Pixelated Readout TPC Development for the Circular e+e- Collider

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On behalf of the CEPC gaseous tracker R&D group

and some inputs from LCTPC international collaboration

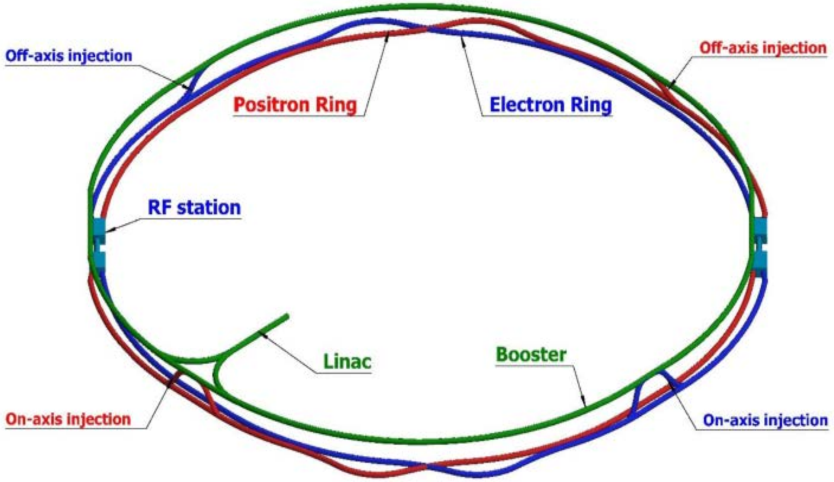
3rd DRD1 Collaboration Meeting, 10 December 2024, CERN

Content

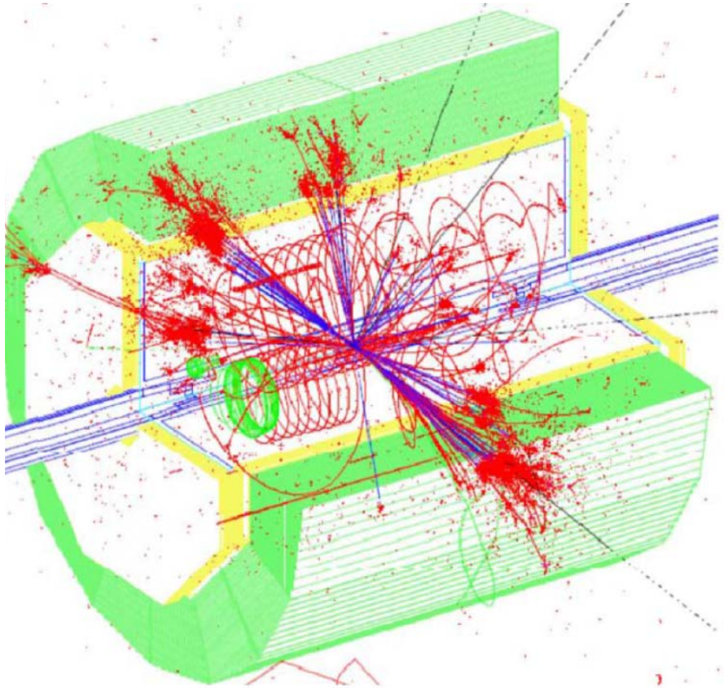
- **Motivation and physics requirements**
- **Status of TPC in LCTPC and CEPC**
- **Pixelated readout TPC for Higgs and Z**
- **Work plan and Summary**

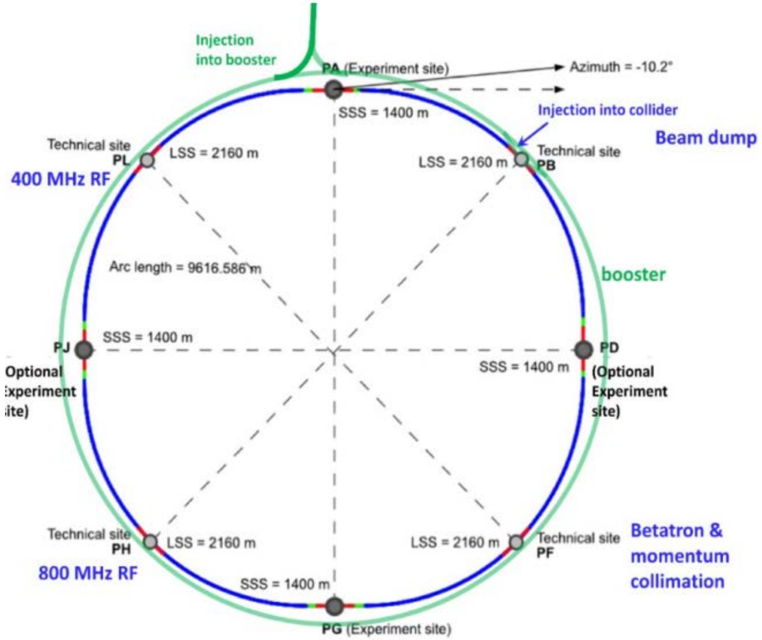
Motivation and physics requirements

- 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)

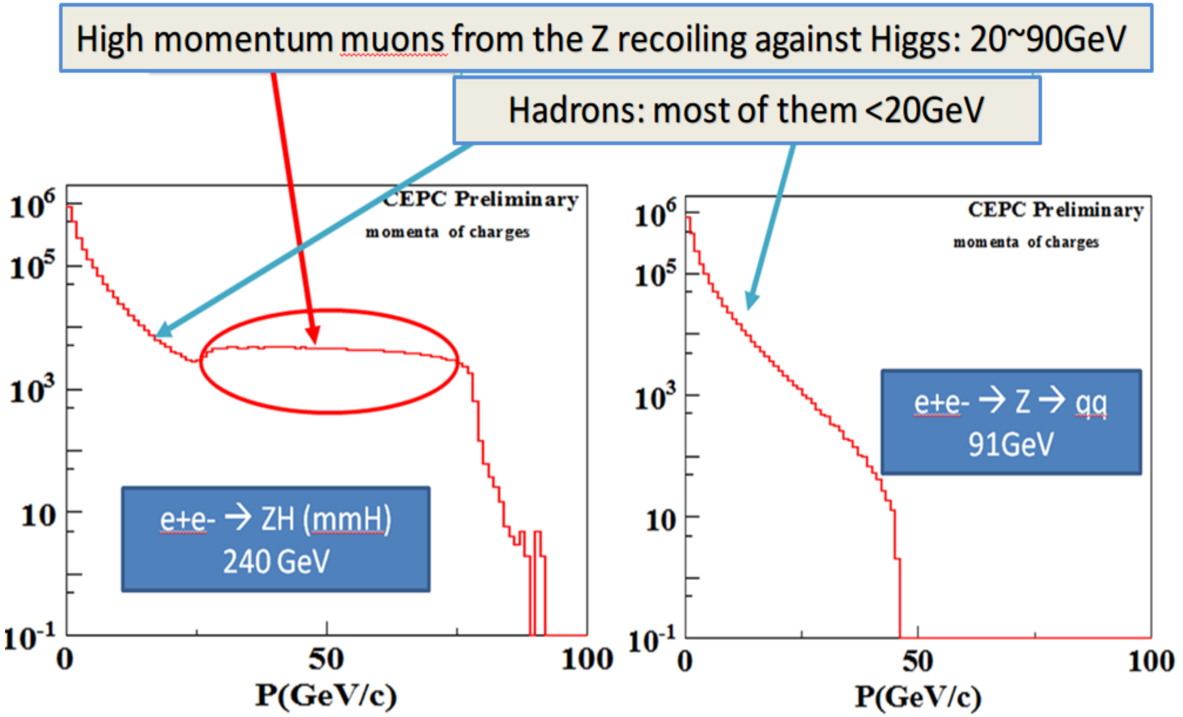
https://arxiv.org/abs/1811.10545

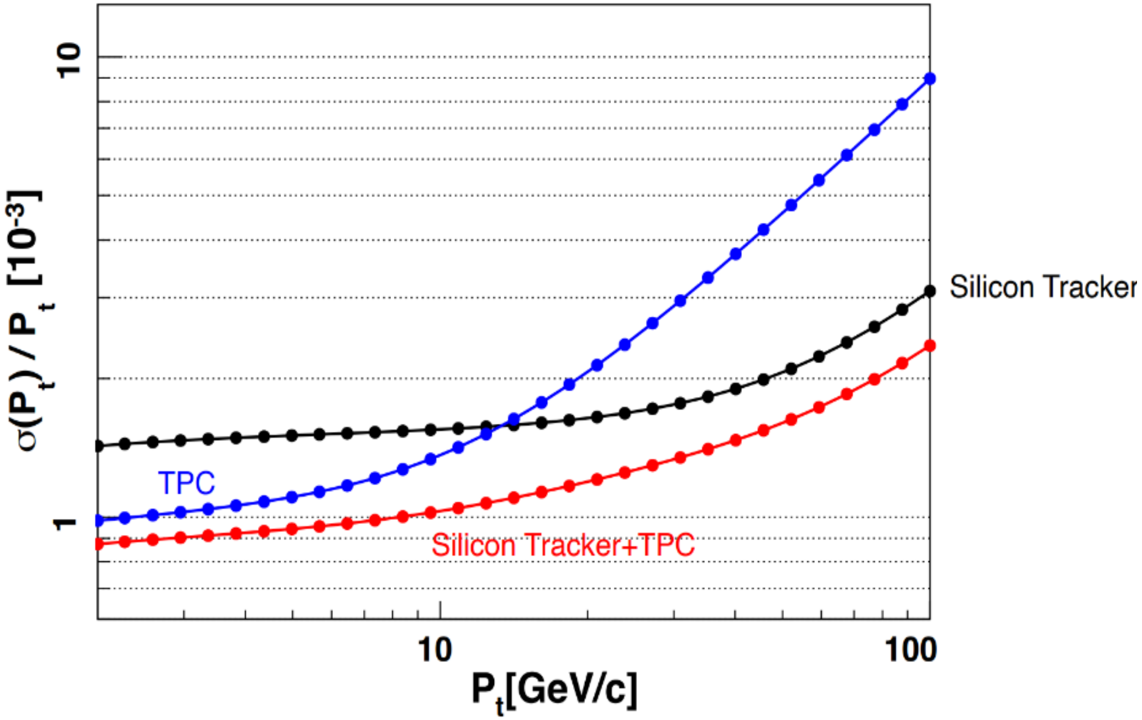
https://arxiv.org/abs/2203.08310

Motivation and physics requirements

- 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





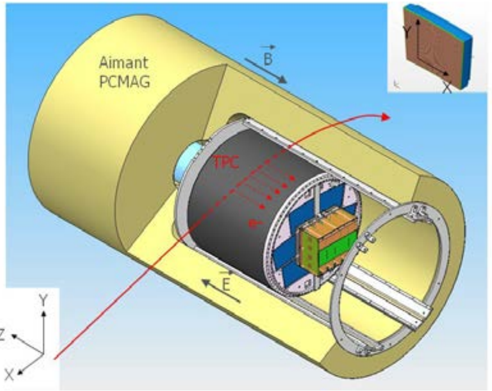
https://doi.org/10.1140/epjc/s10052-018-5876-z

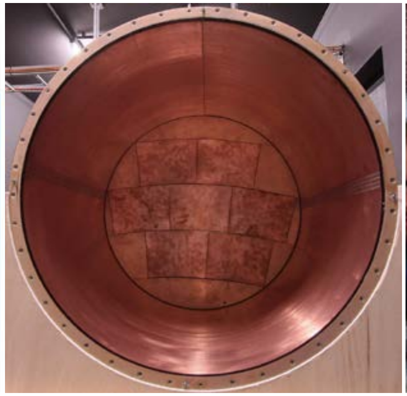
- **Status of TPC in LCTPC and CEPC**

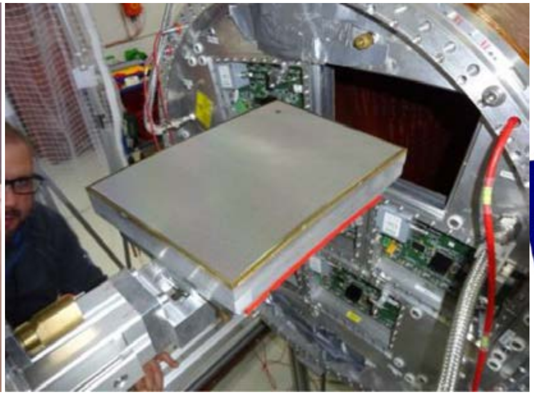
Status of TPC in LCTPC

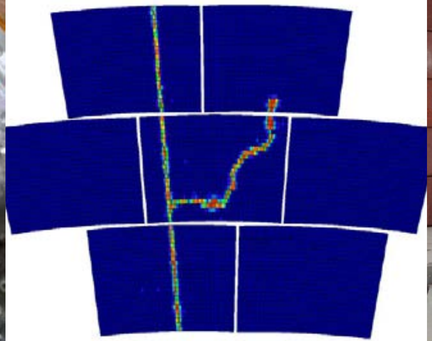
- **Large Prototype** setup has been built to compare different detector readouts under identical conditions and to address integration issues.
  - PCMAG: B < 1.2T, bore Ø: 85cm
  - Two end plates for the LP made from Al with 7 module window
- **LP Field Cage Parameter**
  - Length = 61cm, inner Ø =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

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





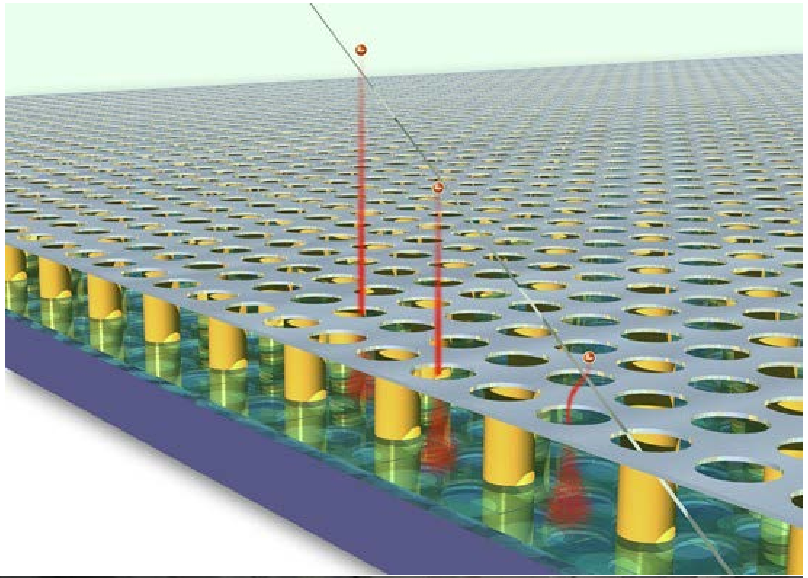


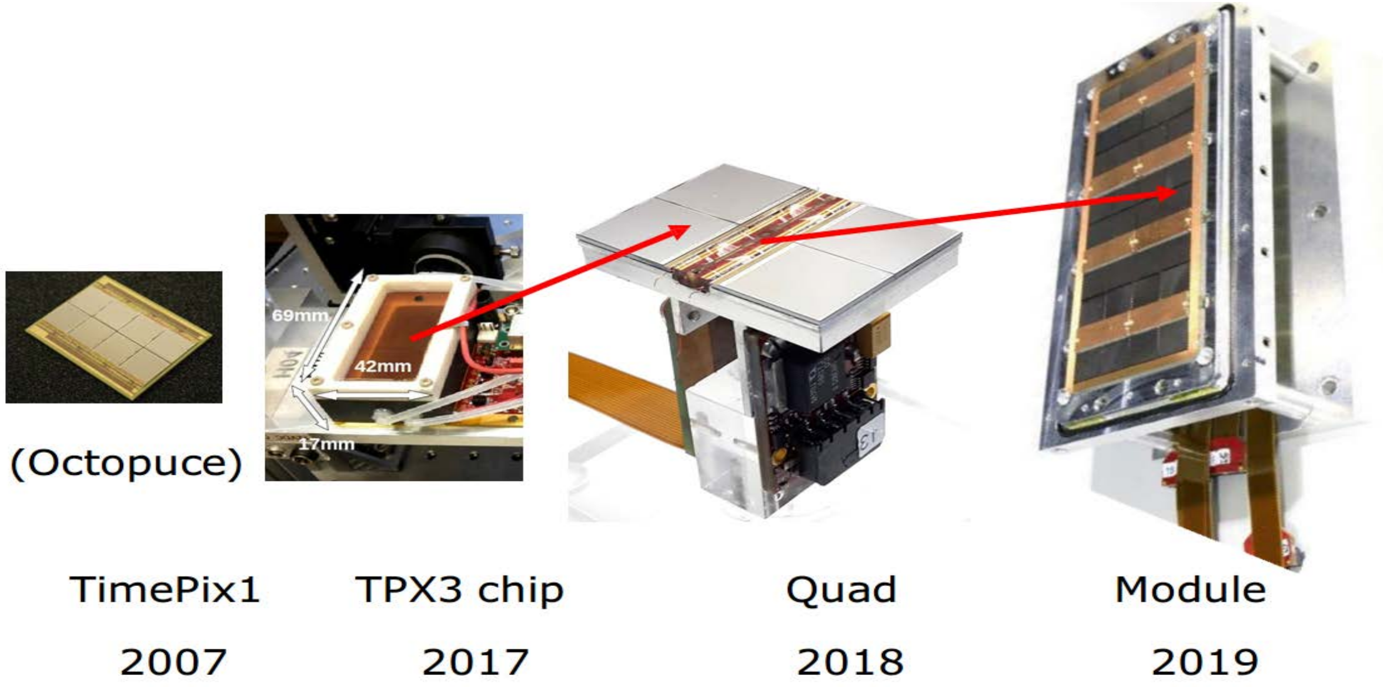


https://doi.org/10.48550/arXiv.2006.08562

Status of TPC in LCTPC

- 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 **)**



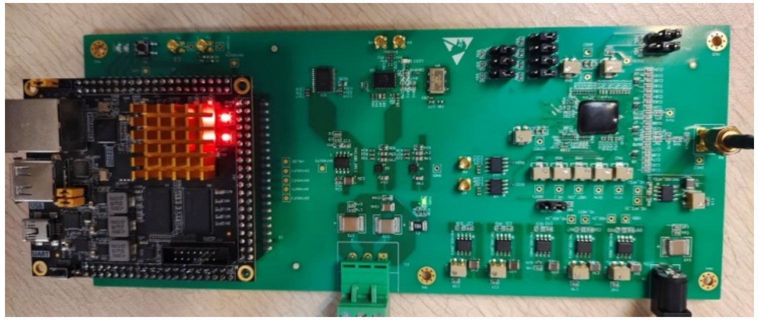


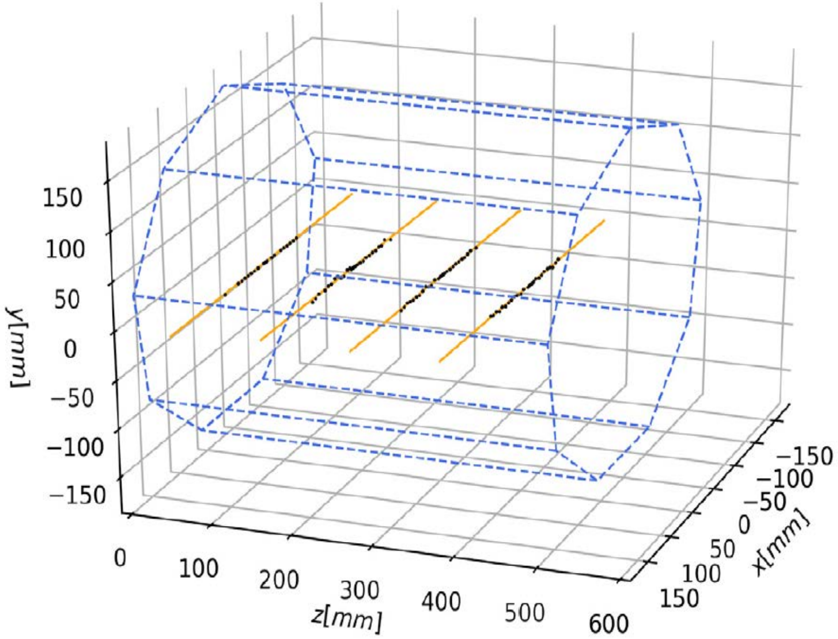
https://arxiv.org/abs/1902.01987

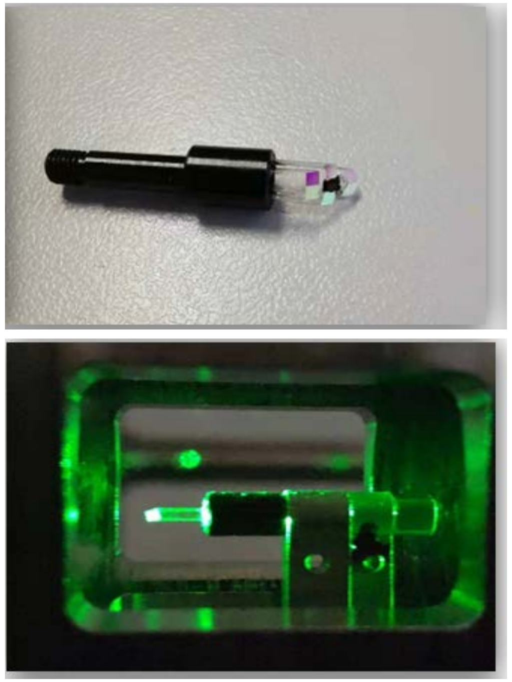
NÌM A535 (2004) 506-510
NIM A845 (2017) 233-235

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 **$\sigma_{r\varphi}$≤100 µm and dE/dx resolution of 3.6%**
  - FEE chip: reach ~**3.0mW/ch with ADC** and the pixelated readout R&D







Status of TPC in CEPC ref-TDR 1

- The CEPC study group is in process to produce TDR of a reference detector(ref-TDR) by June 2025, aiming mainly for domestic endorsement at one IP of the accelerator.
- CEPC community will **continue to aligned the technologies,** and decide the final detectors within the CEPC international collaborations.

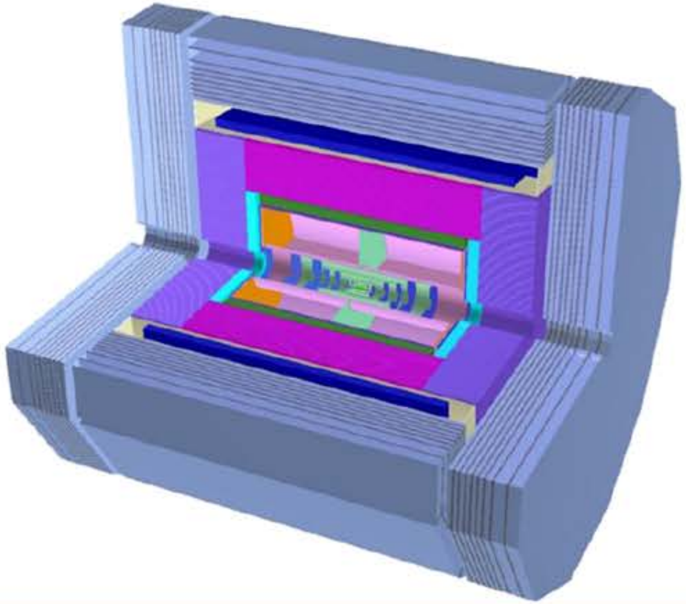
Date	Actions and/or Expectations
Jan 1, 2024	Start the process by comparing different technologies
Jun 30, 2024	Baseline technologies, general geometric configuration and key issues are decided
Oct 31, 2024	Discuss the ref-TDR at the CEPC workshop, report progresses to the CEPC IAC
Dec 31, 2024	The first draft of the ref-TDR is ready for internal reviews
Apr 15, 2025	international review
Jun 30, 2025	The ref-TDR for ready for public reviews
Oct 30, 2025	Submit the ref-TDR for publication

Jianchun Wang's talk
in CEPCWS at Hangzhou.

Status of TPC in CEPC ref-TDR 2

- 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



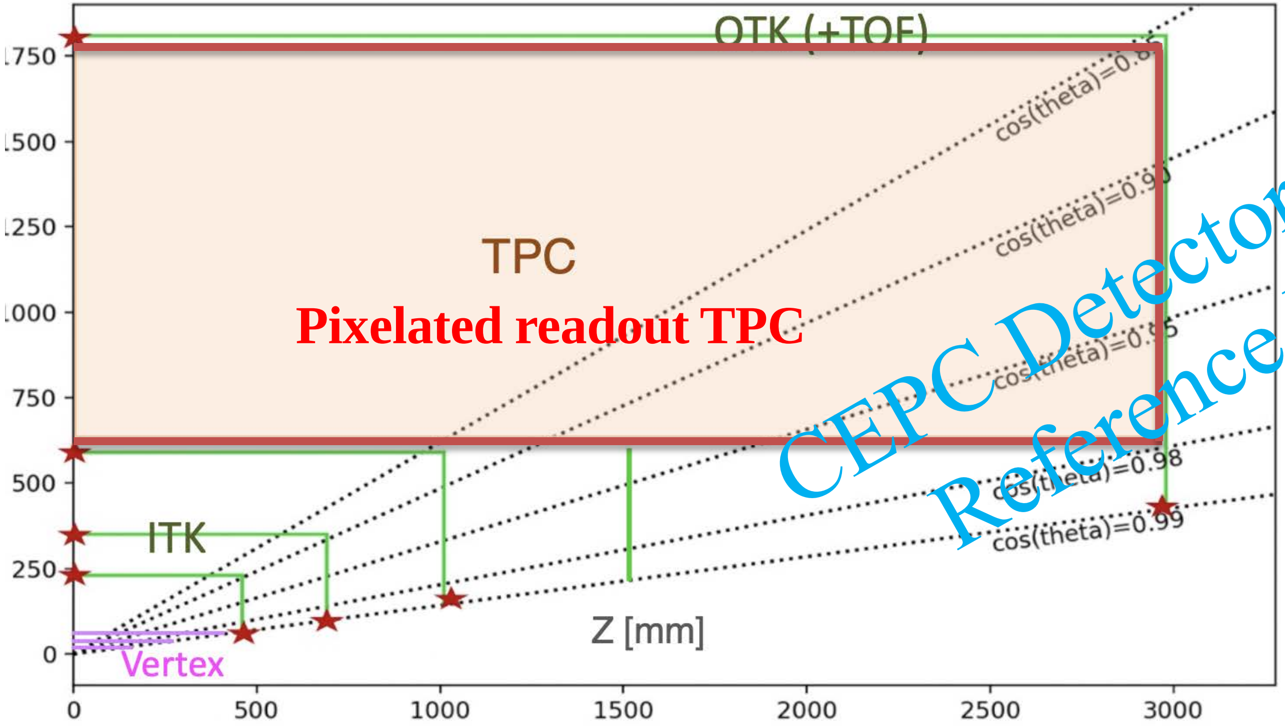
Foundations:
- CEPC Instrumentation R&D
- LHC detector upgrade projects
- other HEP experiments
- progress in HEP worldwide R&D
- development in industry

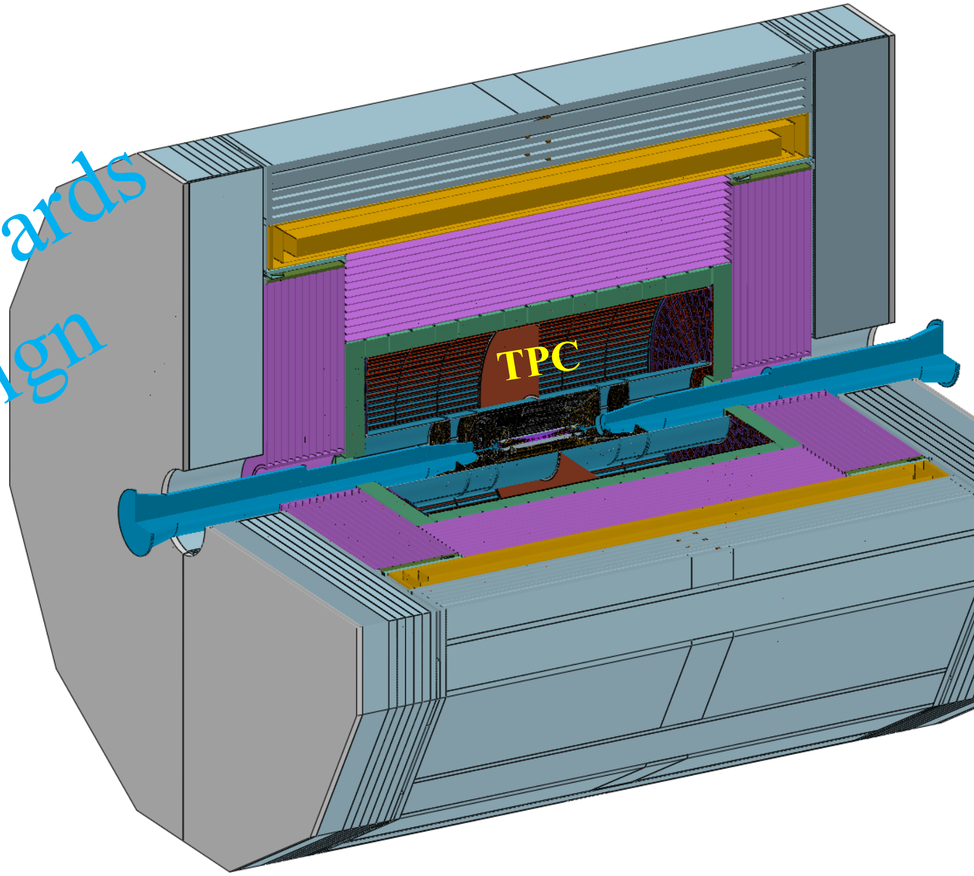
Status of TPC in CEPC ref-TDR 3

- International Detector Review Committee (IDRC) held its inaugural meeting at IHEP, Oct 21-23, 2024 , to review the status and plan of CEPC Ref-TDR .

Baseline design of TPC technology in CEPC ref-TDR

- 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



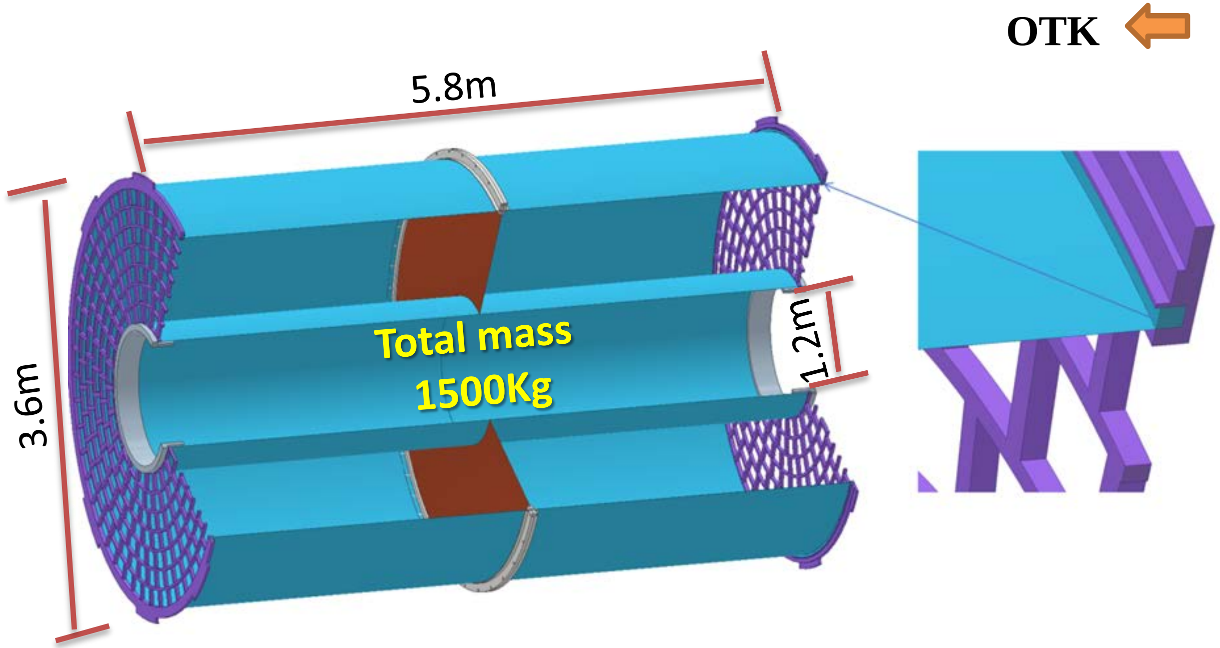


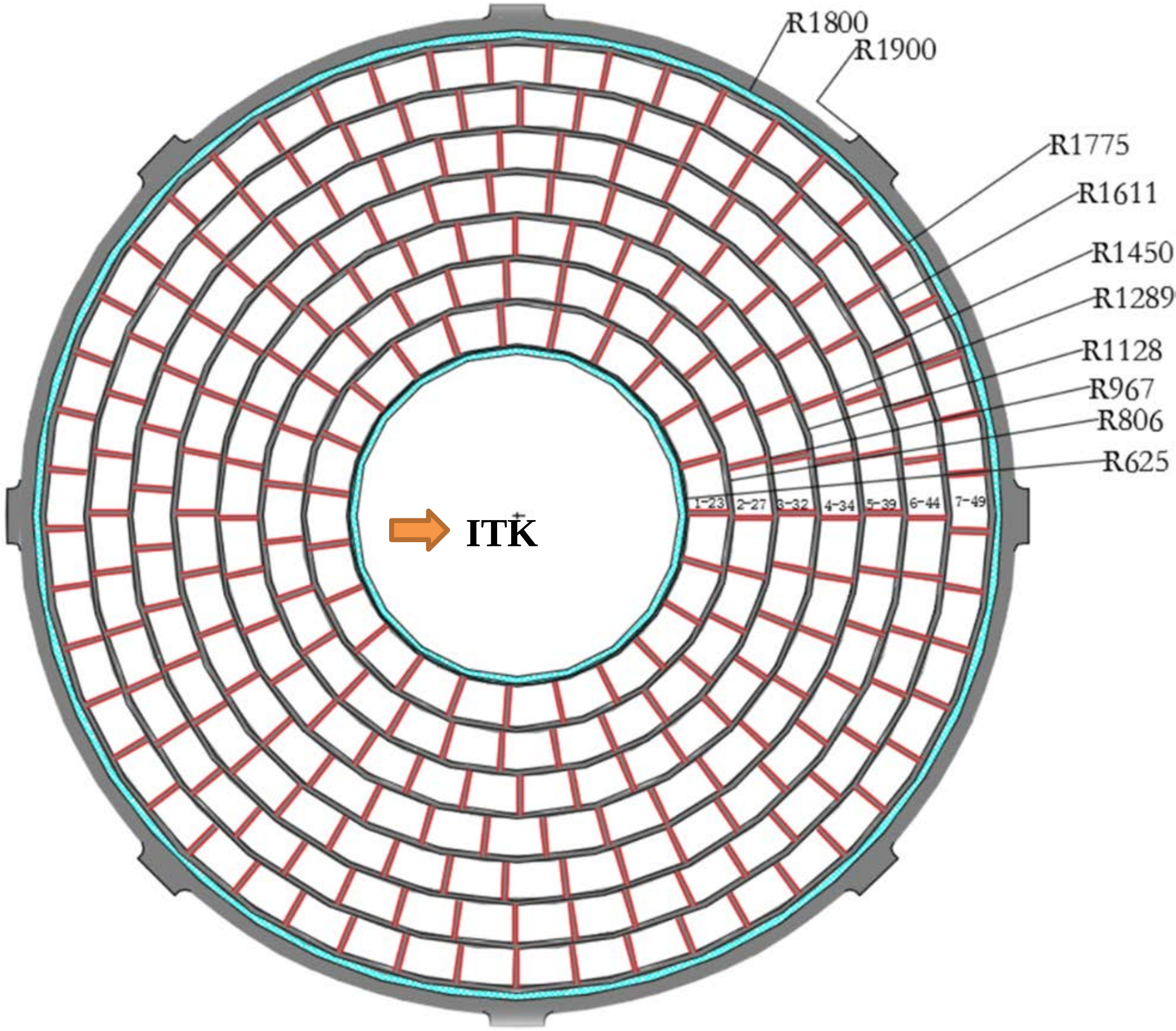
CEPC Detector towards Reference Design

Geometry of the tracking detector system of the CEPC TDR

Parameters of TPC technology in CEPC ref-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



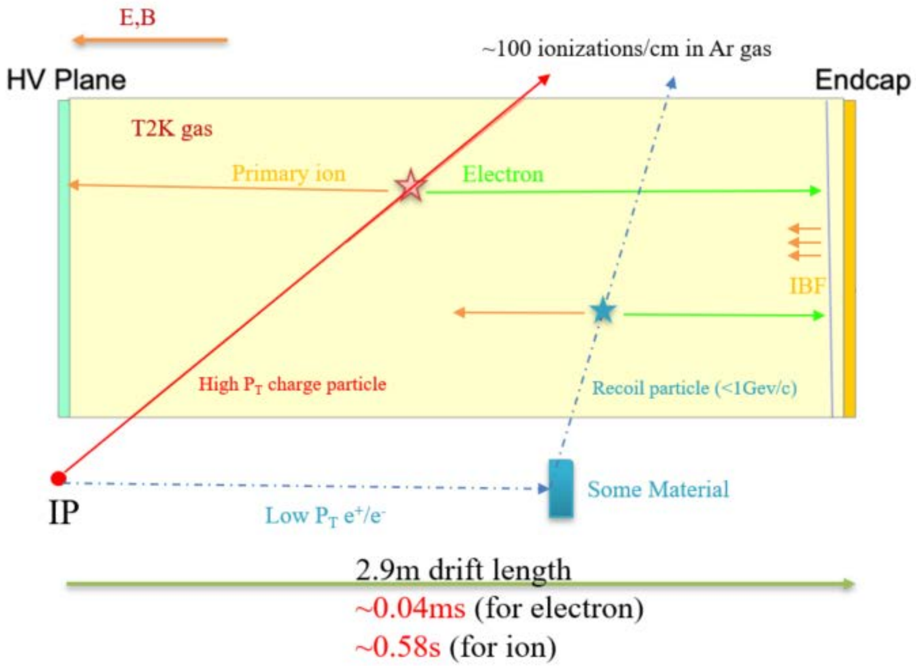


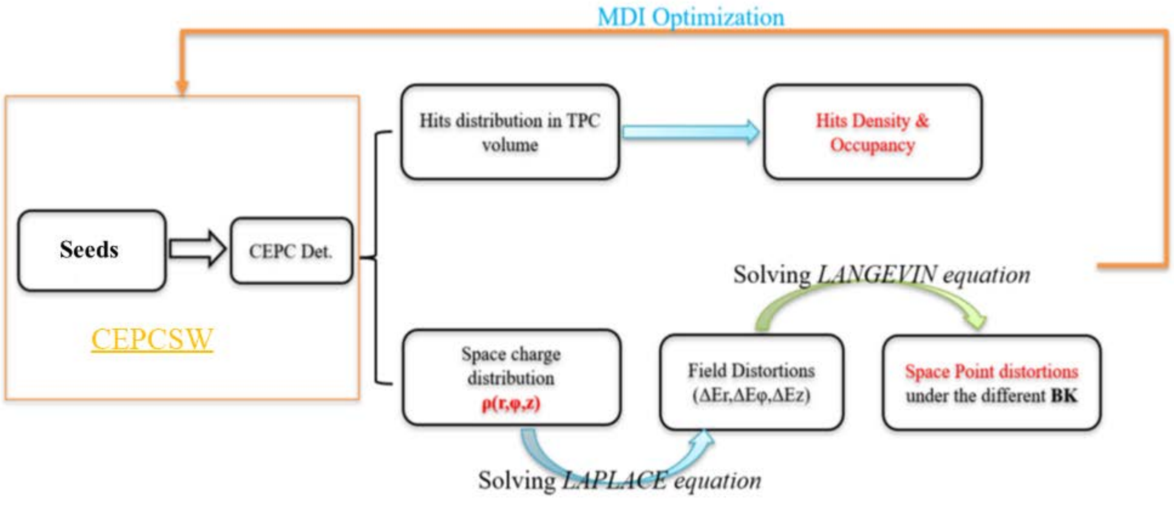
Detailed design of TPC detector in ref-TDR

- **Pixelated readout TPC R&D for Higgs and Z**

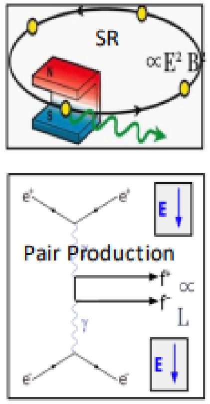
Pixelated readout TPC for Higgs and Z

- Space charge in TPC chamber
  - Physics events: H→ss/cc/sb, Z→qq…(High P_T)
  - Beam background: (Low P_T)
    - Beamstrahlung (Luminosity related)
    - Beam-Gas, Beam Thermal Photon, SR…(Single Beam)
    - Injection background
  - IBF at the MPGDs
- Simulation framework



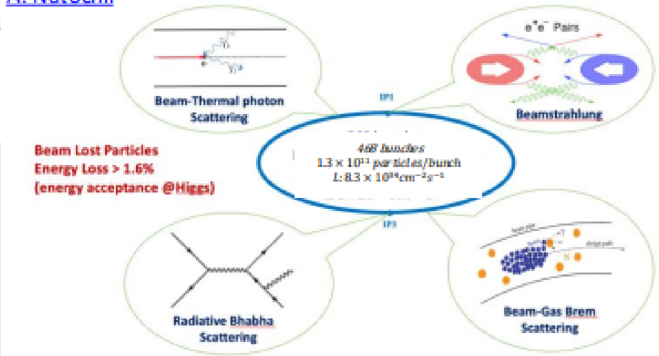


Simulation flow of CEPC Beam Backgrounds



Photon BG

A. Natochii



Beam Loss BG

Background Sources at Higgs @3T

- Higgs Mode background sources
  - I. Pair production (Luminosity related)
  - II. Single Beam (BGB, BGH,Touschek Scatter…)
  - III. Synchrotron Radiation
  - IV. Injection background

IBF×Gain=1, same primary ion level

- At present, only types I and II backgrounds have been generated.
  - Pair production background is about **two orders of magnitude higher** than the Single Beam.
- For Higgs, it is necessary to **optimize the MDI to shield gamma rays of approximately MeV level**.

Bkg type	Space charge density(steady)	Remark	Optimization strategy
Pair + Single Beam	ρ_{sc0} ~ 0.06nC/m^3 (R=60cm) 20um, 2.75m Drift Length @ inner radius	Without low P_T e^-/e^+ (<10MeV) in TPC caused by ~MeV γ	**Acceptable**
Pair + **Single Beam**	ρ_{sc1} ~ 60× ρ_{sc0}	With low P_T e^-/e^+ (<10MeV) in TPC caused by ~MeV γ	Analysis initial position distribution of ~MeV γ (Main contributions) and Add shielding

Background Sources at Tera-Z @3T

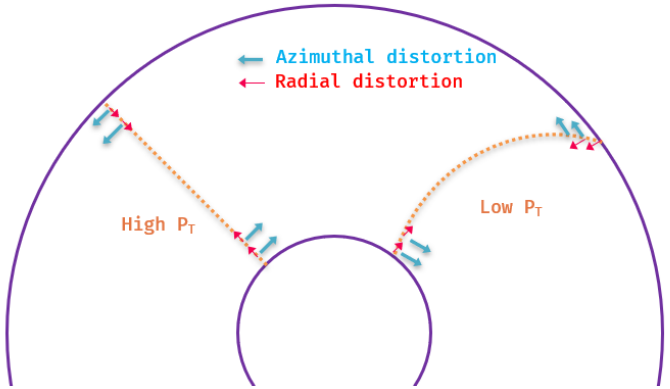
- Tera-Z Mode background sources
  - I. Pair production (Luminosity related)
  - II. Single Beam (BGB, BGH,Touschek Scatter…)
  - III. Synchrotron Radiation
  - IV. Injection background
- At present, only types I and II backgrounds have been generated.
  - At Z-pole, the Single Beam background loss rate increases, with Single Beam being about one order of magnitude higher than Pair.
  - Taking into account all MeV-level low-energy gamma rays (**with types III and IV**), the beam background will cause cm-level distortions. **It is necessary to optimize the MDI.**

IBF×Gain=1, same primary ion level

Bkg type	Space charge density(steady)	Remark	Optimization strategy
Pair production	ρ_{sc0} ~ 0.32nC/m^3 (R=60cm) **150um**, 2.75m Drift Length @ inner radius	Without low P_T e^-/e^+ (<10MeV) in TPC caused by ~MeV γ	
Pair + Single Beam	ρ_{sc1} ~ 15-20× ρ_{sc0} **2500um**, 2.75m Drift Length @ inner radius	Without low P_T e^-/e^+ (<10MeV) in TPC caused by ~MeV γ	**Loss rate control**
Pair + Single Beam	ρ_{sc2} ~ 500-1000× ρ_{sc0} ~cm distortion	With low P_T e^-/e^+ (<10MeV) in TPC caused by ~MeV γ	**Loss rate control and ~MeV γ shielding**

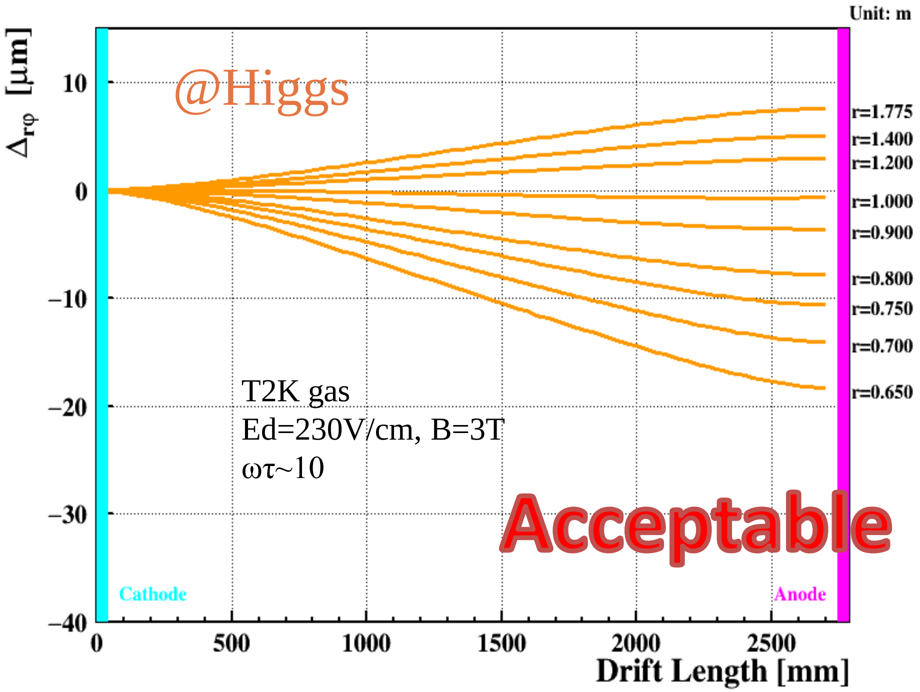
TPC distortion caused by primary ions

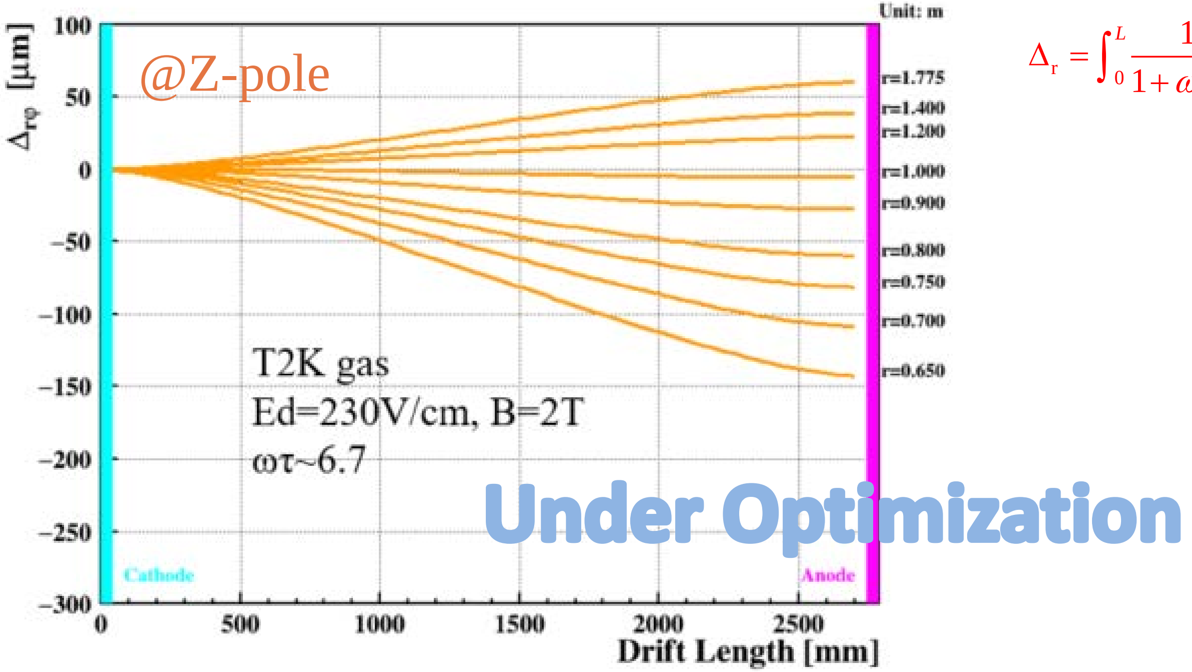
- Radial distortion (Δ_r) is much smaller than azimuthal distortion, almost imperceptible when along the track for most P_T track **IBF×Gain=1, same primary ion level**
  - Azimuthal distortion ($\Delta_{r\varphi}$) has much serous impact both on high/low P_T tracks
  - The maximum $\Delta_{r\varphi}$ is 20μm@Higgs (**acceptable**)
  - The maximum $\Delta_{r\varphi}$ is 150μm@Z-pole (**need to 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 based on Green's function

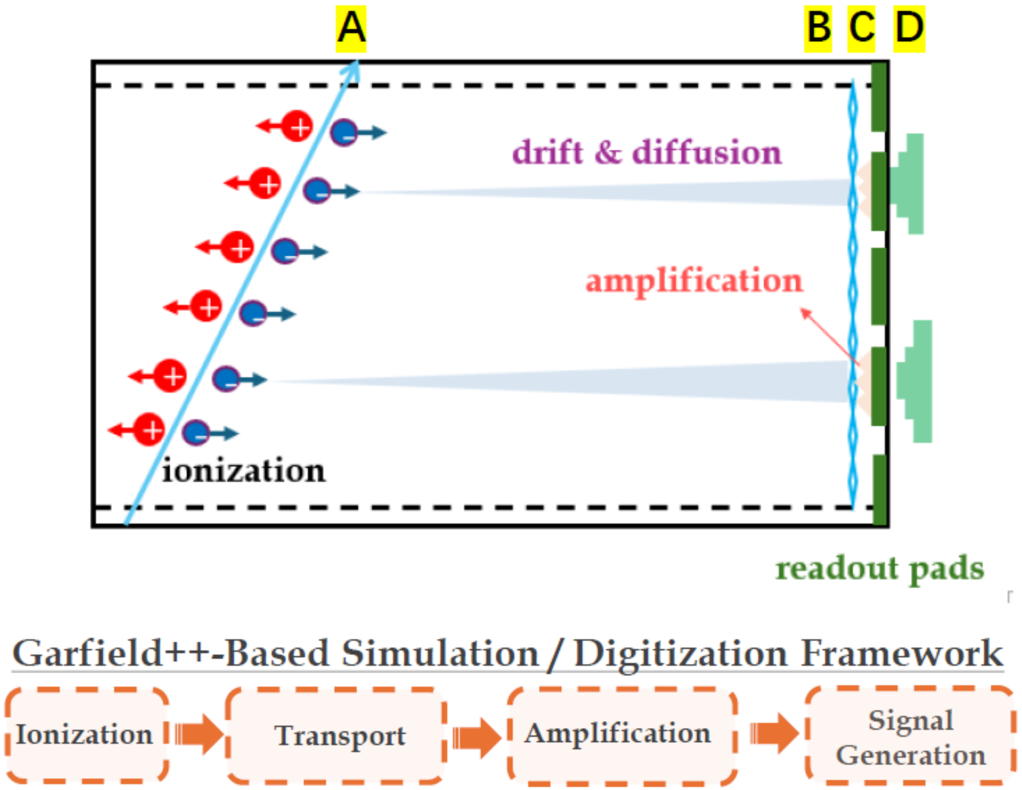
Full Simulation of Pixelated readout TPC

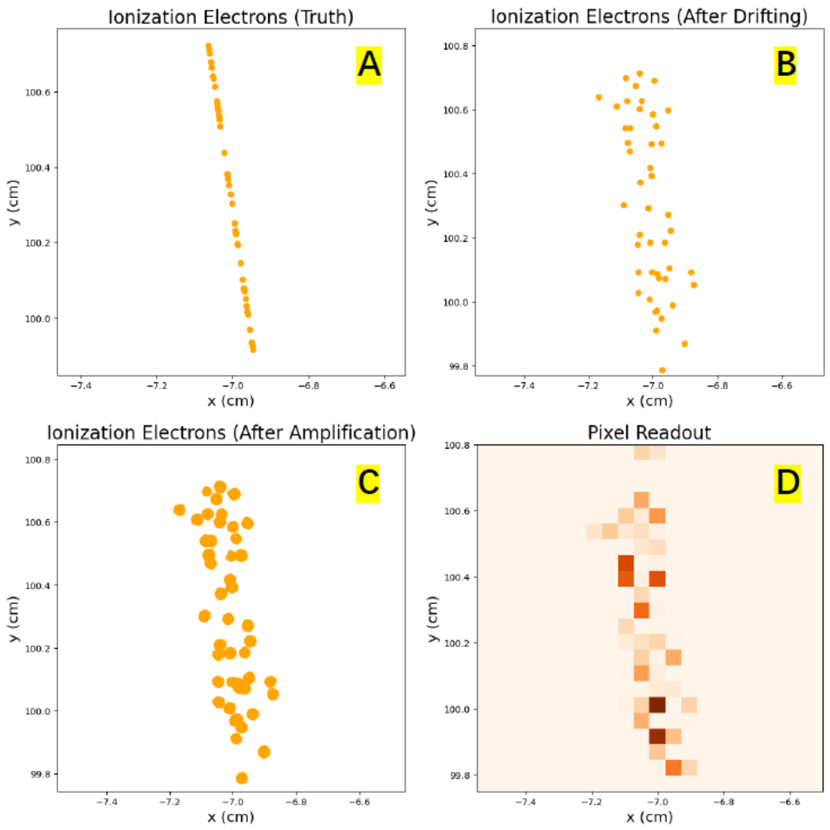
Simulation:

- 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





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

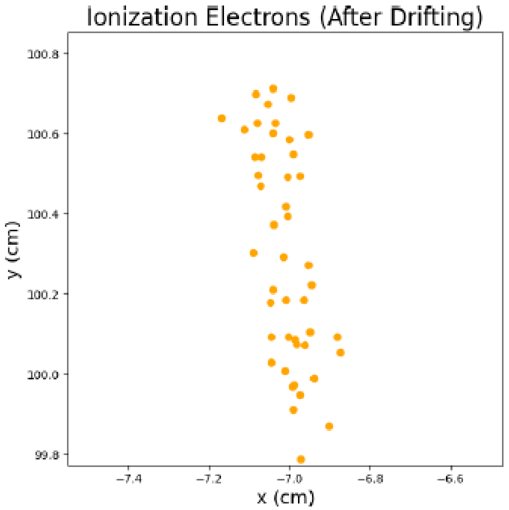
Full Simulation of Pixelated readout TPC – Readout size

17:10 **simulation studies of PID for the CEPC TPC**
Speaker: Dr Guang Zhao (Institute of High Energy Physics (CAS))

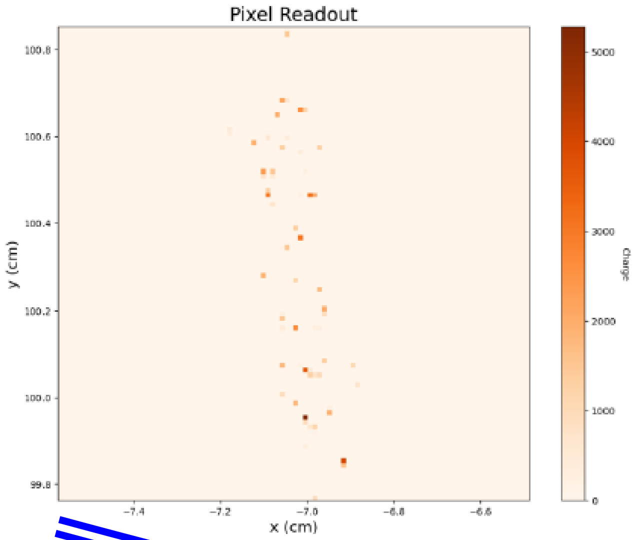
- Simulation of the readouts in pixel sizes
  - Actually, TPX3/4 option existing and the power consumption will be optimized.
  - Optimization started in this ref-TDR at IHEP to meet **Higgs/Z at 3T**.

> - 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

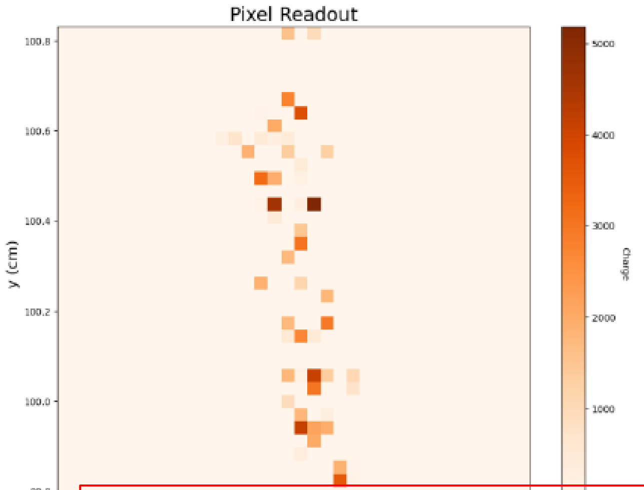
Peter's comment in CEPCWS at Hangzhou.



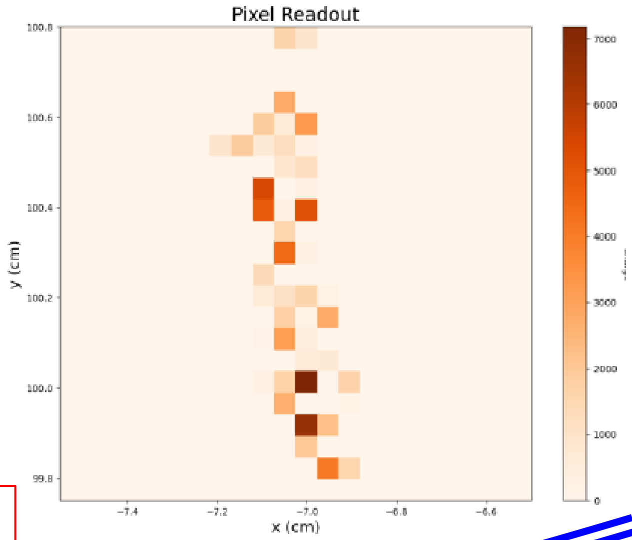
Pixel size = 110 um



Pixel size = 300 um



Pixel size = 500 um



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

Full Simulation of Pixelated readout TPC - Reconstruction

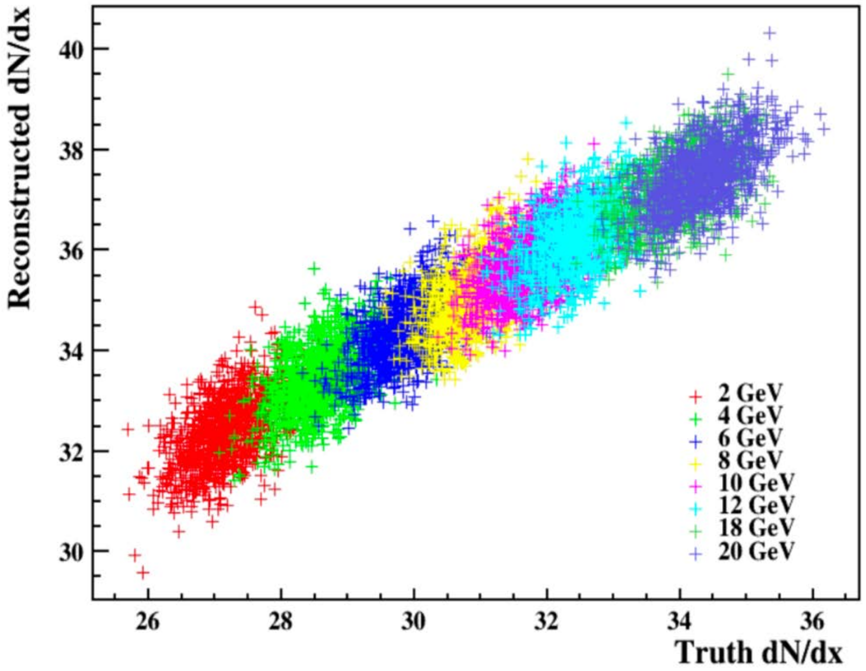
Reconstruction:

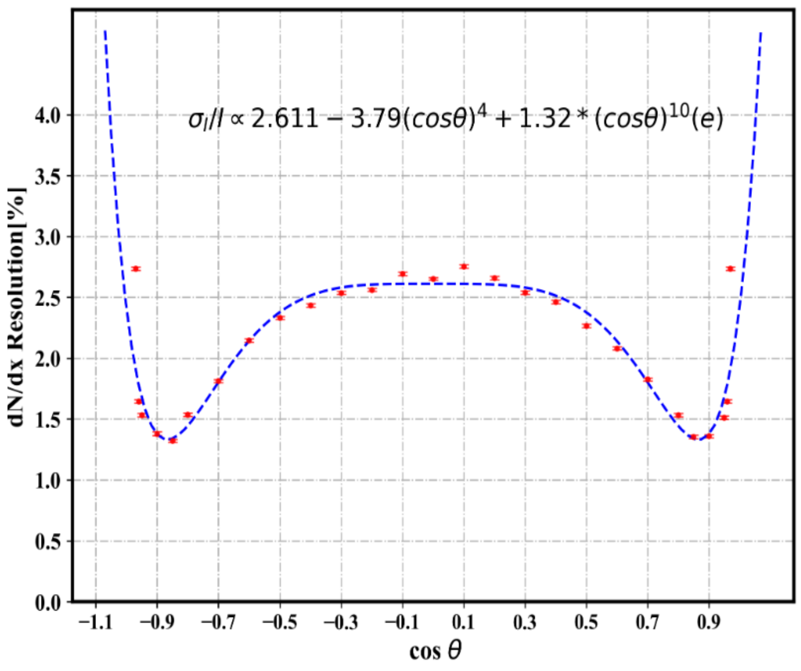
- Reconstruction by counting the number of fired pixels over threshold
- **Reconstruction with good linearity and reliability**

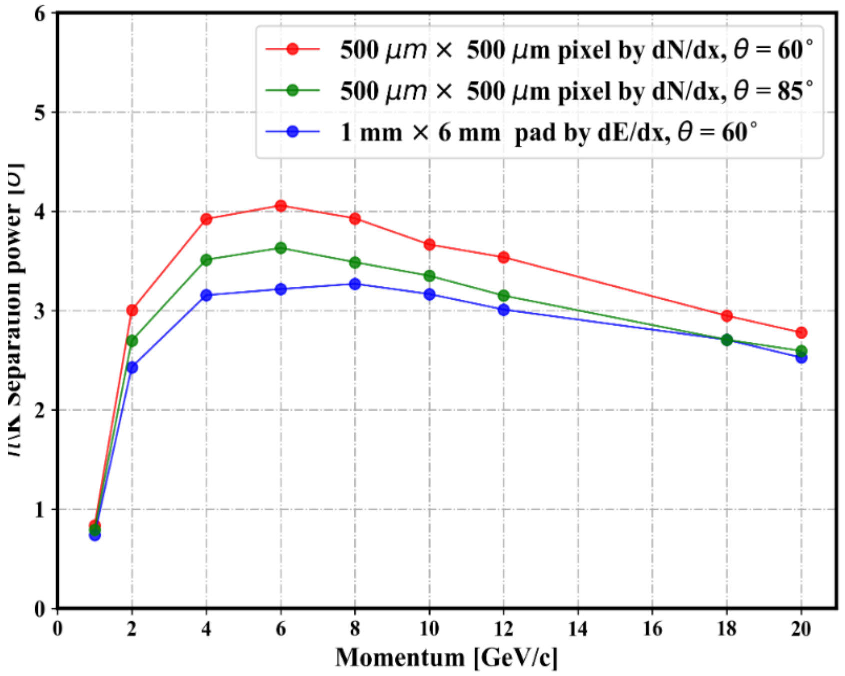
Preliminary PID performance:

- π/k separation power simulation with different momentum

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

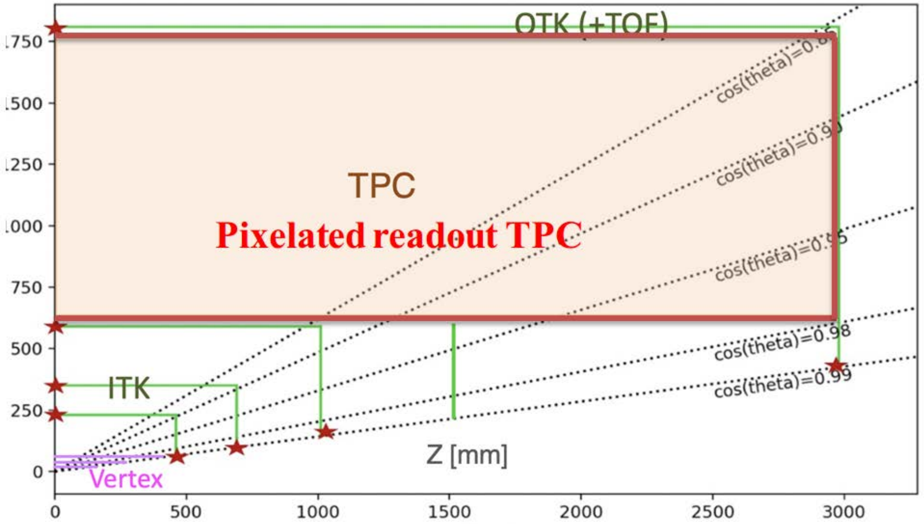


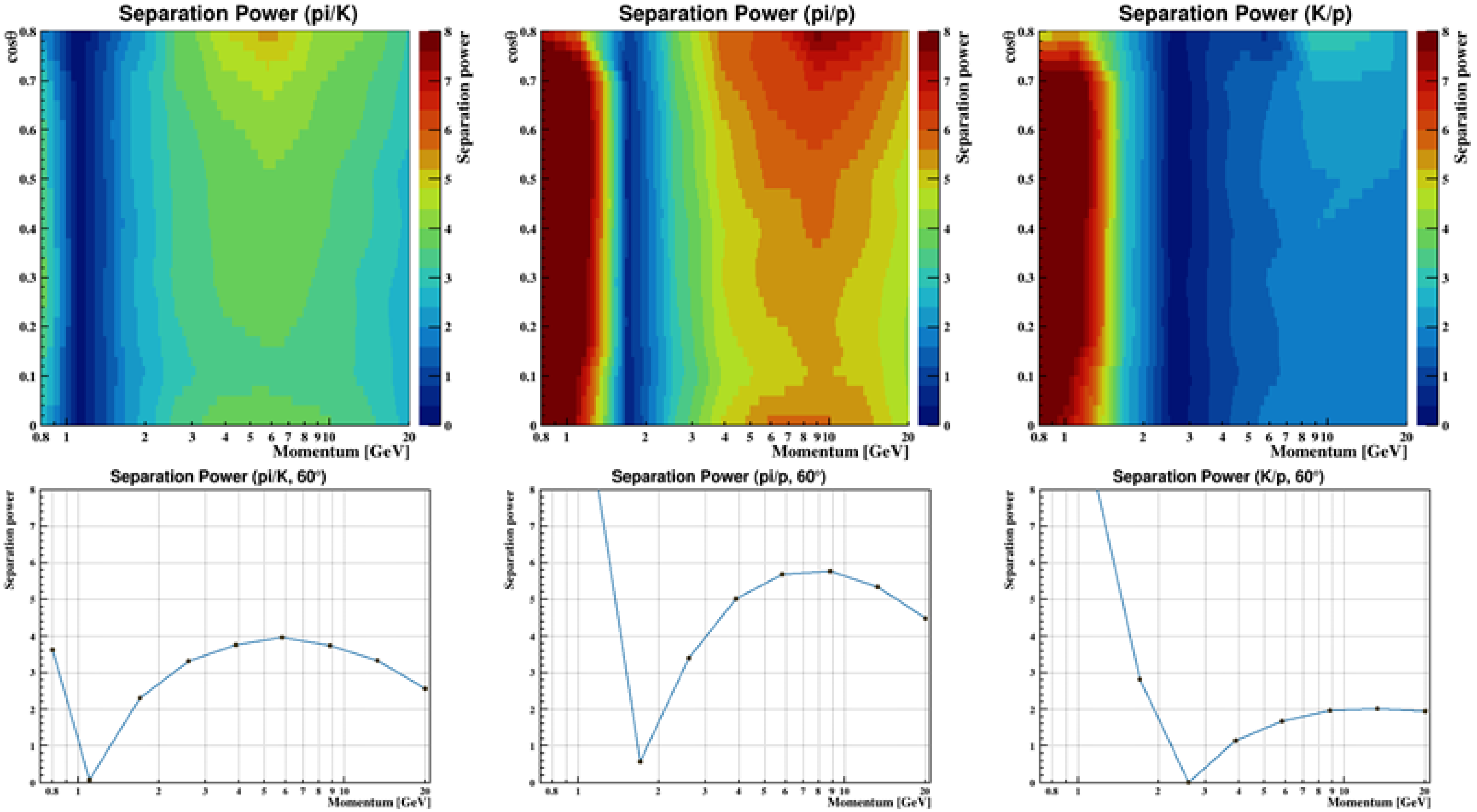




Full Simulation of Pixelated readout TPC – PID performance

- Performance of the pixelated readout TPC
  - Simulation of π/K, π/p, and K/p separation power with varying momentum and cosθ

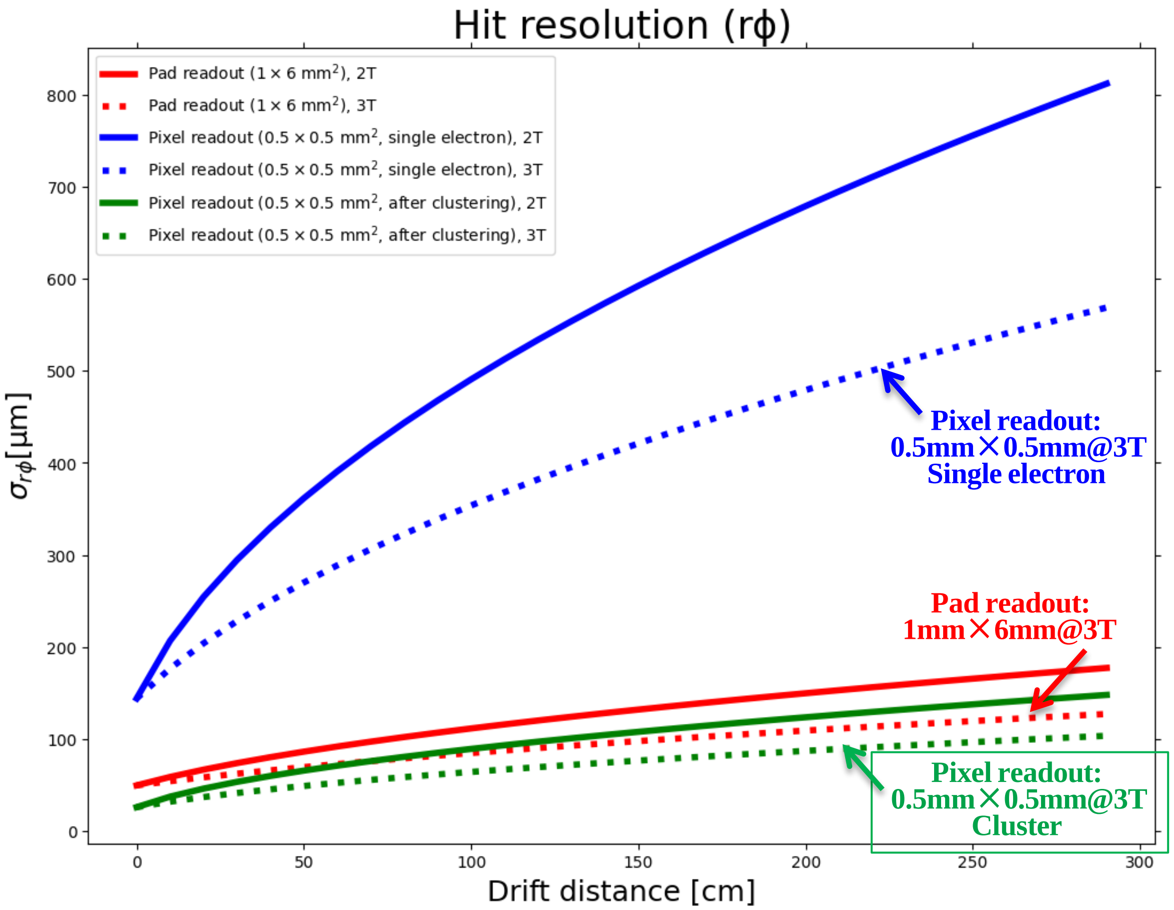




Full Simulation of Pixelated readout TPC – Spatial resolution

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:

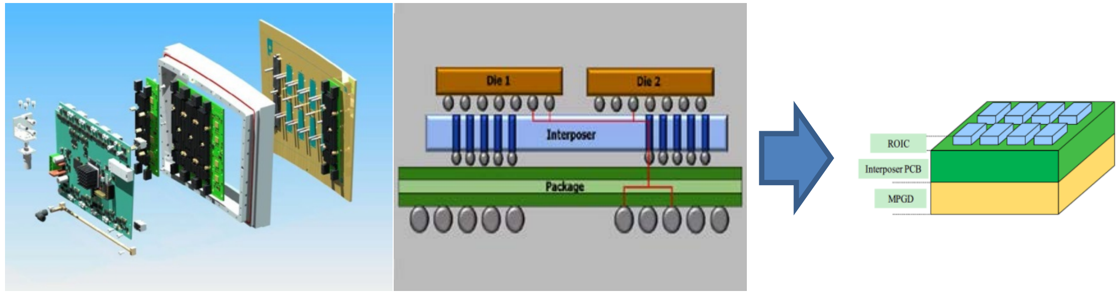
$$\sigma_{r\phi}^{\text{pad}} = \sqrt{(\sigma_{r\phi 0}^{\text{pad}})^2 + \sigma_{\phi 0}^2 \sin^2(\phi_{\text{track}}) + L\frac{D_{r\phi}^2}{N_{\text{eff}}}\sin(\theta_{\text{track}})}$$

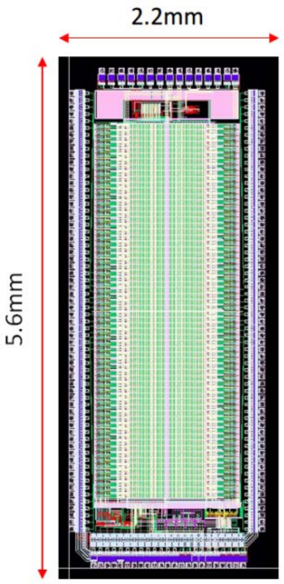
Pixel readout:

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

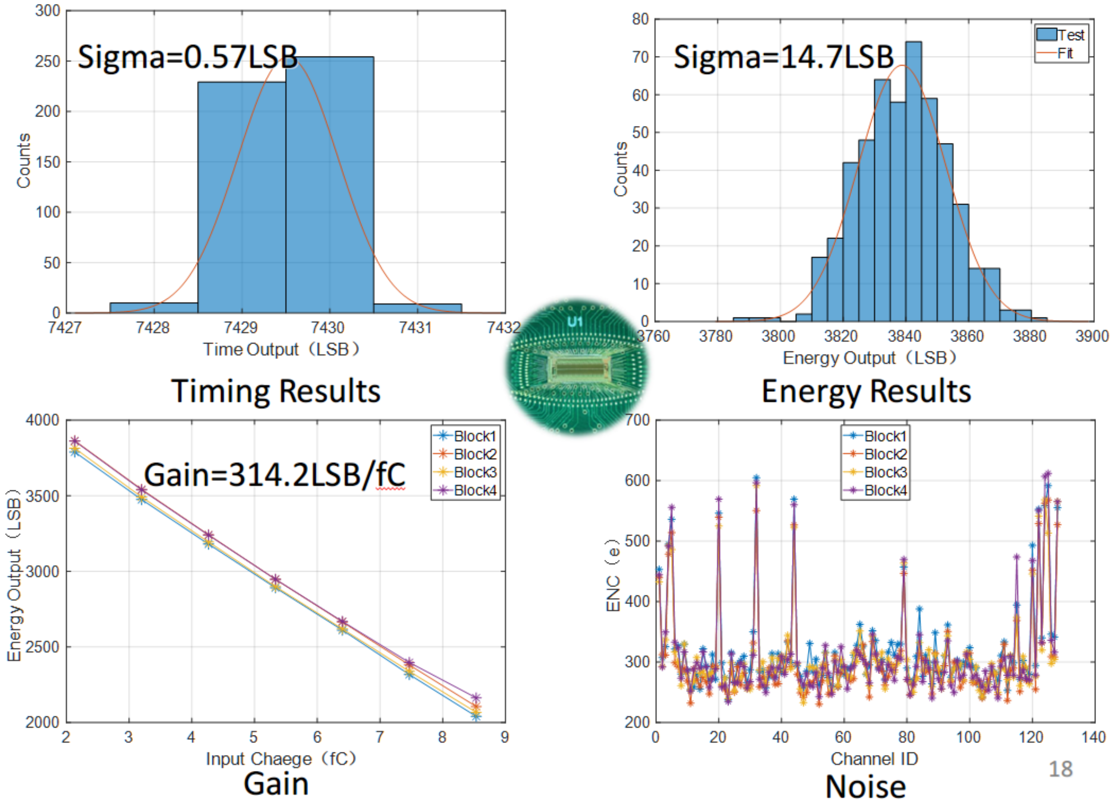
Full Simulation of Pixelated readout TPC – TEPix with 500μm×500μm

- 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)





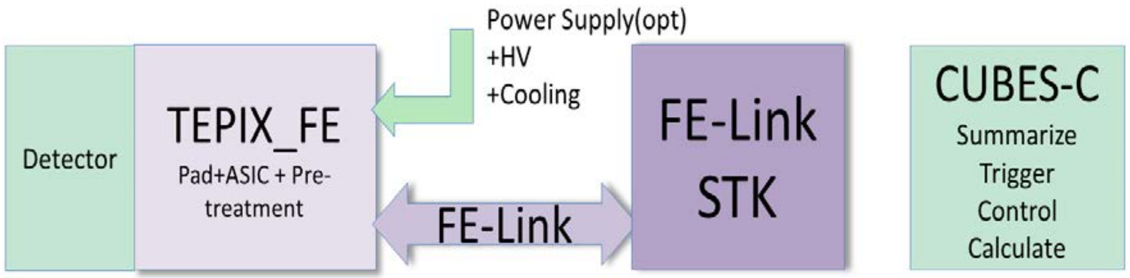
Parameter	Spec
Number of channels	128
Power Consumption	Analog<30mW
	Digital<30mW
ENC	~300 e(high gain)
Dynamic Range	25fC(high gain)
	150fC(low gain)
INL	<1%
Time Resolution	<10ns

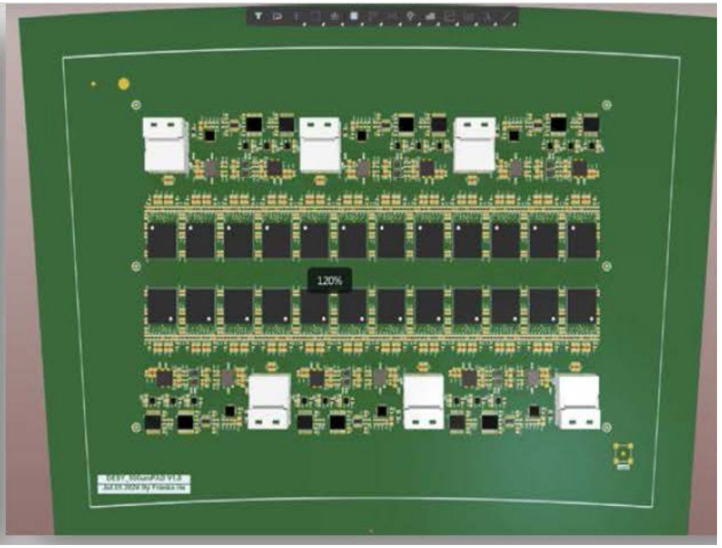


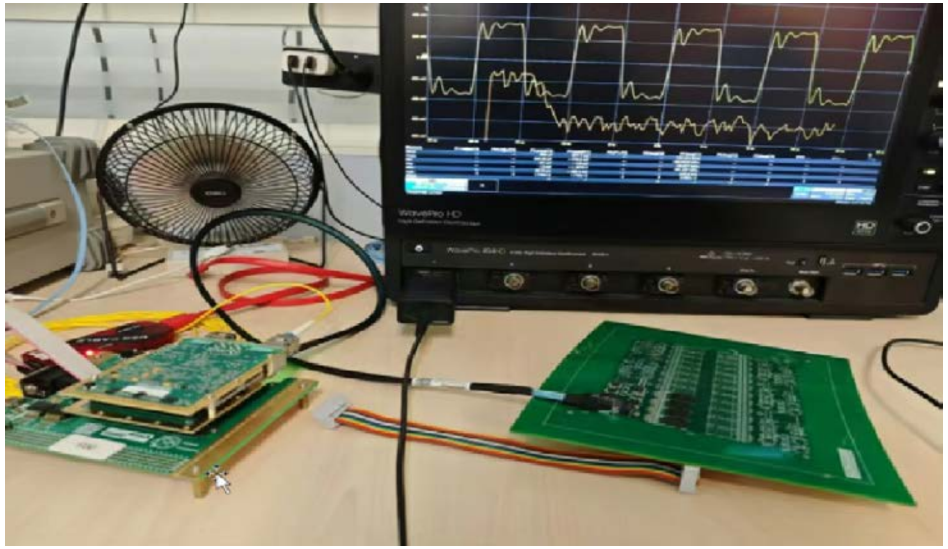
FEE ASIC: TEPIX—Test Results in May

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)**



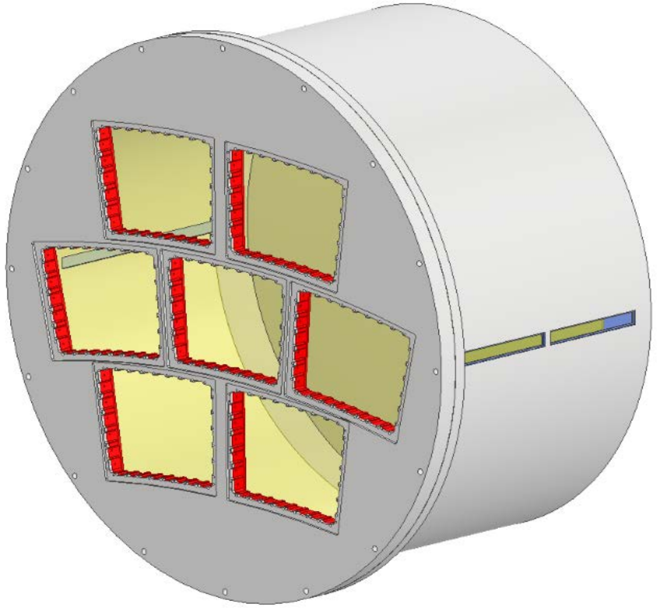




Photos TPC modules assembled for the beam test

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/cm^2 (60nm ASIC)	Optimization 330µm - 500µm
PID resolution	3% (dN/dx)	<3% (dN/dx)
Material budget (barrel)	Carbon Fiber	Full size prototype

Summary

- 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!