11th International Symposium on Nuclear Symmetry Energy
Sep. 18 – 22, 2023, GSI, Darmstadt, Germany

# Studies of nuclear EOS with HIRFL-CSR External-target Experiment

## —— a status report

Zhigang Xiao

Department of Physics， Tsinghua University

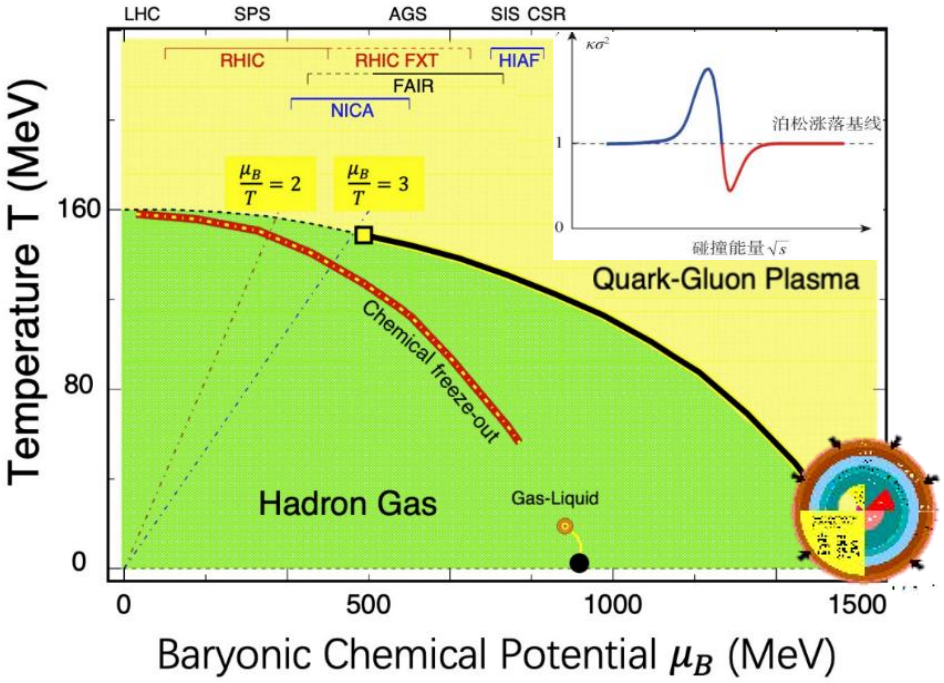
# Outline

- Physics motivation
- Design of CEE spectrometer
- Sub-detector development progress
- Summary

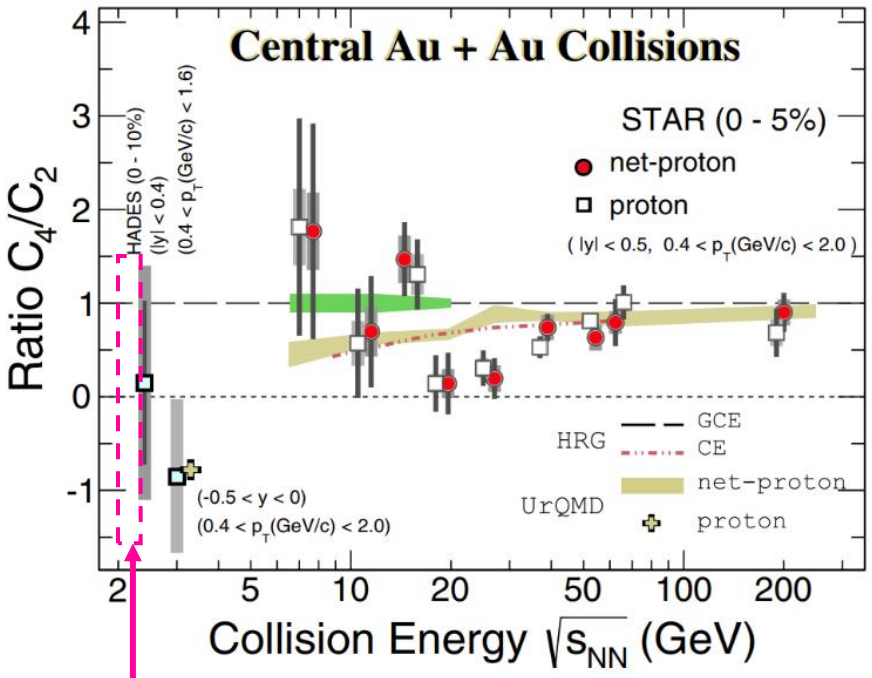
# QCD Phase Diagram

The phase structure at high net baryon density region is a challenge of modern nuclear physics.

To understand the existence of the critical point requires further experiments in a few GeV/u energy region




PRL 128, 202303 (2022)




CEE@HIRFL

# EOS of Asymmetric Matter $E_{sym}(\rho)$

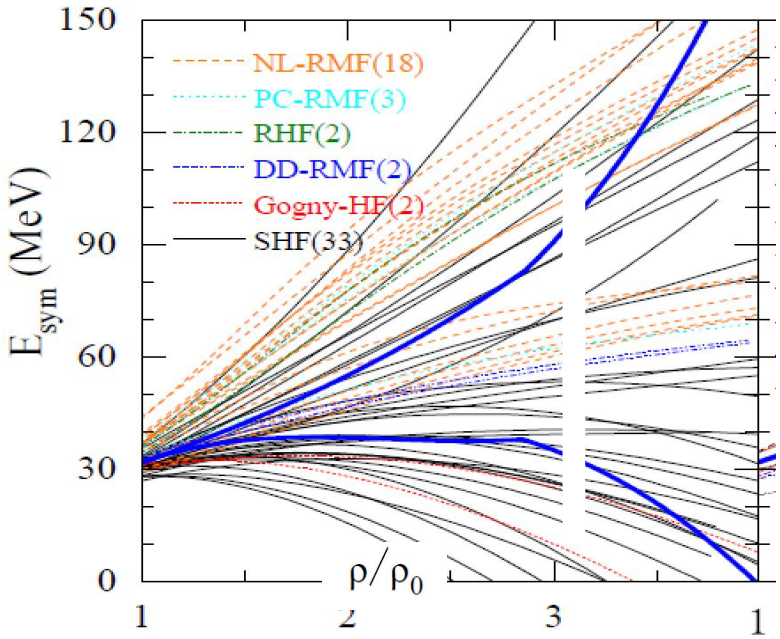
In hadron phase, the euqation of state of nuclear matter, is a key quantity to understand various physics. To understand the $E_{sym}(\rho)$ becomes more essential than ever, since the observation of GW170817.

**Nuclear matter**

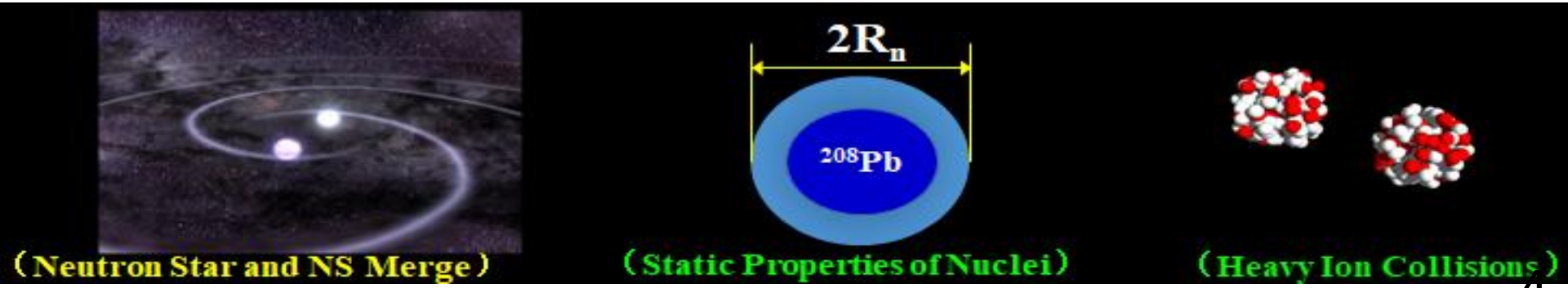
$$E(\rho,\delta) = E_0(\rho) + \delta^2 E_{sym}(\rho)$$

$$\delta = \frac{N-P}{N+P}$$

$$E_{\rm sym}(\rho) = L\frac{\rho-\rho_0}{3\rho_0} + \frac{K_{\rm sym}}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{J_{\rm sym}}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3$$

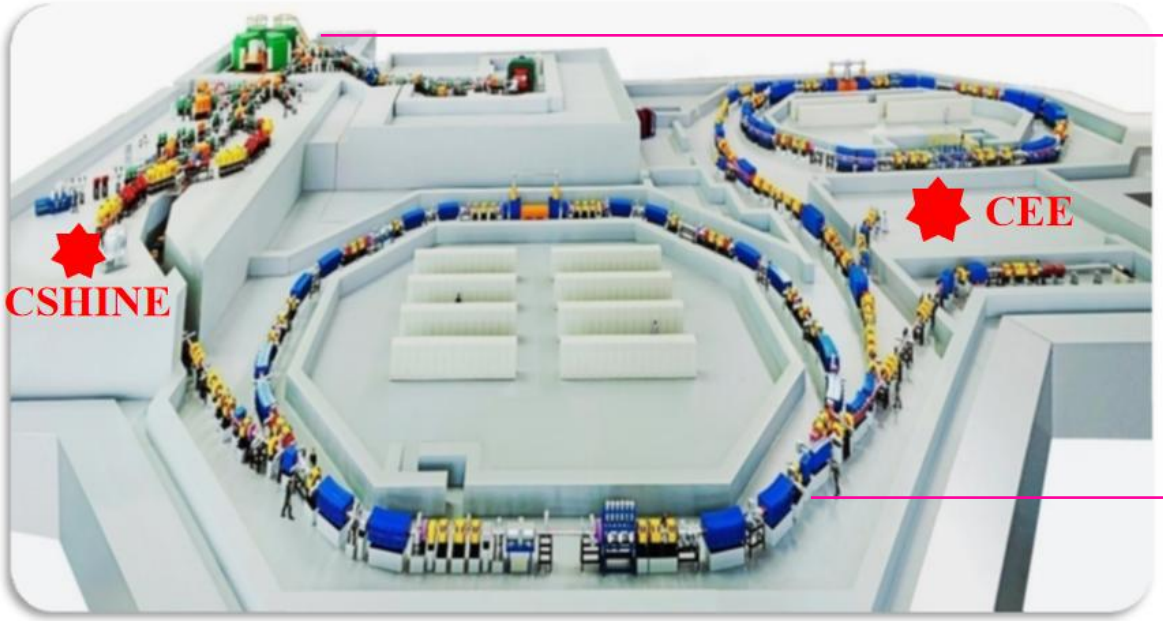



B.A Li et al. Universe, 7, 182(2021)



# HIRFL complex

HIRFL-CSR Complex




**SSC:**
**Kr: ~40 MeV/u**
**Sn: ~30 MeV/u**

for CSHINE and its physics:
cf Talk of Yijie Wang Spet. 18

**CSR:**
**p: 2.8 GeV**
**C: 1.0 GeV/u**
**U: 0.5 GeV/u**

If equipped with an advanced spectrometer:

Search for the QCD phase boundary/CEP at low temperature and high baryon density

Nuclear equation of state at $\rho > 2\rho_0$ regime

Interplay with Neutron Star Physics

hyper-nuclei physics, HBT, and

Short range correlation

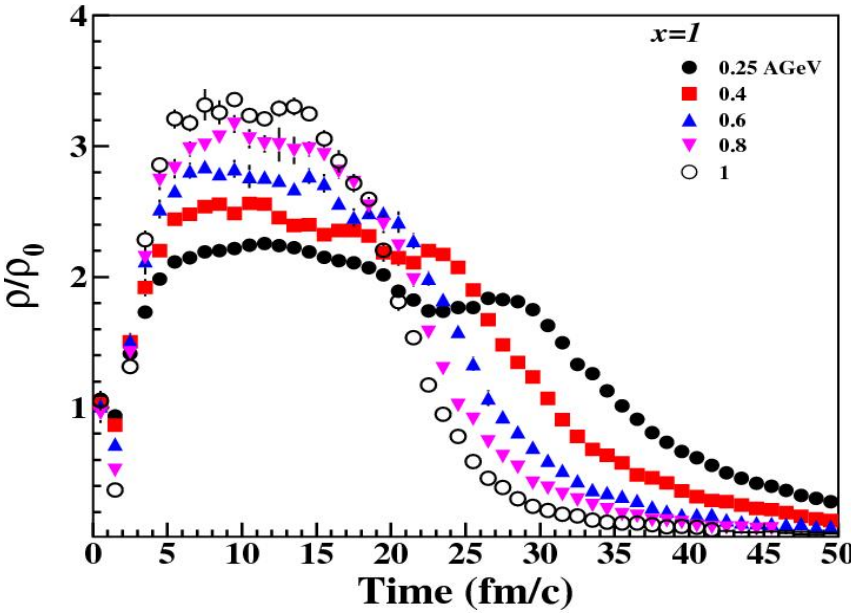
……

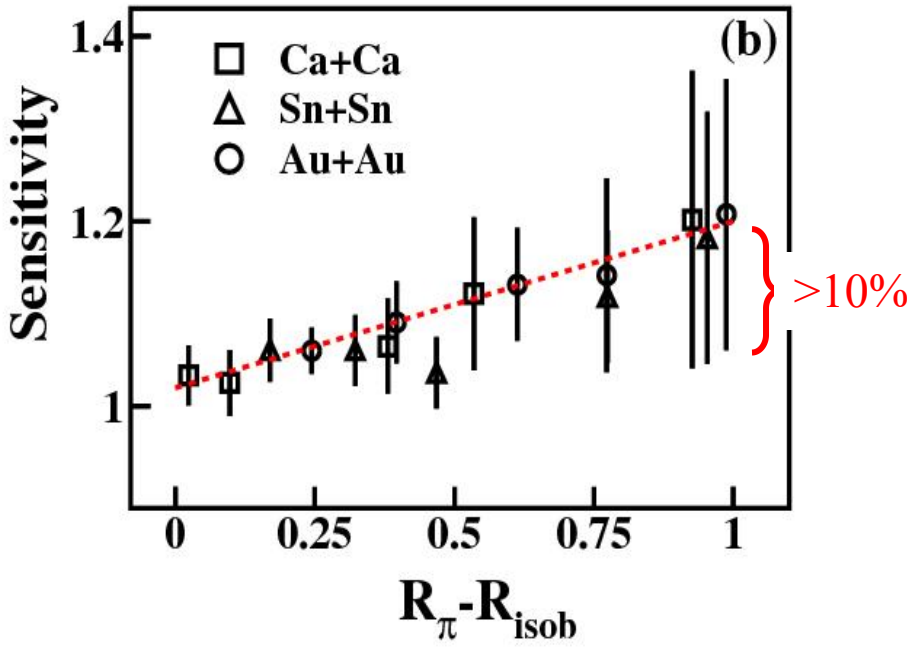
# HICs at GeV/u is favorable for EOS studies

For two reasons:

→ Dense nuclear matter at $2\rho_0$ can be created at $E_{\mathrm{beam}} = 0.5$ GeV/u

→ Due to the large space-time volume, or the highest nuclear stopping, the sensitivity of observables on $E_{\mathrm{sym}}(\rho)$ is more pronounced.



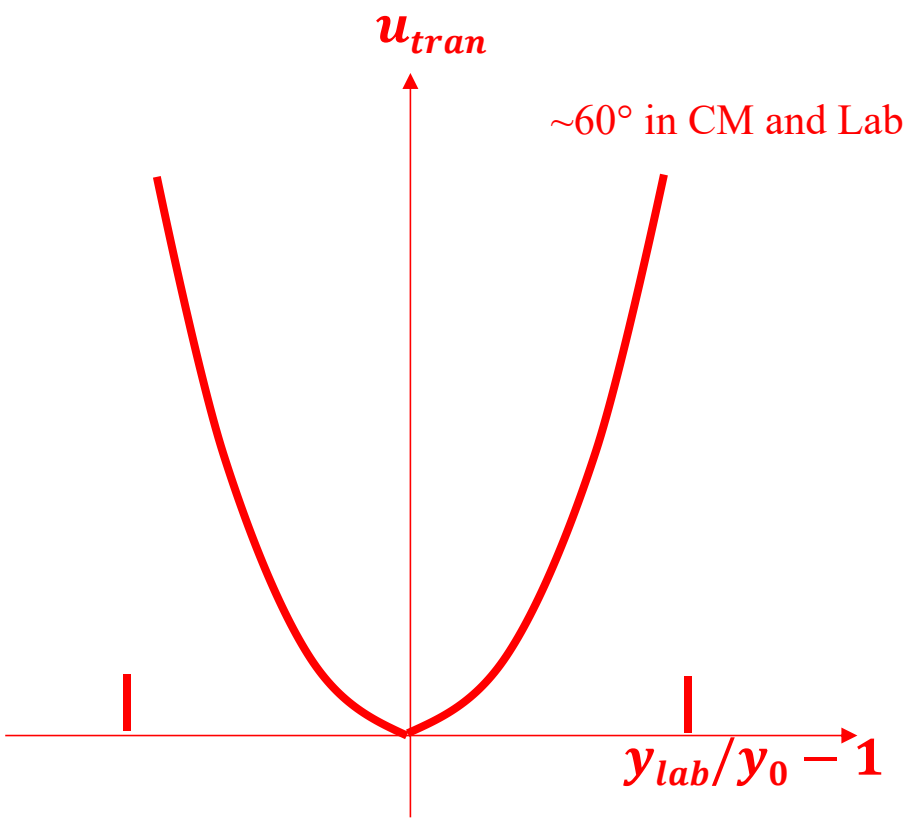




M. Zhang, *ZGX* et al., PRC 80, 034616 (2009); F. Fu, *ZGX* et al, PLB 666, 359 (2008)

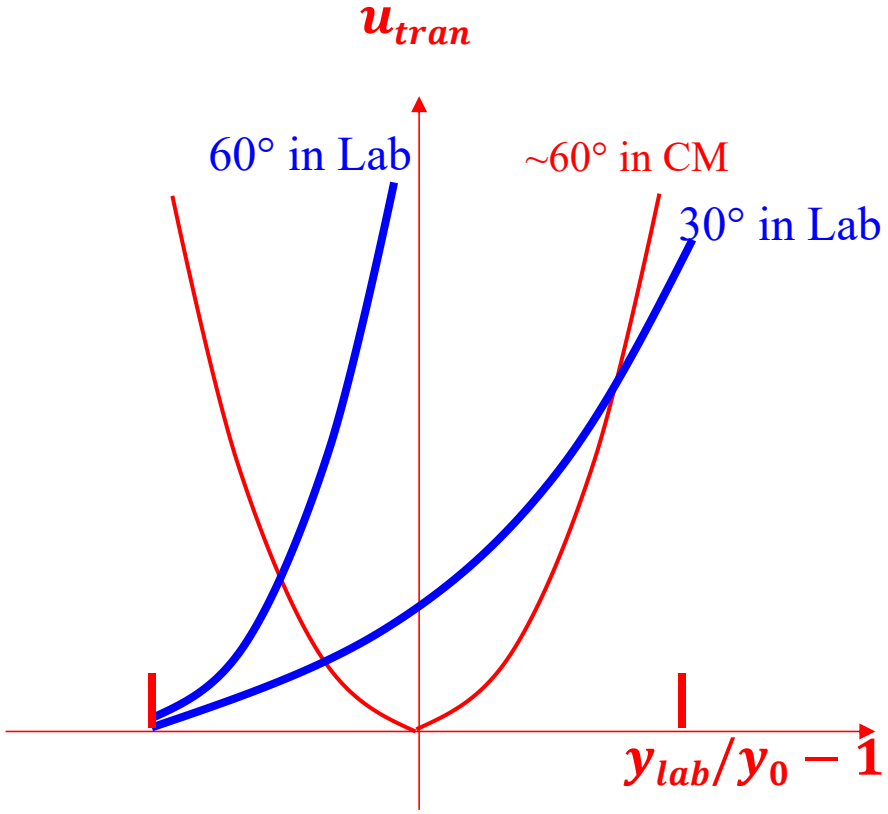
# Design of CEE spectrometer

What kind of spectrometer do we need?

To consider the difference between fixed target experiment and collider experiment




In collider Experiment




In Fixed target experiment

In fixed target experiment， it is important to cover the forward hemisphere in Lab.

# CEE Detection System

- CEE： HIRFL-CSR Extermal-target Experiment

After 8 years' hard work, the construction was started in August 2019, with support from NSFC and CAS

**CEE Spectrometer：**

1) **Super-conducting Dipole Magnet**
2) **Si-PIX Beam Monitor (BM)**
3) **Time Projection Chamber (TPC)**
4) **$T_0$/Inner TOF (iTOF)**
5) **Endcap TOF (eTOF)**
6) **Multi-Wire Draft Chamber (MWDC)**
7) **Zero Degree Counter (ZDC)**
8) **Data Acquisition system (DAQ)**
9) **Trigger system (Trigger)**
10) **Clock system (Clock)**
11) **Technical Support**
12) **Slow Control (SC)**
13) **Software: simulation and analysis**

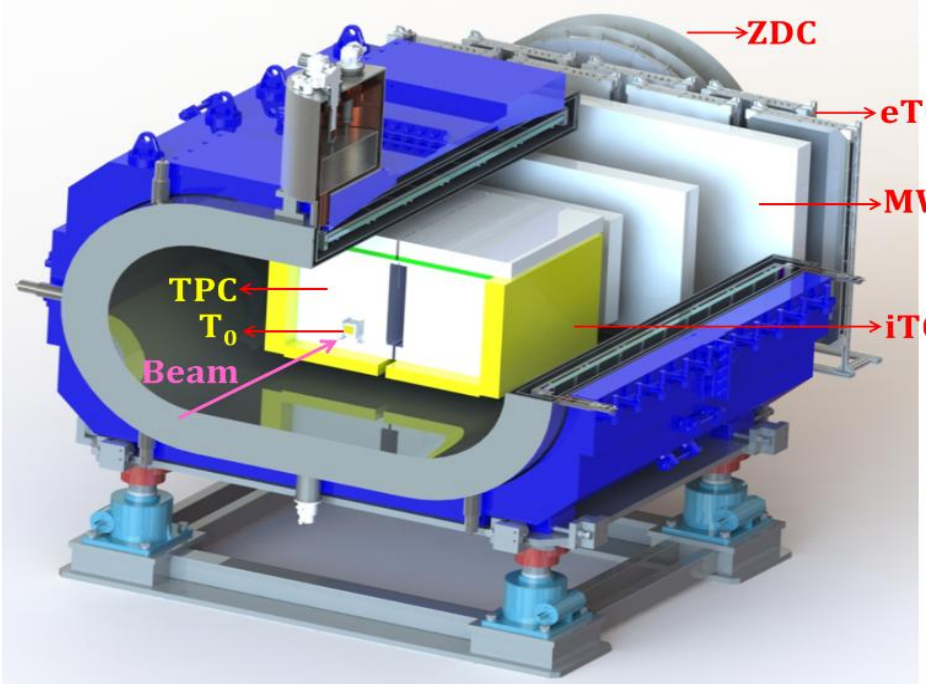



TABLE I. (Color online) Technical indicators of CEE.

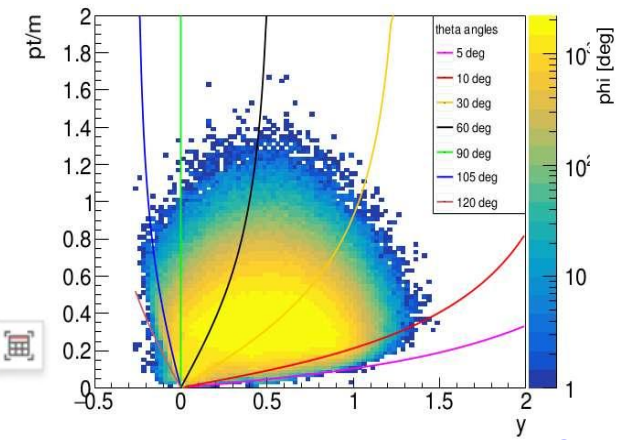
| Item | value |
|---|---|
| Maximum beam energy | 0.5GeV/u(U) – 2.8GeV(p) |
| Bean type | $p \sim U$ |
| Maximum event rate | 10 kHz |
| Acceptance | $> 50\%$ |
| Total channel number | 20k |

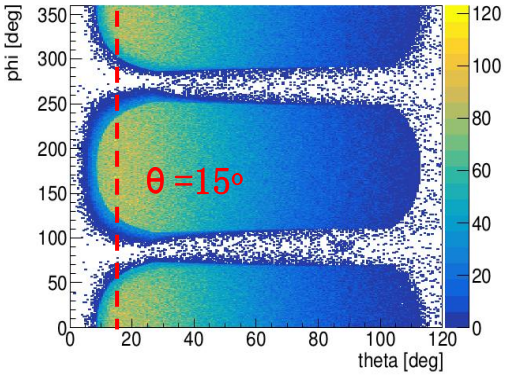
2019.8.15, 1st CEE collaboration meeting

# CEE Simulation studies: PID and coverage

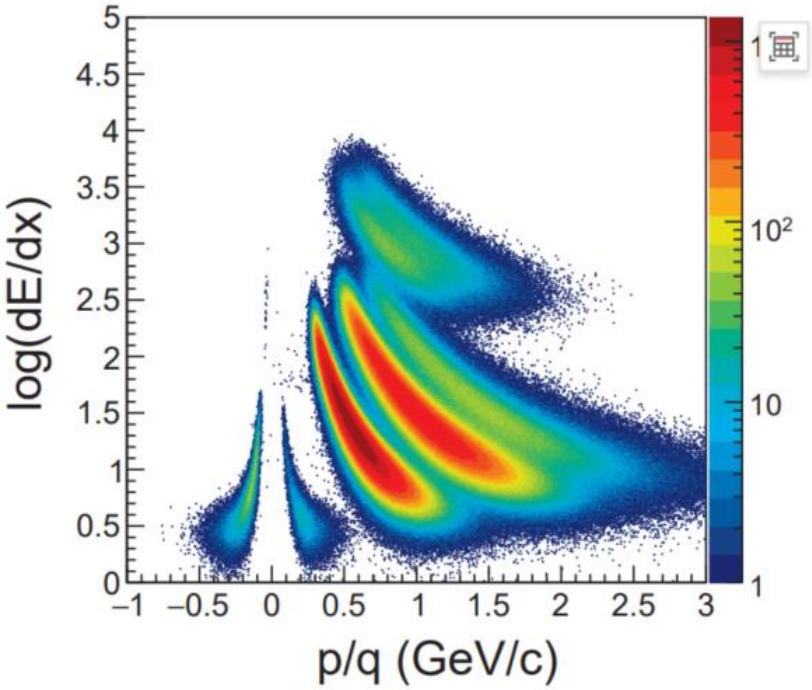
CeeROOT Home page:
https://gitee.com/CEESM/CeeRoot
(Open source)

TPC acceptance

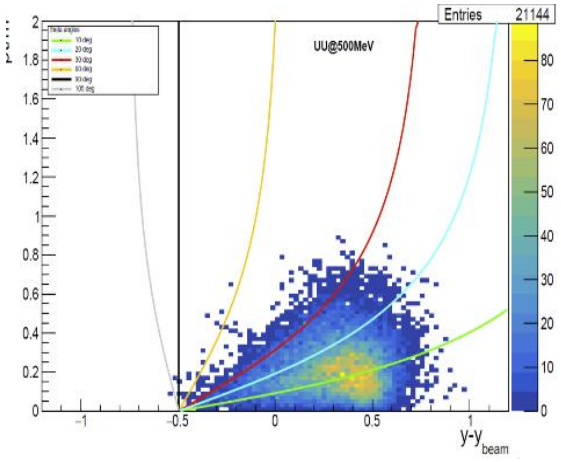


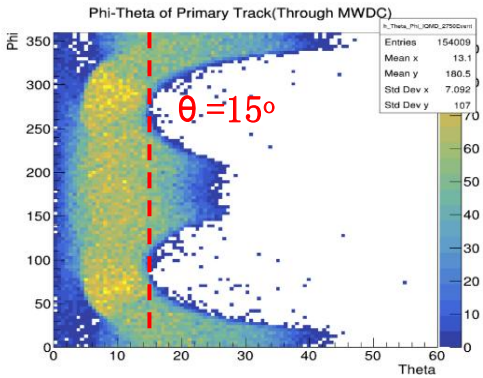




TPC PID




MWDC acceptance



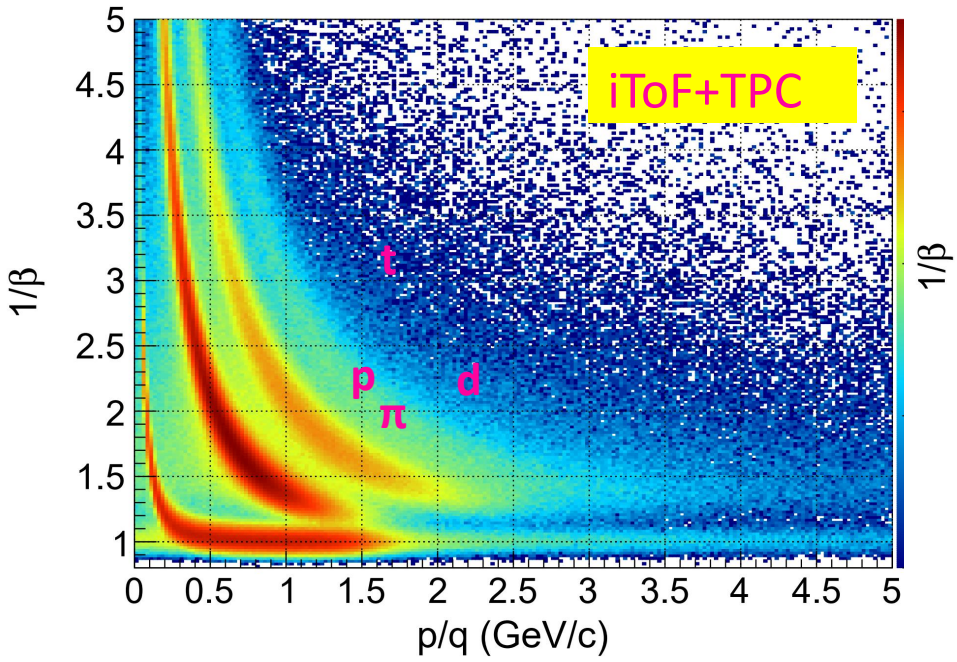
# Simulation studies: PID with TOF

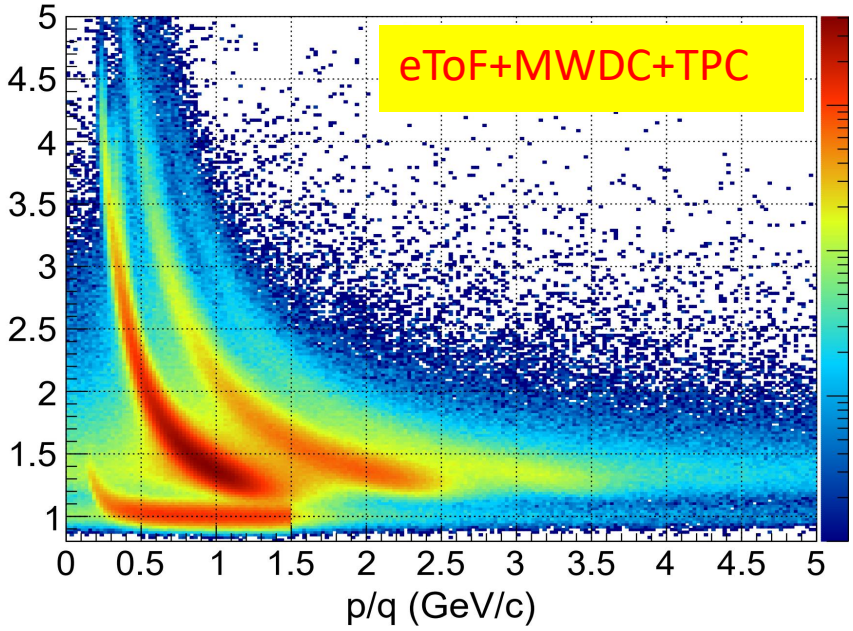
- Time of Flight (ToF) detector fast simulation:

$$\beta = L / t, \quad \frac{\Delta\beta}{\beta} = \sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}, \quad \frac{\Delta L}{L} = 5\%$$

iToF $\Delta t = 50$ ps smearing

eTOF $\Delta t = 80$ ps smearing

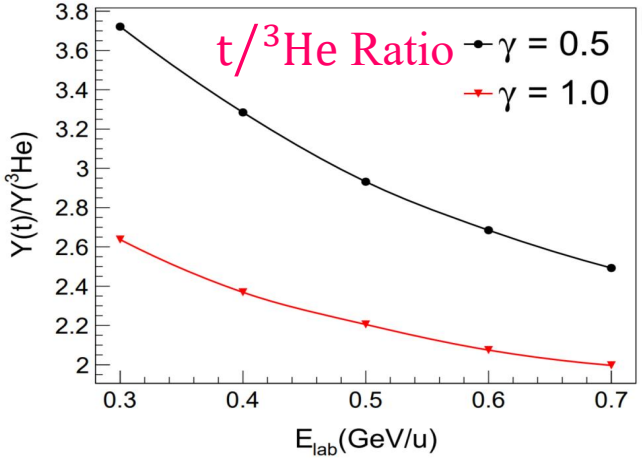


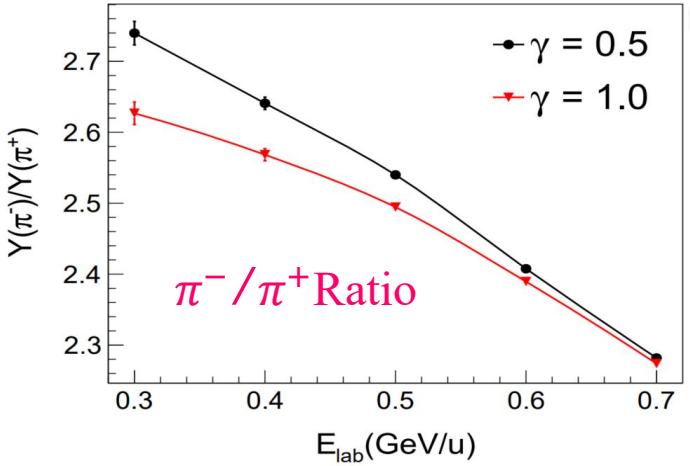



# The potential observables for EOS studies at CEE

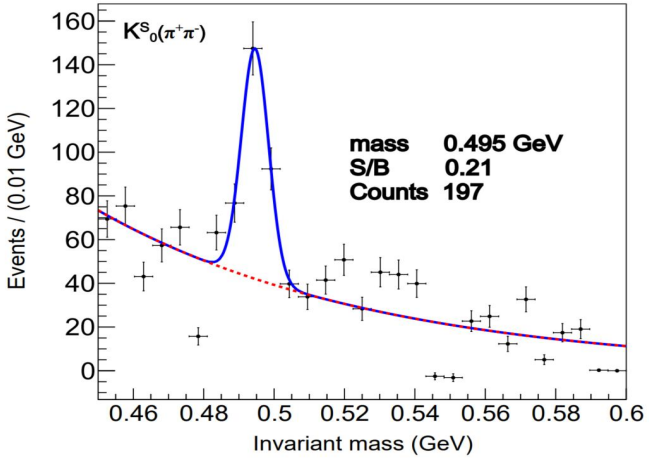
Using UrQMD + Geant4 simulation, one can identify the observables of nuclear EOS.

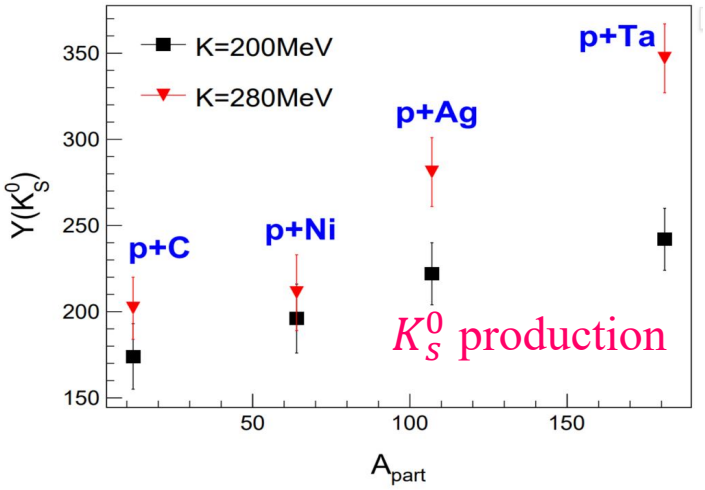
**0.5 GeV/u $^{208}$Pb+ $^{208}$Pb:**




**2.8 GeV p+C, Ni, Ag, Ta:**



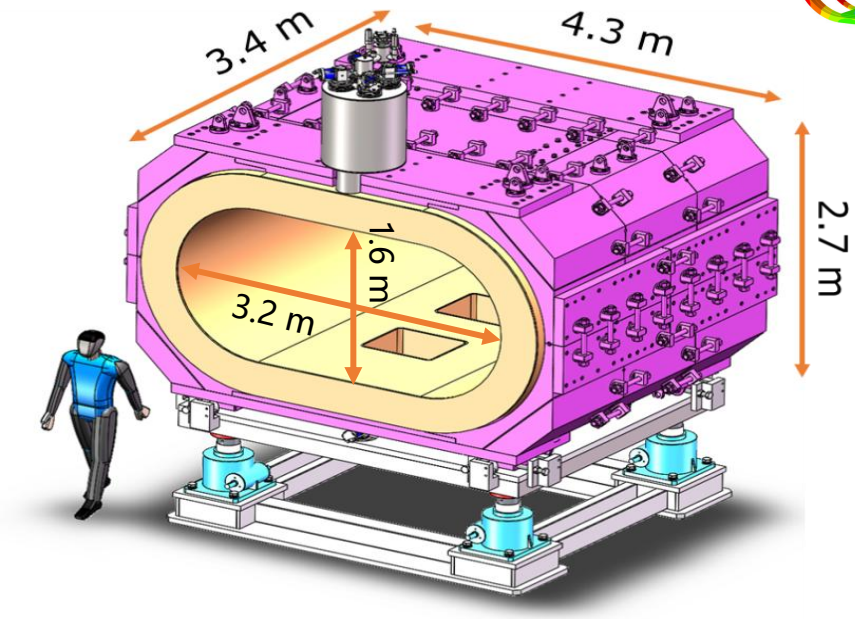

Dong Guo et al., ChinaXiv:2023 07.00040v1

# Outline

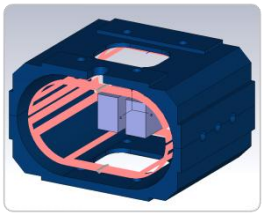
- Physics motivation
- Design of CEE spectrometer
- **Sub-detector Development progress**
- Summary

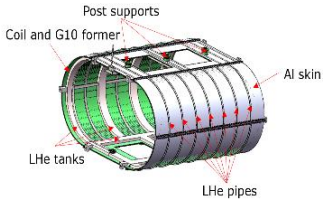
# Super Conducting Dipole Magnet

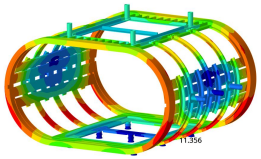
| Quantity | Performance |
|---|---|
| Central Field | 0.5 T |
| Uniform range | 1200×800×900 mm³ |
| Uniformity | ±2.5% |
| Current in operation | 231 A |

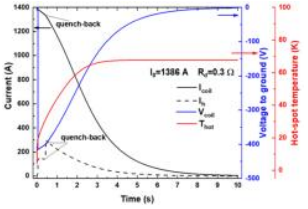



Magnet design







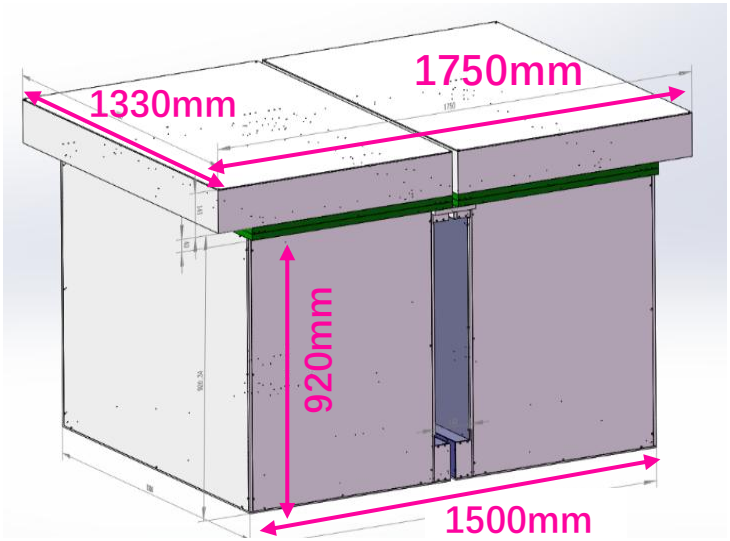

SC Magnet prototype

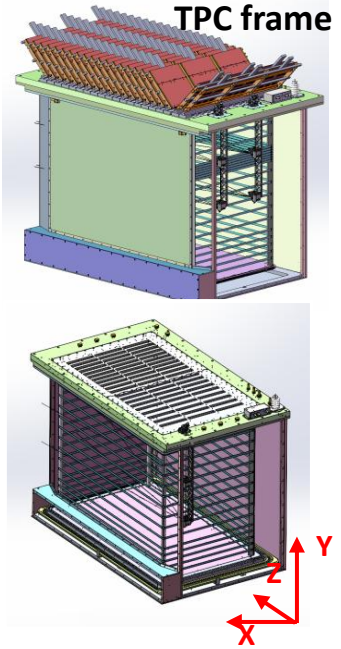
Iron-core production

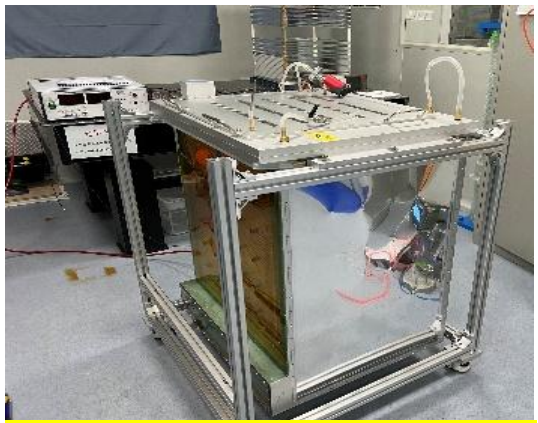
Inner skeleton & Coiling

# TPC development

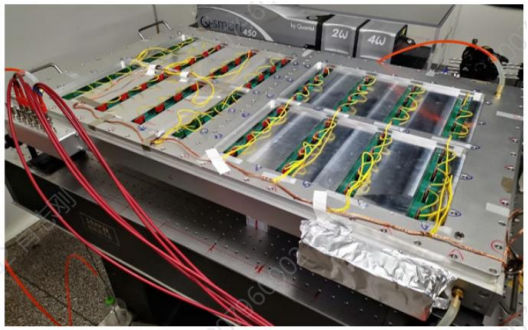
| Quantity | Design index |
|---|---|
| Channels | 15000 |
| Volume | $2 \times 45 \times 80 \times 90$ cm$^2$ |
| $\sigma_{xz}$ | 300 μm |
| 2-track seperation | 3 cm |
| Momentum reso. | 5% |



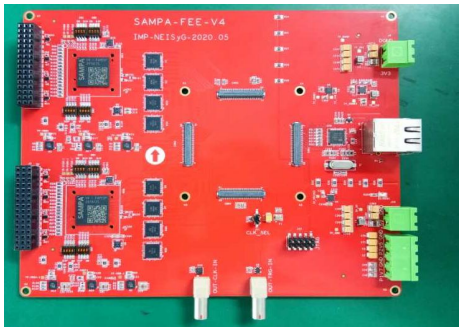



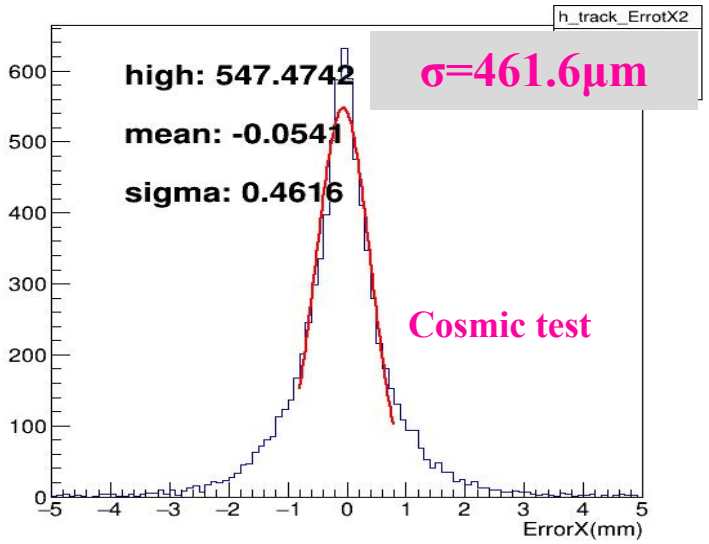



full size TPC prototype



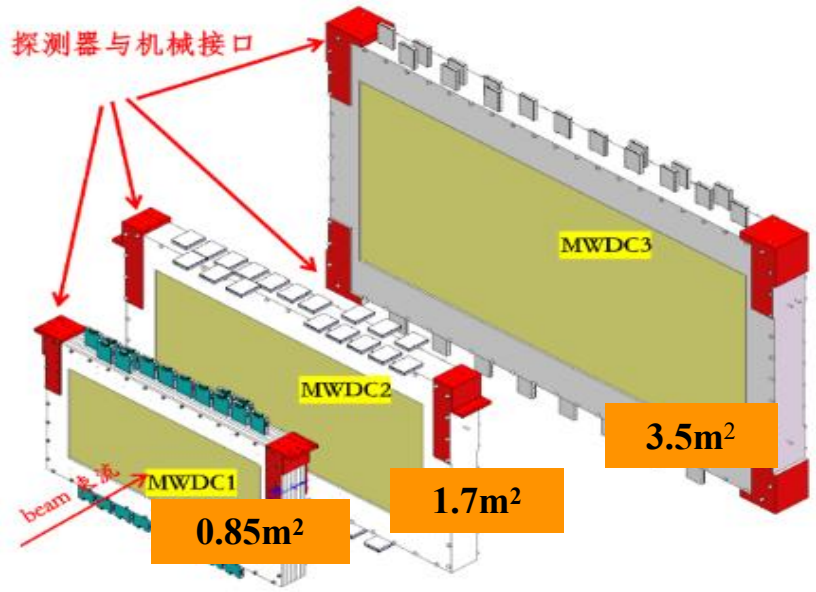
SAMPA-based readout

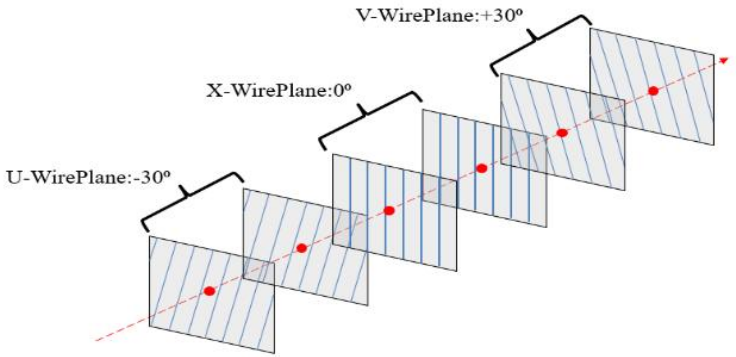


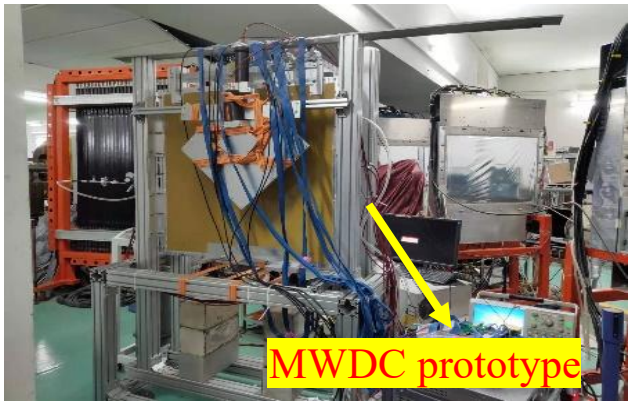



# MWDC development

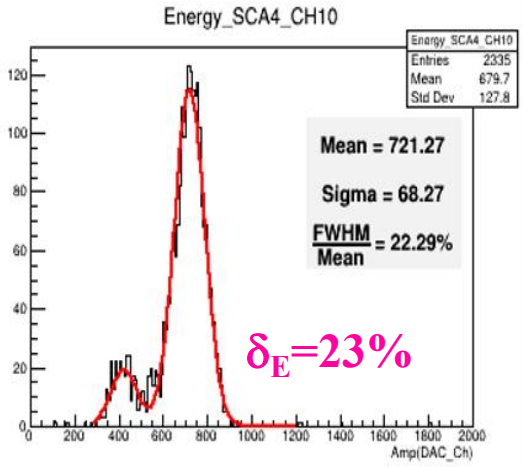
| Quantity | Designed performance |
|---|---|
| Channels | ~3200 |
| Wire layer per module | X、X’、U、U’、V、V’ |
| $\sigma_{xz}$ | 300 μm |
| Energy resolution | > 22% |
| Detection efficiency | > 98% |
| Momentum resolution | <5% |



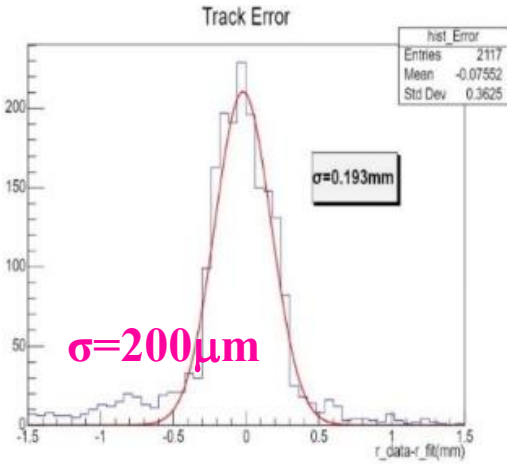




$^{55}$Fe Test (FWHM<23%）



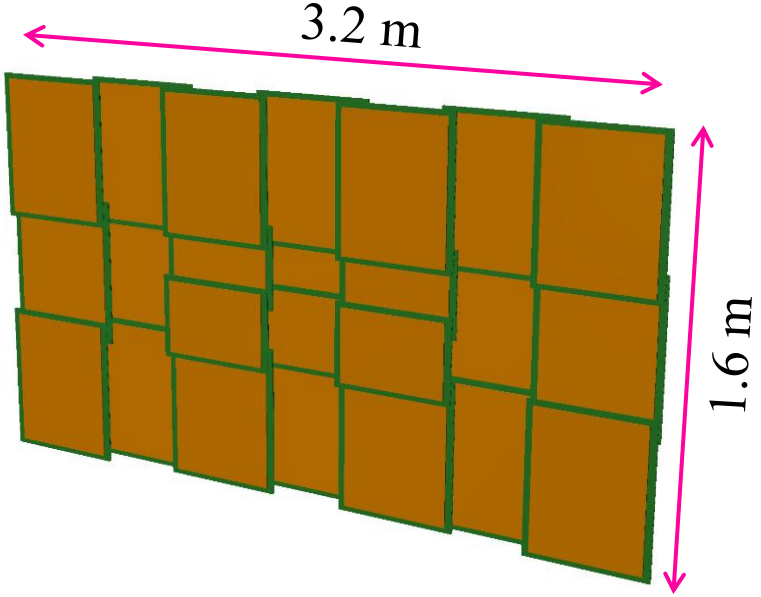

Comic-ray track ~200um



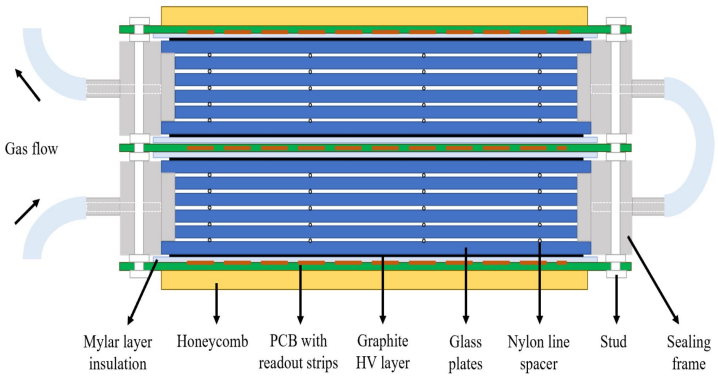
# eTOF development

endcap TOF (eTOF) covers the area downstream of MWDC.

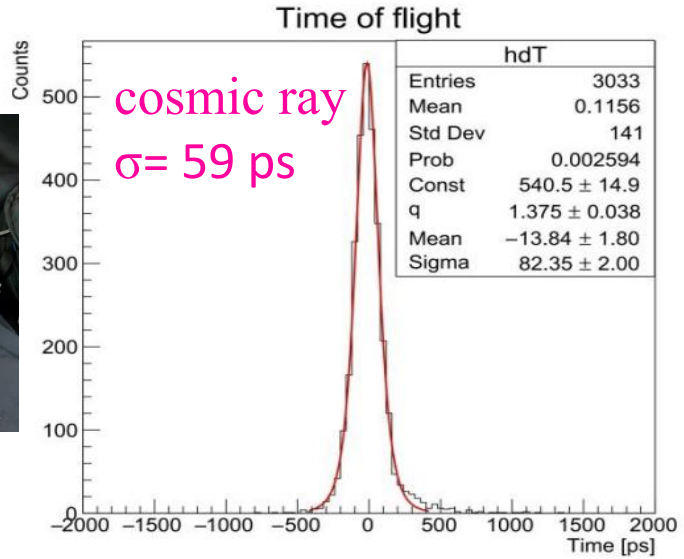
| Quantity | Design index |
|---|---|
| $\sigma_T$ | 60 ps |
| Efficiency | >95% |
| Rate | >10kHz |




eTOF MRPC configuration



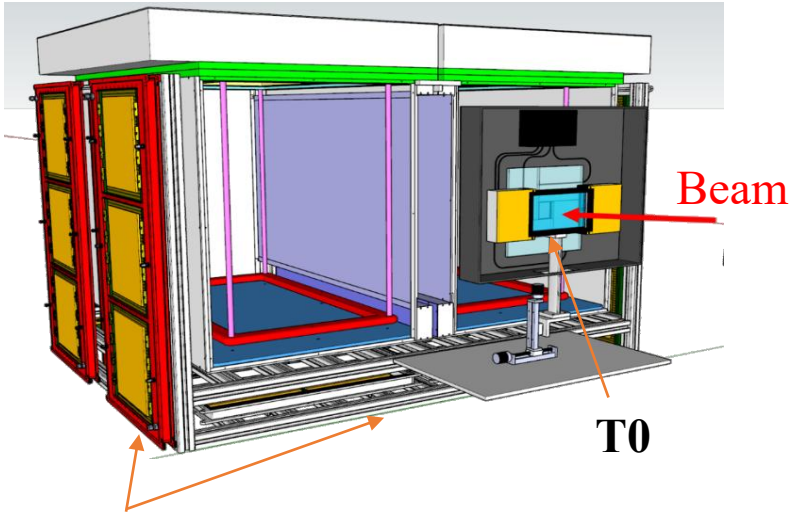

"Self-seal" design



# iTOF development

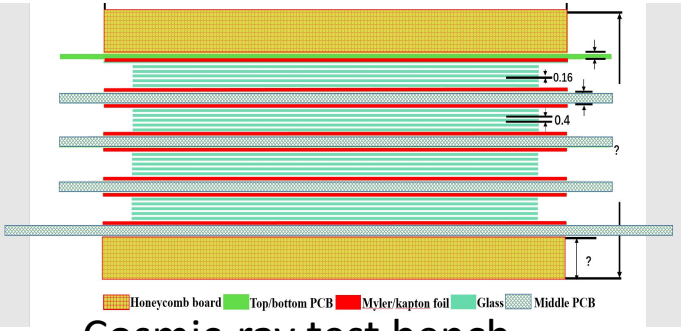
inner TOF (iTOF) surrounds the TPC on three sides.

| Quantity | Design index T0/iTOF |
|---|---|
| $\sigma_T$ | 50ps / 50 ps |
| Efficiency | >99% / >95% |
| Rate | 1MHz / 10kHz |

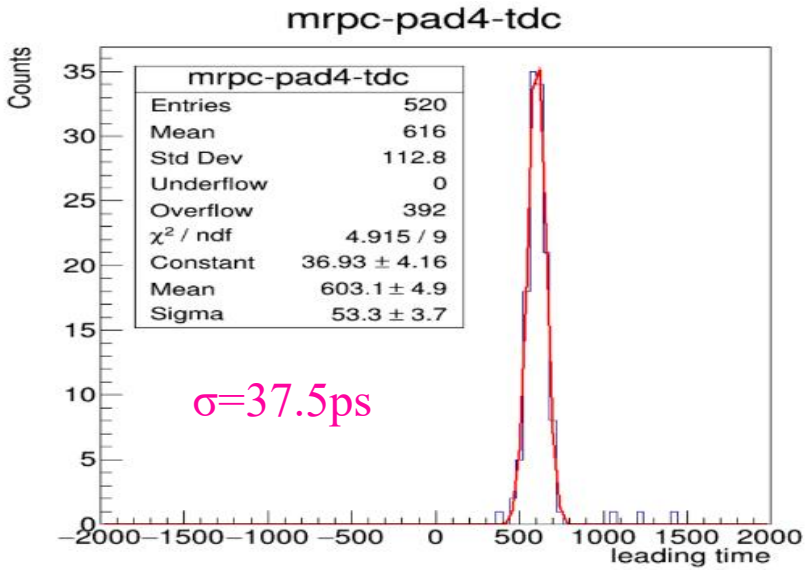



**iTOF: covers 3 side of TPC， left, right and bottom**

MRPC technology




Cosmic-ray test bench

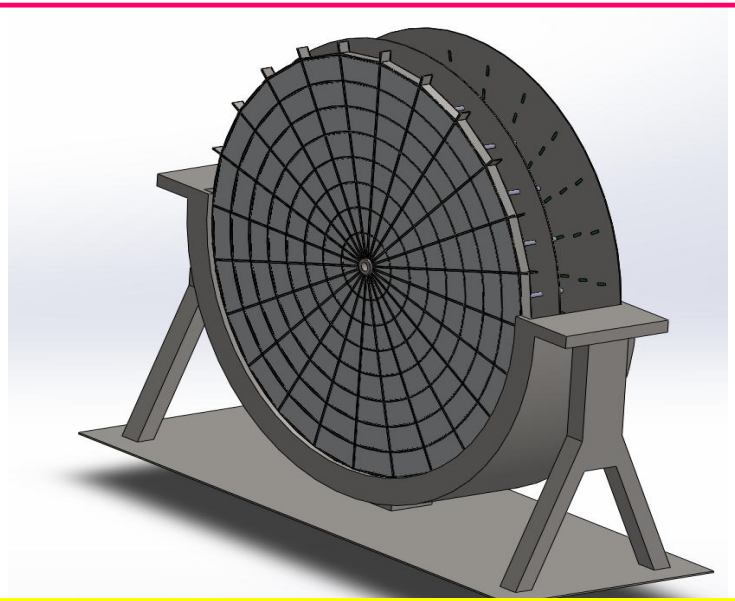


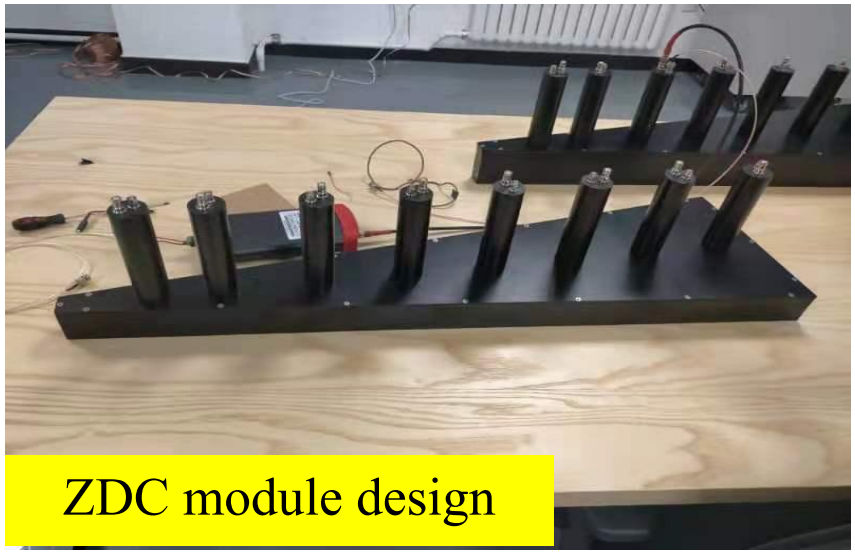
# Zero Degree Counter (ZDC)

**Key Functions:**

- ☐ Event Plane determination
- ☐ Centrality definition

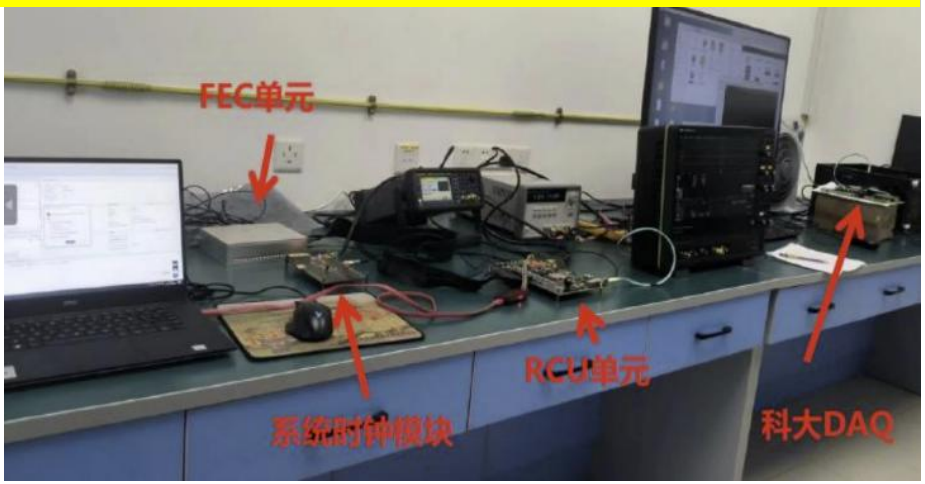
| ZDC Parameters | Design index |
|---|---|
| Charge resolution | ~15% / Z=1-15 |
| Area | 5<R<100 cm² |





ZDC module design

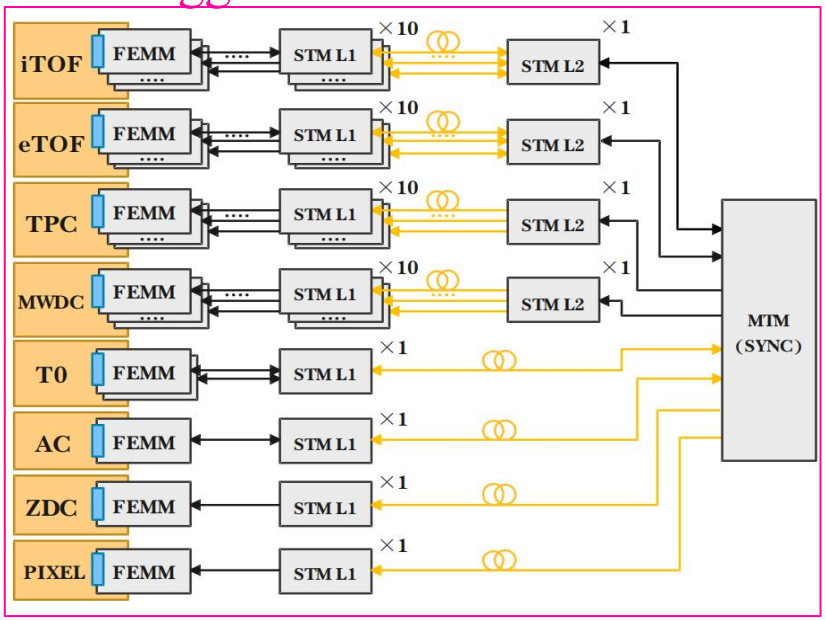
ZDC Module Prototype test



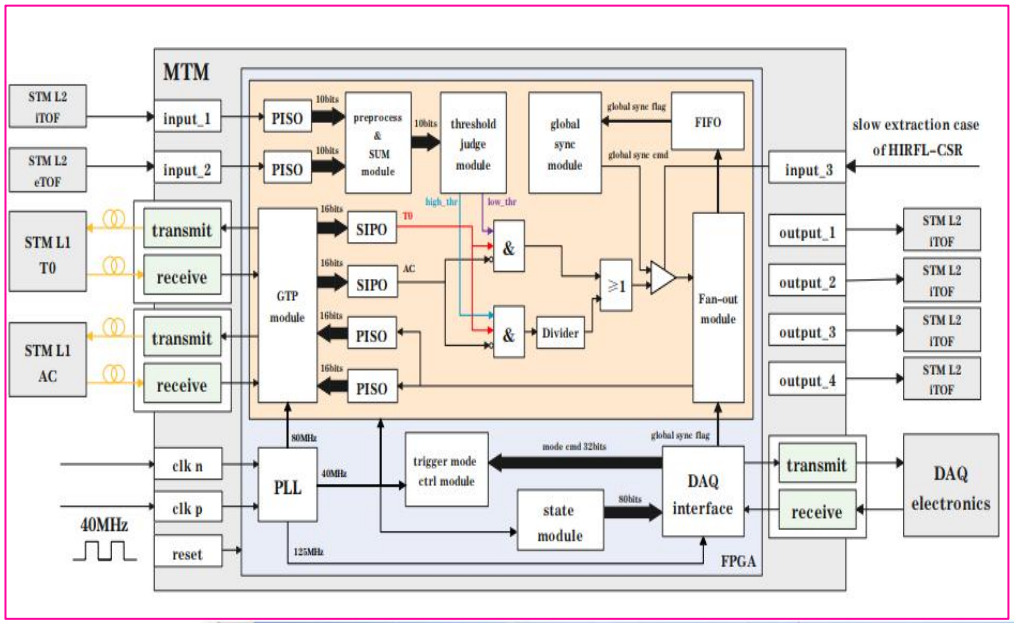
# Trigger System (TS)

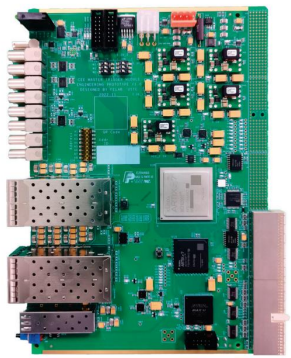
FPGA-based, multi-layer master-slave trigger architecture has been designed, manufactured and tested.

trigger architecture



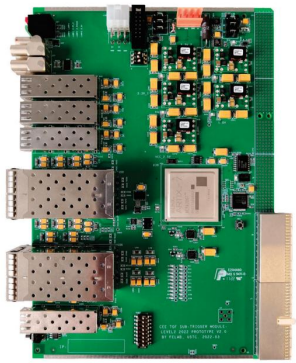

trigger logic calculations



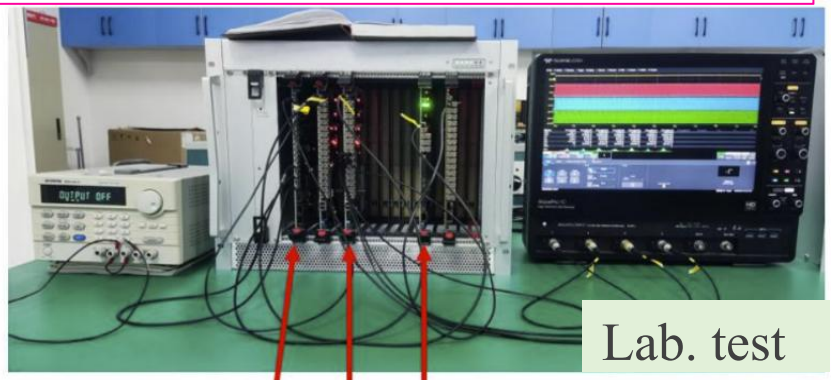



(a)

(b)



(c)

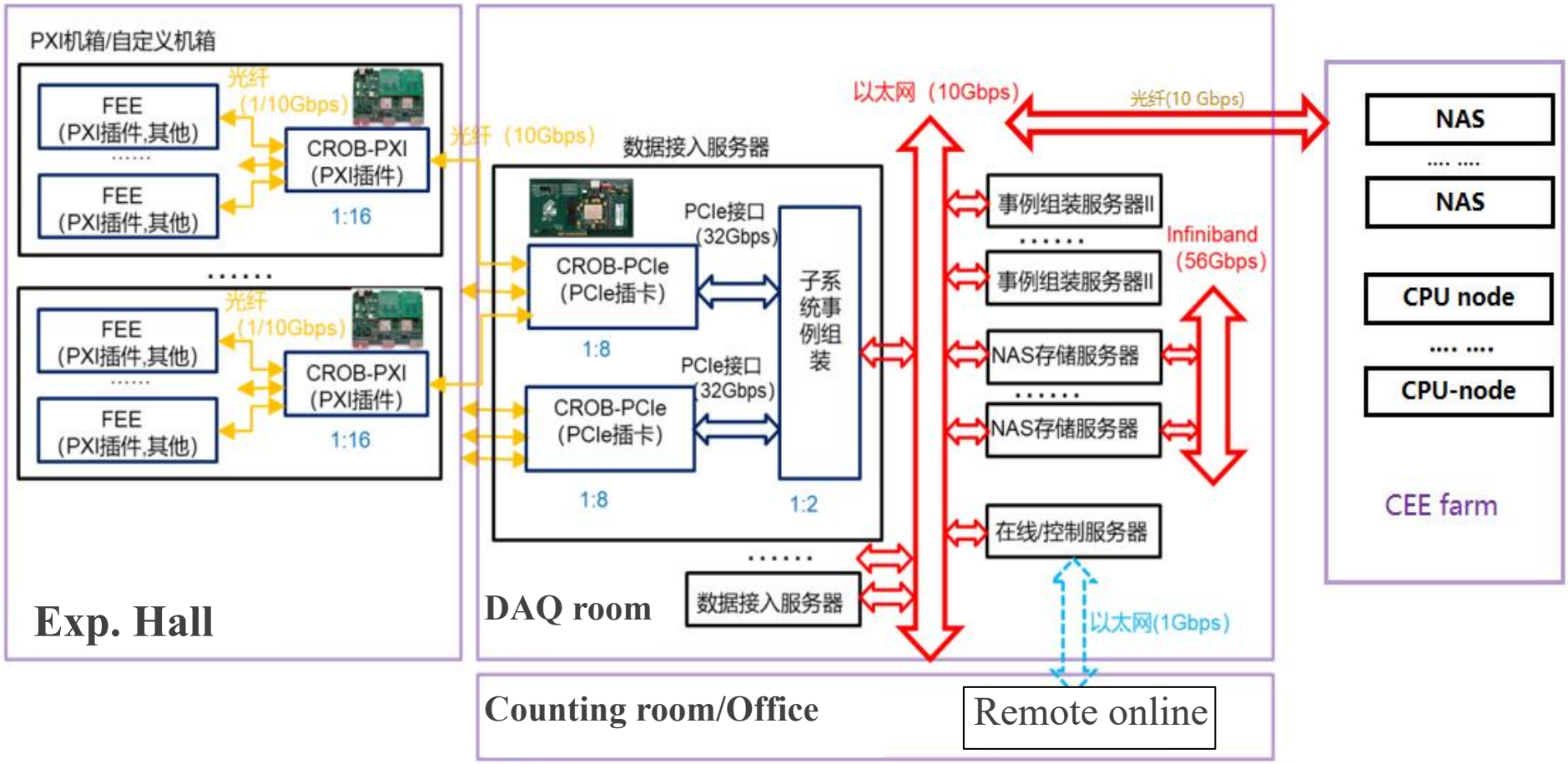



Lab. test

# Data Acquisition System (DAQ)

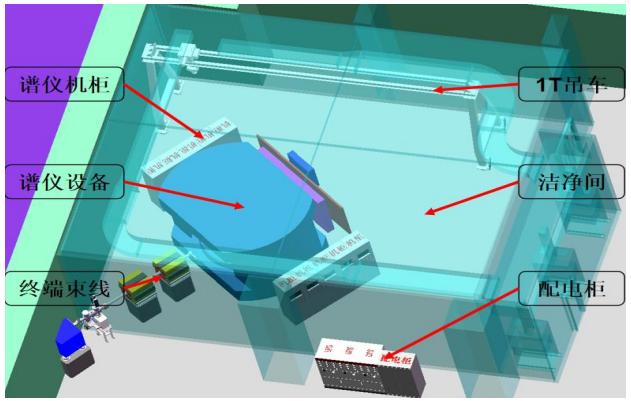
DAQ architecture has been designed and tested, we are building the computing farm.

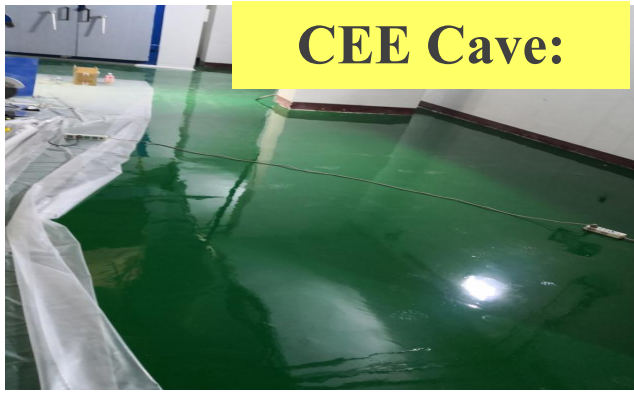
Zero-suppressed data rate：~4.4 Gbyte/s



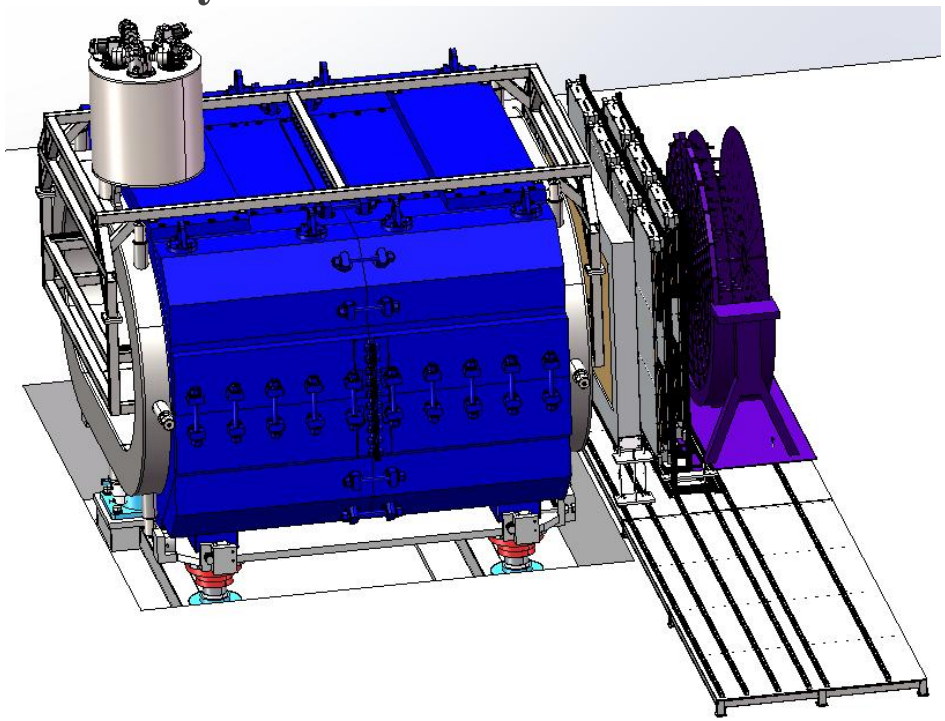
# System Integration & Infrastructure

Experimental hall where CEE resides is ready. Accessaries are prepared.




**Assembly scheme:**



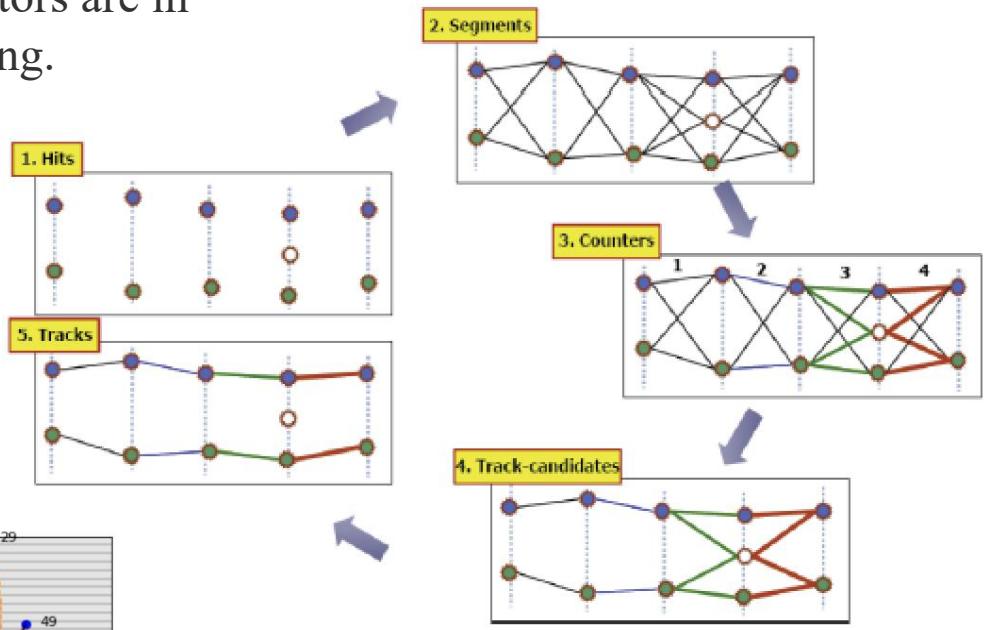
Others issues:

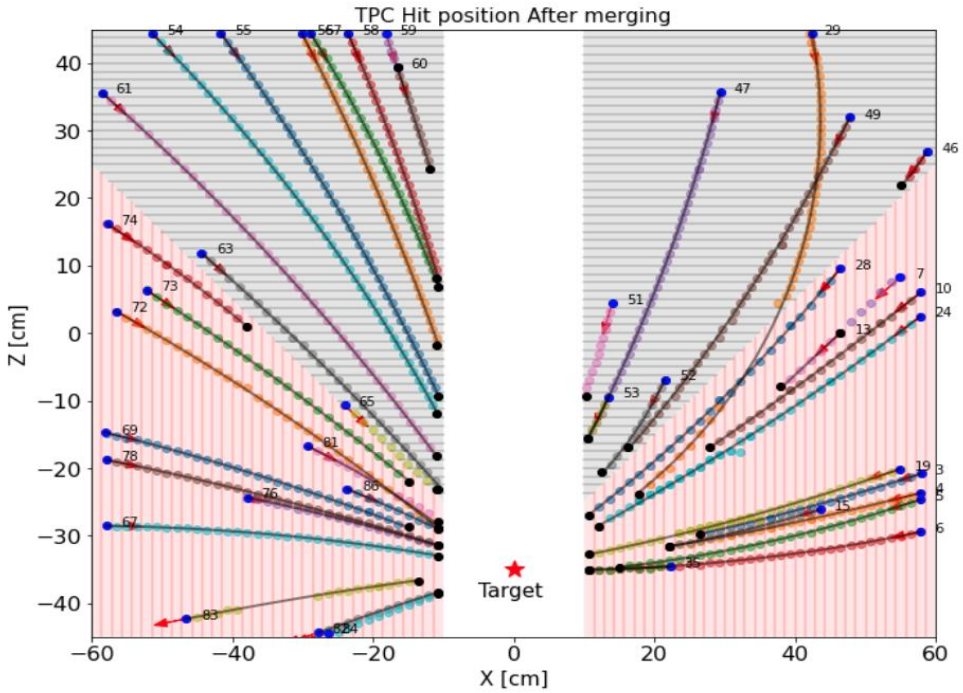
- Accelerator upgrade (in progress)
- Gas system (in progress)
- Beam line optimization (Done)
- Data Storage and Computing (Done)
- Radiation control (Done)

# Tracking in CEE

Tracking software for TPC and MWDC detectors are in development, almost done and tests are ongoing.

- Track finder：Cellular Automaton (CA)
- Track fitting：Kalman filter

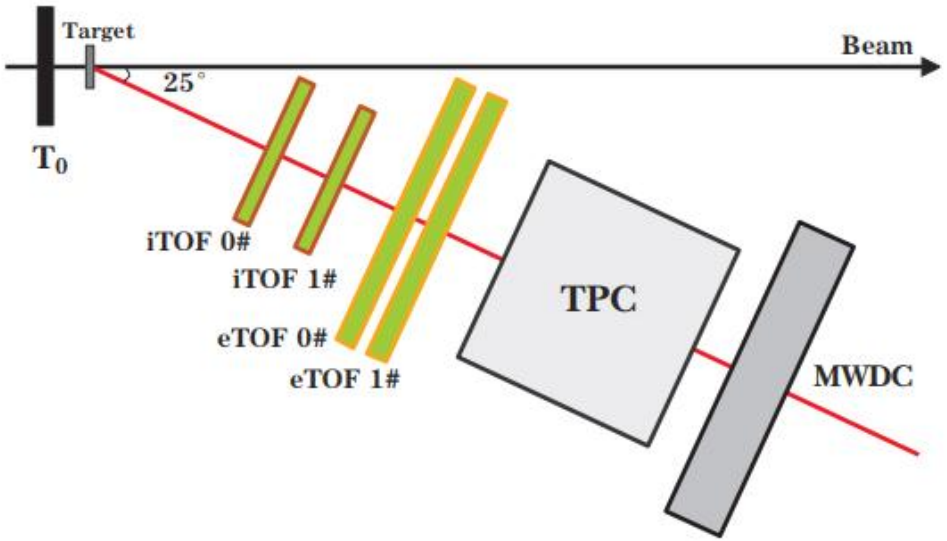


# Beam Test

Beam tests have been done may times. For the lastest one, in May 2023, the prototypes of all subsystems are connected and tested.

- ✓ TOF and tracking detectors
- ✓ Clock system
- ✓ Trigger system
- ✓ DAQ system

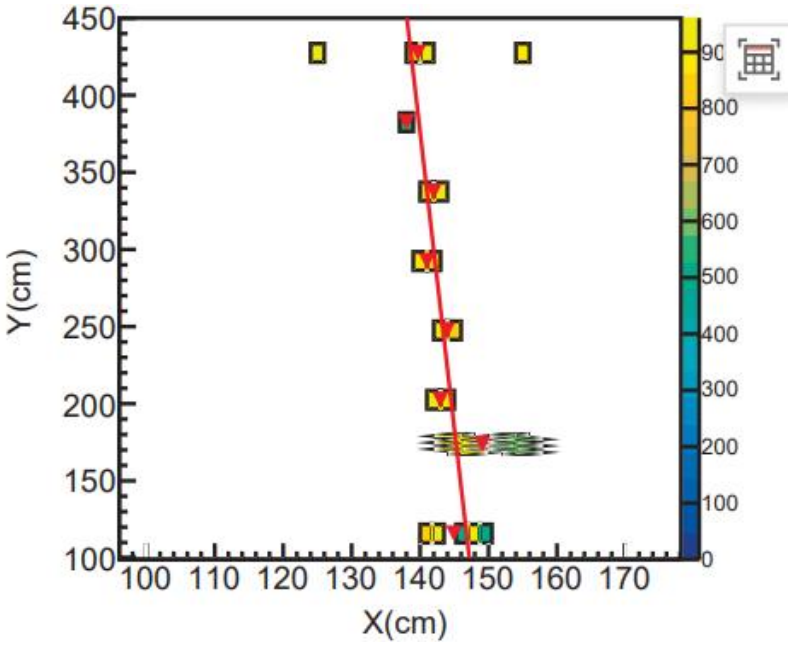



(a)

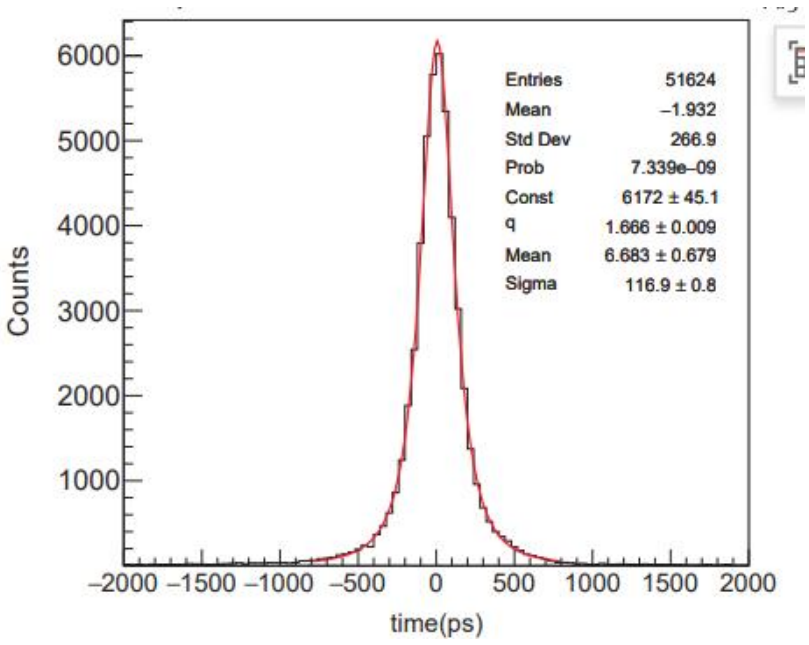
(b)

# Beam Test

Prototypes of tracking and TOF detectors, electronics, global clock, trigger and DAQ systems, all integrated, were working properly in the beam test. Most of the subsystems start the mass production.




✓ a TPC track




✓ Time of fright variation

# Summary

- CEE experiment is feasible for studying nuclear EOS at HIRFL-CSR energy domain (sub GeV/u for HI).
- Progress of the subsystem construction is roughly in line with plan. CEE is scheduled to take data in 2025.
- Simulation and analysis software are in progress.

Question: Do we have some new observables, clear for the sensitive density range, robust against the parameters other than EOS in transport model?