High Granularity Readout TPC R&D for Tera-Z at the Future e+e- Collider

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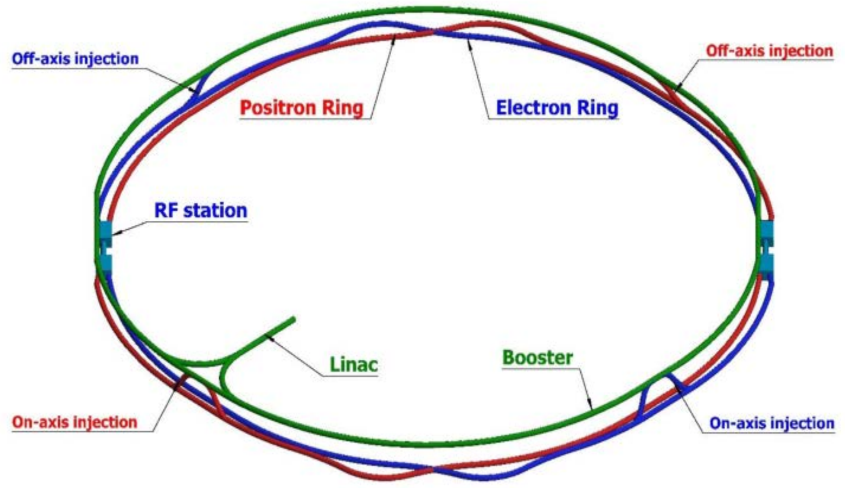
- **Motivation and physics requirements**
- **High granularity readout TPC**
- **Performance and readiness of TPC R&D**
- **Summary**

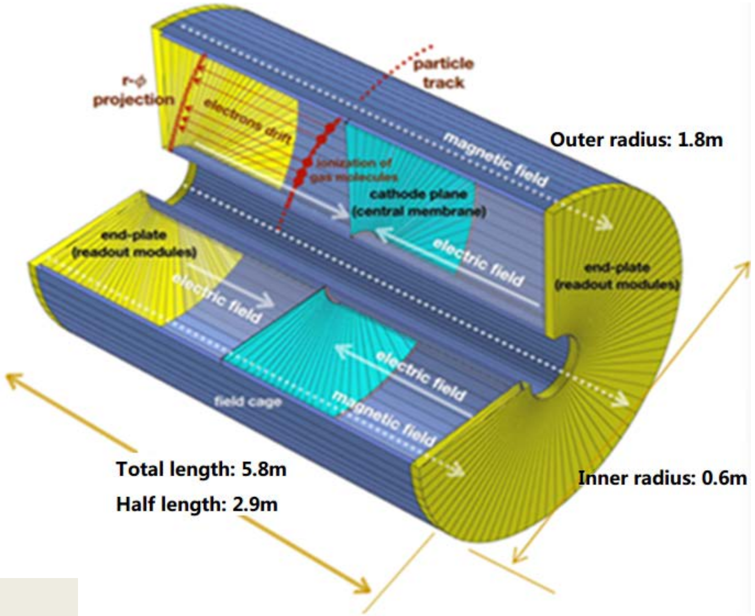
- **Motivation and physics requirements**

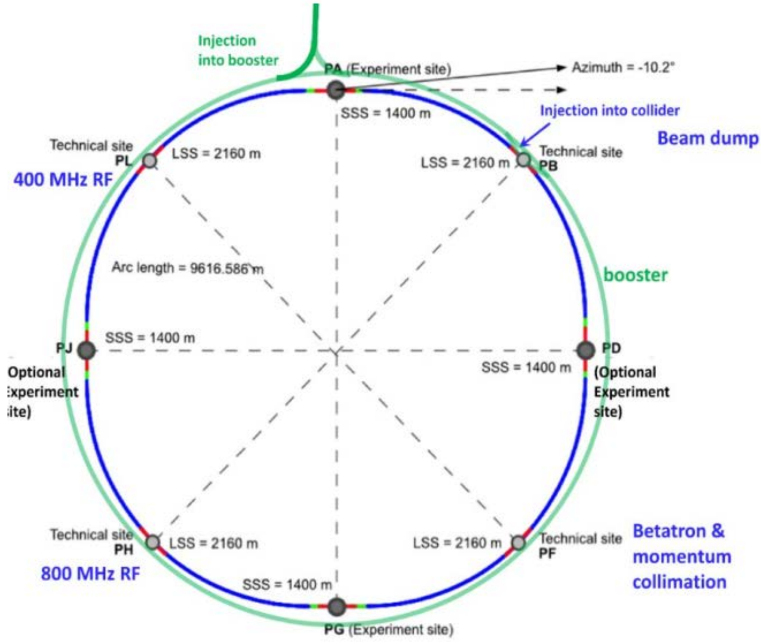
Motivation and physics requirements on e+e- collider

- 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 is a promised candidate as the main track detector in CEPC TDR
- TPC technology can be of interest for other future colliders (EIC, FCC-ee, KEKb…)
- Pixelated readout TPC is potential to **improve PID requirements of Flavor Physics** at e+e- collider.



Circular Electron Positron Collider (CEPC)





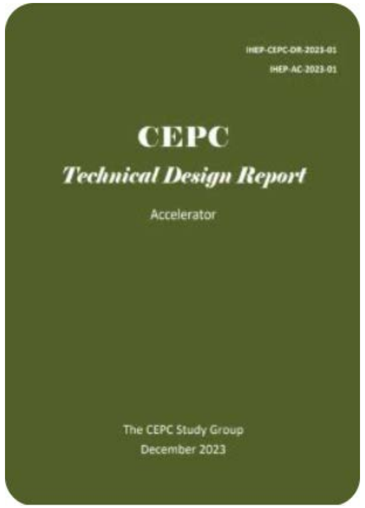
Future Circular Collider (FCCee)

https://arxiv.org/abs/1811.10545

https://arxiv.org/abs/2203.08310

Physics requirements of the track detector

- CEPC operation stages: **10-years Higgs → 2-years Z pole → 1-year W**
- CEPC phy./det. TDR (**preparation**)
  - Physics and detector concept designed under the principle.
  - **Requirements may be with regard to runs of Higgs and Z-pole separately**.
    - Mandatory requirements MUST be met.
    - Detector should primarily meet Higgs and run at Z also.



Chapter 3 of this report outlines that the CEPC is planned to be in operation for 8 months annually, totaling 6,000 hours. This operational schedule is used to calculate the cumulative absorbed doses for magnet coil insulations, as illustrated in Figure 4.2.4.16, considering a 10-year Higgs operation, 2-year Z operation, and 1-year W operation. Figure 4.2.4.17 displays the absorbed doses when an additional 5-year $t\bar{t}$ operation is included. These plots also include the upper limit for absorbed dose in epoxy resin, which is measured at 2×10^7 Gy [11].

CEPC- TDR p116

arXiv:2312.14363

Physics requirements on future circular e+e- collider

- **Phys. Requirements of the track detector**
  - TPC can provide thousands of hits with high spatial resolution compatible with PFA algorithm **(low X_0)**
- Beneficial for jet & differential at higher energy
  - BMR < 4% & pursue 3%
  - Highly requirements for excellent JOI & PID resolution (in Jets)
    - Provide **dE/dx + dN/dx** ~ 2-3%

	Processes @ c.m.s.	Domain	Total Det. Performance	Sub-D
H->ss/cc/sb	vvH @ 240 GeV	Higgs	PFA + JOI (Jet origin id)	All sub-D, especially VTX
Vcb	WW@ 240/160 GeV	Flavor	JOI + Particle (lepton) id	All
W fusion Xsec	vvH @ 360 GeV	Higgs	PFA + JOI	All
α_S	Z->tautau @ 91.2 GeV	QCD	PFA: Tau & Tau final state id	ECAL + Tracker material
B->DK	91.2 GeV	Flavor	PFA + Particle (Kaon) id	All, especially Tracker & ToF
Weak mixing angle	Z	EW	JOI	All
Higgs recoil	llH	Higgs	Leptons id, track dP/P	Tracker, All
H->bb, cc, gg	vvH	Higgs	PFA + JOI	All
	qqH	Higgs	PFA + JOI + Color Singlet id	All
H->inv	qqH	Higgs/NP	PFA	All
H->di muon	qqH	Higgs	PFA, Leptons id	Calo, All
H->di photon	qqH	Higgs	PFA, Photons id	ECAL, All
W mass & Width	WW@160 GeV	EW	Beam energy	NAN
Top mass & Width	ttbar@360 GeV	EW	Beam energy	NAN
Bs->vvPhi	Z	Flavor	Object in jets; MET	All
Bc->tauv	Z	Flavor	-	All
B0->2 pi0	Z	Flavor	Particle/pi-0 in jets	ECAL

Differential Efficiency.
Requirement: Pt threshold ~ o(100) MeV, |cos(theta)| < 0.99
Ref: CDR baseline design

Differential Material Budget.
Requirement: < 10%/50% X0 in Barrel/endcap
Ref: CDR baseline design + BMR & Material Dependence

Differential Resolution of 5 track parameters.
Requirement: In the barrel
δ(D0/Z0) ~ < 3 micro meter at 20 GeV
δ(Pt)/Pt ~ o(0.1%)
Ref: CDR baseline performance

Differential Pid Capability: eff*purity of Kaon id @ Z pole.
Requirement: eff*purity > 90% for all charged Kaon (@ Z pole)
~ relative resolution of dE/dx (or dN/dx) be better than 3%
ToF of 50 ps
Ref: Nuclear Inst. and Methods in Physics Research, A 1047 (2023) 167835

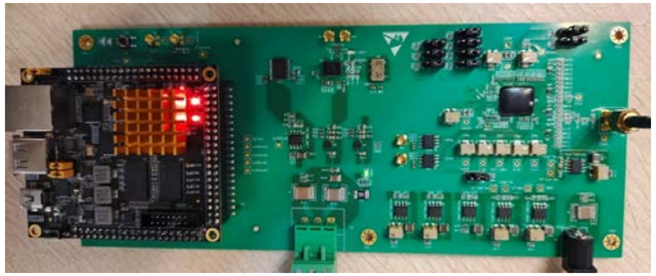
Sep. power: On 3 prong tau decay @ Z pole.
Requirement: efficiency > 99% at 3-prong tau
Ref: CDR baseline performance

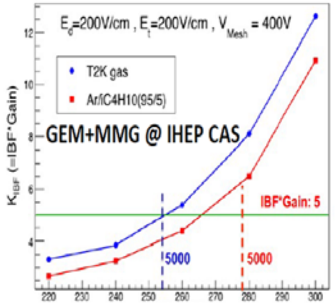
Table from IAS2024 conference in January

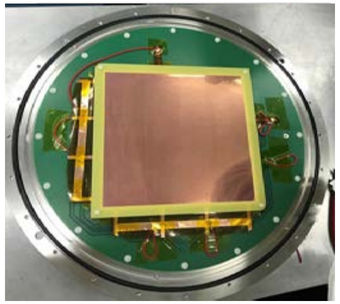
- **High granularity readout TPC for CEPC TDR**

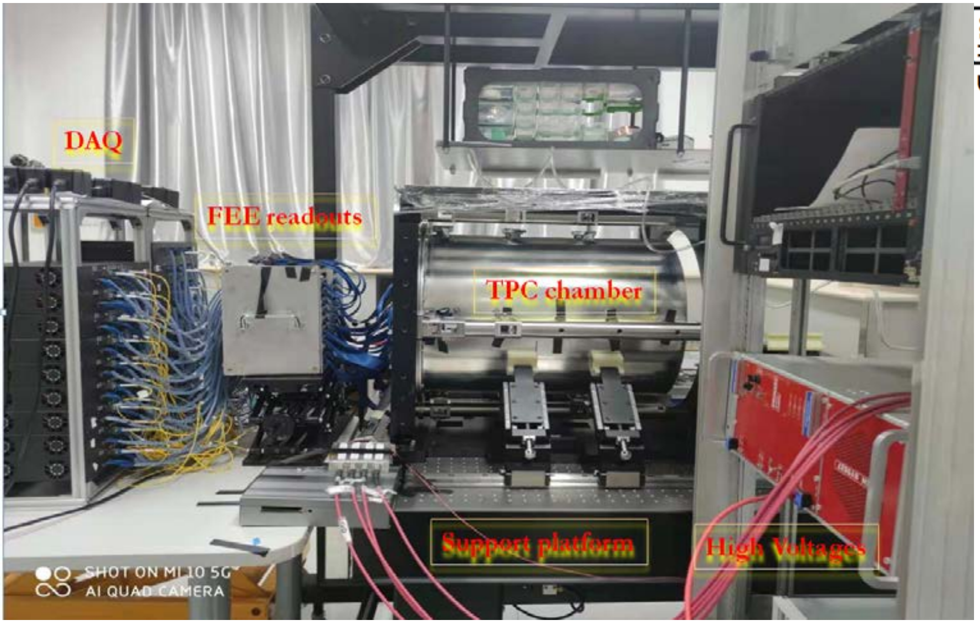
Pad readout TPC – Low power consumption and hybrid readout @IHEP

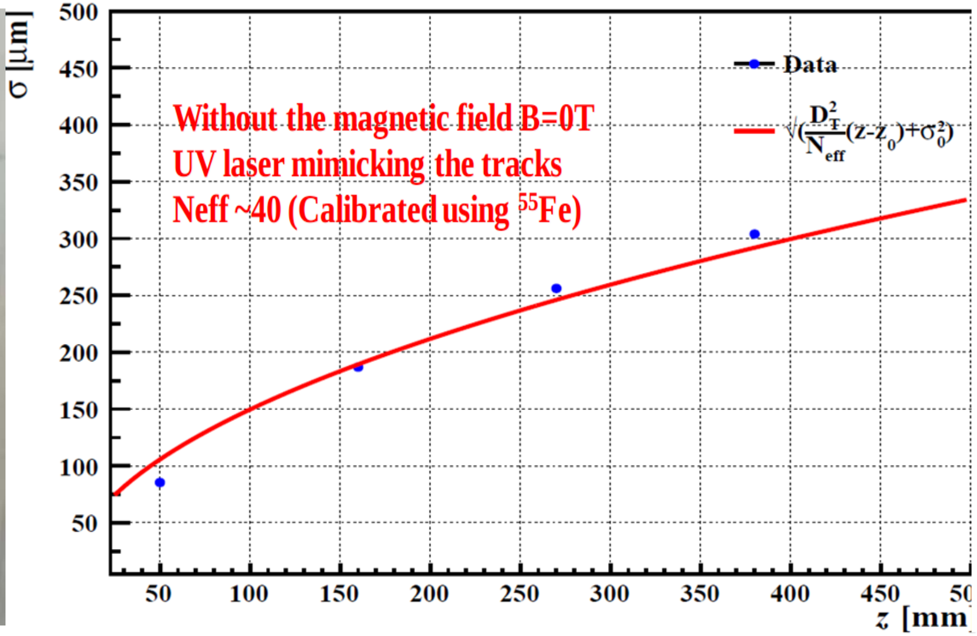
- **Low power consumption ASIC has been developed for TPC readout.**
  - Low power consumption FEE ASIC (**~2.4 mW/ch** including ADC)
- **Hybrid readout module has been developed:**
  - IBF×Gain **~1 at Gain=2000** validation with GEM/MM readout
  - Spatial resolution of **$\sigma_{r\varphi}$≤100 μm** by TPC prototype
  - Pseudo-tracks with 220 layers (**same as the actual size of CEPC baseline detector concept**) and dE/dx is about 3.4 ± 0.3%

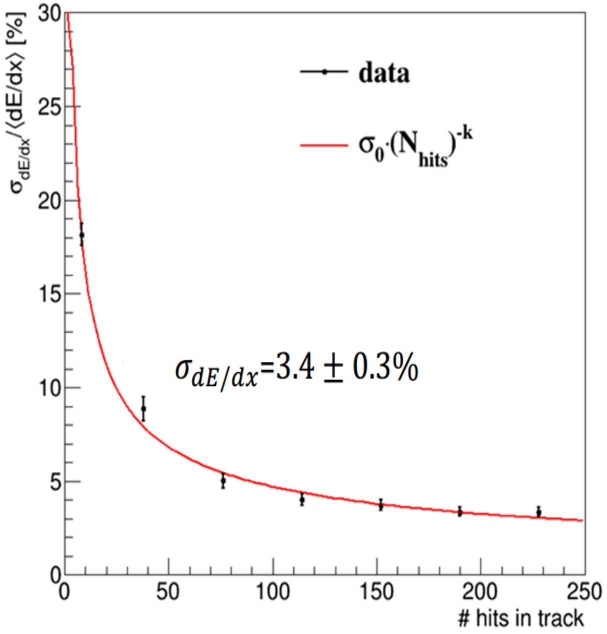








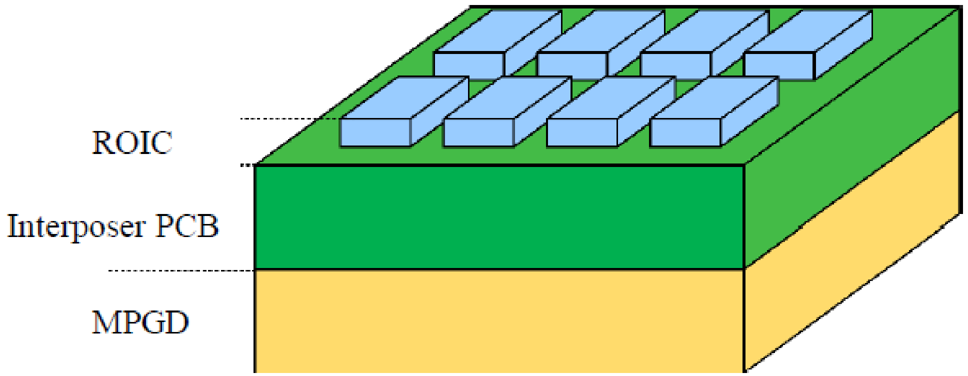


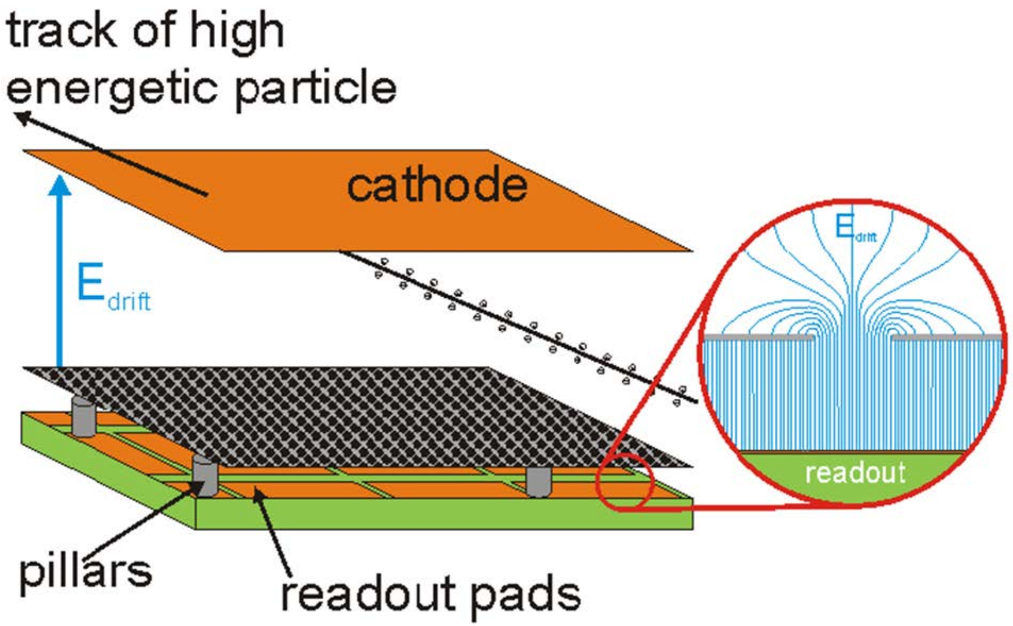


https://doi.org/10.1016/j.nima.2022.167241

Pixelated readout TPC technology for CEPC TDR

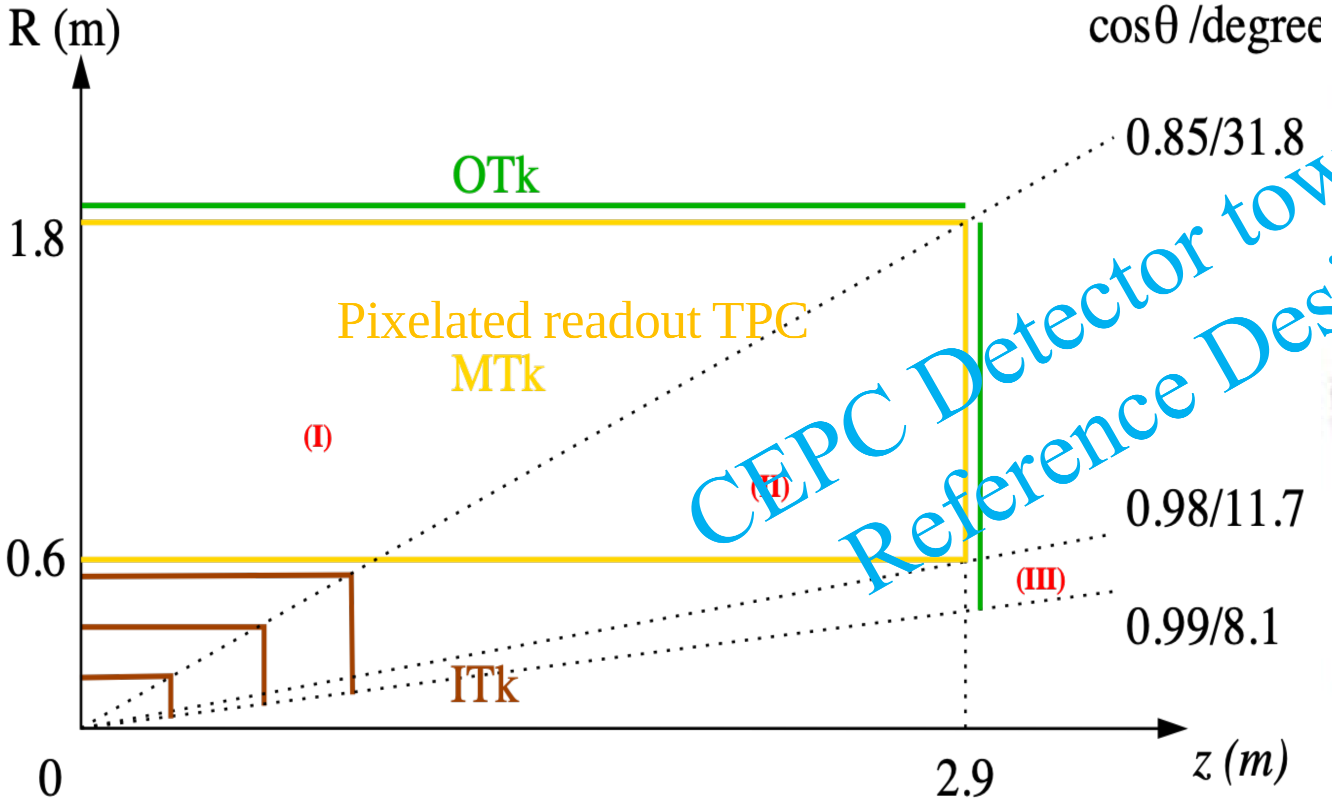
- A pixelated readout TPC is **a good option to provide realistic physics requirements** of Higgs Physical and Tera-Z Physics also (2E36) at CEPC.
  - Pixelated readout→ better resolution → low gain → less distortion
- **Highlights** of Pixelated readout TPC technology for CEPC TDR
  - Can deal with high rates (MHz/cm^2)
  - High spatial resolution → better momentum resolution
  - PID: dE/dx + dN/dx (**In space**)
  - Excellent two tracks separation

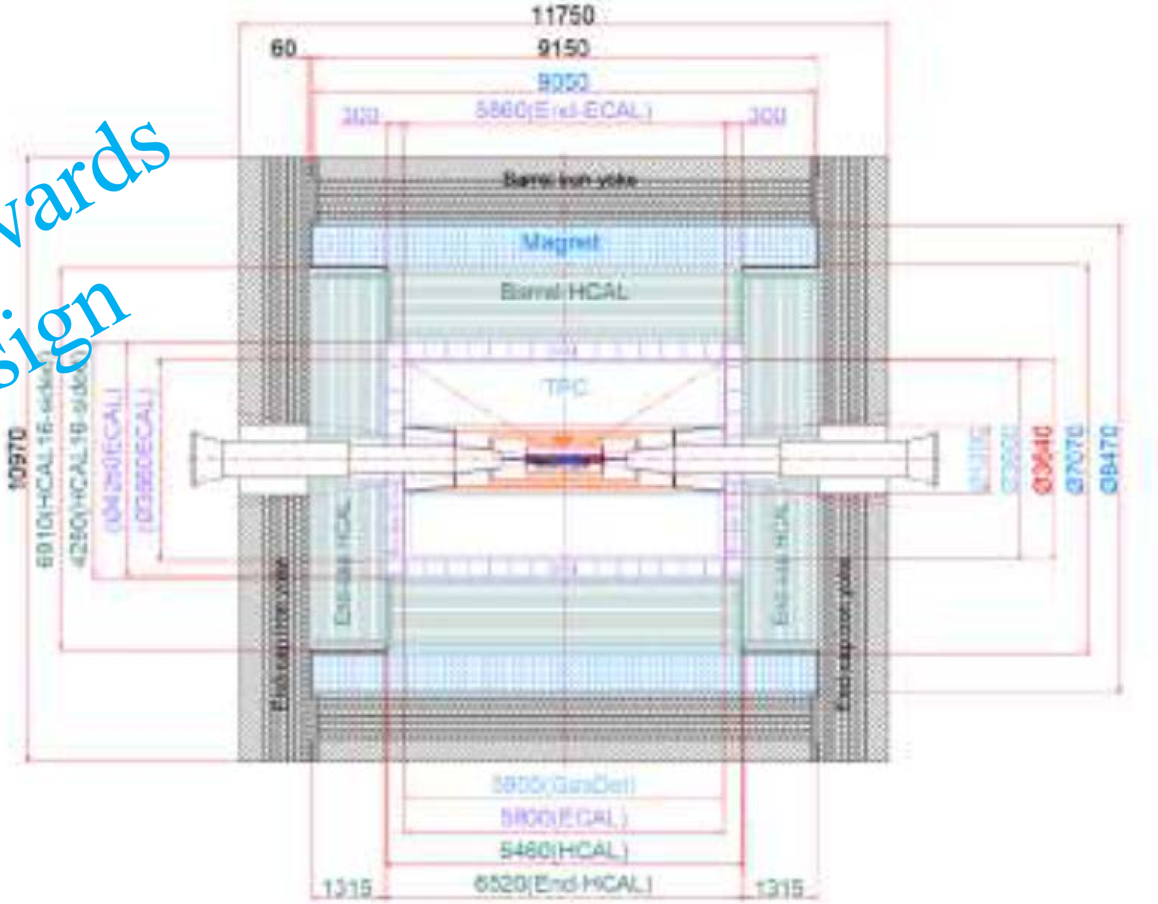




Track detector system in CEPC Phy.&Det. TDR

- The track detector system's geometry finalized.
  - All of physics simulation used the updated geometries for CEPC TDR document
  - Silicon combined with gaseous chamber as the tracker and PID
  - **Baseline:** Pixelated readout TPC as the **main track (MTK)** from radius of 0.6m to 1.8m



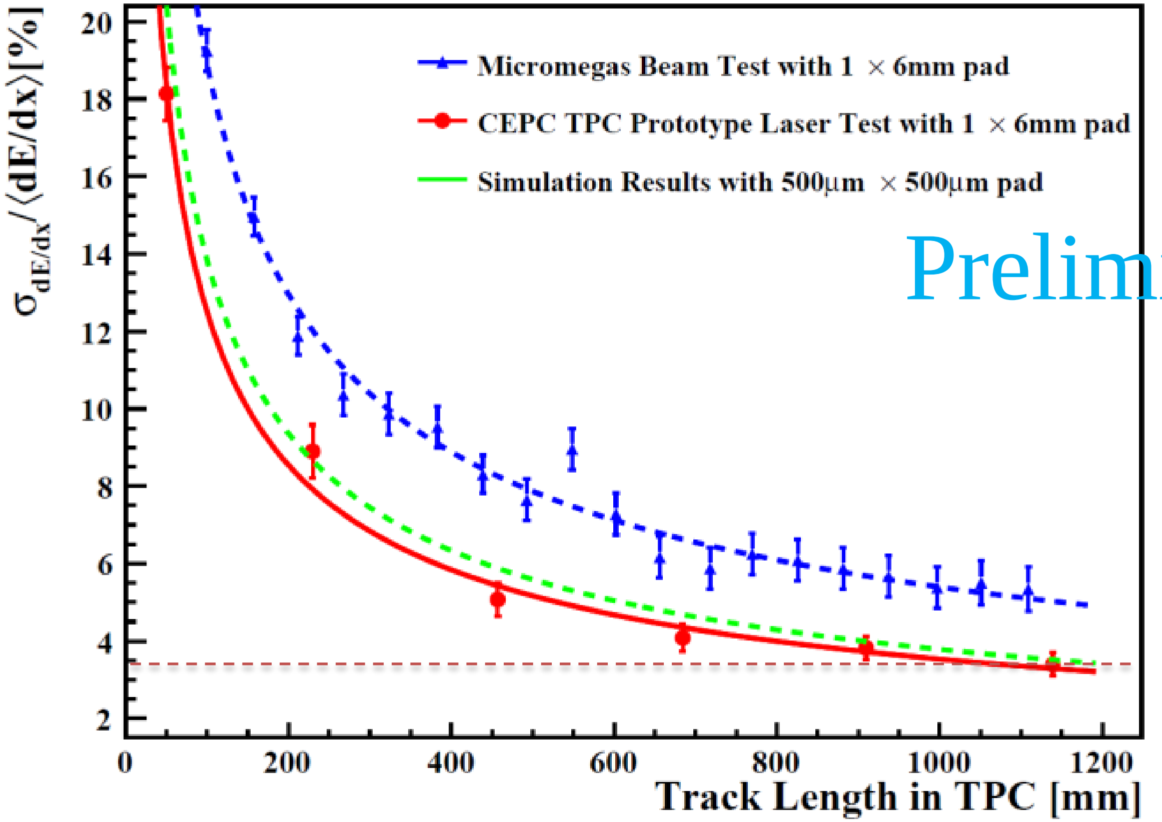


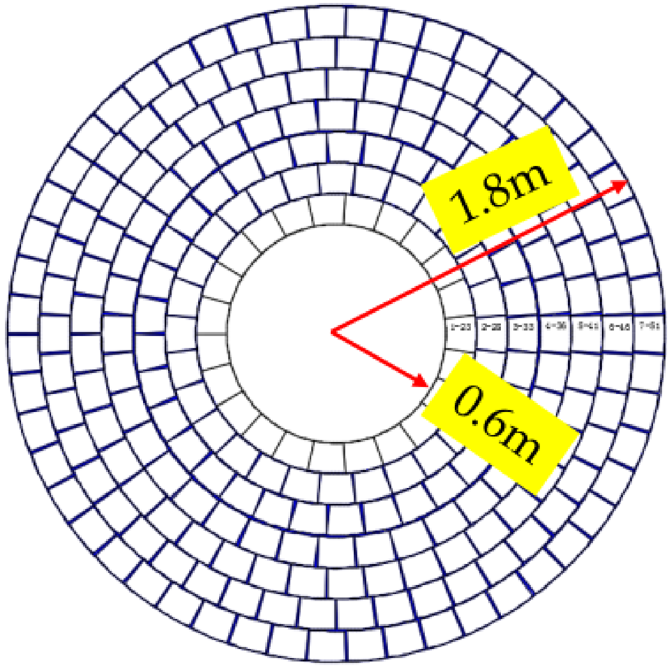
Geometry of the track detector system in CEPC TDR

PID Performance using dE/dx

- A higher granularity is also very helpful for improving dE/dx.
- According to simulation results, for a pad size of 500um, with the current 1.2-meter track length of CEPC, the dE/dx can reach 3.2%.

$$\sigma_{dE/dx} \sim L^{-0.47} \times G^{-0.13}$$





- **Performance and readiness of TPC detector R&D**

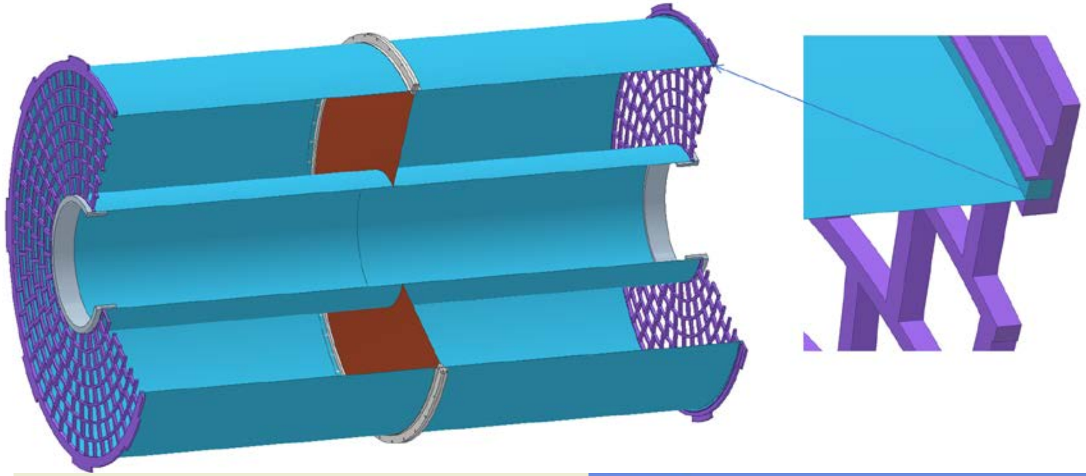
- **Performance studies of the high granularity readout TPC**

Critical key issues

  - **Material budget at endcape/barrel**
  - **Occupancy and hit density**
  - **Improved dE/dx+dN/dx for PID**
  - **Ion backflow suppression**
  - **Reasonable channels and power consumption**
  - **Running at 2 Tesla**
  - **Beamstrahlung and distortion**
  - **Prototype validation**

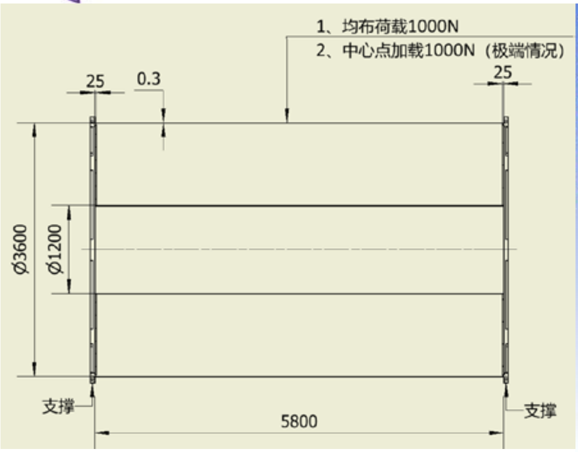
#1. Material budget at endcape/barrel Carbon Fibber √

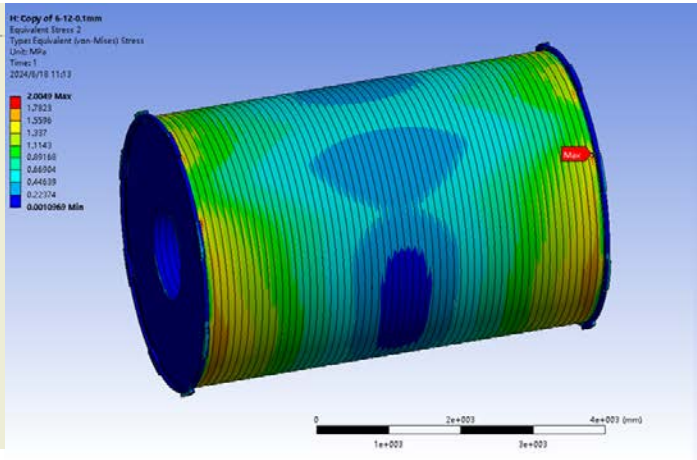
- Consideration of new Carbon Fiber barrel instead of the honeycomb barrel
- **Ultra-light material** of the TPC barrel : **0.63% X_0 in total, including**
  - FEA preliminary calculation: 0.2mm carbon fibber barrel can tolerant of LGAD OTK (**100Kg**)
- Optimization of the connection back frame of the endcap (on going)

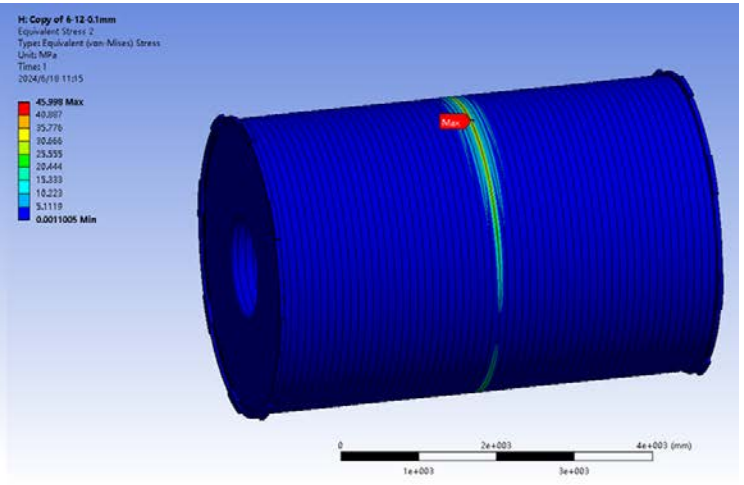


Material budget of TPC barrel

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	0.020	25.28	0.08
Sum of the material budget			**0.63**

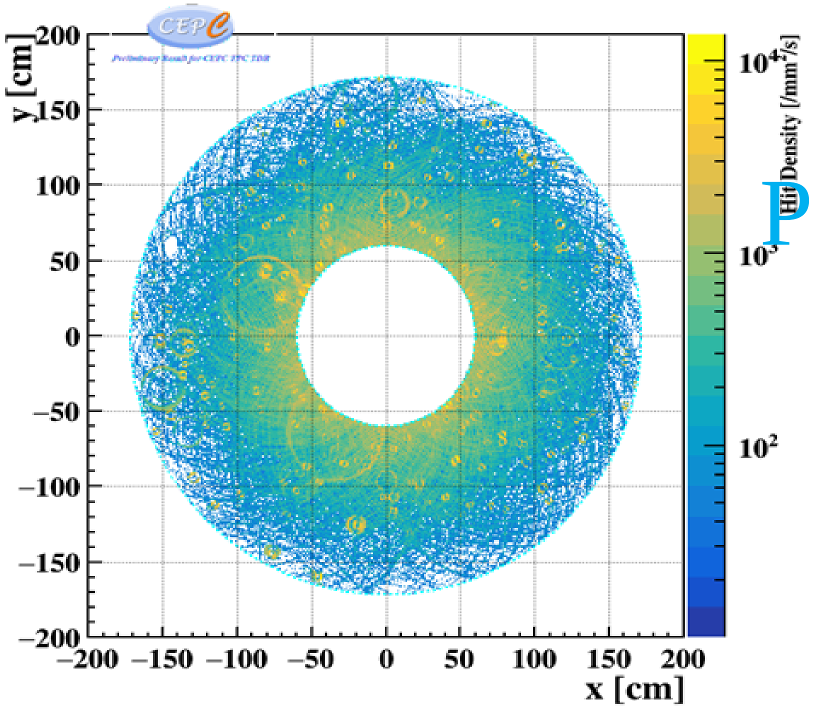


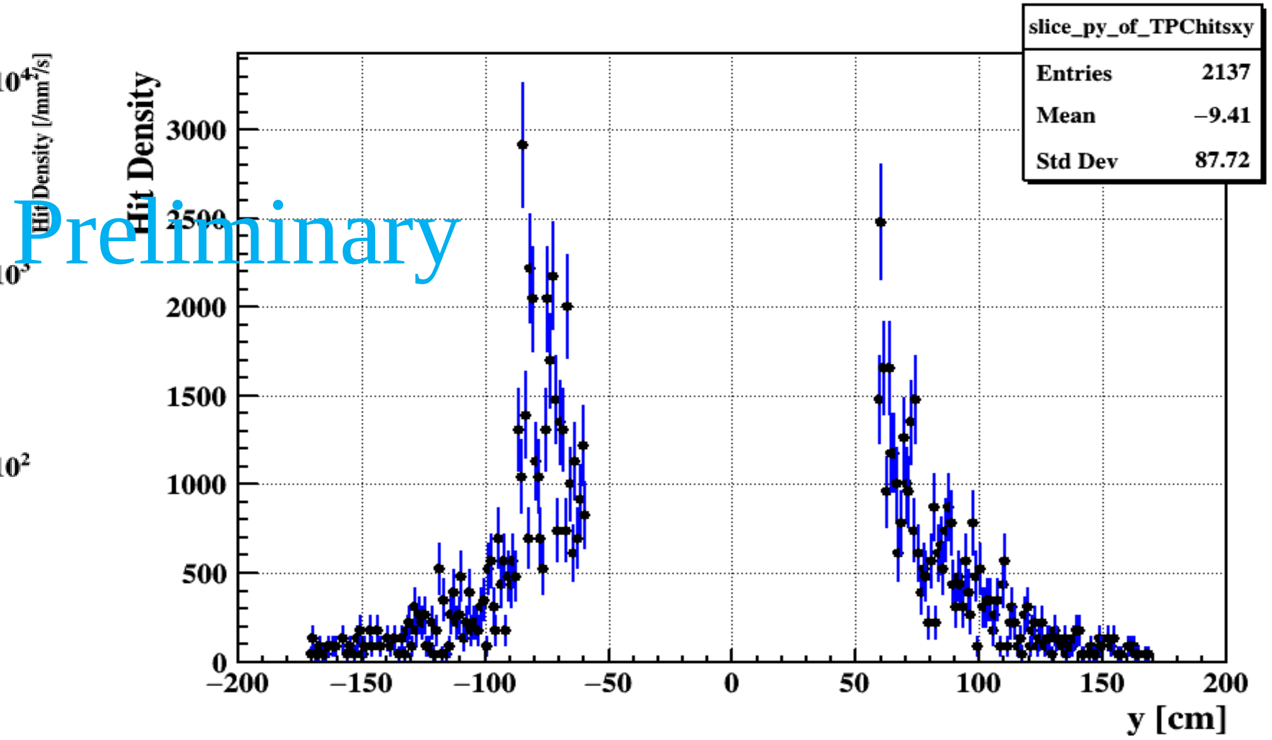




#2. Occupancy and hit density √

- **Low voxel occupancy** : 1E-5 to 1E-6 (cite#2)
- At 2 E36 with Physics event only, even bunch distribution(cite#3).
  - Pixelated readout much **LOWER** inner most occupancy (**0.6m inner radius**)
  - Pixelated readout can easily handle a high hits rate at Z pole. (cite#4)
  - The data at the inner radius @40M BX Z pole@1 Module ~0.05Gbps(Maximum).





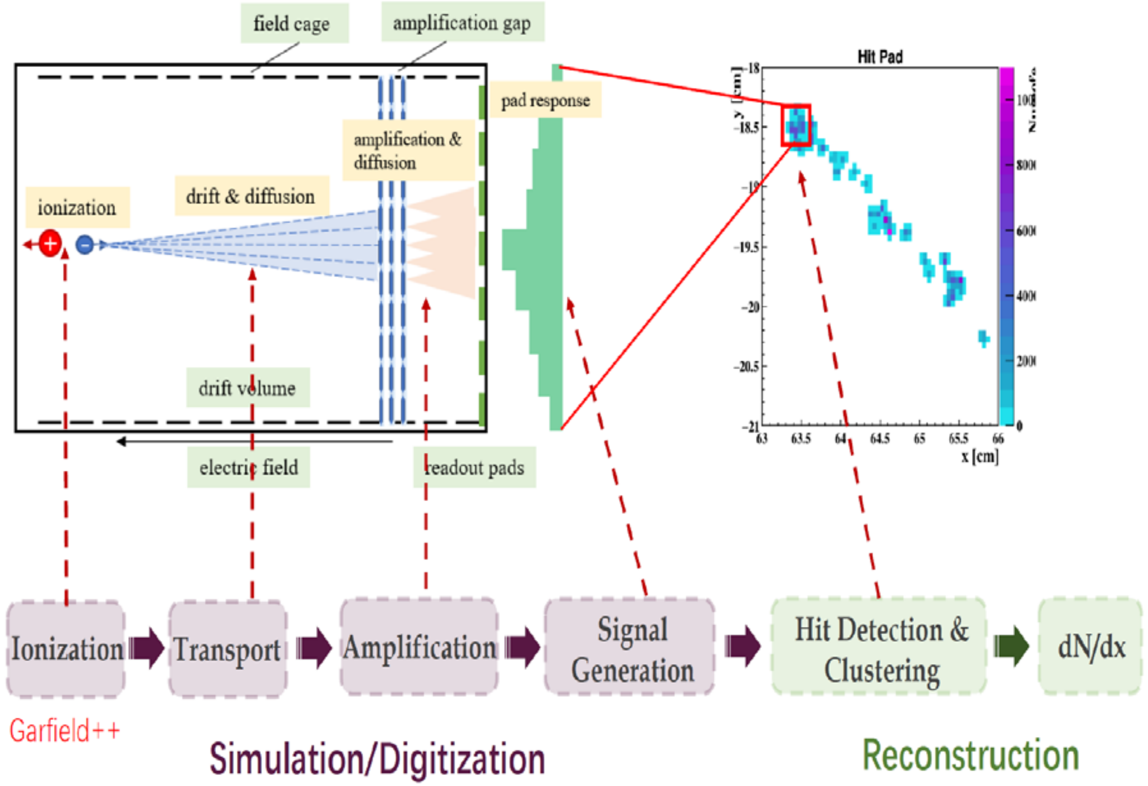
Simulation of Tera-Z/CEPC with the beamstruggle

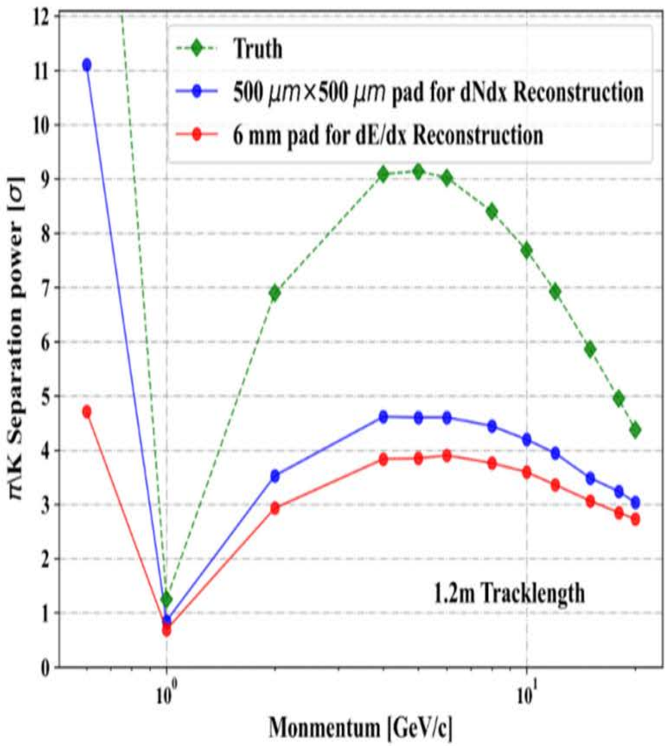
Cite#2 Occupancy in the CLIC
Cite#3 https://doi.org/10.1088/1748-0221/12/07/P07005
Cite#4 GridPix detectors

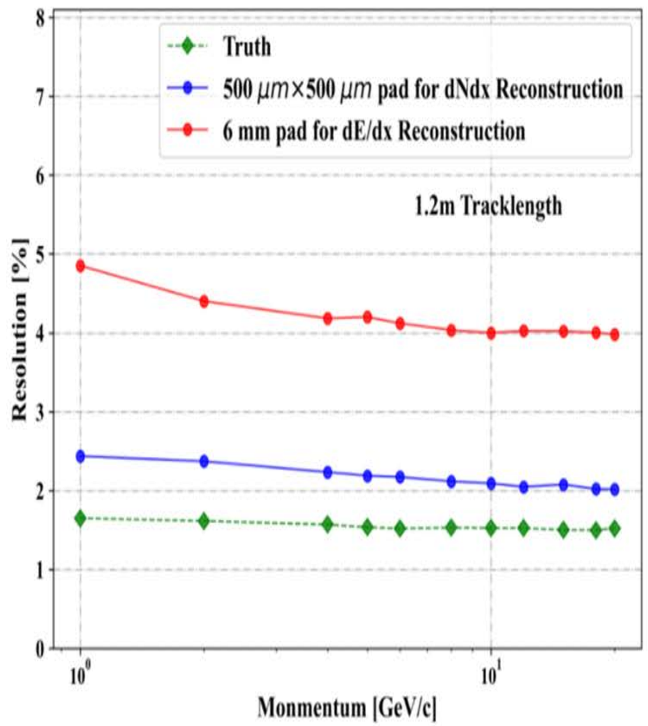
#3. Improved dE/dx+dN/dx √

- Full simulation framework of pixelated TPC developed using Garfied++ and Geant4 at IHEP
- Investigating the π/κ separation power using reconstructed clusters, **a 3σ separation at 20GeV** with 50cm drift length can be achieved
- dN/dx has significant potential for **improving PID resolution**

$$Sp = \frac{|\mu_A - \mu_B|}{\frac{\sigma_A + \sigma_B}{2}}$$





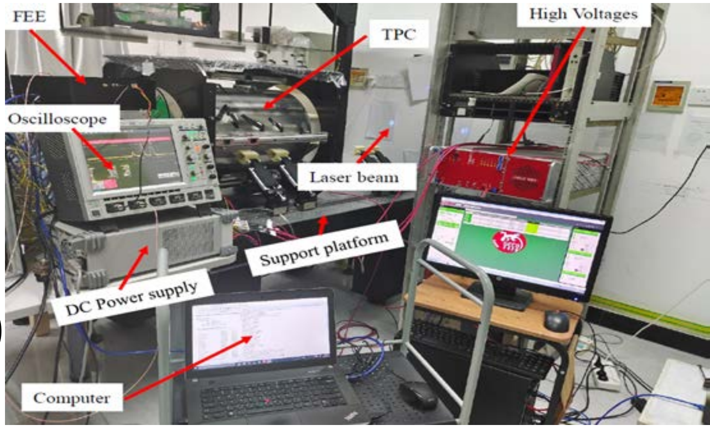


Simulation of TPC detector under 3T/2T and T2K mixture gas

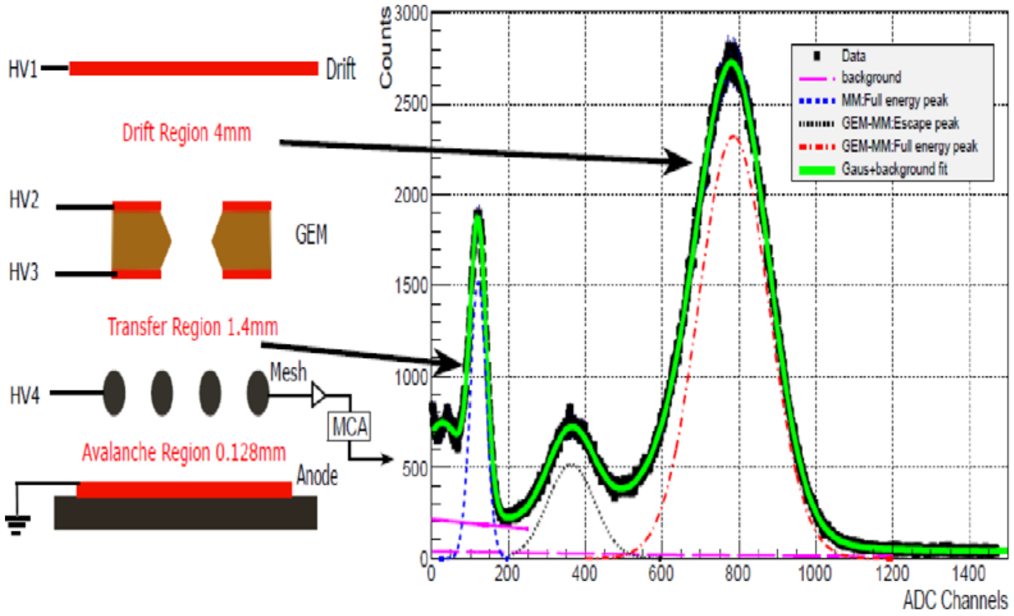
Cite#5 DOI: 10.22323/1.449.0553
Cite#6 EPS-HEP 2023 talk by Yue Chang

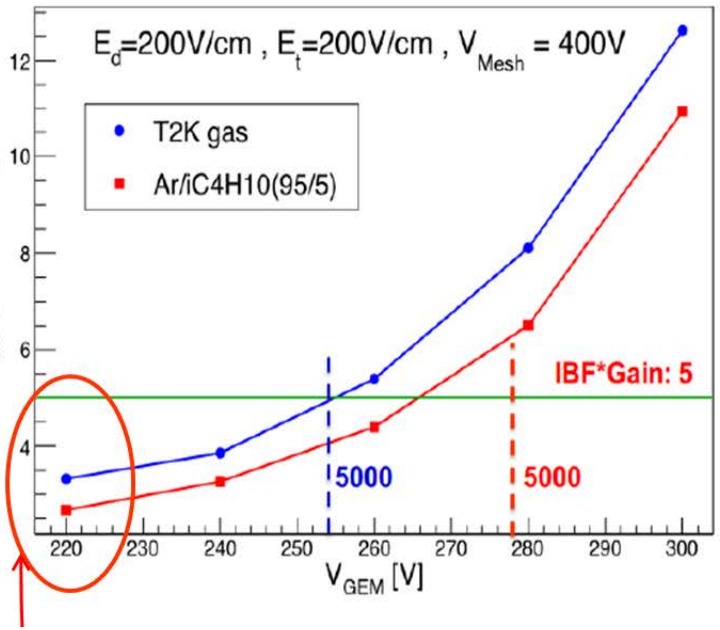
#4. Ion backflow suppression √

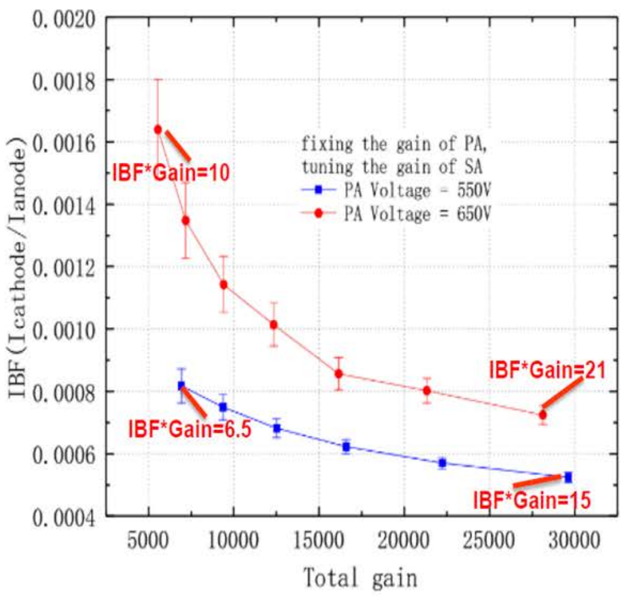
- Achievement by far from TPC module and prototype:
  - Supression ions hybrid TPC module
    - **IBF×Gain ~1 at Gain=2000 validation** with TPC module
  - Spatial resolution of $\sigma_{r\varphi} \leq 100\ \mu m$ by TPC prototype
  - dE/dx for PID: <3.6% (as expected for CEPC baseline detector concept)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



IBF of double mesh MM @USTC/Jianbei Liu





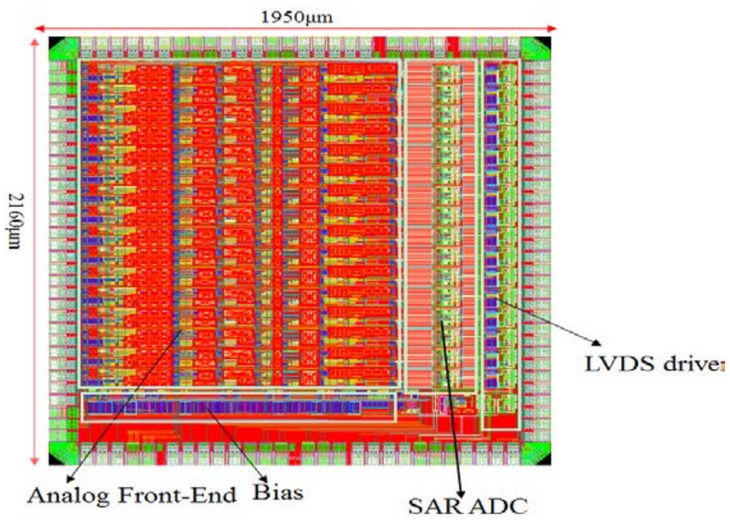


Cite#7: DOI:10.1016/j.nima.2020.164282
Cite#8: CERN-OPEN-2021-012. 2021
Cite#9: IJMPA 36.22 (20212142015

Hybrid TPC module and Double-mesh detector module

#5. Reasonable channels and power consumption √

- Power consumption relative with the high granularity readout
  - Pad readout TPC@1mm×6mm pad size
    - Total channels: **10^6** ; Total power: **<10 kW** using 2-phase CO_2 cooling
  - Pixelated readout TPC at the endcap
    - Total power: **<10 kW**
      - 2-Phase CO_2 cooling
      - **<100mW/cm^2**
  - ASIC chip and TPC prototyping R&D



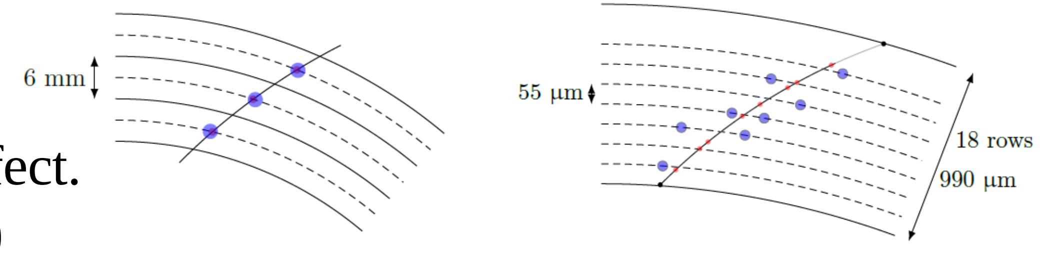
	PASA+ALTRO	Super-ALTRO	SAMPA	WASA_v1
TPC	ALICE	ILC	ALICE upgrade	CEPC
Pad Size	4x7.5 mm^2	1x6 mm^2	4x7.5 mm^2	1x6 mm^2
No. of Channels	5.7× 10^5	1-2 × 10^6	5.7 × 10^5	2 x×10^6
Readout Detector	MWPC	GEM/MicroMegas	GEM	GEM/MicroMegas
Gain	12 mV/fC	12-27 mV/fC	20/30 mV/fC	10-40 mV/fC
Shaper	CR-(RC)^4	CR-(RC)^4	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

Cite#10: DOI: 10.1088/1748-0221/15/02/T02001
Cite#11: DOI: 10.1088/1748-0221/15/05/P05005

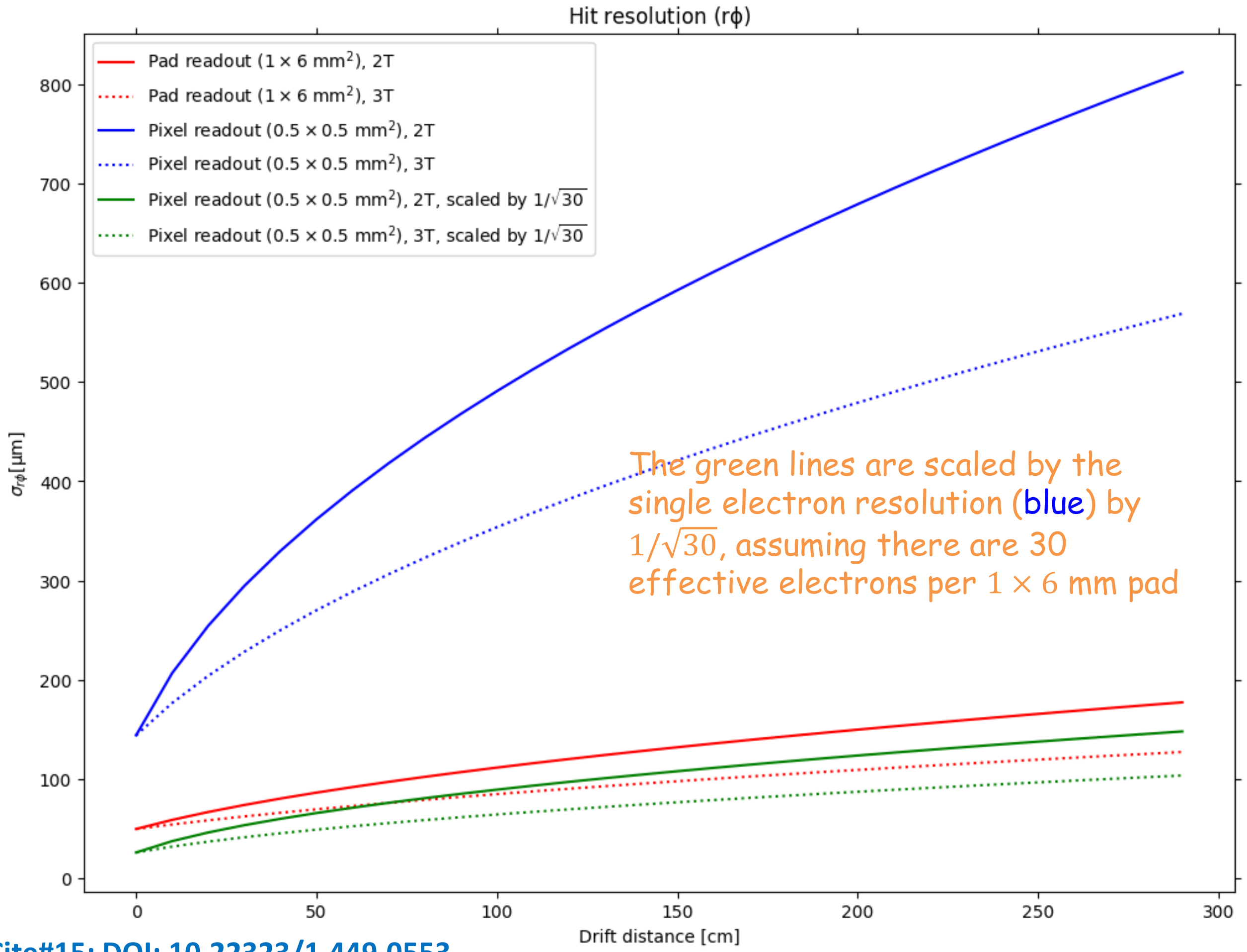
#6. Running at 2 Tesla √

Estimation of the **spatial resolution using pixelated readout**.

- The granularity and the transverse diffusion considered.
- TPC can work well at the 2T B-field **without any E×B** effect.
- Distortion will be considered proportionally at Z (on going)



(a) Pads (b) Pixels



Pad readout:

$$\sigma_{r\phi}^{\text{pad}} = \sqrt{(\sigma_{r\phi 0}^{\text{pad}})^2 + \sigma_{\phi 0}^2 \sin^2(\phi_{\text{track}}) + L\frac{D_{r\phi}^2}{N_{\text{eff}}}\sin(\theta_{\text{track}})\left(\frac{6\text{ mm}}{h_{\text{pad}}}\right)\left(\frac{4.0\text{ T}}{B}\right)^2}$$

- $\phi_{\text{track}} = 0°, \theta_{\text{track}} = 90°$
- $\sigma_{r\phi 0} = 50\mu\text{m}$
- $N_{eff} = 22$
- $D_{r\phi} = 46.9\mu\text{m}/\sqrt{\text{cm}}(2\text{T}), 32.3\mu\text{m}/\sqrt{\text{cm}}(3\text{T})$

Pixel readout:

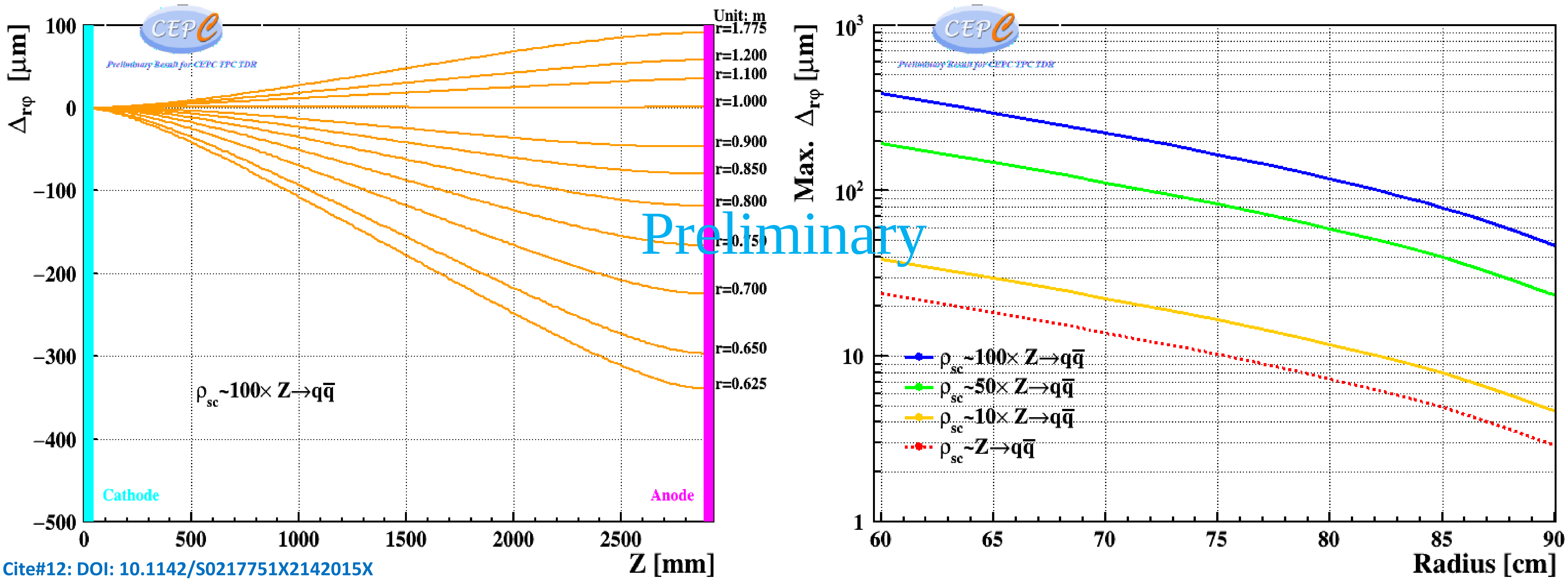
$$\sigma_r^{\text{pixel}} = \sigma_{r\phi}^{\text{pixel}} = \sqrt{(\sigma_{r\phi 0}^{\text{pixel}})^2 + LD_{r\phi}^2\left(\frac{4.0\text{ T}}{B}\right)^2}$$

- $\sigma_{r\phi 0} = \frac{500}{\sqrt{12}} = 144\mu\text{m}$
- $D_{r\phi} = 46.9\mu\text{m}/\sqrt{\text{cm}}(2\text{T}), 32.3\mu\text{m}/\sqrt{\text{cm}}(3\text{T})$

Cite#15: DOI: 10.22323/1.449.0553

#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



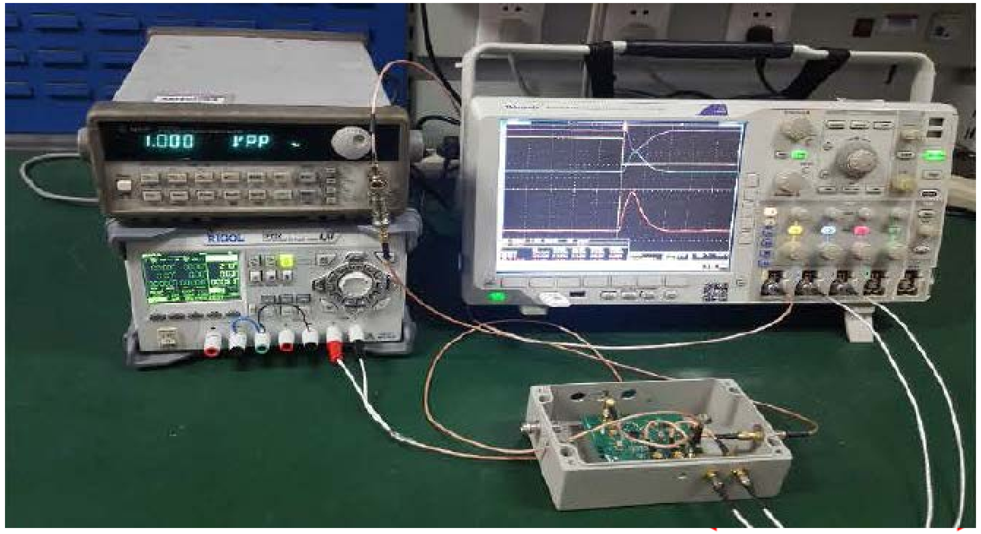
Cite#12: DOI: 10.1142/S0217751X2142015X
Cite#13: DOI: 10.1016/j.nima.2022.167241
Cite#14: DOI: 10.1088/1748-0221/12/07/P07005

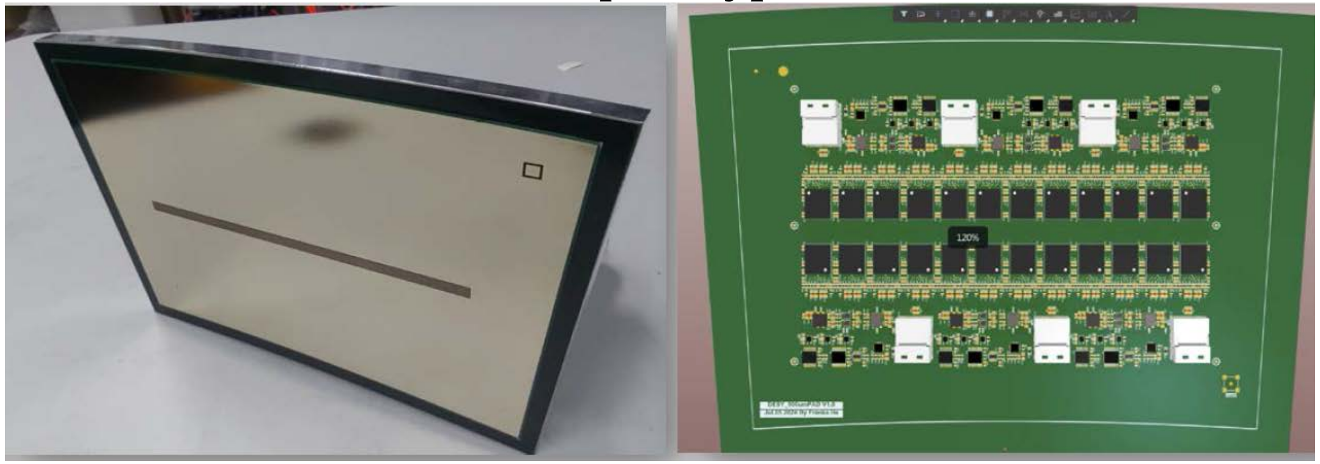
Option concept: Pixelated readout TPC @cosθ≃0.98

Parameters	Higgs run	Z pole run
B-field	3.0T	2.0T
Pad size (mm)/All channels	0.5mm×0.5mm /2×3×10^7	0.5mm×0.5mm /2×3×10^7
Material budget barrel	0.012 X_0	0.012 X_0
Material budget endcap	0.17 X_0	0.17 X_0
Points per track in rφ	2300	2300
σ_{point} in rφ	120μm (full drift)	400μm (full drift)
σ_{point} in rz	≃ 0.1 – 0.4 mm (for zero – full drift)	≃ 0.2 – 0.8 mm (for zero – full drift)
2-hit separation in rφ	0.5mm	0.5mm
K/π separation power @20GeV	3 σ	3 σ
dE/dx	3.2%	3.2%
Momentum resolution normalised: $\sigma_{1/pT} = \sqrt{a^2 + (b/pT)^2}$	a = 1.210 e -5	a = 2.69 e -5
	b = 0.589 e -3	b = 0.90 e -3

#8. Prototype valiadation of pixelated TPC for TDR √

- **R&D on Pixelated TPC readout for CEPC TDR**
  - Pixelated readout TPC ASIC chip developed and **2nd prototype wafer has done** and tested.
  - The TOA and TOT can be selected as the initiation function in the ASIC chip
    - 500μm×500μm pixel readout designed
    - Noise of FEE: 100e
    - Time resolution: 14bit (5ns bin)
    - Power consumption: **~100mW/cm^2**
- **Prototyping pixelated readout TPC detector**
  - The validation of the prototype assembled





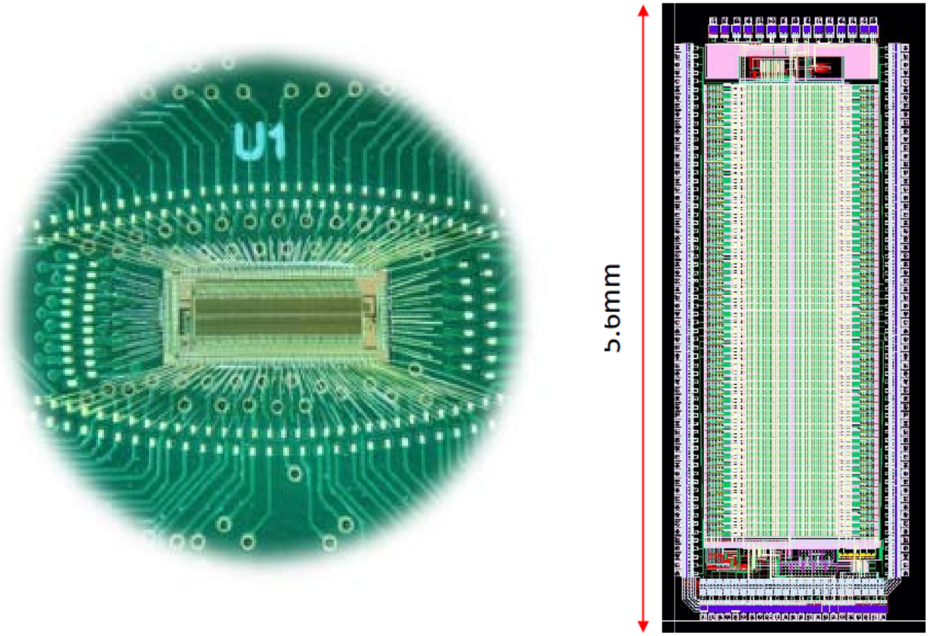


Photo and layout of ASIC Chip R&D for TPC

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Summary

- TPC detector prototype R&D using the pad readout towards the pixelated readout for the future e+e- colliders, espial to the high luminosity Z pole run at CEPC.

- Pixel TPC is in the simulation framework has been developed using Garfied++ and Geant4 at IHEP. To analyze the simulate the performance of the high luminosity Z pole run at CEPC, some validation of TPC prototype have been studies.

- High granularity readout TPC can be as a realistic and promised track detector for CEPC TDR.

- Synergies with CEPC/LCTPC/FCCee/EIC allow us to continue R&D and ongoing, we learn from all of their experiences..

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Many thanks!

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