



High Granularity Readout TPC and Beam Background R&D for Future e^+e^- Collider

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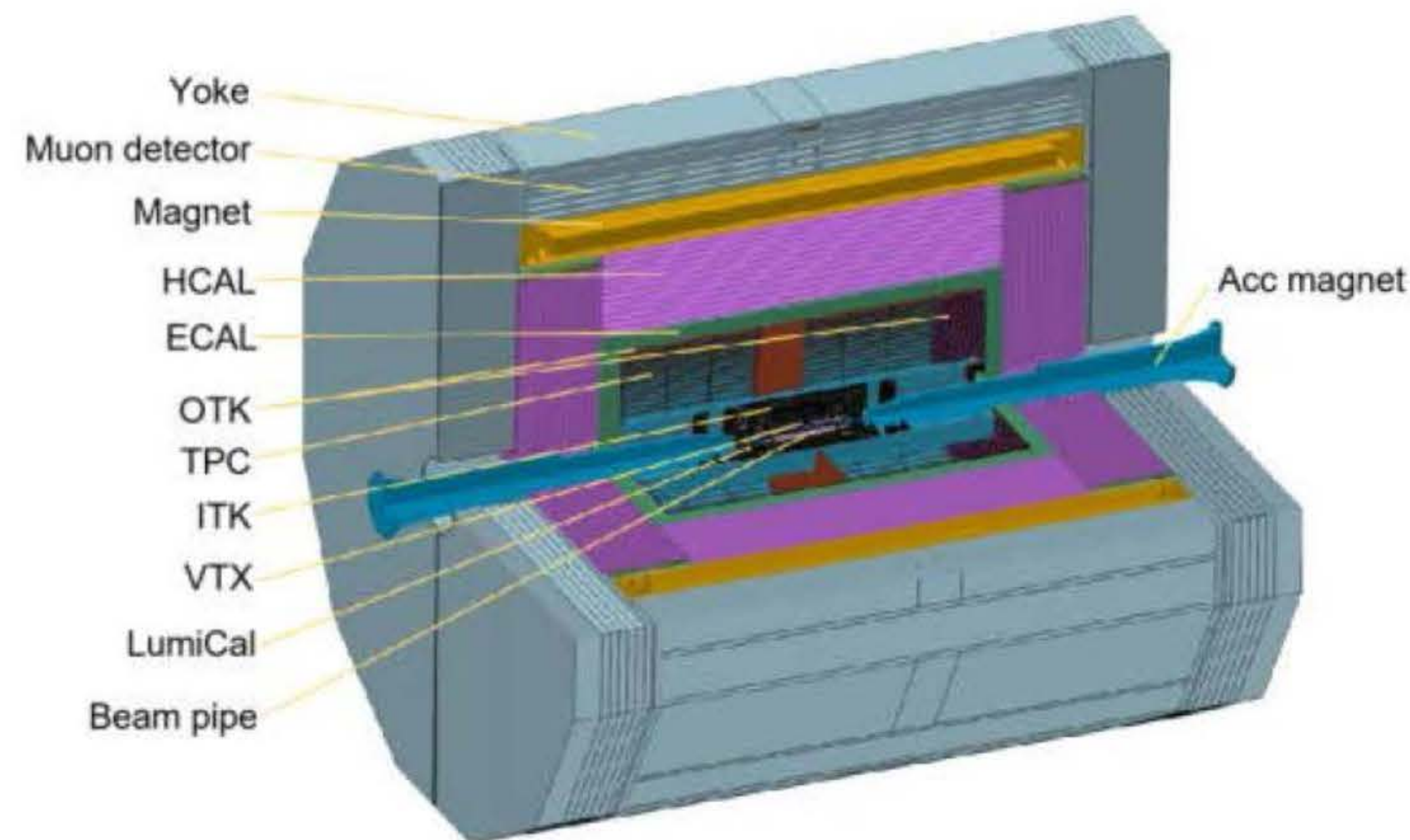
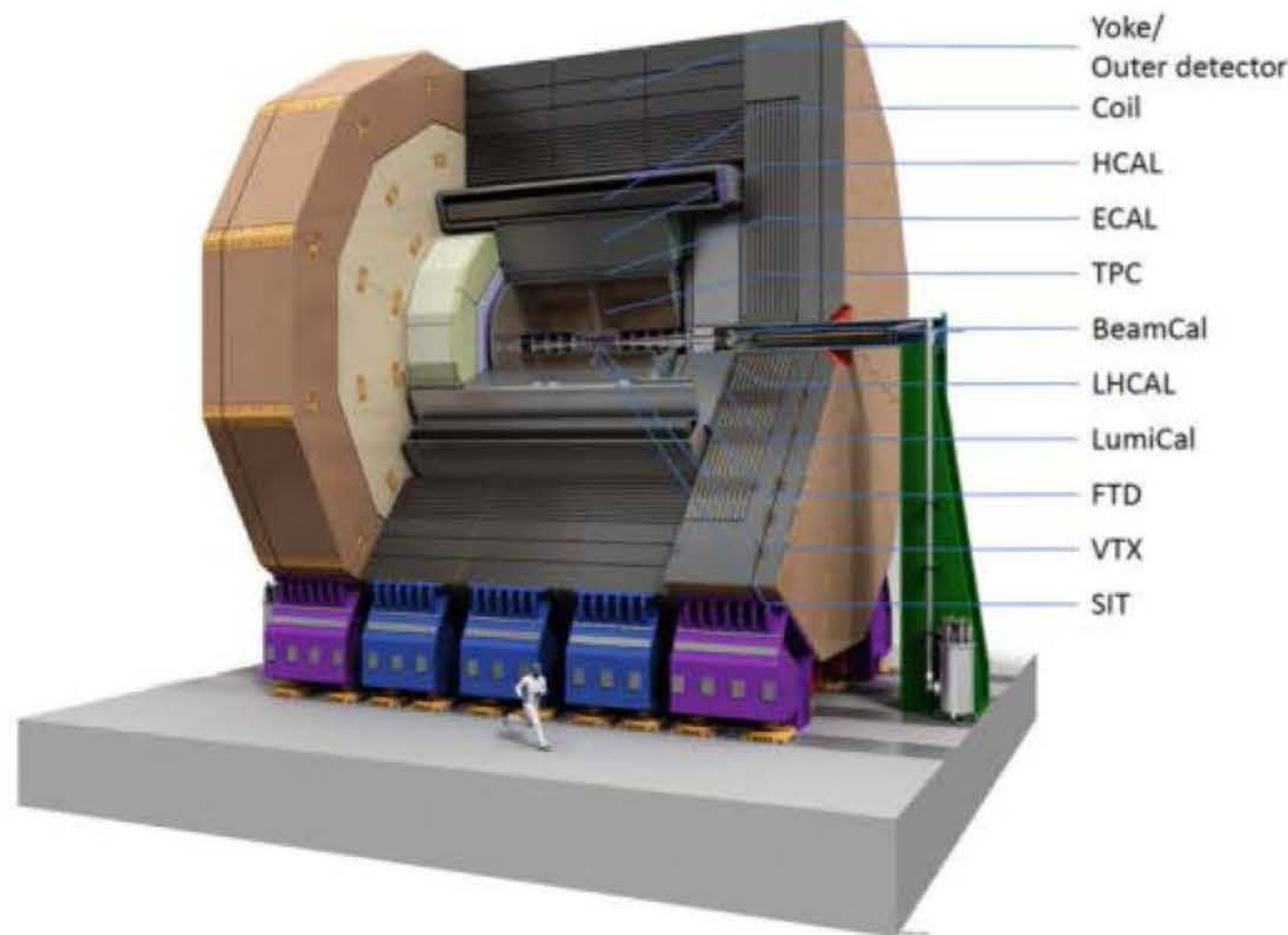
Some good inputs from LCTPC and DRD1 International Collaboration

INSTR2026, University of Science and Technology of China, October 2026, Hefei City

- **Motivation and Physics requirements**
- **TPC Technology R&D at IHEP**
- **Beam background and tracking performance**
- **Summary**

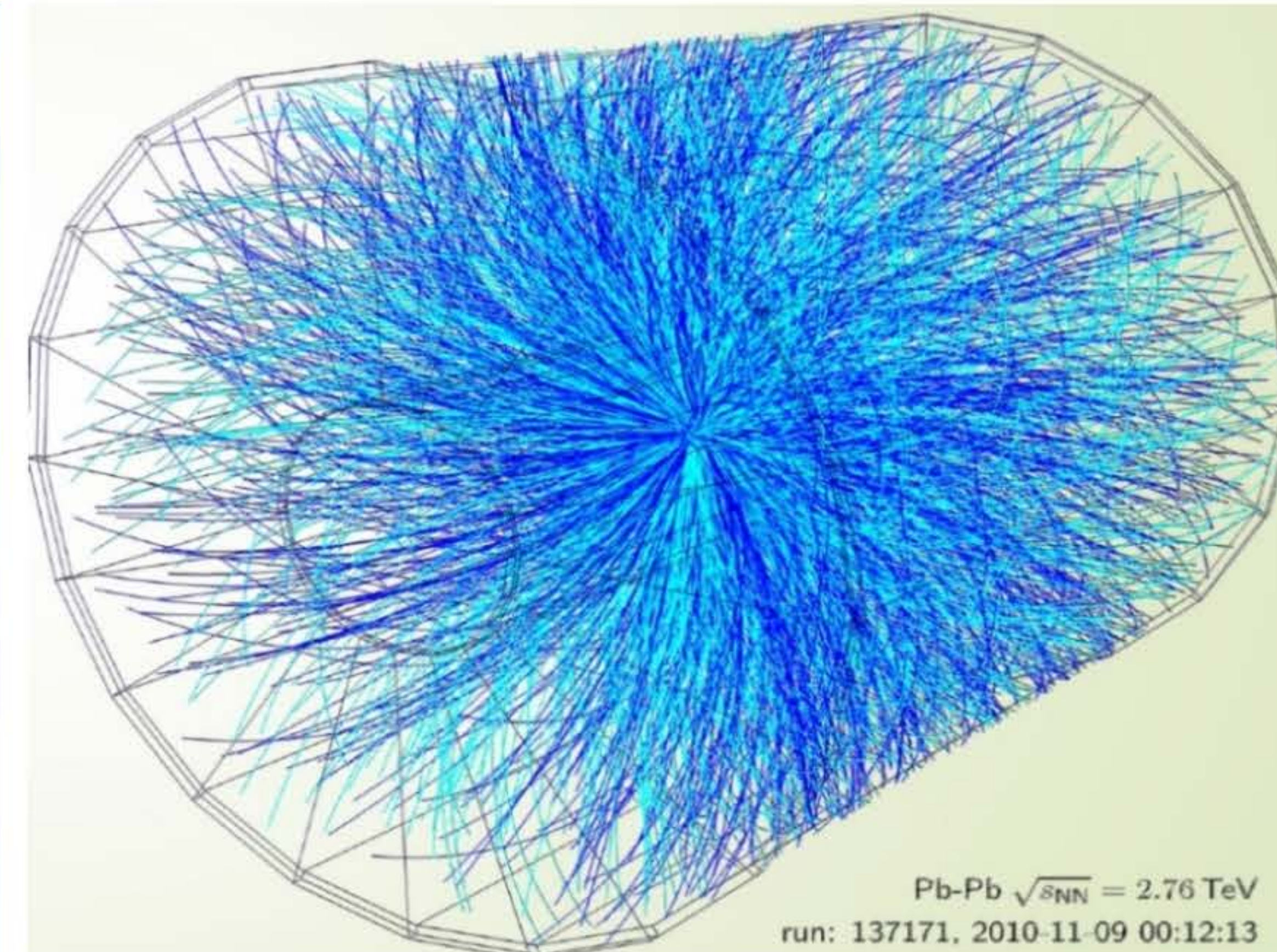
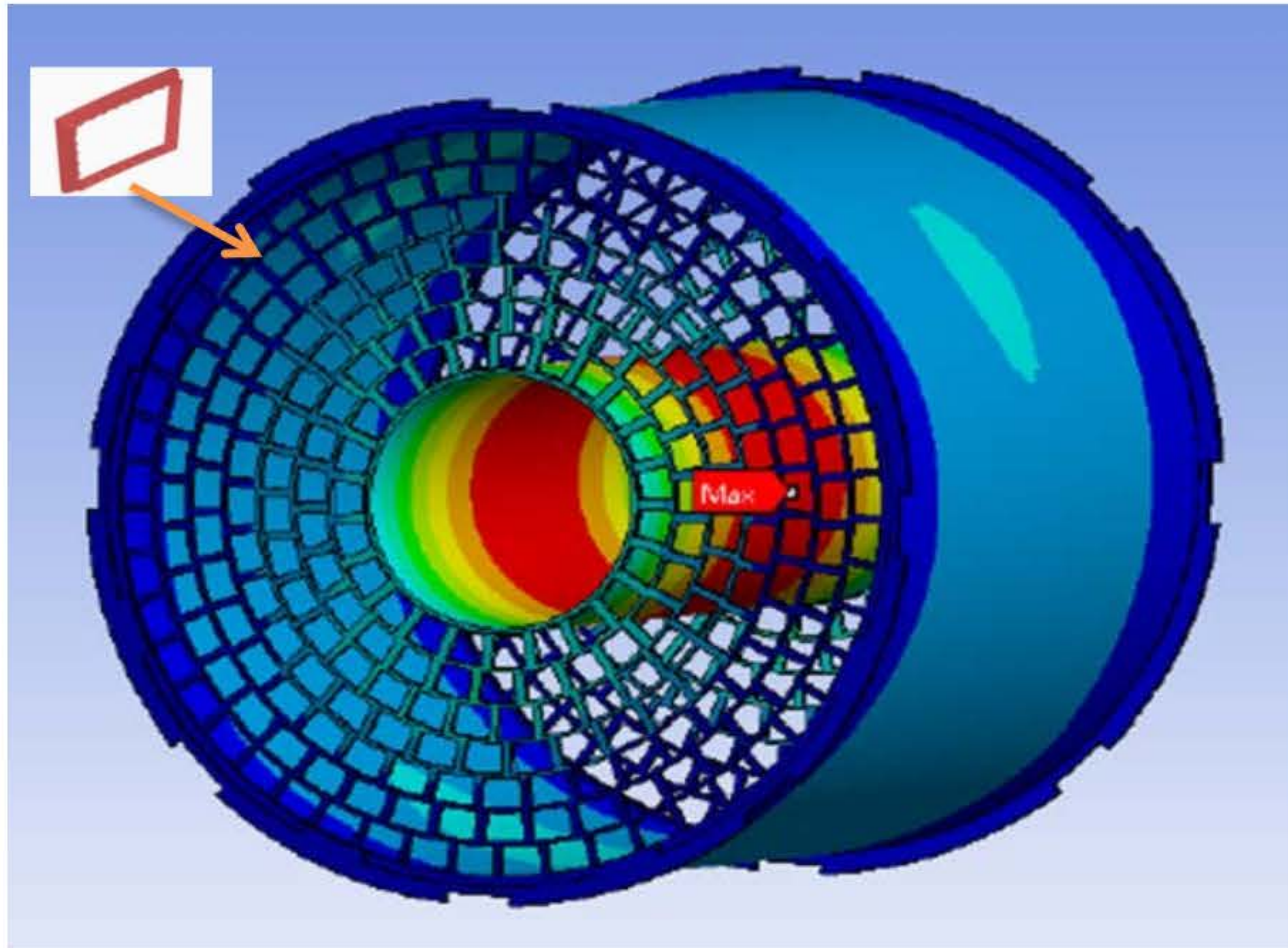
Motivation and physics requirements

- A TPC is the main track detector for some candidate experiments at future e^+e^- colliders.
 - **Baseline main tracking detector of ILD at ILC and AGORA at CEPC**
- TPC technology can be of interest for other future colliders (EIC, FCC-ee).
- High granularity readout readout TPC can improve PID requirements of Flavor Physics at e^+e^- collider and also in the neutrino detection.



Time Projection Chamber Technology

- 3D high precision resolution track reconstruction with the Ultra light material budget
 - High precision resolution ($\sim 100 \mu\text{m}$) with thousands hits per track
 - High momentum resolution ($\sim 10^{-4} \text{ GeV/c}$) and High capabilities for the Particle Identification (**PID: $\sim 3\%$**)
 - A magnetic field parallel to the electric field direction (**Higgs: 3T, Z: 3T or 2T**)
 - Easily installation and replacement modular design
- Considering the technical challenges, performance, risk of detector construction

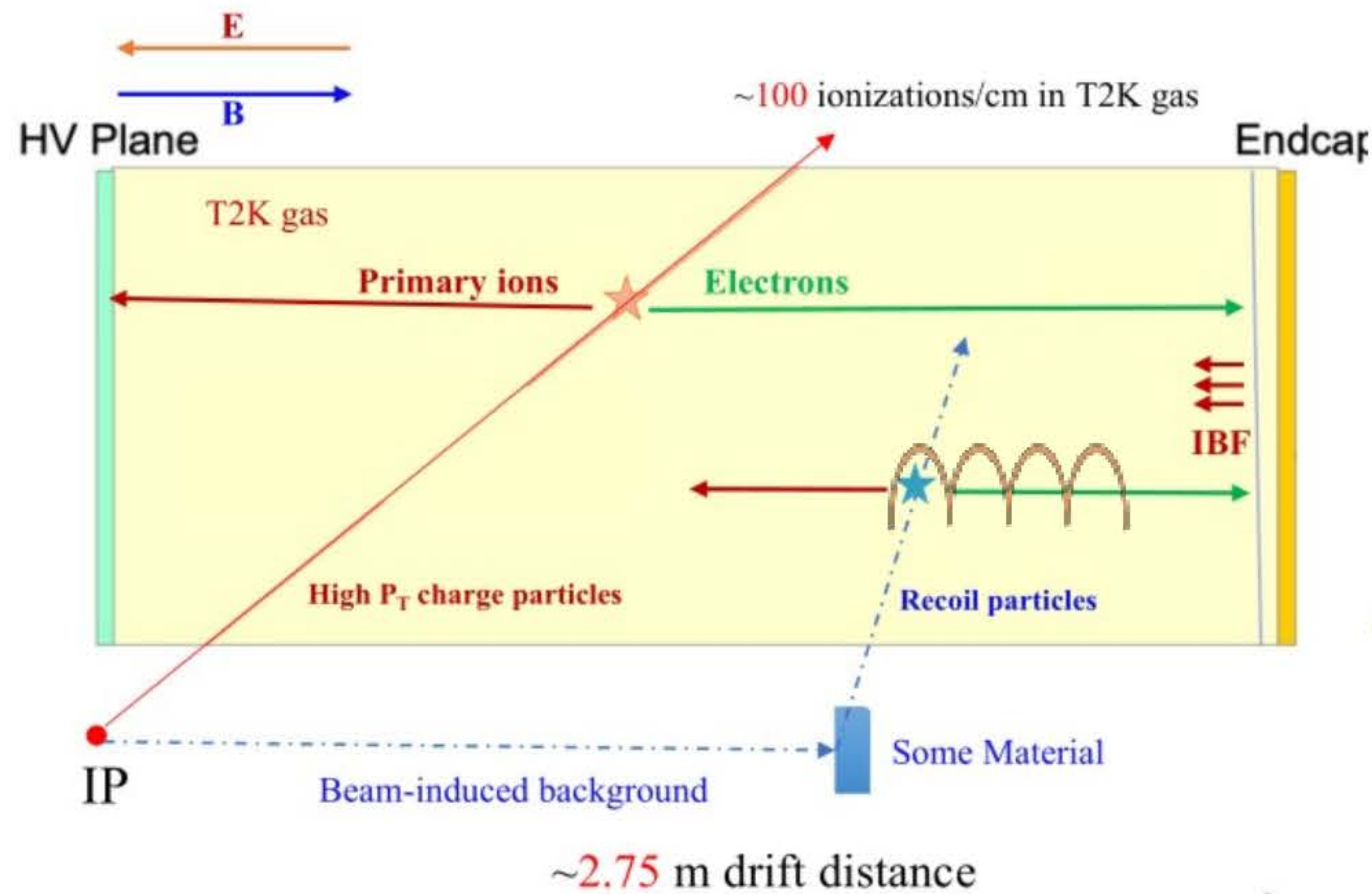


TPC challenges

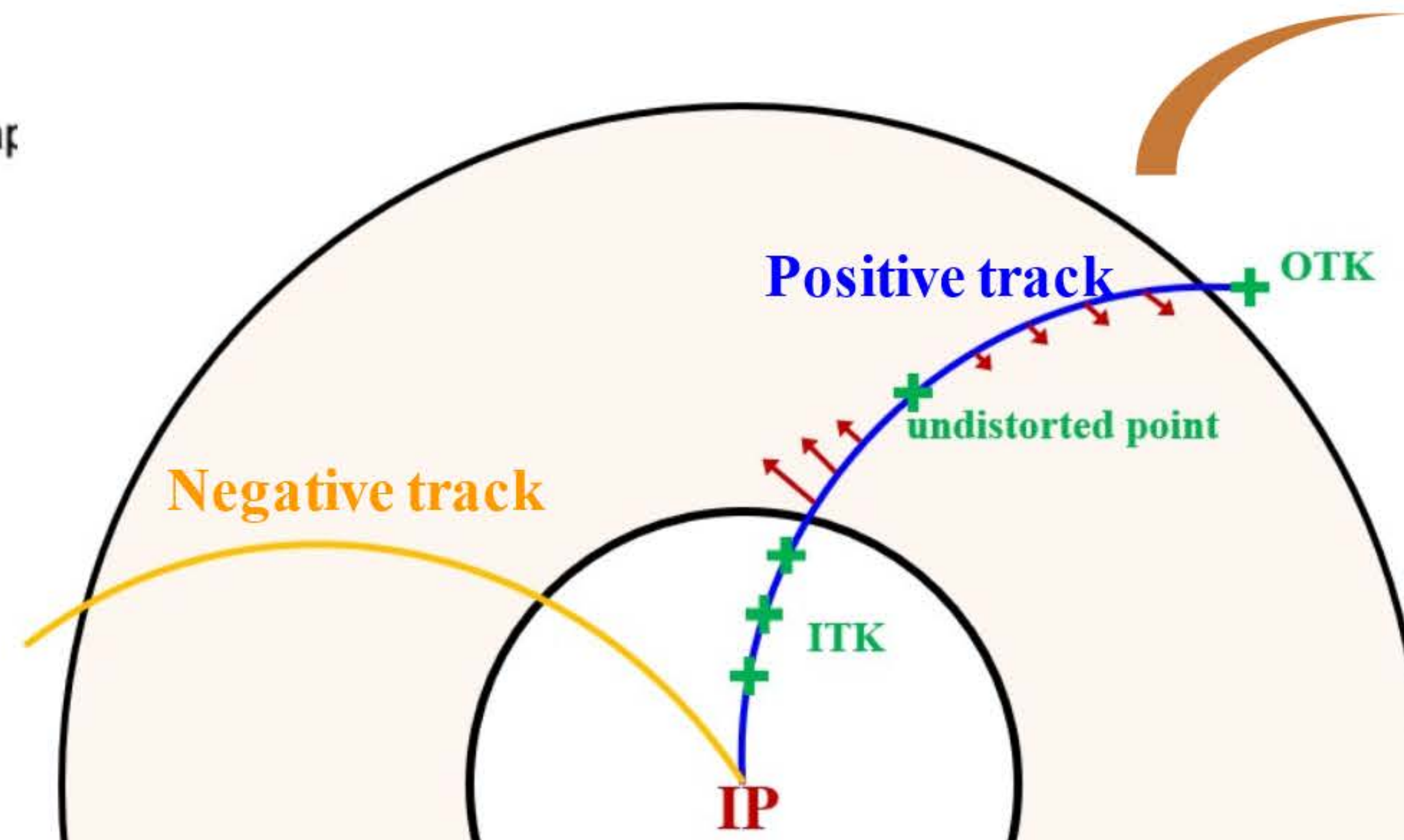
- The Reference Detector is designed and optimized primarily for the **Higgs** and **low-luminosity Z** modes
 - Peak luminosity reaches 10^{34} and $10^{35} \text{ cm}^{-2} \cdot \text{s}^{-1}$, respectively
 - Both in **3T** magnetic field
- Challenges for TPC technology:**
 - Beam-induced background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



**Key critical challenges
& 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**

■ TPC technology R&D at IHEP

TPC Technology for the High Luminosity HEP Factory

TPC technology detector for e^+e^- collider

Pad readout TPC

- To meet Higgs physics
- $1\text{mm} \times 6\text{mm}$ of Pad
- $< 100\text{mW}/\text{cm}^2$
- dE/dx
- Triple, double GEMs
- Micromegas



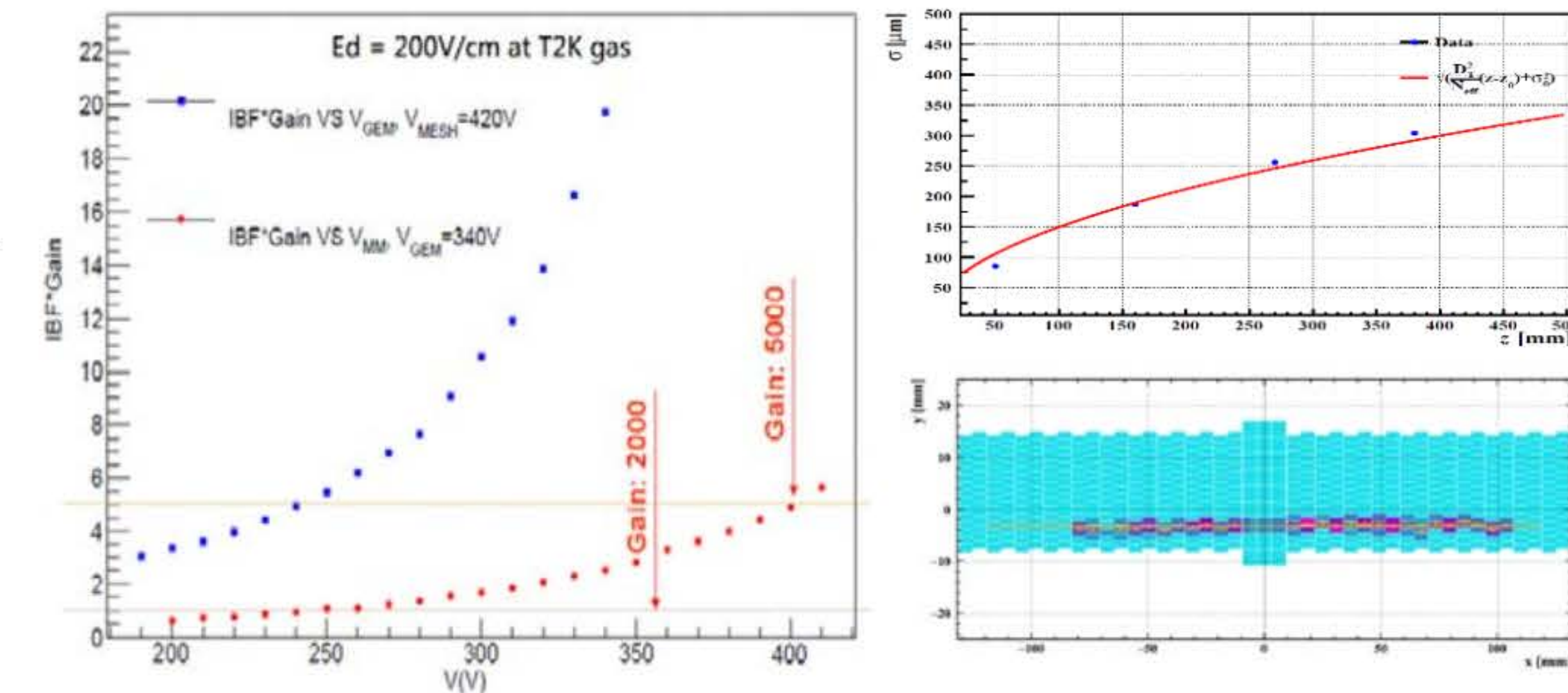
Pixelated readout TPC

- To meet Low-lumi Z physics
- TPX3 and TPX4
- $\sim 1\text{W}/\text{cm}^2$
- $dN/dx + dE/dx$
- GirdPix
- Interposer
- Direct mode

- TPC R&D community initiated the technical comparison and selection, balancing factors including **R&D efforts, detector performance, cost, power consumption and construction risks.**

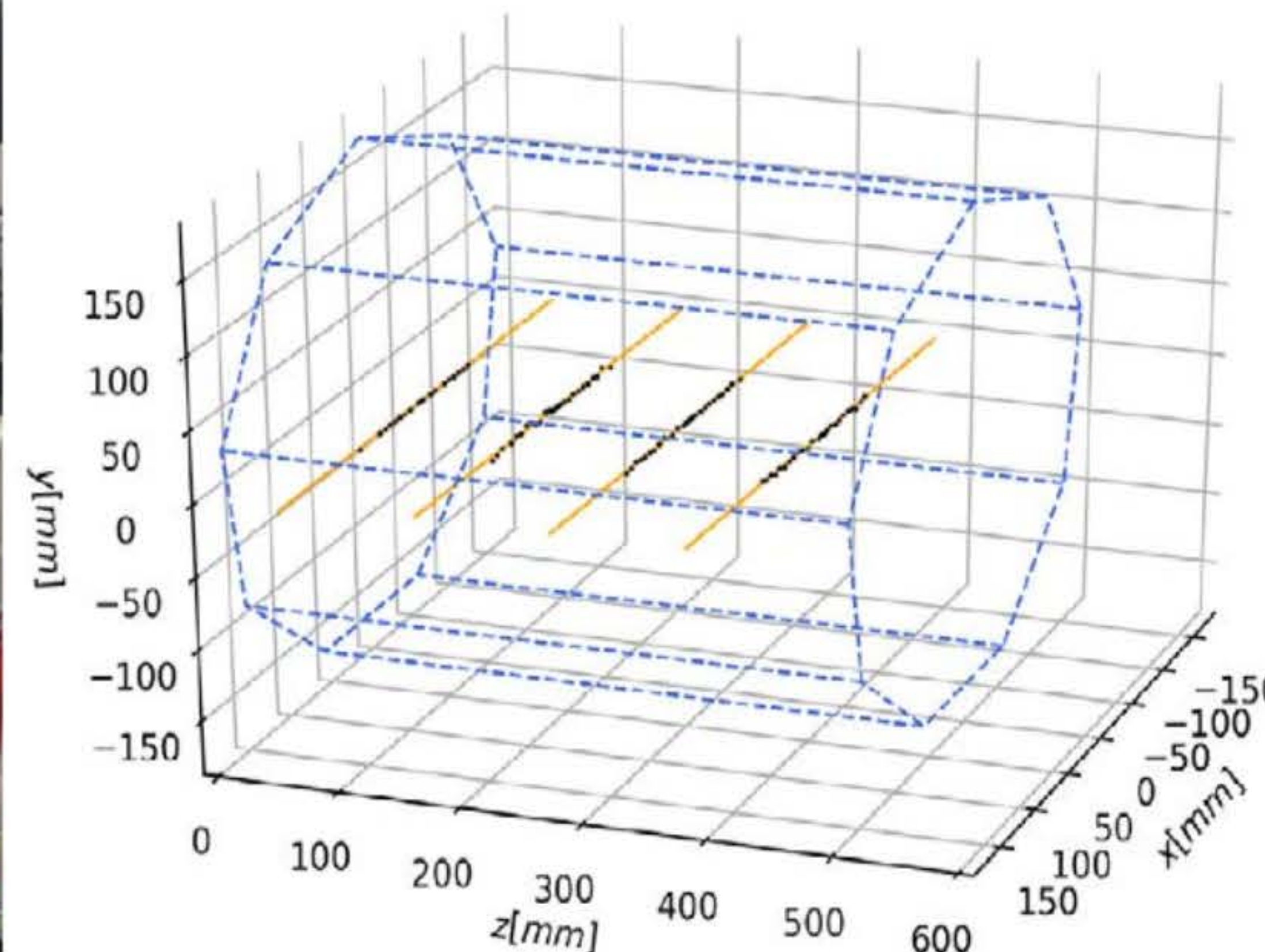
Roadmap of TPC detector R&D at IHEP (Huirong Qi team)

- CEPC TPC detector prototyping roadmap:
 - From TPC module to **TPC prototype R&D** for CEPC
 - Easy-to-install modular design of Pixelated readout TPC for CEPC TDR
- Achievement by far:
 - **IBF × Gain ~1 @ G=2000** validation with hybrid TPC module
 - Spatial resolution of **$\sigma_{r\phi} \leq 100 \mu\text{m}$ and dE/dx resolution of 3.6%**
 - FEE chip: reach **~3.0mW/ch with ADC** and the pixelated readout R&D



Ion suppression TPC module R&D

TPC prototype with integrated 266nm UV laser



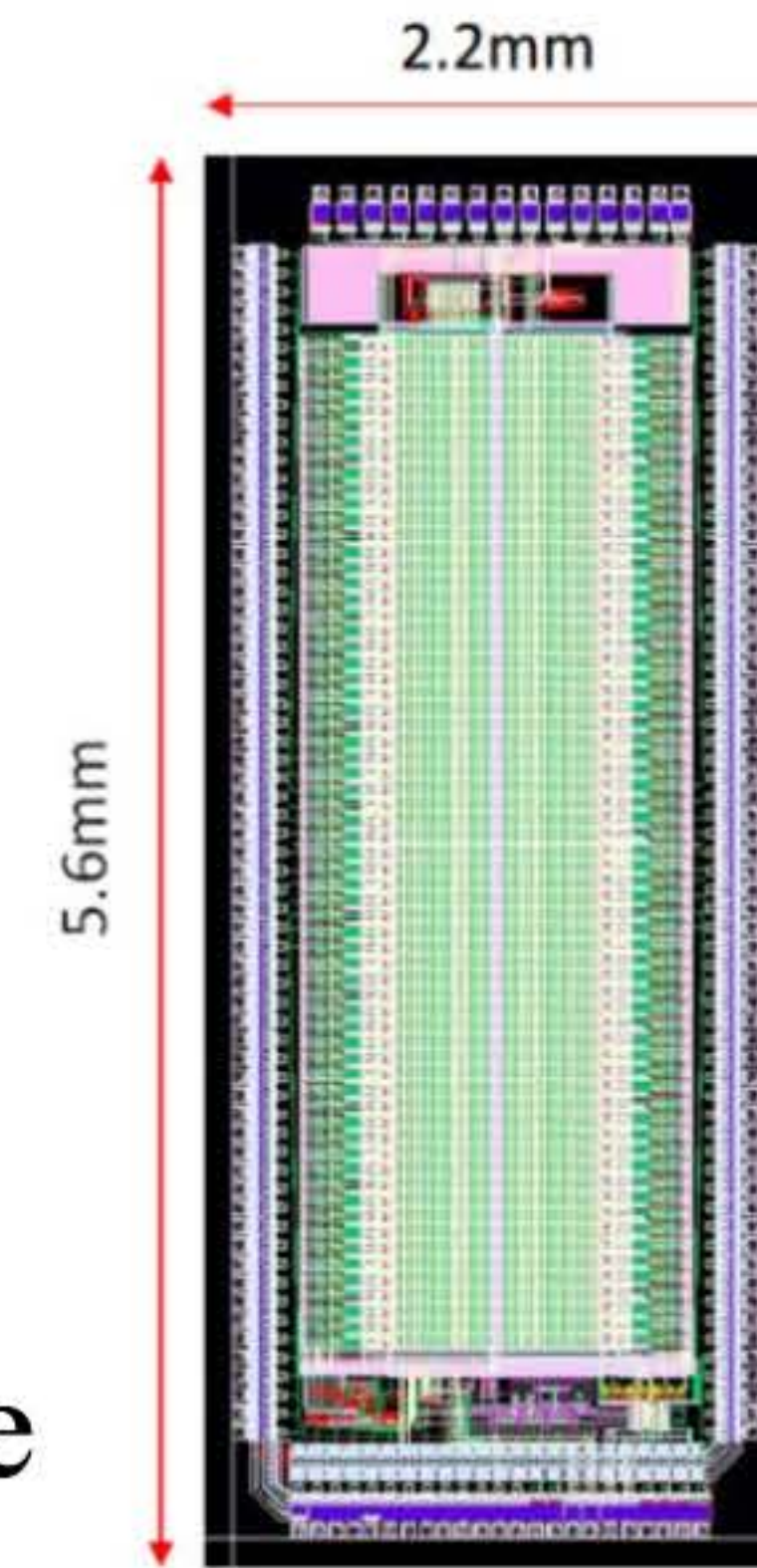
Publications by CEPC TPC group in 2018-2025:

- <https://doi.org/10.1088/1748-0221/18/08/E08002>
- <https://doi.org/10.22323/1.449.0553>
- <https://doi.org/10.1016/j.nima.2022.167241>
- <https://doi.org/10.1109/NSS/MIC44867.2021.9875566>
- <https://doi.org/10.1109/NSS/MIC44845.2022.10399097>
- <https://doi.org/10.1088/1748-0221/15/09/C09065>
- <https://doi.org/10.1088/1748-0221/15/05/P05005>
- <https://dx.doi.org/10.1142/S0217751X20410146>
- <https://doi.org/10.1088/1674-1137/41/5/056003>
- <https://doi.org/10.1088/1748-0221/15/02/T02001>
- <https://doi.org/10.1088/1748-0221/12/07/P07005>
- <https://doi.org/10.1016/j.nima.2025.170776>
- <https://doi.org/10.1088/1748-0221/20/04/P04011>
- <https://doi.org/10.7538/yzk.2024.youxian.0916>

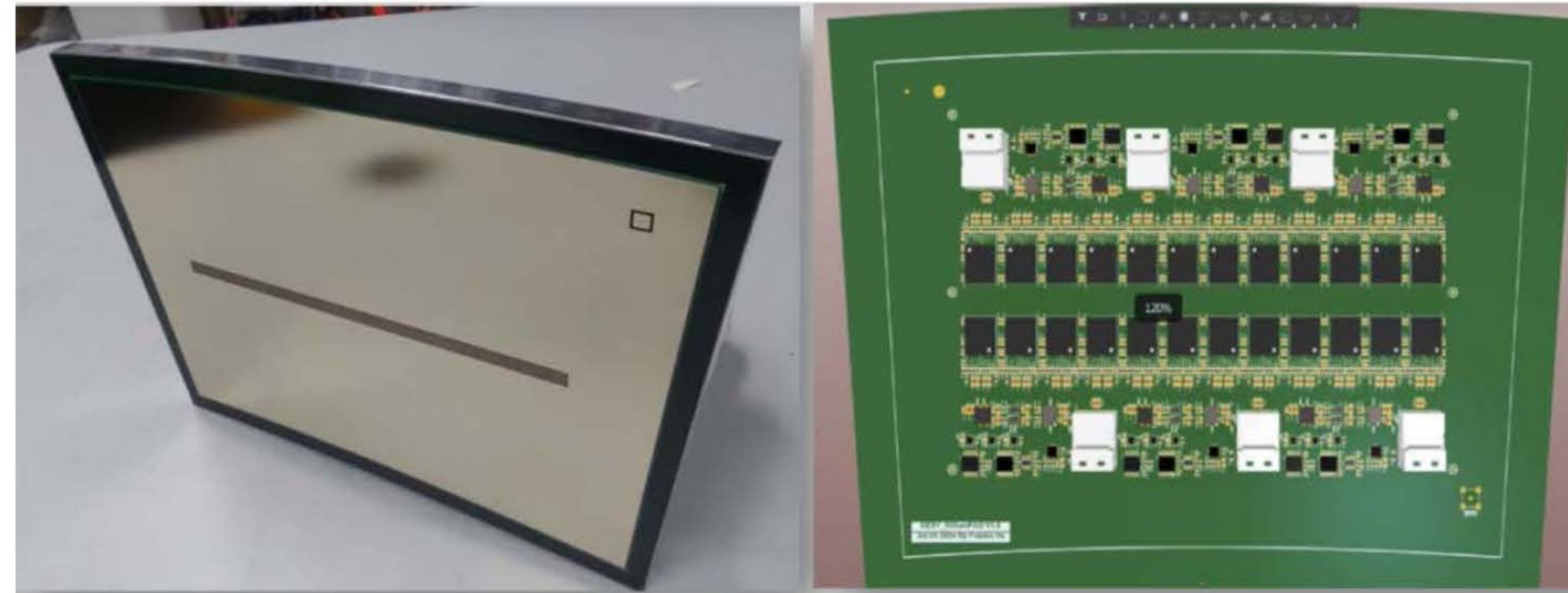
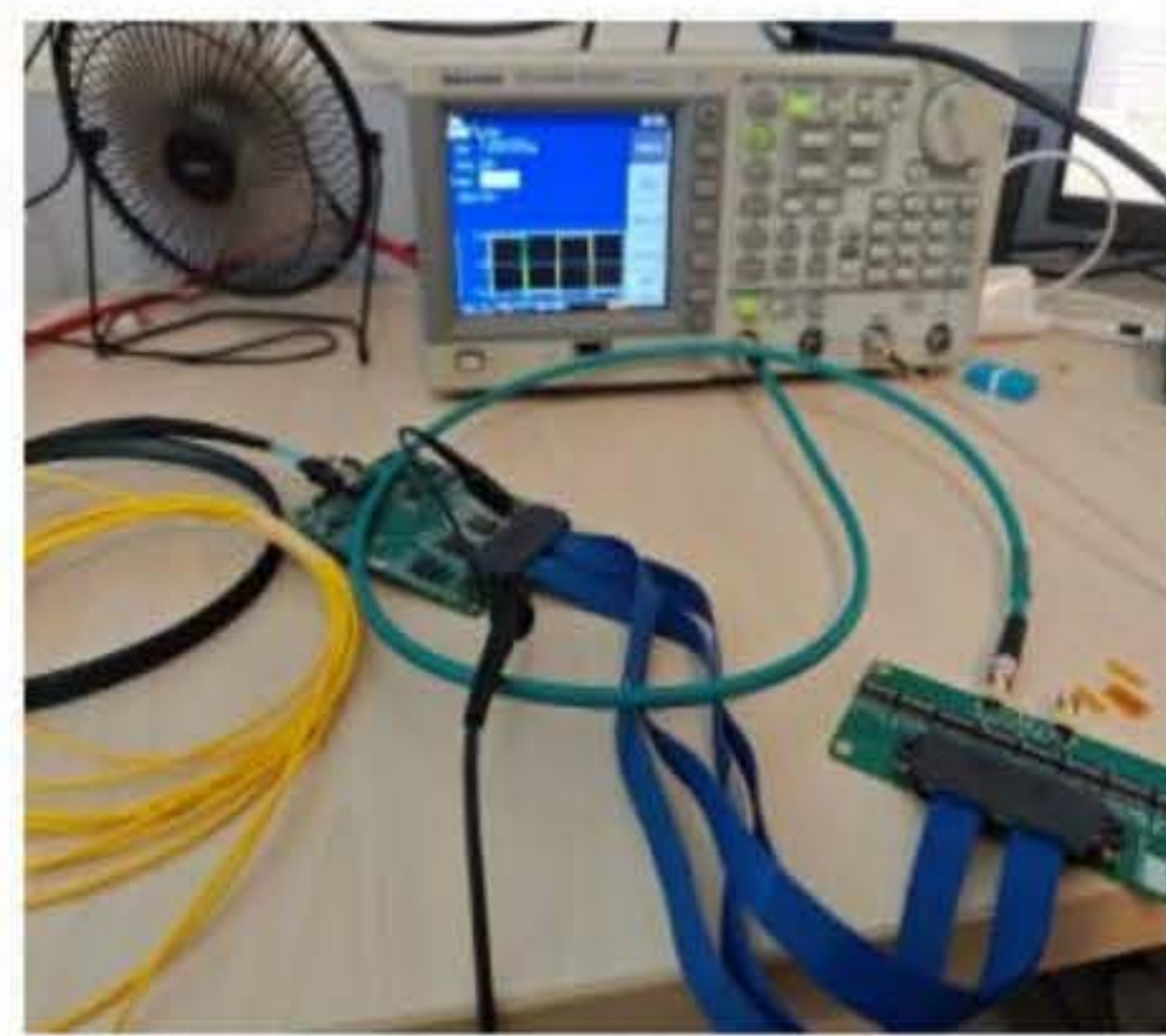
Prototype of the high granularity readout ASIC R&D: TEPIX v1

- 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 $\times$ 5.6 mm
- 40 chip-in-package devices developed and R&D
- Study and evaluate the readout gain and signal-to-noise ratio

**Huirong Qi team in collaboration with
Tsinghua University**

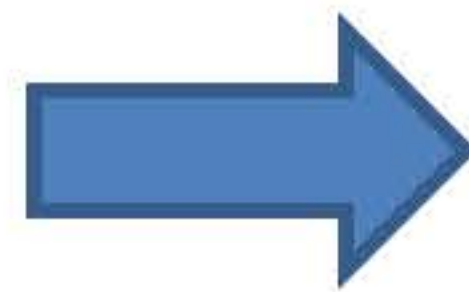


Total number of channels	30 Million per endplate
Pixel size	500 $\mu\text{m} \times 500 \mu\text{m}$
Equivalent Noise Charge (ENC)	100 e^-
Dynamic range	20 fC
Charge buffer dynamic range	8-10 bit
Event rate	12 kHz/cm ² max. in low-lumi. Z mode
Event size	64 bit
Readout bandwidth	<10 Gbps per module with compression
Power consumption	<100 mW/cm ²



■ BG caused by Beamstrahlung and Single-beam

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

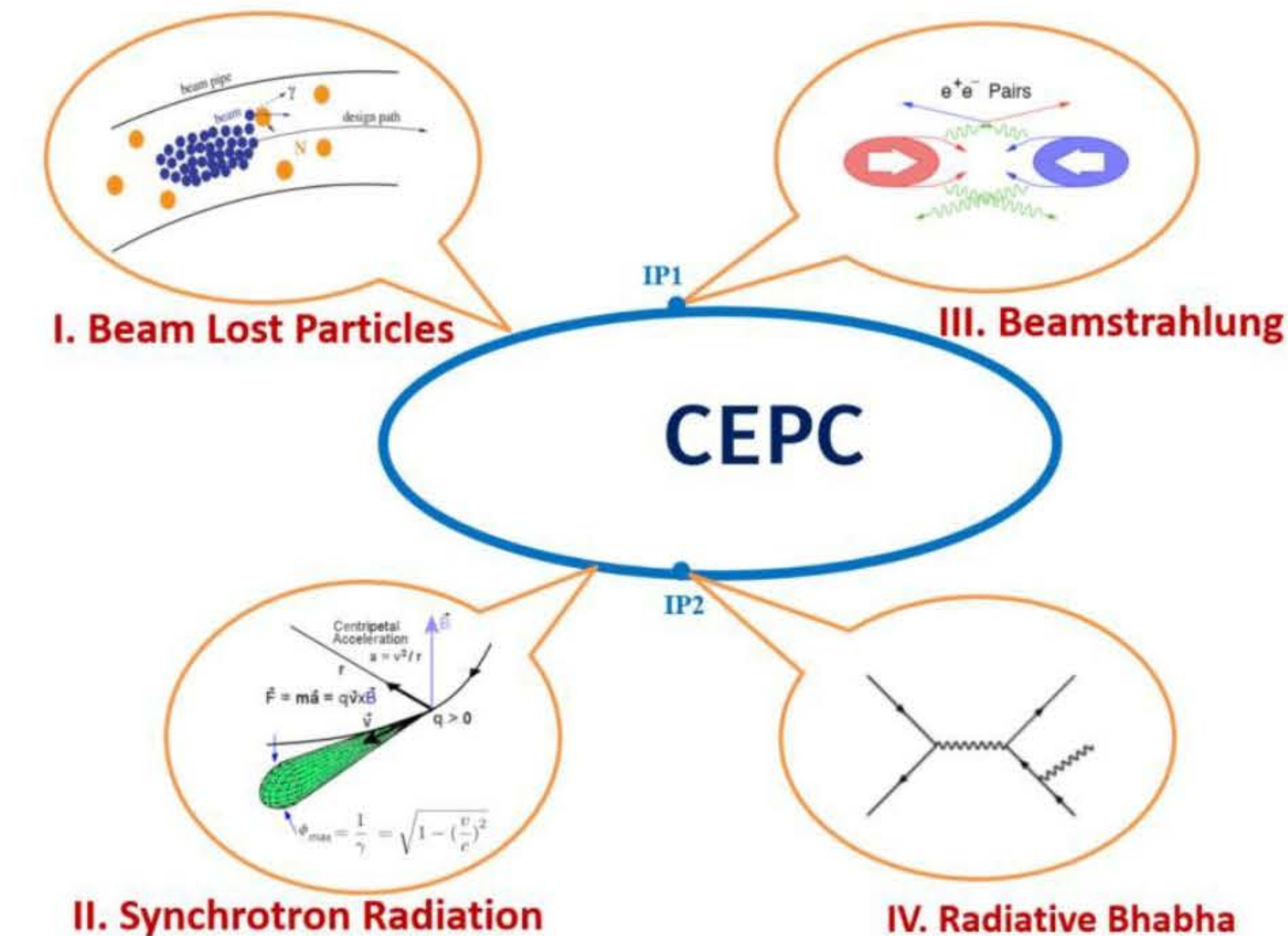


**This full simulation chain, from background generation to space charge solving to performance validation, has been developed by the IHEP TPC group.
Jinxian Zhang, Jianbo Zheng, Xin She and Huirong Qi etc.**

Status of beam-induced background @ CEPC

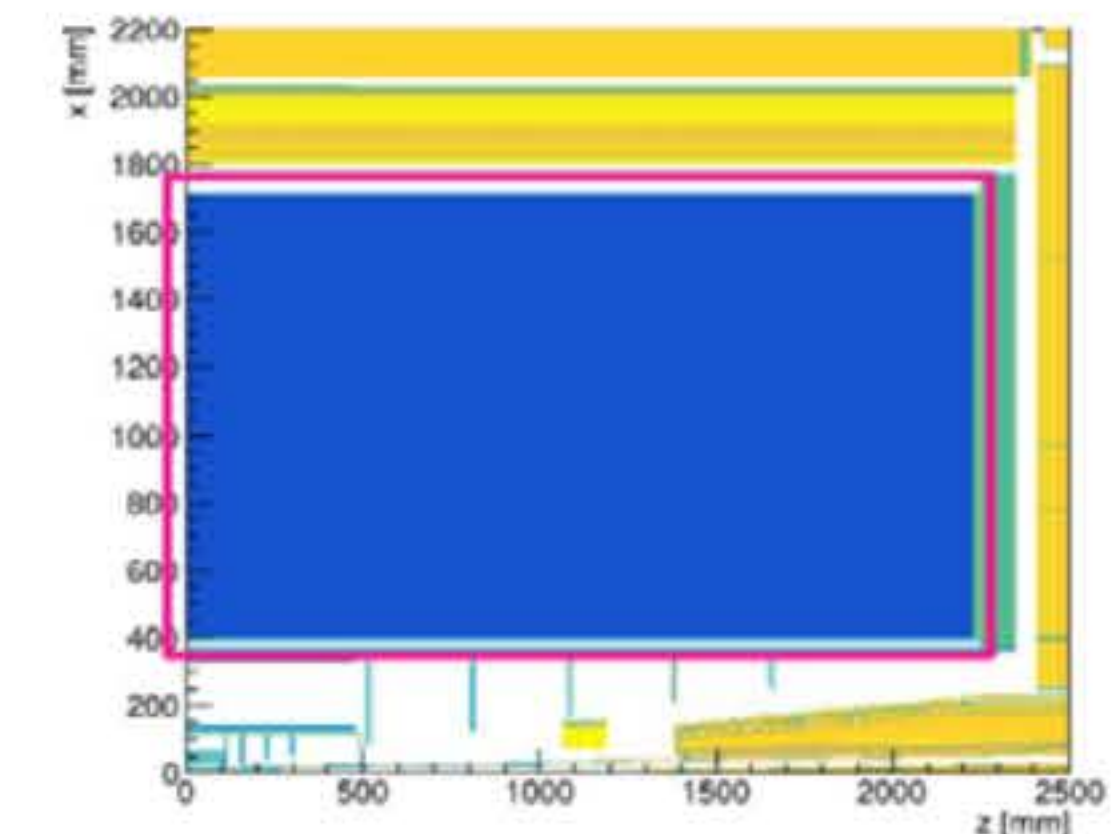
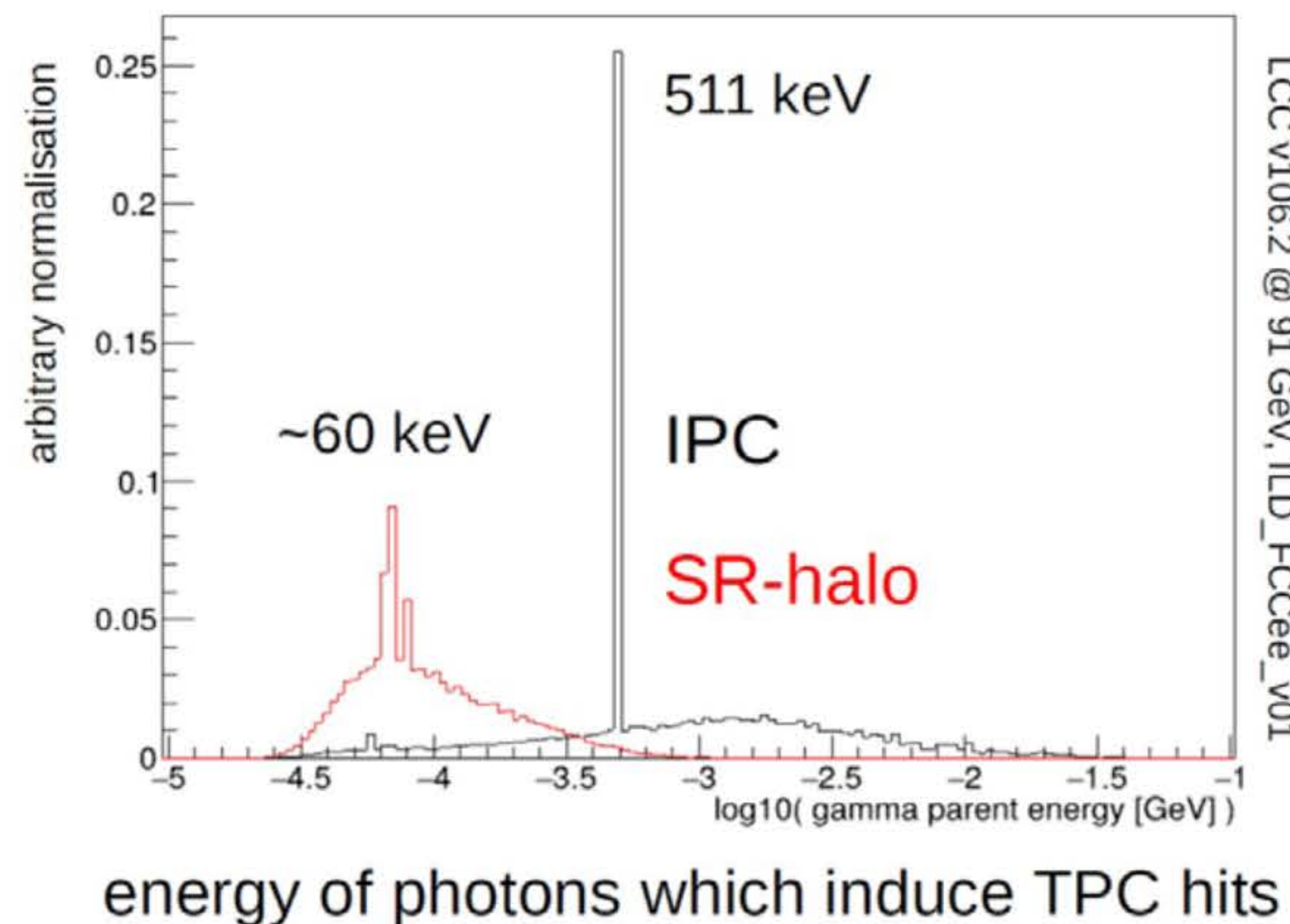
Our Strategy: From Assessment to Optimization

- 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 $\sim 3.3 \text{ nC/m}^3$
 - Max. deviation $\sim 1 \text{ mm level}$ @Low-Luminosity Z mode
- Tracking performance with space charge effect in Higgs and low-luminosity Z modes will be demonstrated.



Synchrotron Radiation @ Tera-Z

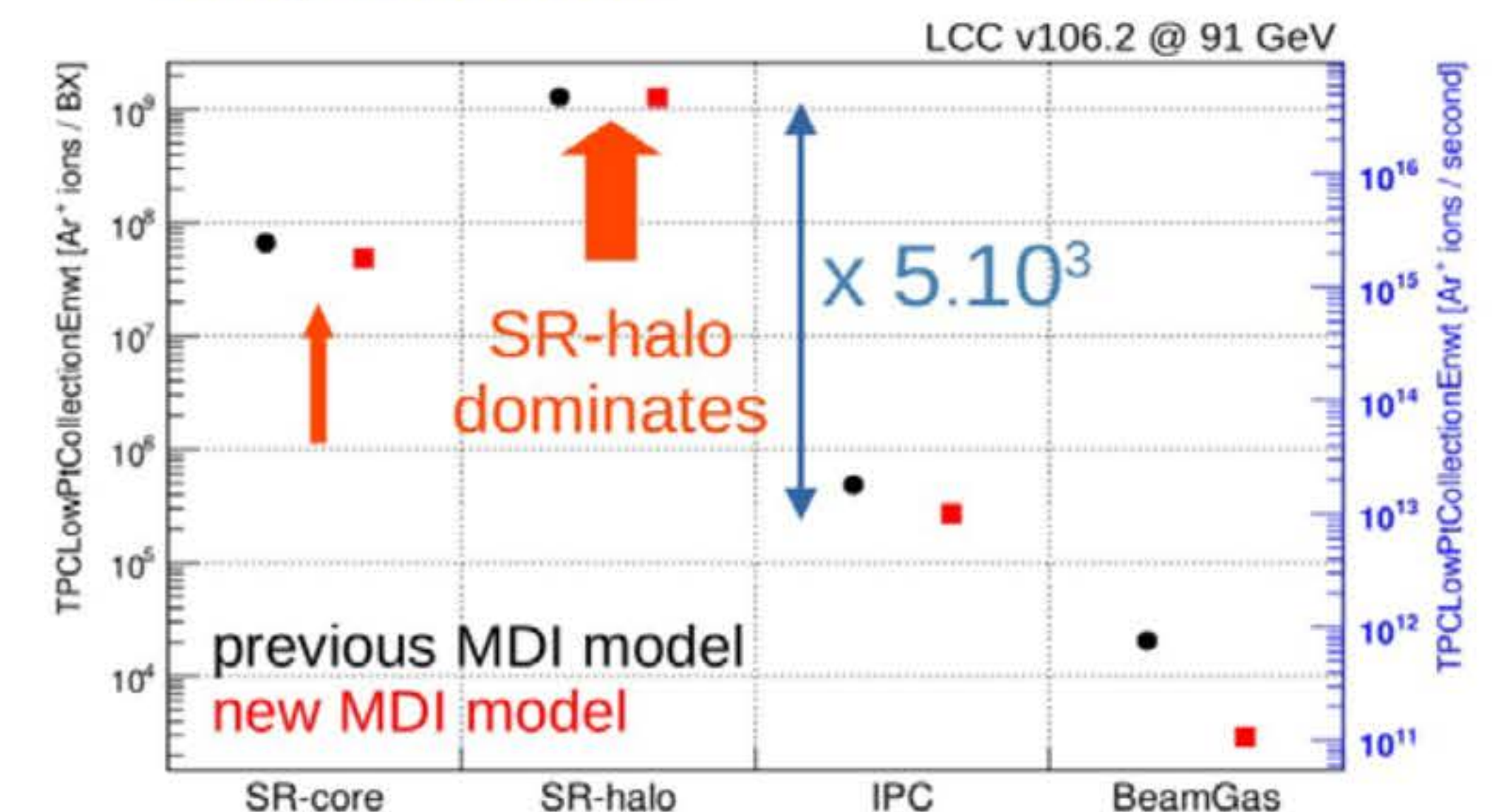
- Daniel provides a massive estimate: all detectors face enormous challenges at Tera-Z in June.
- SR background seems extremely challenging:
 - ~3 orders of magnitude higher than Beamstrahlung, **also much larger than ALICE TPC**
 - We need to carefully evaluate the impact of SR background and optimize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



New MDI description
modest improvement for
some sources,
no change for dominant SR



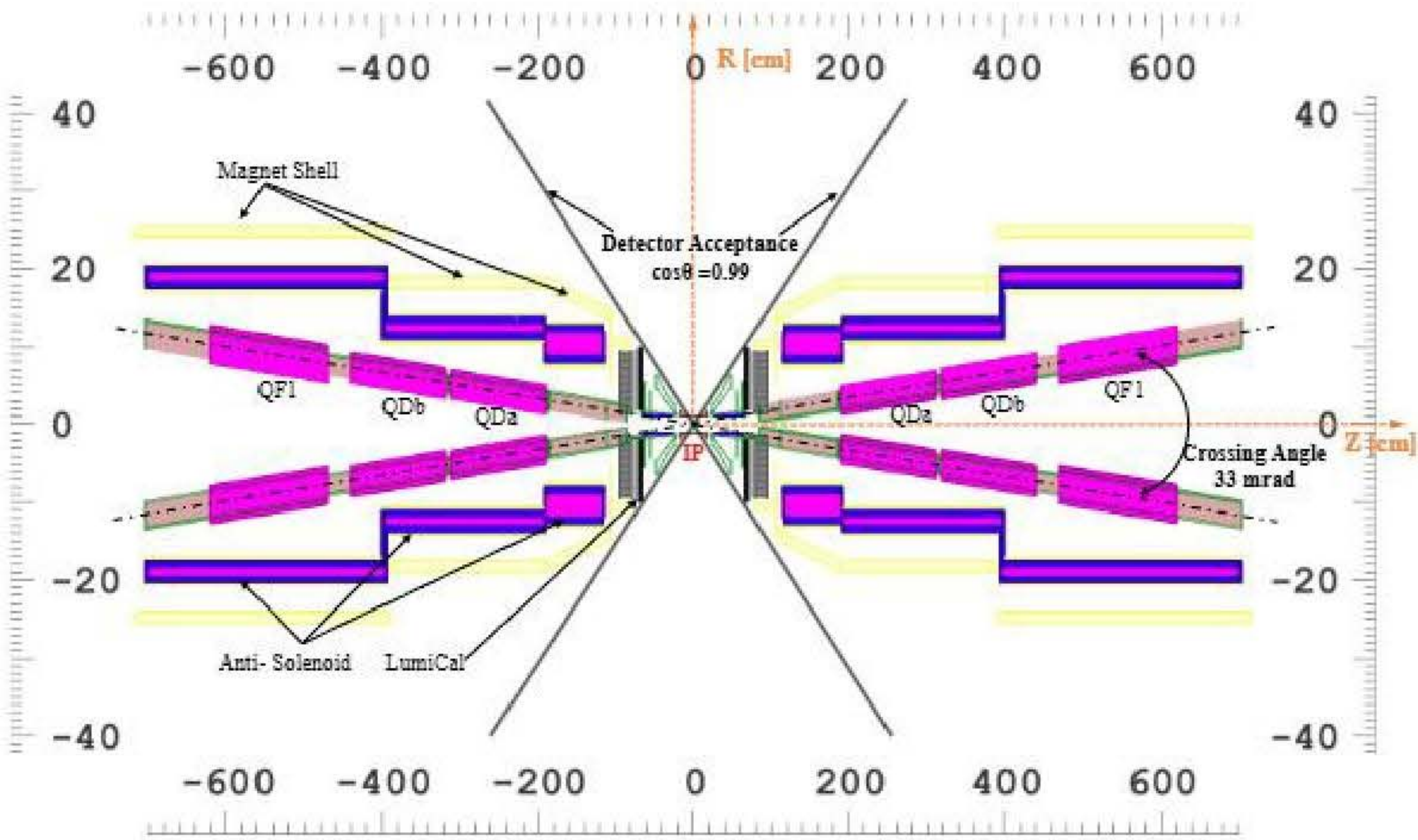
Time Projection Chamber (ILD):
ion production



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/P air 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		

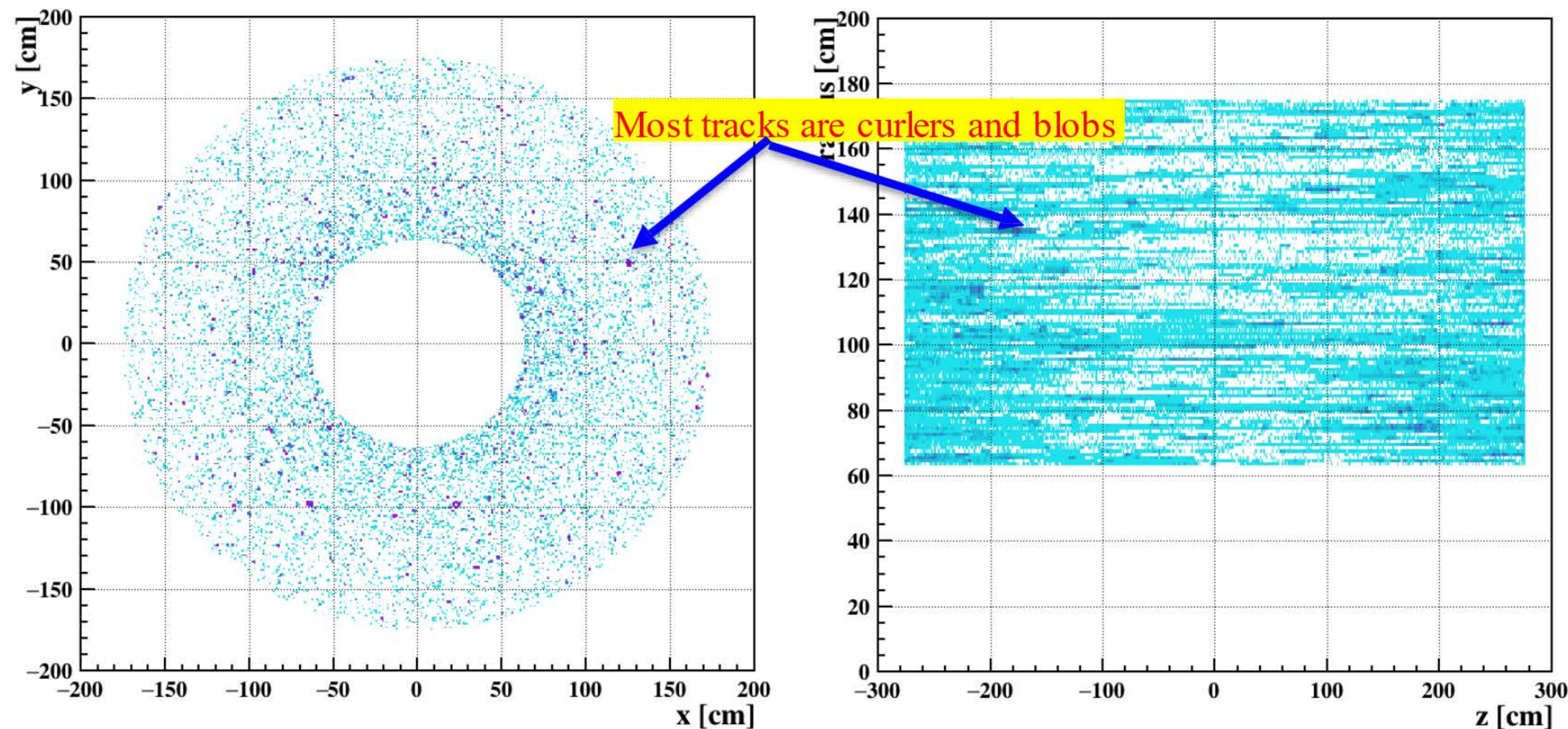


BG events display

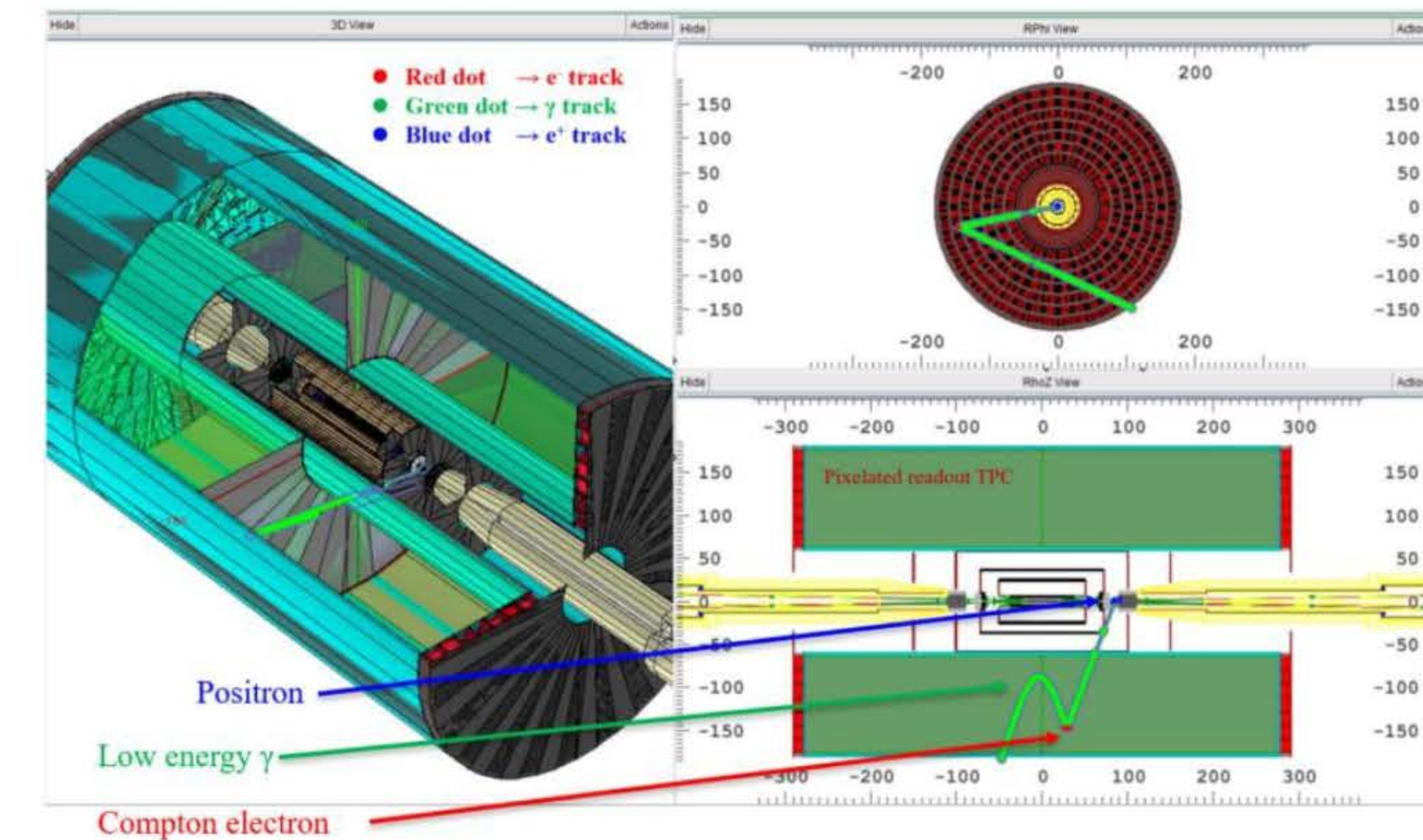
- Very few particles have enough energy to leave TPC
- Most of BG hits consist of more or less randomly distributed **blobs or curlers**
 - Sometimes called “**salt and pepper**” background
 - Caused by extremely low-energy electrons (**<1 MeV**)

Xin She, Huirong Qi etc.
[10.1016/j.nima.2025.170776](https://doi.org/10.1016/j.nima.2025.170776)
European Physics Journey
NIMA

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



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

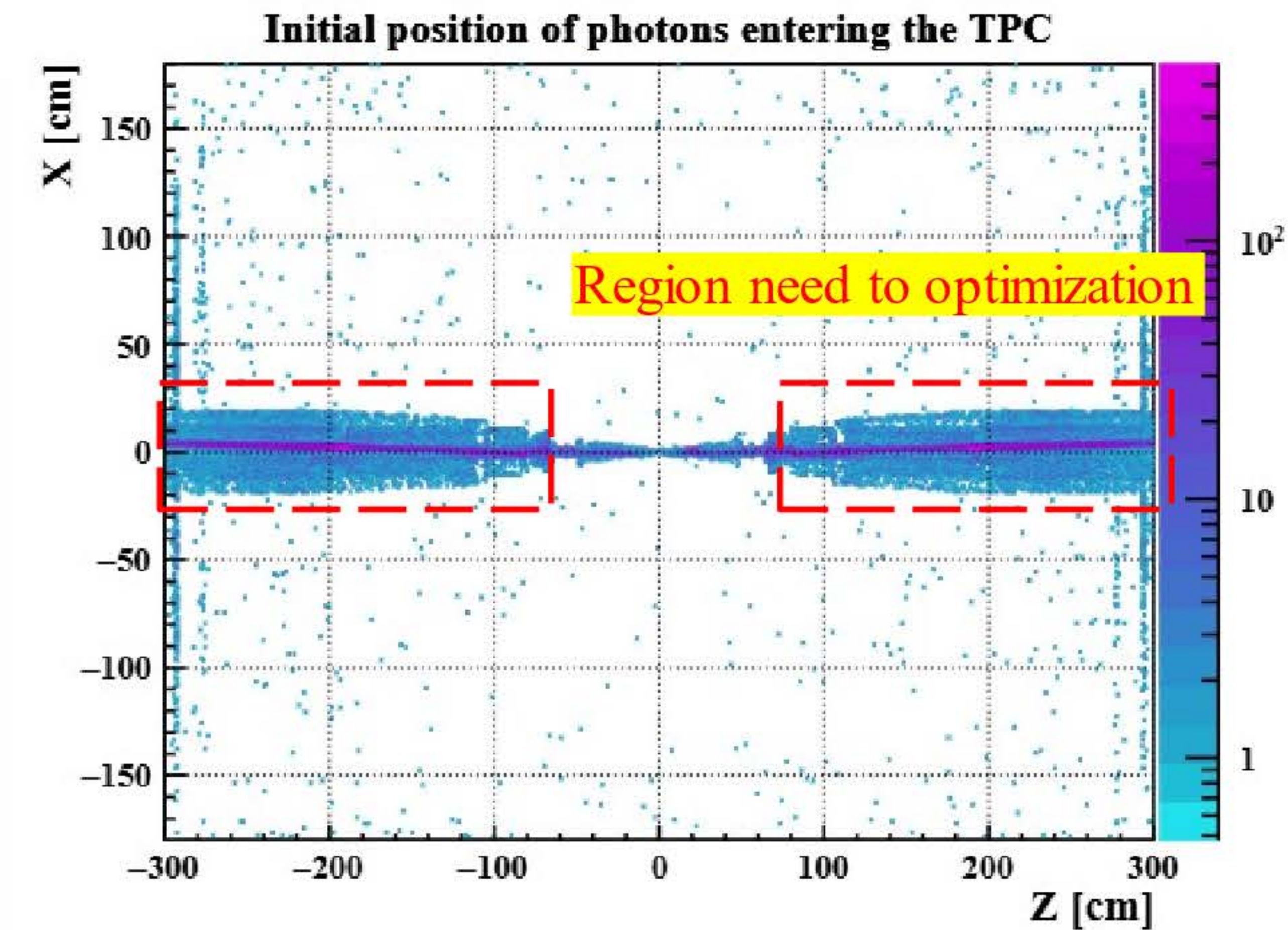
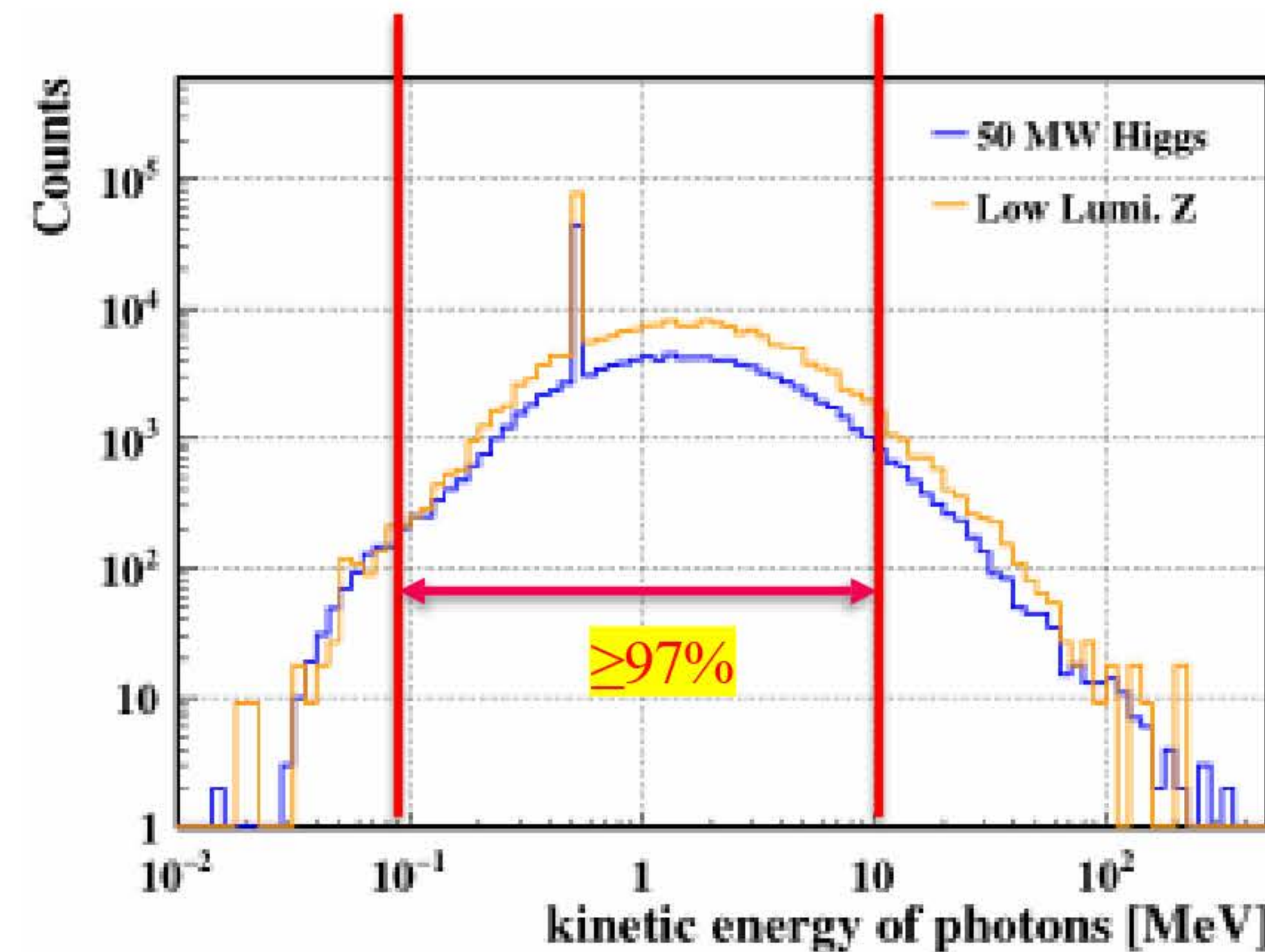
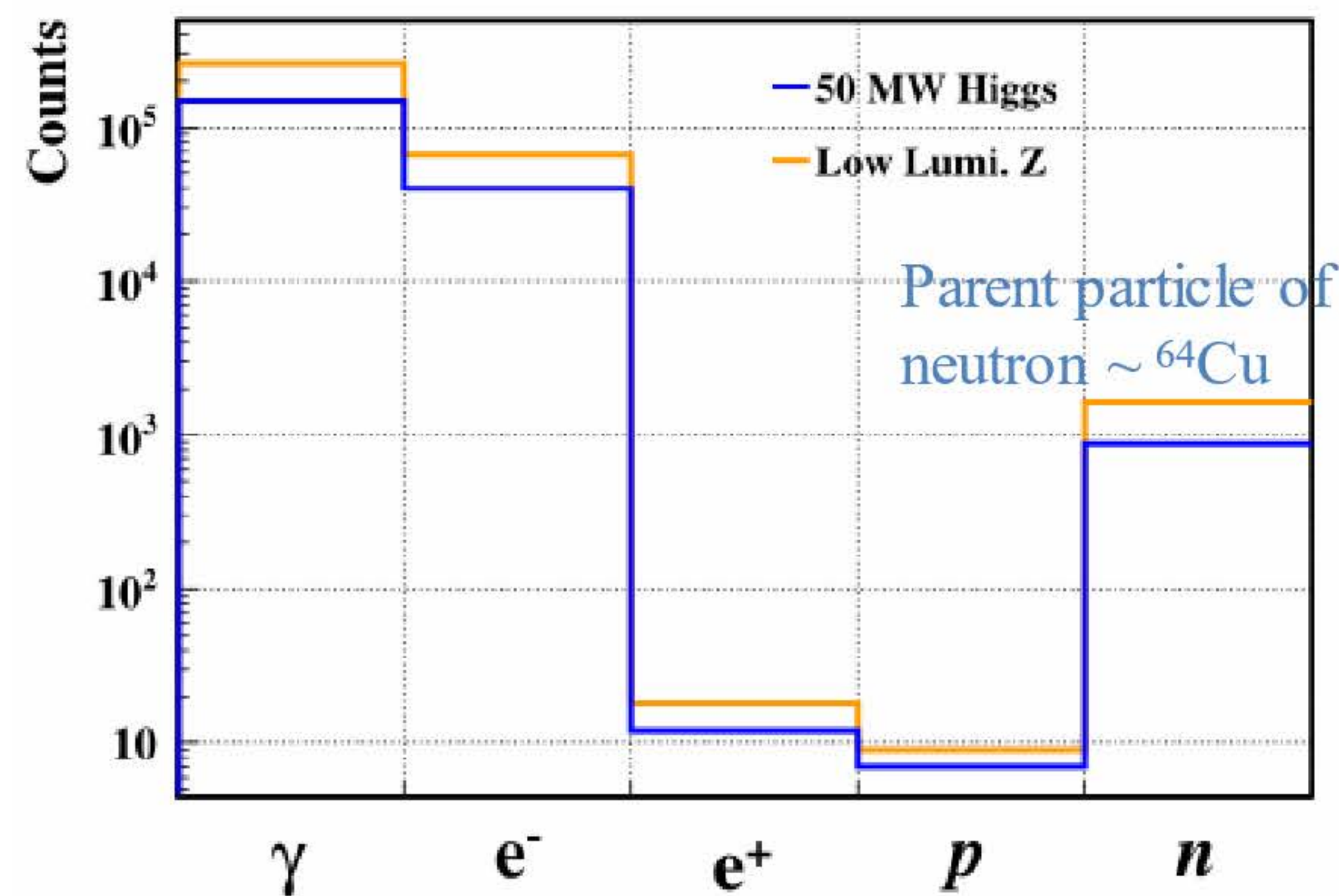


➤ Typical event display:

- 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

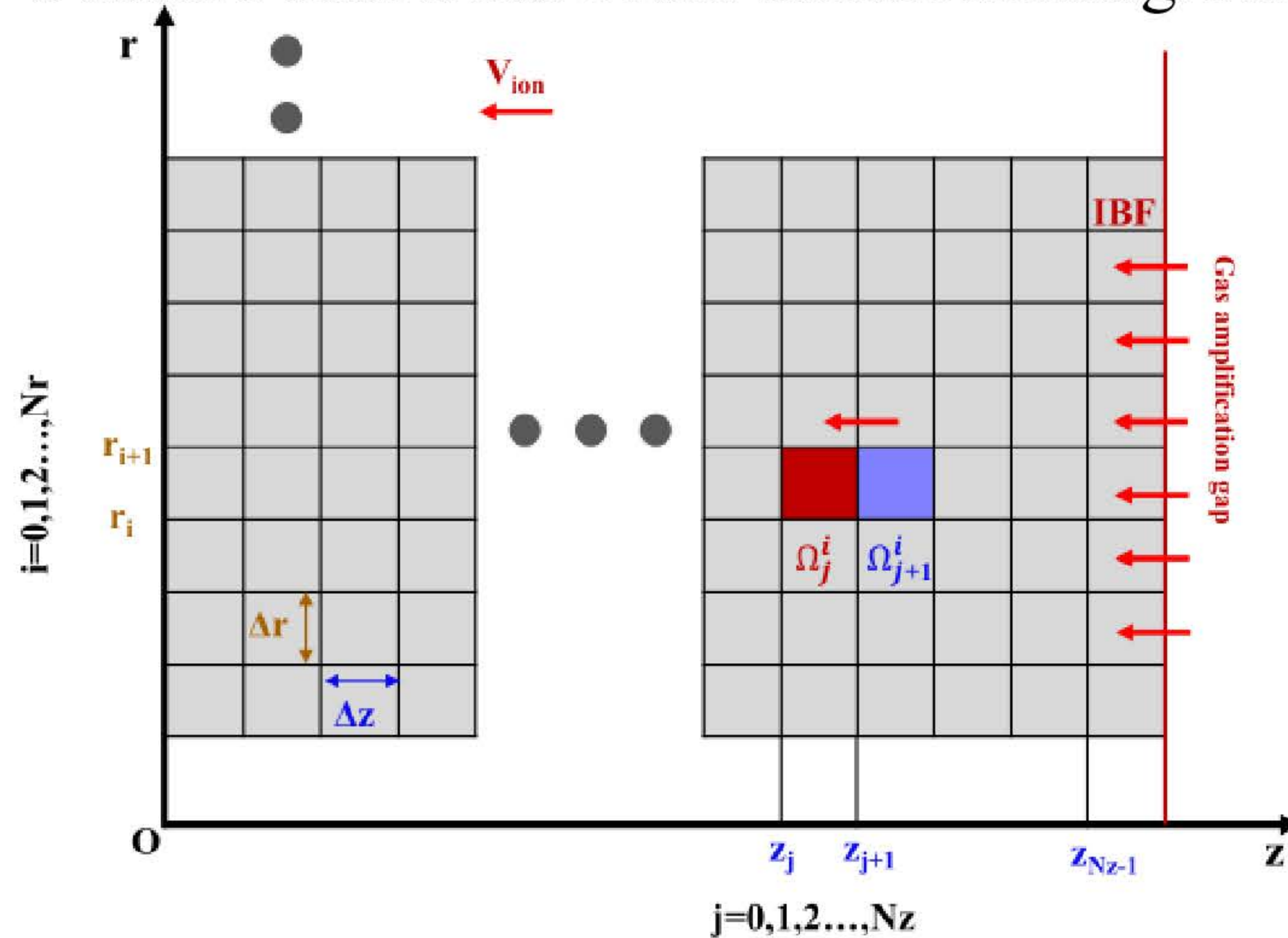
- **Photons** and **electrons** (produced by low energy photons) are the main components in the TPC volume
 - The rest of particles, like positrons, proton and neutron, are negligible
- Low-energy photons (< 10 MeV) are the main contribution of the space charge
 - Photons originating from the **downstream 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 $V_{\text{ion}} = 5 \text{ m/s}$
 - 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

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

Axisymmetric drift-diffusion equation

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

Full FTCS Update Formula

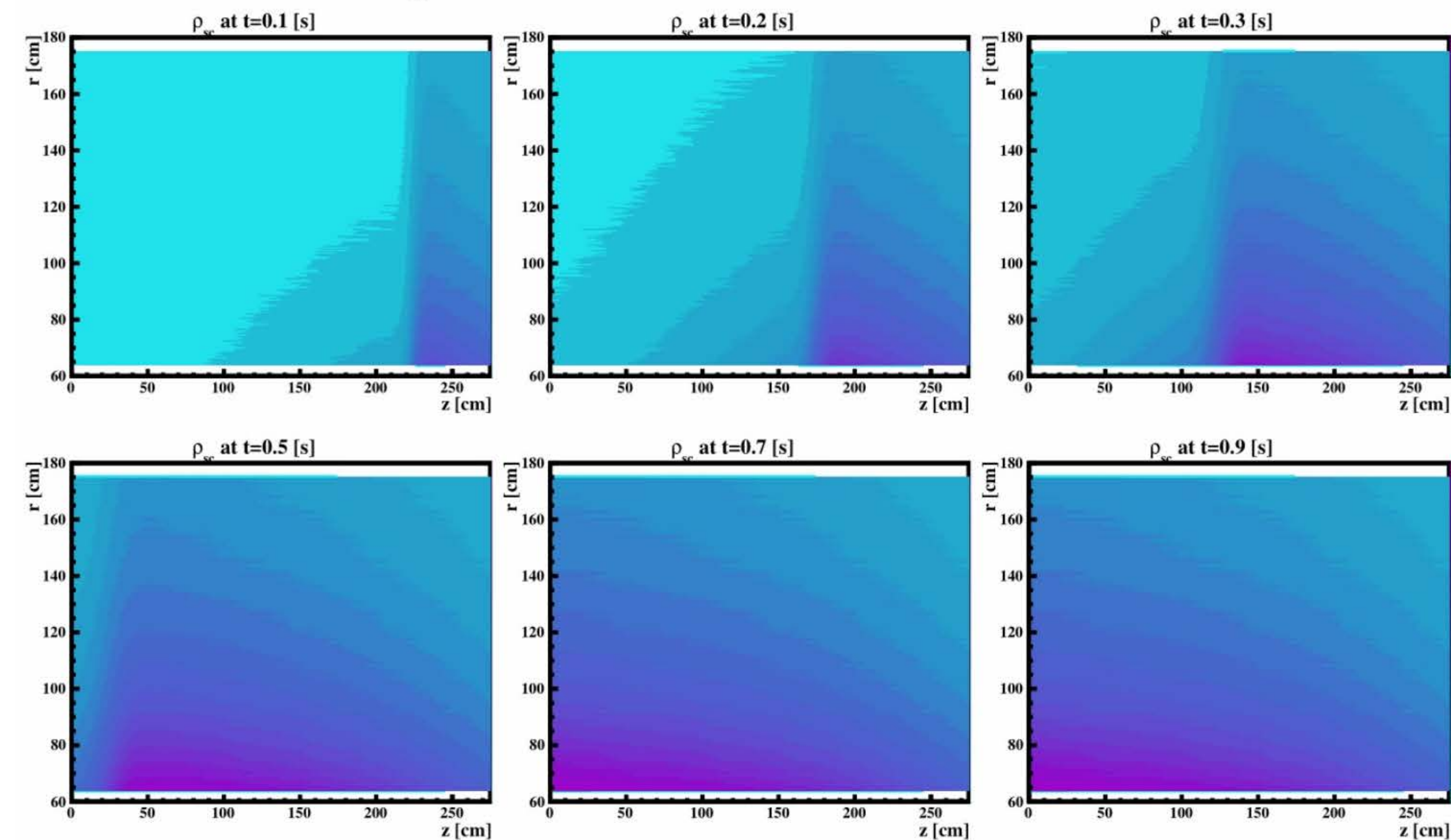
- $S(r,z,t)$: BG source + IBF, from Det. simulation
- $\epsilon = \text{IBF} \times \text{Gain} = 1$
- Grid spacing: $\Delta r = 0.5 \text{ cm}$, $\Delta z = 1 \text{ cm}$ and $\Delta t = 1 \text{ ms}$

Space charge density @ Higgs and Low Z modes

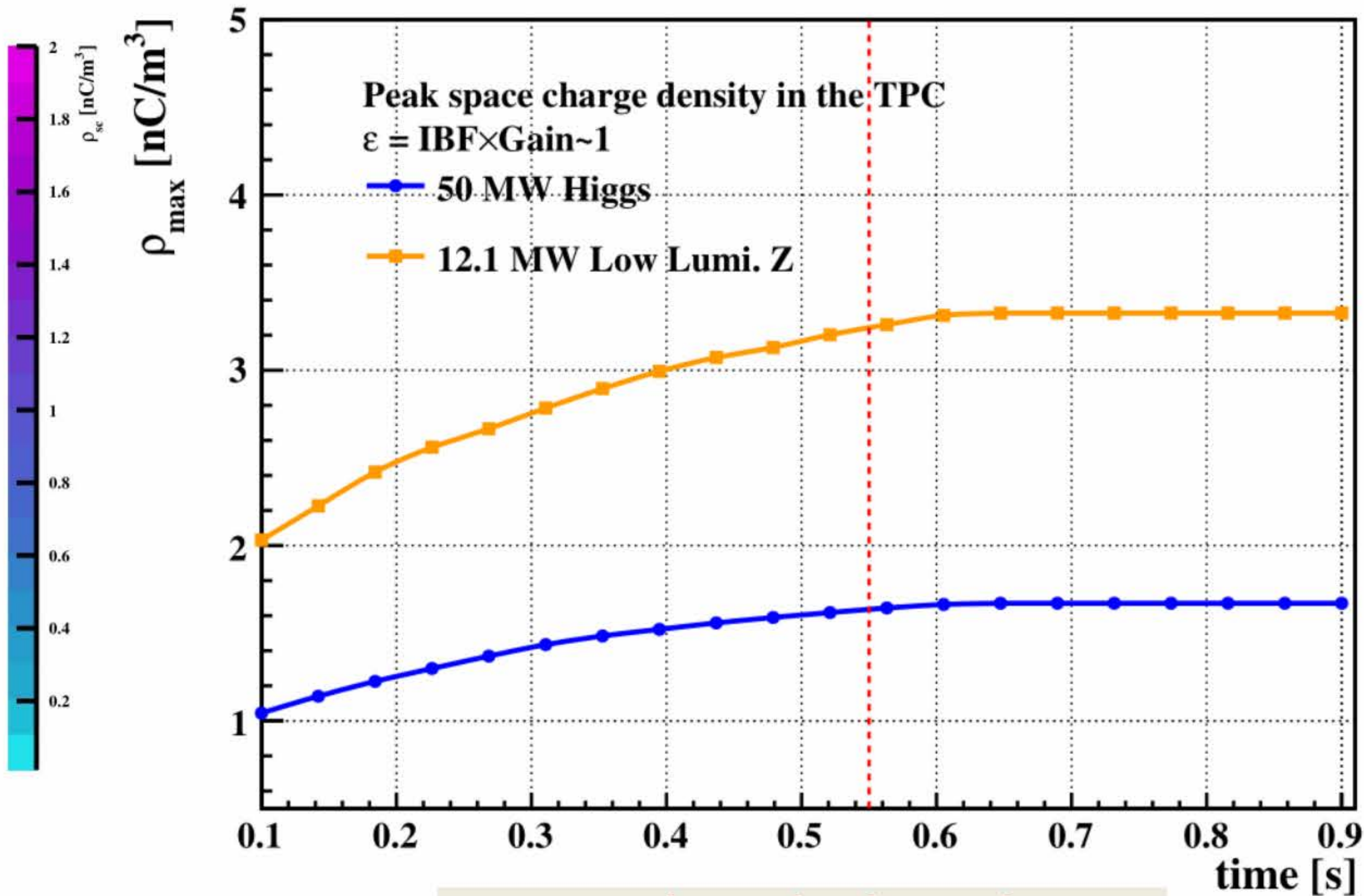
- Time $> 2.75 \text{ m} / V_{\text{ion}} \sim \mathbf{0.55s}$, ion density in the TPC reaches equilibrium
- The max. space charge density @ steady state:
 - $\mathbf{1.7 \text{ nC/m}^3}$ @ 50 MW Higgs mode
 - $\mathbf{3.3 \text{ nC/m}^3}$ @ Low Lumi. Z mode



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



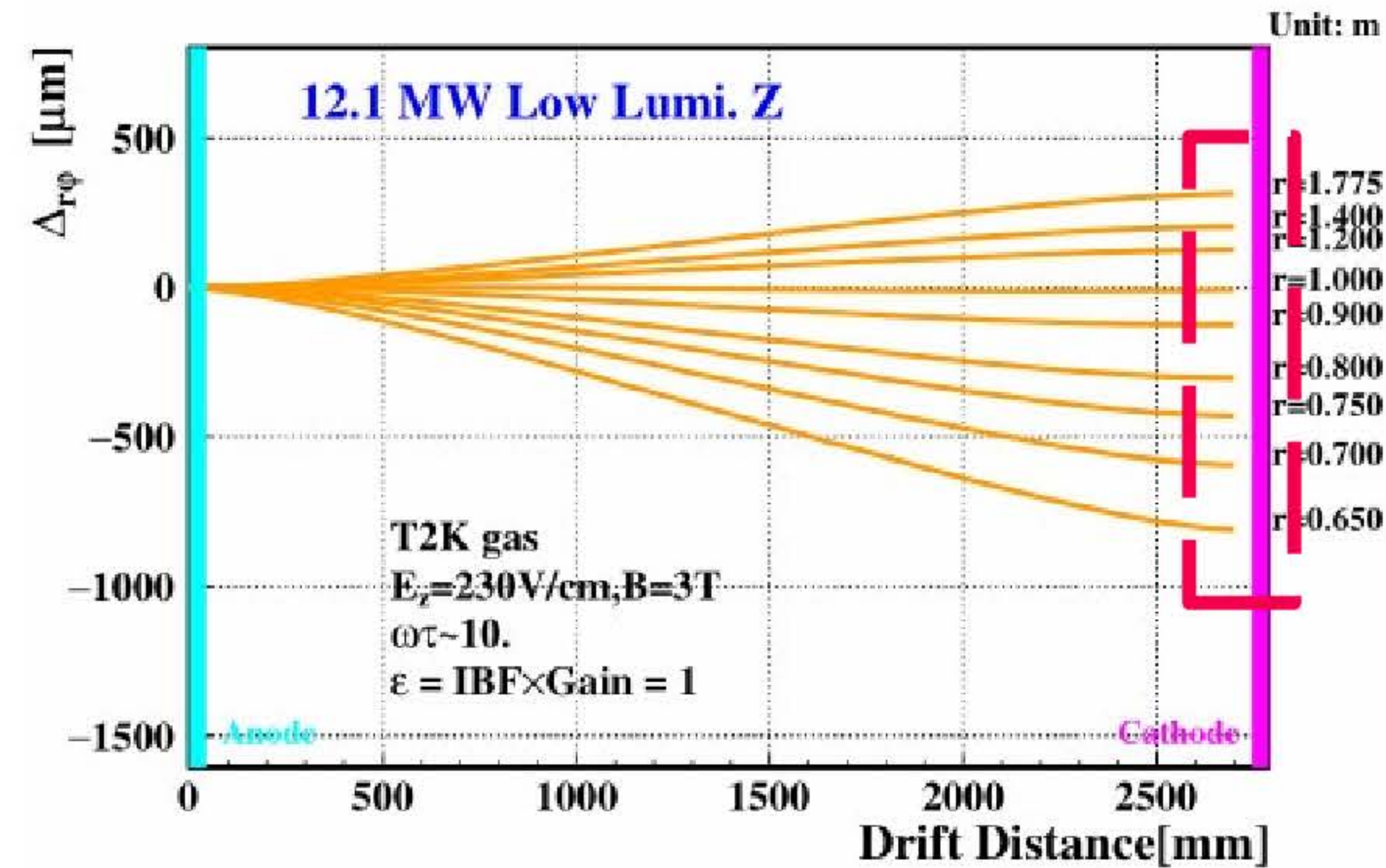
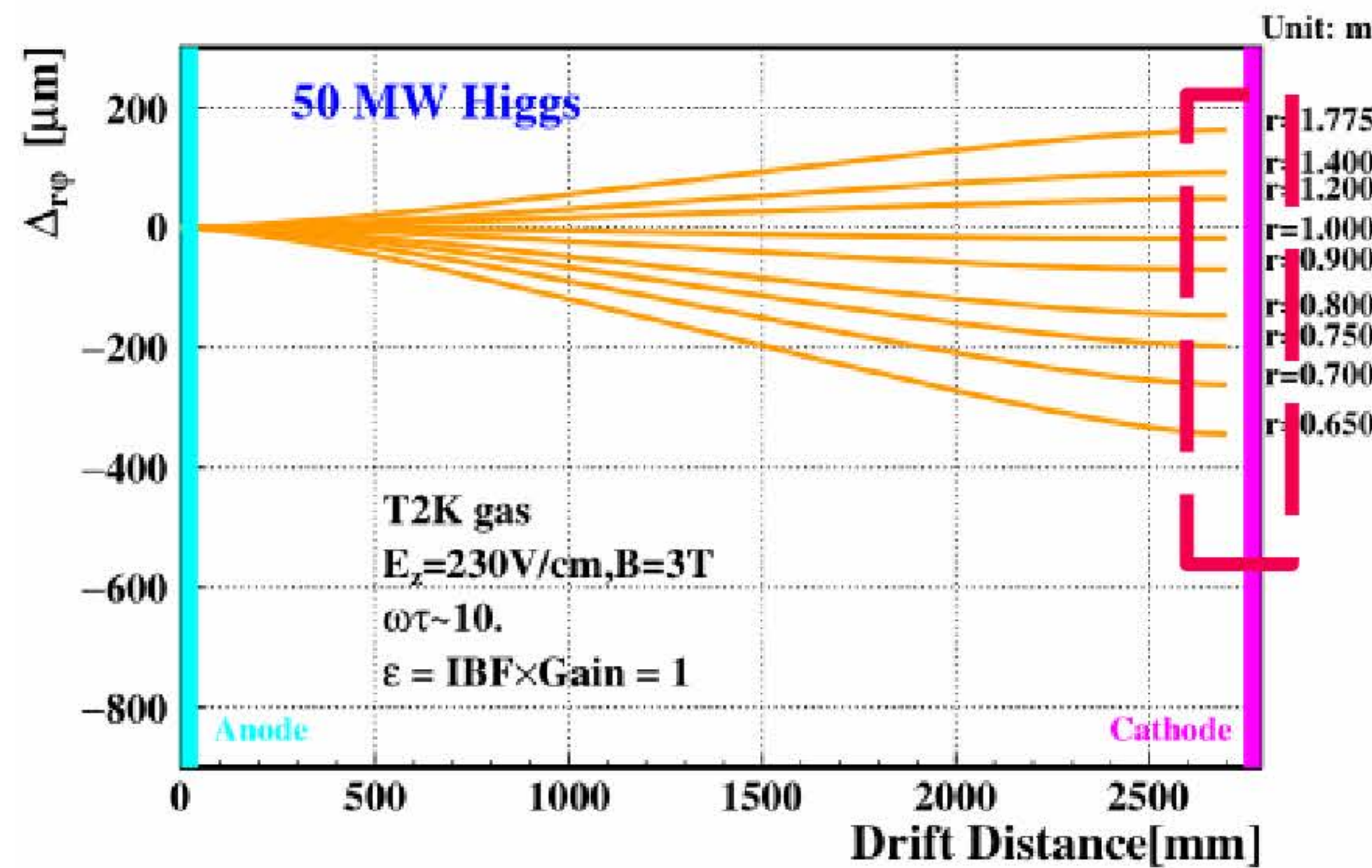
Time evolution of ion density in the TPC @ 50 MW Higgs mode



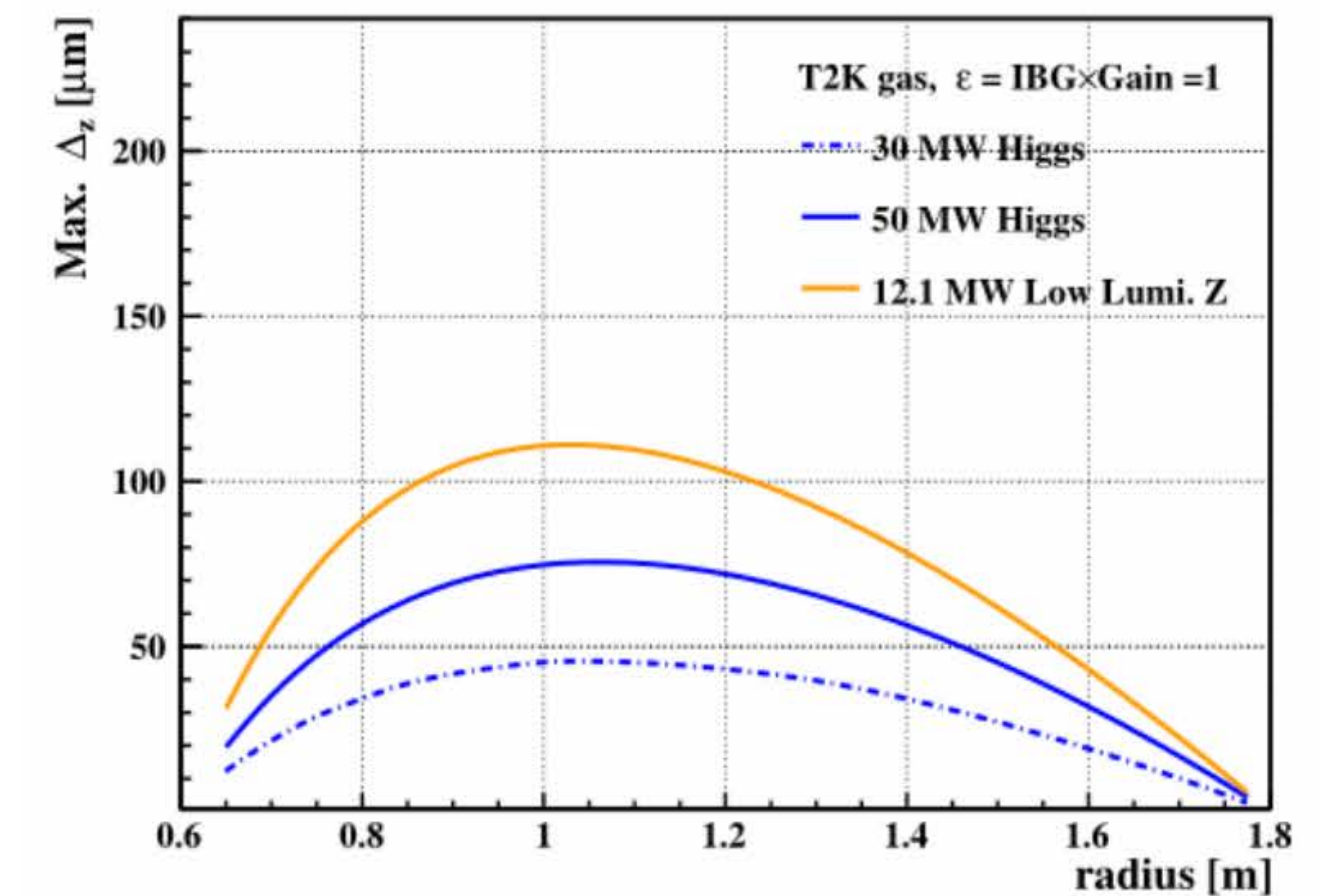
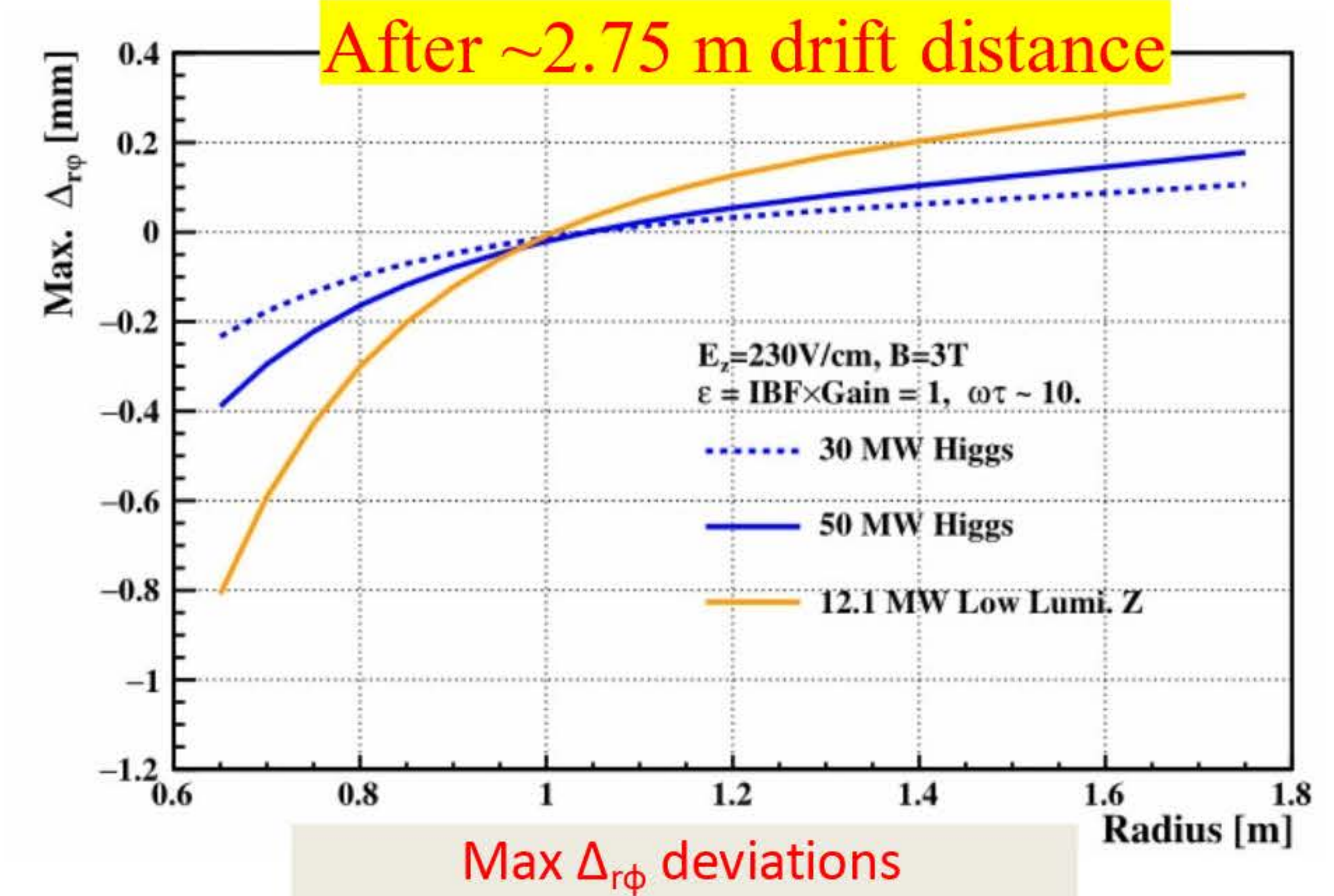
Space charge density v.s. time

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. Δr_ϕ 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



Δr_ϕ Deviations v.s. Drift distance in the Higgs and low-luminosity Z modes



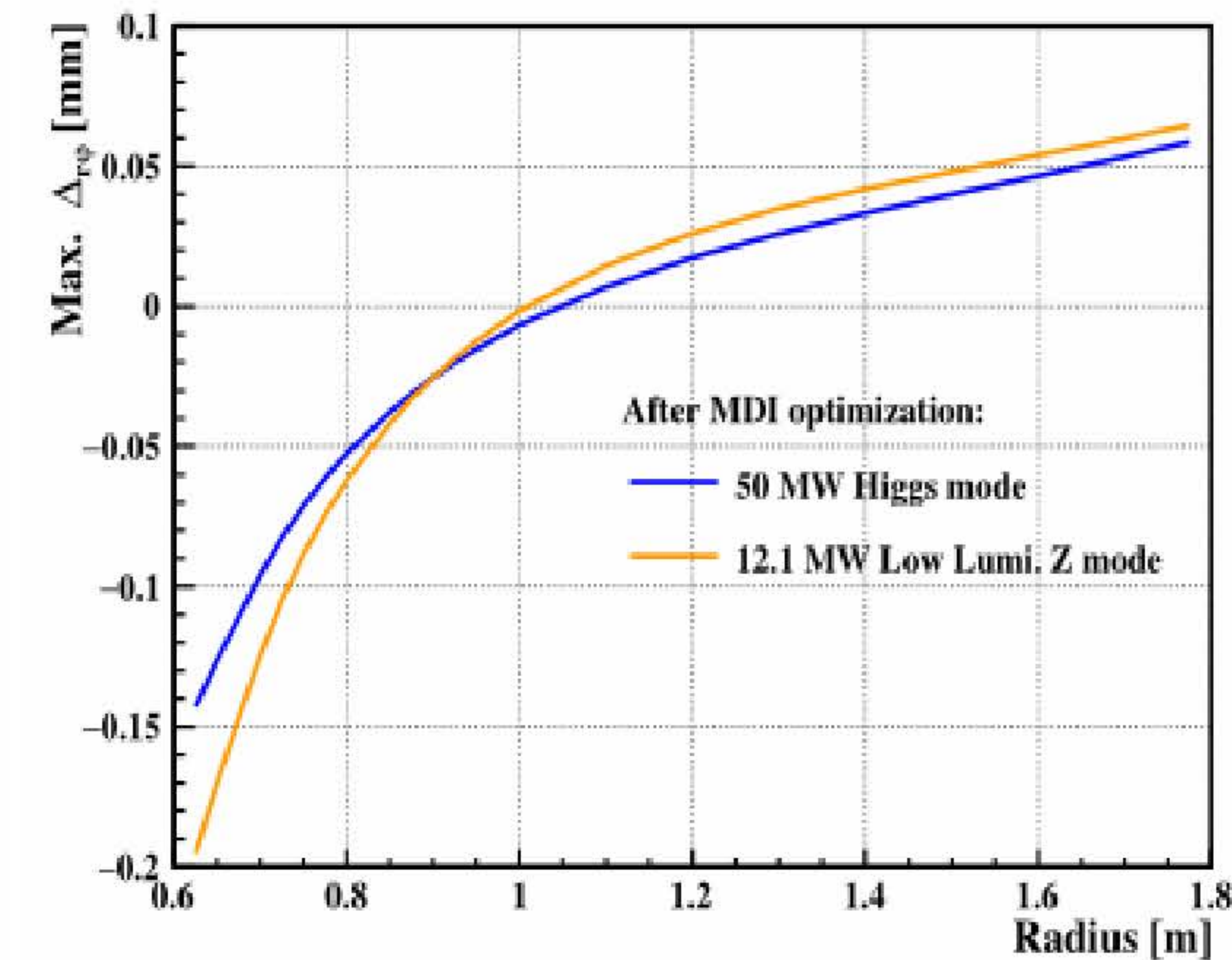
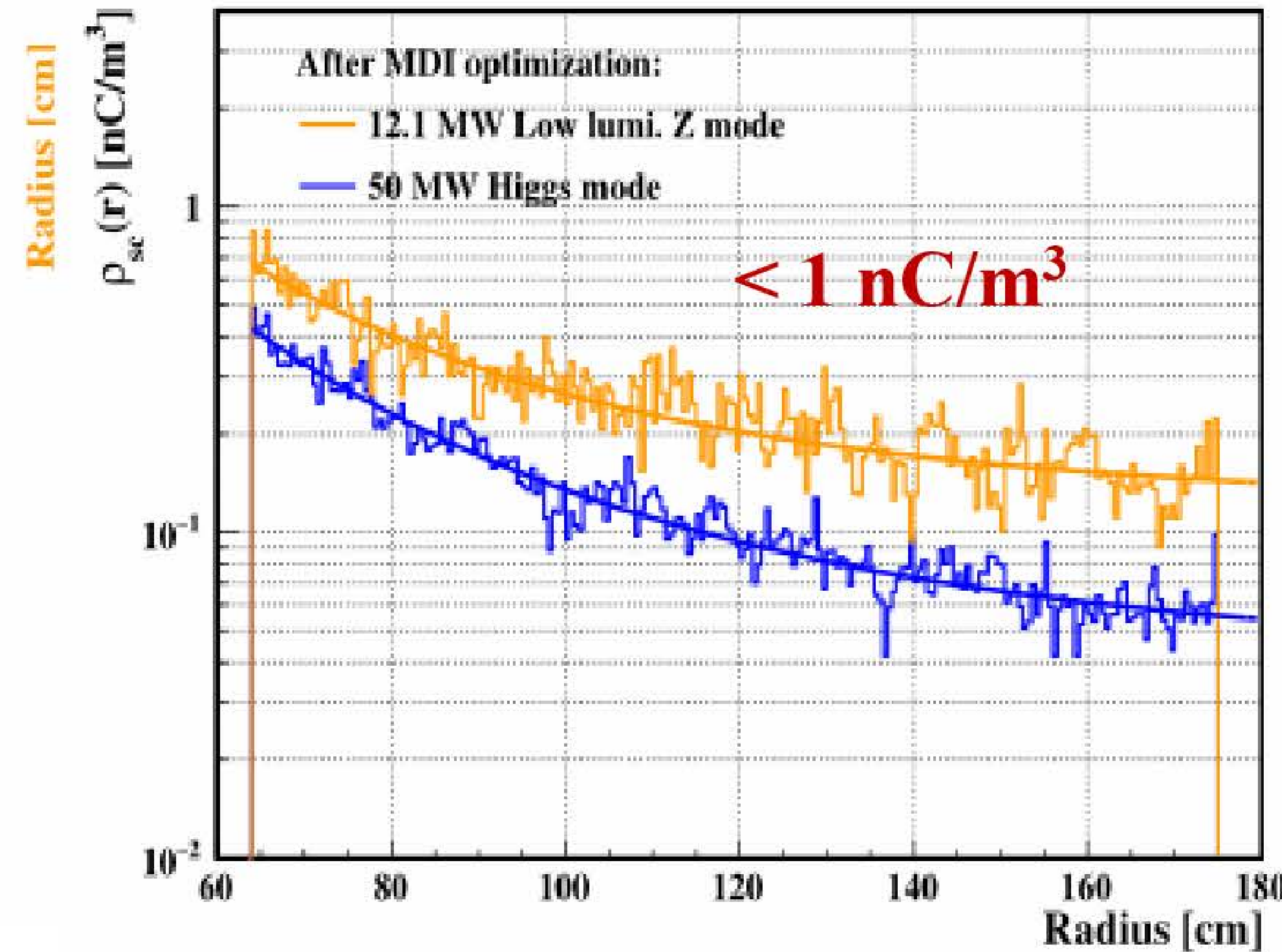
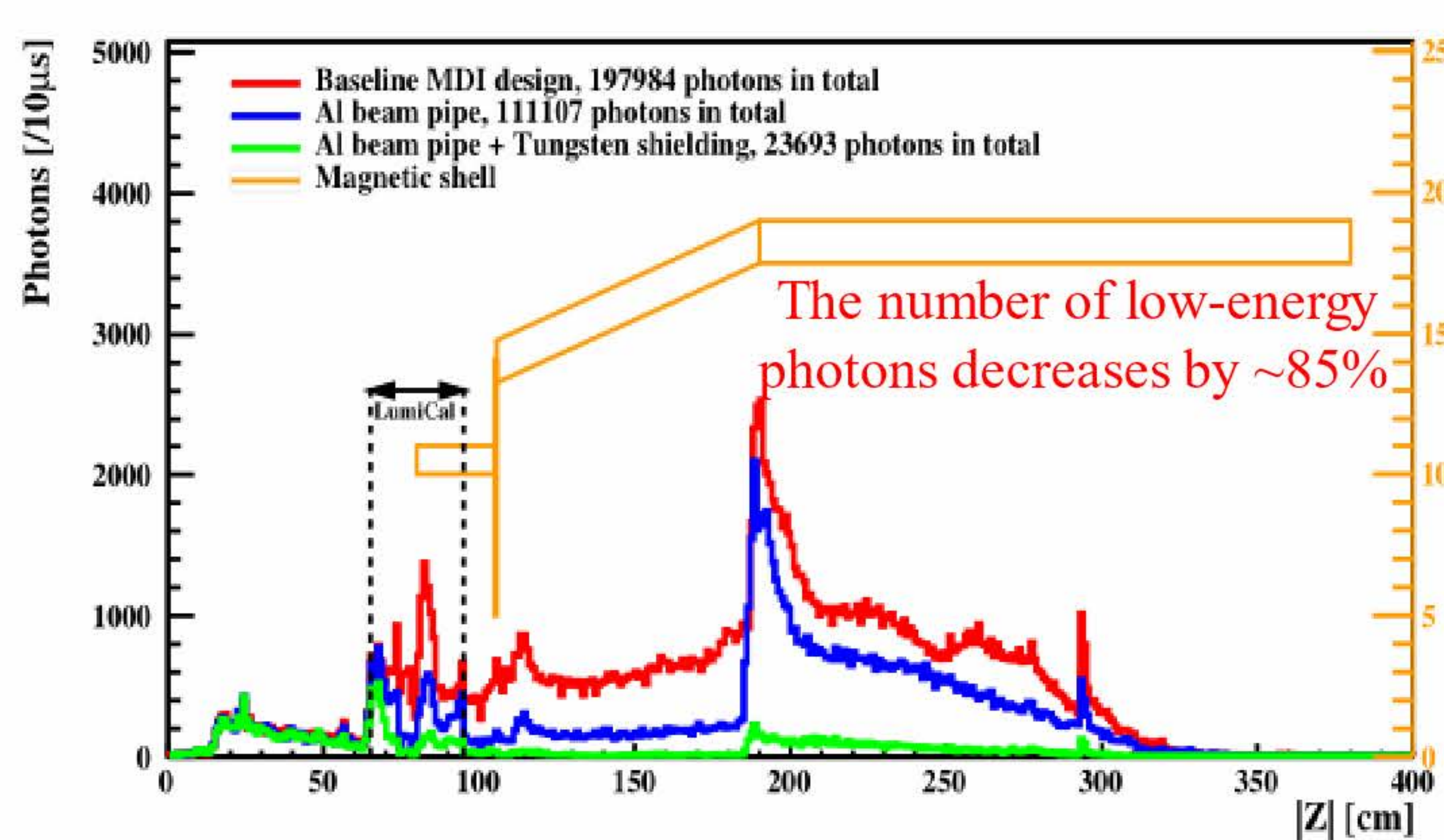
Max Δz deviations

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 $\rightarrow$ Aluminum)
 - Shielding of the magnetic shell (1 mm stainless steel $\rightarrow$ 15mm Tungsten) $\rightarrow$
 - Electron drift deviation in $r\phi < 150 \mu\text{m}$
- 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](https://doi.org/10.1140/epjs/s11734-026-02404-w)
European Physics Journey

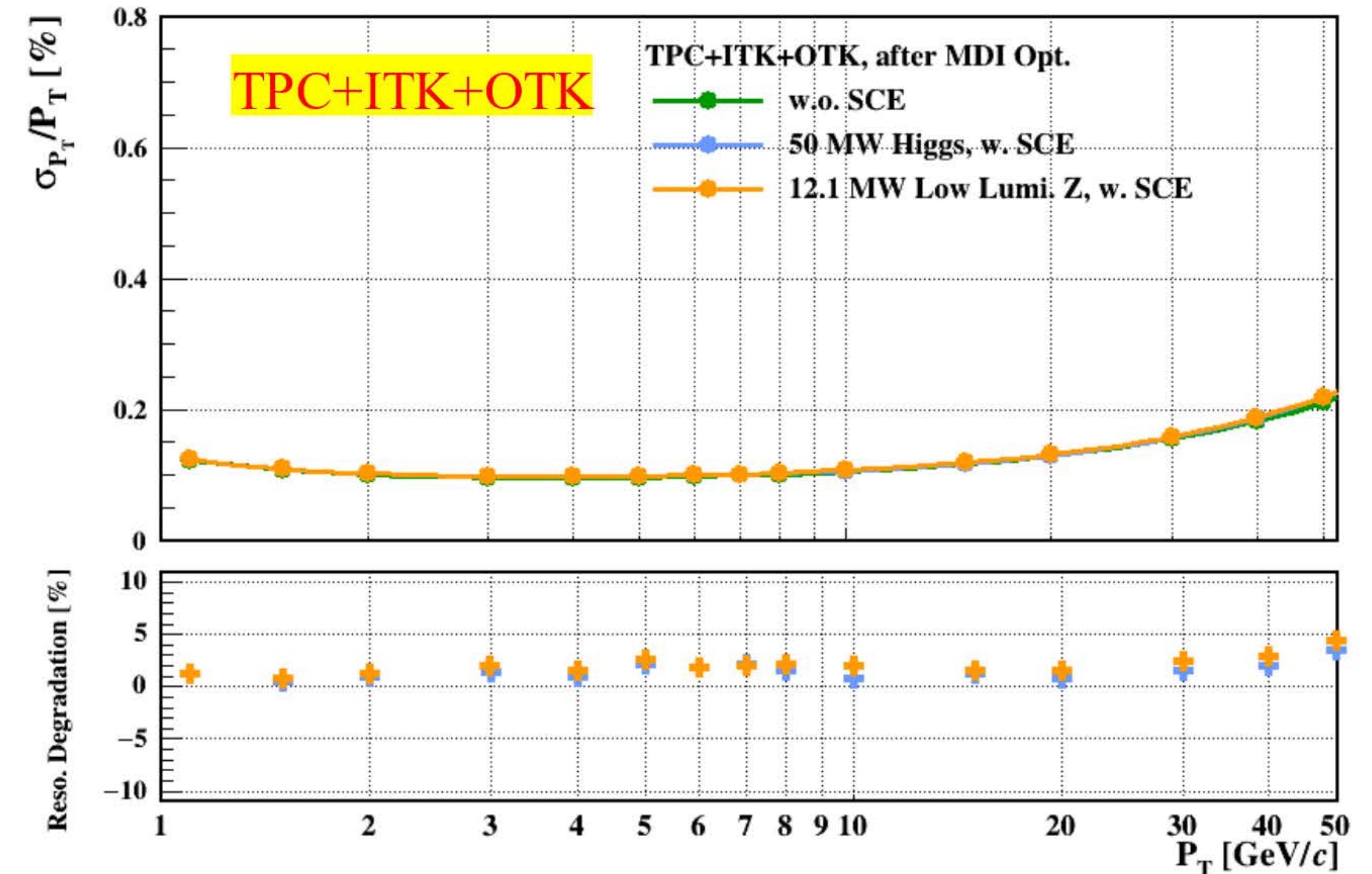
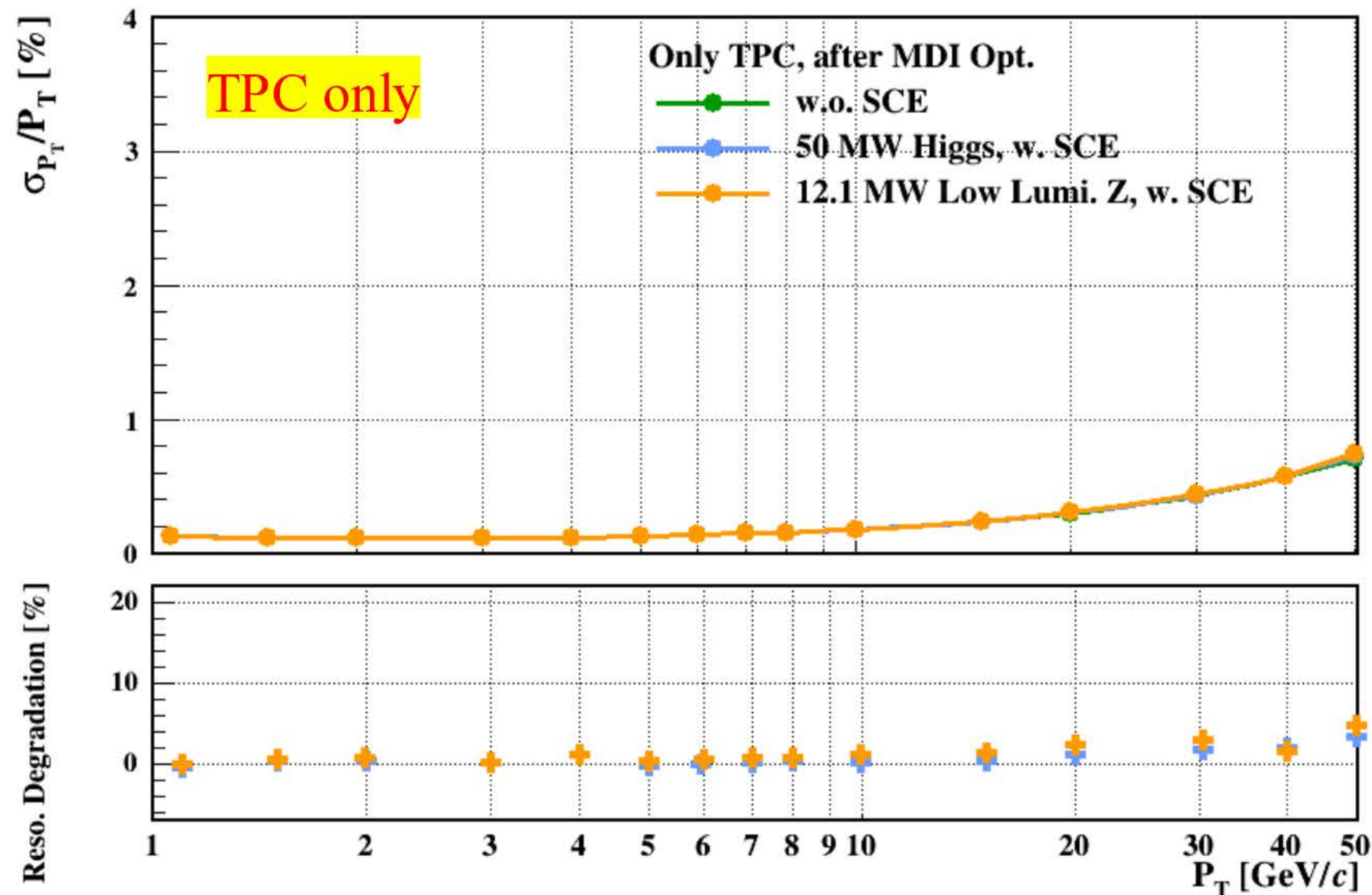
Al beam pipe + W shielding



Distributions of the initial $|z|$ positions entering the TPC and space charge density after optimization, [DOI:10.1140/epjs/s11734-026-02404-w](https://doi.org/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 optimization
 - 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

Summary

- To meet the physics demands of future e^+e^- colliders, **the IHEP team has devoted over than 15 years R&D**, from pad readout to high-granularity readout, combining simulation and experiment validation.
- **High granularity readout TPC** is choose as the baseline detector as main track in CEPC TDR. The full simulation flow of the BG has been established, and the full SR background simulation and MDI collaborative design.
- Synergies with **CEPC and FCCee** allow us to continue R&D and ongoing. Team actively involved in the international collaborations.

Many thanks!



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