Electromagnetic deflection effects in the integrated luminosity measurement at the CEPC

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Overview

- Introduction
- Very forward region at CEPC
- Electromagnetic deflection of the initial state (EMD1)
- Electromagnetic deflection of the final state (EMD2)
- Experimental corrections
- Summary

Introduction

- Challenging control of luminosity systematics at 10^{-4} at the Z^0 pole
- Most sources from mechanics and MDI have been studied and documented in CEPC CDR, CEPC TDR, *JINST 17 P09014(2022)* and *PTEP 10 103H02(2024),* including experimental determination of the beam energy spread and its impact on integrated luminosity and precision EW observables
- Electromagnetic fields of opposite bunches will impact initial states of particles in the bunches of opposite charges prior to interaction – EMD1
- In a similar manner, e^- and e^+ in the final state, whose four-momenta are already altered by EMD1, will be deflected after interaction by the fields of the opposite-charge bunches, which impacts their final states – EMD2
- Both EMD1 and EMD2 will affect the Bhabha count in the luminometer and, consequently, impact the luminosity measurement
- EMD1 and EMD2 haven't been experimentally measured yet, but they can be estimated from simulation

Very forward region at CEPC (assumed in this study)

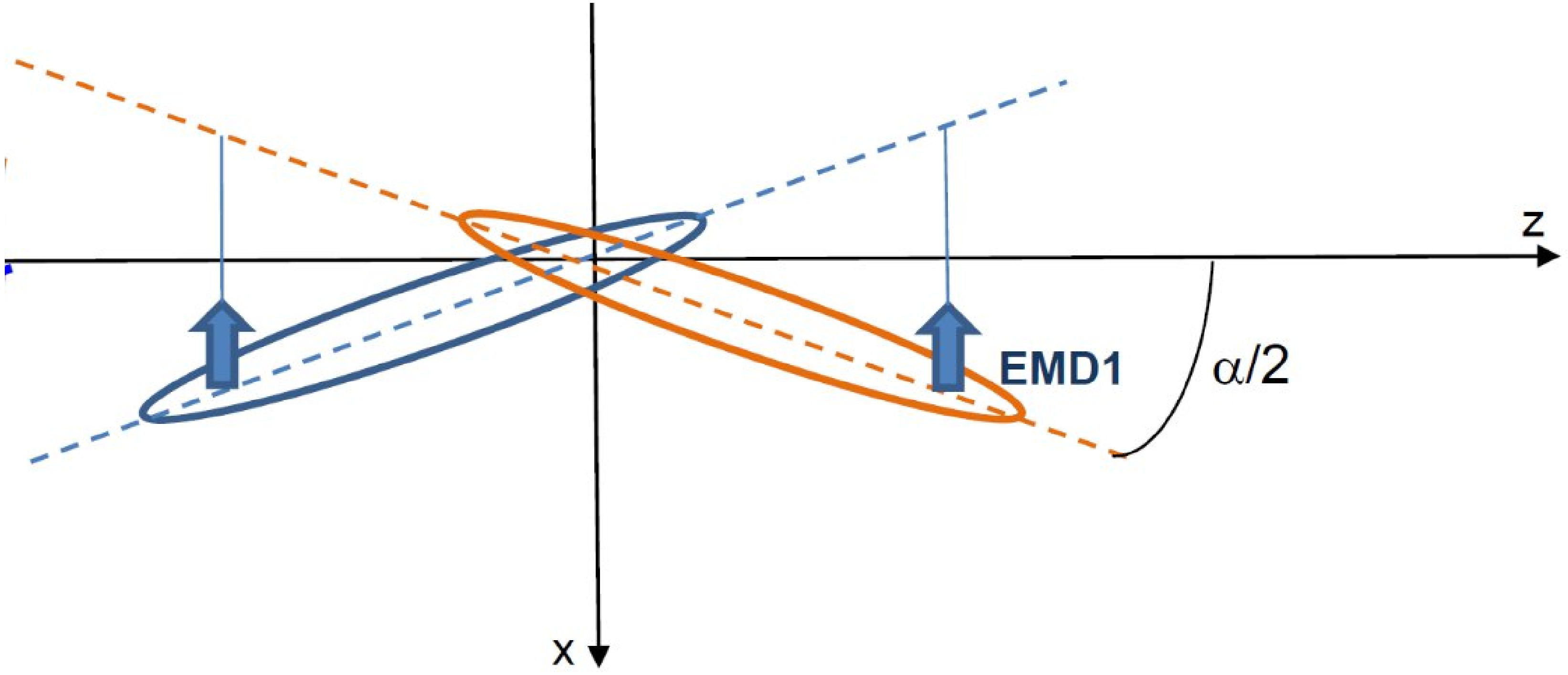
- The luminometer is positioned at 95 cm distance from the interaction point, covering the polar angles from 30 mrad to 105 mrad
- Fiducial volume 53 mrad to 79 mrad, where the energy resolution of a high-energy electron (positron) will be constant due to the shower containment
- EMD effects are discussed assuming head-on collision geometry as if the luminometer's halves would be positioned at the outgoing beams (s-frame), that is 16.5 mrad with respect to the z-axis in the laboratory frame
- Iinstantaneous luminosity at the Z^0 resonance $\mathcal{L}_0=1.15\cdot10^{35}$ cm^{-2} s^{-1}
- Beam parameters taken from the post-CDR studies (arXiv:2102.09627v1)

N (10^{10})	β_x^* **(m)**	β_y^* **(mm)**	σ_x (μm)	σ_y (μm)	σ_z **(mm)**
15	0.2	1.0	6.0	0.036	8.7

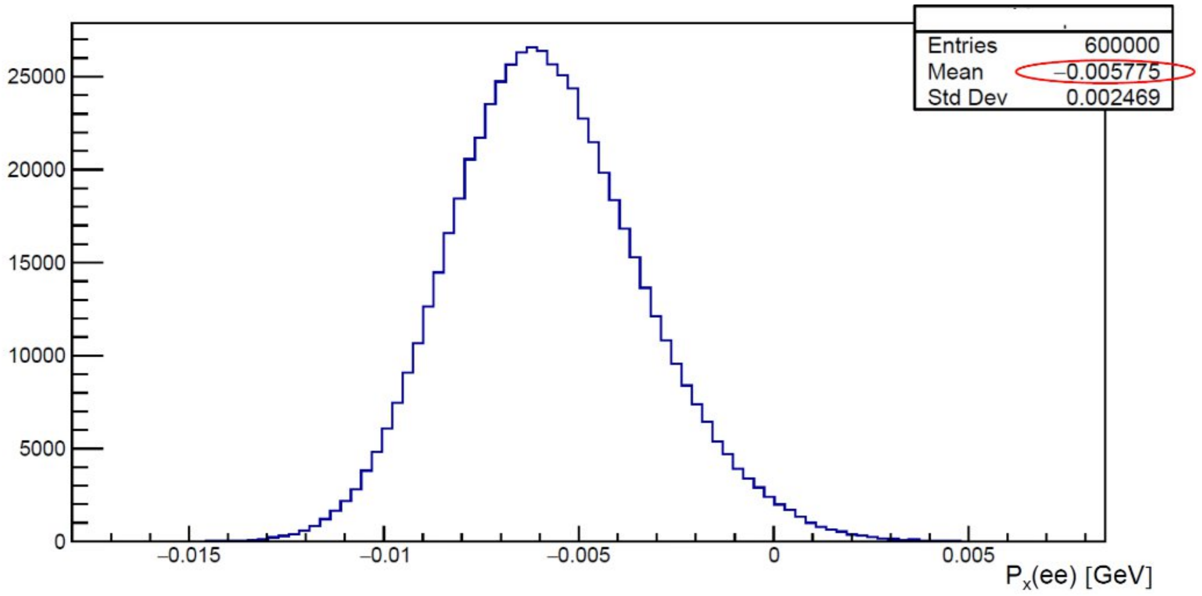
Electromagnetic deflection of the initial state

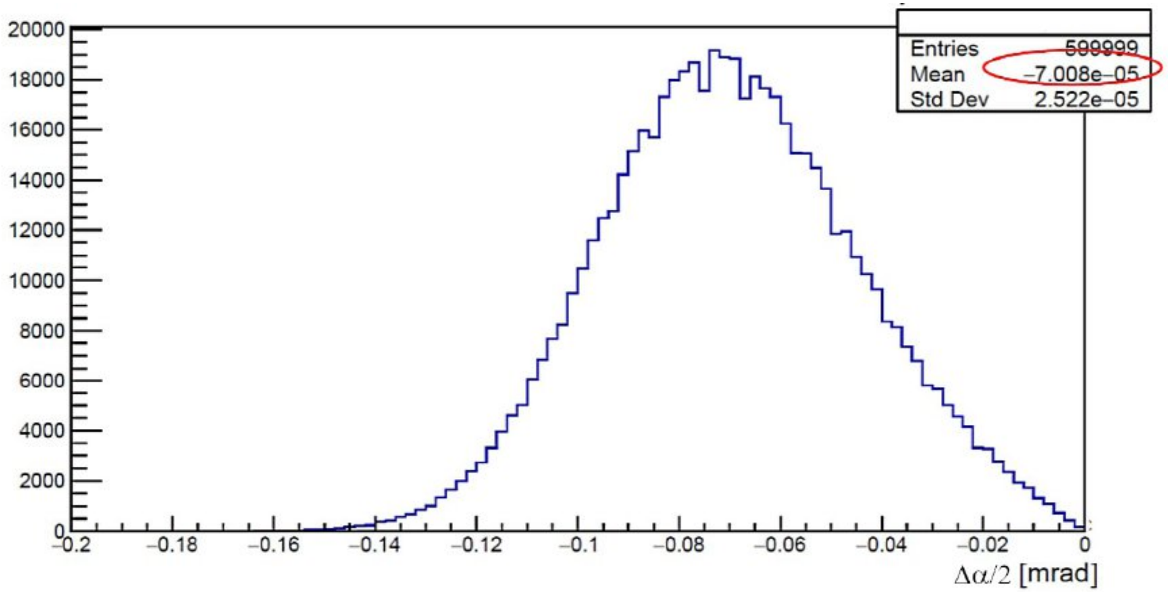
EMD1 – p_x-kick of the initial state (s-axis)

- GuineaPig C++ V.1.2.2 (impact of EM fields of outgoing bunches on initial states)
- BHLUMI V4.04 (Low Angle Bhabha Scattering – LABS)
- E_{beam}= 45.5 GeV
- ~$6 \cdot 10^5$ e^+e^- interacting pairs



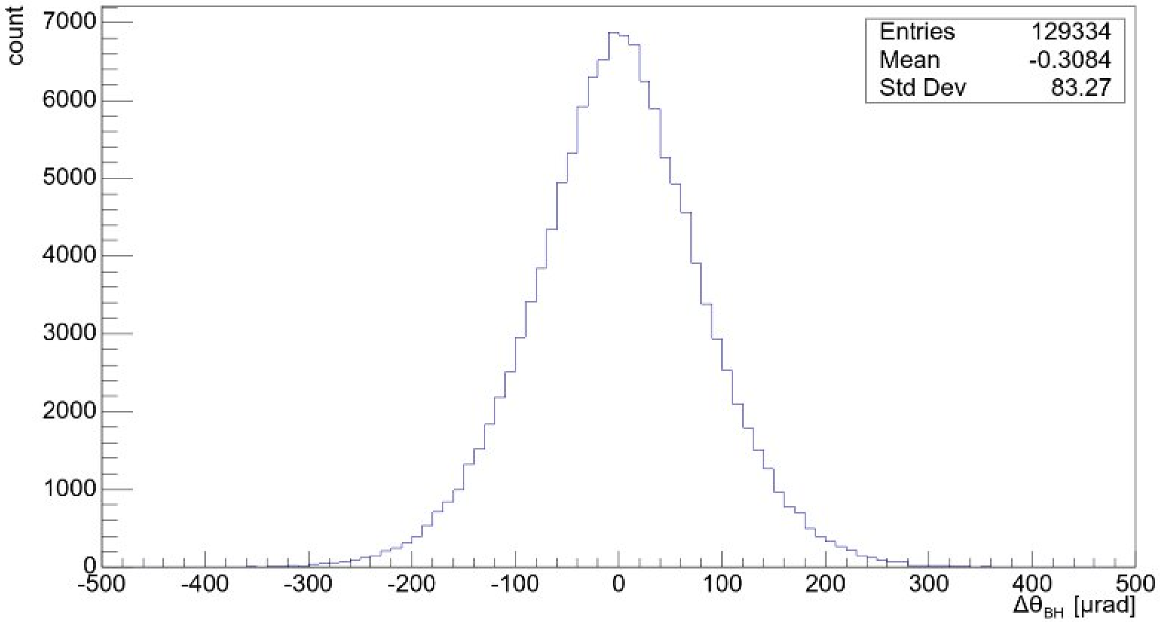
Electromagnetic deflection of the initial state

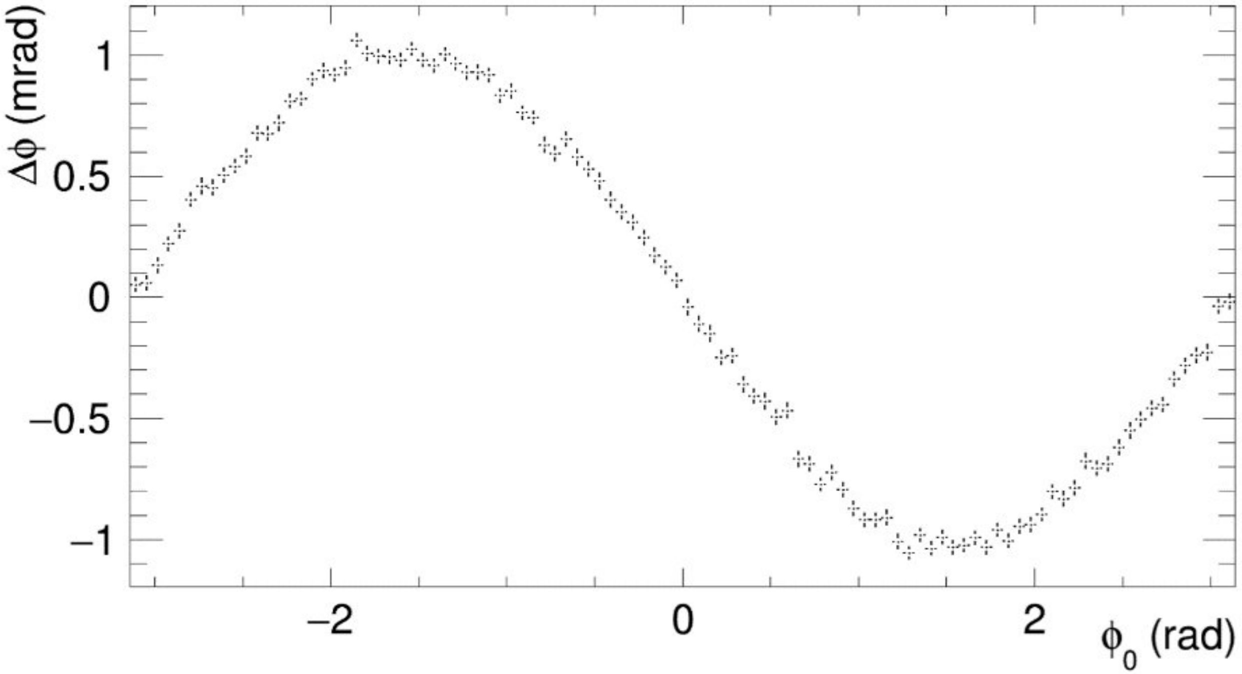




- e^+e^- system receives kick of ~5.8 MeV in x-direction, or ~2.9 MeV per particle in average
- No shift along y-axis
- x-angle effectively reduced for 140 μrad, 70 μrad per beam
- Knowing that energy of the interacting particles (E) depends on change of the crossing angle (Δα), ΔE is found to be ~52 keV per beam

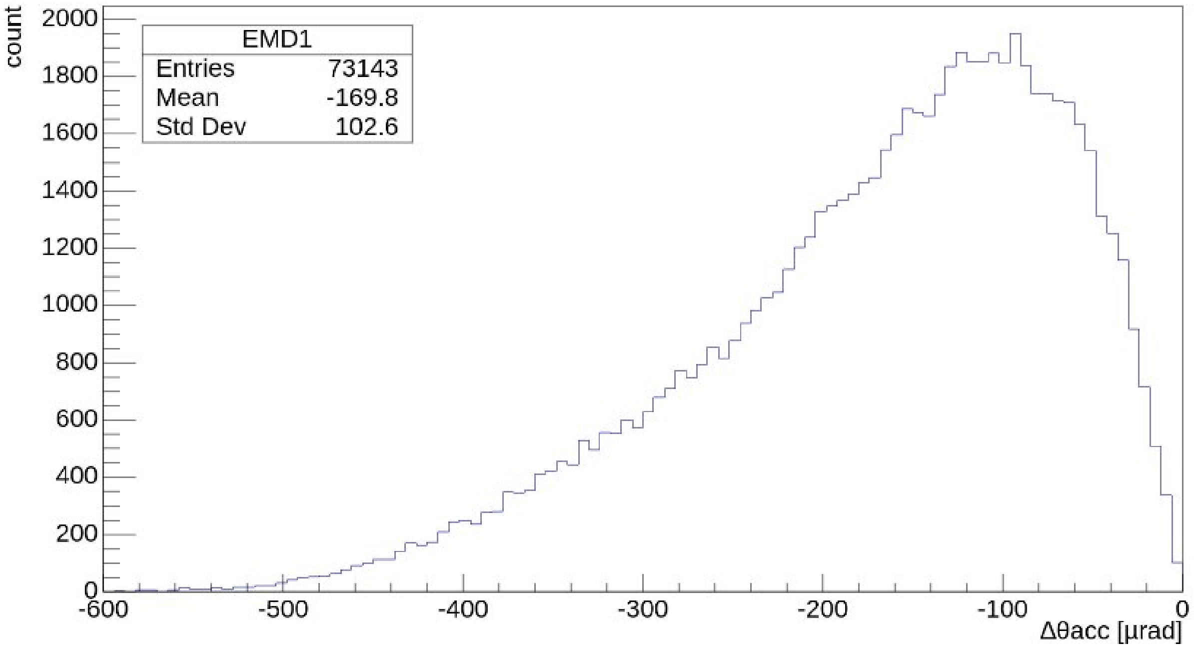
Electromagnetic deflection of the initial state – impact on final state





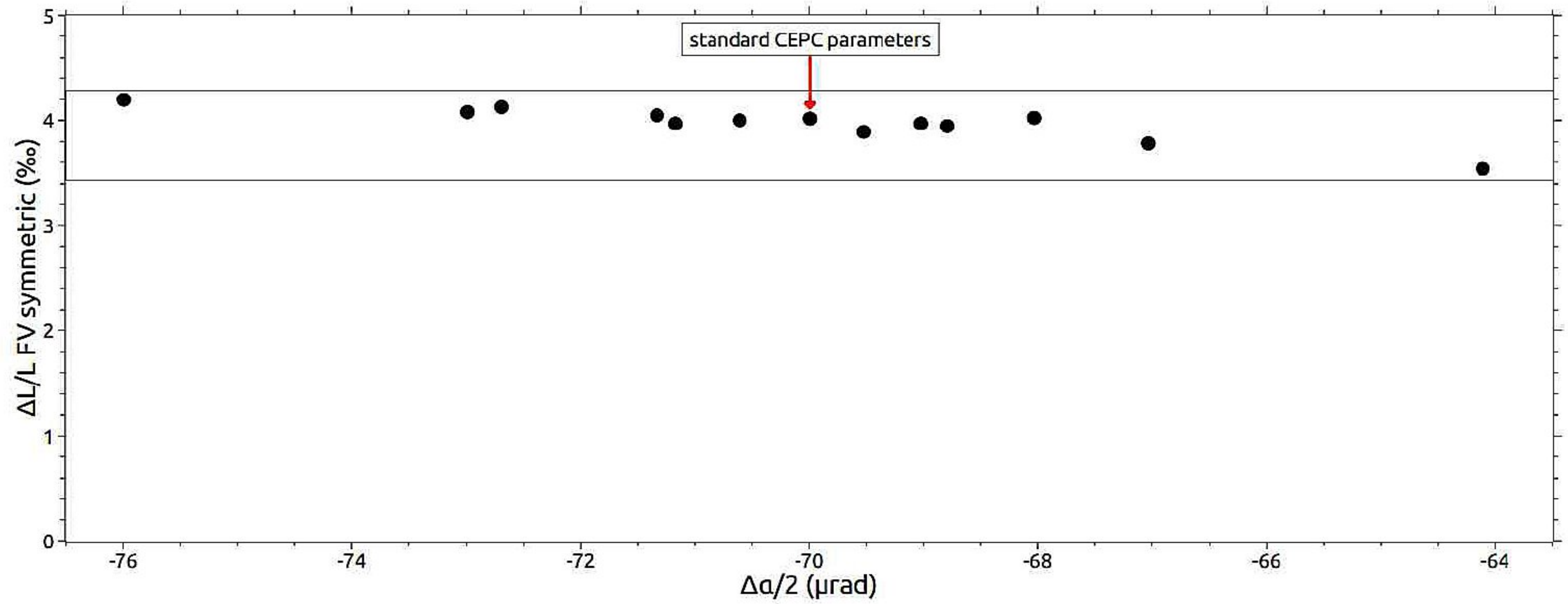
- The EMD1 effect results in smearing of the polar angle of the final state particles ($\Delta\theta_{BH}$) with RMS of ~83 μrad
- Maximal $\Delta\theta_{BH}$ occurs for Bhabha events emitted along the x-axis
- Deviation in azimuthal angles of the Bhabha final states are maximal ($\Delta\phi$ ~ 1 mrad) for LABS events emitted along y-axis ($\phi_0=\pi/2$)

Electromagnetic deflection of the initial state – impact on final state



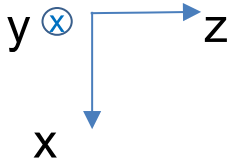
- EMD1 does not bias polar angles of final state e^- and e^+, but changes the angle between them, influencing their back-to-back propagation
- Change of angle between final state electrons and positrons ($\Delta\theta_{acc}$) is in average ~ 170 μrad, affecting LABS count in the luminometer due to the loss of collinearity
- The relative loss of count is found to be ~ $4 \cdot 10^{-3}$ what is ~40 times larger than the $\mathcal{L}_{int}$ precision goal of 10^{-4}
- This loss can be taken as correction to the measured integrated luminosity.

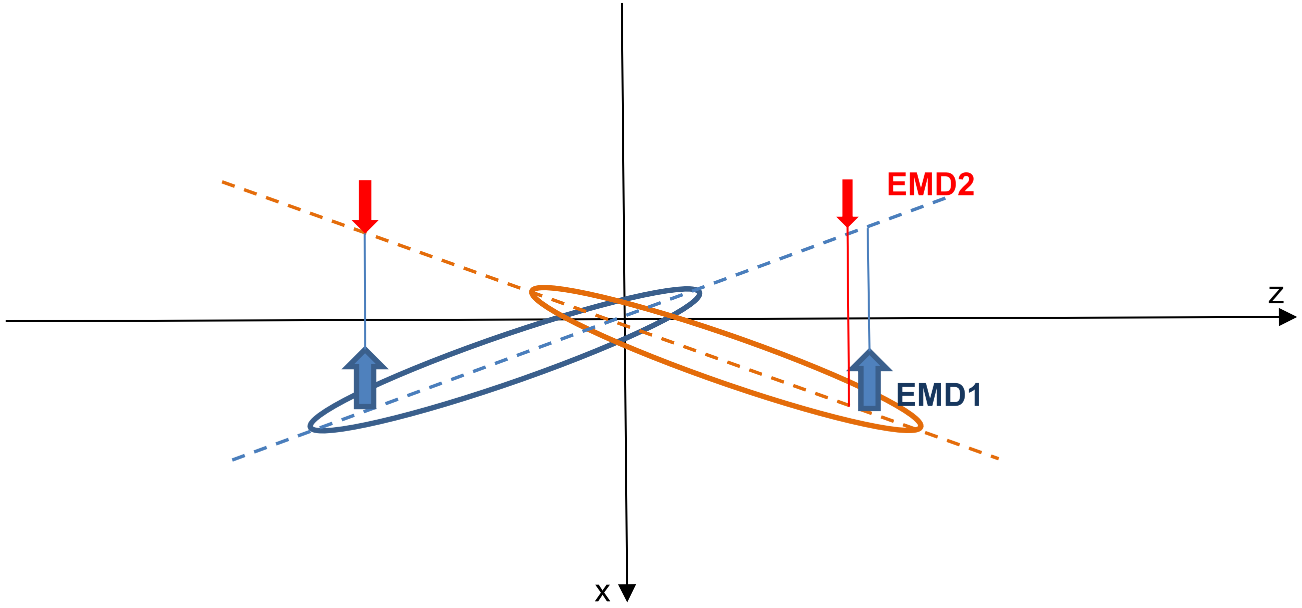
Electromagnetic deflection of the initial state – impact on final state

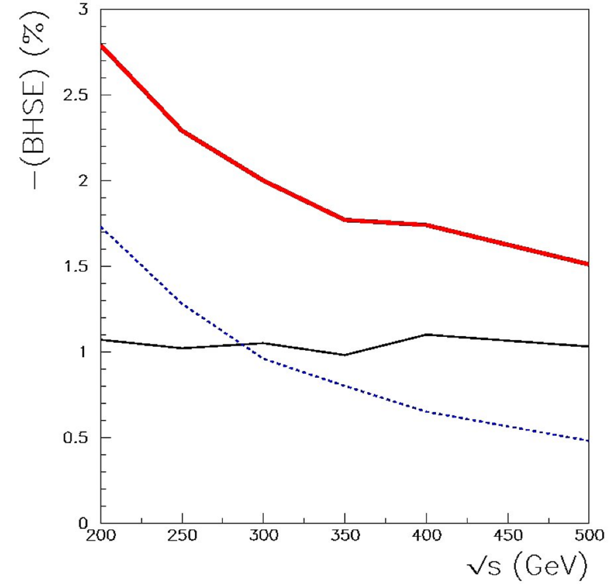


- Variation of beam parameters (bunch charges and dimensions) in the ±10% range w.r.t. the nominal beam size produce deviation of $\Delta\mathcal{L}/\mathcal{L} \sim 2\cdot10^{-4}$
- Asymmetric counting (55-77 mrad counting angles in one half of the luminometer and 53-79 mrad in the other, subsequently applied to the left and right arm of the detector) reduces the uncertainty to $\Delta\mathcal{L}/\mathcal{L} \sim 6\cdot10^{-5}$

Electromagnetic deflection of the final state

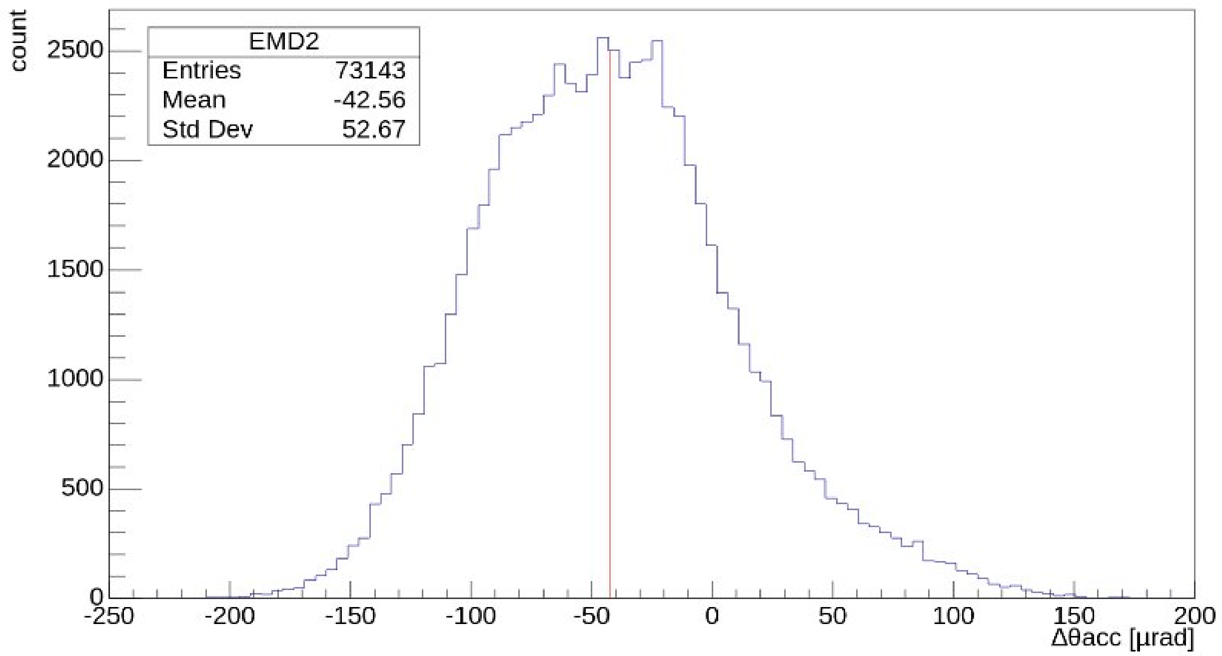


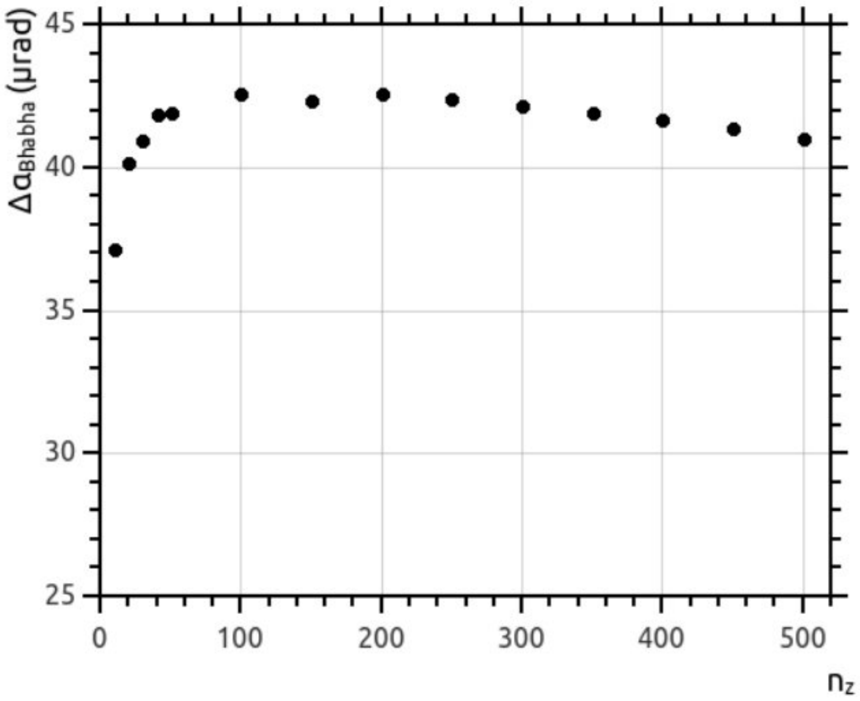




- Final LABS states will also be influenced by electromagnetic fields of the incoming bunches of opposite charges – EMD2
- LABS final states will experience focusing effect towards z-axis
- EMD2 rises with decreasing center-of-mass energy, thus being of relevance at the Z^0 resonance (C. Rimbault et al., 2007 JINST 2 P09001)

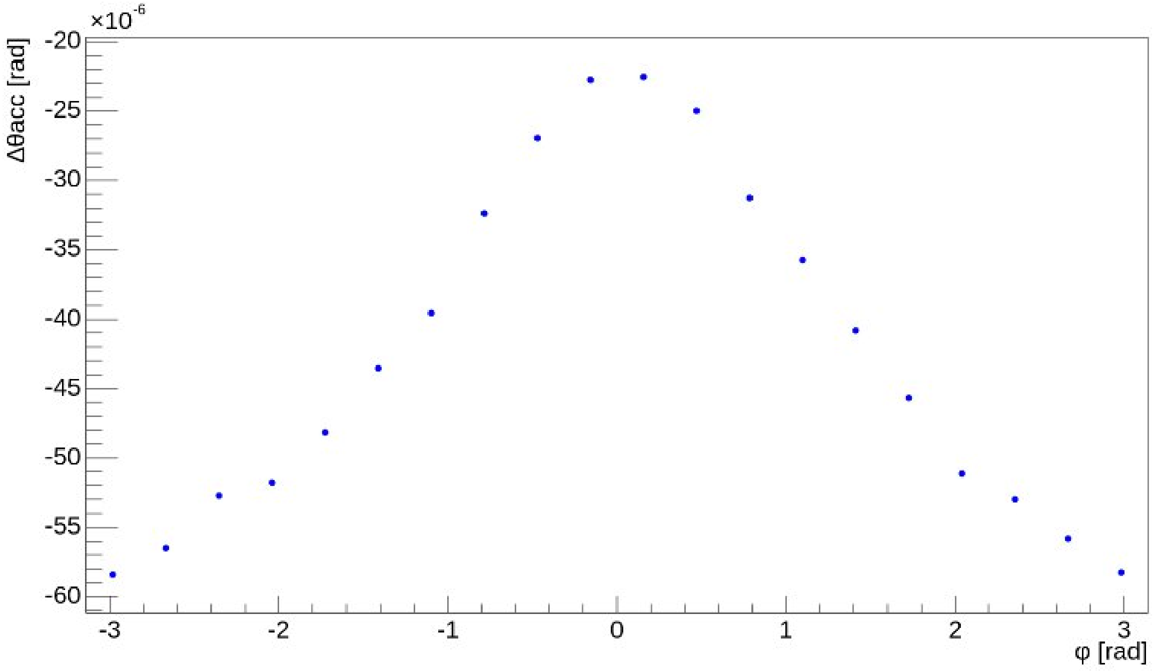
Electromagnetic deflection of the final state

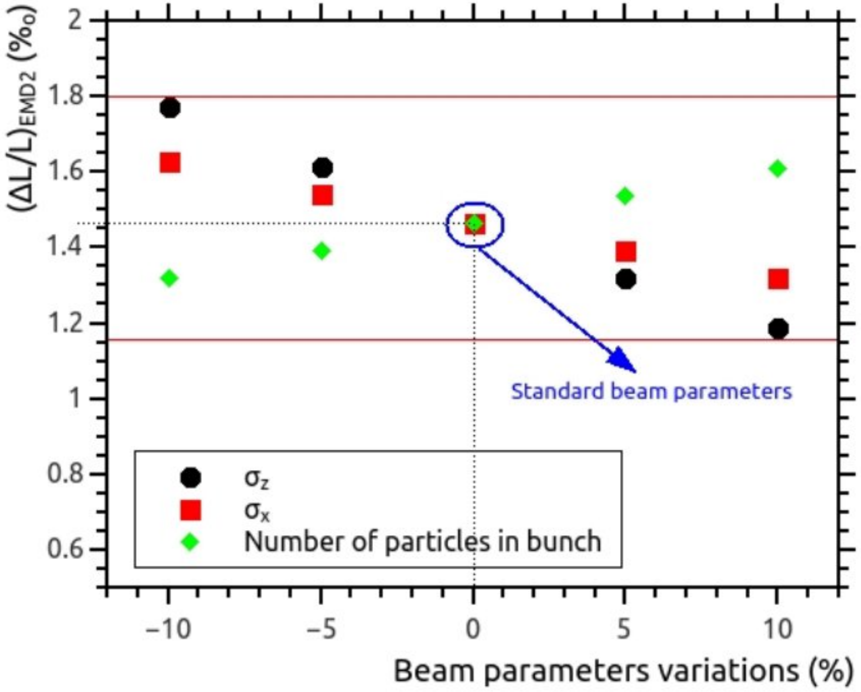




- In the applied setup, EMD2 induced additional change in Bhabha collinearity is ~43 µrad in average
- The effect is in principal sensitive to the simulation settings (GuineaPig); our results are obtained with 250 longitudinal slices (saturation region) and 7 grids

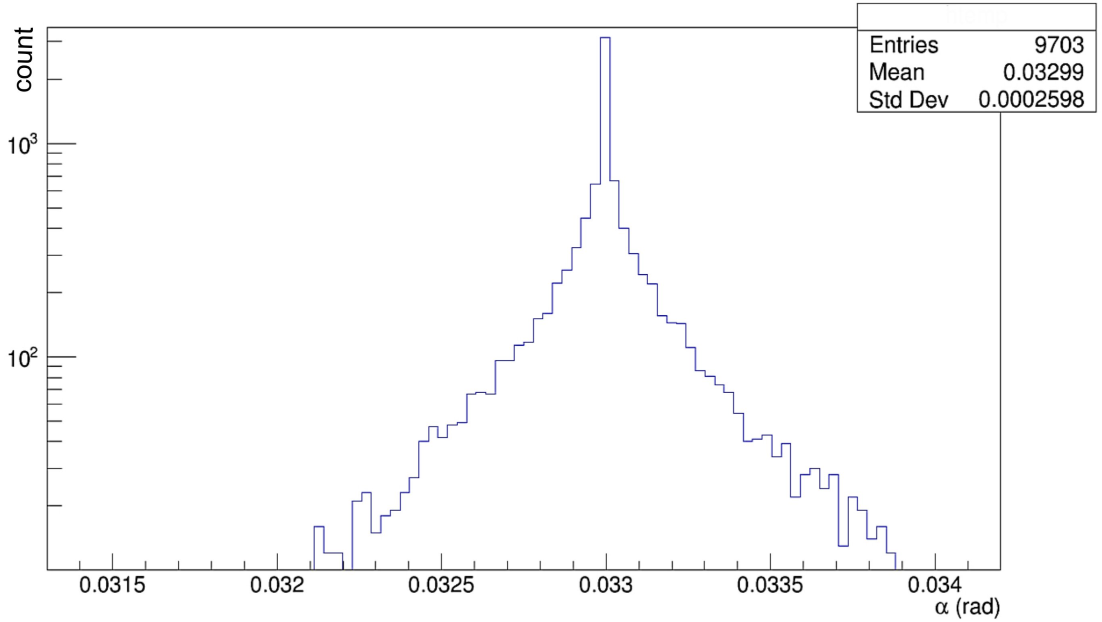
Electromagnetic deflection of the final state





- Change in collinearity of final states $\Delta\theta_{acc}$ caused by EMD2 also depends on the azimuthal angle (ϕ) of the final state particles, being largest for particles emitted along the x axis, similarly to the EMD1
- EMD2-induced count loss in the luminometer is ~$1.4 \cdot 10^{-3}$
- Final state electromagnetic deflection is also relatively insensitive to 10% variation of the bunch parameters and can be corrected from simulation with the relative uncertainty no larger than $3 \cdot 10^{-4}$
- The largest $\Delta\mathcal{L}/\mathcal{L}$ sensitivity is induced by the bunch length variations

Experimental corrections – EMD1



- The crossing angle at CEPC can be precisely determined from the central processes like s-channel di-muon production
- Kinematics of di-muon final states will be precisely determined in the central tracker, where momenta of charged high-energy leptons would be measured with the resolution of $\Delta p_T/p_T^2 \sim 10^{-5}$ GeV^{-1}.
- ~10^4 di-muon events generated at the Z^0 pole with WHIZARD V2.8.3 event generator; muons' momenta smearing of order of ~10^{-5} GeV^{-1} , the crossing angle can be measured with the standard error of ~260μrad/$\sqrt{N_{\mu\mu}}$
- In other words, crossing angle precision of order of ~1 μrad can be achieved with as little as 70 pb^{-1} $\mathcal{L}_{int}$ (a couple of minutes)

Experimental corrections – EMD2

- With the Si-wafers placed in front of the luminometer, ~μrad precision is achievable in angular measurements of LABS electron and positron
- EMD2 induced loss of count can be corrected in a semi-dependent way from simulation, presumably on a basis of experimentally measured acolinearity of LABS final states in the in the luminometer and/or other observables – *ongoing study*
- Additional considerations: possible changes of the luminometer fiducial volume towards smaller polar angles; inclusion of radiative processes

Summary

- The effects of electromagnetic deflection of initial (EMD1) and final Bhabha states (EMD2) are quantified in simulation with the nominal post-CDR CEPC beams

- EMD1 and EMD2, if not corrected, will cause the relative loss of count in the luminometer of $\Delta\mathcal{L}/\mathcal{L} \sim 6\cdot10^{-3}$

- EMD1 will lead to reduction of the crossing angle of ~140 μrad. Measurement of the crossing angle with μrad precision will be possible with the central-tracker reconstruction of di-muon production. From simulation, relative correction of the integrated luminosity can be determined once the crossing angle is known. The correction is of order of $4 \cdot10^{-3}$. Uncertainty of the correction is not larger than $2\cdot10^{-4}$

- EMD2 can be also corrected from simulation if the angle between LABS electron and positron in known with a sufficient precision, presumably of the order of several μrad provided by the Si-wafer placed in front of the luminometer. The correction induced by the EMD2 effect is smaller than $2\cdot10^{-3}$. Variations of the nominal bunch sizes and population not larger than 10%, introduce uncertainty of this correction not larger than $3\cdot10^{-4}$

(Results presented here are submitted to the Progress of Theoretical and Experimental Physics, IF 8.6, arXiv:2511.00687v1 [hep-ex]*)*

THANK YOU!

謝謝