The Impact of Beam-Induced Backgrounds on the CEPC Vertex Detector Performance

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Abstract

The identification of heavy-flavored quarks and τ leptons is a key physics goal of the CEPC. As a crucial component of the tracking system, the CEPC Vertex Detector (VTX) demands exceptional spatial resolution for vertex reconstruction and flavor tagging, with the impact parameter (d_0 , z_0) as its core performance indicator. Due to its proximity to the beampipe, **beam-induced backgrounds (BIBs)** may severely degrade the VTX's performance—thus, assessing such impacts is critical for advancing the CEPC's precision physics program.

Based on the **CEPCSW** simulation framework, this study compares the impact parameter resolutions (d_0 , z_0) of tracks in the CEPC Vertex Detector (VTX) under **BIB-free** and **BIB-included** scenarios (encompassing Pair production and four single-beam backgrounds: BGC, BGB, TSC, BTH) across different incident angles and analyzes the variations of these resolutions with the incident momentum of the signal particle (μ^-).

Introduction

Core Track Parameters: d_0 & z_0

- **d_0** : Signed transverse impact parameter – the closest approach to the beam axis in the r–φ plane.
- **z_0** : Longitudinal coordinate of that point of closest approach.

Extracted from helical track fits in the vertex detector, these parameters set the primary-vertex resolution and directly determine the flavour-tagging performance.

Background Category	Background Type	Abbreviation	Core Definition
Single-beam Background	Beam-Gas Bremsstrahlung	BGB	Beam particles undergo inelastic scattering with residual gas
	Beam-Gas Coulomb Scattering	BGC	Beam particles undergo elastic scattering with residual gas
	Beam-Thermal Photon Scattering	BTH	Interactions between beam particles and beam pipe thermal photons
	Touschek Scattering	TSC	Scattering of particles within the beam bunch via transverse oscillations
Luminosity-related Background	Pair Production	—	Photons from beam-beam interaction produce electron-positron pairs via strong electromagnetic fields

Beam-induced background categories accounted for in this study.

- **Pair production** dominates the beam-induced backgrounds (BIBs) of the CEPC Vertex Detector (**>90%**).
- **Single-beam backgrounds** are effectively suppressed by beam pipe optimization, W/SS shielding, and vacuum enhancement, with **relatively small proportions**.

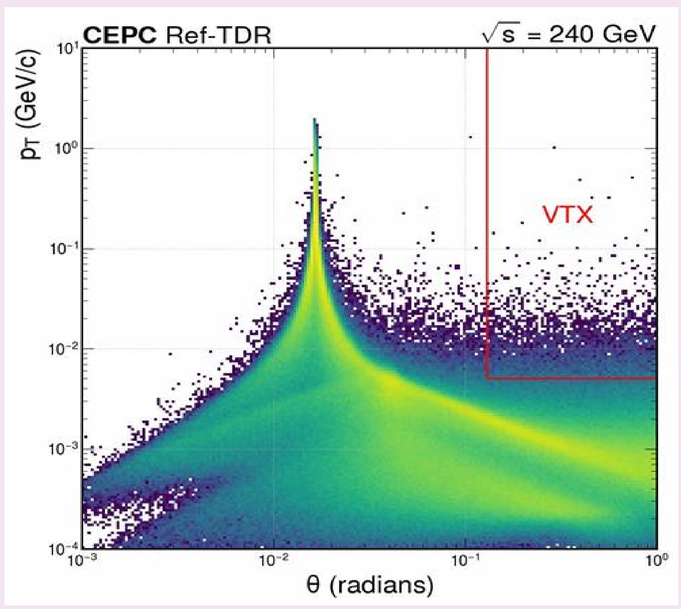

Figure 1: Energy and polar angle distribution of particles out of the pair production beam induced background at Higgs mode. VTX stands for the vertex detector.

BIB Mixing Methods

Signal events are overlaid with beam-induced backgrounds at the SimHit level, preserving energy-time-position merging within each detector cell.

Background Type	Rate ($\times 10^{-7}$ Hz)	Sampling Mode
Pair production	—	Fixed 277 ns window, 1 BX
BGB	6.67	Poisson
BGC	8.78	Poisson
BTH	40.15	Poisson
TSC	63.18	Poisson

Note: Higgs-mode BX = 277 ns beam-crossing period.
Rate data extracted from Higgs-mode background-generation configuration in CEPCSW.

Backgrounds are overlaid on signal events via Poisson sampling or a fixed 277 ns window.

BIB Mixing Results

Inner Solenoidal Magnetic Field

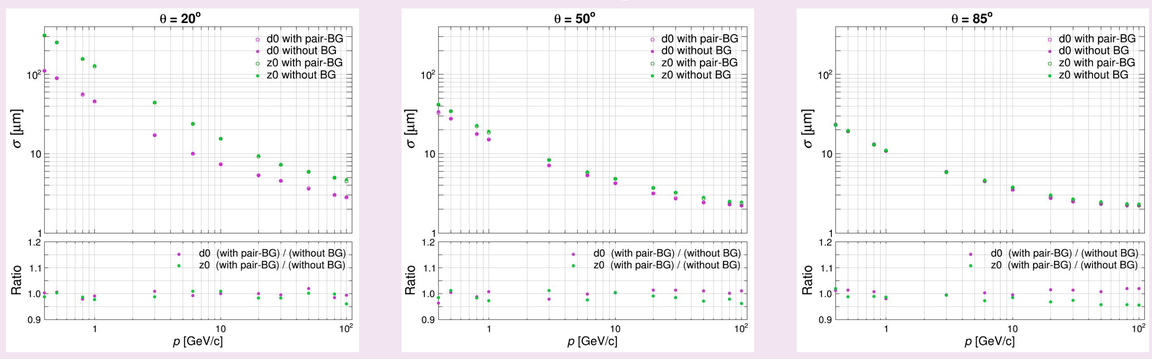

Figure 2,3,4 : d_0 and z_0 resolutions with and without **pair production** background, and their ratio "with / without" , vs. momentum at θ = 20°, 50°, 85°.

- At θ = 20° near-beam region, both d_0 and z_0 resolution ratios fluctuate around 1.0.
- In the 85° end-cap, transverse low-momentum e^+ e^- background supplements scarce Z-hits, driving the z_0 resolution ratio down to 0.95 at 10~100 GeV/c, while additional multiple scattering raises the d_0 resolution ratio by up to 2 %.
- Visible trend: Larger θ enhances z_0 resolution via extra hits but degrades d_0 resolution through multiple scattering.

Non-uniform Magnetic Field

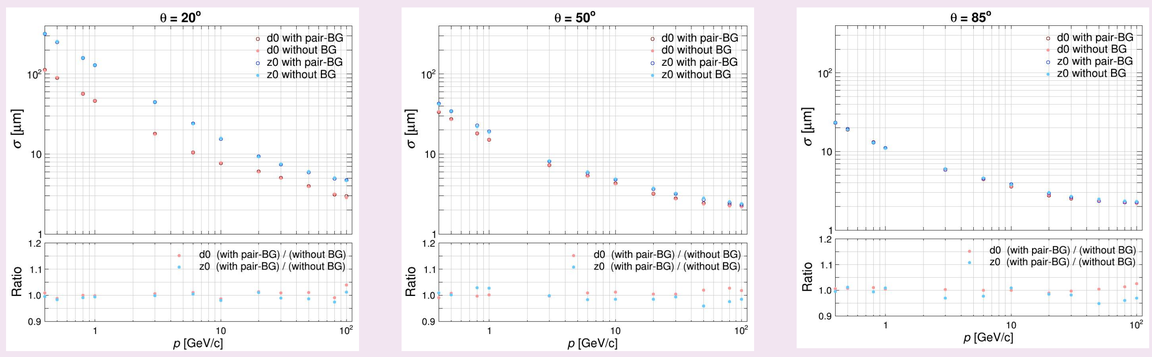

Figure 5,6,7 : d_0 and z_0 resolutions with and without **pair production** background, and their ratio "with / without" , vs. momentum at θ = 20°, 50°, 85°.

- With pair-production background, z_0 resolution improves by 0~5 % while d_0 resolution degrades by 0~4 %.
- Larger θ enhances z_0 resolution markedly.

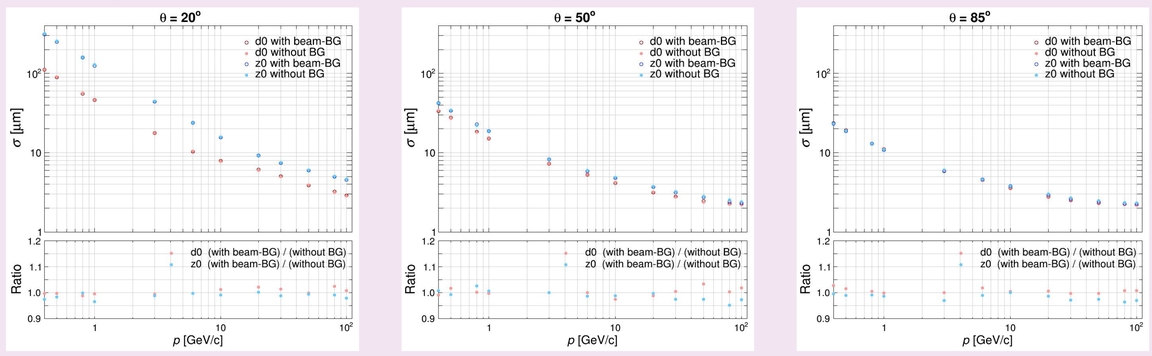

Figure 8,9,10 : d_0 and z_0 resolutions with and without **BIBs** , and their ratio "with / without" , vs. momentum at θ = 20°, 50°, 85°.

- After mixing BIBs, z_0 resolution is enhanced at all three angles, while d_0 resolution in the 85° end-cap shows only marginal improvement.

Inner Solenoid vs. Non-Uniform Field

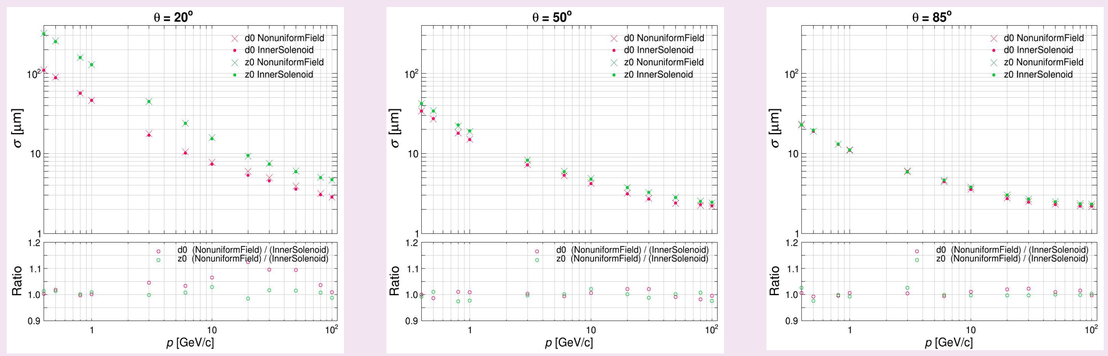

Figure 11,12,13 : d_0 and z_0 resolutions **without background** under Inner Solenoid vs. Non-Uniform Field, and their ratio (Non-Uniform / Inner Solenoid), vs. momentum at θ = 20°, 50°, 85°.

Compared with the Inner Solenoid , for the Non-Uniform Field :

- The fluctuation of z_0 resolution is controlled within ±2%.
- At θ = 20°, the degradation of d_0 resolution even exceeds 10%.
- The current helical track fitting is applicable to uniform magnetic fields, and future work will extend to track reconstruction under non-uniform magnetic fields.

Reference

[1] CEPC Technical Design Report -- Reference Detector
[2] CEPCSW, https://code.ihep.ac.cn/cepc/CEPCSW

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