Status of High Granularity Readout TPC Technology for the CEPC TDR

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- Status of TPC in CEPC TDR
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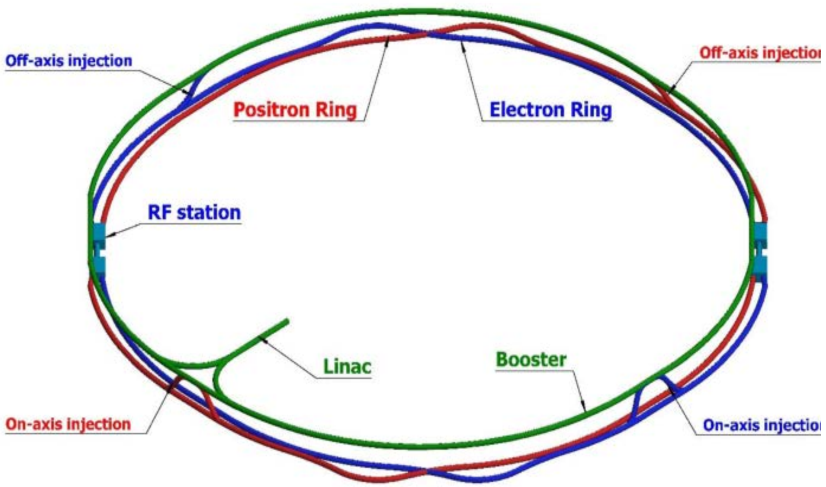
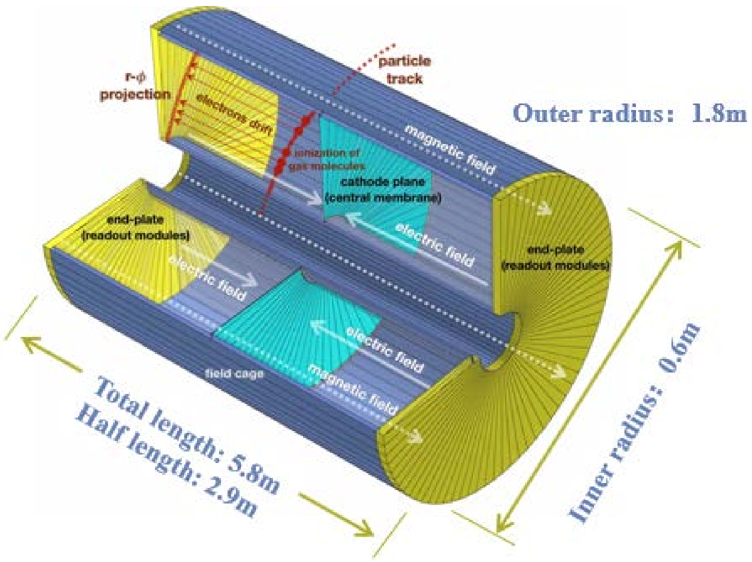
- **Motivation**

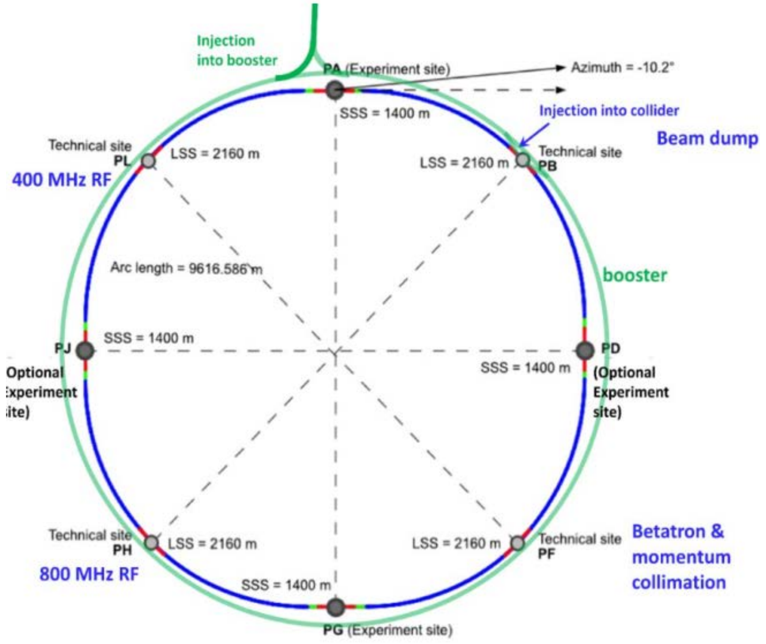
Motivation

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



Circular Electron Positron Collider (CEPC)





Future Circular Collider (FCCee)

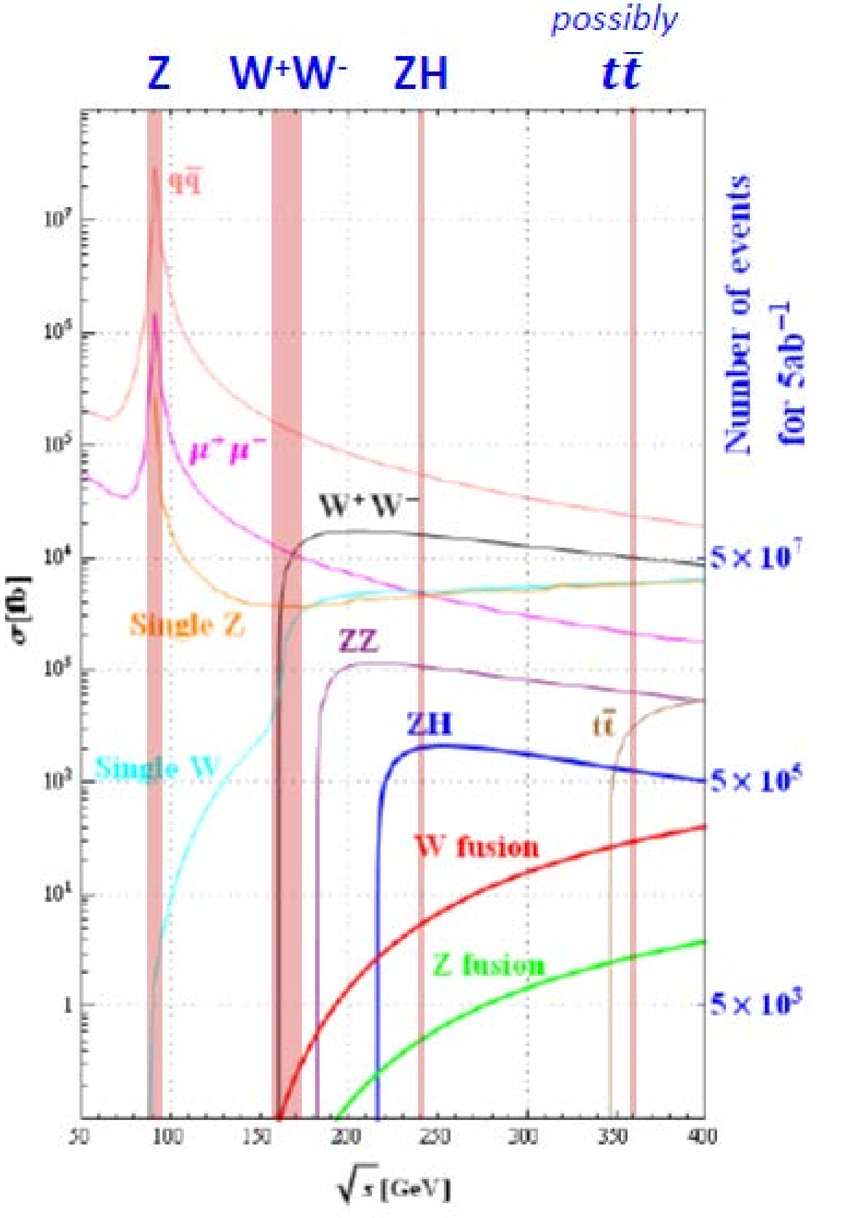
https://arxiv.org/abs/1811.10545

https://arxiv.org/abs/2203.08310

Operation plan in CEPC

- The CEPC Accelerator TDR document was released at the end of 2023.
- In the operation plan, the **first 10-year** operation includes: the Higgs mode, Low-Lumi Z mode, and WW mode (B = 3.0T).
- The accelerator may be upgraded for High-Lumi Z mode and/or tt mode after 10 years operation, subject to physics needs.

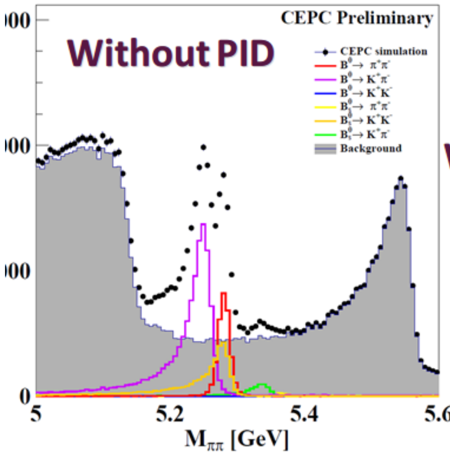
SR Power Per Beam	Luminosity/IP [$\times 10^{34} cm^{-2} s^{-1}$]		
	H	Z	W^+W^-
12.1 MW	-	26	-
30 MW	5.0	-	16
50 MW	8.3	-	26.7



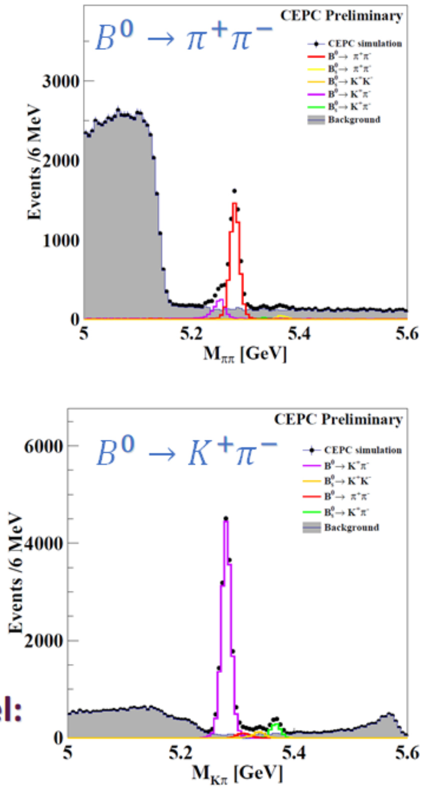
Physics requirements in CEPC

- Circular e+e- collider operation stages in TDR: **10-years Higgs @3T → 2-years Z pole → 1-year W**
- Gaseous tracker leading contribution to PID and the high resolution: jet & differential
  - High granularity readout readout and better than 2σ separation power between πand k for P using dn/dx

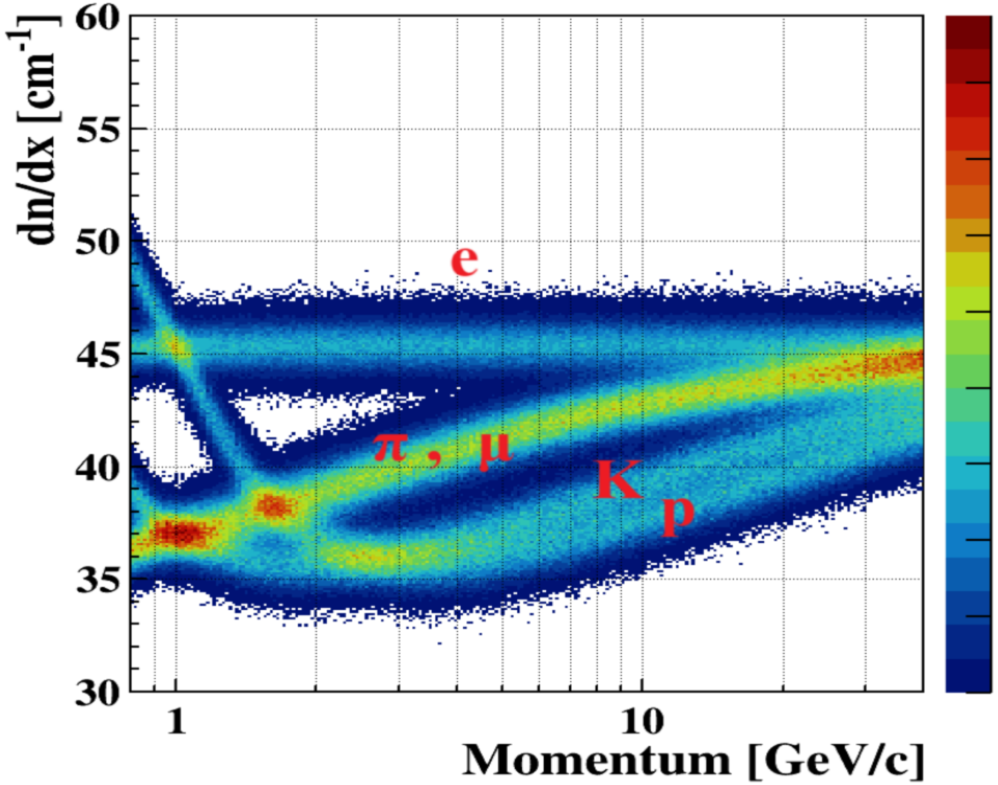
Calibration: Low luminosity Z at 3T
Approximately $10^{35}cm^{-2}s^{-1}$
20% of high luminosity Z



With PID



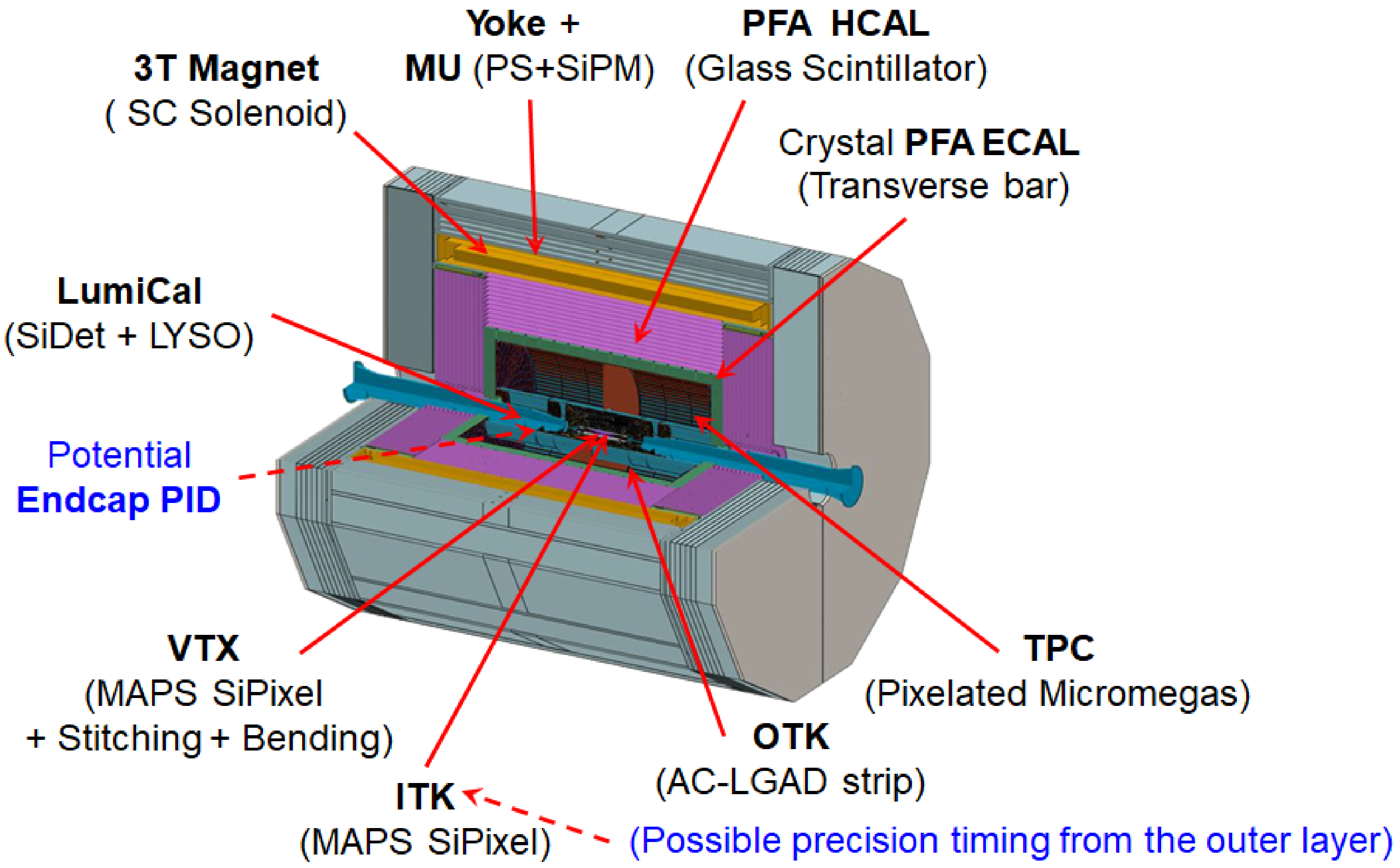
Benchmark channel:
$B^0_{(s)} \to h^+h'^-$



Baseline Detector Design in TDR

- Will explore the possibilities of
  - A forward PID detector inside TPC
  - The outer layer ITK also provides precision timing

- After 10-year operation, the majority will remain, a few may be upgraded, including
  - VTX: for a better performance and radiation tolerance
  - TPC: to deal with higher luminosity



https://arxiv.org/abs/2510.05260

- **Status of TPC in CEPC TDR**

High granularity readout TPC technology in CEPC TDR

→ Peter's talk today
→Yue Chang's talk today

TPC technology detector for e+e- collider

Pad readout TPC
- **To meet Higgs physics**
- **1mm×6mm of Pad**
- **< 100mW/cm^2**
- **dE/dx**

Pixelated readout TPC
- **To meet Low-lumi Z physics**
- **TPX3 and TPX4**
- **~1W/cm^2**
- **dN/dx+dE/dx**

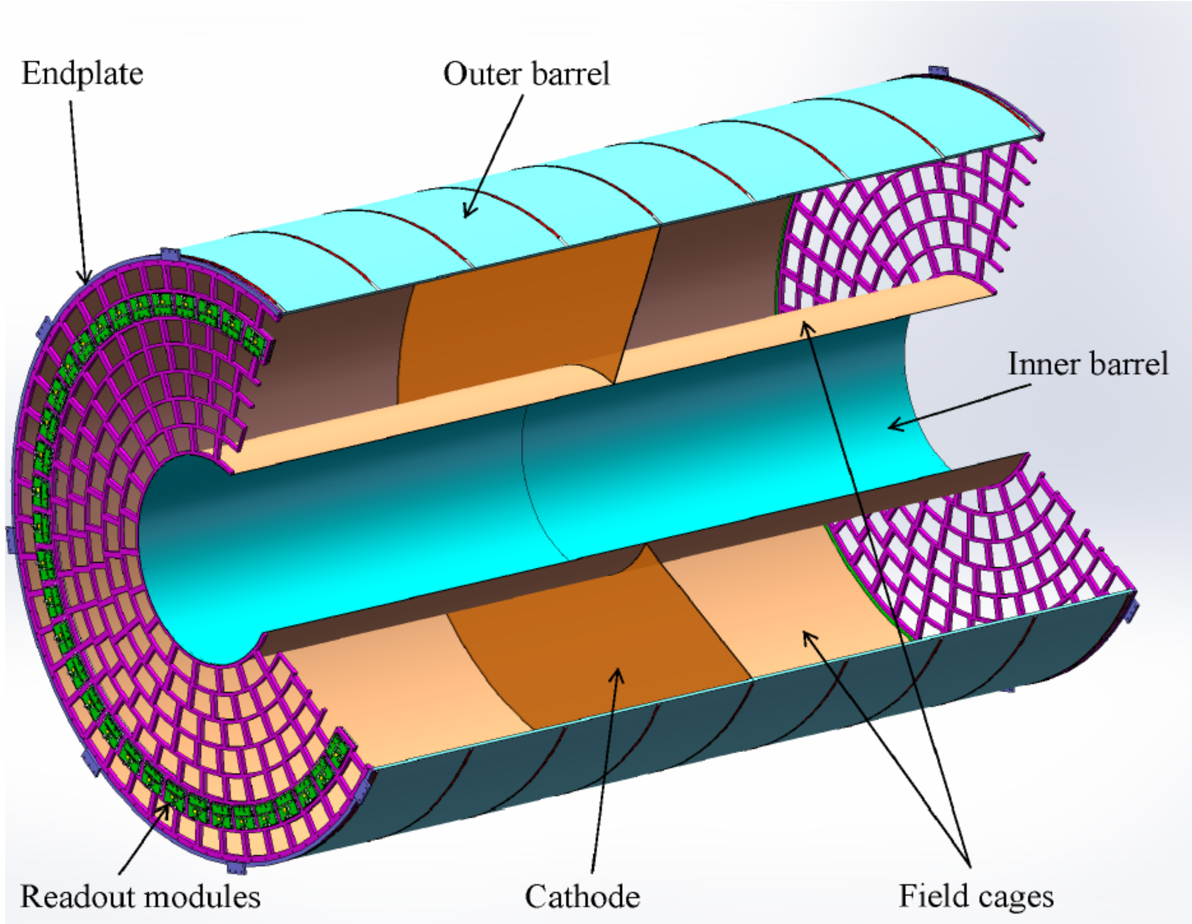
- CEPC community initiated the technical comparison and selection, balancing factors including **R&D efforts, detector performance, cost, power consumption and construction risks**.

Parameters of TPC technology in CEPC TDR

→ Jianbo Zheng's poster

- Requirements
  - Momentum resolution (combined with ITK and OTK): $2 \times 10^{-5} (\text{GeV}/c)^{-1}$
  - PID (combined with OTK): 3σ separation between π, K , p with momenta up to 20 GeV/c
  - Low material budget
- Overall design
  - A chamber (inner and outer cylinders, endplates) + readout modules
  - Total length： 5.8 m
  - R extension: 0.6 - 1.8 m

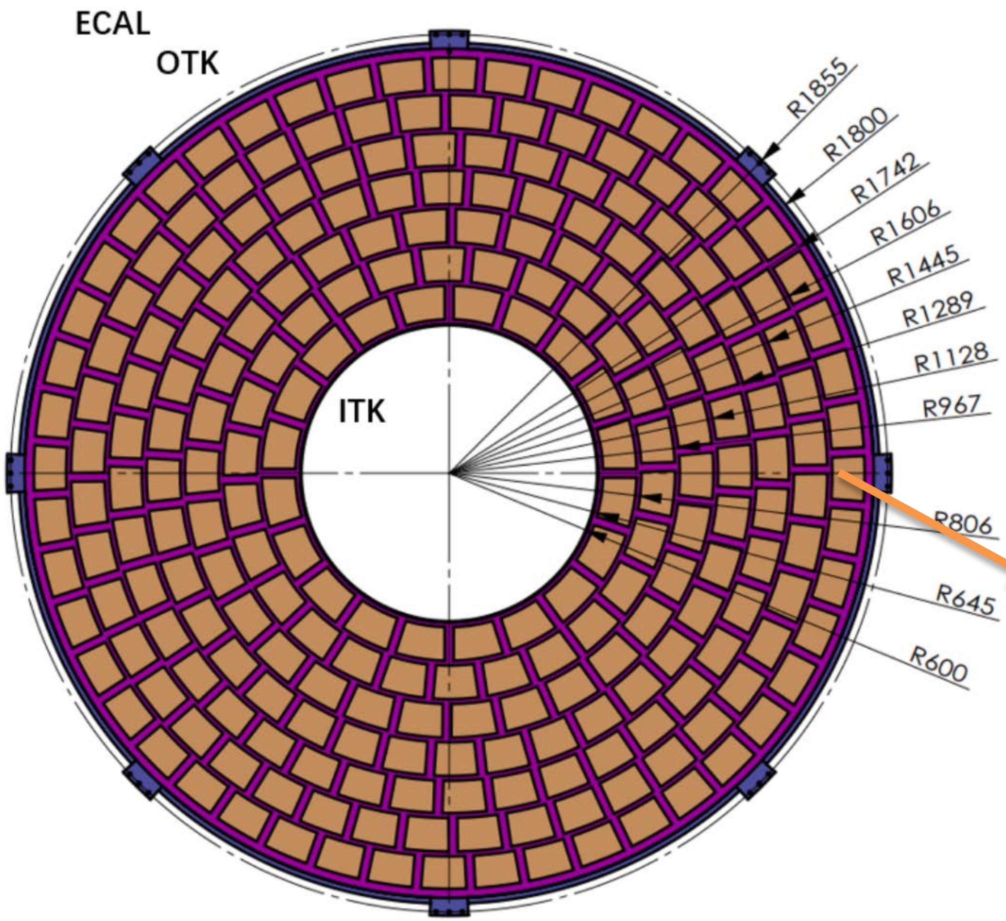
TPC detector	Key Parameters
Modules per endcap	248 modules /endcap
Combined Si detector	OTK and ITK silicon trackers
Geometry of layout	Inner: 1.2m Outer: 3.6m Length: 5.9m
Potential at cathode	- 62,000 V
Gas mixture	T2K: Ar/CF4/iC4H10=95/3/2
Maximum drift time	34μs @ 2.75m
Detector modules	High granularity readout Micromegas

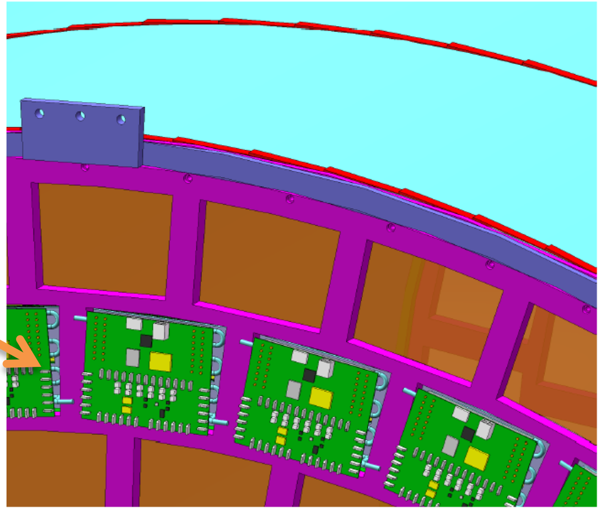


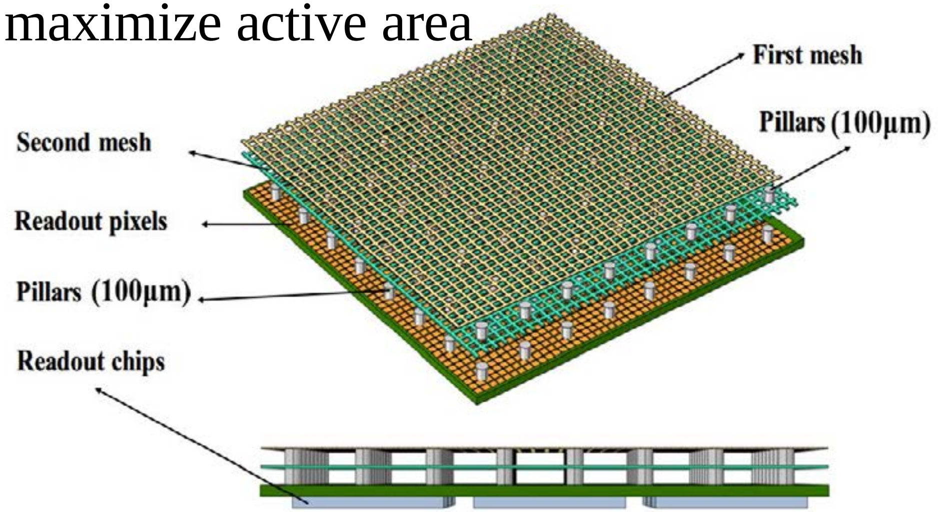
Detailed design of TPC detector in TDR

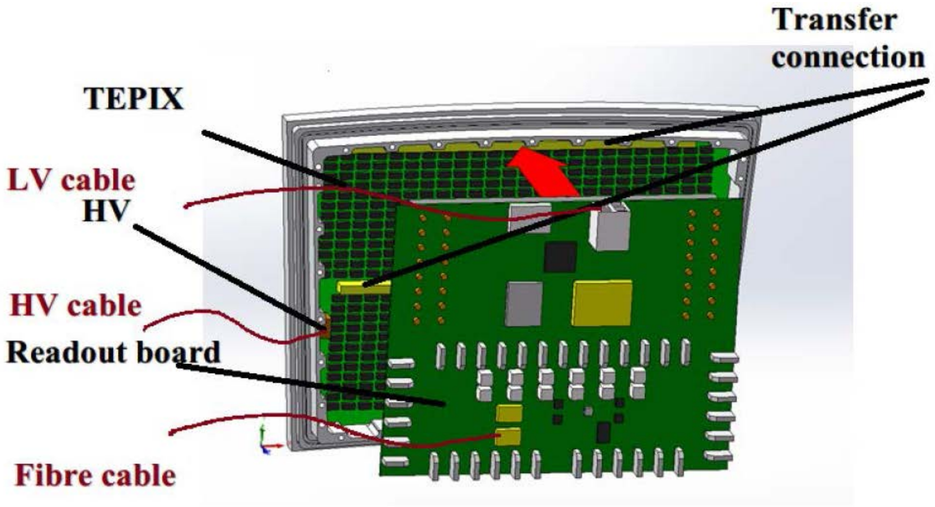
Readout module design

- Readout modules on the endplate
  - 25mm thick aluminum endplate: 7 layers of windows along the radial direction
  - Readout modules with support frame installed in windows to maximize active area



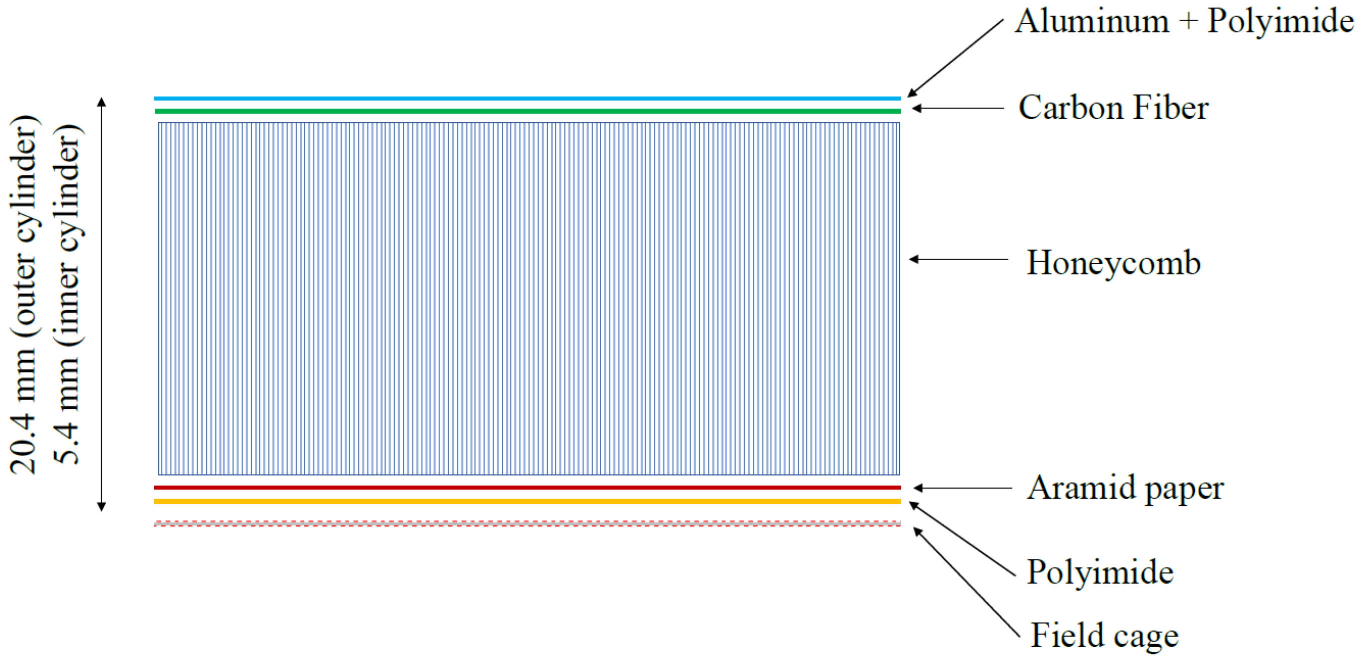






Light barrel design

- To reduce mechanical deformation, improve insulation performance, and minimize the material budget
  - Sandwich structure
    - Outer cylinder thickness: 20.4mm, Material budget: 0.69% X_0
    - Inner cylinder thickness: 5.4mm, Material budget: 0.45% X_0
  - The insulation material is rated at 62 kV and includes a safety factor



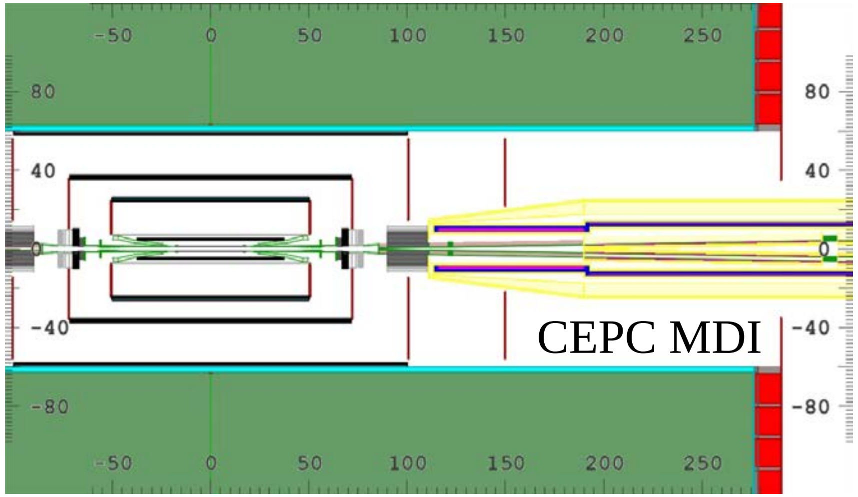
Component	Layers	X [cm]	X_0 [cm]	X/X_0 [%]
		TPC outer wall		
Faraday cage shield	Aluminum	0.005	8.9	0.06
Faraday cage shield substrate	Polyimide	0.005	28.6	0.02
Outer wall support cylinder	Carbon fiber	0.02	25.28	0.08
Outer wall support cylinder	Nomex honeycomb	1.96	800	0.25
Outer wall support cylinder	Aramid paper	0.01	35	0.03
Insulating layer	Polyimide	0.01	28.6	0.03
Mirror strips layer	Copper	0.0012 × 0.95	1.44	0.08
Field cage substrate	Polyimide	0.005	28.6	0.02
Field strips layer	Copper	0.0012 × 0.95	1.44	0.08
Glue	Epoxy	0.02	35.3	0.06
		TPC inner wall		
Field strips layer	Copper layer	0.0012 × 0.95	1.44	0.08
Field cage substrate	Polyimide	0.005	28.6	0.02
Mirror strips layer	Copper	0.0012 × 0.95	1.44	0.08
Insulating layer	Polyimide	0.01	28.6	0.03
Inner wall support cylinder	Aramid paper	0.01	35	0.03
Inner wall support cylinder	Nomex honeycomb	0.46	800	0.06
Inner wall support cylinder	Carbon fiber	0.020	25.28	0.08
Faraday cage shield substrate	Polyimide	0.005	28.6	0.02
Faraday cage shield	Aluminum	0.005	8.9	0.06
Glue	Epoxy	0.02	35.3	0.06

- **Simulation and prototype preparation**

Beam background simulation

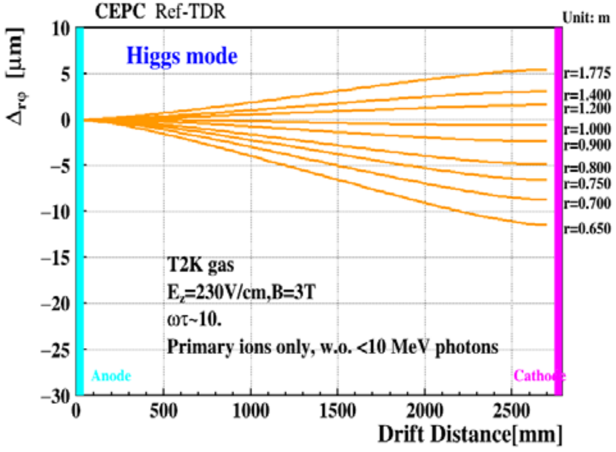
→ Xin She's talk today

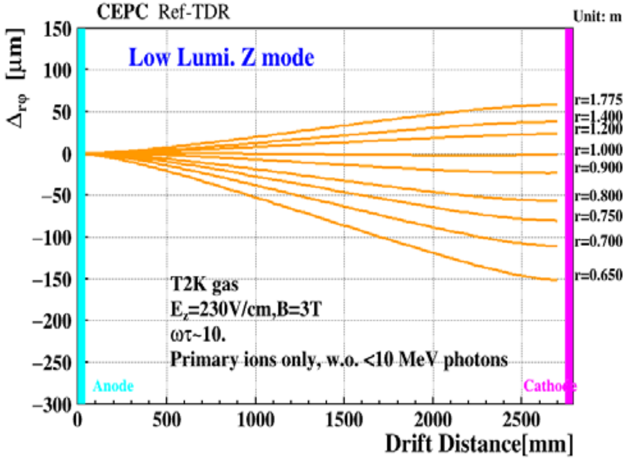
- Space charge in TPC chamber
  - Physics events: H→ss/cc/sb, Z→qq…(High P_T)
- Low-lumi Z background sources
  - I. Pair production (Luminosity related)
  - II. Single Beam (BGB, BGH,Touschek Scatter…)
  - III. Synchrotron Radiation
  - IV. Injection background
- Estimation of the charge density and distortion

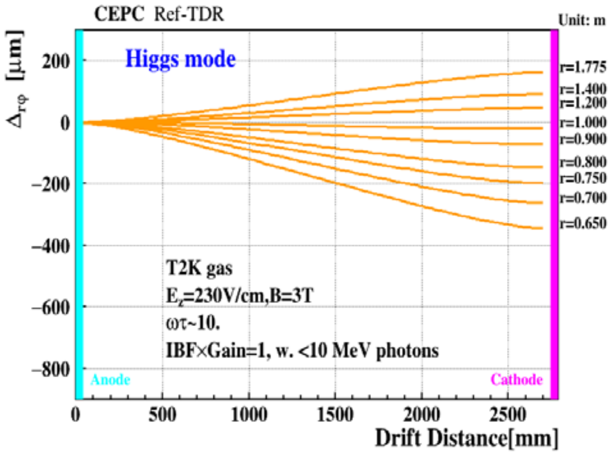


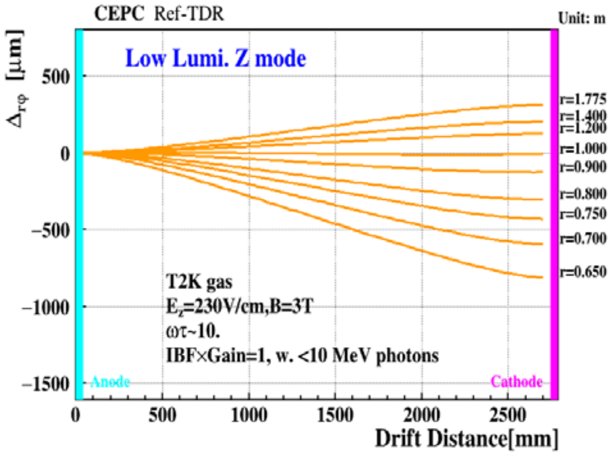
Only primary ions && w.o. low-energy photons and IBF

IBF×Gain =1 && w. low-energy photons



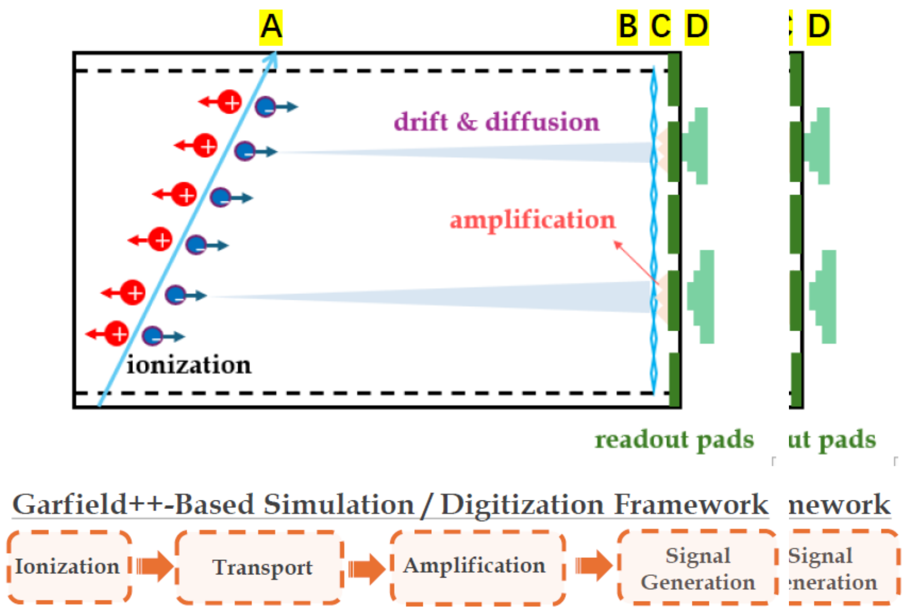


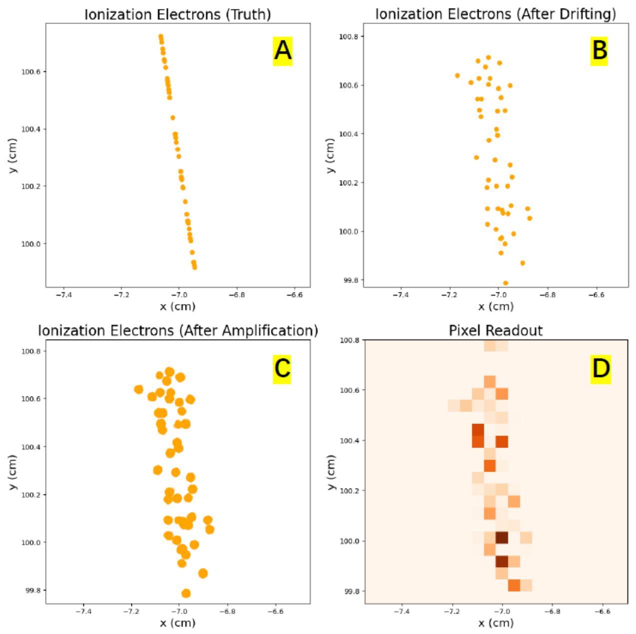


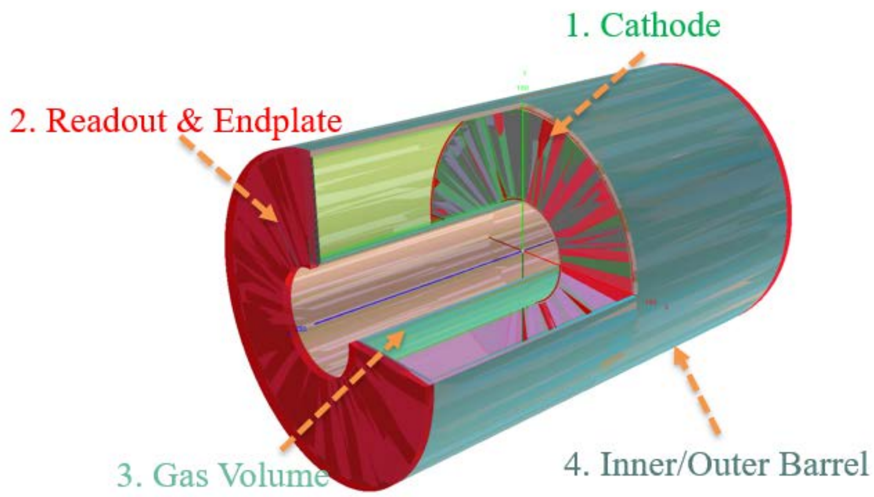


Full Simulation of High granularity readout TPC – Framework

- Sophisticated software for simulation/digitization/reconstruction using Garfield++ and Geant4
  - Geometry implementation based on CEPC TDR
    - Cathode, Micromegas readout and endplate, barrel, gas volume
  - PID with the cluster counting
    - Garfield++ based full simulation and digitization from the primary electron to the signal readout
    - Improved reconstruction based on truncated mean of pixels
  - Tracking: Reconstruction with parameterized hit resolutions

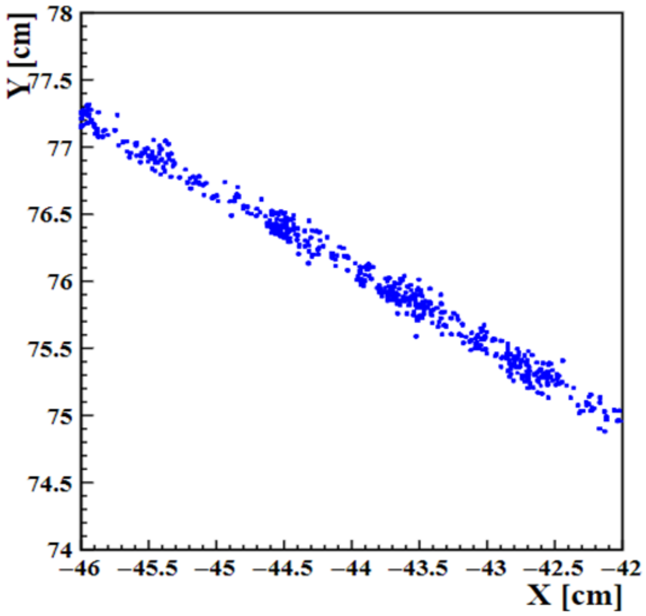




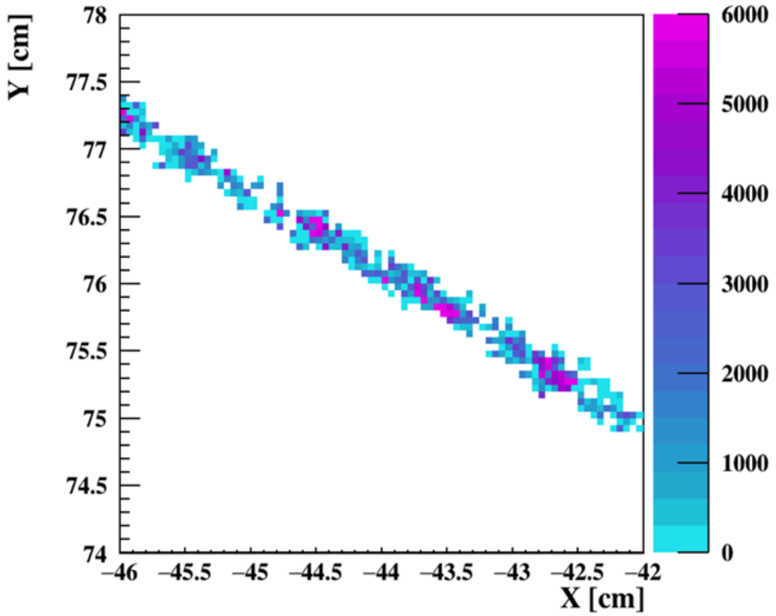


Simulation of TPC detector under 3T and T2K mixture gas

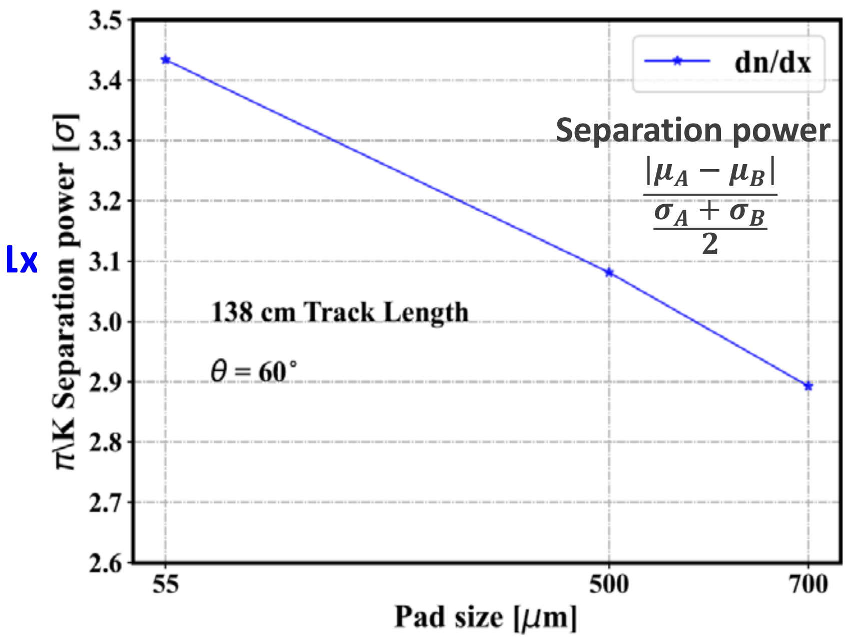
- Simulation results showed that readout size can be optimized at around 500μm.
  - Optimization started in this TDR to meet Higgs/Z at 3T
  - Focused on **100mW/cm^2 and 500μm readout** for TDR (<10kW/endplate, Water cooling option)
- TPX3/4 (55×55μm^2, 110×110μm^2) readout TPC prototype has been validation on DESY beams.
  - Power consumption: 2W/cm^2 ; Low power mode: 1W/cm^2 (**high power consumption!**)



pixel response (55 μm× 55 μm)



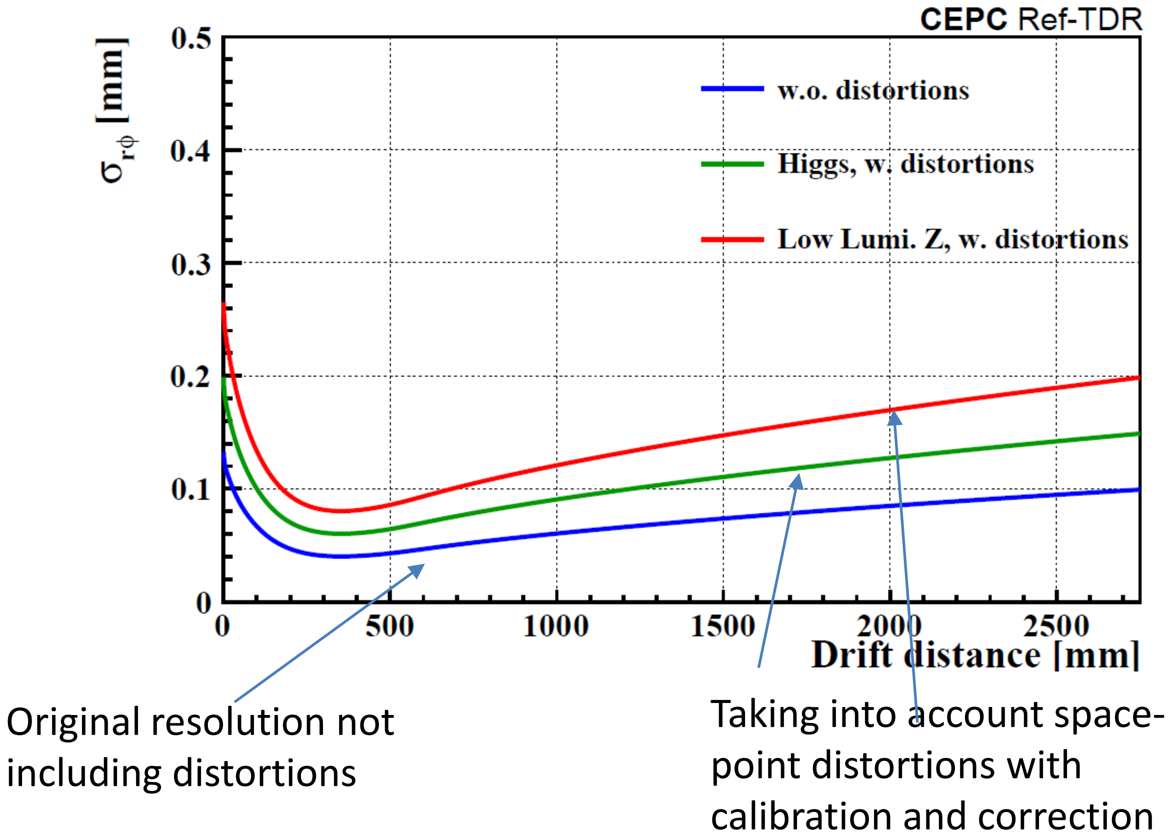
pixel response (500 μm× 500 μm)



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

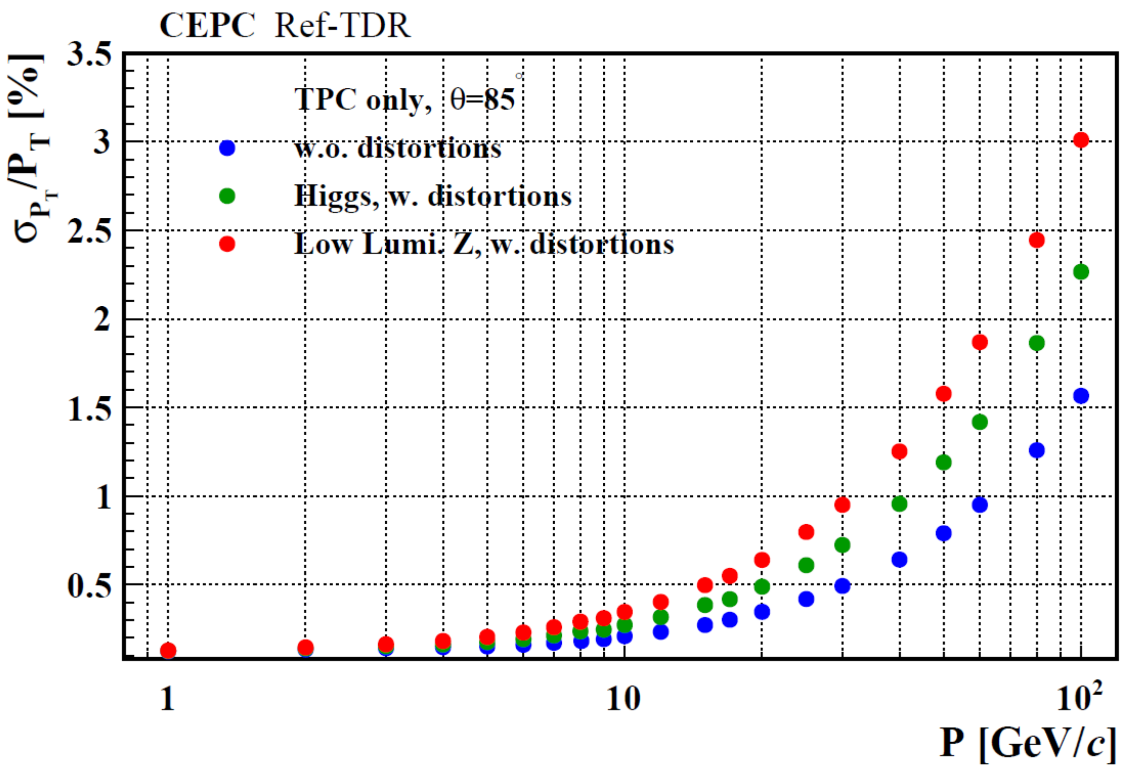
Full Simulation of High granularity readout TPC – Spatial resolution

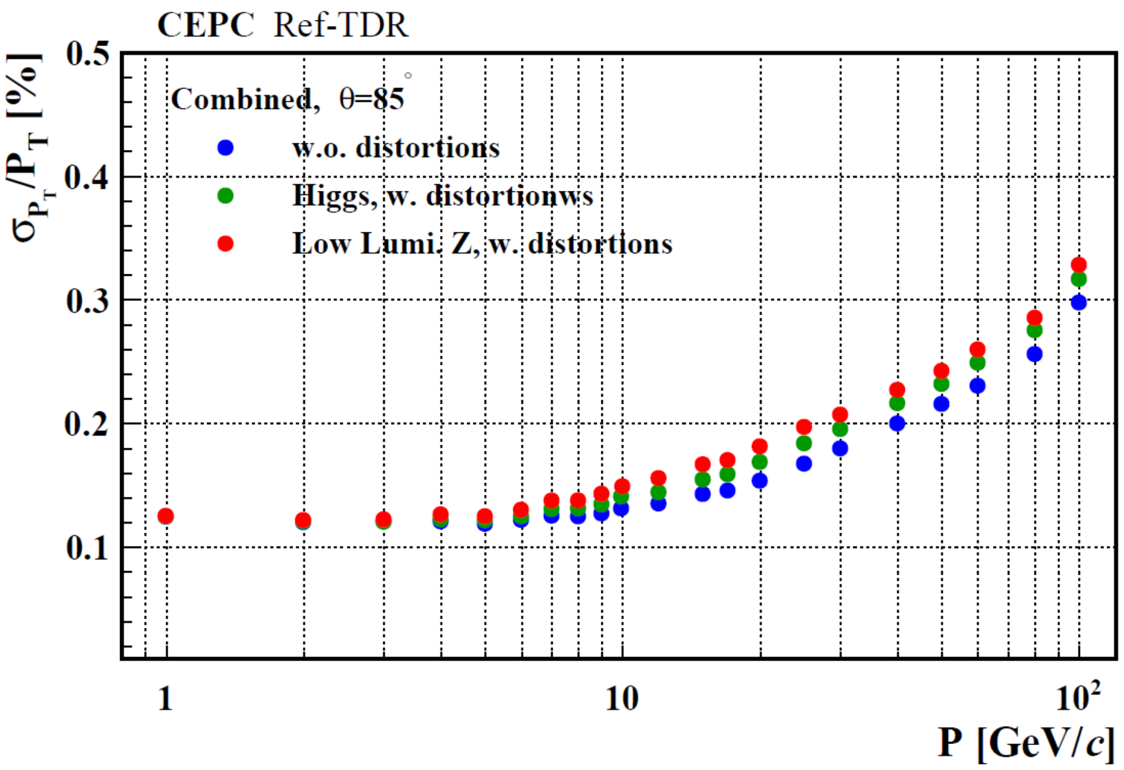
- Impact of space-point distortions on spatial resolution
  - Space-point distortions can be corrected by the data-driven track-based calibration
  - Error contributions to the calibrated spatial resolution :
    - Space-charge distortion: < 80μm in Higgs, <160μm in low-lumi. Z, dependent on L_{drift}
    - NUMF effects on the drift process (after correction with B field map): <65 μm
- Conservatively estimated, the calibrated spatial resolution degrades by ~50% and 100% at the point with the longest drift distance in Higgs and low-luminosity Z modes respectively.



Full Simulation of High granularity readout TPC - Momentum resolution

- Momentum resolution\
  - Compared to idea scenario, momentum resolution with the TPC standalone degrades, especially high momentum
  - 11% degradation after combining the silicon trackers in low lumi. Z mode
- Further simulation with a complicated model is ongoing.



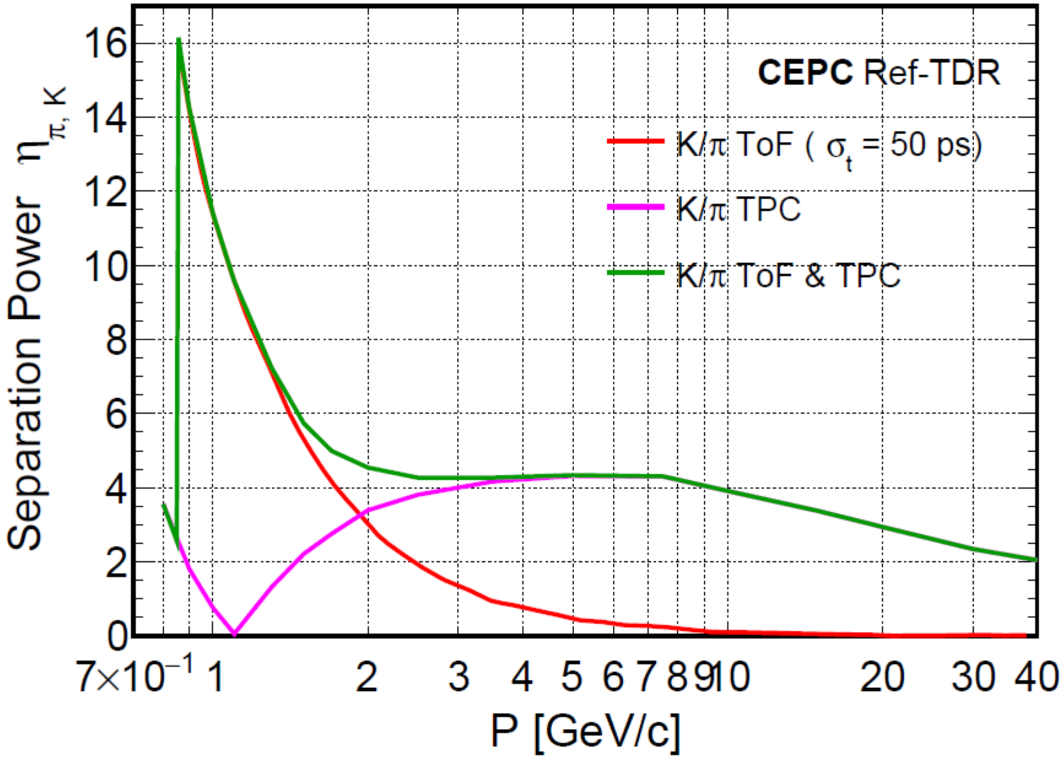


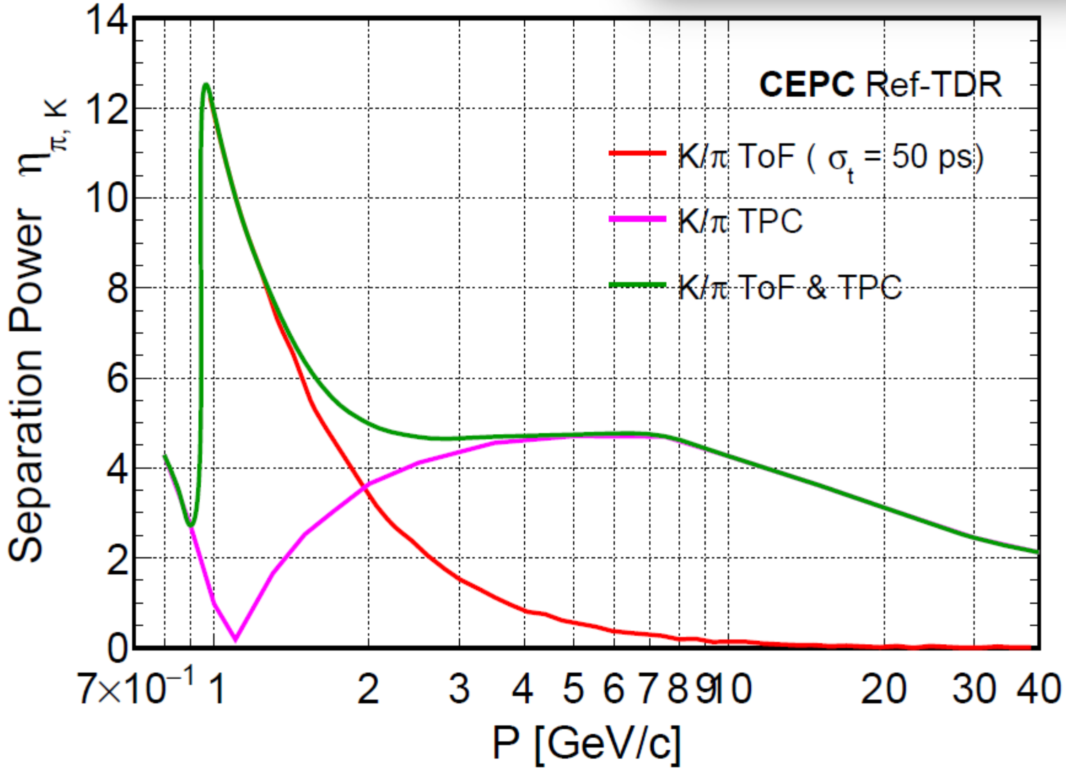
Full Simulation of High granularity readout TPC – PID performance

→ Jinxian Zhang's talk tomorrow

- K/π separation power using the combined information of ToF and TPC
  - ToF information compensates for momentum range of around 1GeV/c
  - Larger than 3σ separation between K/π with momentum up to 20 GeV/c

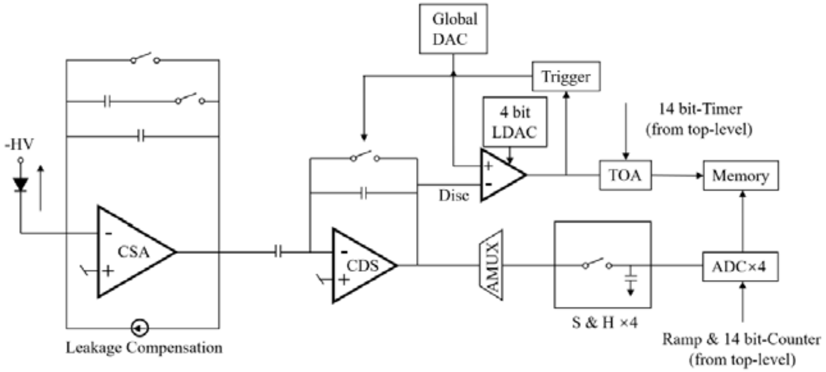
$$\eta_{A,B} = \frac{|\mu_A - \mu_B|}{\sqrt{(\sigma_A^2 + \sigma_B^2)/2}}$$

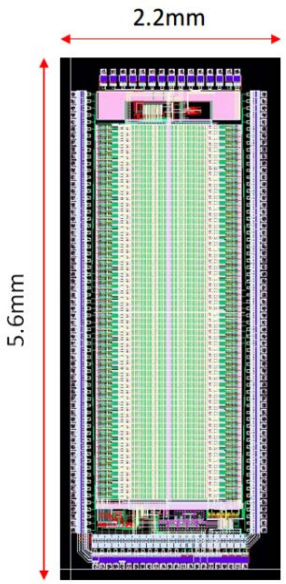




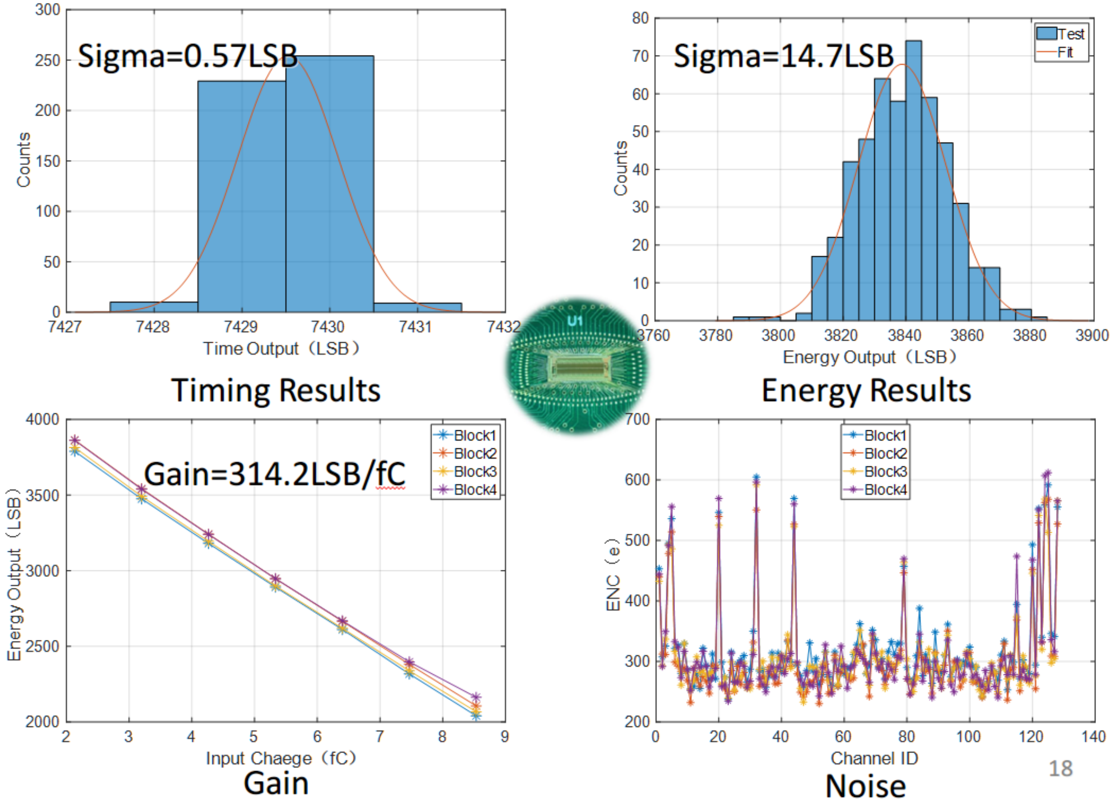
Prototype of the readout ASIC

- High granularity readout Electronics: TEPIX chip
  - Charge-sensitive preamplifier
  - Correlated double sampling shaper
  - 4-channel sample/hold circuits and 10 bit ADC
  - 128 channels using 180 nm process
  - Chip size: 2.2 mm × 5.6 mm





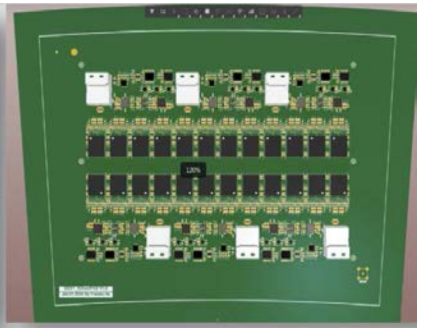
Total number of channels	30 Million per endplate
Pixel size	500 µm × 500 µm
Equivalent Noise Charge (ENC)	100 e^-
Dynamic range	20 fC
Charge buffer dynamic range	8-10 bit
Event rate	12 kHz/cm^2 max. in low-lumi. Z mode
Event size	64 bit
Readout bandwidth	<10 Gbps per module with compression
Power consumption	<100 mW/cm^2

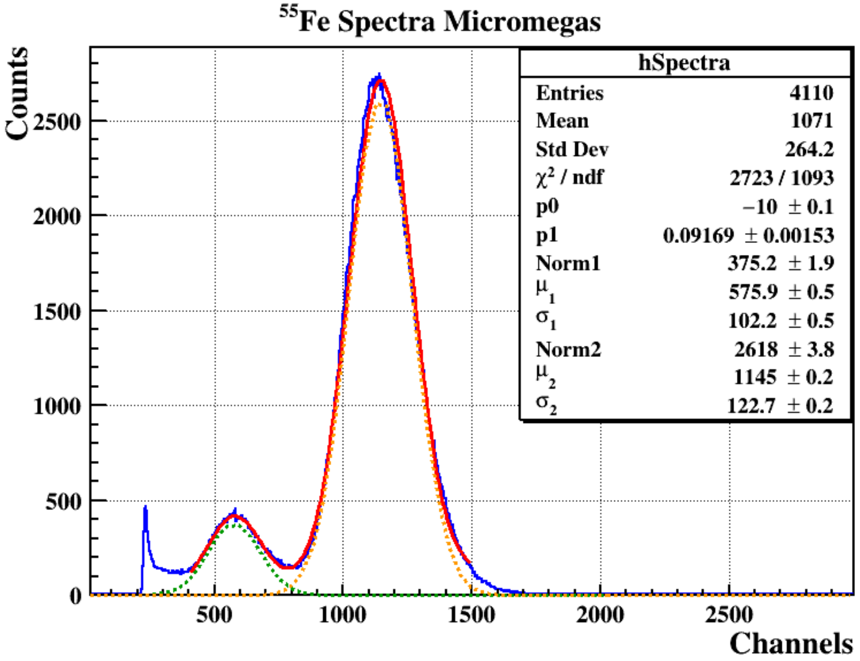


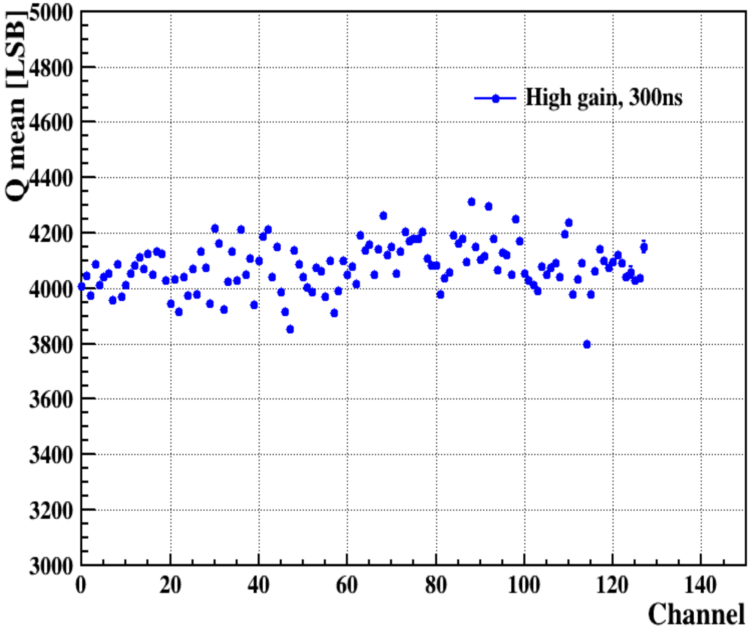
FEE ASIC: TEPIX—Test Results

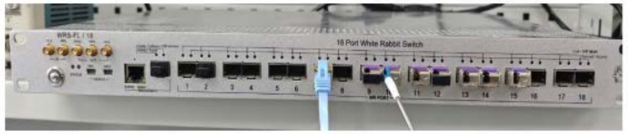
Validation and commissioning of TPC prototype

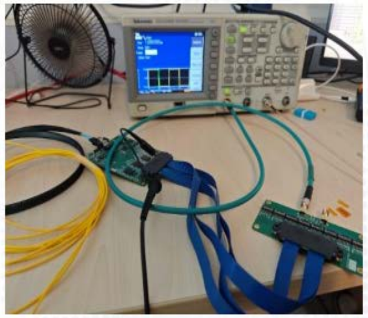
- R&D on High granularity readout TPC readout for CEPC TDR.
  - ASIC chip developed and has been tested at IHEP.
- Energy/Time value of the channels according to the charged injected
  - The uniformity test result of single TEPIX chip : <5%
- A TPC readout module has developed with 10×300 readout channels (24 TEPIX chips).







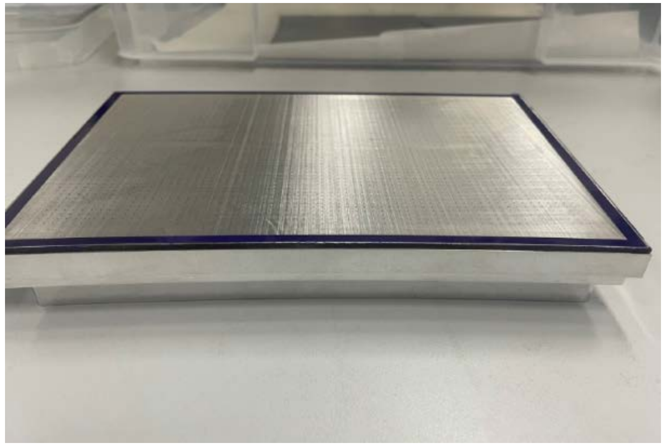




Some test result of Micromegas detector integrated with TEPIX chip

Work plan of TPC R&D

- Short term work plan
  - 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 and DRD1on beam test
  - Development of the full drift length prototype
    - Drift velocity. Attachment coefficient, T/L Diffusion, etc.



Milestones achieved	Short term	Beyond TDR
Ion backflow suppression	IBF×Gain<1 (Gain=2000)	Graphene technology
High granularity readout readout prototype	Validation with beam test	Prototype with Multi-modules
Power consumption ASIC	~100mW/cm^2 (60nm ASIC)	Optimization readout size
PID resolution	3% (dN/dx)	<3% (dN/dx)
Material budget (barrel)	Carbon Fiber	Full size prototype

Summary

- High granularity readout TPC is choose as the baseline detector as main track in CEPC TDR. The simulation framework has been developed using Garfied++ and Geant4.
    - Aiming to Higgs and low luminosity Z run at future e+e- collider
    - Radius of TPC from 0.6 m to 1.8 m, readout size 500μm × 500μm
    - Ultra light material budget of the barrel and endplate
    - dn/dx has much better PID by getting rid of fluctuations from energy deposition and amplification
    - π/K: ~3σ @ 20 GeV/c, ~2σ @ 40 GeV/c
    - Beam-induced backgrounds studied based on Garfield++ and CEPCSW
    - Some validation of TPC prototype have been studies using TEPIX
- All inputs to the CEPC TDR, planning the short and long term R&D activates
- Synergies with CEPC and FCCee allow us to continue R&D and ongoing. Team actively involved in the international collaborations.


Many thanks!