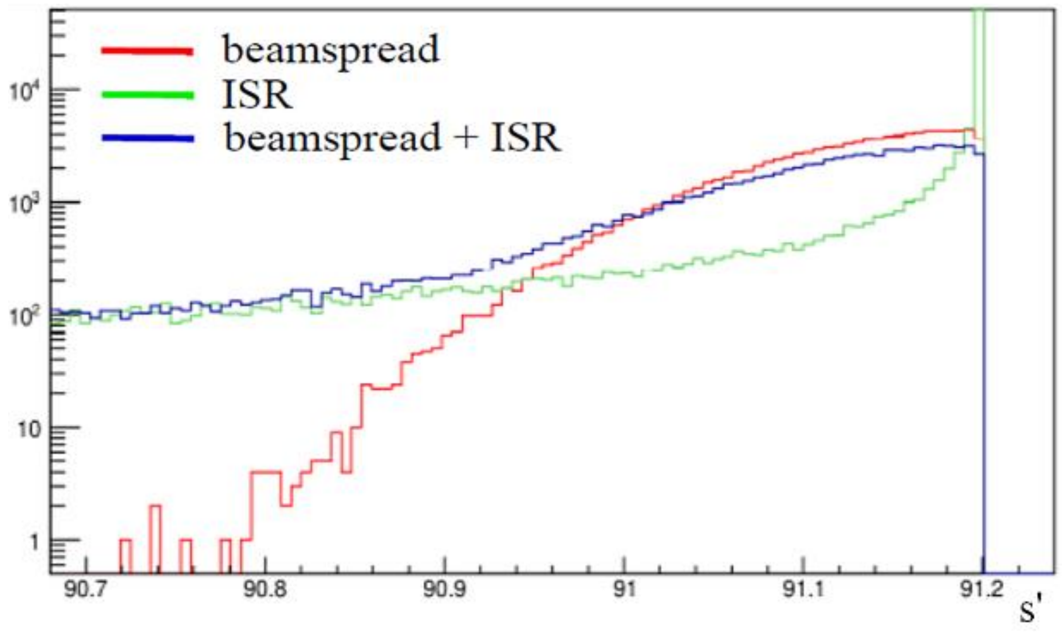
Beam energy spread determination

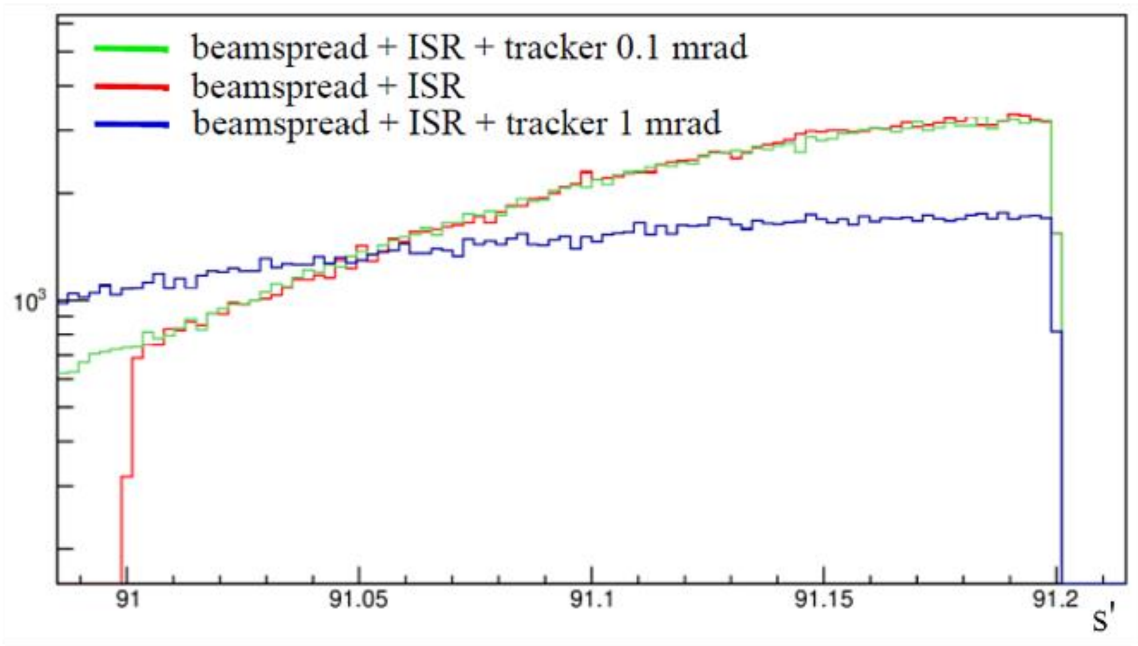
- Motivated by the similar work done by FCCee, we looked into **high x-section, easy to identify, central process**: $e^+e^- \rightarrow \mu^+\mu^-$ (x-section is ~1.5 nb at Z-pole)
- **Rely on the excellent performance of the central tracker** for muon reconstruction (0.1 mrad mean corresponding to 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 like the Initial State Radiation (ISR) and detector angular resolution (Gaussan smearing), to study their impact on the effectice CM energy s'
- 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

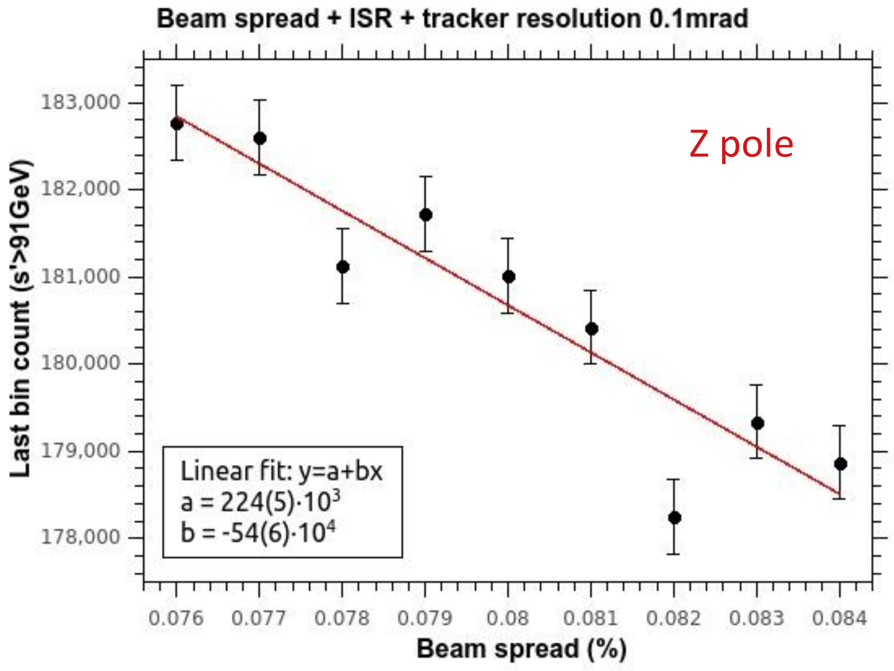
Beam energy spread determination

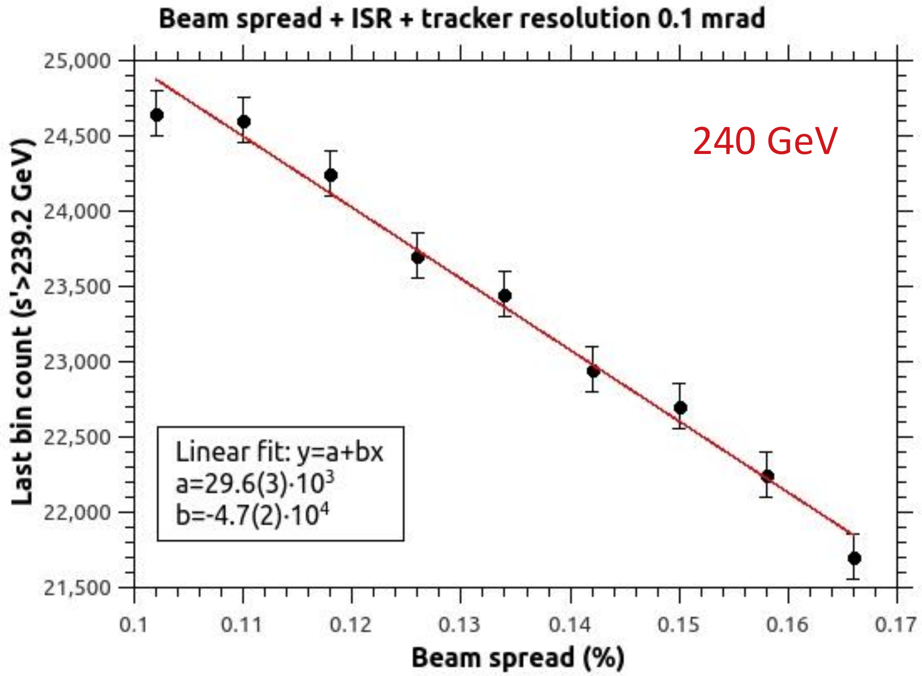




- BES dominates the *s′* shape at energies close to the nominal CM energy
- 0.1 mrad tracker resolution does not affect the *s′* sensitivity to the BES, while tracker resolution of 1 mrad significantly influences the method ➡ **central tracker resolution in polar angle should not be larger than 0.5 mrad/500 µm**

Beam energy spread determination





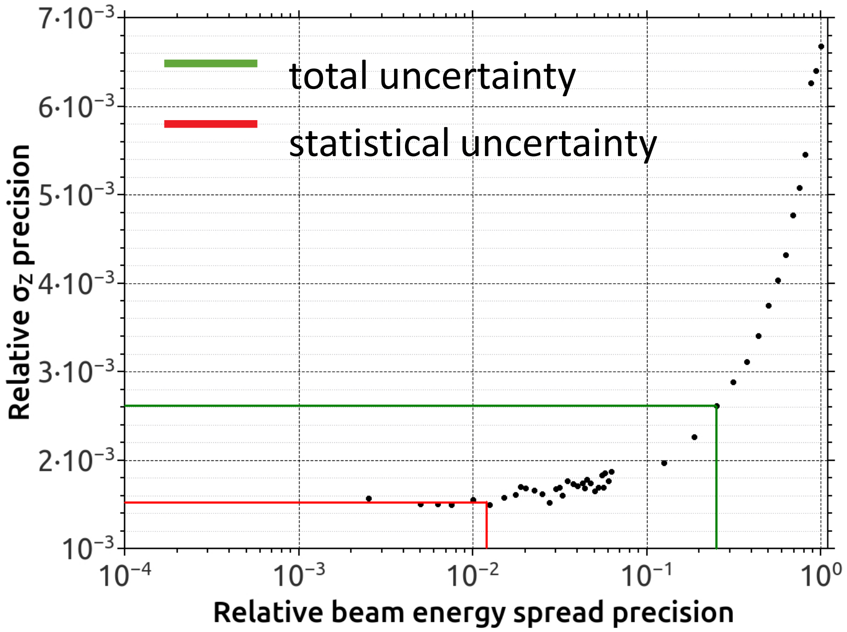
- To exploit *s'* **peak count sensitivity** to the beam-spread values, beam-spread is varied around the nominal value
- The effective beam-spread can be determined from the count of the top-part of the *s'* distribution
- Dependence can be fitted using a simple linear fit where the statistical uncertainty of the **muon count translates to the statistical uncertainty of the beam-spread**, while **uncertainty of the fit introduces systematic uncertainty of the measurement**

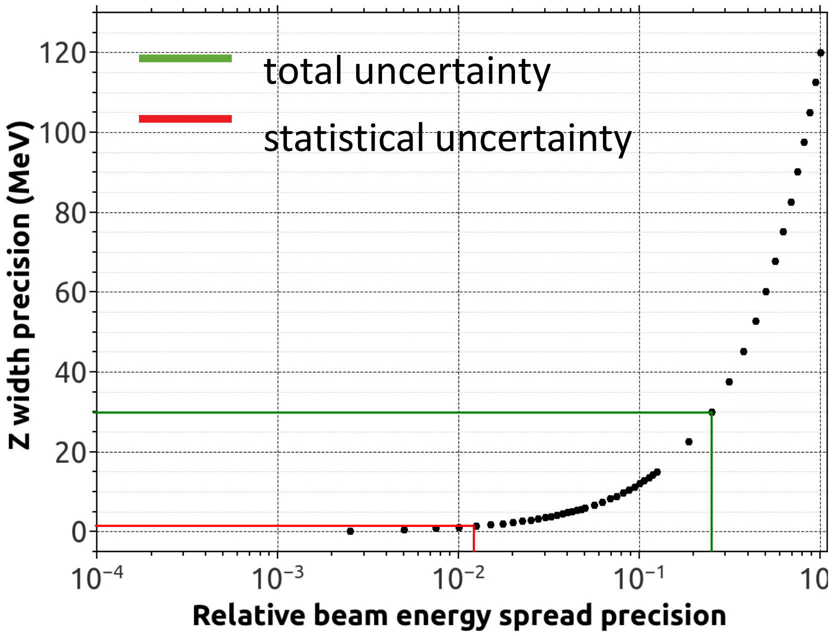
Beam energy spread determination

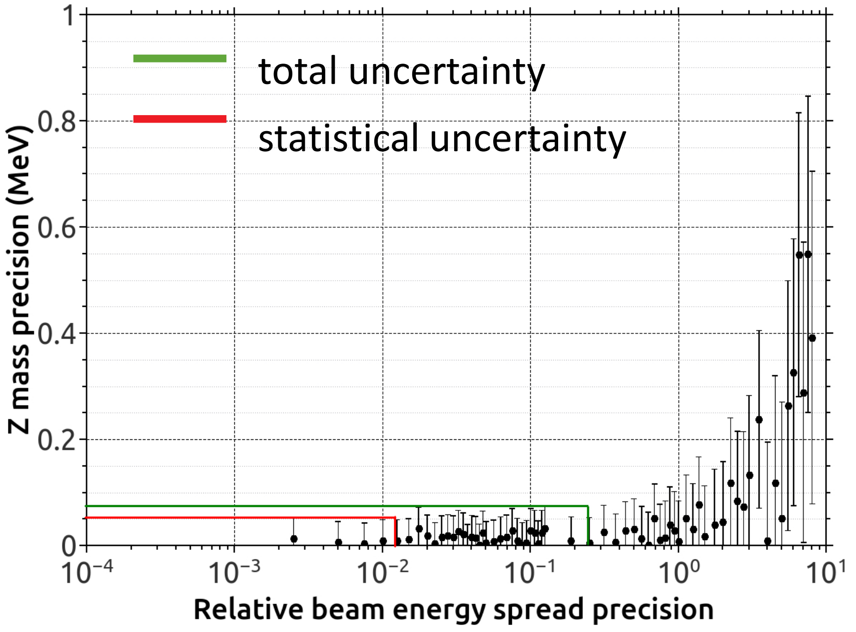
CEPC	L@ IP (cm^{-2} s^{-1})	Nominal BES (%)	Number of events	Cross-section $e^+e^- \to \mu^+\mu^-$	Collecting time	Relative stat. uncertainty BES	Relative total uncertainty BES	Uncertainty E_{beam} (MeV)
Z - pole	$1.02 \cdot 10^{36}$	0.080	$2.5 \cdot 10^5$	1.5 nb	3 min	1.2%	25%	9
240 GeV	$5.2 \cdot 10^{34}$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

- At 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 $1.02 \cdot 10^{36}$ $cm^{-2}s^{-1}$ instantaneous luminosity
- Contribution to the beam energy uncertainty from BES determination is 9 MeV at the Z-pole.

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 N=10^6 $\mu\mu$ events, in order to minimize statistical effects of the samples' sizes (uncertainty on the y-axis)
- Relative BES precision is varied (x-axis) over a wide range to illustrate the dependance
- 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

Conclusion

- A comprehensive list of the systematic uncertainties in integrated luminosity determination have been studied at CEPC (Z^0-pole and 240 GeV)
- The uncertainty of the luminometer **inner radius** at the micron level together with the uncertainty of the **available CM energy** and **beam energy** below the natural BES are posing the most challenging requirements at the Z^0 pole
- 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 $e^+e^- \to \mu^+\mu^-$ events at the Z^0 pole. The accuracy is dominated by the systematic uncertainty of the method
- The **total precision** of the BES determination translates 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!