



Progress of Time Projection Chamber Technology for the future e^+e^- collider and neutrino

Huirong Qi

On behalf of the CEPC gaseous tracker R&D group & LCTPC Collaboration

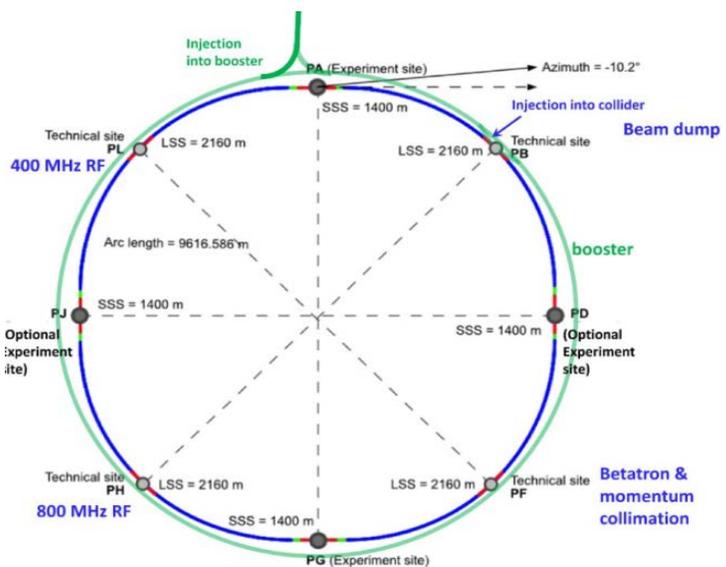
IAS Programme on High Energy Physics, 12 January 2026, HKUST, Hong Kong

- **Motivation**
- **Status of TPC in CEPC TDR**
- **Simulation and prototypes**
- **Work plan and summary**

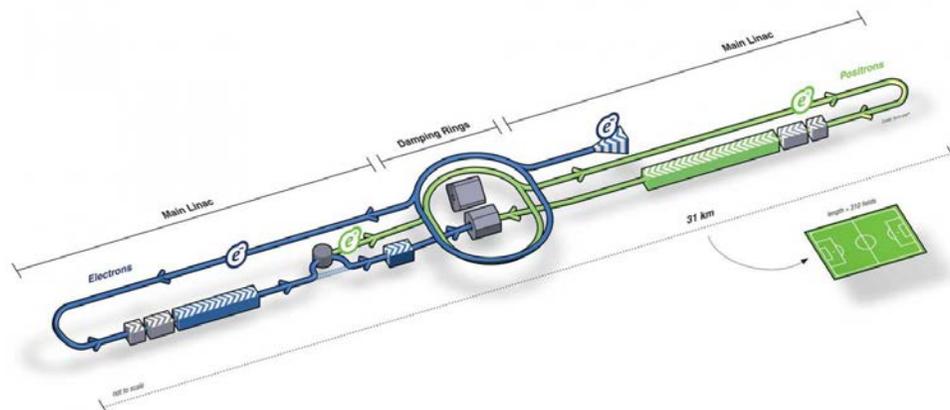
- **Motivation**

Motivation

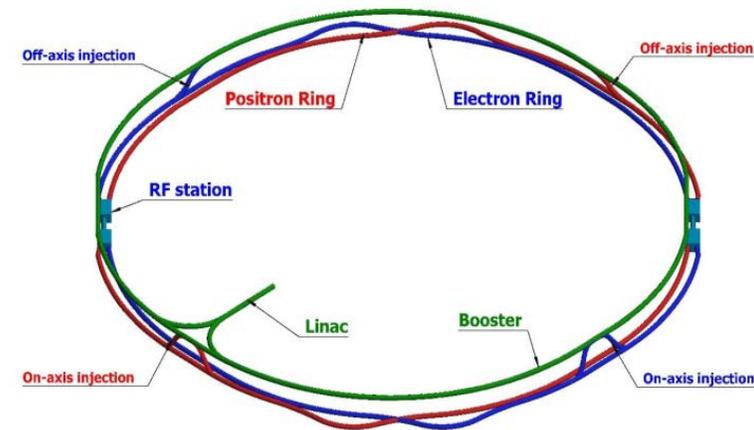
- A TPC is the main track detector for some candidate experiments at future e^+e^- colliders.
 - **Baseline detector concept** of ILD at ILC and CEPC
- TPC technology can be of interest for other future colliders (EIC, FCC-ee).
- High granularity readout readout TPC can improve PID requirements of Flavor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



Future Circular Collider (FCCee)



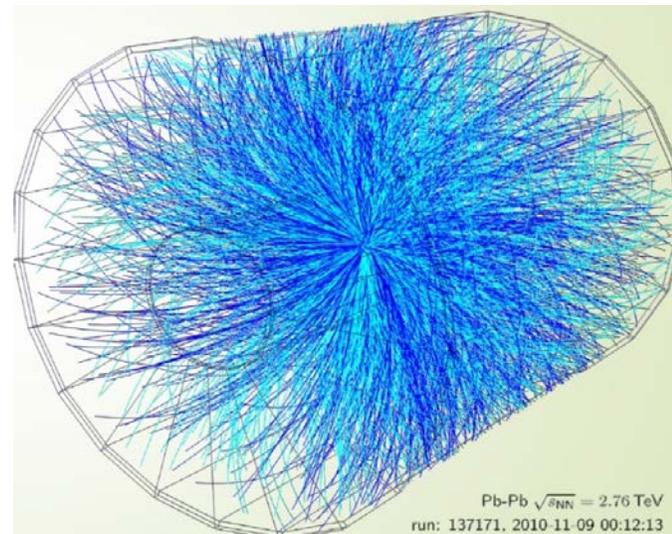
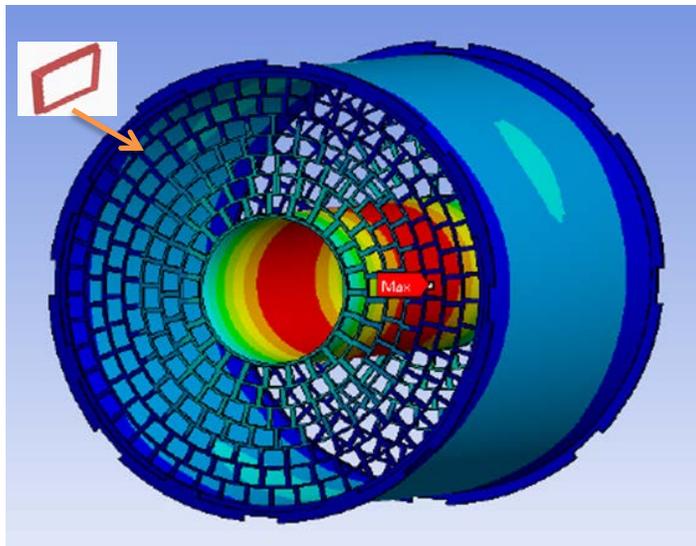
International Linear Collider (ILC)



Circular Electron Positron Collider (CEPC)

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: $\sim 3\%$**)
 - Utilize the timing of drift in the z-direction (**nano-second**)
 - A magnetic field parallel to the electric field direction (**Higgs: 3T, Low-Z: 3T, Tera-Z: 2T**)
 - Easily installation and replacement modular design
- Considering the technical challenges, performance, risk of detector construction

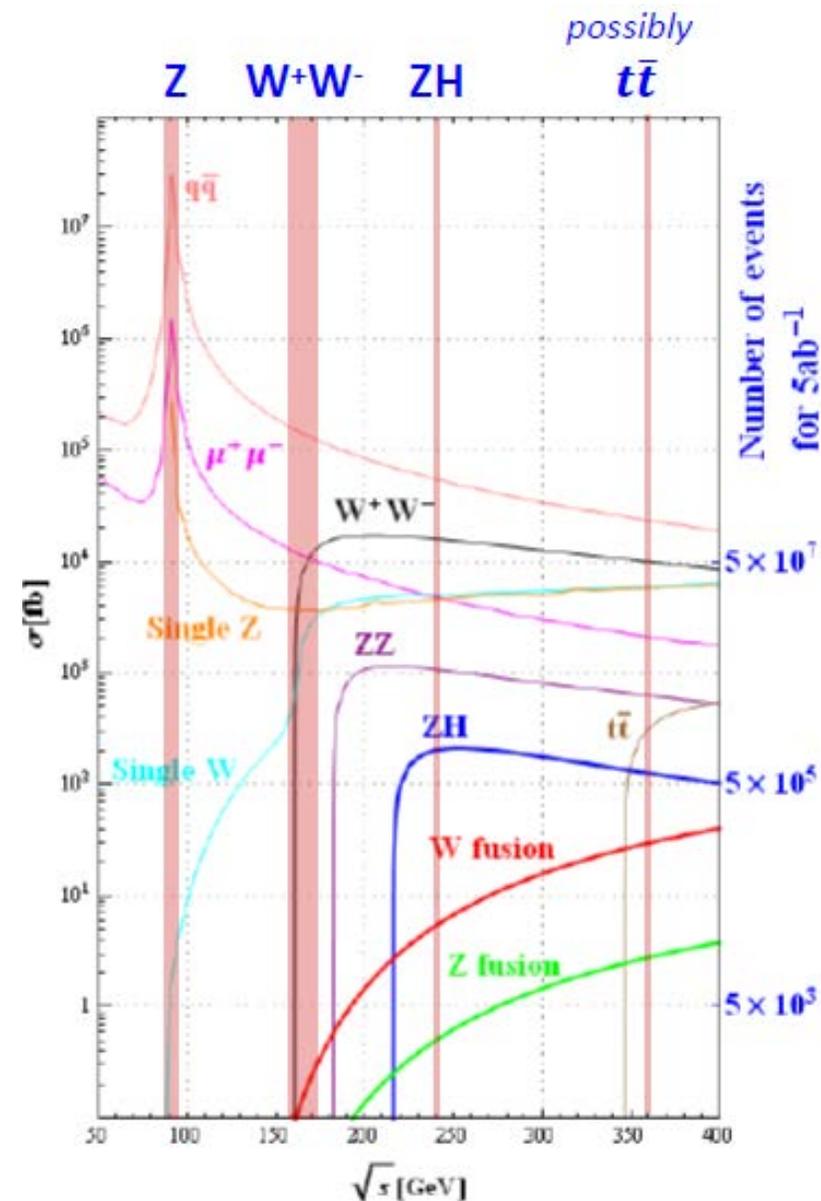


- **TPC detection for future e+e- collider**
 - Material budget at endcap/barrel
 - Occupancy and hit density at Tera-Z
 - **Ion backflow suppression**
 - Running at 2 Tesla
 - **Improved PID**
 - Reasonable readout channels
 - Reasonable power consumption

How to operate at CEPC? (Plans)

- The CEPC Accelerator TDR document was released at the end of 2023.
- In the operation plan, the **first 10-year** operation includes: the Higgs mode, **Low-Lumi Z mode**, and WW mode (B = 3.0T).
- The accelerator may be upgraded for High-Lumi Z mode and/or tt mode after 10 years operation, subject to physics needs.

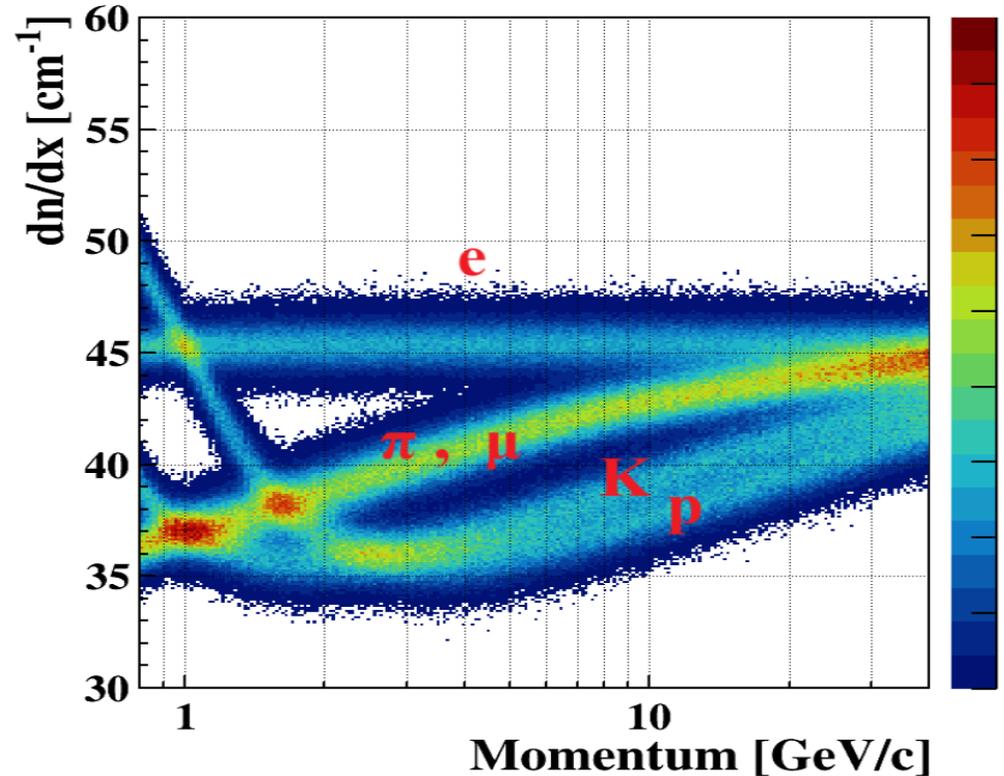
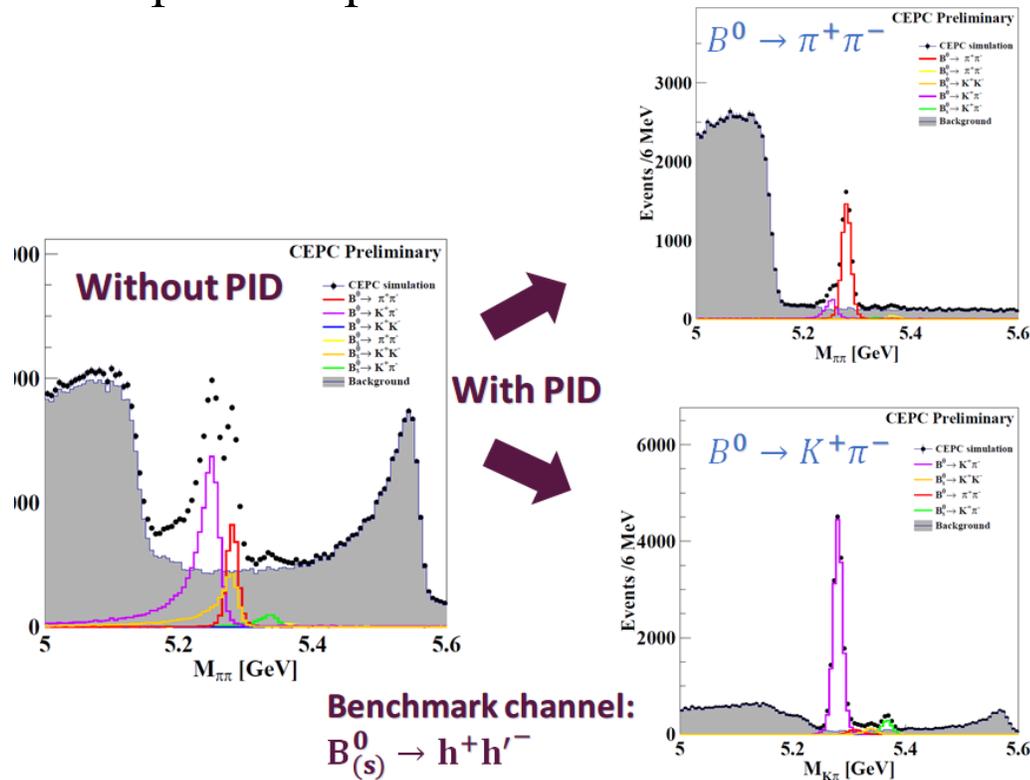
SR Power Per Beam	Luminosity/IP [$\times 10^{34} \text{cm}^{-2} \text{s}^{-1}$]		
	H	Z	W+W-
12.1 MW	-	26	-
30 MW	5.0	-	16
50 MW	8.3	-	26.7



Physics requirements in CEPC

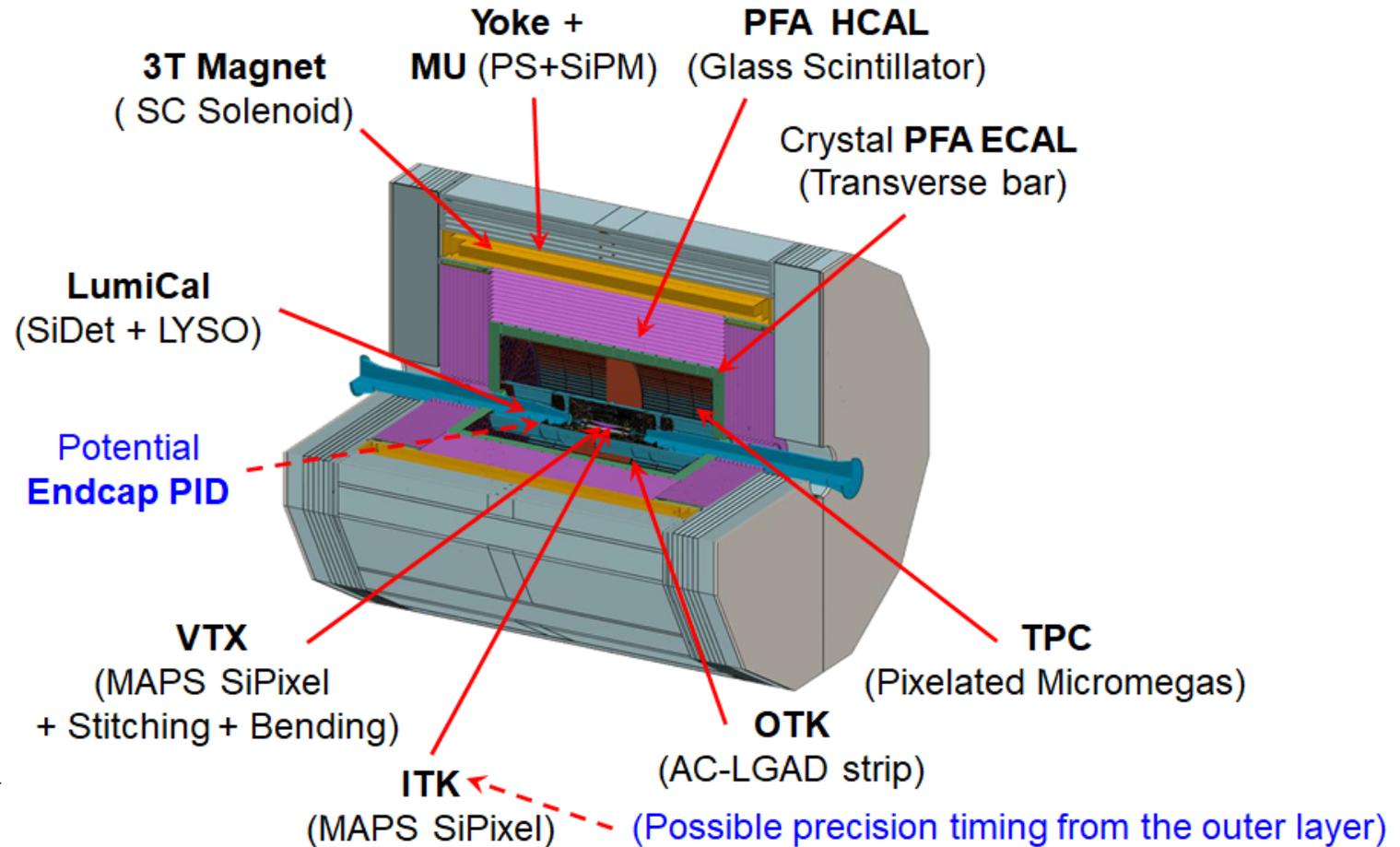
- Circular e+e- collider operation stages in TDR: **10-years Higgs @3T** → **2-years Z pole** → **1-year W**
- Gaseous tracker leading contribution to PID and the high resolution: jet & differential
 - High granularity readout and better than 2σ separation power between π and k for P using dn/dx

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



Baseline Detector Design in 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



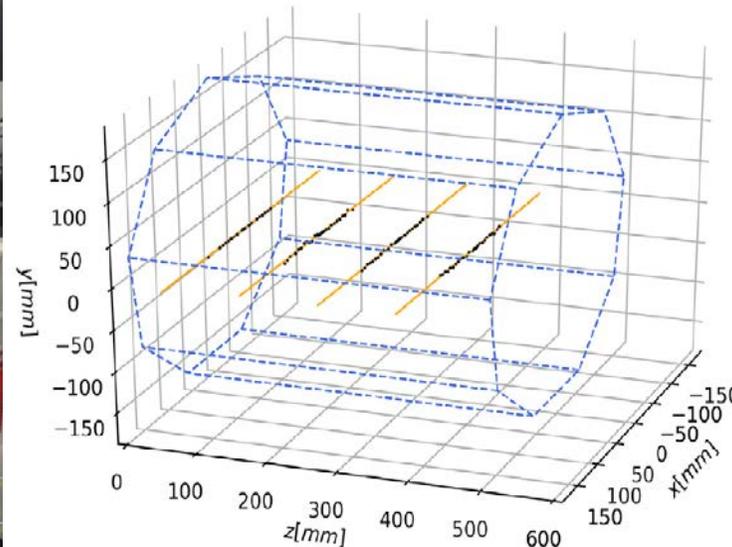
<https://arxiv.org/abs/2510.05260>

- **Status of TPC in CEPC TDR**

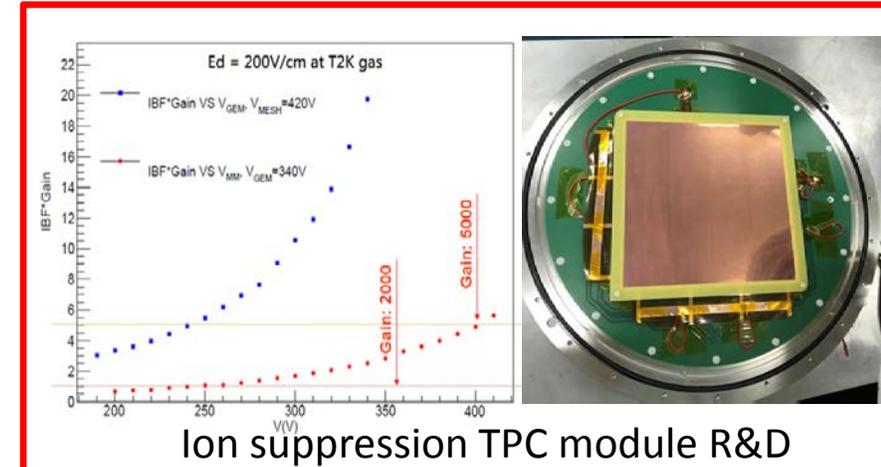
Roadmap of CEPC TPC detector R&D

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

TPC prototype with integrated 266nm UV laser



Achievement



Publications by CEPC TPC group in 2018-2025:

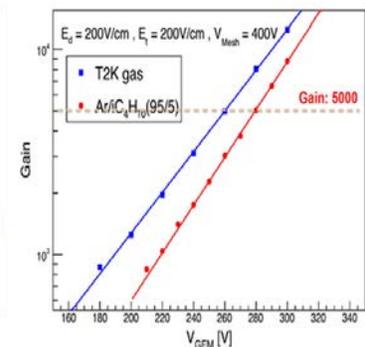
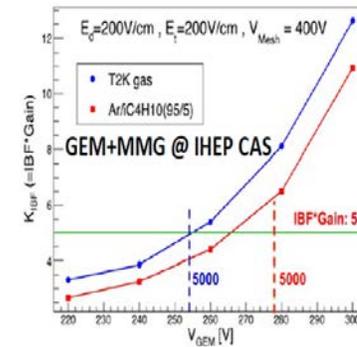
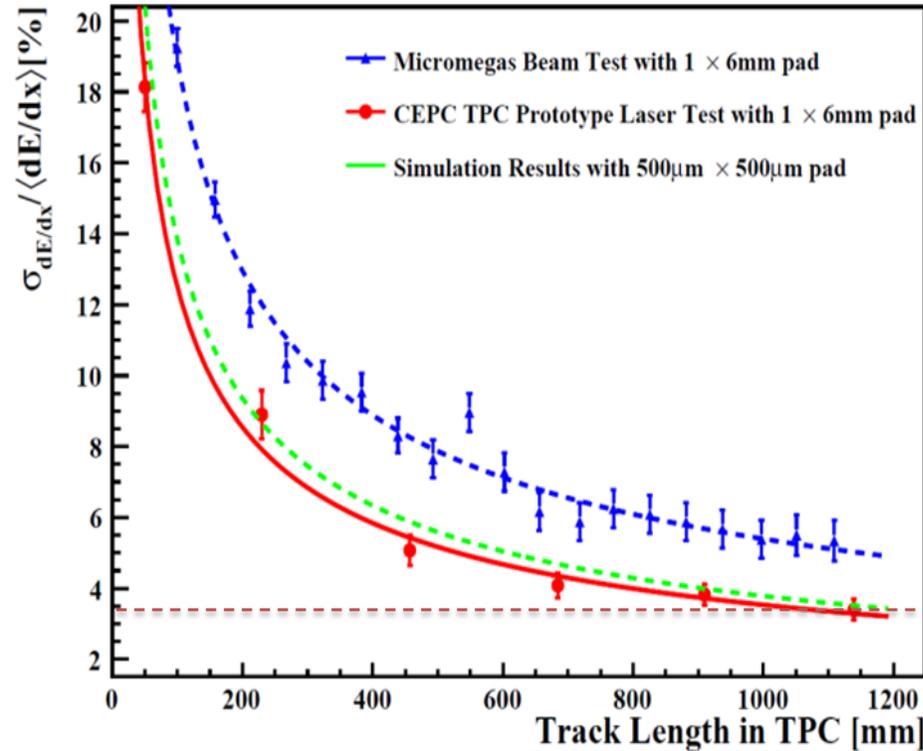
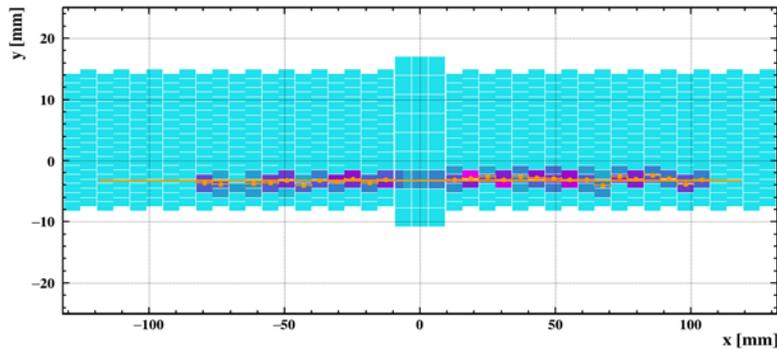
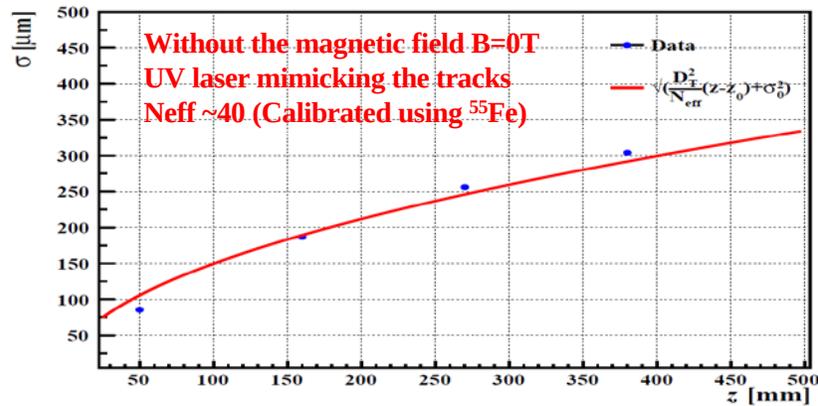
- <https://doi.org/10.1088/1748-0221/18/08/E08002>
- <https://doi.org/10.22323/1.449.0553>
- <https://doi.org/10.1016/j.nima.2022.167241>
- <https://doi.org/10.1109/NSS/MIC44867.2021.9875566>
- <https://doi.org/10.1109/NSS/MIC44845.2022.10399097>
- <https://doi.org/10.1088/1748-0221/15/09/C09065>
- <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>

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

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 detector for e+e- collider

Pad readout TPC

- To meet Higgs physics
- 1mm × 6mm of Pad
- < 100mW/cm²
- dE/dx



Pixelated readout TPC

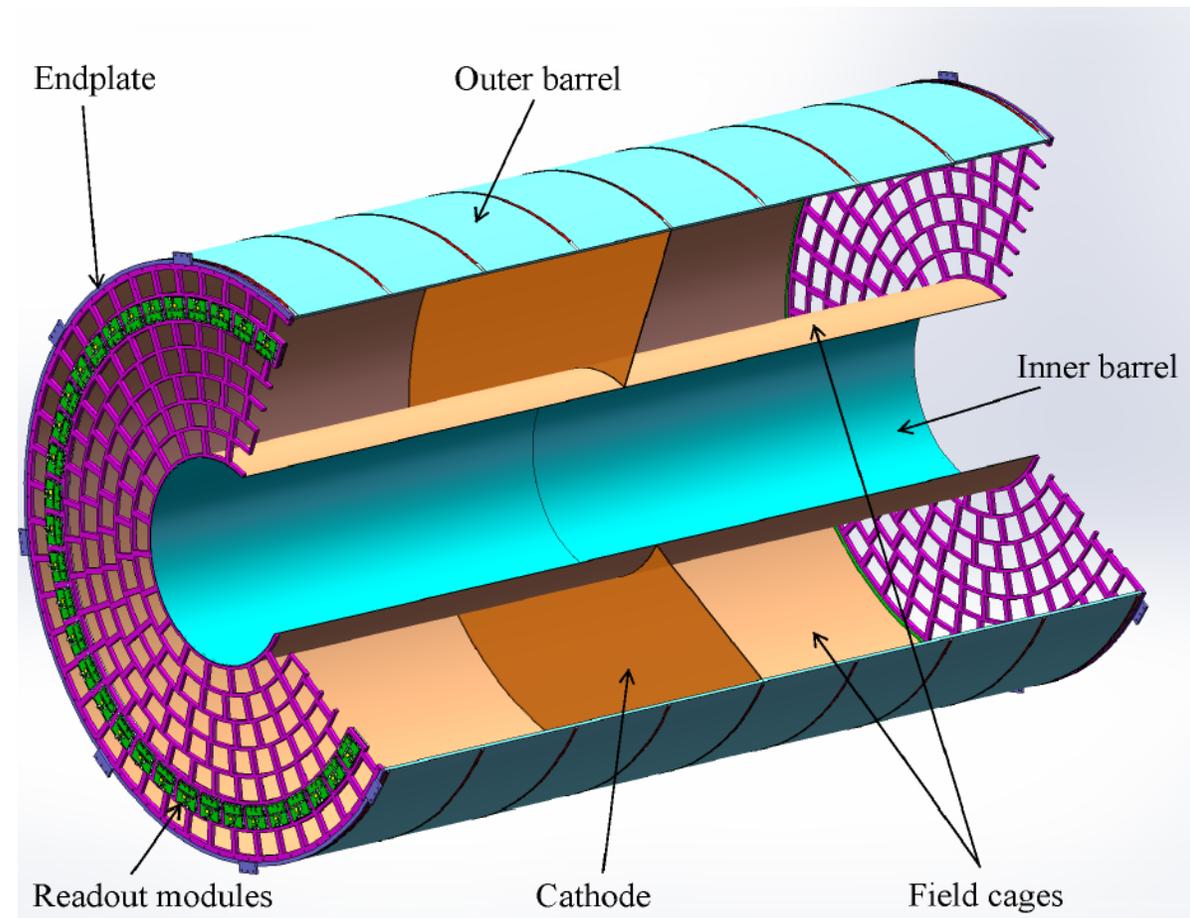
- To meet Low-lumi Z physics
- TPX3 and TPX4
- ~1W/cm²
- dN/dx+dE/dx

- CEPC 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): $2 \times 10^{-5} (\text{GeV}/c)^{-1}$
 - 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

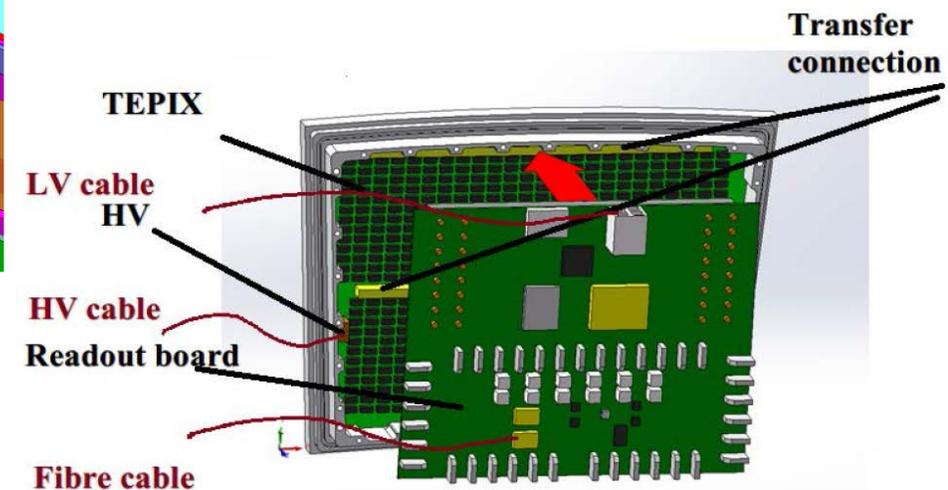
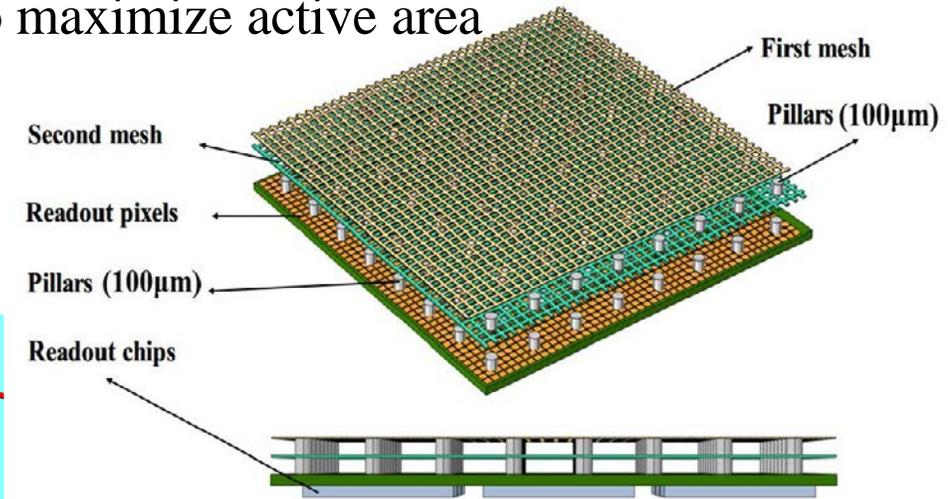
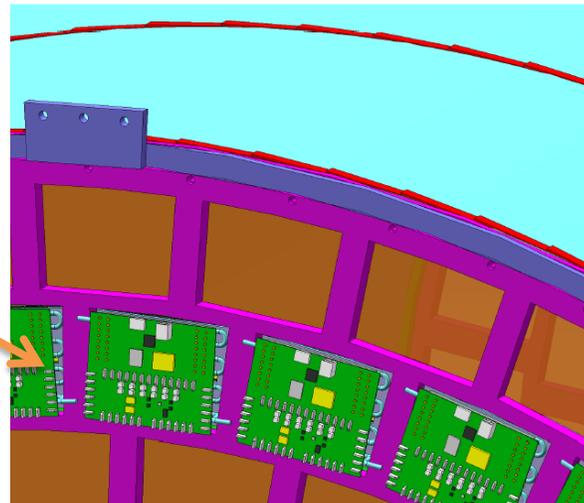
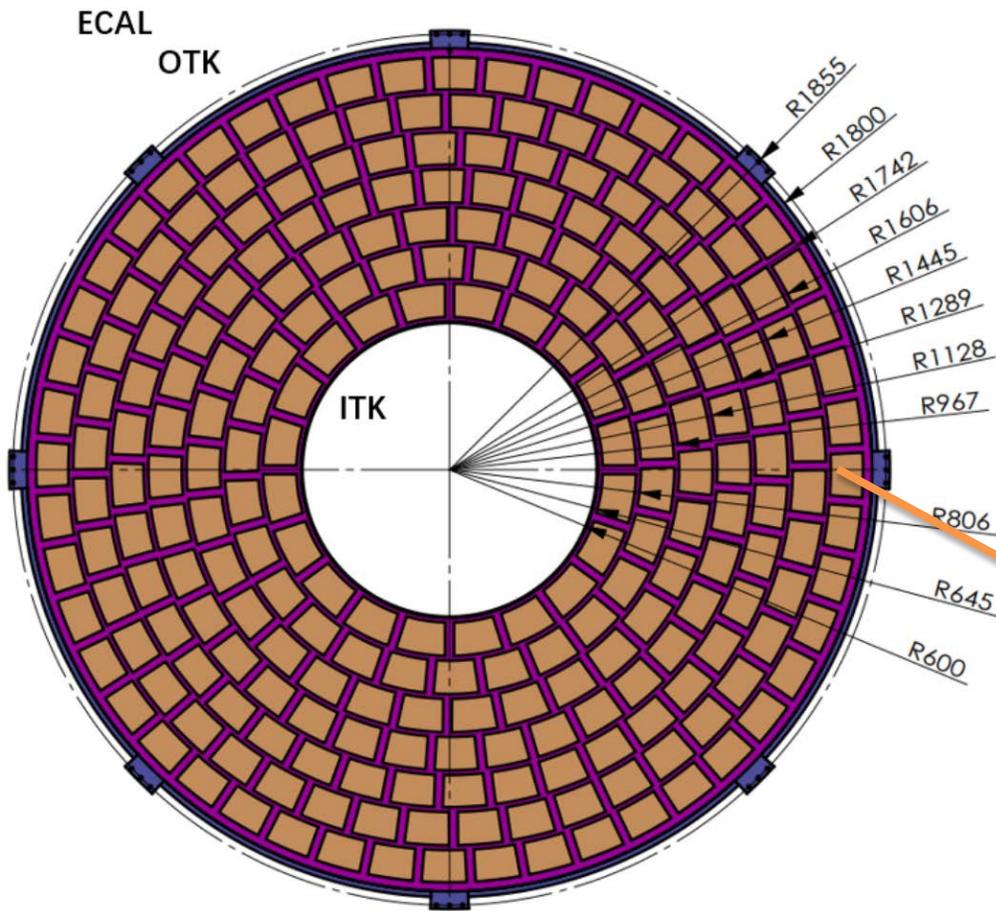
TPC detector	Key Parameters
Modules per endcap	248 modules /endcap
Combined Si detector	OTK and ITK silicon trackers
Geometry of layout	Inner: 1.2m Outer: 3.6m Length: 5.9m
Potential at cathode	- 62,000 V
Gas mixture	T2K: Ar/CF ₄ /iC ₄ H ₁₀ =95/3/2
Maximum drift time	34 μ s @ 2.75m
Detector modules	High granularity readout Micromegas



Detailed design of TPC detector in TDR

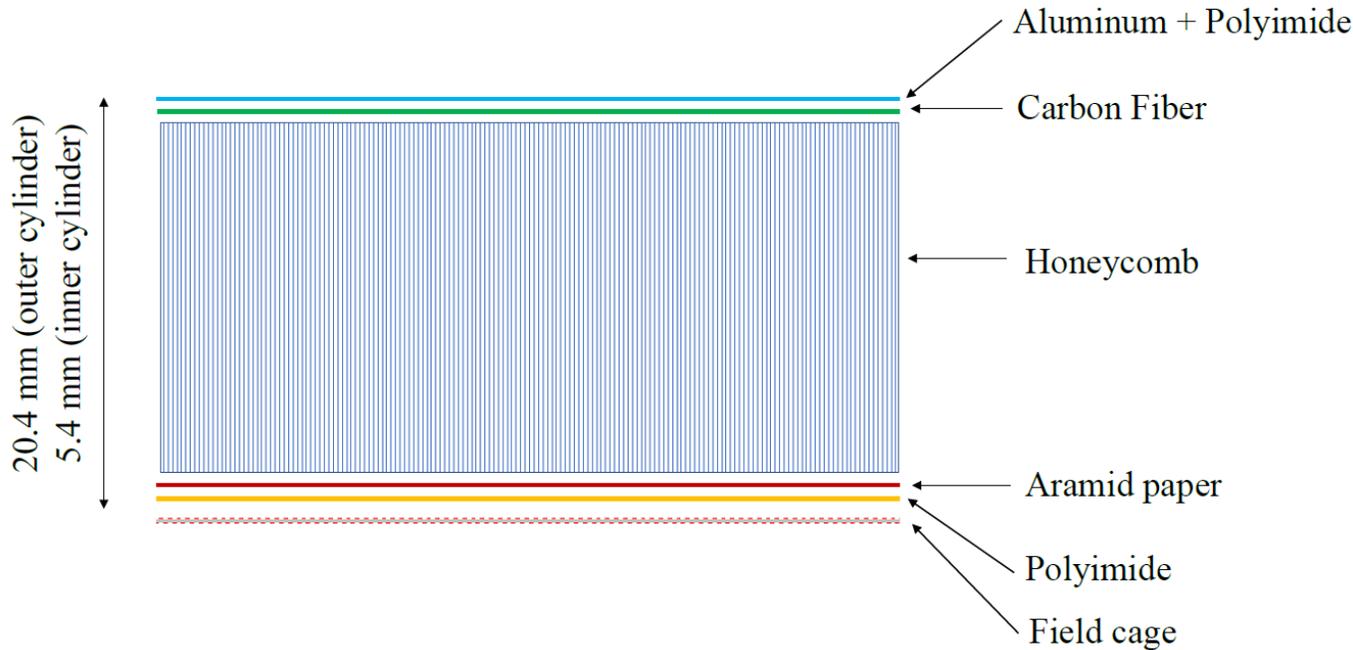
Readout module design

- 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



Light barrel design

- To reduce mechanical deformation, improve insulation performance, and minimize the material budget
 - Sandwich structure
 - Outer cylinder thickness: 20.4mm, Material budget: 0.69% X_0
 - Inner cylinder thickness: 5.4mm, Material budget: 0.45% X_0
 - The insulation material is rated at 62 kV and includes a safety factor

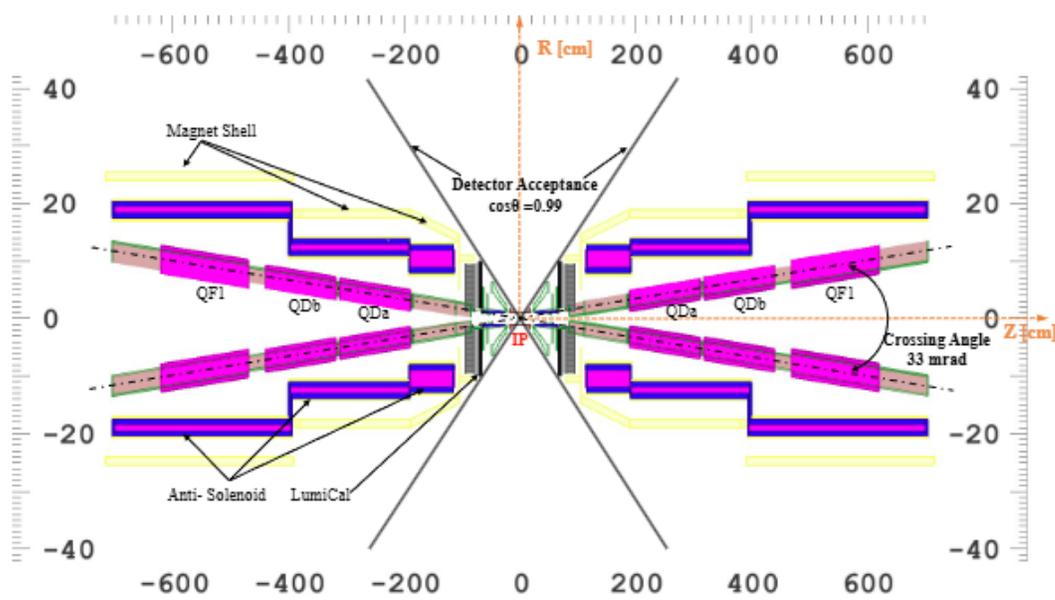


Component	Layers	X [cm]	X_0 [cm]	X/X_0 [%]
TPC outer wall				
Faraday cage shield	Aluminum	0.005	8.9	0.06
Faraday cage shield substrate	Polyimide	0.005	28.6	0.02
Outer wall support cylinder	Carbon fiber	0.02	25.28	0.08
Outer wall support cylinder	Nomex honeycomb	1.96	800	0.25
Outer wall support cylinder	Aramid paper	0.01	35	0.03
Insulating layer	Polyimide	0.01	28.6	0.03
Mirror strips layer	Copper	0.0012×0.95	1.44	0.08
Field cage substrate	Polyimide	0.005	28.6	0.02
Field strips layer	Copper	0.0012×0.95	1.44	0.08
Glue	Epoxy	0.02	35.3	0.06
TPC inner wall				
Field strips layer	Copper layer	0.0012×0.95	1.44	0.08
Field cage substrate	Polyimide	0.005	28.6	0.02
Mirror strips layer	Copper	0.0012×0.95	1.44	0.08
Insulating layer	Polyimide	0.01	28.6	0.03
Inner wall support cylinder	Aramid paper	0.01	35	0.03
Inner wall support cylinder	Nomex honeycomb	0.46	800	0.06
Inner wall support cylinder	Carbon fiber	0.020	25.28	0.08
Faraday cage shield substrate	Polyimide	0.005	28.6	0.02
Faraday cage shield	Aluminum	0.005	8.9	0.06
Glue	Epoxy	0.02	35.3	0.06

- **Simulation and BG and PID**

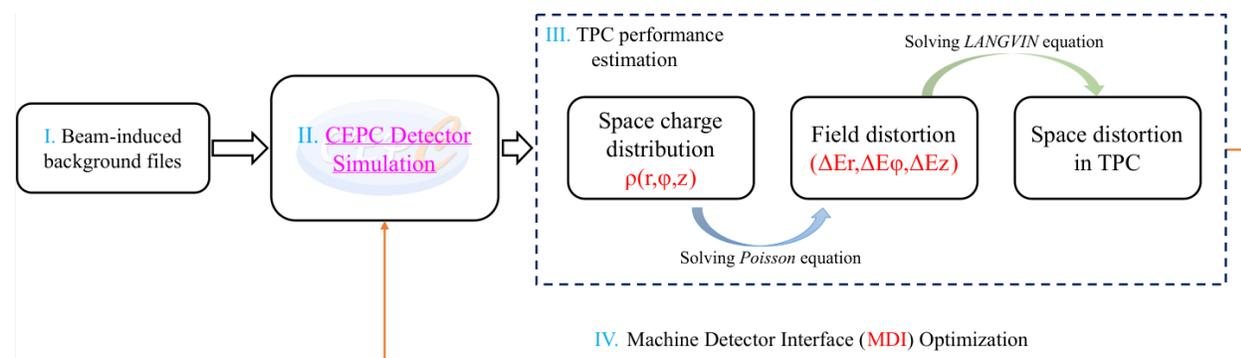
Beam background simulation

- 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

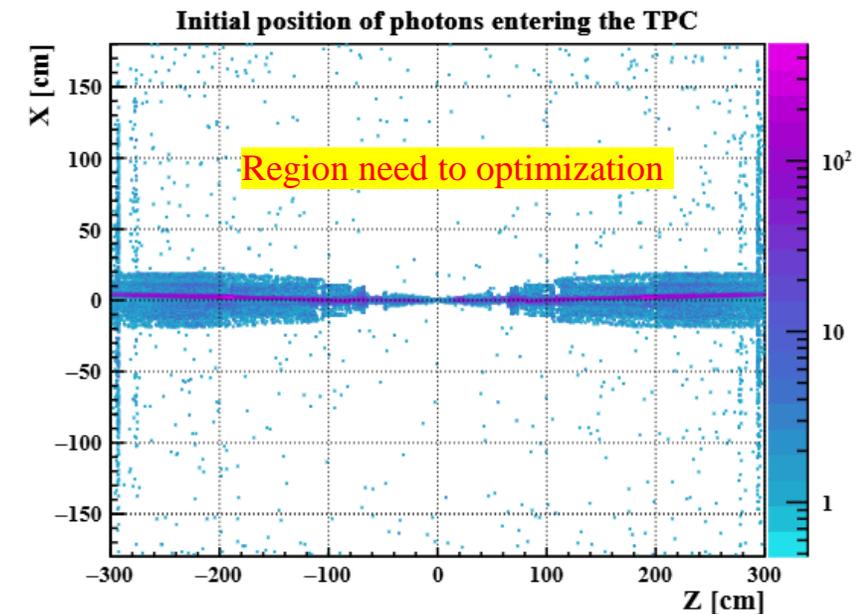
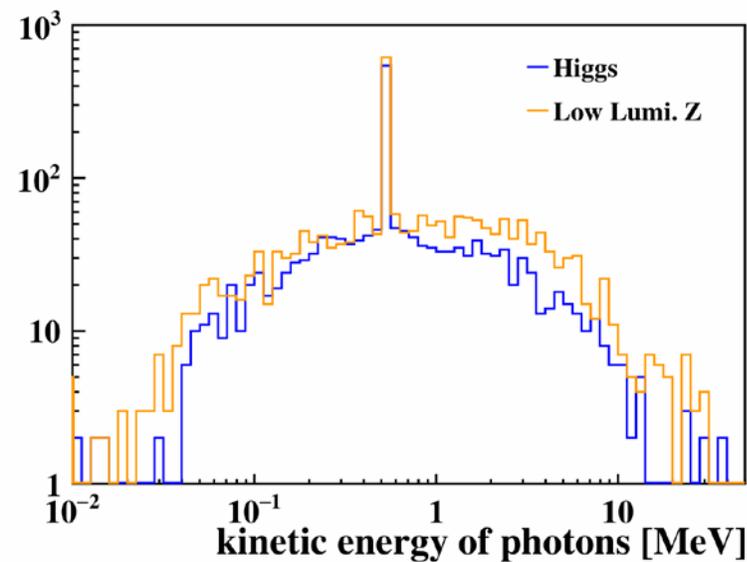
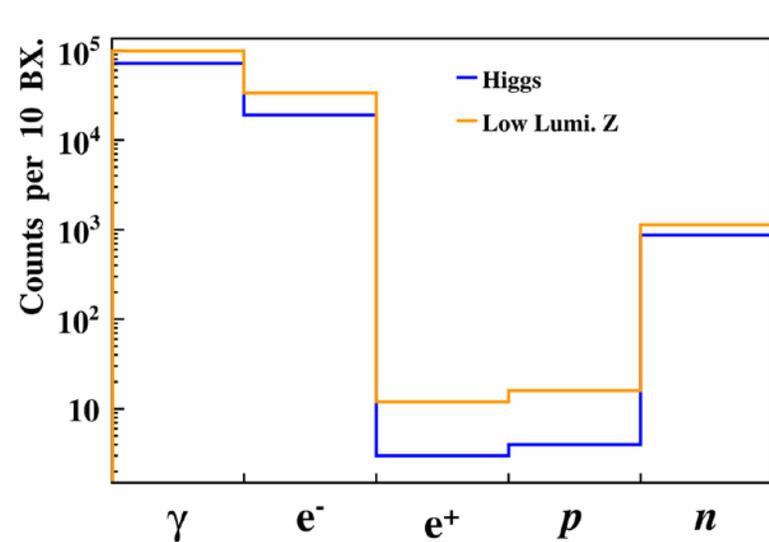
Backgrounds	Generation	Tracking	
Pair production	Guinea-Pig++	SAD	Luminosity related (BS files)
Beam-Gas Coulomb (BGC)	BGC in SAD		Single-Beam (Lost maps)
Beam-Gas Bremsstrahlung (BGB)	PyBGB		
Beam-Thermal Photon (BTH)	PyBTH		
Touschek Scattering (TSC)	TSC in SAD		



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

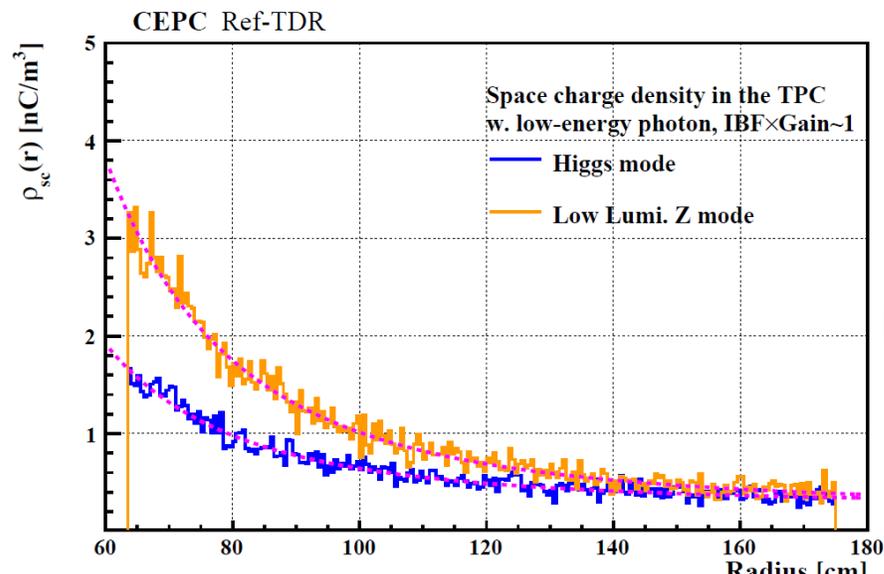
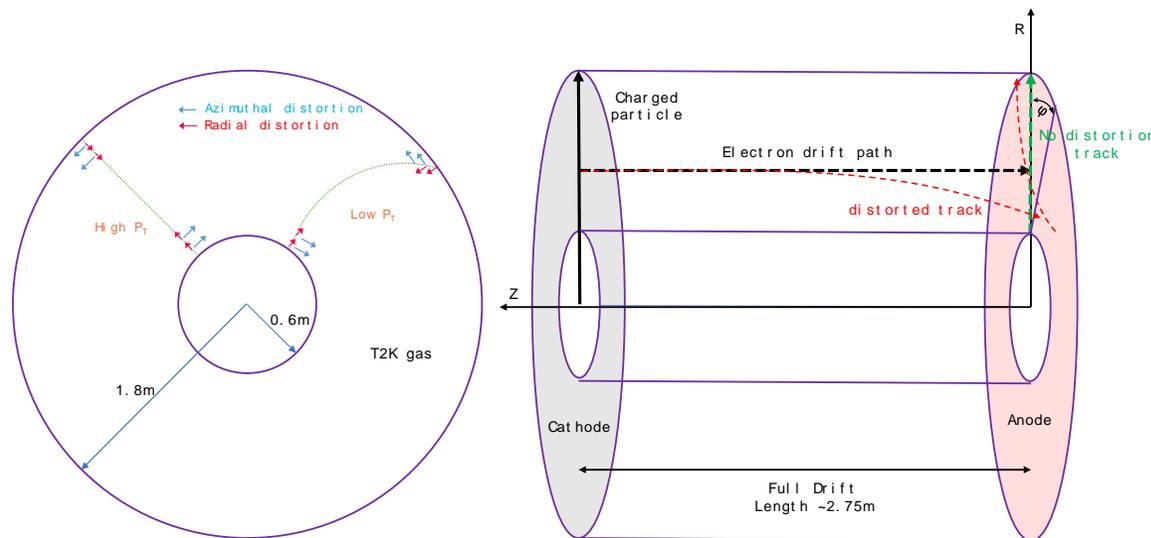
- **Photons** and **electrons** (produced by low energy photons) are the main components in the TPC volume
 - The rest of particles, like positrons, proton and neutron, are negligible
- Low-energy photons (< 10 MeV) are the main contribution of the space charge
 - Photons originating from the **downstream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



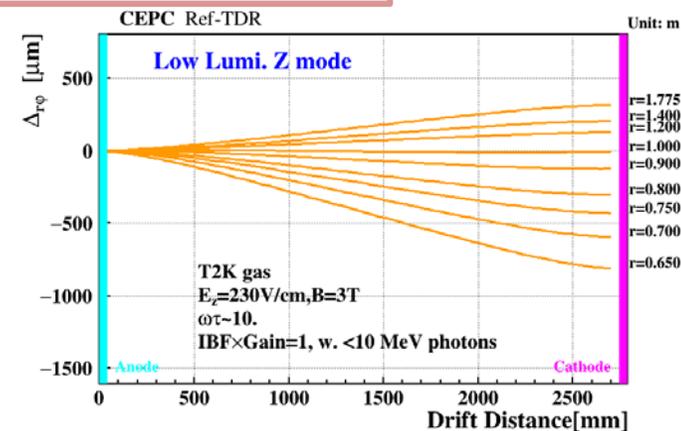
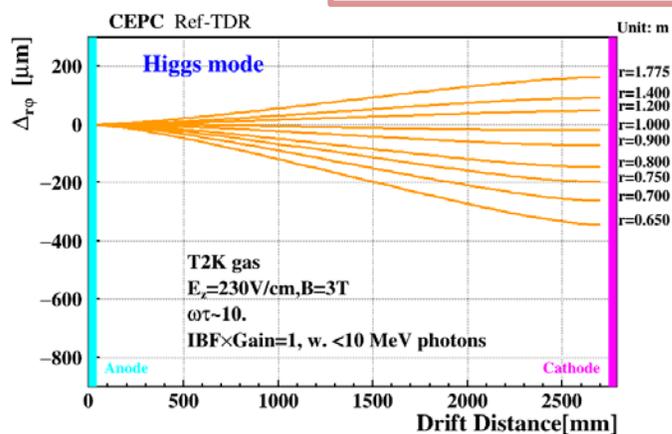
Particle type, Energy and initial position of low-energy photons entering the TPC

Space charge density and deviations

- The max. space charge density reaches **1.7-3.3 nC/m³**
 - 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. $\Delta\varphi$ reaches **800-900 μm** in the low-Z mode (**need to optimization and calibration**)



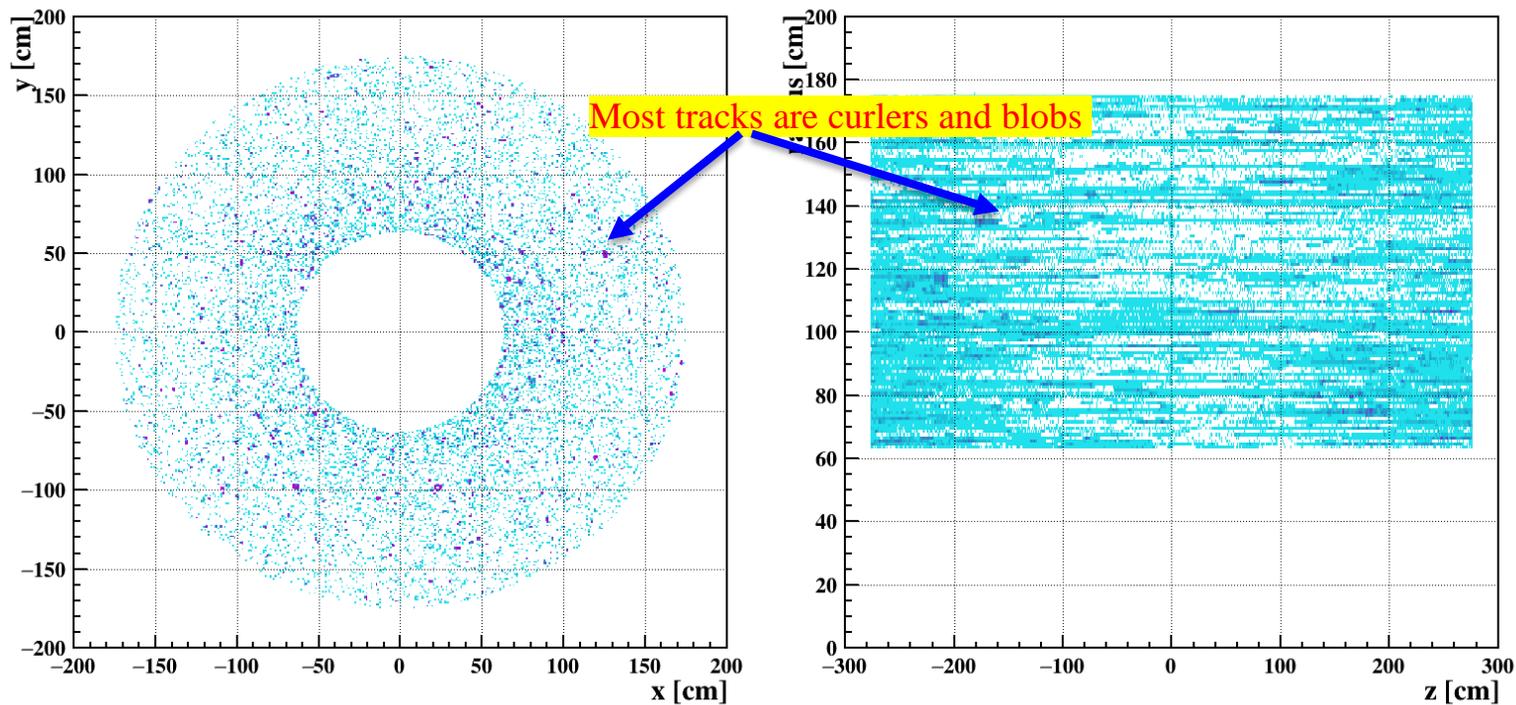
IBF×Gain=1 && w. low-energy photons



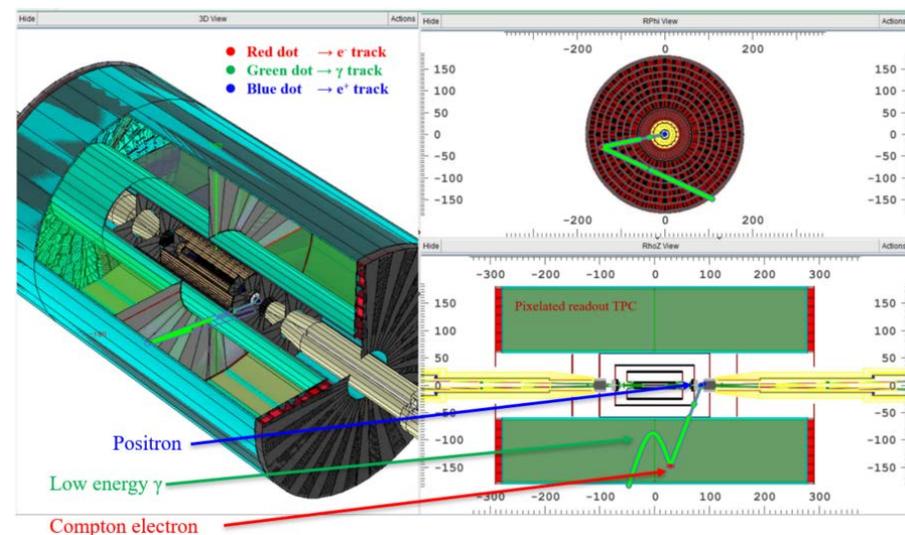
Space charge density and distortions in the Higgs and low-luminosity Z modes

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

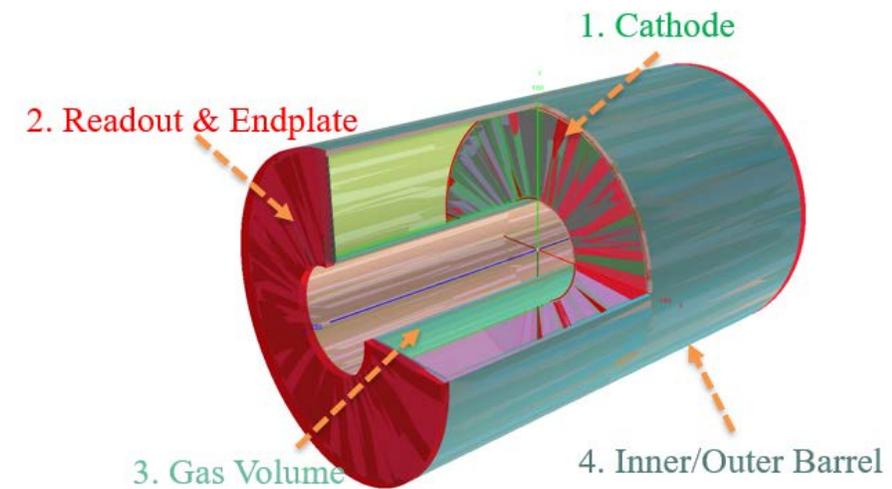
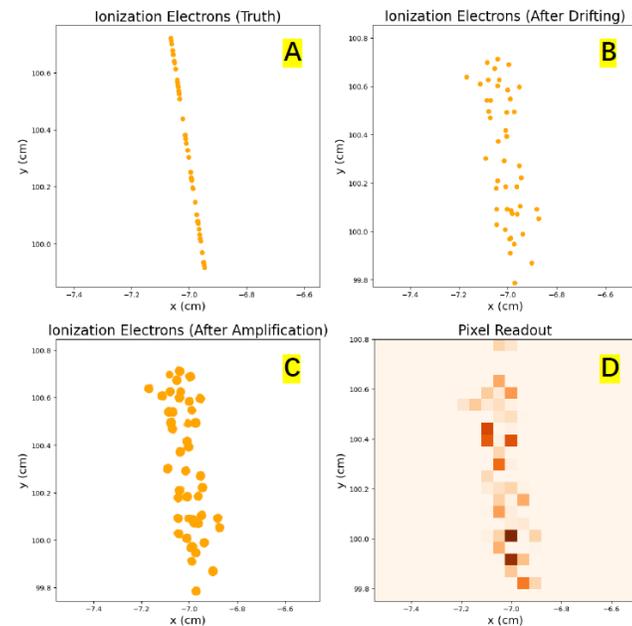
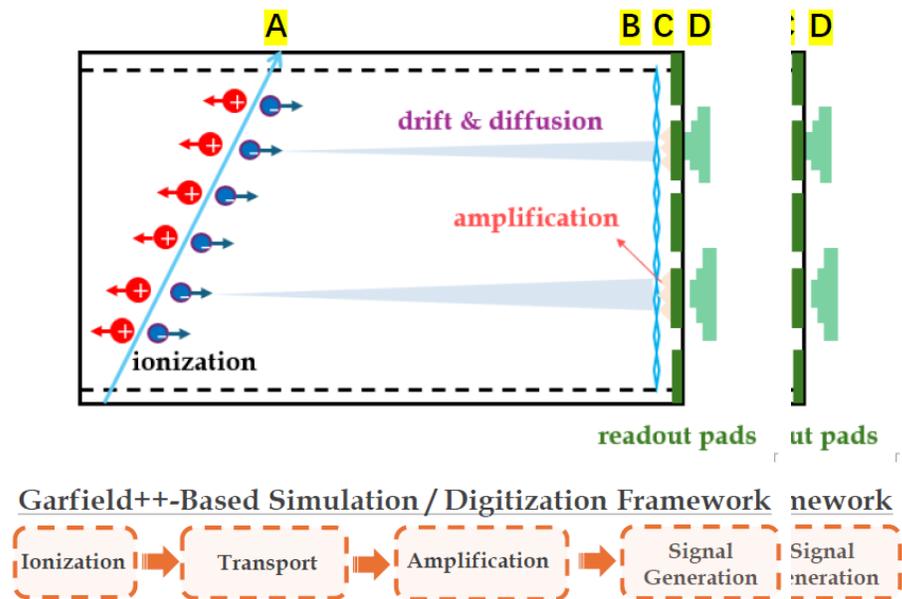


background e^+ annihilation $\rightarrow \gamma(0.511\text{MeV}) \rightarrow \text{Compton } e^-$

- 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

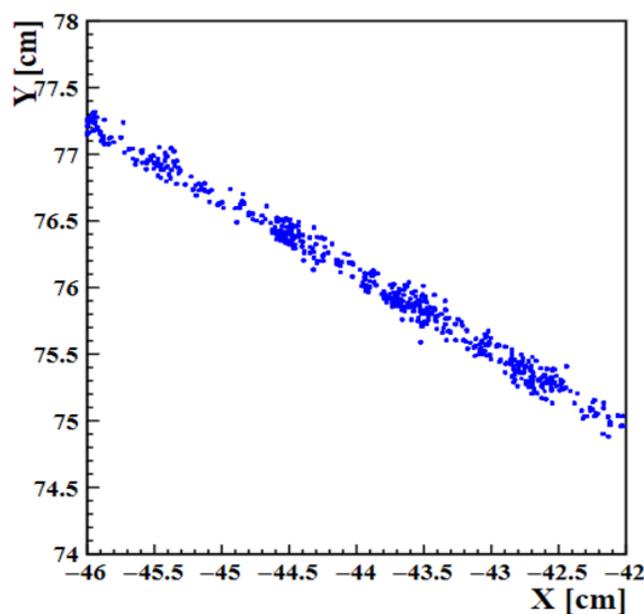
- Sophisticated software for simulation/digitization/reconstruction using Garfield++ and Geant4
 - Geometry implementation based on CEPC TDR
 - Cathode, Micromegas readout and endplate, barrel, gas volume
 - PID with the cluster counting
 - Garfield++ based full simulation and digitization from the primary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



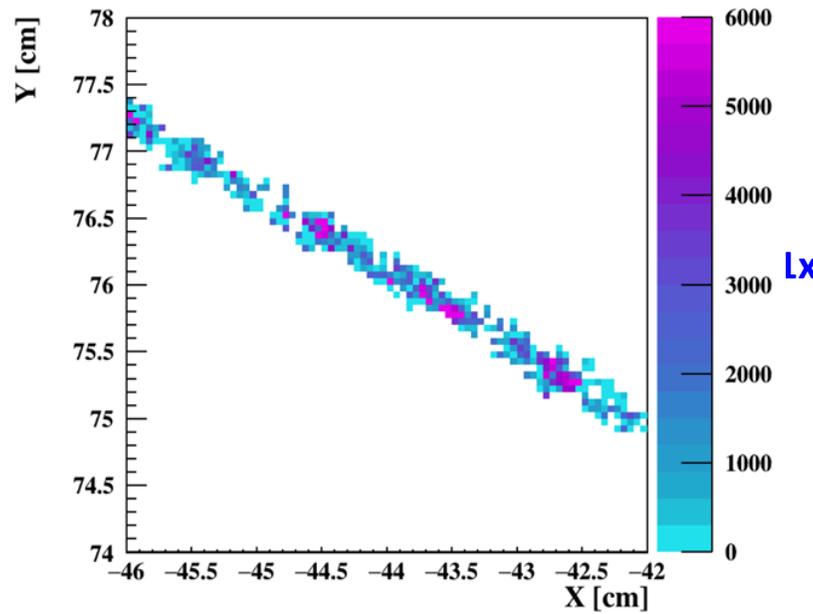
Simulation of TPC detector under 3T and T2K mixture gas

Full Simulation of High granularity readout TPC – Readout size

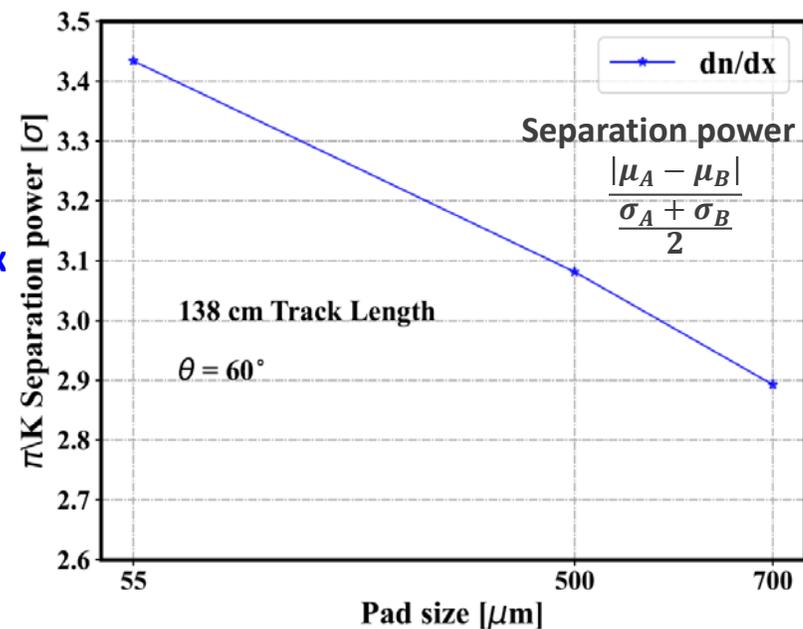
- Simulation results showed that readout size can be optimized at around 500 μm .
 - Optimization started in this TDR to meet Higgs/Z at 3T
 - Focused on **100mW/cm² and 500 μm readout** for TDR (<10kW/endplate, Water cooling option)
- TPX3/4 (55 \times 55 μm^2 , 110 \times 110 μm^2) readout TPC prototype has been validation on DESY beams.
 - Power consumption: 2W/cm² ; Low power mode: 1W/cm² (**high power consumption!**)



pixel response (55 $\mu\text{m} \times 55 \mu\text{m}$)



pixel response (500 $\mu\text{m} \times 500 \mu\text{m}$)

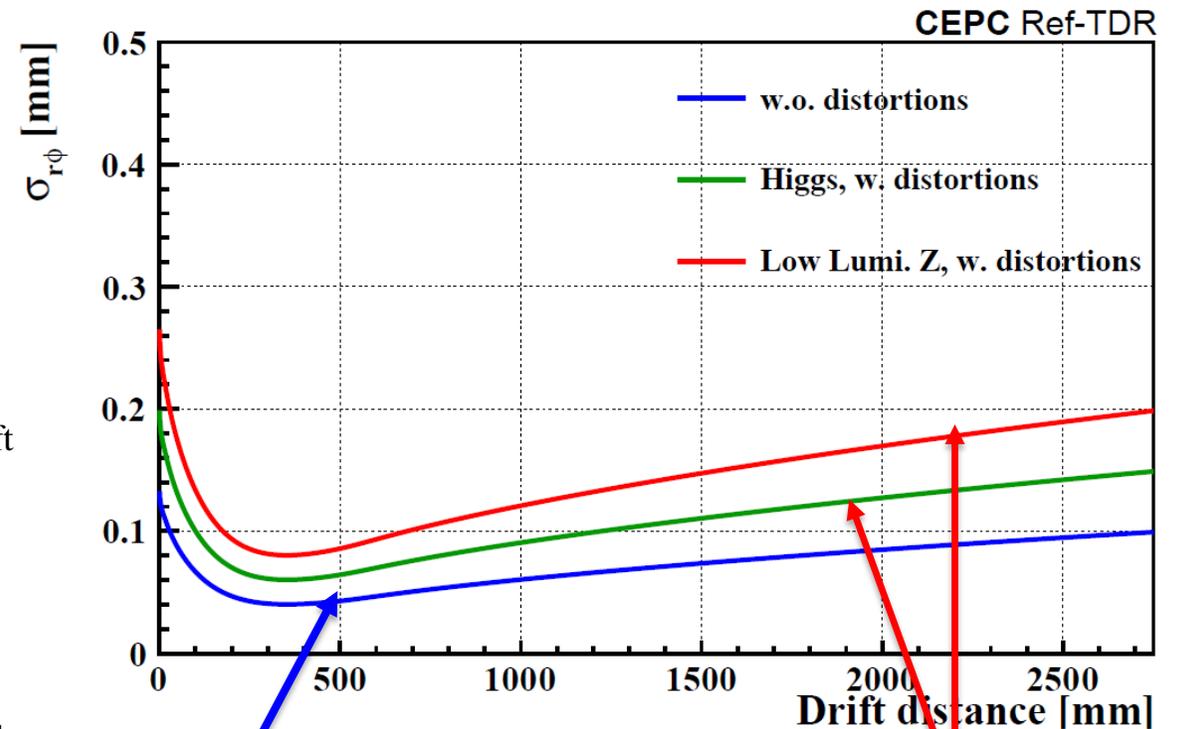


Optimization of readout size. Balancing of performance and cost power consumption, etc.

Full Simulation of High granularity readout TPC – Spatial resolution

- Impact of space-point distortions on spatial resolution
 - Space-point distortions can be corrected by the data-driven track-based calibration
 - Error contributions to the calibrated spatial resolution :
 - Space-charge distortion: $< 80\mu\text{m}$ in Higgs, $< 160\mu\text{m}$ in low-lumi. Z, dependent on L_{drift}
 - NUMF effects on the drift process (after correction with B field map): $< 65\mu\text{m}$
- Conservatively estimated, the calibrated spatial resolution degrades by $\sim 50\%$ and 100% at the point with the longest drift distance in Higgs and low-luminosity Z modes respectively.

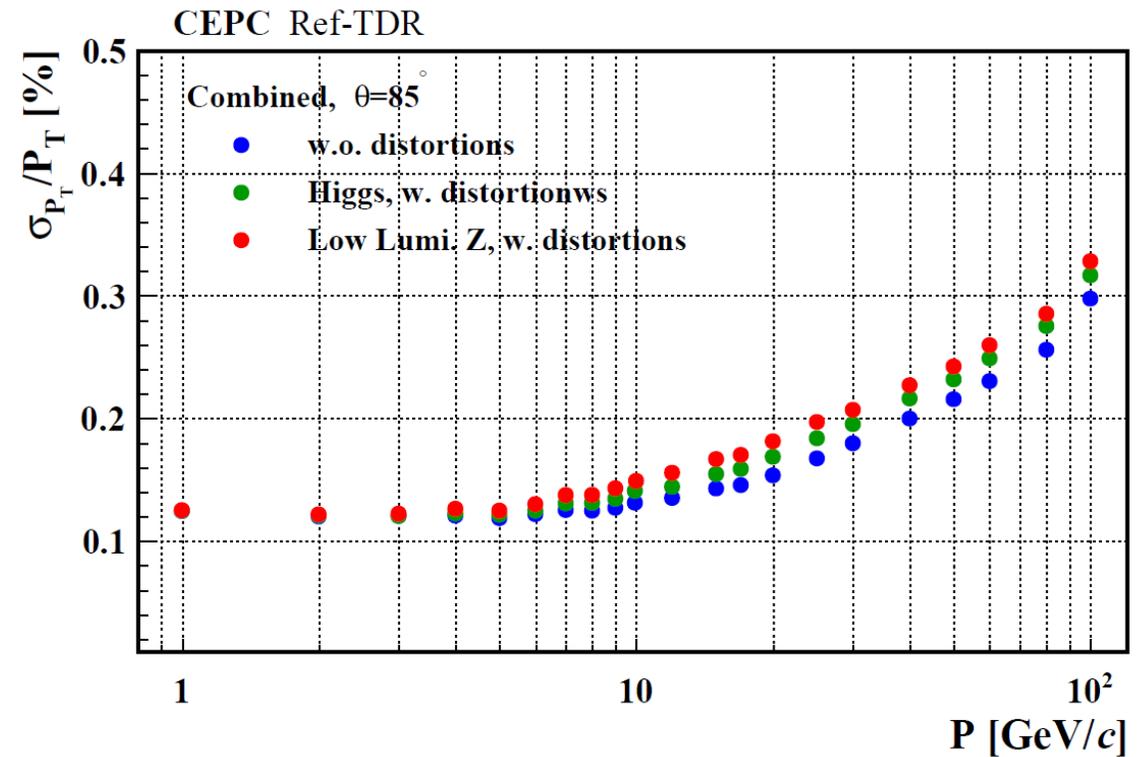
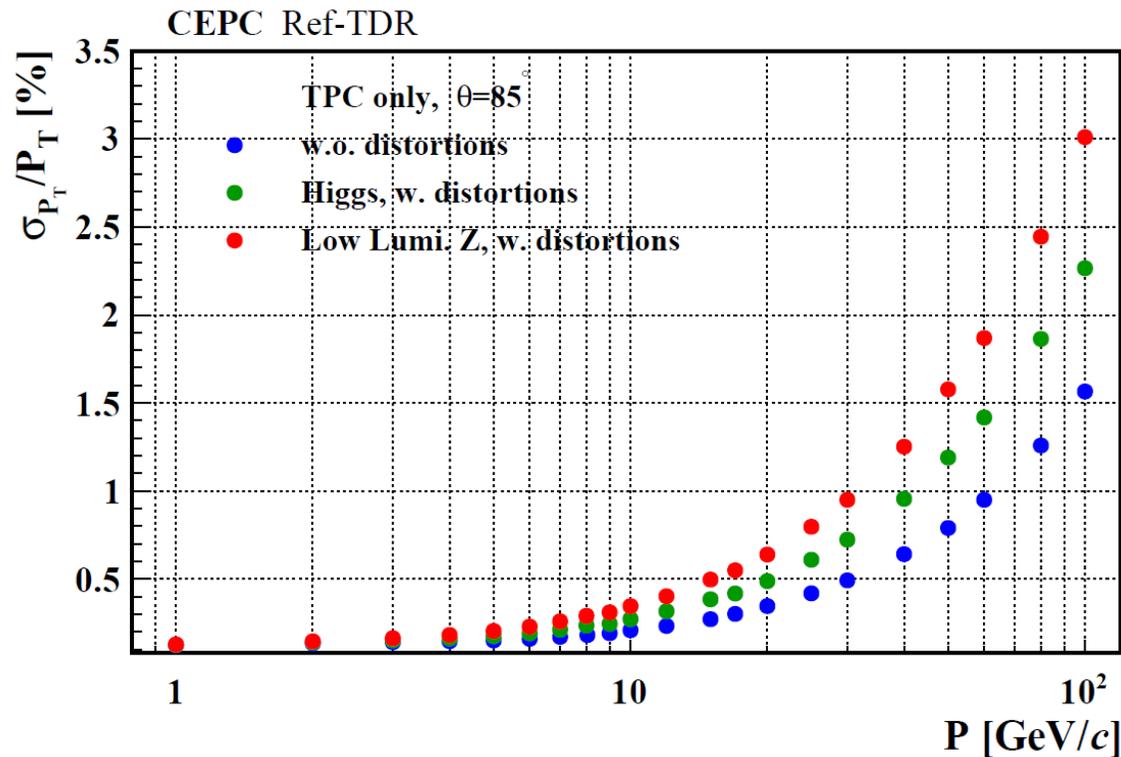
Original resolution not including distortions



Taking into account space-point distortions with calibration and correction

Full Simulation of High granularity readout TPC - Momentum resolution

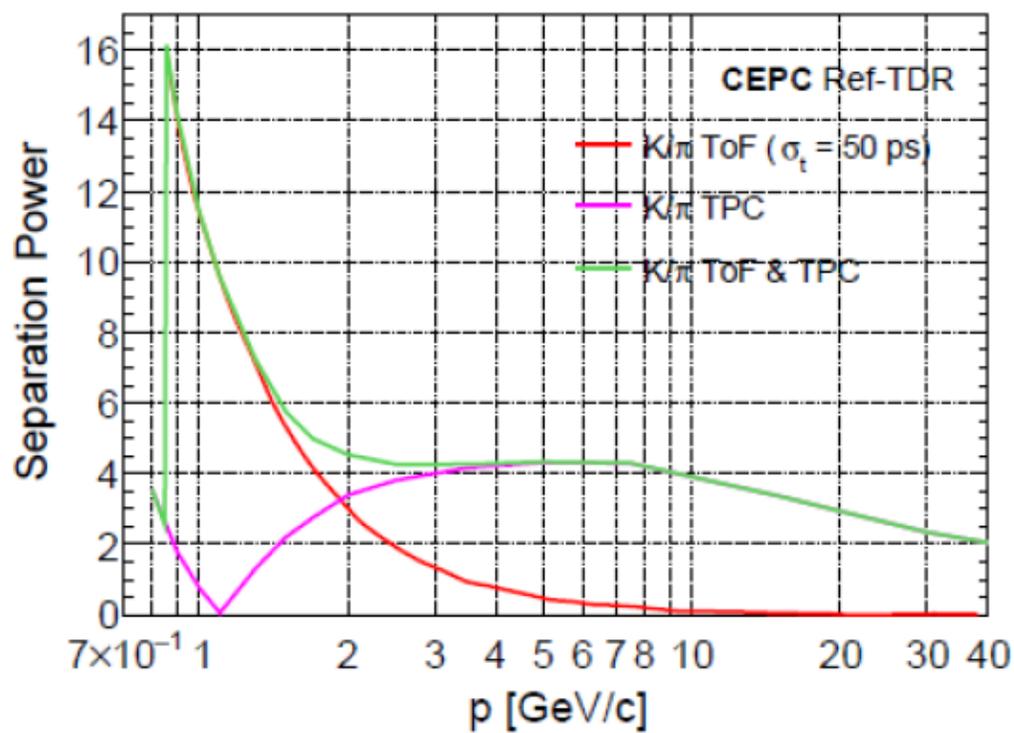
- Momentum resolution
 - Compared to idea scenario, resolution with the TPC standalone degrades seriously for **high momentum particles**
 - **11% degradation** after combining the silicon trackers in low lumi. Z mode
 - Would not suffer too much from the electron drift deviations
- Further simulation with a complicated model is ongoing.



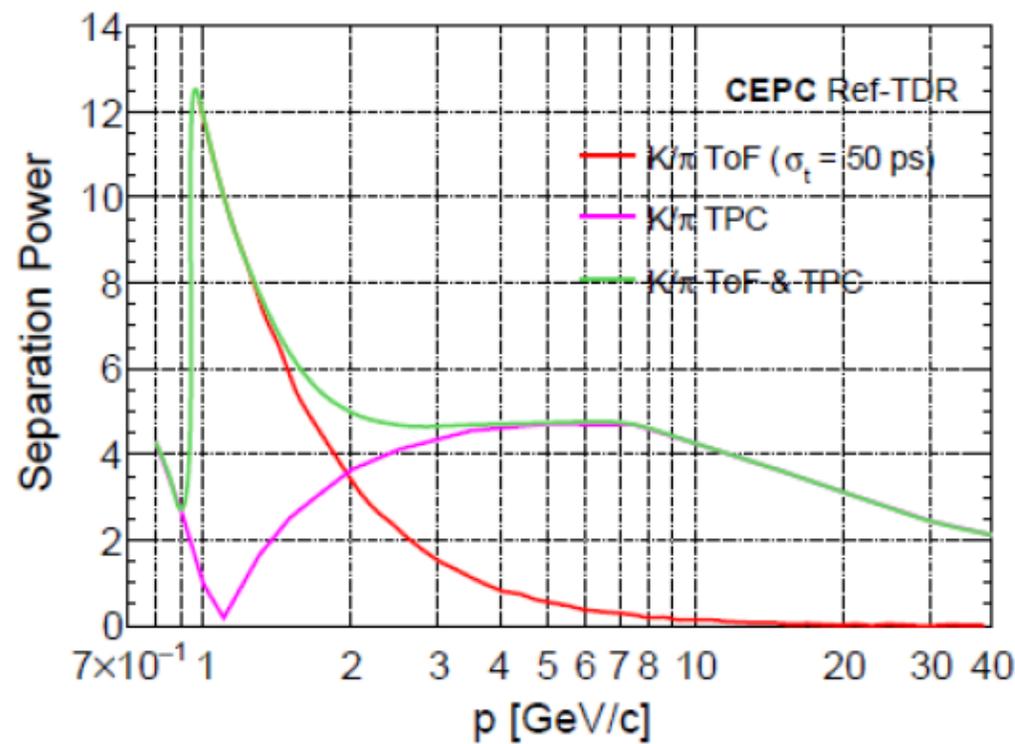
Full Simulation of High granularity readout TPC – PID performance

- K/π separation power using the combined information of ToF and TPC
 - ToF information compensates for momentum range of around 1 GeV/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) $\theta = 85^\circ$

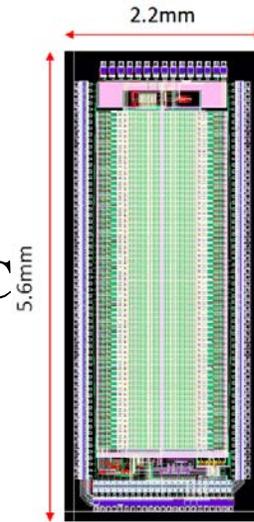


(b) $\theta = 60^\circ$

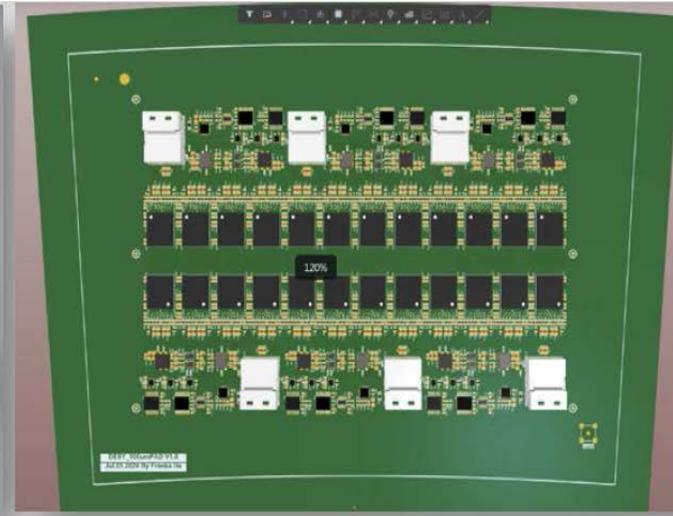
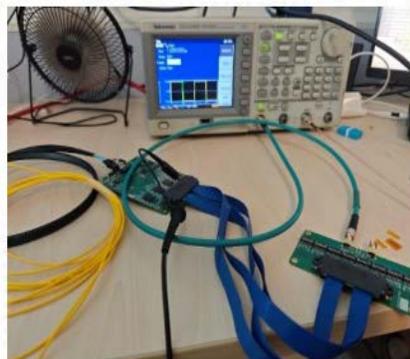
- **Prototypes for e^+e^- and neutrino detection**

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 \times 5.6 mm

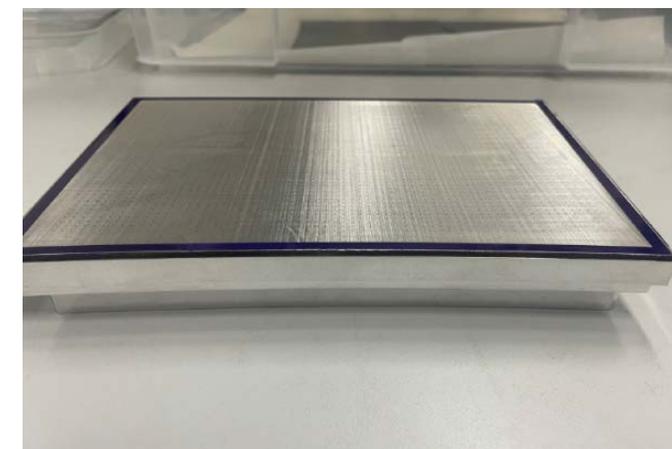
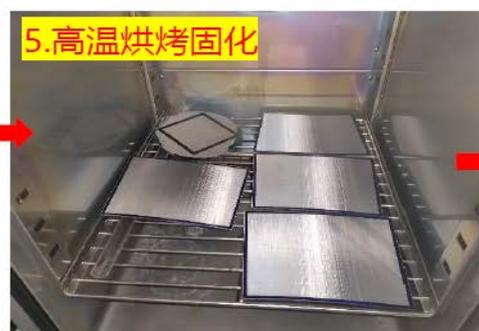
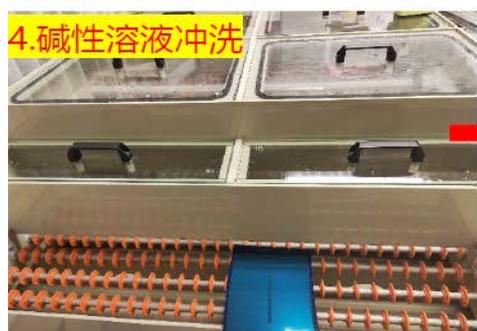
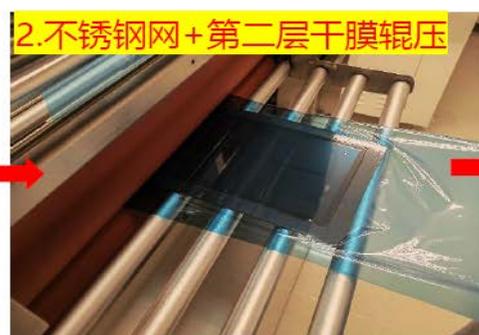
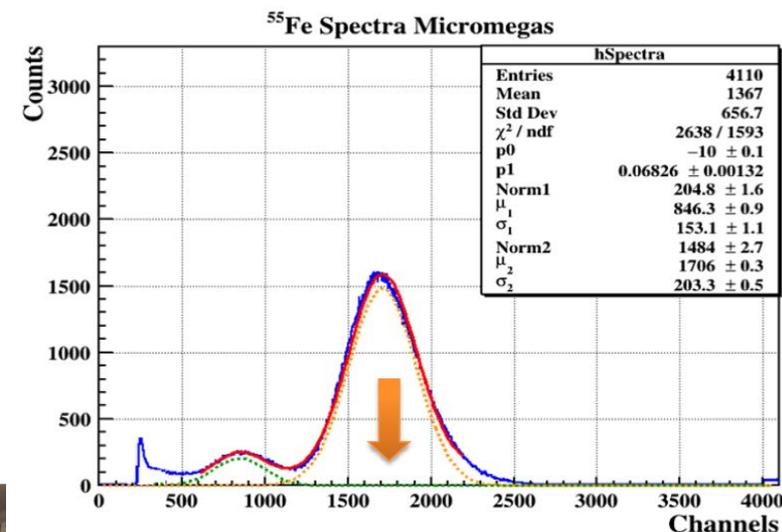


Total number of channels	30 Million per endplate
Pixel size	500 $\mu\text{m} \times 500 \mu\text{m}$
Equivalent Noise Charge (ENC)	100 e^-
Dynamic range	20 fC
Charge buffer dynamic range	8-10 bit
Event rate	12 kHz/cm ² max. in low-lumi. Z mode
Event size	64 bit
Readout bandwidth	<10 Gbps per module with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



Validation and commissioning of TPC prototype

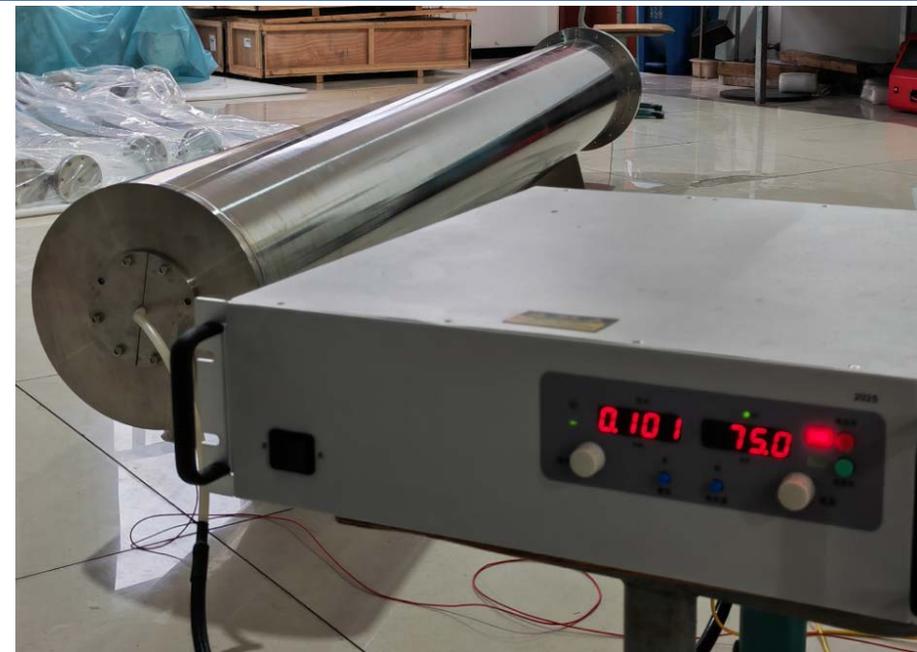
- R&D on High granularity readout TPC readout for CEPC TDR.
 - ASIC chip developed and has been tested at IHEP.
- Energy/Time value of the channels according to the charged injected
 - The uniformity test result of single TEPIX chip : <5%
- A TPC readout module has developed with 10×300 readout channels (24 TEPIX chips), **still needs more debugging.**



Some test result of Micromegas detector integrated with TEPIX chip

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

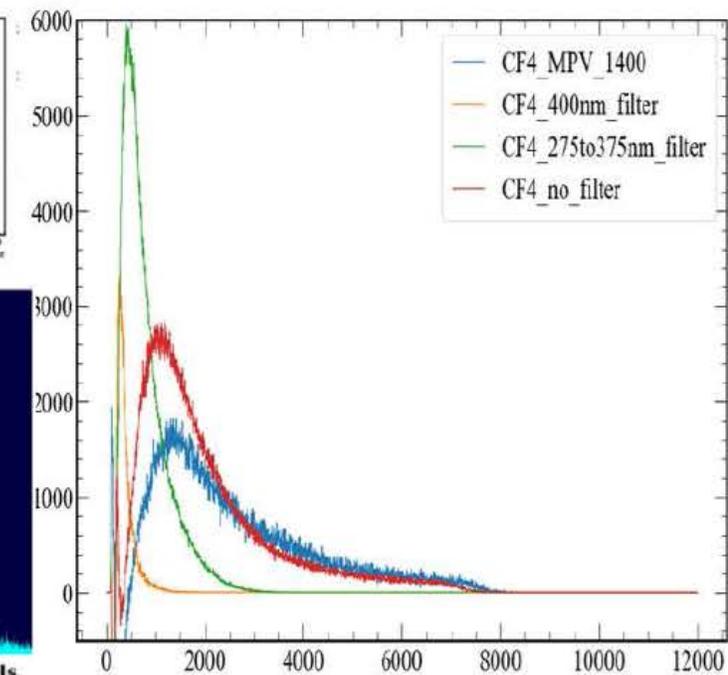
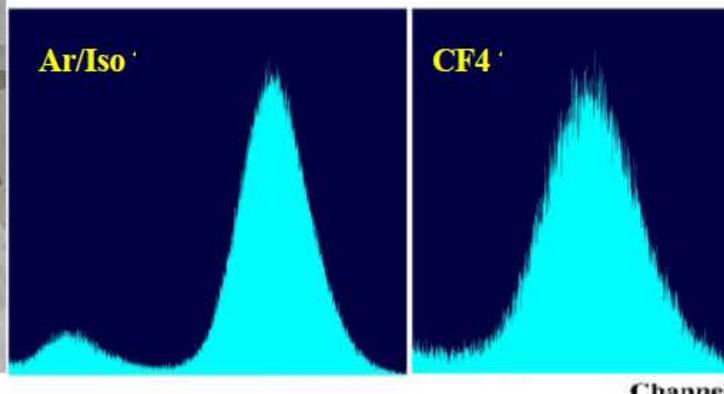
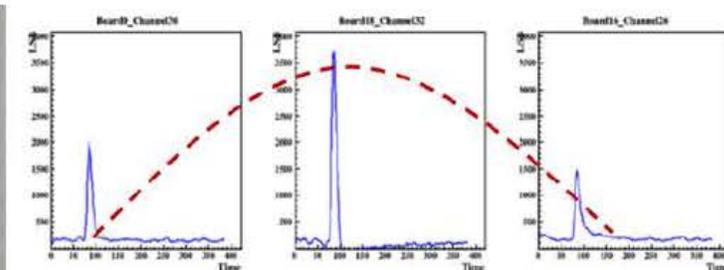
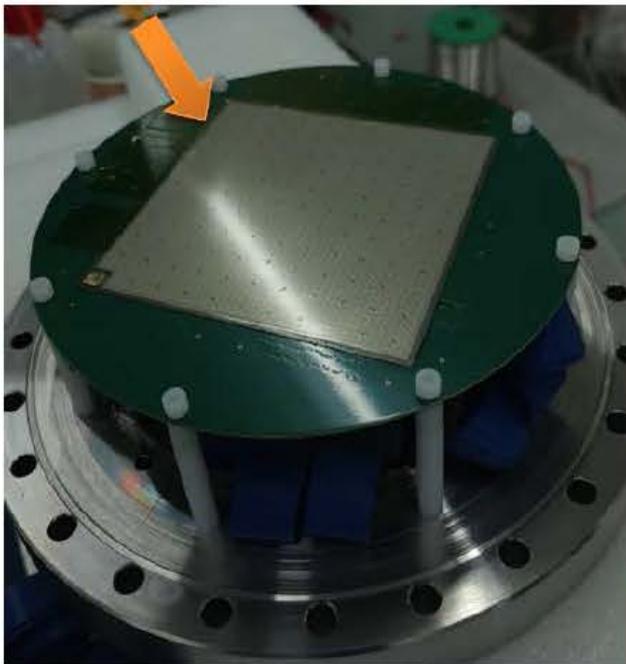
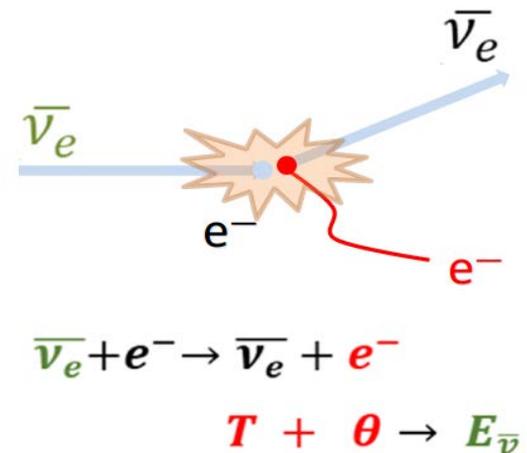


Milestones achieved	Short term	Long term
Ion backflow suppression	IBF × Gain < 1 (Gain=2000)	Graphene technology
High granularity readout readout prototype	Validation with beam test	Prototype with Multi-modules
Power consumption ASIC	~100mW/cm² (60nm ASIC)	Optimization readout size
PID resolution	3% (dN/dx)	<3% (dN/dx)
Material budget (barrel)	Carbon Fiber	Full size prototype

Plans of TPC R&D in neutrino detection

Physics requirements:

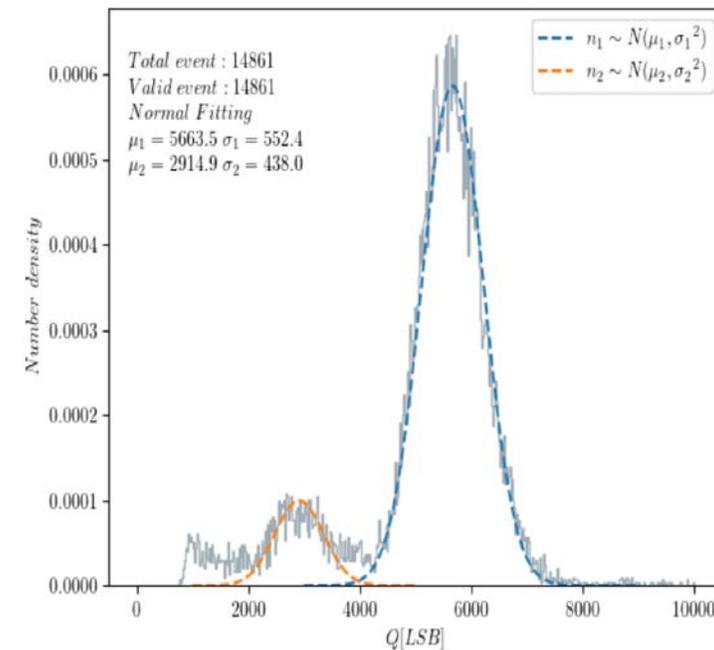
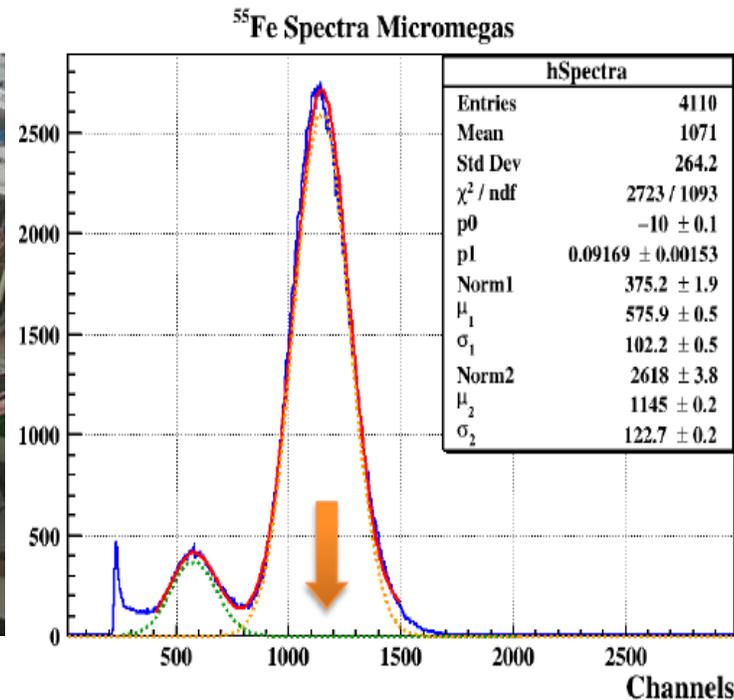
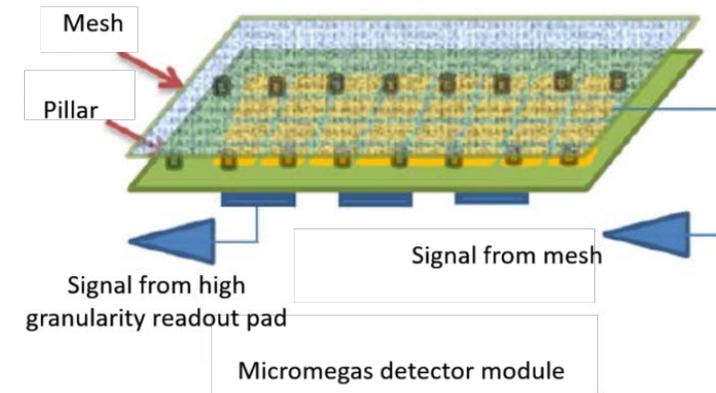
- Detect reactor antineutrinos in the **200 keV – 1 MeV** range with <10% energy resolution for the reactor antineutrino spectrum, at a stand-off distance ≤ 20 m from the reactor core.
- A high **electron-density CF₄ gas** (>500 kg) serves as both TPC target and working fluid. Key issues: control electron attachment and provide a clean primary-scintillation T₀ signal.



Plans of TPC R&D in neutrino detection

Achievement of TPC prototype:

- Completed 700-channel readout of neutrino prototype; Micromegas detector stably operated at 3 atm
- Used Fe-55 source to acquire energy spectrum on mesh; energy spectra obtained through 1 mm \times 1 mm pixel readout and the **two results are consistent.**
- Muon tracks under different pressures are under experimental investigation



- High granularity readout TPC is chosen as the baseline detector as main track in CEPC TDR. The simulation framework has been developed using Garfield++ 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 $500\mu\text{m} \times 500\mu\text{m}$
 - Ultra light material budget of the barrel and endplate
 - dn/dx has much better PID by getting rid of fluctuations from energy deposition and amplification
 - π/K : $\sim 3\sigma$ @ 20 GeV/c, $\sim 2\sigma$ @ 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.
- TPC technology extended to neutrino detection: High-pressure CF4 prototype developed and commissioned.
- Synergies with CEPC and FCCee allow us to continue R&D and ongoing. Team actively involved in the international collaborations.

Lepton Collider Time Projection Chamber


Linear

International Collaboration

FCCee

T2K

EIC

ILC

CEPC

ALICE

Many thanks!