Status of Pixelated and Pad Readout TPC Technology R&D at CEPC

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

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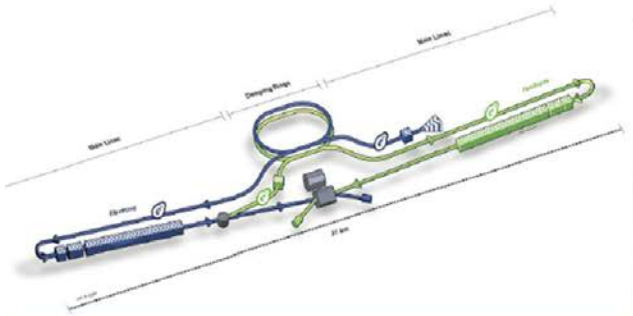
Content

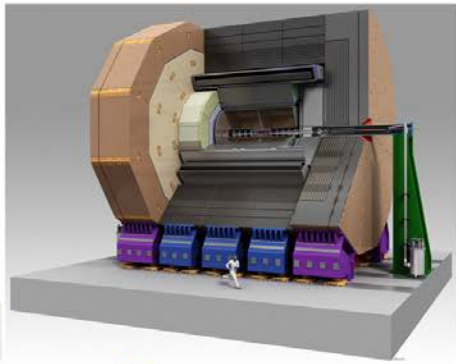
- **Motivation: TPC detector for e+e- colliders**
- **High spatial resolution TPC prototype**
- **Towards PID TPC R&D at CEPC**
- **Summary**

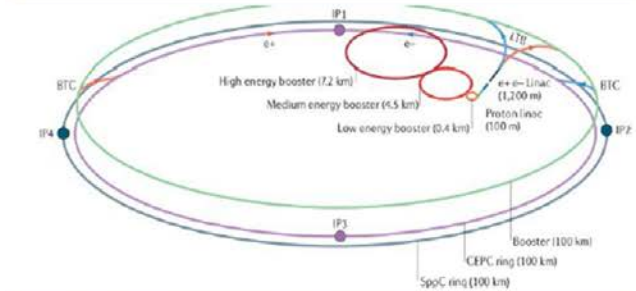
TPC technology for the future e+e- colliders

- 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 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%

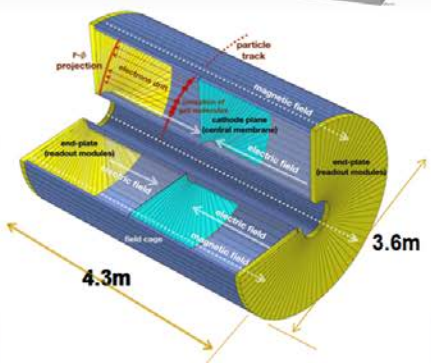


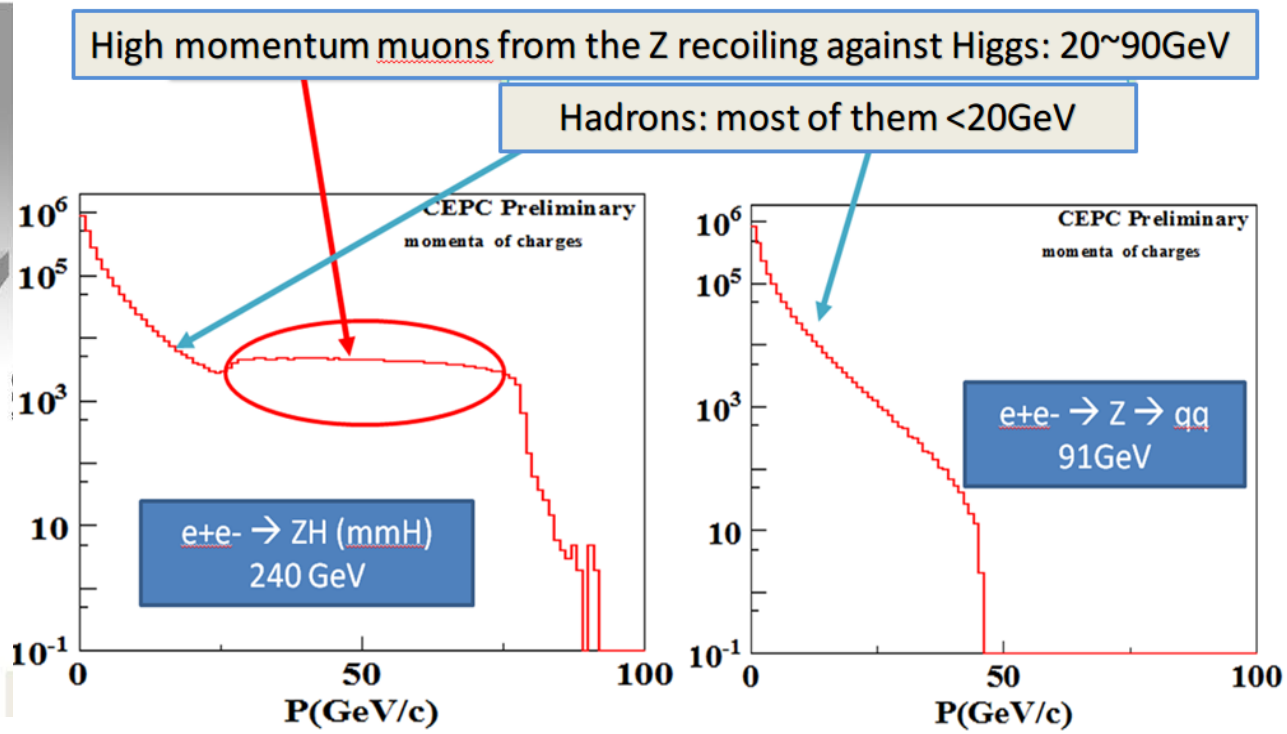
International Linear Collider (ILC)





Circular Electron Positron Collider (CEPC)

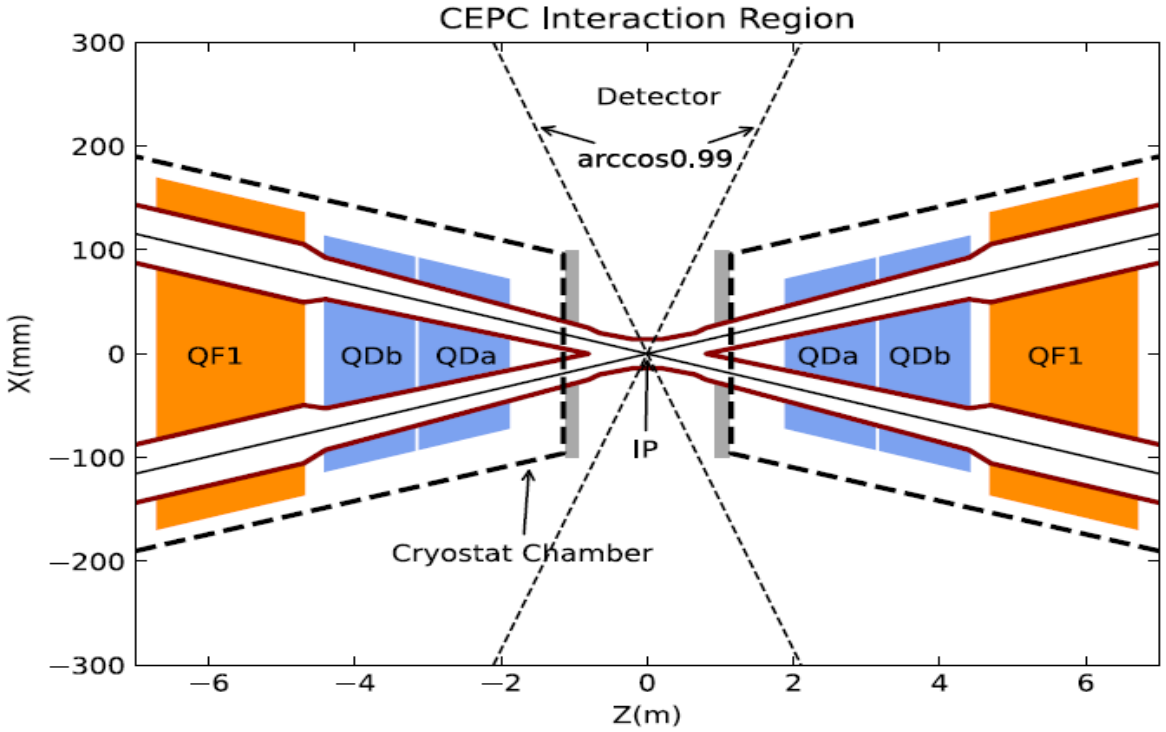


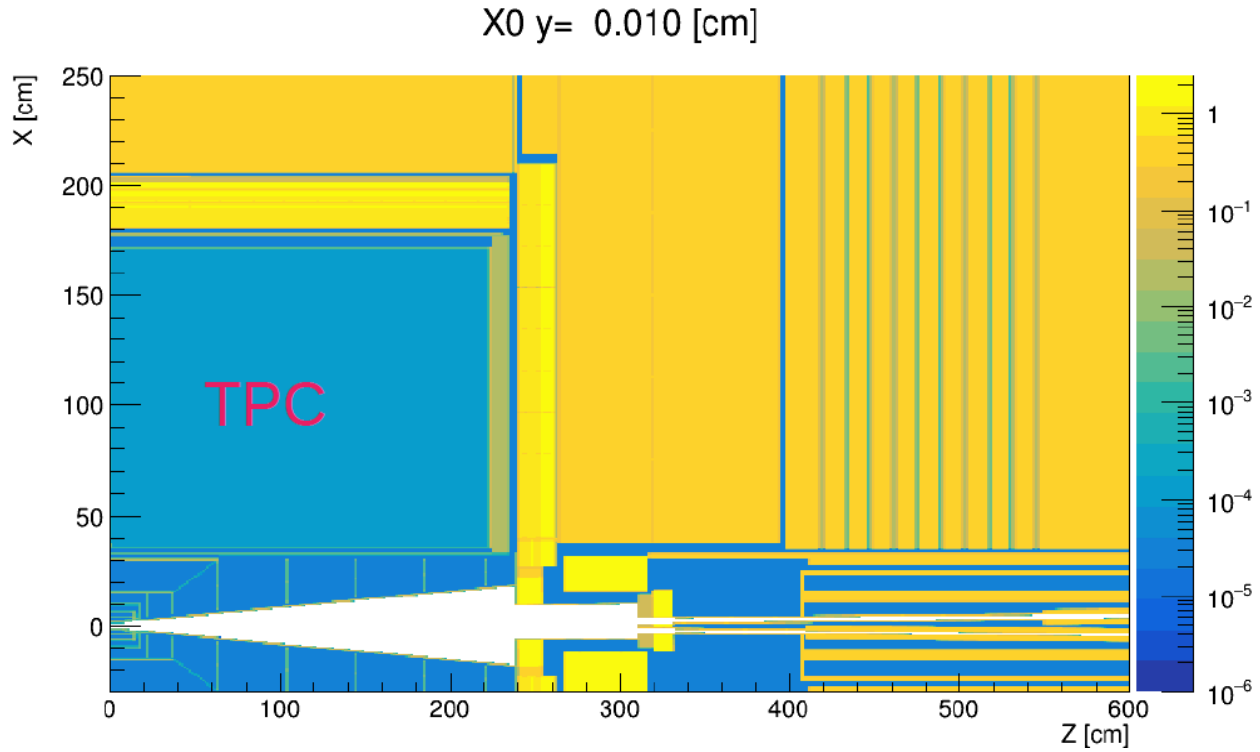


https://arxiv.org/abs/2203.06520

e^+e^- colliders: sources of detector backgrounds at MDI

- In general, this source is well understood and under control: it scales with luminosity, one should transport interaction products away from IP and **shield/mask** sensitive detectors, and exploit detector timing
- 2.0T for Z pole run at CEPC， beam crossing angle of **33mrad** in MDI design
- **Need to mimic the same level of the electrons density in TPC to study the performance**

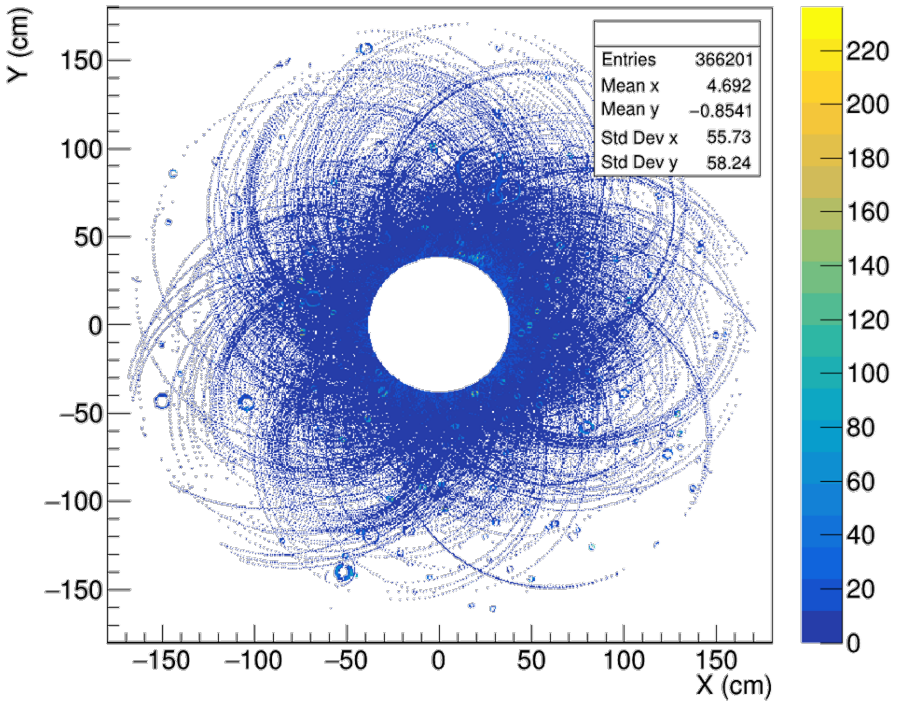




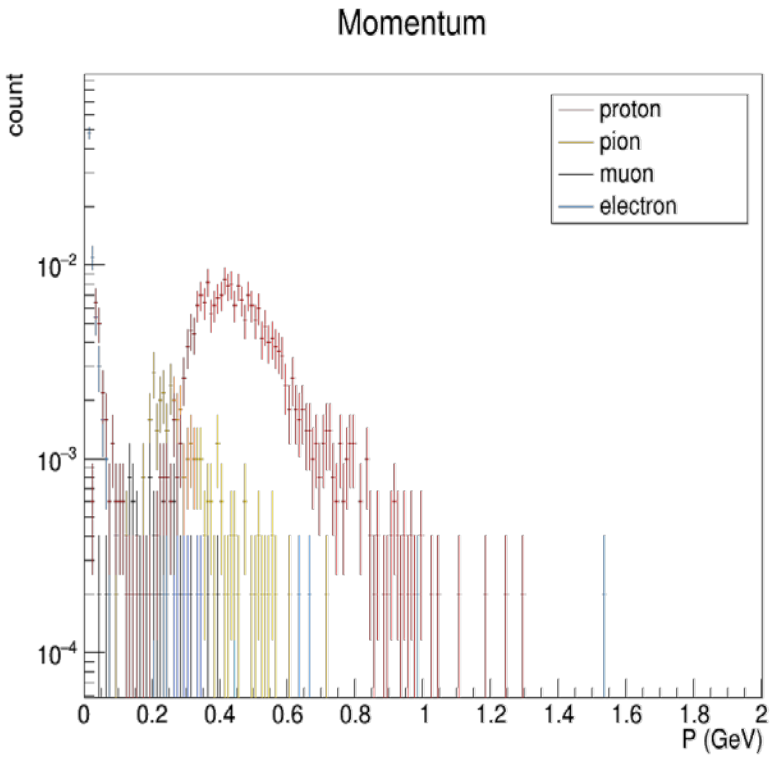
CEPC MDI region

Study the full simulation data of the high luminosity Z at CEPC

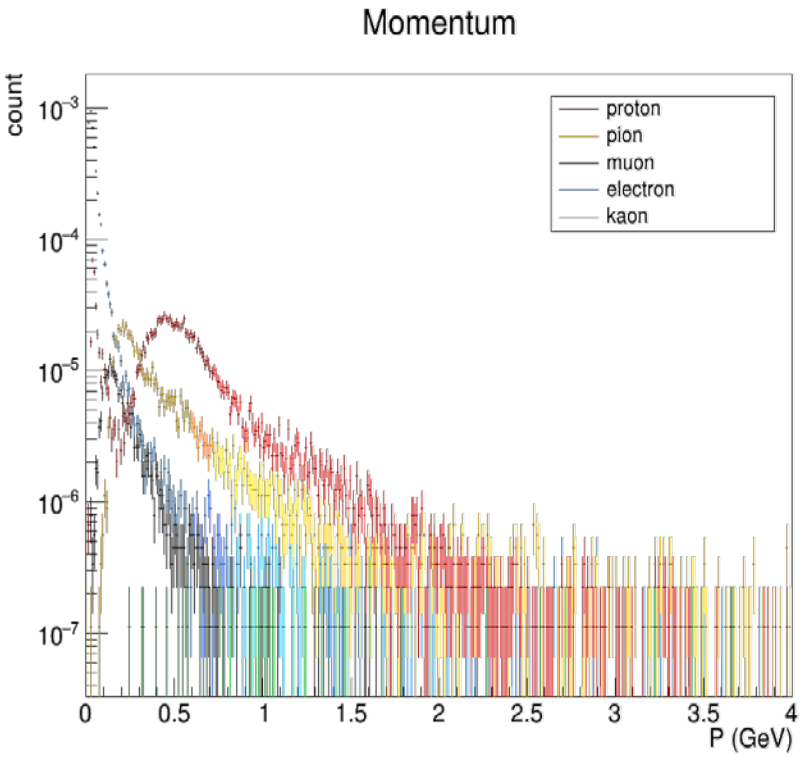
- All data from the full simulation of the **high luminosity Z pole run (2.0T) at CEPC**
- The pair production and beam-gas effect in TPC chamber have been consider to study
- Some particles have been analyzed using **Proton, Pion, Muon and primary electrons** with the different momentum in the TPC chamber



Hitting map of two-photon effect samples



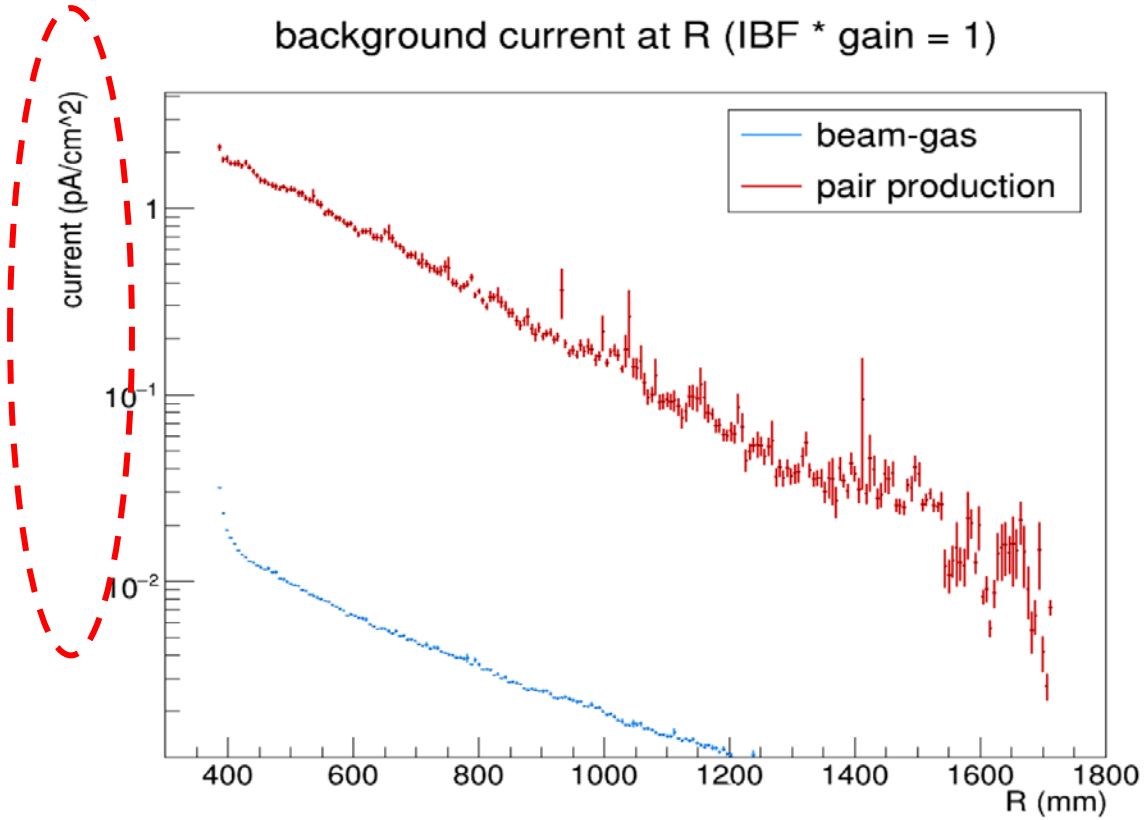
Pair production in TPC chamber



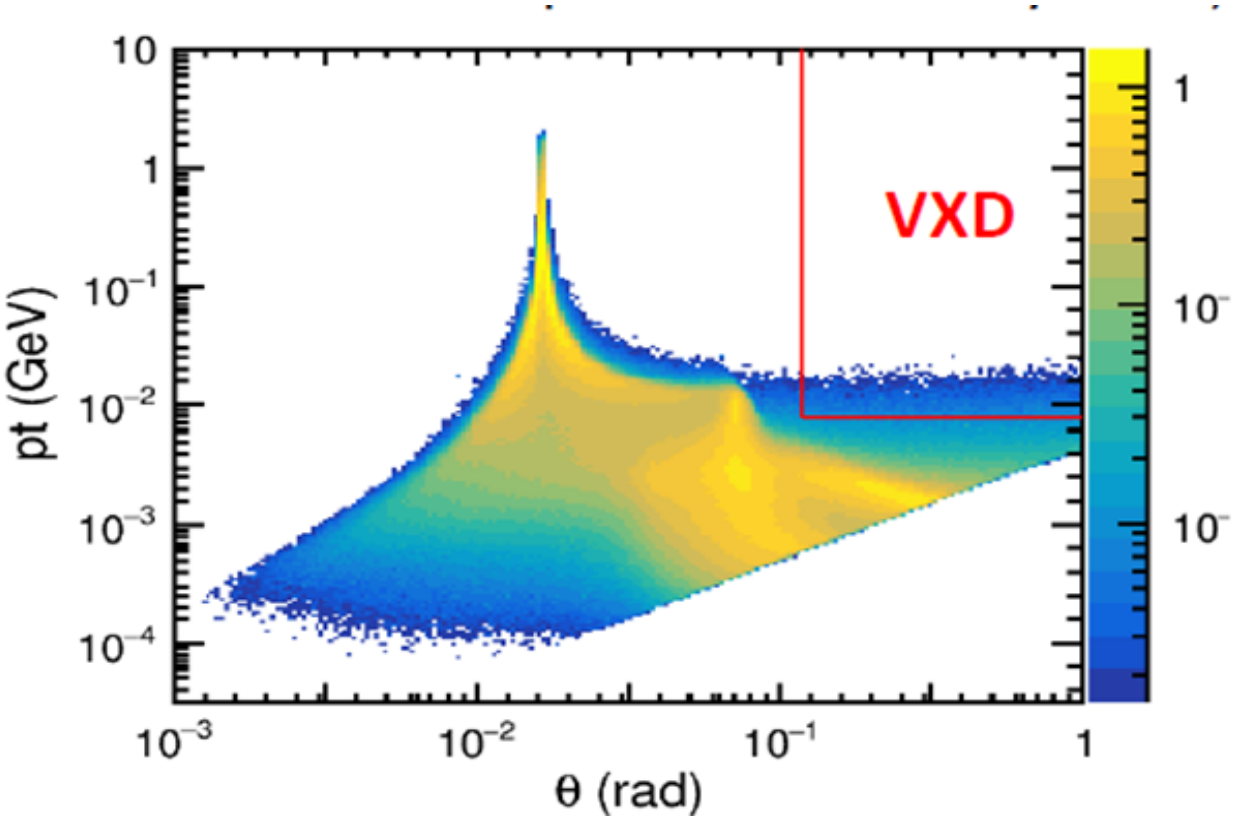
Beam-gas in TPC chamber

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.



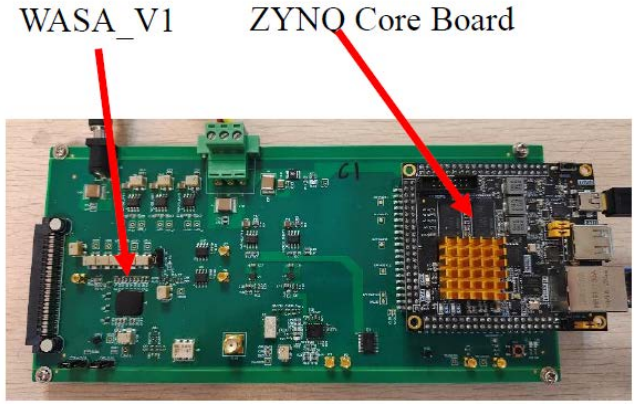
Current of the electrons in TPC chamber

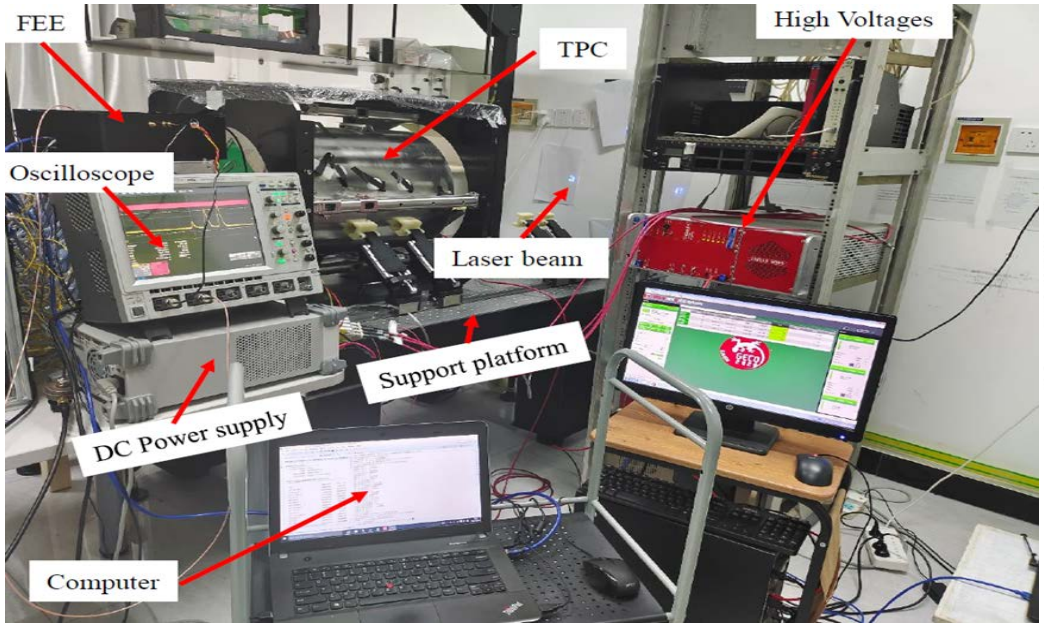


The theta in MDI region

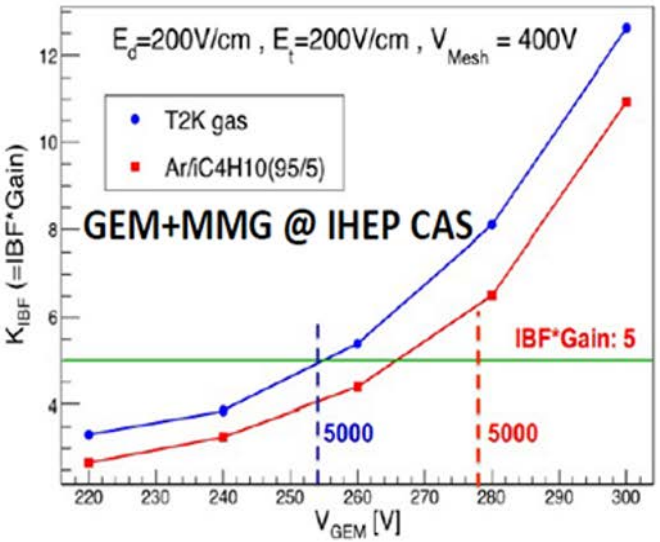
CEPC TPC detector prototyping roadmap

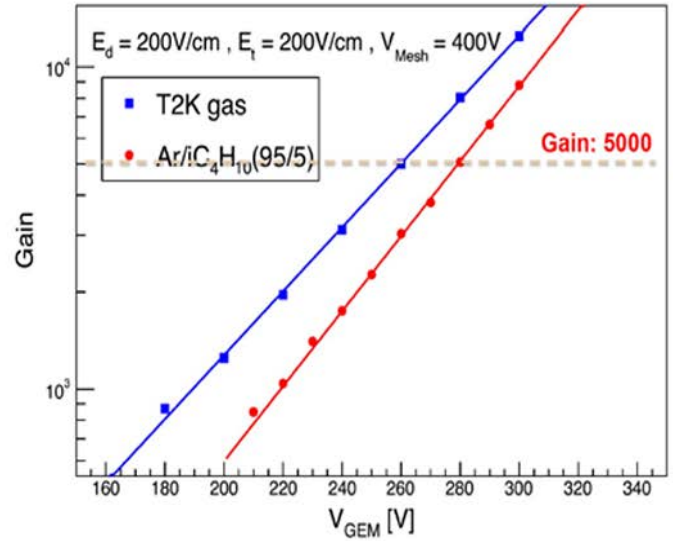
- From TPC module to TPC prototype R&D for beam test
  - Low power consumption FEE ASIC (**reach <5mW/ch** including ADC)
- Achievement by far:
  - Supression ions hybrid GEM+Micromegas module
    - IBF×Gain **~1 at Gain=2000** validation with GEM/MM readout
  - Spatial resolution of **$\sigma_{r\varphi}$≤100 μm** by TPC prototype
  - dE/dx for PID: <4% (as expected for CEPC baseline detector concept)





Low power consumption readout





GEM+Micromegas module R&D

- High spatial resolution TPC prototype

UV laser: Two-photon ionization method (>10uJ/cm^2)

UV laser: Two-photon ionization method (>10uJ/cm^2)

- Some gas can absorb the energy of 2 photons from UV laser and ionized
- Wavelength of UV laser: 266nm (almost: 4.66eV×2)
- Threshold of the ionization energy: **>10uJ/cm^2 @MIP**
- **To mimic the stable laser tracks in chamber**

→ **UV Laser TPC prototype R&D**
Without B field

UV light: Photoelectric effect method (<10uJ/cm^2)

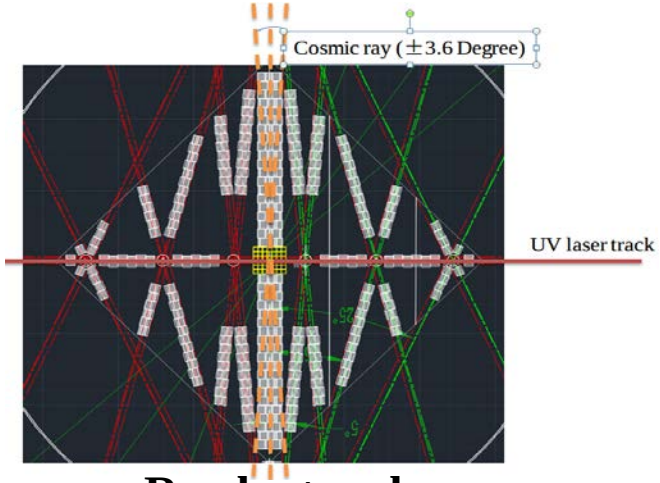
- Explanation of photoelectric effect by A.Einstein
- Each photon carries energy proportional to its frequency $E_\gamma = hf = hc/\lambda$
- One electron absorbs only one photon
- Energy of UV can less than 10uJ/cm^2
- **To study of the stable current of photoelectric**

→ **Massive electrons R&D**
Without influence working gas

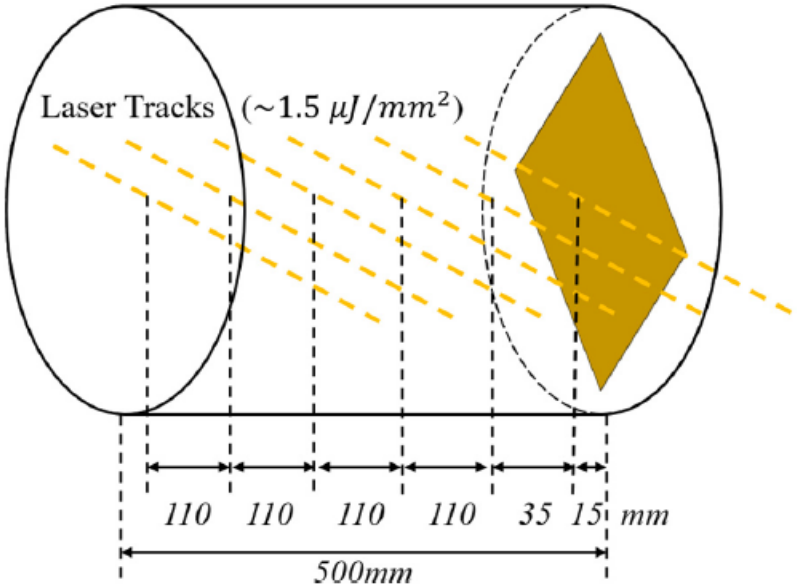
→ **Study the deviation of the tracks**
under the high luminosity

Design and commission of TPC prototype with 266nm UV laser tracks

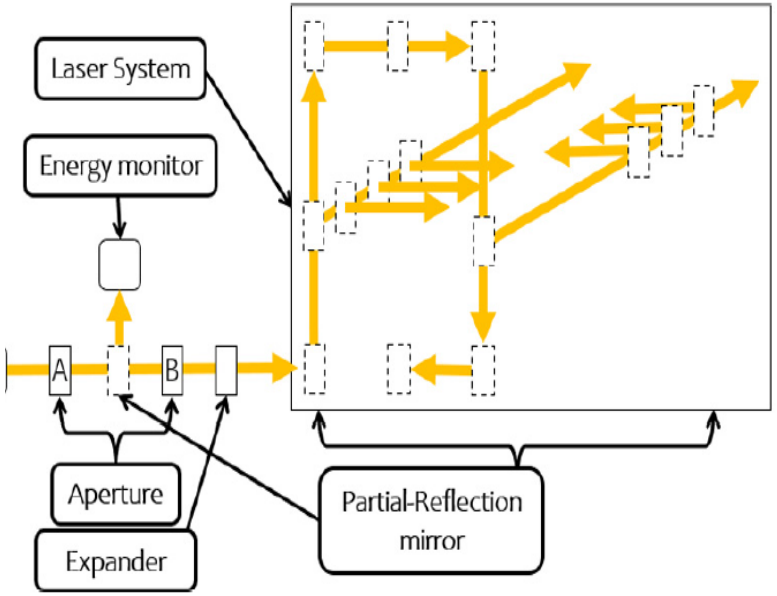
- TPC prototype with separately 6 horizontal laser tracks is designed along the drift length of 500mm
- Effective area of 200mm×200 mm using **1mm×6mm pad readout size**
- Precision value of UV laser's stability **can meet TPC prototype's physical requirement <3.2 μm**
- The laser ionization should be similar to **1-2 MIPs**, which can generate **100-200 electrons** per centimeter in an argon-based gas (**optimization of the laser energy density**)



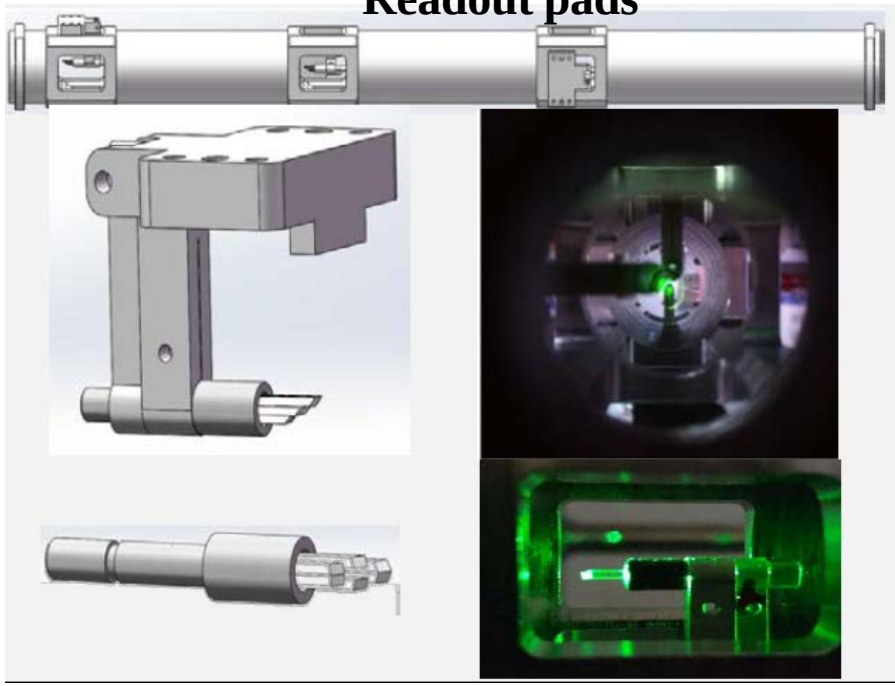
Readout pads



Laser tracks along the drift length



UV laser tracks mapping



UV laser mirror system

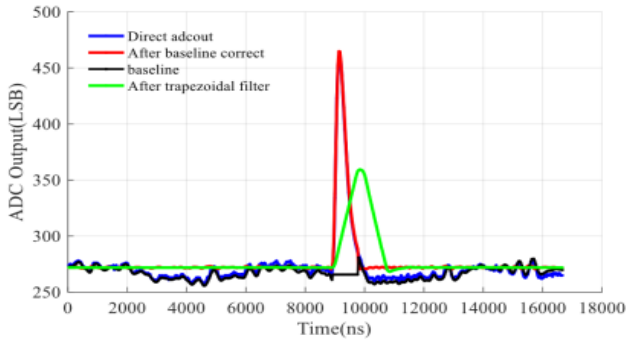
Low power consumption readout ASIC R&D

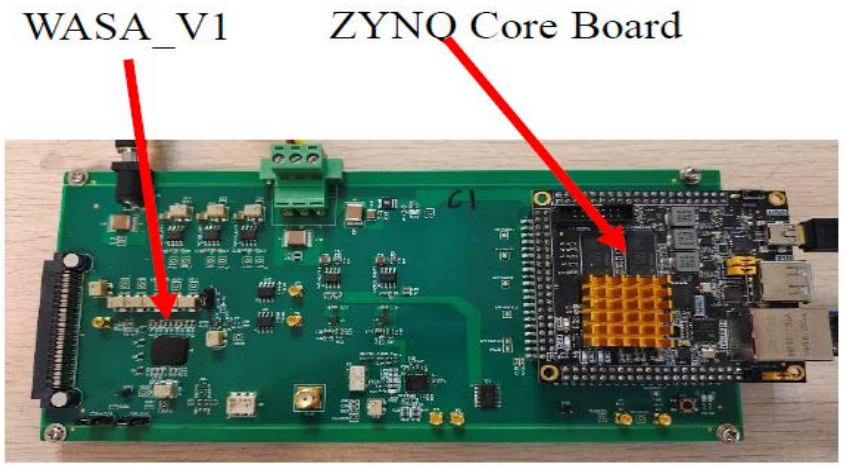
- WASA V1 has been developed: 16 channel AFE+ADC+LVDS data output
- Total power consumption **with ADC function: ~2.4 mW/ch**
- Tested with TPC detector using 128 channels at IHEP

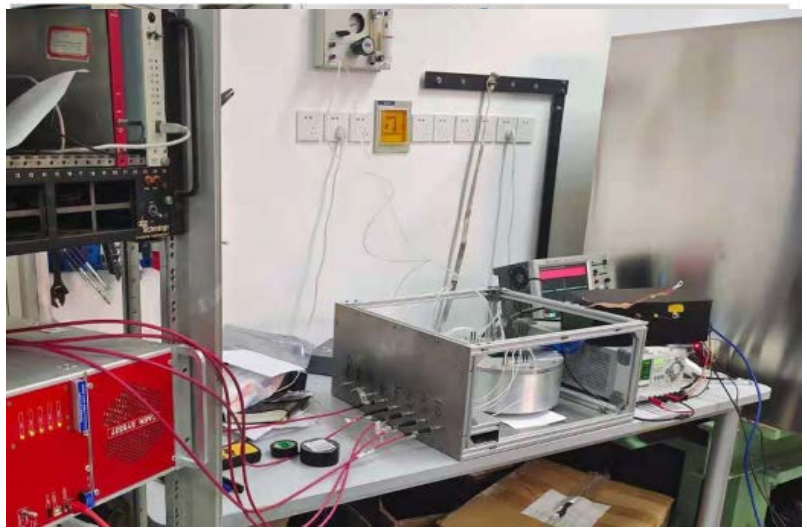
^{55}Fe testing

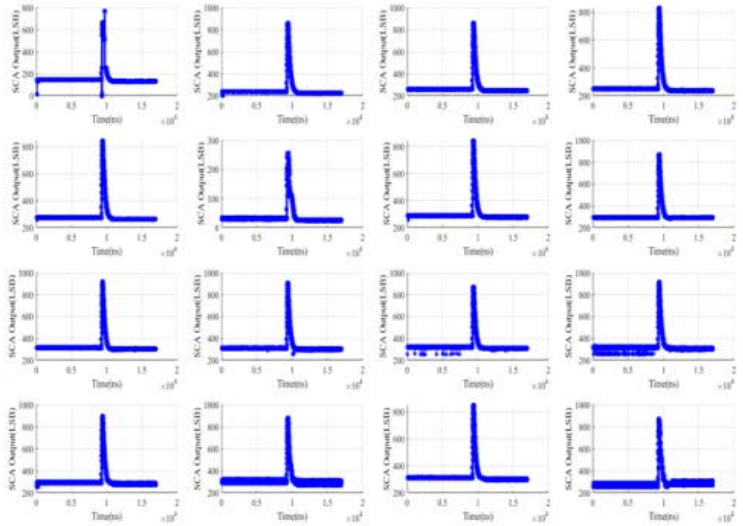
Testing parameters:

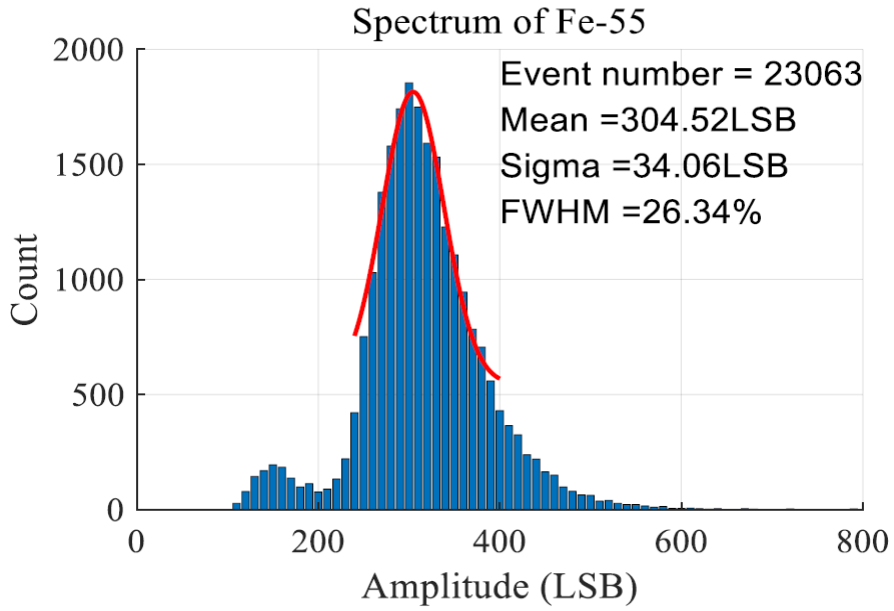
- **GEMs detector: 280V-310 V**
- **E_{drift}: ≤280 V/cm**
- **Operation gases: $Ar/CF_4/iC_4H_{10}$ 95/3/2 (T2K)**
- **Radioactive source: ^{55}Fe@ 1mCi**
- **Successfully commissioned and collected signals using DAQ**







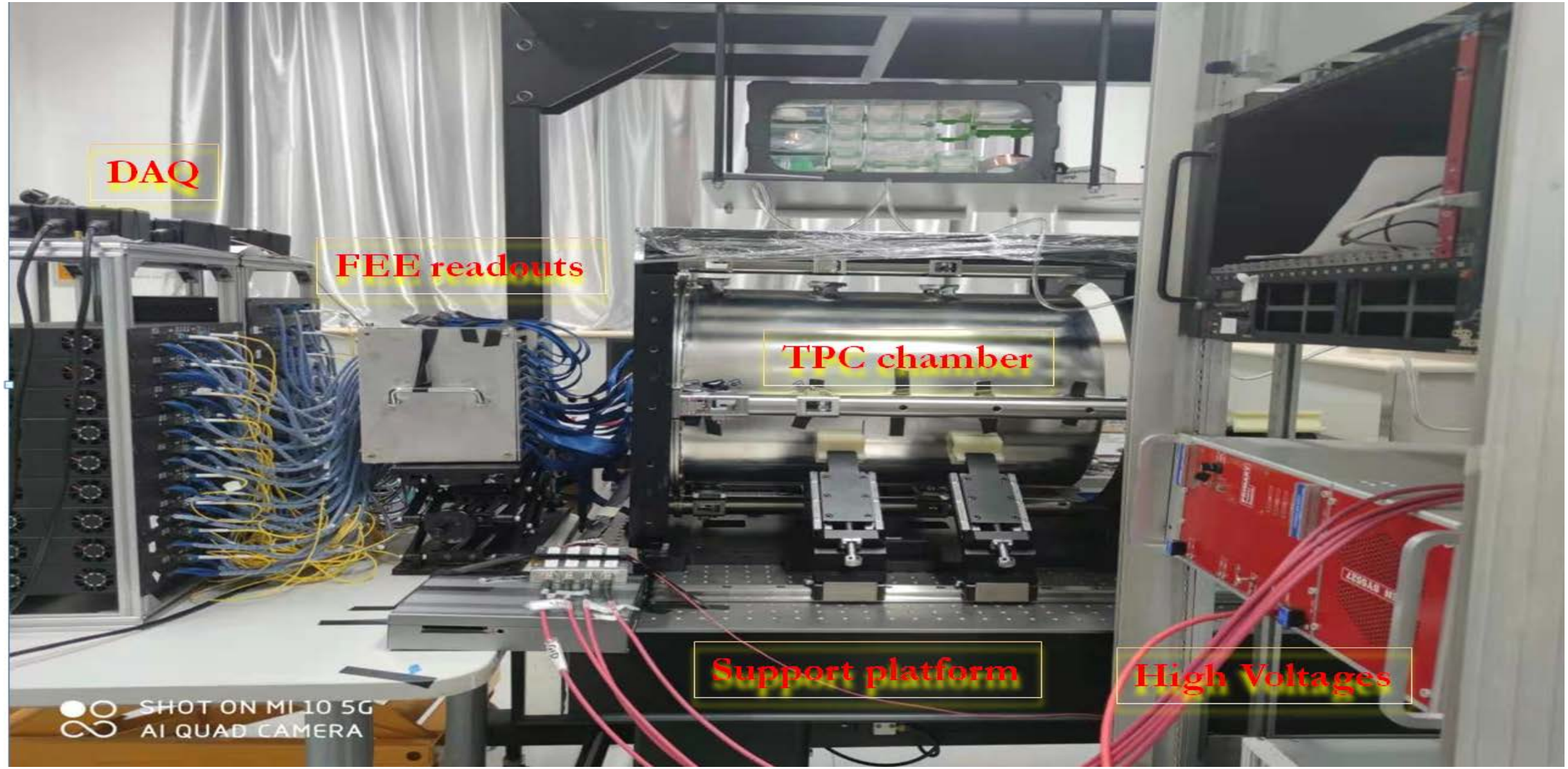




https://doi.org/10.1088/1748-0221/15/05/P05005

Development of Pad TPC prototype

- 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

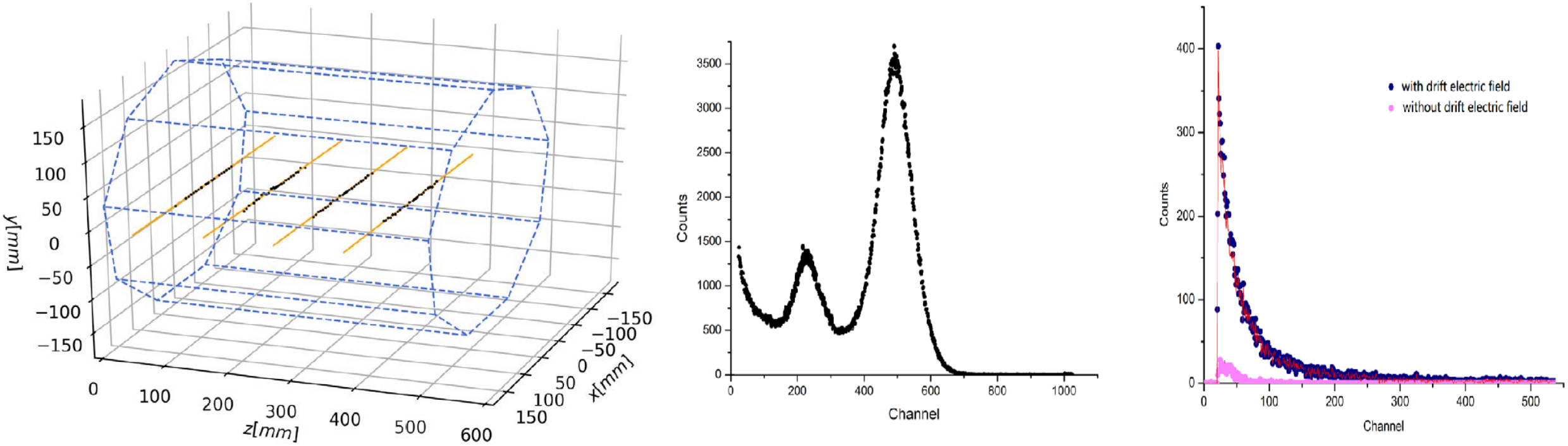


Reconstruction event and energy spectrum of ^{55}Fe/Cosmic ray

- 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.

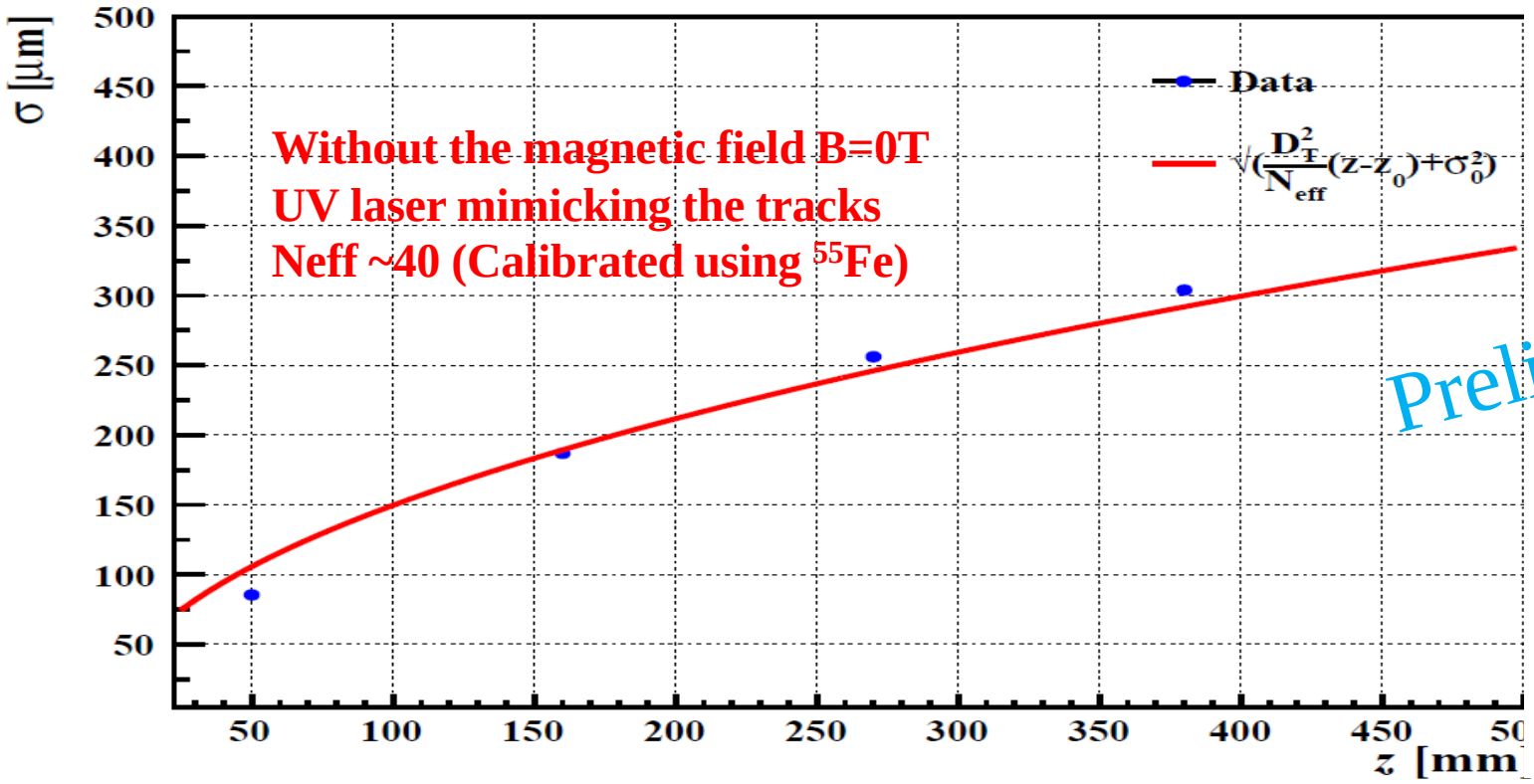
Laser energy monitor	Variation range	$E_{mean} \pm \sigma$
TPC detector	Hit ToA	layer#1 2.6 ~ 2.9 μs
		layer#2 5.7 ~ 6.0 μs
		layer#3 8.2 ~ 8.5 μs
		layer#4 10.5 ~ 11.0 μs
	Trigger pads	≥ 2 for each column
Laser and detector	The laser control chassis triggers the energy monitor and DAQ system at the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

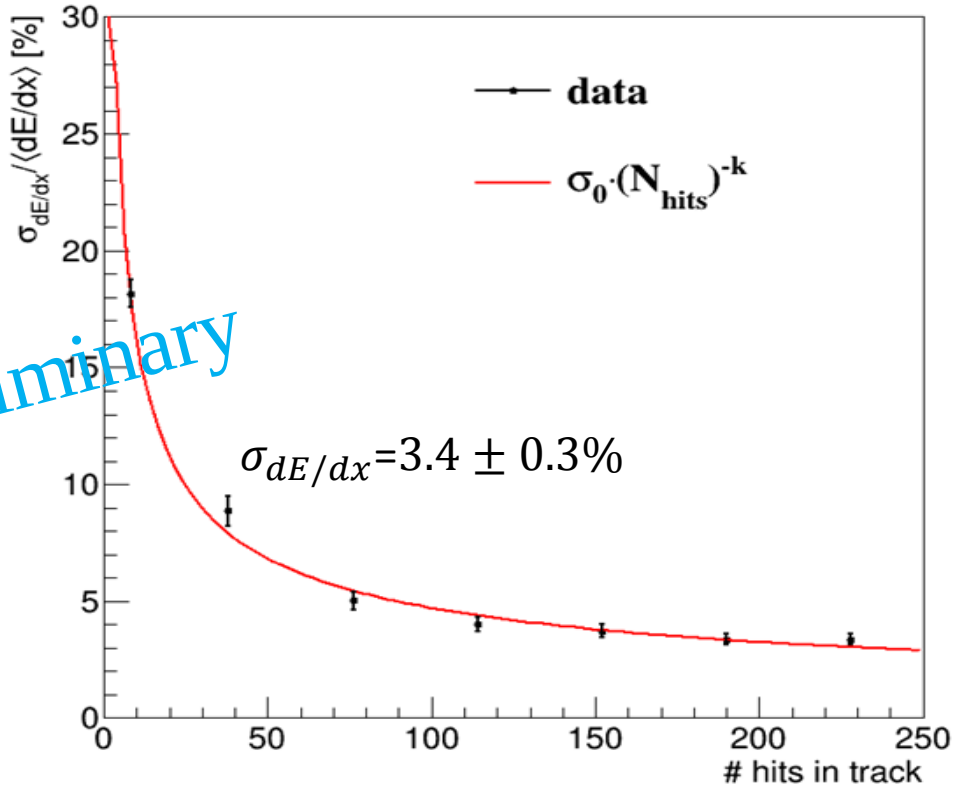


Reconstruction events and ^{55}Fe X-ray spectrum profile(middle) and cosmic ray spectrum(Right)

Pad TPC prototype with 266nm UV laser tracks

- The TPC prototype integrated 266nm UV laser tracks has successfully developed.
- Analysis of UV laser signal, the spatial resolution, dE/dx resolution
  - 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 ± 0.3%



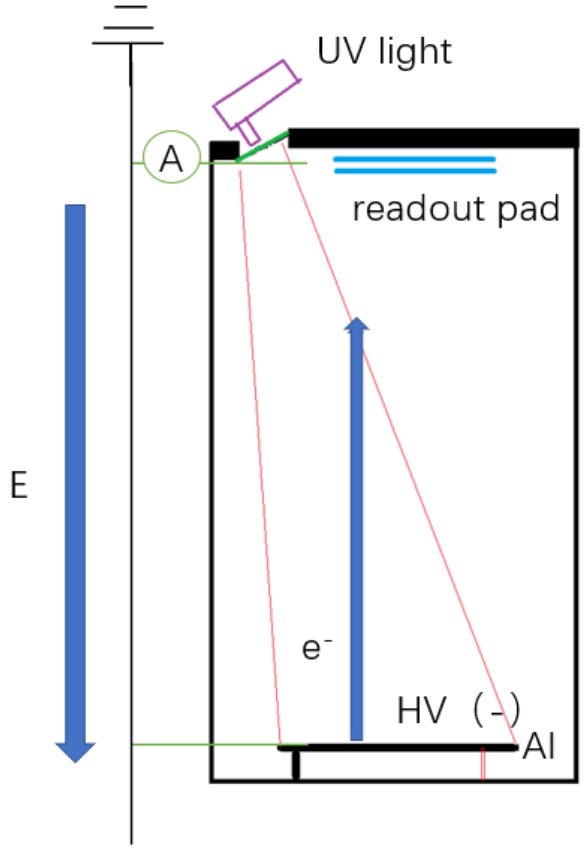


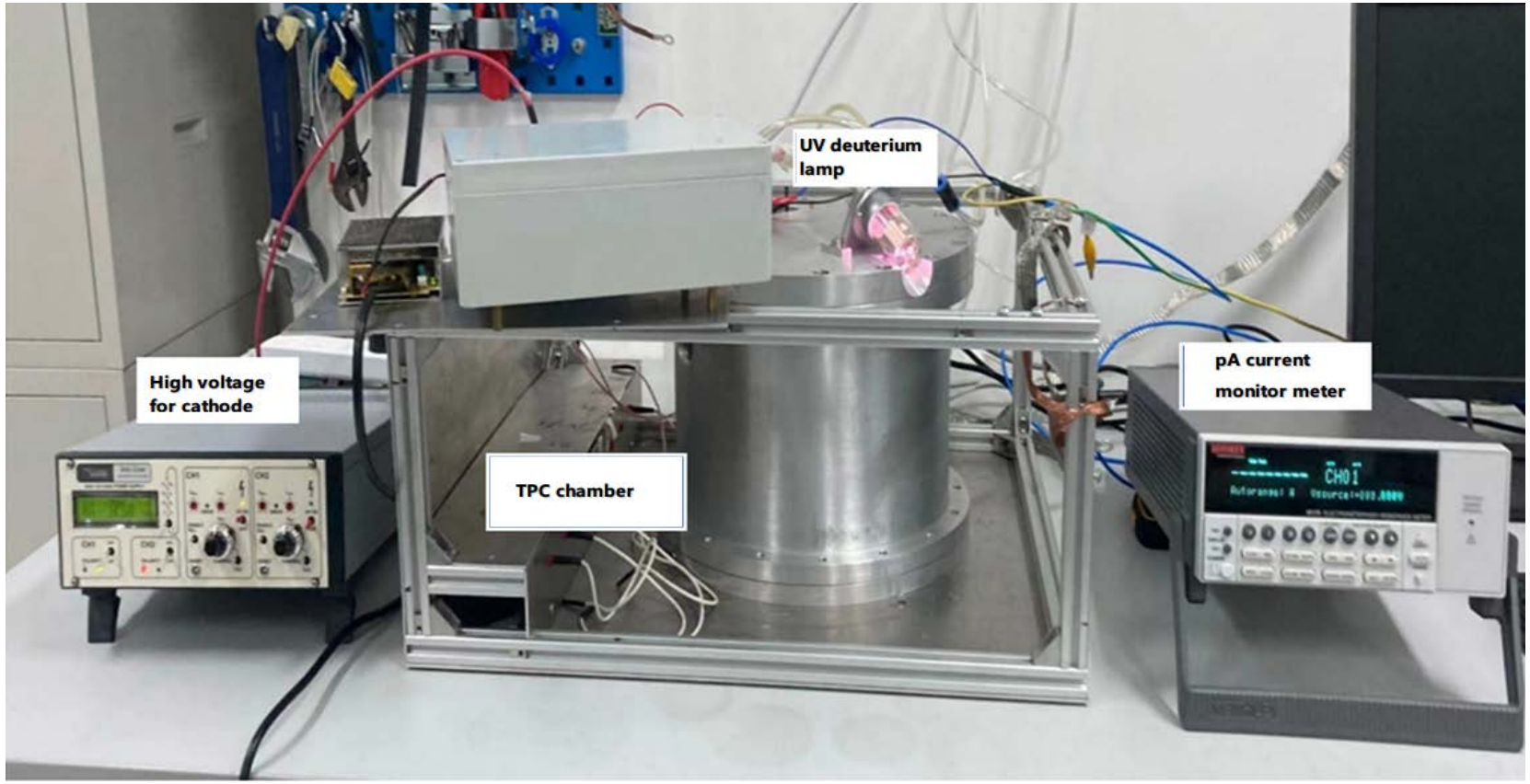
https://doi.org/10.1016/j.nima.2022.167241

Testing the UV light created the massive electrons by photoelectric effect

UV light created the massive primary electrons

- Ions will fill in the drift chamber of TPC to mimic the ions distortion
- **Metal mesh polished Aluminum**: 600/800/1000/1200/1400/2000 (**LPI: Linear Pair)**
- Experimental testing of the current at record detector layers

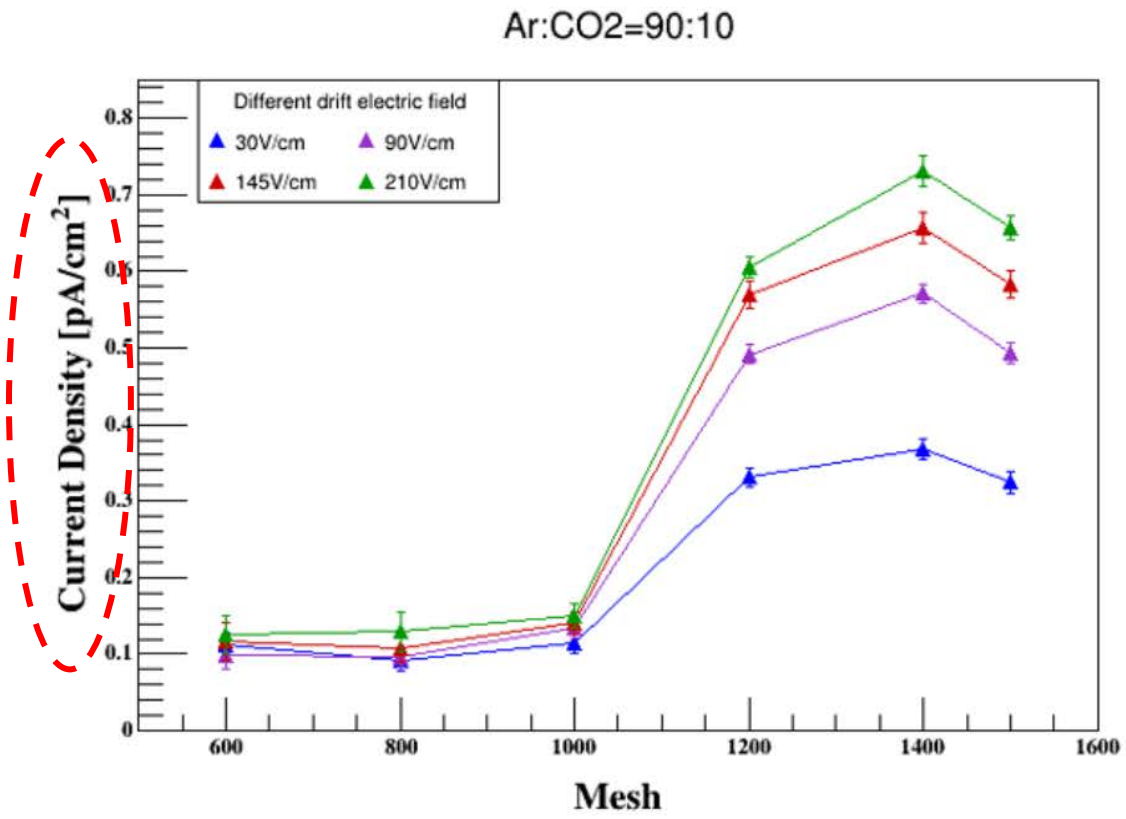


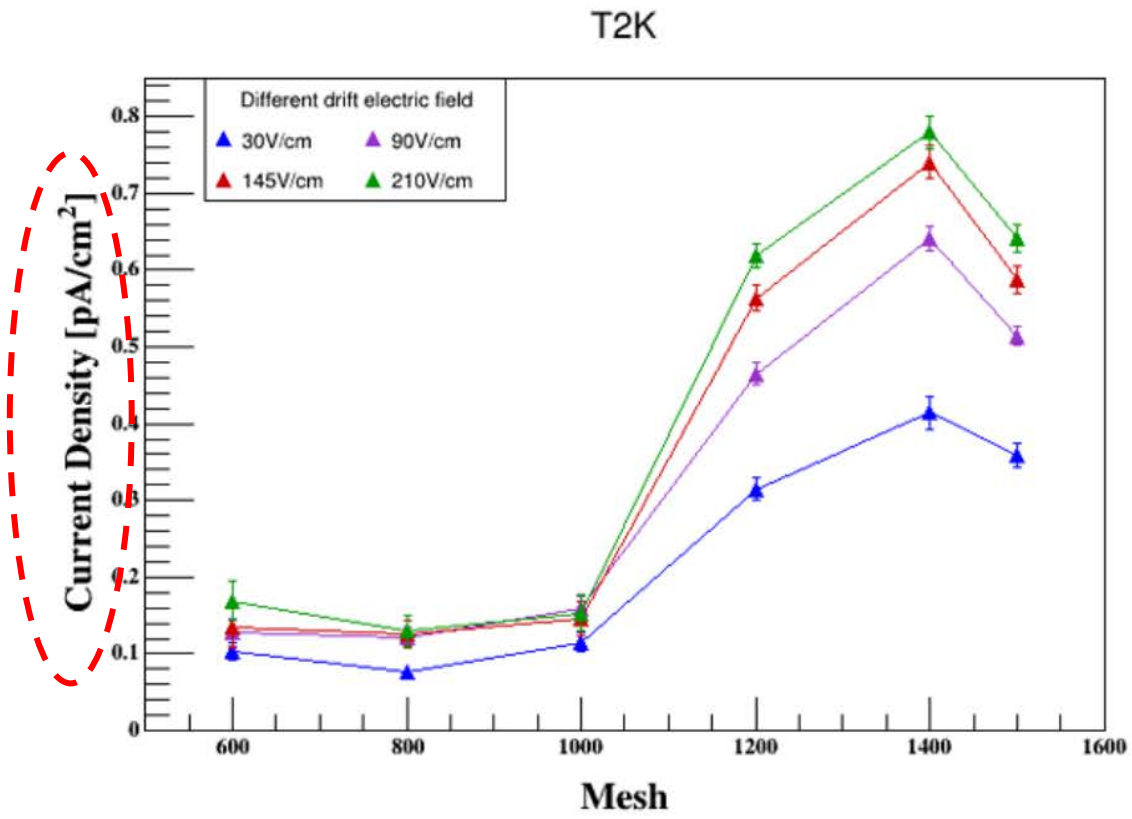


Concept and photo of the experimental study using UV deuterium lamp

Testing the UV light created the massive electrons by photoelectric effect

- The different LPI Aluminum's surface tested the stable current
- The maximum current reached at 1400LPI Aluminum's surface (**Very stable**)
- Detector has been studied under the two different mixture gases
  - Very similar trends **from 30V/cm to 210V/cm (Electric field of drift)**
- The novel method **can meet to study the current** of the electrons using the prototype (**Max.~1pA/cm^2**)





- Towards pixelated readout TPC technology

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
  - Progress presentaion will be prepared soon

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Guang Zhao,
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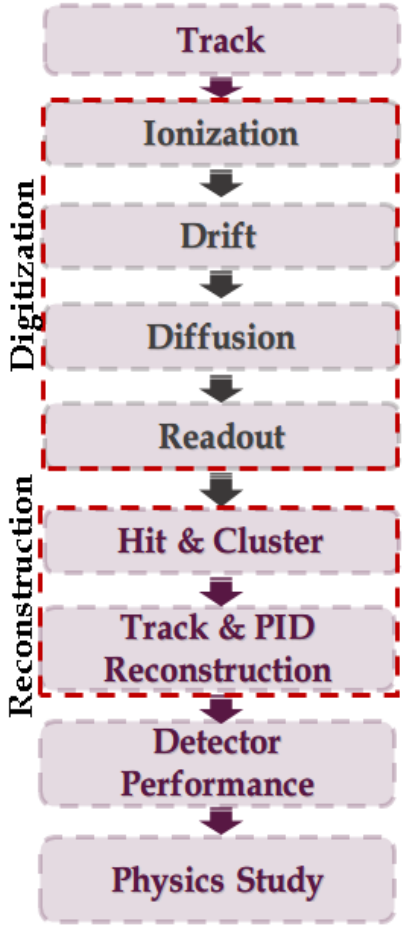
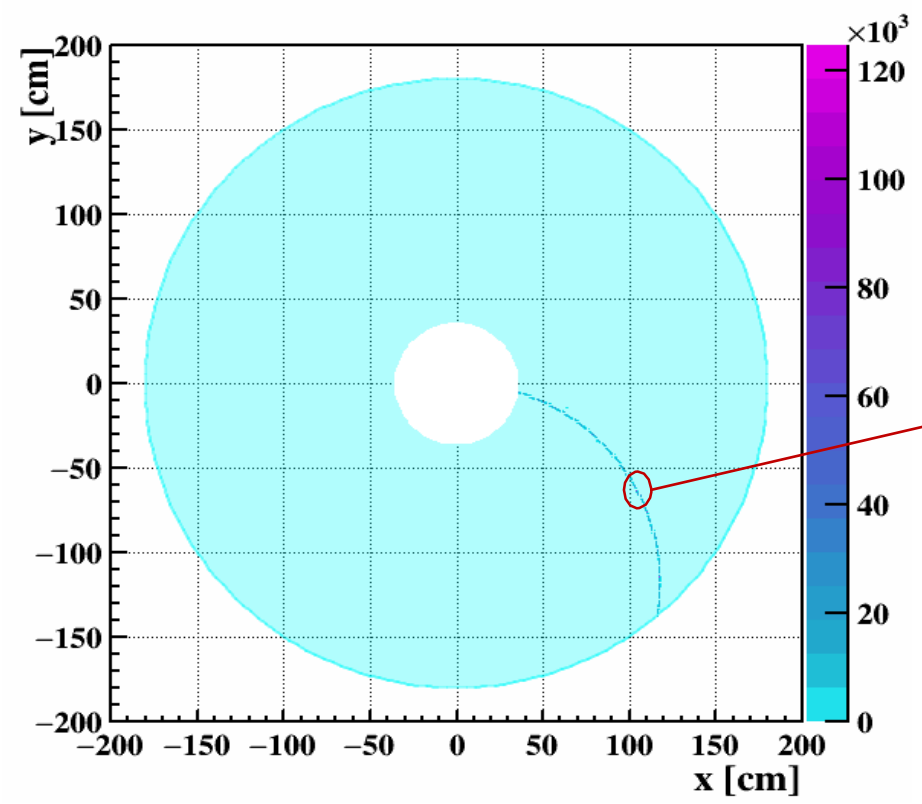
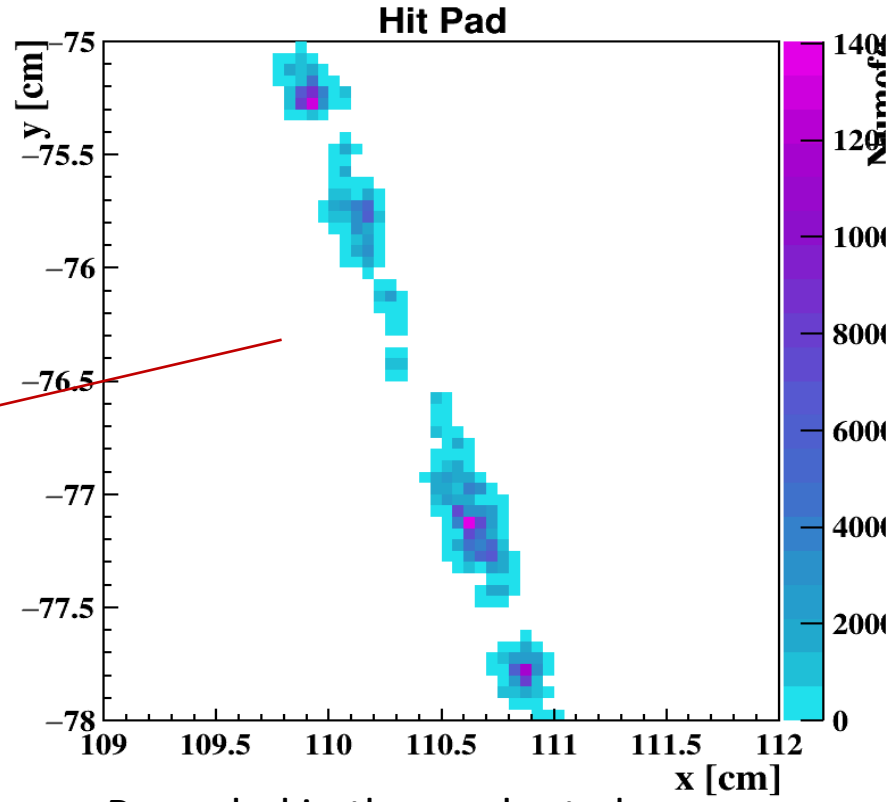






Recorded in the readout plane:
Drift distance = 150mm
Pixel size: 500μm×500 μm

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
  - For full coverage one needs 80 000 chips
  - With the current TPX3 chip one reaches about 60% coverage
  - For the pixel TPC the total power is 160 kW (so 80 kW per endcap)

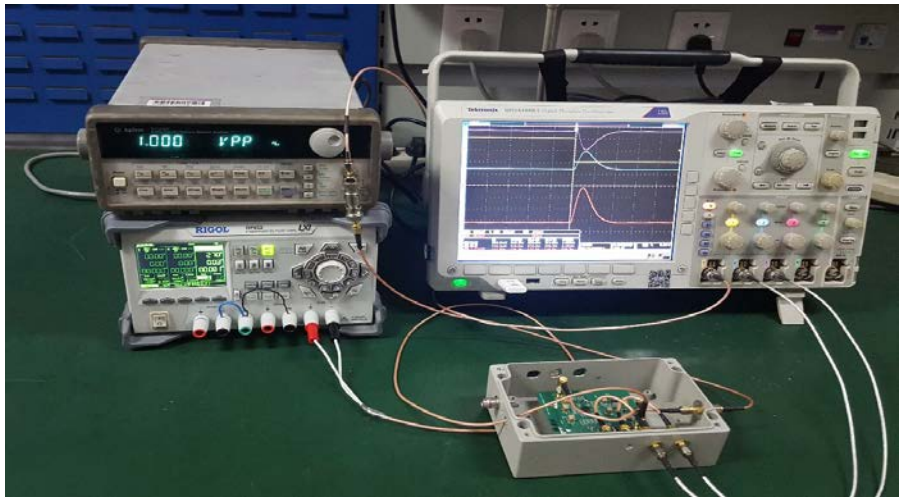
- Low power consumption **is the first requirement** for the pixelated TPC technology to LCTPC
  - TPX3 Gridpixes in low power mode reduces the power consumption for a pixel TPC to **8 kW per endcap** at the cost of a worse time resolution.

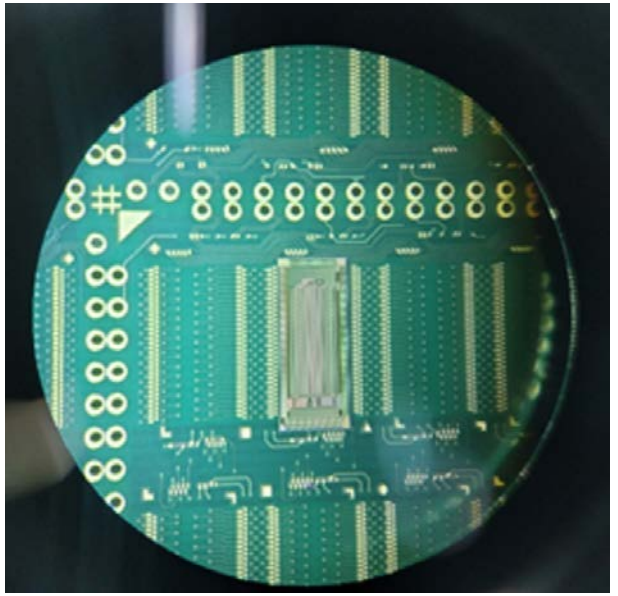
- Ref1 https://iopscience.iop.org/article/10.1088/1748-0221/14/01/C01024
- Ref2 https://iopscience.iop.org/article/10.1088/1748-0221/14/01/C01001

Current R&D effort: 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

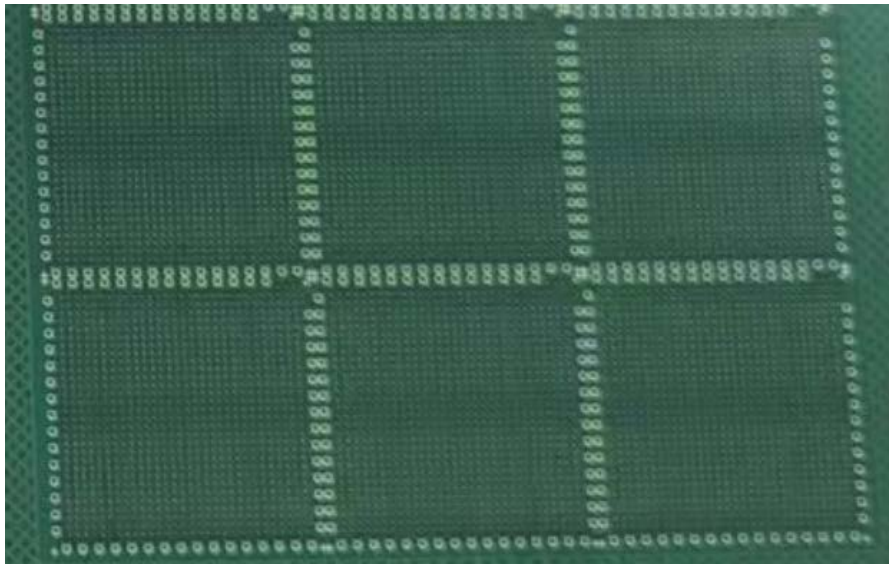




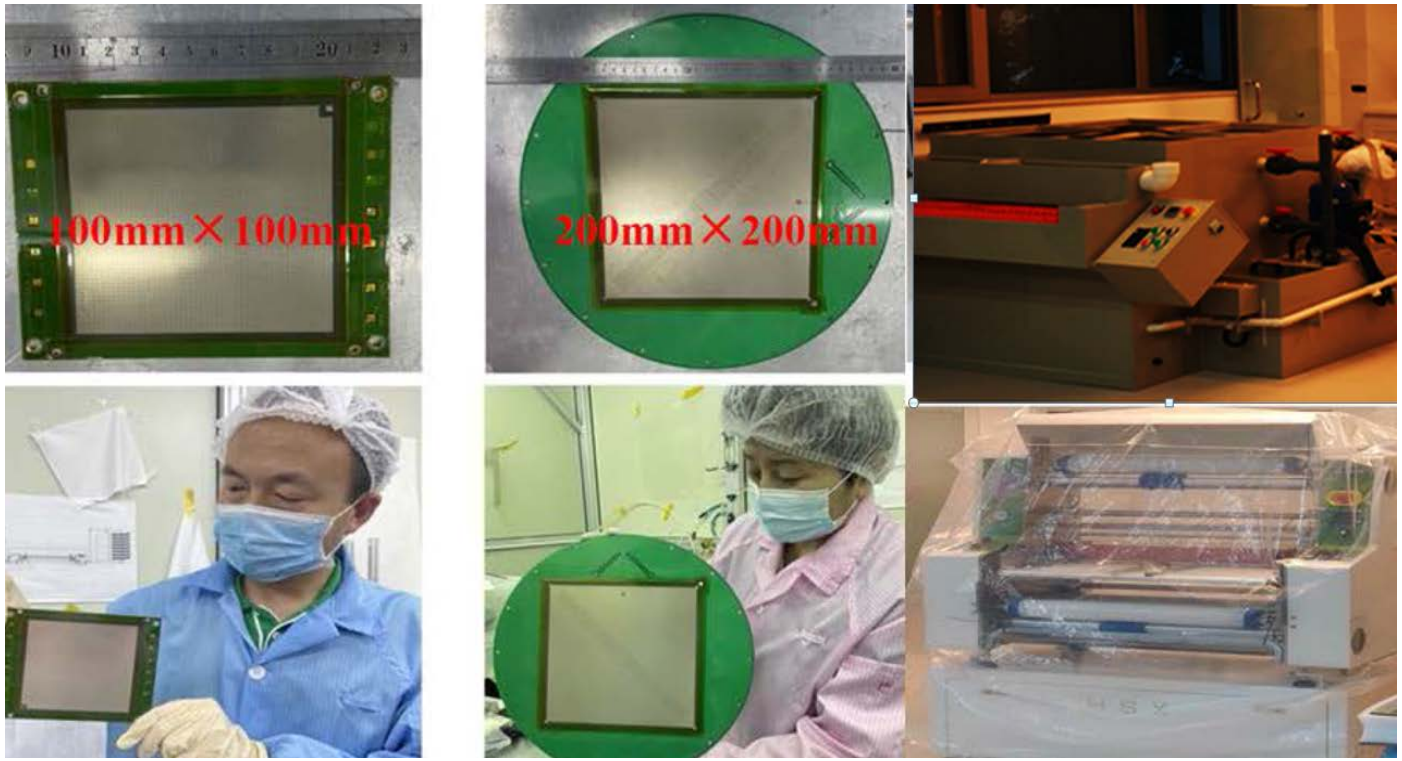
1st readout PCB board and the ASIC layout

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

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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