# Status of TPC with GEM and Micromegas for CEPC Detector R&D

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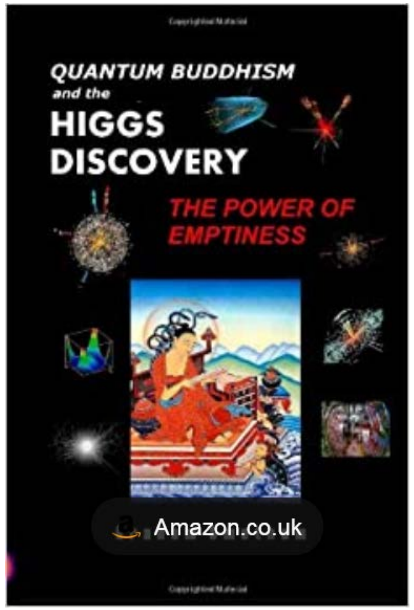
**LCTPC Collaboration Meeting**

**March 12-14, 2024, DESY**

# Content

# Brief reminder about CEPC

- CEPC proposal R&D from 2013-2024, over ten years
- The CEPC accelerator TDR (**released**) and phy./det. TDR (**preparation**).




2012
discovery of the
Higgs boson


Kick-off on Sept. 13, 2013
inspired by the discovery of the Higgs boson at the LHC
CEPC study group formed in Beijing
Accelerator, Physics and Detector groups

CEPC CDR Released on November 14, 2018

PreCDR released , March 2015
CDR released , November 2018
1st Funding from MOST in 2016
2nd Funding from MOST in 2018
3rd Funding from MOST in 2023
Accelerator TDR released in 2023.
Phy.&Det. TDR was prepared and will be released in 2025.

# Brief reminder about CEPC

- 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.
    - Auxiliary requirements, if any, are optional.

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 $2 \times 10^7$ Gy [11].

**CEPC- TDR p116**

# Physics requirements on future circular e+e- collider

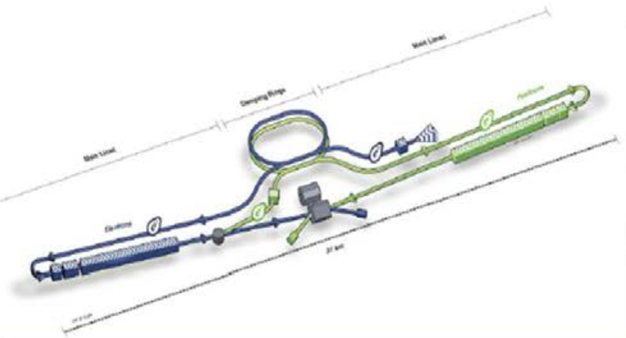
- Performance & Physics benchmarks: defined
- PFA is essential:
  - BMR < 4% & pursue 3%
  - Highly relevant – and even as the pre-request for excellent JOI & Pid (in jets)

| | 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 |
| $\alpha_S$ | 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 |

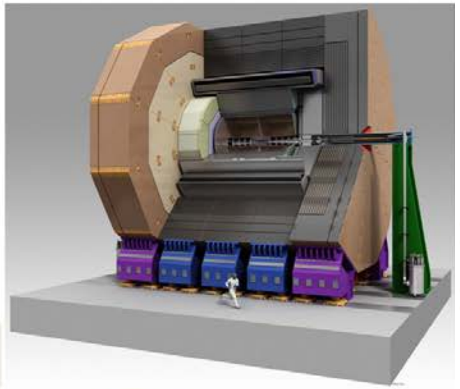
Table from Manqi's talk on IAS2024 conference in January

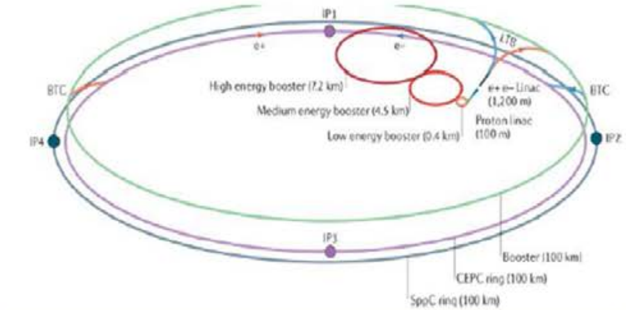
# Motivation: TPC technology for the future e+e- colliders

- A TPC is the main tracking detector for **some candidate experiments at future e+e- colliders**
  - Baseline detector concept of CEPC and ILD at ILC
- Pixelated readout TPC is potential to **improve PID requirements of Flavor Physics** at e+e- collider.
- TPC technology can be of interest for other future colliders (FCC-ee, EIC, KEKb…)

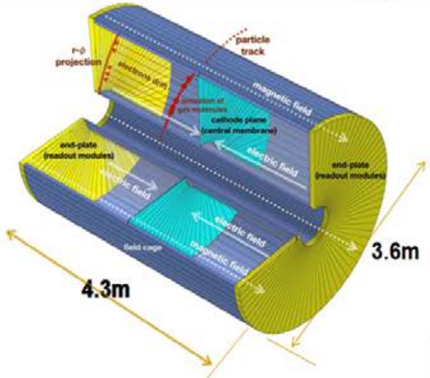


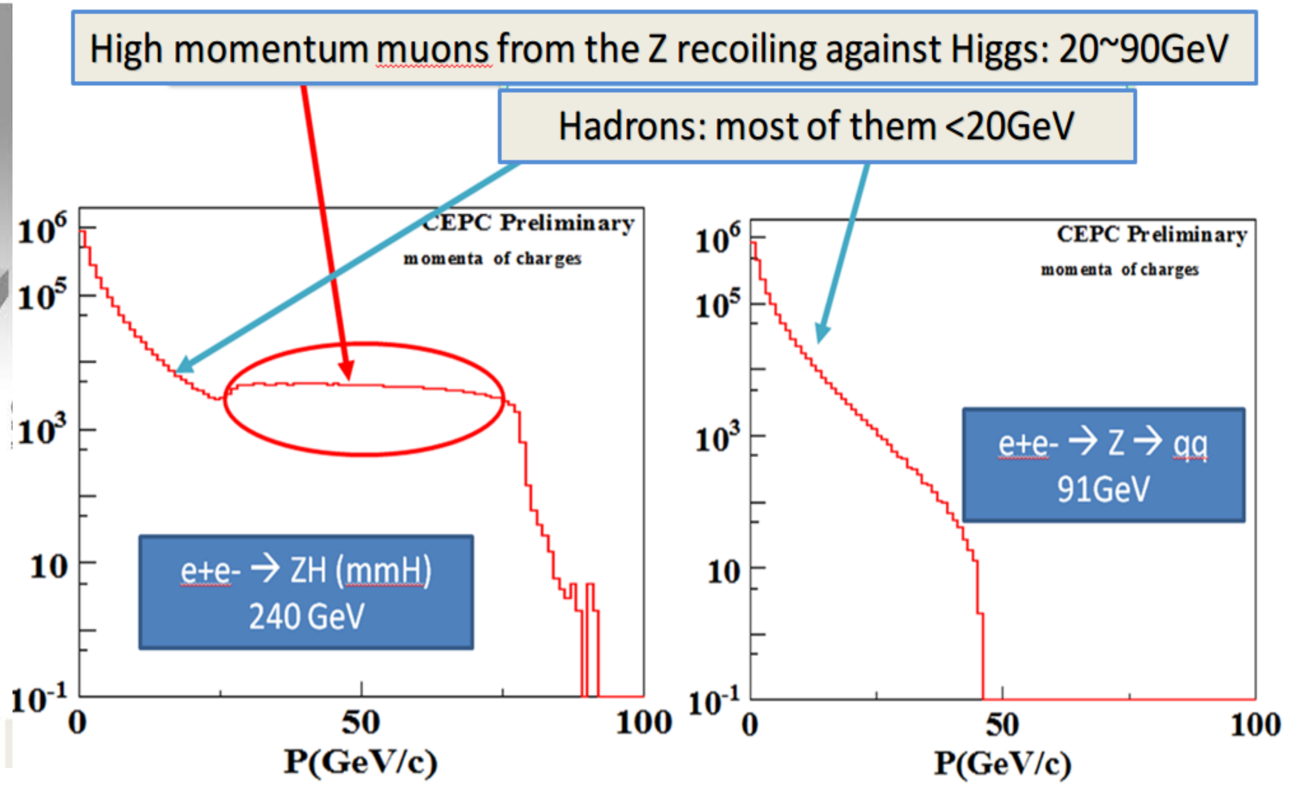
International Linear Collider (ILC)





Circular Electron Positron Collider (CEPC)




https://arxiv.org/abs/2203.06520

# Need control the ions in TPC chamber

<u>**Talk of simulation on 12nd March**</u>

- Simulation results based on CEPC's parameters (**High luminosity at Z pole: $10^{36}$**)
- To investigate and create the massive electrons/ions in the detector chamber to study the deviation
  - Positive ion feedback at Tera-Z **(gain ~2000, IBF ratio ~0.1%)**
- MDI region should be carefully designed and optimized (beam-gas, pair production)

## Electric field analysis

## Cylindrical coordinates

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon} \longrightarrow$$

$$\phi(r,\theta,z) = \sum_{m=-\infty,\infty} \phi_m(r,z) e^{im\theta},$$

$$\phi_m(r,z) = \int_{-\infty}^{\infty} \Phi_m(r,k) e^{ikz} dk,$$

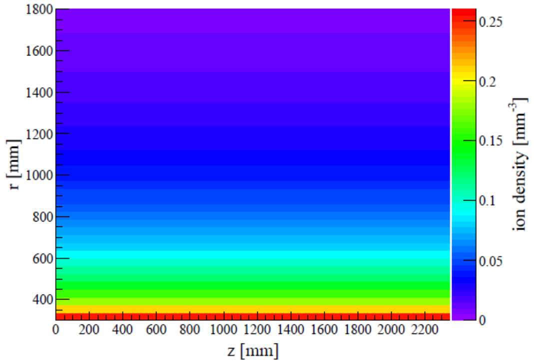
$$\Phi_m(r,k) = K_m(kr) \int_0^r R_m(r',k)\, I_m(kr')\, r' dr' + I_m(kr) \int_r^{\infty} R_m(r',k)\, K_m(kr')\, r' dr'$$

$$R_m(r',k) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \rho_m(r',z')\, e^{-ikz'} dz'$$

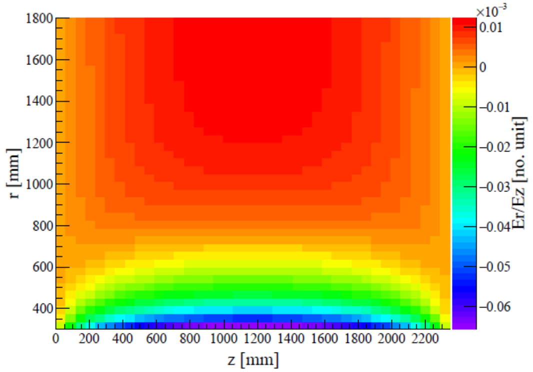
$$\rho_m(r',z') = \frac{1}{2\pi} \oint \frac{\rho(r',\theta',z')}{\epsilon_0} e^{-im\theta} d\theta'$$

Resnati F. Modelling of dynamic and transient behaviours of gaseous detectors[J]. 2017.

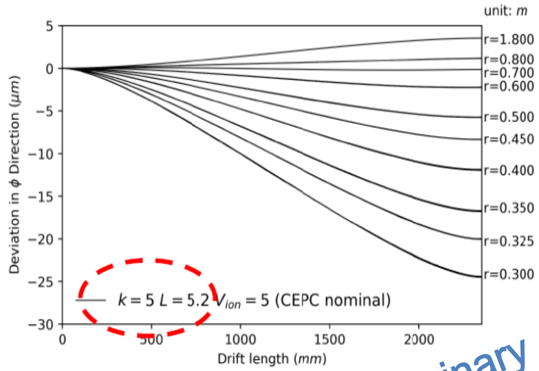
## Ions density in chamber




$E_r/E_z$

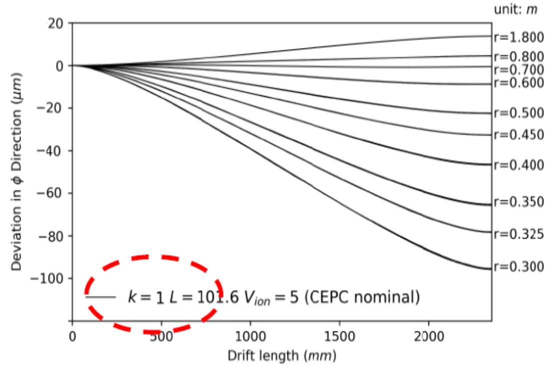



Higgs




Z

Preliminary



- Ion backflow suppression using GEM/Micromegas

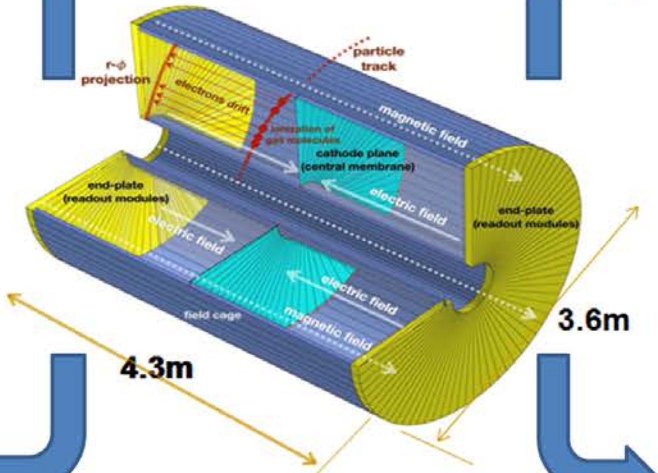
# Motivation: TPC requiremetns from e+e- Higgs/EW/Top factories

- TPC can provide hundreds of hits with high spatial resolution compatible, with PFA design (**low $X_0$**)
  - $\sigma_{1/pt}$ ~$10^{-4}$ $(GeV/c)^{-1}$ with TPC alone and $\sigma_{point}$<100μm in rφ
- **Provide dE/dx and dN/dx with a resolution** <4%
  - Essential for Flavor physics @ Tera Z run

**Pad readout TPC**
- To meet Higgs physics
- 1mm×6mm of Pad
- TPC module
- TPC prototype with UV laser

**TPC track detector for e+e- collider**

**Pixelated readout TPC**
- To meet Z physics
- ~500μm of Pad
- TPC prototype with UV laser track
- dN/dx+dE/dx study



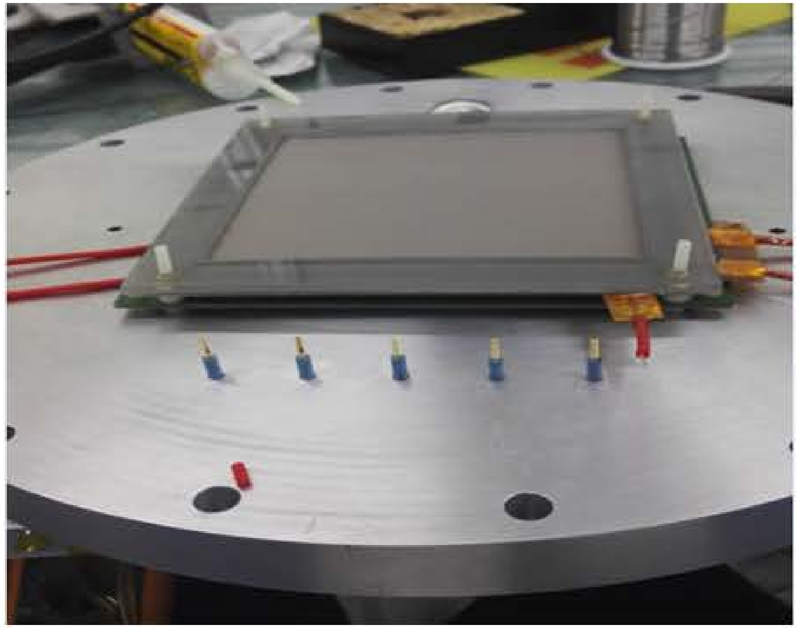

**Ion back flow study**
- Simulation of Ion Backflow
- Test the UV light created the ions by photoelectric effect
- Experimental study

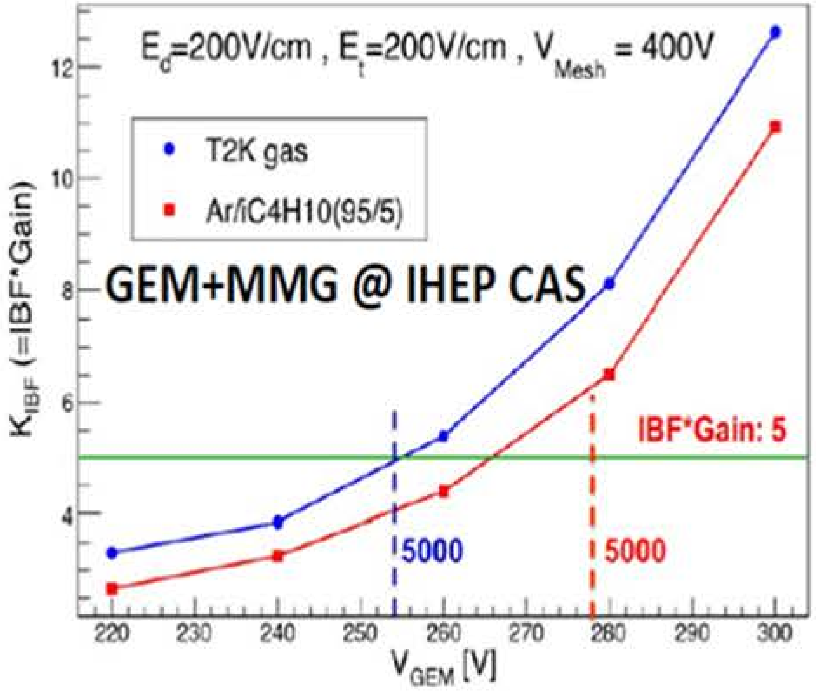
**PID performance Study**
- Simulation of the ionization cluster in space
- PID studies of the different readout TPC prototype
- Experimental study

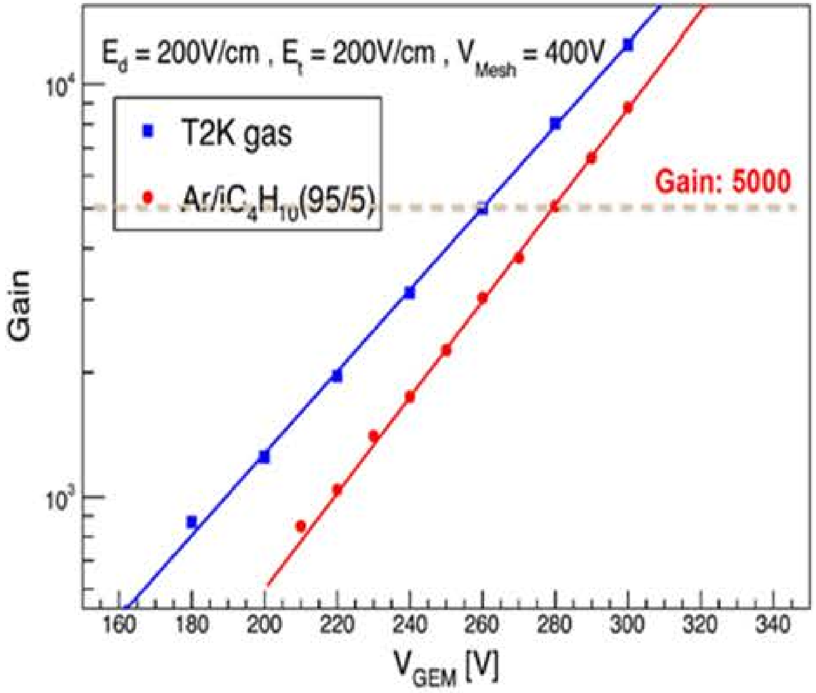
Key issues of TPC technology for e+e- collider

# TPC detector module using GEM+Micromegas@IHEP

- Studies have been done using the different active area of the hybrid TPC detector modules
  - Active area: from 50 mm×50 mm to 200 mm×200 mm
  - Tested under the different mixture gases
- Validated IBF×Gain using the TPC detector module
  - IBF×Gain ≤ 1@Gain/2000



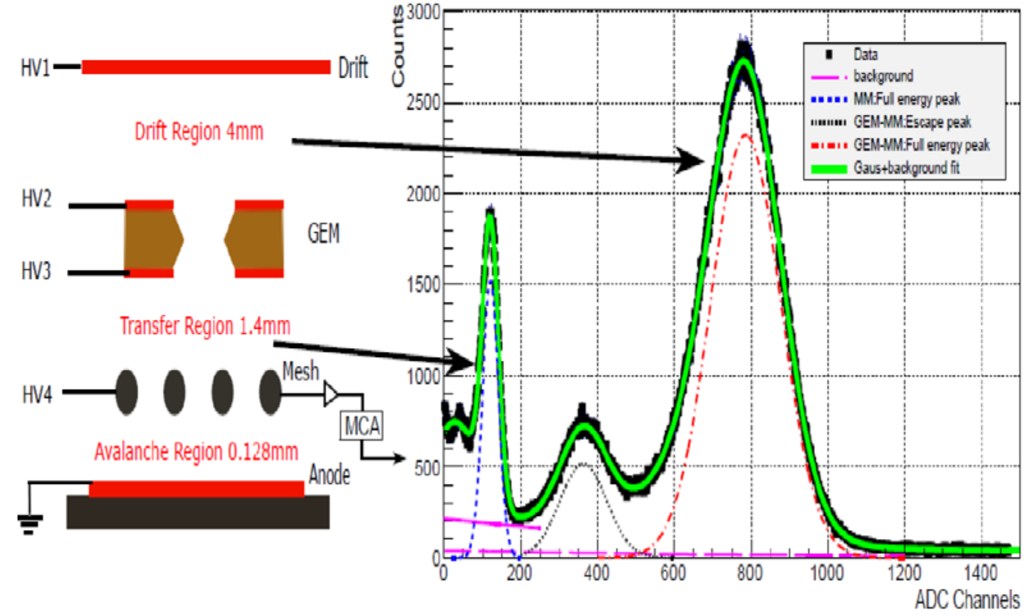


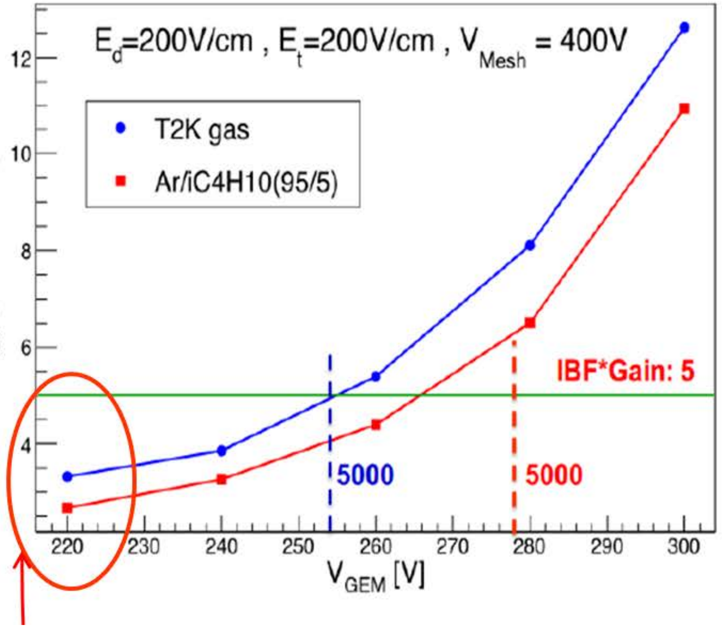




TPC detector module using GEM+Micromegas

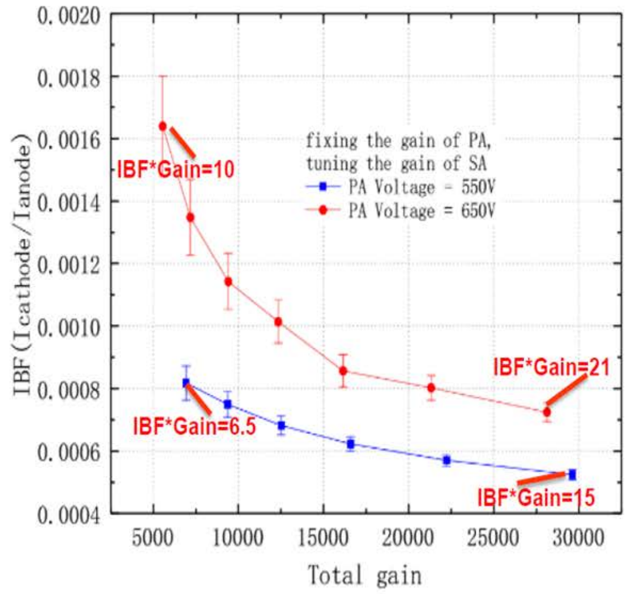
# TPC detector module using GEM+Micromegas

- Studies with hybrid GEM+MM detectors
  - Studies MPGD gas gain<2000, IBF $\times$ Gain $\leq$ 1
- sPHENIX R&D with 2GEM+MMG
- USTC with Double mesh Micromegas detector module




IBF of double mesh MM @USTC/Jianbei Liu

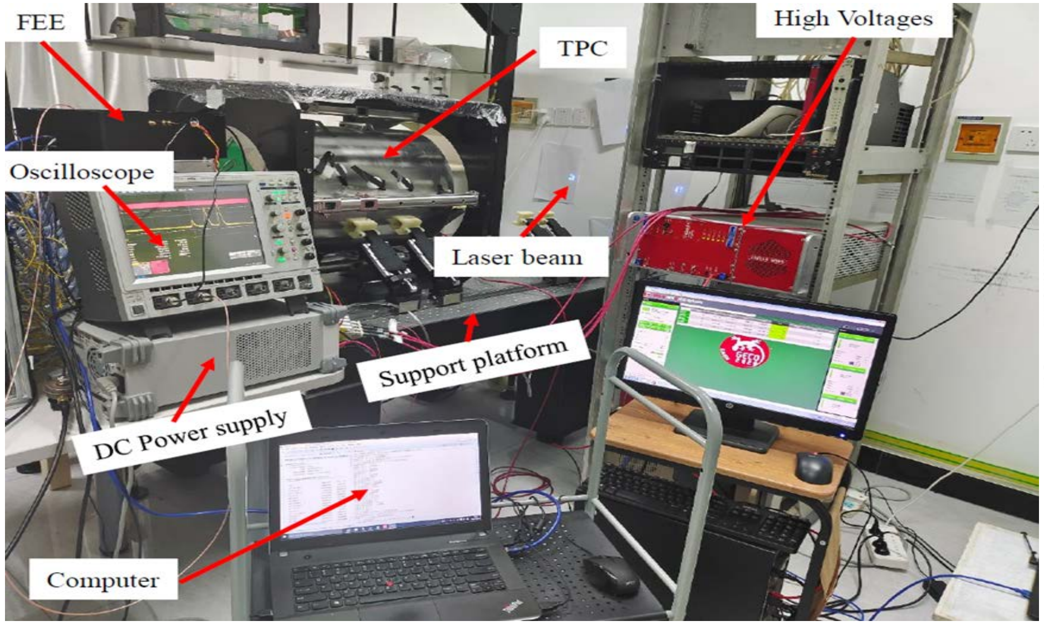



Hybrid GEM+Micromegas and Double-meshs detector module

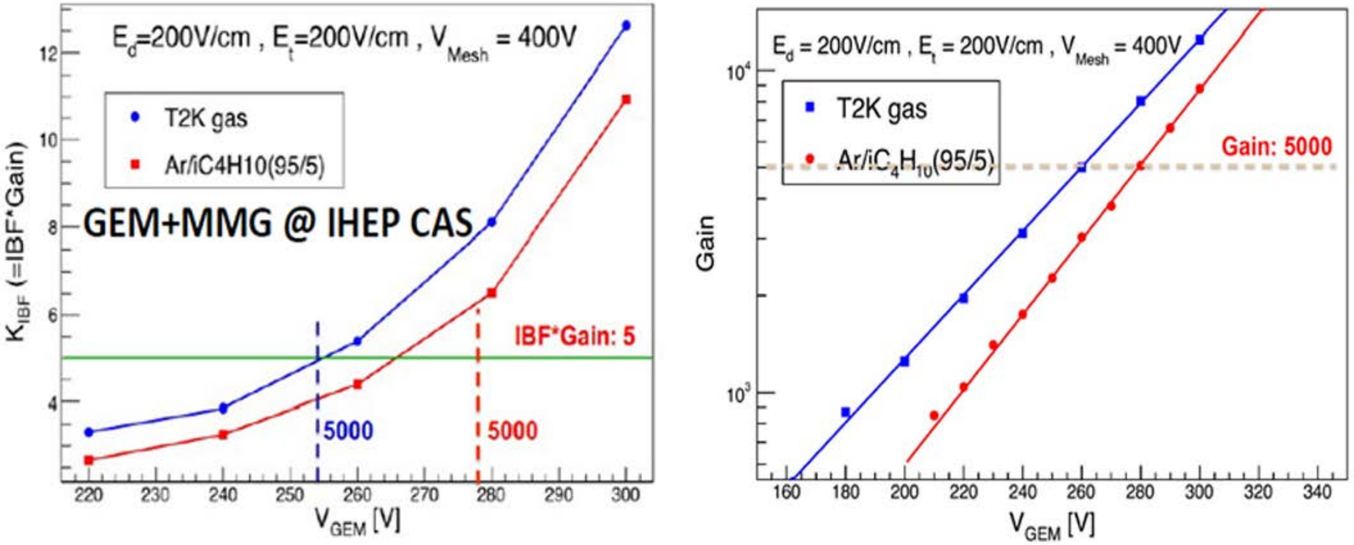
# CEPC TPC detector prototyping roadmap

- From TPC module to TPC prototype R&D for beam test
  - Low power consumption FEE ASIC (**reach <5mW/ch** including ADC)
- Achievement by far:
  - Supression ions hybrid GEM+Micromegas module
    - IBF×Gain **~1 at Gain=2000** validation with GEM/MM readout
  - Spatial resolution of **$\sigma_{r\varphi} \leq 100\ \mu m$** by TPC prototype
  - dE/dx for PID: <4% (as expected for CEPC baseline detector concept)

WASA_V1 ZYNQ Core Board




Low power consumption readout

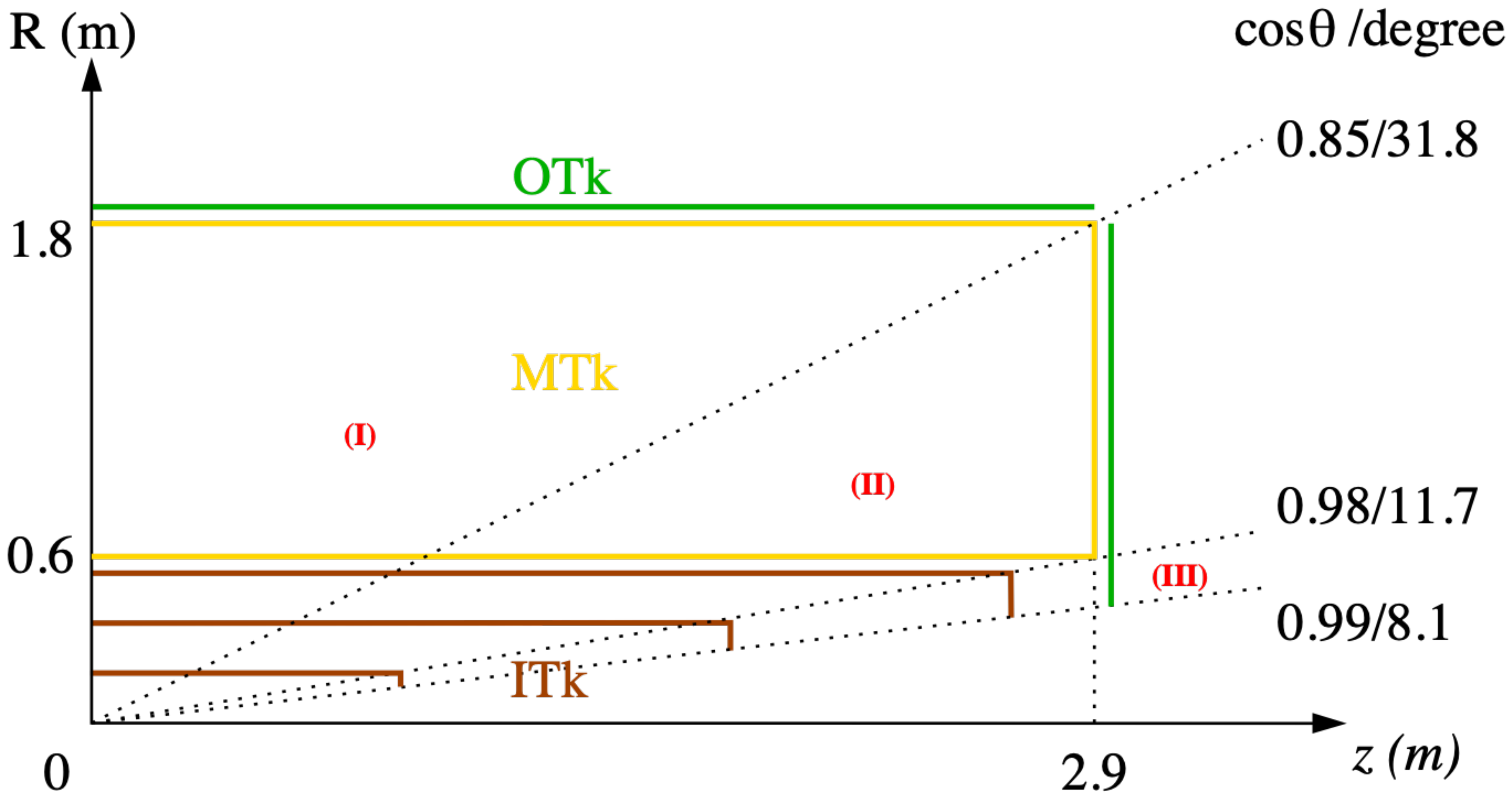



GEM+Micromegas module R&D

- High granularity readout TPC for CEPC TDR
  - TPC **SELECTED** as the baseline track detector

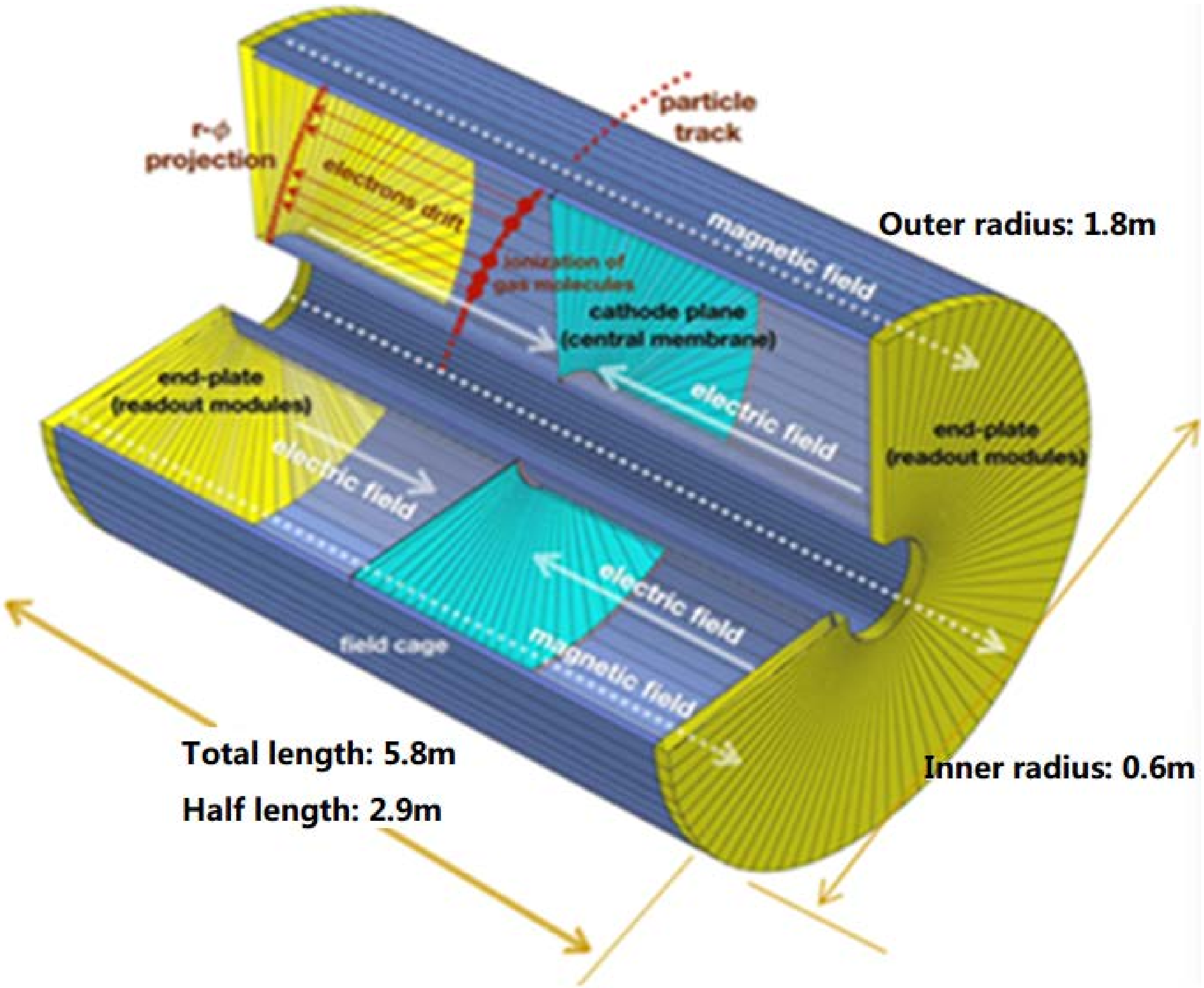
# Track detector system (**Finalized Geometry** in CEPC Phy.&Det. TDR )

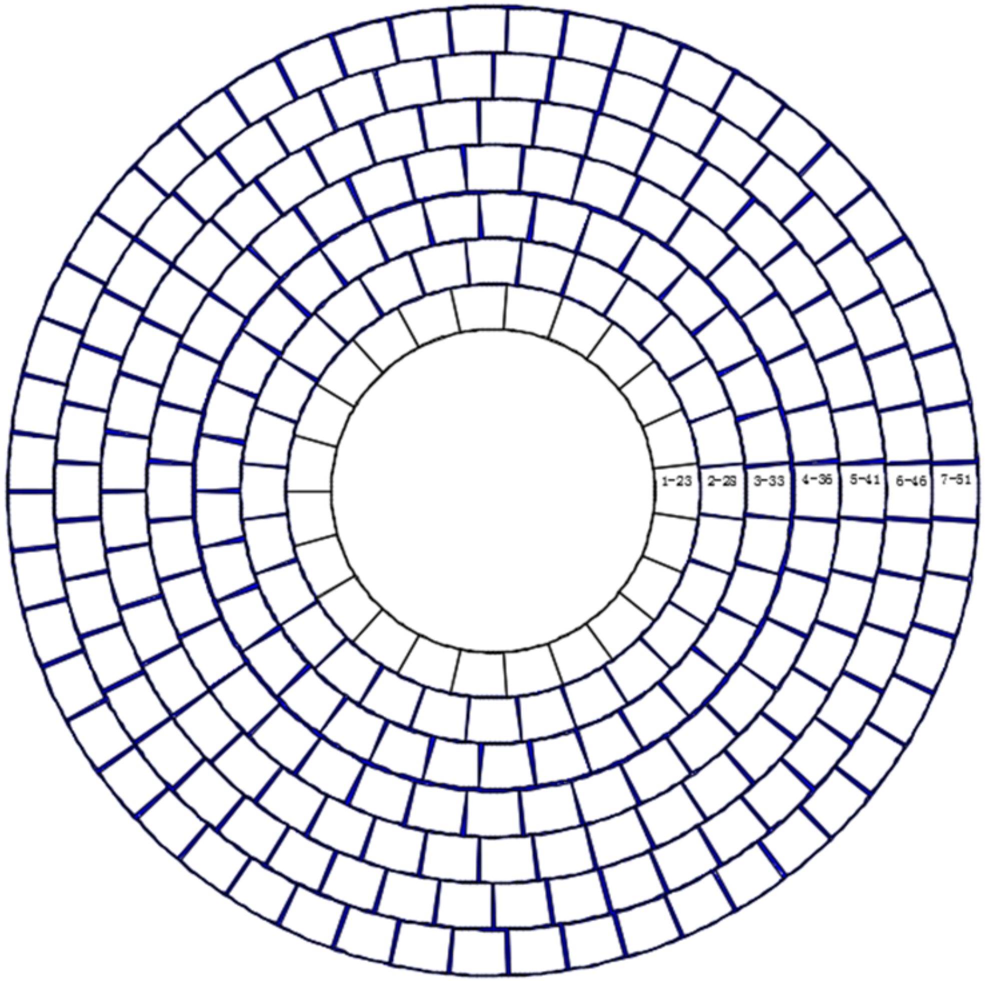
- The track detector system's geometry was finalized.
  - The limited schedule for TDR preparation
  - Converging geometries as quickly as possible in preparation for physics simulation




Almost finalized Geometry of the track detector system

# TPC detector (**Finalized Geometry** in CEPC Phy.&Det. TDR )




Almost finalized Geometry of TPC detector and the Endplate

# High granularity readout -1 @cosθ≃0.98

| Parameters | Higgs run | Z pole run |
|---|---|---|
| B-field | 3.0T | 2.0T |
| Pad size (mm)/All channels | 1.0mm×6.0mm /2×$10^6$ | 1.0mm×6.0mm /2×$10^6$ |
| 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 | 200 | 200 |
| $\sigma_{point}$ in rφ | ≤ 100µm (full drift) | 150µm (full drift) |
| $\sigma_{point}$ in rz | ≃ 0.4 – 0.8 mm (for zero – full drift) | ? (for zero – full drift) |
| 2-hit separation in rφ | < 2mm | < 2mm |
| dE/dx | 4 % | 4 % |
| Momentum resolution normalized: $\sigma_{1/pT} = \sqrt{a^2 + (b/pT)^2}$ | a = 1.82 e -5 | a = 3.32 e -5 |
| | b = 0.60 e -3 | b = 0.92 e -3 |

# High granularity readout -2 @cosθ≃0.98

| Parameters | Higgs run | Z pole run |
|---|---|---|
| B-field | 3.0T | 2.0T |
| Pad size (mm)/All channels | 0.110mm×0.110mm /2×6×$10^8$ (TPX4) | 0.110mm×0.110mm /2×6×$10^8$ (TPX4) |
| Material budget barrel | $\simeq$ 0.012 $X_0$ | $\simeq$ 0.012 $X_0$ |
| Material budget endcap | < 0.20 $X_0$ | < 0.20 $X_0$ |
| Points per track in rφ | 22000 | 22000 |
| $\sigma_{point}$ in rφ | ≤ 100μm (full drift) | ? (full drift) |
| $\sigma_{point}$ in rz | $\simeq$ 0.1 – 0.5 mm? (for zero – full drift) | ? (for zero – full drift) |
| 2-hit separation in rφ | < 0.5mm | < 0.5mm |
| K/π separation power @20GeV | ≤ 3σ | ≤ 3σ |
| Momentum resolution normalised: $\sigma_{1/pT} = \sqrt{a^2 + (b/pT)^2}$ | a = 1.82 e -5 | a = 3.32 e -5 |
| | b = 0.60 e -3 | b = 0.92 e -3 |

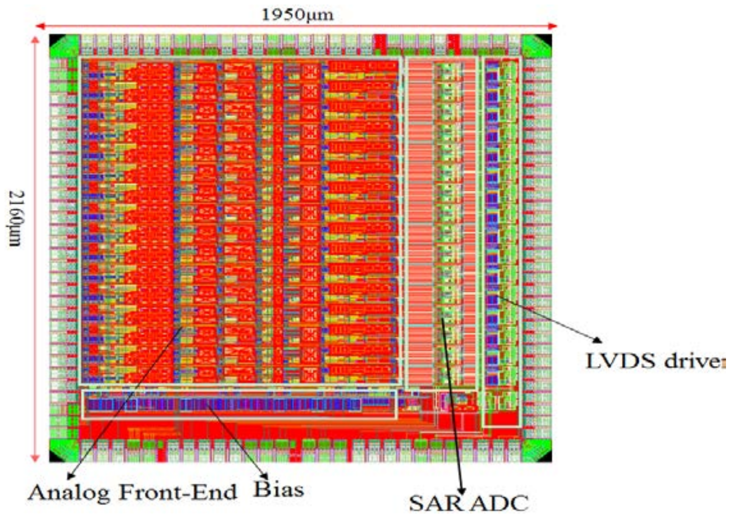
# High granularity readout -3 @cosθ≃0.98

| 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 | $\simeq 0.012\ X_0$ | $\simeq 0.012\ X_0$ |
| Material budget endcap | $< 0.20\ X_0$ | $< 0.20\ X_0$ |
| Points per track in rφ | 2200 | 2200 |
| $\sigma_{point}$ in rφ | ≤ 100μm (full drift) | ? (full drift) |
| $\sigma_{point}$ in rz | ≃ 0.1 – 0.5 mm?<br>(for zero – full drift) | ? (for zero – full drift) |
| 2-hit separation in rφ | < 0.5mm | < 0.5mm |
| K/π separation power @20GeV | ≤ 3σ | ≤ 3σ |
| Momentum resolution normalised: $\sigma_{1/pT} = \sqrt{a^2 + (b/pT)^2}$ | a = 1.82 e -5 | a = 3.32 e -5 |
| | b = 0.60 e -3 | b = 0.92 e -3 |

# Power Consumption – TPC

- **Power consumption relative with the high granularity readout**
  - Pad readout TPC@1mm×6mm@IHEP
  - Total channels: **$10^6$**
    - WASA ASIC chip: 3.5mW/ch@40 MS/s
  - High granularity readout TPC： **$3\times10^7$**
  - Total power: **<10 kW**
    - **<100mW/cm$^2$**

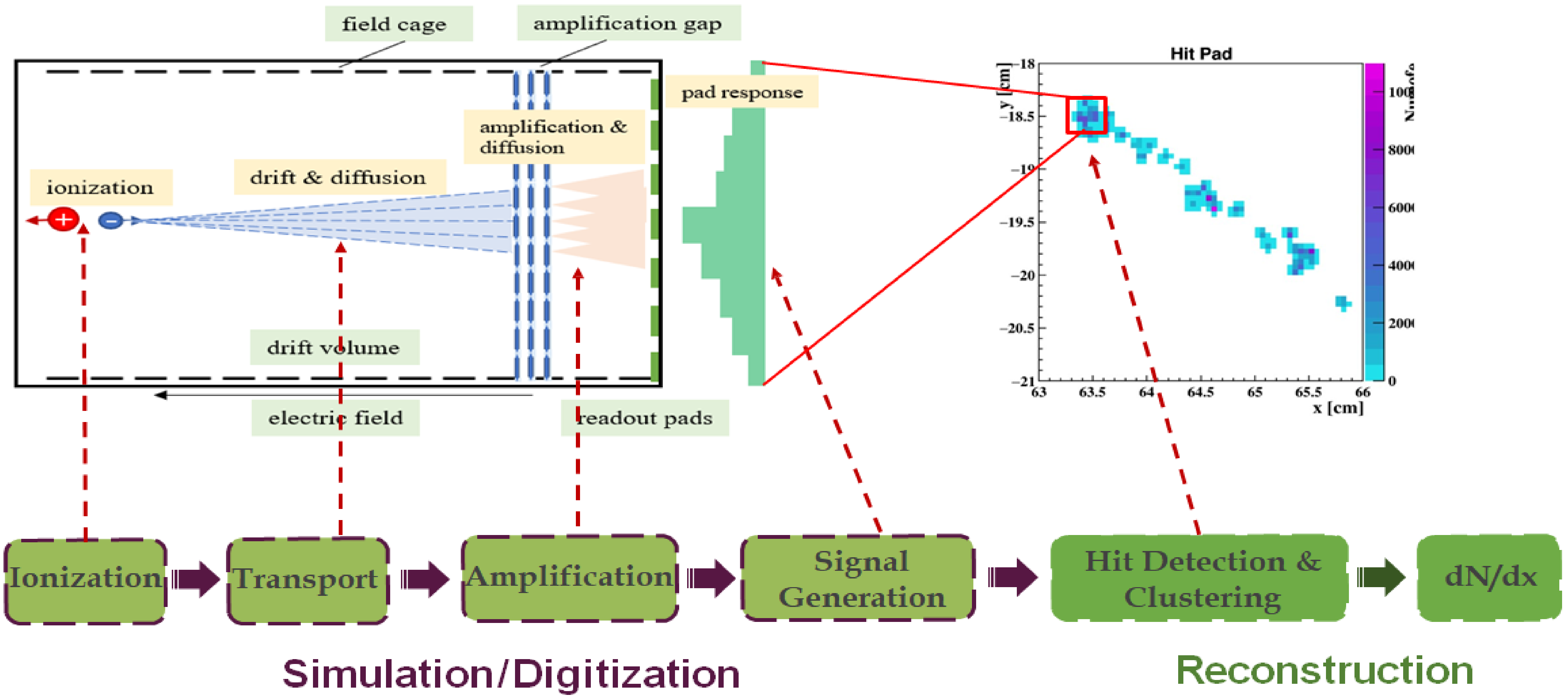
| | AGET | PASA+ALTRO | Super-ALTRO | SAMPA |
|---|---|---|---|---|
| **TPC** | T2K | ALICE | ILC | ALICE upgrade |
| **Pad尺寸** | 6.9x9.7 mm$^2$ | 4x7.5 mm$^2$ | 1x6 mm$^2$ | 4x7.5 mm$^2$ |
| **通道数** | 1.25 x $10^5$ | 5.7x $10^5$ | 1-2 x $10^6$ | 5.7 x $10^5$ |
| **读出结构** | MicroMegas | MWPC | GEM/MicroMegas | GEM |
| **增益** | 0.2-17 mV/fC | 12 mV/fC | 12-27 mV/fC | 20/30 mV/fC |
| **成型方式** | CR-(RC)$^2$ | CR-(RC)$^4$ | CR-(RC)$^4$ | CR-(RC)$^4$ |
| **达峰时间** | 50 ns-1us | 200 ns | 30-120 ns | 80/160 ns |
| **ENC** | 850 e @ 200ns | 385 e | 520 e | 482 e @ 180ns |
| **波形采样方式** | SCA | ADC | ADC | ADC |
| **采样率** | 1-100 MSPS | 10 MSPS | 40 MSPS | 10 MSPS |
| **精度** | 12 bit(external) | 10 bit | 10 bit | 10 bit |
| **功耗** | <10 mW/ch | 32 mW/ch | 47.3 mW/ch | 17 mW/ch |
| **CMOS工艺** | 350 nm | 250 nm | 130 nm | 130 nm |




# Simulation of the pixelated TPC - ongoing

- All detailed simulation **starting** at IHEP using Garfied++ and Geant4
  - Setup the new simulation framework
  - TPC detecror module simulated **under 2T and T2K gas** from CEPC CDR

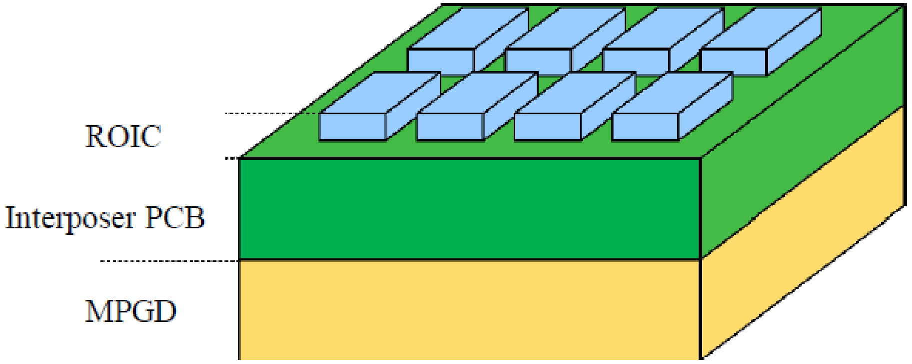
Talk of simulation on 13rd March



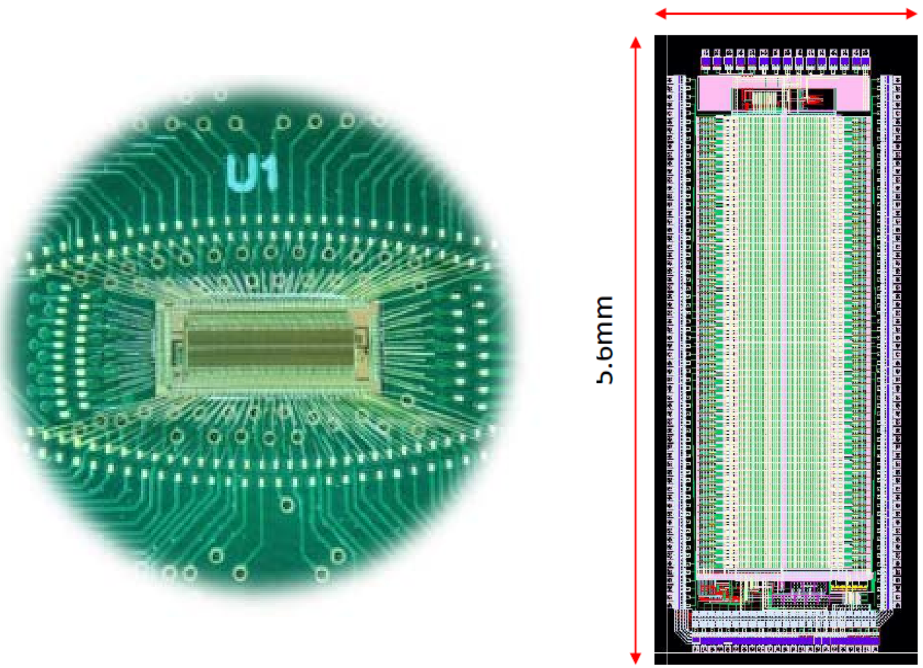
# **Current R&D effort**: Pixelated TPC R&D for CEPC

- **R&D on Macro-Pixel TPC readout for CEPC**
  - Macro-Pixel TPC ASIC chip was started to developed and **2nd prototype wafer has done**.
  - The first version ROIC has been received and under testing.
  - The **TOA and TOT** can be selected as the initiation function in the ASIC chip.
    - 1mm×6mm → 500μm×500μm pixel readout
    - Time resolution: **14bit** (5ns bin)
    - Time discriminator: TOA (Time of Arrival)
    - **Power consumption: <1mW/pixel (1$^{st}$ prototype)**
      - **~400mW/cm$^2$**
      - **~100mW/cm$^2$ (Goal and final design)**
    - Technology: 180nm CMOS -> 60nm CMOS
    - High metal coverage: 4-side bootable

**Collated with Tsinghua**




Principle of Macro-Pixel TPC readout




1$^{st}$ readout PCB board and the ASIC layout

# Summary

- TPC detector prototype using the pad have been developed for the future e+e- colliders.
- Is it necessary to optimize the readout pad size to reach a reasonable readout number?
    - Power consumption relative with the high granularity readout
    - Amount output detector data relative with the high granularity readout
- Optimization performance of the reasonable readout TPC
    - PID requirements for both Higgs physics and Z-physics
- Synergies with LCTPC/CEPC/FCCee/EIC 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!