High Precision Time Projection Chamber Technology R&D for Future e+e- Collider

Huirong Qi

on behalf of CEPC TPC Study Group

and some inputs from LCTPC international collaboration

Institute of High Energy Physics, CAS

July 19, 2024, Prague, Czech

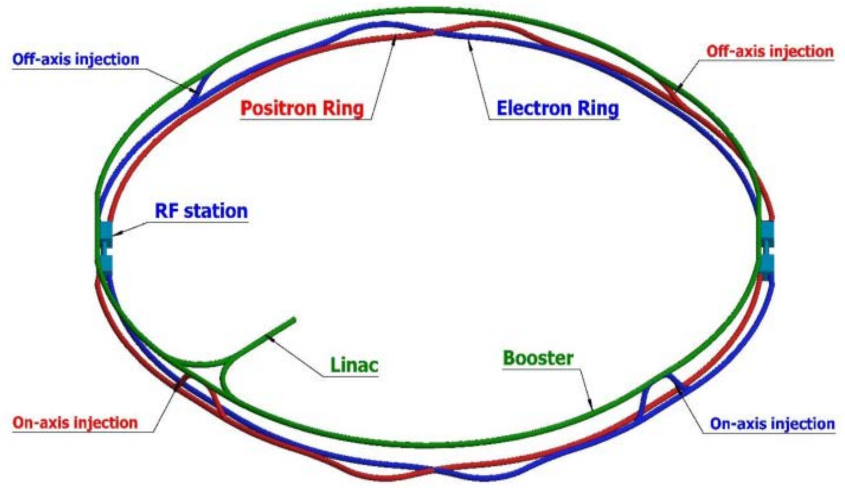
Content

- **Motivation and physics requirements**
- **High precision TPC R&D**
- **Updated pixelated readout TPC R&D**
- **Summary**

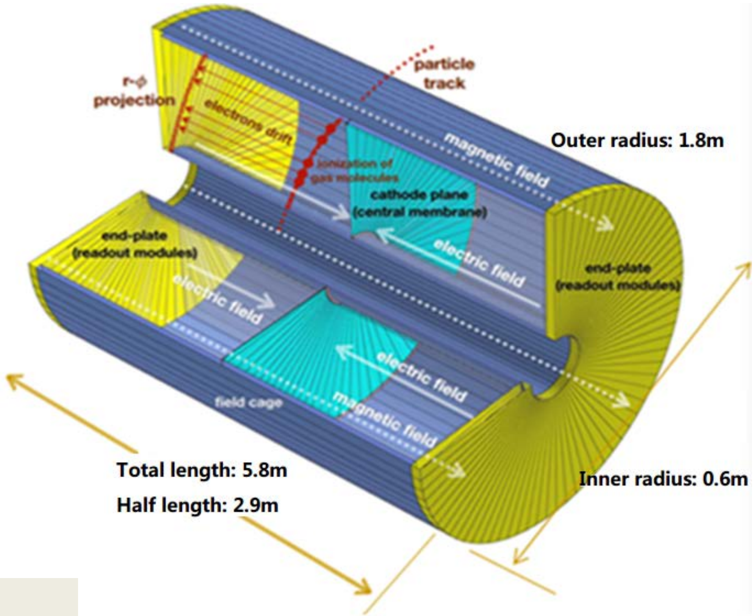
- **Motivation and physics requirements**

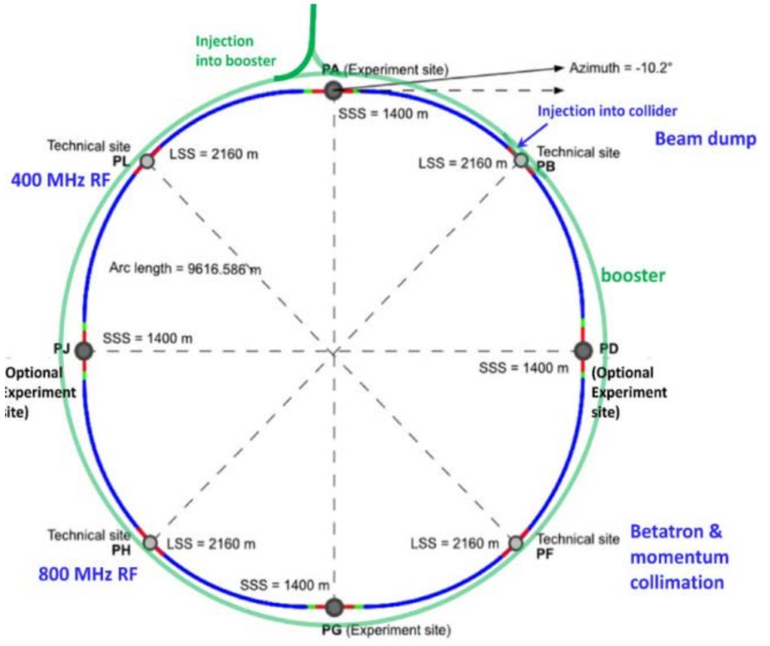
Motivation and physics requirements on e+e- collider

- 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 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

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

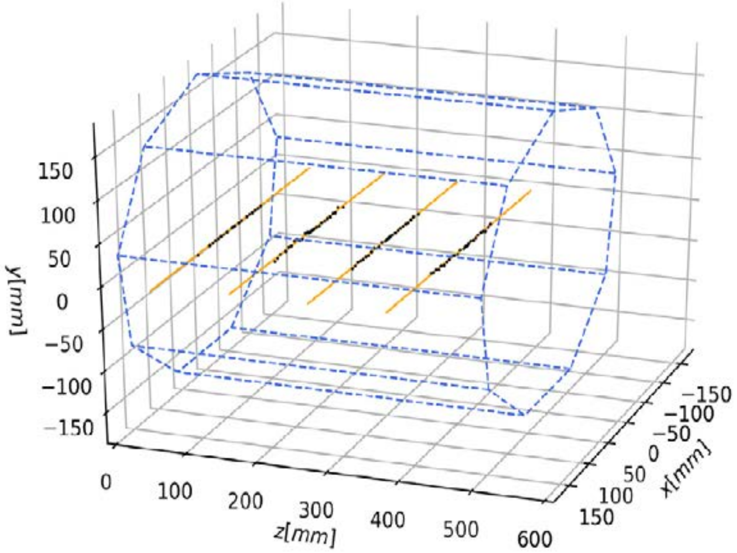
arXiv:2312.14363

- **High precision resolution TPC R&D**

Roadmap of CEPC TPC detector R&D

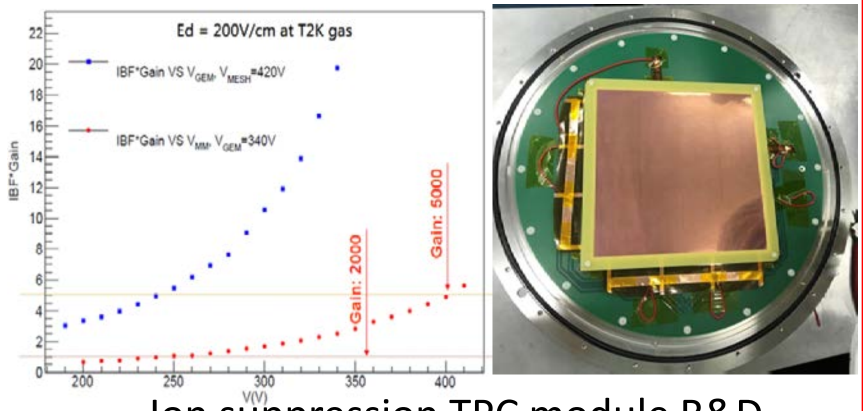
- **CEPC TPC detector prototyping roadmap:**
  - From TPC module to **TPC prototype R&D for Higgs and Tera-Z**
  - Easy-to-install modular design of Pixelated readout TPC for CEPC TDR
- **Achievement by far:**
  - **IBF×Gain ~1 @ G=2000** validation with hybrid TPC module
  - Spatial resolution of **$\sigma_{r\varphi}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

TPC prototype with integrated 266nm UV laser

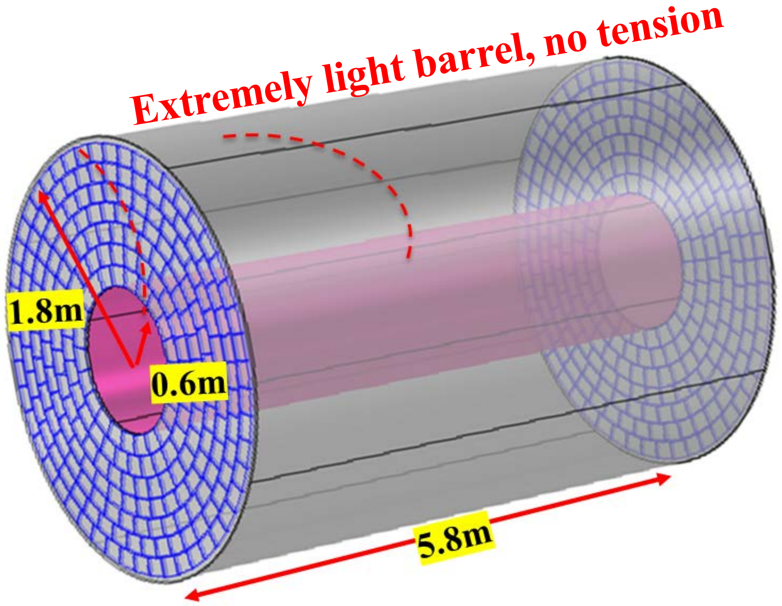


https://doi.org/10.1016/j.nima.2022.167241

Achievement



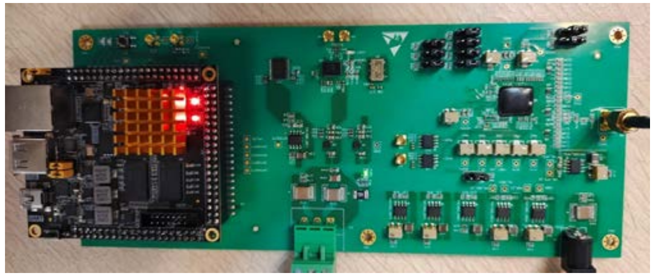
Ion suppression TPC module R&D

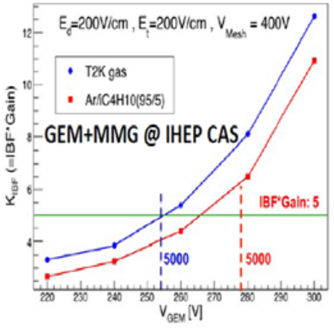


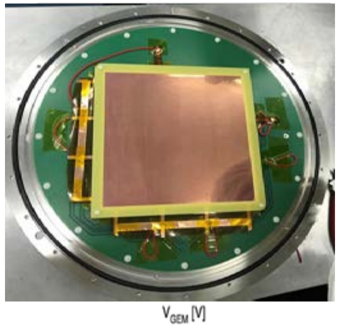
Geometry of TPC for CEPC TDR

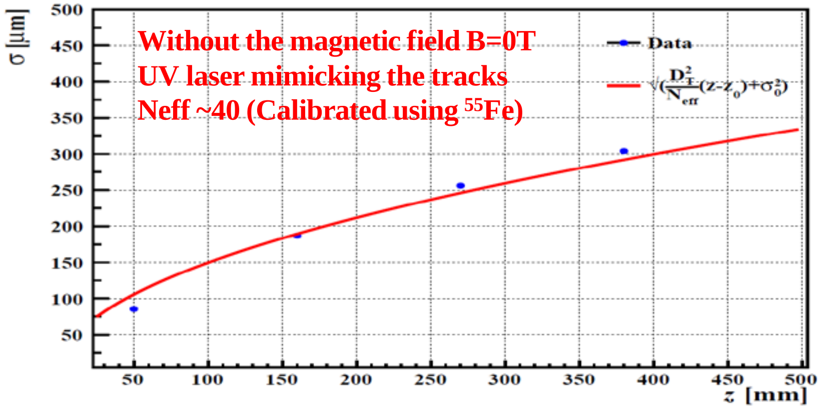
Highlights of TPC prototype integrated with 266nm UV laser tracks

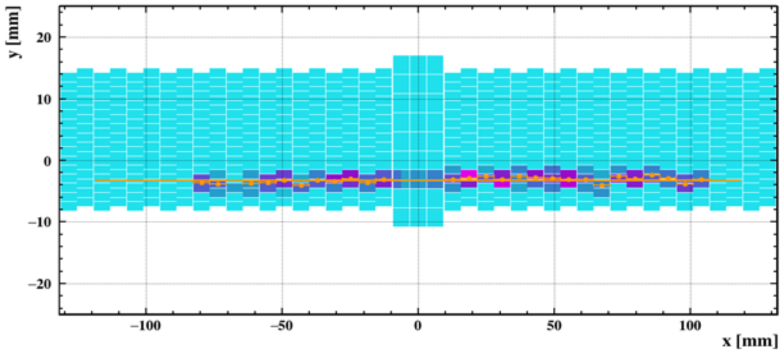
- **Highlights of CEPC TPC R&D and toward reasonable pixelated readout TPC**
  - Massive production and assemble MPGD lab has been setup at IHEP
  - TPC prototype integrated 266nm UV laser tracks has been studied and analyzed the UV laser signal, all are pretty good to Higgs run.
  - Track reconstruction and the spatial resolution of Pad readout TPC prototype are analyzed.

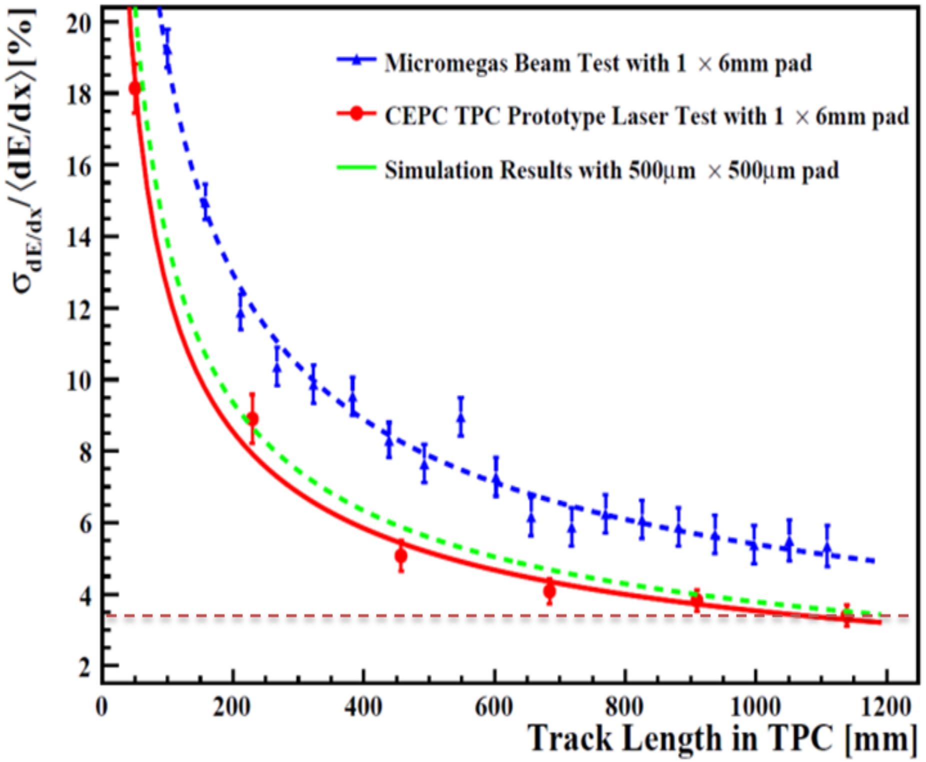










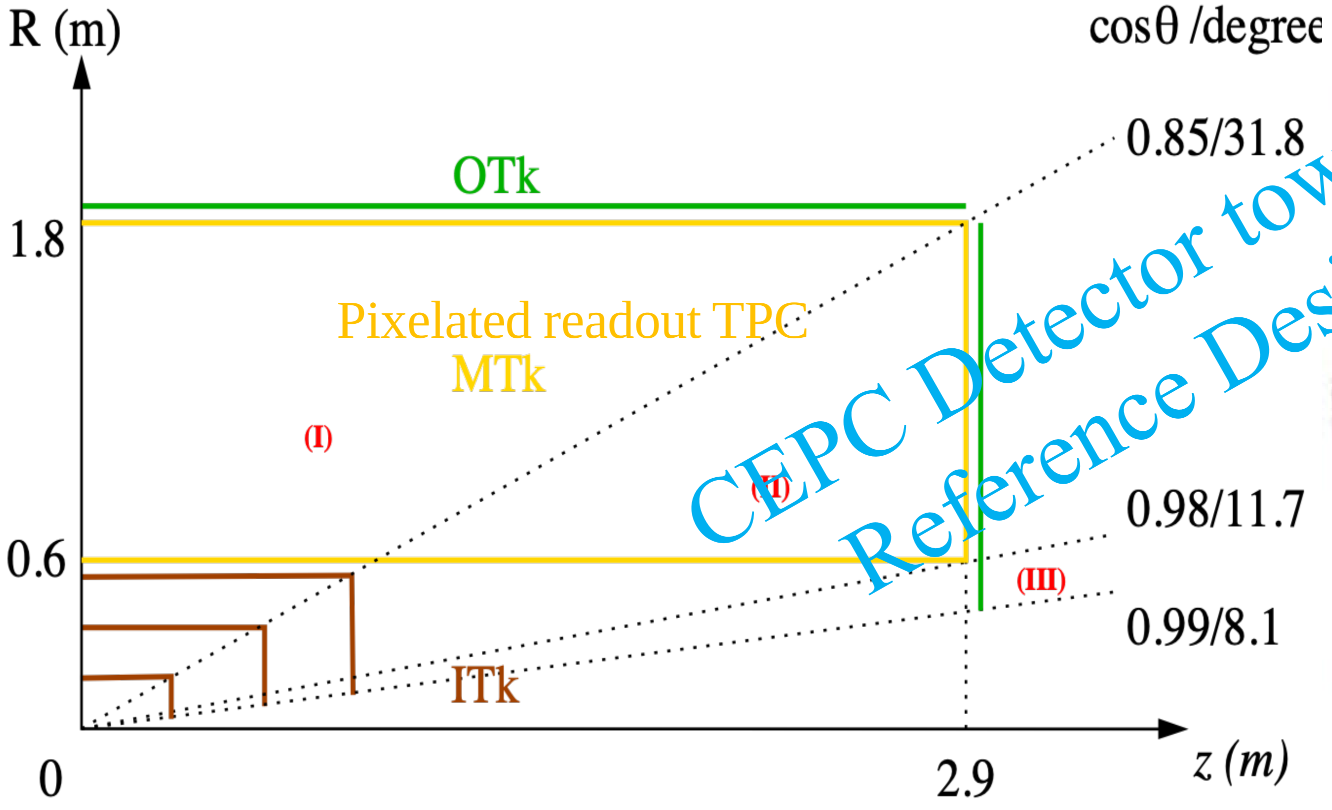


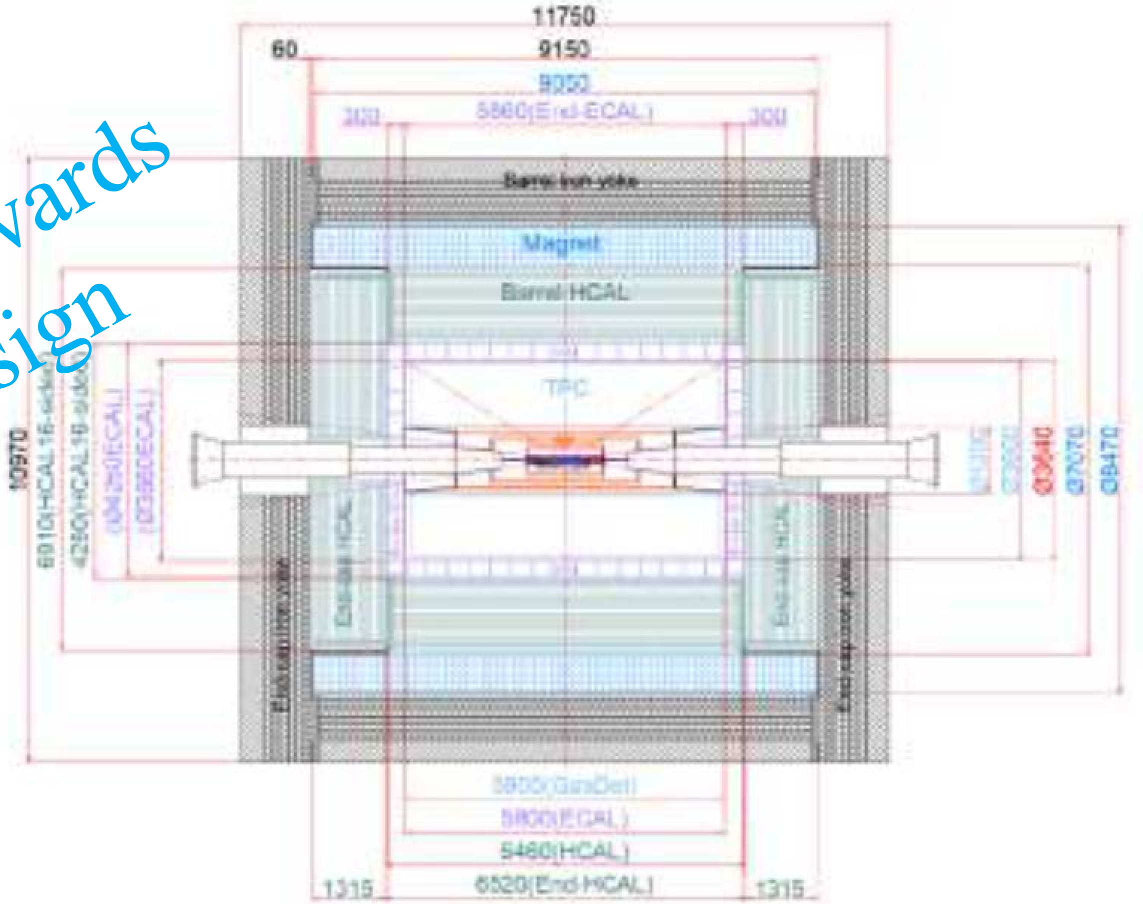
Publications by CEPC TPC group in 2018-2024:

- 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

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





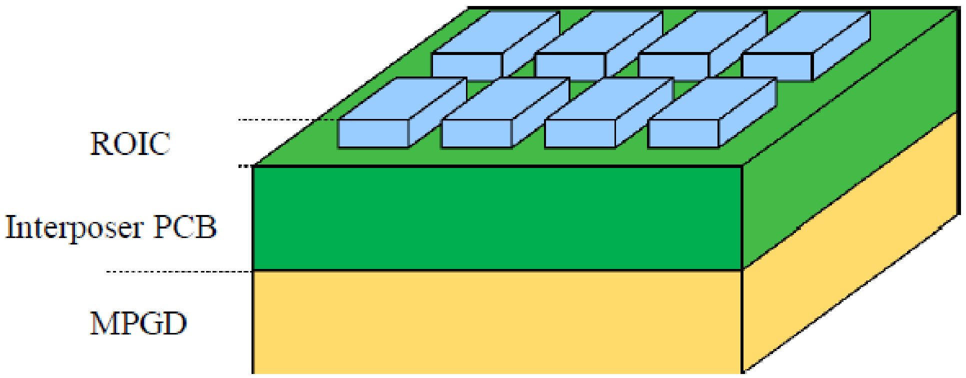
CEPC Detector towards Reference Design

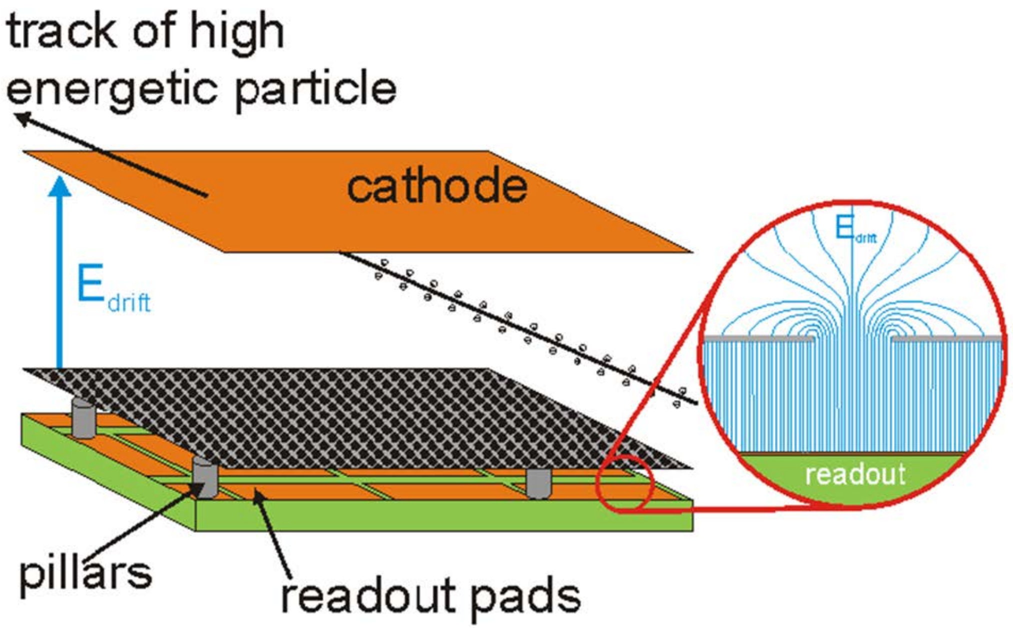
Geometry of the track detector system in CEPC TDR

- **Updated pixelated readout TPC R&D**

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

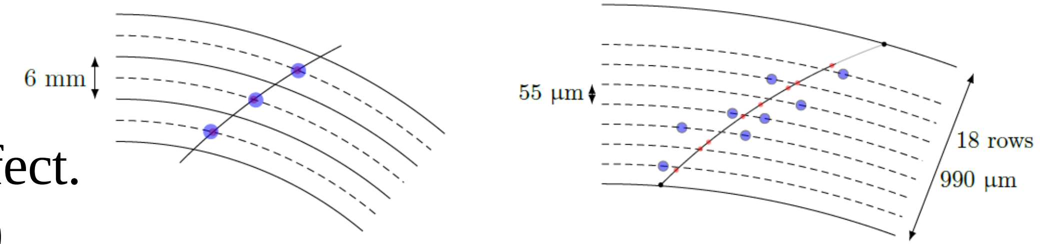




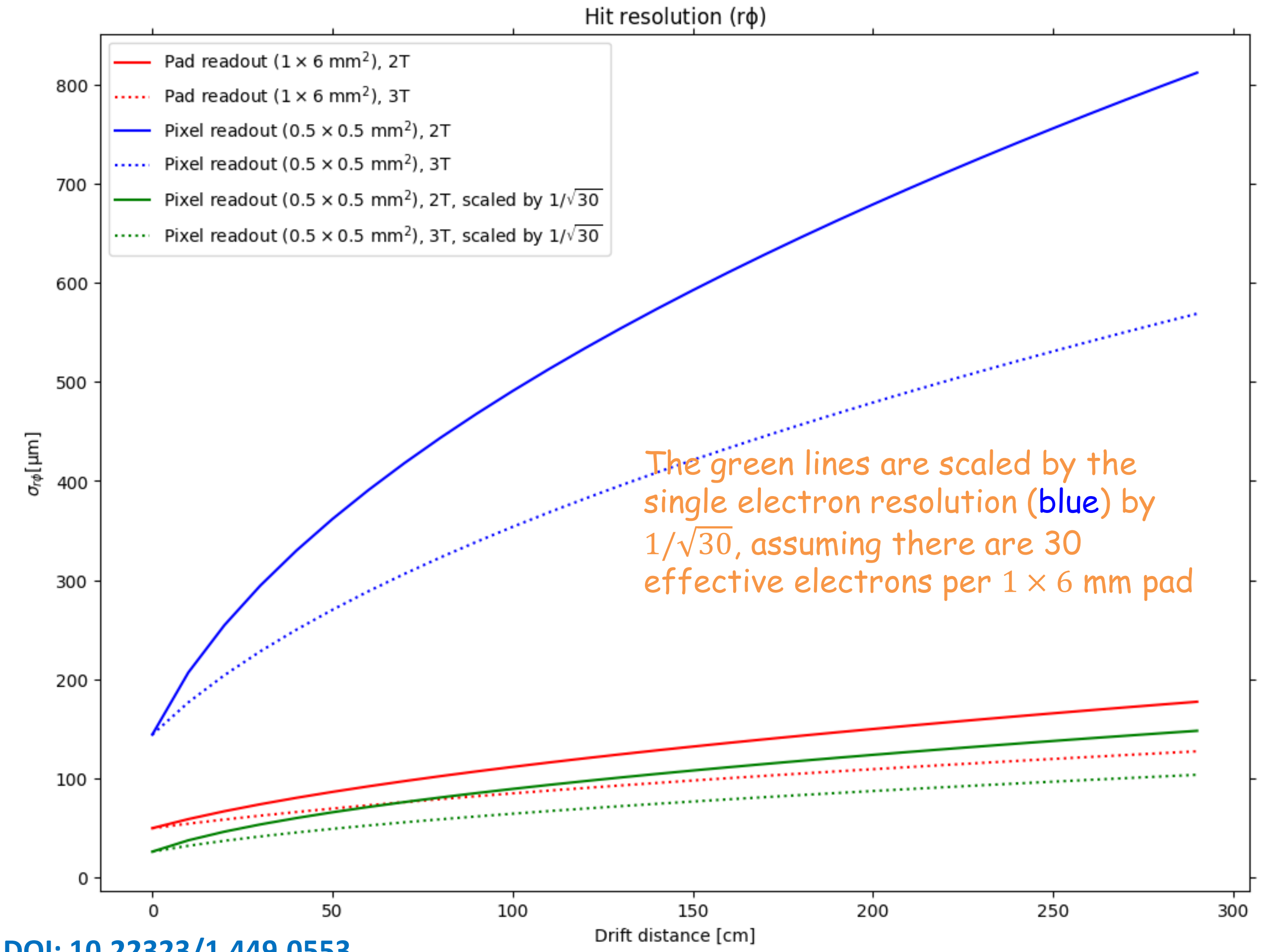
Operation on high luminosity Tera-Z at 2 Tesla

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:

$$\sigma_{r\phi}^{\text{pad}} = \sqrt{(\sigma_{r\phi0}^{\text{pad}})^2 + \sigma_{\phi0}^2 \sin^2(\phi_{\text{track}}) + L\frac{D_{r\phi}^2}{N_{\text{eff}}}\sin(\theta_{\text{track}})\left(\frac{6\text{ mm}}{h_{\text{pad}}}\right)\left(\frac{4.0\text{ T}}{B}\right)^2}$$

- $\phi_{track} = 0°, \theta_{track} = 90°$
- $\sigma_{r\phi0} = 50\mu\text{m}$
- $N_{eff} = 22$
- $D_{r\phi} = 46.9\mu\text{m}/\sqrt{\text{cm}}(2\text{T}), 32.3\mu\text{m}/\sqrt{\text{cm}}(3\text{T})$

Pixel readout:

$$\sigma_r^{\text{pixel}} = \sigma_{r\phi}^{\text{pixel}} = \sqrt{(\sigma_{r\phi0}^{\text{pixel}})^2 + LD_{r\phi}^2\left(\frac{4.0\text{ T}}{B}\right)^2}$$

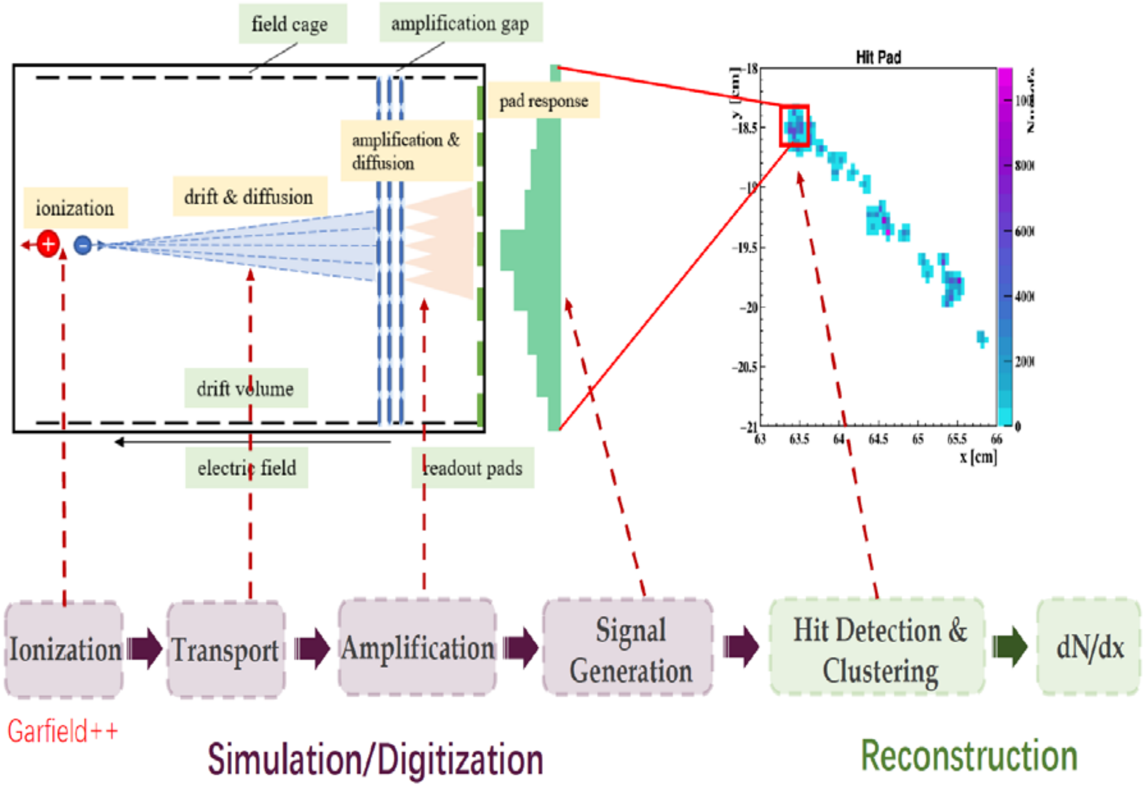
- $\sigma_{r\phi0} = \frac{500}{\sqrt{12}} = 144\mu\text{m}$
- $D_{r\phi} = 46.9\mu\text{m}/\sqrt{\text{cm}}(2\text{T}), 32.3\mu\text{m}/\sqrt{\text{cm}}(3\text{T})$

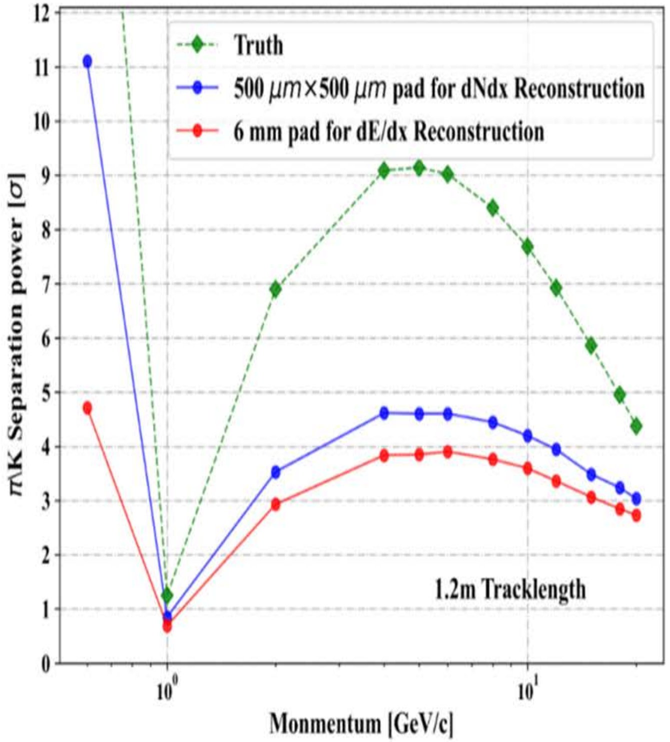
DOI: 10.22323/1.449.0553

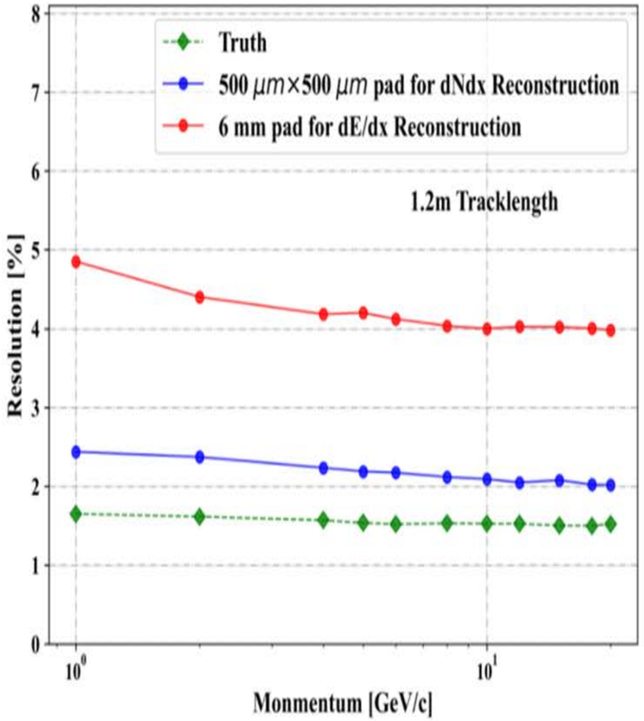
Improved dE/dx+dN/dx in space

- 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**

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







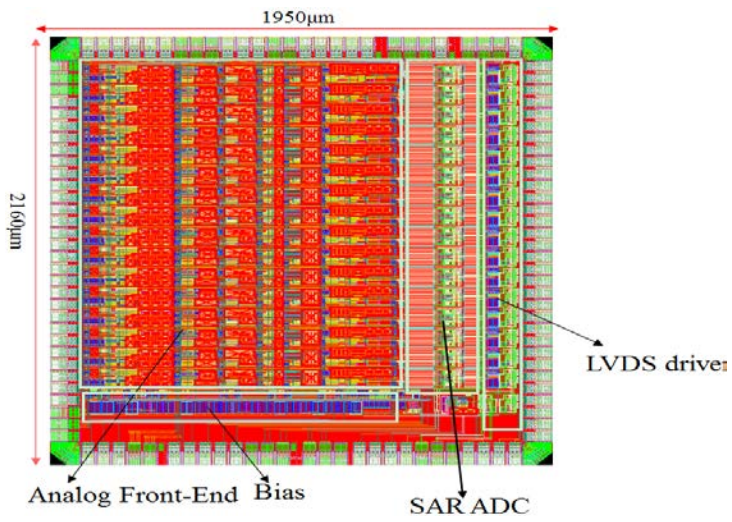
Simulation of TPC detector under 3T/2T and T2K mixture gas

DOI: 10.22323/1.449.0553
EPS-HEP 2023 talk by Yue Chang

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



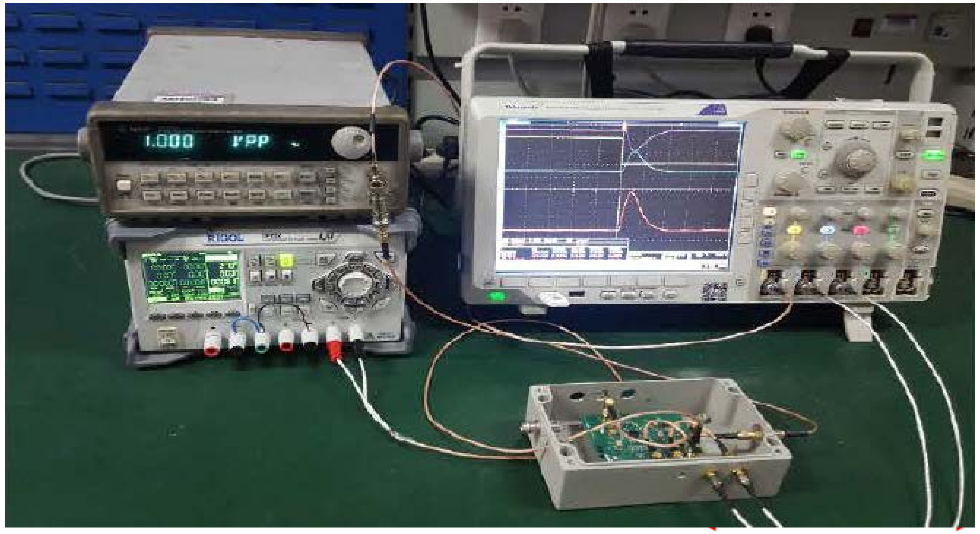
DOI: 10.1088/1748-0221/15/02/T02001
DOI: 10.1088/1748-0221/15/05/P05005

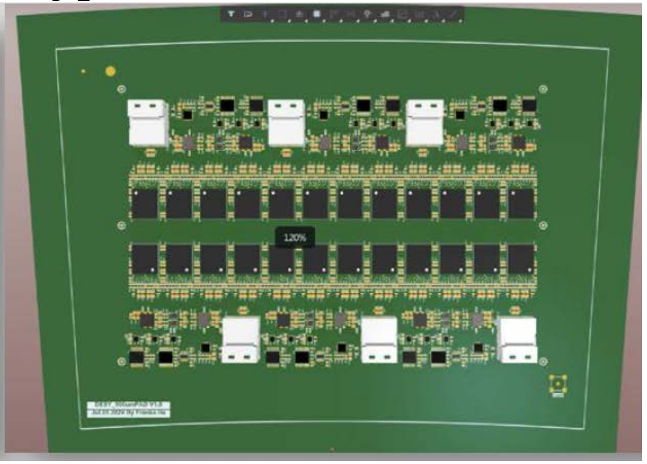
Optimization concept option: Pixelated readout TPC @cosθ≃0.98

Parameters	Higgs run	Z pole run
B-field	3.0T	2.0T
Readout size (mm)/All channels	0.5mm×0.5mm /2×3×10^7	0.5mm×0.5mm /2×3×10^7
Material budget barrel (X_0)	0.59%	0.59%
Material budget endcap (X_0)	15%	15%
Points per track in rφ	2300	2300
σ in rφ	120μm (full drift)	400μm (full drift)
σ 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

Prototype validation of pixelated TPC for CEPC 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





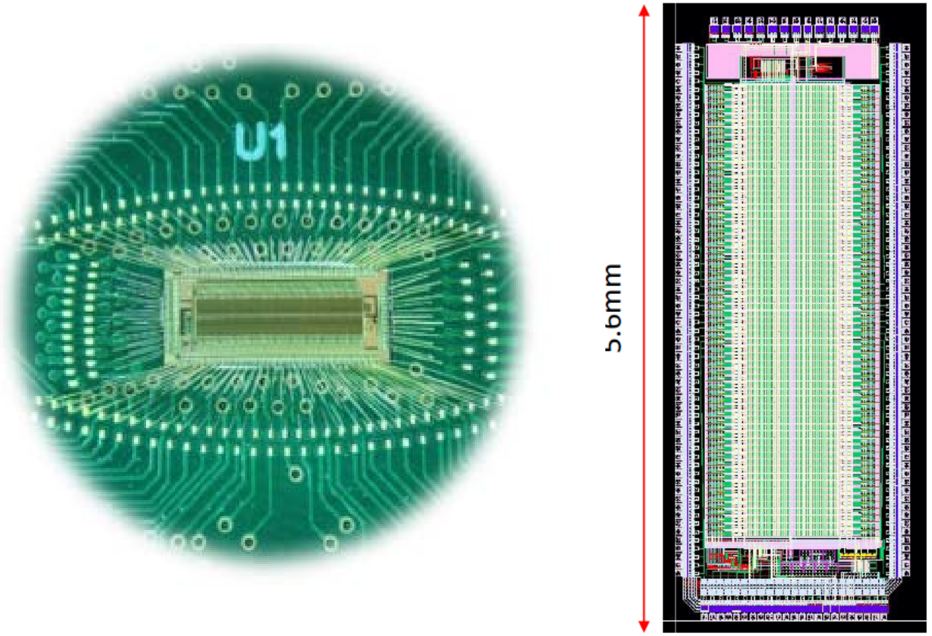


Photo and layout of ASIC Chip R&D for TPC

ILD conference 2024 January by Zhi Deng

Summary and outlook

- 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 future e+e- collider.

- 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.

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

We kindly acknowledge the following funding agencies, collaborations:

- National Key Programme for S&T Research and Development (Grant NO.: 2016YFA0400400)
- National Natural Science Foundation of China (Grant NO.: 11975256)
- National Natural Science Foundation of China (Grant NO.: 11535007)
- National Natural Science Foundation of China (Grant NO.: 11775242)
- National Natural Science Foundation of China (Grant NO.: 11675197)

Many thanks!