Analysis of the beam background for TPC at the high luminosity Z-pole on CEPC

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CONTENTS

TPC: CEPC Gaseous Tracker

- In the latest design of the Circular Electron-Positron Collider (CEPC) detector, the time projection chamber (TPC) is chosen as the main tracker detector.

- TPC features:
  - Simple geometry
  - Computable process
  - Working stability
  - 3-D tracking (precision: ~ 100µm)
  - PID based on dN/dx & dE/dx

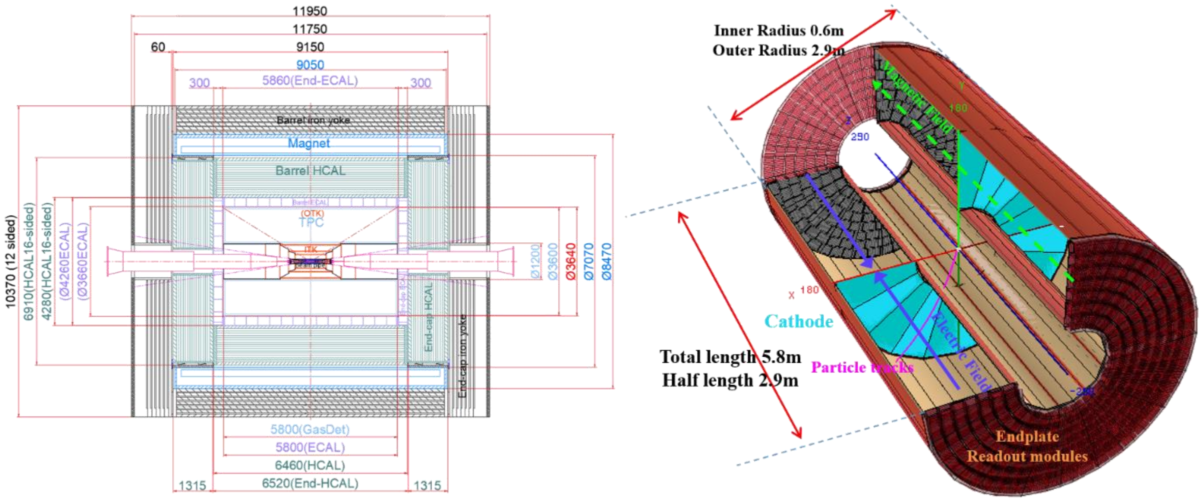


Fig: Detector Geometry & TPC Geometry in CEPC TDR

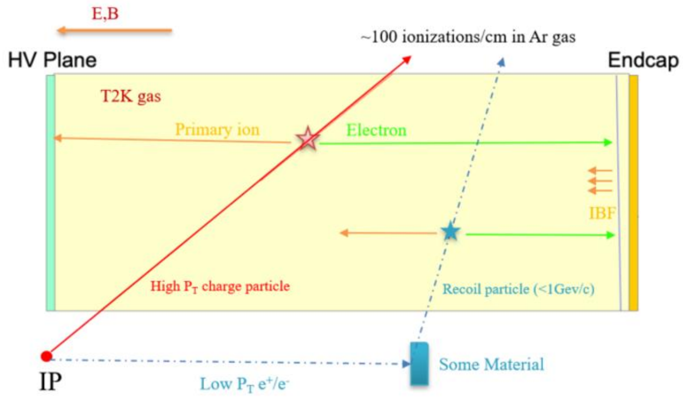
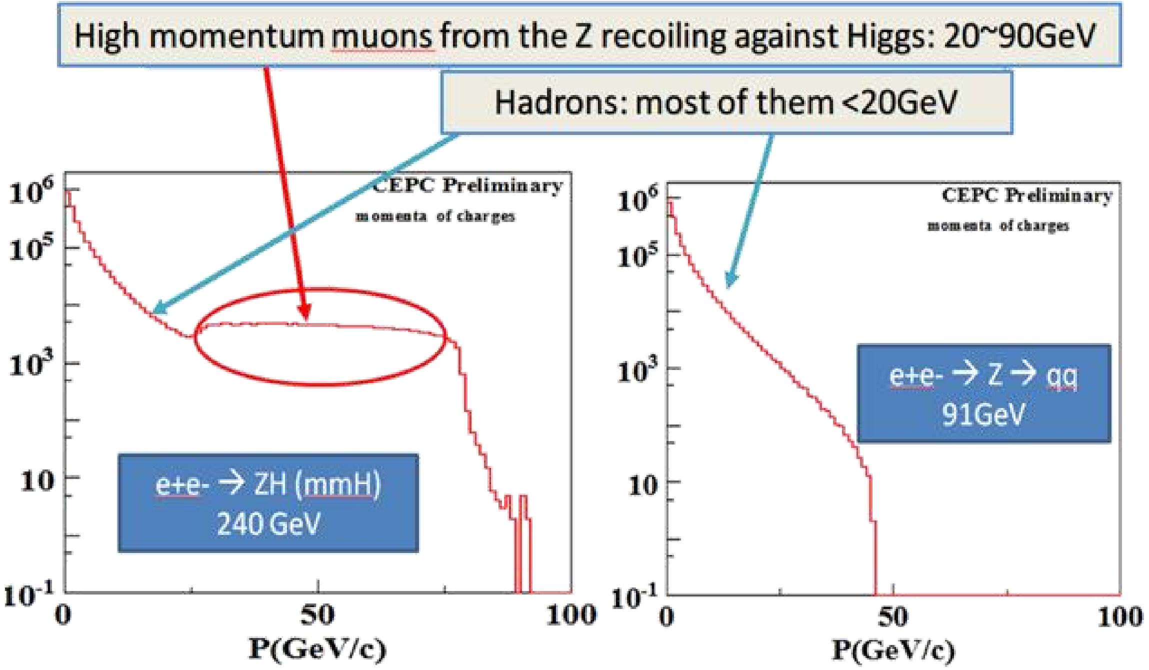


Fig: A sketch of TPC working process

Physics Requirements

- CEPC operation stages in the TDR:
- 10-years Higgs → 2-years Z-pole → 1-year W

- Physics requirements of the tracker
  - High momentum resolution for Higgs and Z
  - PID for the flavor physics and jet substructure



Technical Challenges of TPC at Tera-Z

- TPC's main challenge is space charge and additional electrical field in high event rate environment.
  - Caused by the ionization process and positive ion backflow.
- Which is, in CEPC, the high luminosity Z-pole mode.
  - CEPC TDR is considering running low-luminosity Z-pole mode intermittently in Higgs-mode for short periods of time.
- Serving for the CEPC detector TDR, our study investigated part of the background in CEPC Z-pole mode affecting TPC, giving a preliminary estimation.

Table: Operating parameters for different modes of CEPC

Mode	Higgs	Z	W	tt
Energy (GeV)	120	45.5	80	180
Bunch number	446	13104	2162	58
Bunch spacing (ns)	355	23	154	2714
Bunch population (10^{11})	1.3	2.14	1.35	2.0
Luminosity ($10^{34}cm^{-2}s^{-1}$)	8.3	192	26.7	0.8

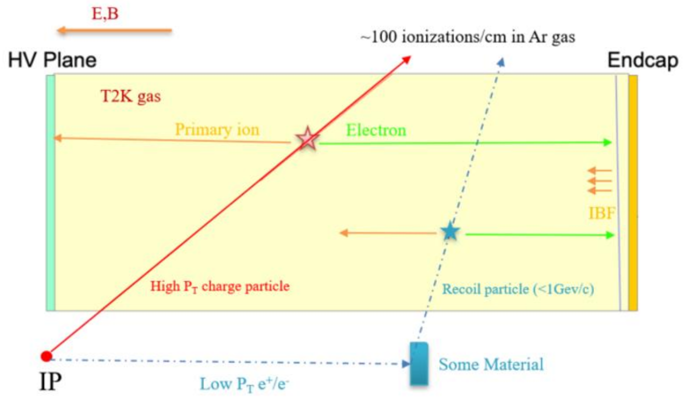


Fig: A sketch of TPC working process

Investigating Beam Backgrounds in CEPC

- Beam backgrounds we need to deal with:
  - Single beam background (beam loss):
    - Touschek scattering
    - Beam-gas scattering
    - Beam thermal photon scattering
    - Synchrotron radiation
    - …
  - Pair production (beamstrahlung, luminosity related)
  - Injection background
    - Not considered yet

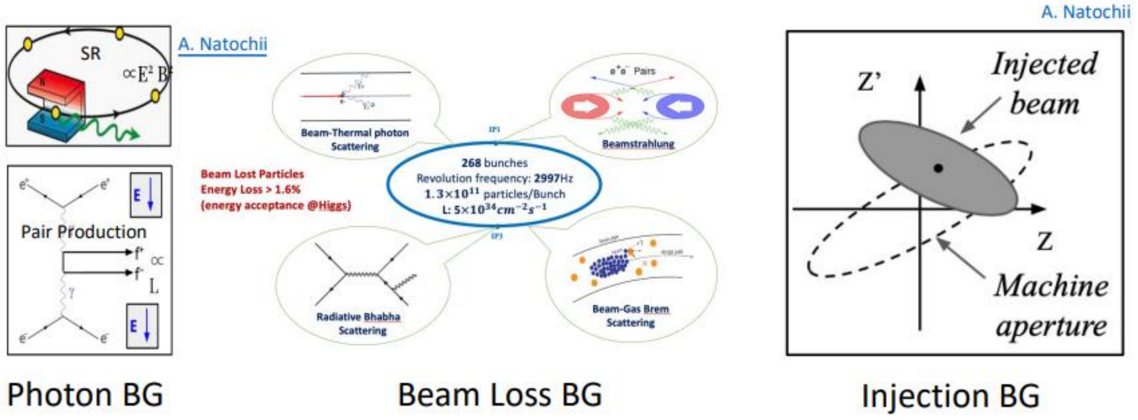


Fig: Different kinds of background

Table: Simulation software of backgrounds

Background	Generation	Tracking	Detector Simulation
Synchrotron Radiation	BDSim	BDSim/Geant4	CEPCSW/FLUKA
Beamstrahlung/Pair Production	Guinea-Pig++	SAD	
Beam-Thermal Photon	PyBTH		
Beam-Gas Bremsstrahlung	PyBGB		
Beam-Gas Coulomb	BGC in SAD		
Radiative Bhabha	BBBREM		
Touschek	TSC in SAD		

Simulation: TPC Parameters

Table: TPC parameters in CEPC TDR

Inner radius	63.5 cm
Outer radius	175.0 cm
Maximum drift length	275.0 cm
Pixel size	500 μm × 500 μm
Data sampling rate	40 MHz
Working gas	T2K gas, Ar : CF_4 : iC_4H_{10} = 95 : 3 : 2, 1 atm

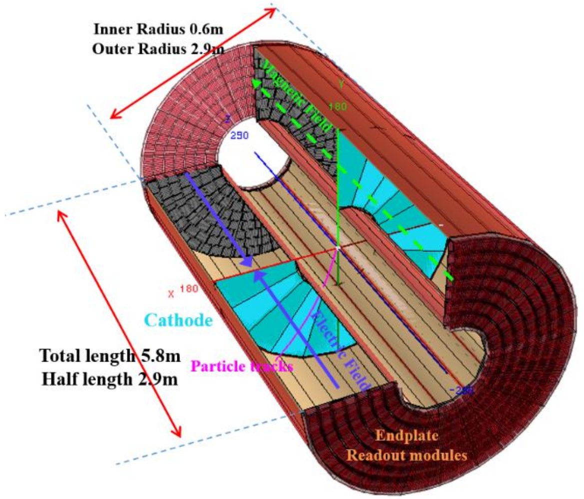


Fig: A sketch of TPC geometry

- Mode: Z-pole
- Pair production + Single Beam, 3700BX
- Software: CEPCSW (2024/8/12)

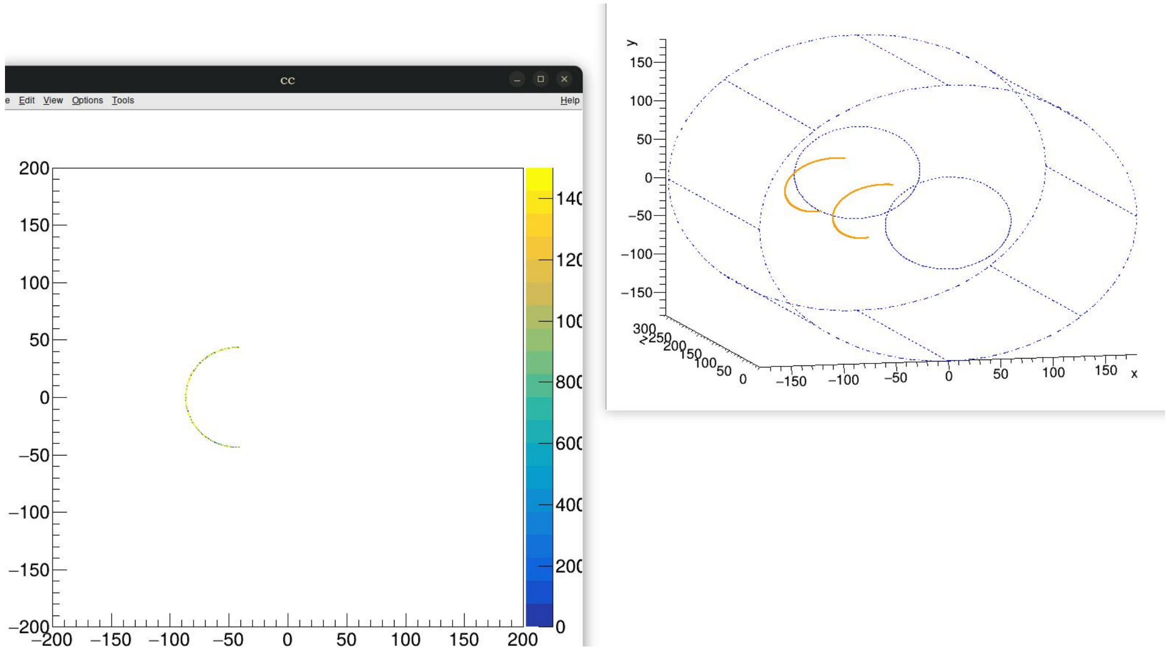


Fig: A typical track in pixel TPC

Simulation: Tracking and Energy Deposition

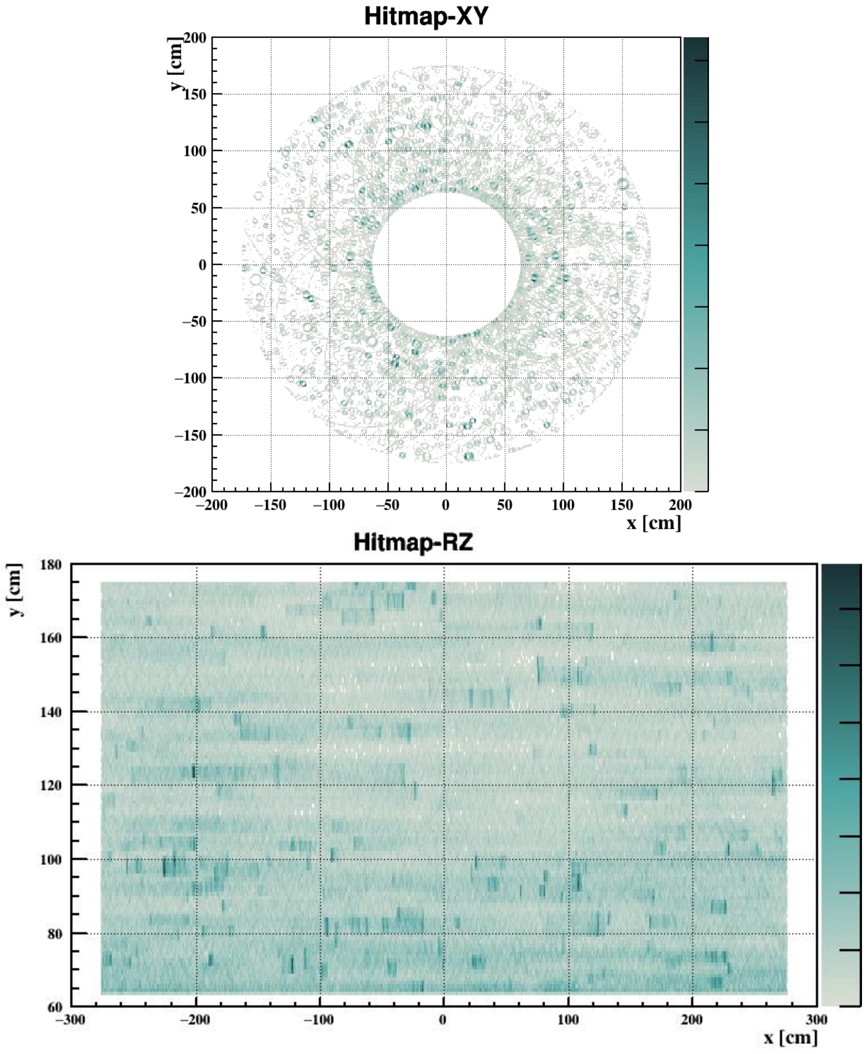


Fig: Background hit map on x-y and r-z plane

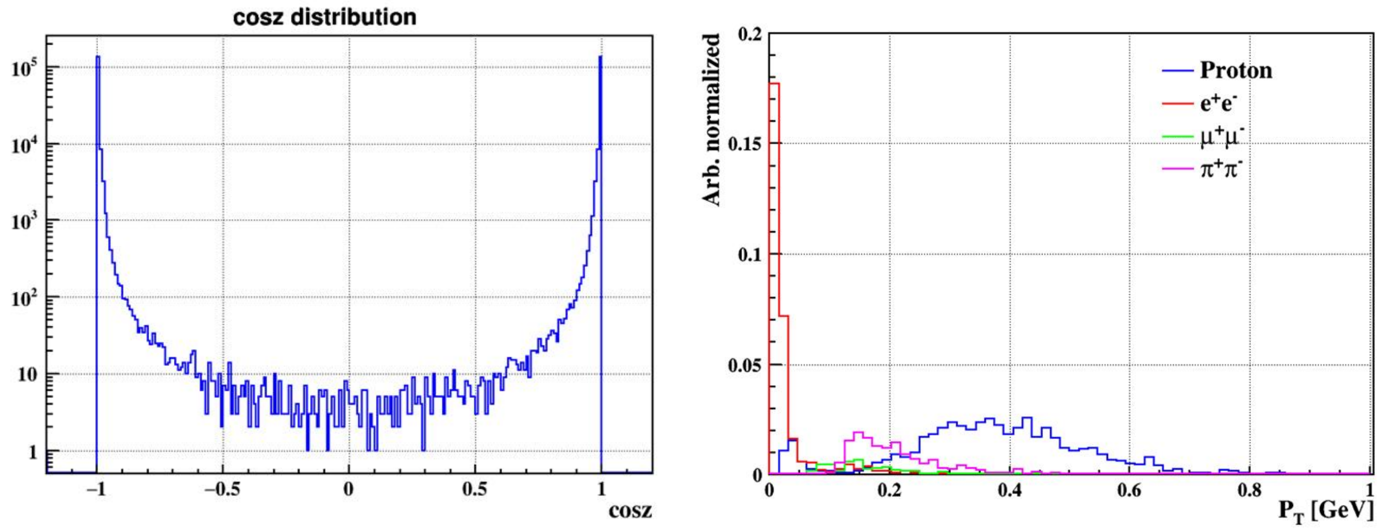
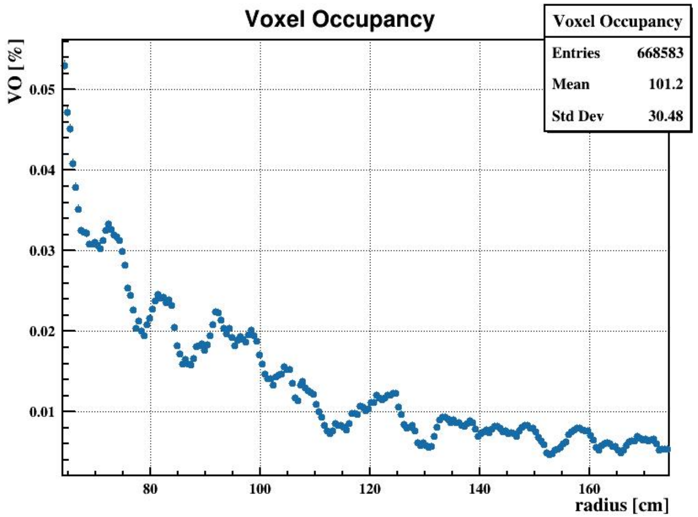


Fig: direction and p_T distribution

- Background introduces a large number of low-p_T particles in the chamber, which cause the most of the energy deposition.
- $E_{dep} \propto$ Ionization

Simulation: Voxel Occupancy and Hit Rate



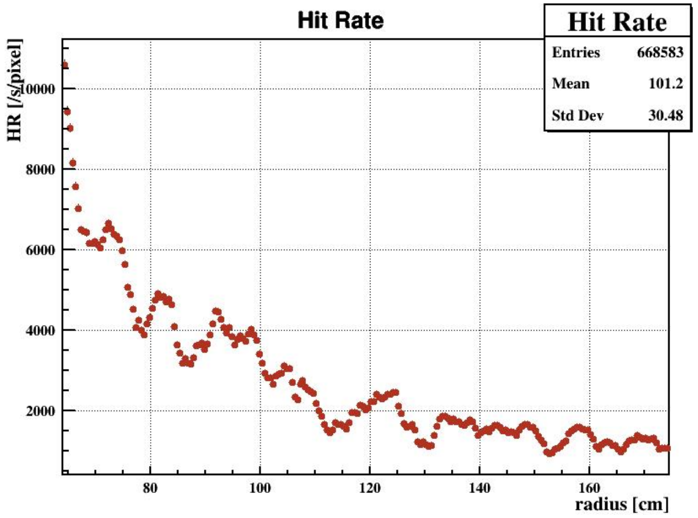


Fig: Background voxel occupancy and hit rate

- Background voxel occupancy and hit rate: whether TPC can work and detect physical events in the working environment.
- VO = hit rate per pixel × time window × sampling rate
  - Pixel size: 500μm×500μm
  - Sampling rate: 40MHz (25ns/sampling)
  - Time window for a hit: 20 sampling
- TPC can function properly in the environment.

Table: Background voxel occupancy and hit rate

	Inner layer	Outer layer
Voxel occupancy	0.05%	0.005%
Hit rate (/s/pixel)	10000	1000

Calculating Electrical Field and Distortion

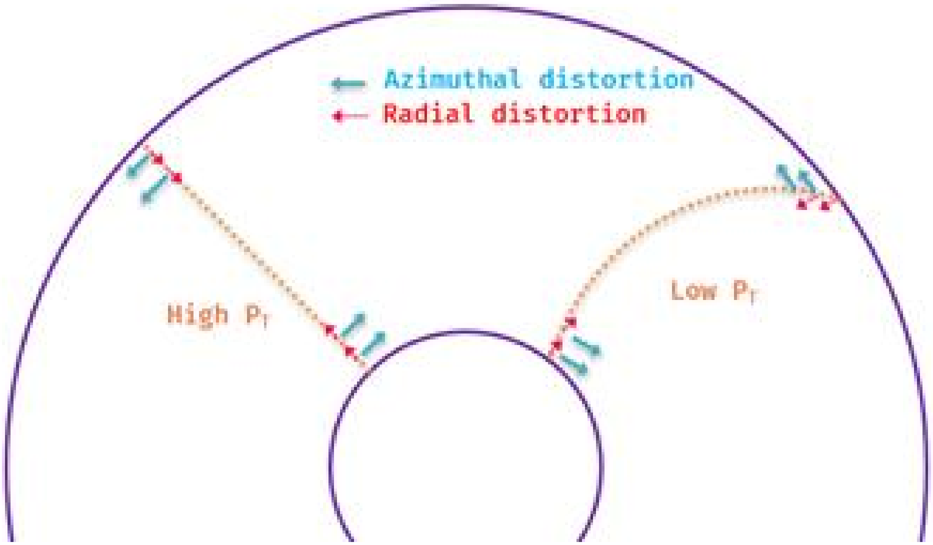


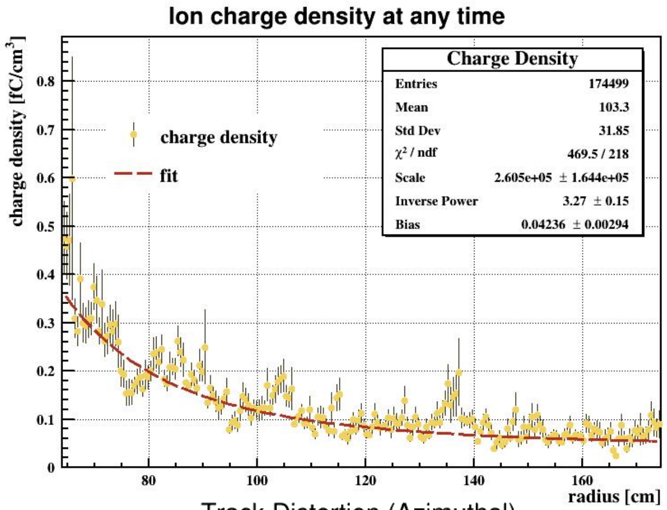
Fig: Distortion of particle tracks

- Electrical field caused by background can be solved analytically based on Green's function:
- $\Delta G(\boldsymbol{x}, \boldsymbol{x}') = -4\pi\delta(\boldsymbol{x}, \boldsymbol{x}')$
- $\phi_{\text{ion}}(\boldsymbol{x}) = \int_D \mathrm{d}^3 x G(\boldsymbol{x}, \boldsymbol{x}')\rho_{\text{ion}}(\boldsymbol{x}')$

- And the distortion is given by:
- $\Delta_{r\varphi} = \int_0^L \frac{\omega\tau}{1+\omega^2\tau^2} \times \frac{E_r}{E_z} \mathrm{d}z$ (azimuthal)
- $\Delta_r = \int_0^L \frac{1}{1+\omega^2\tau^2} \times \frac{E_r}{E_z} \mathrm{d}z$ (radial, negligible)

- Therefore, giving a distribution of spacial charge density, distortion is predictable.

Calculating Electrical Field and Distortion



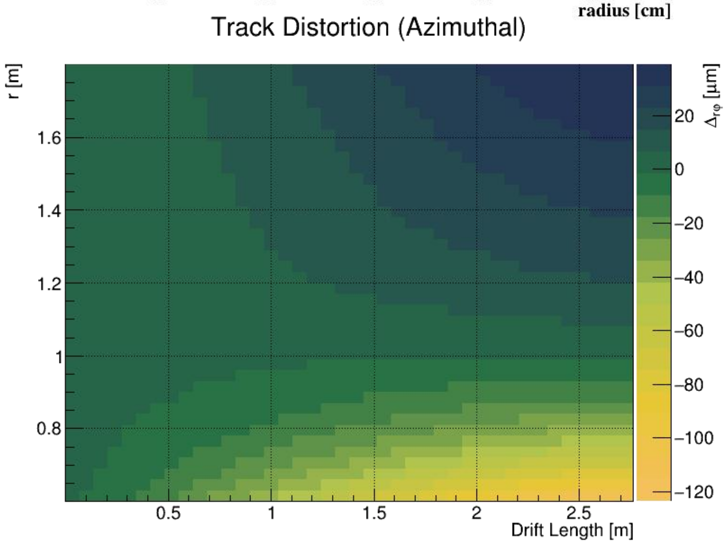
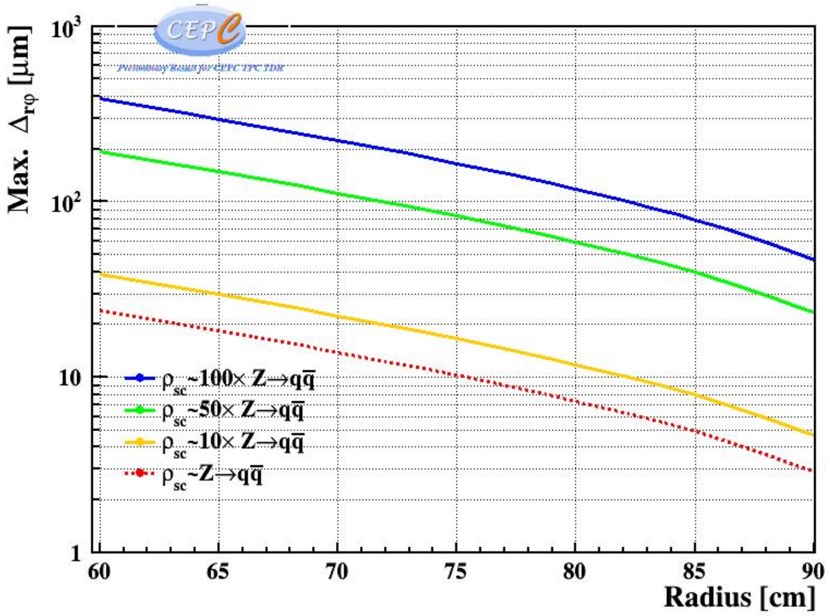


Fig: Spatial charge density and azimutial distortion

- As a tentative estimate, only pair-production part is considered, while single beam part remains under discussion.
- Assume a steady spatial charge distribution uniform in z direction. The spatial charge density is calculated by:
- $\rho_{\text{ion}}(\boldsymbol{x}) = \rho_{\text{ion}}(r) = \frac{\mathrm{d}E_{\text{dep}}/\mathrm{d}V}{I_{\text{T2K}}} \times \frac{L_{\text{max dirft length}}}{v_{\text{ion}}}$
- And fitted with:
- $\rho_{\text{ion}}(\boldsymbol{x}) = \rho_{\text{ion}}(r) = \frac{A}{r^B} + C$
- For pair-production background, the maximum $\Delta_{r\varphi}$ is ~ 120 μm.
- Estimate: single beam background is ~ 5 × pair-production.
  - Further investigation and optimization is needed.

Calculating electrical field and distortion

- More estimation:
  - Maximum distortion with e^+e^- to qq at Z-pole (physics events only)
  - Maximum distortion under the different beamstrahlung background （×10, ×50 , ×100 times physics events)
- MDI design at Z need to be carefully optimized with MDI group in CEPC.



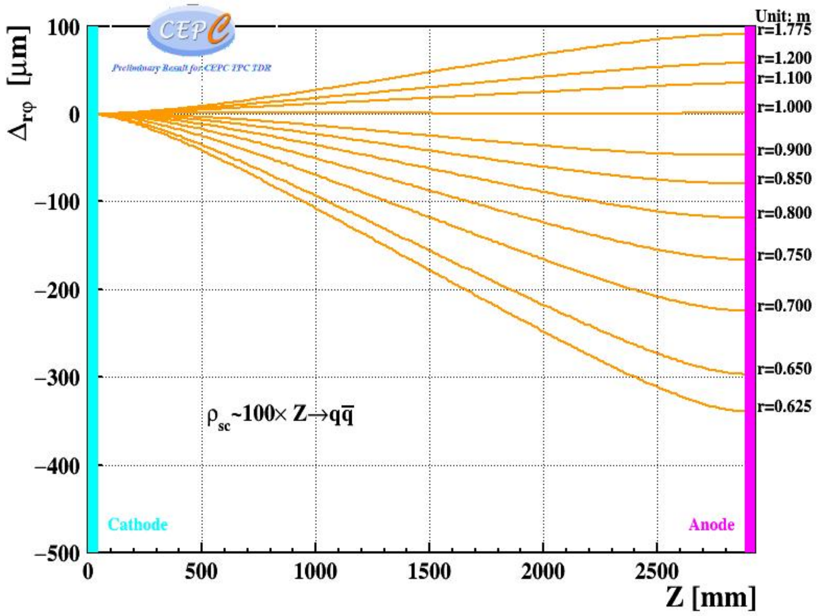


Fig: Calculating distortion for different levels of background

Conclusion

- The pixelated TPC is the baseline gaseous track detector with good performance of 3-D track reconstruction and PID resolution. The voxel occupancy is acceptable when TPC operate at the high luminosity Z-pole.
- Beam induced background has significant impact on TPC, especially at high luminosity Z-pole on CEPC. The results of the simulation and analysis gave the hit rate in the TPC chamber.
- With the calculating electrical field and distortion, the results showed that MDI design at Tera-Z need to be carefully optimized with MDI group in CEPC.

THANKS

Backup

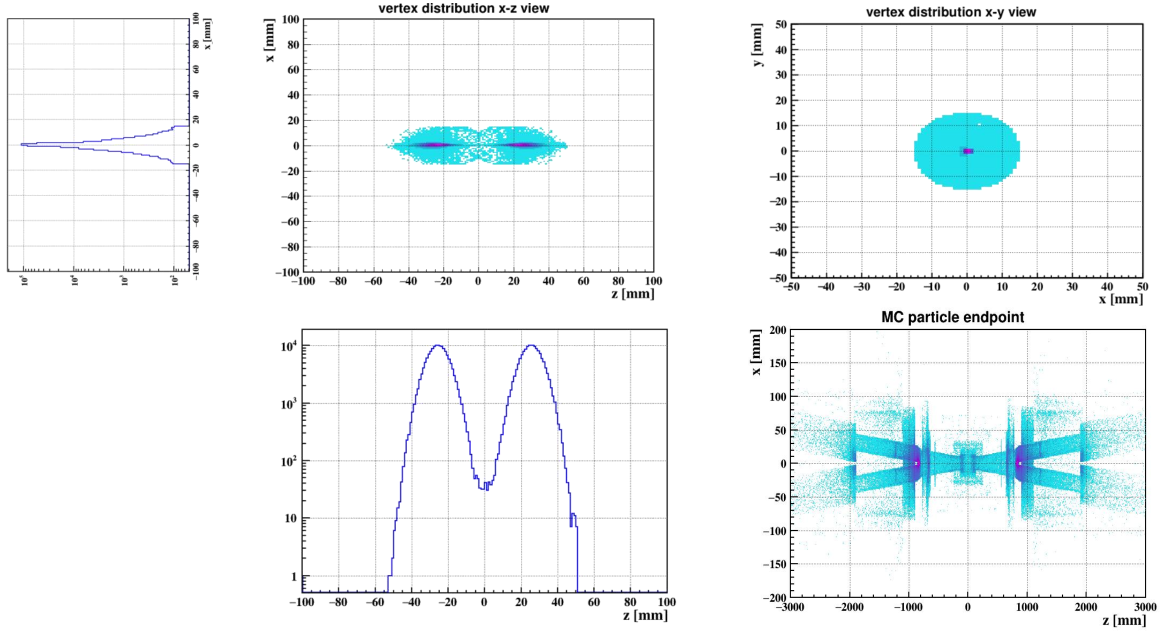


Fig: Vertex and endpoint distribution

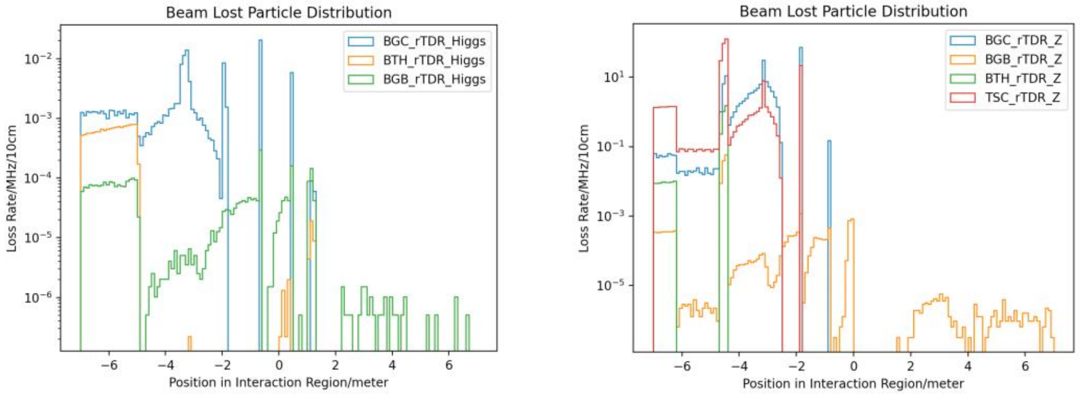


Fig: Beam lost particle distribution (one beam)

Backup

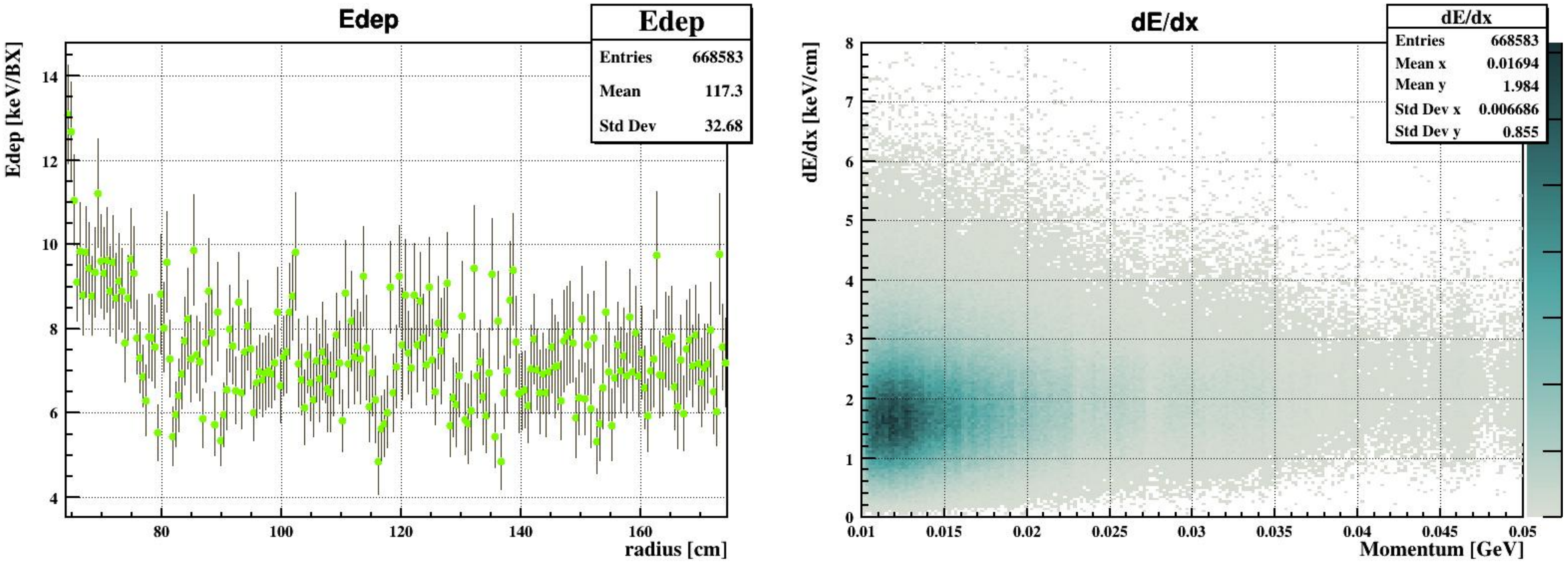


Fig: Background energy deposition and dE/dx