Impact of Beam-Induced Background on Time Projection Chambers at Future e^+e^- Colliders

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Outline

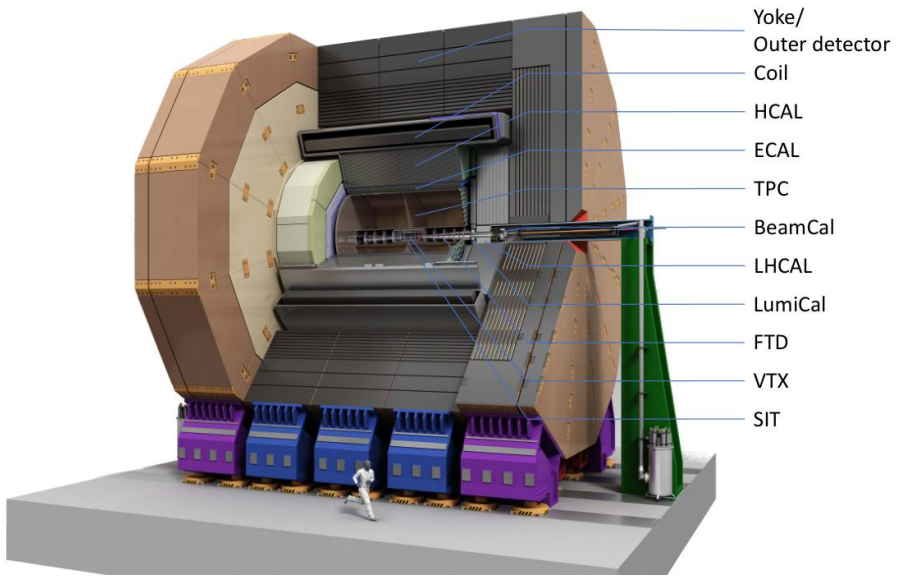
- Motivation and physics requirements
- Beam Background Studies in TPC
- Space Charge Effects & Background Optimization
- Summary

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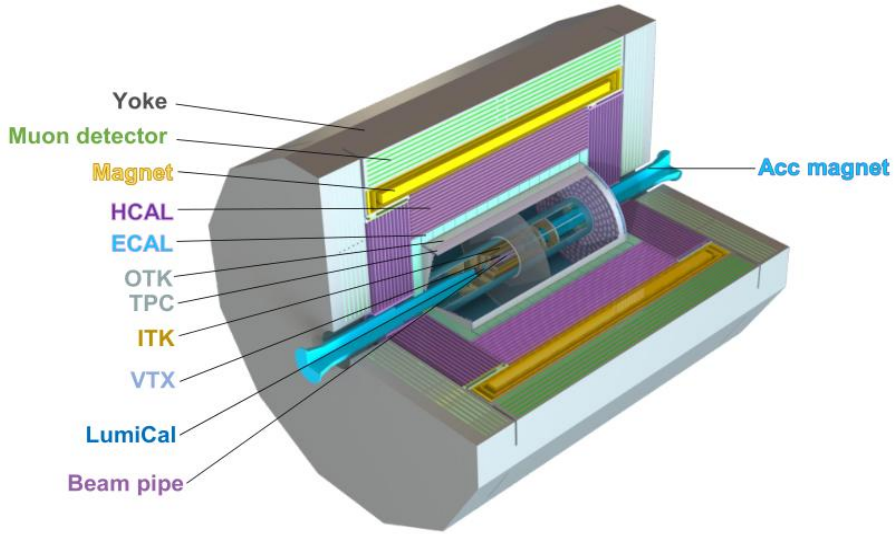
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Advantages of TPC

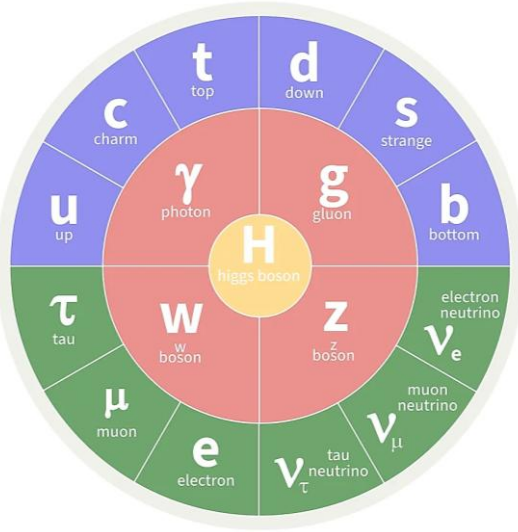
- **The discovery of the Higgs reveals the origin of elementary particle masses, but its physics still requires large detectors to understand**
  - **EW symmetry breaking, matter-antimatter asymmetry, early universe evolution, dark matter** ⟹ **e^+e^- Higgs factories**
- **TPC offers low material budget, precise 3D track reconstruction, and excellent PID**
  - e^+e^- experiments (**PEP, ALEPH**)
  - Heavy ion experiments (**ALICE, STAR**)
  - Neutrino & dark matter experiments (**PANDA X, T2K**)
  - Baseline main tracker option for future e^+e^- colliders (**AGORA、FCC-ee、ILD**)



ILD, Arxiv:1306.6327

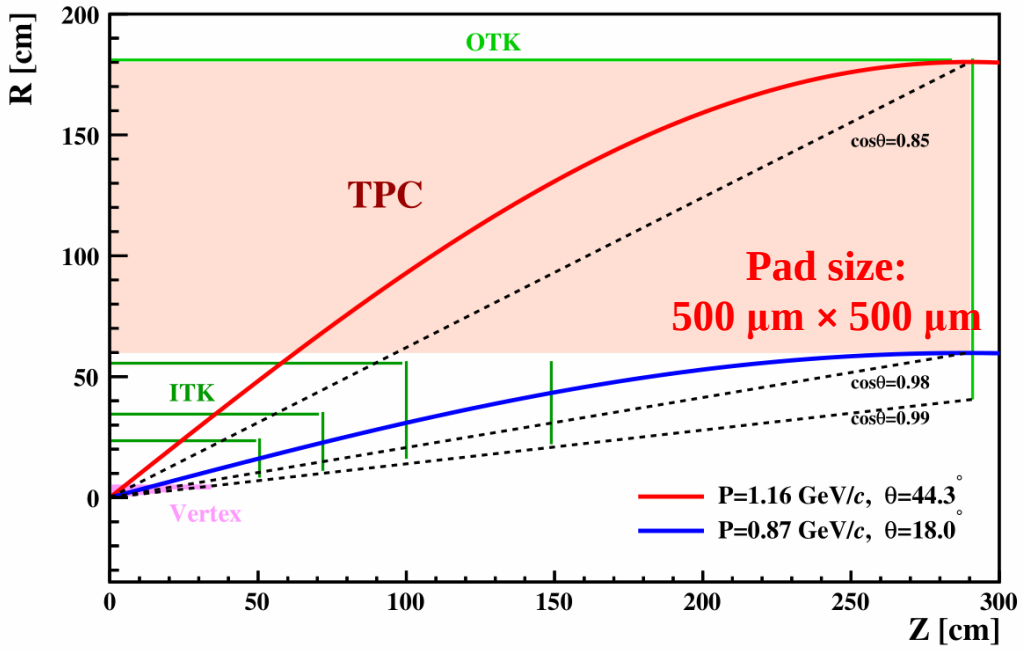


AGORA, Arxiv:2510.05260

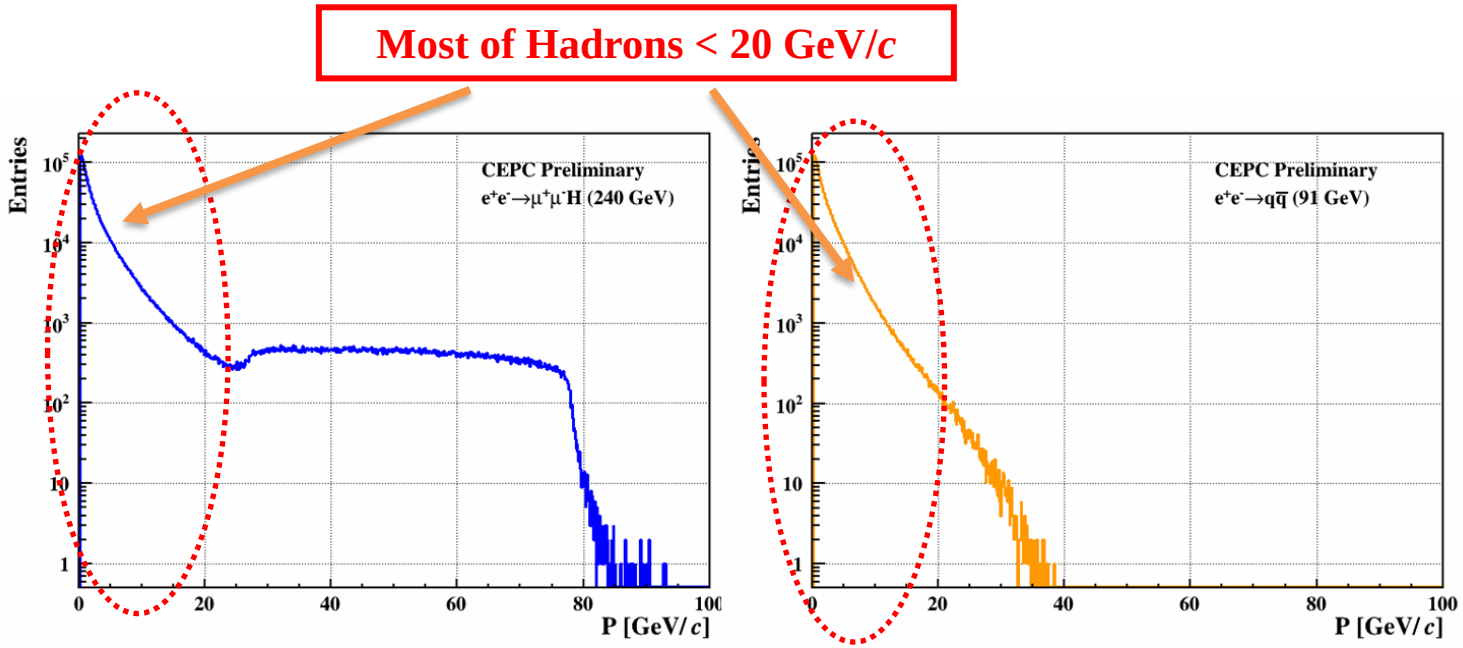


CEPC Requirements

- **CEPC baseline tracker:** high granularity readout TPC + silicon detectors (VTX, ITK, OTK).
- **Tracking plays a central role in future collider experiments:**
  - Overall momentum resolution: σ_{PT}/P_T ~0.3% (P_T < 100 GeV/*c*)
  - TPC momentum resolution σ_{PT}/P_T ~ 0.5—1% → Low gas material budget → **Improved low-p_T resolution**
  - PID performance: 3σ π/K separation (**1—20 GeV/*c***) → **TPC (dN/dx~3%)+OTK(~50 ps)**



CEPC tracker system R-Z layout

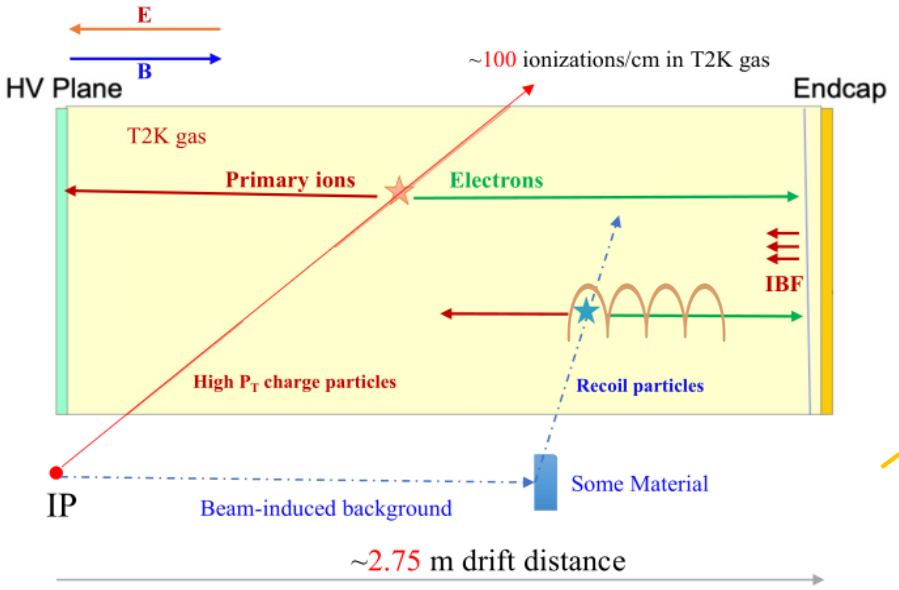


CEPC momentum distribution of final-state charged particles
(left) $e^+e^-\to\mu^+\mu^-H$, (right) $e^+e^-\to q\bar{q}$

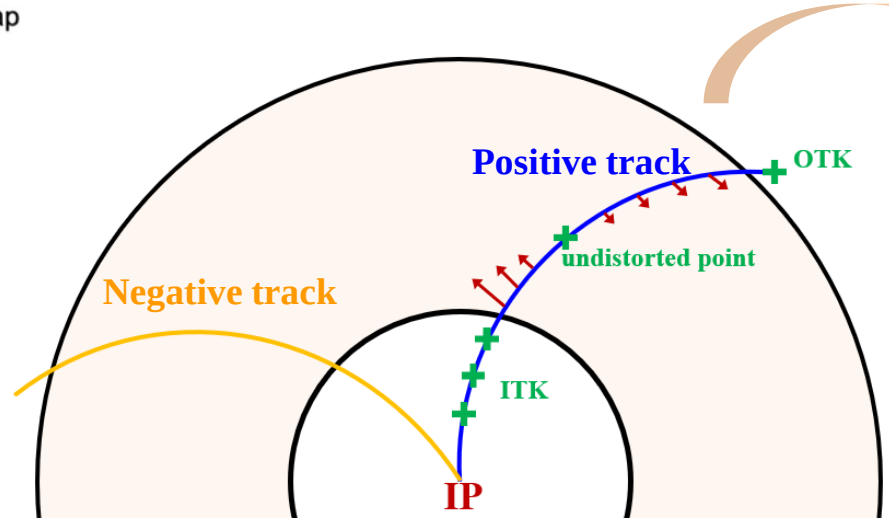
Key Issues in TPC

- **AGORA detector design targets future Higgs (H) and low luminosity Z**
  - Peak luminosity reaches 10^{34} and 10^{35} $cm^{-2}\cdot s^{-1}$
  - Detector field: 3T
- **TPC as main tracker poses significant challenges:**
  - High luminosity beam backgrounds → main source of positive ions
  - Positive ion accumulation → Space Charge Effects

Key Research Challenges



Schematic of space charge sources in TPC



Schematic of space charge induced measurement point distortion

$$\left(\frac{\sigma_{P_T}}{P_T^2}\right)_{meas.} = \frac{\sigma_{r\varphi}}{0.3BL_0^2}\sqrt{\frac{720}{N+4}}$$

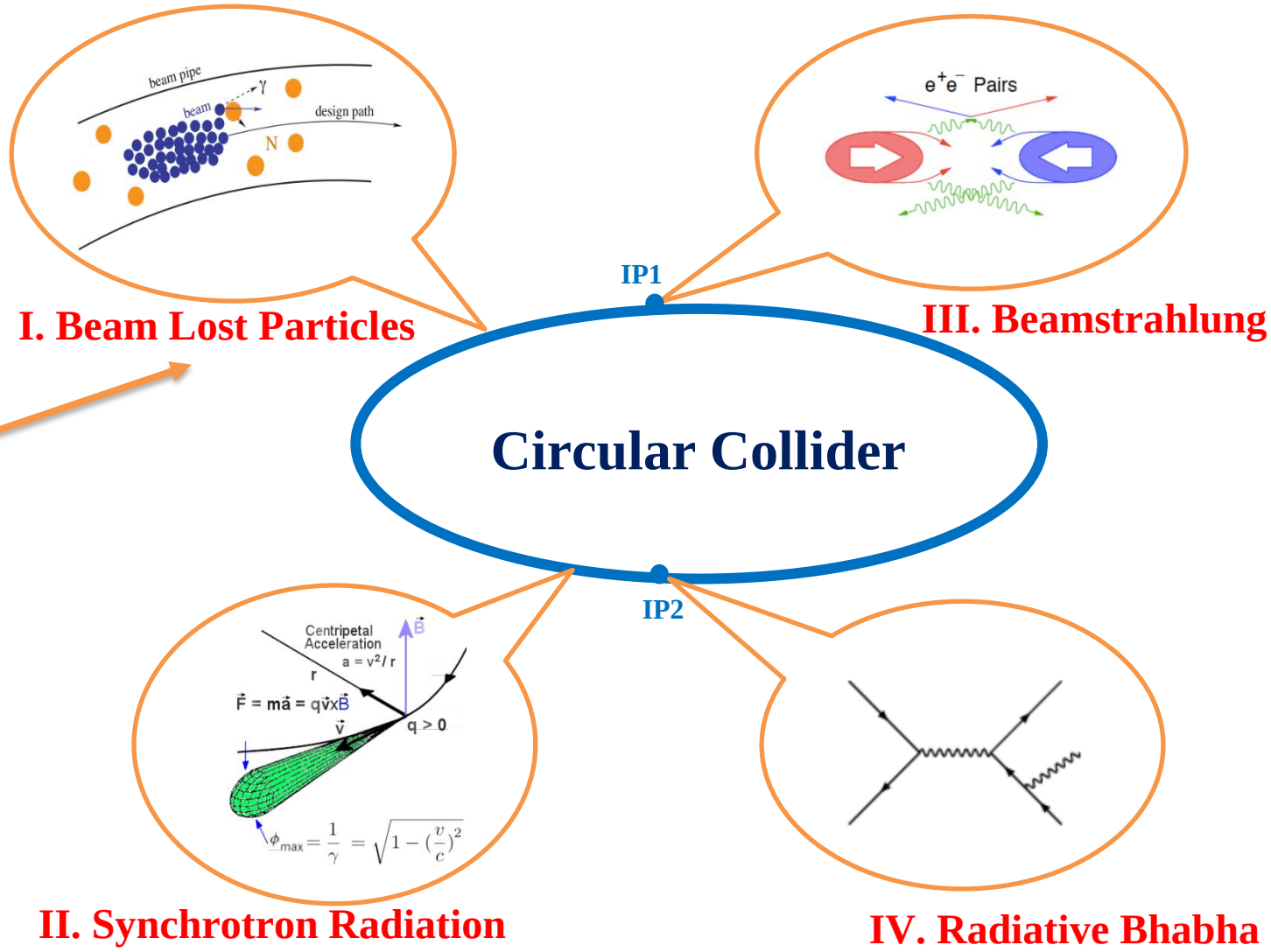
Degraded momentum resolution and systematic biases

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Beam Background Types

- **Beam background categories:**
  - Single Beam
  - Luminosity-related
- **Single beam (ring-wide distribution)**
  - Beam-gas scattering (BGS)
  - Beam-thermal photon (BTH)
  - Touschek scattering (TSK)
  - Synchrotron radiation (SR)
- **Luminosity-related (near interaction point)**
  - Radiative Bhabha (RBB)
  - Beamstrahlung



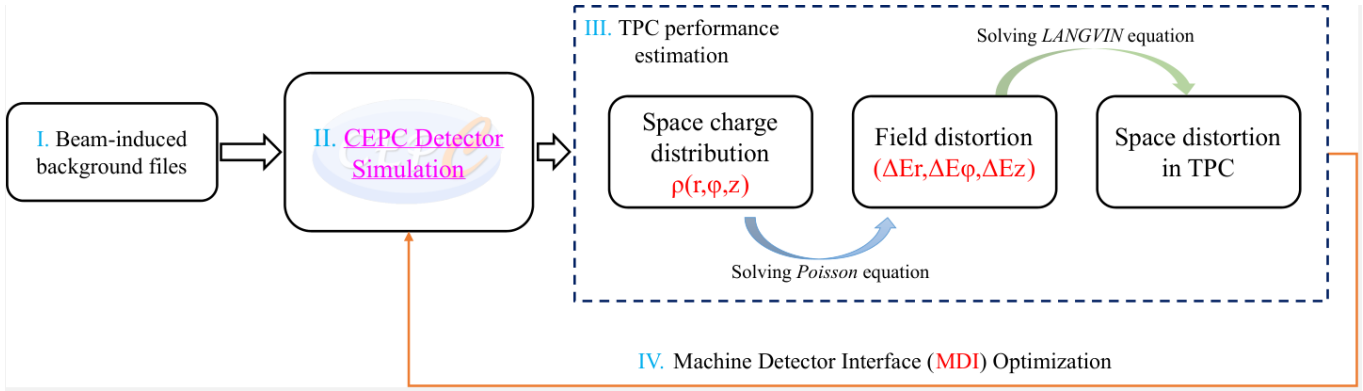
Beam Background Simulation Framework

- **For the MDI region, a comprehensive beam background simulation framework is established**
  - Luminosity-related: **Beamstrahlung**
  - Single beam: **BGC, BGB, BTH, TSK**

Detailed results reported in CEPC Ref-TDR

- **Evaluation of space charge effects on TPC tracking performance, with optimization to suppress backgrounds**

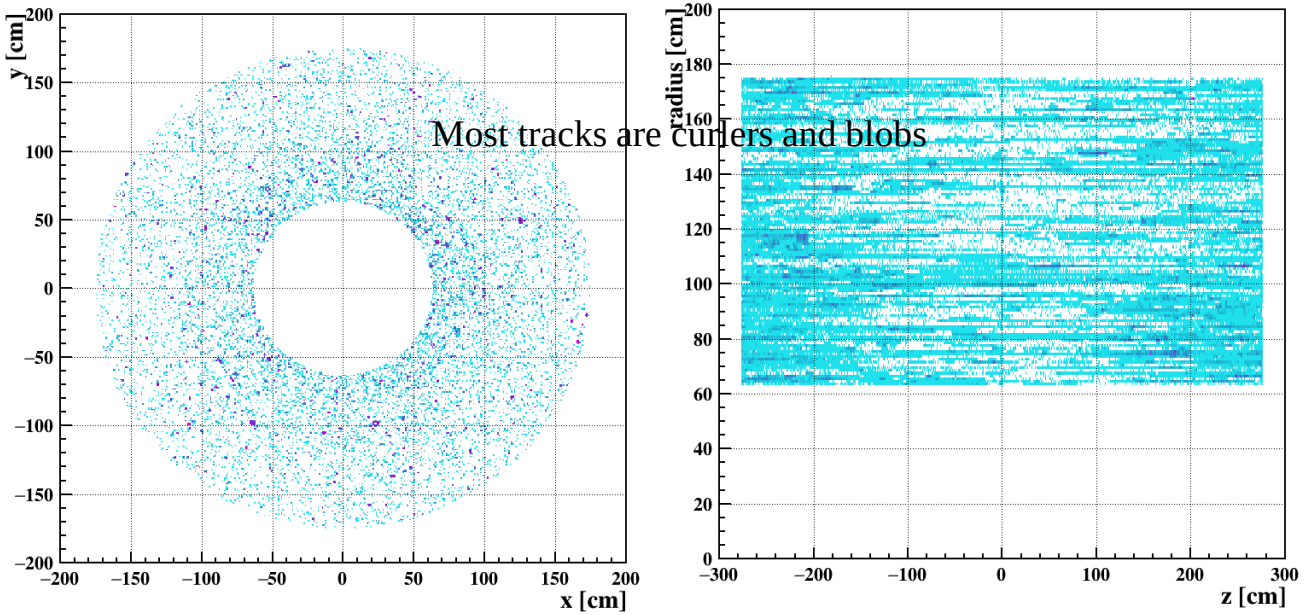
Backgrounds	Generation	Tracking	
Beamstrahlung/ Pair production	Guinea-Pig++	SAD	Luminosity related (BS files)
Beam-Gas Coulomb (BGC)	BGC in SAD		Single-Beam (Lost maps)
Beam-Gas Bremsstrahlung (BGB)	PyBGB		
Beam-Thermal Photon (BTH)	PyBTH		
Touschek Scattering (TSK)	TSK in SAD		



TPC beam background simulation workflow

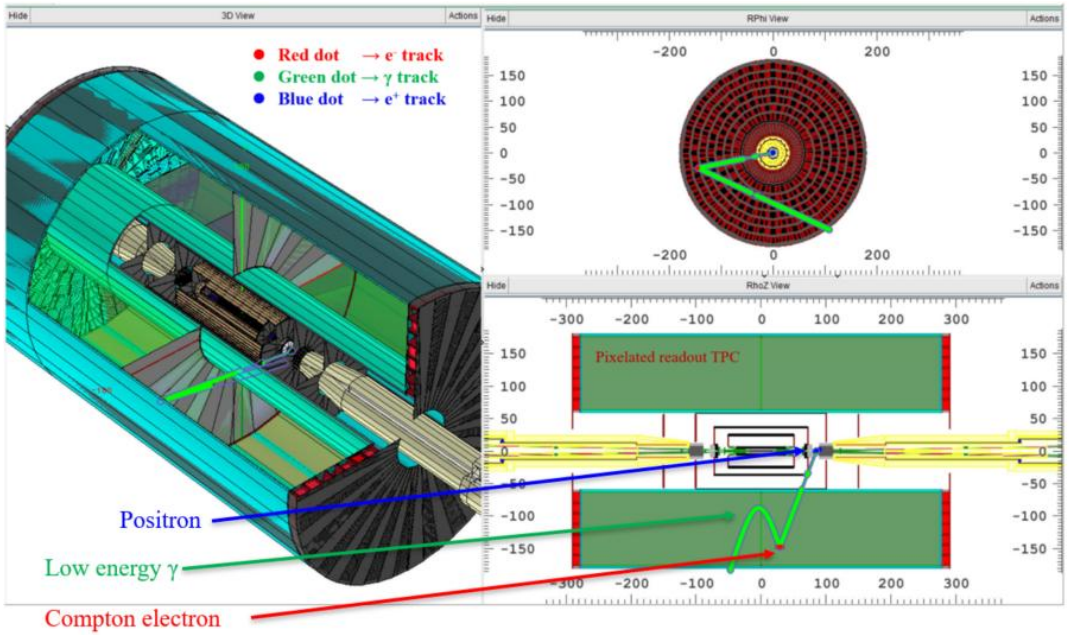
Typical Background Event Display

- **Unlike physics events, TPC background hits appear as small curlers and blob-like tracks**
  - Cause: very **low-energy electrons** (< 1 MeV)
  - Source: **photons interacting with the TPC working gas**
- **A few higher-momentum tracks exit TPC outer barrel**



50 MW Higgs mode 100 bunch crossings: TPC background hit map

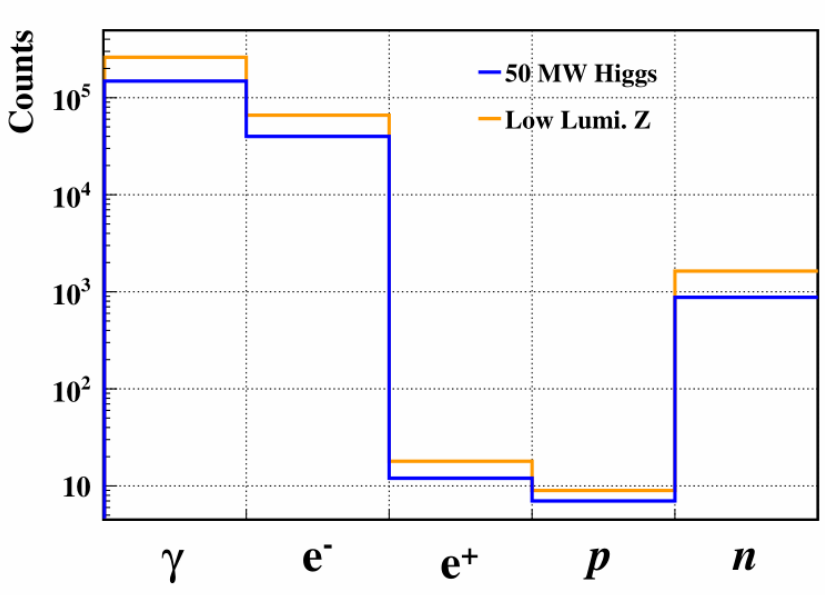
$background\ e^{+} annihilation \rightarrow \gamma(0.511 MeV) \rightarrow Compton\ e^{-}$



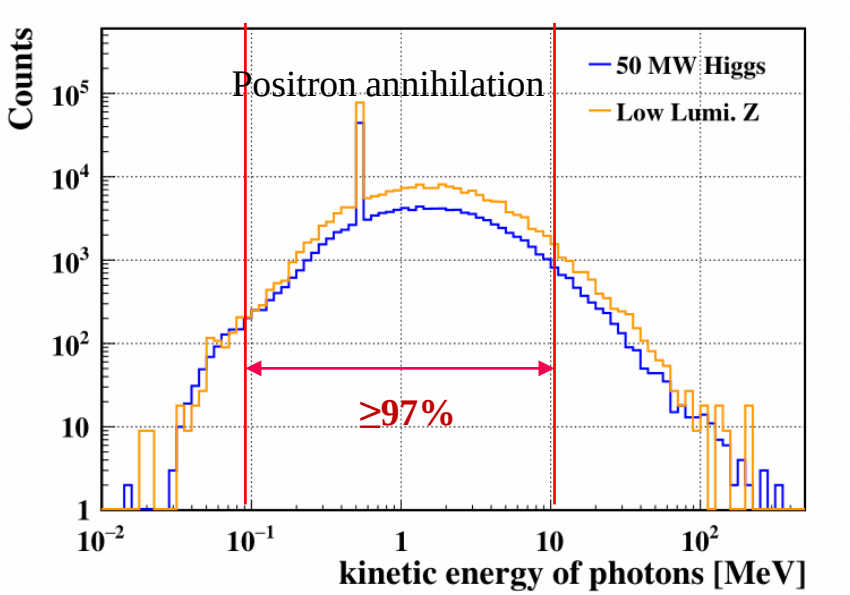
Event display of low-energy background electron production in TPC

Background Particle Analysis

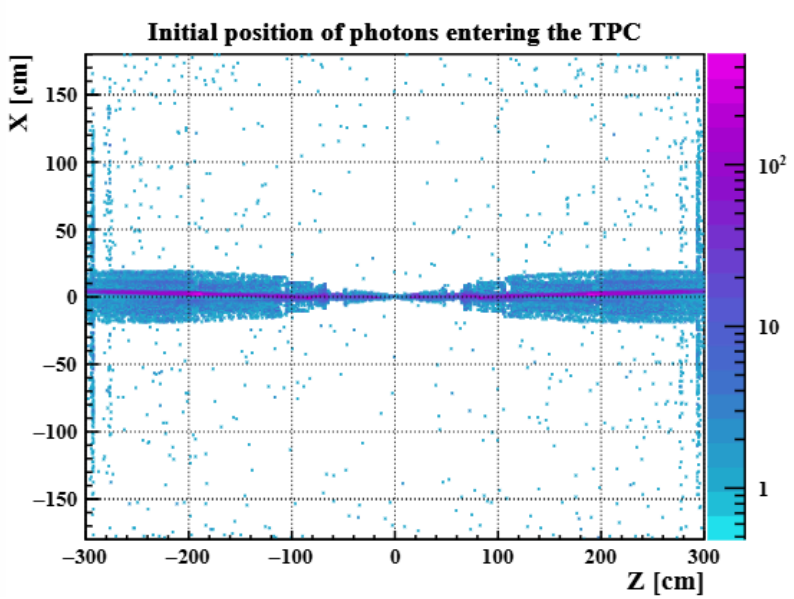
- **Entering TPC main background particles in the sensitive volume——photons and electrons:**
  - More than positrons, protons, and neutrons
- **Identified low-energy photons below 10 MeV as the main source of space charge in the TPC**
  - TPC space charge mainly from secondary low-energy photons downstream of MDI
  - Main photon processes: **Bremsstrahlung and Positron annihilation**



Per unit time entering TPC background particle type distribution



Energy distribution of low-energy photons in beam background particles

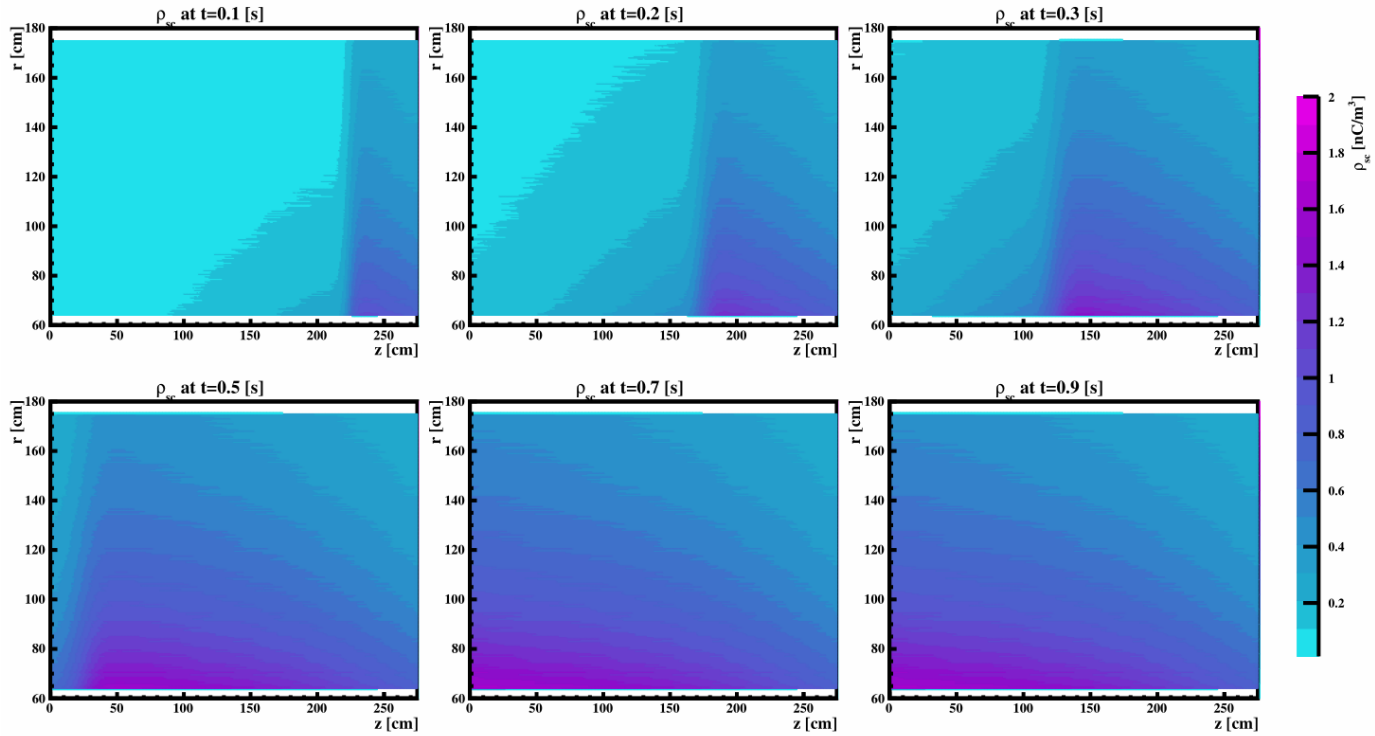


Low-energy photon production region

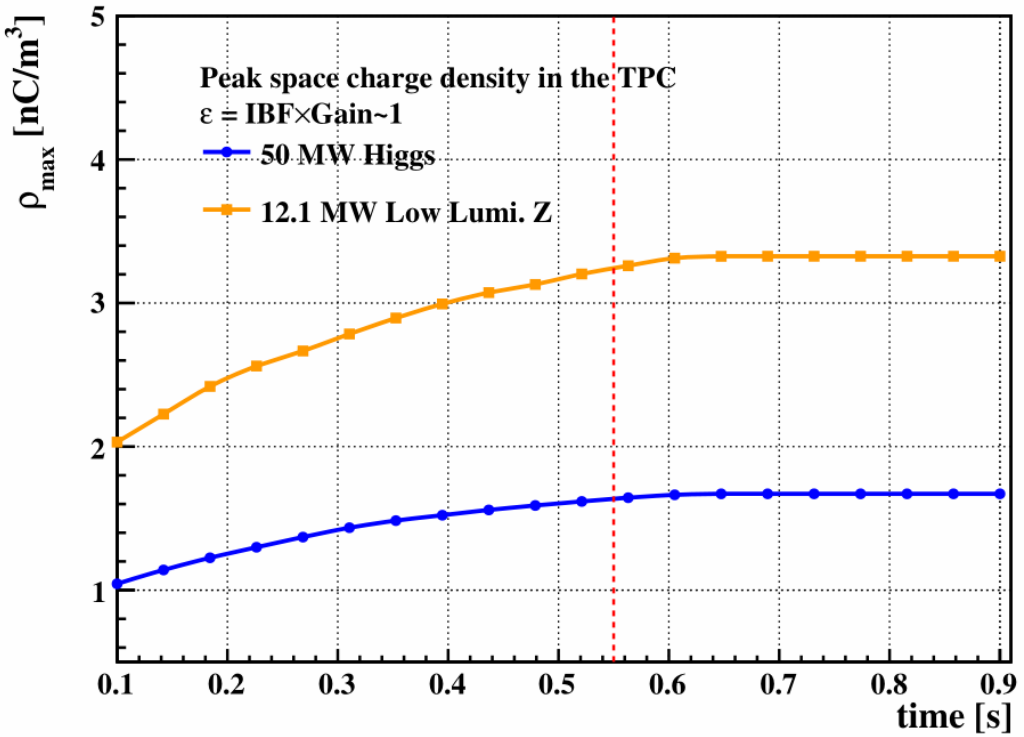
TPC Space Charge Density

- **Considering beam background sources, ion backflow, and ion drift-diffusion, the time evolution of positive ion density is obtained**
- **Max space charge density for both modes: 1.7 and 3.3 nC/m^3**
  - TPC ion density reaches equilibrium after **0.55 s**
  - Between ILC and ALICE

Experiment	Max. ρ_{sc}	IBF×Gain	Deviation level
ALICE	120 nC/m^3	20	$\mathcal{O}$(cm)
ILD @ ILC	0.05 nC/m^3	1	< 10 μm



Time evolution of positive ion density in the TPC



Positive ion charge density for both modes

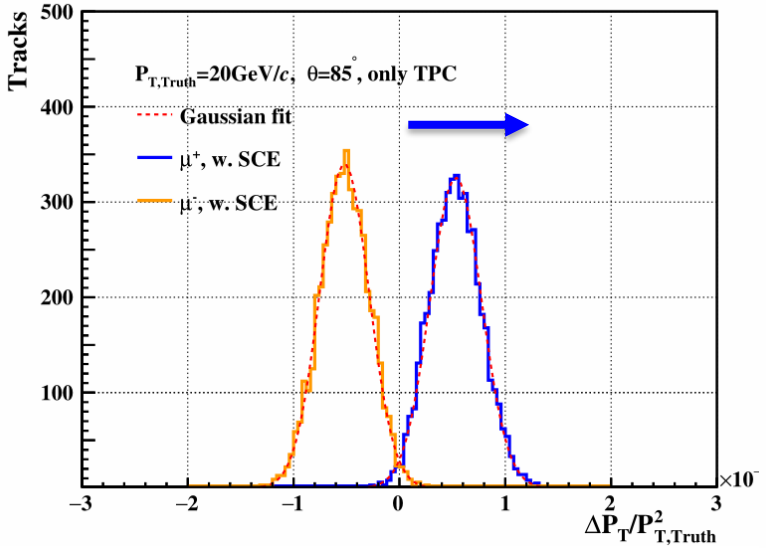
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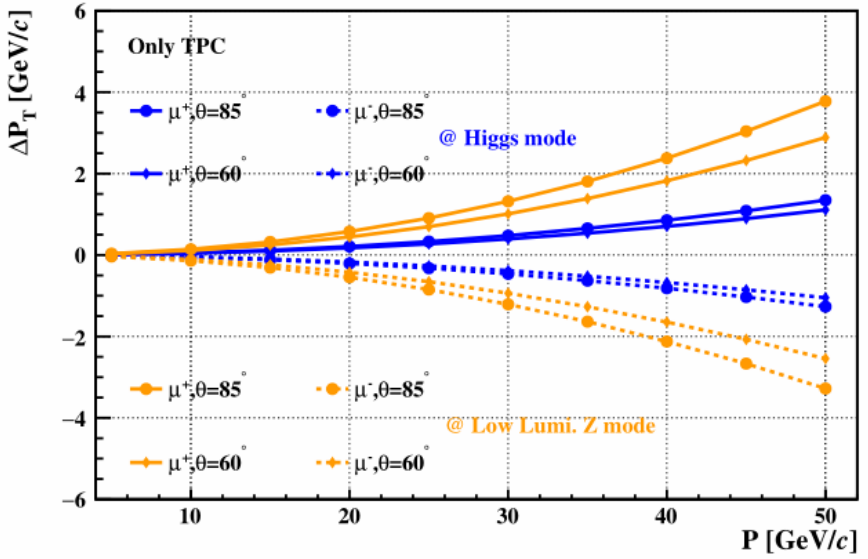
Space Charge Effects (1): Momentum Central Value

- **Incorporating beam background simulation results, space charge effects are included in the TPC track reconstruction**
  - Space charge effects introduce additional biases, depending on particle charge, incident angle, and momentum
  - Momentum measurements for positively charged particles are biased high, and negatively charged particles biased low

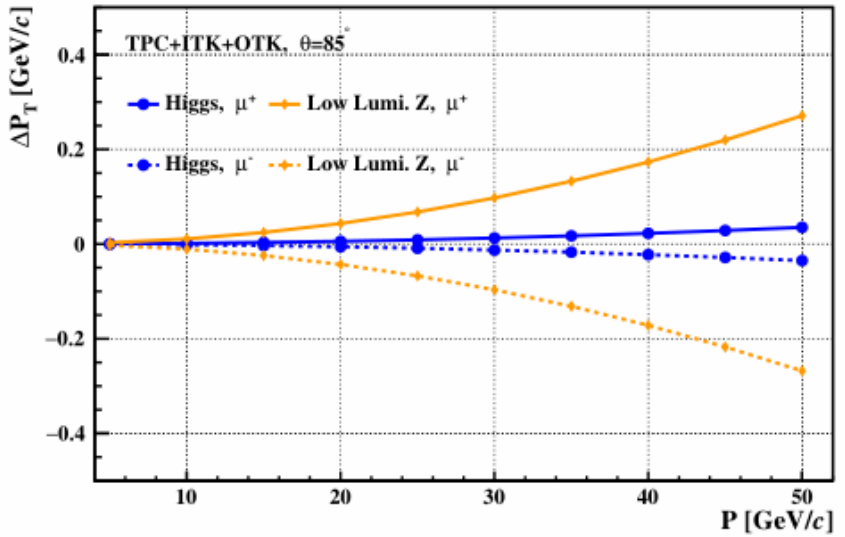
    → **systematic errors**
- **Impact of space charge effects on the momentum central value under different modes**
  - Shows a quasi-quadratic parabolic growth trend with momentum
  - **Combining ITK and OTK effectively suppresses the transverse momentum bias**



Reconstructed momentum distribution of 20 GeV/c μ considering space charge effects



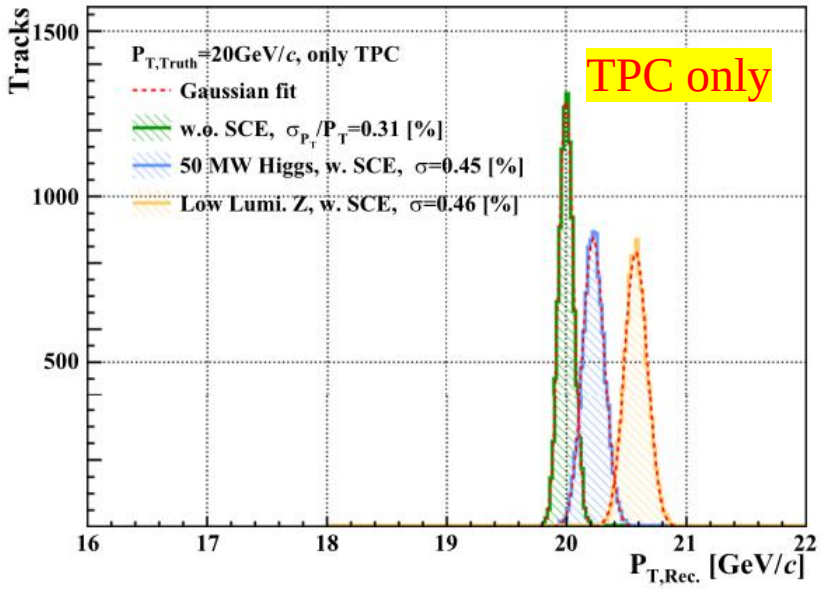
TPC reconstructed momentum bias vs. momentum and angle

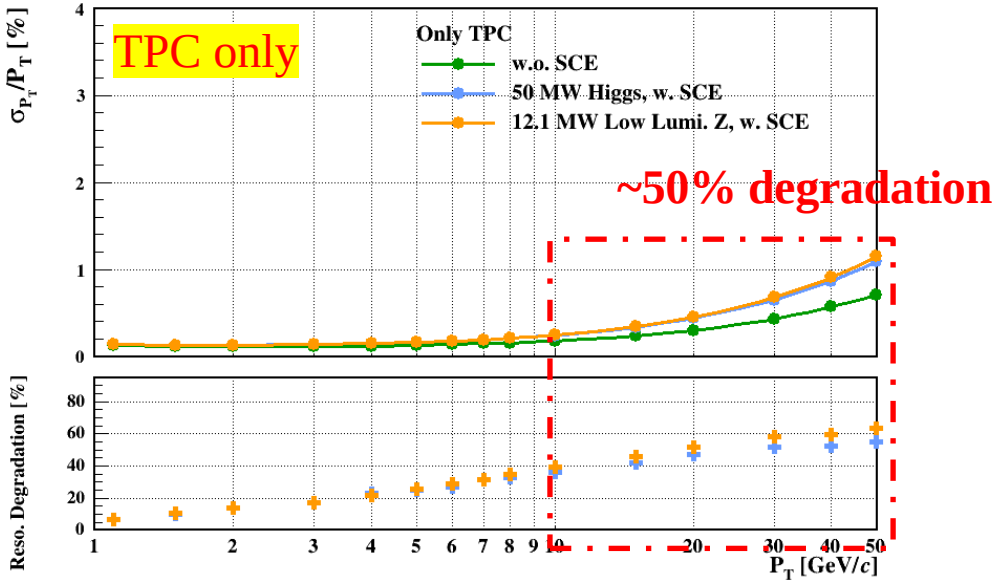


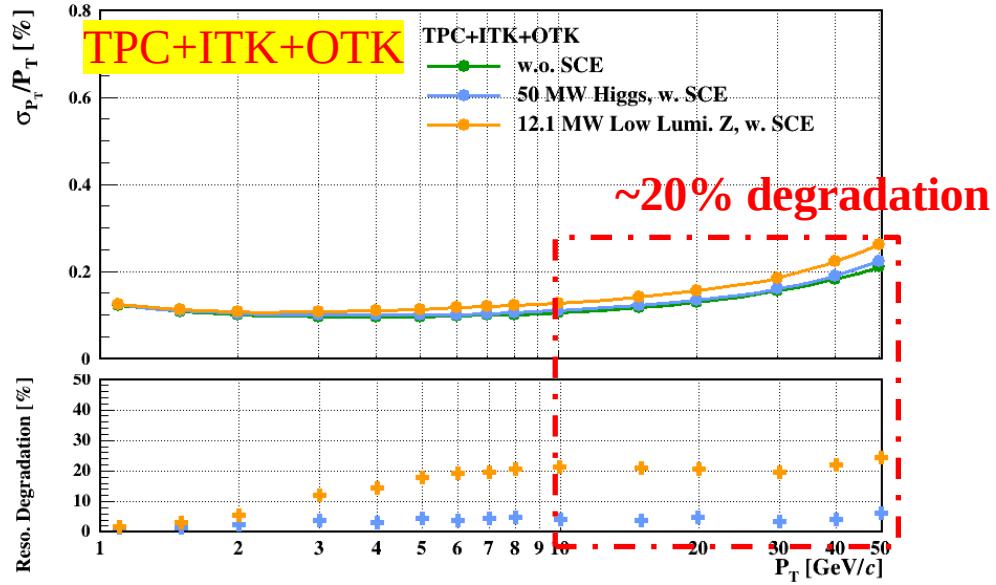
Reconstructed momentum bias vs. momentum after combining ITK and OTK

Space Charge Effects (2): Momentum Resolution

- **Impact of space charge effects on momentum resolution under different modes**
  - Random incidence at different angles leads to varying momentum biases
    → **overall degradation of reconstructed momentum resolution**
- **Space charge effects mainly impact the reconstruction of high momentum particles above 10 GeV/c**
  - P_T>10 GeV/c, TPC momentum resolution degrades by over 50%
  - Combining ITK and OTK, degradation is over 20% for Low Lumi. Z mode, and **<10% for 50 MW H mode**





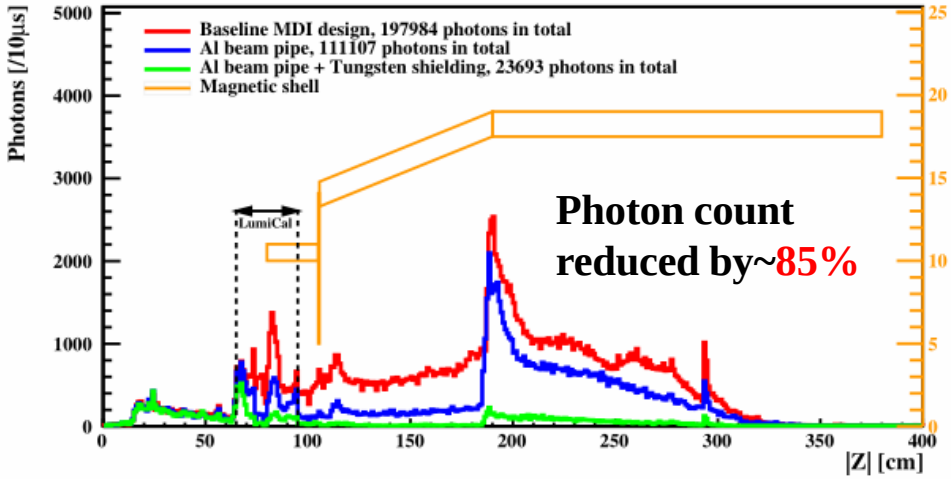


MDI Region Design Optimization

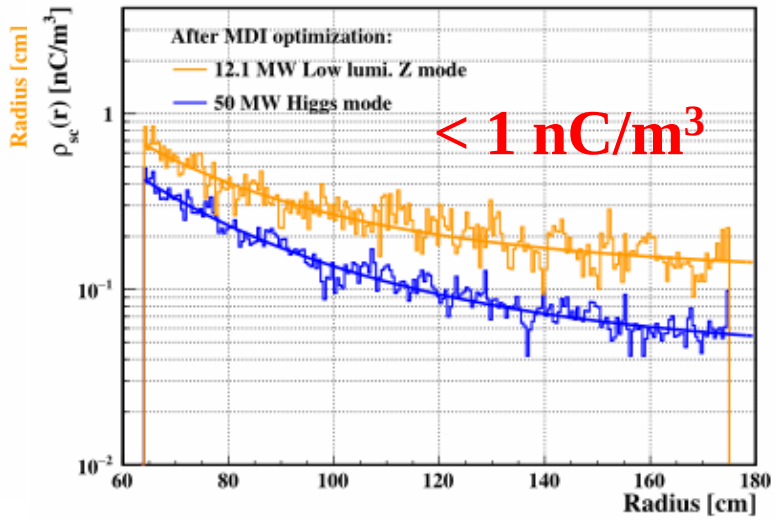
- **Optimization of the MDI region to control beam background sources:**
  - Optimized downstream accelerator components: beam pipe material, added shielding
  - Low-energy photons entering the TPC per unit time reduced by ~**85%**
  - After optimization, max space charge for both modes is **< 1 nC/m³**

→ **Al beam-pipe + Tungsten shielding**

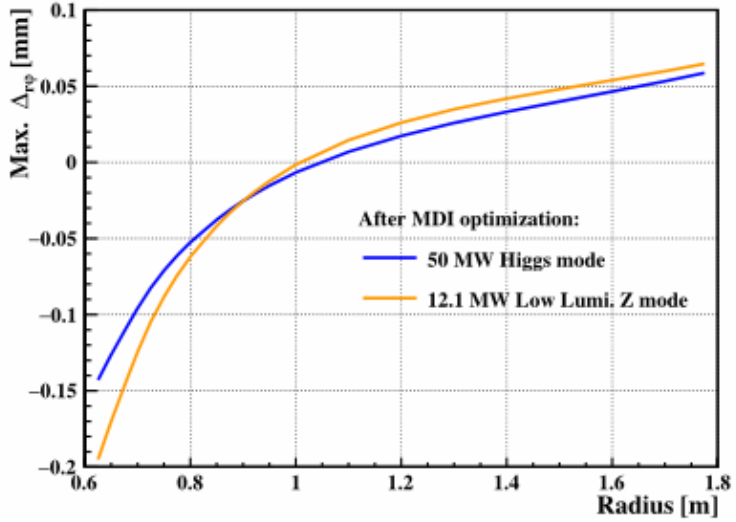
- **For most regions (radius > 0.7 m), electron drift bias in the rφ direction is < 150 μm**



Distribution of low-energy photons entering the TPC along the z-axis before and after MDI optimization



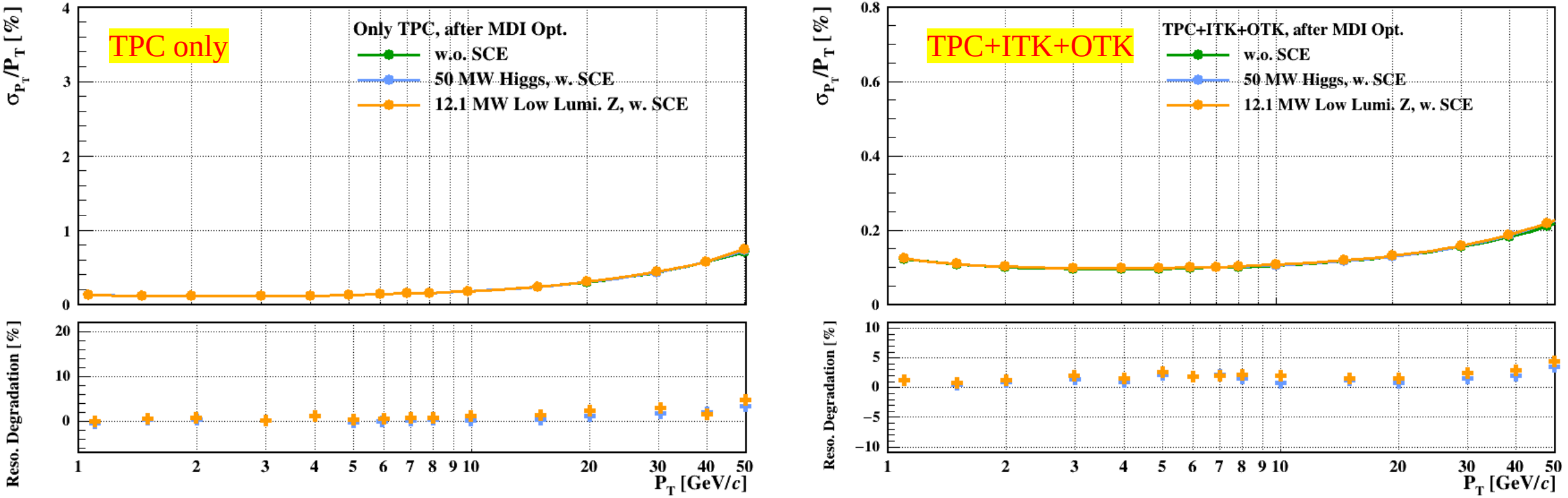
Space charge distribution in the TPC after MDI optimization



Maximum drift bias vs. TPC radius

Performance after MDI Region Optimization

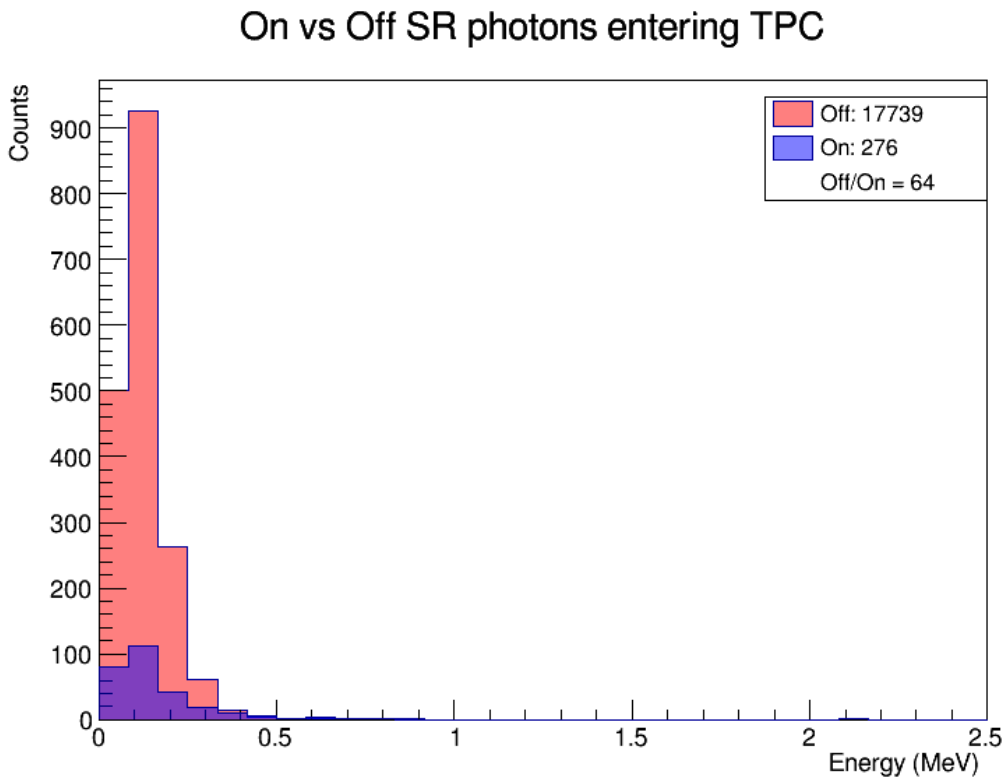
- **After MDI optimization, momentum resolution of TPC only and combined with ITK and OTK is improved**
  - TPC only momentum resolution degradation **< 10%**
  - Combined with ITK and OTK, momentum resolution degradation **< 5%**， basically meeting the CEPC tracking requirements
- **Provides design references for CEPC detector, actual engineering construction, and similar international machines**



Reconstructed momentum resolution performance of TPC only (left) and combined TPC+ITK+OTK (right) after MDI optimization

Synchrotron Radiation Preliminary Progress

- **SR photons enter the TPC, produce positive ions, and cause space charge distortion**
- **MDI group has optimized the mask system to block SR photons**
  - Added new shielding and smaller mask holes
  - Beam core photon escape: **1773900 → 27600 per bunch (after $\times 10^{11}/10^{9}$)**
- **Next steps**
  - Evaluate space charge from SR photons entering the TPC
  - Check momentum resolution after SR
  - Optimize working gas to reduce ion production
  - Explore new methods to suppress ion backflow
  - Halo SR is still under study



Summary

- **High granularity readout TPC as the CEPC baseline main tracker**
  - Identified beam background as a key technical challenge affecting TPC tracking
  - Clarified the generation mechanism and sources of space charge in the TPC
  - Systematically established a beam background study workflow, evaluating the impact of various beam backgrounds on TPC performance in the CEPC experimental environment
- **SR backgrounds pose significant challenges to various future detector designs**
  - Optimization of MDI design to shield low-energy photons
  - Optimized TPC working gas to reduce primary positive ion generation
  - Explored novel experimental research on positive ion backflow suppression
- **Conducted experimental research on high granularity readout TPC prototypes to further verify their PID and tracking performance**

Thank You

