# Progress of CEPC TPC Towards the TDR

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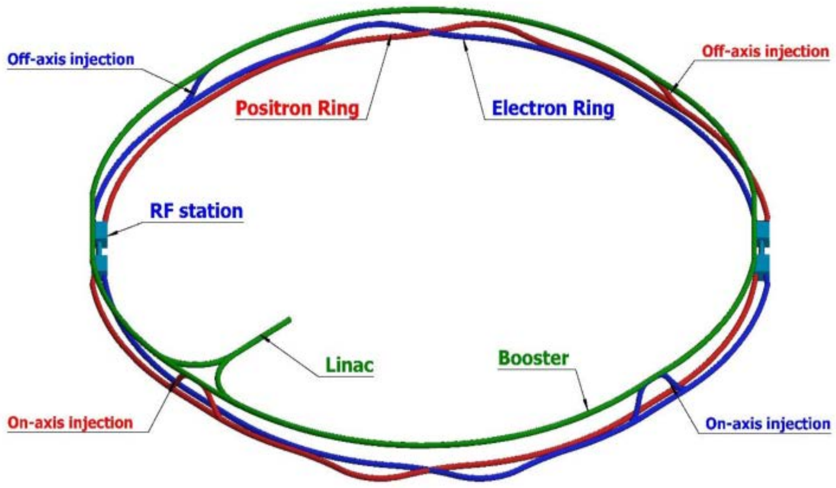
# Content

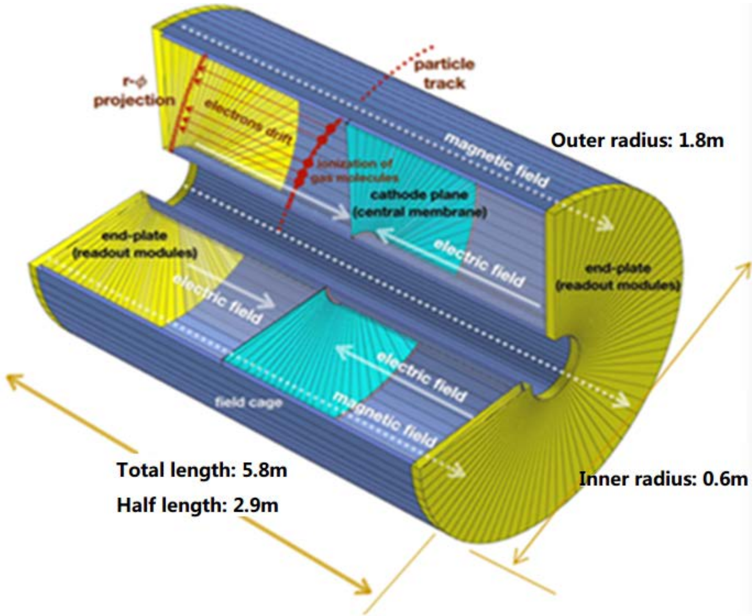
- Motivation and physics requirements
- Technical challenges and R&D efforts
- Detail design of CEPC TPC
- Simulated performance
- Summary

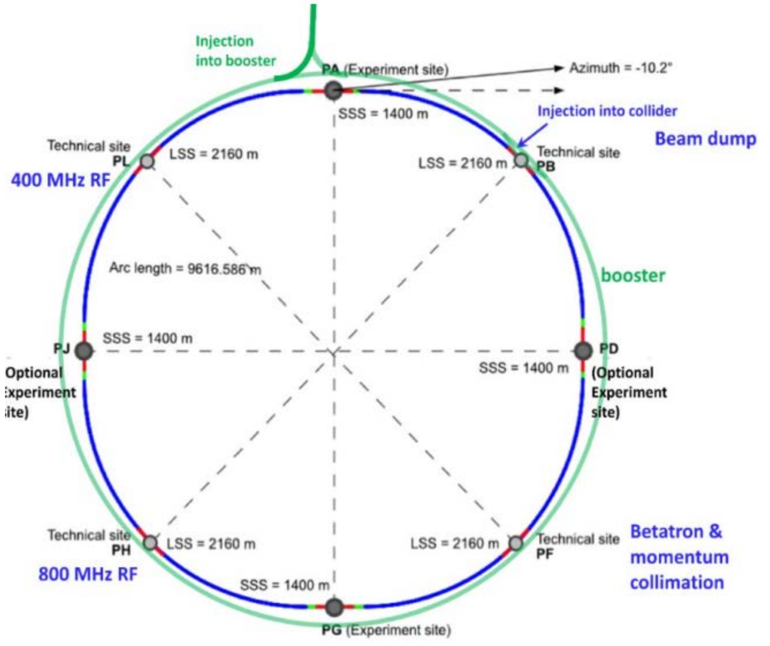
# Motivation on e+e- collider

- A TPC is the main track detector for **some candidate experiments at future e+e- colliders.**
  - Baseline detector concept of ALICE, STAR, CEPC CDR and ILD at ILC
- TPC technology can be of interest for other future colliders (EIC, FCC-ee, KEKb…)
- Pixelated readout TPC can improve PID requirements of **Flavor Physics at e+e- collider.**




Circular Electron Positron Collider (CEPC)



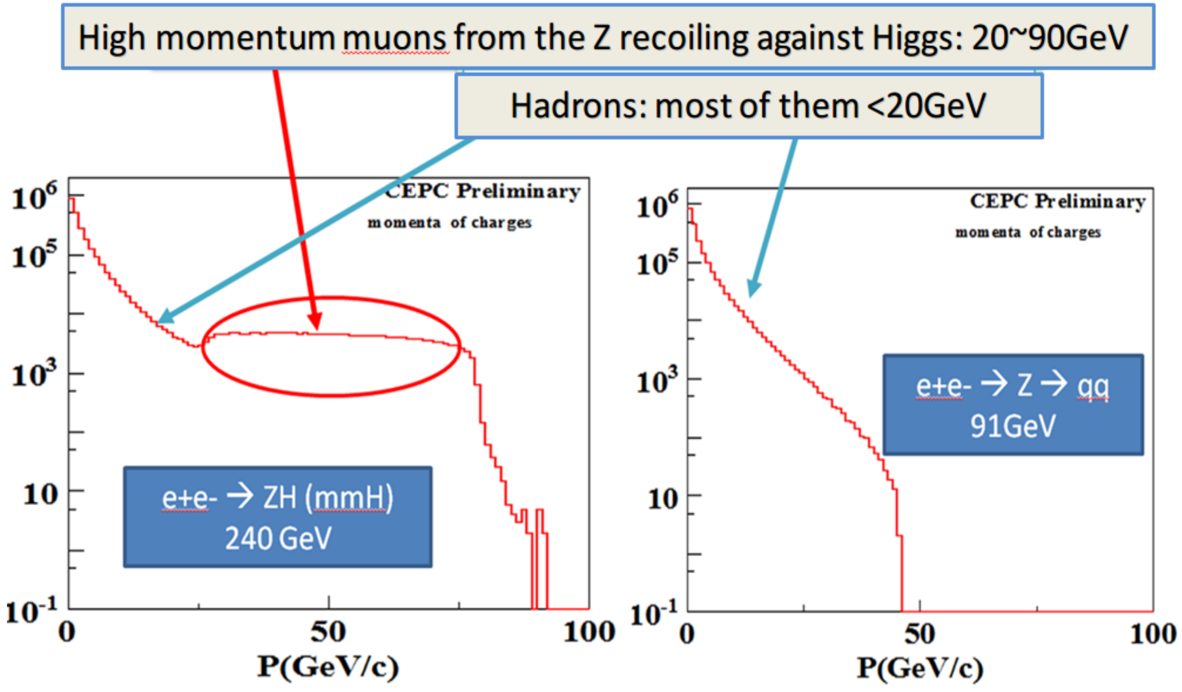

Future Circular Collider (FCCee)

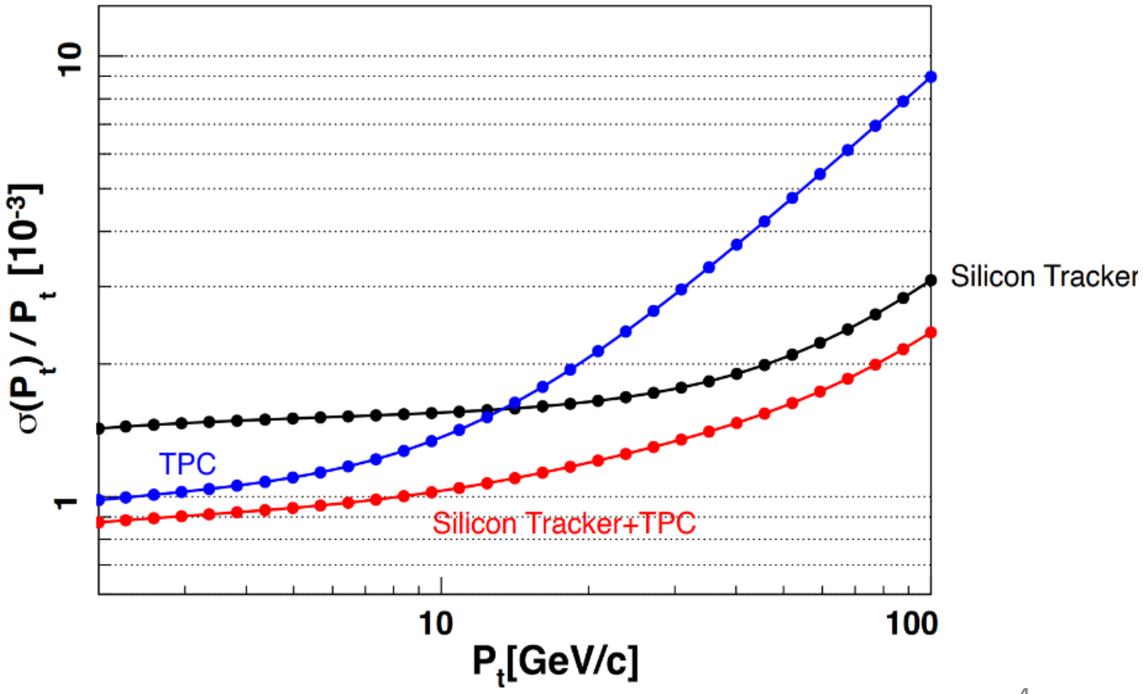
https://arxiv.org/abs/1811.10545

https://arxiv.org/abs/2203.08310

# Physics requirements

- CEPC operation stages in the TDR: **10-years Higgs → 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

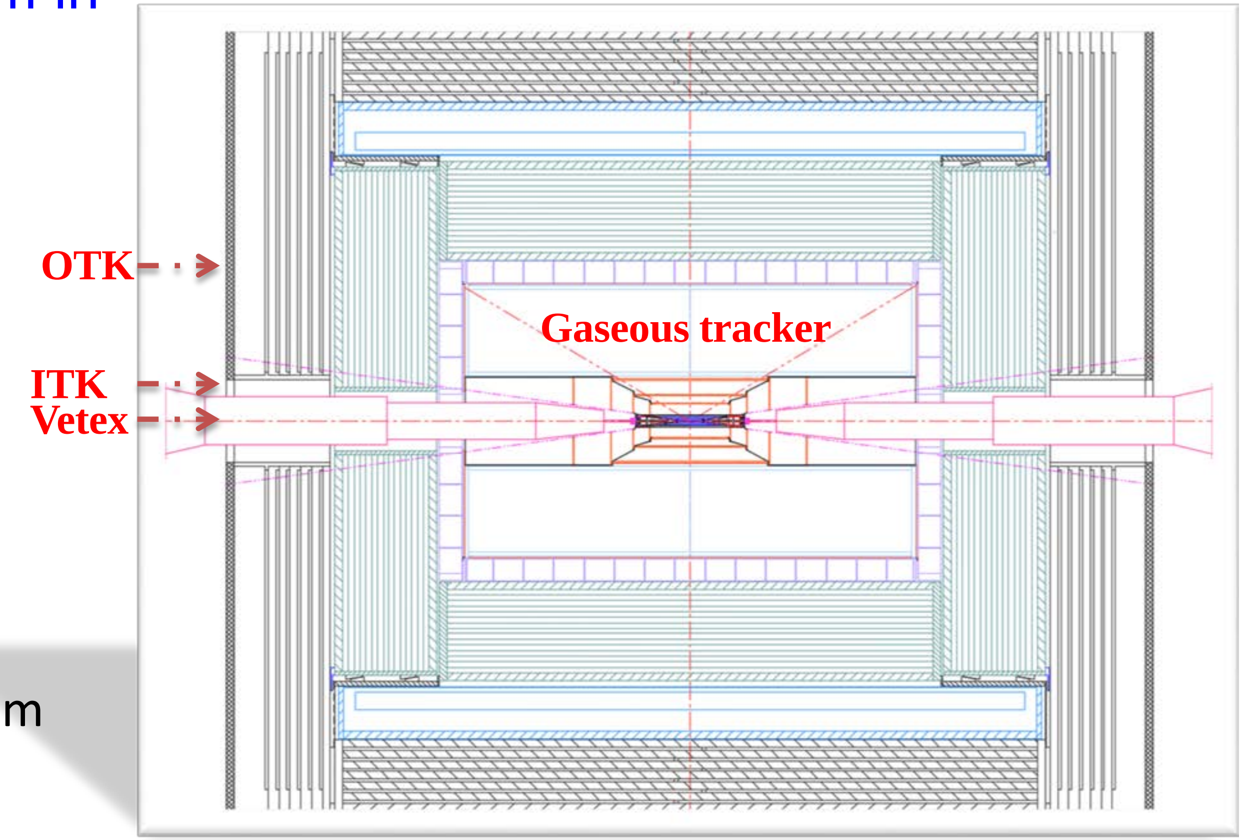



https://doi.org/10.1140/epjc/s10052-018-5876-z

# Large gaseous tracker

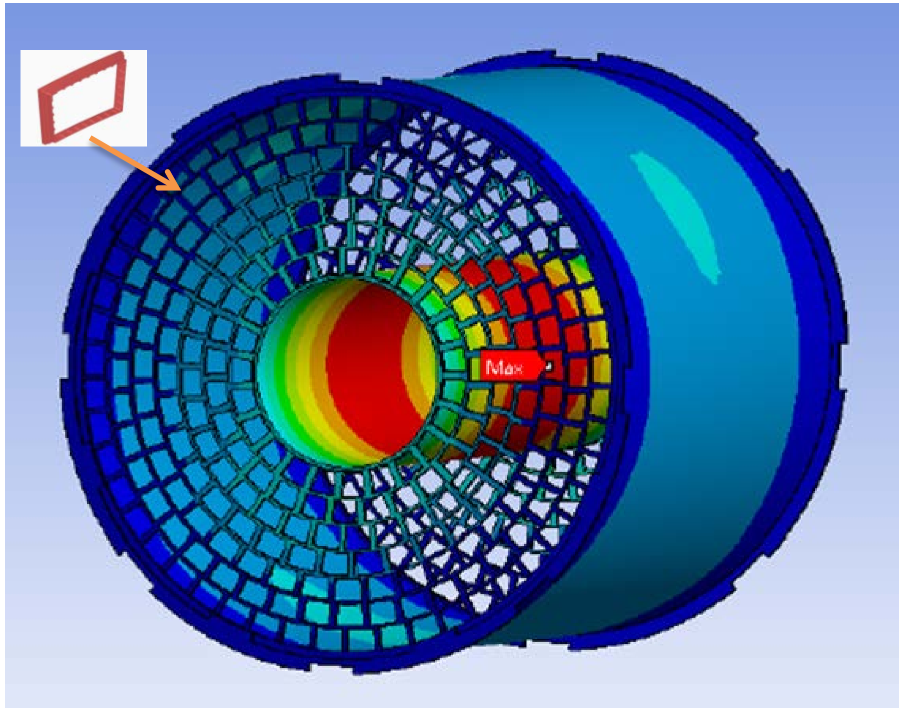
- The detector adopts a hybrid tracking system in CEPC ref-TDR.
- Large gaseous tracker
  - PID of charged hadrons:
    - Benefit flavor tagging and jet substructure study
    - Reduce combination background
  - Quasi-continuous tracking: track finding
  - Ultra light material budget
    - Improved performance at the low momentum (<15GeV/c)
    - The total materials (~0.65% $X_0$) is equivalent to **about 1 layer of a silicon tracker detector**.

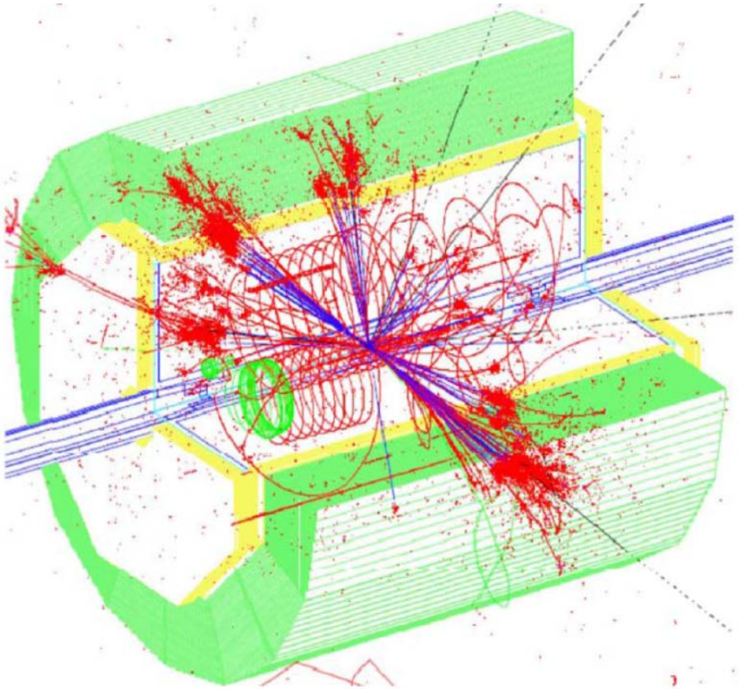



Schematic diagram of the detector

# TPC Detector Technology

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

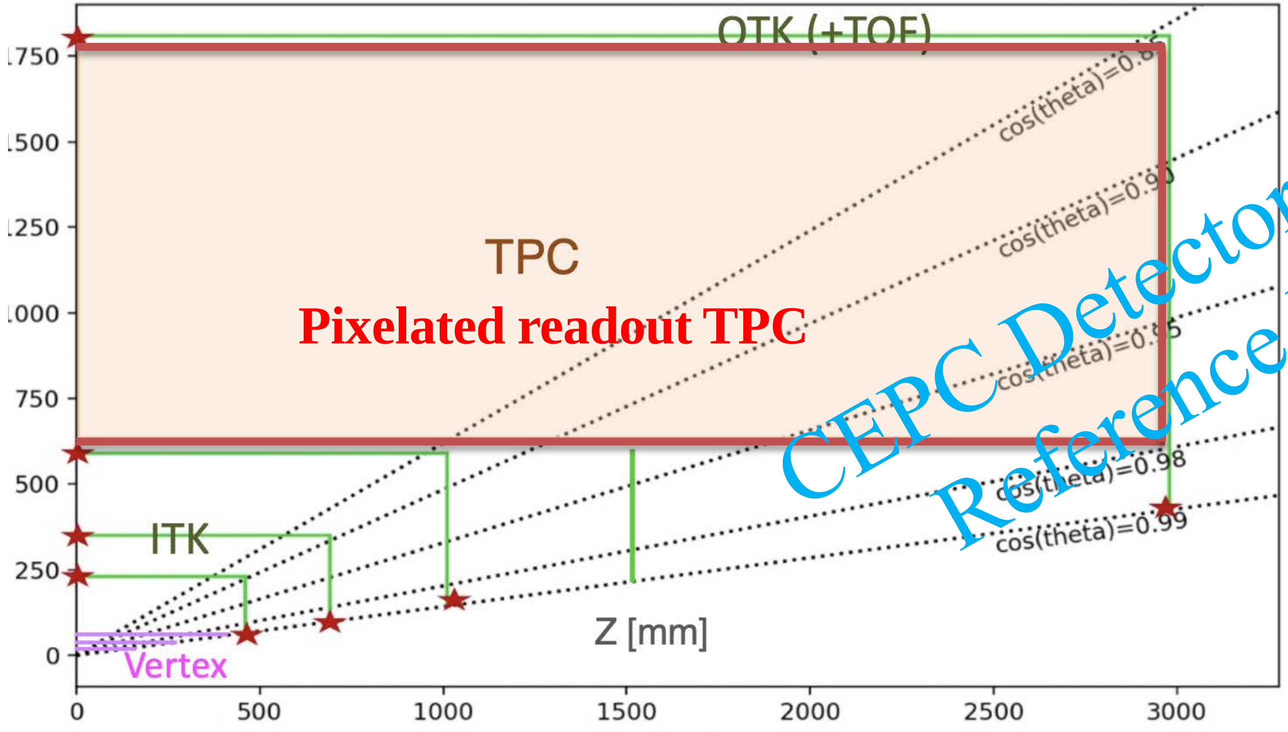


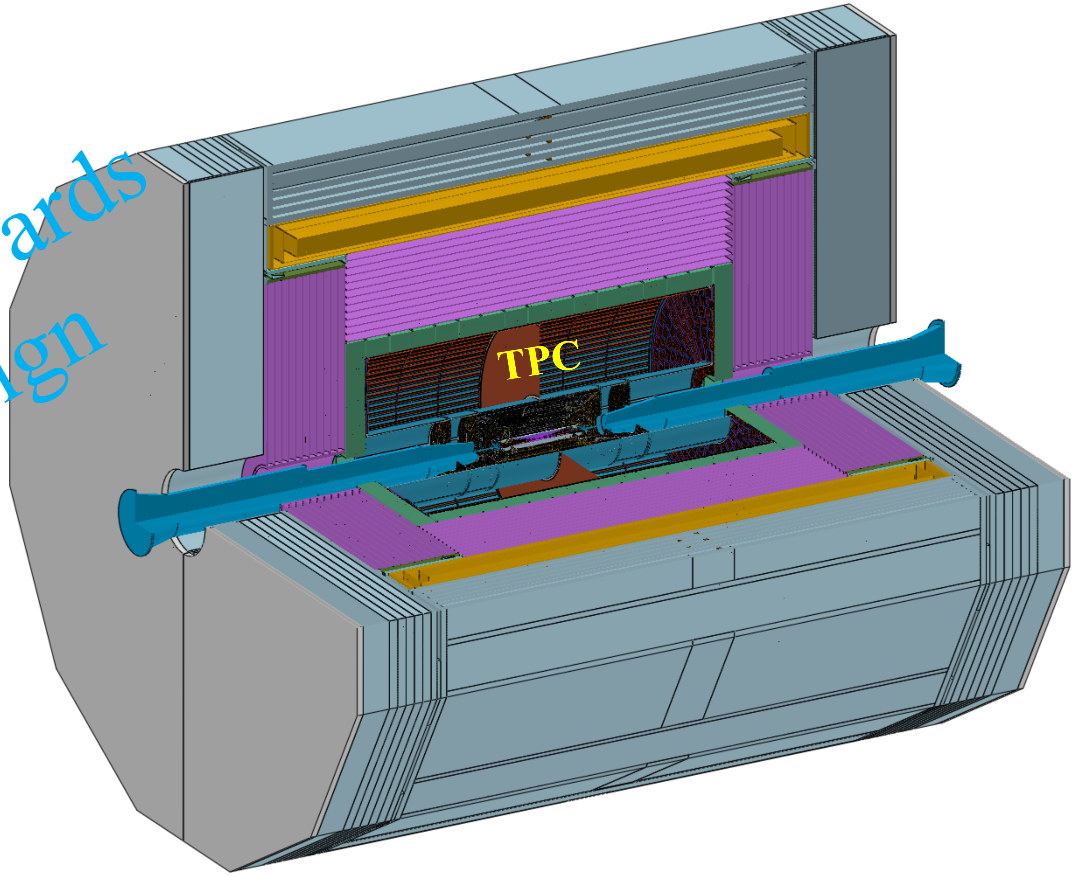



Time Projection Chamber

# Baseline gaseous detector: Pixelated TPC

- 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

# Main Technical Challenges

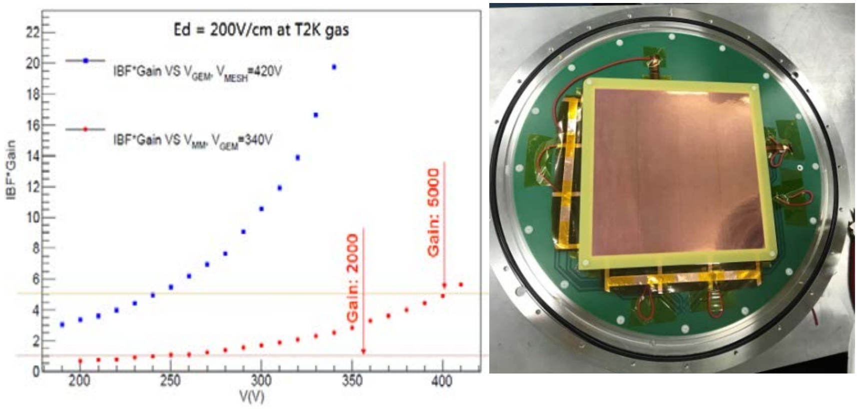
- **Pixelated readout TPC gaseous tracker**

Critical key items

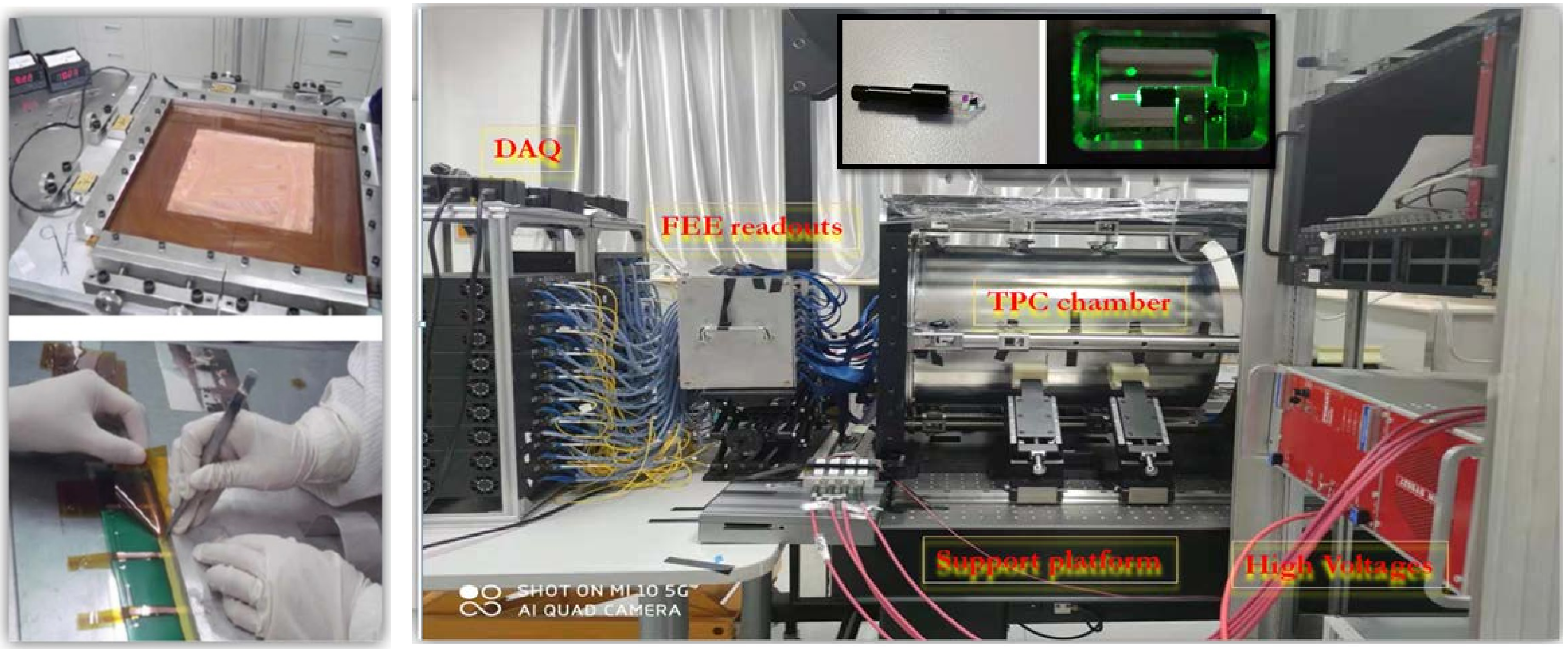
- **Material budget at endcap/barrel √**
- **Occupancy and hit density at Tera-Z √** → **Jinxian Zhang's talk**
- **Ion backflow suppression √**
- **Running at 2 Tesla √**
- **To meet the PID requirement √**
- **Optimization of number of channels (ongoing)**
- **Acceptable power consumption (ongoing)**

# TPC prototype R&D efforts and results

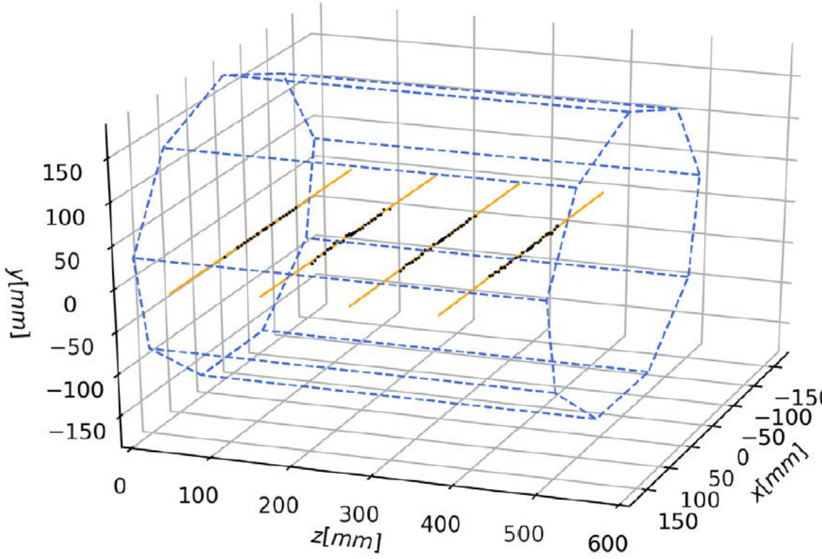
- **CEPC TPC detector prototyping roadmap:**
  - From TPC module to TPC prototype R&D for Higgs and Tera-Z
- **Achievement so far:**
  - **IBF×Gain ~1 @ G=2000** validation with a hybrid TPC module
  - Spatial resolution of **$\sigma_{r\phi}$≤100 μm and dE/dx resolution of 3.6%**
  - FEE chip: reach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




Ion suppression TPC module R&D



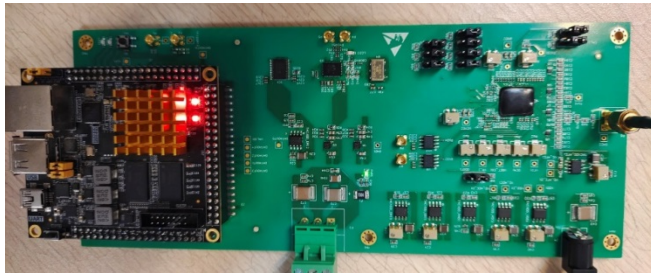

TPC prototype with integrated 266nm UV laser

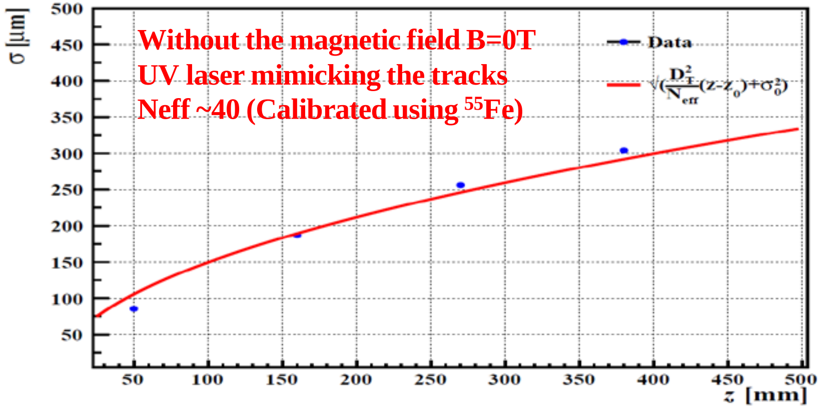


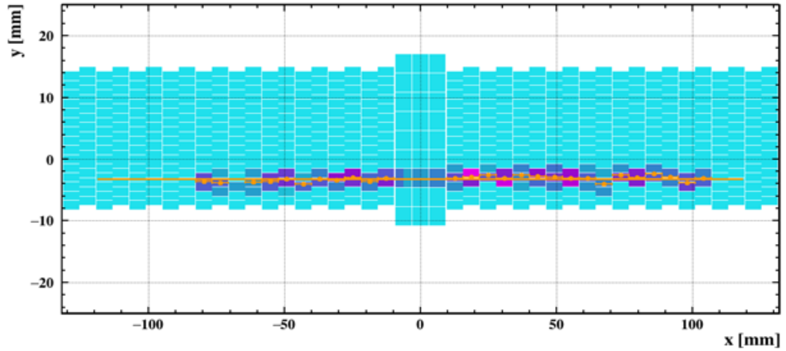

Track reconstruction

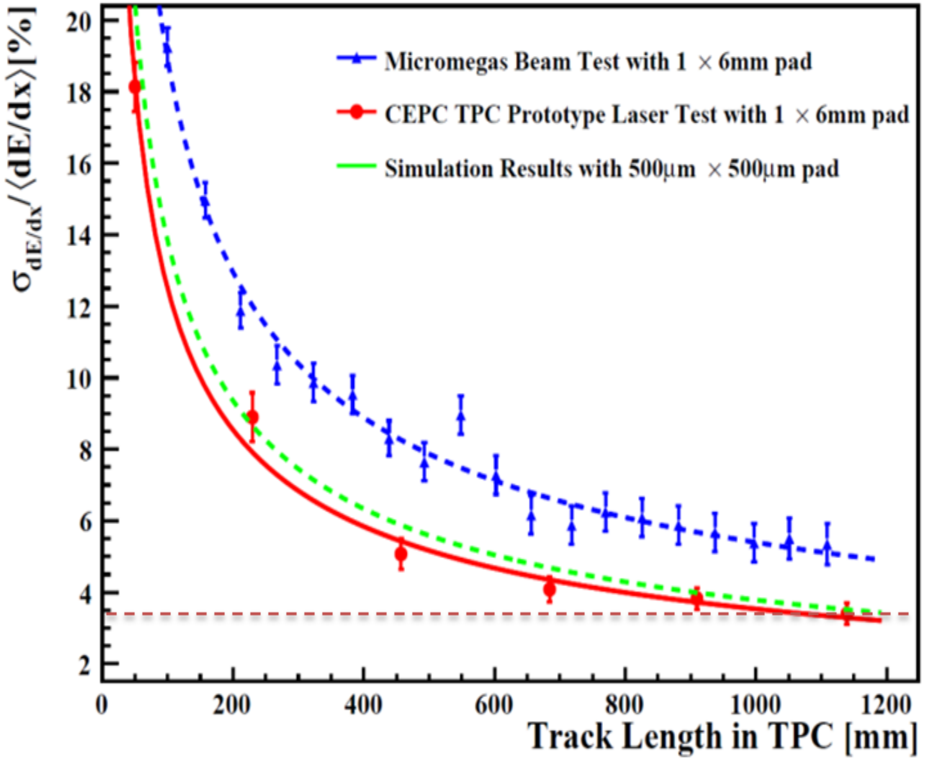
# Highlights of TPC prototype R&D

- **Highlights of R&D of CEPC pad-readout TPC, and toward pixelated-readout TPC**
  - A lab for MPGD assembly and mass production has been set up at IHEP.
  - A TPC prototype integrated 266nm UV laser tracks has been constructed. The UV laser signals are analyzed, proving that the TPC is good for the Higgs run.
  - **Easy-to-install modular design** of Pixelated readout TPC for CEPC TDR.





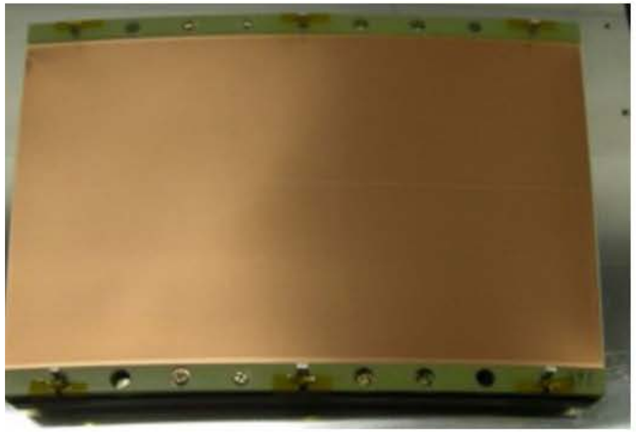
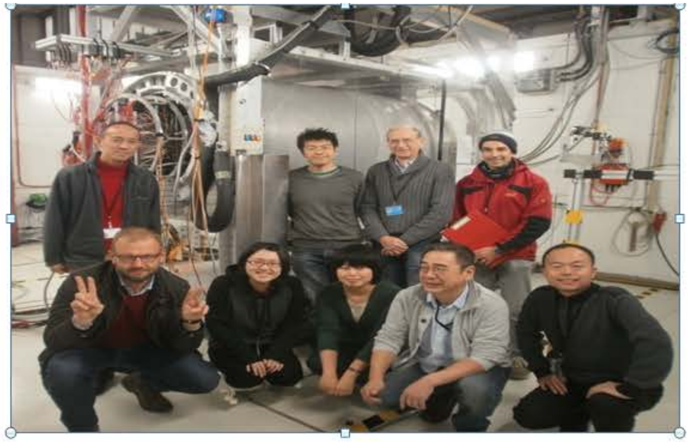
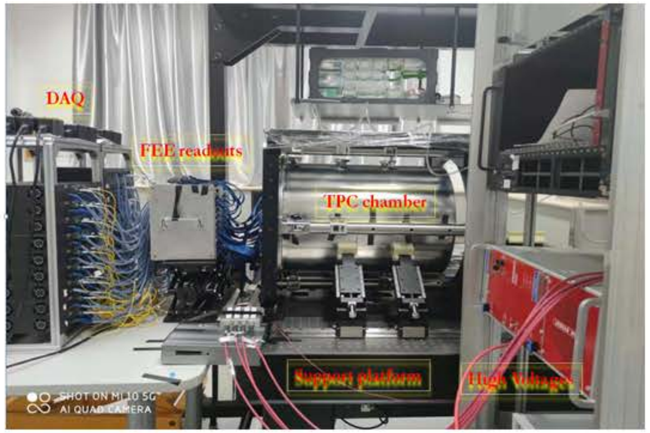

**Publications by CEPC TPC group in 2018-2024:**

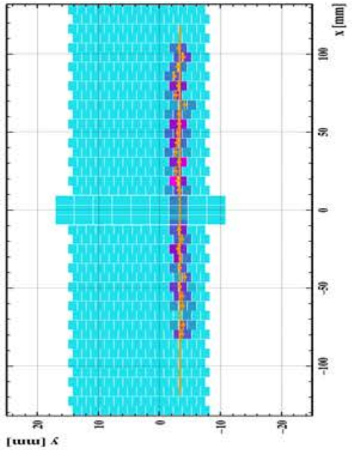
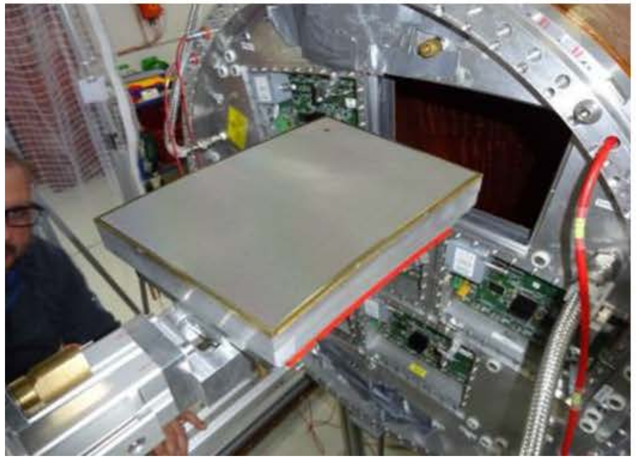
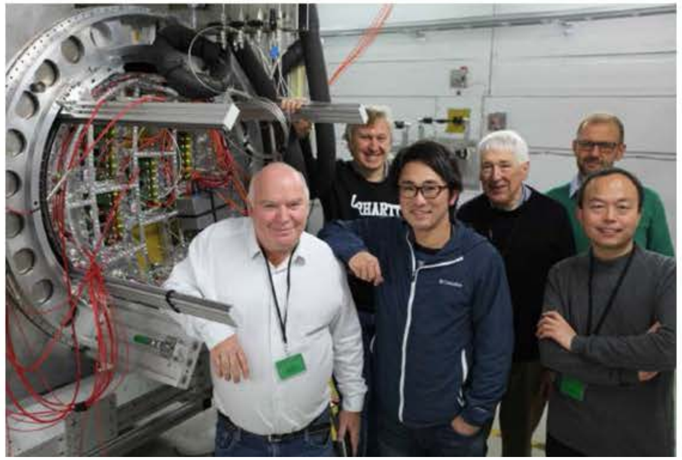
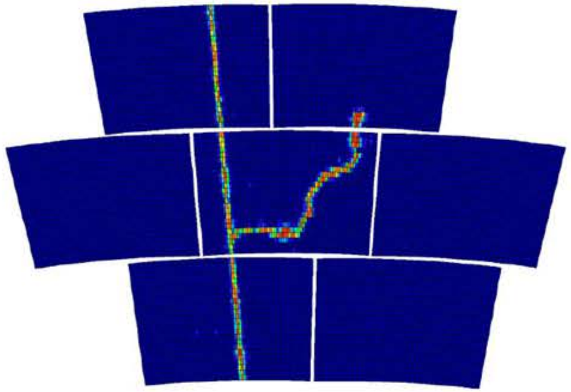
- https://doi.org/10.1088/1748-0221/18/08/E08002
- https://doi.org/10.22323/1.449.0553
- https://doi.org/10.1016/j.nima.2022.167241
- https://doi.org/10.1109/NSS/MIC44867.2021.9875566
- https://doi.org/10.1109/NSS/MIC44845.2022.10399097
- https://doi.org/10.1088/1748-0221/15/09/C09065
- https://doi.org/10.1088/1748-0221/15/05/P05005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

# Active international collaboration

- **Active 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 $\sigma_{r\varphi} \leq 100$ µm
  - 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

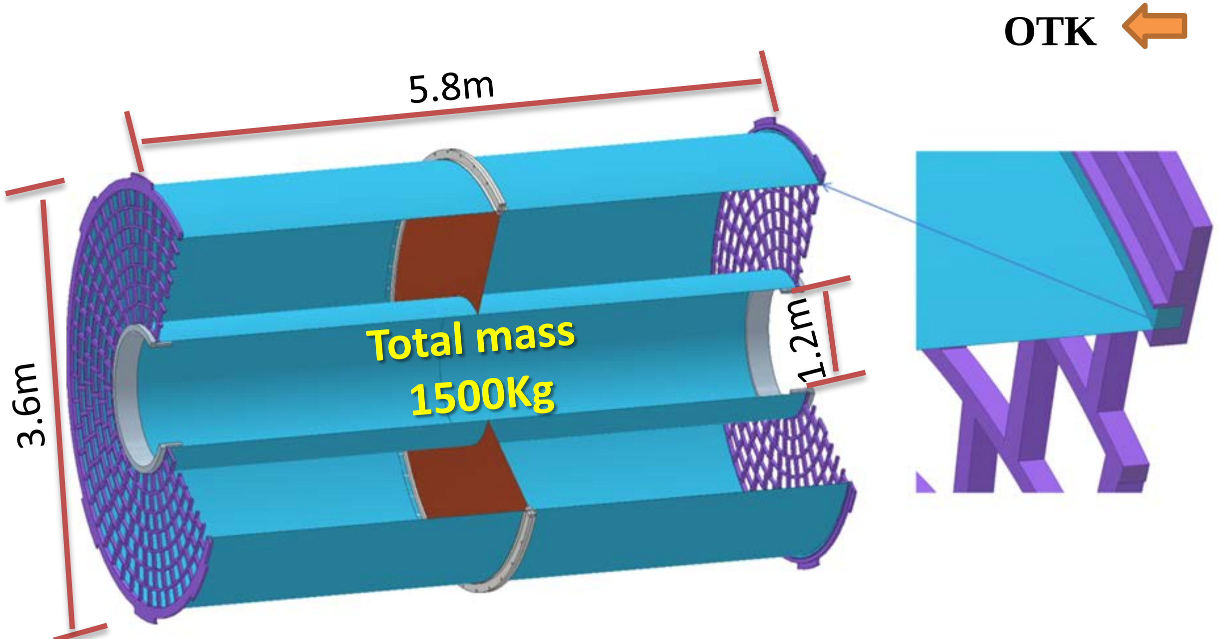




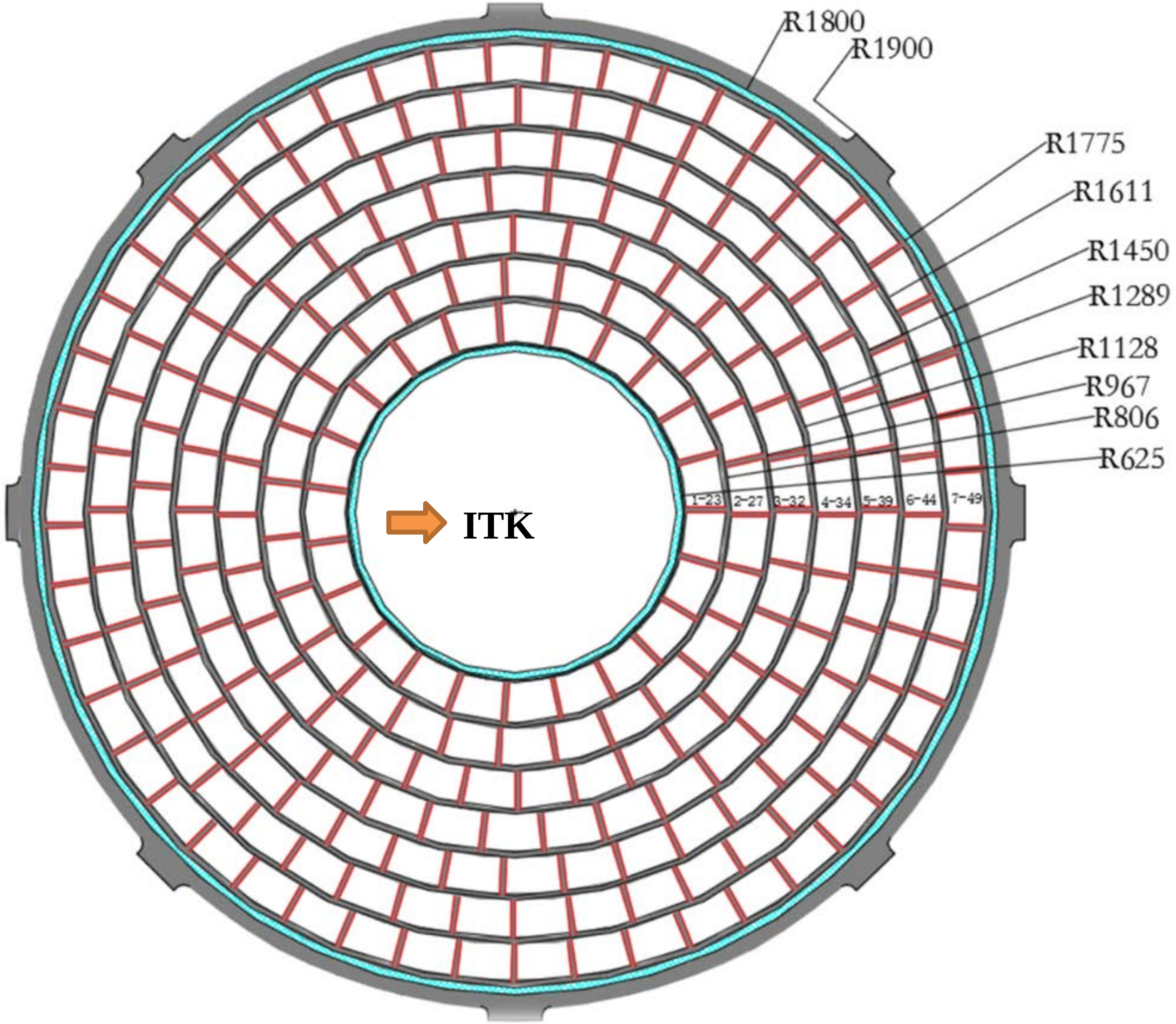






# Detailed design and performance of The Baseline: TPC

# 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 |

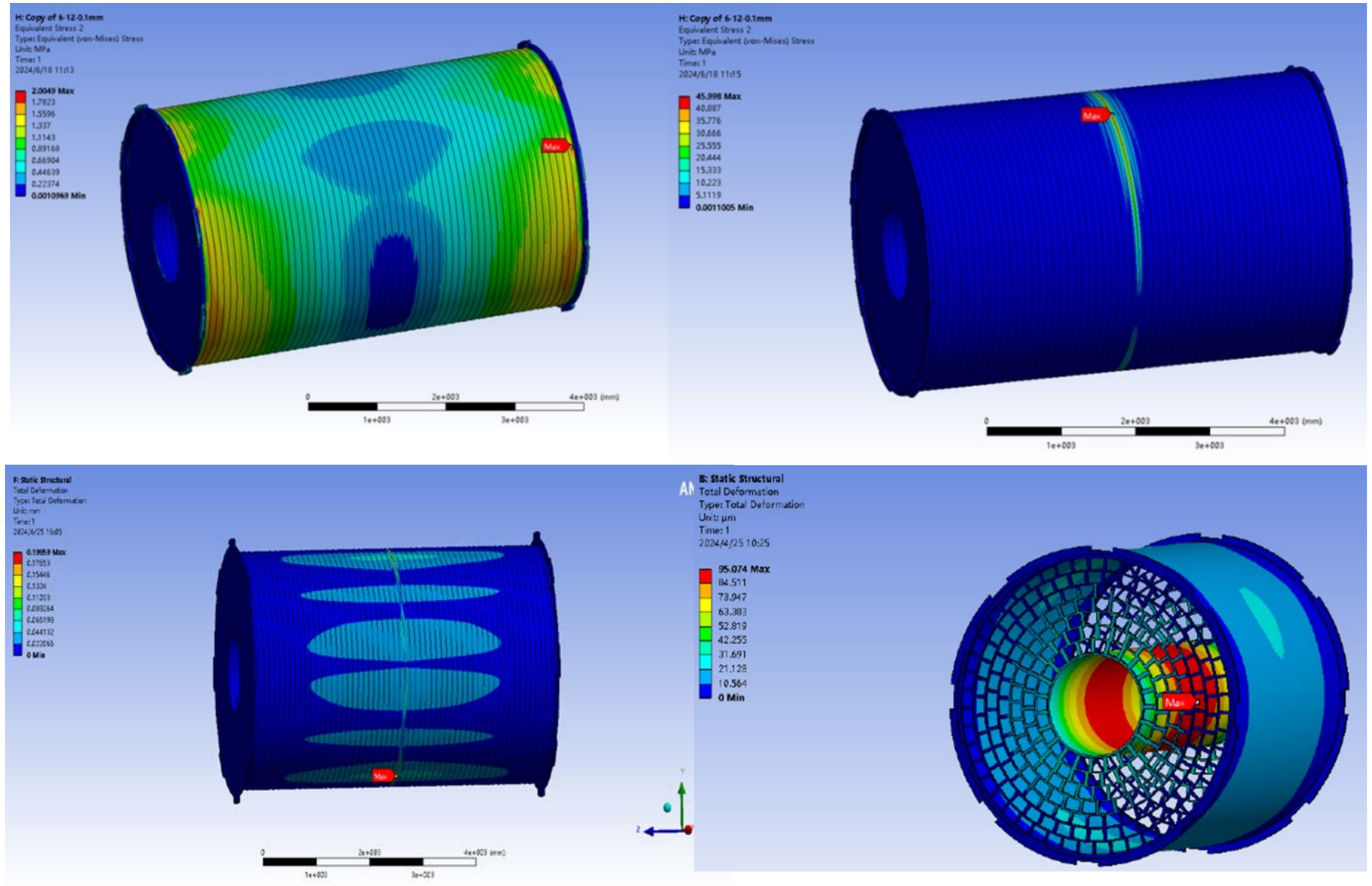



Detailed design of TPC detector in ref-TDR

# Ultra-light barrel and FEA analysis

- Consideration of new the **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 support 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** |

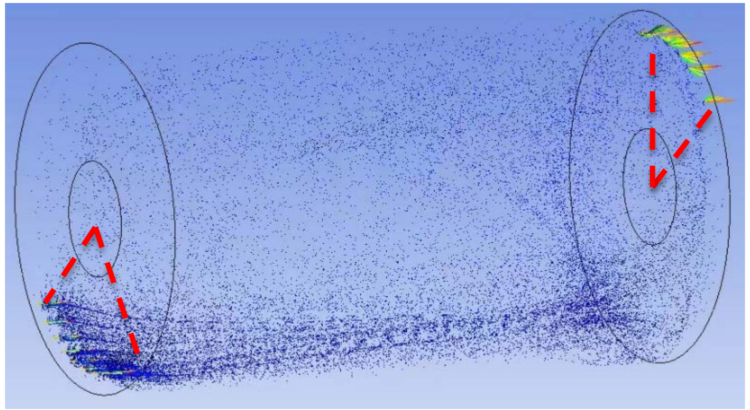
- **Low material of the TPC endcap**

  15%$X_0$ in total, including

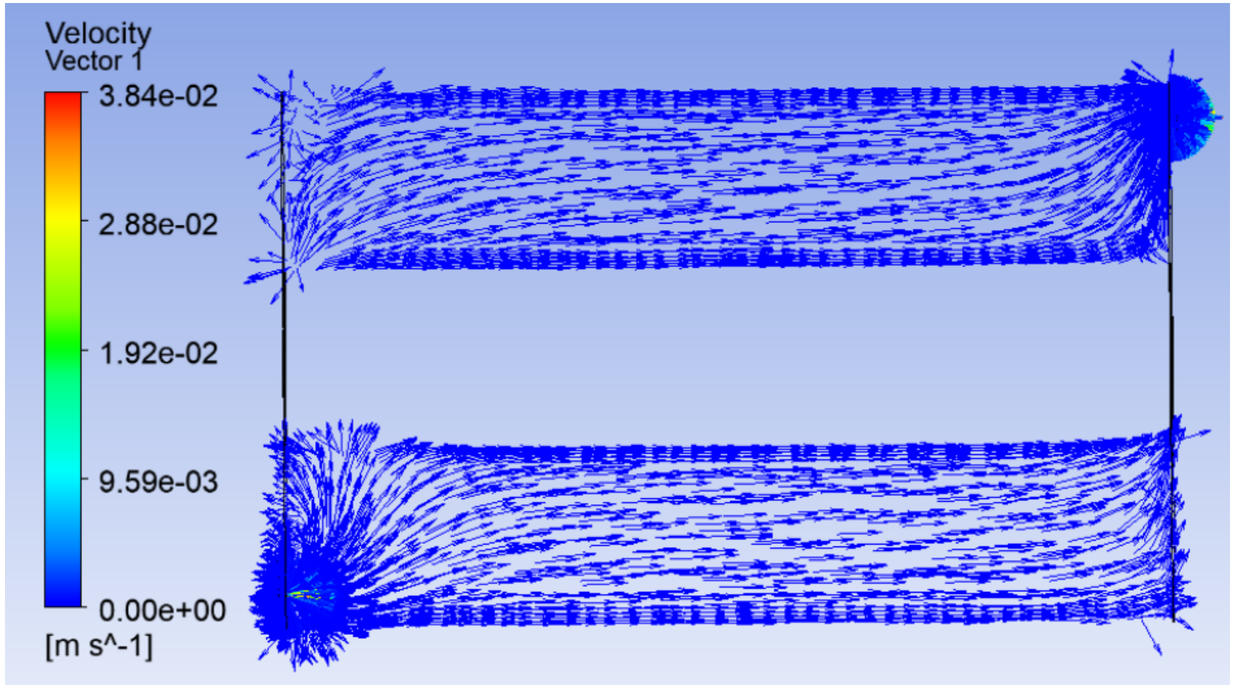
| | |
|---|---|
| Readout plane, front-end-electronics | 4% |
| Cooling | 2% |
| Power cables | 9% |

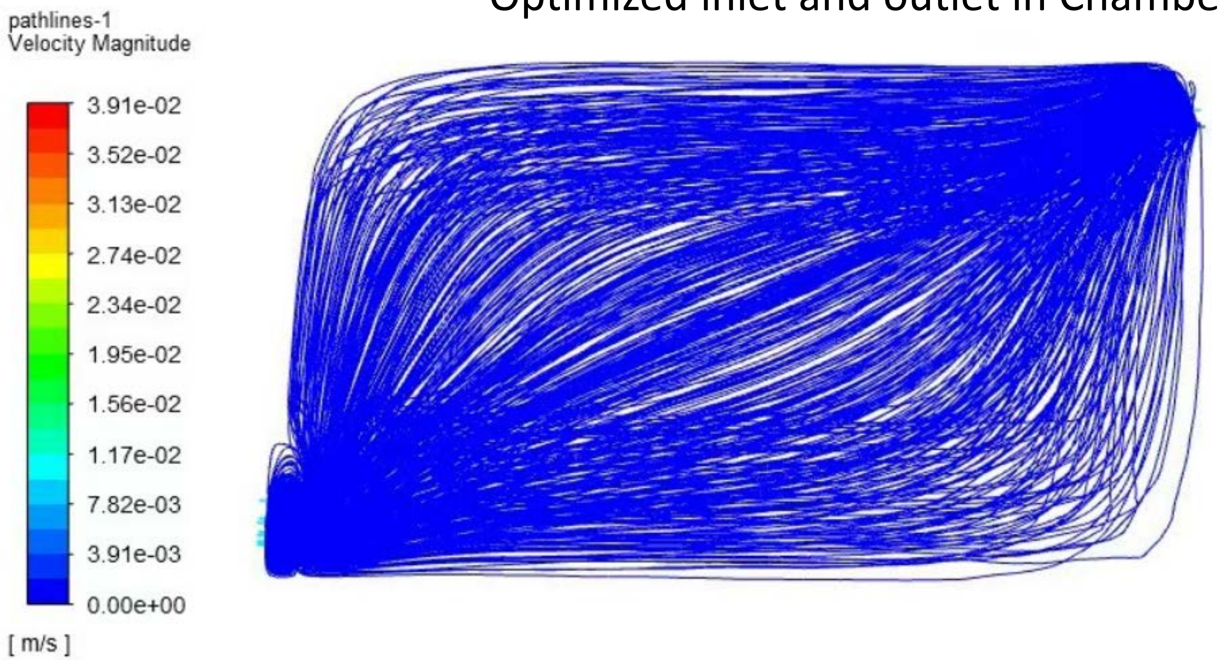
# Optimization of Gas flow in the Chamber

- Uniformity of gas distribution **higher than 99%** 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

Yue Chang's talk

## Simulation:

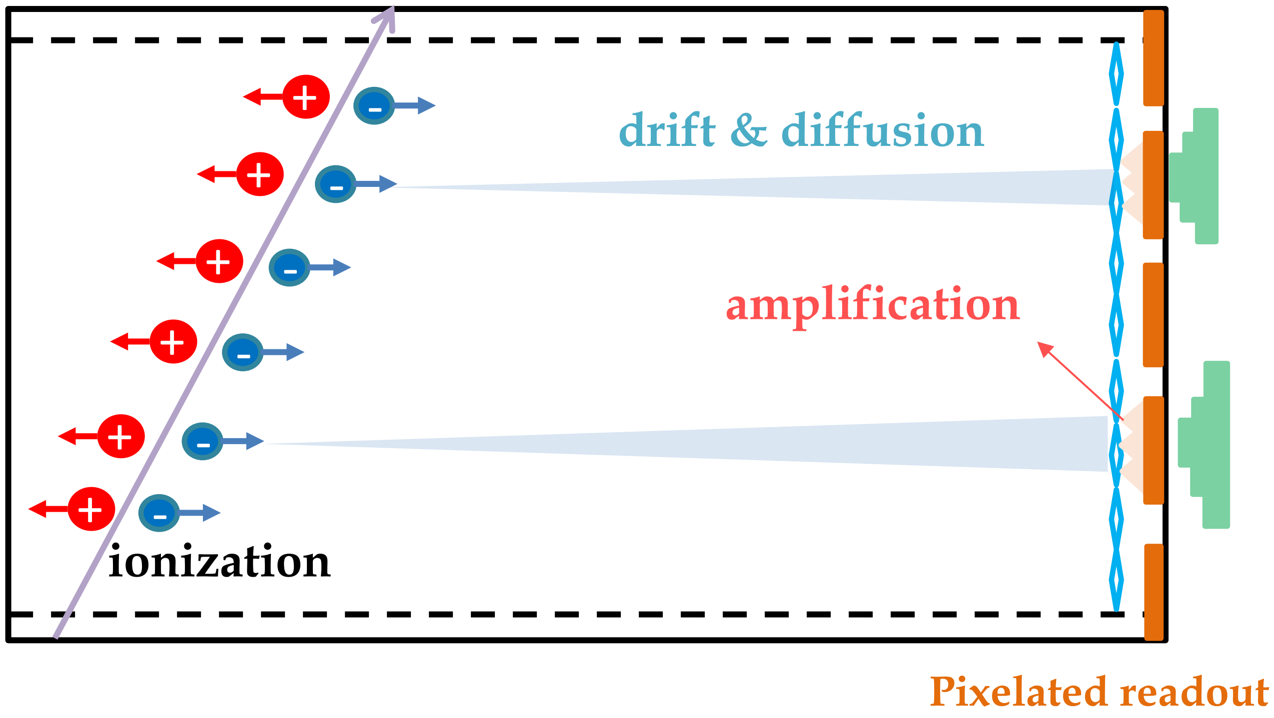
- With the full TPC geometry
- Ionization simulated with Garfield++
- Drift and diffusion from parameterized model based on Garfield++

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

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

**Simulation / Digitization Framework**

Ionization → Transport → Amplification → Signal Generation




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 the pixelated readout TPC

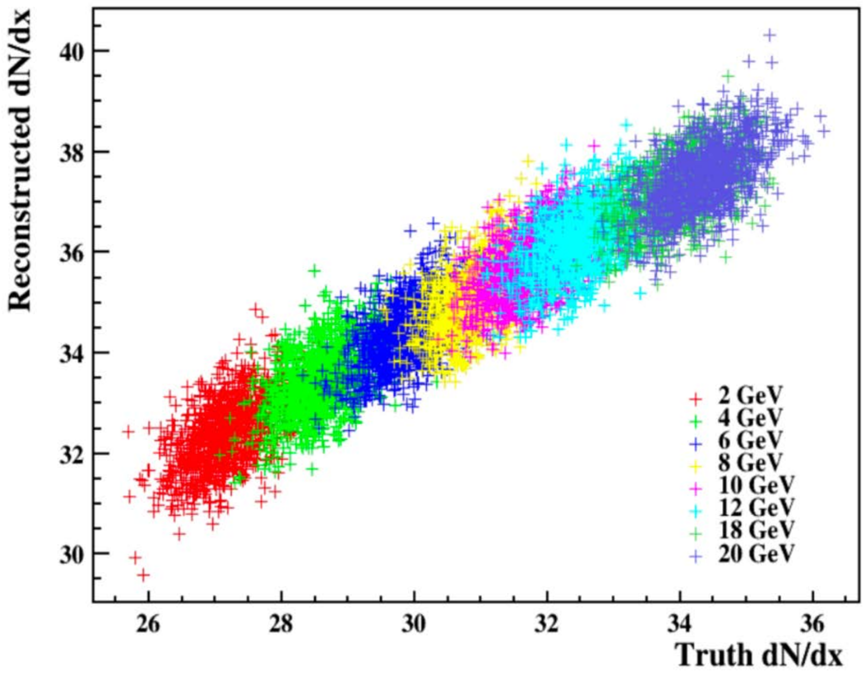
## Reconstruction:

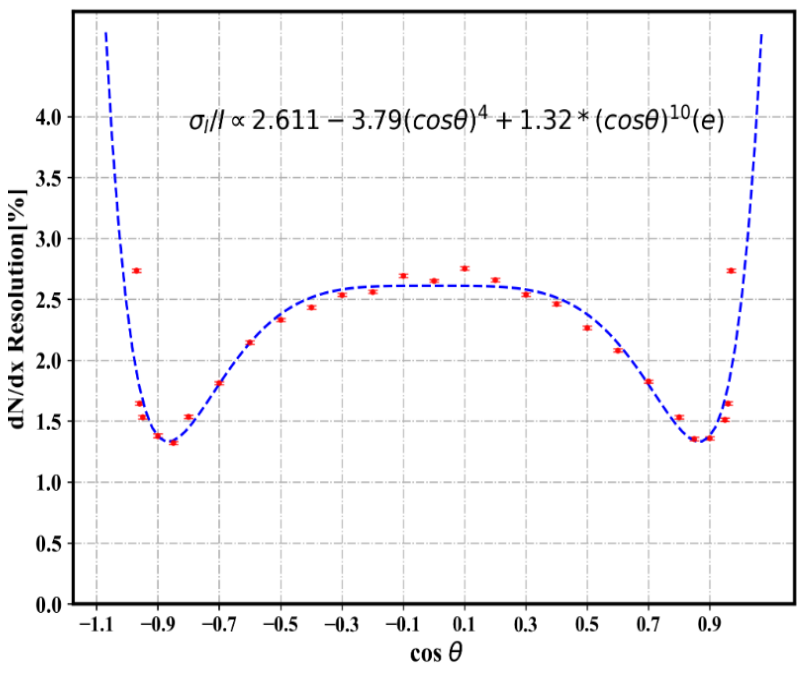
- Reconstruction by counting the number of fired pixels over threshold
- **Reconstruction with good linearity and reliability**

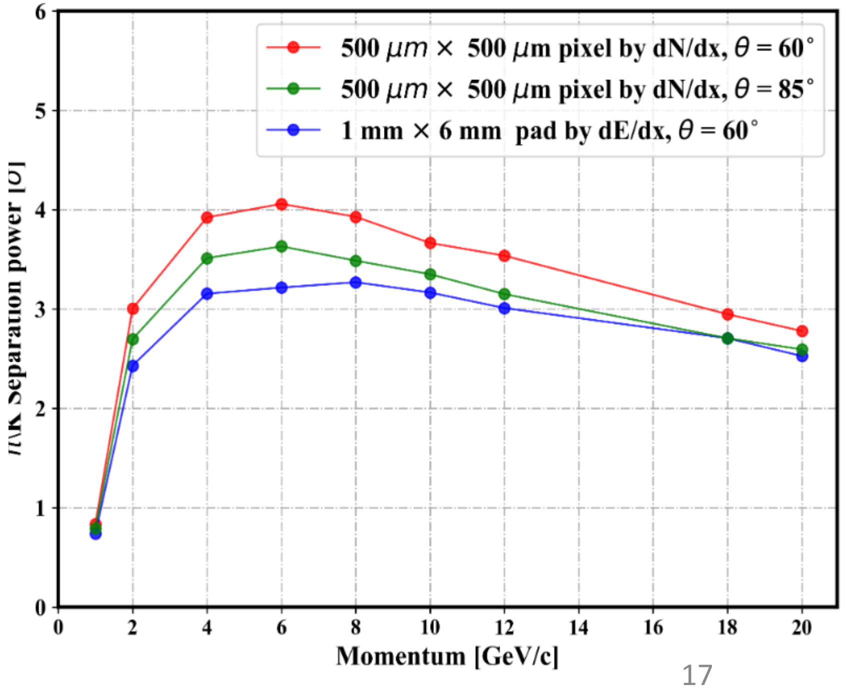
## Preliminary PID performance:

- $\pi/k$ separation power simulation with different momentum

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



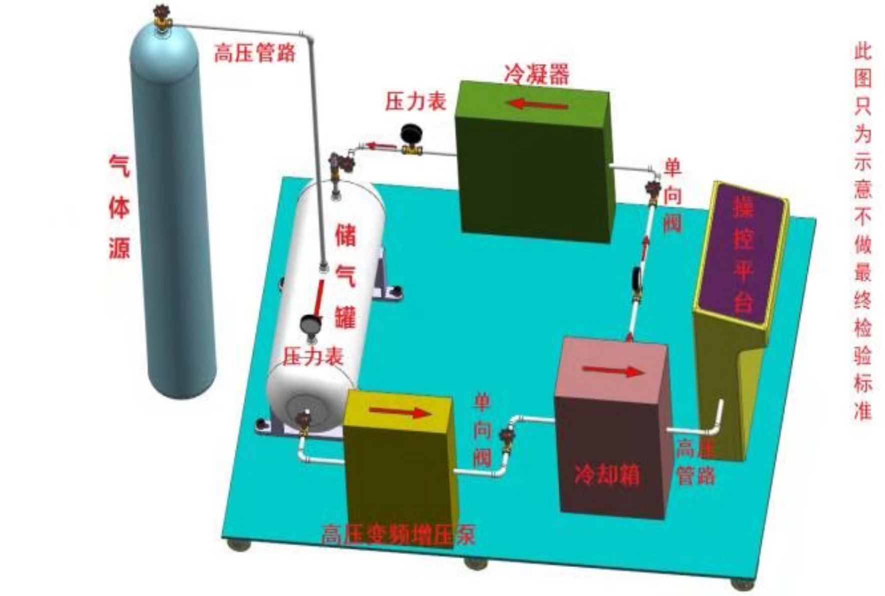



# Optimization of the readout size

Peter's talk

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

| | PASA+ALTRO | Super-ALTRO | SAMPA | WASA_v1 |
|---|---|---|---|---|
| TPC | ALICE | ILC | ALICE upgrade | CEPC |
| Pad Size | 4x7.5 $mm^2$ | 1x6 $mm^2$ | 4x7.5 $mm^2$ | 1x6 $mm^2$ |
| No. of Channels | $5.7\times 10^5$ | $1\text{-}2 \times 10^6$ | $5.7 \times 10^5$ | $2 \times 10^6$ |
| Readout Detector | MWPC | GEM/MicroMegas | GEM | GEM/MicroMegas |
| Gain | 12 mV/fC | 12-27 mV/fC | 20/30 mV/fC | 10-40 mV/fC |
| Shaper | CR-$(RC)^4$ | CR-$(RC)^4$ | CR-$(RC)^4$ | CR-RC |
| Peaking time | 200 ns | 30-120 ns | 80/160 ns | 160-400 ns |
| ENC | 370+14.6 e/pF | 520 e | 246+36 e/pF | 569+14.8 e/pF |
| Waveform Sampler | Pipeline ADC | Pipeline ADC | SAR ADC | SAR ADC |
| Sampling Rate | 10 MHz | 40 MHz | 10 MHz | 10-100 MHz |
| Sampling Resolution | 10 bit | 10 bit | 10 bit | 10 bit |
| Power: AFE | 11.7 mW/ch | 10.3 mW/ch | 9 mW/ch | 1.4 mW/ch |
| Power: ADC | 12.5 mW/ch | 33 mW/ch | 1.5 mW/ch | 0.8 mW/ch@40 MHz |
| Power: Digital Logics | 7.5 mW/ch | 4.0 mW/ch | 6.5 mW/ch | 2.7 mW/ch@40 MHz |
| Total Power | 31.7 mW/ch@10MHz | 47.3 mW/ch@40 MHz | 17 mW/ch@10 MHz | 4.9 mW/ch@40 MHz |
| CMOS Process | 250 nm | 130 nm | 130 nm | 65 nm |



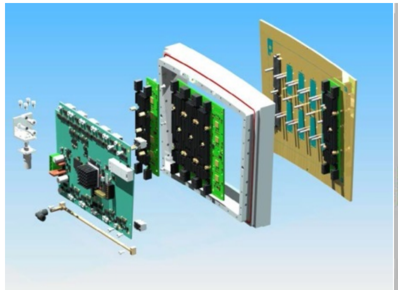

2-phase CO2 cooling for TPC module

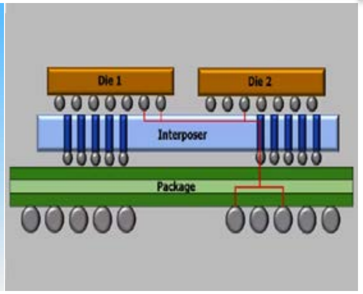
DOI: 10.1088/1748-0221/15/02/T02001
DOI: 10.1088/1748-0221/15/05/P05005

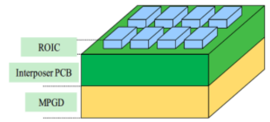
# Detailed design of electronics and BEC

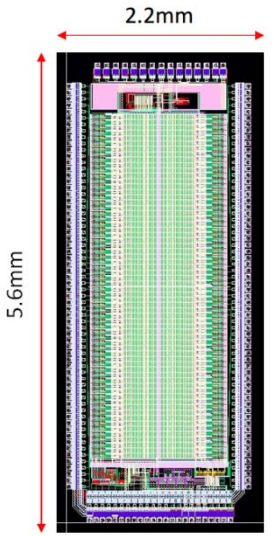
Zhi Deng's talk

- 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)

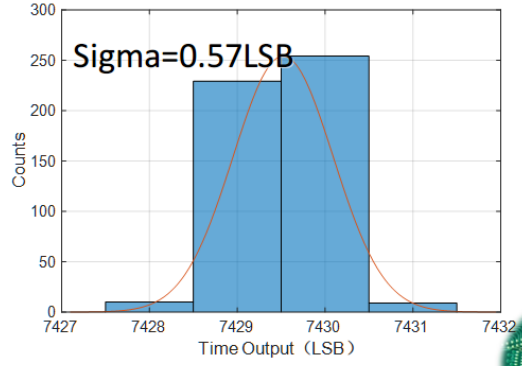




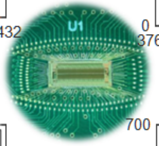



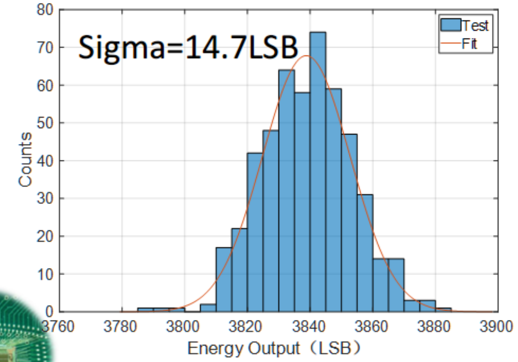




| Parameter | Spec |
|---|---|
| Number of channels | 128 |
| Power Consumption | Analog<30mW |
| | Digital<30mW |
| ENC | ~300 e(high gain) |
| Dynamic Range | 25fC(high gain) |
| | 150fC(low gain) |
| INL | <1% |
| Time Resolution | <10ns |

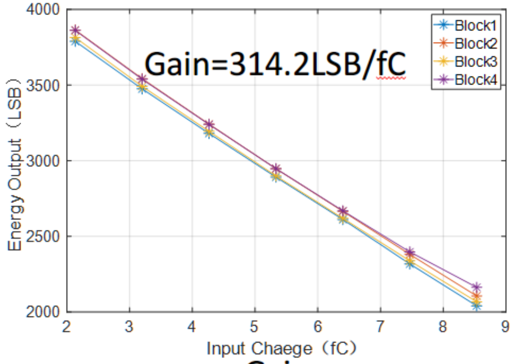



Timing Results

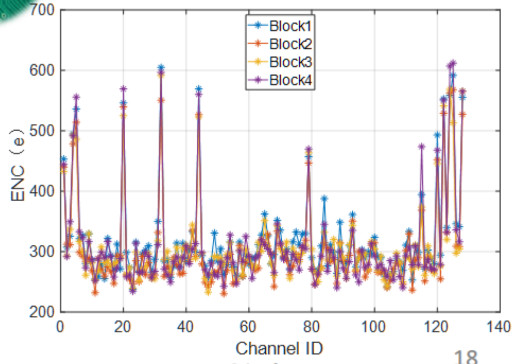





Energy Results




Gain



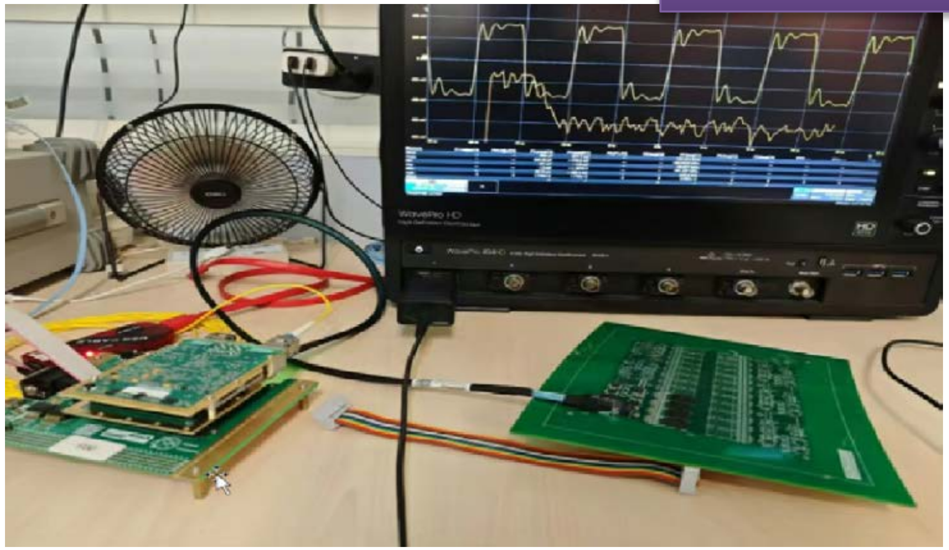

Noise

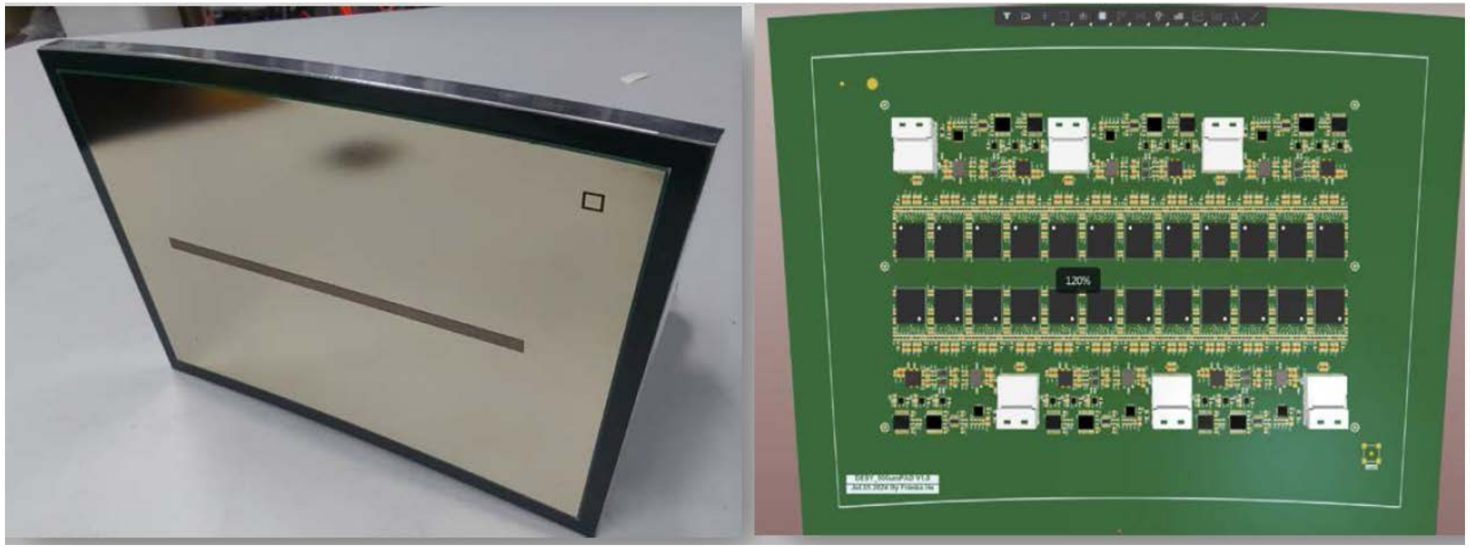
FEE ASIC: TEPIX—Test Results in May

# Validation and commissioning of TPC prototype

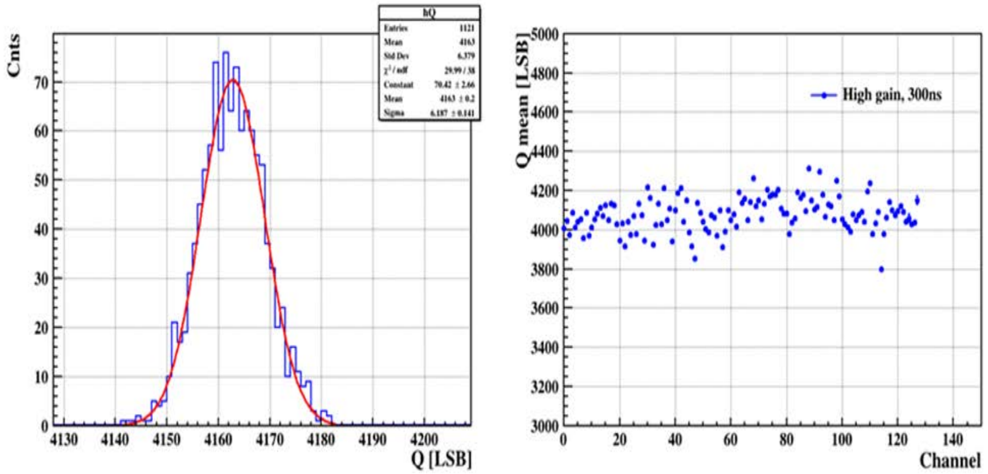
Xin She's talk

- **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)**





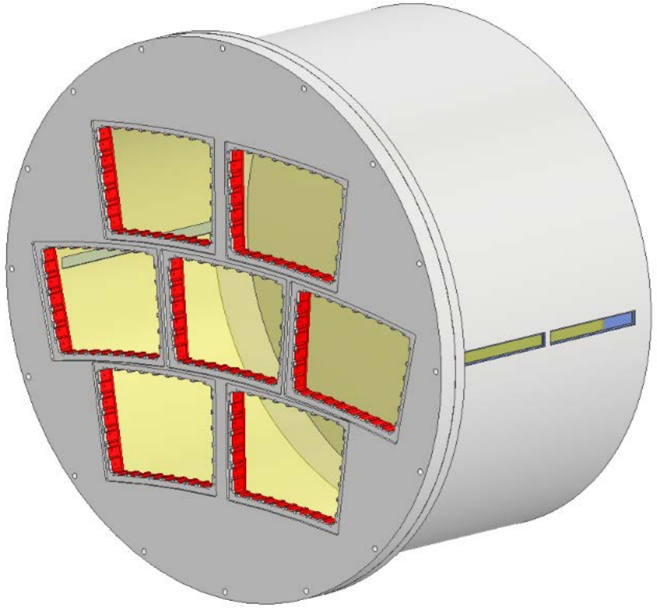
Photos TPC modules assembled for the beam test




Amplitude (left) and Uniformity/ch (right)

# 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 pixelated 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/cm$^2$ (60nm ASIC) | Optimization 330µm - 500µm |
| PID resolution | 3% (dN/dx) | <3% (dN/dx) |
| 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 of contributions will input to CEPC ref-TDR in next few months.**


# Thank you for your attention!

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