
Status of TPC detection technology R&D for the circular e^+e^- collider

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Manqi Ruan, Gang Li, Linghui Wu and some inputs from LCTPC collaboration

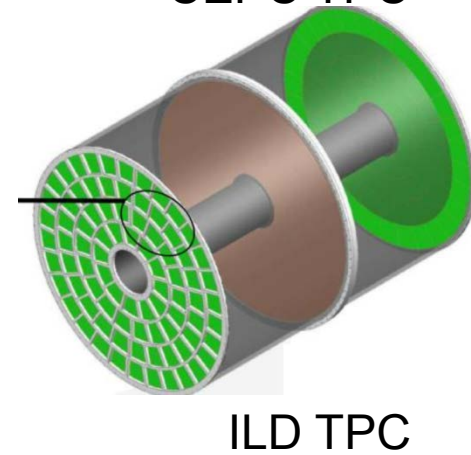
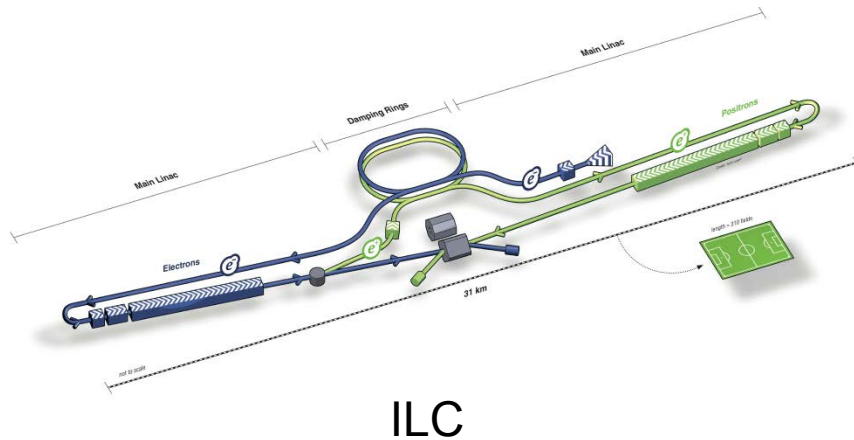
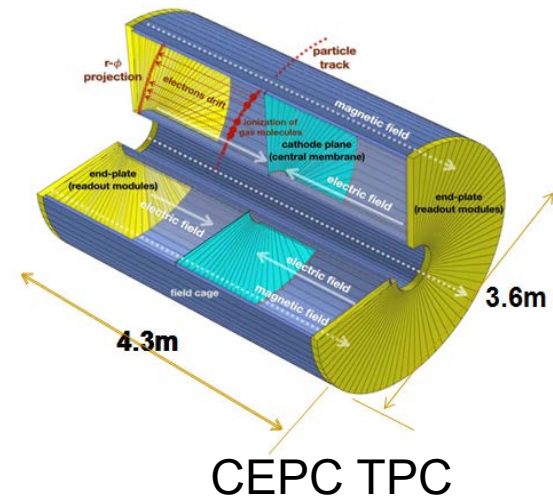
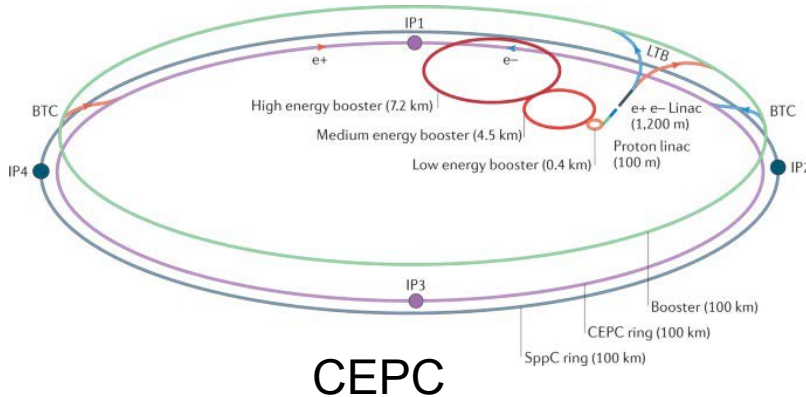
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Content

- **Motivation**
- **TPC technology R&D**
- **Feasibility of pixelated readout**
- **Prototype R&D plan**
- **Summary**

TPC detector@ Future e+e- Colliders

- TPC detector acts the key role at the future e+e- Colliders
- Some advantages of TPC detector
 - Operation under **3 T magnetic field**
 - Large number of **3D** space points
 - **Very low material** budget

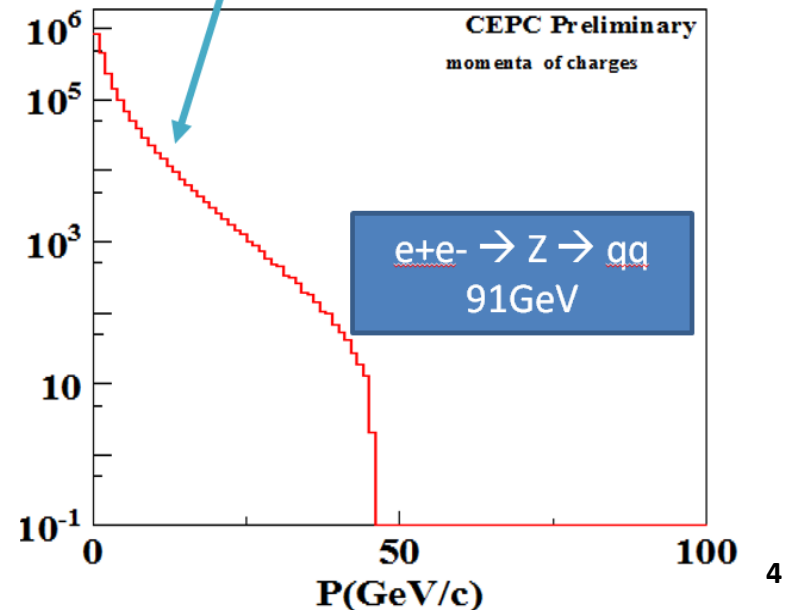
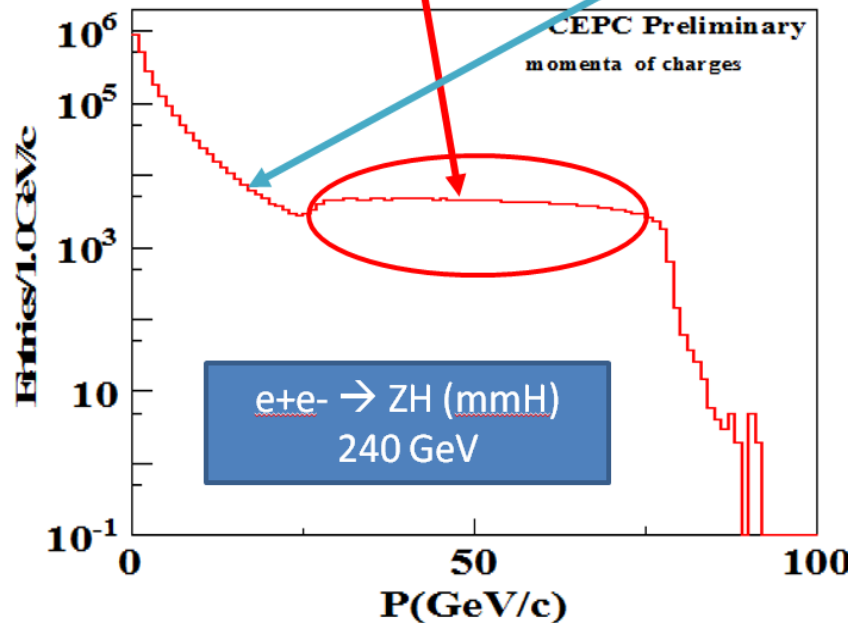


Physics requirements

- Provide decent #Hits (for track finding) with high spatial resolution compatible with PFA design (low material)
 - $dP/p \sim 0.1\%$
- Provide $dE/dx + dN/dx < 3\%$
 - Essential for Flavor @ Z pole
 - Beneficial for jet & differential at higher energy

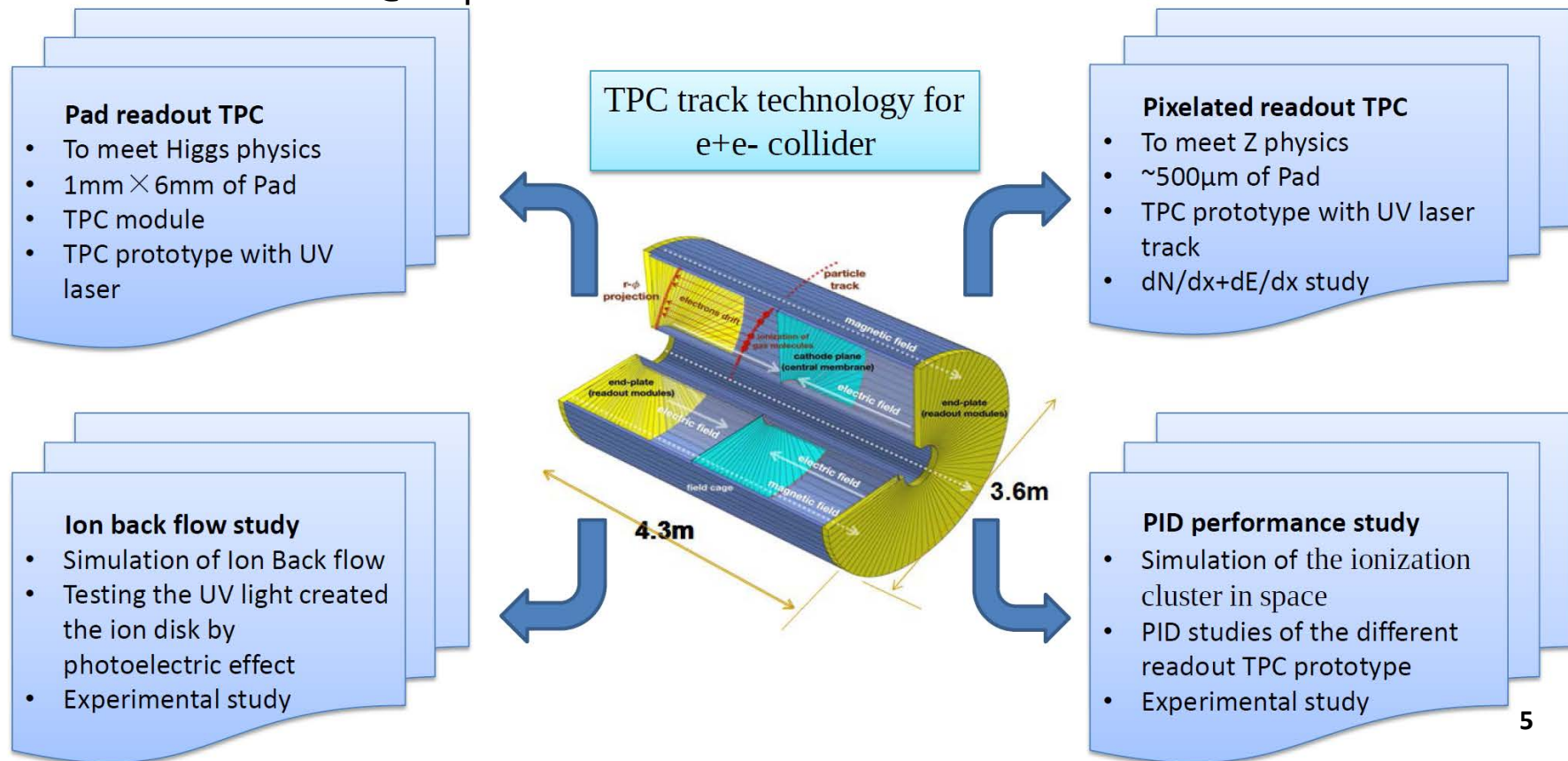
High momentum muons to recoil Higgs: 20 ~ 90 GeV

Hadrons: most of them < 20 GeV



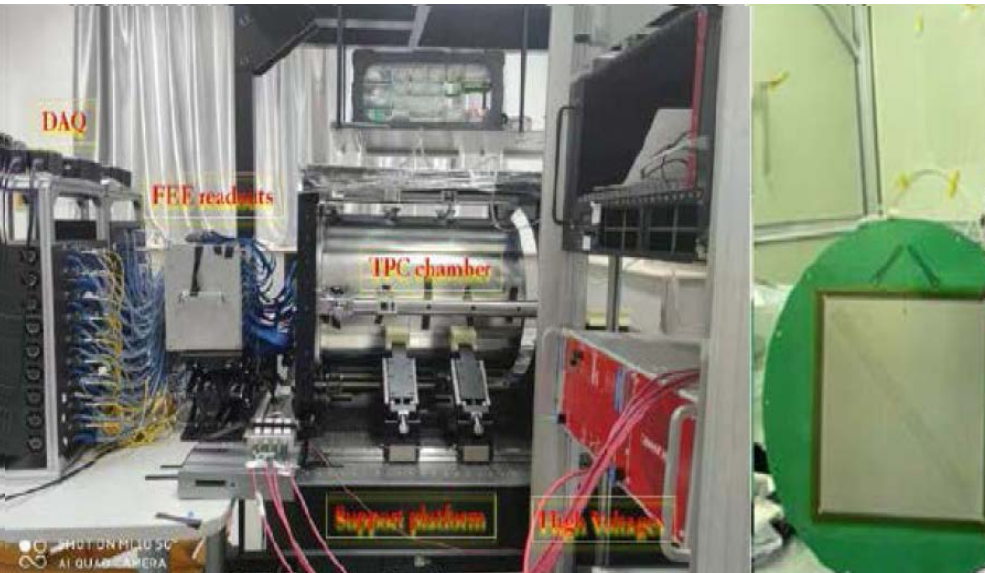
Motivation: Challenges of TPC

- **Pad readout TPC** operational at modest Lumi @ Higgs, with 3 T B-field or higher.
- **Pixelated readout TPC** operational at high Lumi (2×10^{36}) @ Z & 2 T B-Field
 - CEPC @ Z pole with 50 MW: 1.92×10^{36}
 - FCC ee @ Z pole 2.3×10^{36}



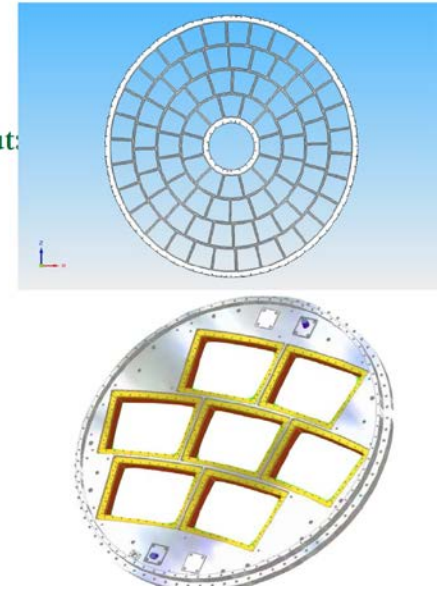
Pad TPC technology for CEPC

- At a circular collider CEPC there is place for different experiments, one of the detector concept could use a TPC as the main tracker.
- For Higgs, W and top running **no problem** for all TPC read out technologies.
- Laser TPC prototype has been successfully developed **in last 6 years** at IHEP.



Pad TPC for collider

- Active area: $2 \times 10 \text{m}^2$
- One option for endplate readout:
 - GEM or Micromegas
 - $1 \times 6 \text{mm}^2$ pads
 - **10^6 Pads**
 - 84 modules
 - Module size: $200 \times 170 \text{mm}^2$
 - Readout: Super ALTRO
 - CO_2 cooling



Pixelated TPC technology for CEPC

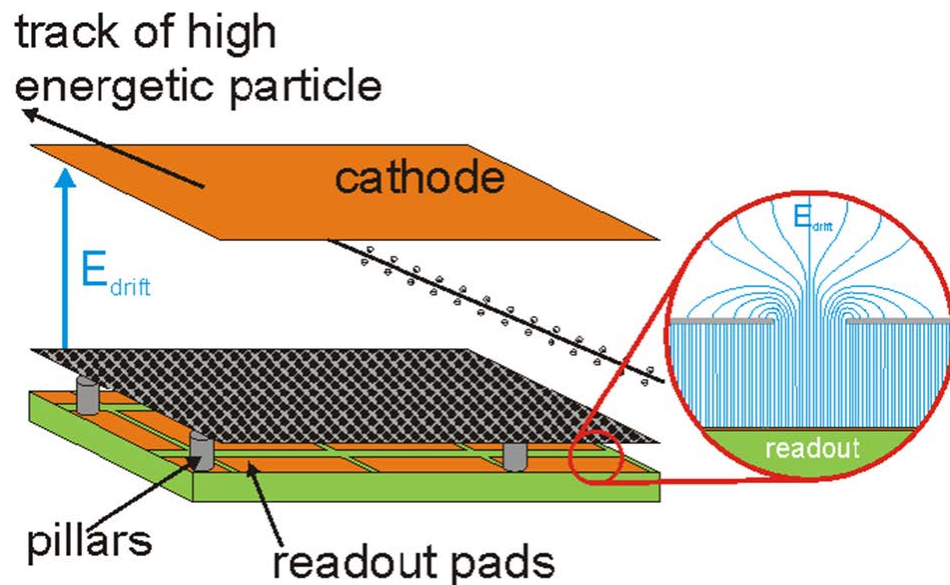
- A pixelated TPC is a good option to provide realistic physics requirements and can work **at high luminosity** (2×10^{36}) on CEPC.
- Pixelated \rightarrow better resolution \rightarrow low gain (< 2000) \rightarrow less distortion
- Pixelated readout TPC is a realistic option to provide at CEPC
 - Can deal with high rates (MHz/cm²)
 - High spatial resolution \rightarrow better momentum resolution
 - **dE/dx + Cluster counting** (In space)
 - Excellent two tracks separation

Standard charge collection:

Pads (1 mm \times 6 mm)/ long strips

Instead:

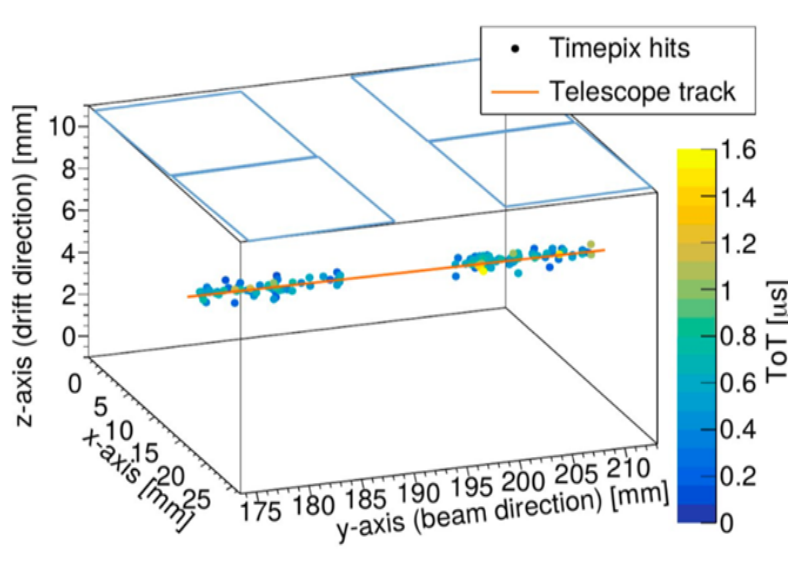
Bump bond pads are used as charge collection pads.



How to identify the clusters and achieve dN/dx

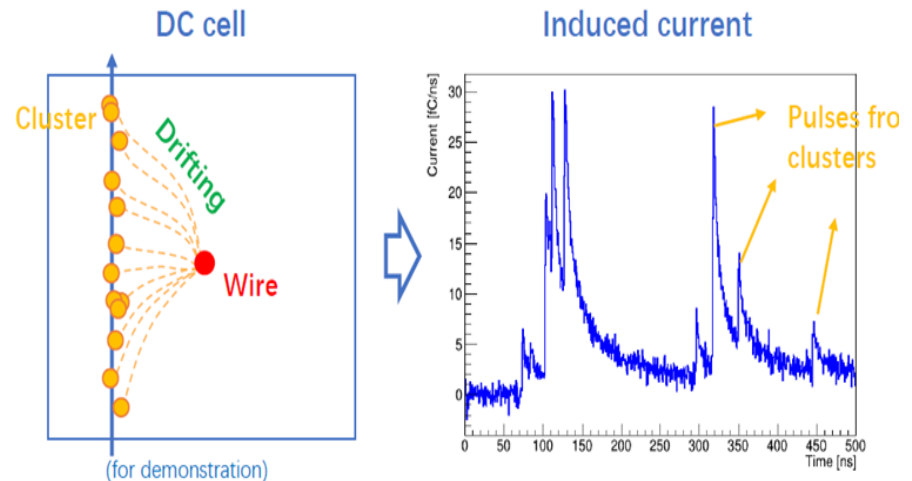
In Space - TPC

- Challenging of the low power consumption electronics ($>40\text{mV/fC}$ needed at 2000 of gas gain)
- Pixelated readout - high granularity
- \rightarrow the reasonable pixilation reveals the underlying cluster structure in 3D chamber



In Time - Wire Chamber

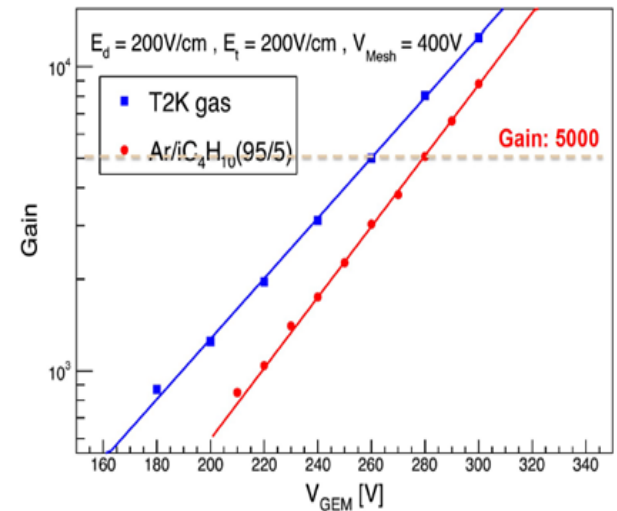
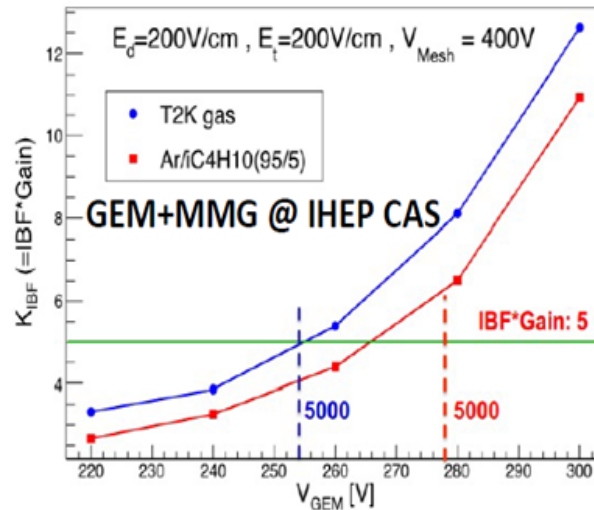
- Challenging of the fast-shaping electronics ($\sim \text{ns}$ needed)
- De-couple the charge collection from the cluster counting altogether
- \rightarrow optical, with $\sim(\text{sub})\text{ns}$ continuous readout sensors



-
- **Status of TPC detector R&D at IHEP**
 1. **TPC detector module with the ions suppression**
 2. **Status of TPC prototype using UV laser**
 3. **Low power consumption readout**

#1. TPC detector module R&D

- Studies have been done using the different active area of the hybrid TPC detector modules
 - Active area: from **50 mm×50 mm to 200 mm×200 mm**
 - Tested under the different mixture gases
- Validated $\text{IBF} \times \text{Gain}$ using the TPC detector module
 - $\text{IBF} \times \text{Gain} \leq 5 @ \text{Gain}/5000$
 - Gas gain < 2000, $\text{IBF} \times \text{Gain} \leq 1$ using MPGD as readout



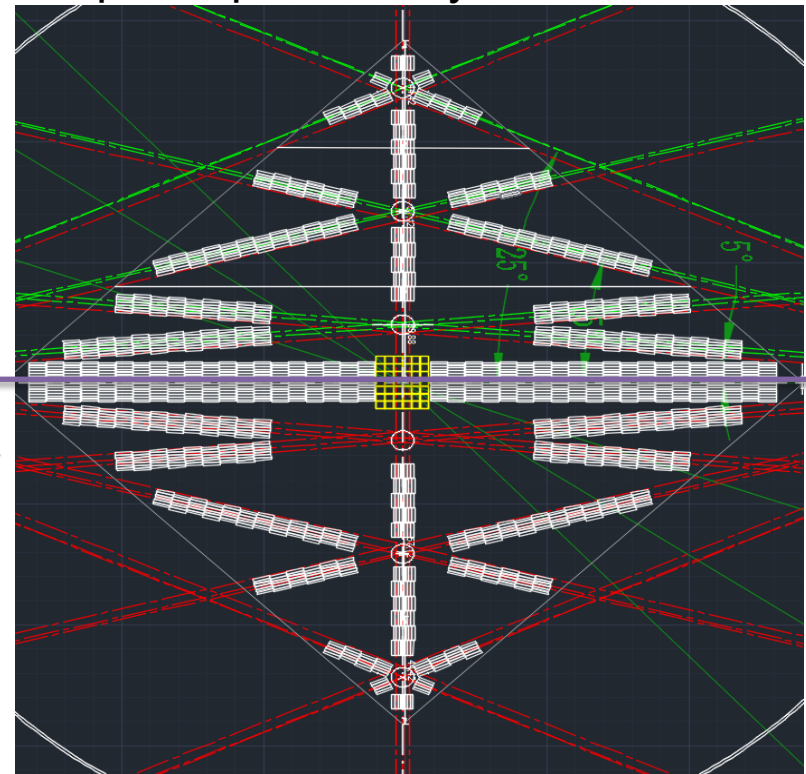
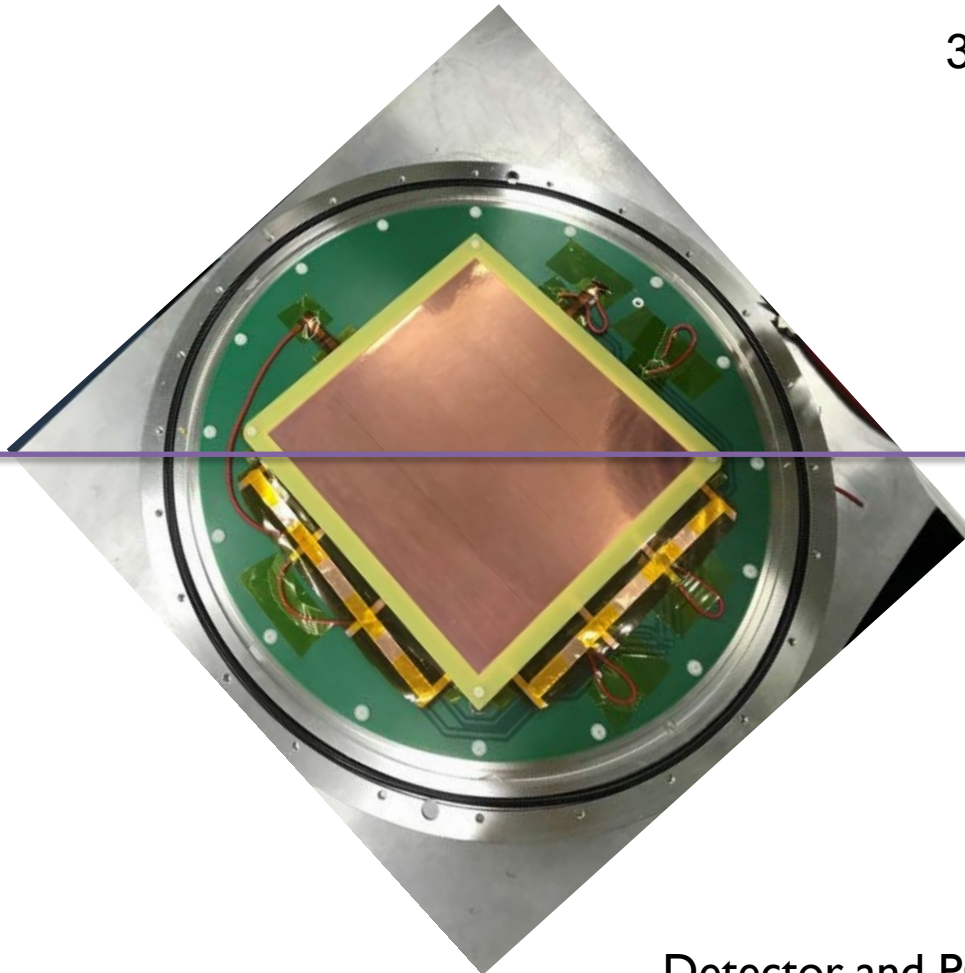
Results of different sizes of the hybrid TPC detector modules

#2. TPC readout R&D

- Designed TPC readout pads to cover the specific the UV laser
- To study the PID using **266nm UV laser track** ($\varnothing 0.85\text{mm}$)

Pad size: $1\text{mm} \times 6\text{mm}$

38 hit points per track by UV laser



Detector and PCB readout board

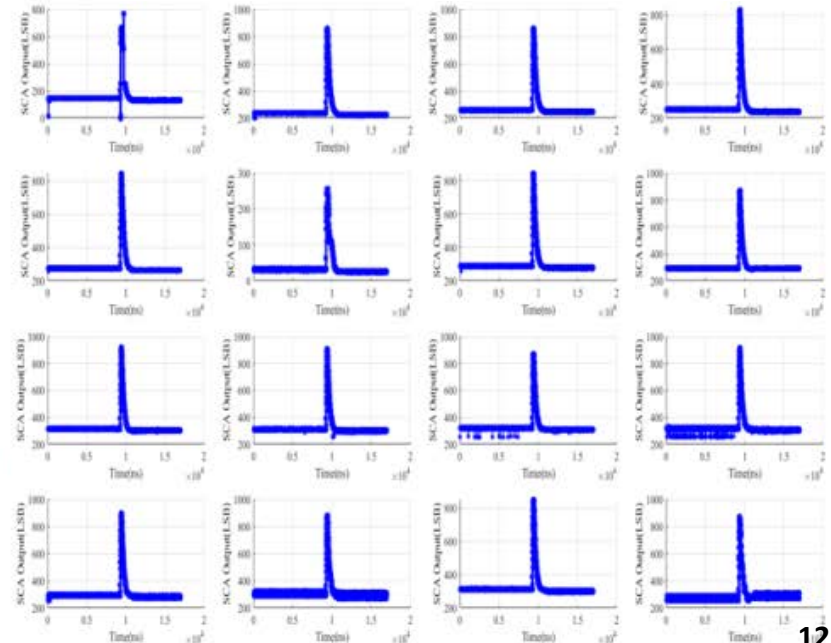
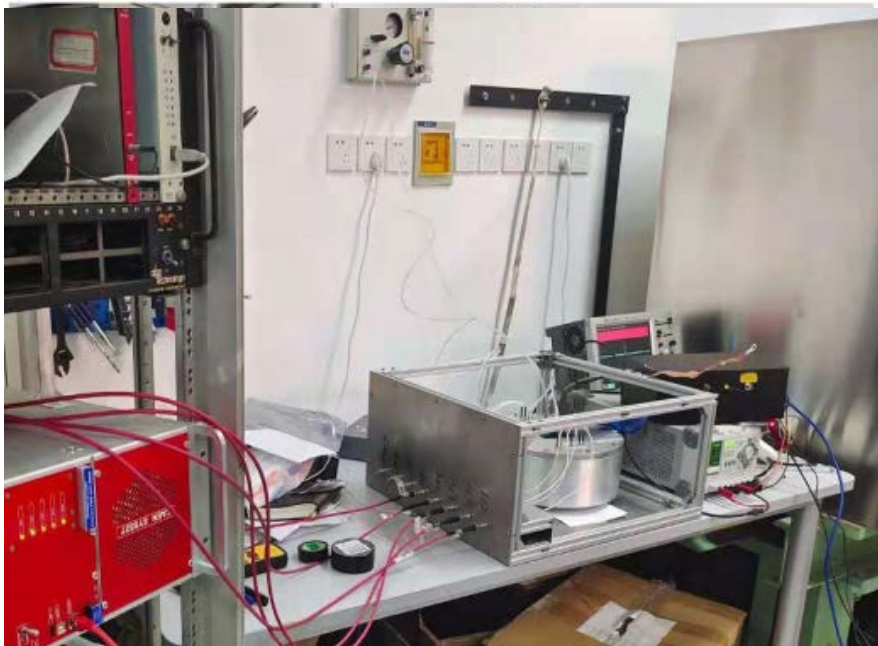
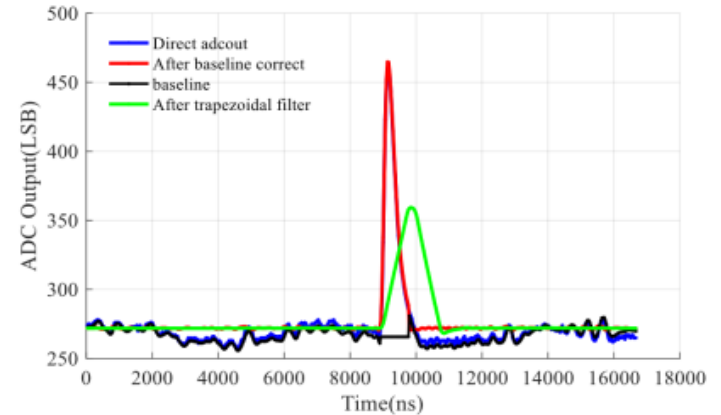
#3. Electronics commissioning testing

Successfully testing and collected signals using the electronics

⁵⁵Fe testing

Testing parameters:

- GEMs detector: 280V-310 V
- $E_{\text{drift}}: \leq 280 \text{ V/cm}$
- Operation gases: Ar/CF₄/iC₄H₁₀ 95/3/2 (T2K)
- Radioactive source: ⁵⁵Fe@ 1mCi
- Successfully commissioned and collected signals using DAQ

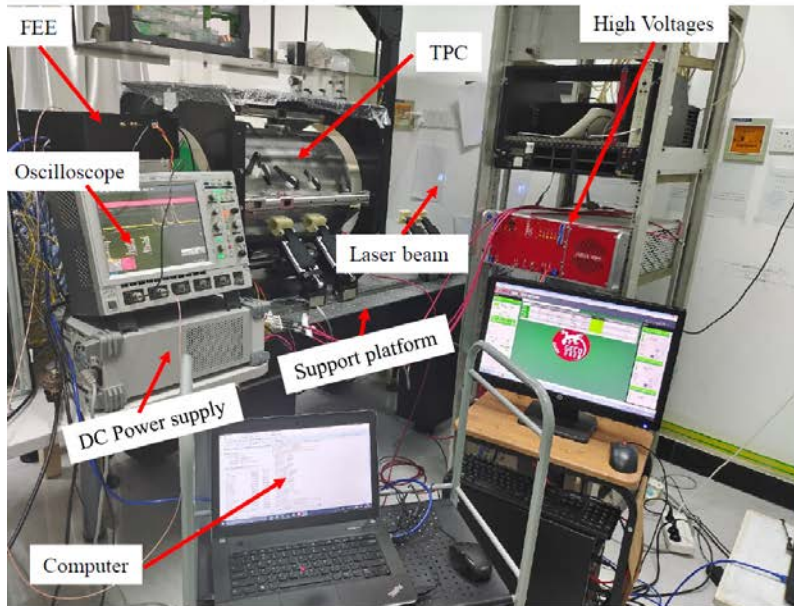
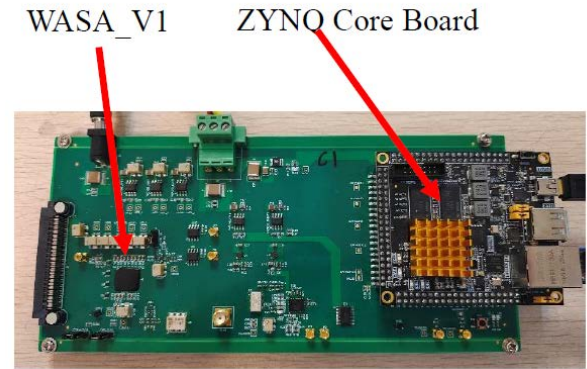


Transient output waveform @30 MS/s

#4. Low power consumption readout

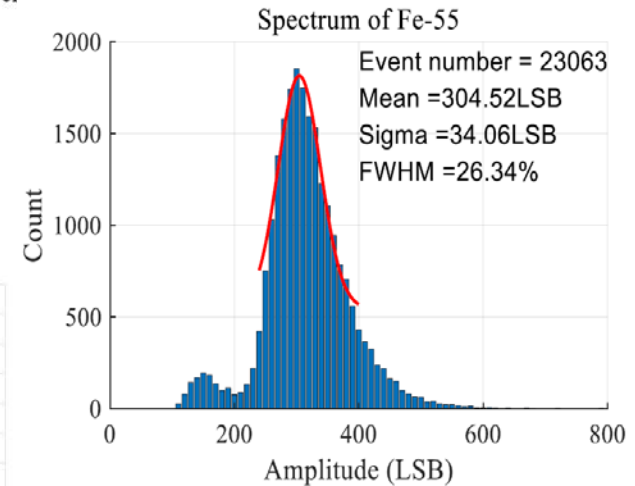
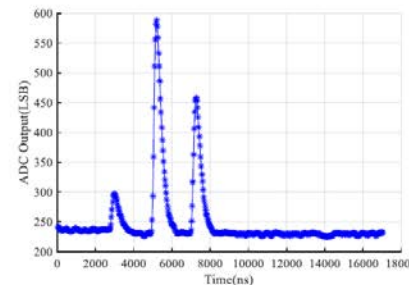
- WASA V1 has been developed: 16 channel AFE+ADC+LVDS data output
- Total power consumption with ADC function: **~2.4 mW/ch**
 - AFE in 1.4 mW/ch and ADC in 1 mW/ch
- Tested with TPC detector using 64 channels at IHEP
 - All channels collected the energy spectrum of ^{55}Fe

Test Results: Laser Tracks



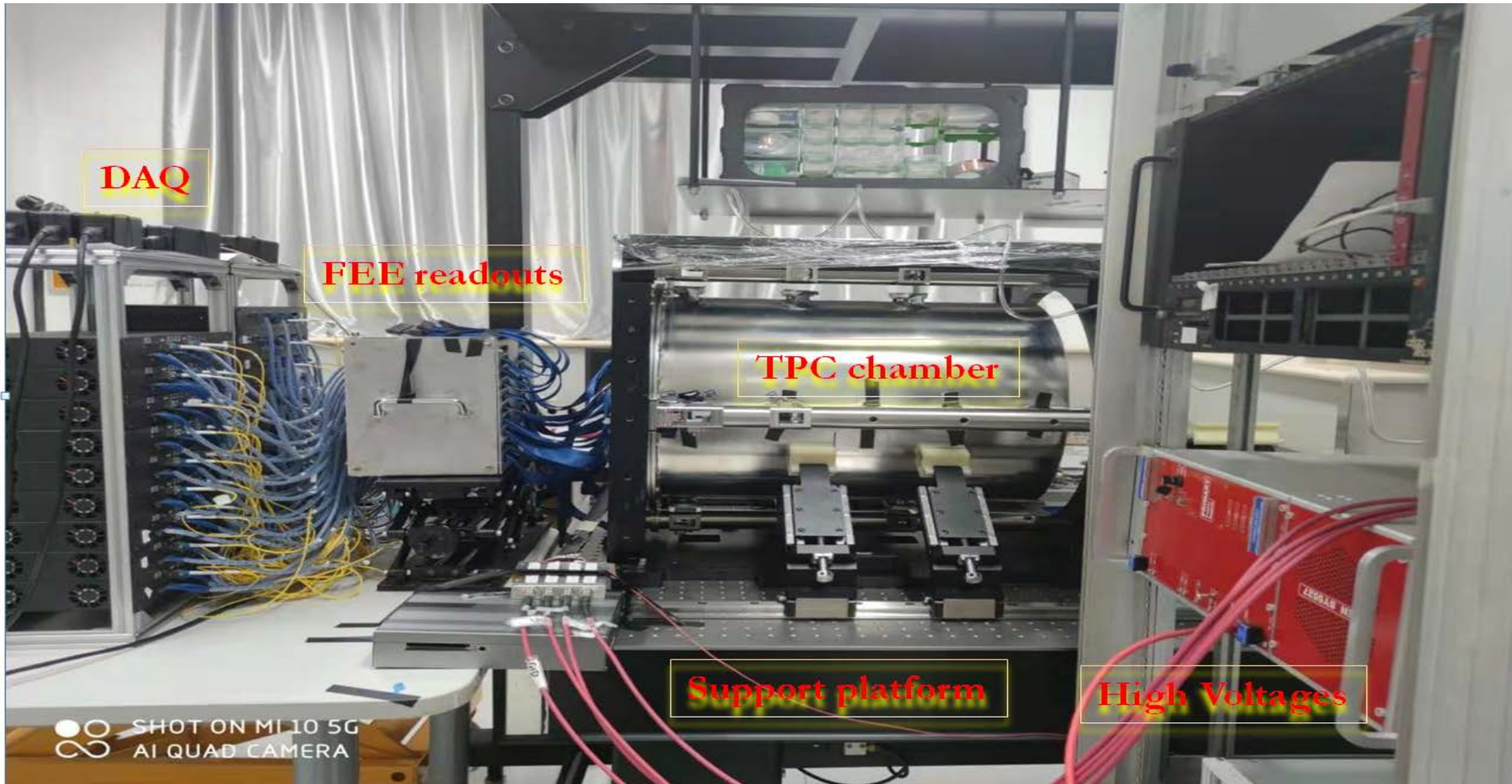
TPC Work Conditions:

- GEM: 280 V
- Drift Field: 9000 V/50 cm = 180 V/cm
- Gas: Ar/CF₄/iC₄H₁₀ 95/3/2 (T2K)
- Laser: 7.2 mJ @20 Hz
- Sampling Rate: 30 MS/s



#5. TPC prototype R&D

- Successfully to develop the TPC prototype integrated UV laser tracks
- **Spatial resolution, dE/dx resolution** achieved with the pseudo-tracks (**DONE**)

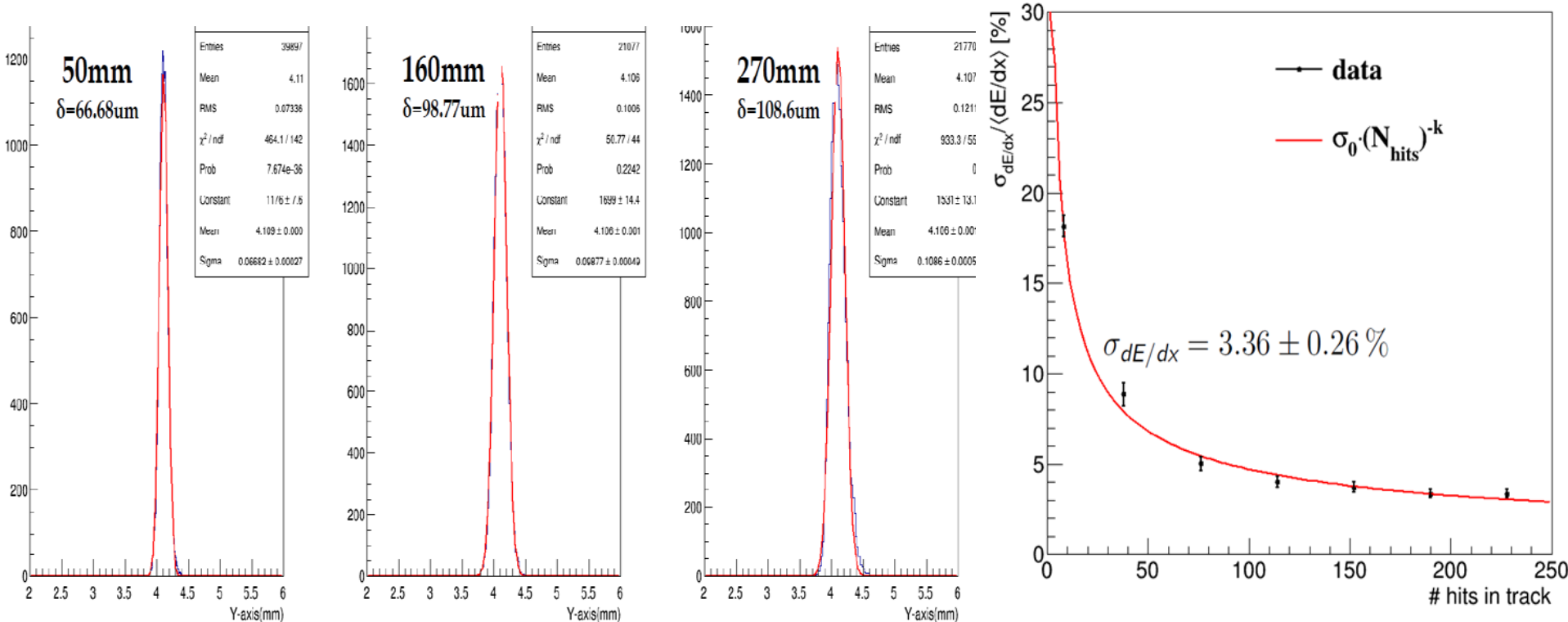


TPC prototype R&D using 266nm UV laser tracks

#6. Spatial resolution and dE/dx

- Spatial resolution can reach to **about 100 μm along the drift length** of the TPC prototype and it can meet the physics requirement of CEPC
- Pseudo-tracks with 220 layers (**same as the actual size of CEPC detector concept**) and dE/dx can reach to $3.36 \pm 0.26\%$

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

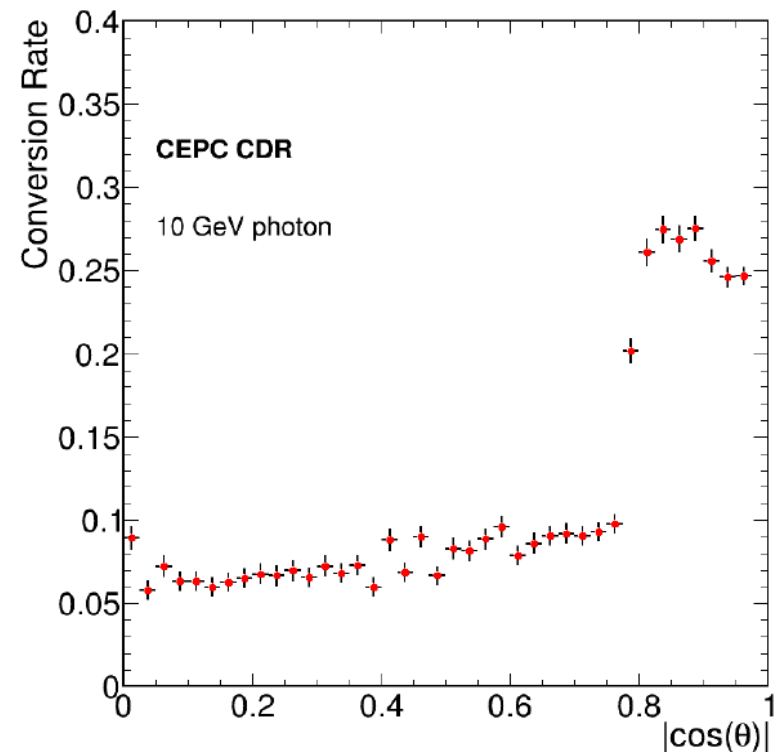
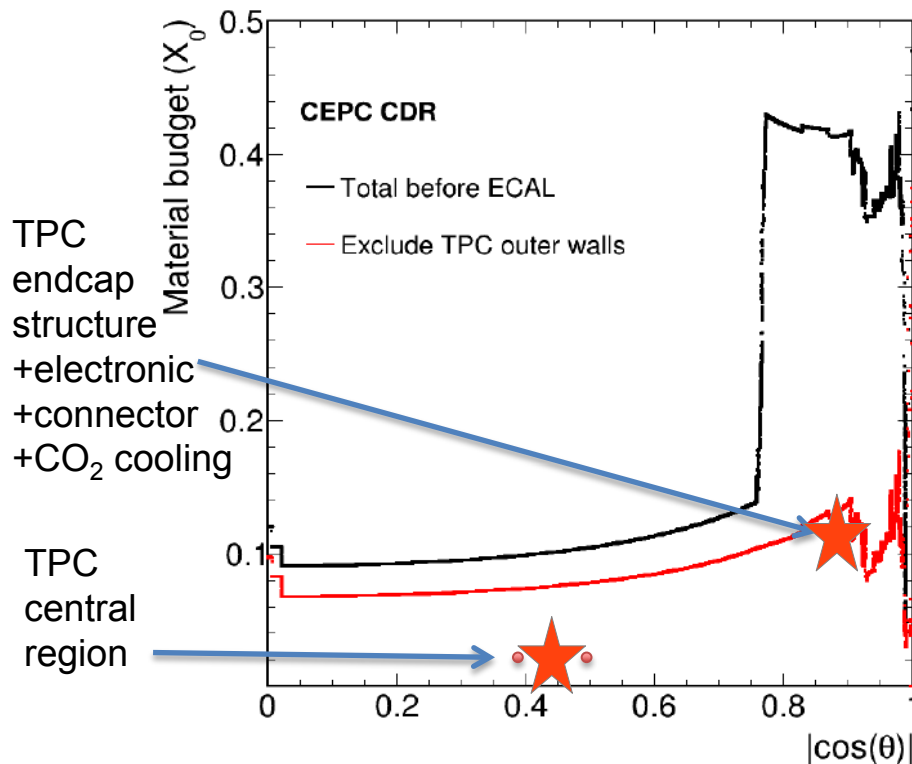


Results of the spatial resolution and dE/dx

-
- **Feasibility of pixelated readout TPC**
 1. **Material budget of endplate/barrel**
 2. **Ions affect and distortion**
 3. **Occupancy**
 4. **Running at 2 Tesla**

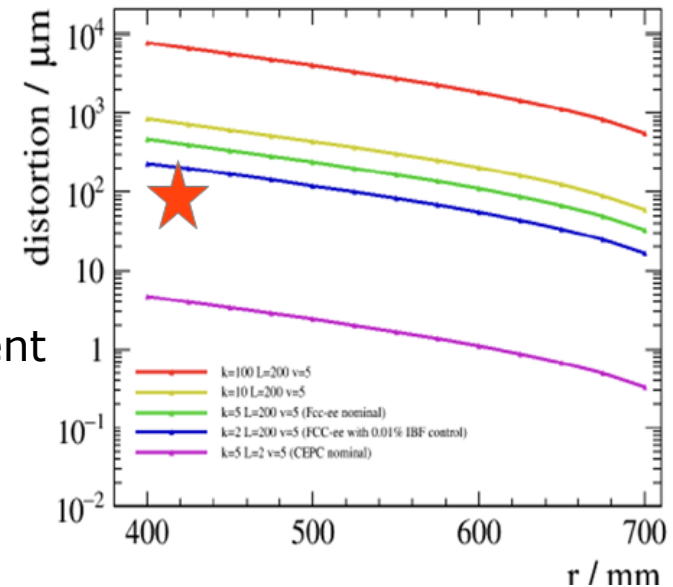
#1. Material budget of endplate/barrel (OK)

- Typical requirement: $\sim 0.1 X_0$ at Barrel.
- At CDR setup (Pad TPC): conservative implementation of material budget
 - $0.1 X_0$ at Barrel, $0.4 X_0$ at endplate (sufficient for any readout with cooling)
 - Sizeable effects on detector performance, but tolerable
 - Observed on Photon conversion, PFA, ...
- **Pixelated readout TPC can reduce the material from CDR setup**



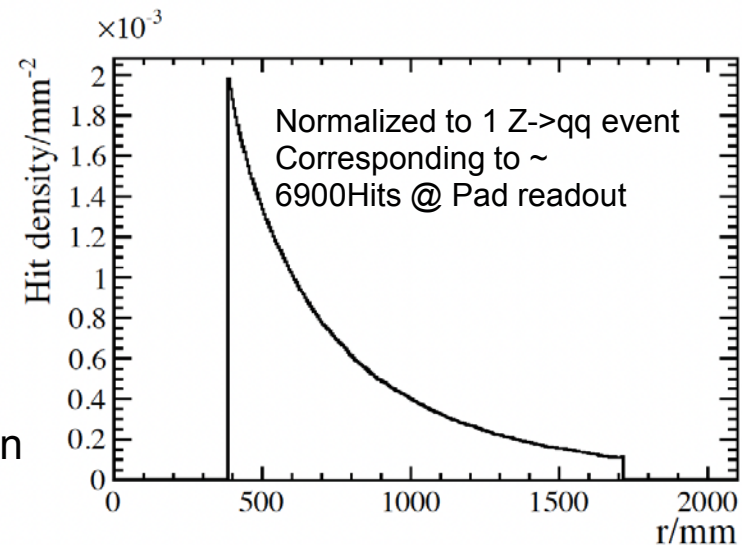
#2. Ions affect and distortion

- Distortion: proportional to event rate, ion back flow and gain. Largest distortion occurs at the inner region
- Analysis ([cite#1](#)) shows that at
 - $\text{IBF} \times \text{Gain} \sim 1$
 - $\text{Lumi} \sim 2 \times 10^{36}$
 - Hit from Physics event only
 - Distortion $\sim 100 \mu\text{m}$ at pixelated size
 - Might limit spatial/momentum measurement
- Open question: to be addressed by R&D
 - Correction by at least 1 order of magnitude?
==> future simulation studies...
 - **In-situ calibration** with Laser system/Z-> $\mu\mu$ event ([cite#2](#))
==> laser system test ... collaborative studies with LCTPC
 - Contribution from other sources, **especially at Z pole**
==> MDI, Beam background



#3. Occupancy (Safe)

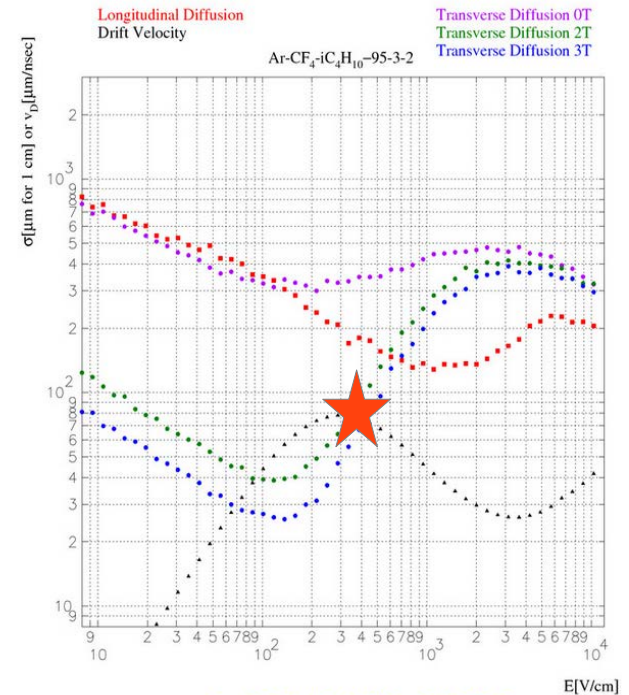
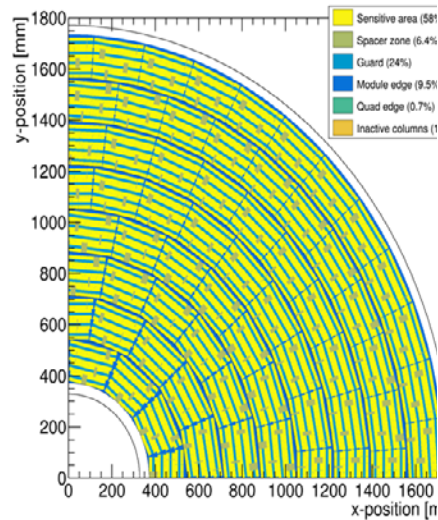
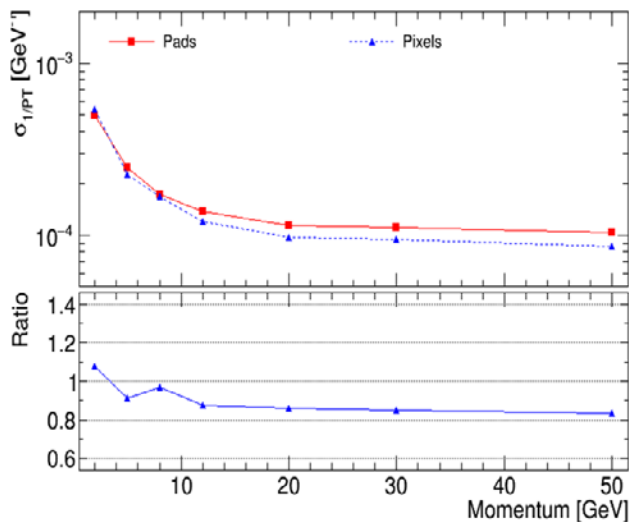
- Low voxel occupancy : 1×10^{-5} to 1×10^{-6} (cite#3)
- At 2×10^{36} with Physics event only, even bunch distribution(cite#4).
 - Pad readout ($1 \text{ mm} \times 6 \text{ mm}$), inner most occupancy 1×10^{-4}
 - Pixelated readout ($55 \mu\text{m} \times 55 \mu\text{m}$), much **LOWER** inner most occupancy $\sim 1 \times 10^{-6}$
- Pixelated readout can easily handle a high hits rate at Z pole.
 - The test beam showed GridPix TPC prototype can handle up to 2.6M hits/s per chip (cite#5).
- Reconstruction algorithm with high Pile Up need to be developed.



➡ **Marlin TPC software package**

#4. Running at 2 Tesla

- TPC can work well at the 2 T B-field **without any $E \times B$ effect.**
- Momentum resolution is better (>20%) compared with the pad readout technology at the same geometry ([cite#5](#)).
- Pixelated technology: **$\sim 10,000$ hits/track; Pad: 220 hits/track**
- Transverse diffusion constant is same level at 2 T & 3 T
- Open question: to be addressed by R&D
 - **Optimized TPC geometry** at 2 T B-field
 - Beam induced background at 2 T B-field



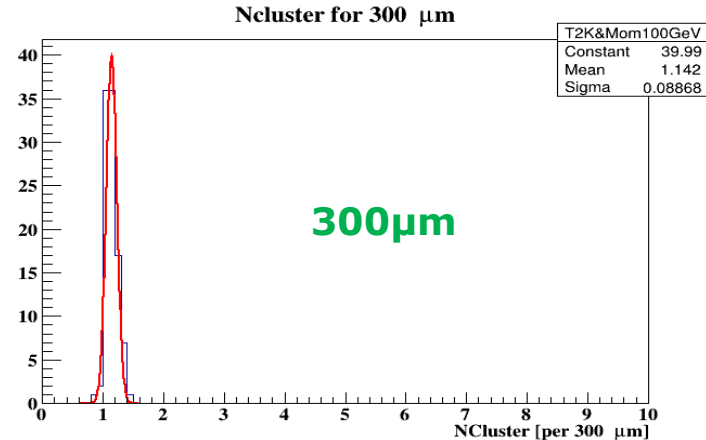
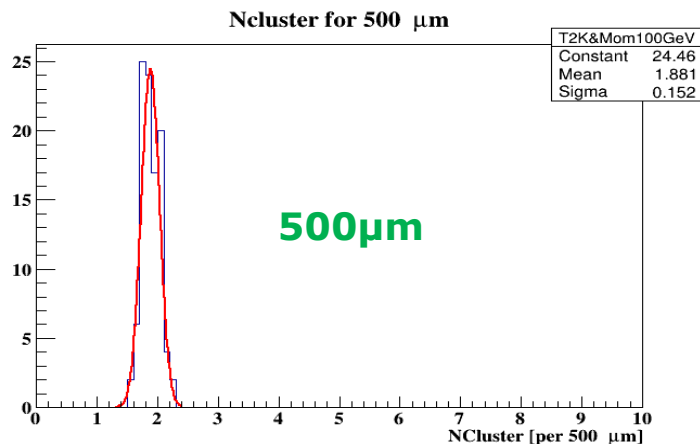
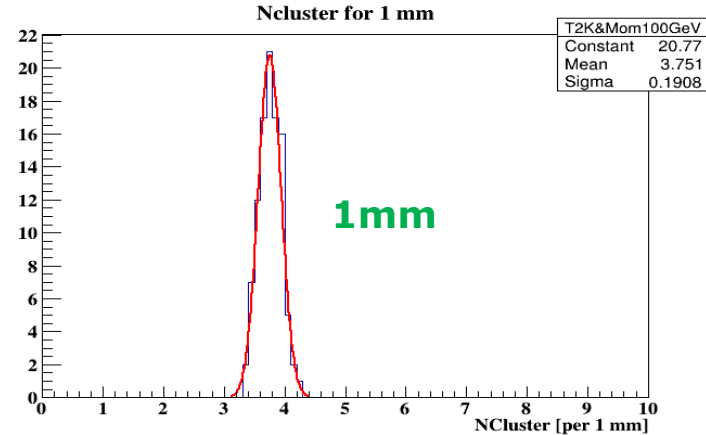
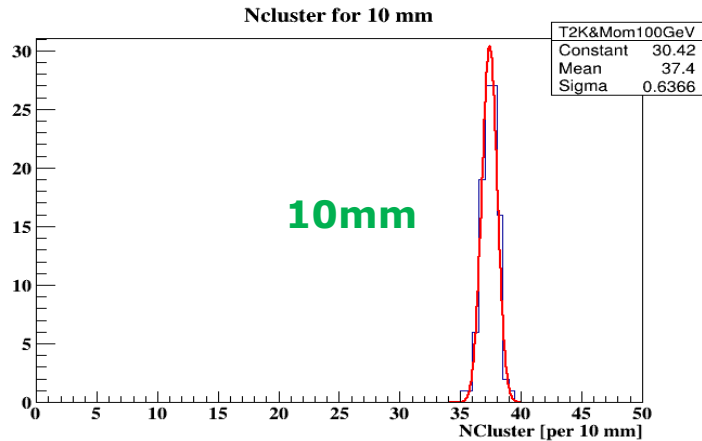
[Ar-CF4-iC4H10_95-3-2](#)

New prototype R&D plan

- **Pixelated simulation and realized R&D**
 - **Simulation of the primary cluster**
 - **Optimization of cluster/pixel size**

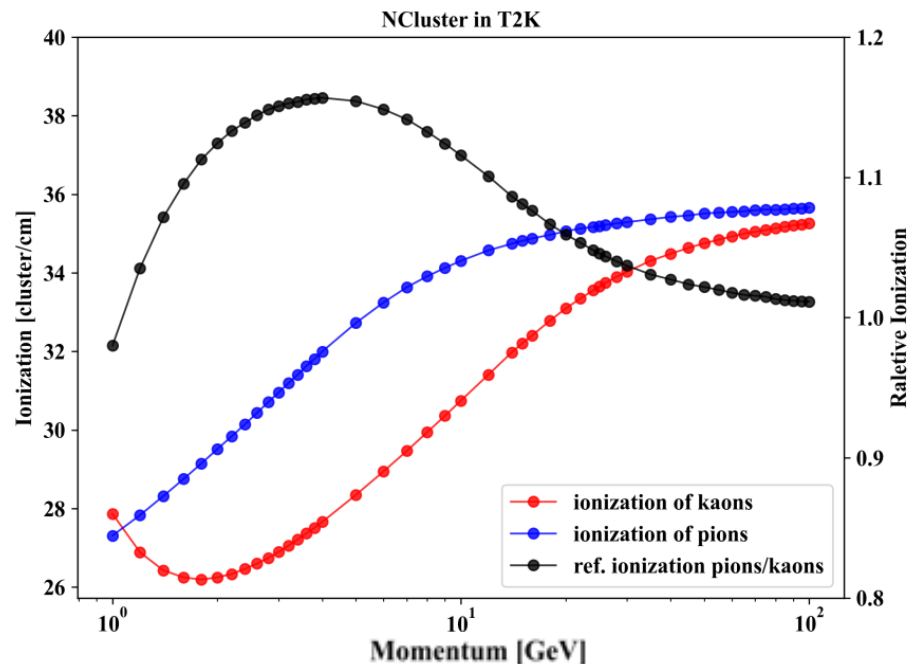
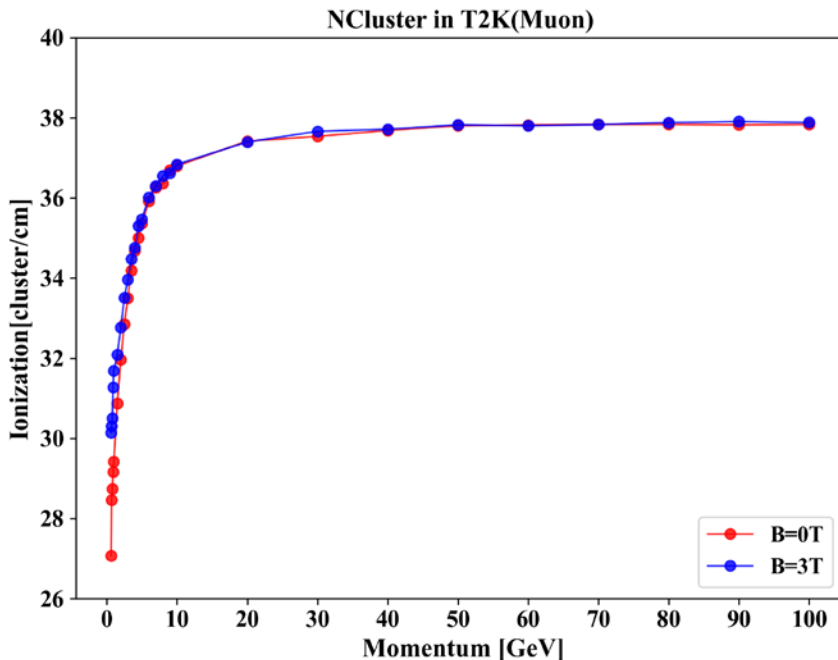
Simulation of the primary cluster at T2K

- Simulation: Running 10000 events using Garfield++
- Simulation result show that the **primary cluster profile** along the drift length
- For **300 μ m-500 μ m**, the standard deviation of the primary cluster distribution can keep in the same level



Primary cluster profile at T2K - $\pi/\kappa/\mu$

- Simulation of the particles: **Pion, Muon, Kion, 0.5GeV – 100GeV**
- Variation of $N_{\text{cluster}}(\text{cm})$ with the different momentum of the specific incident particle
- Comparing the N_{cluster} of muon under different magnetic fields (0T and 3T)
- **Separation of pions and kaons** with the different momentum at T2K
 - Open question: to be addressed by R&D -> dN/dx -> High granularity readout

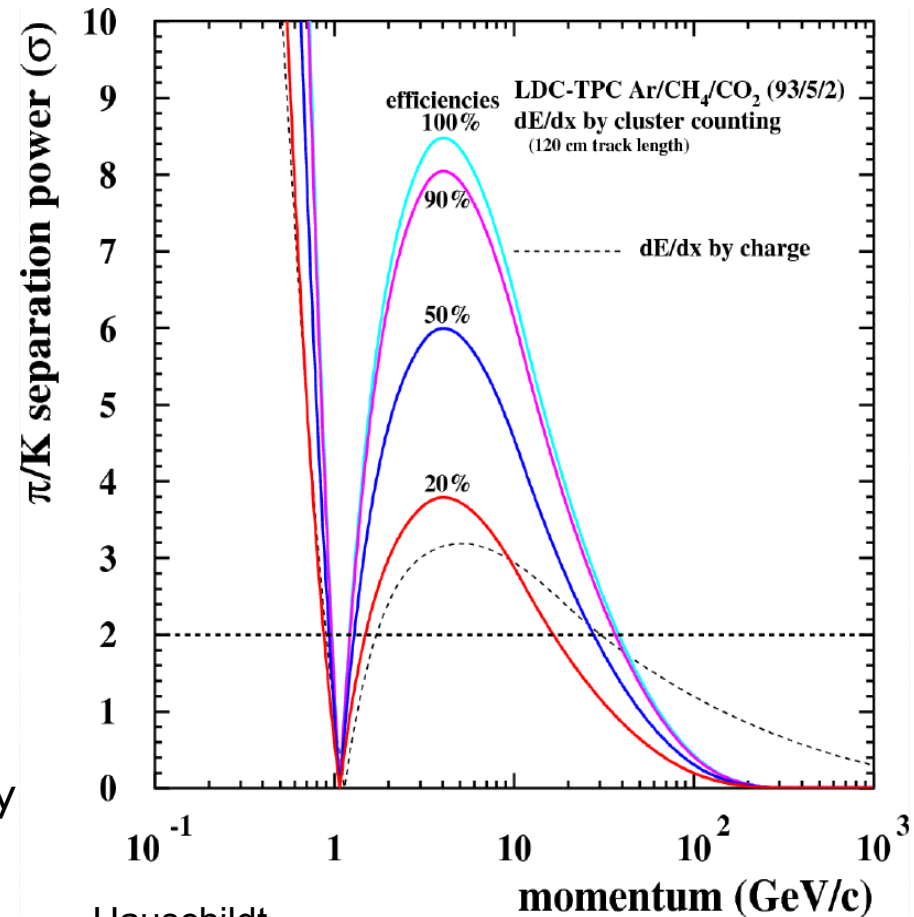


High granularity for improved PID in TPC

- For traditional dE/dx detection, the charge summation can be expected using the gravity method.
- In most experimental study from small to large TPC
 - L and N are correlated.
 - Constant L and changing granularity $G = N/L$

$$\frac{\sigma_{dE/dx}}{\langle \mu_{dE/dx} \rangle} \propto L^{-0.45} G^{-0.13}$$

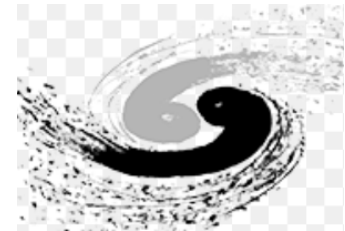
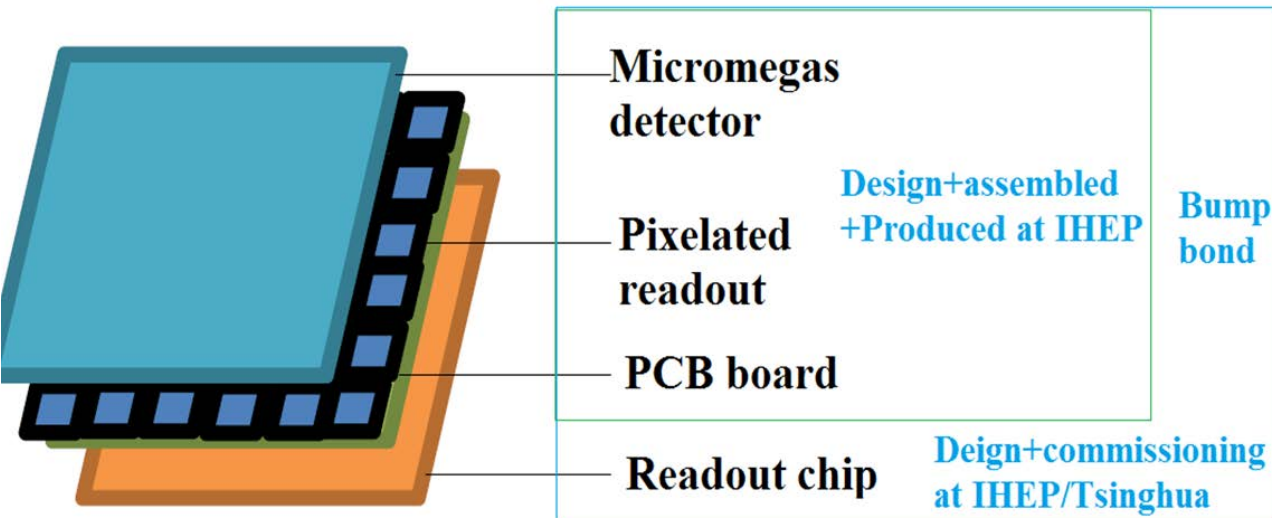
- If pad size is at the level of cluster distances of primary ionization
 - **i.e. $\sim 300\text{-}500 \mu\text{m}$ in Ar-based**
 - Cluster counting becomes effective
- **PID improvement**
 - The potential of better resolution by at least a factor 2



Prototype plan at IHEP

- Realization of pixelated technology collaborated with Tsinghua

Bump bond pixelated readout with Micromegas detector	Module size	To be addressed by R&D
<ul style="list-style-type: none"> $\geq 300 \mu\text{m} \times 300 \mu\text{m}$ Developed the readout chip by Tsinghua University Developed the Micromegas detector sensor at IHEP Development of the new module and prototype in the end of 2022 	1-2 cm ²	<ul style="list-style-type: none"> Research on pixelated readout technology realization Optimization of cluster profile and pad size Study of the 'dN_{cl}+dx'
	100 cm ²	<ul style="list-style-type: none"> Study the distortion using UV laser tracks and UV lamp to create ions disk In-situ calibration with UV Laser system Study of the 'dE/dx+dN_{cl}/dx'



Tsinghua University
University

Summary

- Pad readout TPC can operate @ CEPC W/Higgs operation, with 3 T B-field or higher.
 - Spatial resolution can reach to about 100 μm along the drift length of the TPC prototype and it can meet the physics requirement of CEPC.
 - A laser TPC prototype has been successfully developed and studied at IHEP in the last 6 years. Ionback flow can be reduced to 1 level at gain 2000.
- High Lumi operation (2×10^{36}) @ Z with 2 T B-Field is challenge for gaseous.
 - Pixelated readout TPC is promising, compared to Pad readout.
 - Material budget, construction cost, power & cooling, Occupancy is OK.
 - Lower Ion backflow at low gain (to be addressed by R&D).
 - Potential for dN/dx , essential for PID.
- R&D plan focus on the Pixelated TPC readout & prototype, optimization to the local configuration (for dN/dx , power consumption, ...) and global geometry optimization (inner Radius, etc)
- Collaborated with LCTPC international group, and any cooperation is welcome

Many Thanks