CEPC Gaseous Tracker

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Content

- Motivation and physics requirements
- Technology survey and our choice
- Technical challenges and R&D efforts
- Detailed design including electronics, cooling and mechanics
- Performance from simulation
- Research team and working plan
- Summary

Motivation

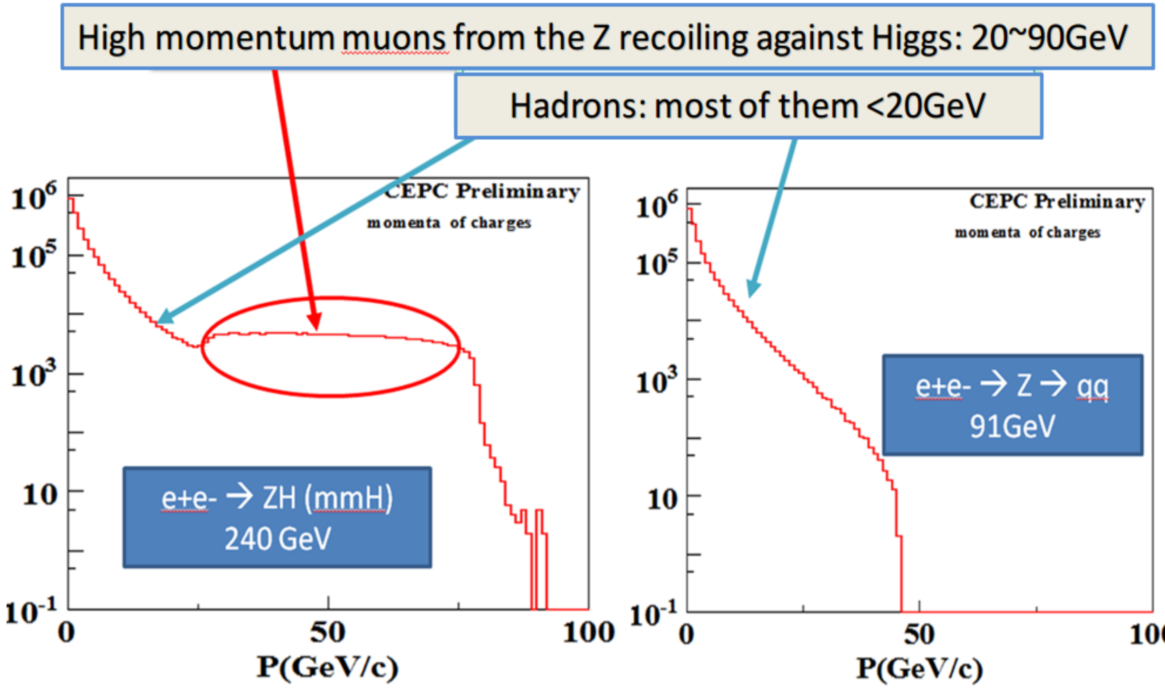
- This talk relates to the CEPC Physics and Detector Ref-TDR.
  - Chapter 6: Gaseous tracker
  - Draft of content listed →

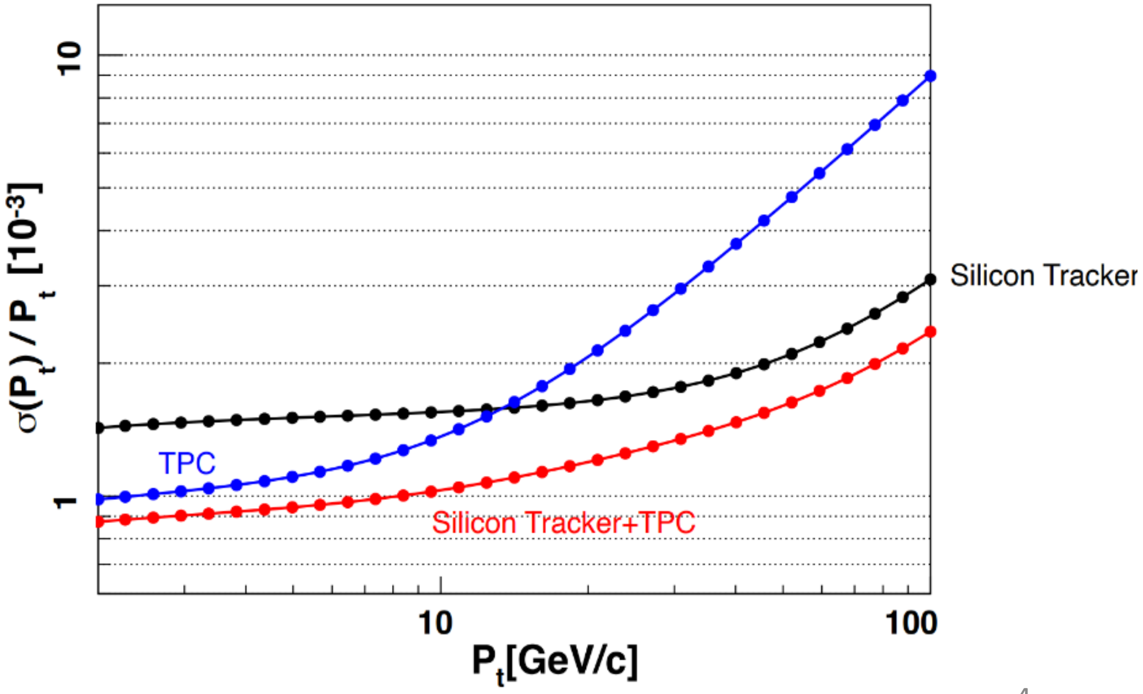
Chapter 6 Gaseous Trackers

Physics requirement

- CEPC operation stages in TDR: **10-years Higgs → 2-years Z pole → 1-year W**
- Physics Requirements of tracker
  - High momentum resolution for Higgs and Z
  - PID of charged hadrons for flavor physics and jet substructure

$$\sigma_{1/pT} = \sqrt{a^2 + (b/pT)^2}$$

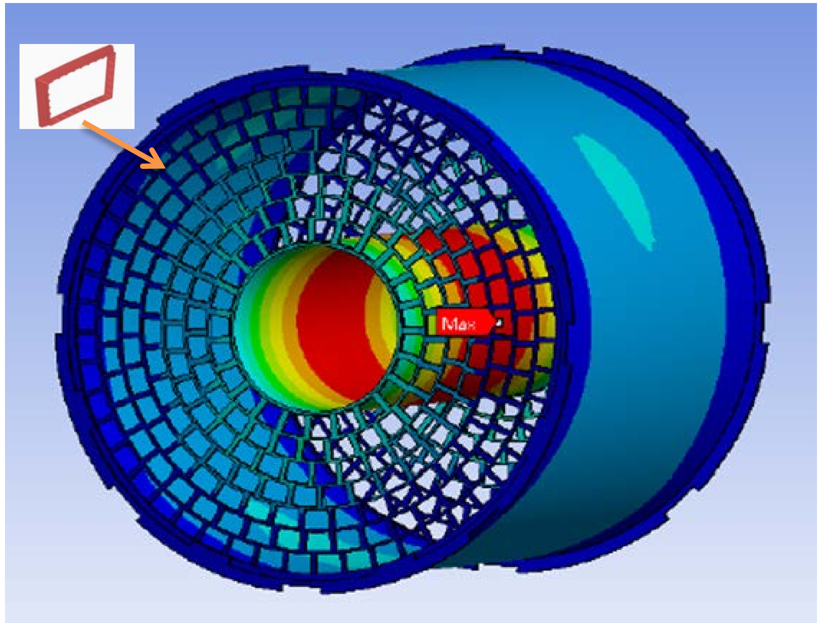




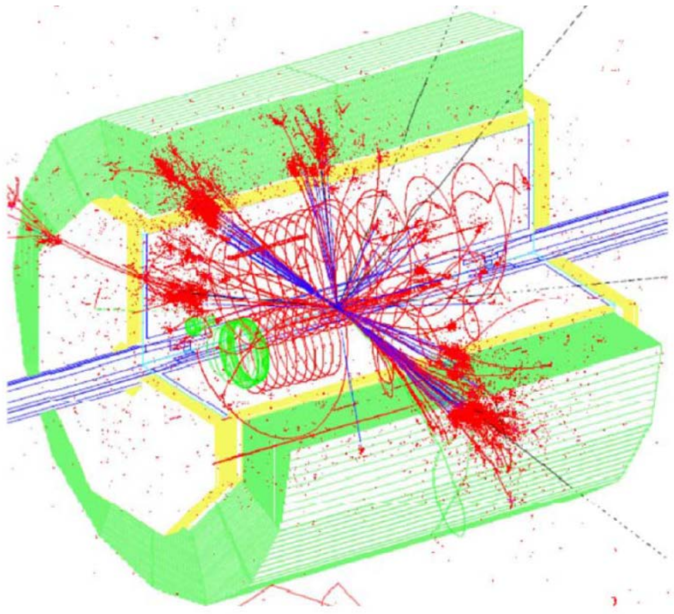
https://doi.org/10.1140/epjc/s10052-018-5876-z

Technology survey and our choice

- 3D precise track reconstruction with Ultra light material budget
  - High spatial resolution (~**100 μm**) with thousands hits per track
  - High precision tracking and High **Particle Identification** resolution (**~3%**)
  - Operation at **Higgs (3T) and Tera-Z (2T)**; Modular design and easily installation
- Considering the technical challenges, performance, risk of the detector construction



Modular design

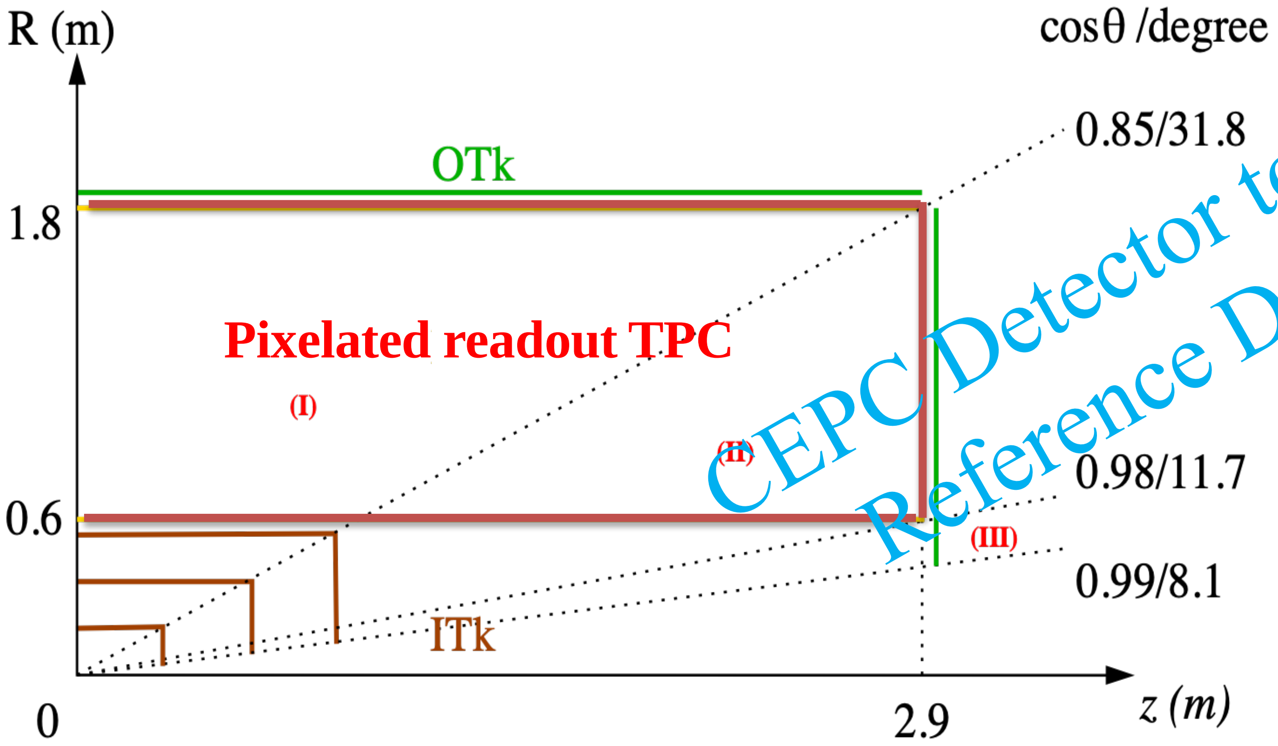


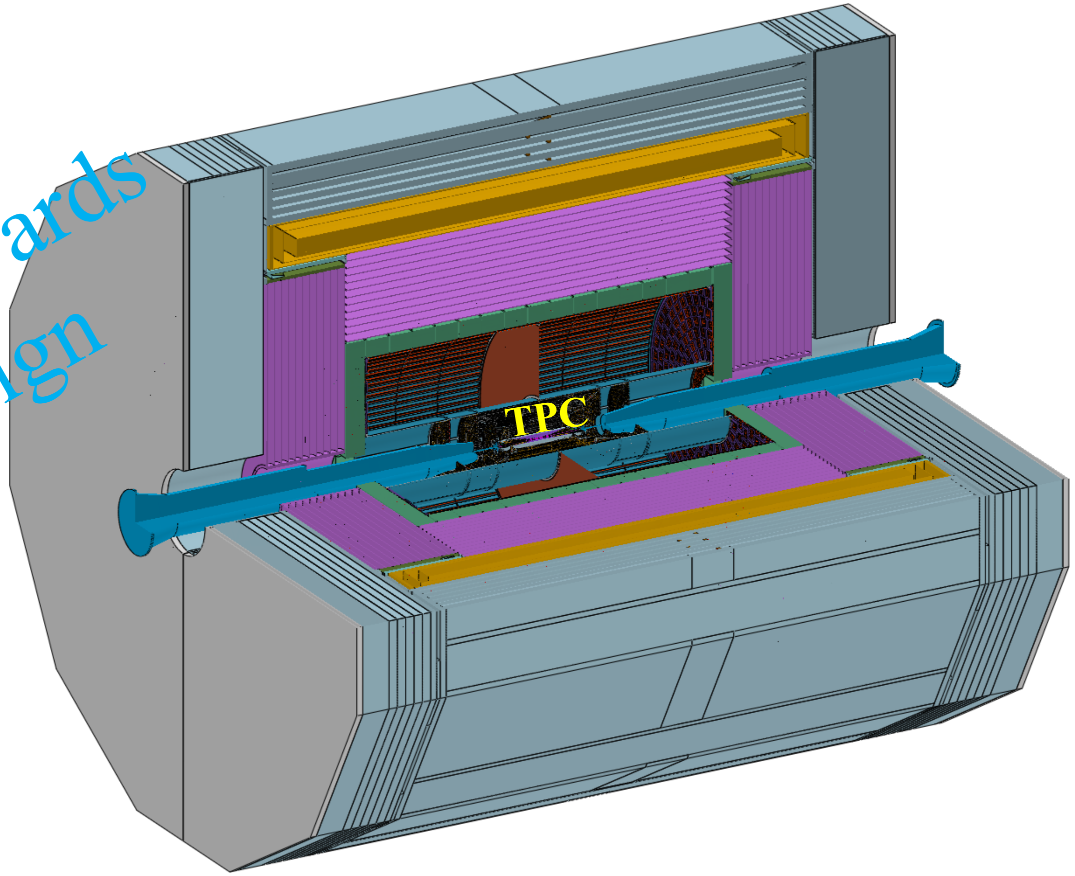
Time Projection Chamber

Drift Chamber

Baseline track detector: Pixelated TPC

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





Geometry of the track detector system in CEPC TDR

Technical challenges and R&D efforts

Main Technical Challenges

- **Pixelated readout TPC (Baseline)**

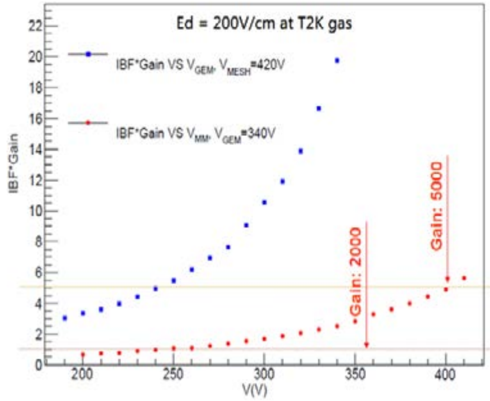
Critical key issues

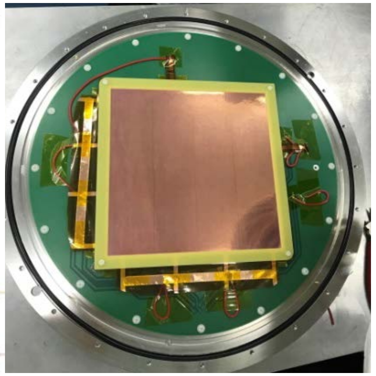
  - **Material budget at endcap/barrel √**
  - **Occupancy and hit density at Tera-Z √**
  - **Ion backflow suppression √**
  - **Running at 2 Tesla √**
  - **Improved PID √**
  - **Reasonable channels(ongoing)**
  - **Reasonable power consumption (ongoing)**

- **DC (Alternative at Tera-Z)**
  - **dN/dx for PID √**
  - **Risk the 5.8m wires and tension (ongoing)**

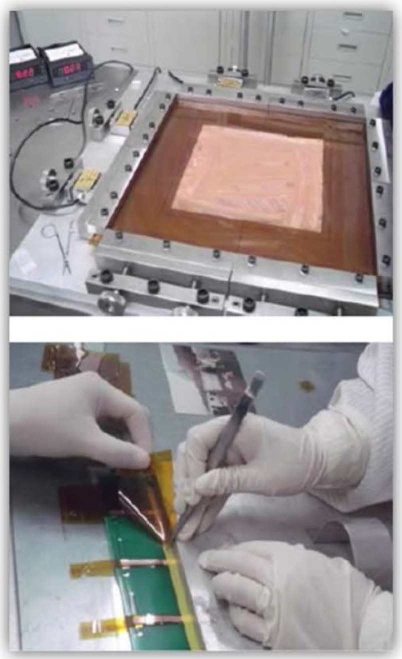
TPC prototype R&D efforts and results

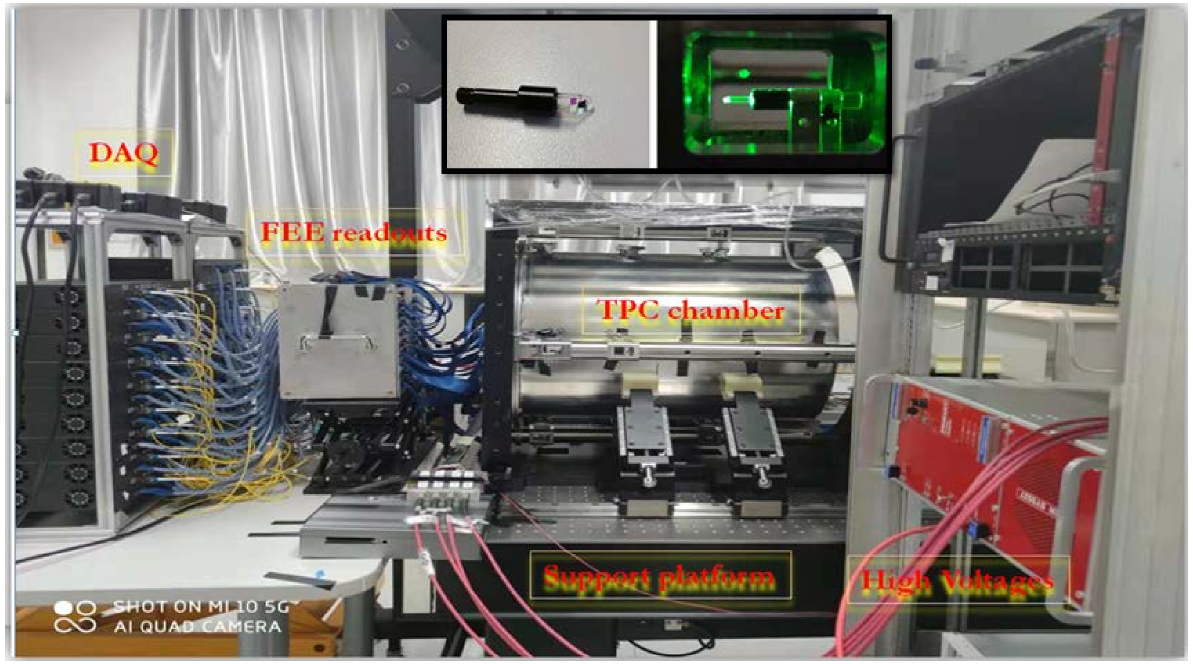
- **CEPC TPC detector prototyping roadmap:**
  - From TPC module to TPC prototype R&D for Higgs and Tera-Z
- **Achievement by far:**
  - **IBF×Gain ~1 @ G=2000** validation with hybrid TPC module
  - Spatial resolution of **$\sigma_{r\varphi} \leq 100\ \mu m$ and dE/dx resolution of 3.6%**
  - FEE chip: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



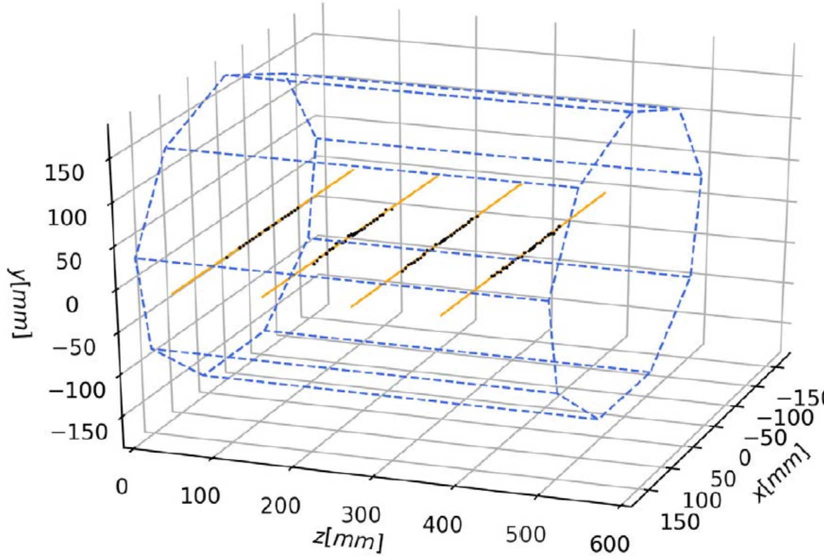


Ion suppression TPC module R&D





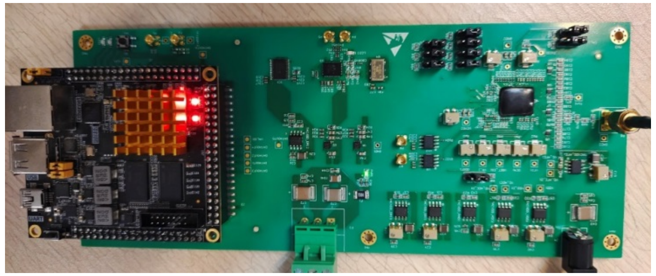
TPC prototype with integrated 266nm UV laser

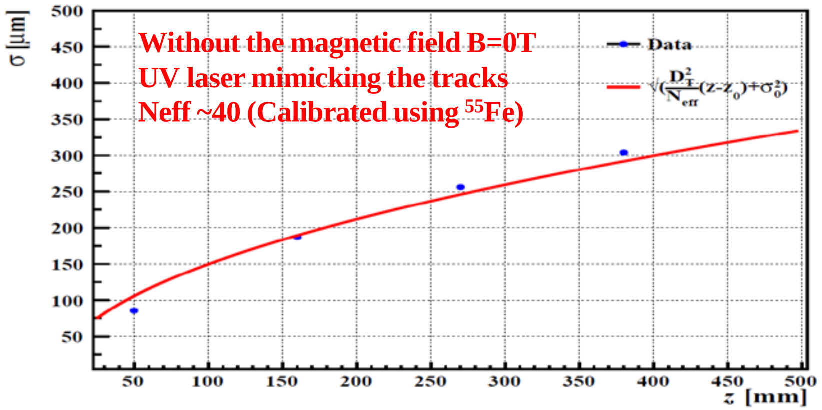


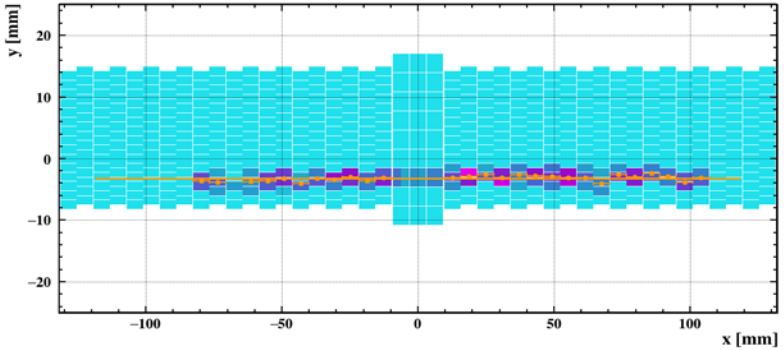
Track reconstruction

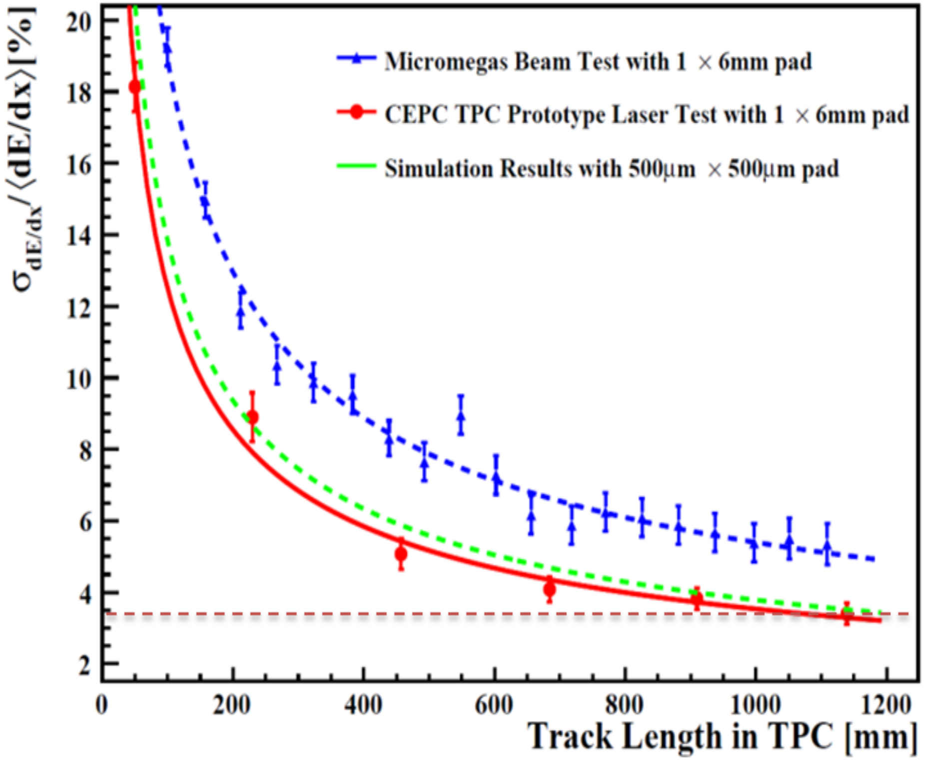
Highlights of TPC prototype R&D

- **Highlights of CEPC pad readout TPC R&D and toward the pixelated readout TPC**
  - Massive production and assembly MPGD lab has been set up at IHEP.
  - TPC prototype integrated 266nm UV laser tracks has been studied and analyzed the UV laser signal, all are pretty good to Higgs run.
  - **Easy-to-install modular design** of Pixelated readout TPC for CEPC TDR









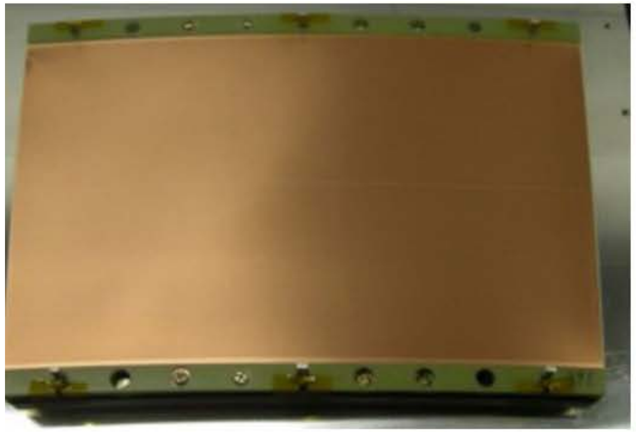
Publications by CEPC TPC group in 2018-2024:

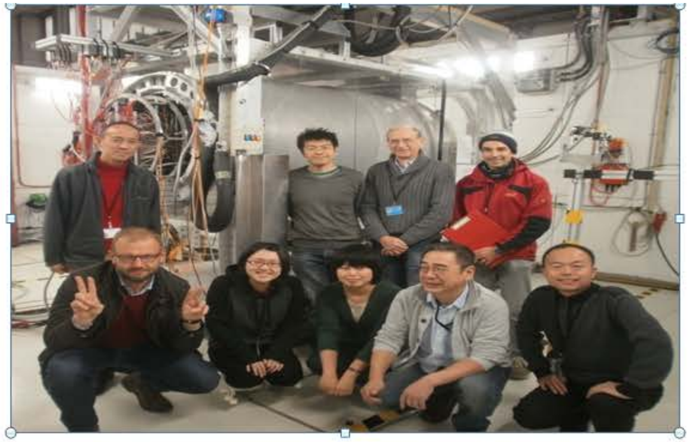
- https://doi.org/10.1088/1748-0221/18/08/E08002
- https://doi.org/10.22323/1.449.0553
- https://doi.org/10.1016/j.nima.2022.167241
- https://doi.org/10.1109/NSS/MIC44867.2021.9875566
- https://doi.org/10.1109/NSS/MIC44845.2022.10399097
- https://doi.org/10.1088/1748-0221/15/09/C09065
- https://doi.org/10.1088/1748-0221/15/05/P05005
- 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

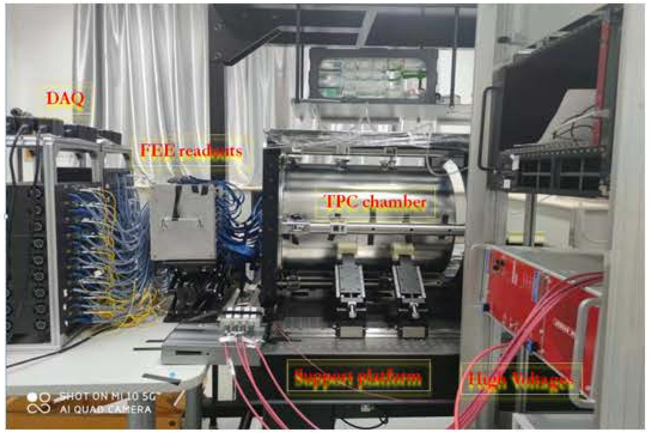
Activity international collaboration

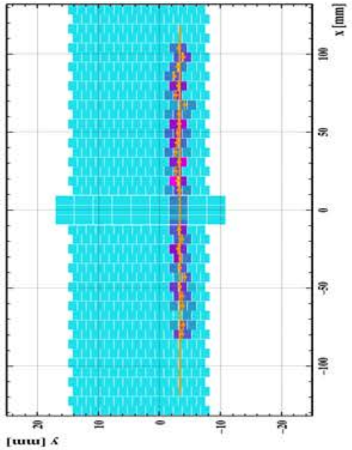
- **Activity collaboration:** Pixelated readout and Pad readout from IHEP and LCTPC collaboration
  - Large Prototype setup have been built to compare different detector readouts for Tera-Z
  - PCMAG: B < 1.0T, bore Ø: 85cm, Spatial resolution of $\sigma_{r\phi} \leq 100\ \mu m$
  - Collaboration implement improvements in **a pixelated readout TPC for CEPC TDR**

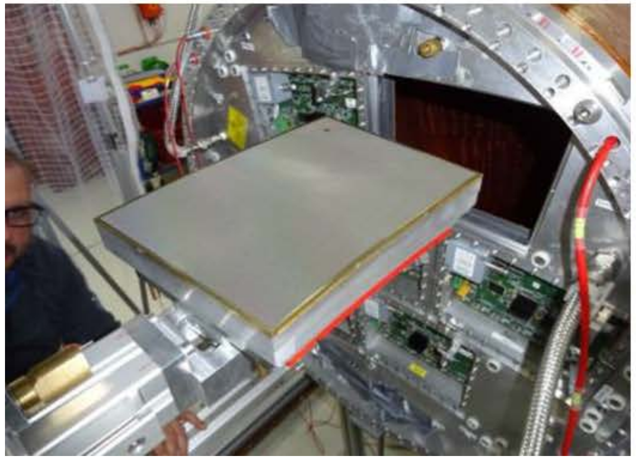
ArXiv. (2023)2006.08562
NIM A (2022) 167241
ArXiv (2022)2006.085
JINST 16 (2021) P10023
JINST 5 (2010) P10011
NIM A608 (2009) 390-396

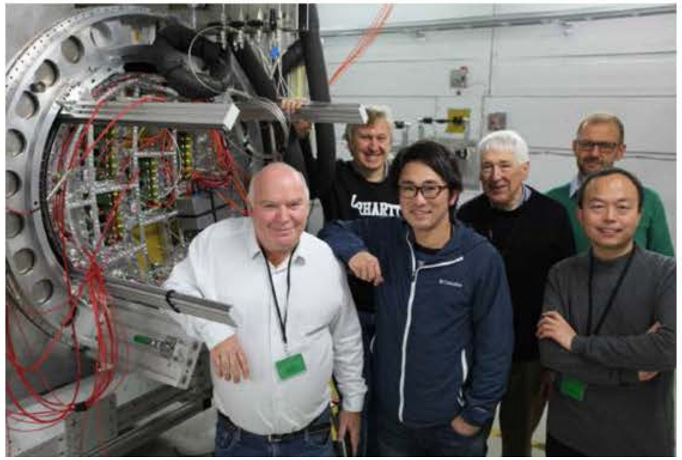


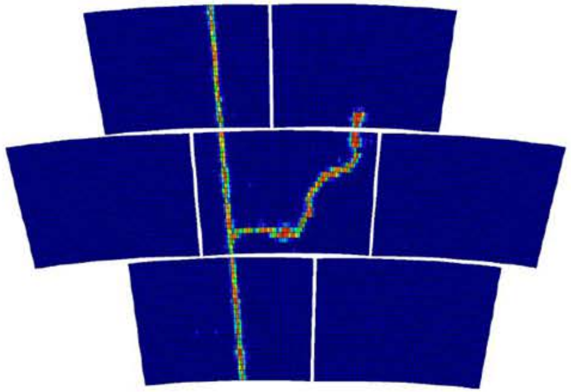








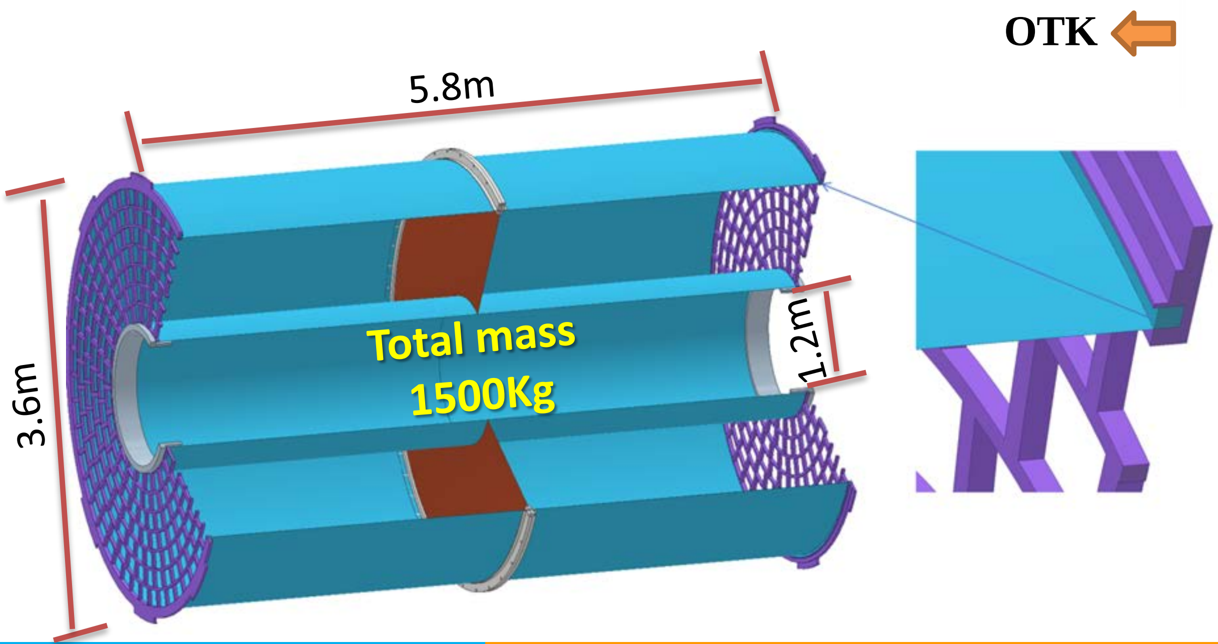


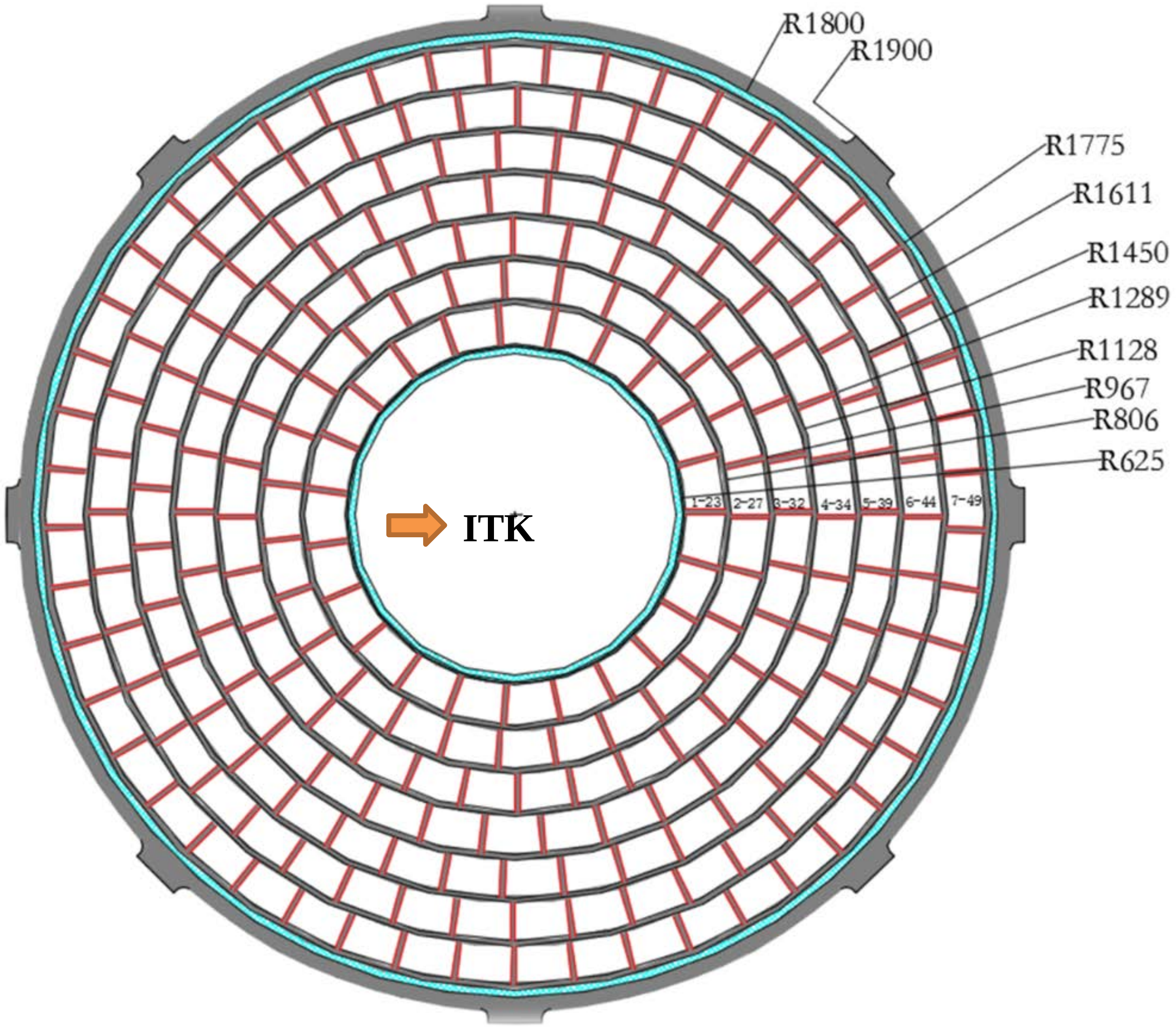


Detailed design and performance of Baseline: TPC

Detailed design of mechanics

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

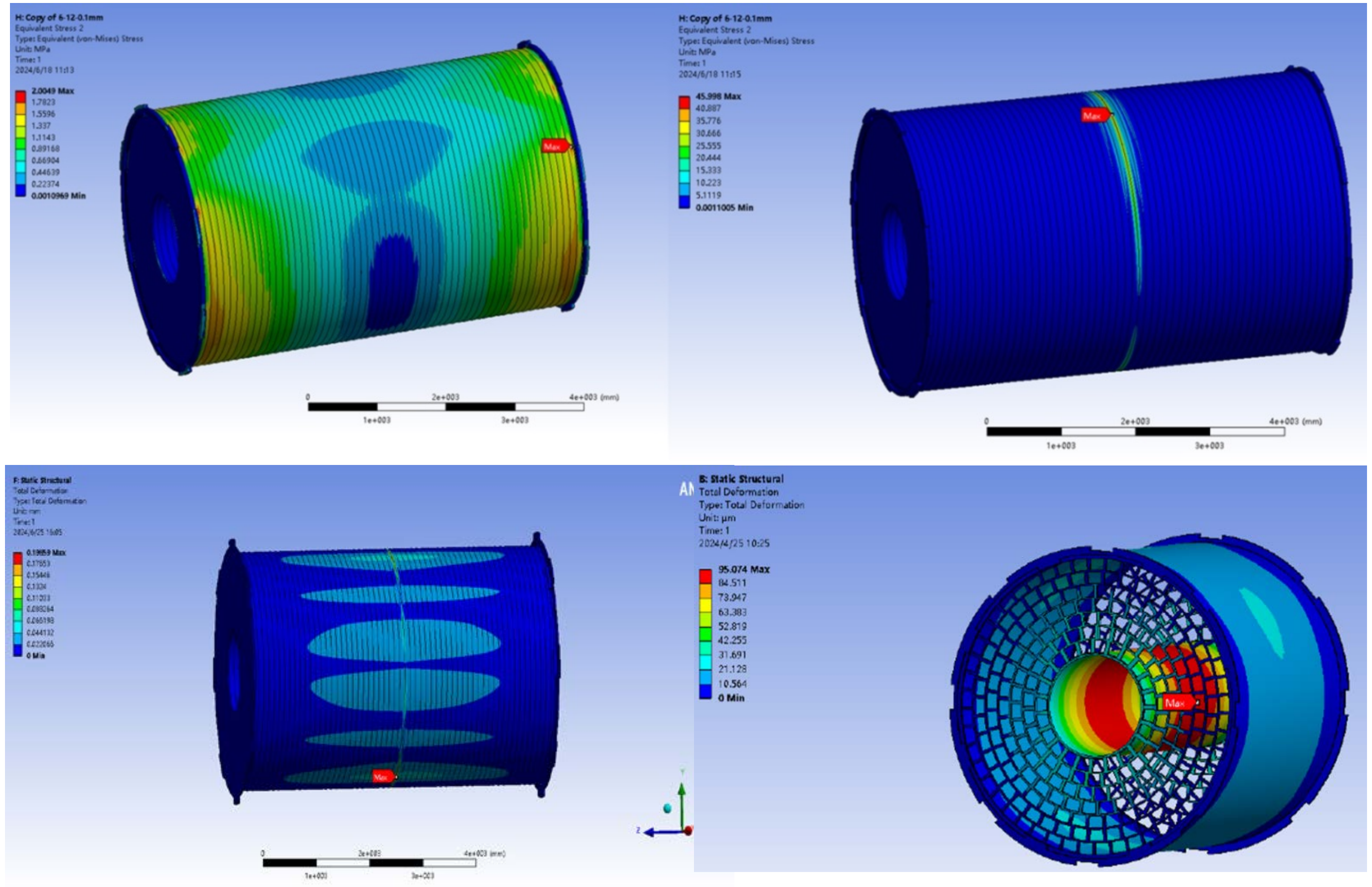




Detailed design of TPC detector in ref-TDR

Ultra-light barrel and FEA analysis

- Consideration of new Carbon Fiber barrel instead of the honeycomb barrel (**~2% X_0**)
- **Ultra-light material** of the TPC barrel (QM55 CF) : **0.59% X_0 in total, including**
  - FEA preliminary calculation: 0.2mm carbon fibber barrel can tolerant of OTK (**~200Kg**)
- Optimization of the connection back frame of the endcap (on going)



Material budget of TPC barrel

Layer of the barrels	D[cm]	X_0[cm]	d/X_0[%]
Copper shielding	0.001	1.45	0.07
CF outer barrel	0.020	25.28	0.08
Mirror strips	0.003	1.35	0.19
Polyimide substrate	0.005	32.65	0.02
Field strips	0.003	1.35	0.19
CF inner barrel	0.010	25.28	0.04
Sum of the material budget			**0.59**

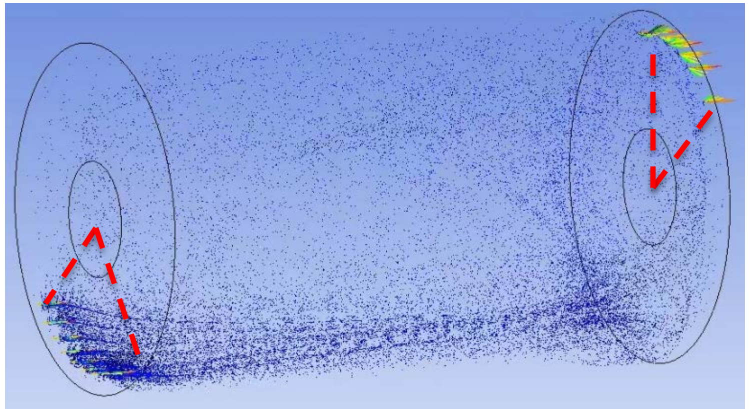
- **Low material of the TPC endcap**

15%X_0 in total, including

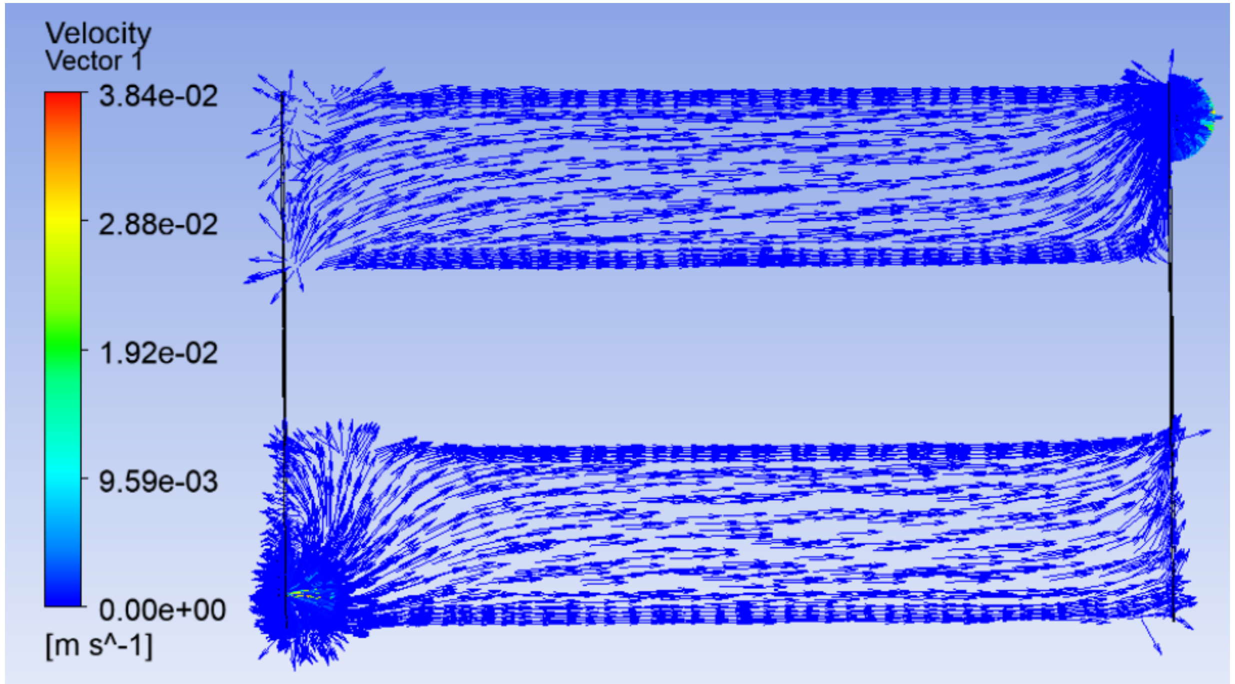
Readout plane, front-end-electronics	4%
Cooling	2%
Power cables	9%

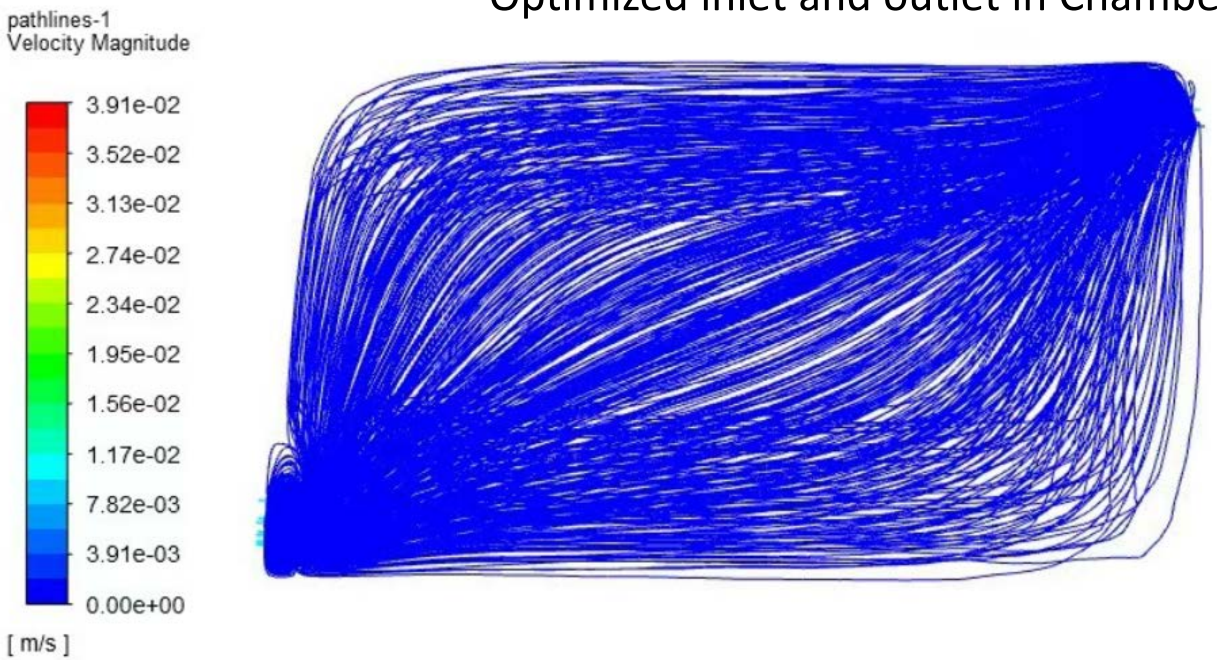
Optimization of Gas flow in Chamber

- Requirement: Gas uniformity of **99% or more** in large TPC chamber
  - **8 Ø10mm** gas inlets + **8 Ø10mm** gas outlets (opposite, 90°/endcap)
  - Working Gas Flow: 0.3 – 0.5 L/min
  - Eco-friendly gas and the **gas recycling system** also considered.
    - Online monitoring system: O_2 (ppm) and H_2O (ppm)



Optimized inlet and outlet in Chamber

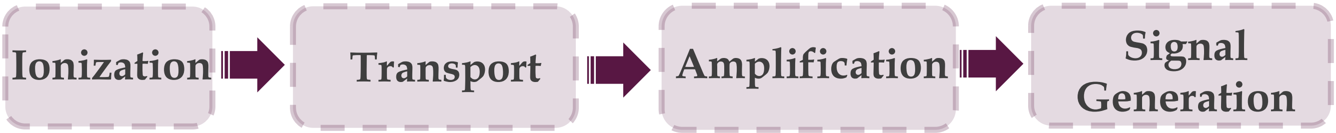




Simulation of gas flow and uniformity distribution in TPC Chamber

Full Simulation of Pixelated readout TPC

Simulation / Digitization Framework

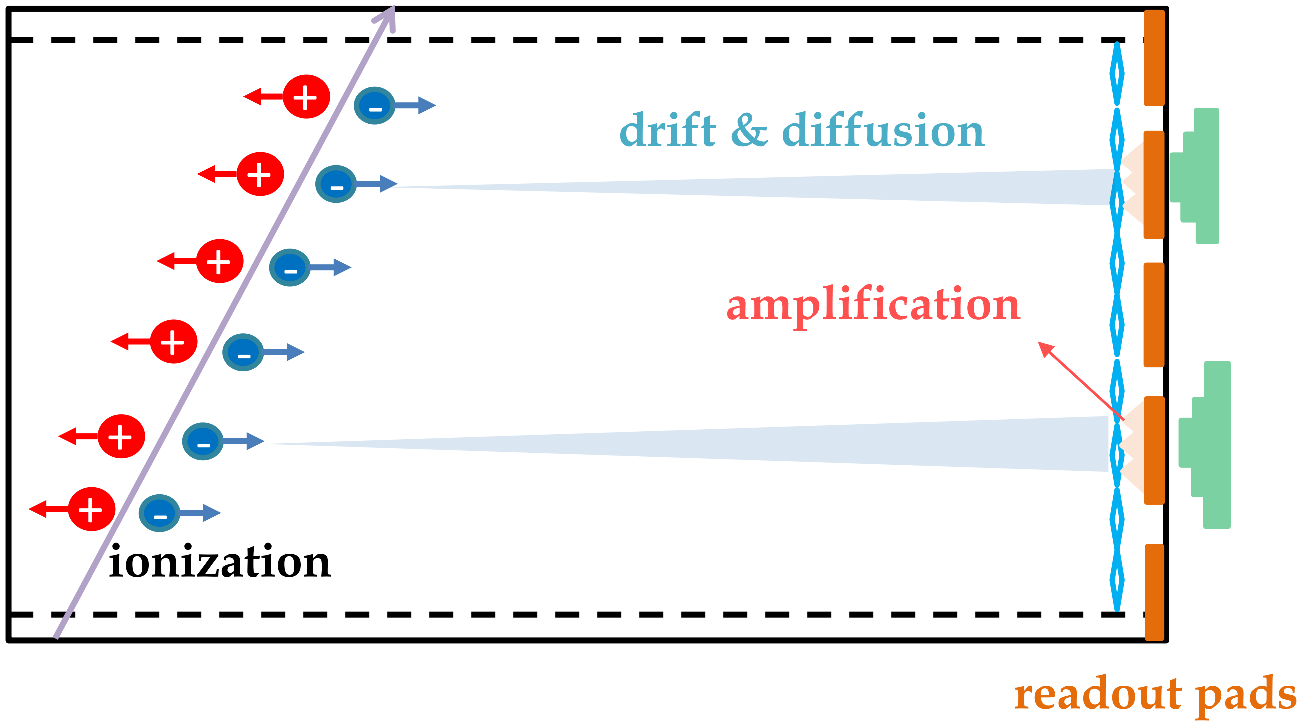


Simulation:

- Full geometry TPC
- Ionization simulated by Garfield++
- Drift and diffusion from parameterized model based on Garfield++ simulation

Digitization (Refer to the TPC module and prototype**):**

- Electronic noise: 100 e-
- Amplification:
  - Number of electrons: 2000
  - Signal size in space: 100 µm



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

DOI: 10.22323/1.449.0553
EPS-HEP 2023 talk by Yue Chang

Performance of Pixelated readout TPC

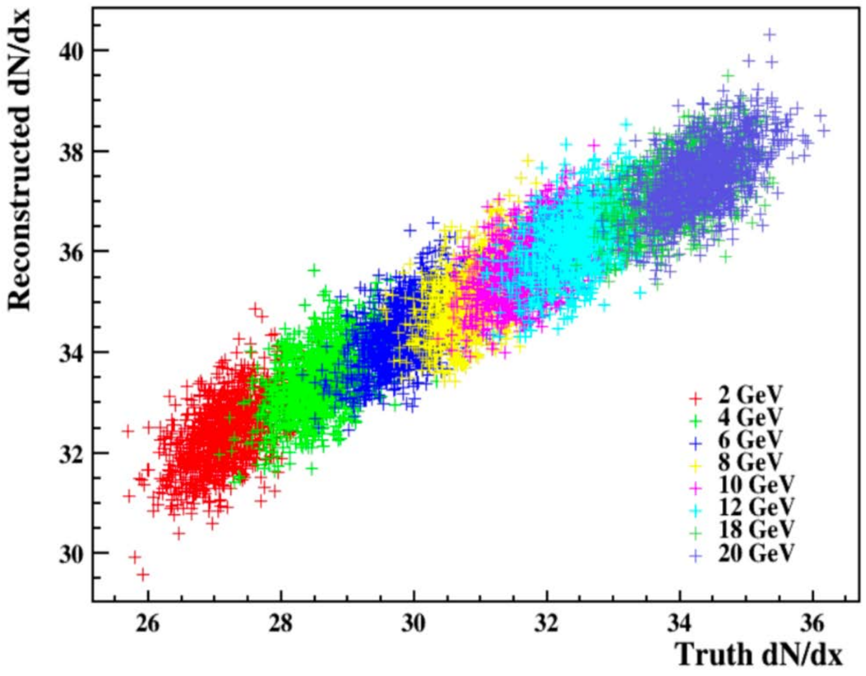
Reconstruction:

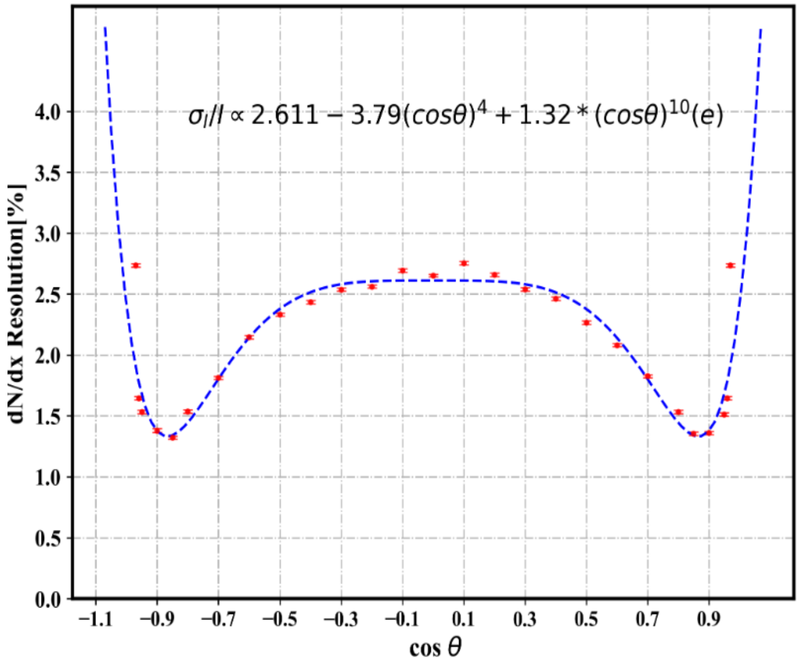
- Reconstruction by counting the number of fired pixels over threshold
- **Reconstruction with good linearity and reliability**

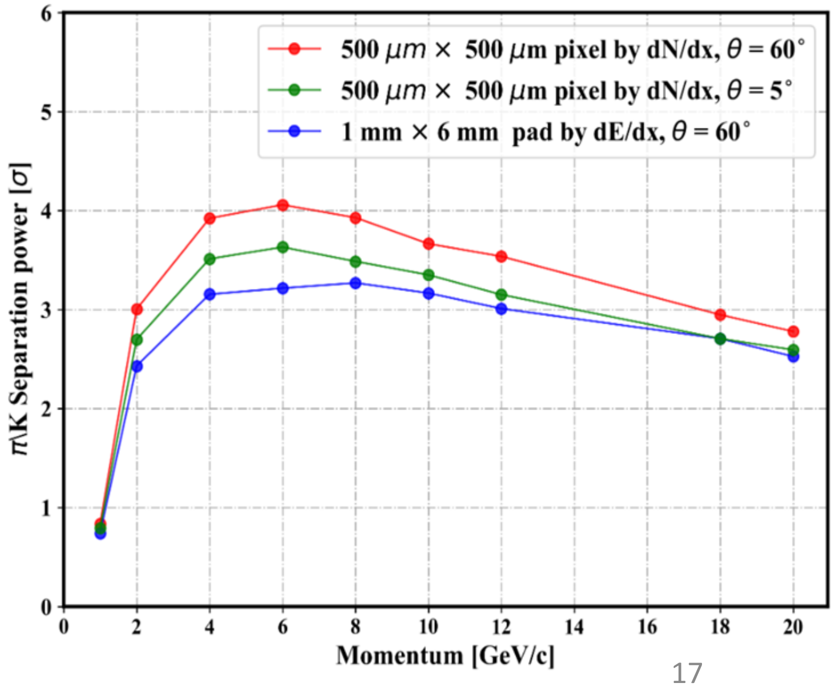
Preliminary PID performance:

- π/k separation power simulation with the different momentum

$$\text{Separation power: } \frac{|\mu_A-\mu_B|}{\frac{\sigma_A+\sigma_B}{2}}$$

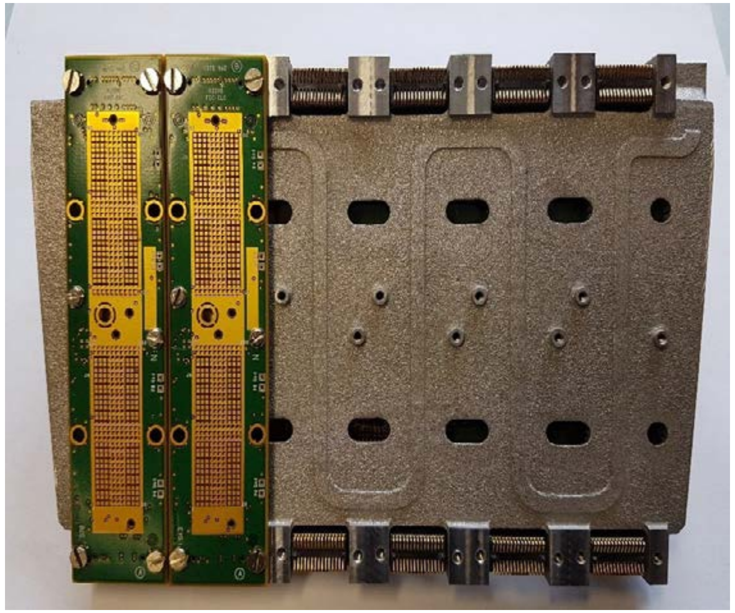


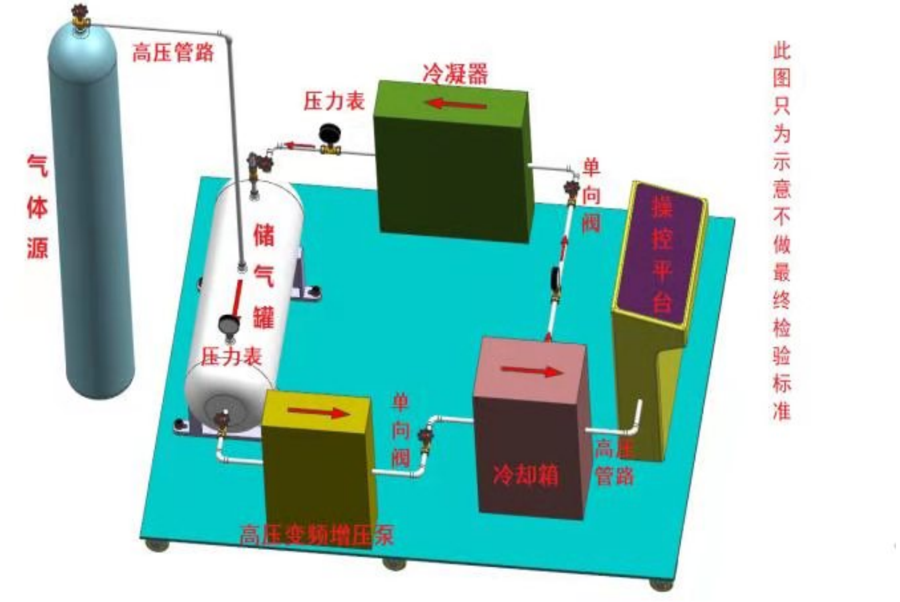




Optimization of the readout size

- Timepix (55µm×55µm) readout TPC prototype has been validated four times using DESY beam.
  - Power consumption: 2W/cm^2 ; Low power mode: 1W/cm^2 (**Too high power consumption.**)
- Simulation results showed that readout size can be optimized at 500µm×500µm.
  - Readout channels and power consumption need to be studied.
  - Focused on **100mW/cm^2 and 500µm readout** for CEPC ref-TDR (2-phase CO_2 cooling **OK!**)



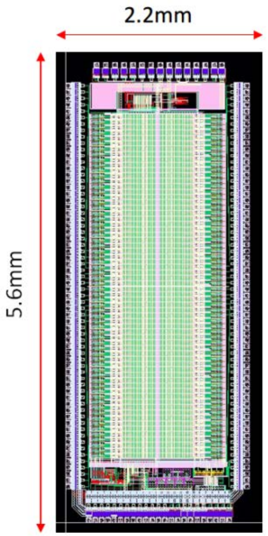


2-phase CO2 cooling for TPC module

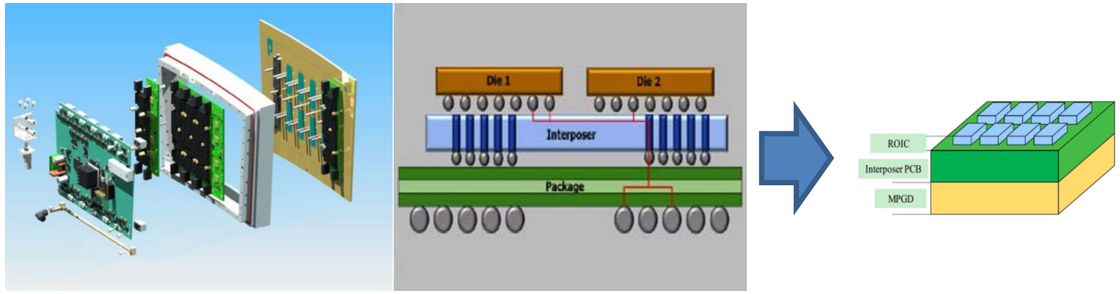
DOI: 10.1088/1748-0221/15/02/T02001
DOI: 10.1088/1748-0221/15/05/P05005

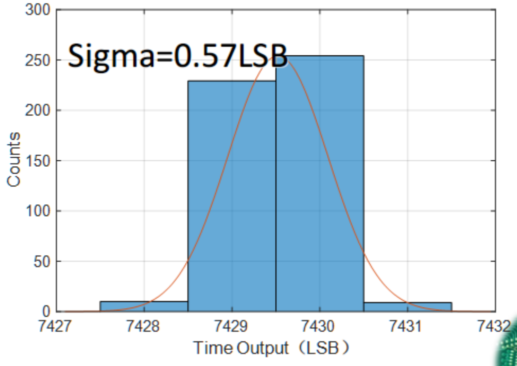
Detailed design of electronics and BEC

- 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)

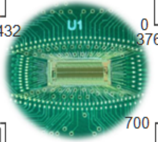


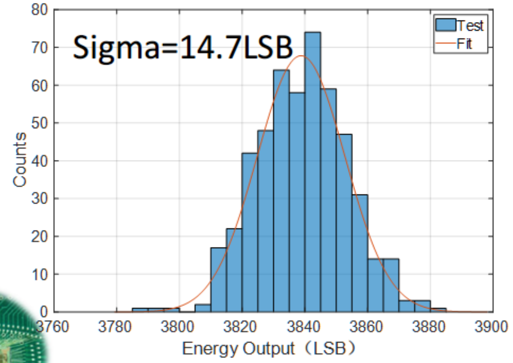
Parameter	Spec
Number of channels	128
Power Consumption	Analog<30mW
	Digital<30mW
ENC	~300 e(high gain)
Dynamic Range	25fC(high gain)
	150fC(low gain)
INL	<1%
Time Resolution	<10ns



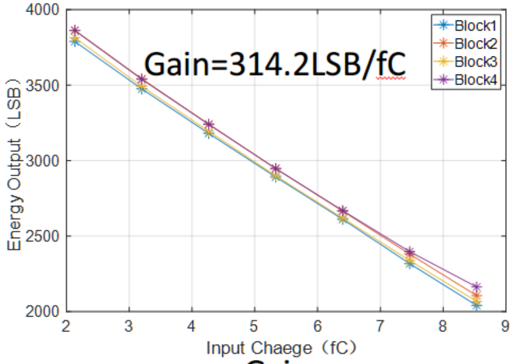


Timing Results

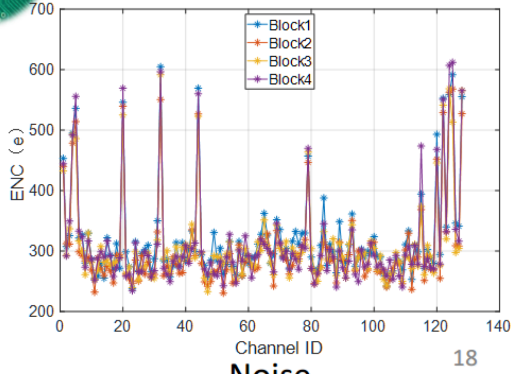




Energy Results



Gain

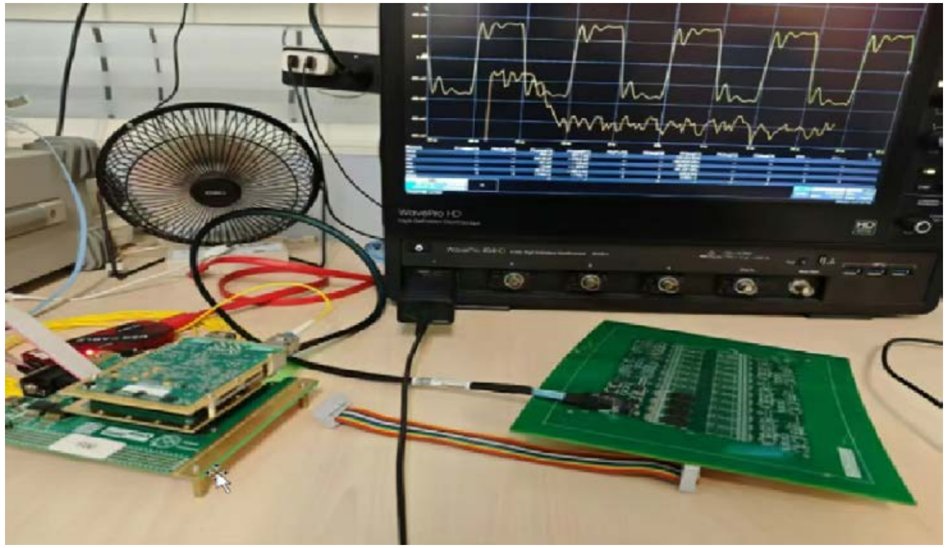


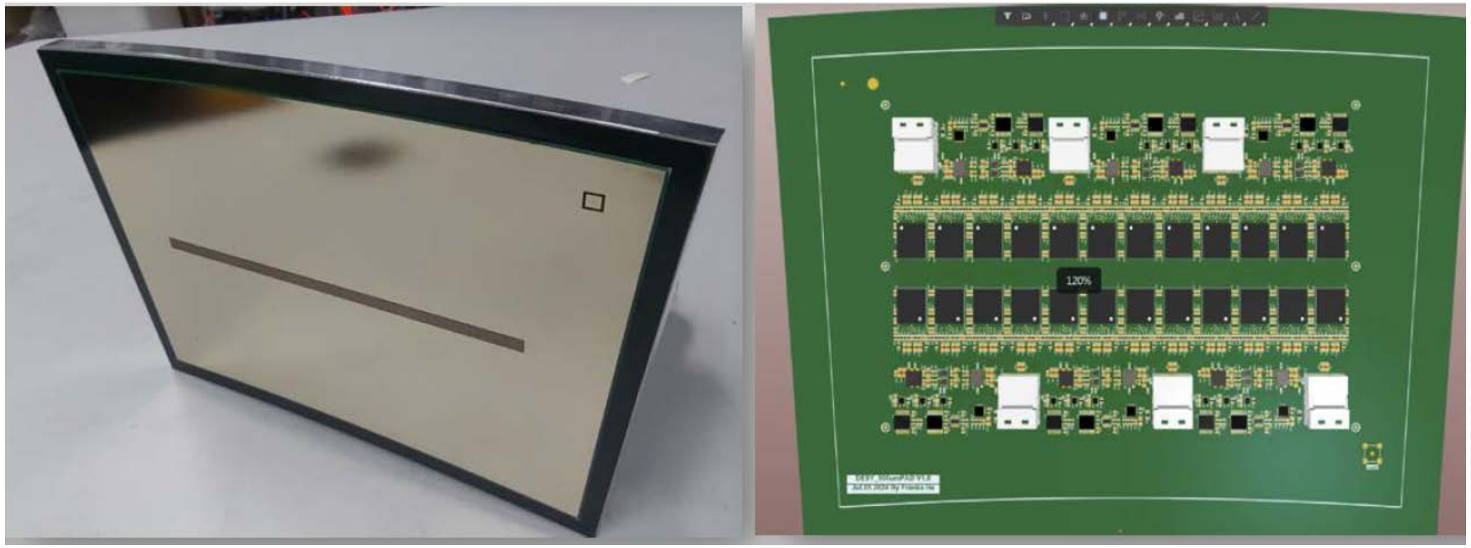
Noise

FEE ASIC: TEPIX—Test Results in May

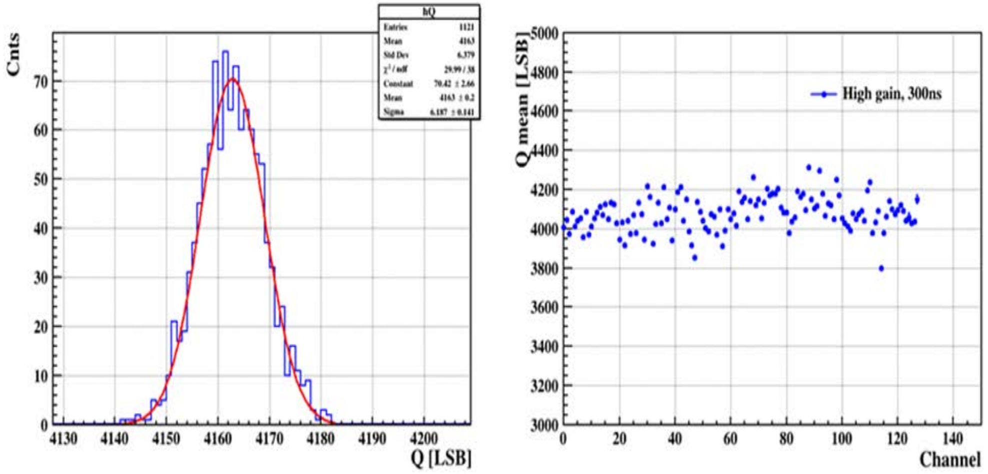
Validation and commissioning of TPC prototype

- **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. (November, 2024 and January, 2025)**





Photos TPC modules assembled for the beam test



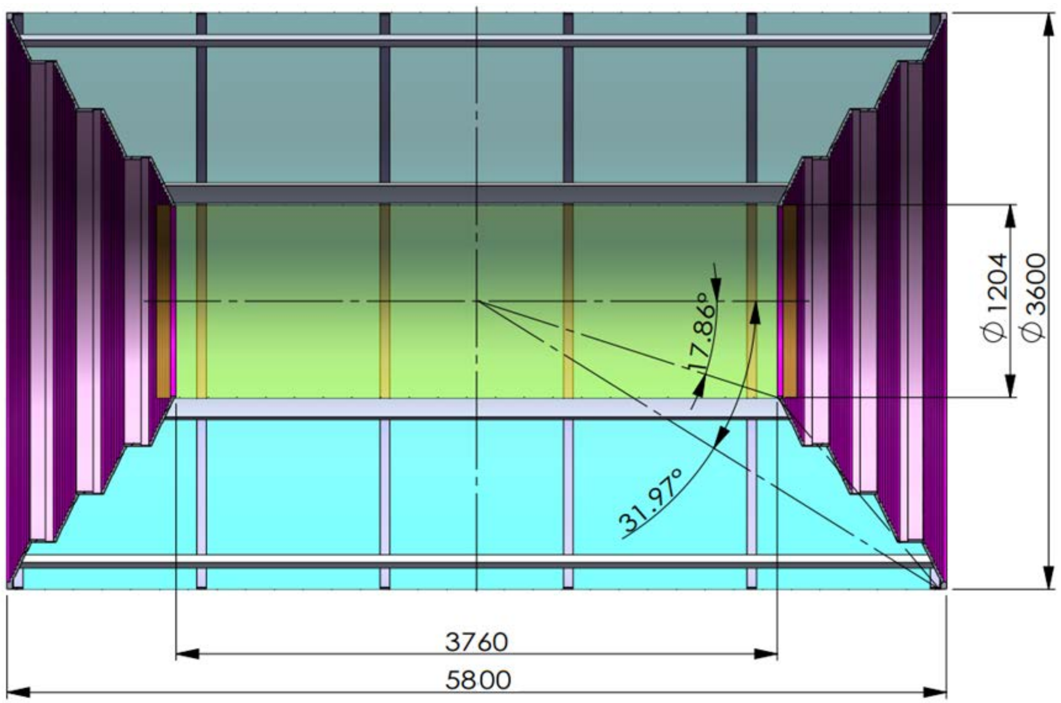
Amplitude (left) and Uniformity/ch (right)

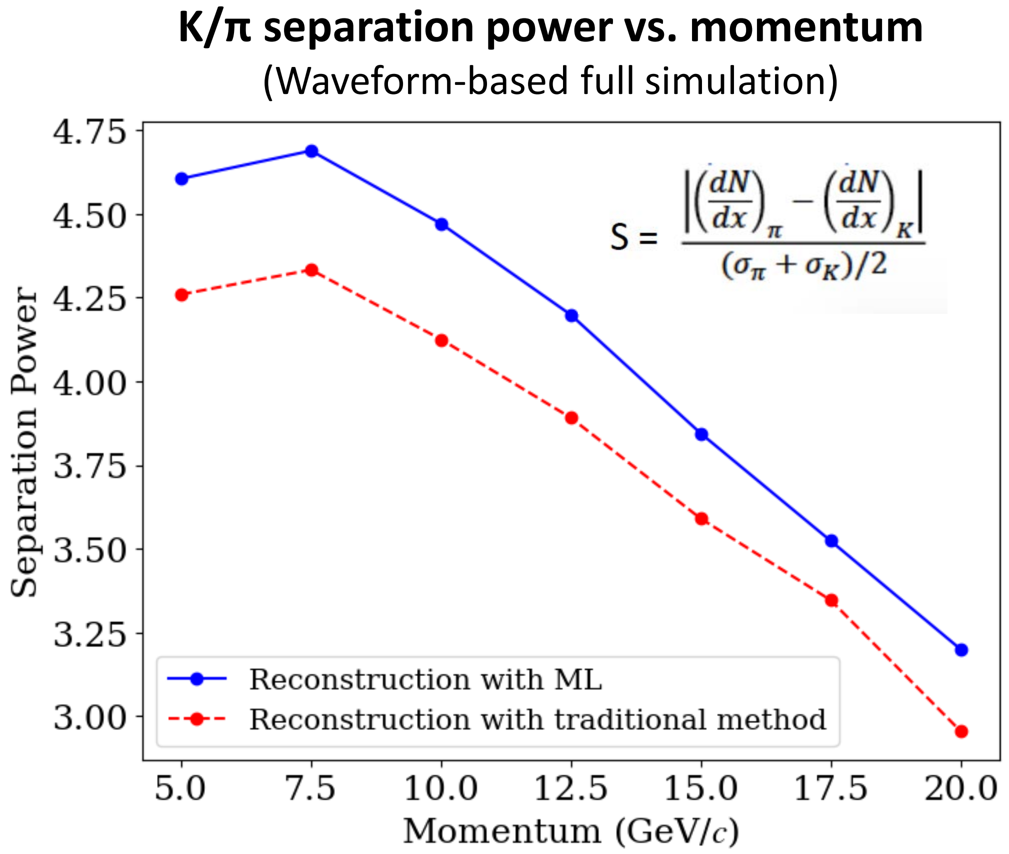
Performance of pixelated readout TPC

Parameters	Higgs run	Z pole run
B-field	3.0 T	2.0 T
Readout size (mm)/All channels	0.5mm×0.5mm /2×3×10^7	0.5mm×0.5mm /2×3×10^7
Layers per track in rφ	2300	2300
Material budget barrel (X_0)	0.59 %	0.59 %
Material budget endcap (X_0)	15 %	15 %
$\sigma_{r\varphi}$ (cluster level)	120μm (full drift)	400μm (full drift) w. distortion
σ_z (cluster level)	≃ 0.6 - 1.0 mm (for zero – full drift)	≃ 0.6 - 1.0 mm (for zero – full drift)
2-hit separation in rφ	0.5 mm	0.5 mm
K/π separation power @20GeV	2.6 σ	2.6 σ
dE/dx	< 3.0 %	< 3.0 %
Momentum resolution normalized: $\sigma_{1/pT} = \sqrt{a^2 + (b/pT)^2}$	a = 1.9 e -5	a = 3.3 e -5
	b = 0.8 e -3	b = 1.5 e -3

To update in ref-TDR with Full simulation

Detailed design of DC for Tera-Z

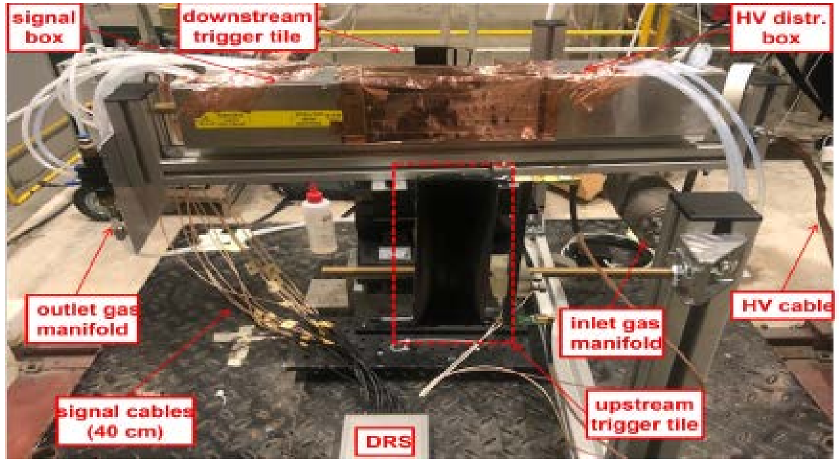


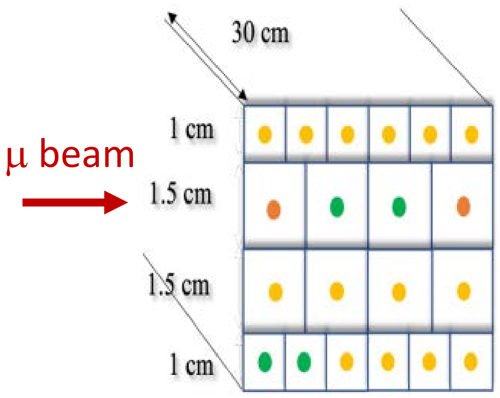


- CF frame structure
- Length: 5800 mm; Outer diameter: 3600 mm; Inner diameter: 1200 mm
- Thickness of each end plate: 20 mm, Weight: 880 kg
- Gas mixture: He + iC_4H_{10} (90/10)
- Cell size: 18mm x 18mm, number of cells: 26483
- Material: 0.16% X_0 for Gas+Wires, 0.21%X_0 for inner and outer cylinders
- Finite element analysis: Endplate deformation 2.7mm, CF frame deformation 1.1mm

International collaboration of DC

- **Beam tests at CERN organized by the IDEA DC group (led by Franco Grancagnolo and Nicola De Filippis)：**
- **Cooperation on**
  - Data taking
  - Data analysis
  - Reconstruction algorithm study



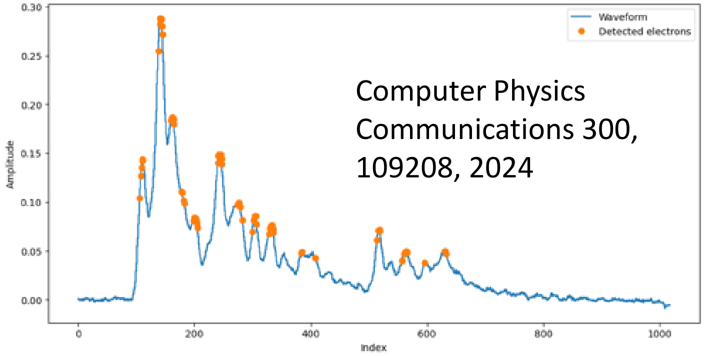


He + iC_4H_{10}

90/10, 85/15, 80/20

- 15μm (Mo+Au)
- 20μm (W+Au)
- 25μm (W+Au)

Waveform reconstruction with ML (domain adaptation)



Computer Physics Communications 300, 109208, 2024

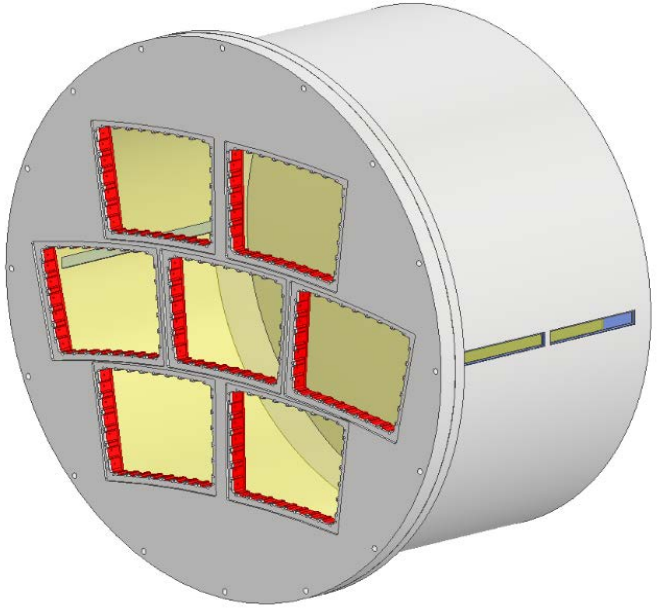
Research Team

- Core of the research team (**10 staffs + TPC group**)
  - IHEP: Huirong Qi, Linghui Wu, Guang Zhao, Mingyi Dong, Yue Chang, Xin She, Jinxian Zhang, Junsong Zhang
  - Tsinghua: Zhi Deng, Canwen Liu, Guanghua Gong, Feng He, Jianmeng Dong, Yanxiao Yang
- Collaboration of the research team (**6 staffs +10 students + 5 LCTPC members**)
  - **TPC:** CIAE, Shandong University, Nankai University, Zhengzhou University and Liaoning University
  - **DC:** Wuhan University, Jilin University
  - **TPC and DC**: DRD1 collaboration and LCTPC collaboration
- Organization of team
  - Regular weekly meeting from April 2024
  - Collaboration regular meeting with some international groups

Shared editing chapter from overleaf

Working plan

- Short term working 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 working plan (**next 3-5 years**)
  - Development of pixelated TPC prototype with low power consumption FEE
    - Beam test collaborated with LCTPC collaboration
  - 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/cm^2 (60nm ASIC)**	**Optimization 330µm - 500µm**
Improved PID	**3% (dN/dx) and π/k S_p**	**<3% (dN/dx) and π/k S_p**
Material budget (barrel)	**Carbon Fiber**	**Full size prototype**

Summary

- TPC detector prototype R&D using pad readout towards pixelated readout for Higgs and Z pole run at the future e^+e^- collider. DC will be as the alternative detector at Tera-Z.

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

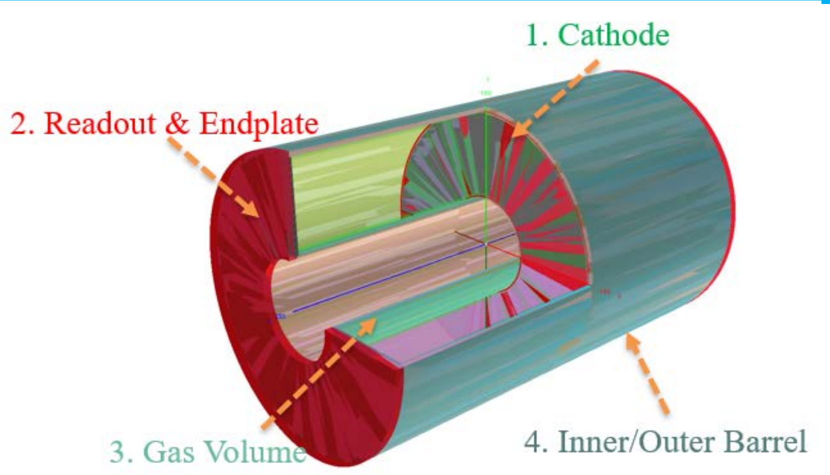
Thank you for your attention!

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

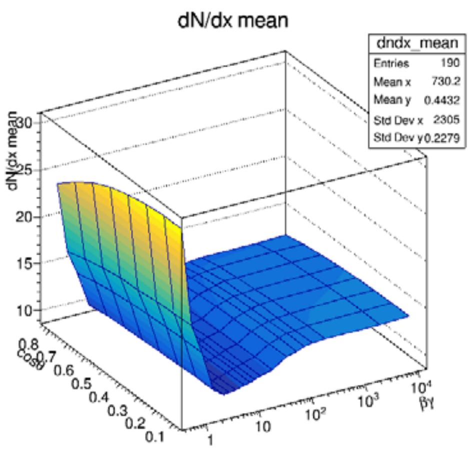
Backup of TPC R&D

TPC software updated in CEPCSW

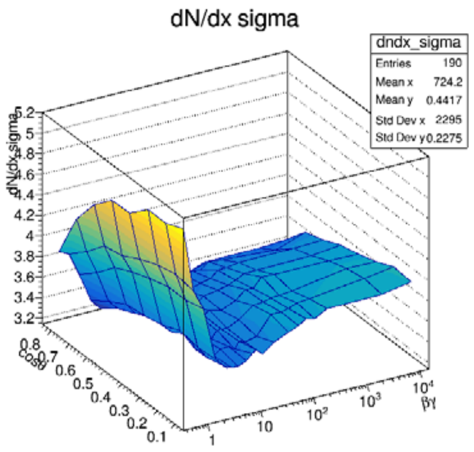
- TPC software updated in CEPCSW to simulate the performance
  - **Geometry** implementation based on CEPC Ref-TDR
    - Cathode, Micromegas readout and endplate, barrel, gas volume
  - **PID** using dN/dx implementation with a parameterized model
    - Track-level dN/dx by parameterization from Garfield++-based full simulation



Parameterized dN/dx

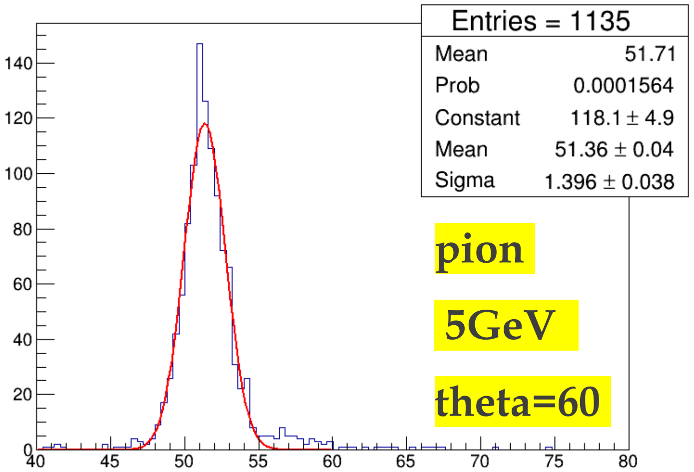


dN/dx mean

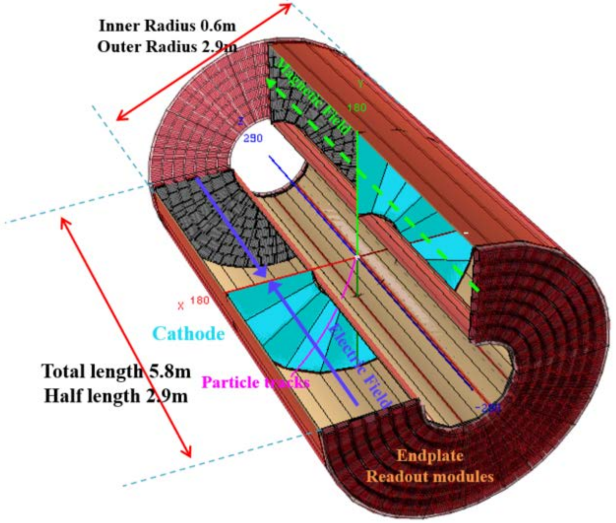


dN/dx sigma

dN/dx simulation in CEPCSW

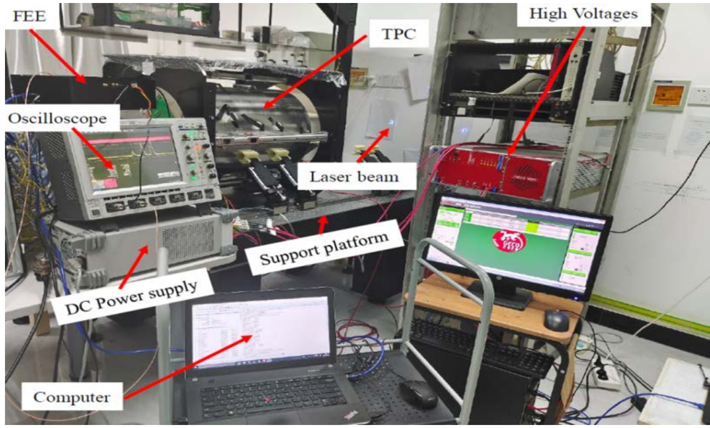


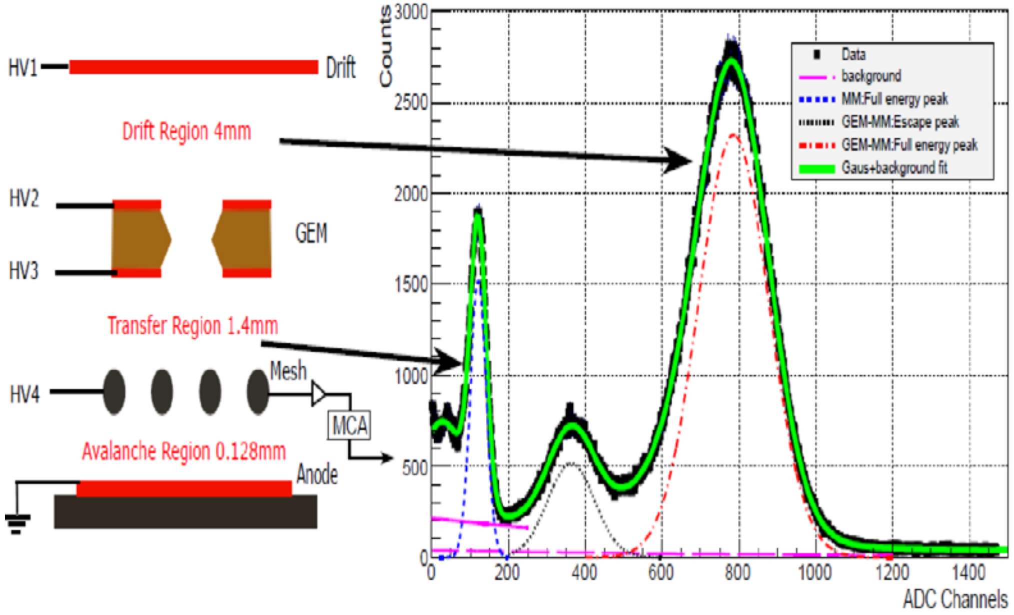
Relative resolution: ~2.7% (Sigma/Mean)

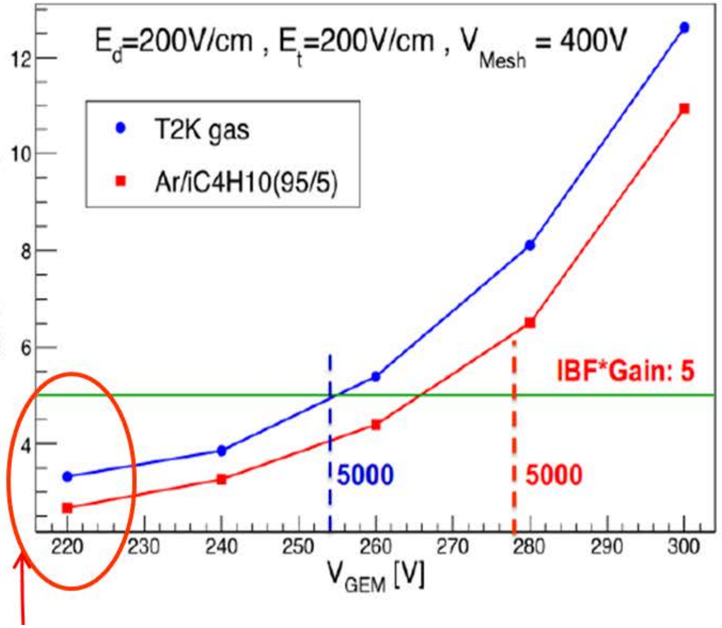


Ion back flow R&D and results

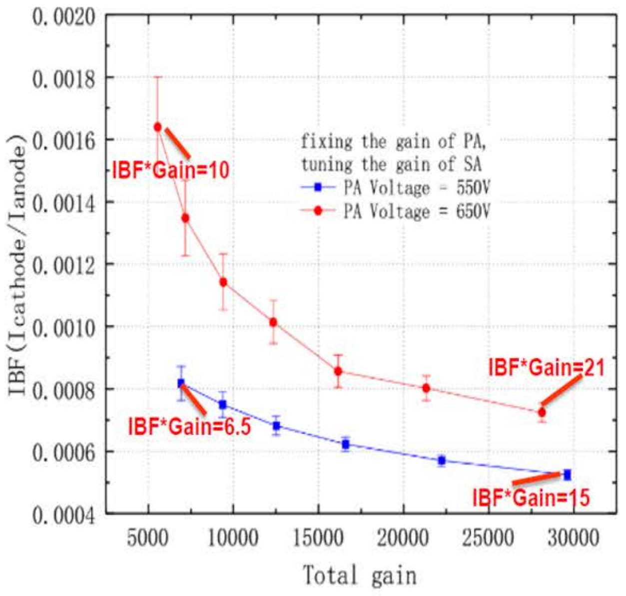
- Achievement by far from TPC module and prototype:
  - Supression ions hybrid TPC module
    - **IBF×Gain ~1 at Gain=2000 validation** with TPC module
  - Spatial resolution of **$\sigma_{r\varphi} \leq 100\ \mu m$** by TPC prototype
  - dE/dx for PID: <3.6% (as expected for CEPC baseline detector concept)
  - Graphene foil suppression (on going @ Shangdong University)







IBF of double mesh MM @USTC/Jianbei Liu

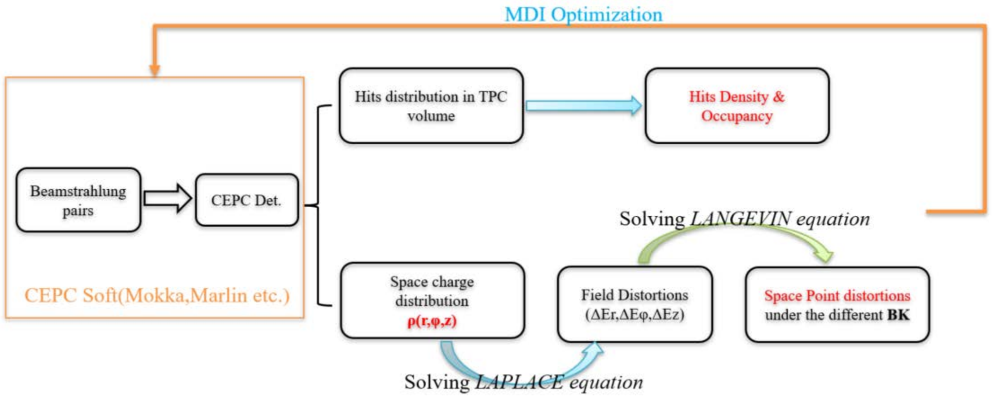


Cite#4: DOI:10.1016/j.nima.2020.164282
Cite#5: CERN-OPEN-2021-012. 2021
Cite#6: IJMPA 36.22 (20212142015

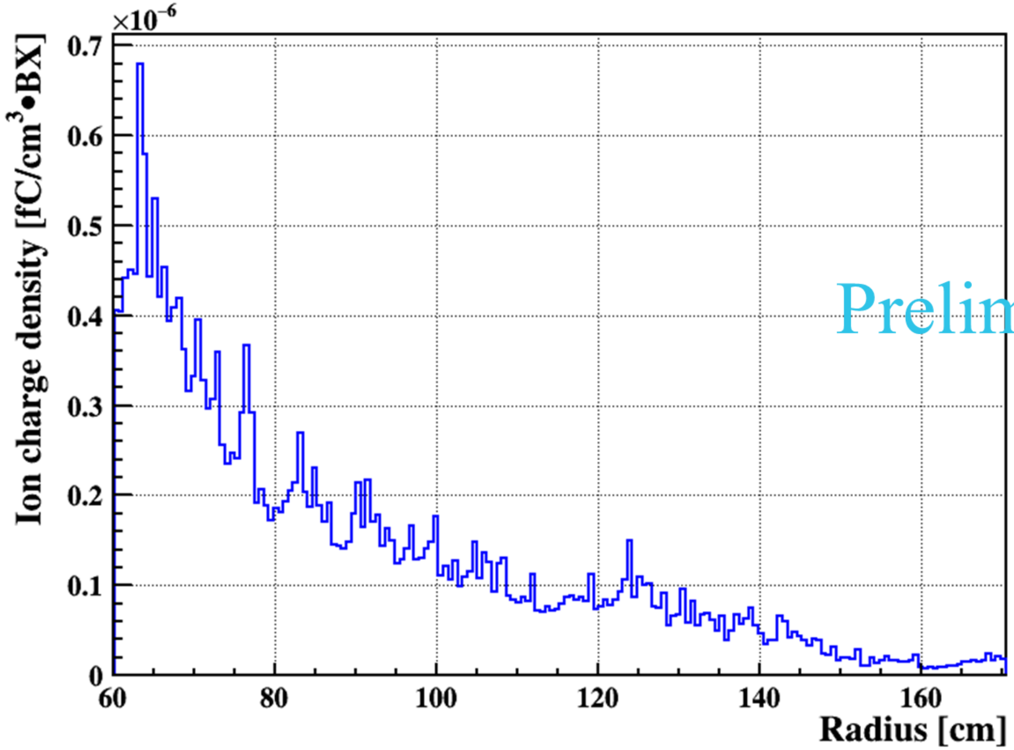
Hybrid TPC module and Double-mesh detector module

Updated of the hits density & occupancy at Tera-Z with BK

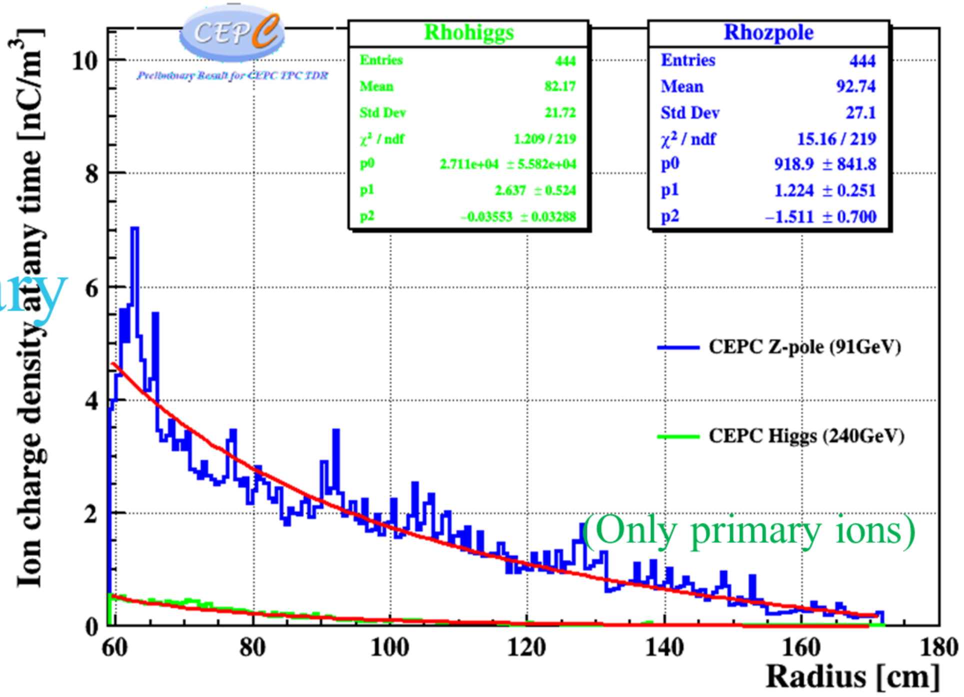
- **Updated simulation results from CEPCSW**
  - Single BX , ρ_{sc}(single BX)~ 0.6e-6 nC/m^3/BX @Z-pole
  - ρ_{sc}(steady state)~ ρ_{sc}(single BX) × BX freq. × max. drift time × 50% × η = 5.46 nC/m^3 (r=60cm) @Z-pole
    - ×5 smaller than FCCee -91



Ionization efficiency(90%)



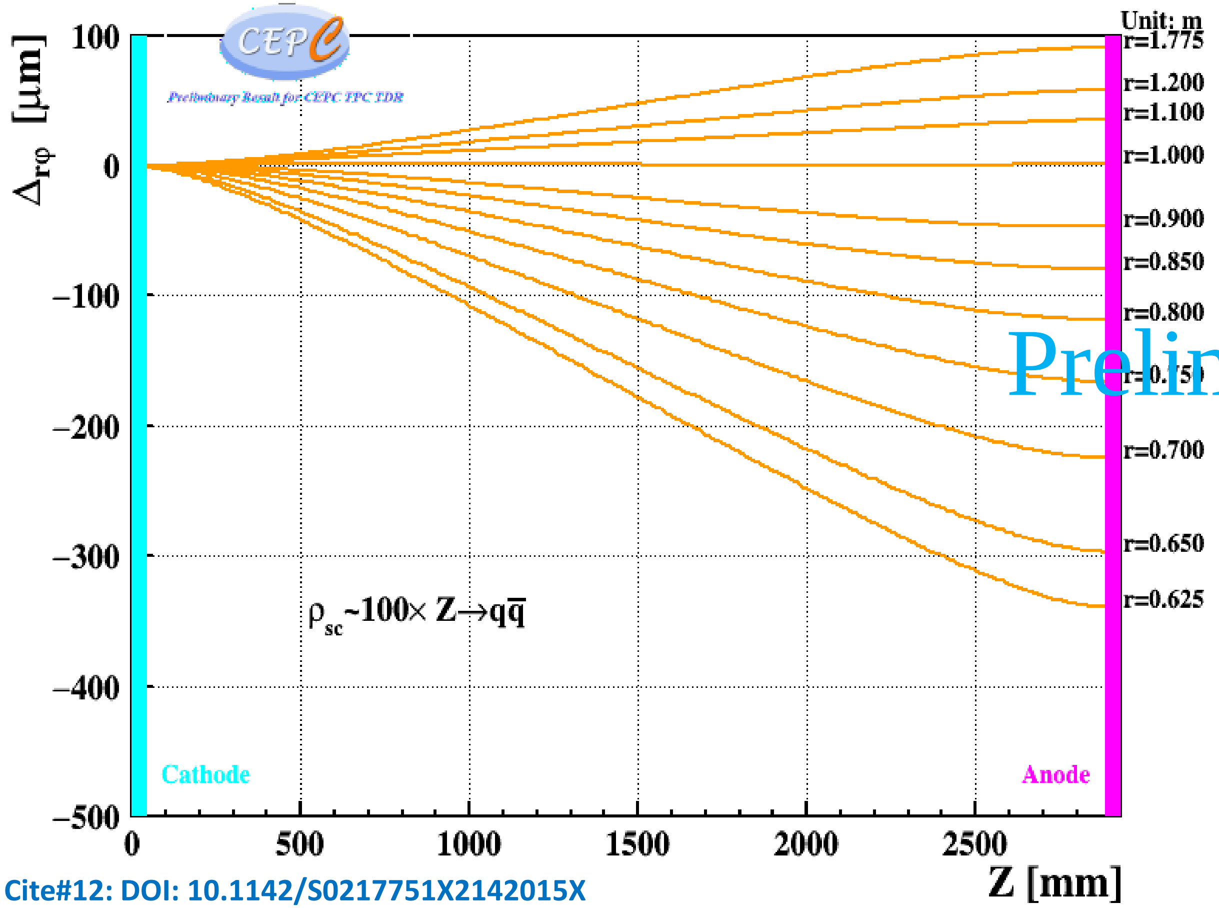
Preliminary

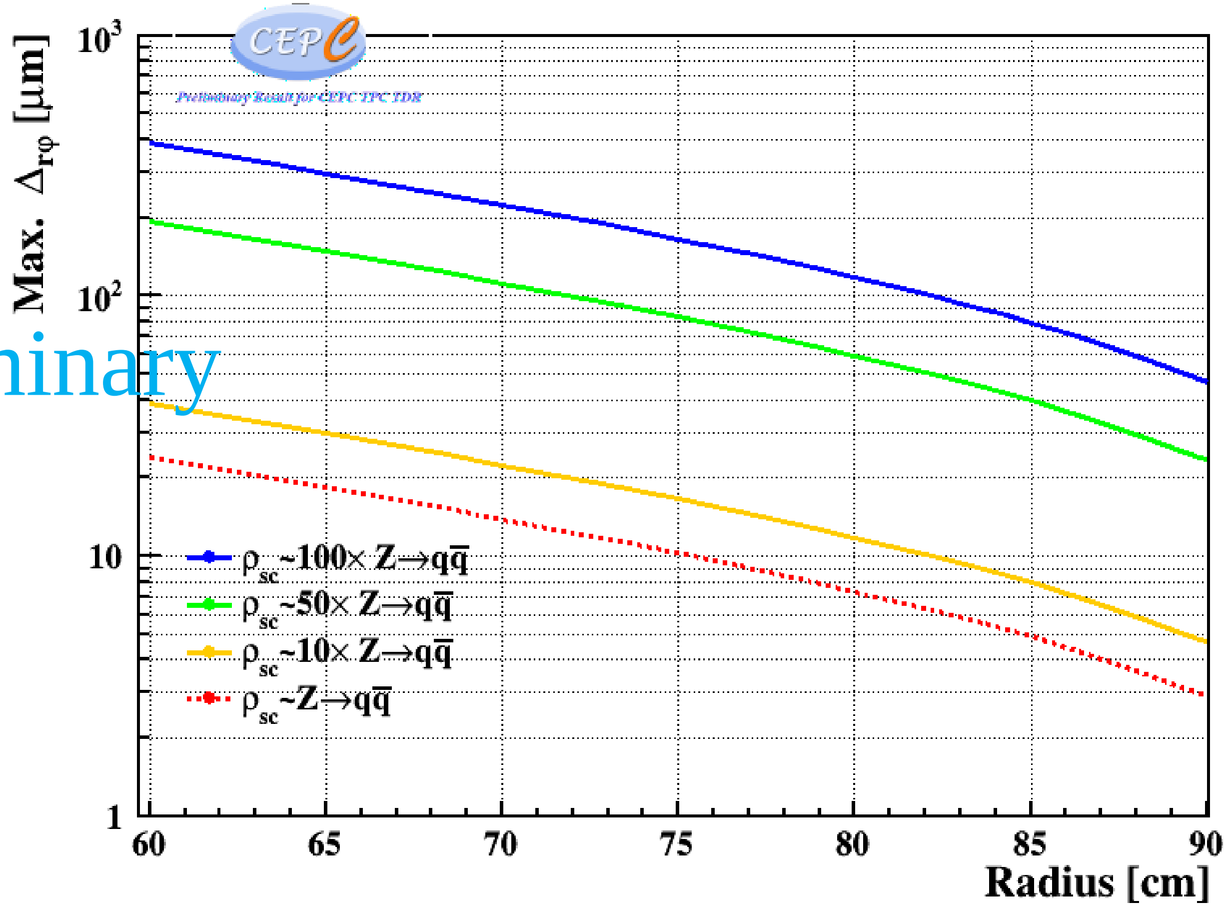


$\rho_{sc}(r)$ (single BX) distribution Left & $\rho_{sc}(r)$ (steady state) Right

#7. Beamstrahlung and distortion √

- Maximum distortion with e+e- to qq at Z pole (Physics events only)
- Maximum distortion under the different Beamstrahlung background (×10, ×50 , ×100 times Physics events)
  - MDI design at Z need carefully optimized with MDI group in CEPC





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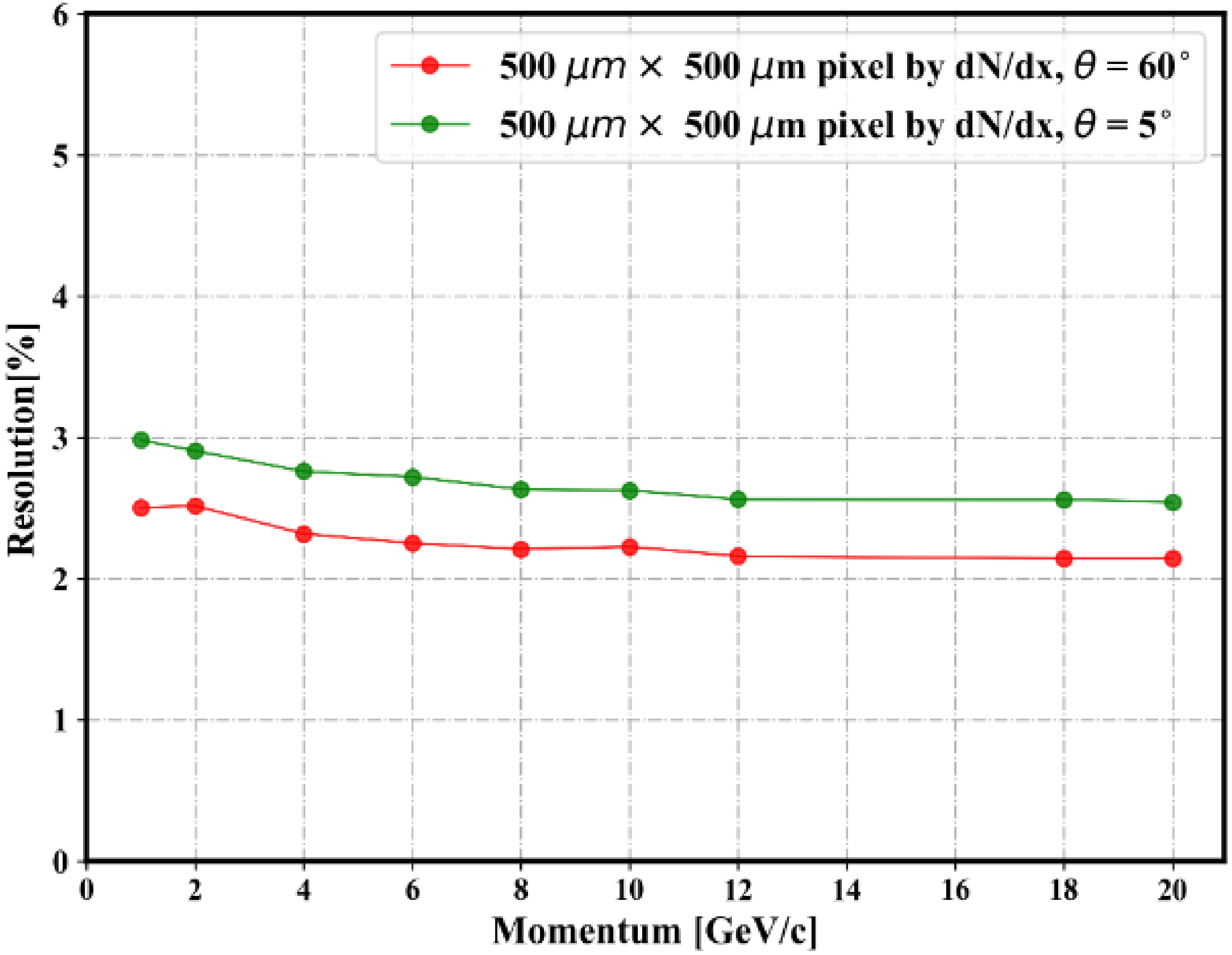
Cite#13: DOI: 10.1016/j.nima.2022.167241
Cite#14: DOI: 10.1088/1748-0221/12/07/P07005

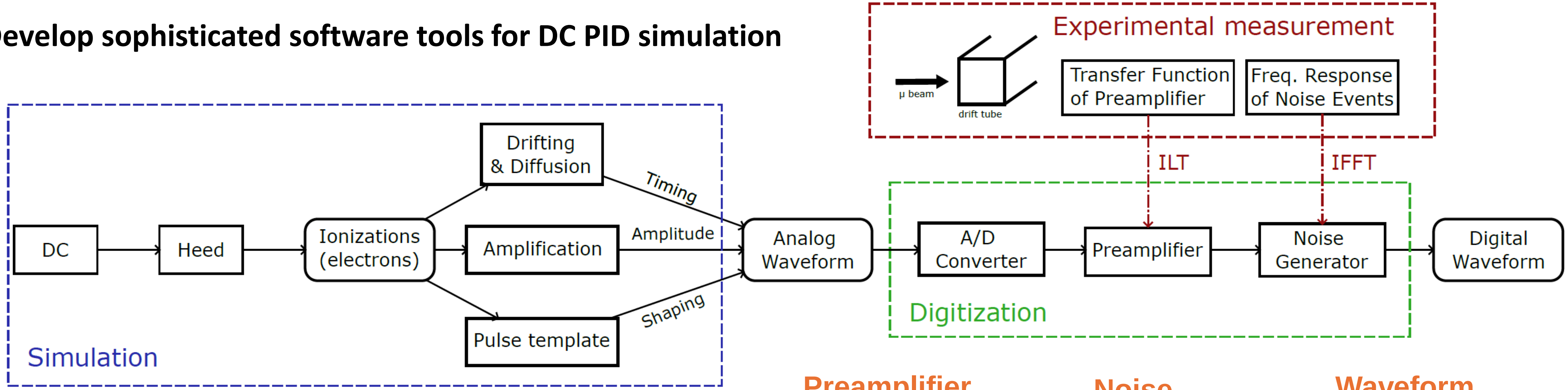
Momentum resolution



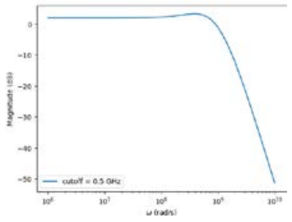
Backup of DC R&D

Waveform-based full simulation

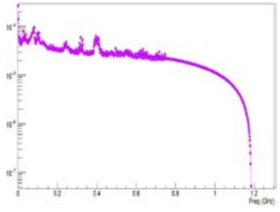
Develop sophisticated software tools for DC PID simulation



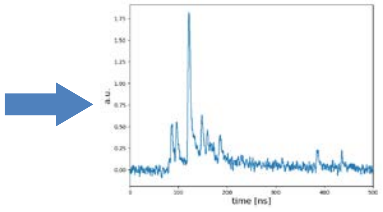
Preamplifier



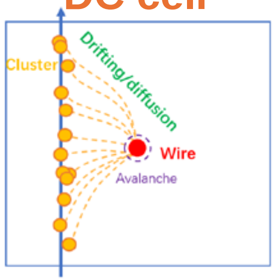
Noise



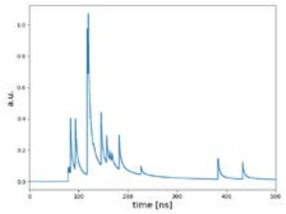
Waveform

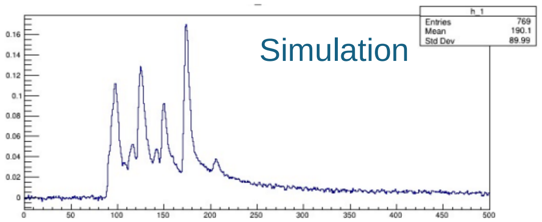


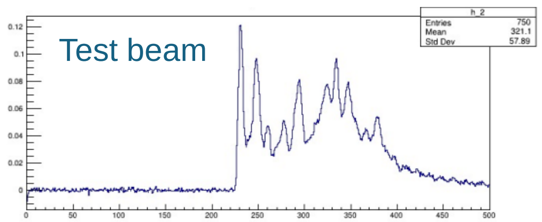
DC cell



Induced signal







Tuned MC is comparable to data