Pixelated Readout TPC Technology R&D for future Circular e+e- Collider

Huirong Qi
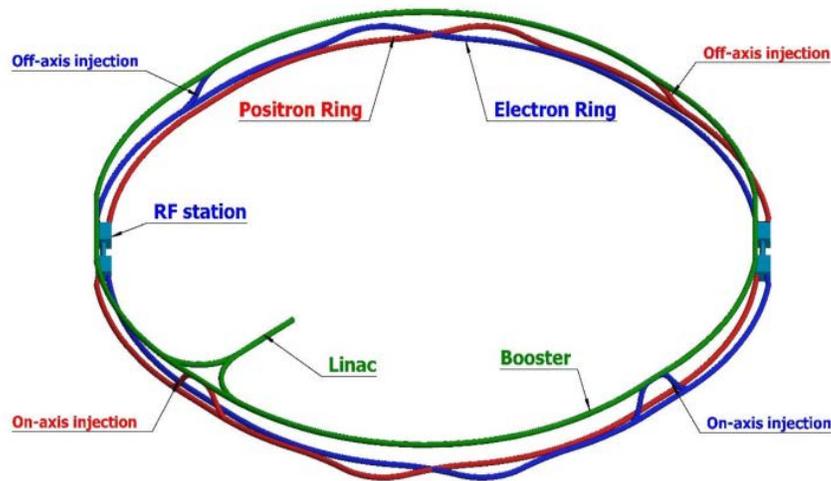
On behalf of the CEPC gaseous tracker R&D group

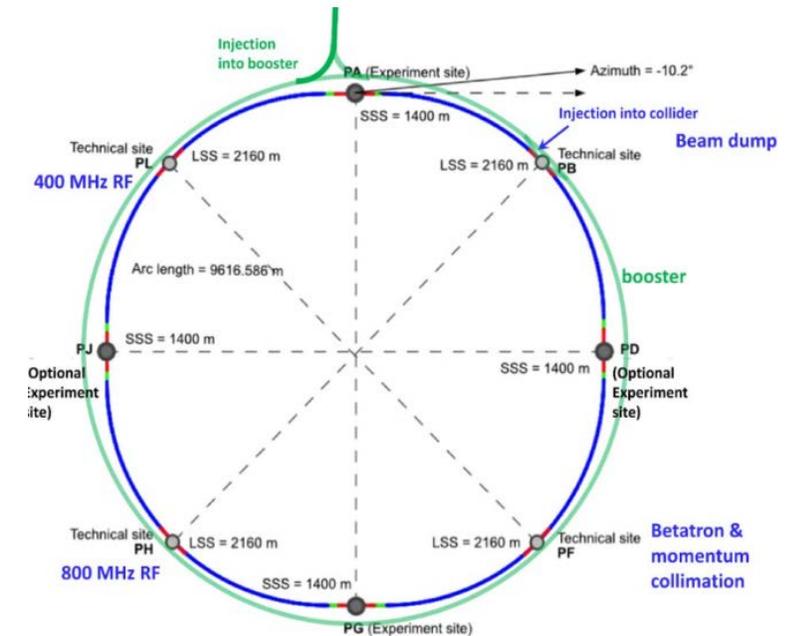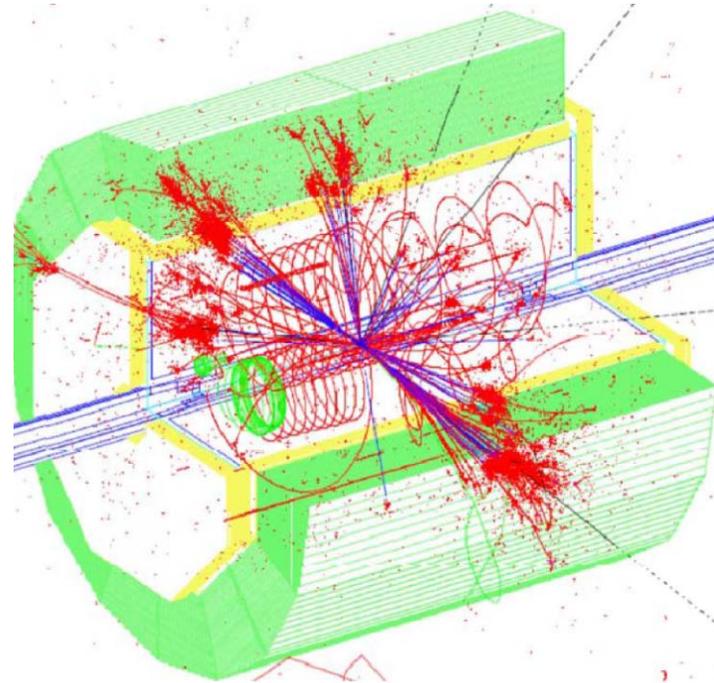**and some inputs from LCTPC international collaboration**

- **Motivation and physics requirements**

- **Status of TPC in CEPC and LCTPC**

- **Pixelated readout TPC for Higgs and Z**

- **Work plan and Summary**

- 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)
- Pixelated readout TPC can improve **PID requirements of Flavor Physics at e+e- collider**.

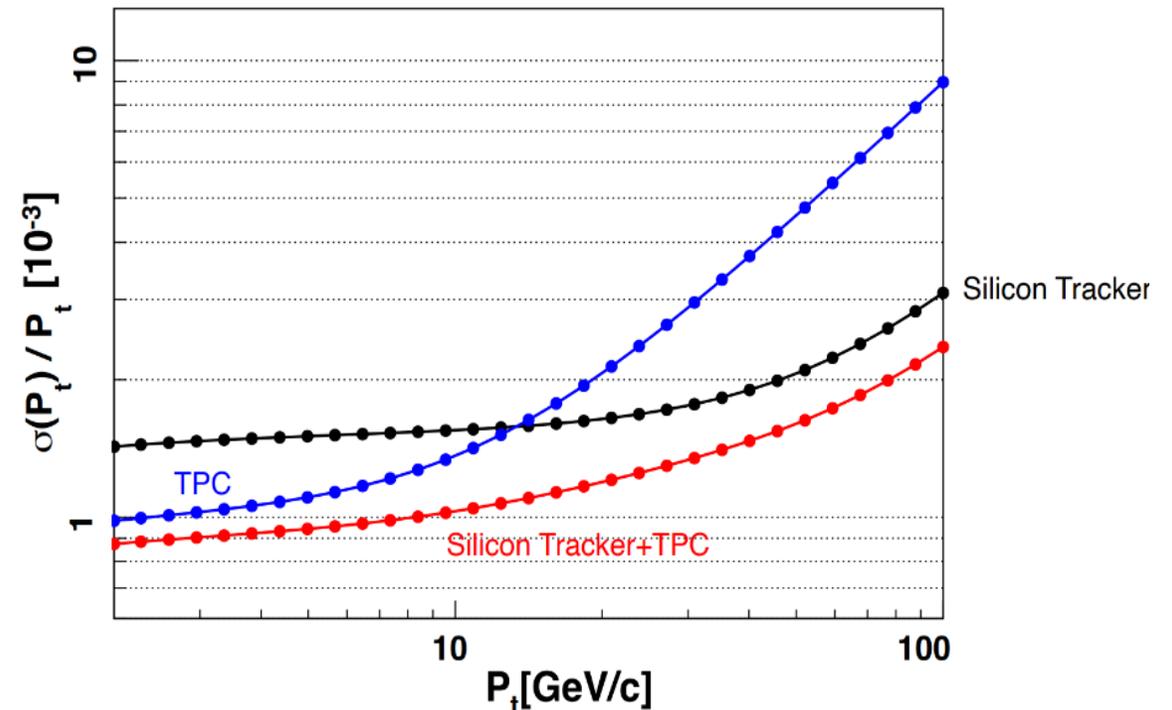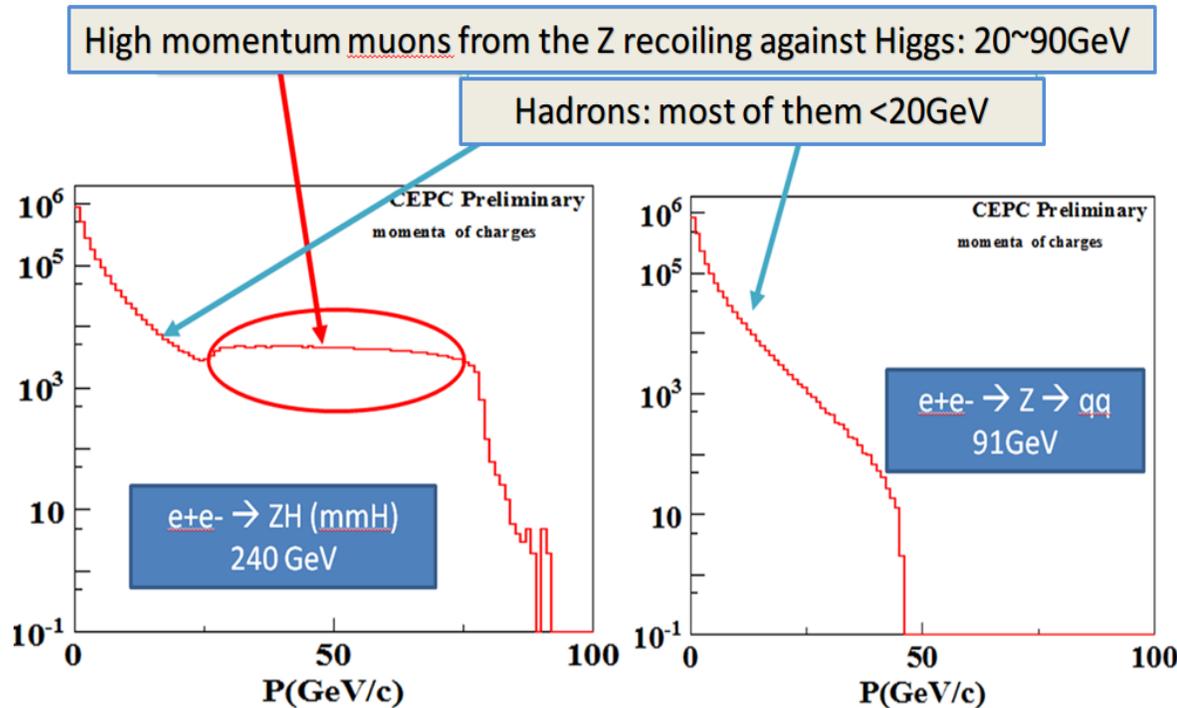**Circular Electron Positron Collider (CEPC)**

Future Circular Collider (FCCee)

https://arxiv.org/abs/1811.10545

https://arxiv.org/abs/2203.08310

- Circular e+e- collider operation stages in TDR: **10-years Higgs @3T → 2-years Z pole → 1-year W**

- Physics Requirements of the tracker
    - High momentum resolution for Higgs and Z
    - PID for the flavor physics and jet substructure

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

High momentum muons from the Z recoiling against Higgs: 20~90GeV

Hadrons: most of them <20GeV

https://doi.org/10.1140/epjc/s10052-018-5876-z
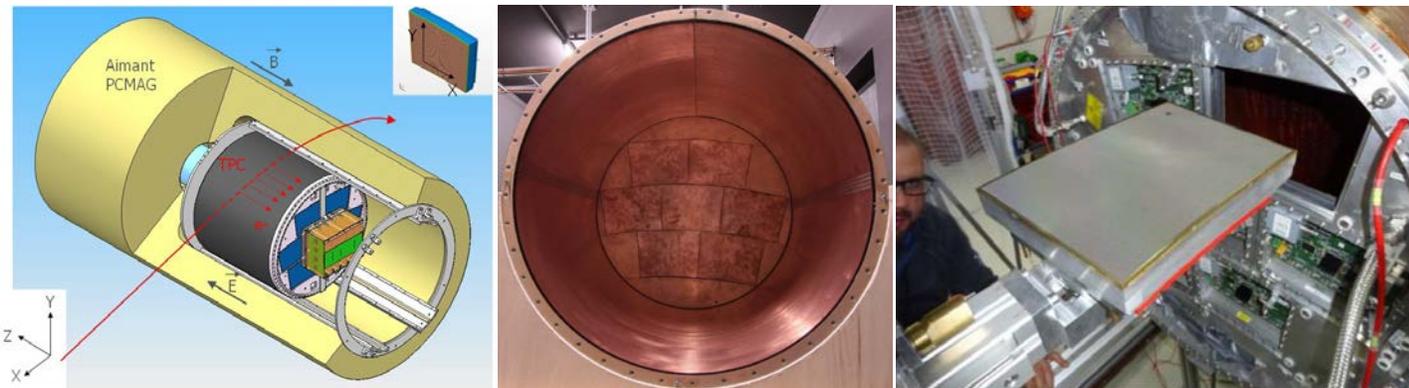
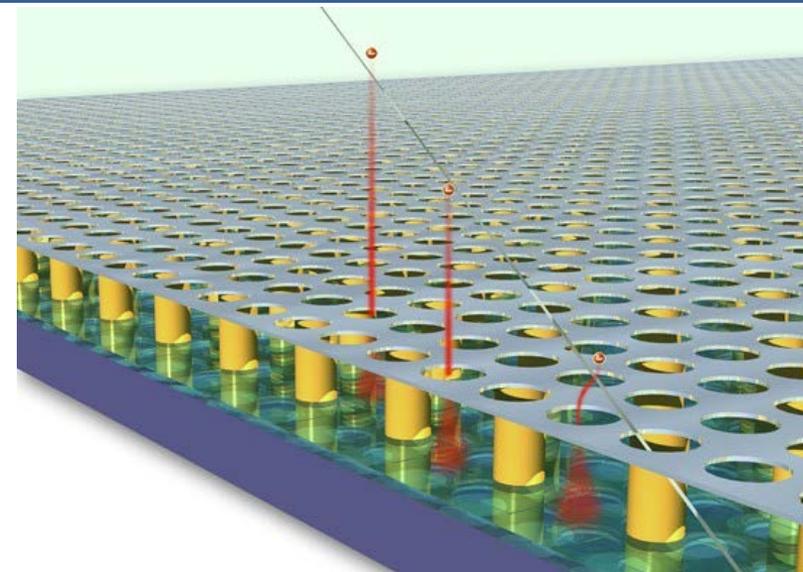- **Status of TPC in CEPC and LCTPC**

- **Large Prototype** setup has been built to compare different detector readouts under identical conditions and to address integration issues.
  - PCMAG: B < 1.2T, bore Ø: 85cm
  - Two end plates for the LP made from Al with 7 module window
- **LP Field Cage Parameter**
  - Length = 61cm, inner Ø = 72cm drift field up to E ≈ 350V/cm
  - Made of composite materials: 1.24 % X_0

JINST 5: P10011, 2010
JINST 16: P10023, 2021

https://doi.org/10.48550/arXiv.2006.08562
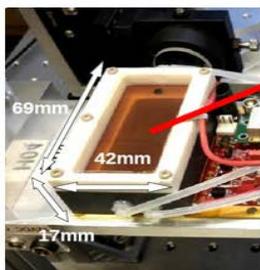
- GridPix detector have moved from Timepix to Timepix3 ASICs. Tests with quad devices have been successfully done under B=1.0T at DESY in 2021 and 2022.
- Very high detection efficiency results in **excellent tracking and dE/dx performance.** Timepix4 development is ongoing.
  - All results showed that **a pixel TPC is realistic.(**~10^6 events **)**
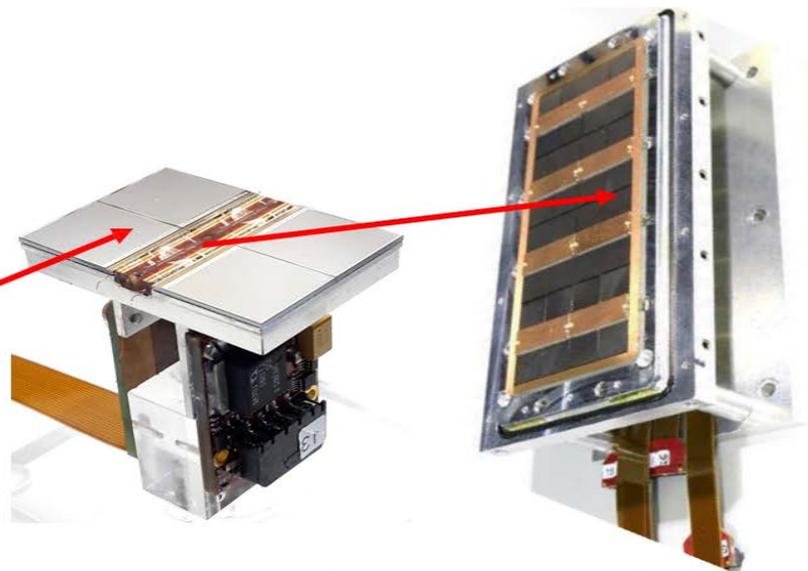

NÌM A535 (2004) 506-510
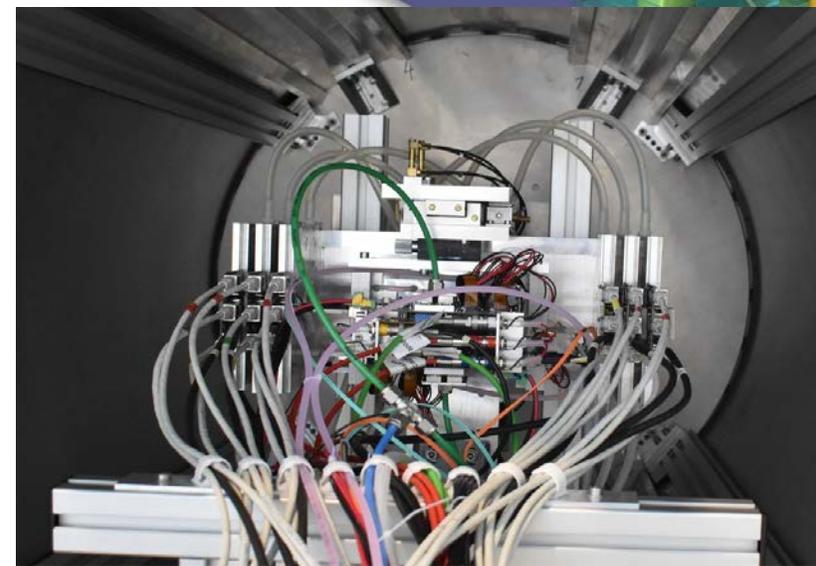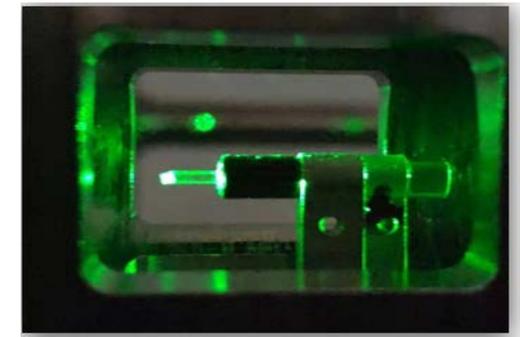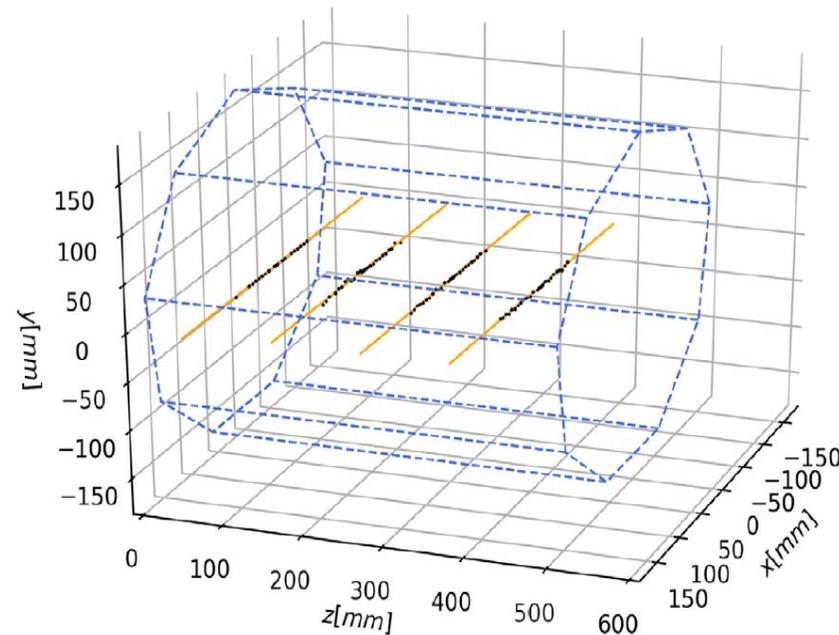NIM A845 (2017) 233-235

CEPCTPC prototype R&D efforts and results
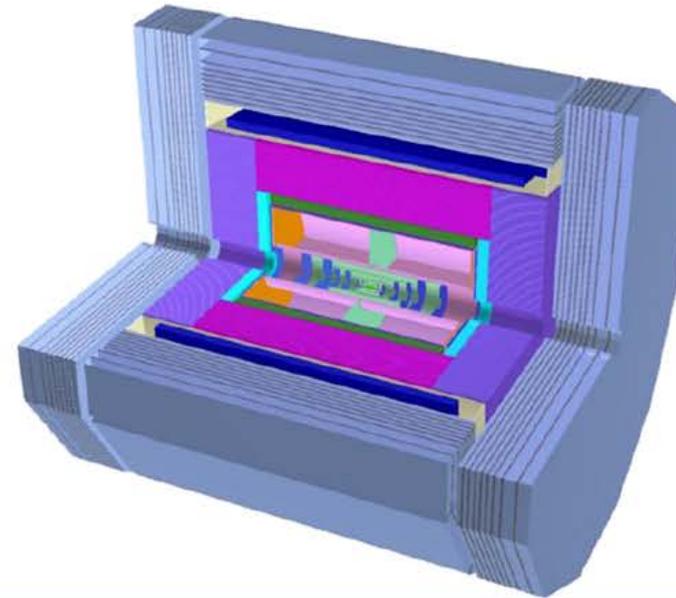
- **CEPC TPC detector prototyping roadmap:**
  - From TPC module to TPC prototype R&D for Higgs and Tera-Z
- **Achievement so far:**
  - **IBF×Gain ~1 @ G=2000** validation with a hybrid TPC module
  - Spatial resolution of $\sigma_{r\varphi} \leq 100$ **µm and dE/dx resolution of 3.6%**
  - FEE chip: reach ~**3.0mW/ch with ADC** and the pixelated readout R&D

- From January 2024, the CEPC community initiated the technical comparison and selection, balancing factors including **R&D efforts, detector performance, cost, power consumption and construction risks**.

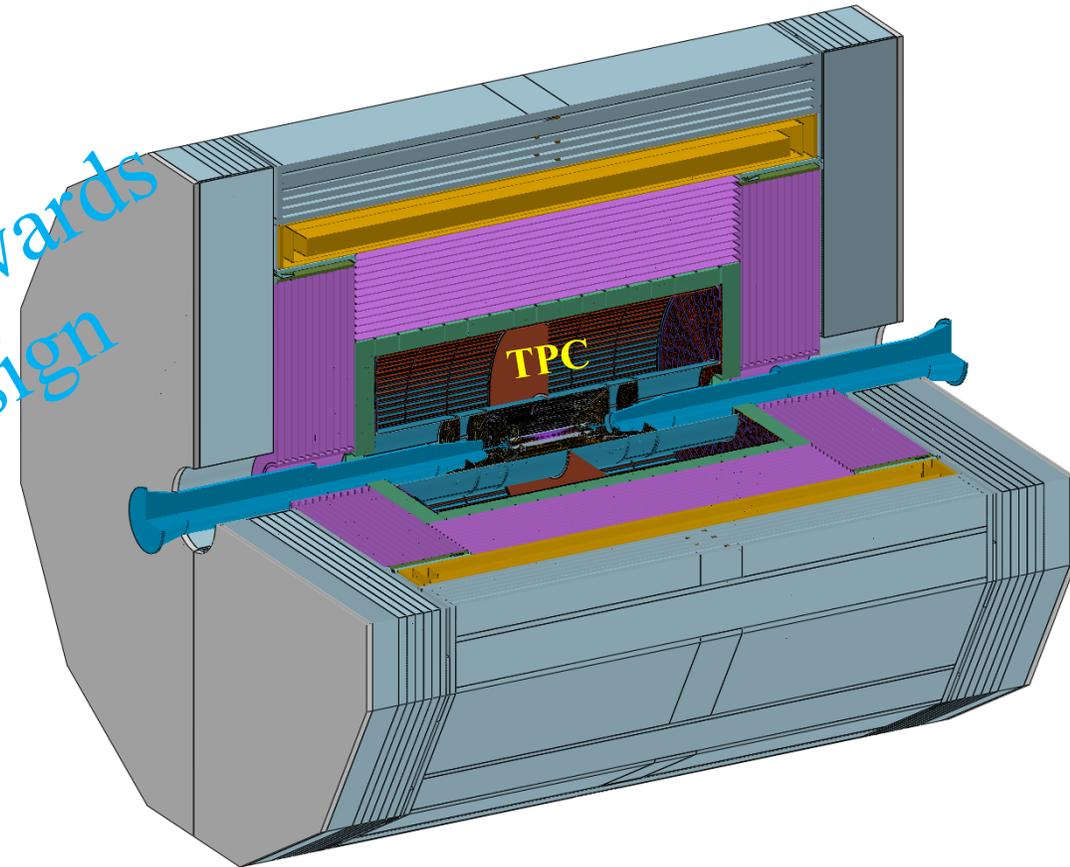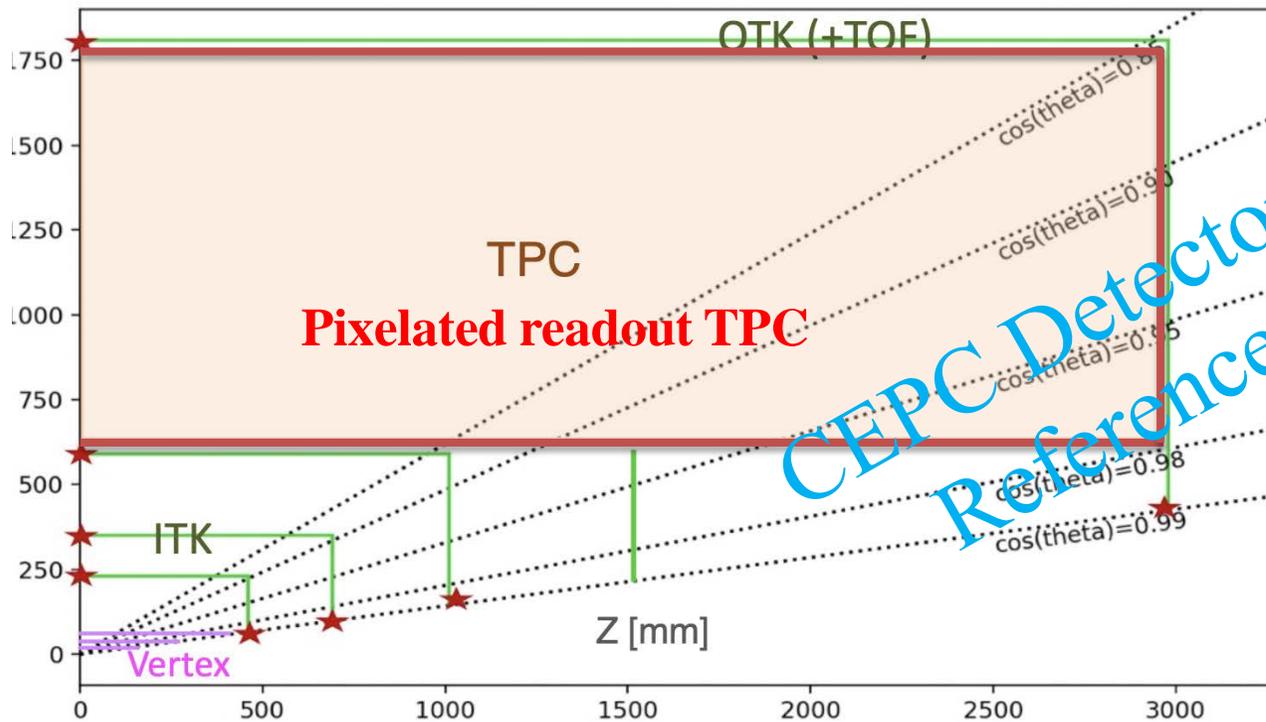| System	Technologies	
	Baseline	For comparison
Beam pipe	Φ20 mm	
LumiCal	SiTrk+Crystal	
Vertex	CMOS+Stitching	CMOS Pixel
Tracker	CMOS SiDet ITrk	
	Pixelated TPC	PID Drift Chamber
	AC-LGAD OTrk	SSD / SPD OTrk
		LGAD ToF
ECAL	4D Crystal Bar	PS+SiPM+W, GS+SiPM, etc
HCAL	GS+SiPM+Fe	PS+SiPM+Fe, etc
Magnet	LTS	HTS
Muon	PS bar+SiPM	RPC
TDAQ	Conventional	Software Trigger
BE electr.	Common	Independent

Foundations:
- CEPC Instrumentation R&D
- LHC detector upgrade projects
- other HEP experiments
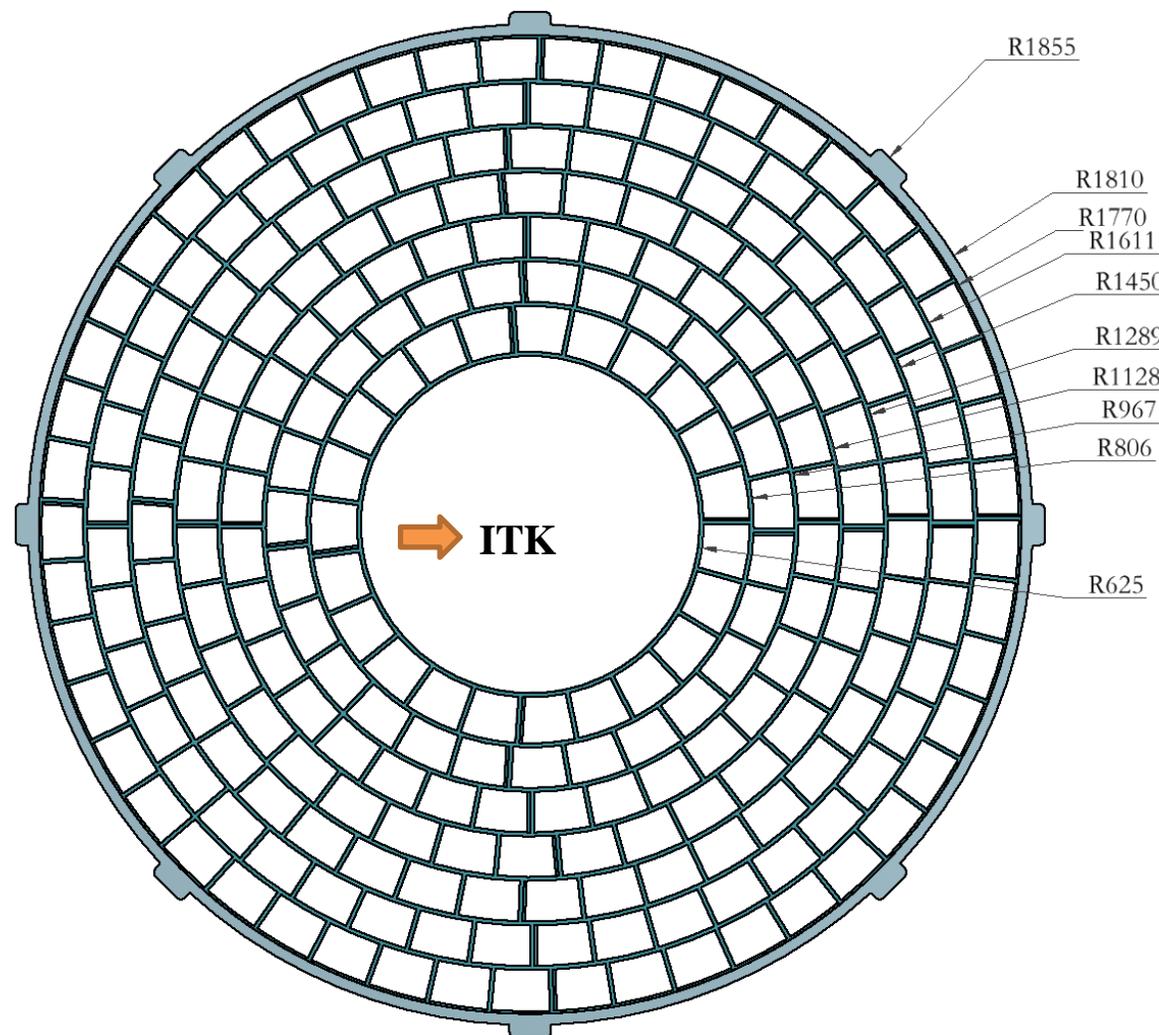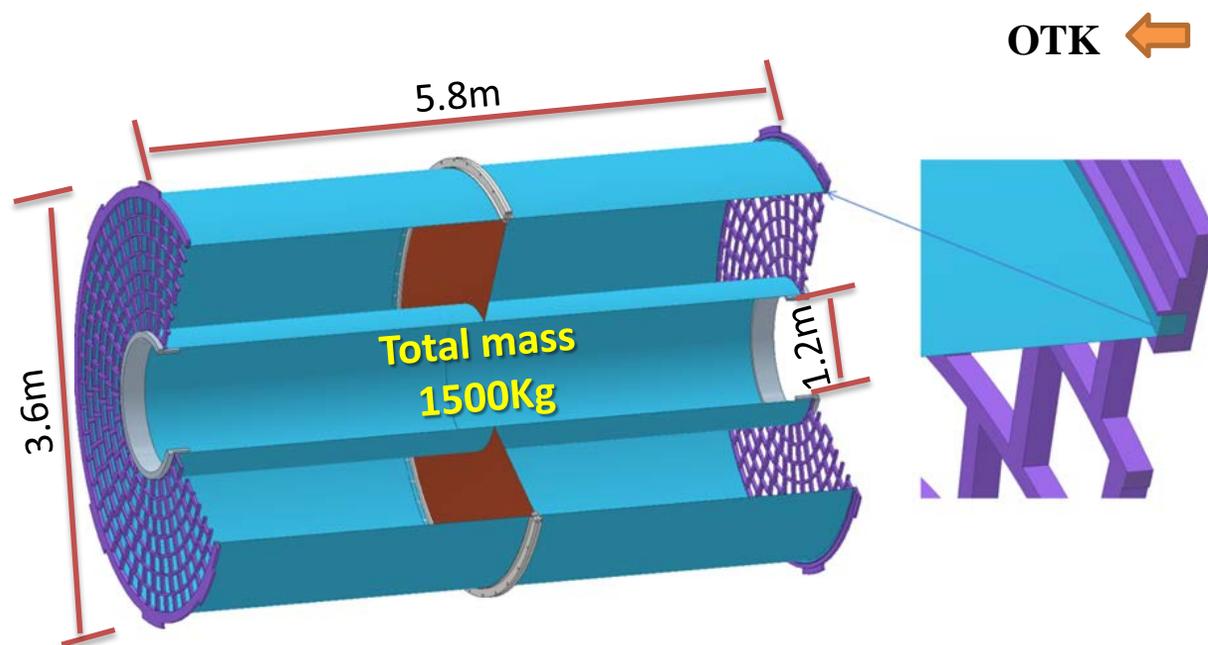- progress in HEP worldwide R&D
- development in industry

- Tracking system: Silicon combined with gaseous chamber for the tracking and PID
  - Pixelated readout TPC as the **baseline gaseous detector** in the CEPC ref-TDR
    - Radius of TPC from 0.6m to 1.8m

Geometry of the tracking detector system of the CEPC TDR

TPC detector	Key Parameters
Modules per endcap	248 modules /endcap
Module size	206mm×224mm×161mm
Geometry of layout	Inner: 1.2m Outer: 3.6m Length: 5.9m
Potential at cathode	- 62,000 V
Gas mixture	T2K: Ar/CF4/iC4H10=95/3/2
Maximum drift time	34µs @ 2.75m
Detector modules	Pixelated Micromegas

OTK

ITK

5.8m

3.6m

1.2m

Total mass 1500Kg
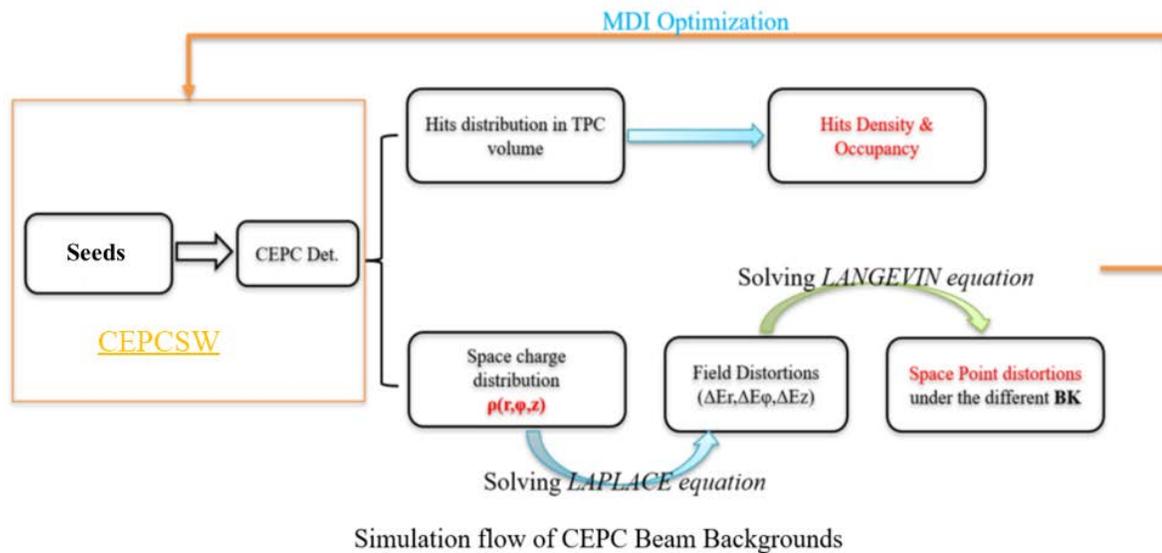
R1855
R1810
R1770
R1611
R1450
R1289
R1128
R967
R806
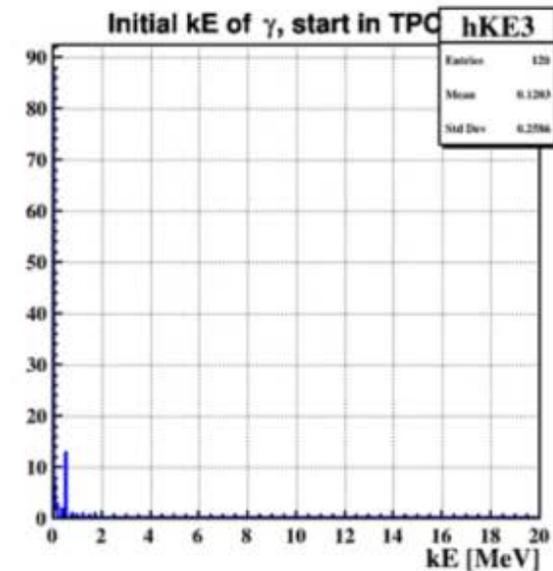R625

Detailed design of TPC detector in ref-TDR

- **Pixelated readout TPC R&D for Higgs and Z**
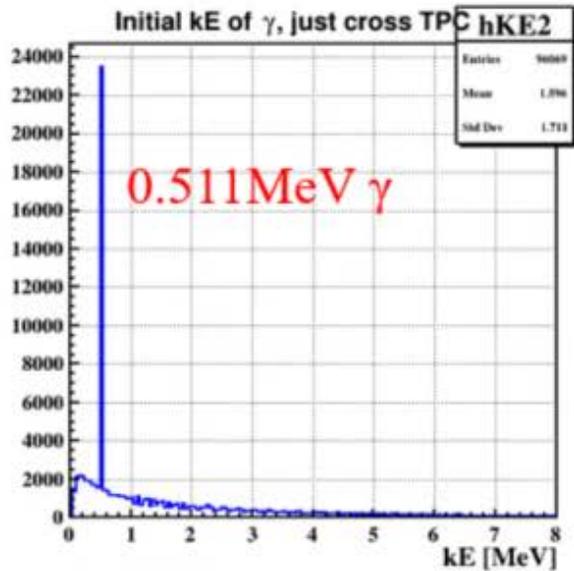
- Space charge in TPC chamber
  - Physics events: H→ss/cc/sb, Z→qq...(High P_T)
- Higgs/Z background sources
  - I. Pair production (Luminosity related)
  - II. Single Beam (BGB, BGH,Touschek Scatter...)
  - III. Synchrotron Radiation
  - IV. Injection background
- Simulation framework

~100 ionizations/cm in Ar gas

HV Plane | T2K gas | Endcap
Primary ion | Electron
High P_T charge particle | Recoil particle (<1Gev/c)
IP | Low P_T e+/e- | Some Material
IBF

2.9m drift length
~0.04ms (for electron)
~0.58s (for ion)

MDI Optimization

Seeds → CEPC Det. → Hits distribution in TPC volume → Hits Density & Occupancy

CEPCSW

Space charge distribution ρ(r,φ,z) → Field Distortions (ΔEr,ΔEφ,ΔEz) → Space Point distortions under the different BK

Solving *LANGEVIN* equation
Solving *LAPLACE* equation

Simulation flow of CEPC Beam Backgrounds

SR ∝ $E^2 B$
A. Natochii
Pair Production
Photon BG

Beam-Thermal photon Scattering
Beam Lost Particles Energy Loss > 1.6% (energy acceptance @Higgs)
Radiative Bhabha Scattering
Beamstrahlung
Beam-Gas Brem Scattering
e+e- Pairs
468 bunches
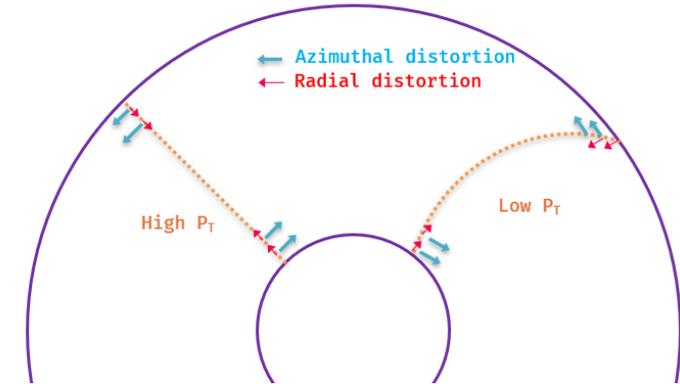1.3 × 10^11 particles/bunch
L: 8.3 × 10^34 cm^-2 s^-1

Beam Loss BG

- **γ energy distribution (10BX WholeLZ241204 log)**
  - 1.2e+7 tracks (γ,e-,e+...) in total
  - 8.4e+6 γ tracks (~70.0%)
  - 9.9e+4 γ will cross TPC and ~2454 γ will interact with T2K gas through "compt, phot, conv" process, 96096 γ just cross TPC without energy deposit
  - ~1.3% γ energy > 10 MeV
  - Large number of 0.511 MeV γ (through e+ annihilation)
  - Average energy deposit: 27.12 MeV/BX by sum all secondary e- dE, small less than the result from .root file (32.3 MeV/BX)
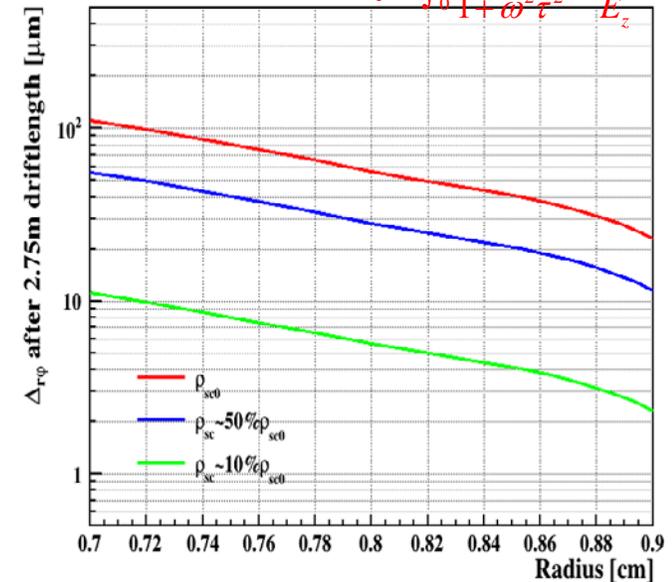 - **So, low energy γ is the main contributions of beam background for TPC, similar to Higgs mode.**
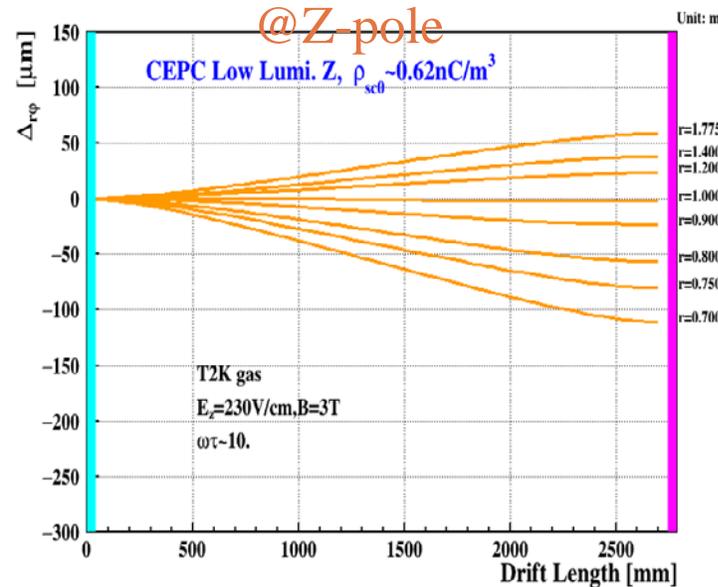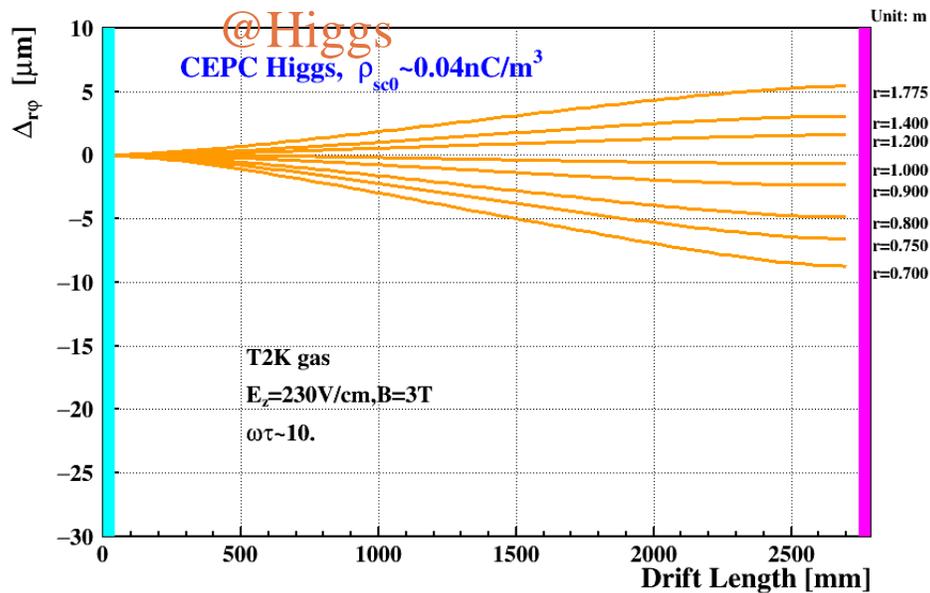
TPC distortion caused by primary ions

- Radial distortion (Δ_r) is much smaller than azimuthal distortion, almost imperceptible when along the track for most P_T track   **IBF×Gain=1, same primary ion level**

  - Azimuthal distortion ($\Delta_{r\varphi}$) has much serous impact both on high/low P_T tracks
  - The maximum $\Delta_{r\varphi}$ is $10\mu m$@Higgs (**acceptable**)
  - The maximum $\Delta_{r\varphi}$ can be reduced to $<100\mu m$@Z-pole (**optimization of MDI**)
    - Including Pair + Single Beam

$$\Delta_{r\varphi} = \int_0^L \frac{\omega\tau}{1+\omega^2\tau^2} \times \frac{E_r}{E_z} dz$$

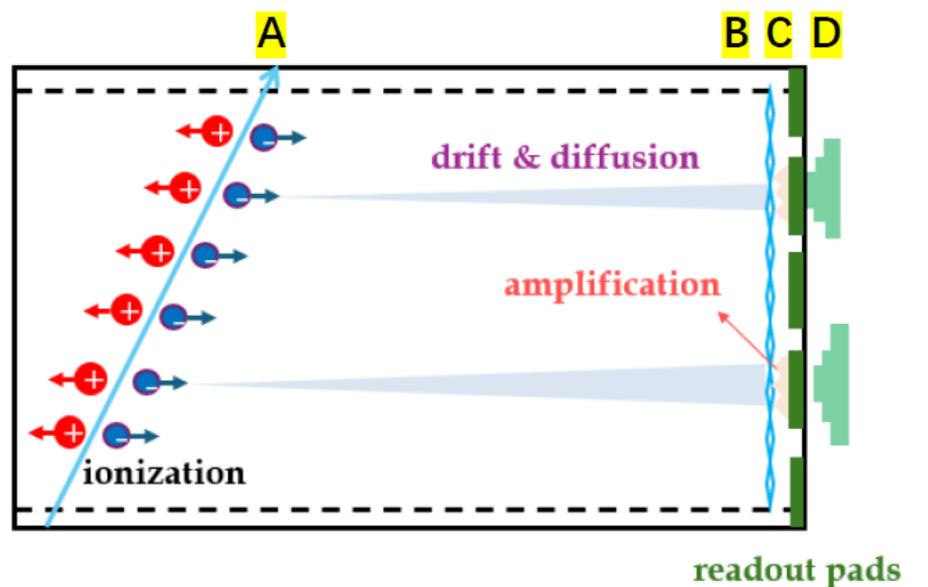$$\Delta_r = \int_0^L \frac{1}{1+\omega^2\tau^2} \times \frac{E_r}{E_z} dz$$

Numerical calculation results of TPC distortion

Simulation:

- With the full TPC geometry
- Ionization simulated with Garfield++
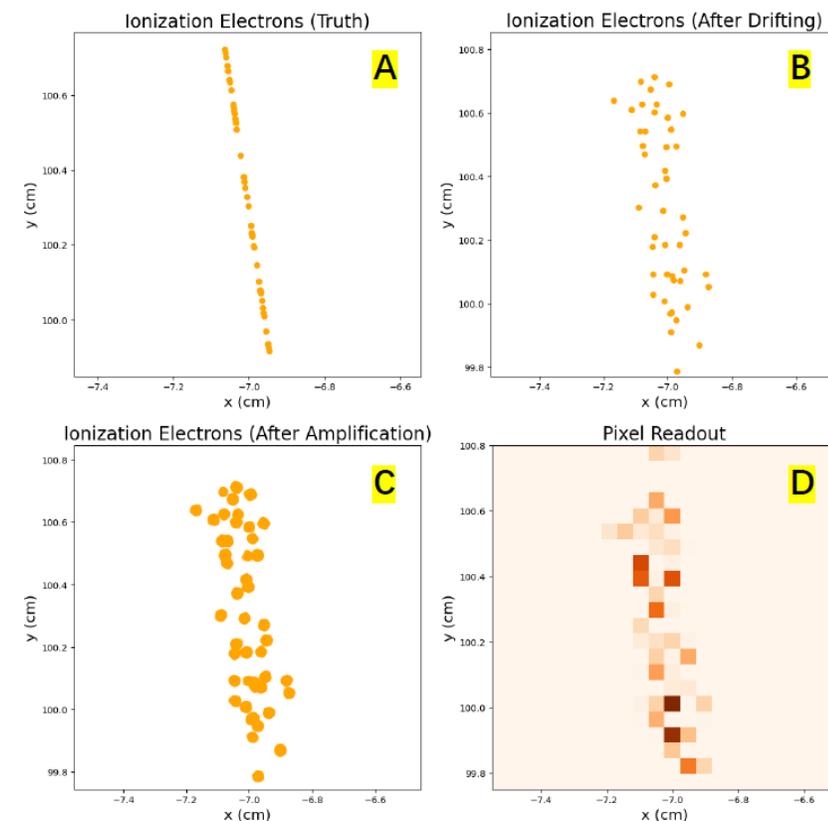- Drift and diffusion from parameterized model
  based on Garfield++

Digitization (Refer to the TPC module and prototype):

- Electronic noise: 100 e-
- Amplification:
  - Number of electrons: 2000
  - Profile of signal size : 100µm

Garfield++-Based Simulation/Digitization Framework

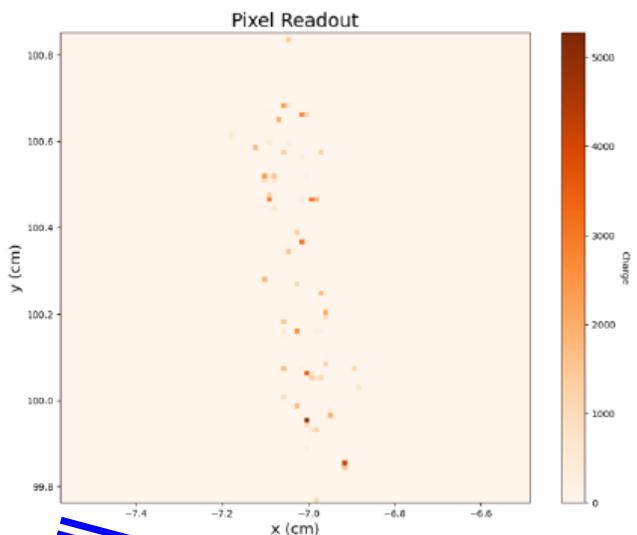Simulation of TPC detector under 3T/2T and T2K mixture gas

- Simulation of the readouts in pixel sizes
  - Actually, TPX3/4 option existing and the power consumption will be optimized.
  - Optimization started in this ref-TDR at IHEP to meet **Higgs/Z at 3T**.
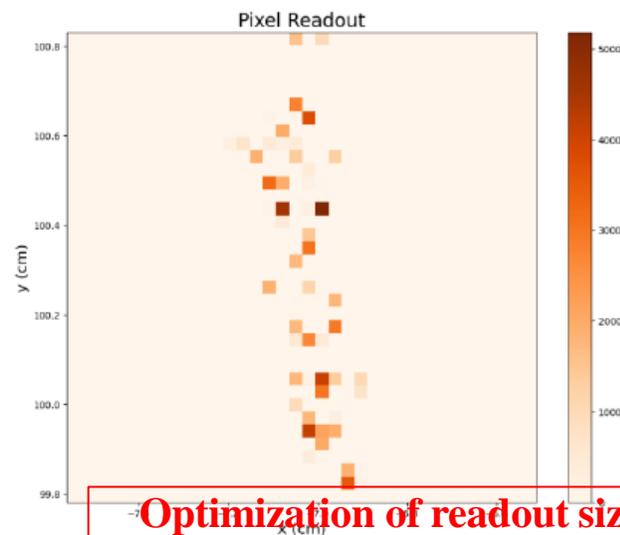
■ Concerning pixel sizes for a TPC
  ■ A pixel size of 55 (110) microns is optimal; one can profit from cluster counting and high precision tracking
  ■ Larger pixel/pad sizes have larger occupancies and one should question whether they can handle the very high beam-beam rate
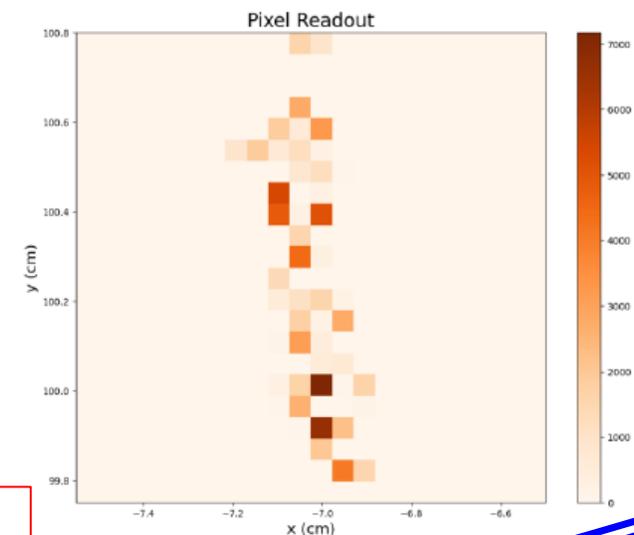
Peter's comment
in CEPCWS at Hangzhou.

Pixel size = 110 um Pixel size = 300 um Pixel size = 500 um

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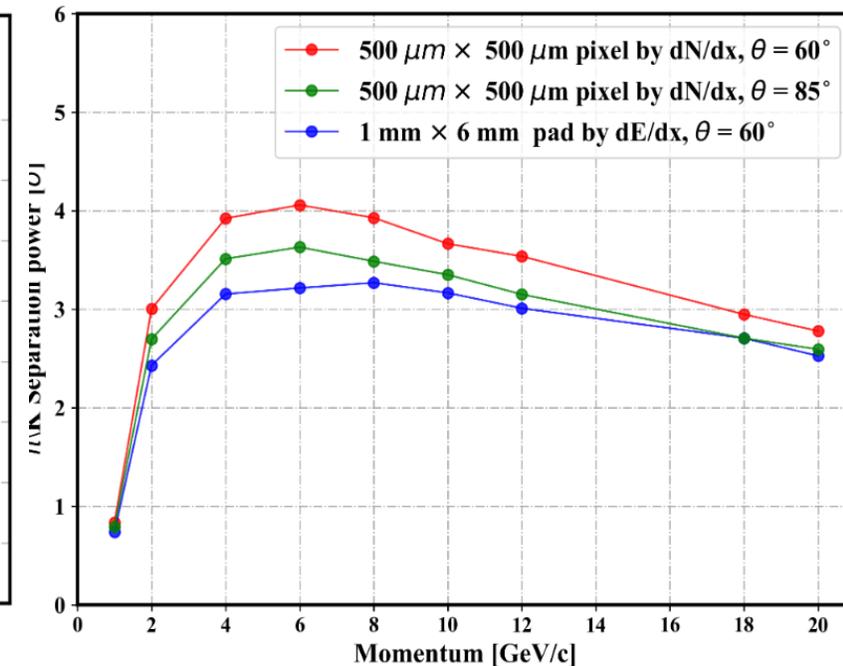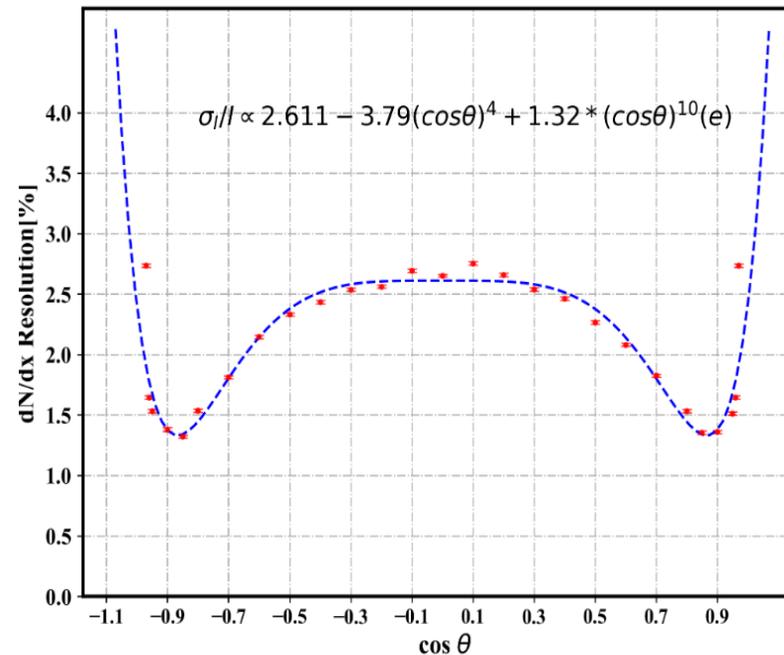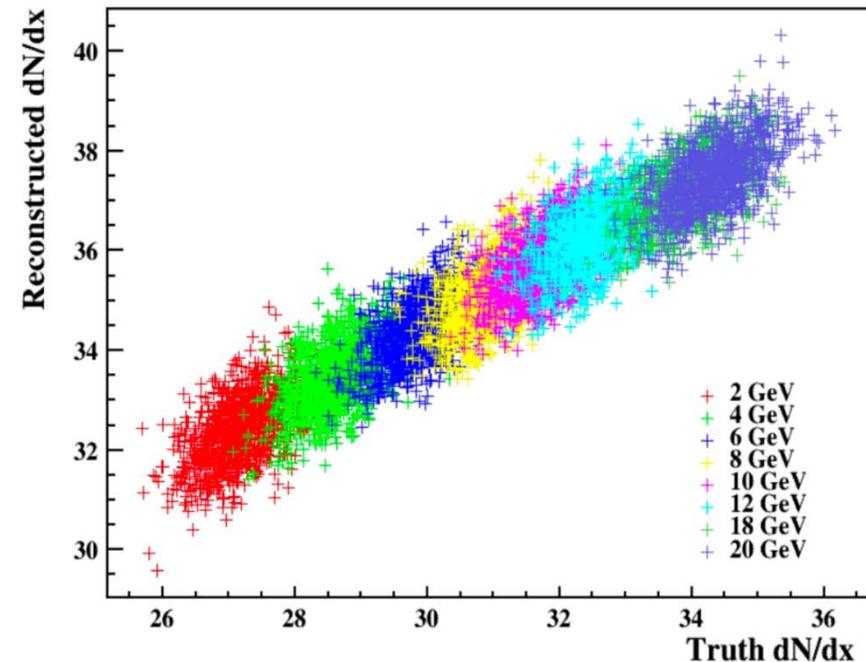
Reconstruction:

- Reconstruction by counting the number of fired pixels over threshold

- **Reconstruction with good linearity and reliability**
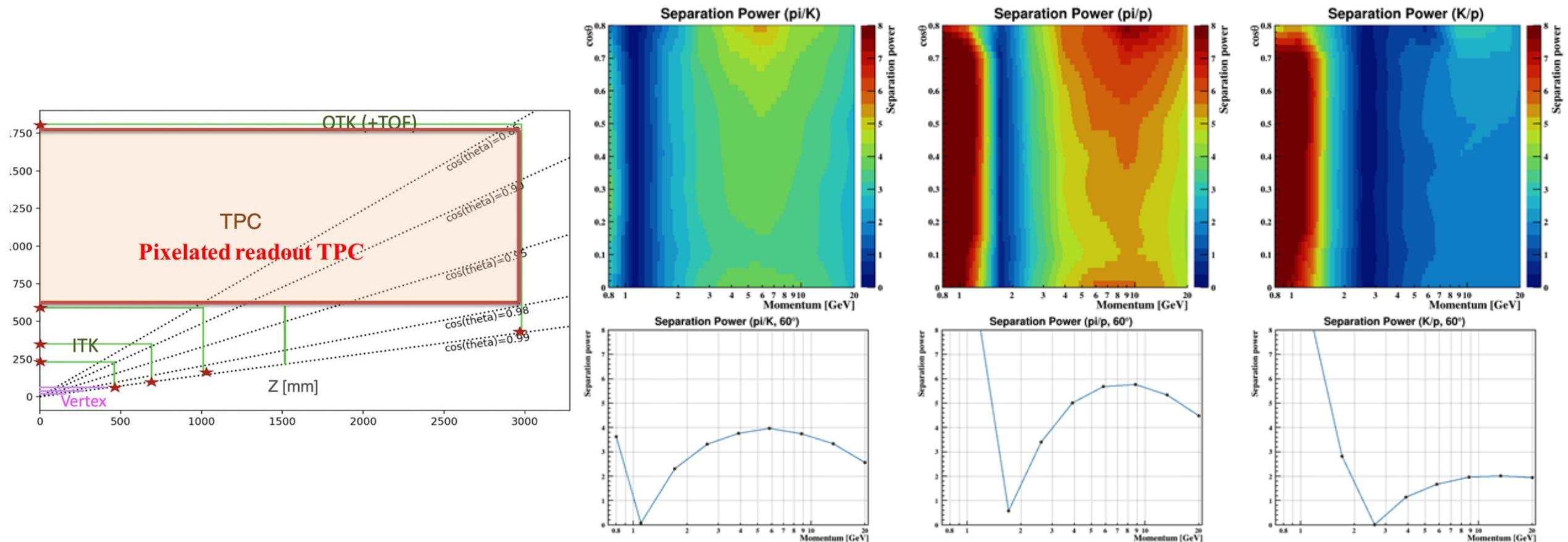
Preliminary PID performance:

- π/k separation power simulation with different momentum

$$\text{Separation power: } \frac{|\mu_A - \mu_B|}{\frac{\sigma_A + \sigma_B}{2}}$$
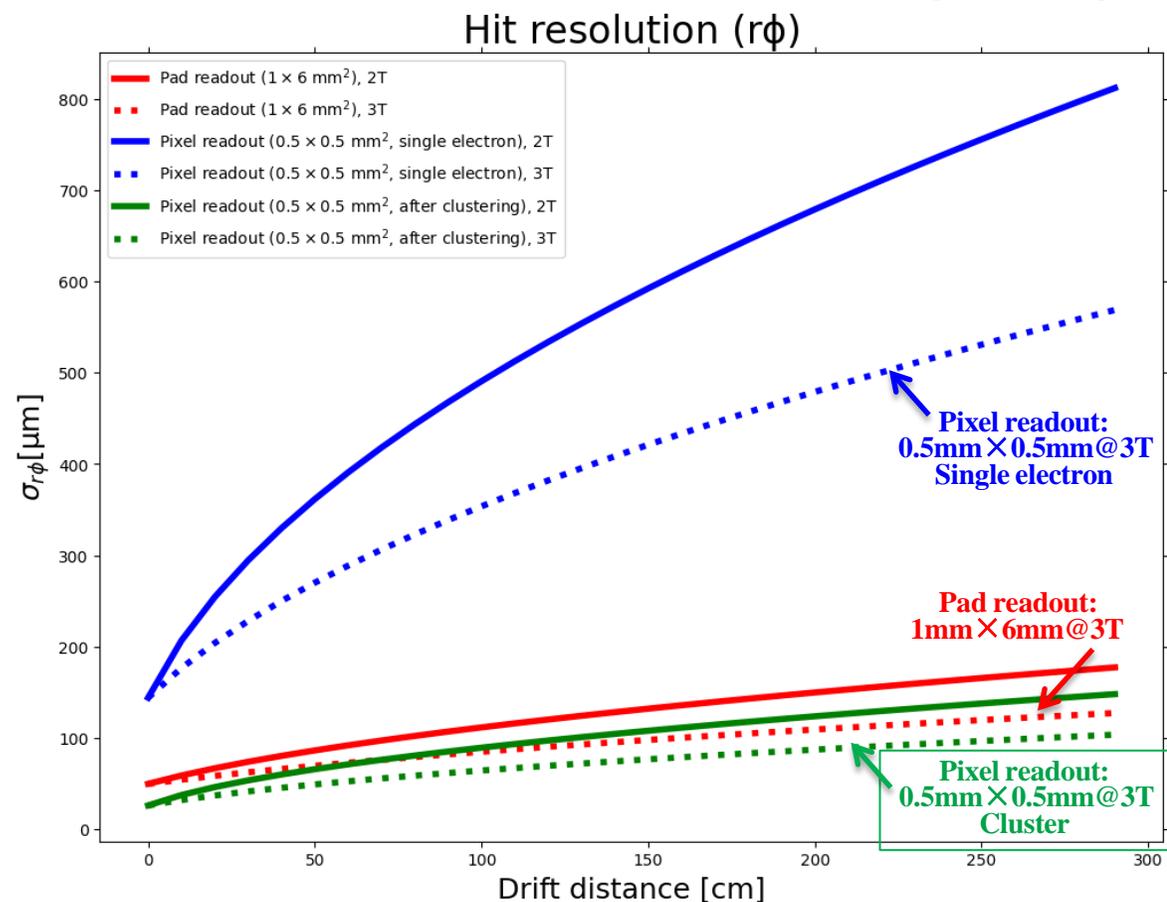
- Performance of the pixelated readout TPC
  - Simulation of π/K, π/p, and K/p separation power with varying momentum and cosθ

Estimation of the **spatial resolution using pixelated readout**.

- The granularity readout and the transverse diffusion are also taken into consideration..
- TPC can operates effectively at 3T B-field.
- Pixelated readout TPC can achieves superior spatial resolution at 3T compared to 2T.
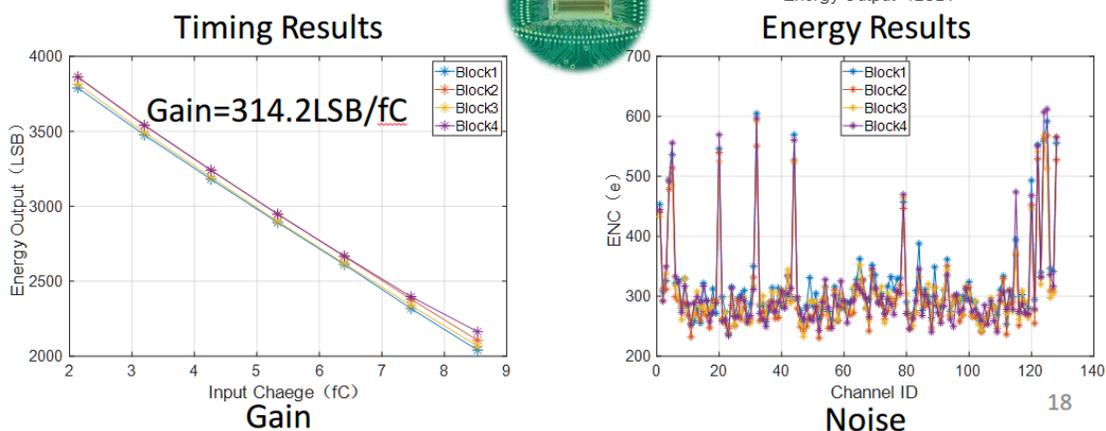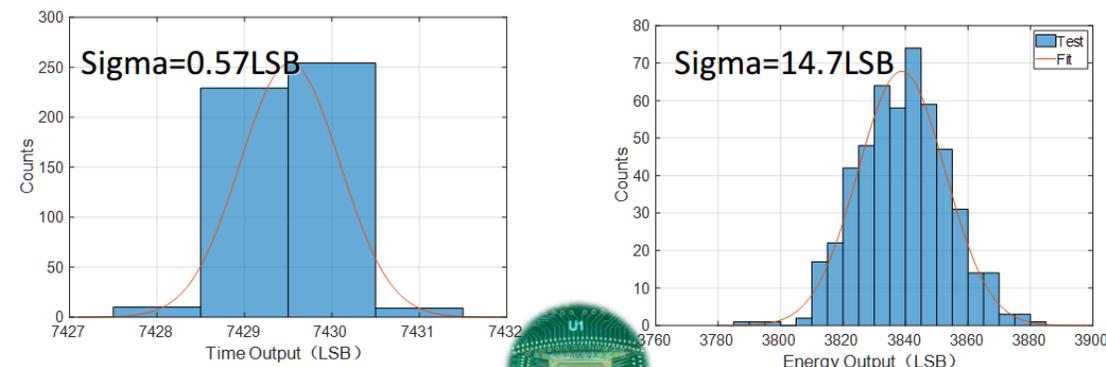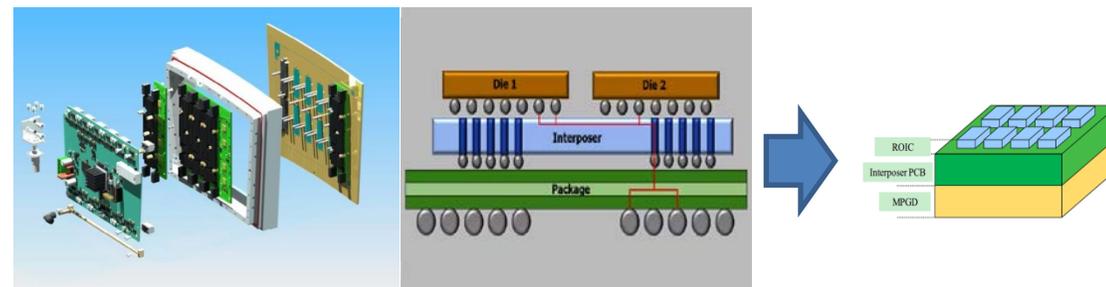

Pad readout:

$$\sigma_{r\phi}^{\mathrm{pad}} = \sqrt{(\sigma_{r\phi 0}^{\mathrm{pad}})^2 + \sigma_{\phi 0}^2 \sin^2(\phi_{\mathrm{track}}) + L\frac{D_{r\phi}^2}{N_{\mathrm{eff}}}\sin(\theta_{\mathrm{track}})}$$

Pixel readout:

$$\sigma_{r\phi}^{\mathrm{pixel}} = \sqrt{(\sigma_{r\phi 0}^{\mathrm{pixel}})^2 + LD_{r\phi}^2}$$

Full Simulation of Pixelated readout TPC – TEPix with 500μm×500μm

- Pixelated Readout Electronics: TEPix development
  - Multi-ROIC chips + Interposer PCB as RDL
  - Four-side bootable
- TEPix: Low power Energy/Timing measurement
  - Low power consumption: 0.5mW/ch@2nd Chip
  - Timing: 1 LSB(<10ns)
  - Noise: 300e- (high gain)

Parameter	Spec
Number of channels	128
Power Consumption	Analog<30mW
	Digital<30mW
ENC	~300 e(high gain)
Dynamic Range	25fC(high gain)
	150fC(low gain)
INL	<1%
Time Resolution	<10ns

Sigma=0.57LSB

Timing Results

Sigma=14.7LSB

Energy Results

Gain=314.2LSB/fC

Gain

Noise

FEE ASIC: TEPIX—Test Results in May

Validation and commissioning of TPC prototype

- **R&D on Pixelated TPC readout for CEPC TDR.**
  - ASIC chip developed and **2nd prototype wafer has been done** and tested.
  - The TOA and TOT can be selected as the initiation function in the ASIC chip
- **Beam test of the pixelated readout TPC prototype in preparation. (April –May , 2025)**

Photos TPC modules assembled for the beam test

Work plan

- Short term work plan (**before June, 2025**)
  - Optimization of TPC detector for CEPC ref-TDR
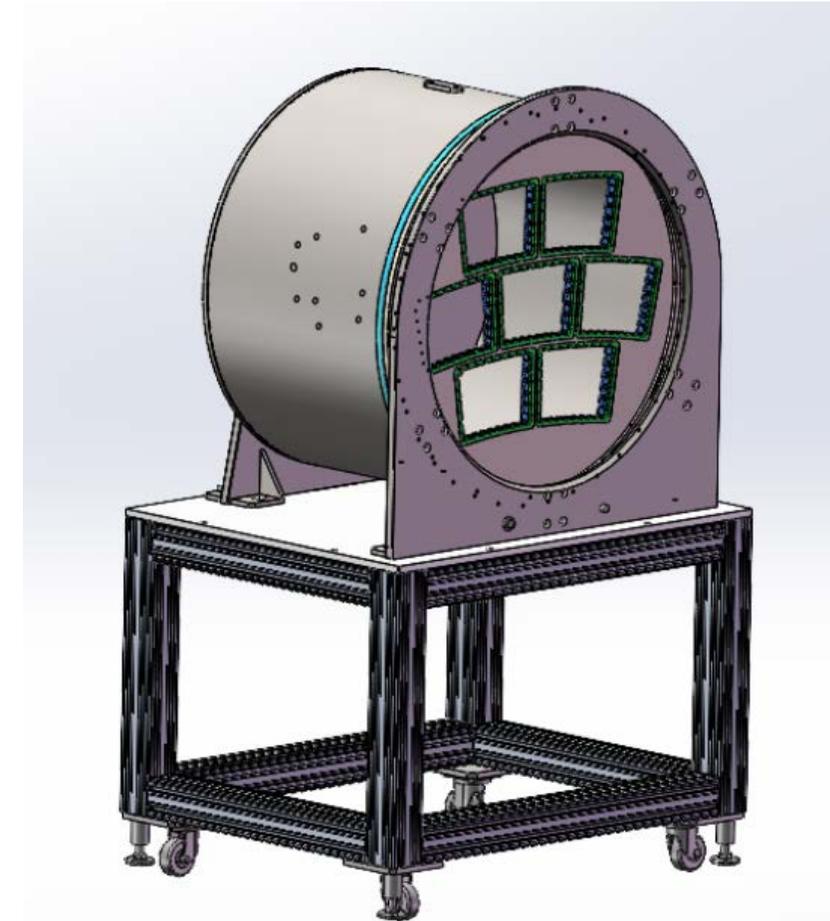 - Prototyping R&D and validation with the test beam
    - mechanics, manufacturing, beam test, full drift length prototype
  - Performance of the simulation and Machine Learning algorithm
- Long term work plan (**next 3-5 years**)
  - Development of TPC prototype with low power consumption FEE
    - Collaboration with LCTPC collaboration on beam test
  - Development of the full drift length prototype
    - Drift velocity. Attachment coefficient, T/L Diffusion, etc.

Milestones achieved	Before June, 2025	Beyond TDR
Ion backflow suppression	IBF×Gain<1 (Gain=2000)	Graphene technology
Pixelated readout prototype	Validation with beam test	Prototype with Multi-modules
Power consumption ASIC	~100mW/cm² (60nm ASIC)	Optimization 330μm - 500μm
PID resolution	3% (dN/dx)	<3% (dN/dx)
Material budget (barrel)	Carbon Fiber	Full size prototype

- In LCTPC collaboration, TPC detection technology R&D using the pad readout towards the pixelated readout for Higgs and Z run at the future e+e- collider.

- Pixelated TPC is chosen as the baseline gaseous tracker in CEPC ref-TDR. The simulation results show that both of PID performance and the momentum resolution are good. Validation with TPC prototype in preparation before TDR.

- Synergies with CEPC/DRD1/FCCee/EIC/LCTPC allow us to continue R&D and ongoing with the significant international collaboration. All of contributions will input to CEPC ref-TDR in next few months.

Many thanks!