Study of a High Granularity Readout TPC for Particle Identification at Future e^+e^- Colliders

Huirong Qi

Institute of High Energy Physics, CAS

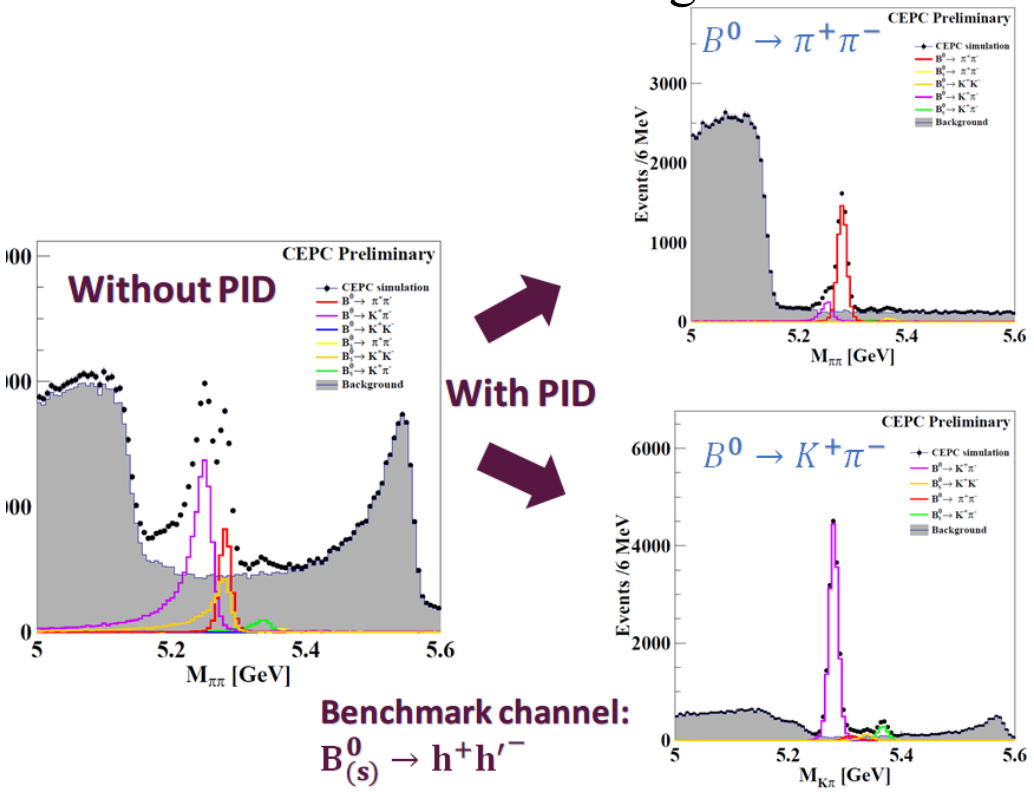
CPAD 2026 Instrumentation and detector R&D workshop, 21 October 2026, Seattle, WA

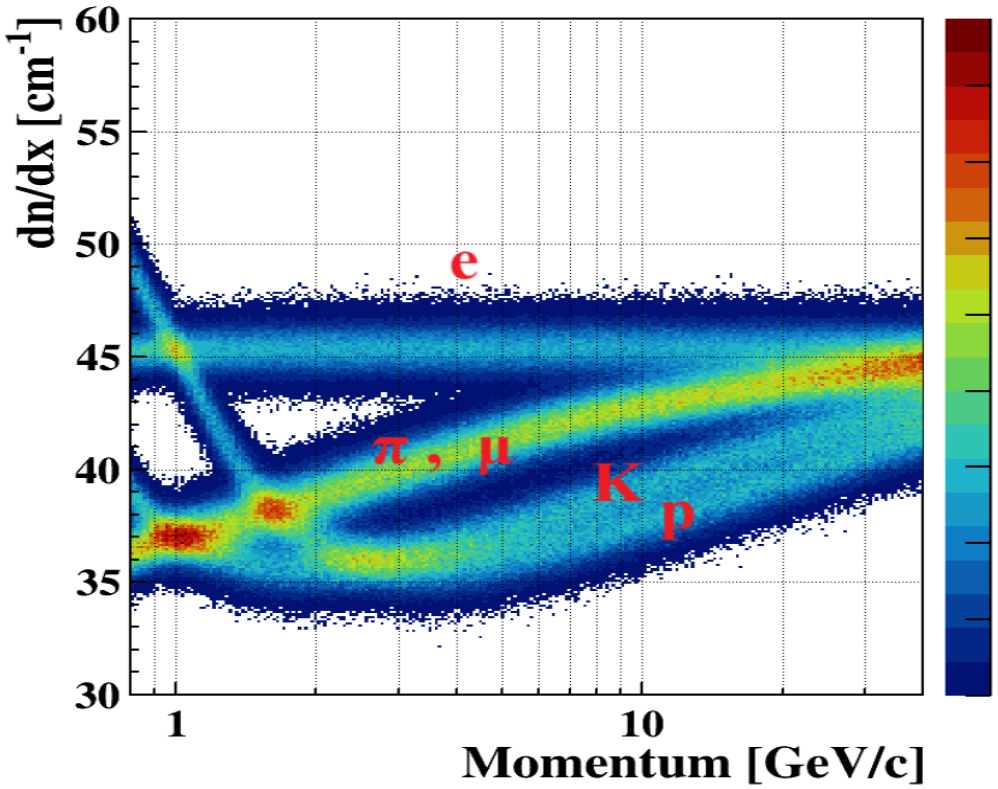
Content

- **Motivation**
- **Status of TPC in CEPC TDR**
- **Simulation and prototypes**
- **Summary**

Physics requirements in CEPC / FCCee

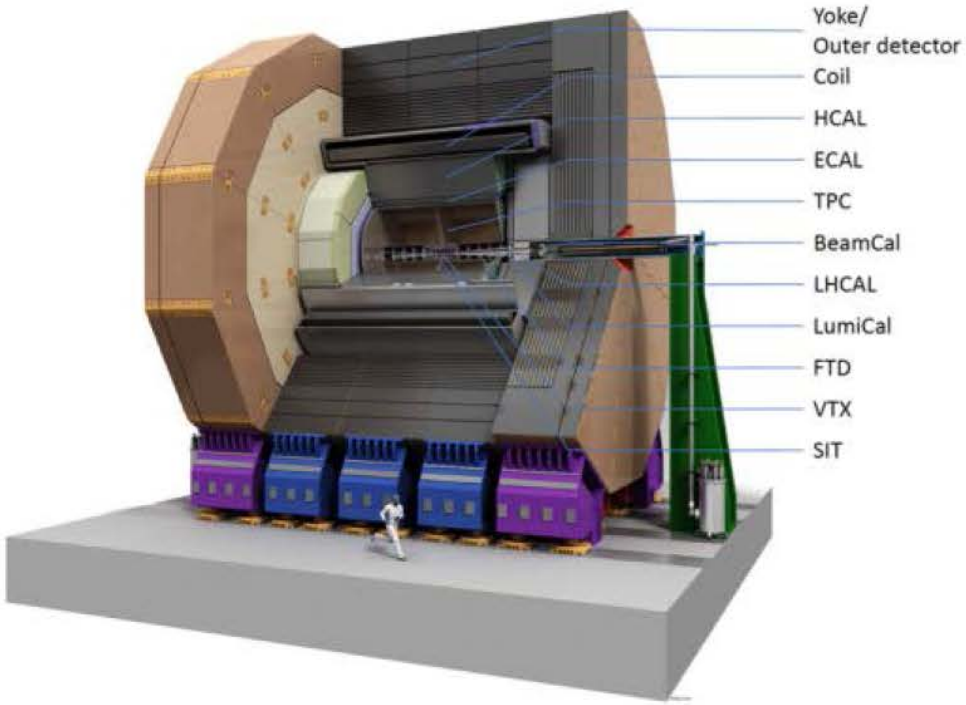
- Circular e+e- collider operation stages in TDR: **10-years Higgs @3T → 2-years Z pole → 1-year W**
- Gaseous tracker leading contribution to PID and the high resolution: jet & differential
  - High granularity readout readout and better than 2σ separation power between πand k for P using dn/dx

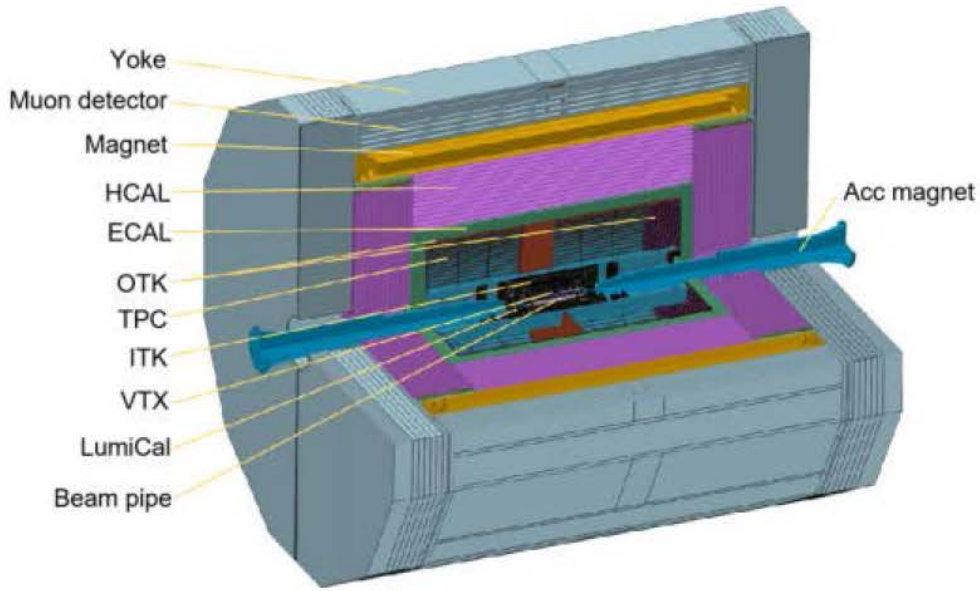




Motivation and physics requirements

- 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.



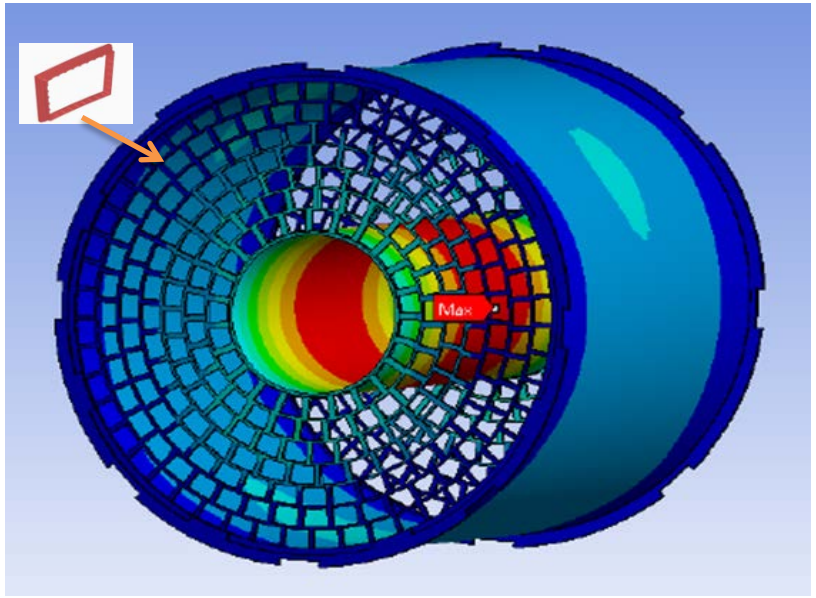


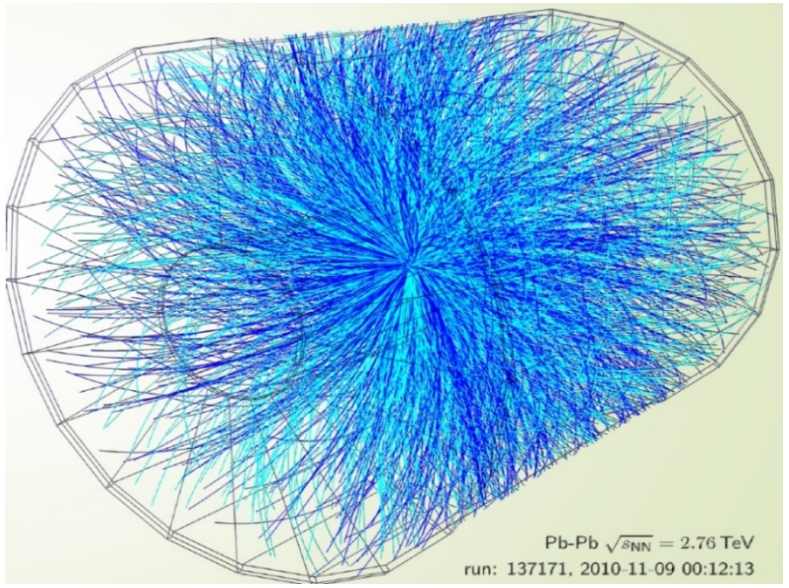
https://arxiv.org/abs/1811.10545

https://arxiv.org/abs/2203.08310

Time Projection Chamber Technology

- 3D high precision resolution track reconstruction with the Ultra light material budget
  - High precision resolution (**~100 µm**) with thousands hits per track
  - High momentum resolution (**~10^{-4} GeV/c**) and High capabilities for the Particle Identification (**PID: ~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

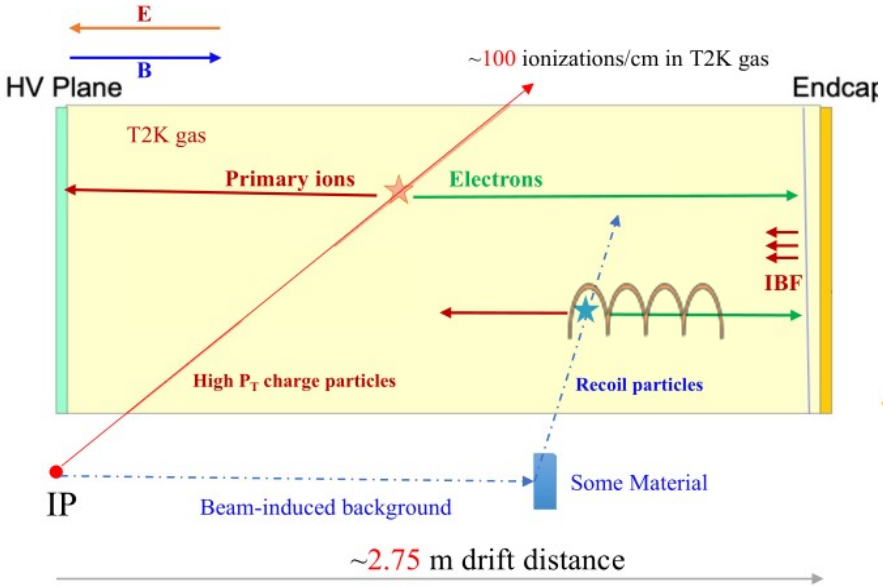




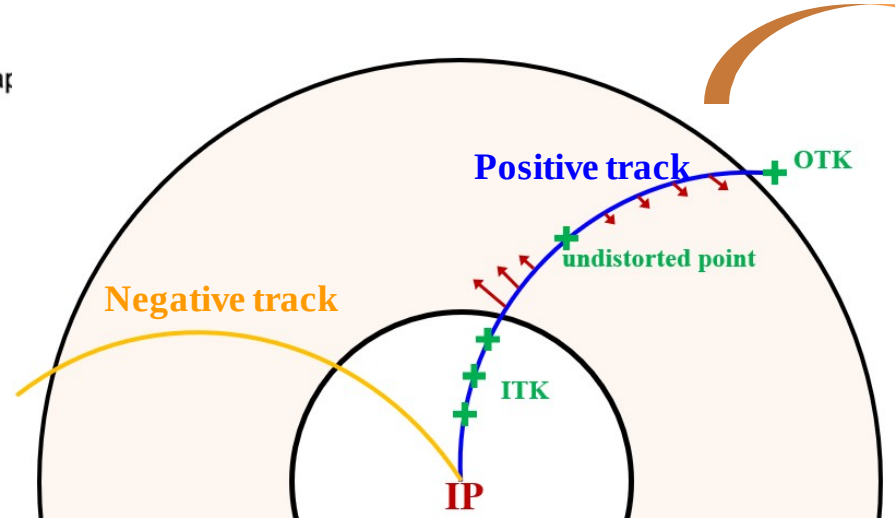
TPC challenges

- The Reference Detector is designed and optimized primarily for the Higgs and low-luminosity Z modes
  - Peak luminosity reaches $\mathbf{10^{34}}$ and $\mathbf{10^{35}}$ $\mathbf{cm^{-2}\cdot s^{-1}}$, 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

- **Status of TPC in CEPC TDR**

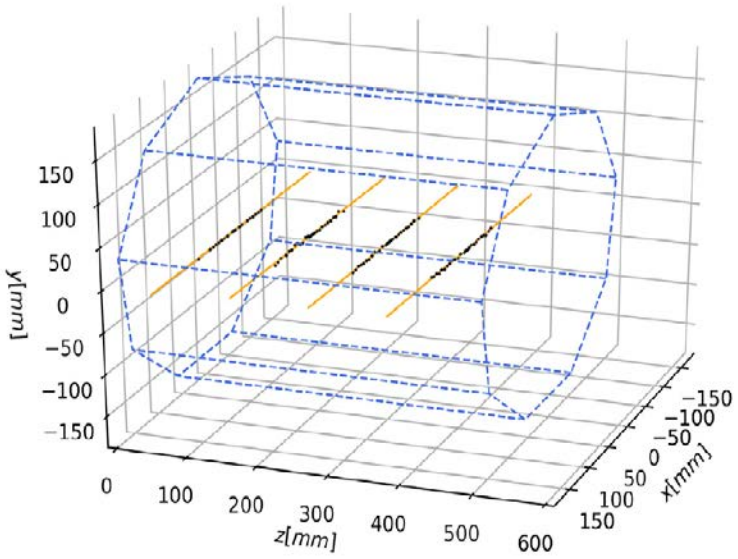
Roadmap of CEPC TPC detector R&D

- **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 **$\sigma_{r\varphi}$≤100 μm and dE/dx resolution of 3.6%**
  - FEE chip: reach ~**3.0mW/ch with ADC** and the pixelated readout R&D

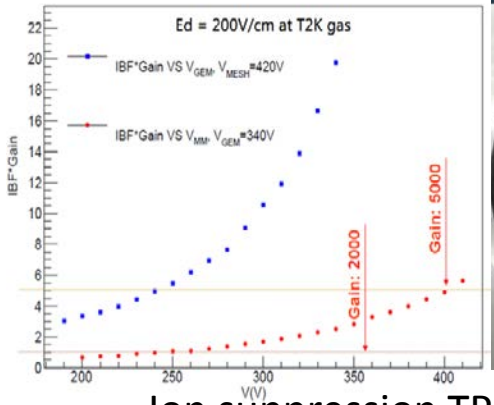
TPC prototype with integrated 266nm UV laser

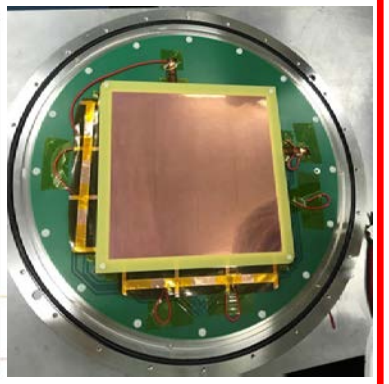


https://doi.org/10.1016/j.nima.2022.167241



Achievement





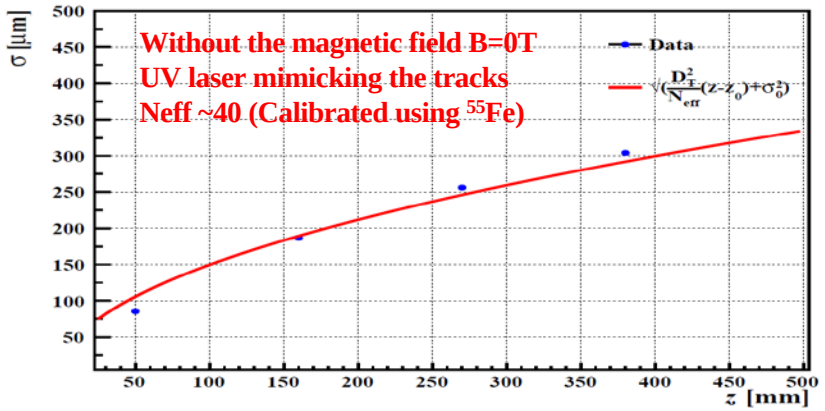
Ion suppression TPC module R&D

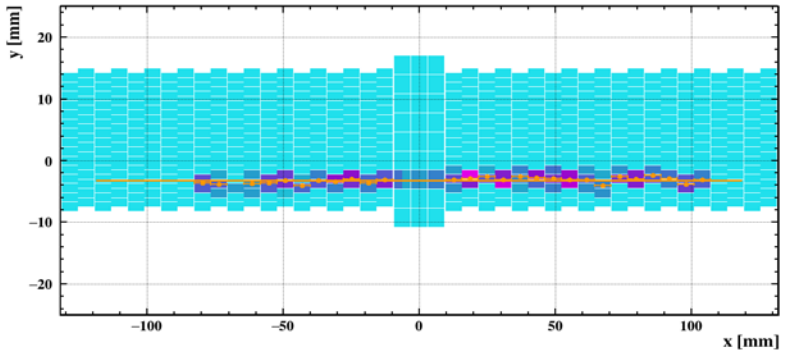
Publications by CEPC TPC group in 2018-2025:

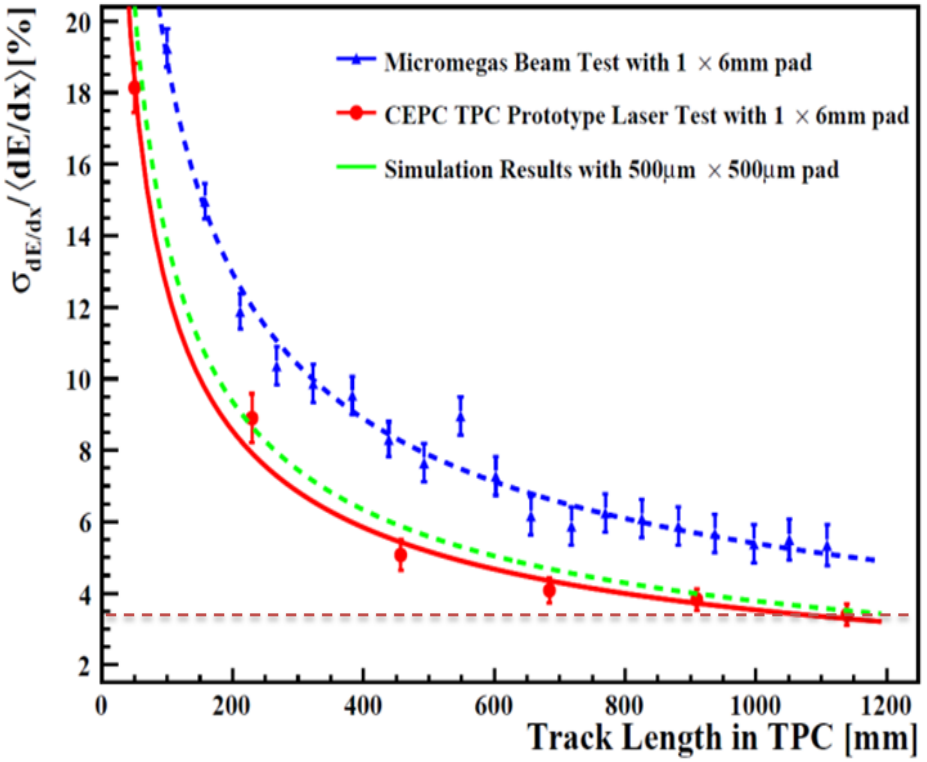
- https://doi.org/10.1088/1748-0221/18/08/E08002
- https://doi.org/10.22323/1.449.0553
- https://doi.org/10.1016/j.nima.2022.167241
- https://doi.org/10.1109/NSS/MIC44867.2021.9875566
- https://doi.org/10.1109/NSS/MIC44845.2022.10399097
- https://doi.org/10.1088/1748-0221/15/09/C09065
- https://doi.org/10.1088/1748-0221/15/05/P05005
- https://dx.doi.org/10.1142/S0217751X20410146
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- https://doi.org/10.7538/yzk.2024.youxian.0916

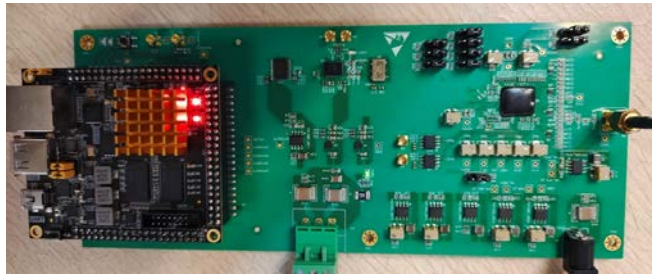
Highlights of TPC prototype integrated with 266nm UV laser tracks

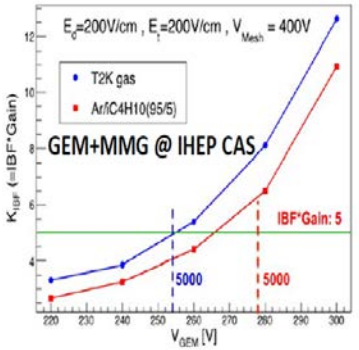
- **Highlights of CEPC TPC R&D and toward reasonable readout TPC**
  - TPC prototype integrated 266nm UV laser tracks has been studied
  - Reconstruction of the tracks and analyzed the UV laser signal
  - Spatial resolution of Pad readout TPC prototype are analyzed
  - PID performance of Pad readout TPC prototype are analyzed

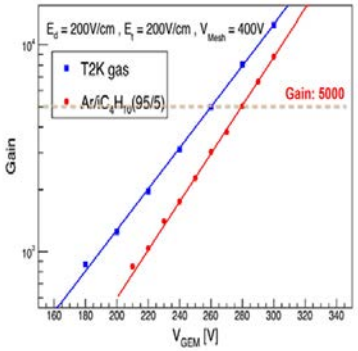












TPC Technology for the High Luminosity HEP Factory

TPC technology detector for e+e- collider

Pad readout TPC
- To meet Higgs physics
- 1mm×6mm of Pad
- < 100mW/cm^2
- dE/dx
- Triple, double GEMs
- Micromegas



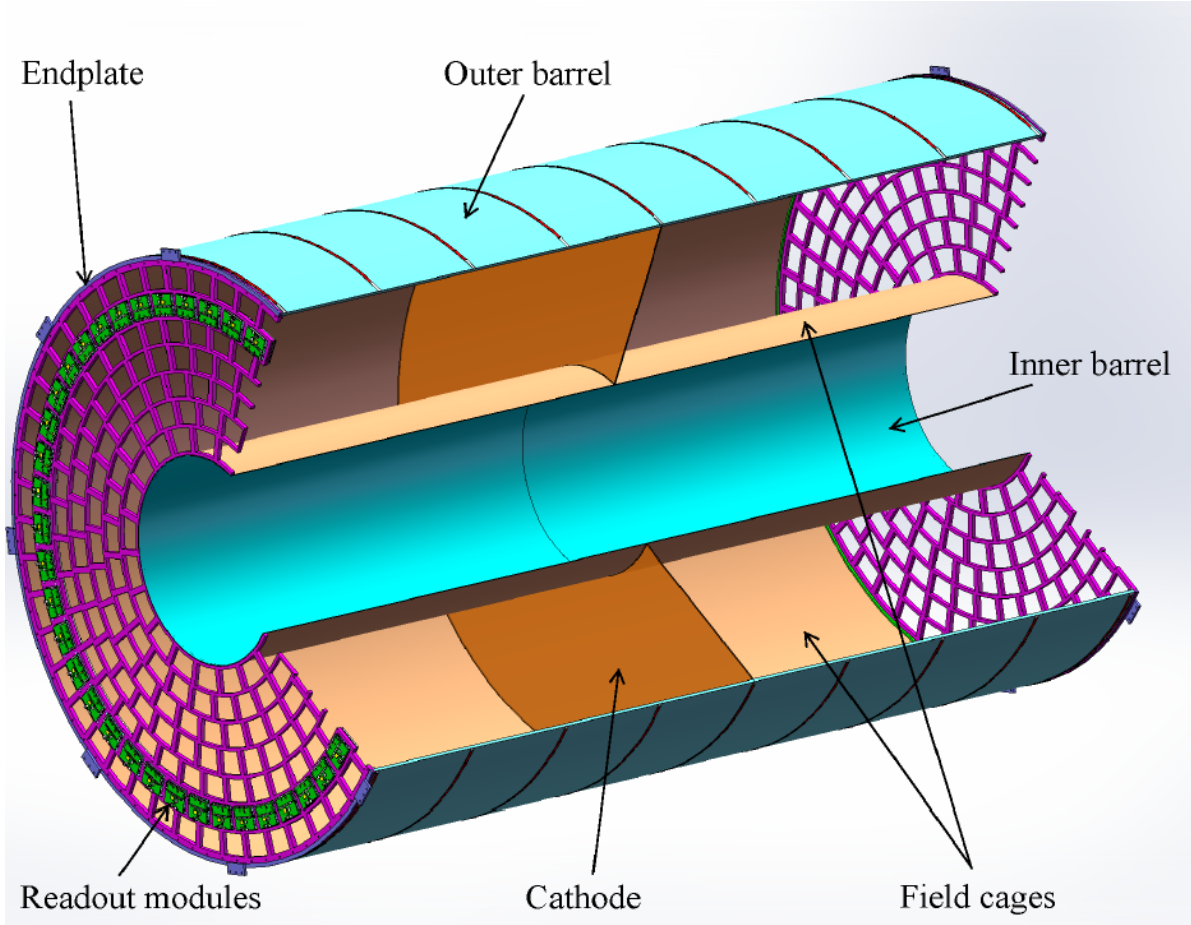
Pixelated readout TPC
- To meet Low-lumi Z physics
- TPX3 and TPX4
- ~1W/cm^2
- dN/dx+dE/dx
- GirdPix
- Interposer
- Direct mode

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

Parameters of TPC technology in CEPC TDR

- 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
  - Low material budget
- Overall design
  - A chamber (inner and outer cylinders, endplates) + readout modules
  - Total length： 5.8 m
  - R extension: 0.6 - 1.8 m

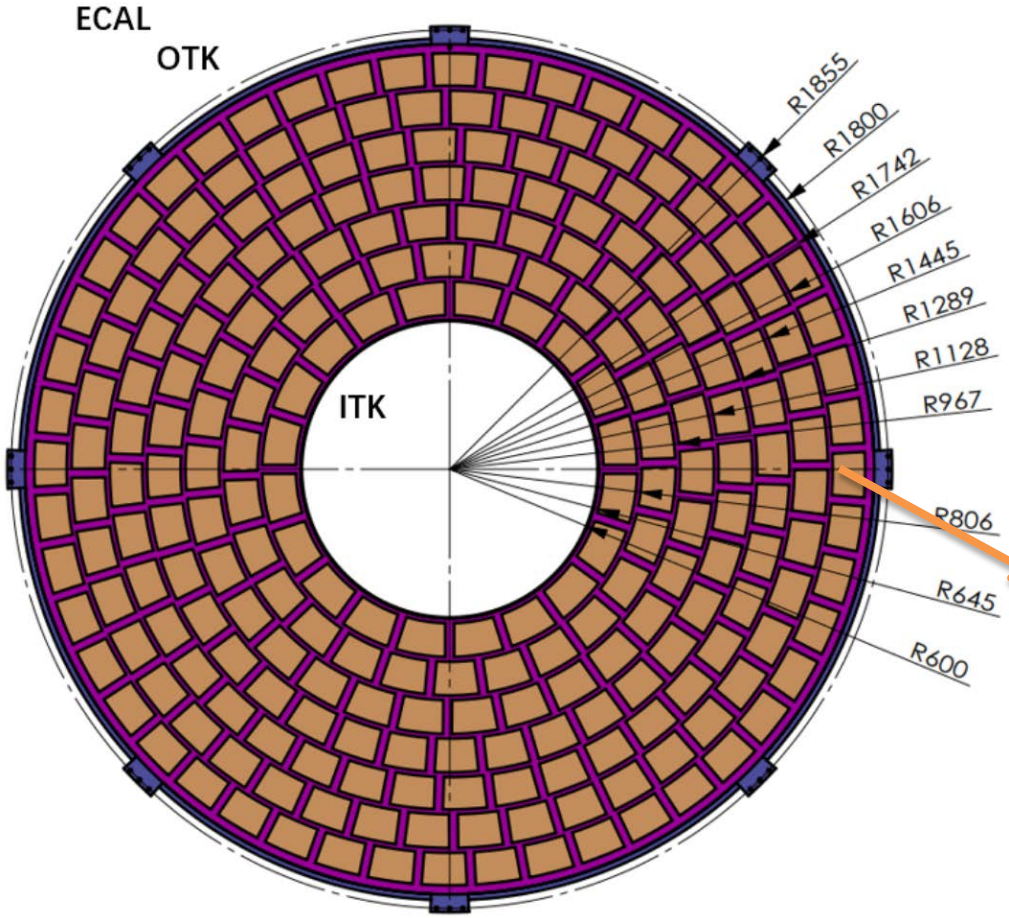
TPC detector	Key Parameters
Modules per endcap	248 modules /endcap
Combined Si detector	OTK and ITK silicon trackers
Geometry of layout	Inner: 1.2m Outer: 3.6m Length: 5.9m
Potential at cathode	- 62,000 V
Gas mixture	T2K: Ar/CF4/iC4H10=95/3/2
Maximum drift time	34μs @ 2.75m
Detector modules	High granularity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

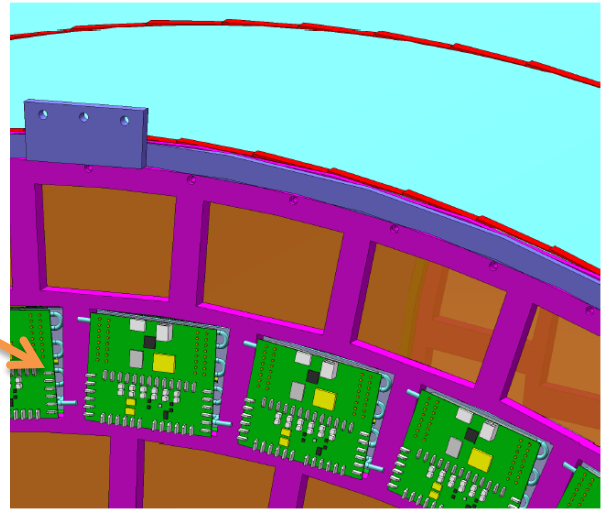


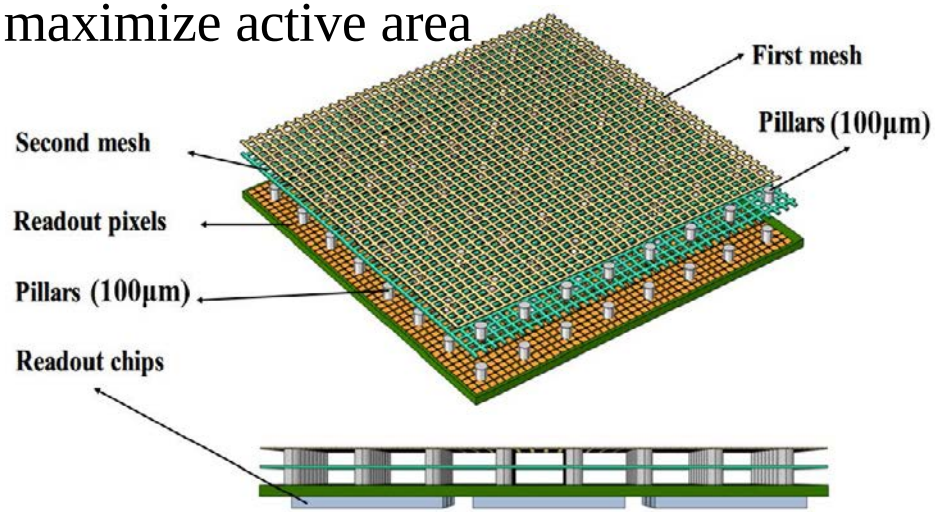
Detailed design of TPC detector in TDR

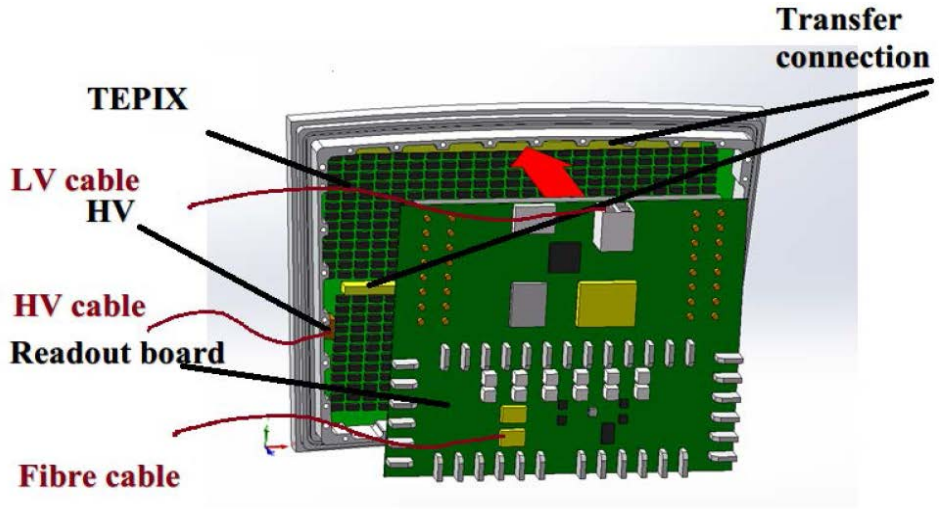
Readout module design

- Readout modules on the endplate
  - 25mm thick aluminum endplate: 7 layers of windows along the radial direction
  - Readout modules with support frame installed in windows to maximize active area





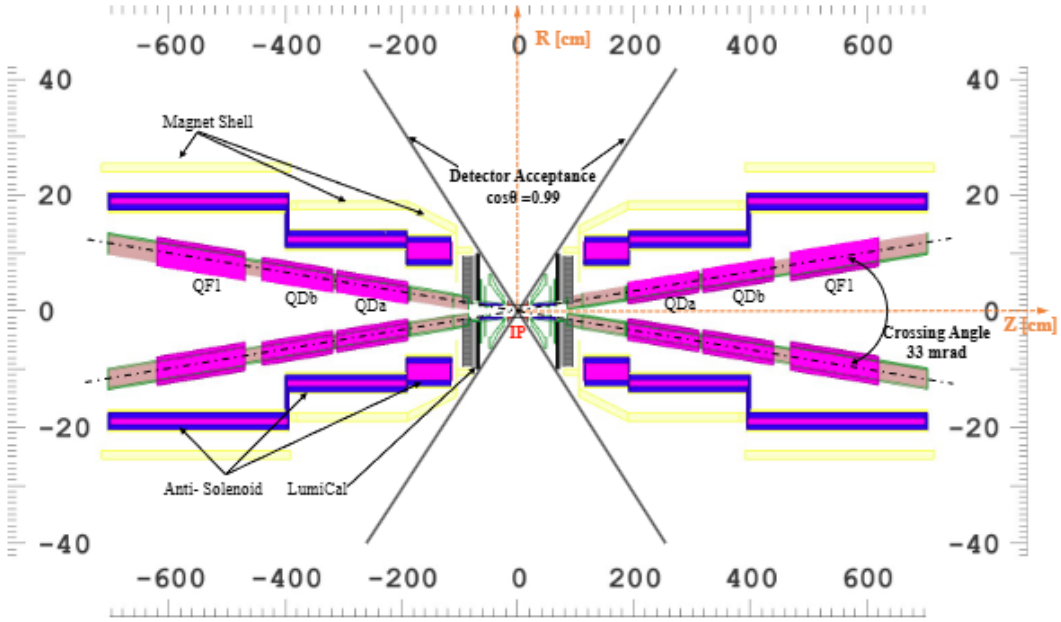




- **Simulation and BG and PID**

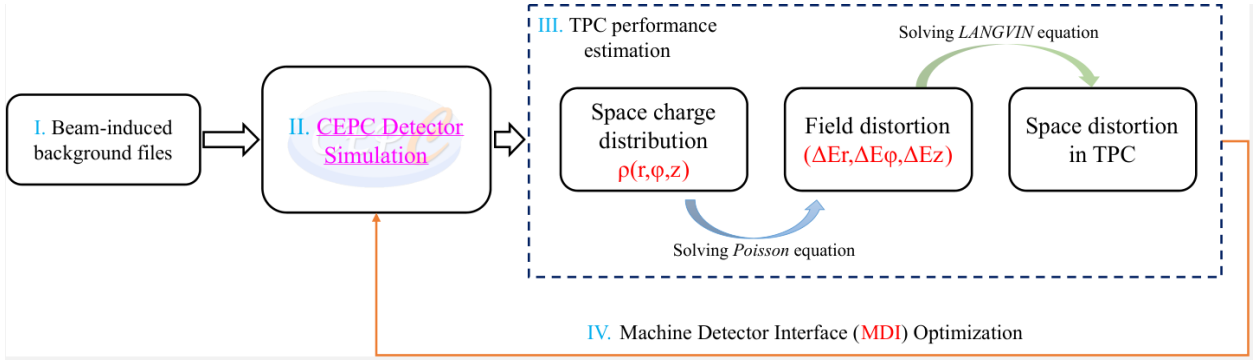
Beam background simulation

- 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



MDI designs in the CEPC ref-TDR

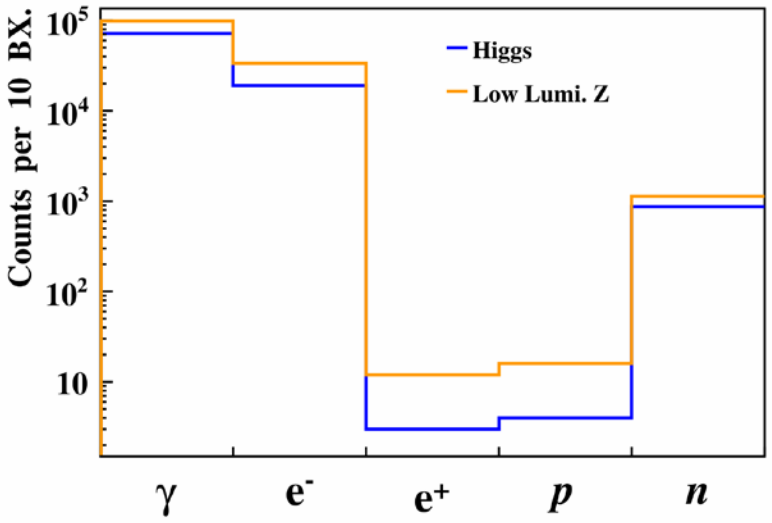
Backgrounds	Generation	Tracking	
Pair production	Guinea-Pig++	SAD	Luminosity related (BS files)
Beam-Gas Coulomb (BGC)	BGC in SAD		Single-Beam (Lost maps)
Beam-Gas Bremsstrahlung (BGB)	PyBGB		
Beam-Thermal Photon (BTH)	PyBTH		
Touschek Scattering (TSC)	TSC in SAD		

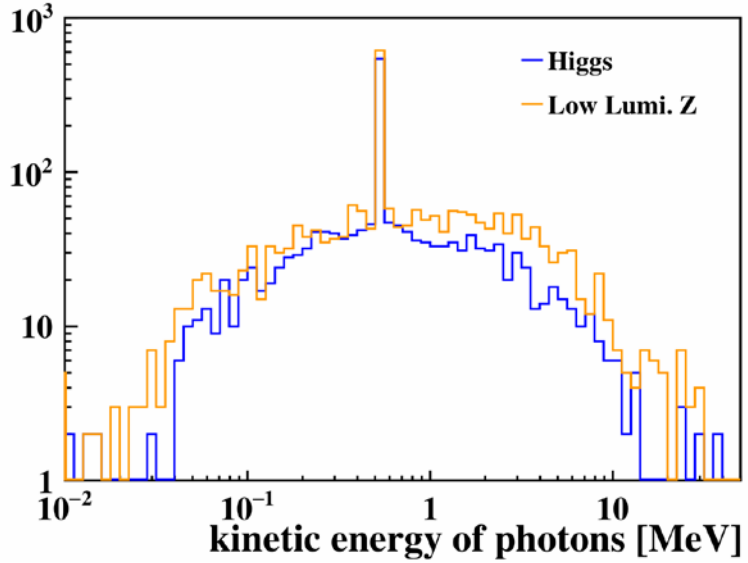


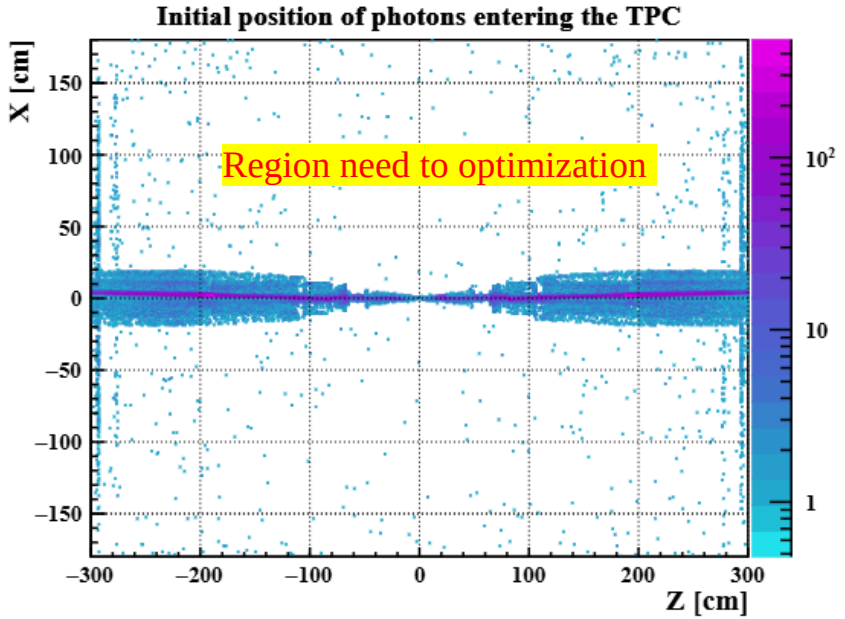
estimate number of **primary ions** produced in the TPC per bunch crossing
→ geant4 energy deposit / effective ionisation potential of Ar [26 eV]

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



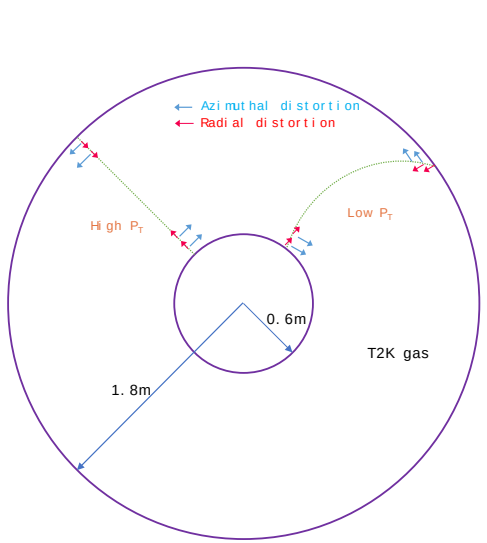


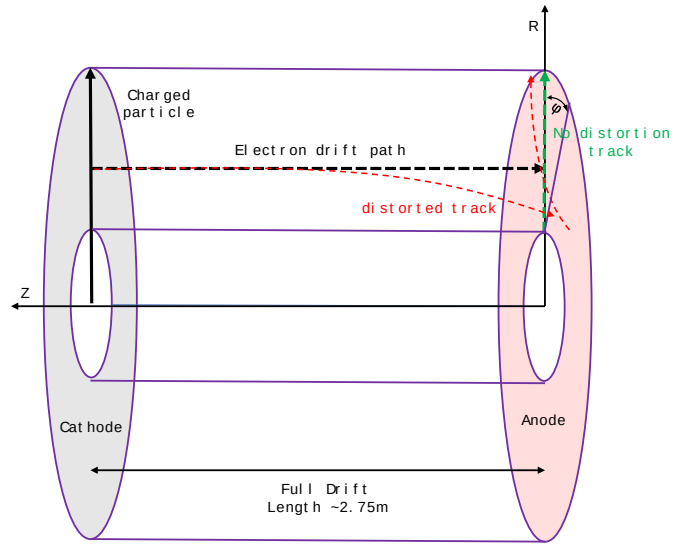


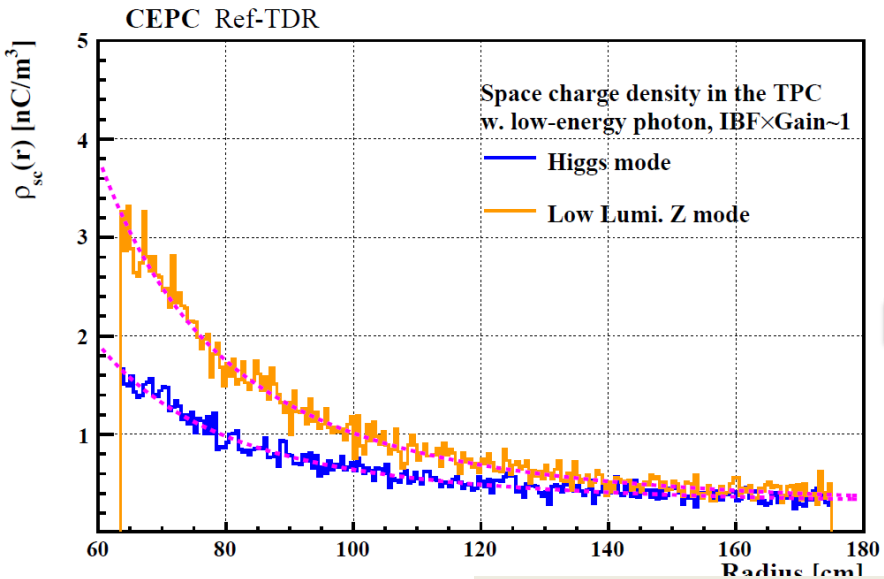
Particle type, Energy and initial position of low-energy photons entering the TPC

Space charge density and deviations

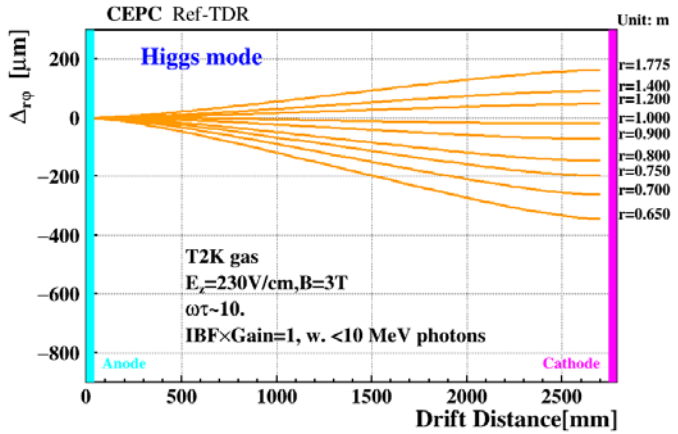
- The max. space charge density reaches 1.7-3.3 nC/m^3
  - With the contributions of the IBF (IBF×Gain~1) and low-energy photons
- Deviations occur both in radial and azimuthal directions along the electron drift paths
  - Azimuthal deviations have much serious impact on momentum measurement
  - The max. Δrφ reaches 800-900μm in the low-Z mode (need to optimization and calibration)

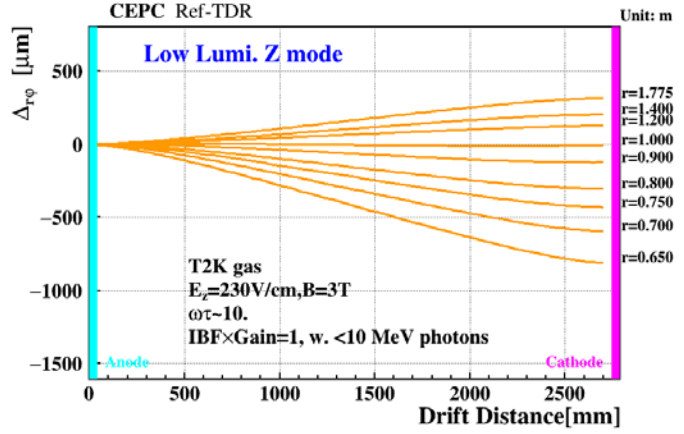






IBF×Gain=1 && w. low-energy photons

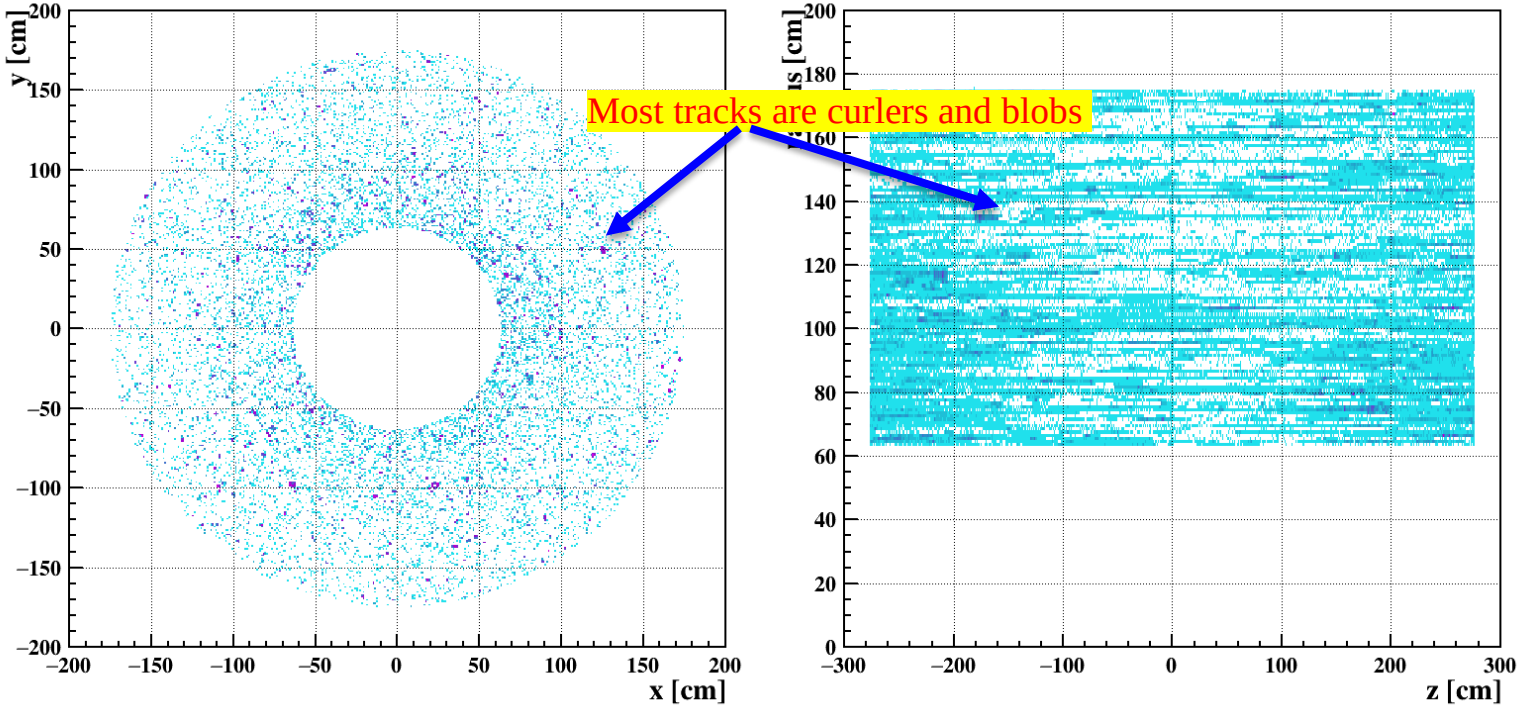




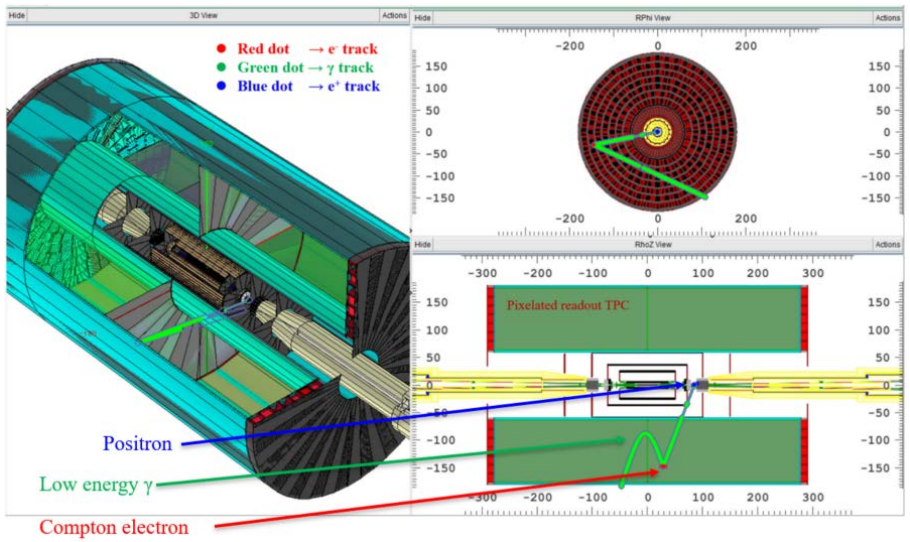
Space charge density and distortions in the Higgs and low-luminosity Z modes

BG hits in the TPC

- Very few tracks of particles that have enough energy to leave TPC
  - Most of BG hits consists of more or less randomly distributed blobs or curlers
  - Sometimes called “salt and pepper” background
- Caused by extremely low-energy photons



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

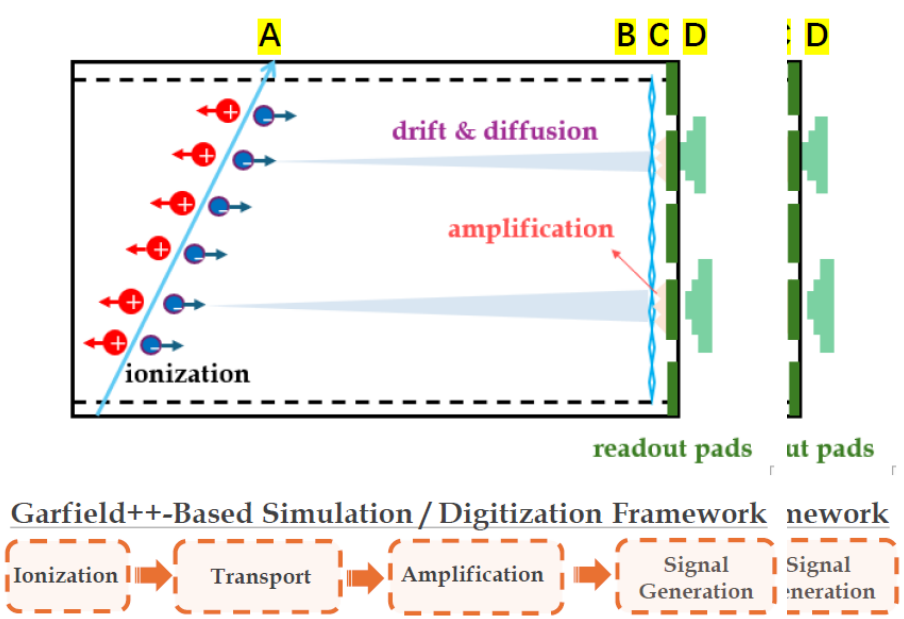


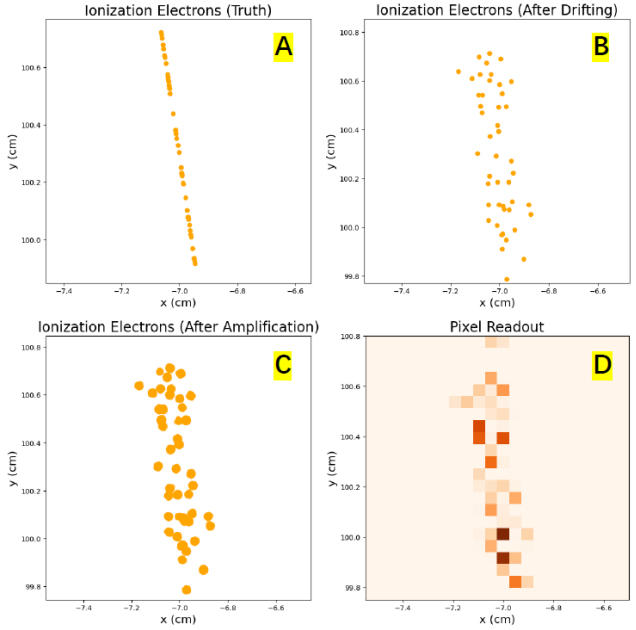
$background\ e^{+} annihilation \rightarrow \gamma(0.511 MeV) \rightarrow Compton\ e^{-}$

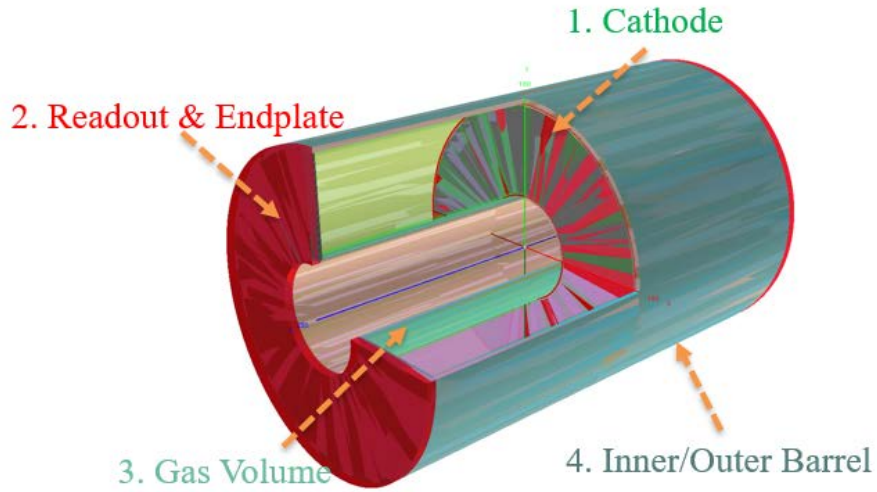
- Typical event display:
  - e+ annihilation
  - Low energy (0.511 MeV) γ incident TPC and interact with the T2K gas
  - generate secondary Compton electron

Full Simulation of High granularity readout TPC – Framework

- Sophisticated software for simulation/digitization/reconstruction using Garfield++ and Geant4
  - Geometry implementation based on CEPC TDR
    - Cathode, Micromegas readout and endplate, barrel, gas volume
  - PID with the cluster counting
    - Garfield++ based full simulation and digitization from the primary electron to the signal readout
    - Improved reconstruction based on truncated mean of pixels
  - Tracking: Reconstruction with parameterized hit resolutions



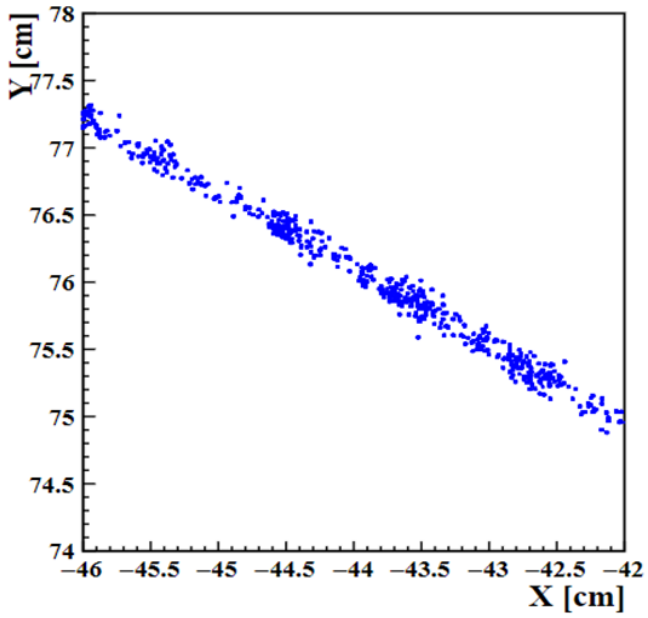




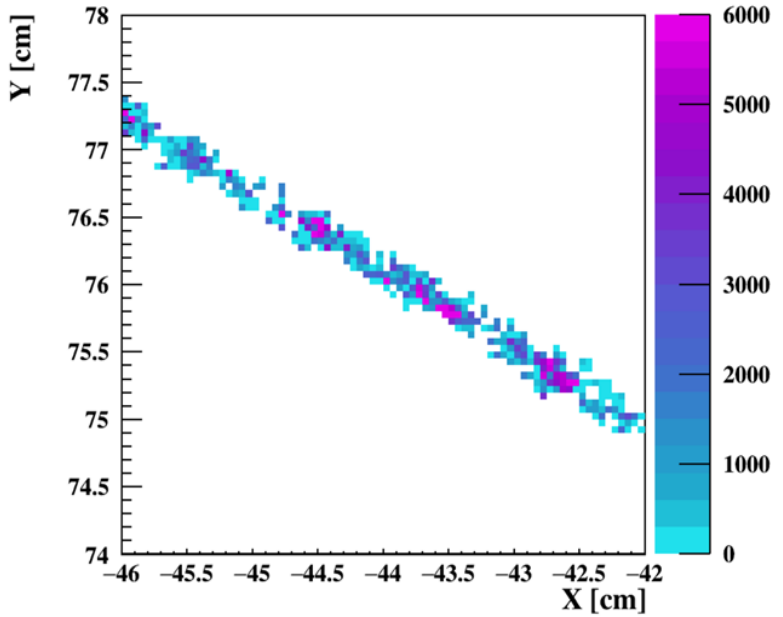
Simulation of TPC detector under 3T and T2K mixture gas

Full Simulation of High granularity readout TPC – Readout size

- Simulation results showed that readout size can be optimized at around 500μm.
  - Optimization started in this TDR to meet Higgs/Z at 3T
  - Focused on **100mW/cm^2 and 500μm readout** for TDR (<10kW/endplate, Water cooling option)
- TPX3/4 (55×55μm^2, 110×110μm^2) readout TPC prototype has been validation on DESY beams.
  - Power consumption: 2W/cm^2 ; Low power mode: 1W/cm^2 (**high power consumption!**)

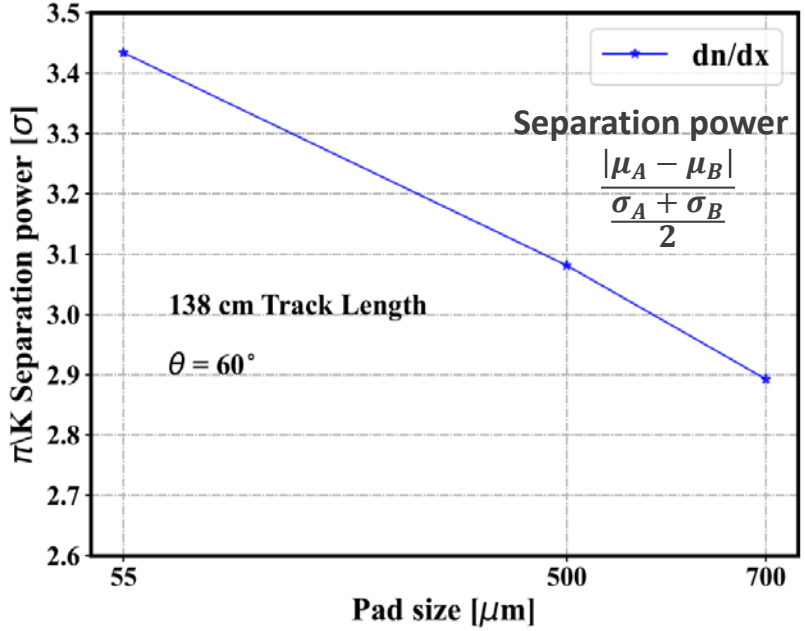


pixel response (55 μm× 55 μm)



pixel response (500 μm× 500 μm)

Lx

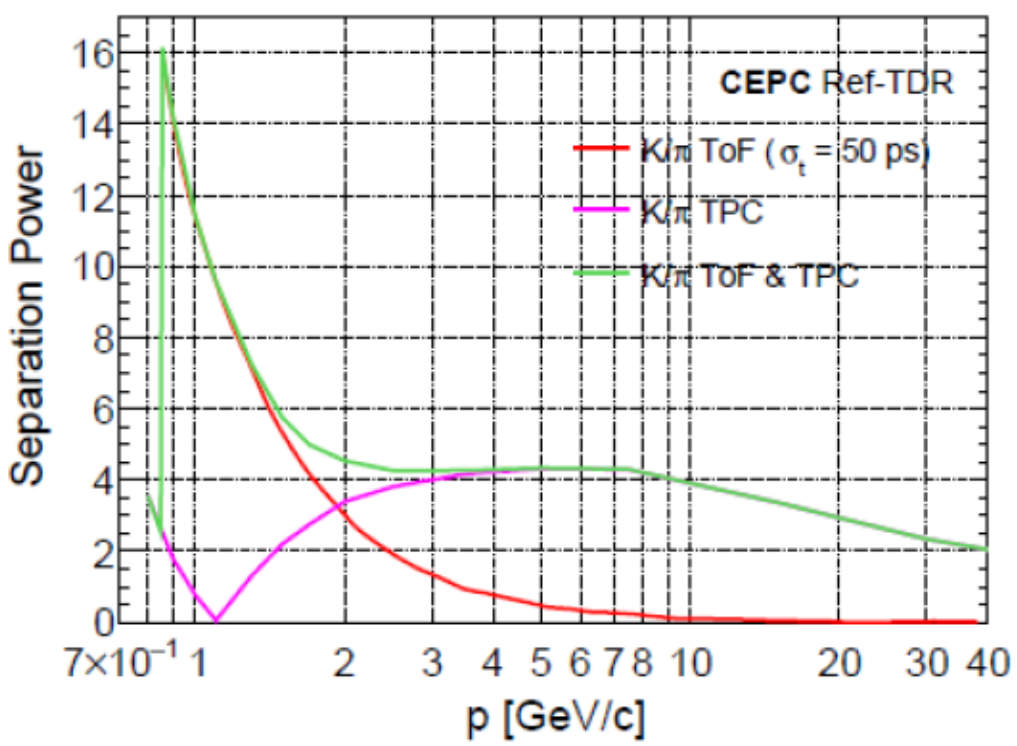


Optimization of readout size. Balancing of performance and cost power consumption, etc.

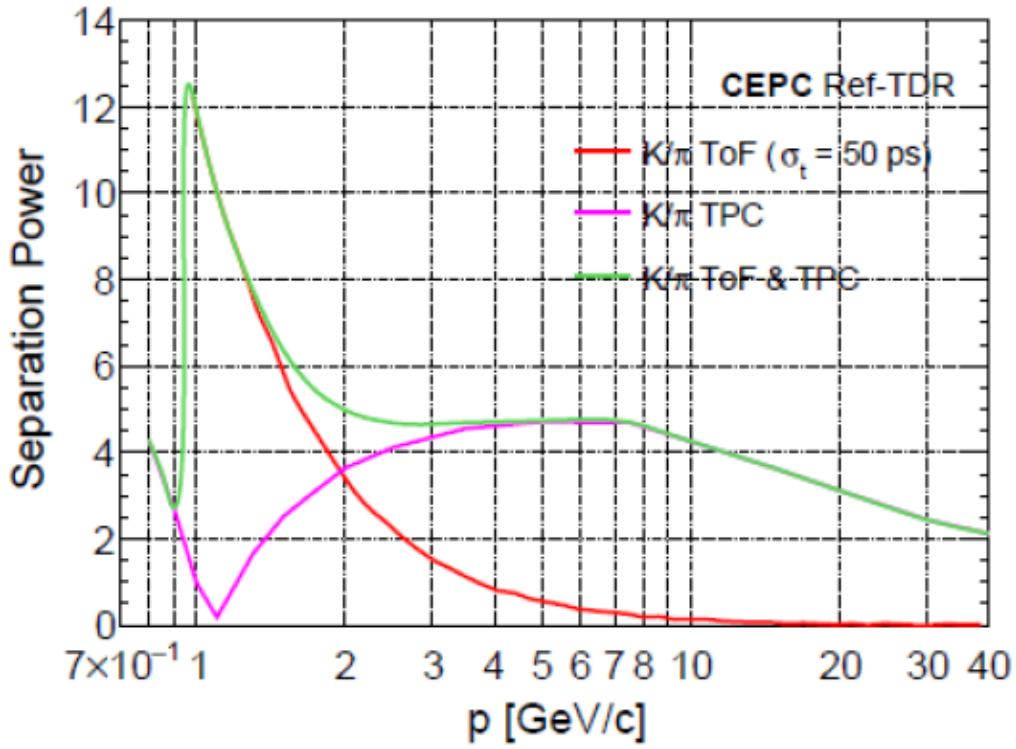
Full Simulation of High granularity readout TPC – PID performance

- K/π separation power using the combined information of ToF and TPC
  - ToF information compensates for momentum range of around 1GeV/c
  - Larger than 3σ separation between K/π with momentum up to 20 GeV/c

$$\eta_{A,B} = \frac{|\mu_A - \mu_B|}{\sqrt{(\sigma_A^2 + \sigma_B^2)/2}}$$



(a) $\theta = 85°$

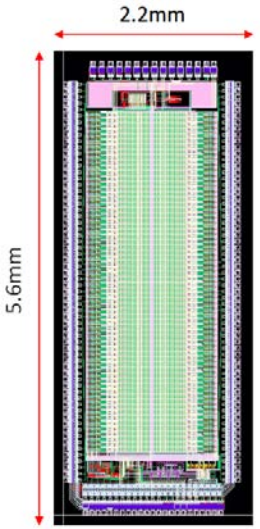


(b) $\theta = 60°$

- **High granularity readout prototype R&D**

Prototype of the readout ASIC

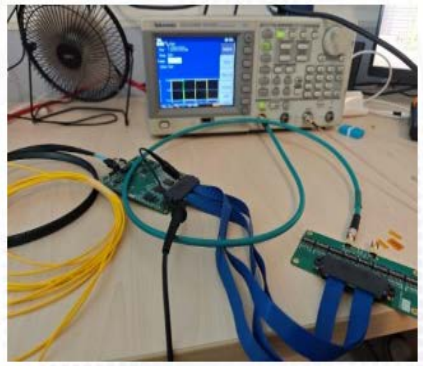
- High granularity readout Electronics: TEPIX chip
  - Charge-sensitive preamplifier
  - Correlated double sampling shaper
  - 4-channel sample/hold circuits and 10 bit ADC
  - 128 channels using 180 nm process
  - Chip size: 2.2 mm × 5.6 mm



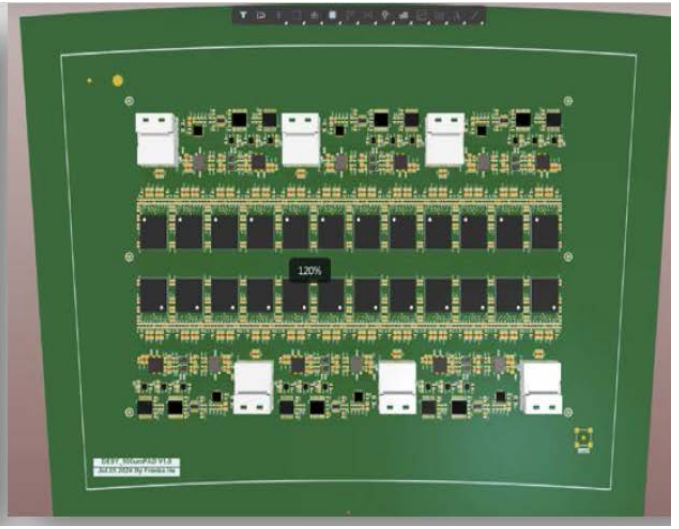
Total number of channels	30 Million per endplate
Pixel size	500 μm × 500 μm
Equivalent Noise Charge (ENC)	100 e^-
Dynamic range	20 fC
Charge buffer dynamic range	8-10 bit
Event rate	12 kHz/cm^2 max. in low-lumi. Z mode
Event size	64 bit
Readout bandwidth	<10 Gbps per module with compression
Power consumption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





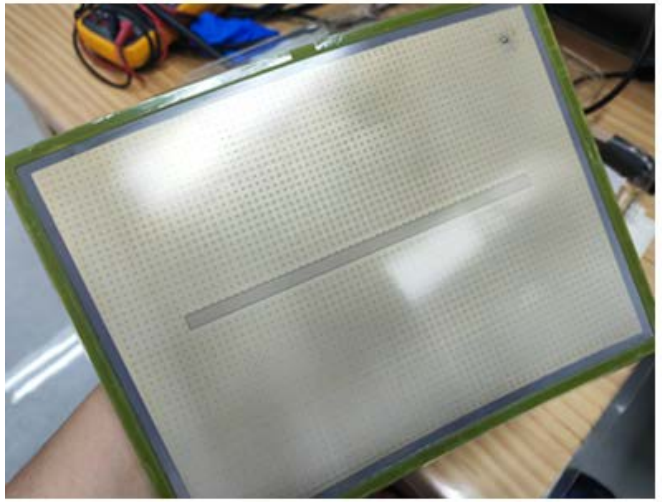


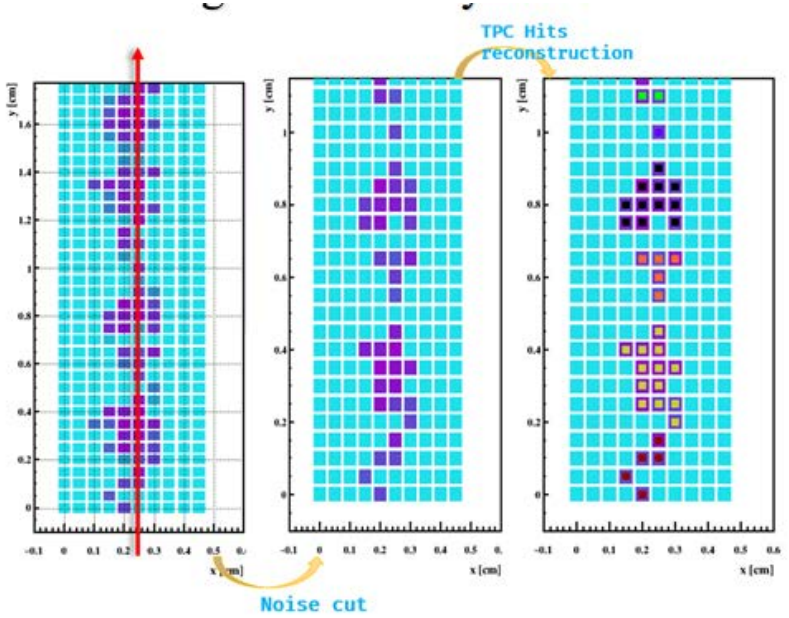




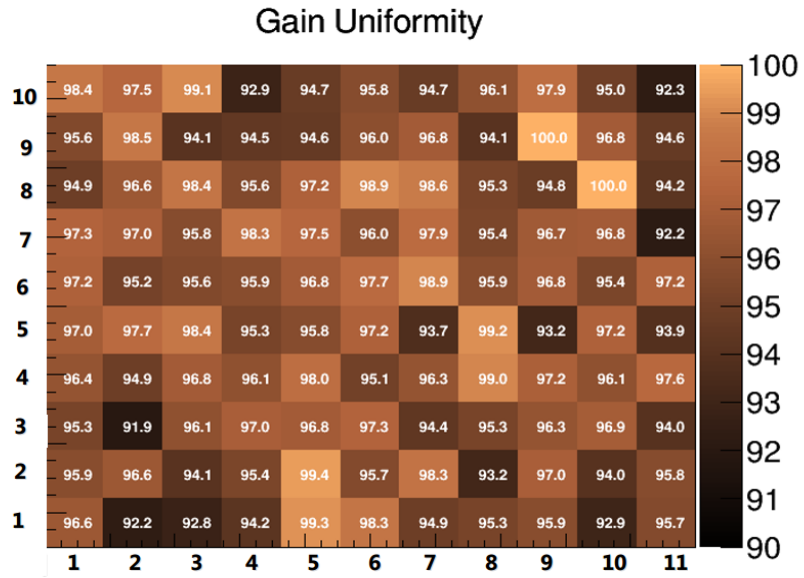
Validation and commissioning of TPC prototype

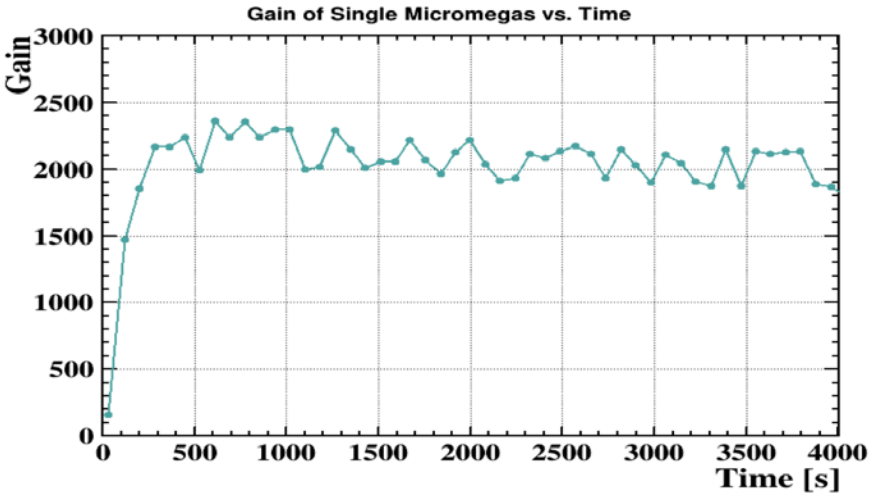
- The Micromegas detector integrated with the readout chip has been successfully developed.
- The detector operates at a gain of 2000–3000, exhibiting good gain uniformity. Detector with the DAQ system is currently under joint commissioning.
- Based on Garfield++, KalTest and a pixel-type TPC simulation framework
  - Offline data-processing code developed
  - Time-stamp misalignment across multiple channels





Detector integrated with the high granularity readout

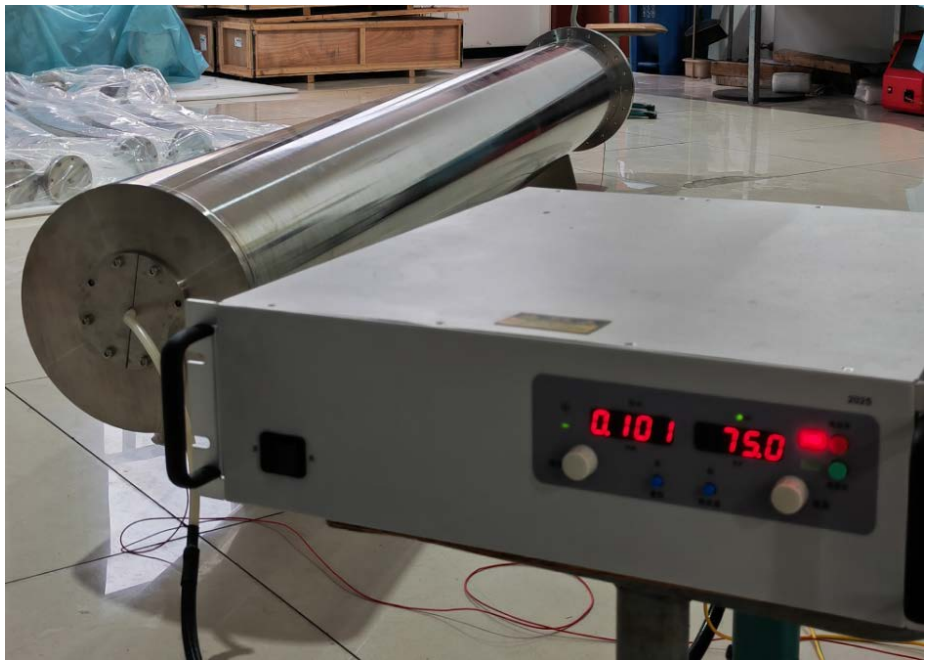




Gain and gain uniformity of the detector

Plans of TPC R&D

- Development of TPC prototype with low power consumption FEE
  - Collaboration with LCTPC and DRD1 group
- Prototyping R&D and validation with the test beam
  - mechanics, manufacturing, beam test, full drift length prototype
- Development of the full drift length prototype
  - Drift velocity. Attachment coefficient, T/L Diffusion, etc.
- Performance of the simulation and Machine Learning algorithm



Milestones achieved	Short term	Long term
Ion backflow suppression	IBF×Gain<1 (Gain=2000)	Graphene technology
High granularity readout readout prototype	Validation with beam test	Prototype with Multi-modules
Power consumption ASIC	~100mW/cm^2 (60nm ASIC)	Optimization readout size
PID resolution	3% (dN/dx)	<3% (dN/dx)
Material budget (barrel)	Carbon Fiber	Full size prototype

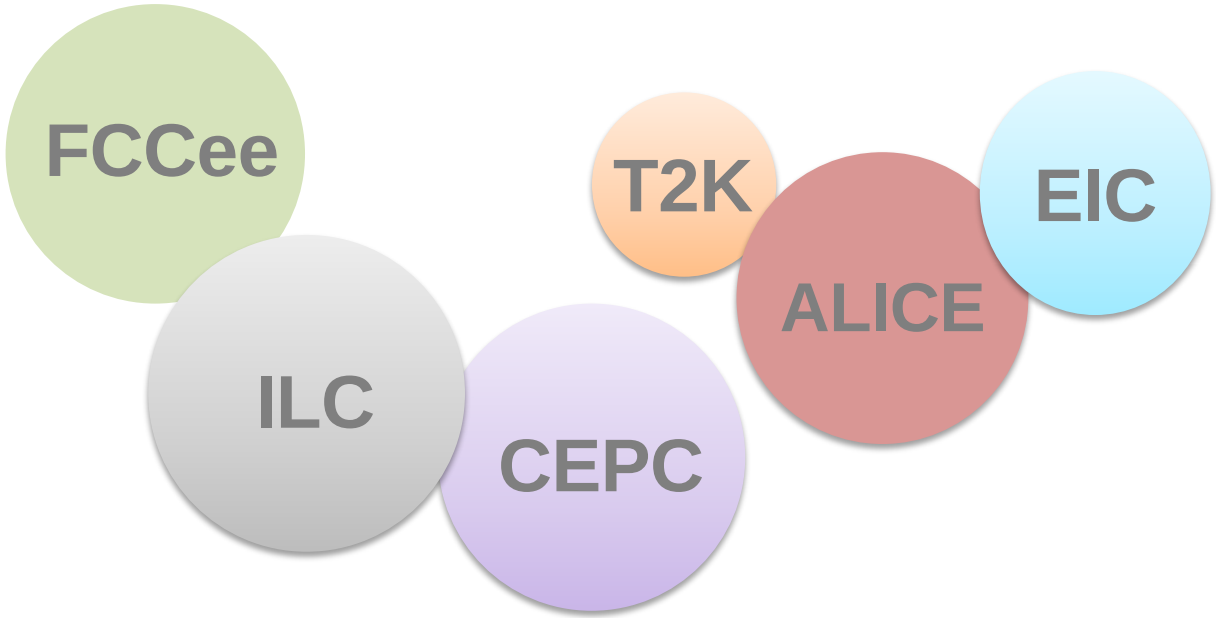




Summary

- High granularity readout TPC is choose as the baseline detector as main track in CEPC TDR. The simulation framework has been developed using Garfied++ and Geant4.
  - Aiming to Higgs and low luminosity Z run at future e+e- collider
  - Radius of TPC from 0.6 m to 1.8 m, readout size 500μm × 500μm
  - dn/dx has much better PID by getting rid of fluctuations from energy deposition and amplification
  - π/K: ~3σ @ 20 GeV/c, ~2σ @ 40 GeV/c
  - Beam-induced backgrounds studied based on Garfield++ and CEPCSW
  - Some validation of TPC prototype have been studies using TEPIX

- All inputs to the CEPC TDR, planning the short and long term R&D activates.
- Synergies with CEPC and FCCee allow us to continue R&D and ongoing. Team actively involved in the international collaborations.



Many thanks!