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

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On behalf of the LCTPC Collaboration

ILD group meeting, 12 November, 2024

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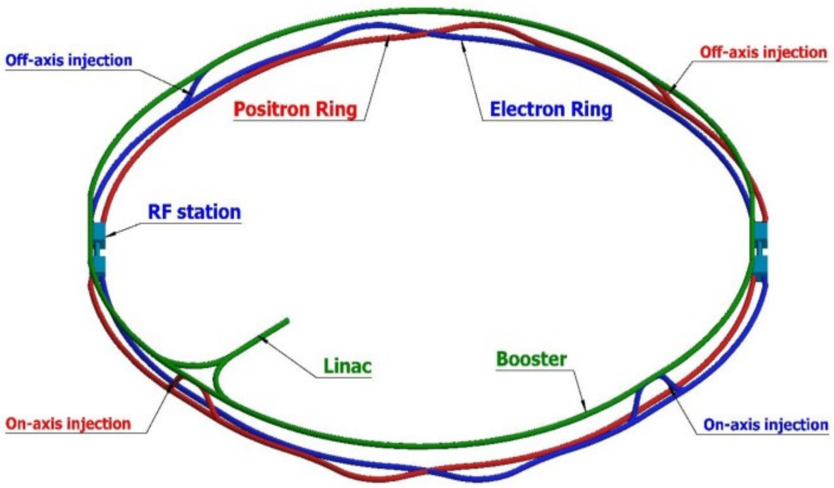
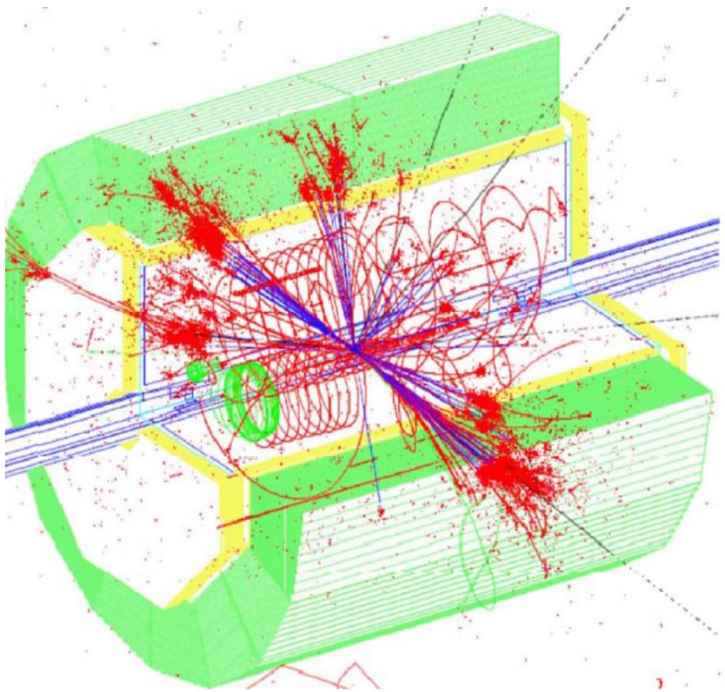
- **Motivation and physics requirements**
- **Status of TPC in LCTPC and CEPC**
- **Pixelated readout TPC for Higgs and Z**
- **Work plan and Summary**

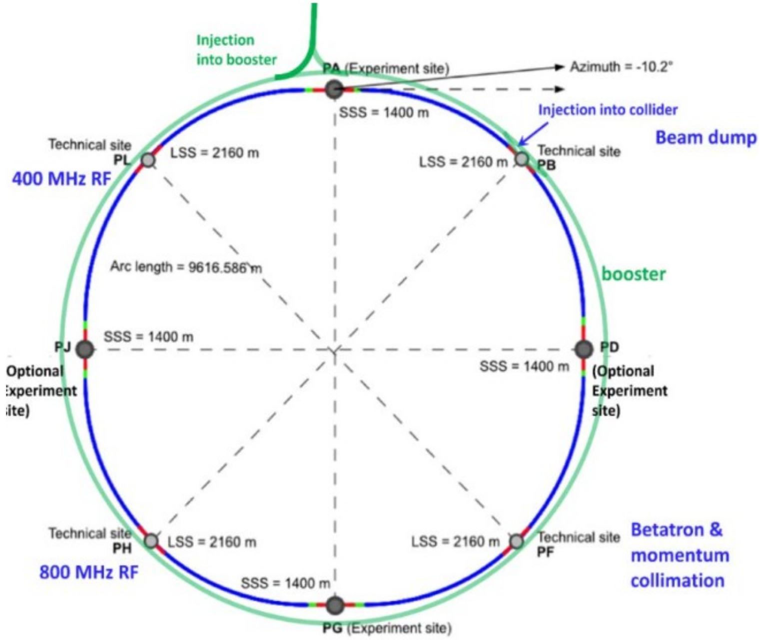
Motivation and physics requirements

- 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)

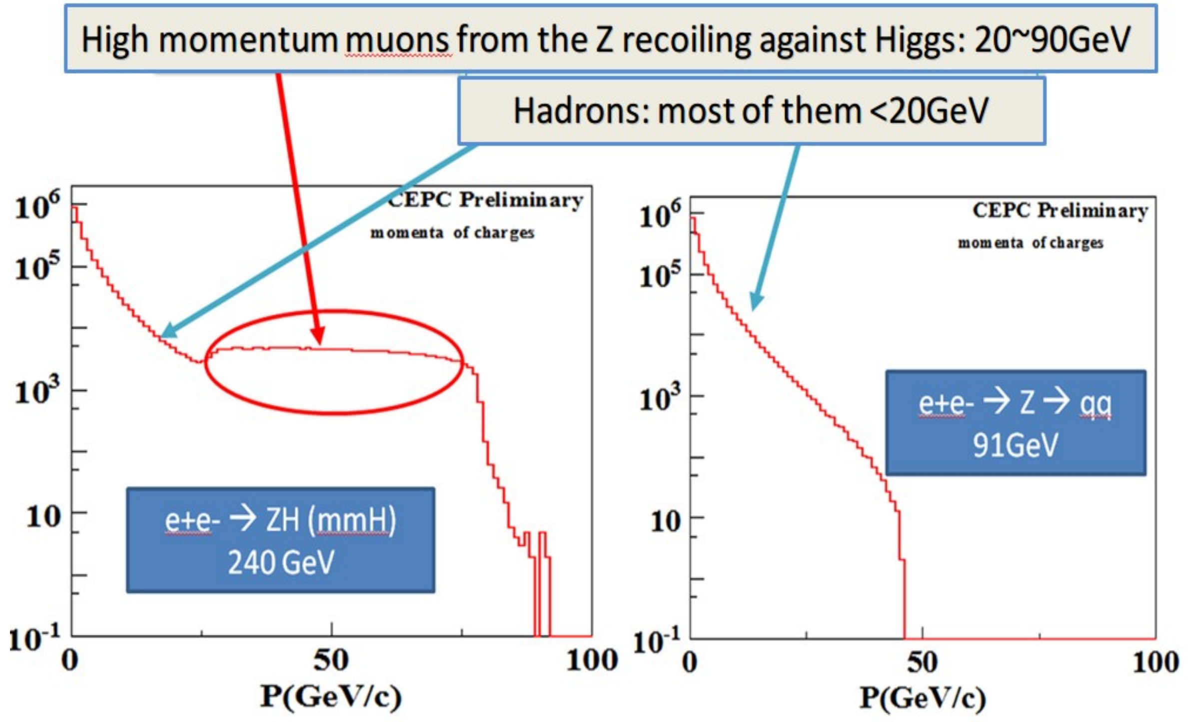
https://arxiv.org/abs/1811.10545

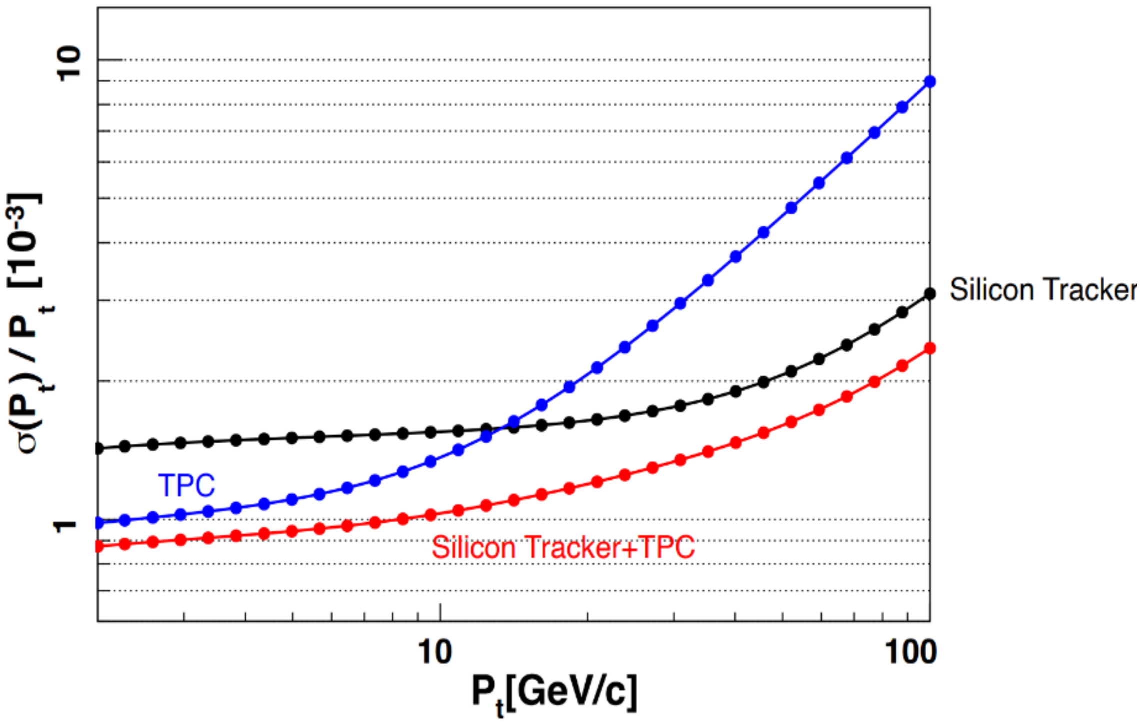
https://arxiv.org/abs/2203.08310

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



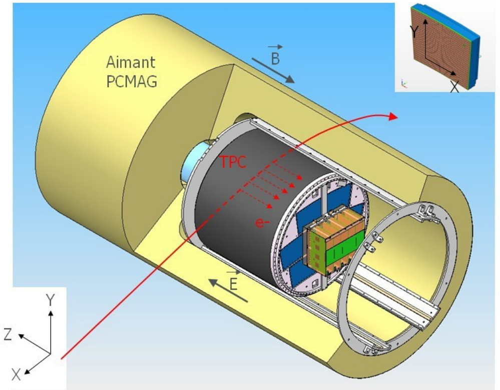


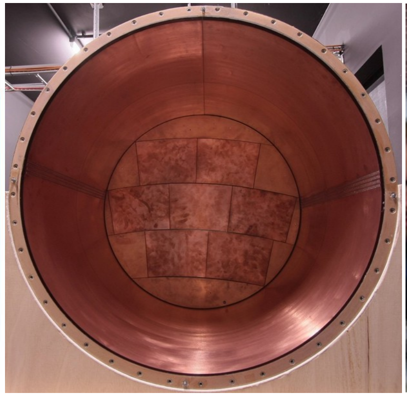
https://doi.org/10.1140/epjc/s10052-018-5876-z

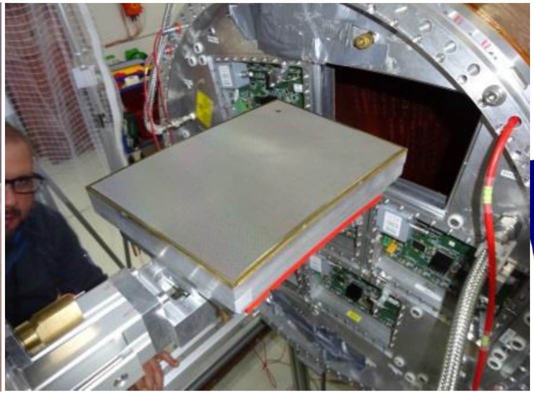
Status of TPC in LCTPC and CEPC

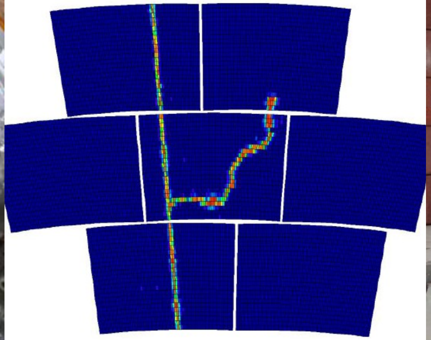
- **Large Prototype** setup has been built to compare different detector readouts under identical conditions and to address integration issues.
  - PCMAG: B < 1.2T, bore Ø: 85cm
  - LP support structure (3D movable) Beam and cosmic trigger
    - Silicon tracker inside PCMAG LYCORIS (single point res.: 7μm)
- **LP Field Cage Parameter**
  - Length = 61cm, inner Ø = 72cm drift field up to E ≈ 350V/cm
  - Made of composite materials: 1.24 % X_0
- **Modular End Plate**
  - Two end plates for the LP made from Al with 7 module windows
  - ALTRO based readout electronics (7212 channels)

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





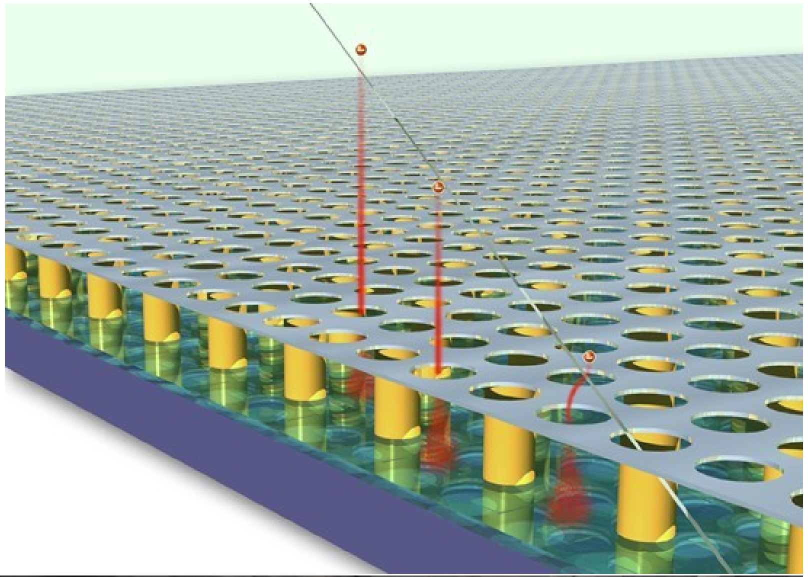


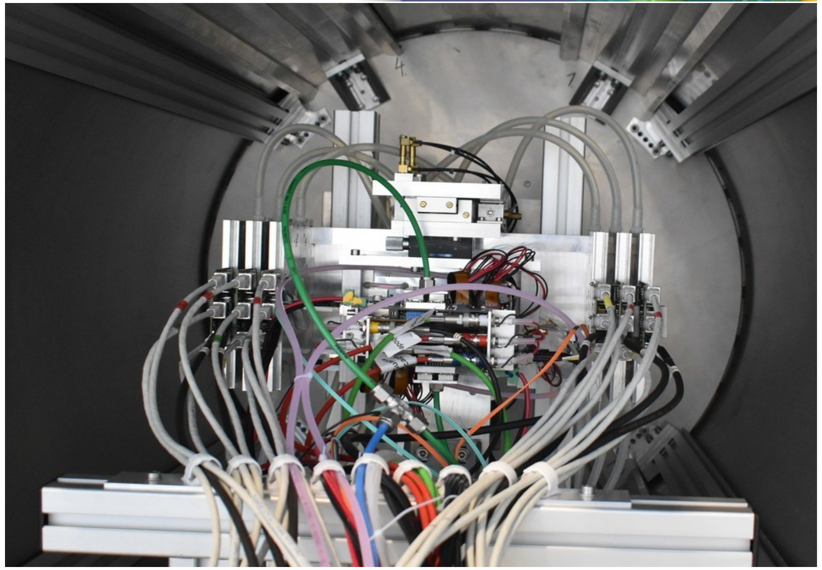


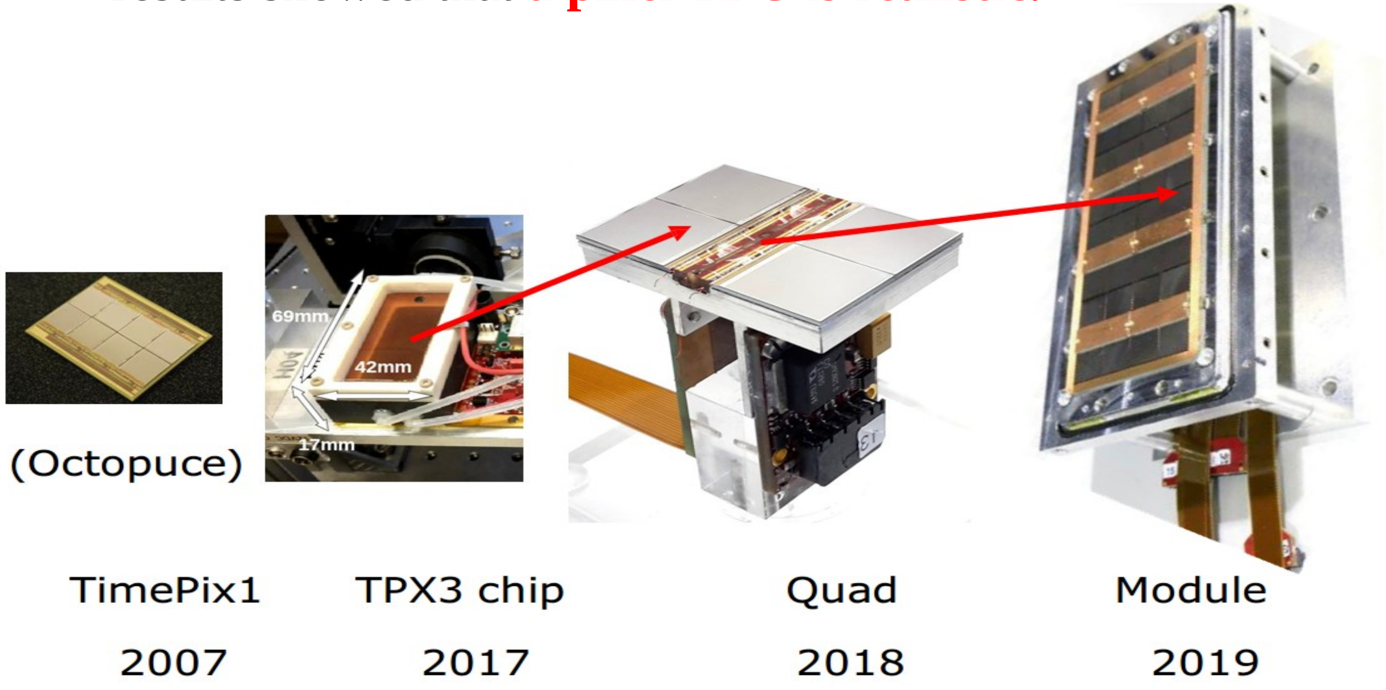
https://doi.org/10.48550/arXiv.2006.08562

Status of TPC in LCTPC and CEPC

- GridPix detector have moved from Timepix to Timepix3 ASICs. Tests with single and quad devices have been successfully done.
  - A module **with 32 GridPixes has been constructed** and was in a test beam in 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.
  - During the test beam ~10^6 events were successfully collected, all results showed that **a pixel TPC is realistic.**





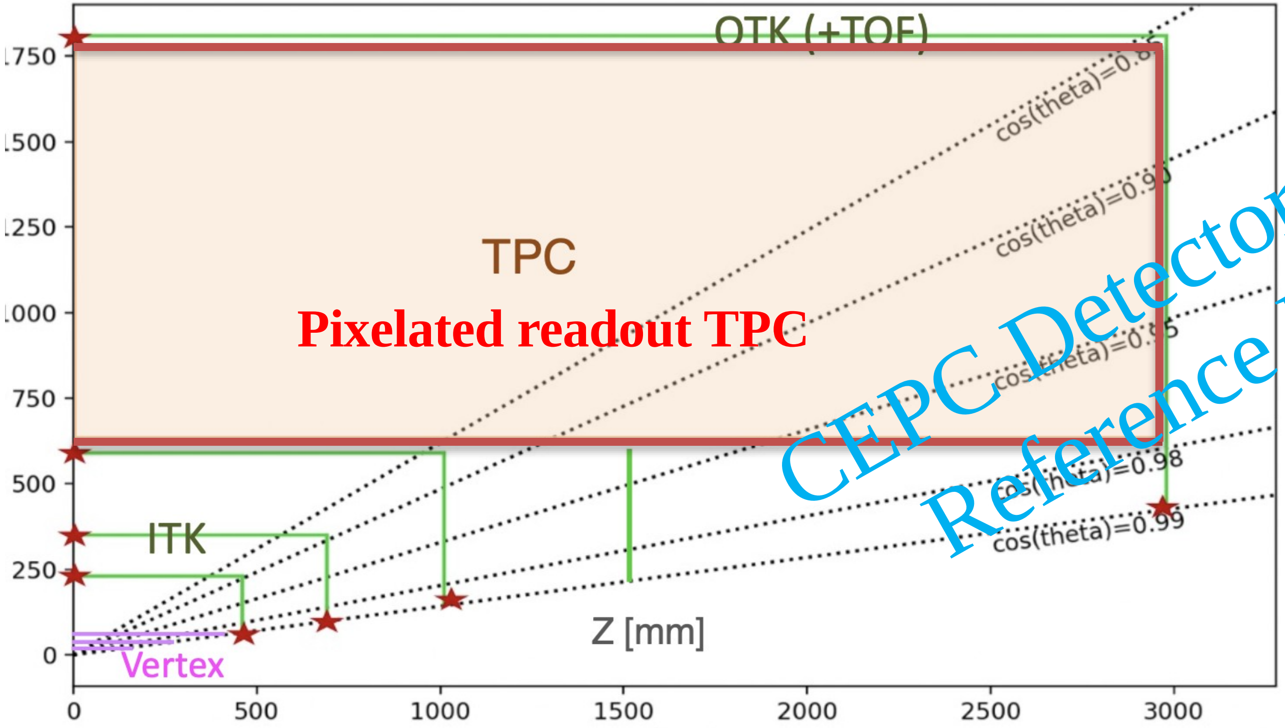


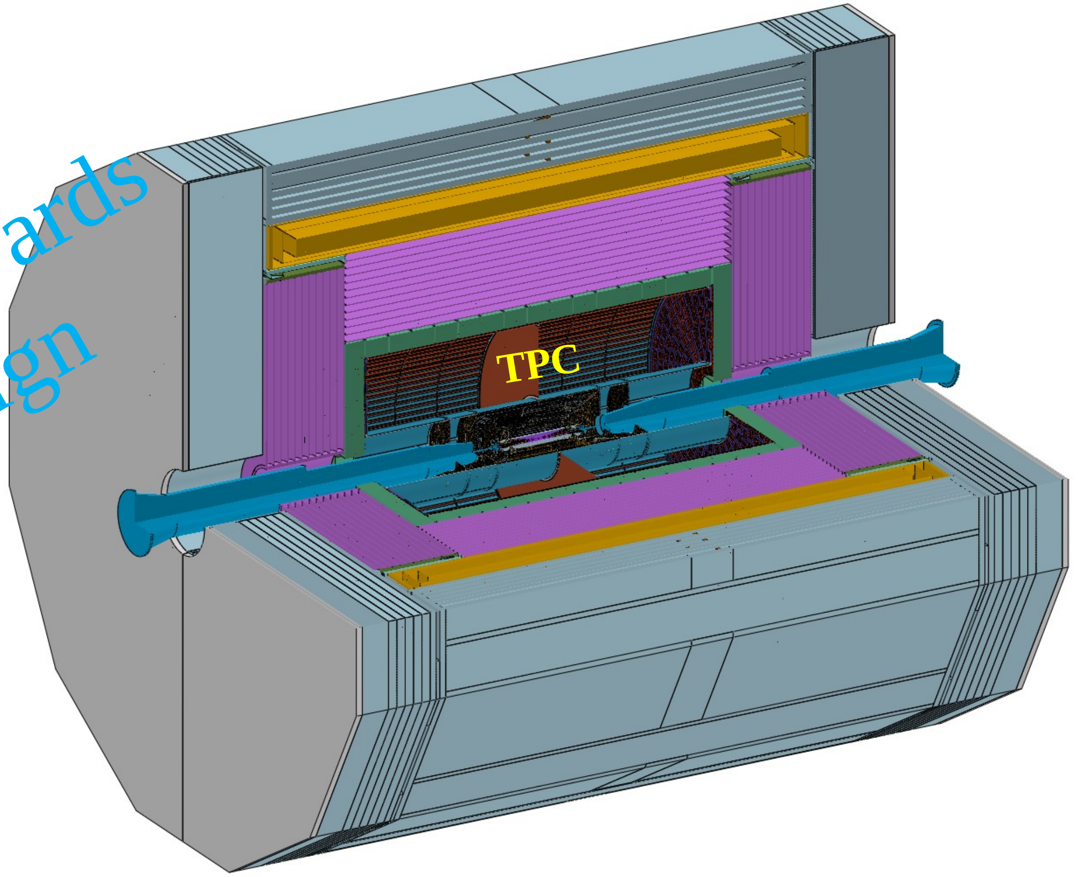
NÌM A535 (2004) 506-510
NIM A845 (2017) 233-235

https://arxiv.org/abs/1902.01987

Status of TPC in LCTPC and CEPC

- 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

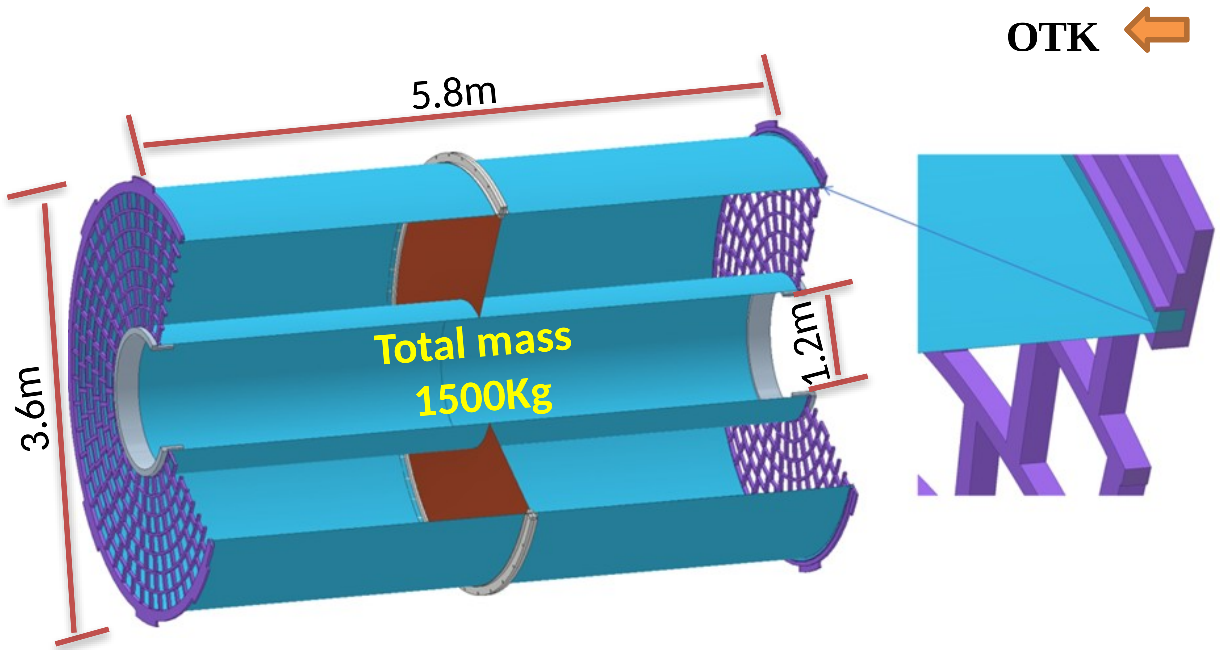


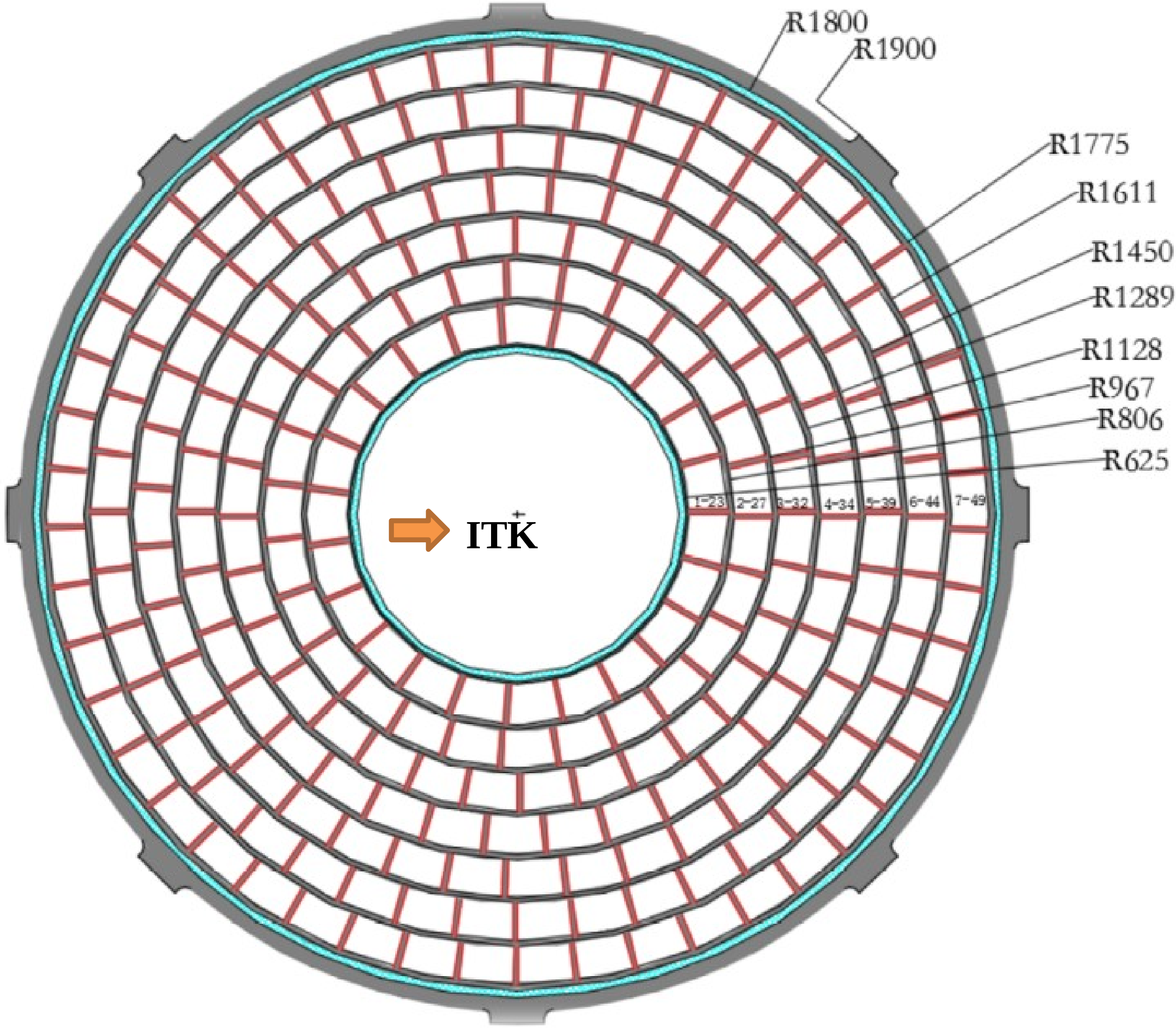


Geometry of the tracking detector system of the CEPC TDR

Status of TPC in LCTPC and CEPC

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

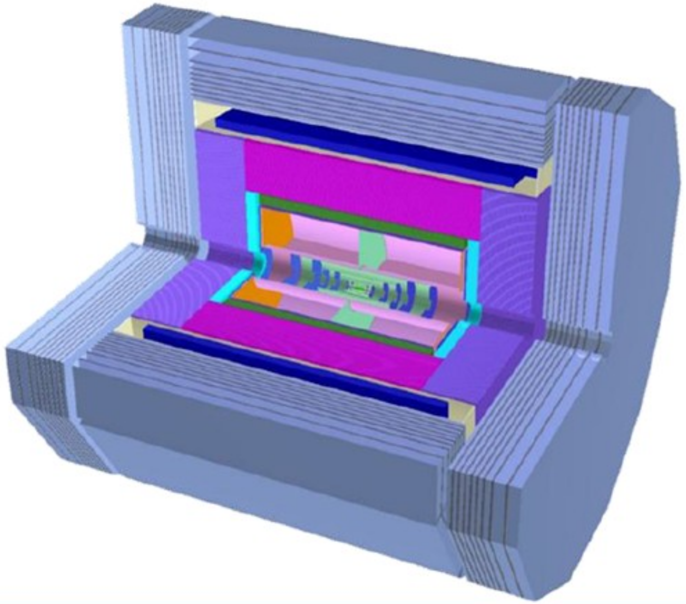
Status of TPC in LCTPC and CEPC

- 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 .

Status of TPC in LCTPC and CEPC

- 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 LCTPC and CEPC

- 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.

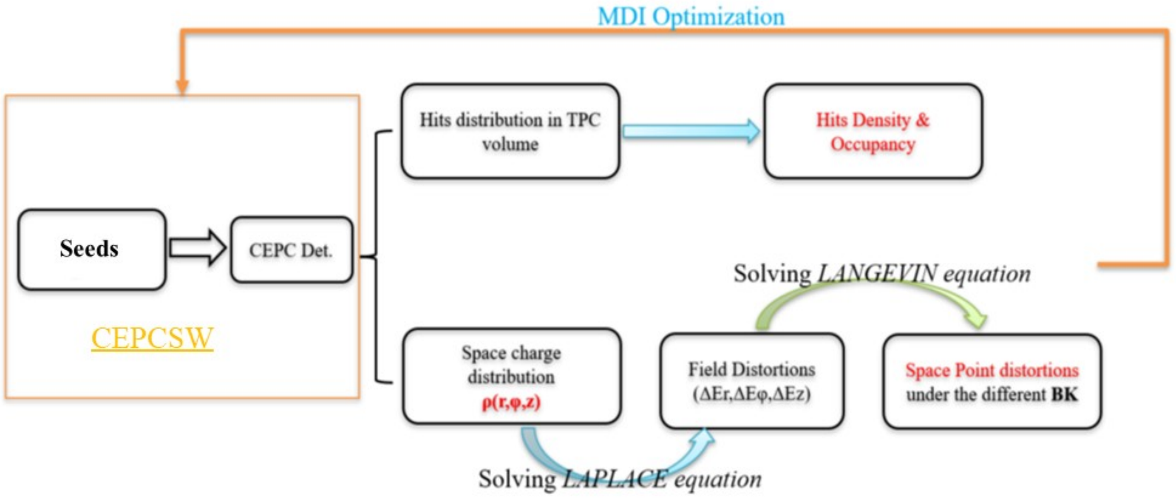
Date	Actions and/or Expectations
Jan 1, 2024	Start the process by comparing different technologies
Jun 30, 2024	Baseline technologies, general geometric configuration and key issues are decided
Oct 31, 2024	Discuss the ref-TDR at the CEPC workshop, report progresses to the CEPC IAC
Dec 31, 2024	The first 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.

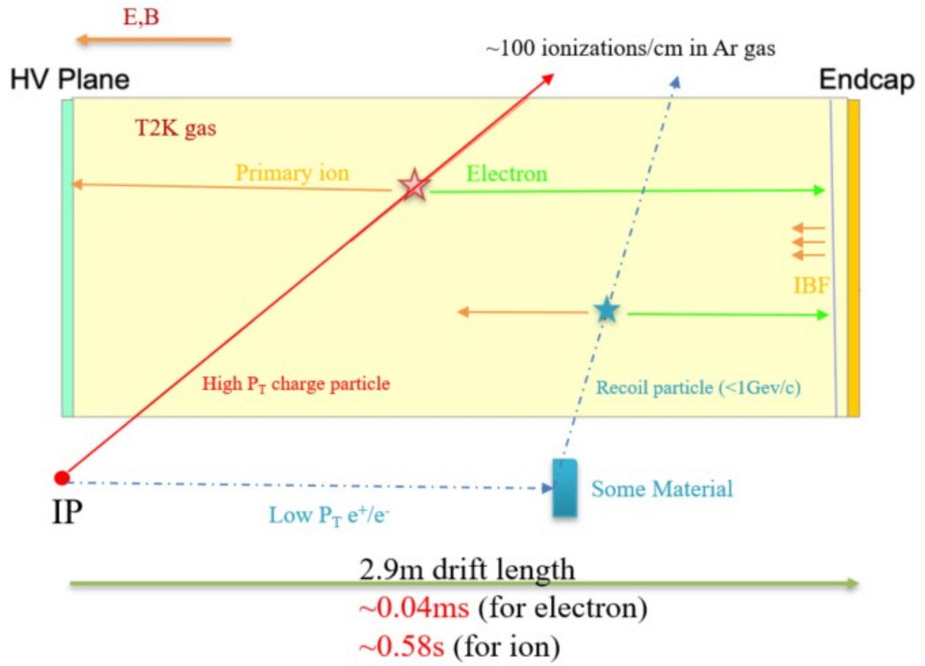
- **Pixelated readout TPC for Higgs and Z**

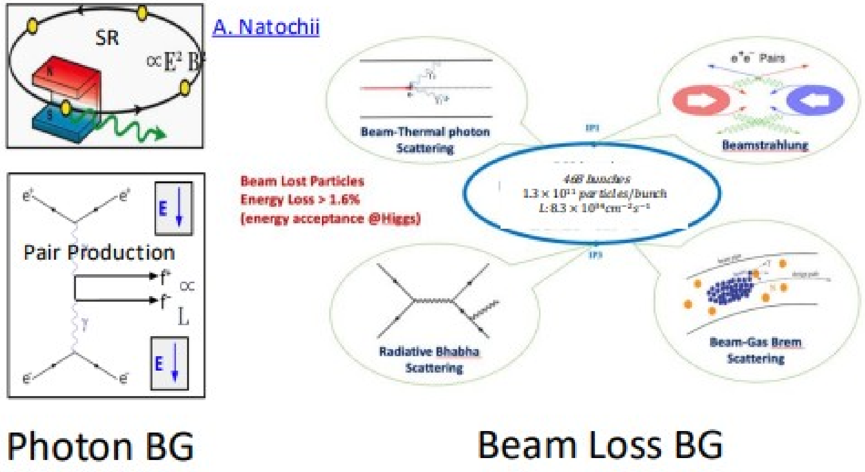
Pixelated readout TPC for Higgs and Z

- 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





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

IBF×Gain=1, same primary ion level

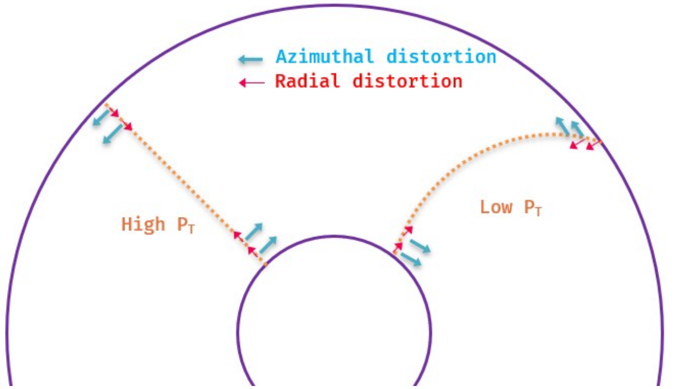
- At present, only types I and II backgrounds have been generated.
  - At Z-pole, the Single Beam background loss rate increases, with Single Beam being about one order of magnitude higher than Pair.
  - Taking into account all MeV-level low-energy gamma rays (**with types III and IV**), the beam background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

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

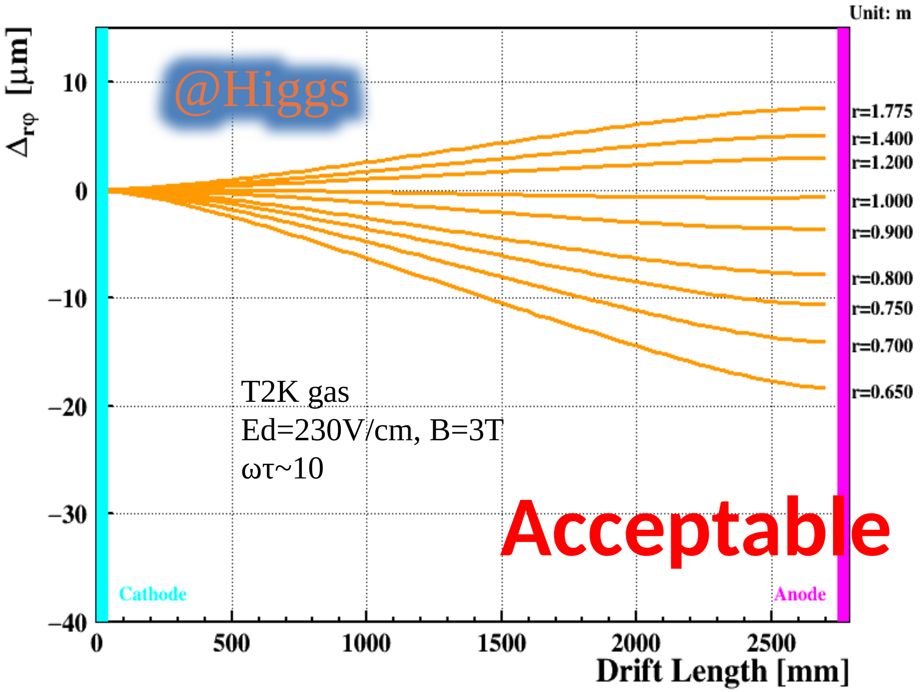
- Radial distortion (Δ_r) is much smaller than azimuthal distortion, almost imperceptible when along the track for most P_T track
  - Azimuthal distortion ($\Delta_{r\varphi}$) has much more serious impact both on high/low P_T track
  - The maximum $\Delta_{r\varphi}$ is 20μm@Higgs (**acceptable**)
  - The maximum $\Delta_{r\varphi}$ is 150μm@Z-pole (**need to optimization of MDI**)
    - Including Pair + Single Beam

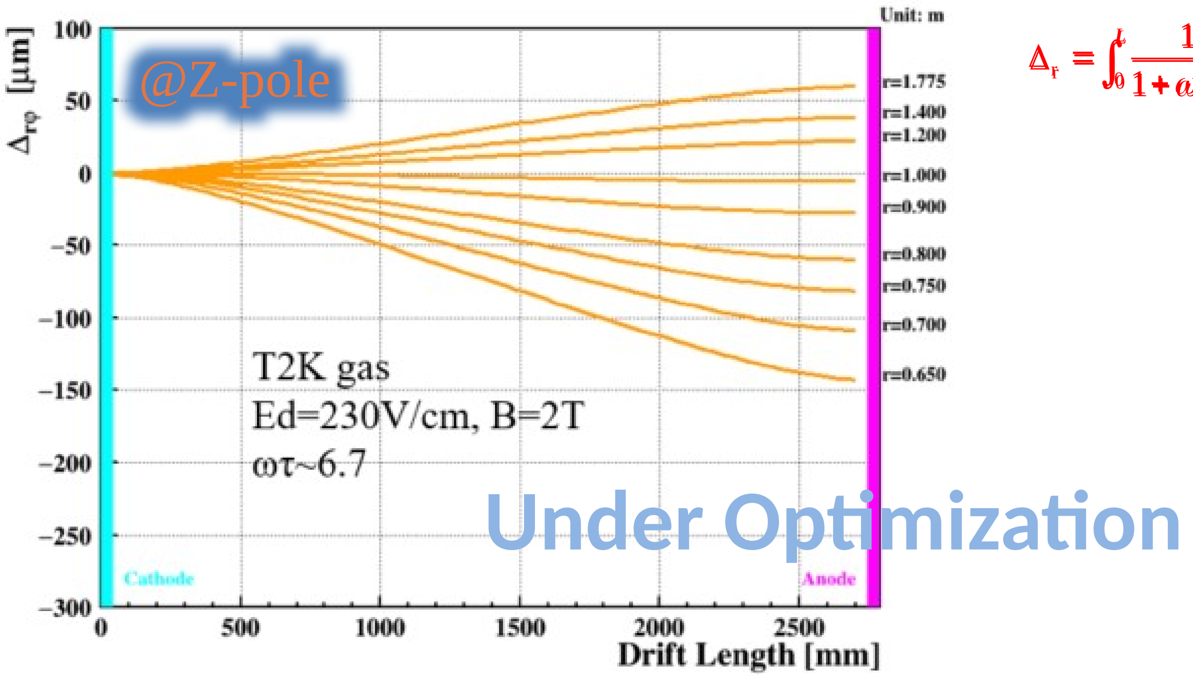
IBF×Gain=1, same primary ion level



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

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





Numerical calculation results of TPC distortion based on Green's function

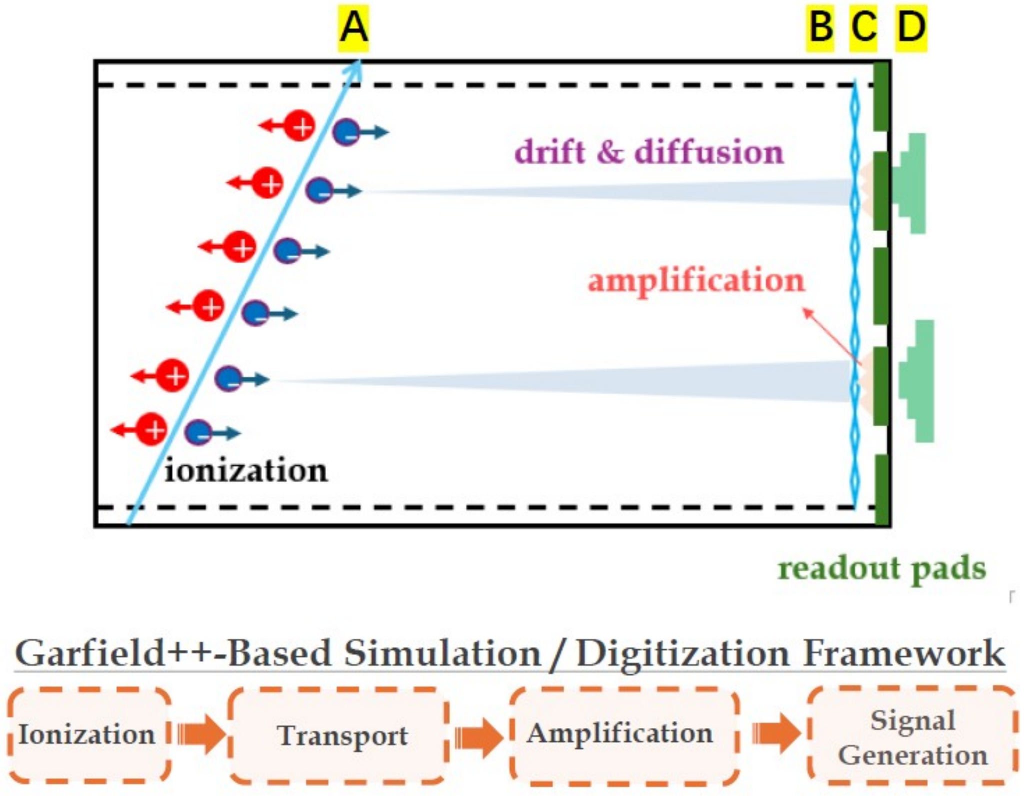
Full Simulation of Pixelated readout TPC

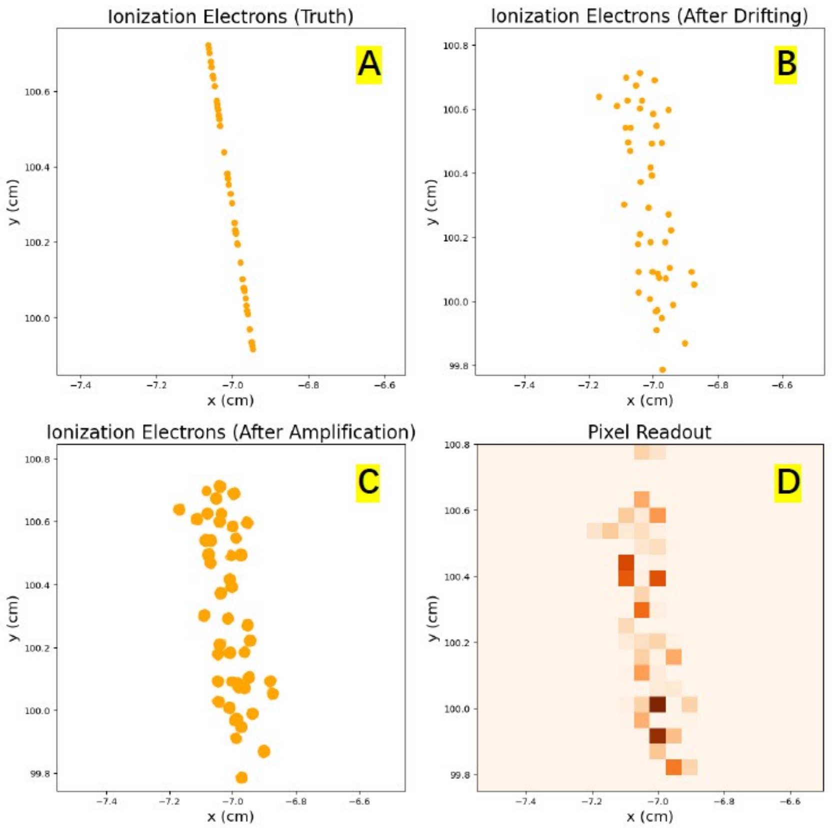
Simulation:

- 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





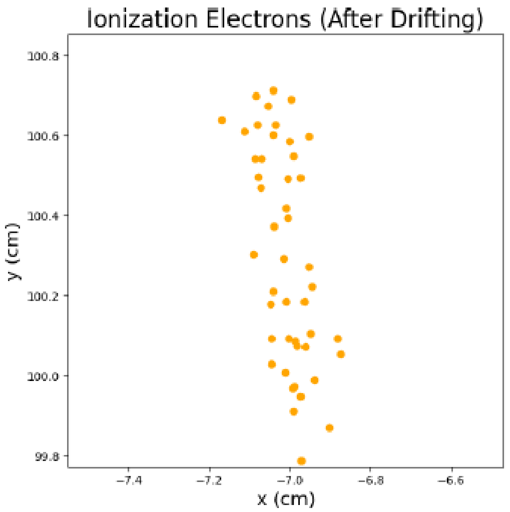
Simulation of TPC detector under 3T/2T and T2K mixture gas

Full Simulation of Pixelated readout TPC – Readout size

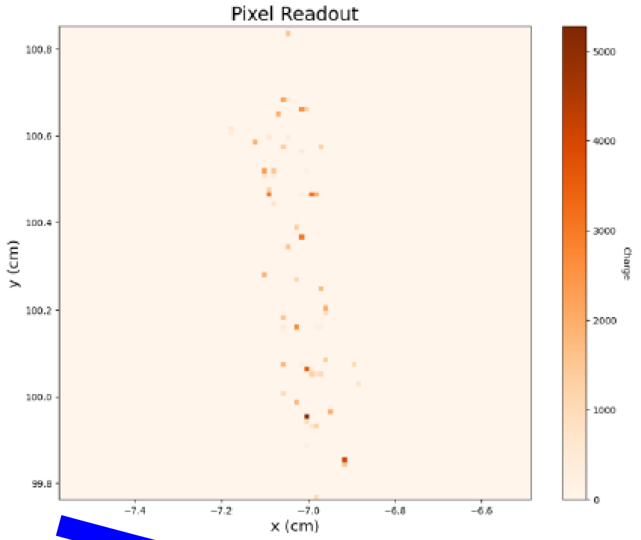
- Simulation of the readouts in pixel sizes
  - Actually, TPX3/4 option existing and the power consumption will be optimized.
  - Optimization started in this ref-TDR at IHEP to meet **Higgs/Z at 3T**.

- 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

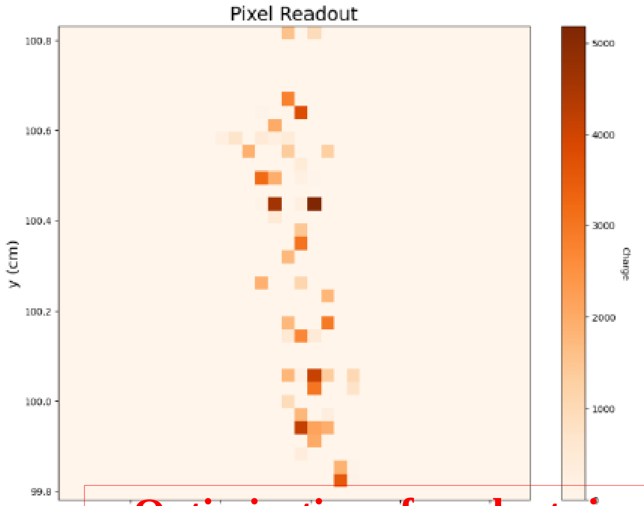
Peter's comment in CEPCWS at Hangzhou.



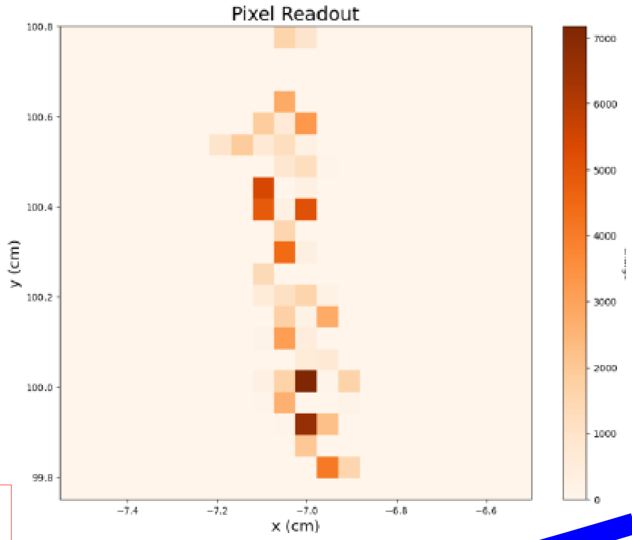
Pixel size = 110 um



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

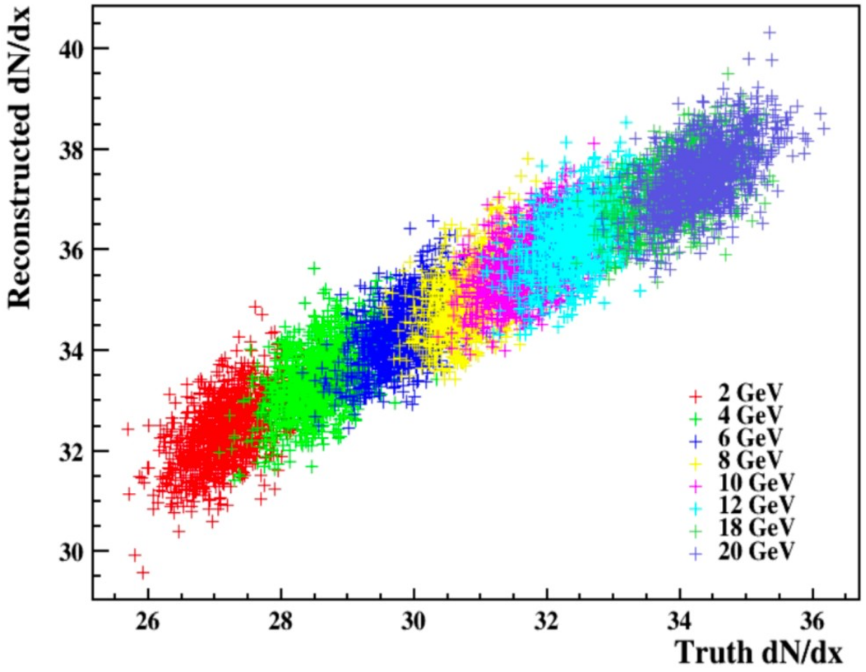
Reconstruction:

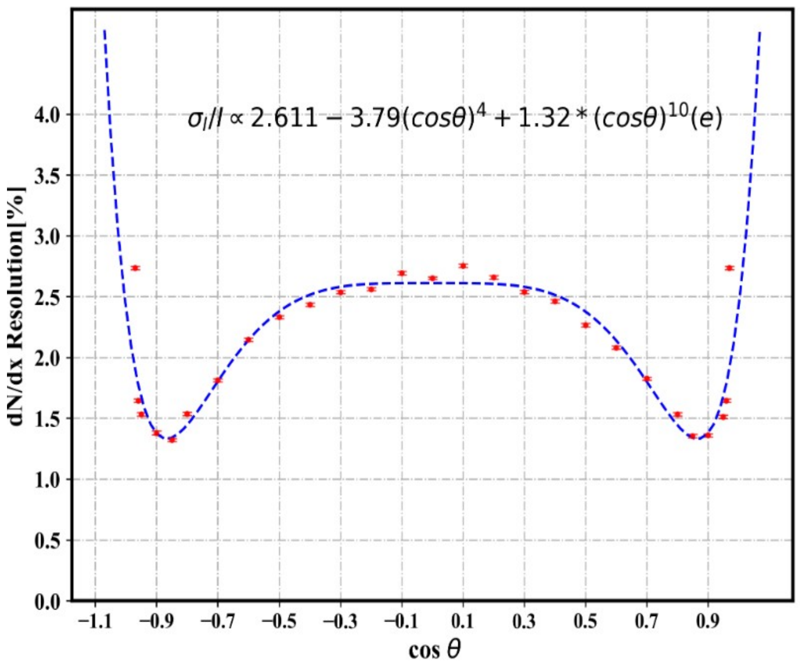
- Reconstruction by counting the number of fired pixels over threshold
- **Reconstruction with good linearity and reliability**

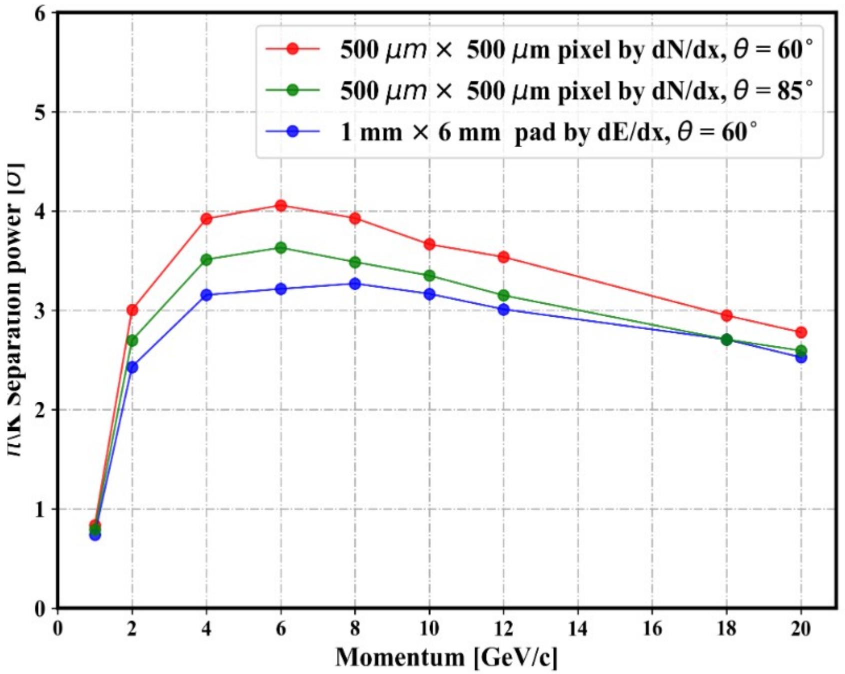
Preliminary PID performance:

- π/k separation power simulation with different momentum

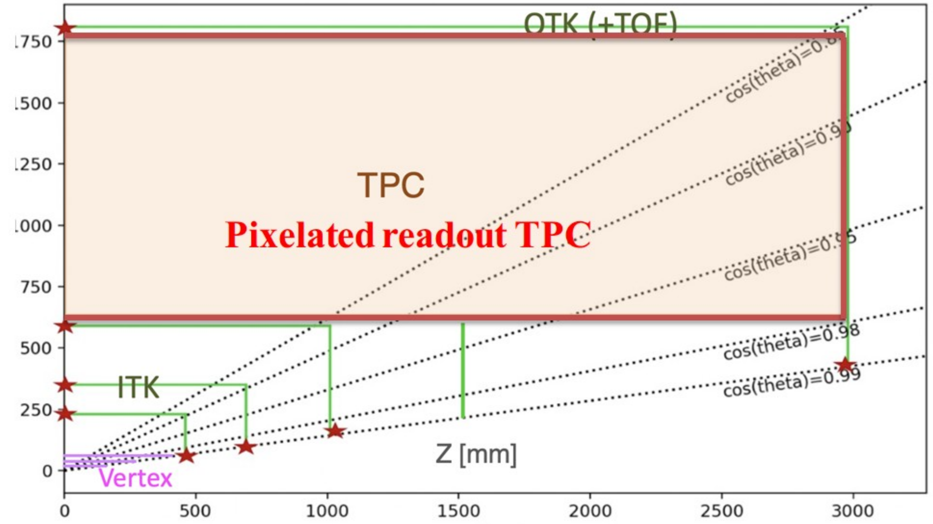
Separation power:

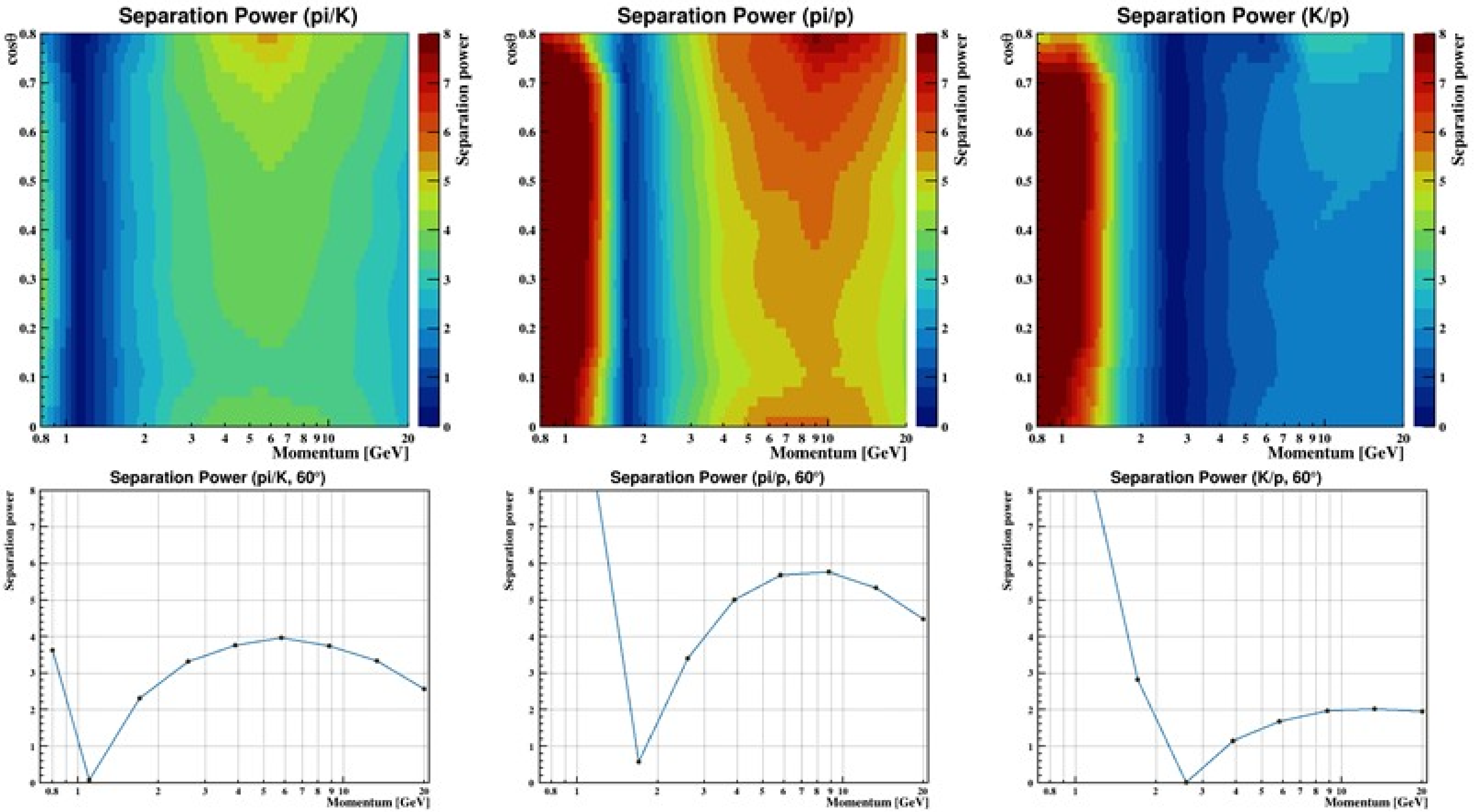






- Performance of the pixelated readout TPC
  - Simulation of π/K, π/p, and K/p separation power with varying momentum and cosθ

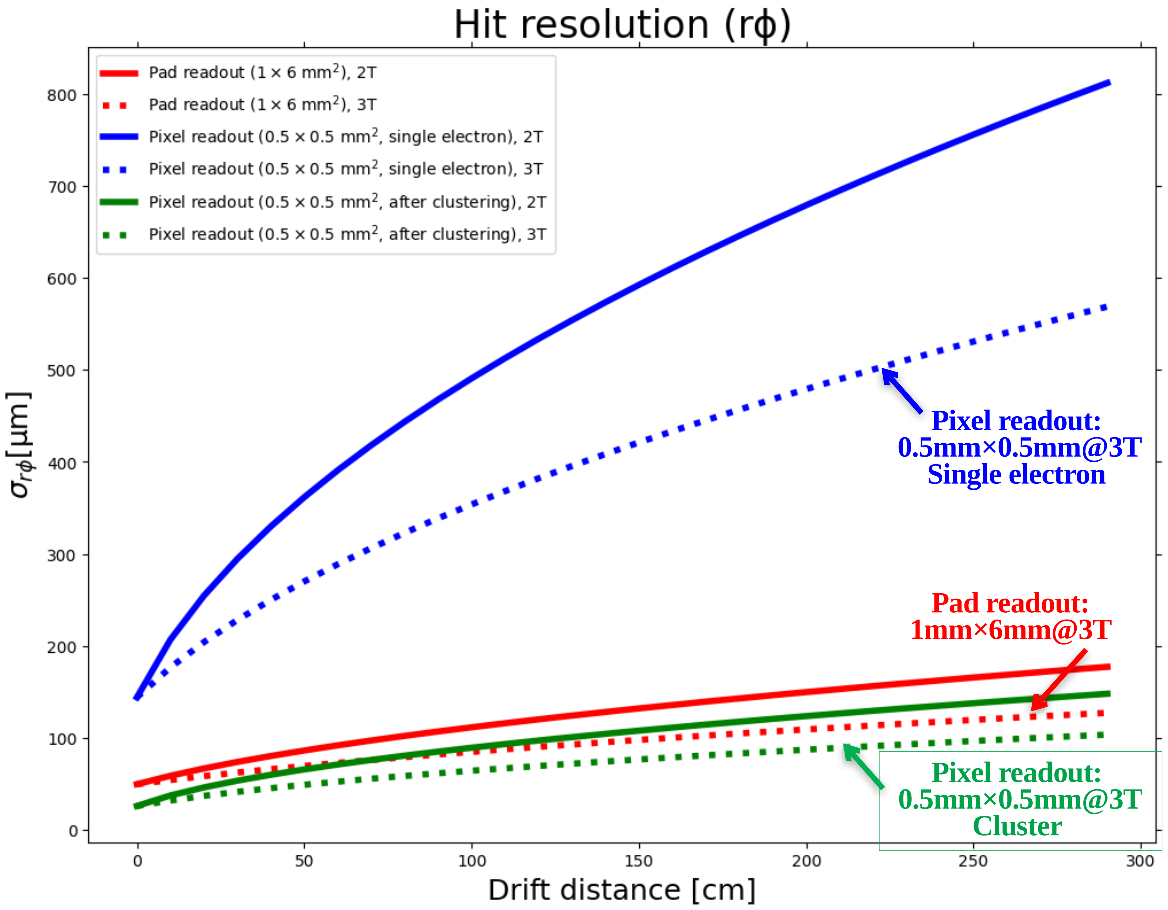




Full Simulation of Pixelated readout TPC – Spatial resolution

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:

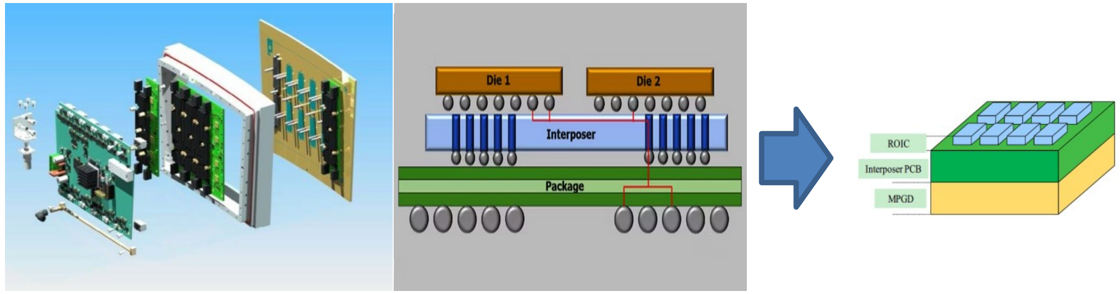
$$\sigma_{r\phi}^{\text{pad}} = \sqrt{(\sigma_{r\phi 0}^{\text{pad}})^2 + \sigma_{\phi 0}^2 \sin^2(\phi_{\text{track}}) + L\frac{D_{r\phi}^2}{N_{\text{eff}}}\sin(\theta_{\text{track}})}$$

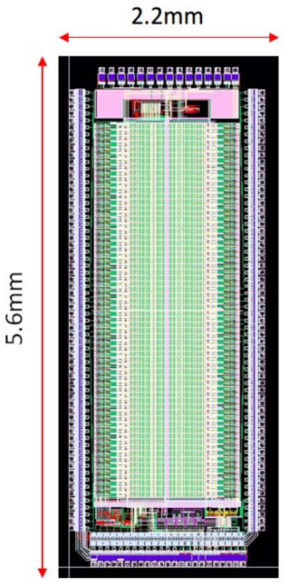
Pixel readout:

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

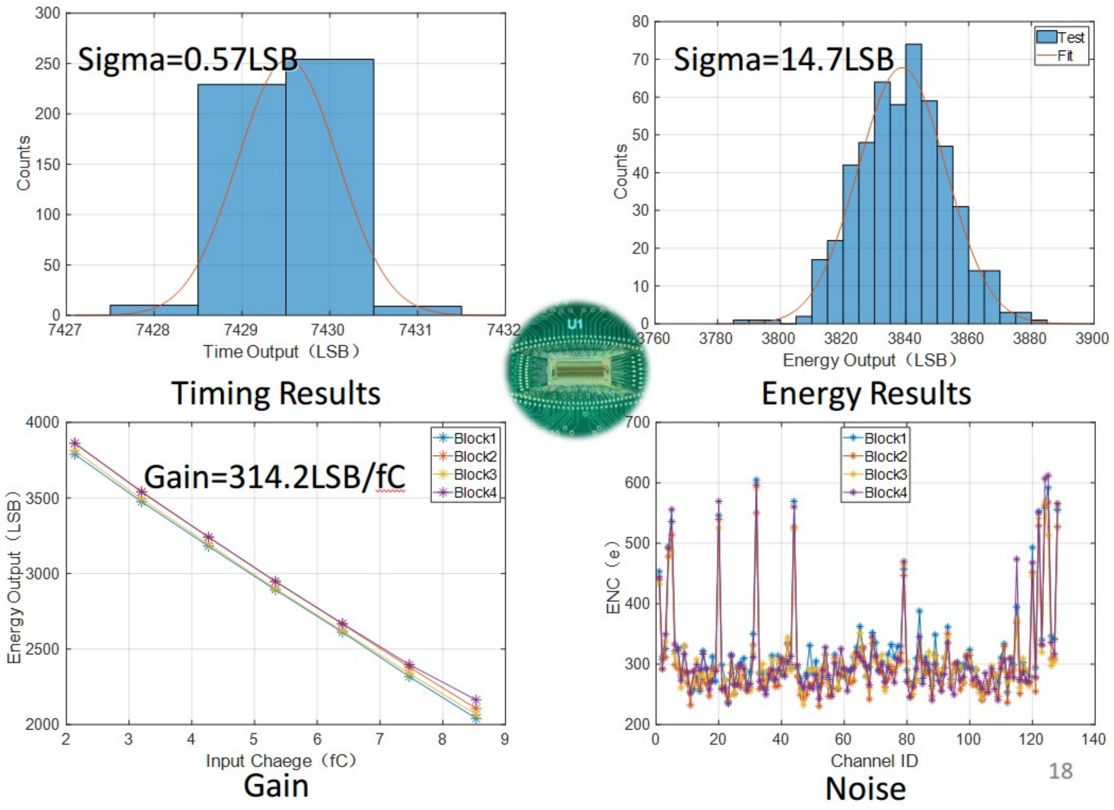
Full Simulation of Pixelated readout TPC – TEPix with 500μm×500μm

- 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)



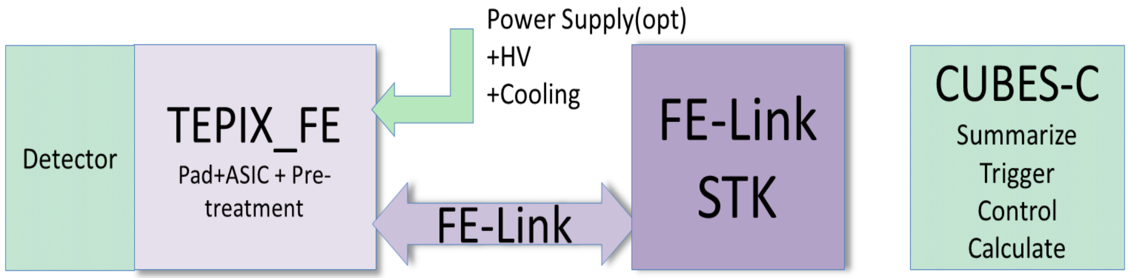


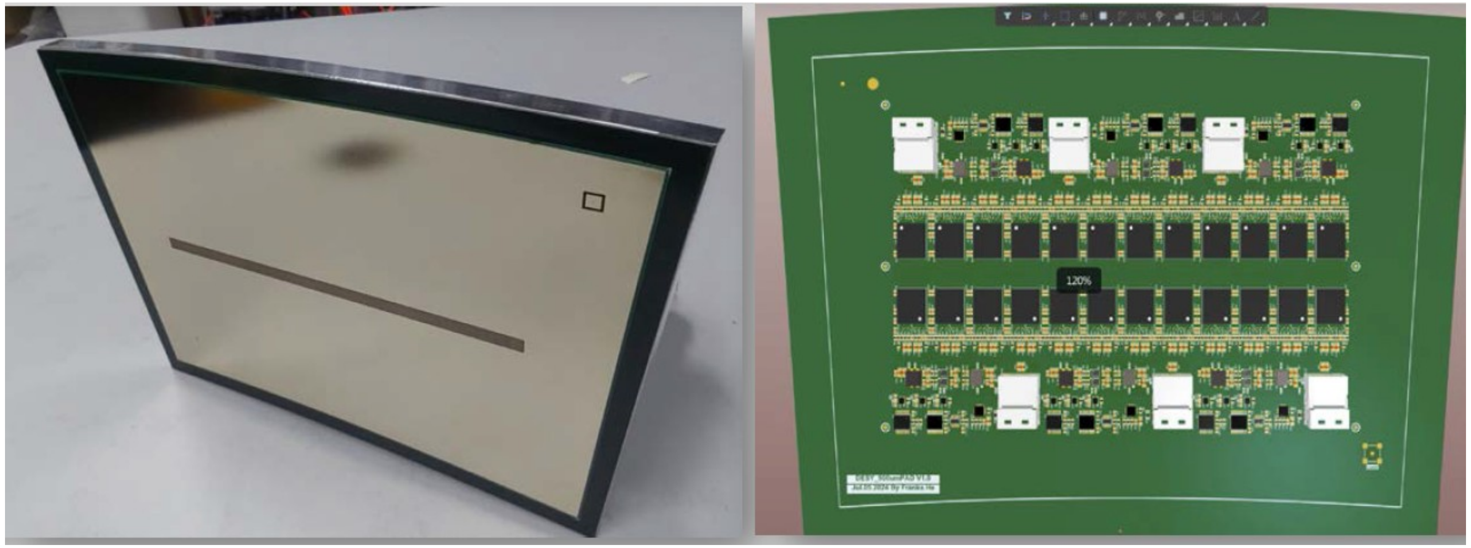
Parameter	Spec
Number of channels	128
Power Consumption	Analog<30mW
	Digital<30mW
ENC	~300 e(high gain)
Dynamic Range	25fC(high gain)
	150fC(low gain)
INL	<1%
Time Resolution	<10ns

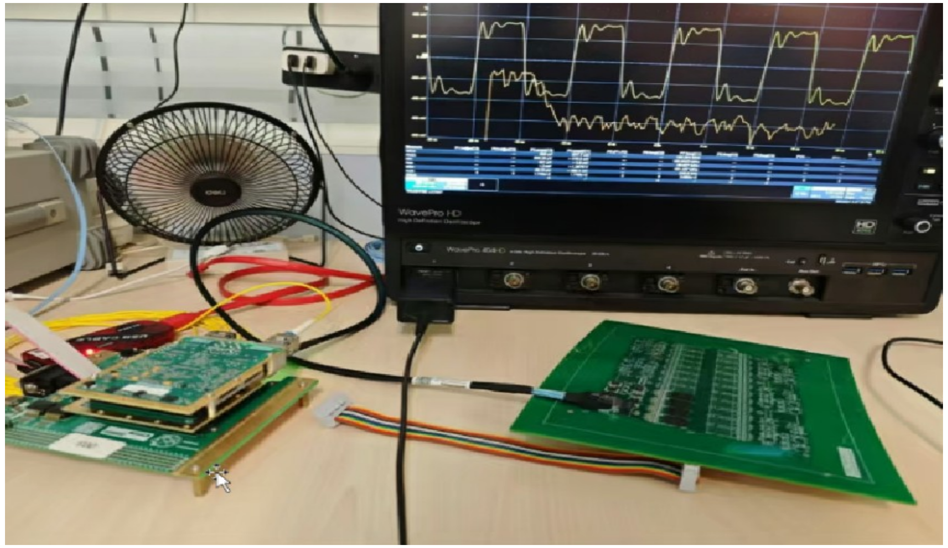


FEE ASIC: TEPIX—Test Results in May

- **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. (January and March, 2025)**



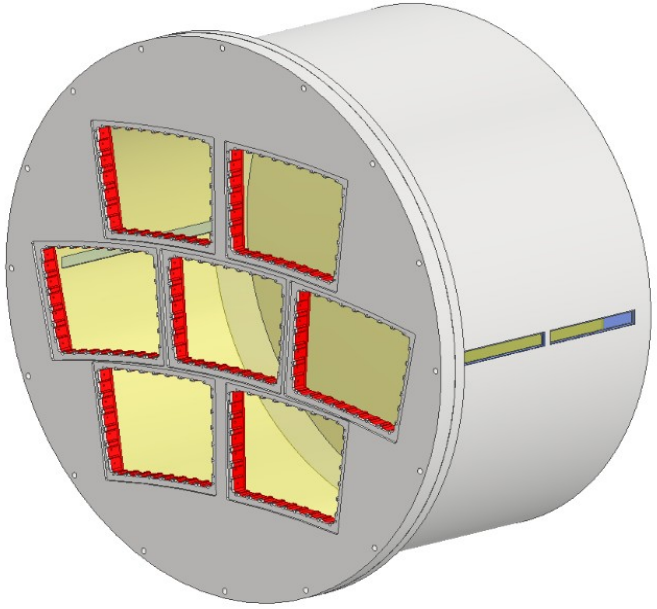




Photos TPC modules assembled for the beam test

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/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!

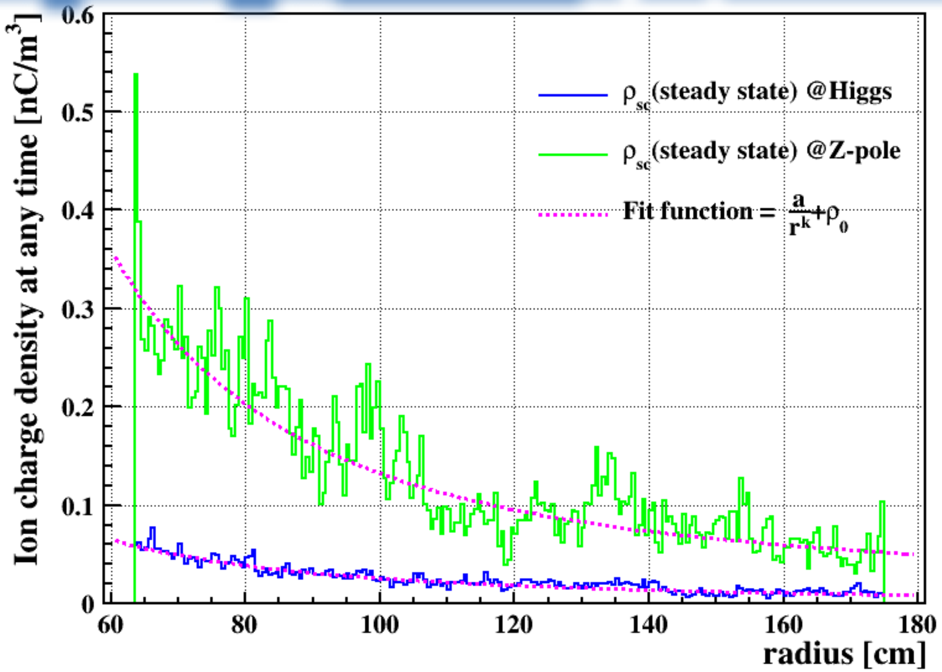
Backup1: Space charge density in TPC (only Pair)

- Number of primary ions can be calculated by Edep/effective ionization potential of Ar [26 eV]
- The ion charge density at any time is given by:

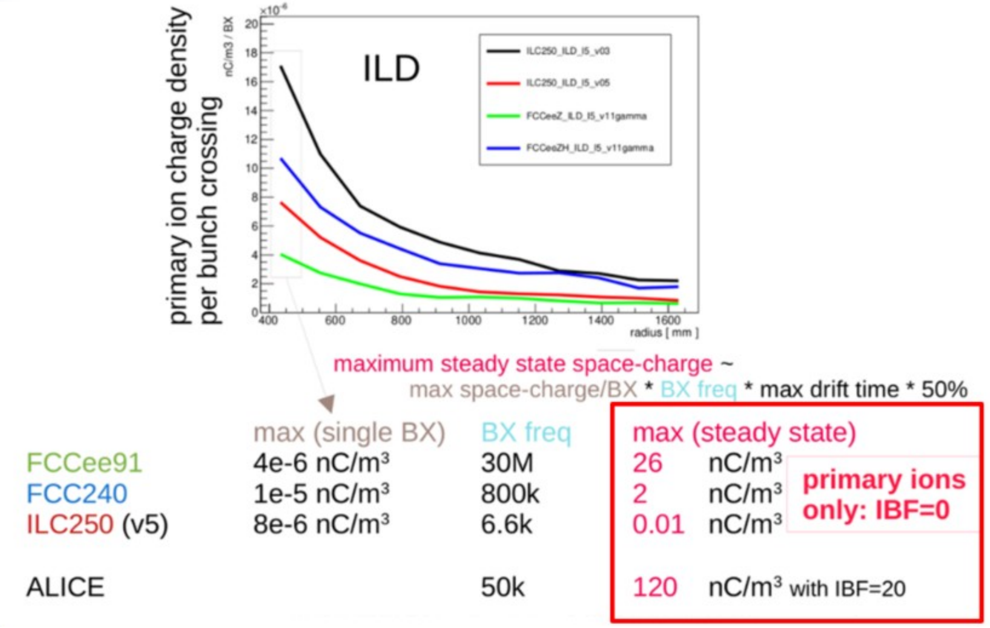
~0.55s assuming 5m/s ion drift velocity

Ref Daniel Jeans' slides

  - ρ_{sc} ~ primary ions/BX × BX frequency × max drift time of ion × 50% [ion already reached cathode]
  - BX frequency: 1/23ns @Z-pole, 1/355ns @Higgs
- The space charge in CEPC TPC is ~50× smaller than FCCee, ref KEK ***Daniel Jeans*** simulation results



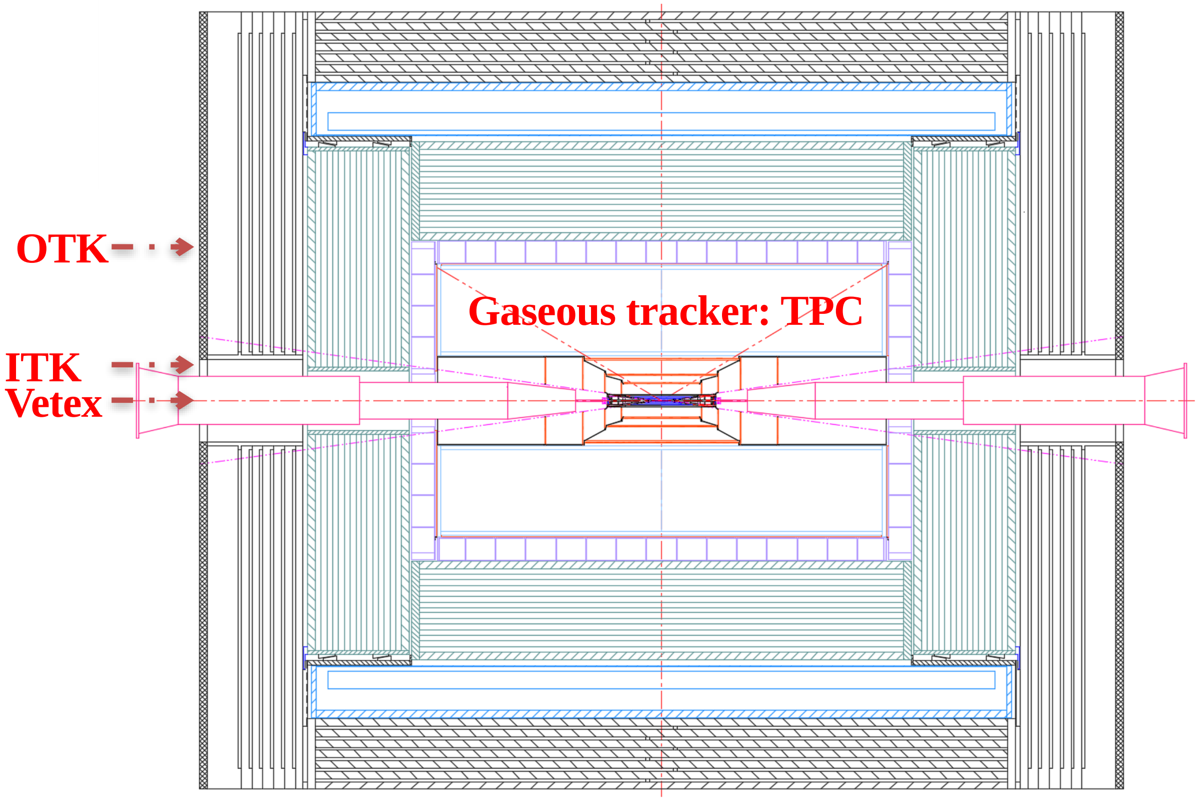
Space charge density at Higgs/Z-pole mode



Beam background in a TPC at a circular collider

Large gaseous TPC in ILD-like concept

- The detector adopts a hybrid tracking system in ILD-like concept.
- **Large gaseous tracker: TPC**
  - 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% X0) is equivalent to **about 1 layer of a silicon tracker detector**.



Schematic diagram of the detector