Feasibility study of Pad and Pixelated Readout TPC technology at CEPC

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On behalf of CEPC TPC study group and Special thanks to LCTPC collaboration

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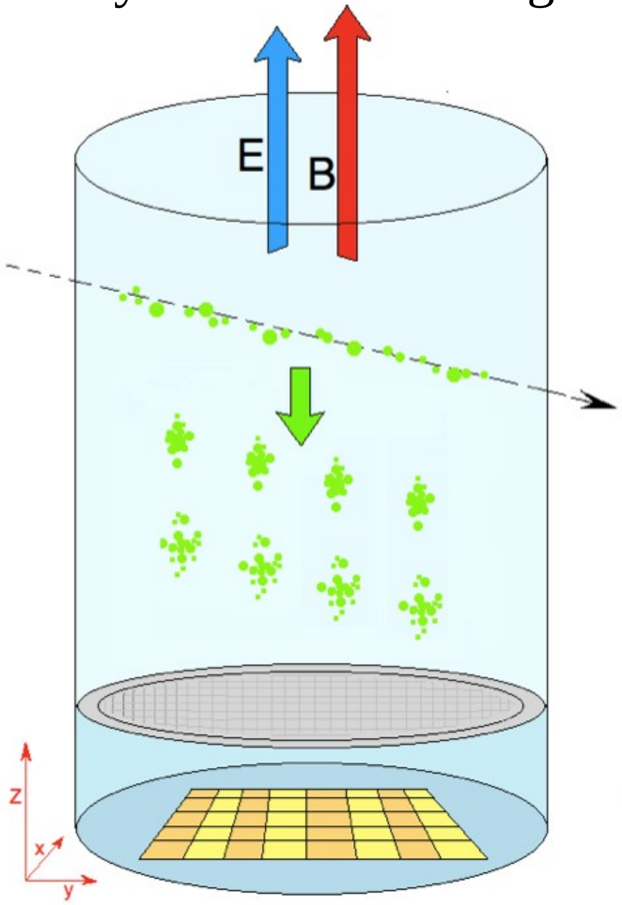
Content

- **Motivation: TPC detector for e+e- colliders**
- **High spatial resolution TPC prototype**
- **Towards PID TPC at CEPC**
- **Summary**

What is Time Projection Chamber?

- Operating principle: **Electric field and magnetic field are applied in parallel** in the TPC
  - 3-Dimensional (x, y, z) information
  - Momentum measurement, PID
  - Very low material budget



Principle of TPC detector

Momentum resolution

$$\frac{\sigma_{p_\perp}}{p_\perp} = \sqrt{\left(\frac{\alpha' \sigma_x}{BL^2}\right)^2 \left(\frac{720}{N+4}\right) p_\perp^2 + \left(\frac{\alpha' C}{BL}\right)^2 \frac{10}{7} \left(\frac{X}{X_0}\right)}$$

measurements — multiple scattering

$p_\perp$: transverse momentum
σ_x : position resolution
B : strength of B-Field
N : # of measurement points
L : track detection length
$\frac{X}{X_0}$: radiation length of gas
α', C : constant

R.L. Gluckstern, NIM 24 (1963), 381

TPC only... $\frac{\sigma_{p_\perp}}{p_\perp} \approx 1 \times 10^{-4}\, p_\perp\, GeV/c$

Position resolution

$$\sigma_x = \sqrt{\sigma_0^2 + \frac{C_d^2 \cdot z}{N_{eff}}}$$

z: drift length
Neff: effective number of electron
Cd: diffusion constant of gas

depends on drift length

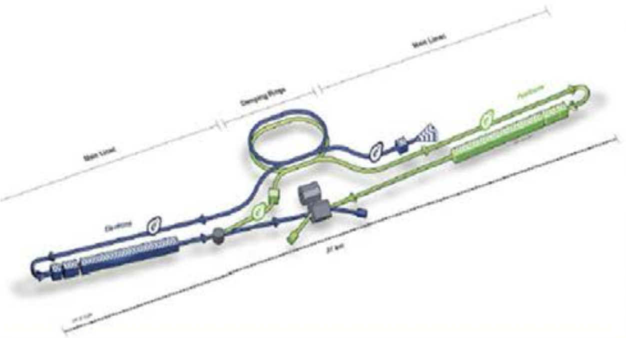
small position resolution σ_x

$$\sigma_x \approx 100\ \mu m$$

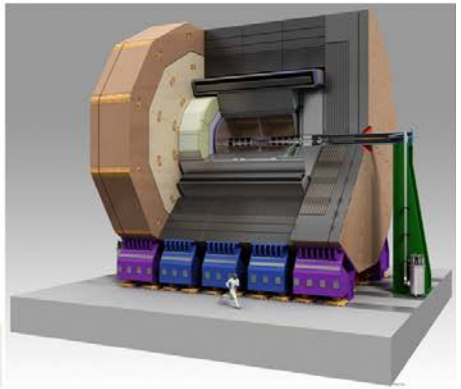
even at the large drift length of $2.2\ m$

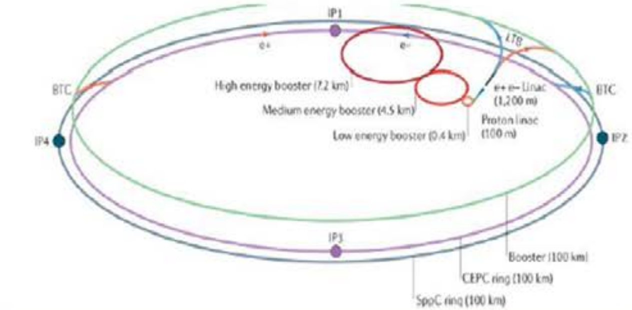
Motivation: TPC technology for the future e+e- colliders

- A TPC is the main tracking detector for **some candidate experiments at future e+e- colliders**
  - Baseline detector concept of CEPC and ILD at ILC
- Pixel TPC is in the simulation package (MarlinTPC) **as the default track detector** in 2023
- TPC technology can be of interest for other future colliders (FCC-ee, EIC, KEKb…)

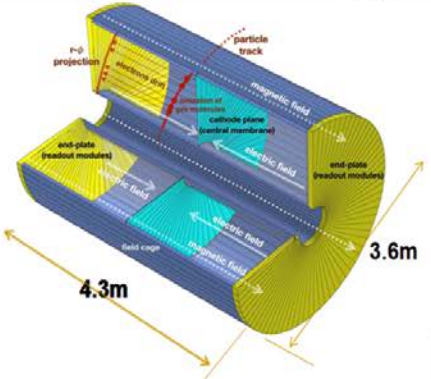


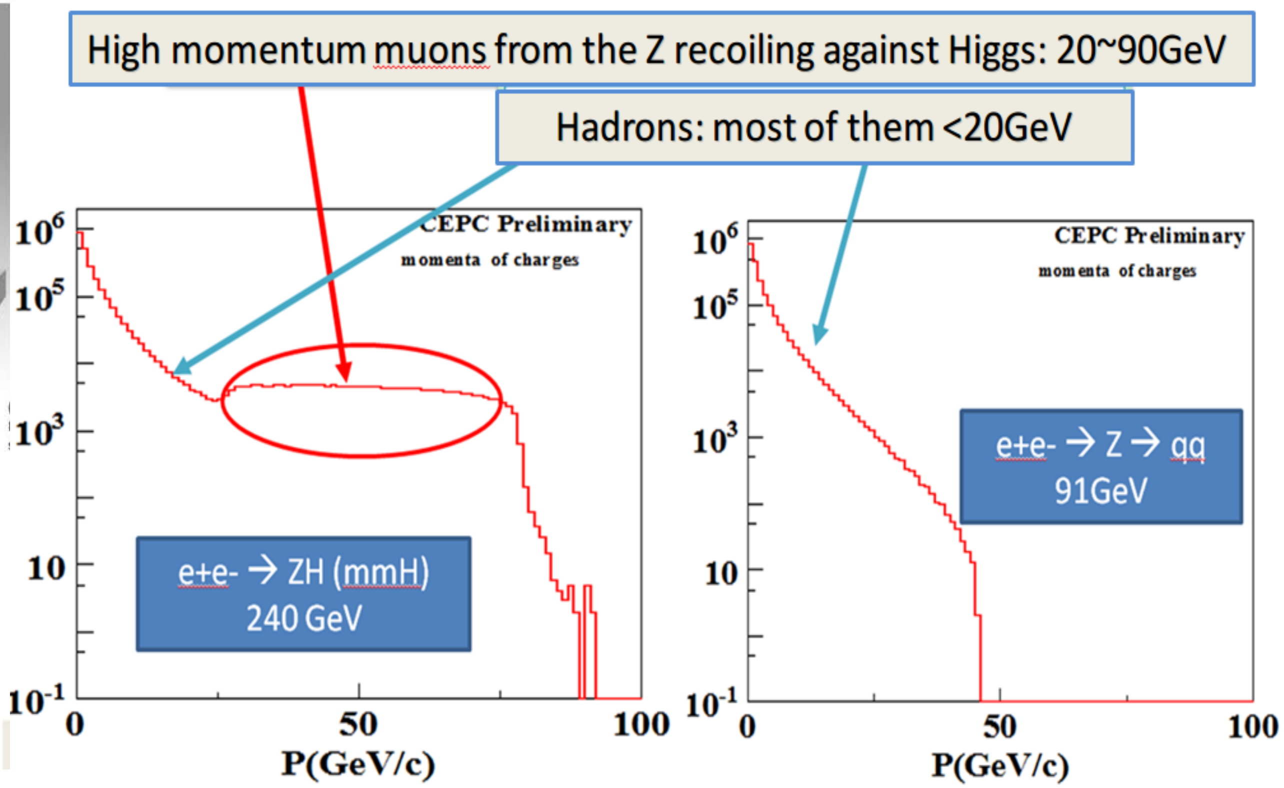
International Linear Collider (ILC)





Circular Electron Positron Collider (CEPC)

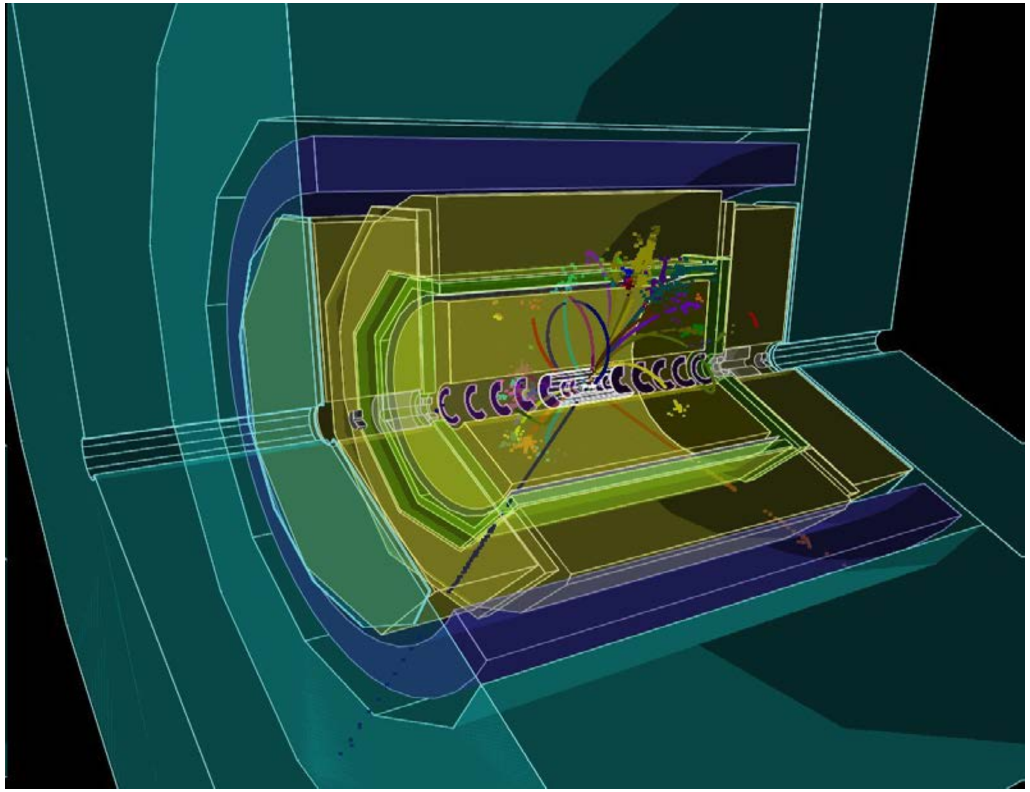




https://arxiv.org/abs/2203.06520

Motivation: TPC requiremetns from e+e- Higgs/EW/Top factories

- TPC can provide hundreds of hits with high spatial resolution compatible, with PFA design (**very low material** in detector chamber)
    - $\sigma_{1/pt}$ ~10^{-4} $(GeV/c)^{-1}$ with TPC alone and σ_{point}<100μm in rϕ
- **Provide dE/dx and dN/dx with a resolution** <4%
    - Essential for Flavor physics @ Z run
    - Beneficial for jet at higher energy

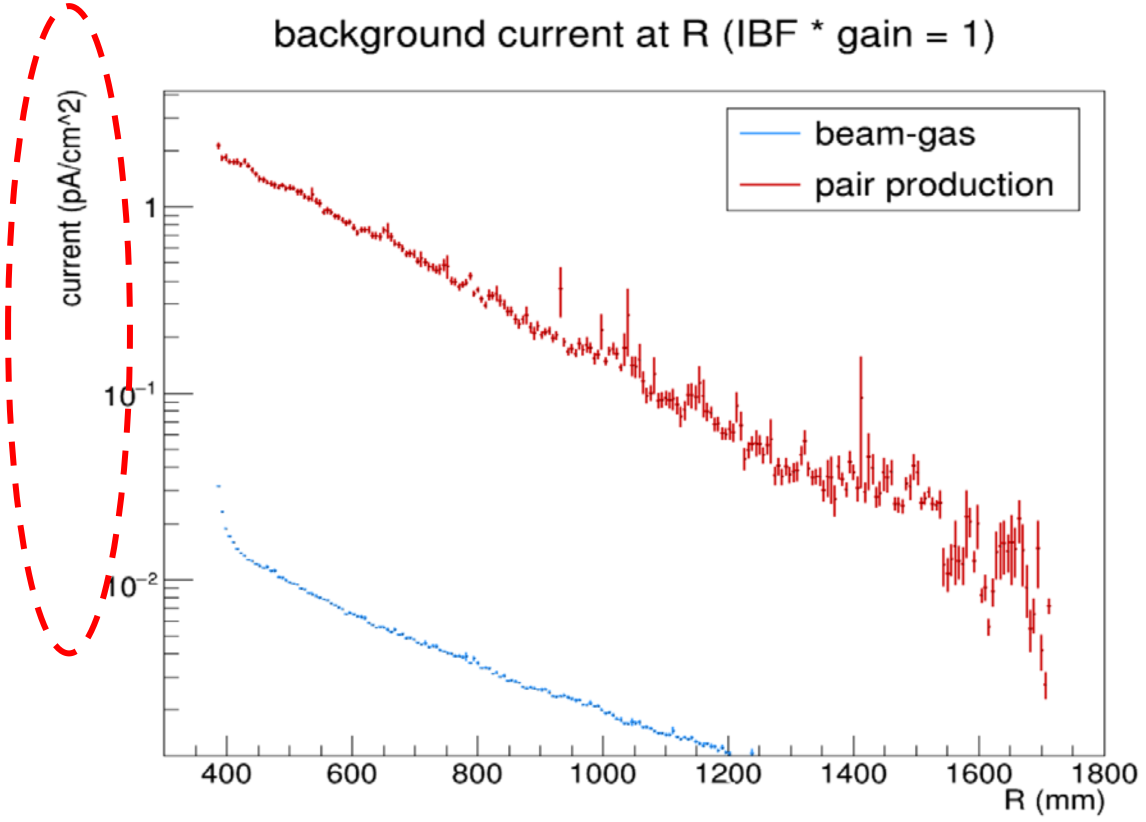


Physics requirements of TPC

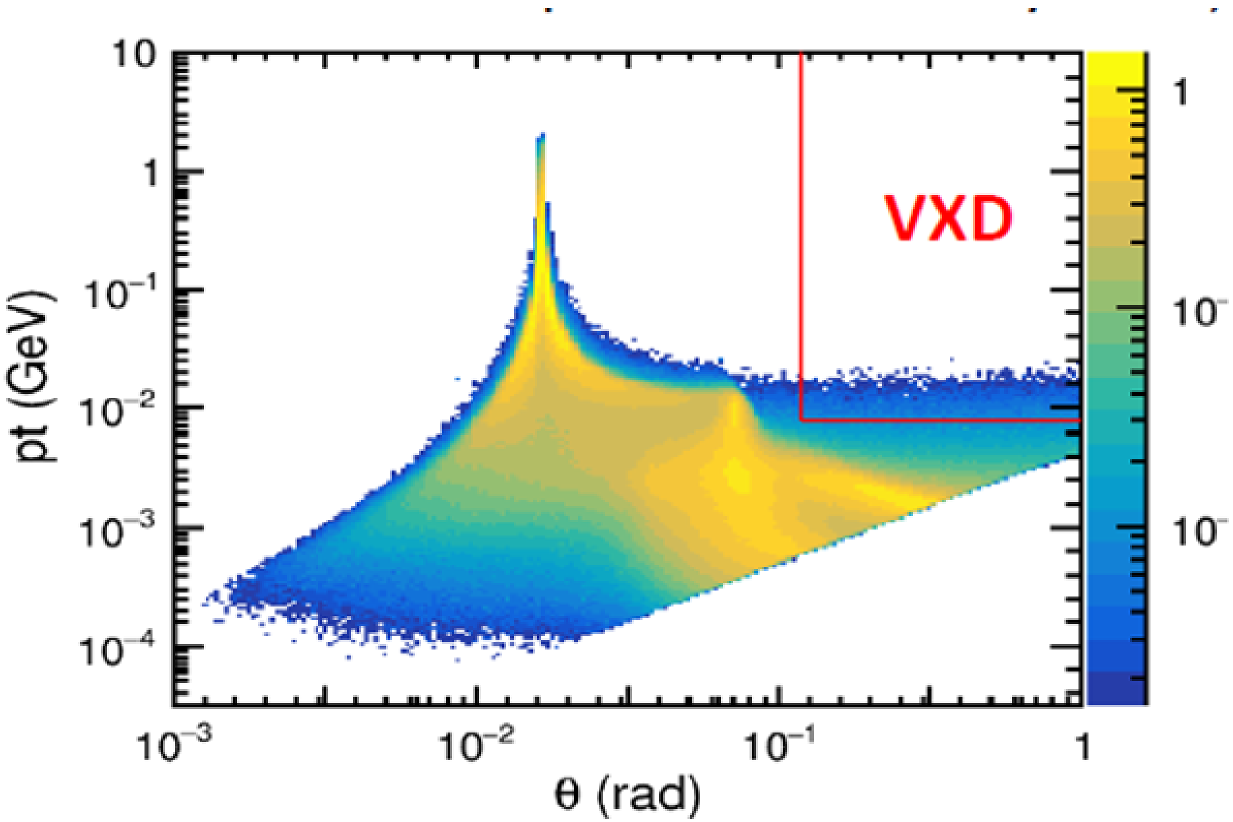
Parameter			
Geometrical parameters	r_{in}	r_{out}	z
	329 mm	1808 mm	± 2350 mm
Solid angle coverage	up to $\cos\theta \simeq 0.98$ (10 pad rows)		
TPC material budget	$\simeq 0.05\ X_0$ including outer fieldcage in r		
	$< 0.25\ X_0$ for readout endcaps in z		
Number of pads/timebuckets	$\simeq$ 1-2 $\times\ 10^6$/1000 per endcap		
Pad pitch/ no.padrows	$\simeq$ 1$\times$ 6 mm^2 for 220 padrows		
σ_{point} in $r\phi$	$\simeq$ 60 μm for zero drift, $<$ 100 μm overall		
σ_{point} in rz	$\simeq 0.4 - 1.4$ mm (for zero – full drift)		
2-hit resolution in $r\phi$	$\simeq 2$ mm		
2-hit resolution in rz	$\simeq 6$ mm		
dE/dx resolution	$\simeq 5$ %		
Momentum resolution at B=3.5 T	$\delta(1/p_t) \simeq 10^{-4}$/GeV/c (TPC only)		

Feasibility study the full simulation data of the high luminosity Z at CEPC

- The currents of the electrons in TPC chamber reach to about 1pA/cm^2
  - **IBF×Gain ≤1 at 2T**
  - Beam-gas and pair production in the chamber
- The theta in the MDI region is pretty good to TPC chamber from the simulation results.



Current of the electrons in TPC chamber

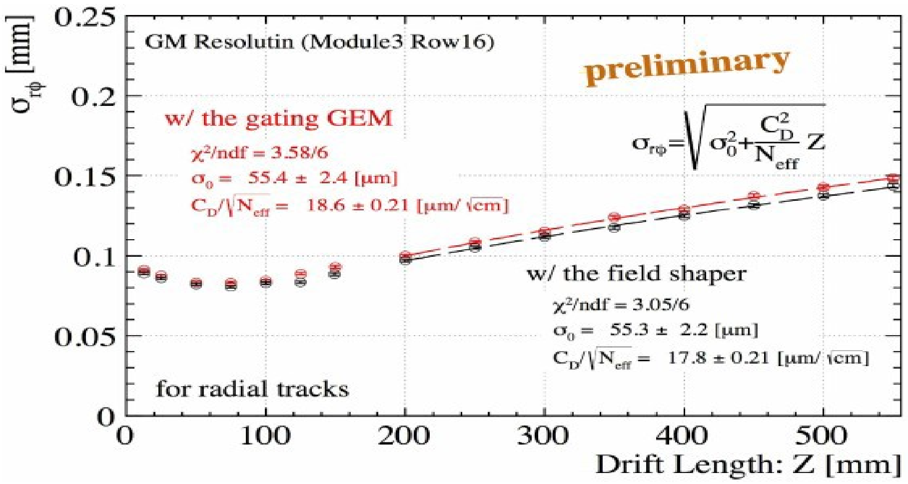


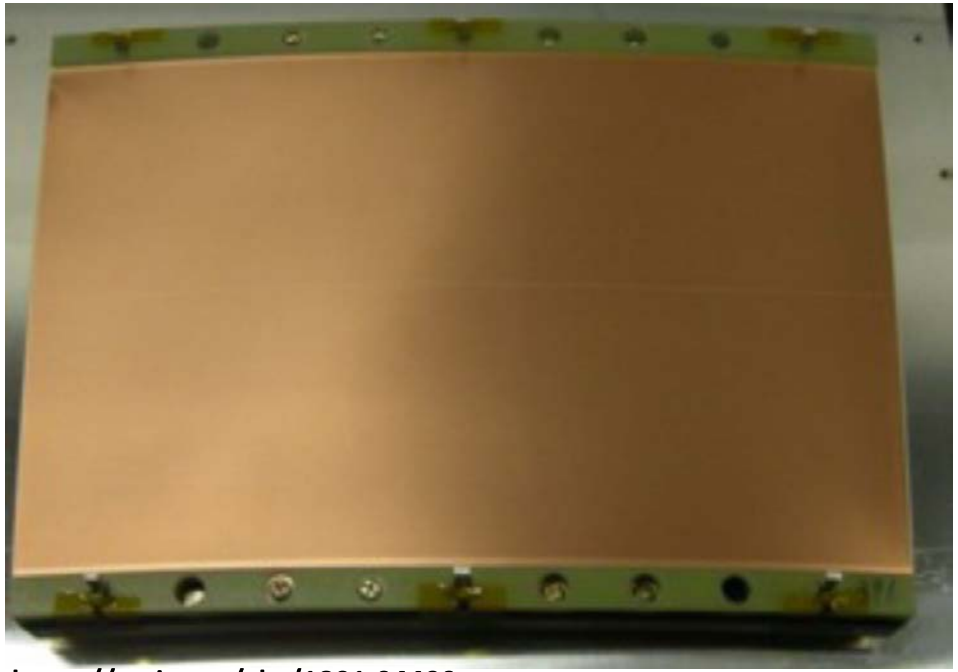
The theta in MDI region

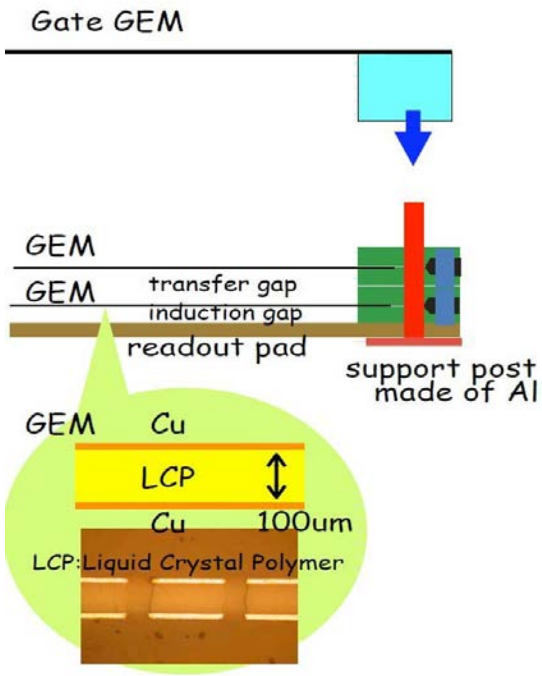
- Status of the Pad readout TPC for e+e- colliders

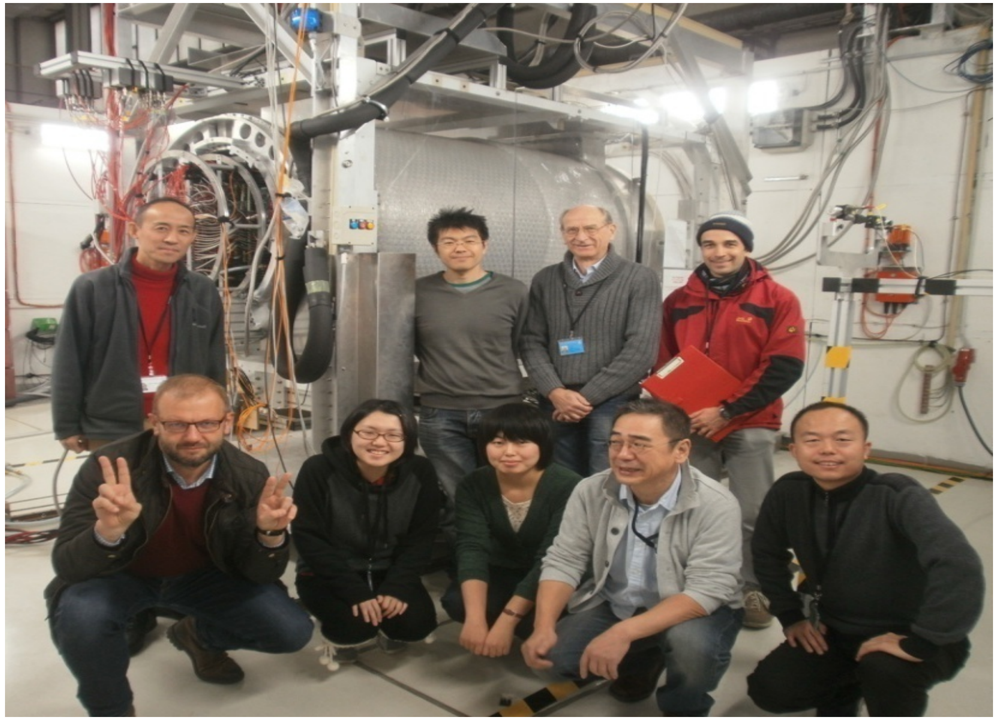
Pad readout TPC technology – GEMs readout @LCTPC

- **TPC prototype have been studied the beam under 1.0T.**
  - GEMs with 100μm LCP insulator
  - Standard GEM from CERN
- Design idea of the GEM Module:
  - **No frame** at modules both sides
  - Spatial resolution of $\sigma_{r\phi} \leq 100$ μm, more stability by the broader arcs at top and bottom





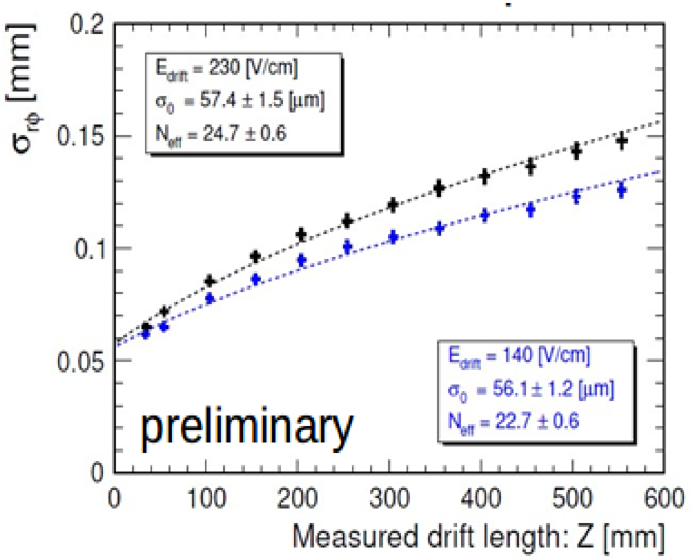


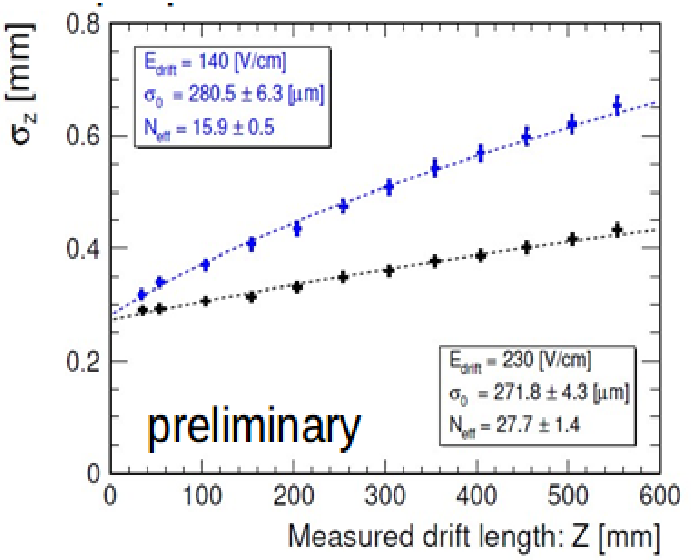


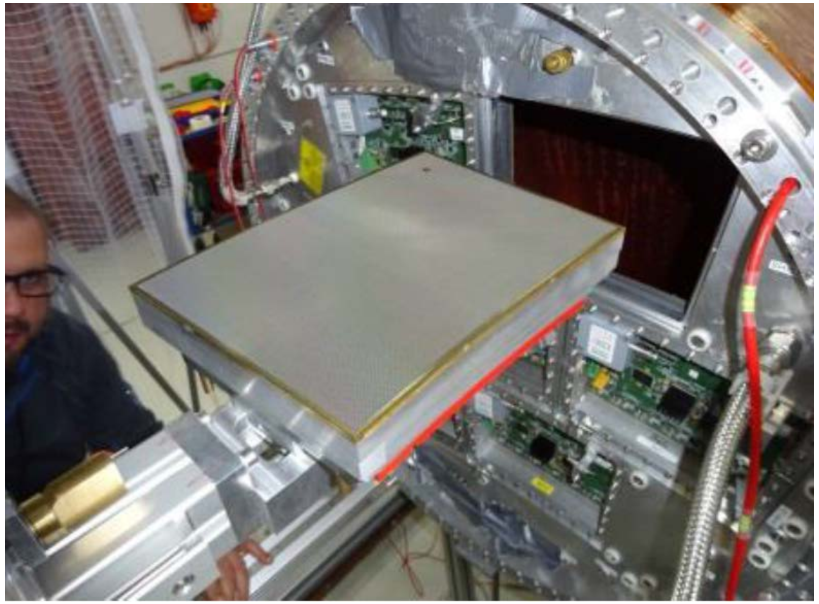
https://arxiv.org/abs/1801.04499

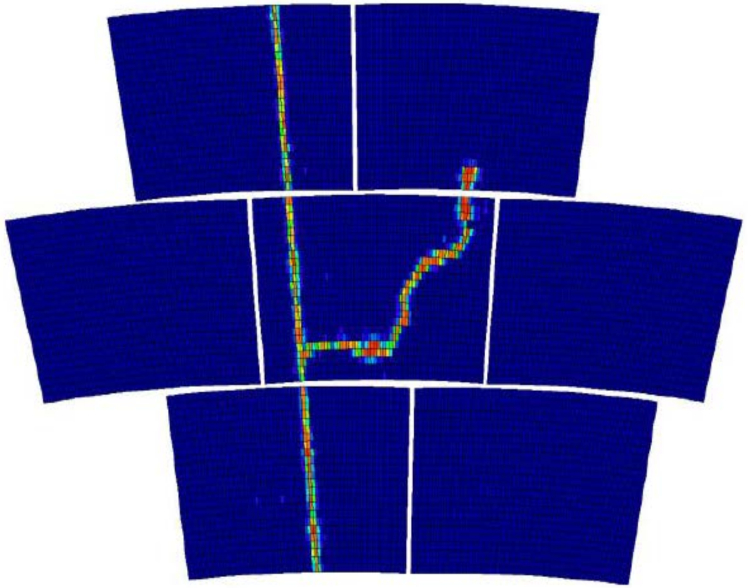
Pad readout TPC technology - Resistive Micromegas readout @LCTPC

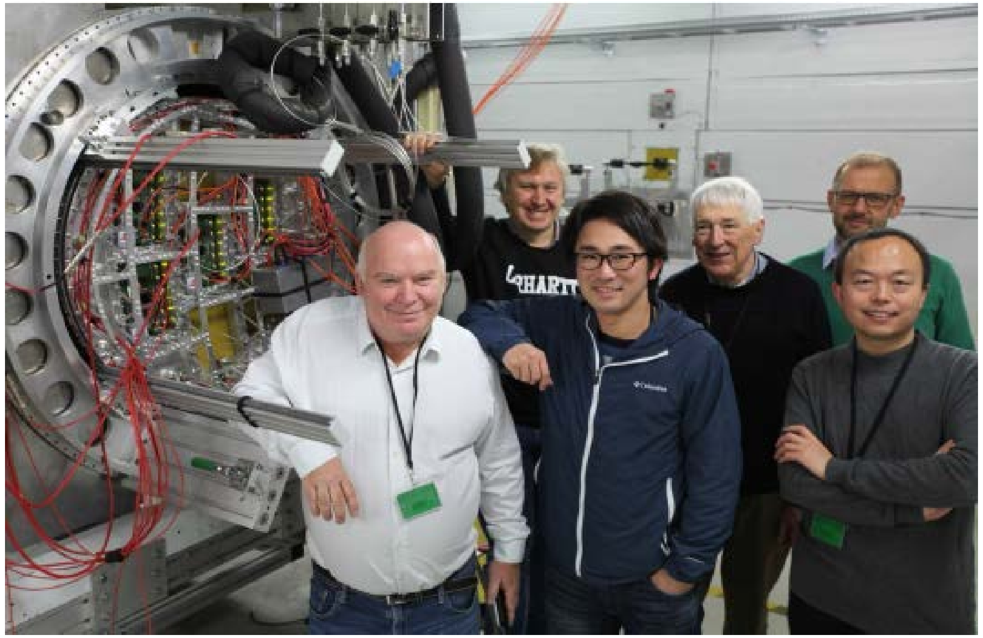
- **Resistive Micromegas has been studied by the beam under 1.0T.**
  - Bulk-Micromegas with 128 μm gap size between mesh and resistive layer.
- HV scheme of the module (ERAM) places grid on ground potential
  - Spatial resolution of $\sigma_{r\phi} \leq 100$ μm







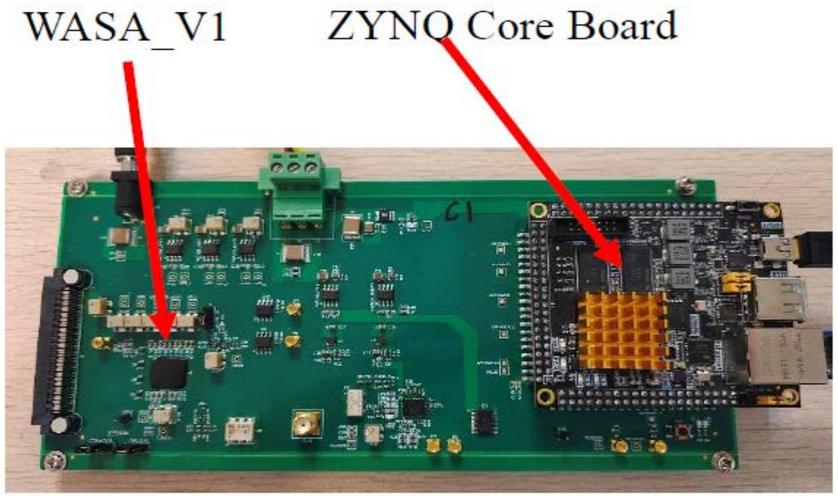


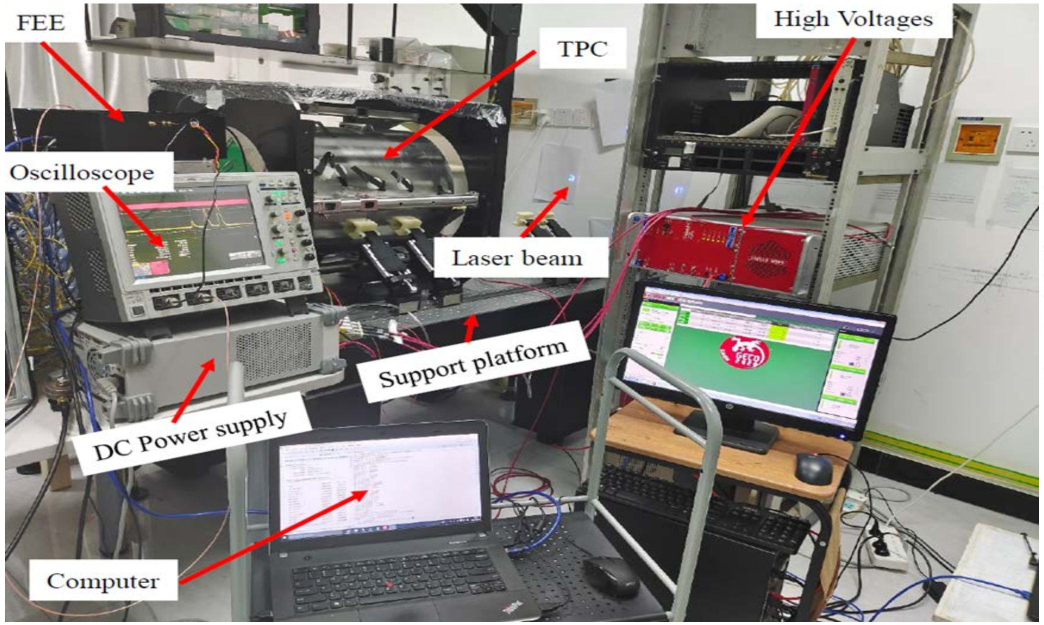


https://doi.org/10.1016/j.nima.2019.162798

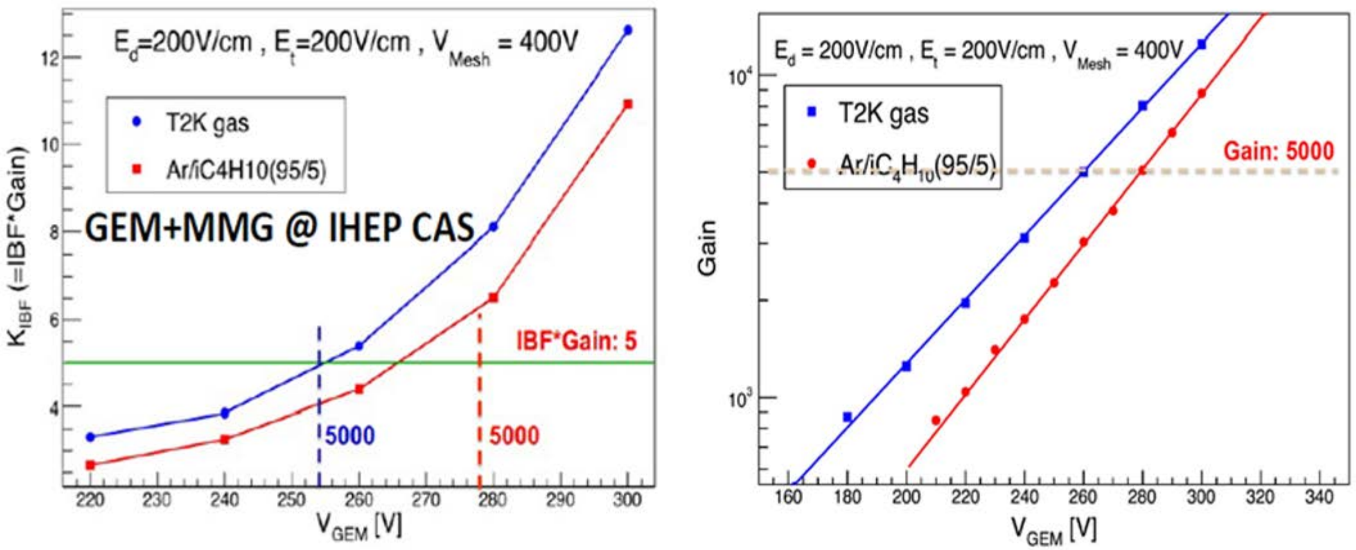
Pad readout TPC technology –Hybrid readout @IHEP/Tsinghua

- **Low power consumption ASIC has been developed for TPC readout.**
  - Low power consumption FEE ASIC (**~2.4 mW/ch** including ADC)
- **Hybrid readout module has been developed:**
  - Supression ions hybrid GEM+Micromegas module
    - IBF×Gain **~1 at Gain=2000** validation with GEM/MM readout
  - Spatial resolution of $\sigma_{r\varphi} \leq 100\ \mu m$ by TPC prototype
  - dE/dx for PID: <4% (as expected for CEPC baseline detector concept)





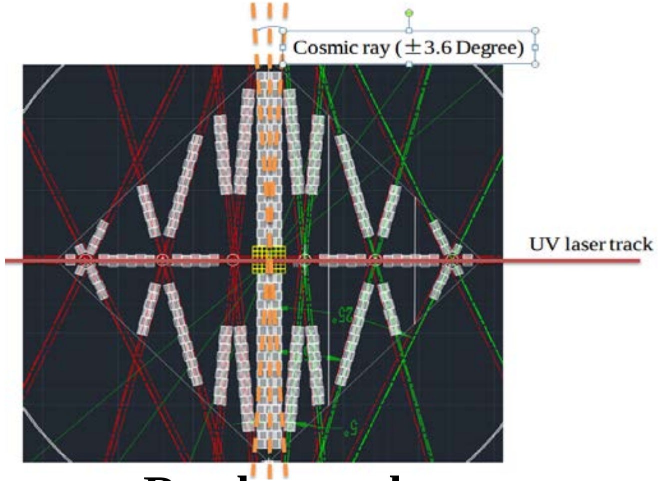
Low power consumption readout



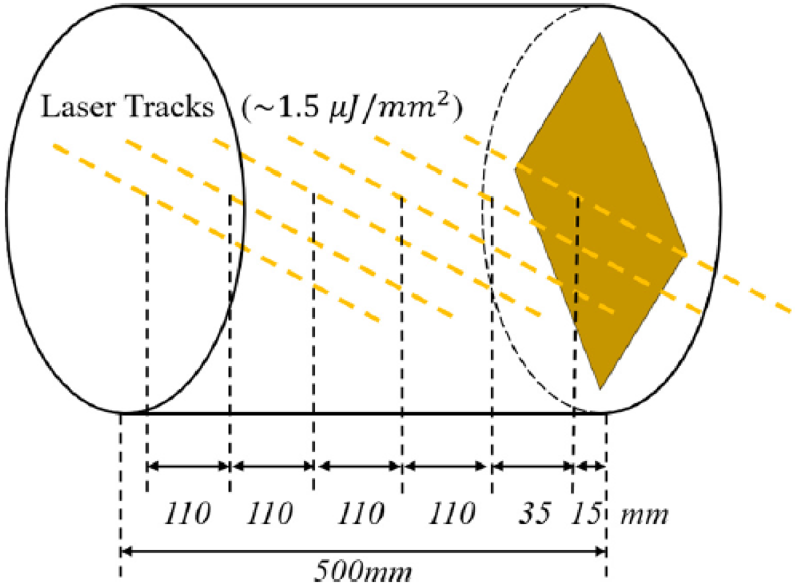
GEM+Micromegas module R&D

Pad readout: 266nm UV laser tracks @IHEP

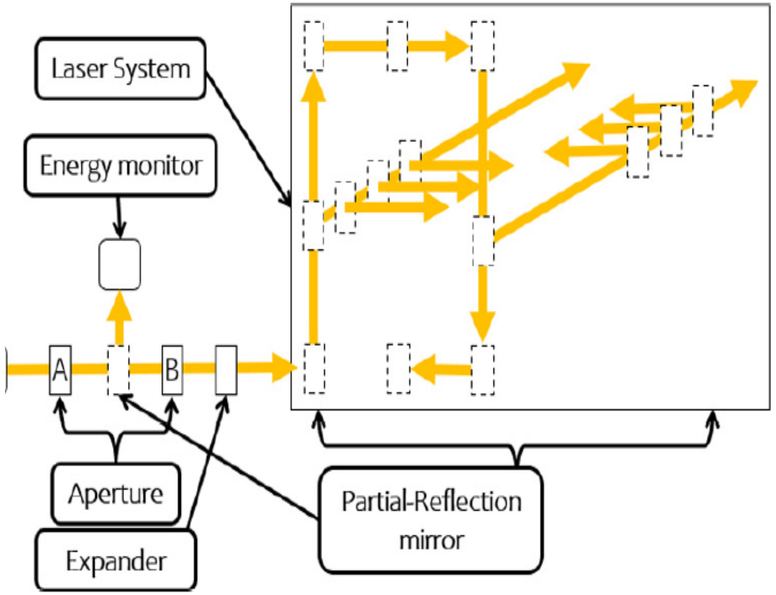
- **TPC prototype has been successfully integrated with UV laser tracks.**
  - TPC prototype with separately 6 horizontal laser tracks is designed along the drift length of 500mm
  - Effective area of 200mm×200 mm using **1mm×6mm pad readout size**
  - The laser ionization can generate **100-200 electrons** per centimeter in an argon-based gas (**optimization of the laser energy density**)



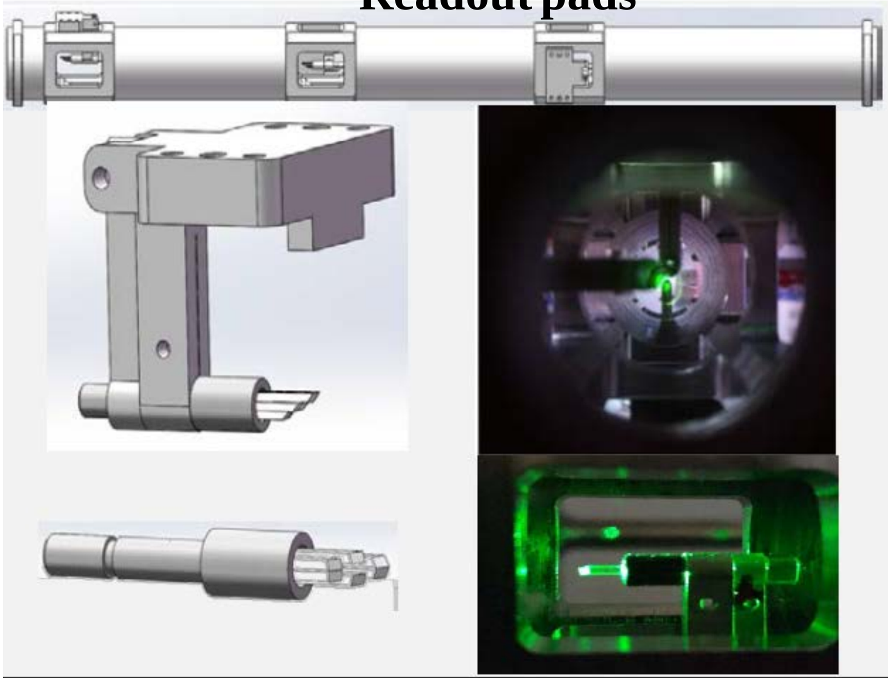
Readout pads



Laser tracks along the drift length



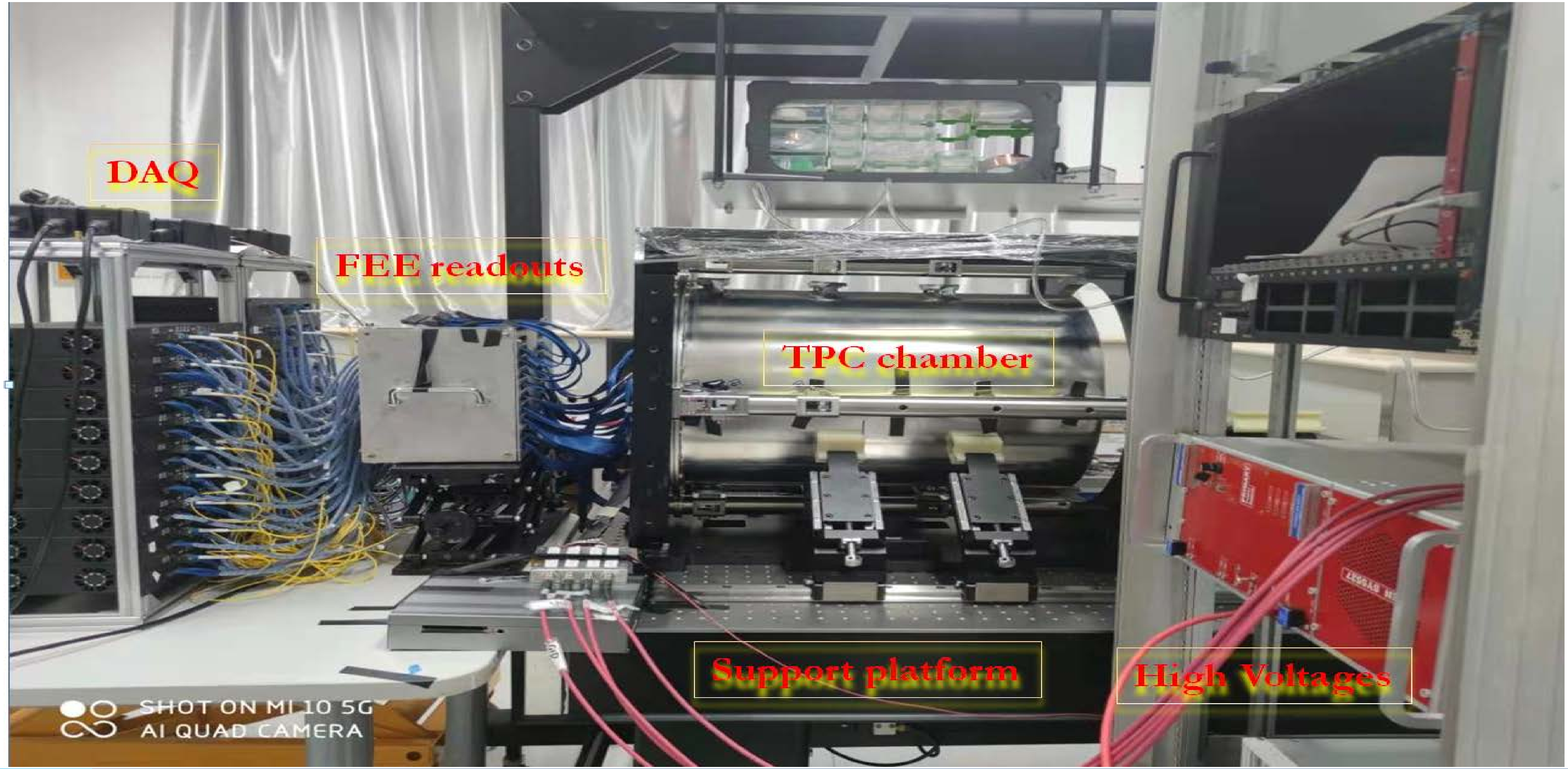
UV laser tracks mapping



UV laser mirror system

Development of Pad TPC prototype for CEPC

- Successfully to develop the TPC prototype integrated UV laser tracks at IHEP, CAS
- Experimental studies of the **spatial resolution, dE/dx resolution** achieved with the pseudo-tracks

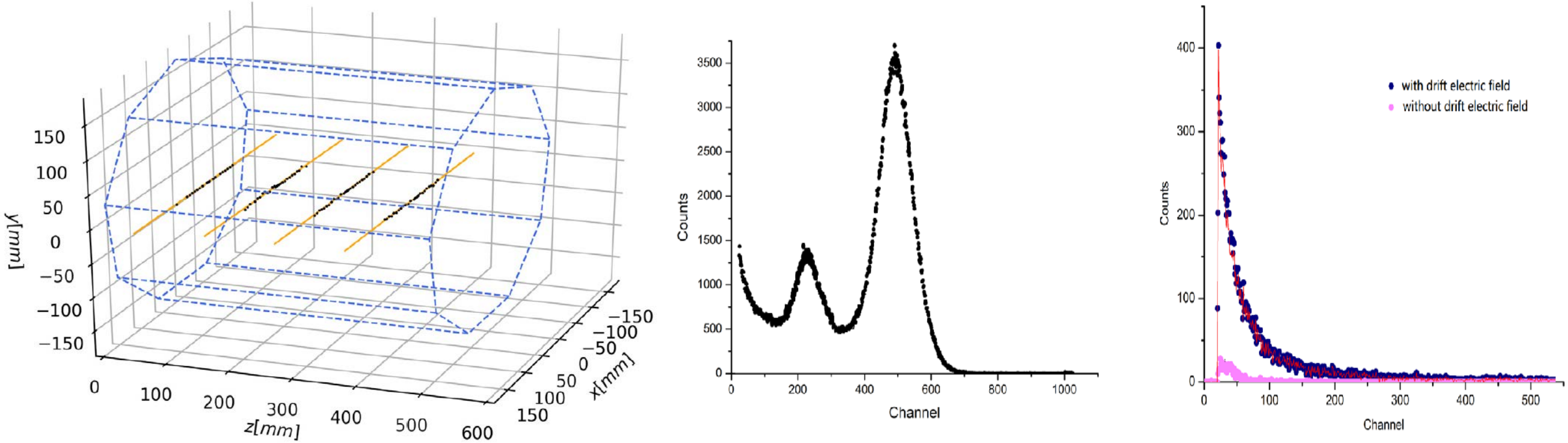


Event reconstruction and energy spectrum of ^{55}Fe/Cosmic ray

- TPC detector prototype can study the UV laser track, 55Fe radiation source and the cosmic ray.
- TPC prototype was checked after one year development
  - ^{55}Fe X-ray spectrum profile is very good
  - **Detector gain just shift 2% than one year before.**
- The Landau distribution of the cosmic ray's energy spectrum was successfully obtained.

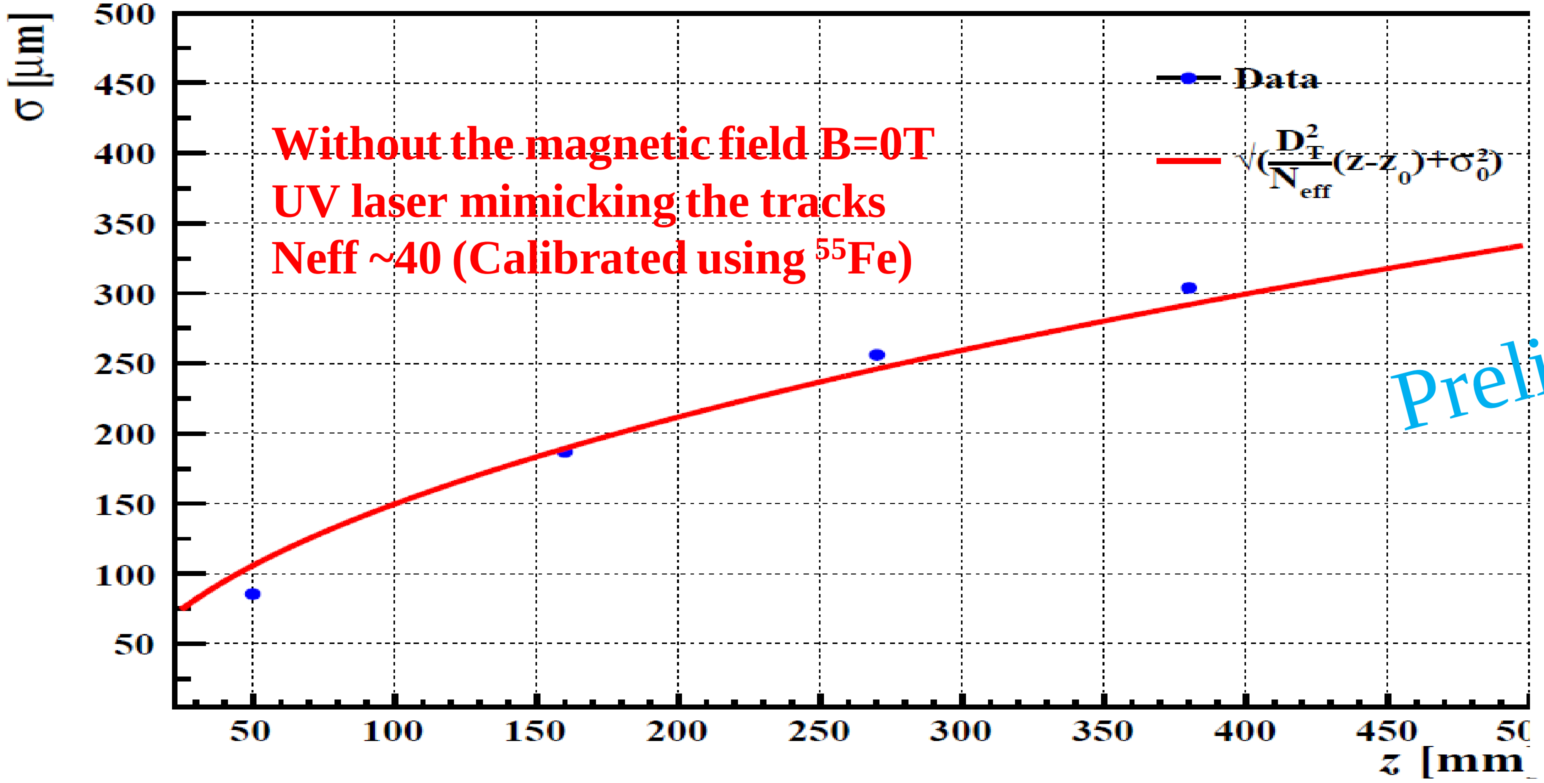
Summary of the event selection cuts.

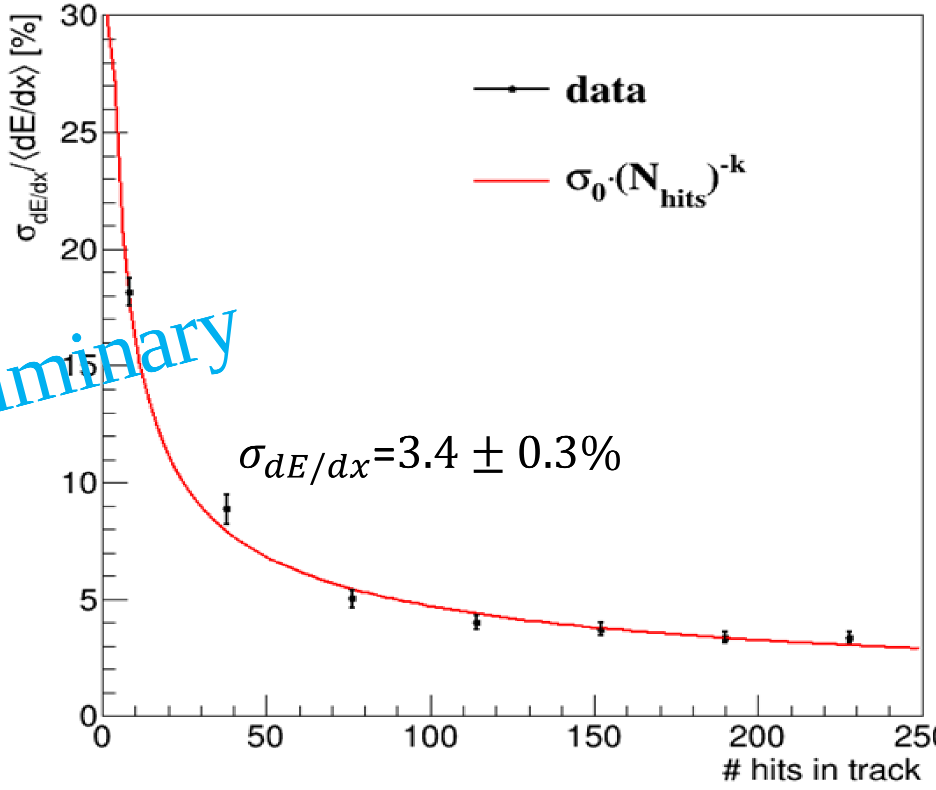
Laser energy monitor	Variation range	$E_{mean} \pm \sigma$
TPC detector	Hit ToA	layer#1 2.6 ~ 2.9 μs
		layer#2 5.7 ~ 6.0 μs
		layer#3 8.2 ~ 8.5 μs
		layer#4 10.5 ~ 11.0 μs
	Trigger pads	≥ 2 for each column
Laser and detector	The laser control chassis triggers the energy monitor and DAQ system at the same time.	



Reconstruction events and ^{55}Fe X-ray spectrum profile(middle) and cosmic ray spectrum(Right)

- **TPC prototype integrated 266nm UV laser tracks has been studied and analyzed the UV laser signal, the spatial resolution and dE/dx resolution, all are pretty good to Higgs run.**
  - Spatial resolution can be less than **100 μm along the drift length** of TPC prototype
  - Pseudo-tracks with 220 layers (**same as the actual size of CEPC baseline detector concept**) and dE/dx is about 3.4 $\pm$ 0.3%





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

- Towards pixelated readout TPC for PID at Tera Z

Pad and pixelated readout TPC technology

- For Higgs, W and top running, **no problem** for all TPC readout technologies.
- Pixelated readout TPC is **a good option** at high luminosity Z on circular e+e- collider (2x36 $cm^{-2}s^{-1}$)
  - Pixelated readout TPC is a realistic option to provide
    - High spatial resolution **under 2T or 3T magnetic field**
    - Better momentum resolution
    - High-rate operation (MHz/cm^2)
    - dE/dx and Cluster counting (**in space**)
    - Excellent two tracks separation

TimePix1	TPX3 chip	Quad	Module
2007	2017	2018	2019

GridPixes

Standard charge collection:

Pads (1 mm×6 mm)/ long strips

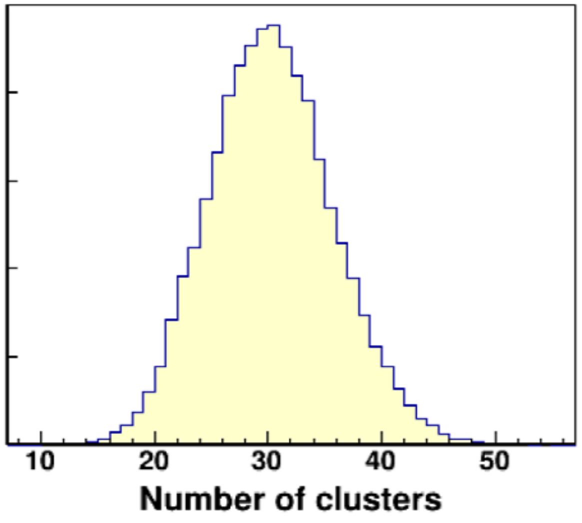
Pixelated readout:

Bump bond pads are used as charge collection pads.

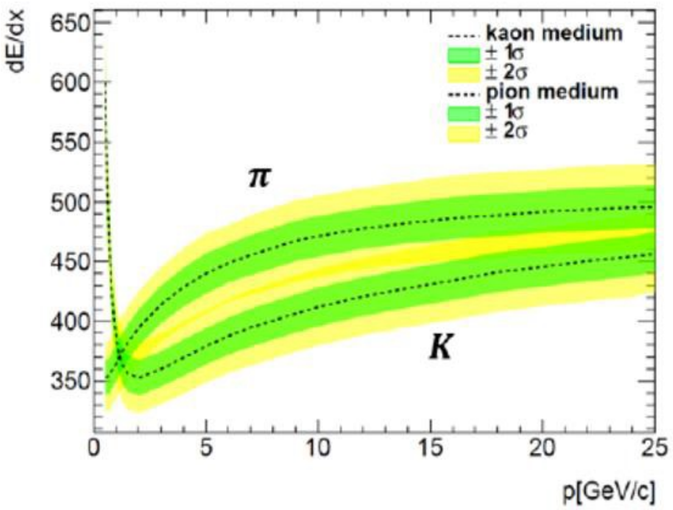
55µm× 55 µm or larger

Cluster counting measurement: dN/dx

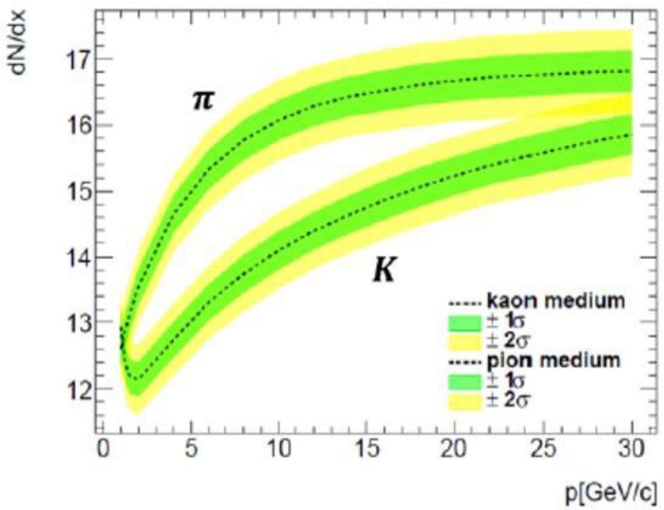
- **dN/dx: Number of primary ionization clusters per unit length**
  - Ideal measurement of ionization, clean in statistics
  - Poisson distribution ➔ Get rid of the secondary ionizations
  - Small fluctuation ➔ **Potentially, a factor of 2 better resolution** than dE/dx



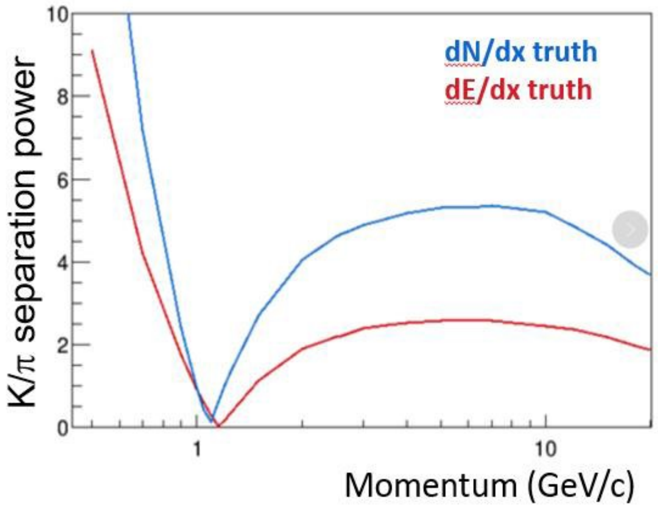
dE/dx



dN/dx

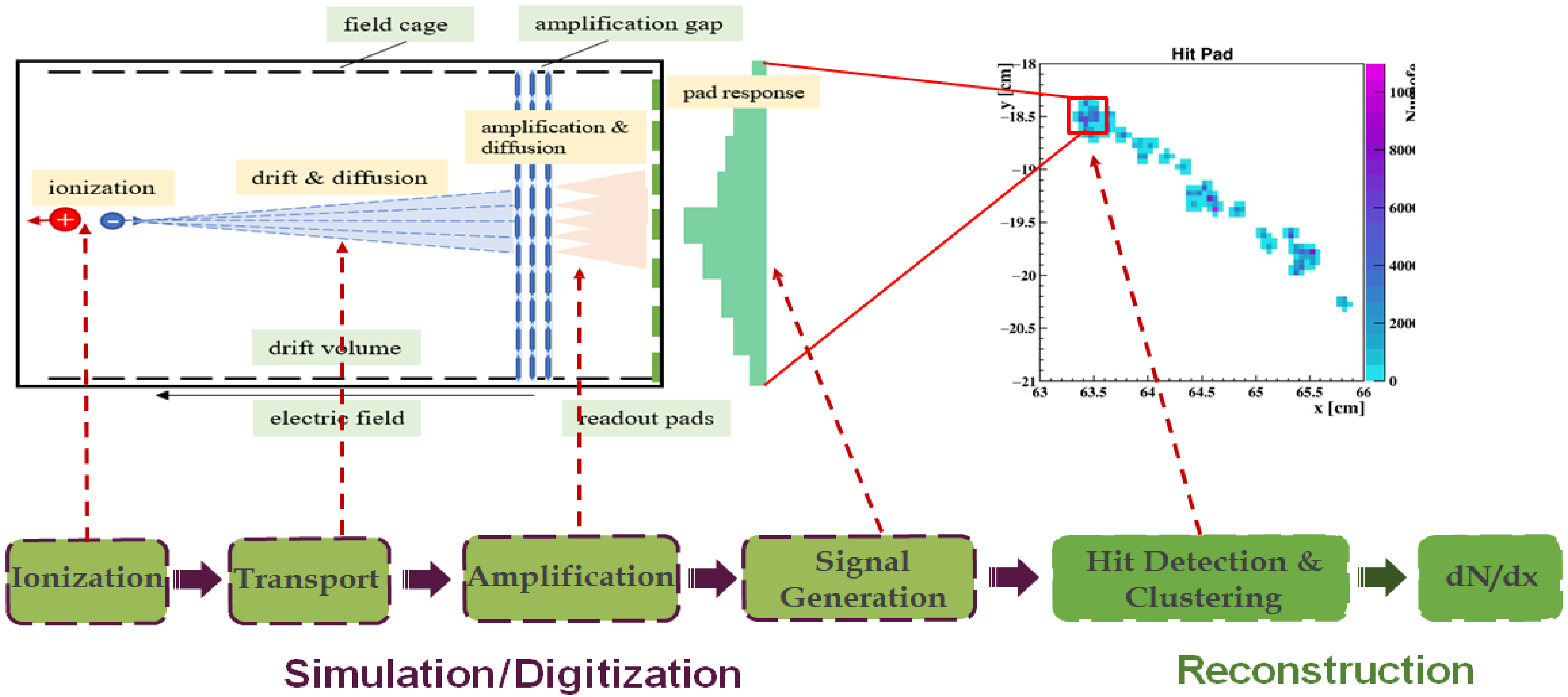


K/π separation power
dN/dx vs dE/dx



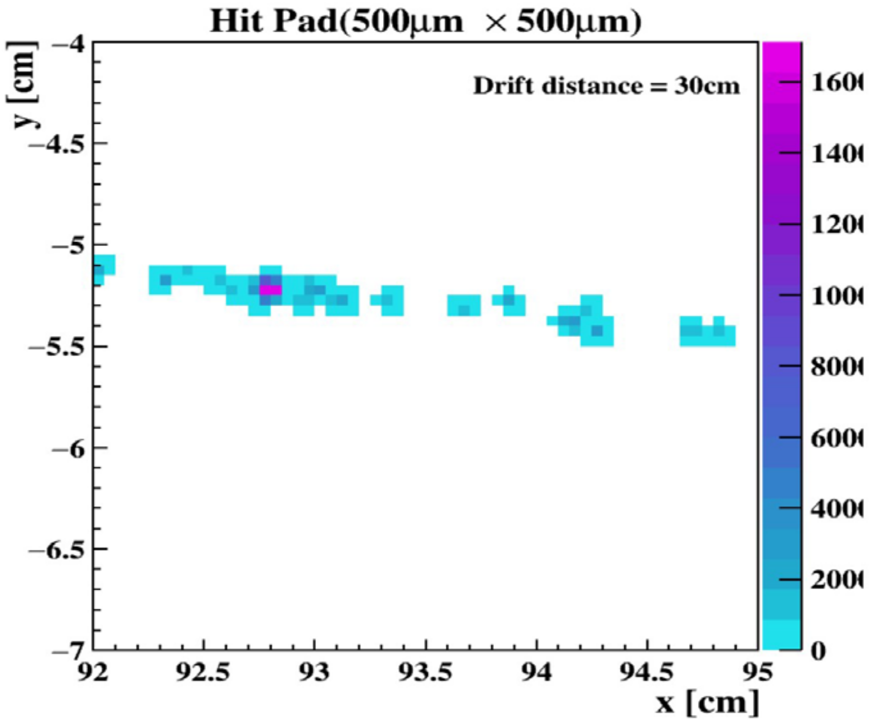
Simulation of the pixelated TPC - ongoing

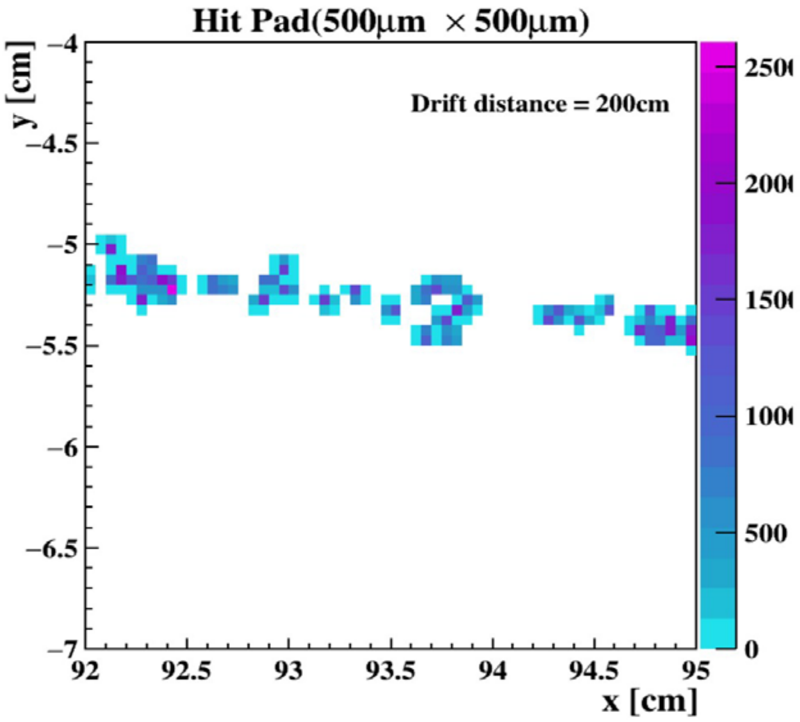
- All detailed simulation **starting** at IHEP using Garfied++ and Geant4
  - Setup the new simulation framework
  - TPC detecror module simulated **under 2T and T2K gas** from CEPC CDR

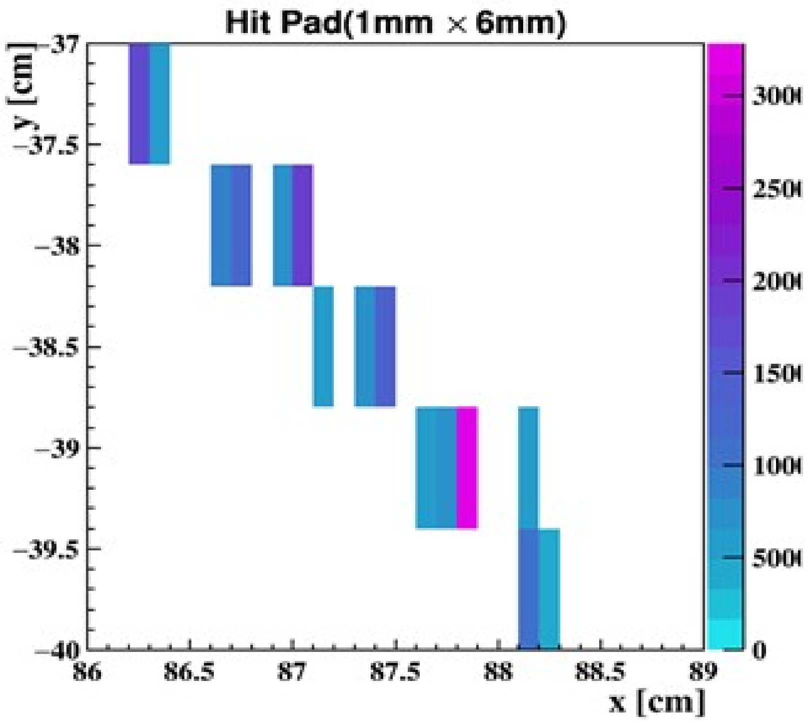


Current R&D effort: Pixelated TPC simulation

- Pixelated readout is essential for cluster detection.
  - Readout assuming a pixel size of **0.5×0.5 mm²**
  - Most electrons are separatable
  - Electrons from the same cluster are spatially localized



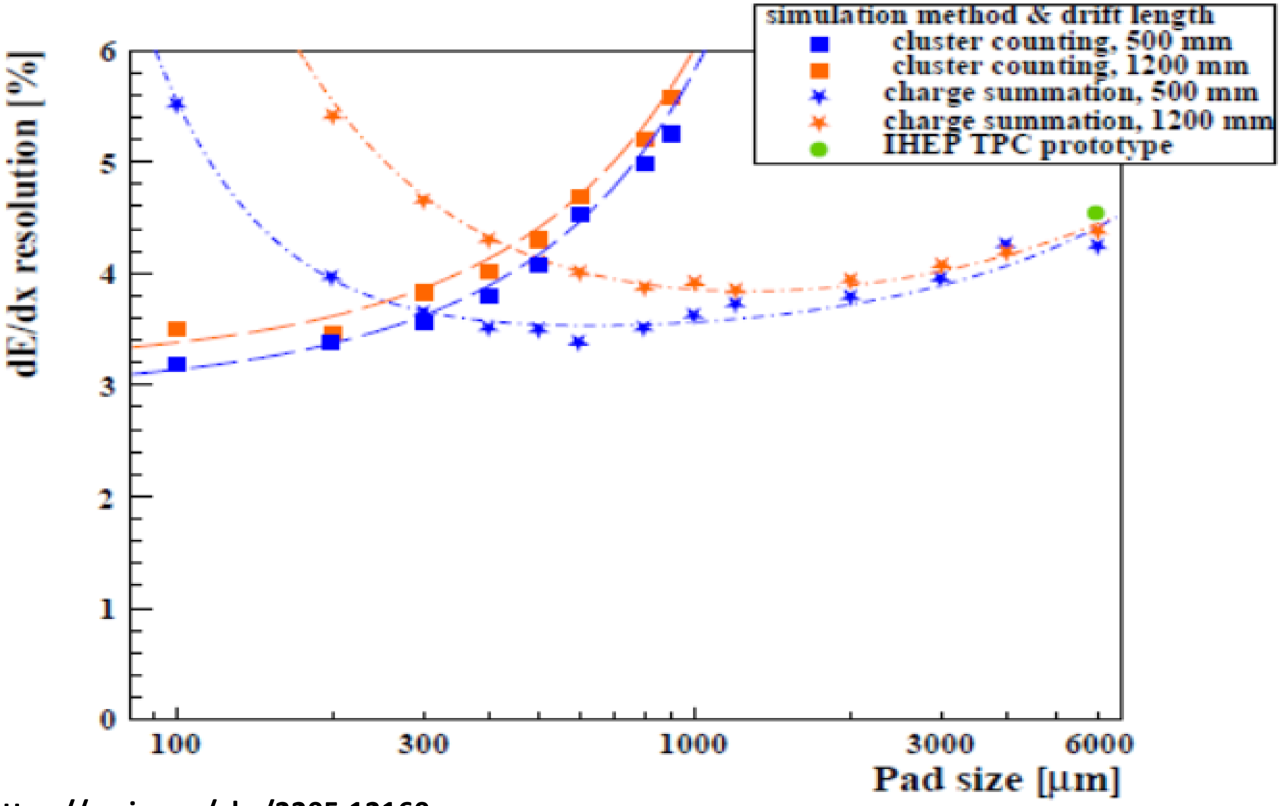




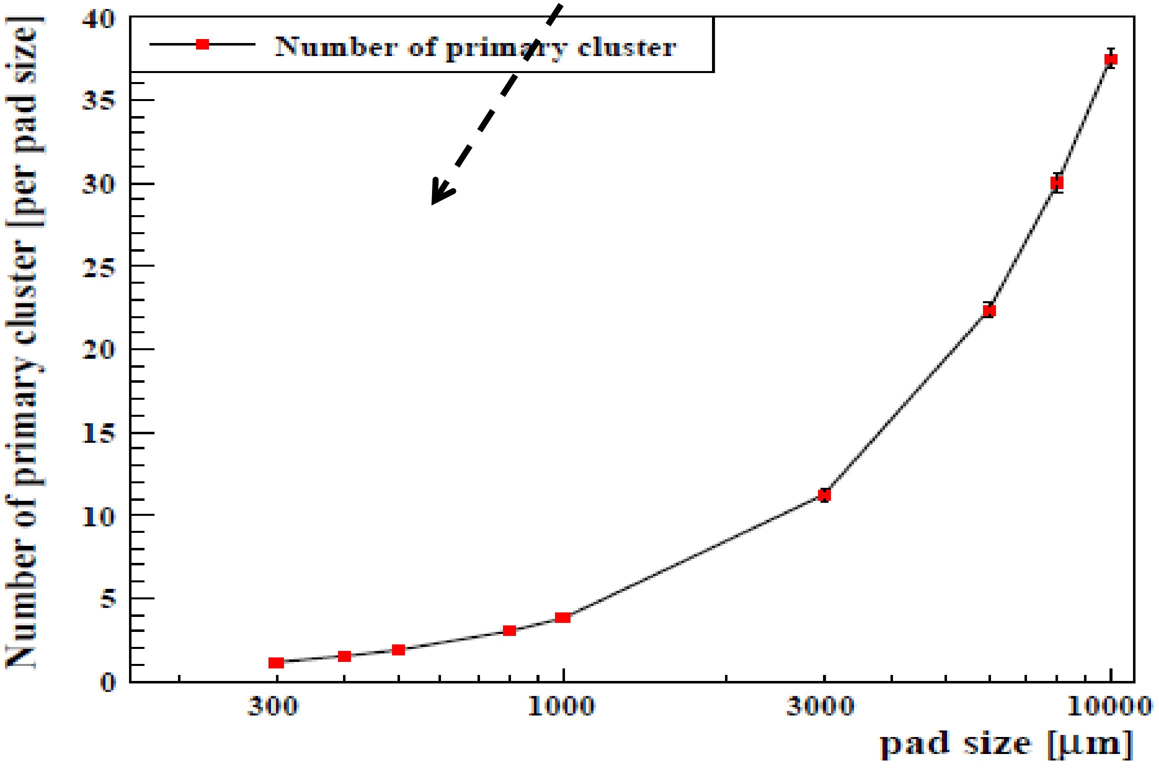
Pixelated Readout (500μm x 500μm) Pad Readout (1x6 mm)

High granularity for improved PID at TPC

- Current full pad TPC reconstruction: 6mm pads → **~4.8% dE/dx resolution**
- Smaller pad size improved momentum resolution via dE/dx and dN/dx → Pad toward pixel pad
- Smaller pad size improved the voxel occupancy (10^{-4} level)
    - Pad size of about 500μm can record **~1 primary cluster along track length** at T2K gas
    - High **readout granularity** VS the primary cluster size optimization



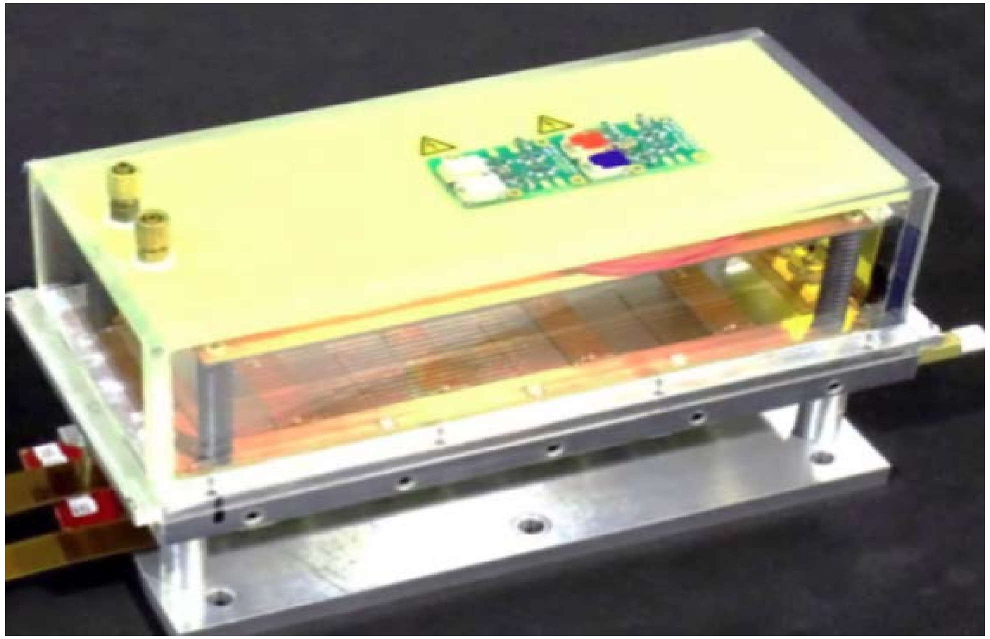
Simulation of the primary cluster along the drift length

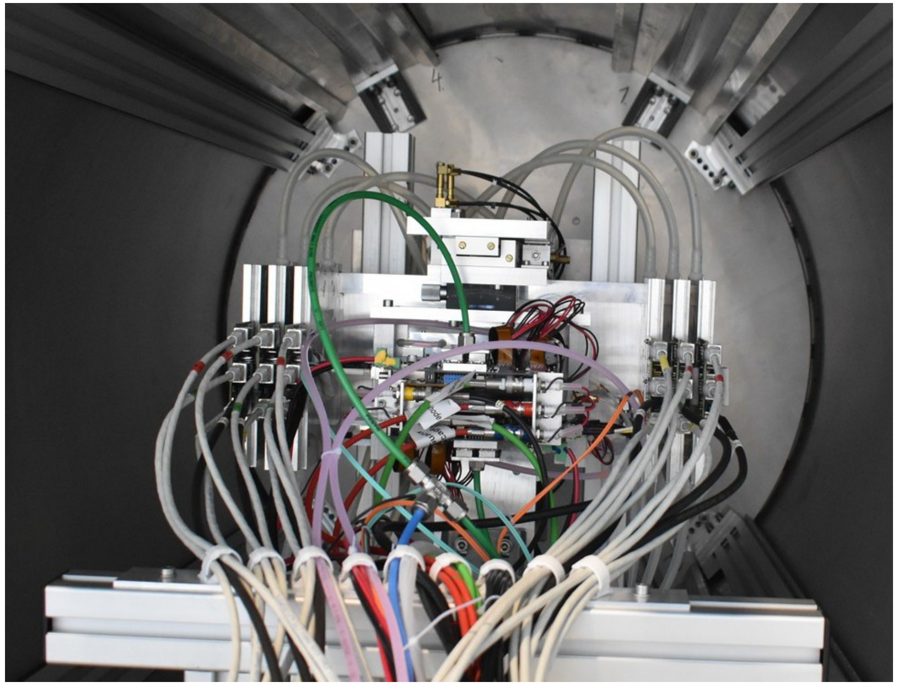


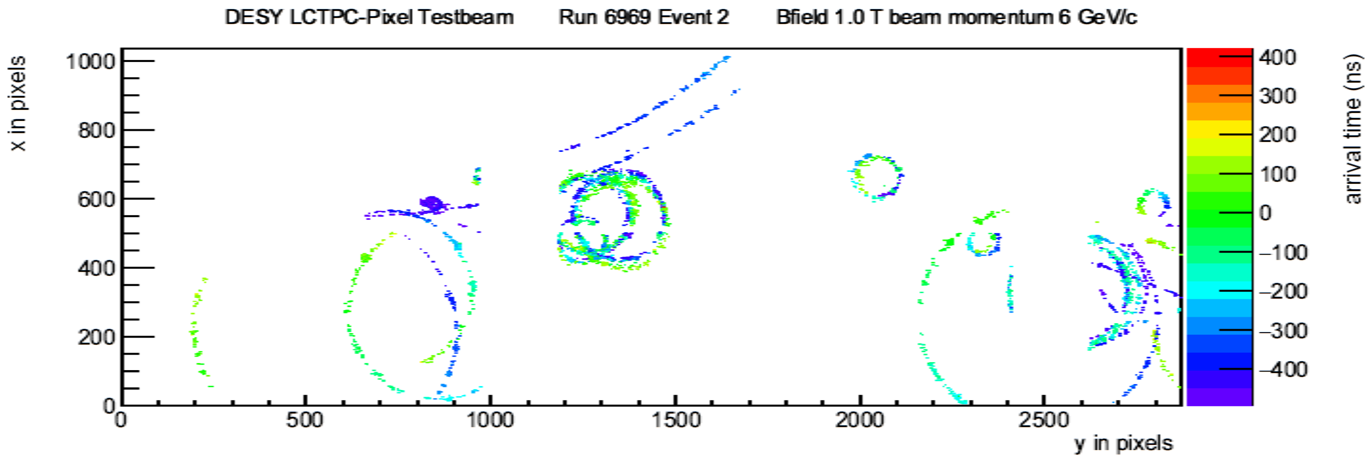
https://arxiv.org/abs/2205.12160

Pixelated TPC technology – Large scale readout @LCTPC

- Pixelated TPC prototype with GridPixes:
  - 8-QUAD module (2x4 quads) with field cage
    → 8-Quad GridPixes covered **an active area of 39.6×28.4 cm²**
  - ~**100-120 chips/module** 240 module/endcap (full size 10m²)
    → 50000-60000 GridPixes
- During the test beam ~10^6 events were successfully collected, all results showed that **a pixel TPC is realistic.**







DESY testbeam in June 2021

Same goal: Low power consumption pixelated TPC technology IHEP/LCTPC

- R&D @ IHEP based on **0.5×0.5 mm^2 pixels and electronics uses a power of <0.2mW/channel**.
  - For all the active area of 160 000 cm^2 one has 64 M channels and **<1.2 kW** power consumption
  - > 89% coverage in the endplate

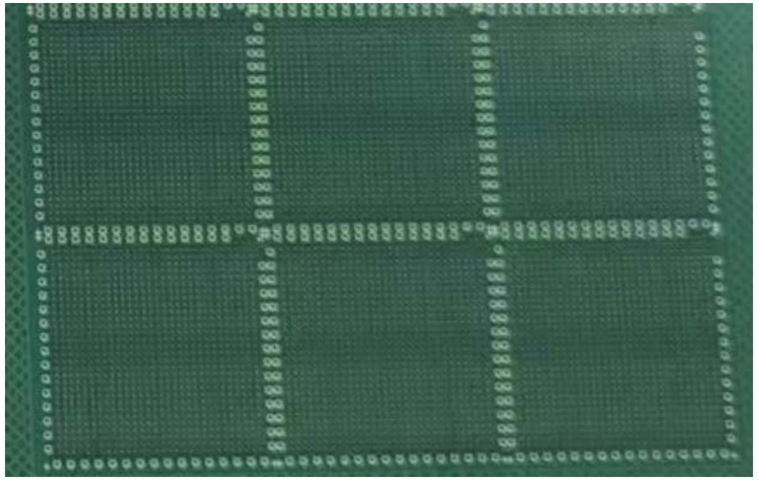
- Current TPX3 chip has 256×256 channels and a surface of 1.41×1.41 cm^2
- Power consumption ~2W/chip; this means 30 mW/channel
- A full pixel TPC in the detector will have a total area 160 000 cm^2

- Low power consumption **is the first requirement** for the pixelated TPC technology to LCTPC
  - TPX3 Gridpixes in low power mode reduces the power consumption for a pixel TPC to **8 kW per endcap** at the cost of a worse time resolution.

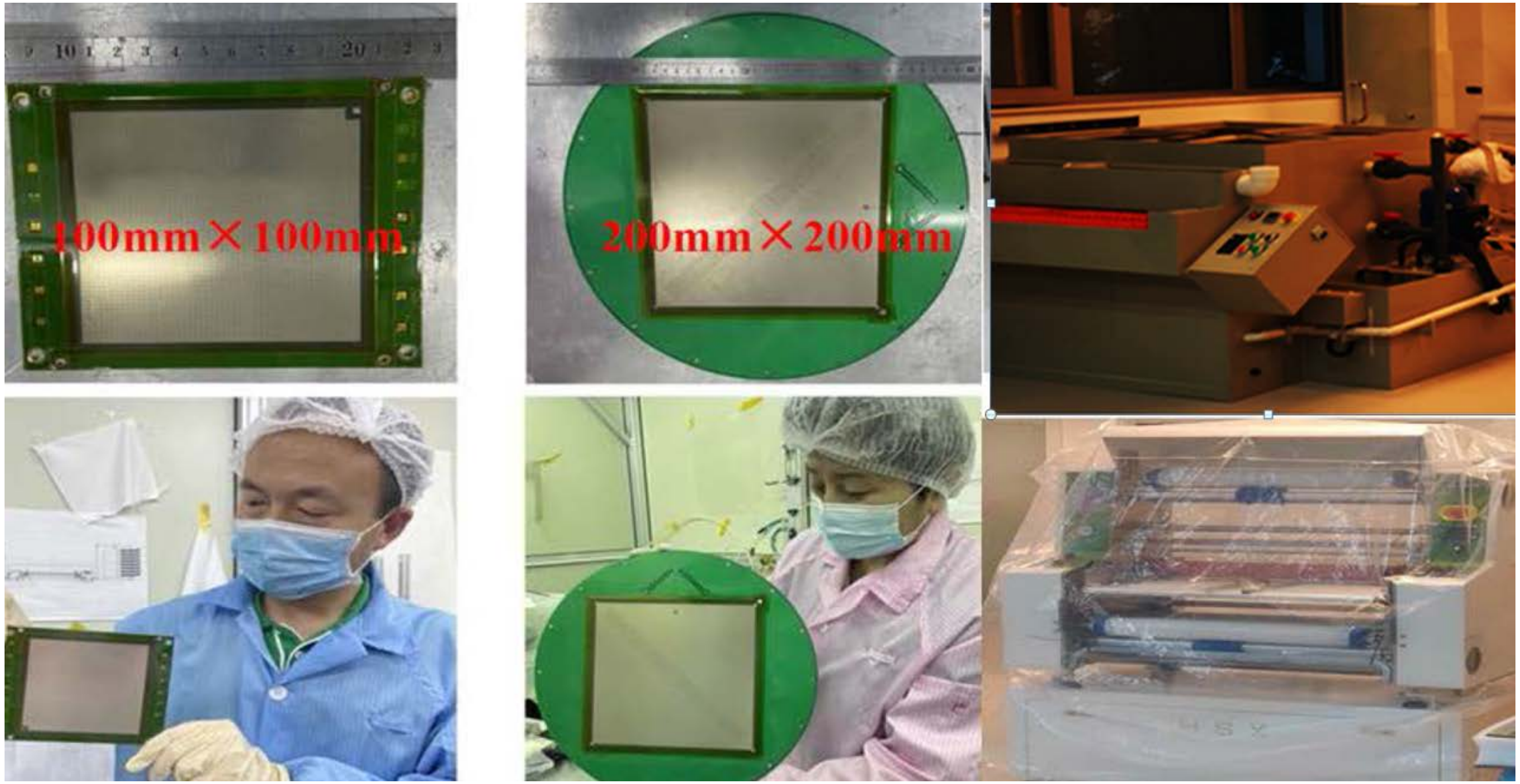
- Ref1 https://iopscience.iop.org/article/10.1088/1748-0221/14/01/C01024
- Ref2 https://iopscience.iop.org/article/10.1088/1748-0221/14/01/C01001

Current R&D effort: detector production integrated with PCB and ROIC

- R&D on detector production integrated with PCB and ROIC will be assembled.
  - **All are ready**, and some good discussion and inputs from LCTPC collaboration.
  - First step: the Micromegas was produced using the raw interposer PCB
  - Second step: Bump boding the ROIC with the interposer PCB to collaborate with Tsinghua



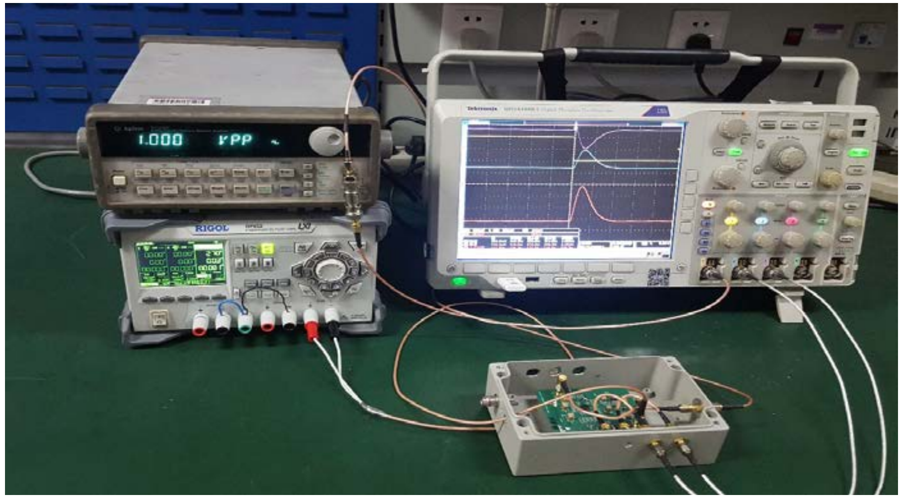
Raw interposer PCB

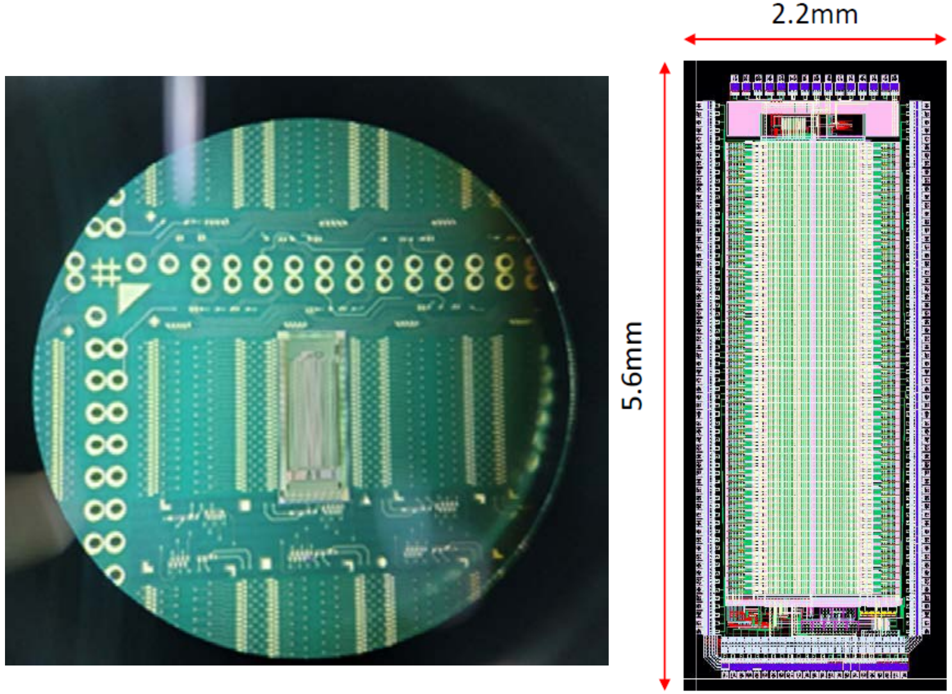


Detector production in the laboratory

Current R&D effort: Pixelated TPC R&D for CEPC

- **R&D on pixel TPC readout for CEPC**
  - Pixel TPC ASIC chip was started to developed in 2023 and 1st prototype wafer standalone tested in May.
    - **Power consumption: <1.1mW/ch (1st prototype)**
      - **<400mW/cm^2 (Test)**
  - 2nd prototype wafer design done (simulation power: 0.2mW/ch)
    - **< 100mW/cm^2 (Goal and final design)**
  - The TOA and TOT can be selected as the initiation function in the ASIC chip.
    - 1mm×6mm → 500µm×500µm pixel readout → 330µm
    - Higher precision and higher rate (MHz/cm^2)
    - Gain of the amplification: >40mV/fC
    - Channels: 32
    - Time resolution: **14bit** (5ns bin)
    - Time discriminator: TOA (Time of Arrival)
    - Technology: 180nm CMOS -> 60nm CMOS
    - High metal coverage: 4-side bootable





1st readout PCB board and the ASIC layout

Summary

- **In CEPC TPC study group, TPC detector prototype R&D using the pad readout towards the pixelated readout for the future e+e- colliders.**
- **To analyze the simulation data of the high luminosity Z pole run at CEPC, some update results of TPC prototype have been studies, UV light can created the enough massive primary electrons in the chamber to study.**
- **Pixel TPC is in the simulation package as the default track detector in 2023. The requirements of the low power consumption pixelated TPC technology became as the general proposal from LCTPC collaboration and IHEP. The updated progress on the interposer PCB integrated with ROIC are ongoing.**
- **Synergies with CEPC/LCTPC/FCCee/EIC allow us to continue R&D and ongoing, we learn from all of their experiences.**

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