TPC feasibility at high-Lumi Z
Inner radius, ITK/OTK & MDI optimization

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Some good inputs from LCTPC and DRD1 International Group

Institute of High Energy Physics, CAS

ILD TPC meeting , September 07, 2026

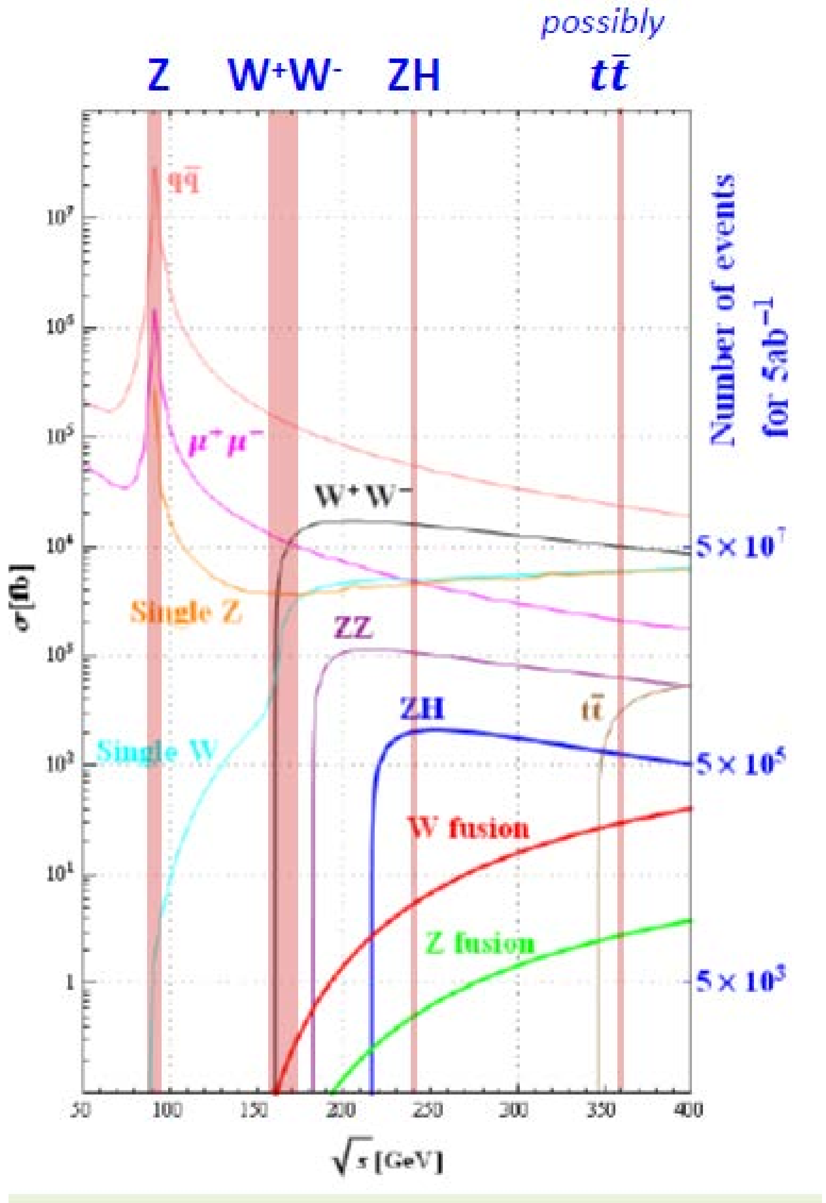
Content

- Motivation and physics requirements
- TPC concept and geometry
- MDI optimization: Beam-induced background
- Tracking performance with ITK/OTK
- Summary

How does the TPC operate at future e^+e^- collider?

- Future e^+e^- collider (FCC-ee or CEPC) both elevate a High-Lumi Z pole run phase to a key operating stage alongside the Higgs program, making **flavor physics** an important physics goal.
- In the operation plan, the first 10-year operation includes: **Low/High-Lumi Z mode**(B = 3.0T) , Higgs mode, and WW mode.
- The accelerator may be upgraded for High-Lumi Z mode and/or tt mode after 10 years operation, subject to physics needs.

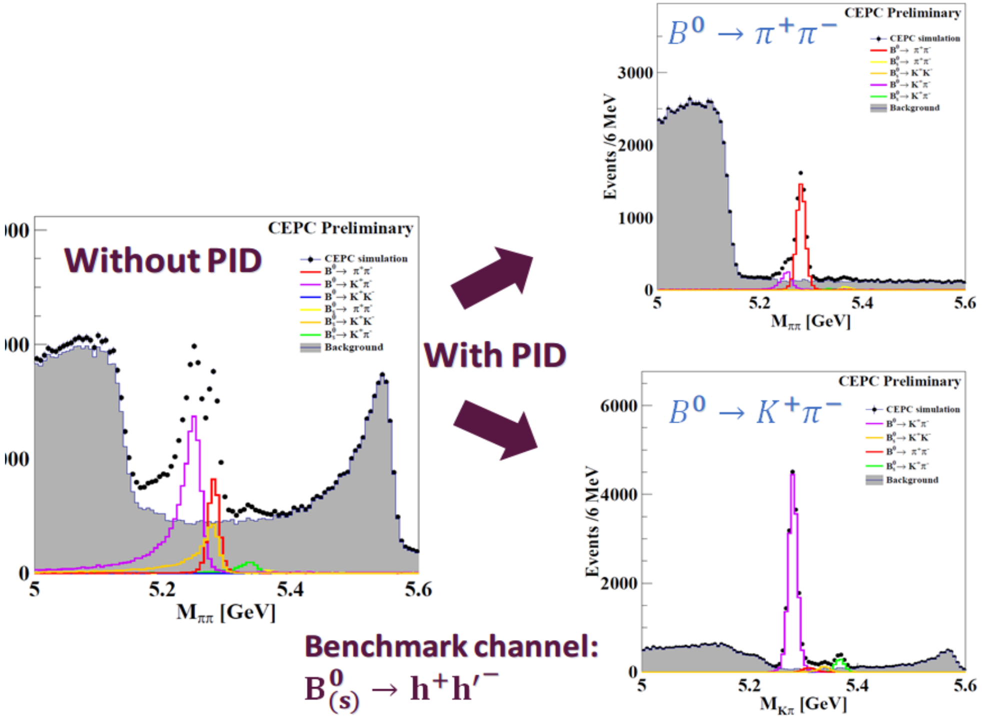
SR Power Per Beam	Luminosity/IP [$\times 10^{34} cm^{-2} s^{-1}$]		
	H	Z	W^+W^-
12.1 MW	-	26	-
30 MW	5.0	-	16
50 MW	8.3	-	26.7

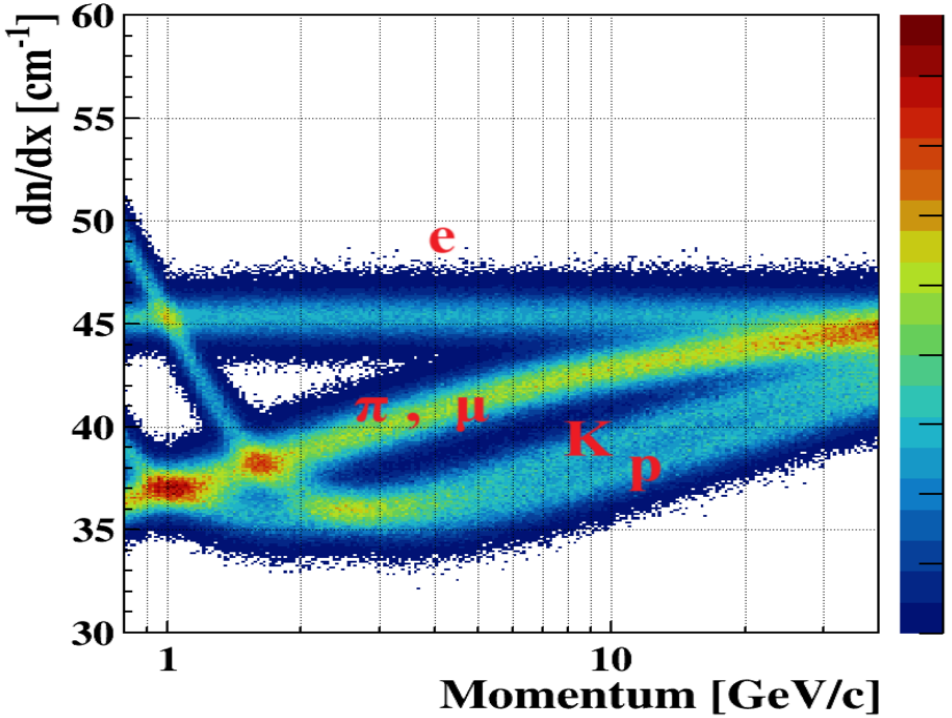


TPC for precision Flavor physics and Particle Identification

- Circular e^+e^- collider operation stages in TDR: **Higgs @3T → 2-years Z pole → 1-year W**
- Gaseous tracker leading contribution to PID and the high resolution: jet & differential
  - High granularity readout readout and better than **3σ** separation power between **π** and **k** for **p** using dn/dx

Calibration: Low luminosity Z at 3T
Approximately 10^{35}cm^{-2}s^{-1}
20% of high luminosity Z





TPC Technical Challenges

- **TPC detection for future** e^+e^- **collider**
  - **Material budget at endcape/barrel**
  - **Occupancy and hit density at Tera-Z**
  - **Ion backflow suppression**
  - **Running at 3 Tesla**
  - **Improved PID**
  - **Reasonable readout channels**
  - **Reasonable power consumption**

TPC Technology for the High Luminosity HEP Factory

- 20 years of LCTPC collaboration R&D (since 2007), large Prototype TPC and extensive DESY beam-test campaigns.
  - MPGD **readout technologies**: GEM / Micromegas / GridPix
  - Demonstrated required **spatial resolution and tracking performance**
  - **dE/dx performance** demonstrated at the few-percent level
  - **Ion-backflow** suppression, gating, gas properties
- The feasibility of an MPGD-based TPC for a Higgs factory has been demonstrated.
- TPC R&D community initiated the technical comparison and selection, balancing factors including R&D efforts, detector performance, cost, power consumption and construction risks.

We keep pushing the technology forward.

TPC technology detector for Future e+e- colliders

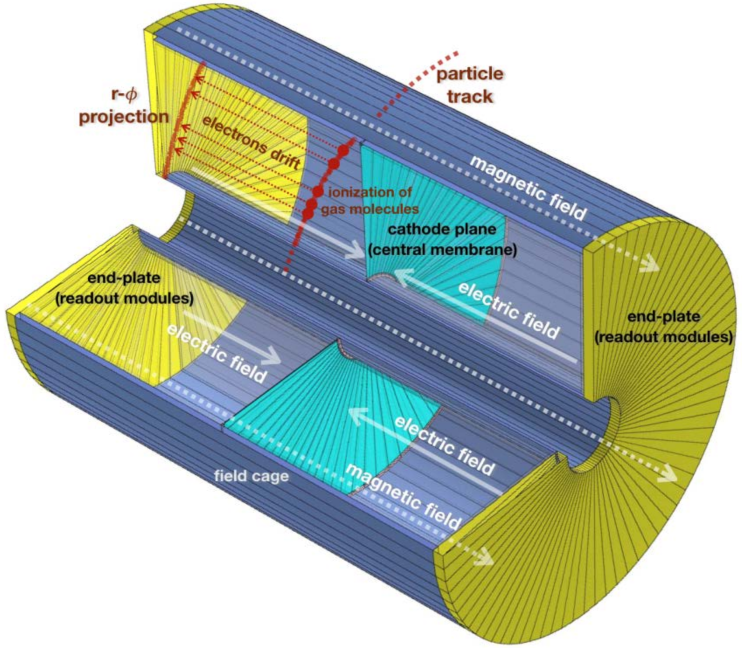
Pad readout TPC
- To meet Higgs physics
- 1mm×6mm of Pad
- < 100mW/cm²
- dE/dx
- Triple, double GEMs
- Micromegas

Pixelated readout TPC
- To meet Low-lumi Z physics
- TPX3 and TPX4
- ~1W/cm²
- dN/dx+dE/dx
- GirdPix
- Interposer
- Direct mode

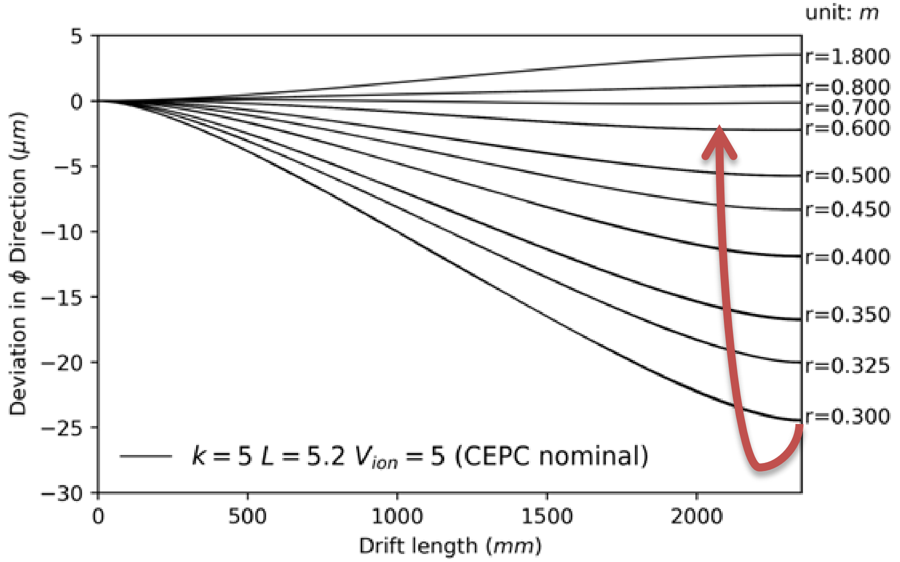
- **TPC concept and geometry**

Inner radius of TPC concept

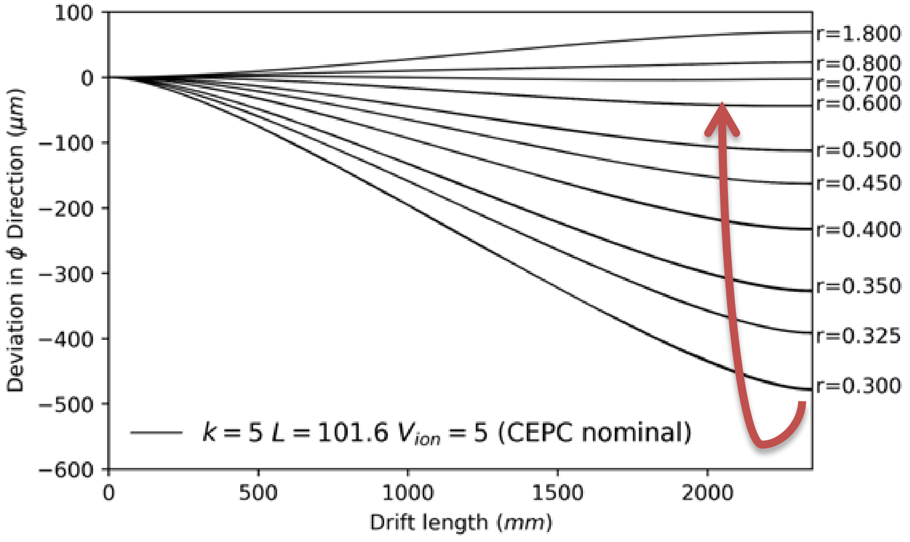
- CEPC CDR studies show that distortion near the TPC inner radius meets the significant at high luminosity and background level, basing on the ILD concept design parameters.
  - Increasing the TPC inner radius from **0.3 m to 0.6 m improves distortion by nearly an order of magnitude**
  - A larger inner radius is favored within physics requirements
  - Option design: add an inner silicon tracker



https://arxiv.org/abs/1811.10545



Higgs

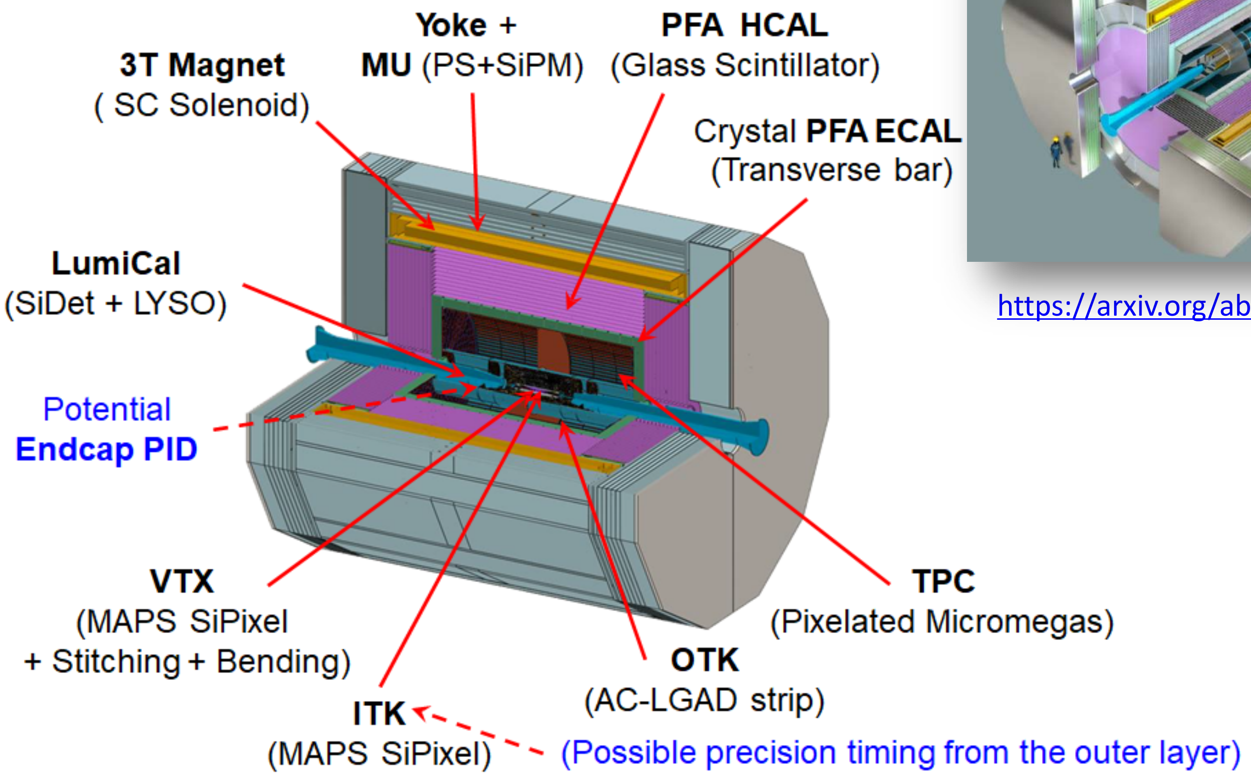


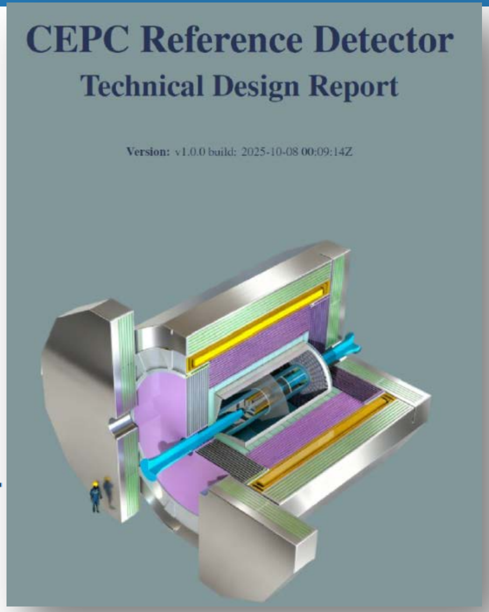
Z

Baseline Detector Design in CEPC TDR

- Will explore the possibilities of
  - A forward PID detector inside TPC
  - The outer layer ITK also provides precision timing

- After 10-year operation, the majority will remain, a few may be upgraded, including
  - VTX: for a better performance and radiation tolerance
  - TPC: to deal with higher luminosity



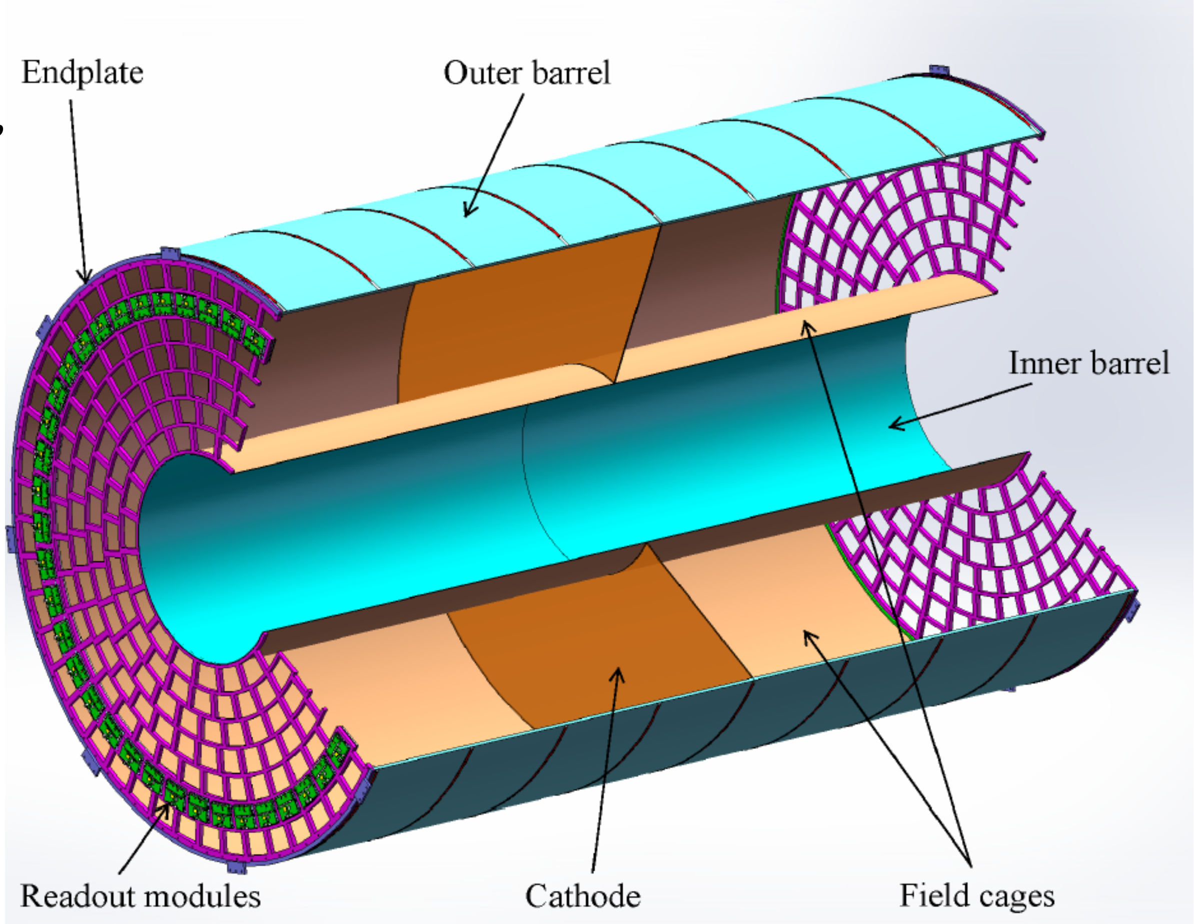


https://arxiv.org/abs/2510.05260

TPC detector design with some optimization

- Requirements
  - Momentum resolution (combined with **ITK and OTK**)
    $2 \times 10^{-5}\,(\mathrm{GeV}/c)^{-1}$
  - PID (combined with OTK): 3σ separation between π, K , p with momenta up to 20 GeV/c
- Overall design
  - Total length：5.8 m
  - r extension: **0.6 - 1.8 m**

TPC detector	Key Parameters
Modules per endcap	248 modules /endcap
Combined Si detector	OTK and ITK silicon trackers
Geometry of layout	Inner: 1.2m Outer: 3.6m Length: 5.9m
Potential at cathode	- 62,000 V
Gas mixture	T2K: Ar/CF4/iC4H10=95/3/2
Maximum drift time	34μs @ 2.75m
Detector modules	High granularity readout Micromegas



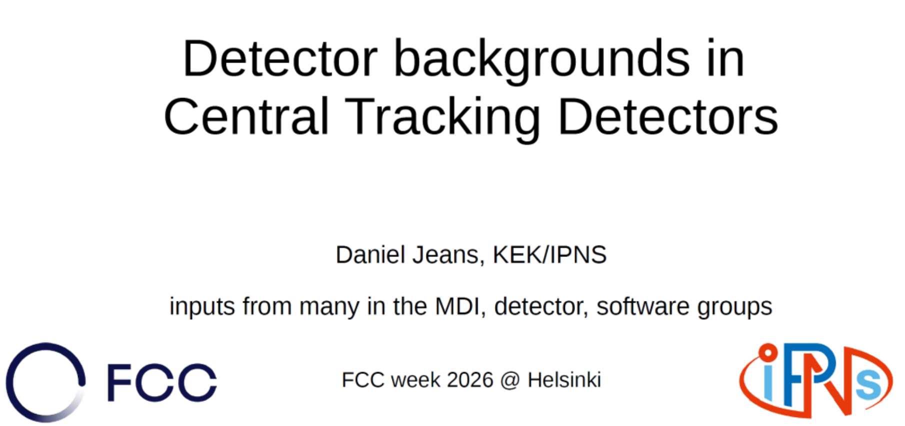
Detailed design of TPC detector

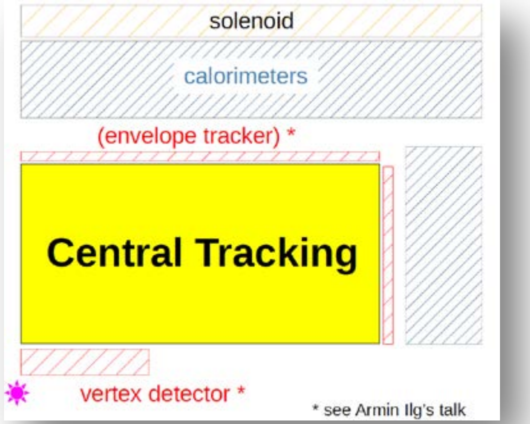
- **MDI optimization: Beam-induced background**

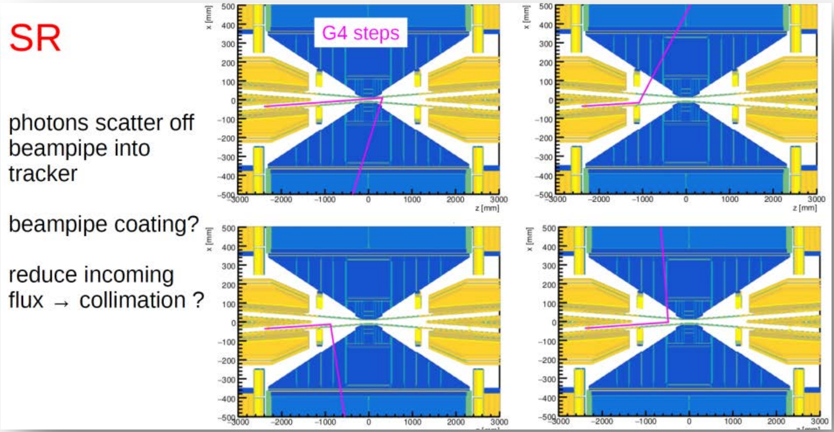
  (Dr. Xin She)

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

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

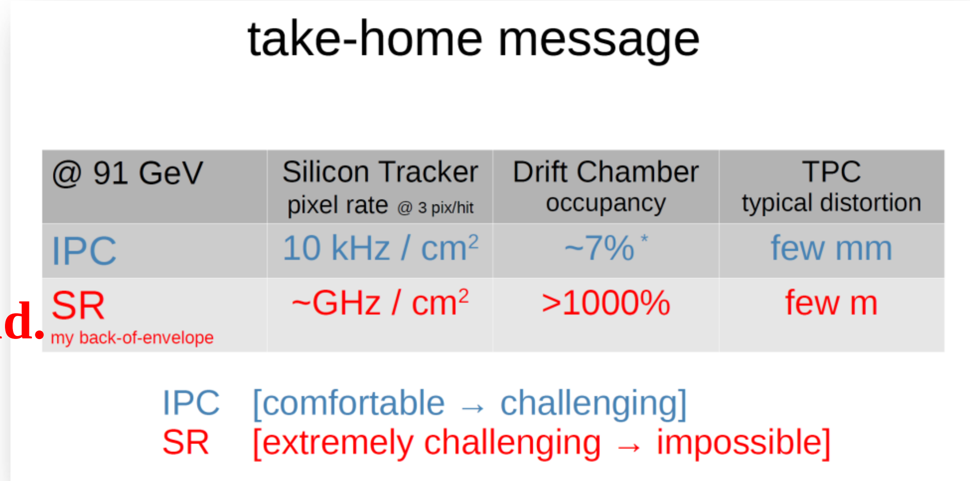






- Silicon pixel hit rate: **~GHz/cm²** (vs. ~10 kHz/cm² for IPC)
- Drift chamber occupancy: **>1000%**
- TPC distortion: **few meters** (without optimization)

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



take-home message

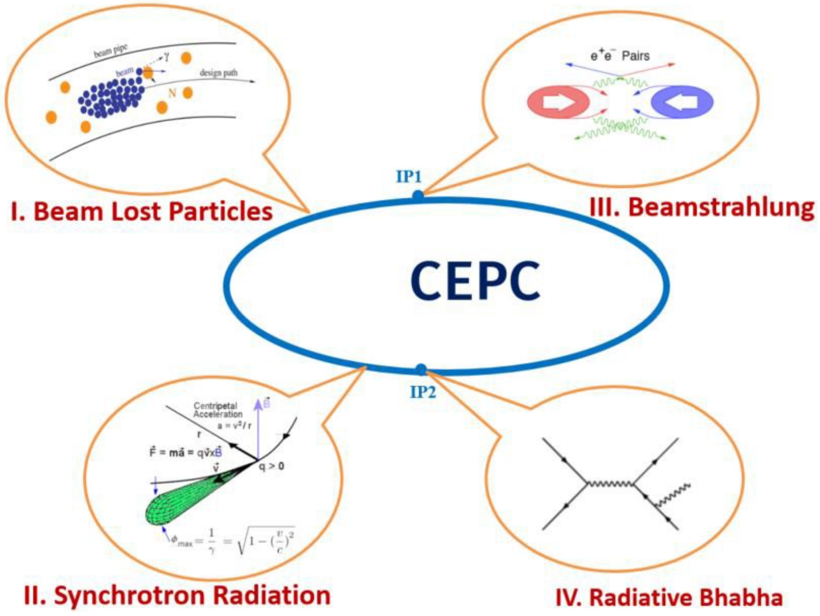
@ 91 GeV	Silicon Tracker pixel rate @ 3 pix/hit	Drift Chamber occupancy	TPC typical distortion
IPC	10 kHz / cm^2	~7% *	few mm
SR my back-of-envelope	~GHz / cm^2	>1000%	few m

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

Status of beam-induced background @ CEPC

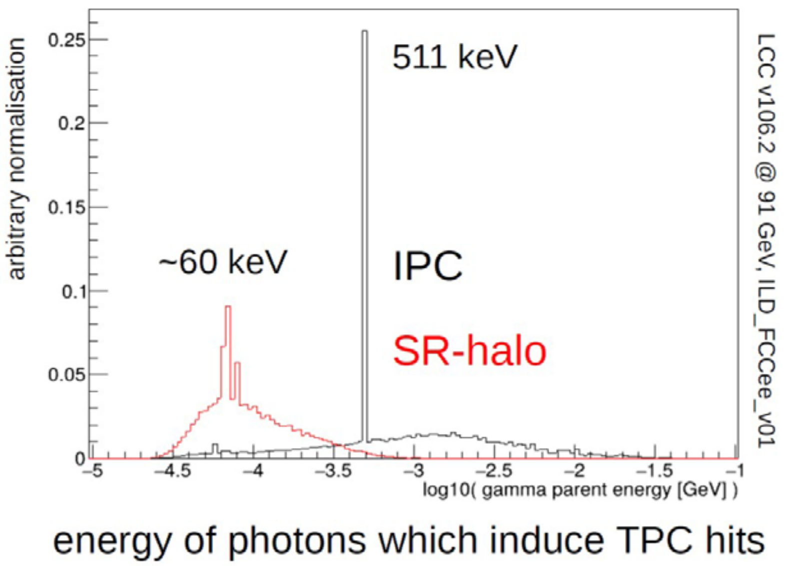
Our Strategy: From Assessment to Optimization

- 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.**

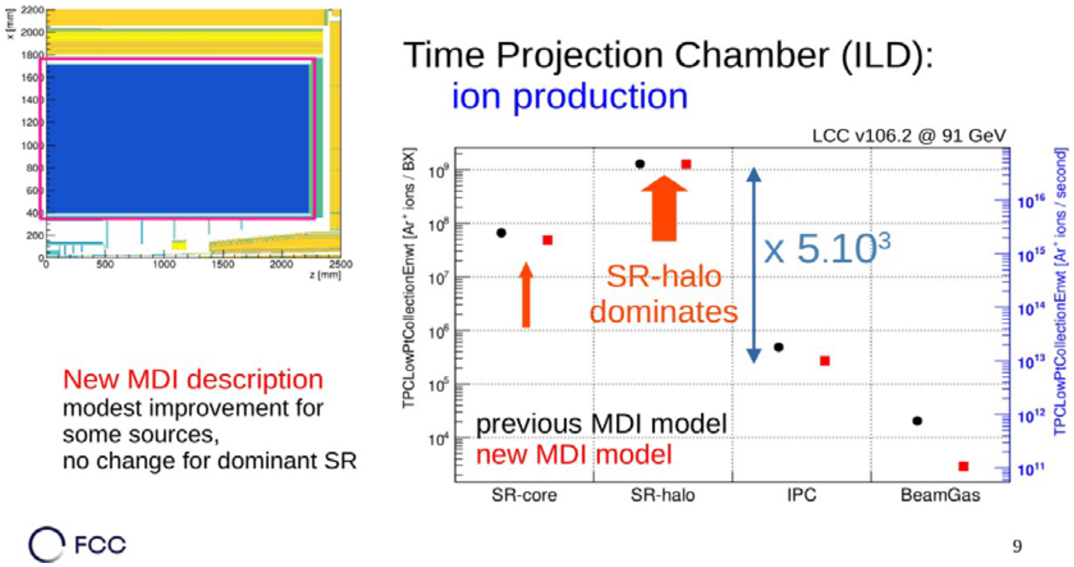


Synchrotron Radiation @ Tera-Z

- **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



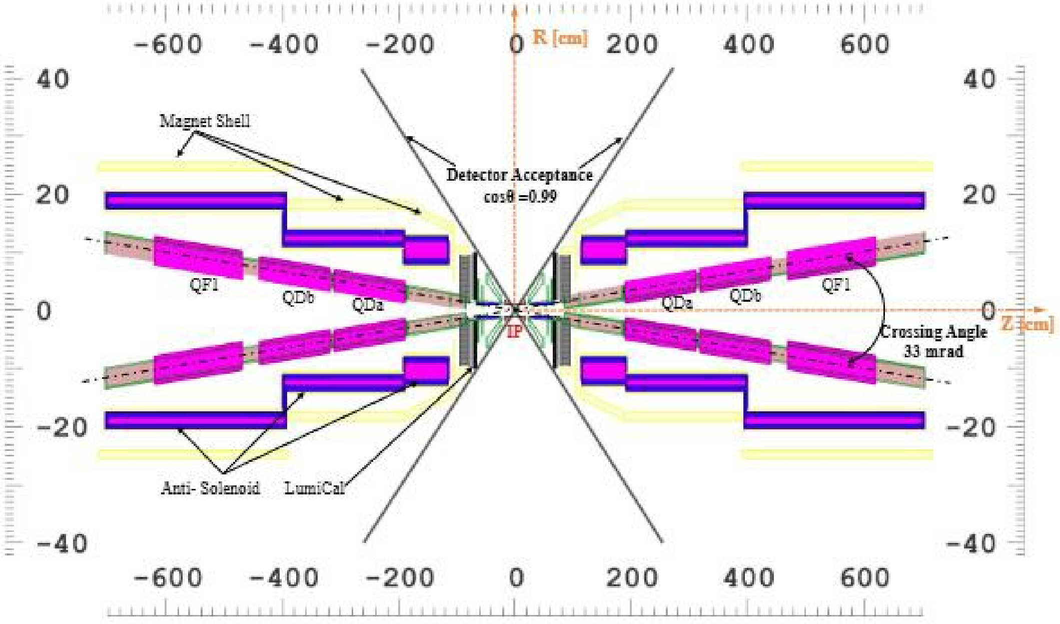
energy of photons which induce TPC hits



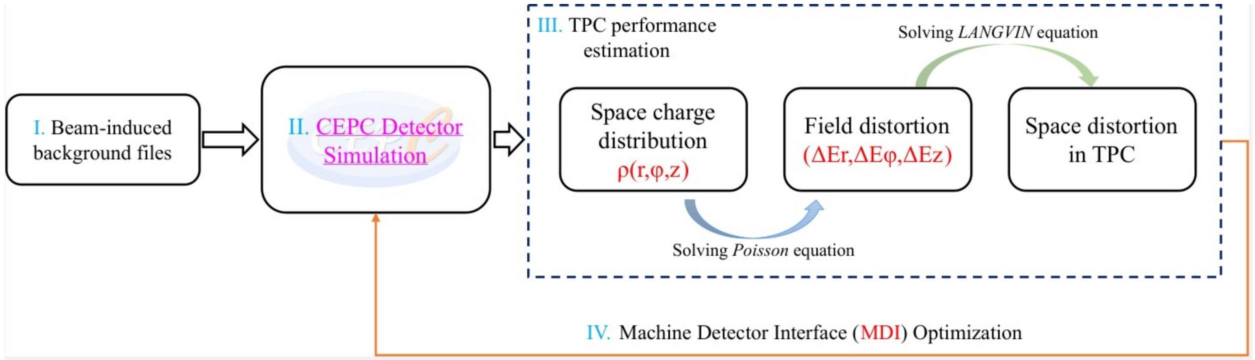
Simulation flow of beam-induced background

- 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

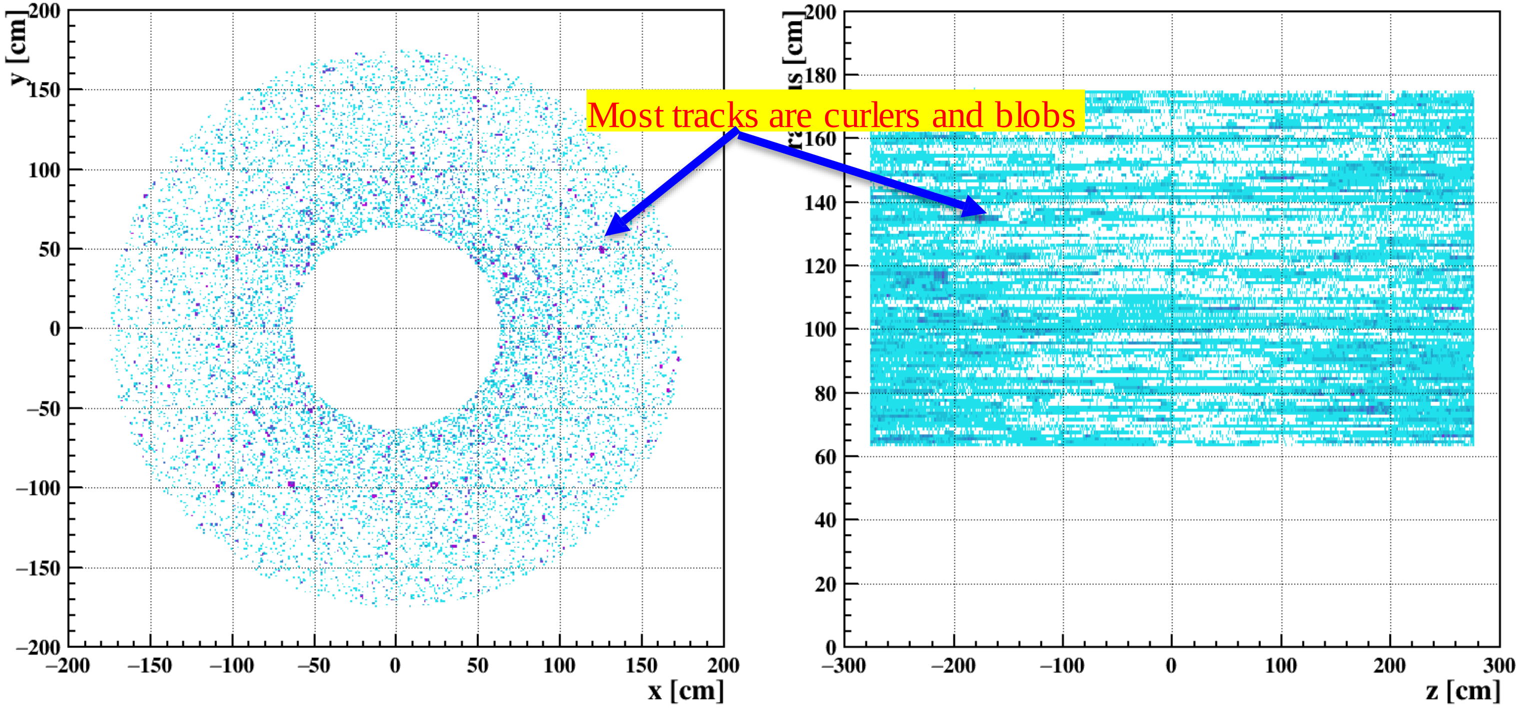


estimate number of **primary ions** produced in the TPC per bunch crossing
→ geant4 energy deposit / effective ionisation potential of Ar [26 eV]

BG events display

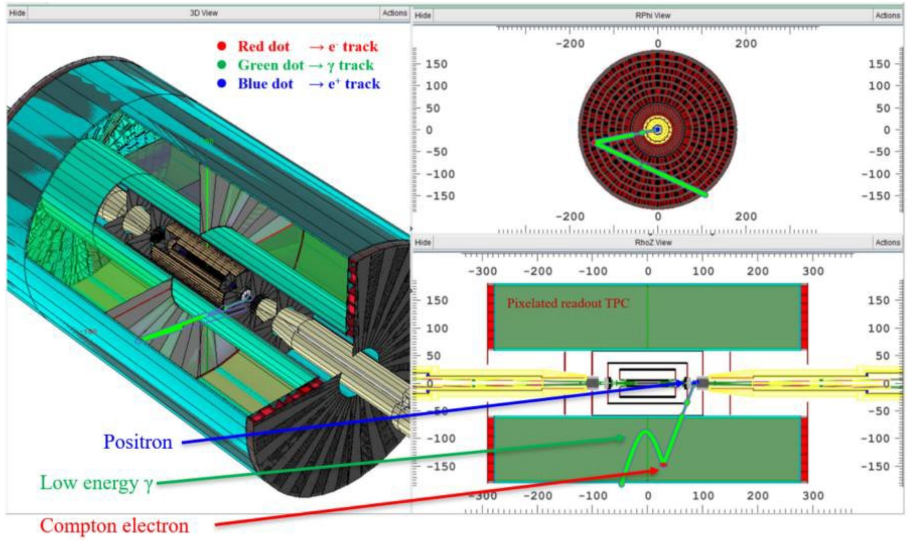
- Very few particles have enough energy to leave TPC
- Most of BG hits consist of more or less randomly distributed blobs or curlers
  - Sometimes called "salt and pepper" background
  - Caused by extremely low-energy electrons (<1 MeV)

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



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

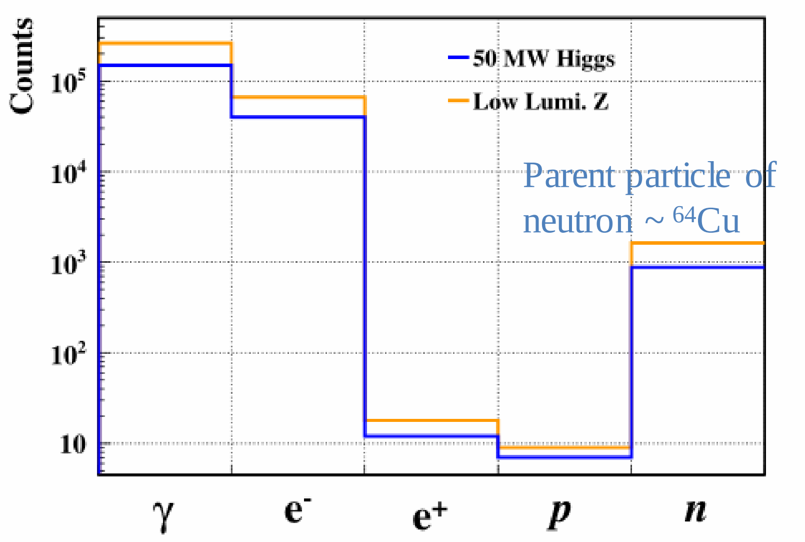
$background\ e^{+}annihilation \rightarrow \gamma(0.511MeV) \rightarrow Compton\ e^{-}$

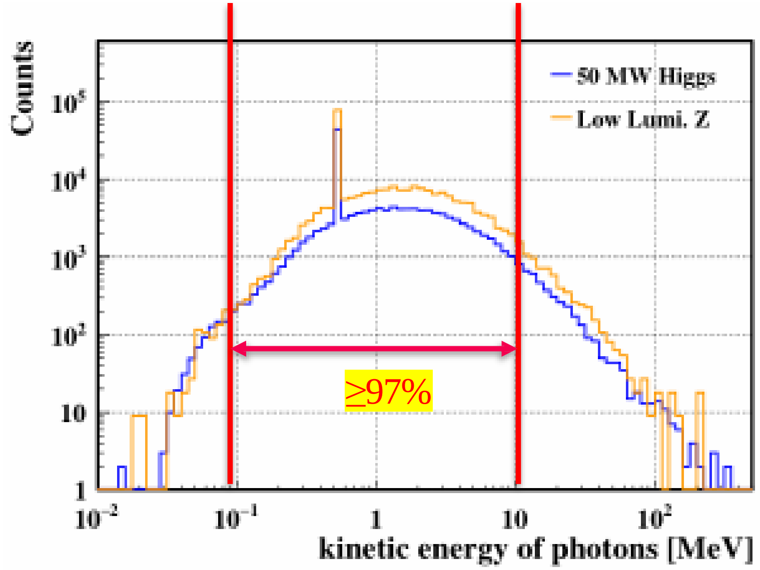


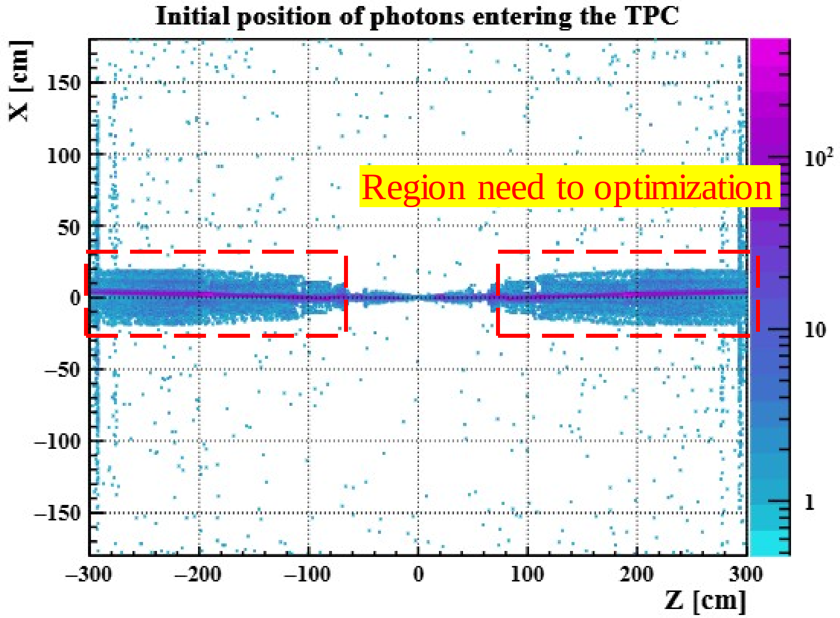
➢ Typical event display：
- e+ annihilation
- Low energy (0.511 MeV) γ incident TPC and interact with the T2K gas
- generate secondary Compton electron

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



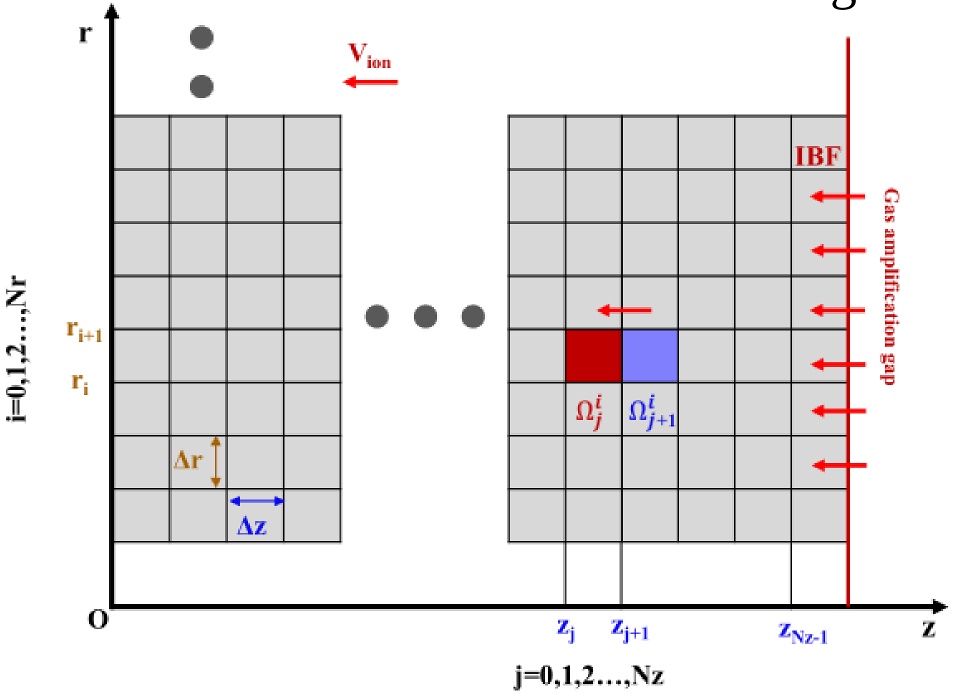




Particle type, Energy and initial position of low-energy photons entering the TPC

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

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

Axisymmetric drift-diffusion equation

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

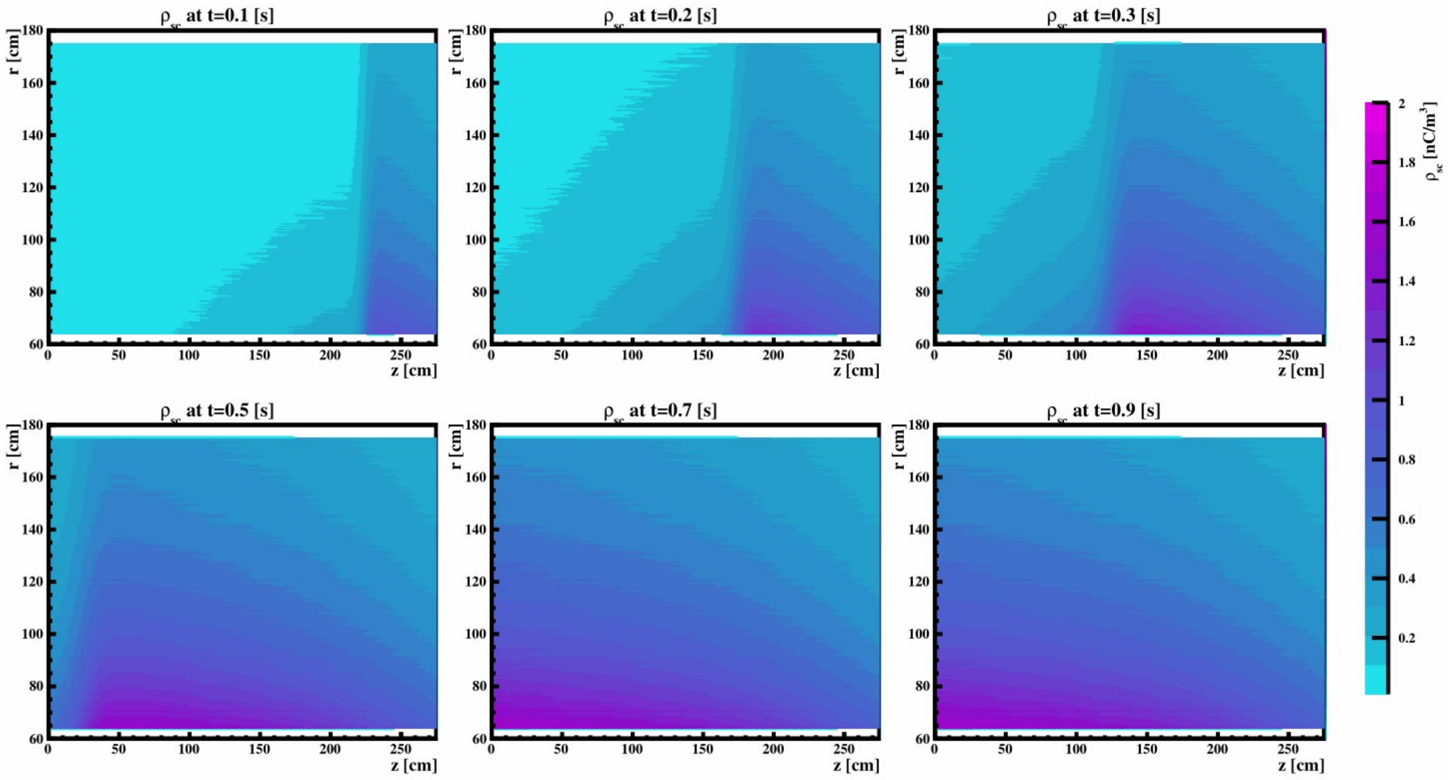
Full FTCS Update Formula

- 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

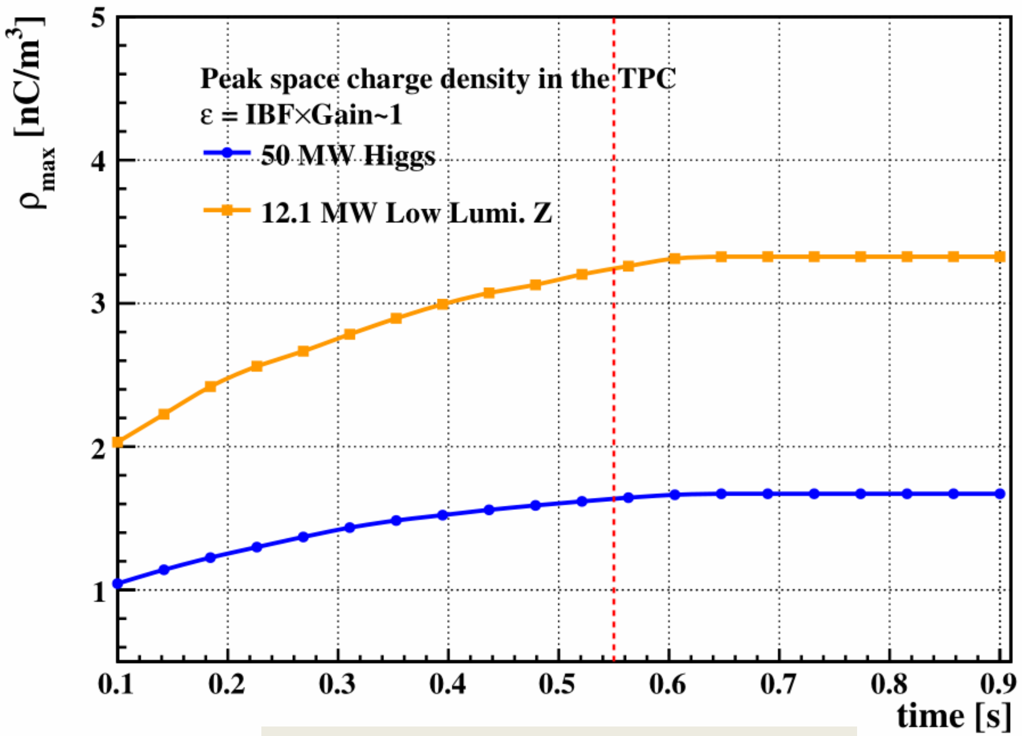
Space charge density @ Higgs and Low Z modes

- 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



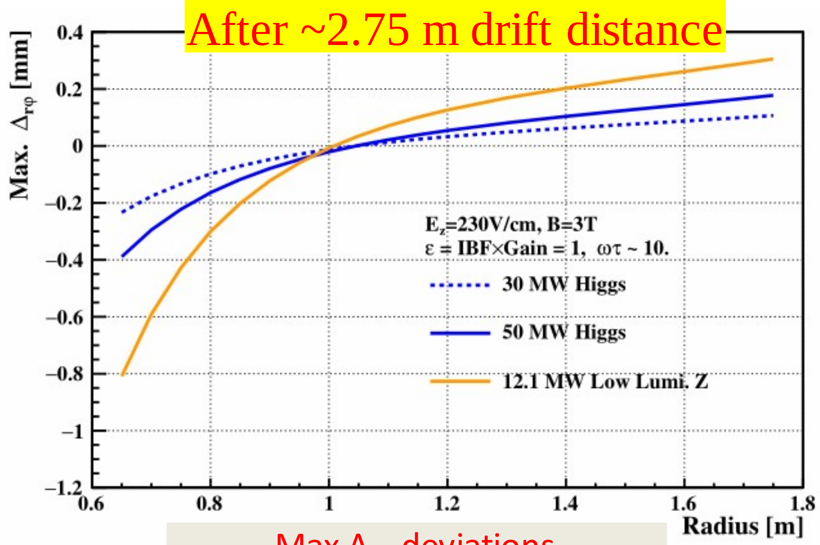
Time evolution of ion density in the TPC @ 50 MW Higgs mode



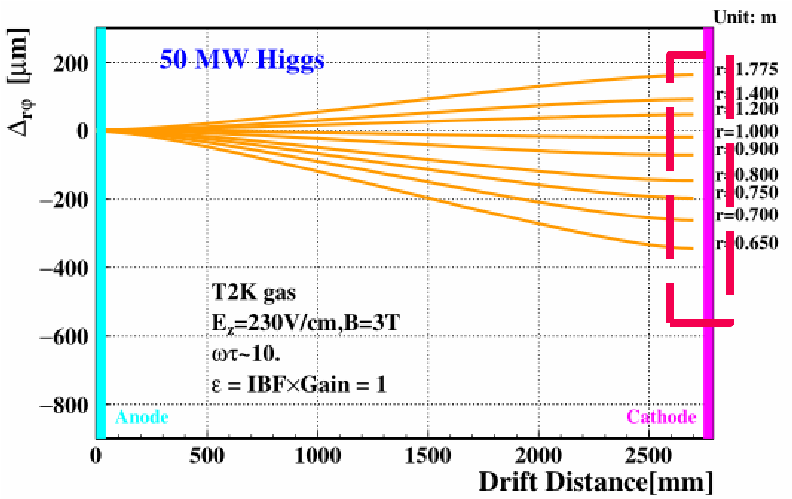
Space charge density v.s. time

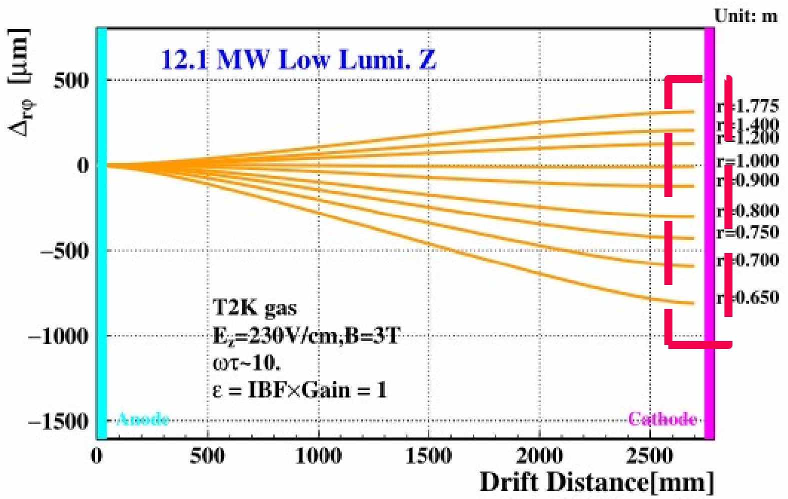
Deviations along electron drift path

- 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

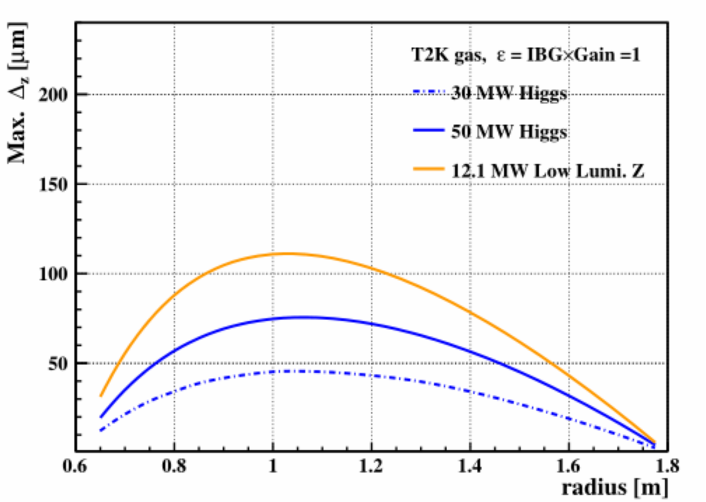


Max $\Delta_{r\phi}$ deviations





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



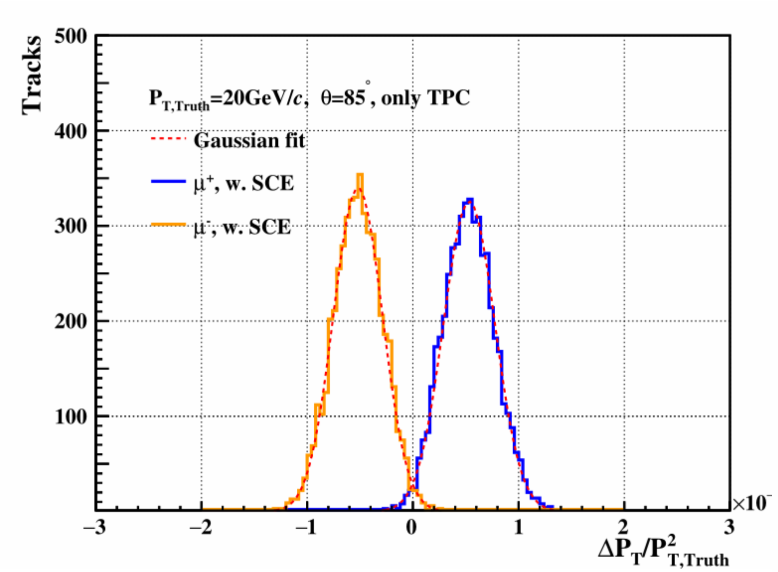
Max Δ_z deviations

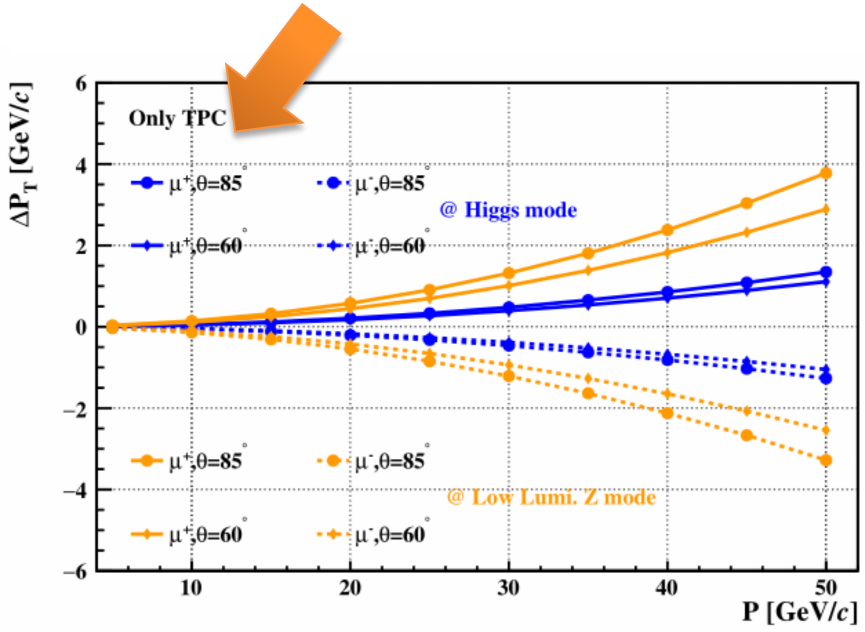
TPC tracking performance estimation

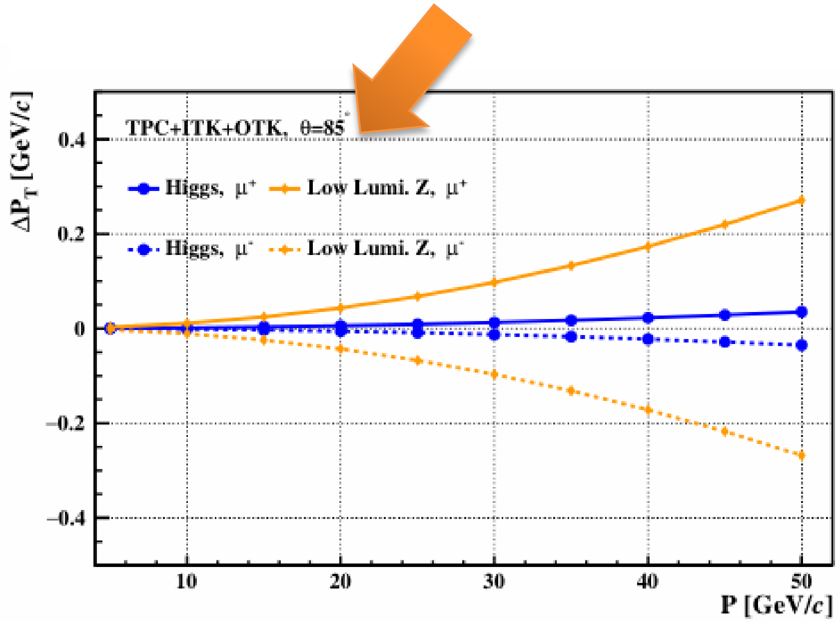
- Momentum resolution with Space Charge Effect (Dr. Xin She and Dr. Yue Chang)
- MDI region optimization (Dr. Xin She and Dr. Haoyu Shi)
- Momentum resolution after MDI optimization (Dr. Xin She, Dr Linghui Wu and Dr. Guang Zhao)

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**



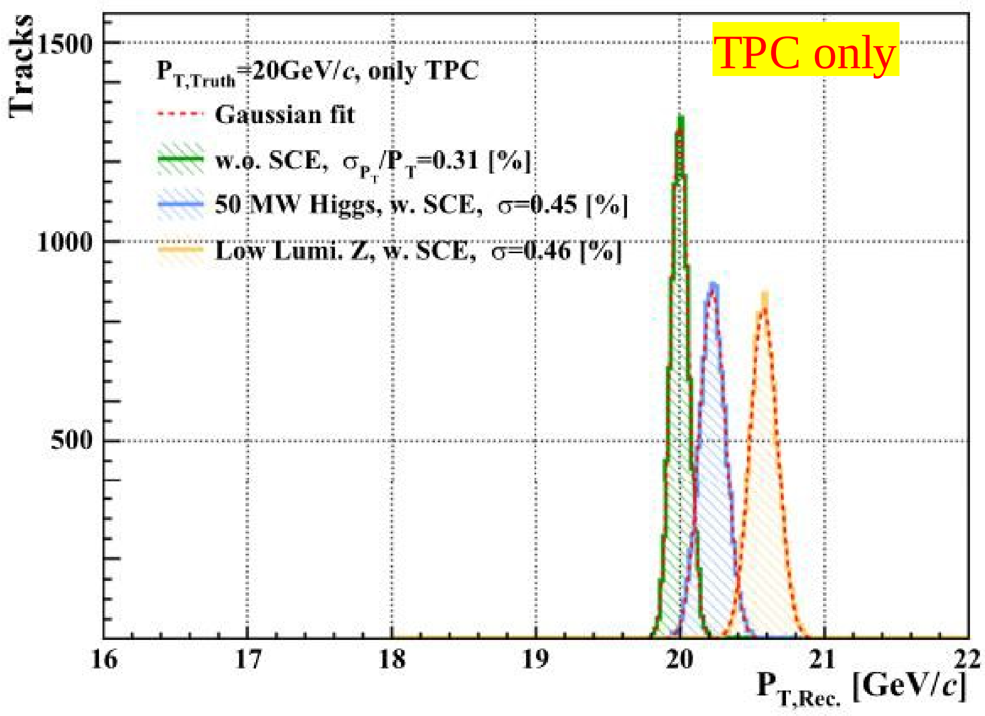




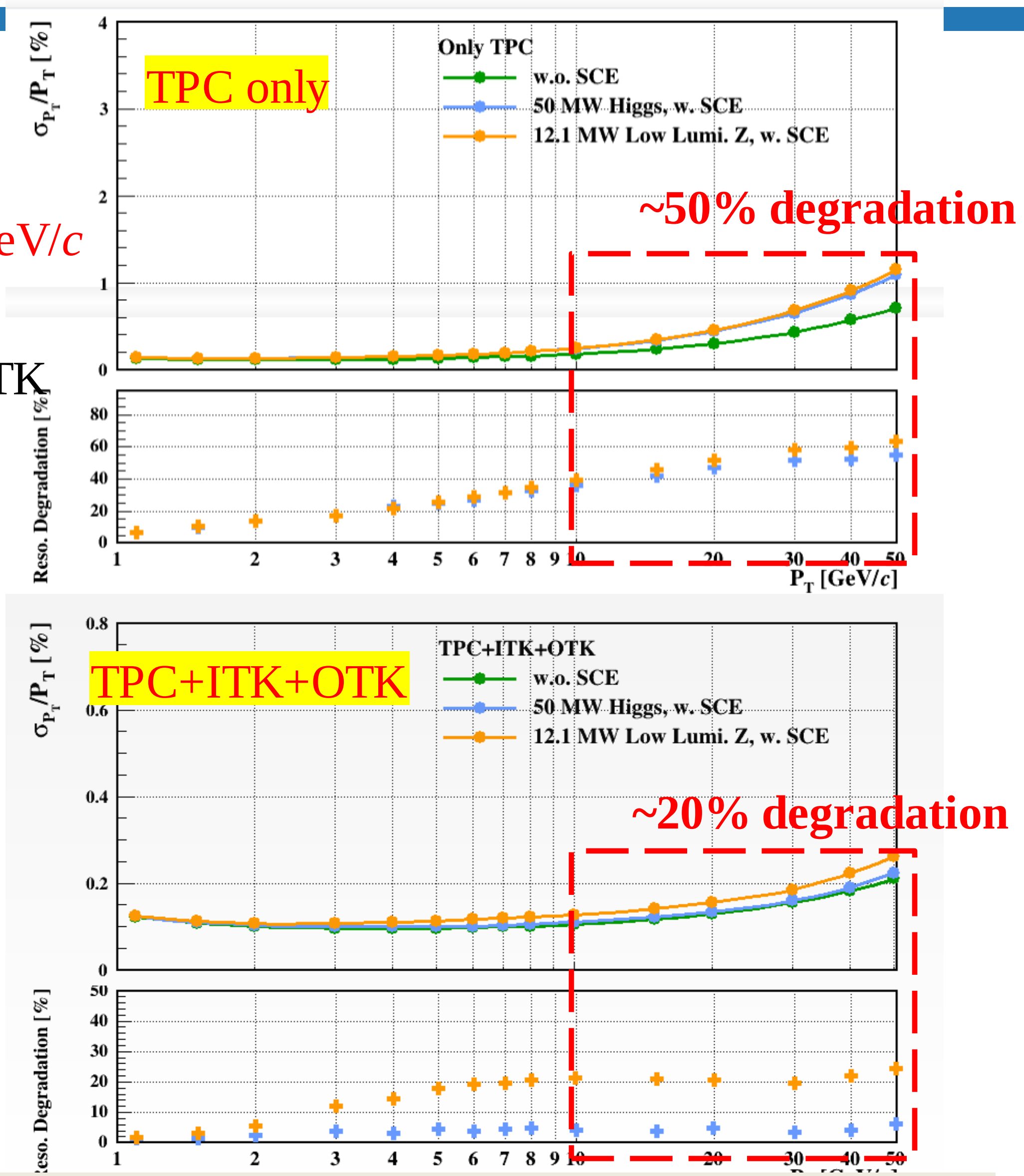
Impact on momentum measurement of the space charge effect

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



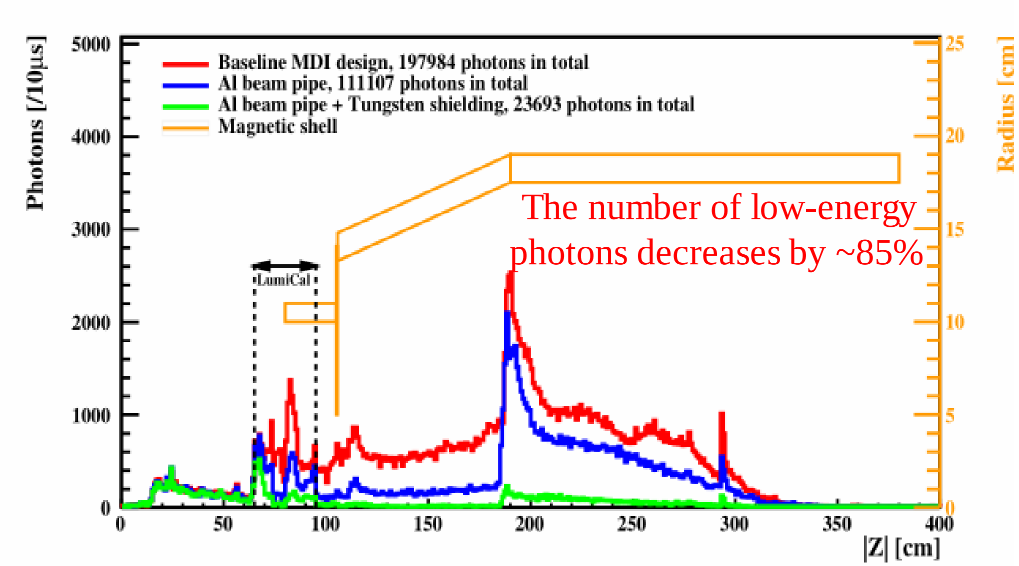
Curves of P_T resolution versus P_T, with space charge effect

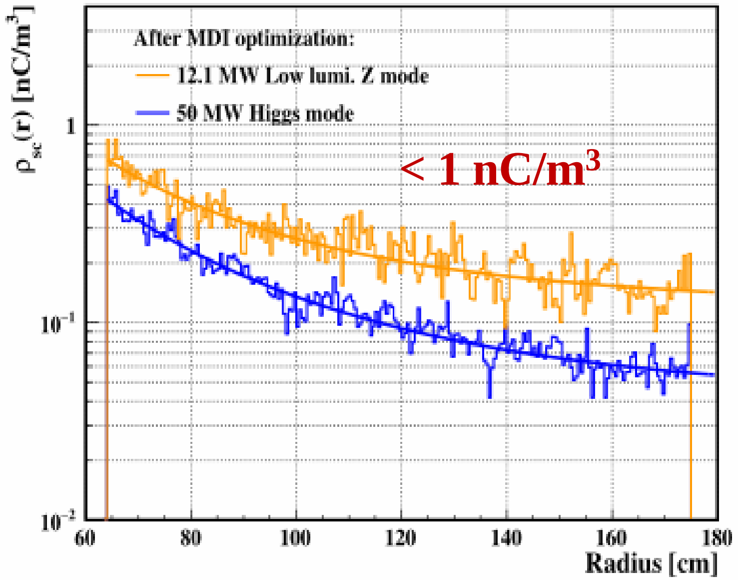
Space charge migration— After MDI region optimization

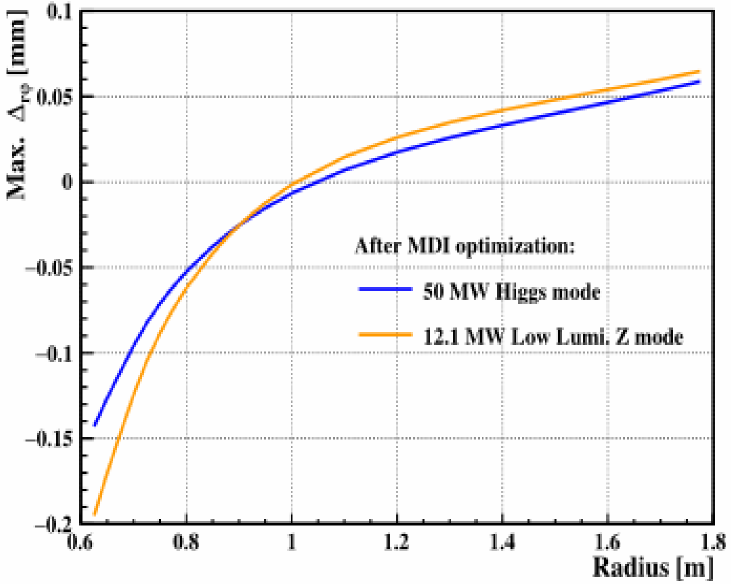
- The low-energy photons (<10 MeV) are the main contribution of space charge in the TPC
- Some optimization can reduce the space charge by approximately one orders of magnitude.
  - Lighter beam pipe material (Copper → Aluminum)
  - Shielding of the magnetic shell (1 mm stainless steel → 15mm Tungsten)
  - Electron drift deviation in rφ < 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



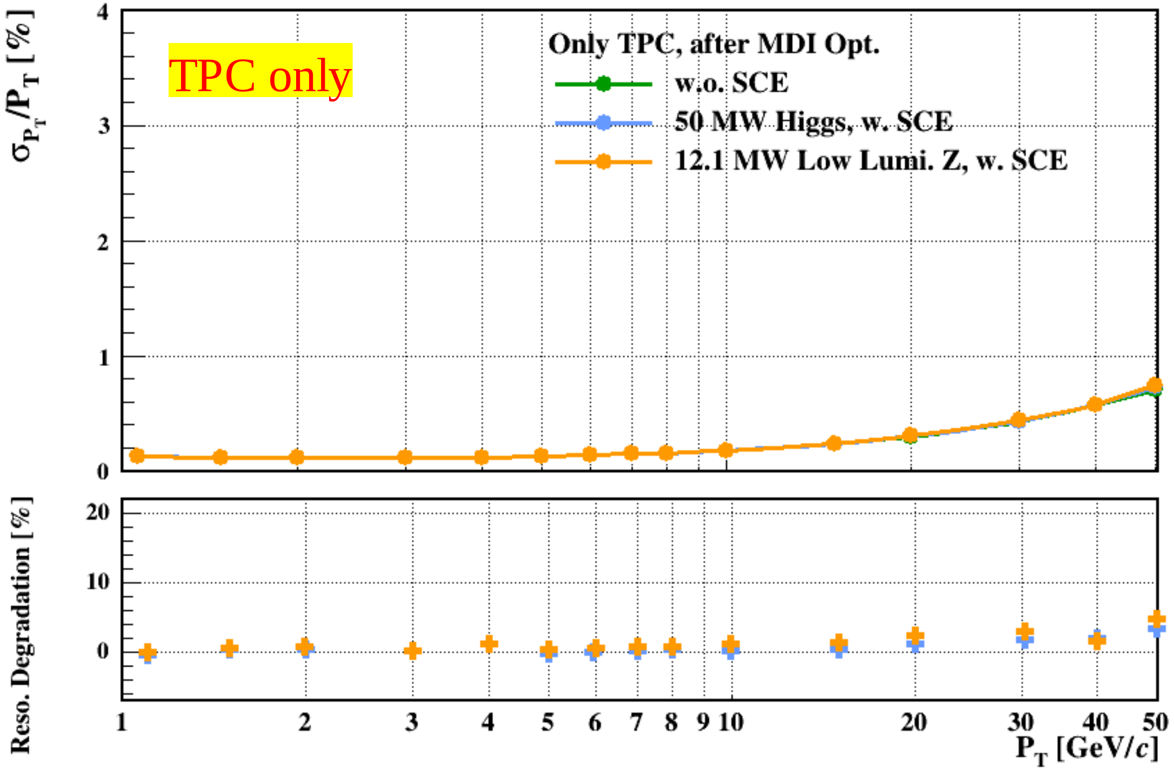


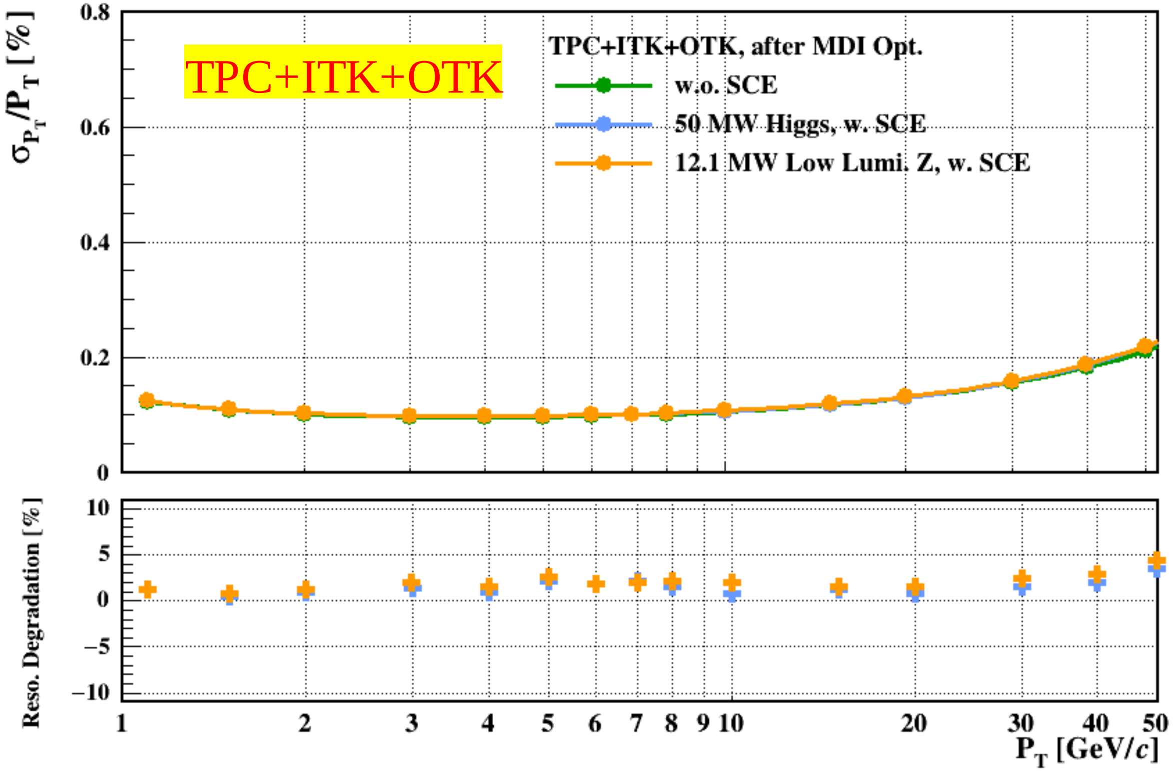


Distributions of the initial |z| positions entering the TPC and space charge density after optimization, DOI:10.1140/epjs/s11734-026-02404-w

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





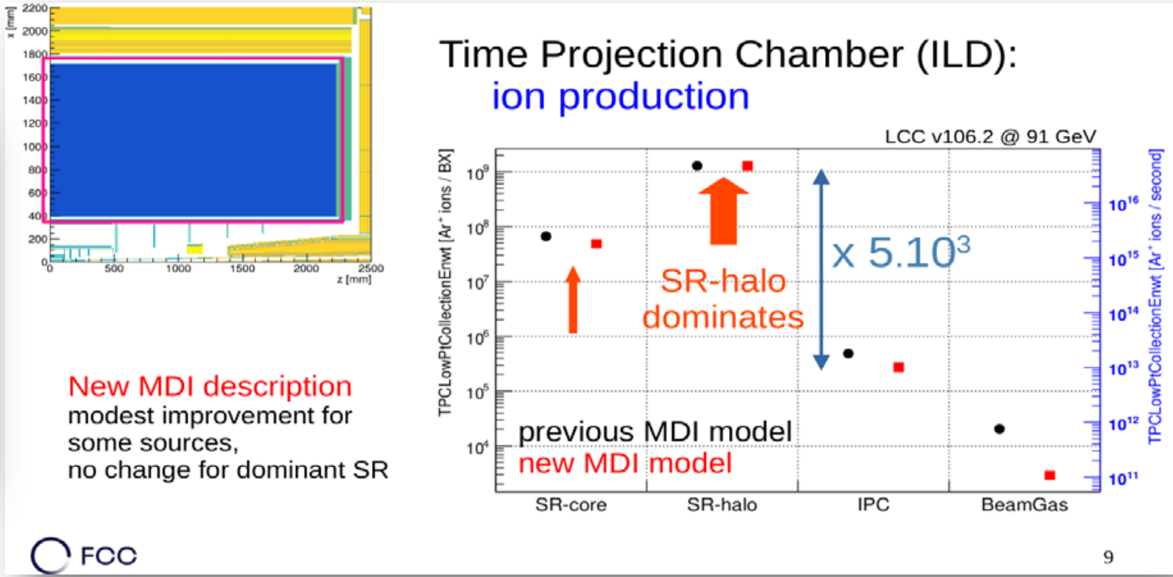
Curves of P_T resolution versus P_T, with space charge effect after MDI optimization

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)

@ 91 GeV	Silicon Tracker pixel rate @ 3 pix/hit	Drift Chamber occupancy	TPC typical distortion
IPC	10 kHz / cm²	~7% *	few mm
SR my back-of-envelope	~GHz / cm²	>1000%	few m

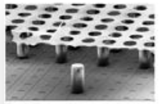
IPC [comfortable → challenging]
SR [extremely challenging → impossible]



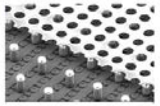
High-granularity readout meets the higher rate and readout demands

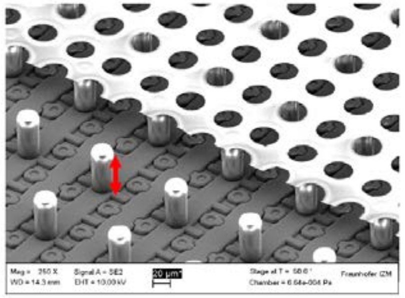
- Within the LCTPC collaboration, studies on readout pads of different sizes have been carried out.
  - TPX3 and TPX4 (Bonn and NIKHEF)
  - TEPIX (IHEP and Tsinghua University)

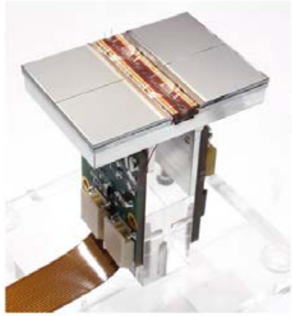
Optimization of readout
Jinxian Zhang's talk



GridPix based on Timepix3

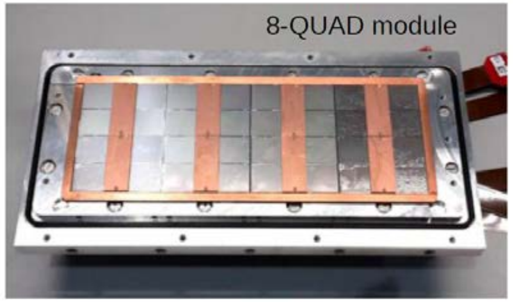




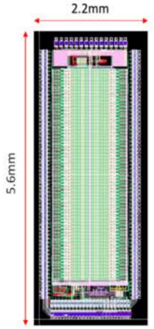


- Number of pixels: 256 × 256 pixels
- Pixel pitch: 55 × 55 µm²
- ENC: ~ 60 e⁻
- Charge and time available for each hit
- Timing resolution: 1.56 ns
- Zero suppression on chip (sparse readout)
- Output rate up to 5.12 Gbps

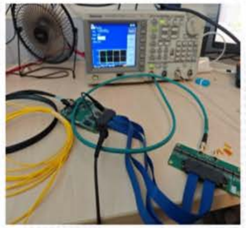
8-QUAD module



- High granularity readout Electronics: TEPIX v1
  - Charge-sensitive preamplifier
  - Correlated double sampling shaper
  - 4-channel sample/hold circuits and 10 bit ADC
  - 128 channels using 180 nm process
  - Chip size: 2.2 mm × 5.6 mm
- 40 chip-in-package devices were tested in two batches; full-readout Micromegas readout has not yet been completed.



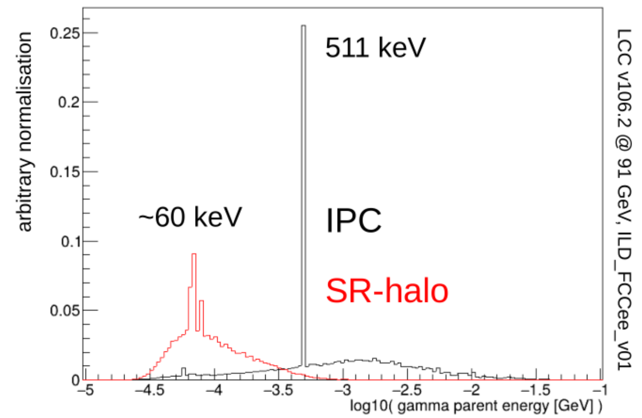
Total number of channels	30 Million per endplate
Pixel size	500 µm × 500 µm
Equivalent Noise Charge (ENC)	100 e^-
Dynamic range	20 fC
Charge buffer dynamic range	8-10 bit
Event rate	12 kHz/cm² max. in low-lumi. Z mode
Event size	64 bit
Readout bandwidth	<10 Gbps per module with compression
Power consumption	<100 mW/cm²



Summary

Summary

- Studies show that a larger TPC inner radius (~0.6 m) is needed for the High-Lumi Z challenge and physics requirements, this enlargement also allows adding ITK and OTK to enhance flavor-physics performance.
- The full simulation flow of the BG has been established, and the full SR background simulation and MDI collaborative design.
- TPC is feasible at Z operation with systematic MDI optimization and silicon tracker combination, the high granularity readout TPC module has been developed integrated with GridPix at LCTPC and TEPIX chips at IHEP.



energy of photons which induce TPC hits

Beyond responding:
A serious assessment of the challenge

Many thanks!