Beam Background at Z Operation: TPC Feasibility under MDI Constraints

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Some good inputs from LCTPC and DRD1 International Group
Institute of High Energy Physics, CAS

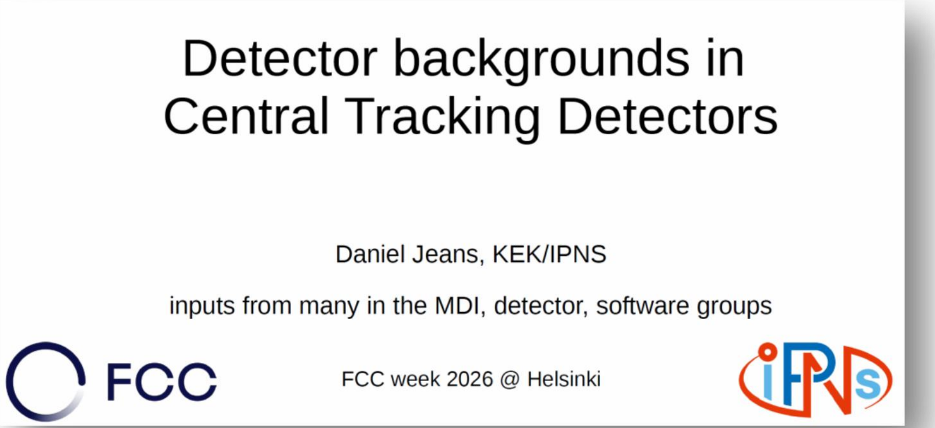
CEPC Day , July 27, 2026

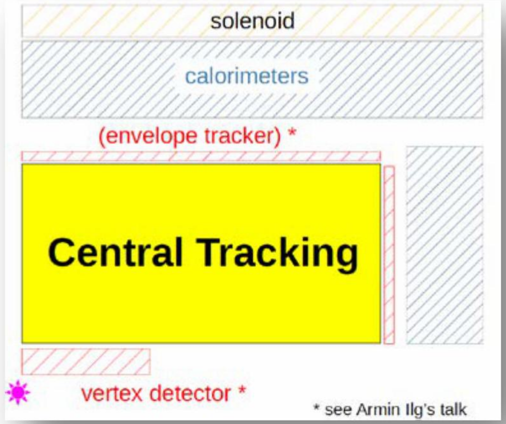
Content

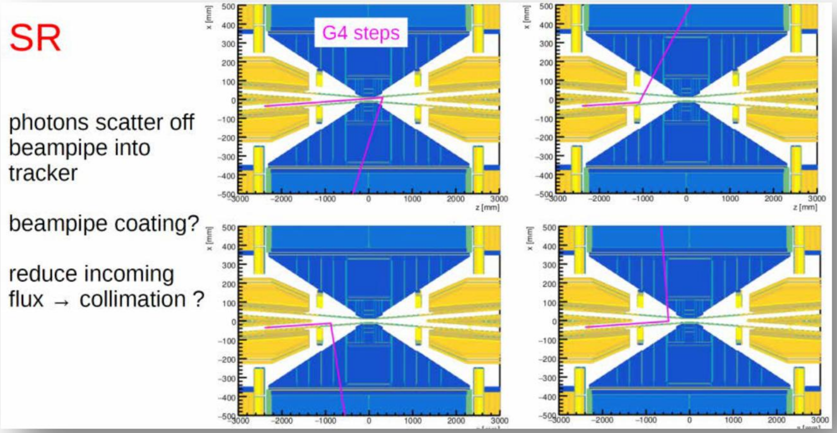
- Motivation and Physics requirements
- Beam-induced background in TPC chamber
- Tracking performance estimation
- Summary

The Wake-Up Call from FCCee Week: A Challenge for All Detectors

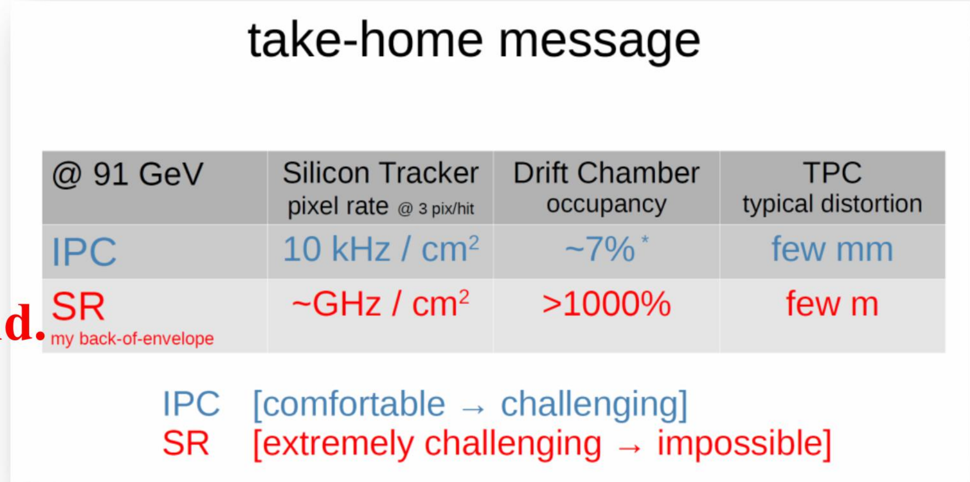
- At 2026 FCCee week conference, Daniel from KEK presented a striking estimate.







- Silicon pixel hit rate: **~GHz/cm²** (vs. ~10 kHz/cm² for IPC)
- Drift chamber occupancy: **>1000%**
- TPC distortion: **few meters** (without optimization)


take-home message

@ 91 GeV	Silicon Tracker pixel rate @ 3 pix/hit	Drift Chamber occupancy	TPC typical distortion
IPC	10 kHz / cm^2	~7% *	few mm
SR my back-of-envelope	~GHz / cm^2	>1000%	few m

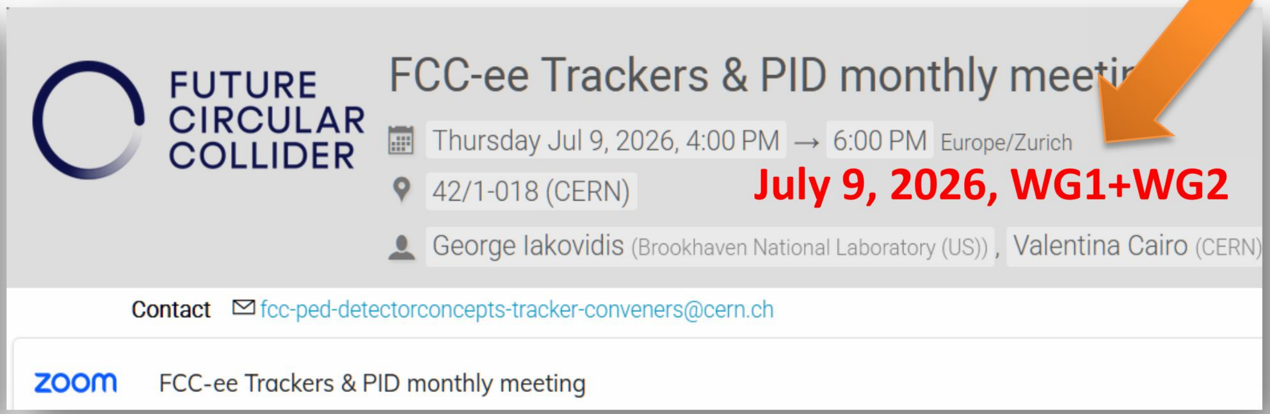
IPC [comfortable → challenging]
SR [extremely challenging → impossible]

- **Every detector technology at Z operation faces the background.**
  - The question is: how does each detector concept respond?

DRD1 and FCCee groups meeting: R&D Results & Positive Feedback

- This raised a very direct, very serious question for those of us working on TPC:
  - Is the TPC still feasible under these conditions?
  - Or do we need to fundamentally rethink the detector concept for the Z-pole operation?
- Based on our work presented at DRD1 and FCCee group in June and July
  - The positive feedback: the message was clear that we need to carefully consider.
    - **Approach validation and need concrete path.**

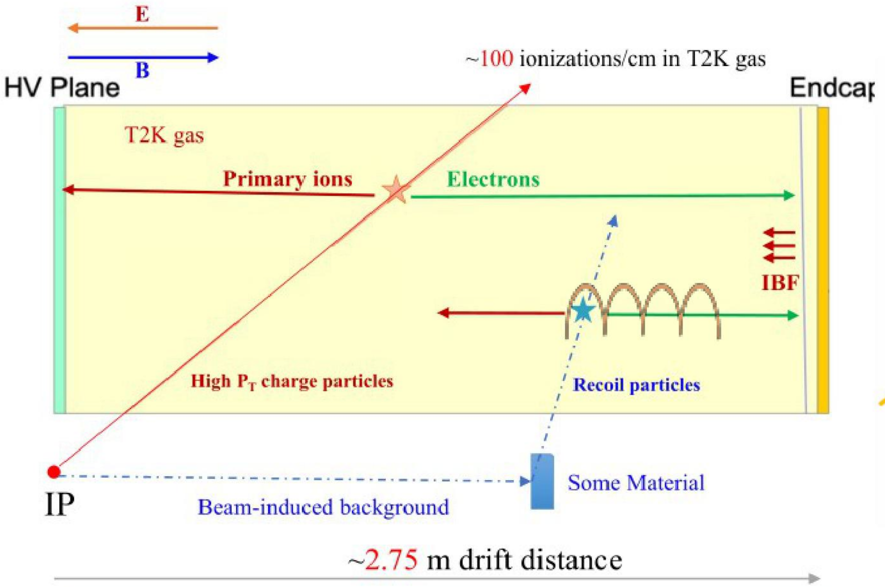
- This is not a **TPC specific problem**. Every detector concept at CEPC/FCCee faces this beam background — silicon trackers, drift chambers, calorimeters.
  - For TPC, some detailed studies results are what I'll show in this talk today.



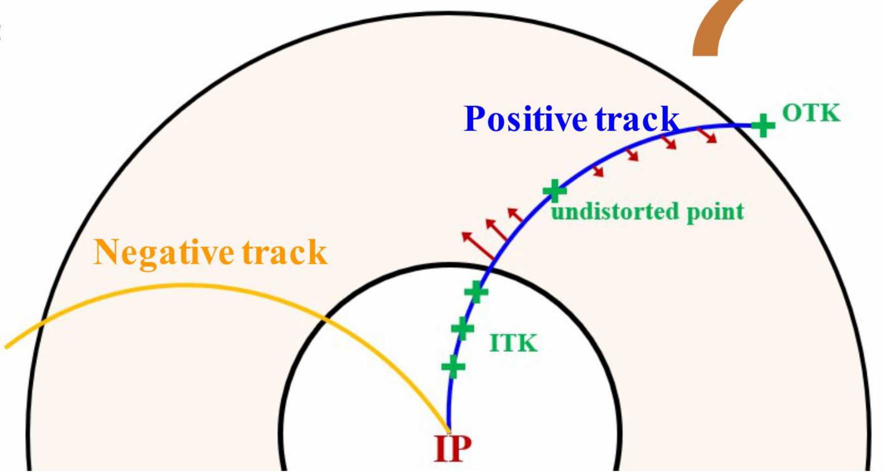
TPC challenges

- The Reference Detector is designed and optimized primarily for the Higgs and low-luminosity Z modes
  - Peak luminosity reaches **10^{34}** and **10^{35} $cm^{-2} \cdot s^{-1}$**, respectively
  - Both in 3T magnetic field
- **Challenges for TPC technology:**
  - Beam-induced background
  - Space Charge effect and distortions

Key Unresolved Problems
& Community-Wide Priorities



Schematic diagram of ion sources in the TPC



Schematic diagram of space charge effect

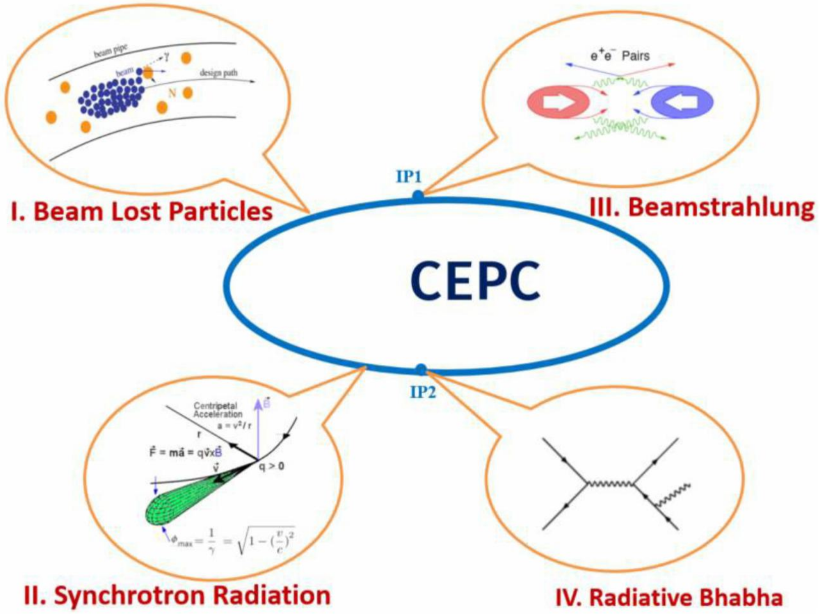
$$\left(\frac{\sigma_{P_T}}{P_T^2}\right)_{meas.} = \frac{\sigma_{r\varphi}}{0.3BL_0^2}\sqrt{\frac{720}{N+4}}$$

Degradation of the tracking performance

Status of beam-induced background @ CEPC

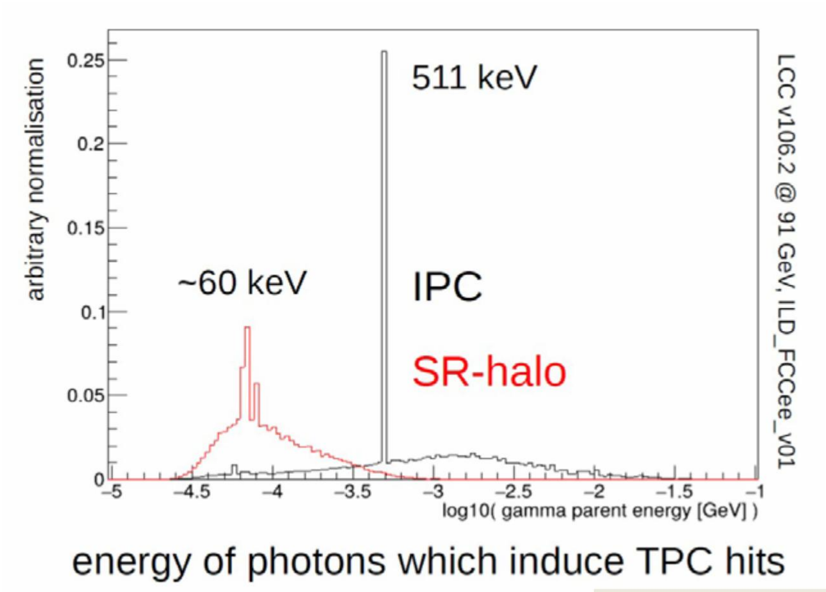
Our Strategy: From Assessment to Optimization

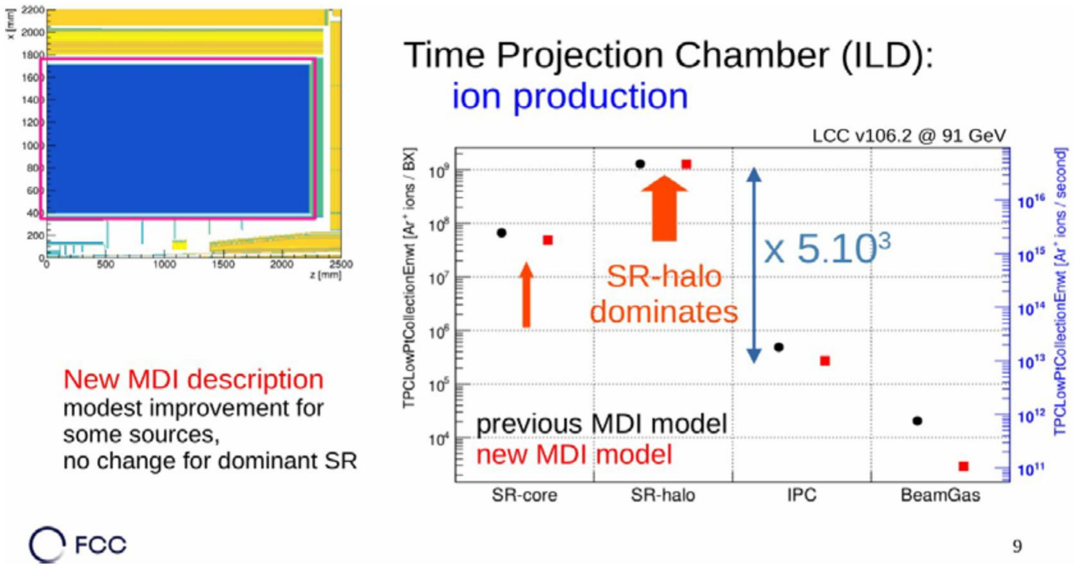
- The Beam-induced background be roughly classified into two categories:
  - I. Single-Beam: Beam-Gas, Touschek,…, **Synchrotron Radiation (SR);**
  - II. Luminosity-related: Beamstrahlung (incoherent pair creation dominant) , RBB
- Space charge generated by Beamstrahlung and Single-beam (without SR background) have been estimated at CEPC
  - Max. charge density ~3.3 nC/m^3
  - Max. deviation ~ 1 mm level @Low-Luminosity Z mode
- **Tracking performance with space charge effect in Higgs and low-luminosity Z modes will be demonstrated.**



Synchrotron Radiation @ Tera-Z

- **Daniel provides a massive estimate: all detectors face enormous challenges at Tera-Z in June.**
- **SR background seems extremely challenging:**
  - ~3 orders of magnitude higher than Beamstralhung, **also much larger than ALICE TPC**
  - We need to carefully evaluate the impact of SR background and optimize MDI design
    - Try to Shield 60 keV photons effectively by lead and tungsten materials





Daniel Jeans' talk at FCC week Conference last week

BG caused by Beamstrahlung and Single-beam

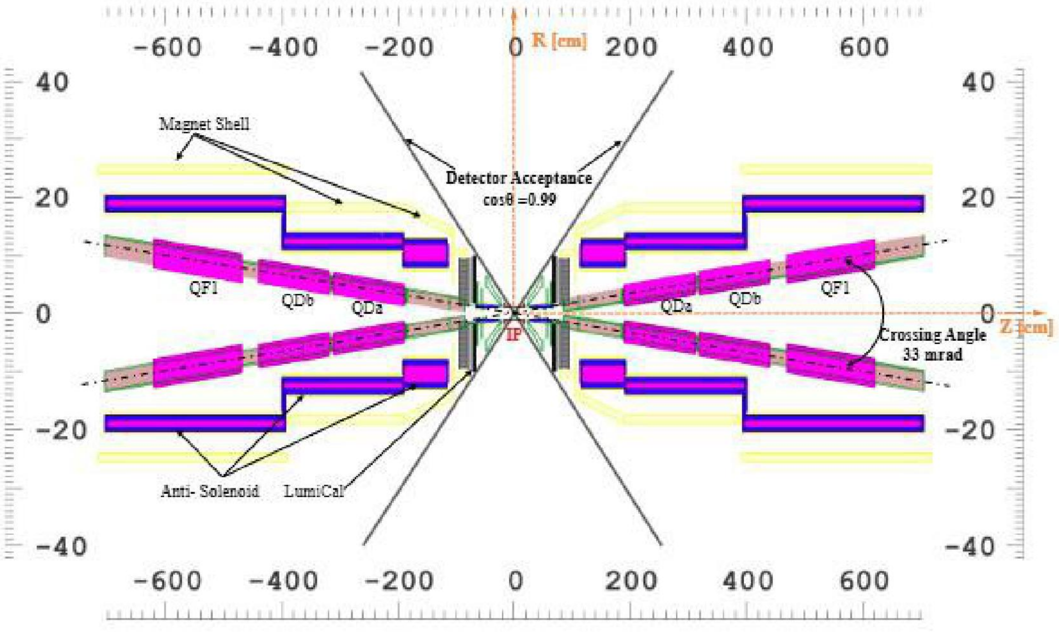
- CEPC MDI design
- Beam-induced backgrounds simulation
- Space charge density caused by BG
- Electron drift deviations

This full simulation chain, from background generation to space charge solving to performance validation, has been developed by the IHEP TPC group.
Jinxian Zhang, Huirong Qi, Jianbo Zheng and Xin She etc.

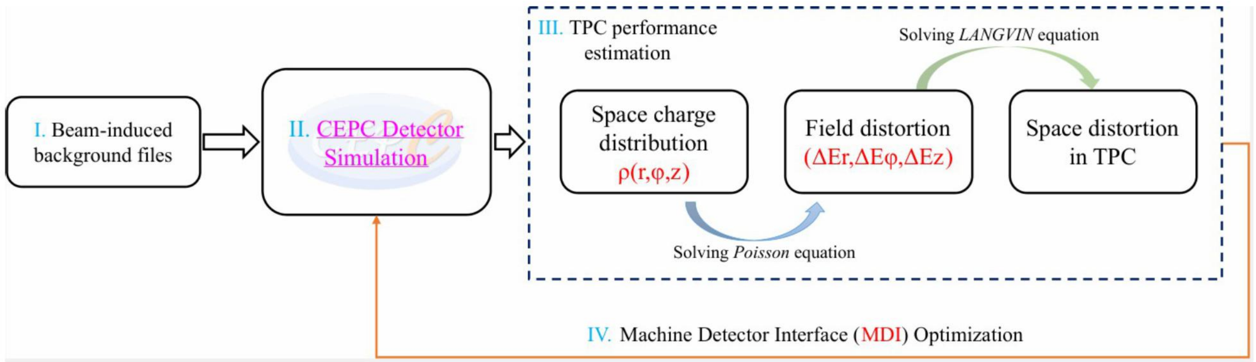
Simulation flow of beam-induced background

- MDI stands for "Machine-Detector Interface", **33 mrad** crossing angle
- Beam-induced backgrounds seeds generation
  - Pair production (beamstrahlung) → luminosity related
  - Single-Beam (BGC,BGB,BTH,TSC) → Single Beam
- Full Detector simulation in CEPCSW (based on Geant4)
- TPC space charge density and distortions estimation

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 (TSC)	TSC in SAD		



MDI designs in the CEPC ref-TDR



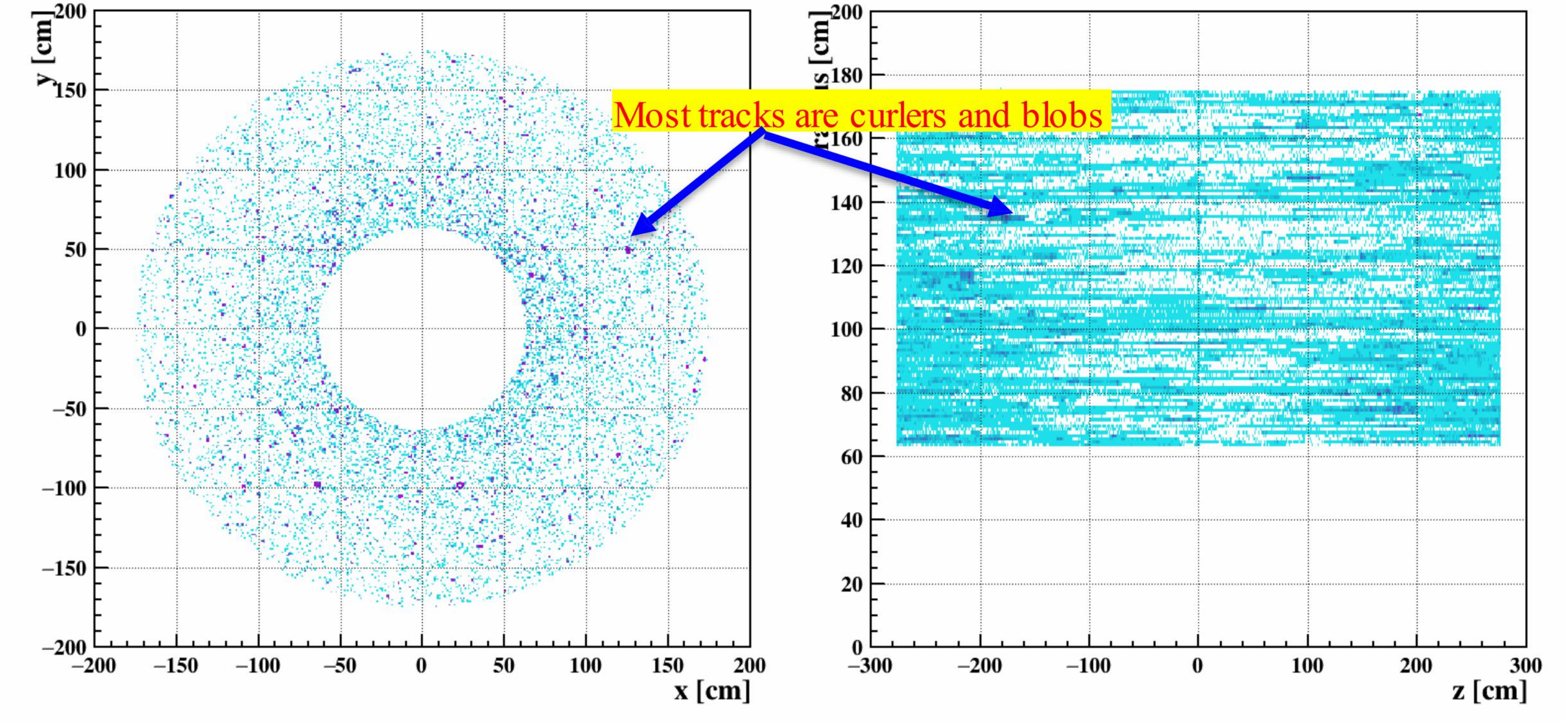
estimate number of **primary ions** produced in the TPC per bunch crossing
→ geant4 energy deposit / effective ionisation potential of Ar [26 eV]

BG events display

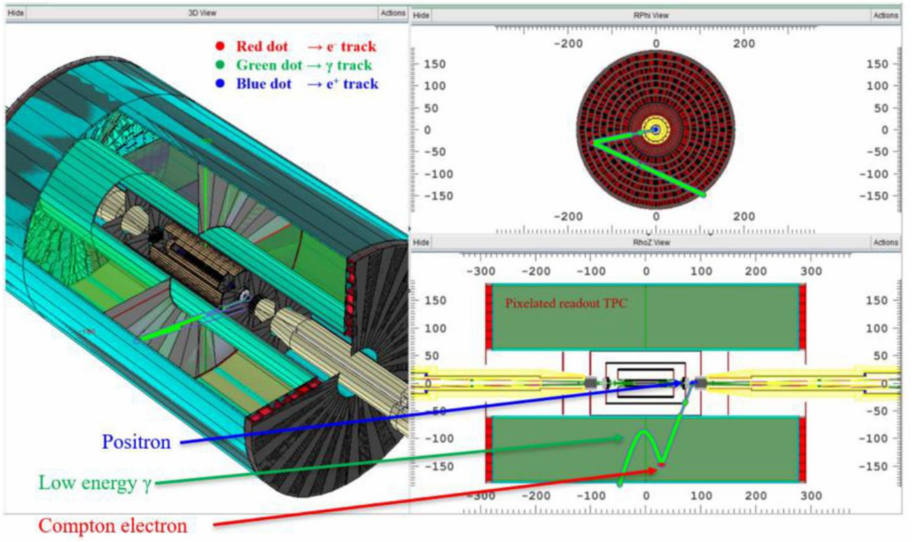
- Very few particles have enough energy to leave TPC
- Most of BG hits consist of more or less randomly distributed blobs or curlers
  - Sometimes called “salt and pepper” background
  - Caused by extremely low-energy electrons (<1 MeV)

Xin She, Huirong Qi etc.
10.1016/j.nima.2025.170776
European Physics Journey
NIMA

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



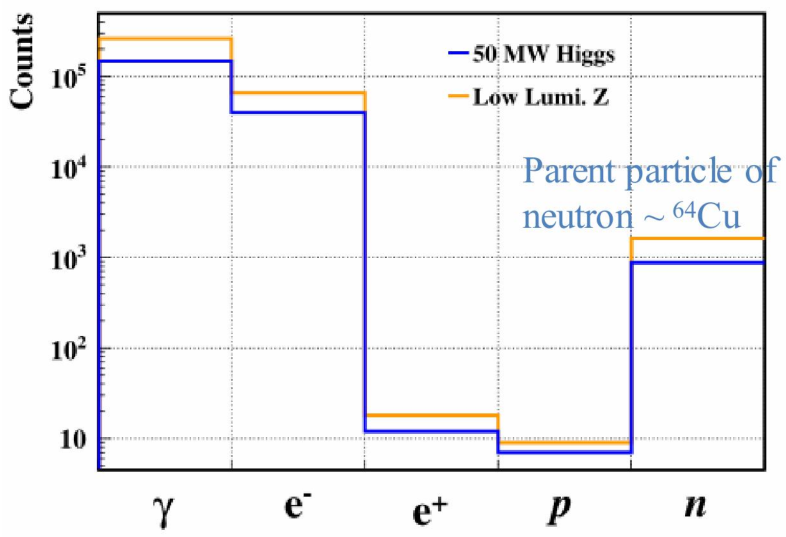
TPC hits distributions at the xy and rz plane from 100 BX crossings

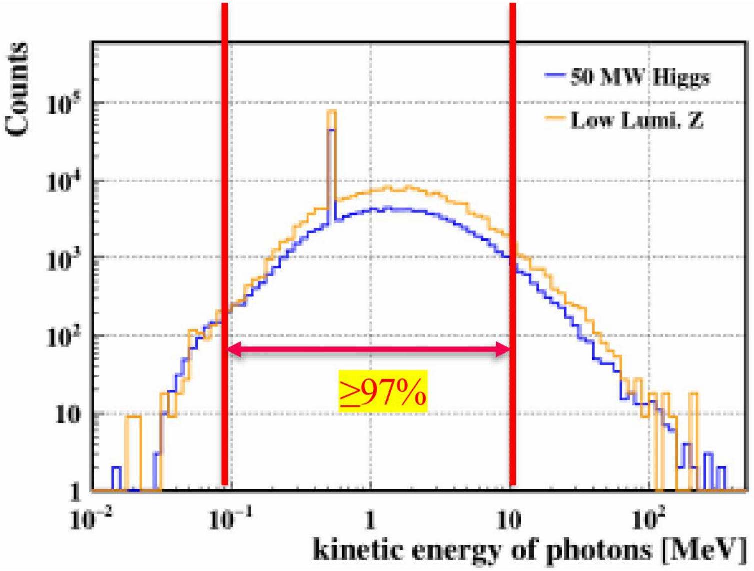


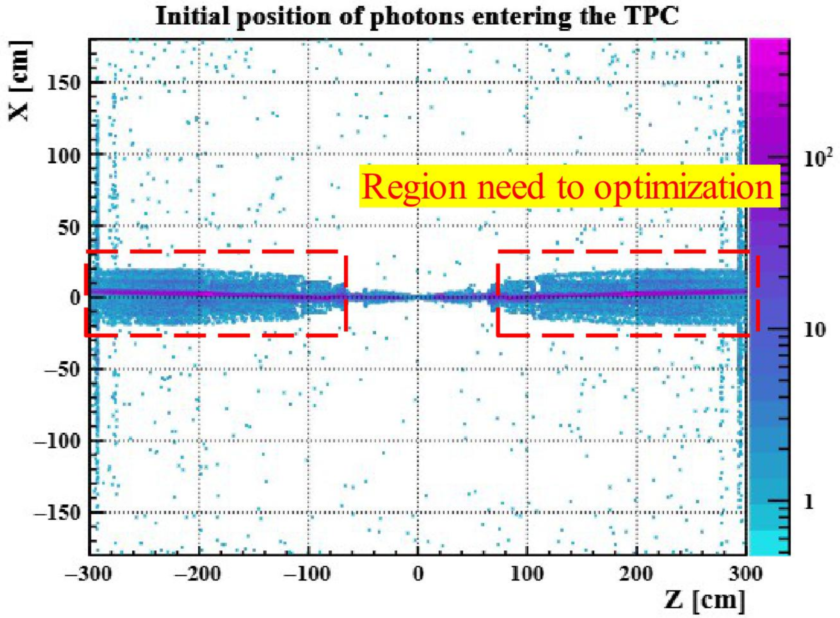
- Typical event display：
  - e+ annihilation
  - Low energy (0.511 MeV) γ incident TPC and interact with the T2K gas
  - generate secondary Compton electron

BG Particles in the TPC

- Photons and electrons (produced by low energy photons) are the main components in the TPC volume
  - The rest of particles, like positrons, proton and neutron, are negligible
- Low-energy photons (< 10 MeV) are the main contribution of the space charge
  - Photons originating from the downstream beam pipe make a significant contribution



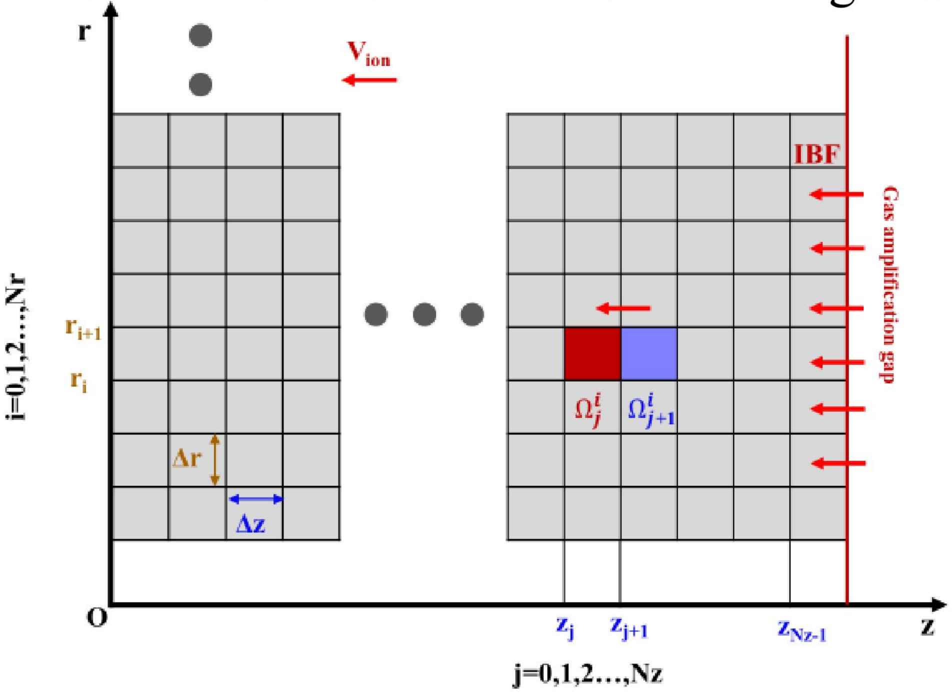




Particle type, Energy and initial position of low-energy photons entering the TPC

Solving Space charge density in the TPC

- Space charge density in the TPC can be calculated with some assumptions
  - Azimuthal (φ) symmetry
  - Constant ion drift velocity, here assuming V_{ion} = 5 m/s
  - The rate of ions created by beam-induced background is stable, i.e. S(r,z,t) is stable
- Positive ions from beam-induced background, IBF and ion diffusion effect are considered



Finite Difference Method to solve ion density in the TPC

$$\frac{\partial N_{\rm ion}(r,z,t)}{\partial t} = S(r,z,t) - \vec{\nabla}\cdot\left(\vec{V}_{\rm ion}\,N_{\rm ion} - D\,\vec{\nabla}N_{\rm ion}\right)$$

Axisymmetric drift-diffusion equation

$$N_{i,j}^{n+1} = N_{i,j}^{n} + \Delta t\, S_{i,j}^{n} - \frac{\Delta t}{r_i \Delta r}\left[r_{i+1/2}F_{r,i+1/2,j} - r_{i-1/2}F_{r,i-1/2,j}\right] - \frac{\Delta t}{\Delta z}\left[F_{z,i,j+1/2} - F_{z,i,j-1/2}\right]$$

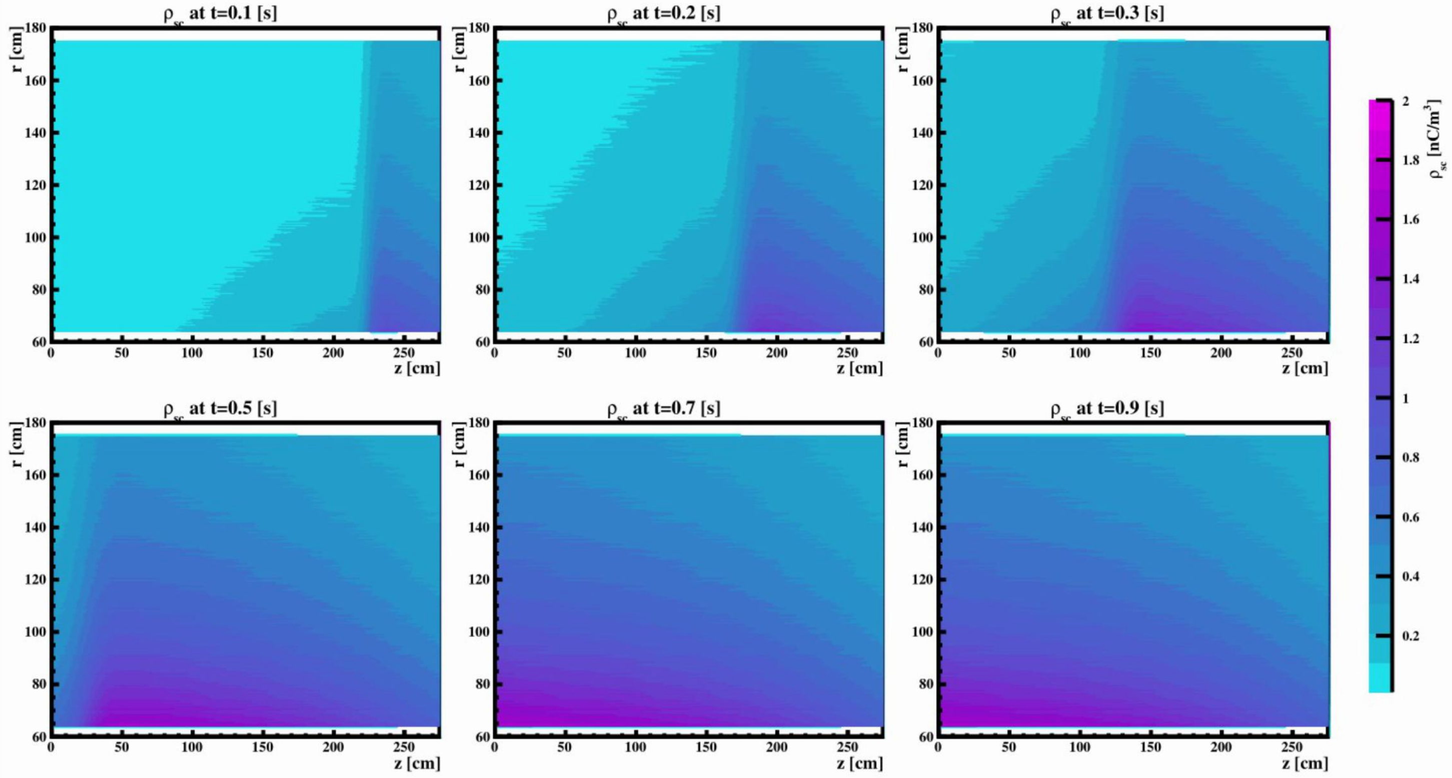
Full FTCS Update Formula

- S(r,z,t):BG source + IBF, from Det. simulation
- ε = IBF×Gain =1
- Grid spacing: Δr = 0.5 cm，Δz = 1 cm and Δt = 1 ms

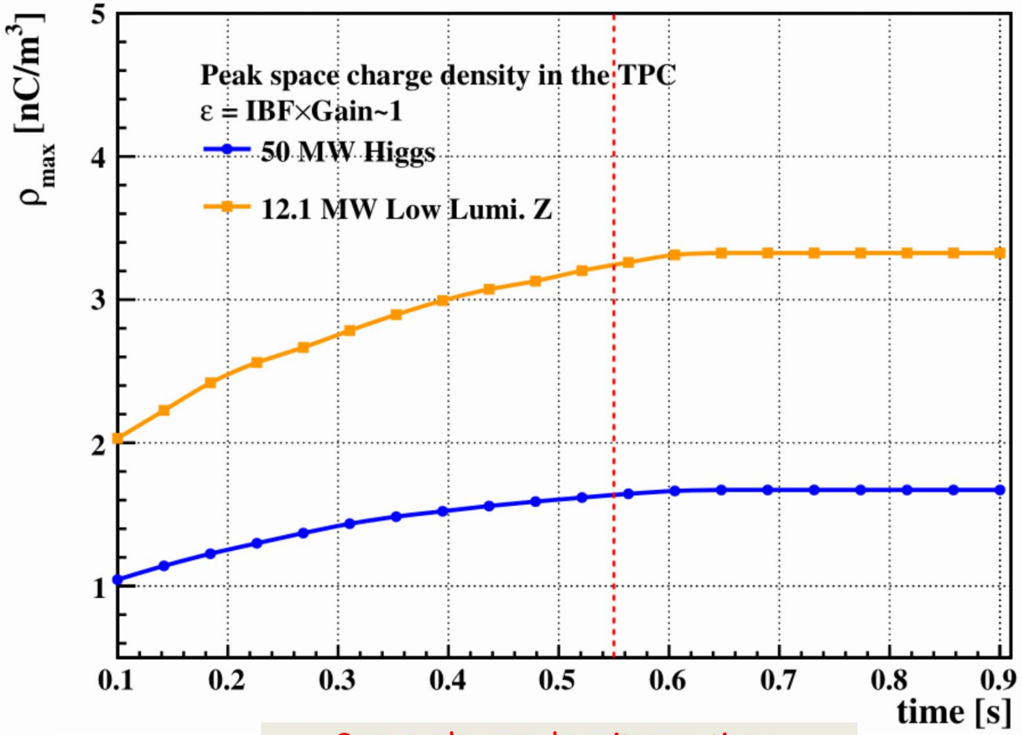
Space charge density @ Higgs and Low Z modes

- Time > 2.75 m / V_{ion} ~ **0.55s**, ion density in the TPC reaches equilibrium
- The max. space charge density @ steady state:
  - 1.7 nC/m³ @ 50 MW Higgs mode
  - 3.3 nC/m³ @ Low Lumi. Z mode

Experiment	Max. ρ_{sc}	IBF × Gain	Deviation level
ALICE	120 nC/m³	20	$\mathcal{O}$(cm)
ILD @ ILC	0.05 nC/m³	1	< 10 μm



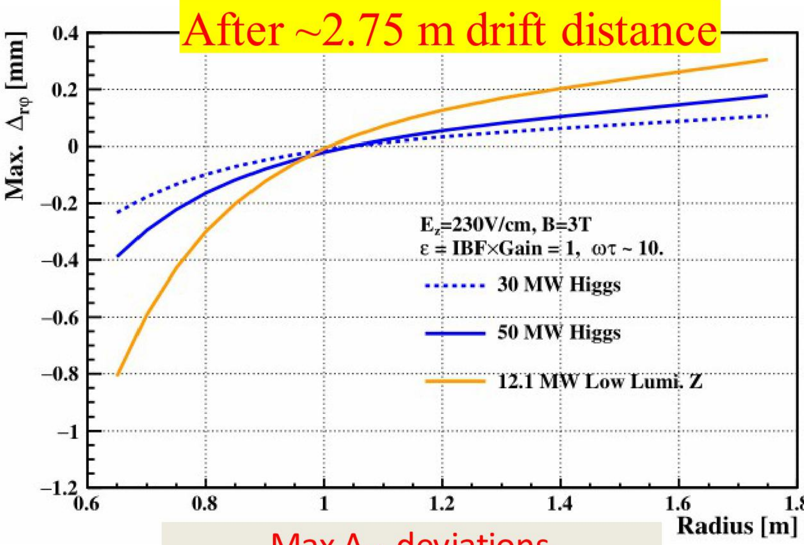
Time evolution of ion density in the TPC @ 50 MW Higgs mode



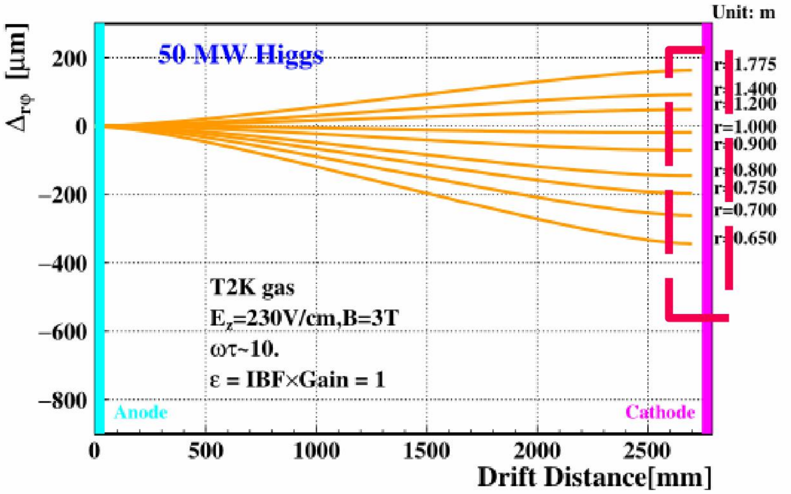
Space charge density v.s. time

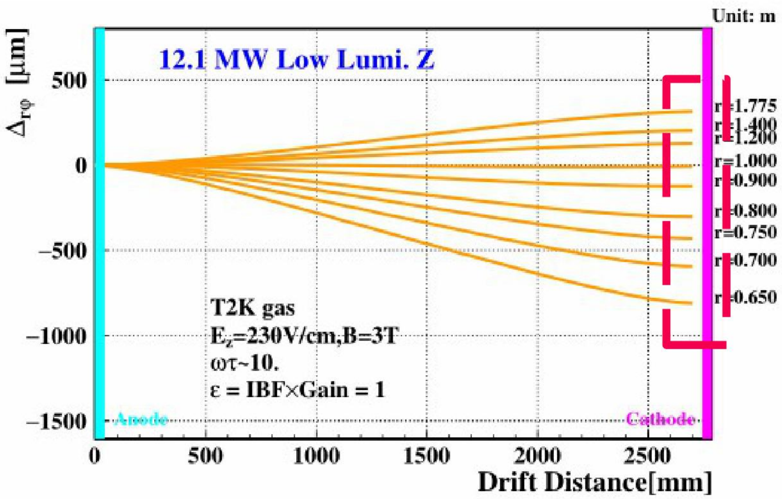
Deviations along electron drift path

- Deviations occur in radial, azimuthal and z directions along the electron drift paths:
  - Azimuthal deviations have much serious impact on momentum measurement
  - The max. $\Delta r\varphi$ reaches 800 μm in the low-Z mode (need to optimization and calibration)
  - Deviations in z direction can be negligible: the max. Δz can be less than 120 μm @ Low Lumi. Z and 50 MW Higgs

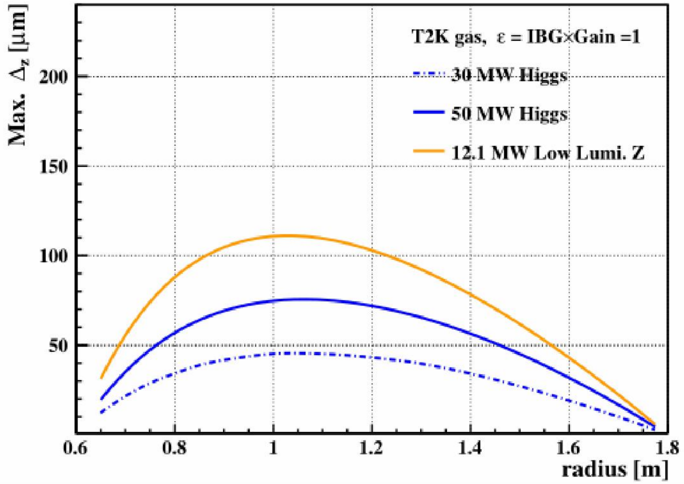


Max $\Delta_{r\phi}$ deviations





$\Delta_{r\phi}$ Deviations v.s. Drift distance in the Higgs and low-luminosity Z modes



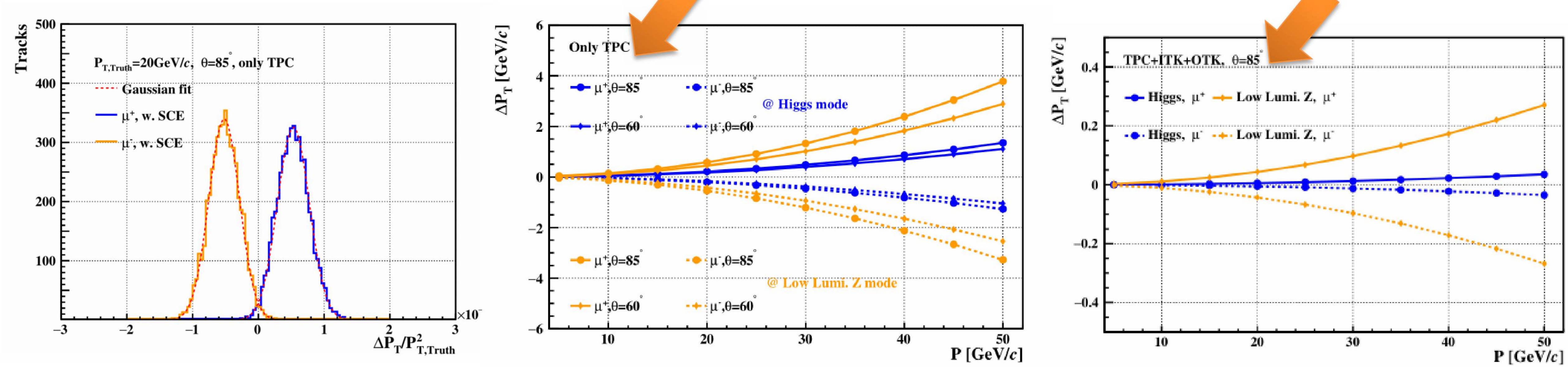
Max Δ_z deviations

TPC tracking performance estimation

- Momentum resolution with Space Charge Effect (**SCE**)
- MDI region optimization
- Momentum resolution after MDI optimization

Influence on momentum measurement 1

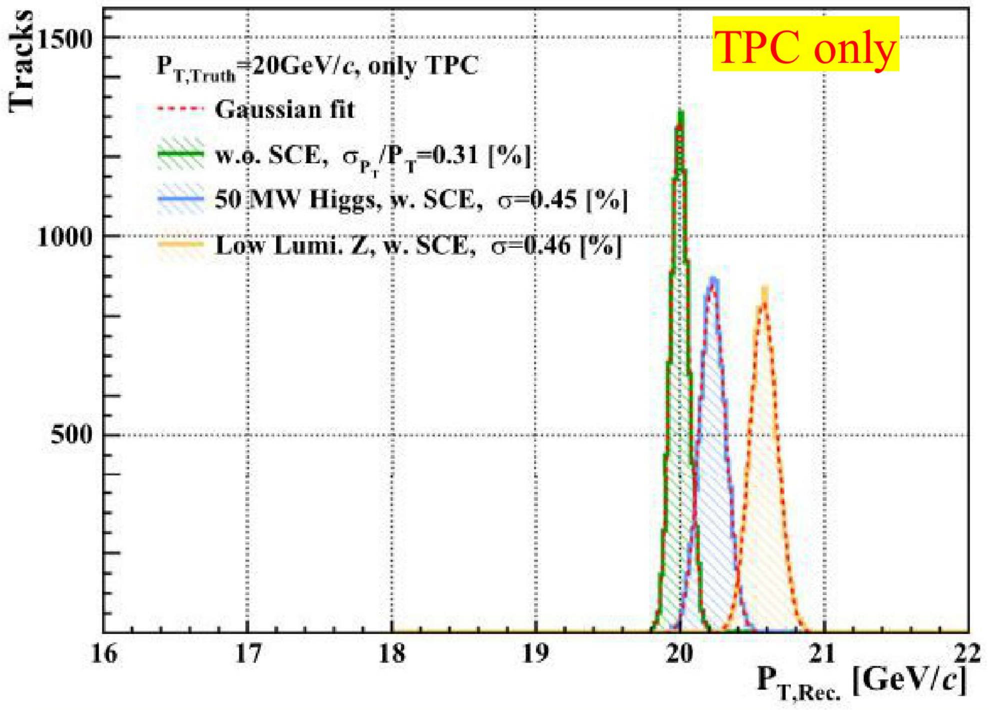
- Systematic impacts caused by the space charge effect:
  - The drift deviations are serious at the inner radius and much small around the centre of the TPC
  - Resulting in either straightening or bending of the measured tracks (the momenta of μ^+ are expected to be shifted towards higher values and μ^- towards lower values)
    - ΔP_T shows a quadratic parabola-like increasing trend with momentum (particle charge, θ and momentum dependence)
  - **Combined ITK/OTK tracking effectively suppresses transverse momentum bias**



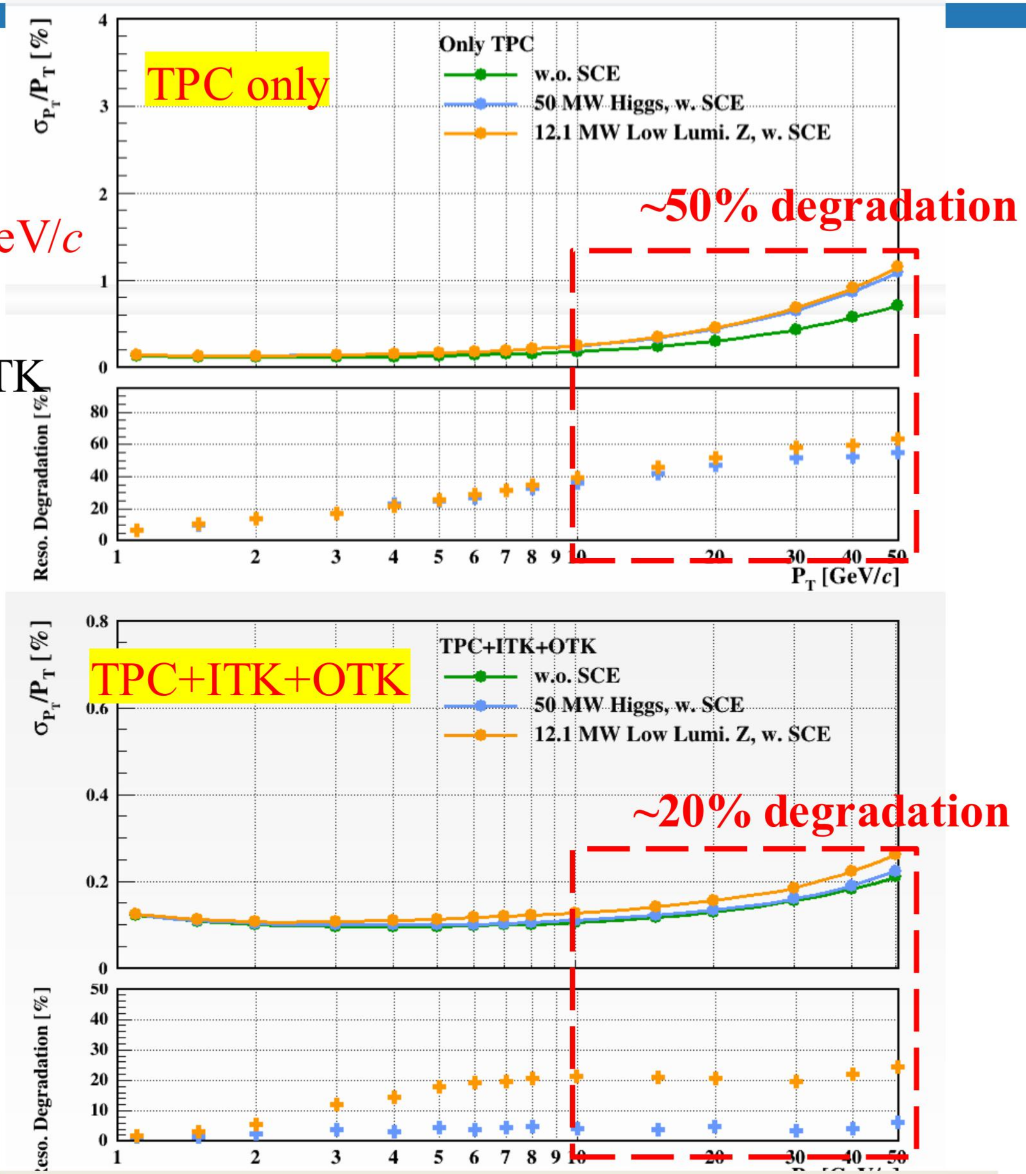
Impact on momentum measurement of the space charge effect

Influence on momentum measurement 2

- Momentum degradation caused by the space charge effect:
  - Leads not only to a bias in P_T, but also to degraded resolution
  - Mainly affects the reconstruction of high-P_T particles above 10 GeV/c
  - ~50 % degradation @ 50 GeV/c (TPC only)
  - Less than 20 % degradation @ 50 GeV/c after combining ITK+OTK



P_T distributions of μ+ particles, reconstructed by the TPC



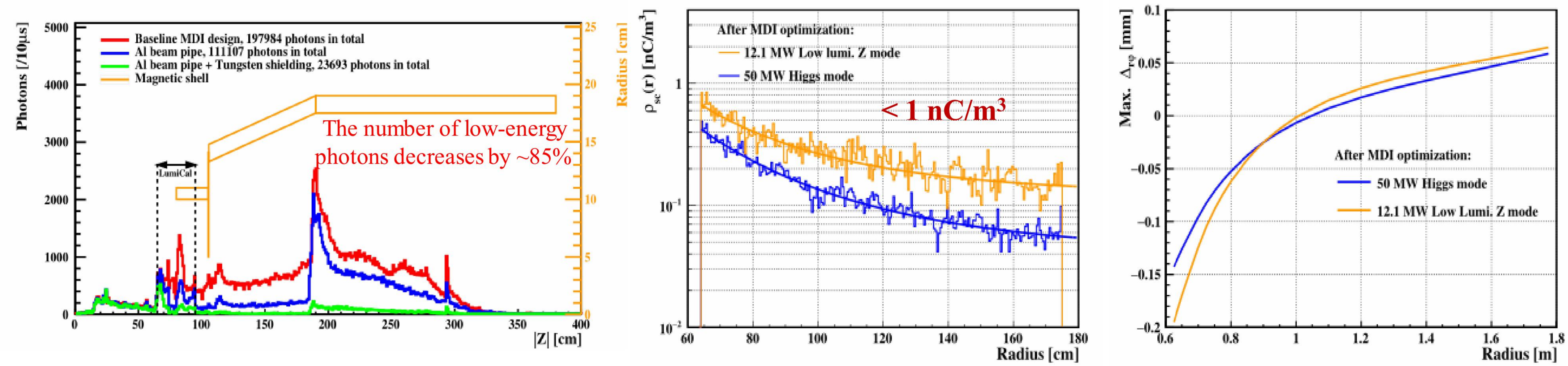
Curves of P_T resolution versus P_T, with space charge effect

Space charge migration— After MDI region optimization

- The low-energy photons (<10 MeV) are the main contribution of space charge in the TPC
- Some optimization can reduce the space charge by approximately one orders of magnitude.
  - Lighter beam pipe material (Copper → Aluminum)
  - Shielding of the magnetic shell (1 mm stainless steel → 15mm Tungsten)
  - Electron drift deviation in $r\varphi$ < 150 μm
- The max. space charge density can be less than 0.8 nC/m^3 at Low Lumi. Z mode after optimization.

Xin She, Huirong Qi etc.
10.1140/epjs/s11734-026-02404-w
European Physics Journey

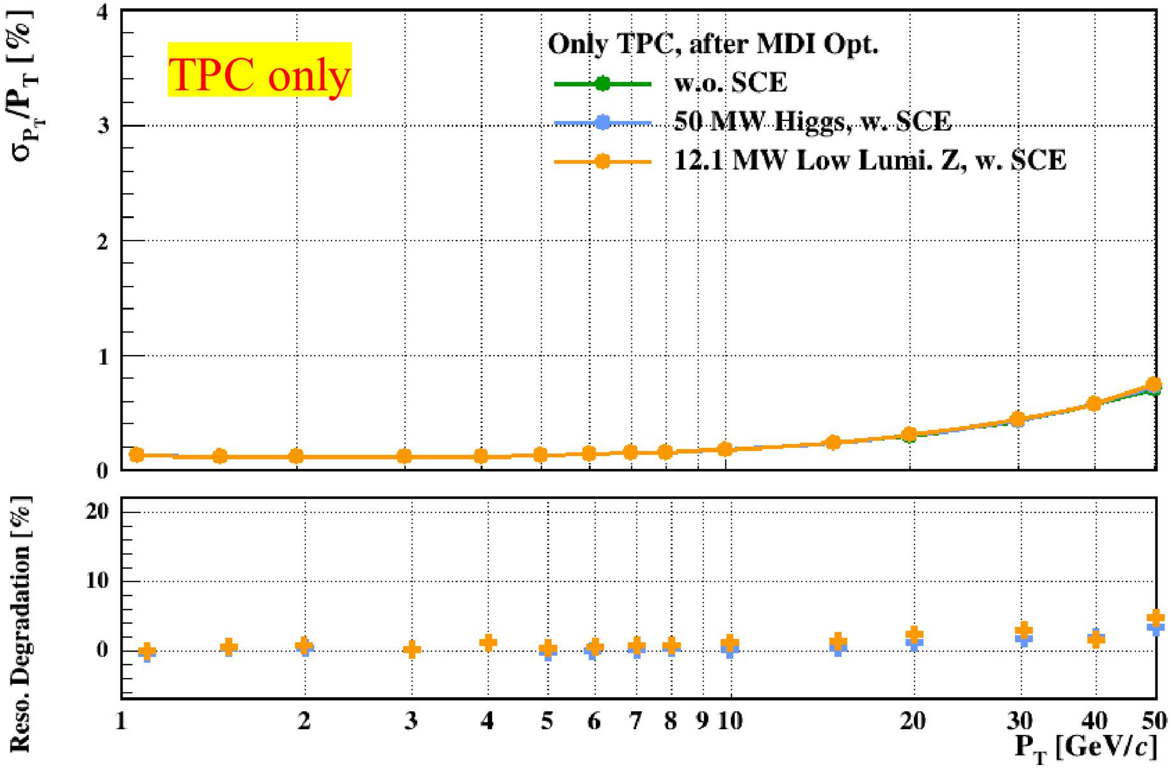
Al beam pipe + W shielding

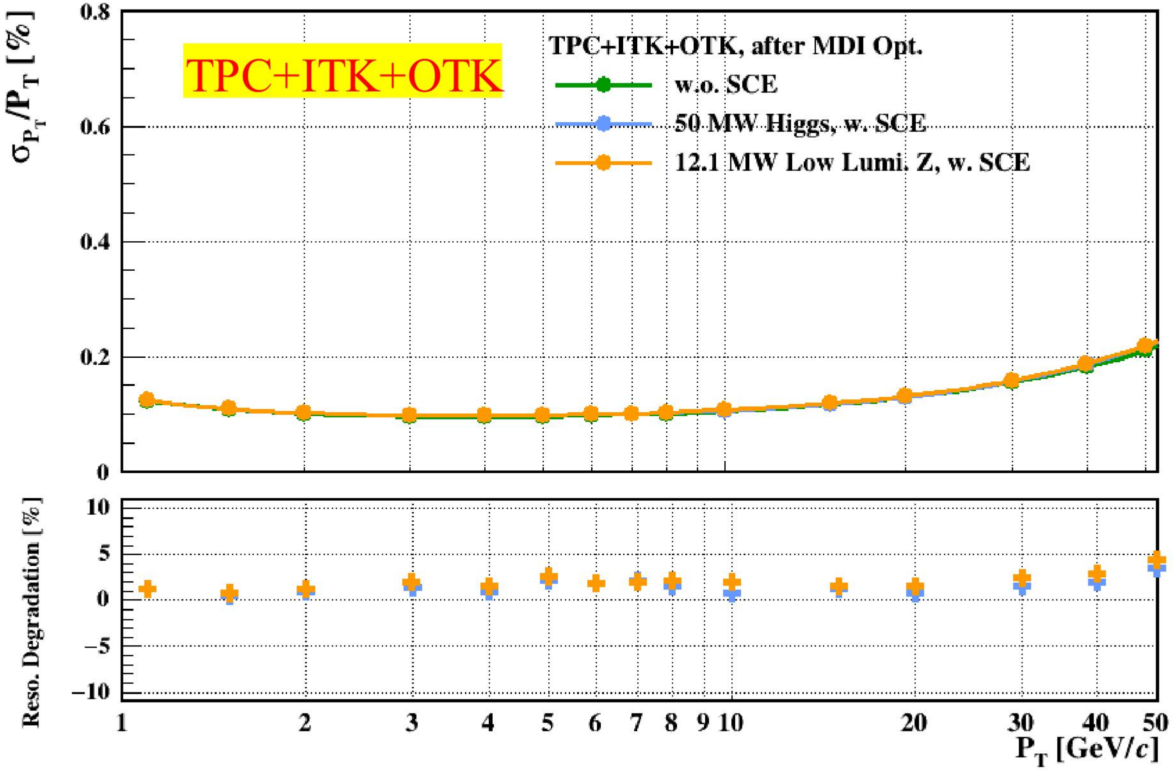


Distributions of the initial |z| positions entering the TPC and space charge density after optimization, DOI:10.1140/epjs/s11734-026-02404-w

Tracking performance after MDI Opt.

- The momentum resolution of TPC itself, as well as when combined with ITK and OTK, is significantly improved
  - The P_T resolution degradation is better than 5% after the optimatzation
  - Basically meets the tracking requirements of CEPC if the space charge can be suppressed below 1 nC/m^3





Curves of P_T resolution versus P_T, with space charge effect after MDI optimization

Synchrotron Radiation Background Challenges at Z pole Operation

- Toward Higher-Luminosity Z pole Operation
  - Beamstrahlung-induced space charge effect becomes dominant
    - Space charge density: ~10 nC/m³
    - Max. electron drift deviation: ~2–3 mm
  - SR background results: Silicon, drift chamber, and TPC concepts all face extreme challenges
  - **Ongoing study** — implications for all high-luminosity colliders (CEPC and FCCee)

Collaboration with the FCC-ee group in the next half of 2026
DESY group: Coordination with Jenny List; Xin She — postdoc offer accepted
KEK group: Engagement with Daniel Jeans on background studies

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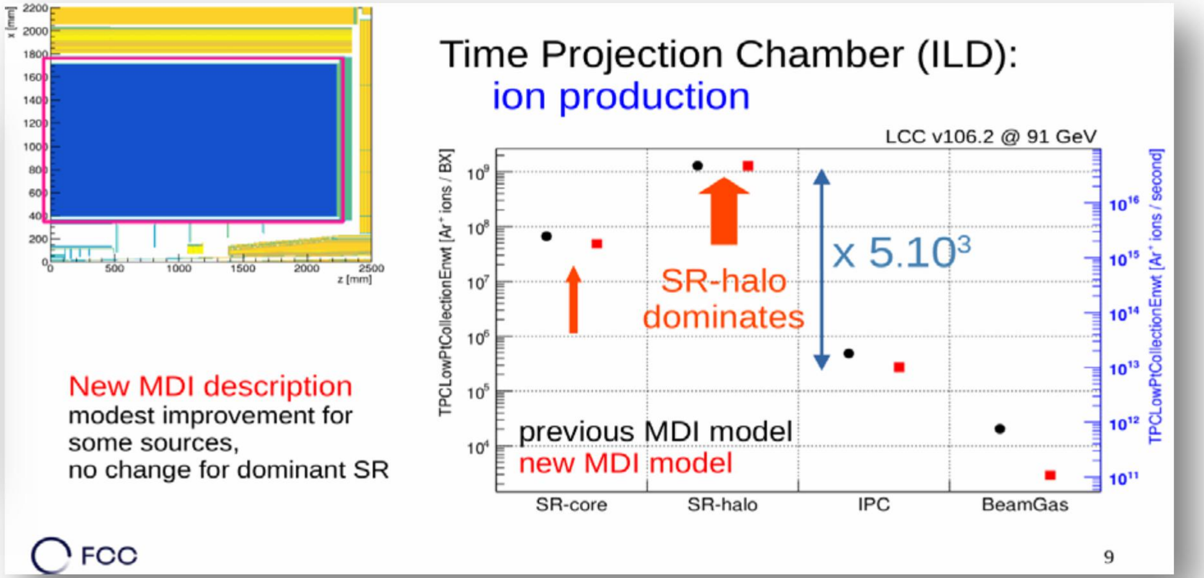


Summary

Summary

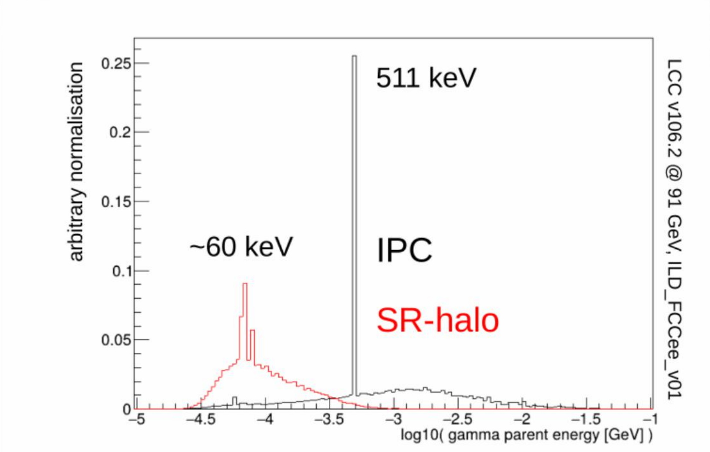
- Daniel Jeans presented a new background estimate that caught everyone's attention. Every detector technology at CEPC/FCCee faces this background.

- The full simulation flow of the BG has been established

  - Space charge effect predominantly impacts the reconstruction of high-P_T (>10 GeV/c) particles

  - Tracking performance would not suffer too much from the deviations by combining inner and outer silicon detectors

- Ongoing: full SR background simulation and MDI collaborative design
- TPC is feasible at Z operation — with systematic MDI optimization and silicon tracker combination



energy of photons which induce TPC hits

Beyond responding to Daniel:
A serious assessment of the challenge

Many thanks!