CEE at CSR and future HIAF

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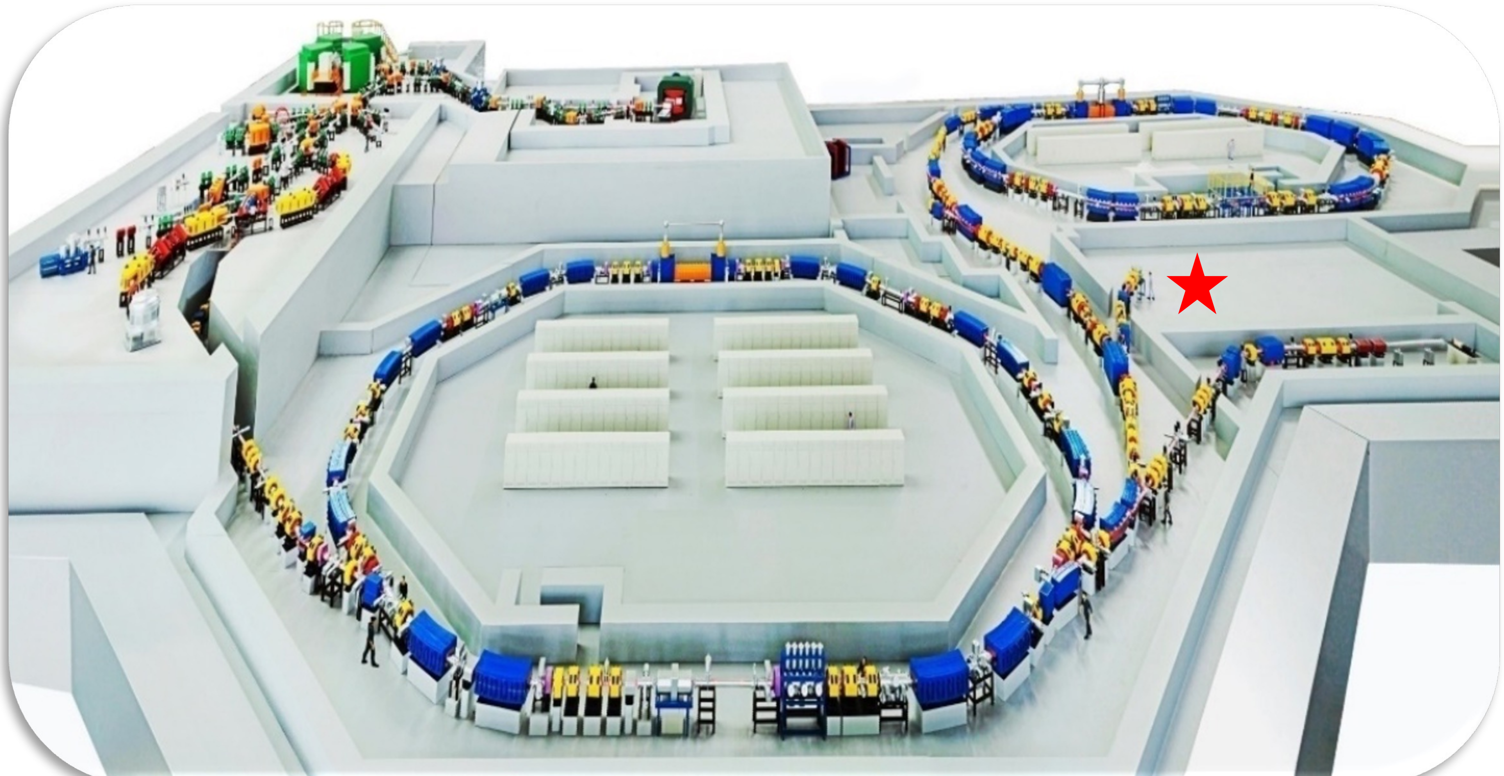
Outline

- CEE (@CSR & @HIAF)
- SRC @ CEE - some (very preliminary) thoughts
- New spectrometer at HIAF high energy terminal
- SRC @ HIAF new spectrometer - some (very preliminary) thoughts
- Summary

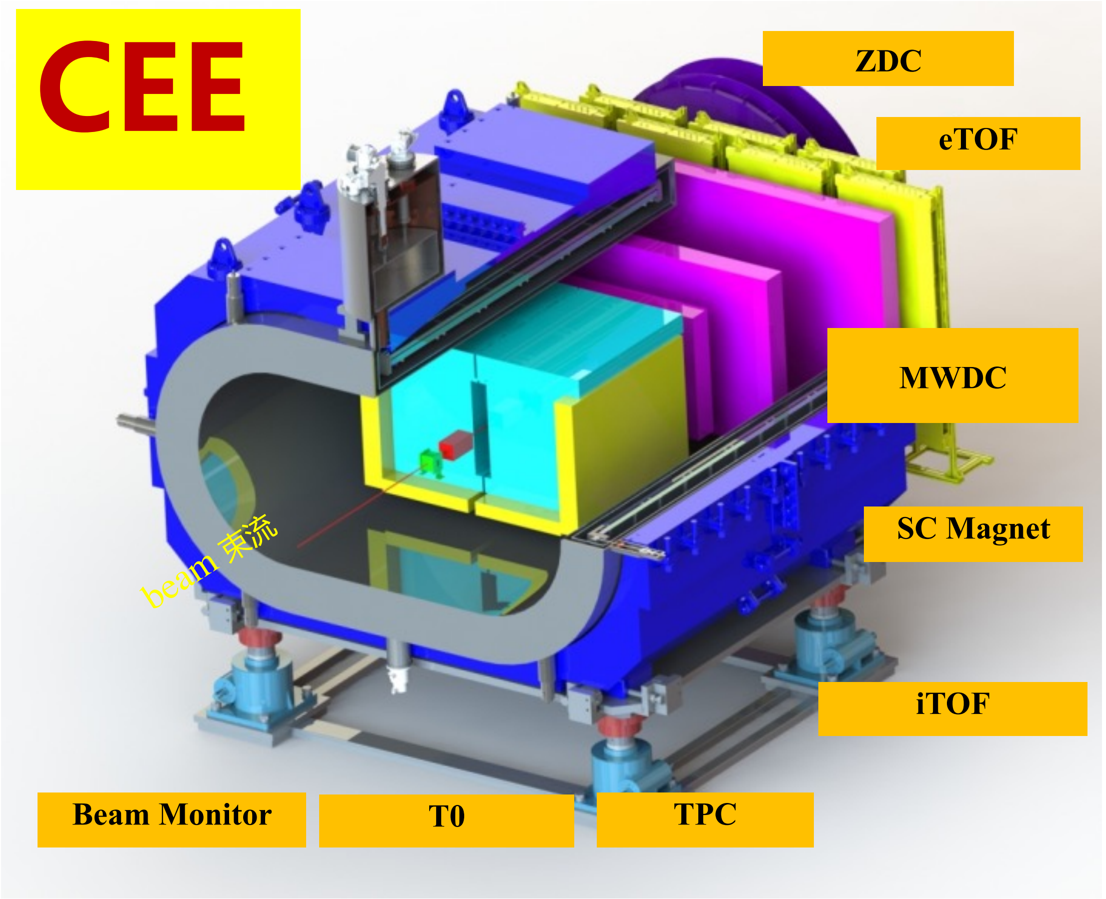
HIRFL-CSR

HIRFL-CSR beam
p 2.8 GeV
C 1 GeV/u
U 0.5 GeV/u



- Heavy Ion Research Facility in Lanzhou (HIRFL) – Cooler Storage Ring (CSR)

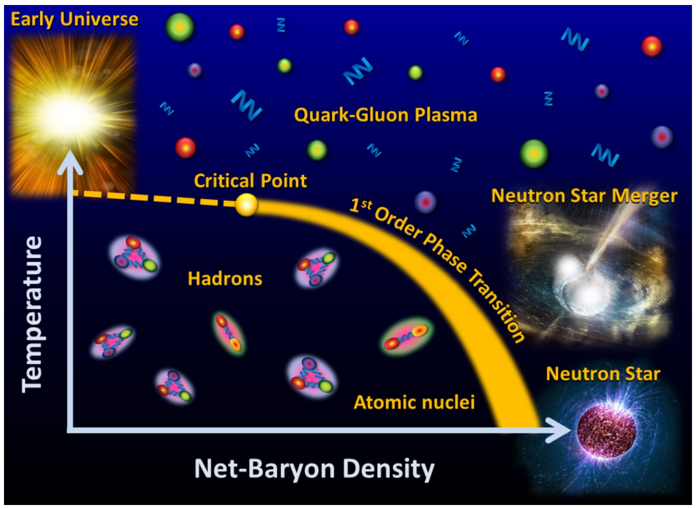
CEE

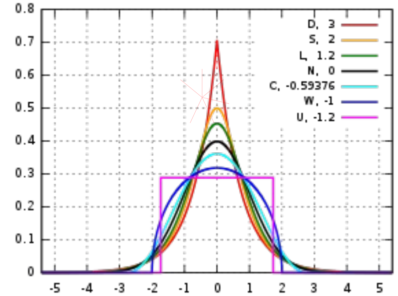


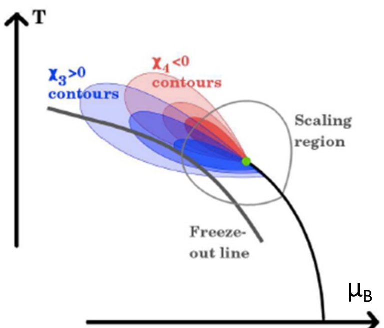
- Super-conducting Dipole Magnet
- Time Projection Chamber (TPC)
- Multi-Wire Draft Chamber (MWDC)
- T0/Inner TOF (iTOF)
- External TOF (eTOF)
- Si-PIX Beam Monitor (BM)
- Zero Degree Counter (ZDC)

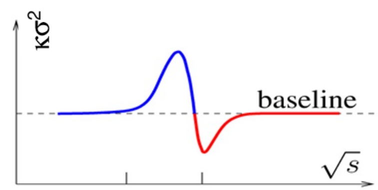
- CSR External-target Experiment (CEE)
- Will finish with construction and begin data-taking in 2024

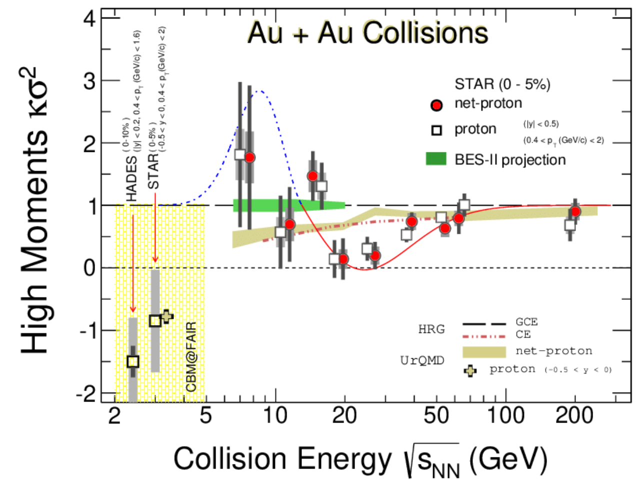
Physics at CEE – QCD phase diagram





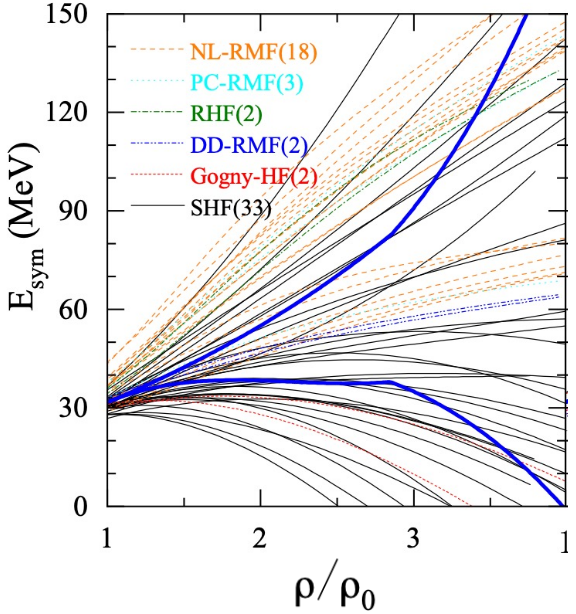


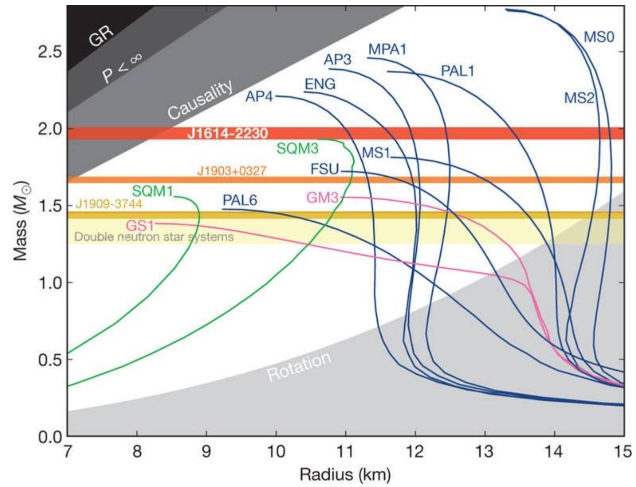


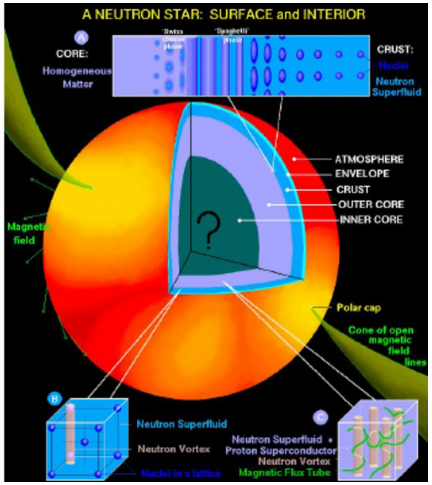


- Search for the critical point in the QCD phase diagram

Physics at CEE – nuclear matter EOS

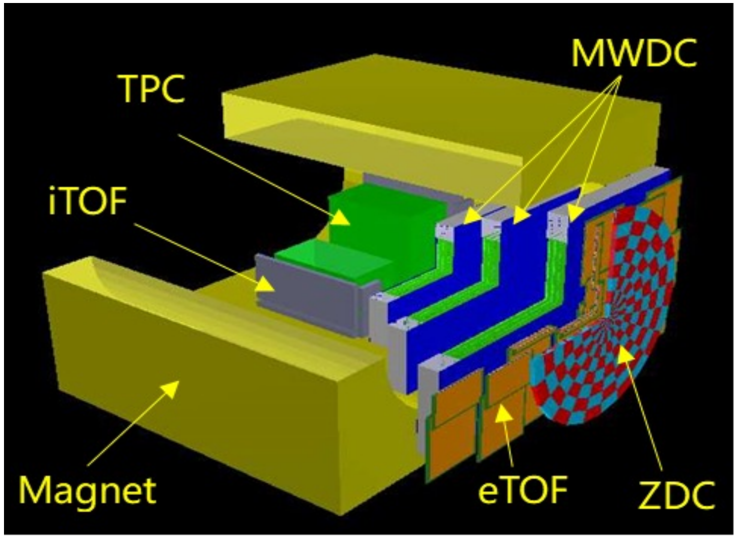




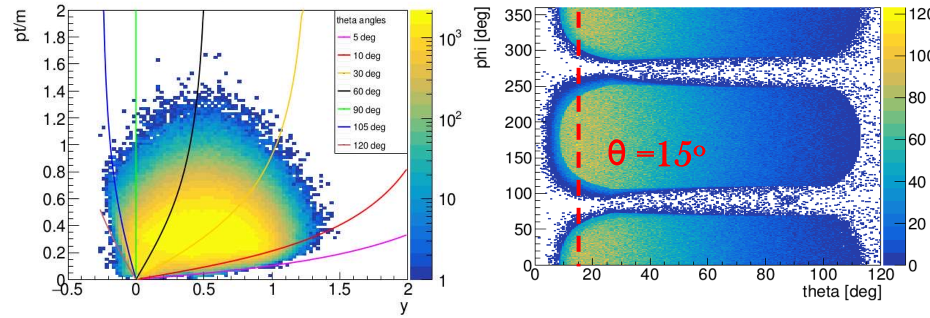


- Nuclear matter equation of state (EOS) ⇒ neutron star structure and properties

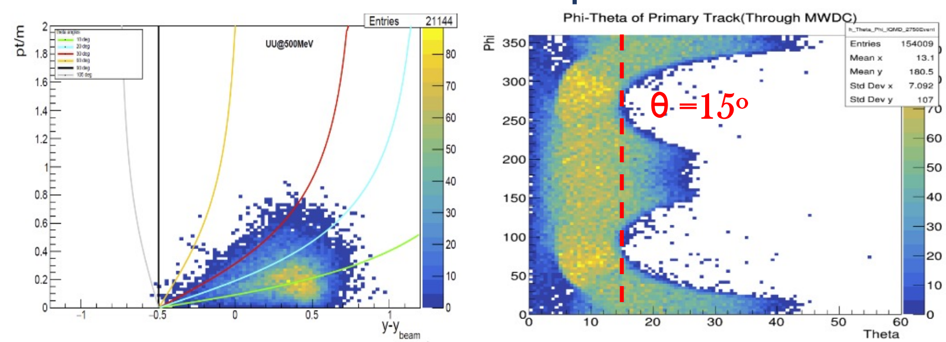
CEE – key parameters



TPC acceptance

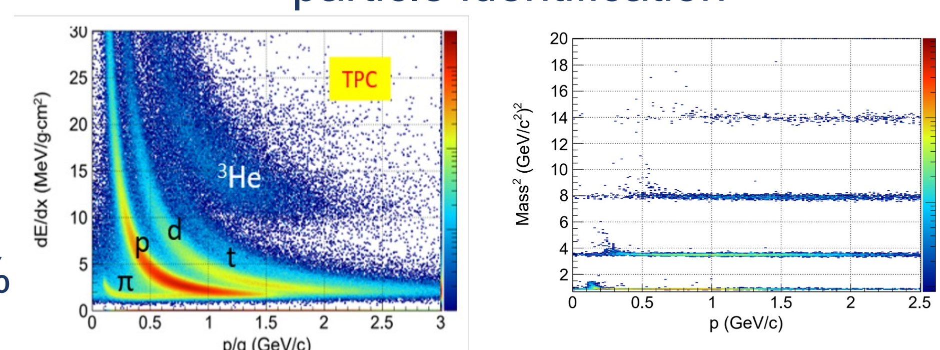


MWDC acceptance

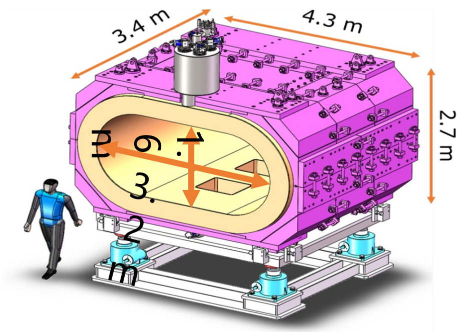


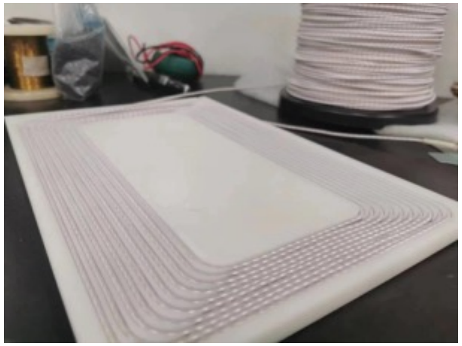
- 10kHz event rate
- Good acceptance and identification ability for charged particles
  - $\pi^{+/-}$, $K^{+/-}$, p, d, t, ^{3}He, ^{4}He
- Typical momentum resolution ~<5%

particle identification

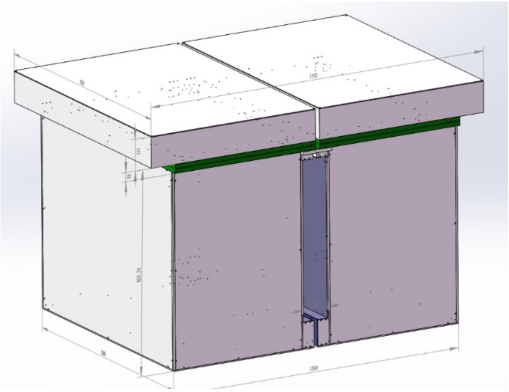


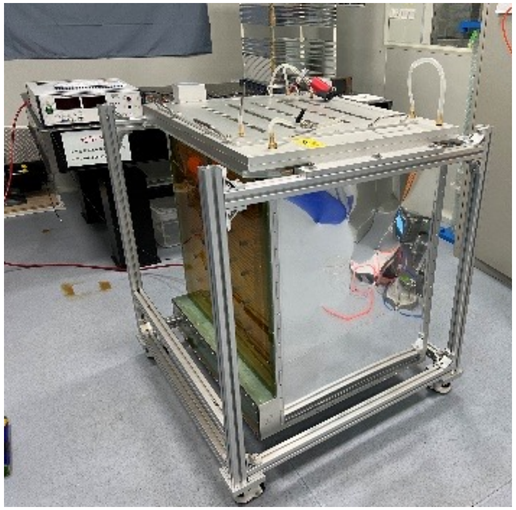
CEE - status



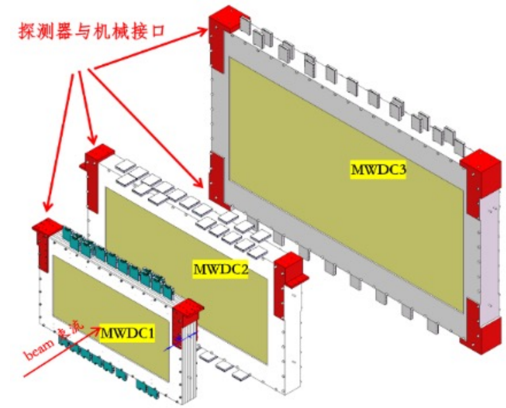


Dipole magnet



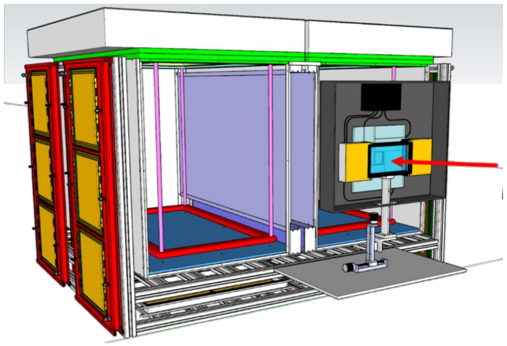


TPC

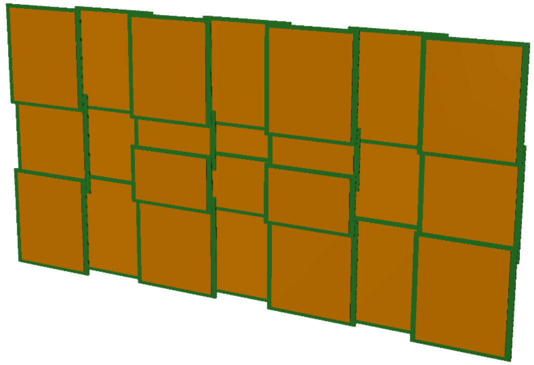


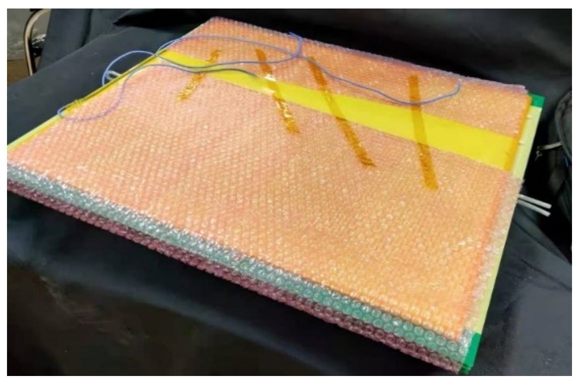
MWDC

CEE - status

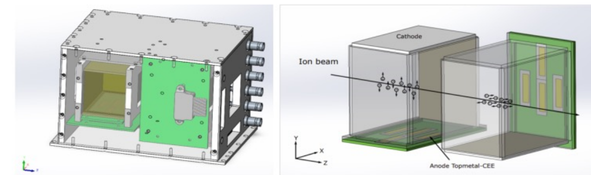


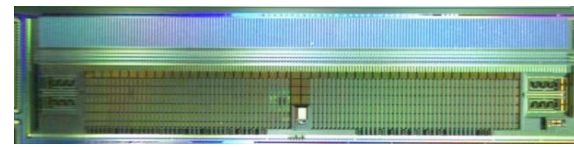
iTOF & T0

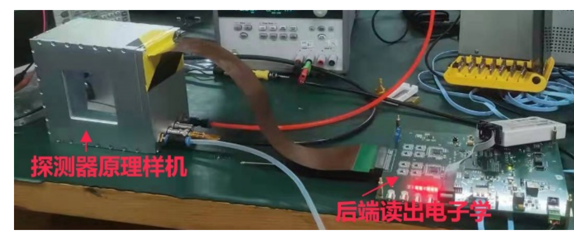




eTOF

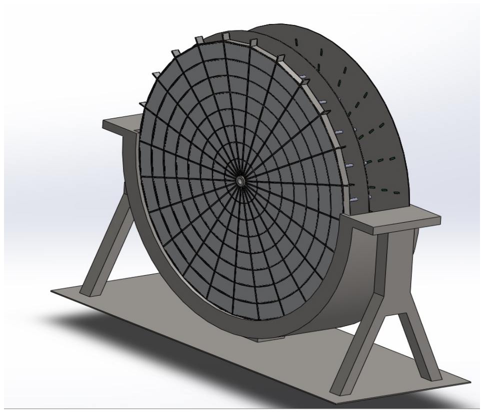




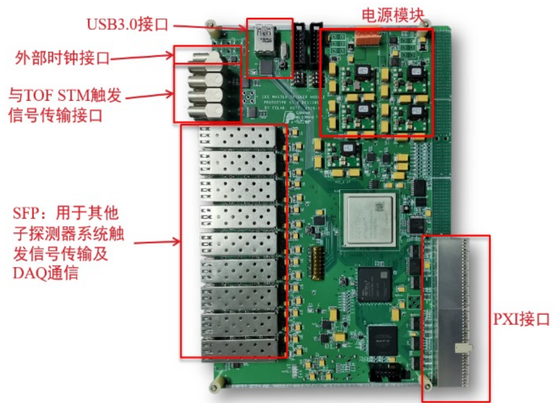


Beam monitor

CEE - status



ZDC

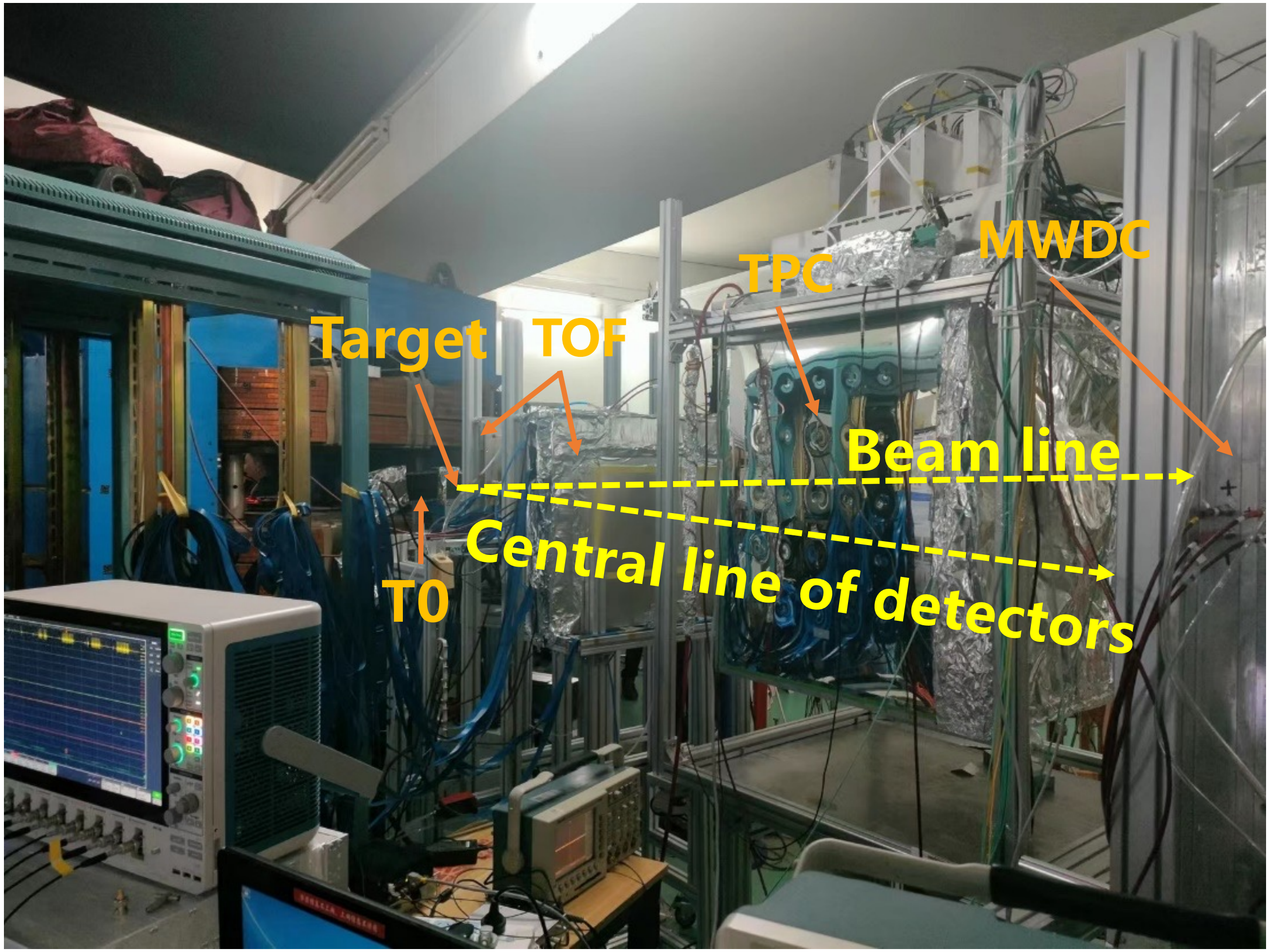


trigger system

clock system

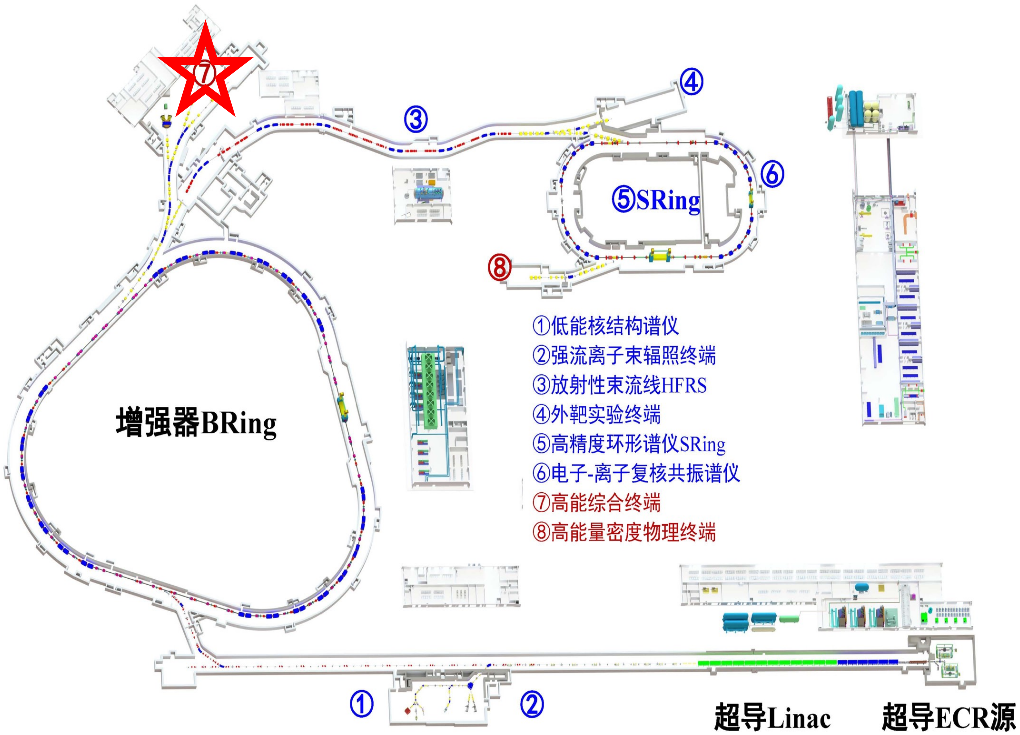
- All sub-systems have been finished with prototype development, and are in either final engineer design or massive production stage

CEE - status



- 1st beam test with most of the subsystems in August 2023
- Plan to finish assembling, commission and begin taking data in 2024

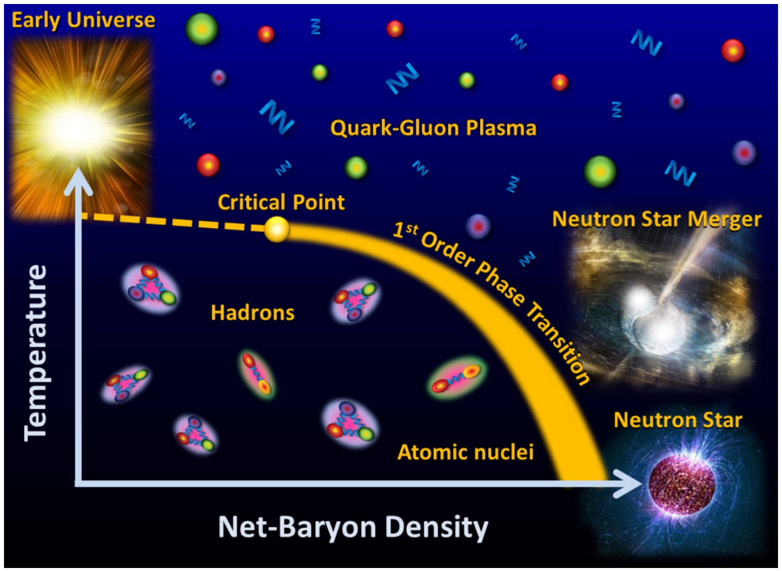
HIAF & HIAF-U

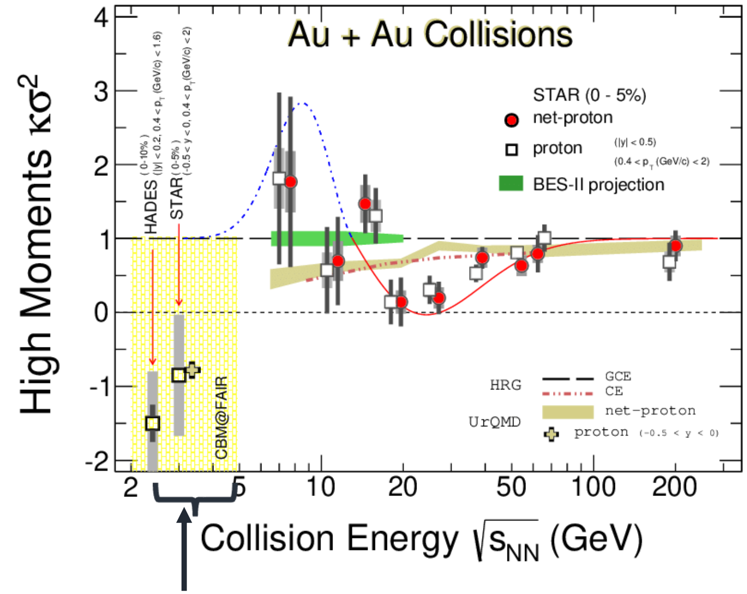


	E_k (GeV/u)	$\sqrt{s_{NN}}$ (GeV)
HIAF U beam	0.8-2.45	2.24-2.85
HIAF-U U beam	2.95-9.1	3.01-4.54
HIAF p beam	<9.3	<4.58

- HIAF(HIAF-U) can provide U beam with energy of 0.8-2.45 GeV/u (2.95-9.1 GeV/u)
  - nuclear matter phase structure, equation of state, hypernucleus
- High-intensity proton beam up to 9.3GeV
  - light hadron physics, η meson physics

CEE @ HIAF

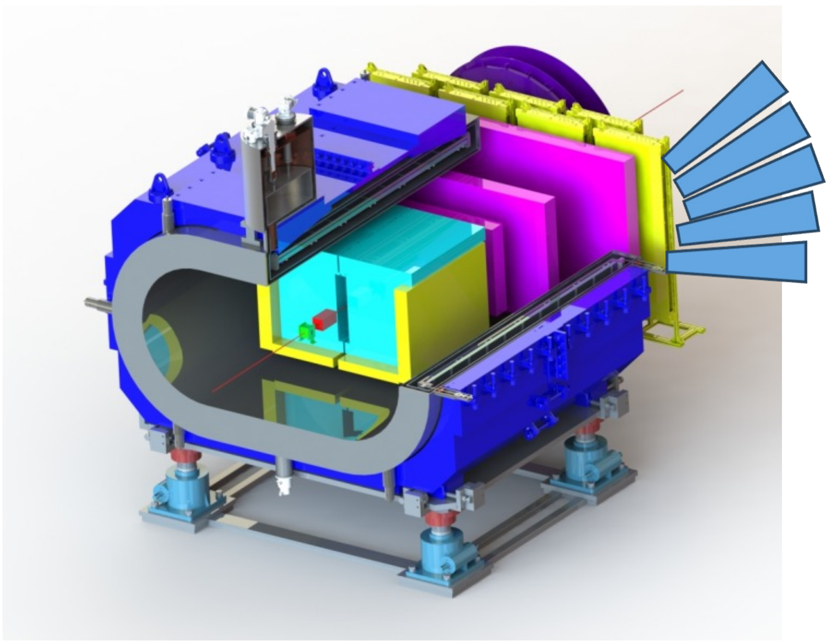


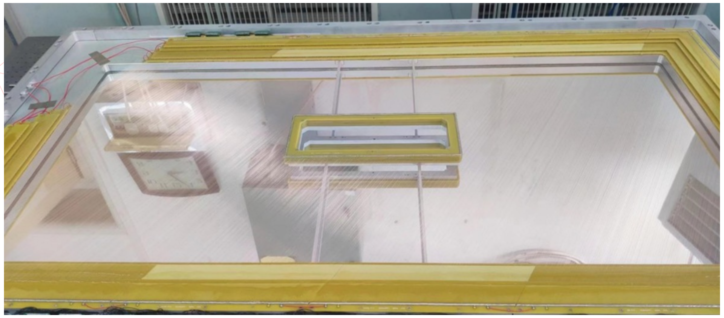


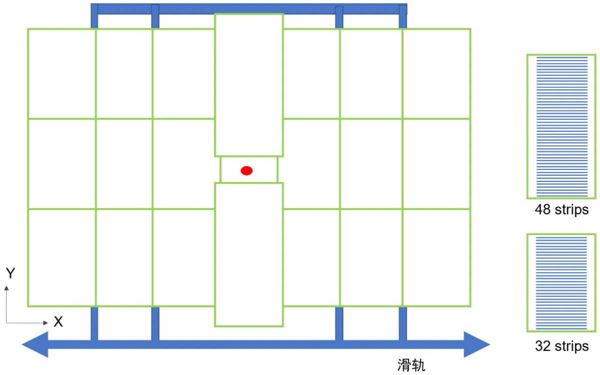
HIAF & HIAF U

- HIAF can provide heavy ion beam with a larger energy range than CSR
- After ~3 years of running at CSR, we plan to move CEE to HIAF
- Scan a wider range of the QCD phase diagram
- Study EOS at higher baryon density

SRC studies at CEE – some preliminary thoughts





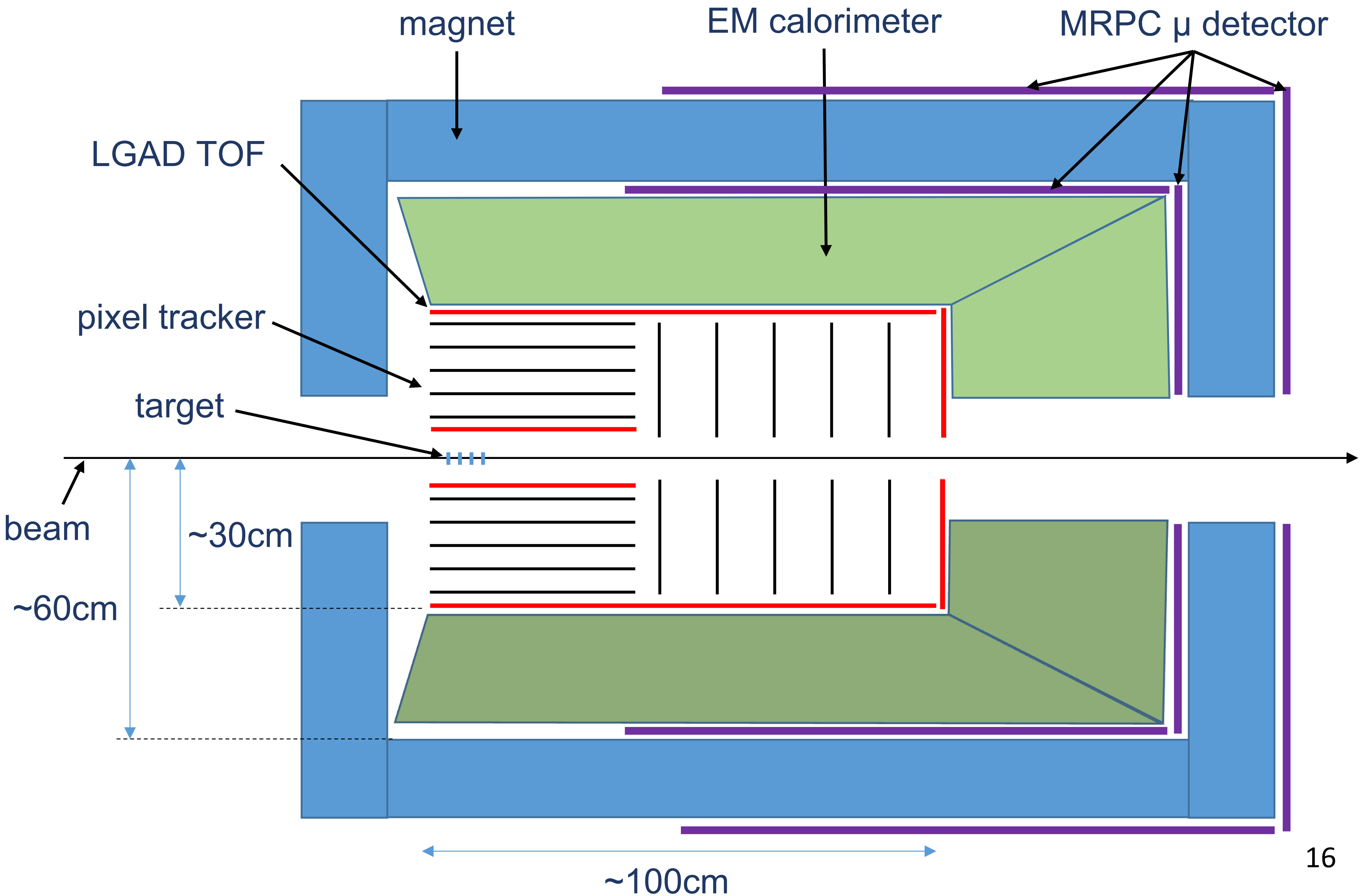


- CEE can detect and identify charged particles, including p
- However, MWDC and eTOF are designed to avoid the beam
    - To tag beam fragments, may need small tracking & PID detectors to fill the gap
- 1-2 arc(s) of calorimeters may be added for neutrons (full coverage may cost too much

Outline

- CEE (@CSR & @HIAF)
- SRC @ CEE - some (very preliminary) thoughts
- New spectrometer at HIAF high energy terminal
- SRC @ HIAF new spectrometer - some (very preliminary) thoughts
- Summary

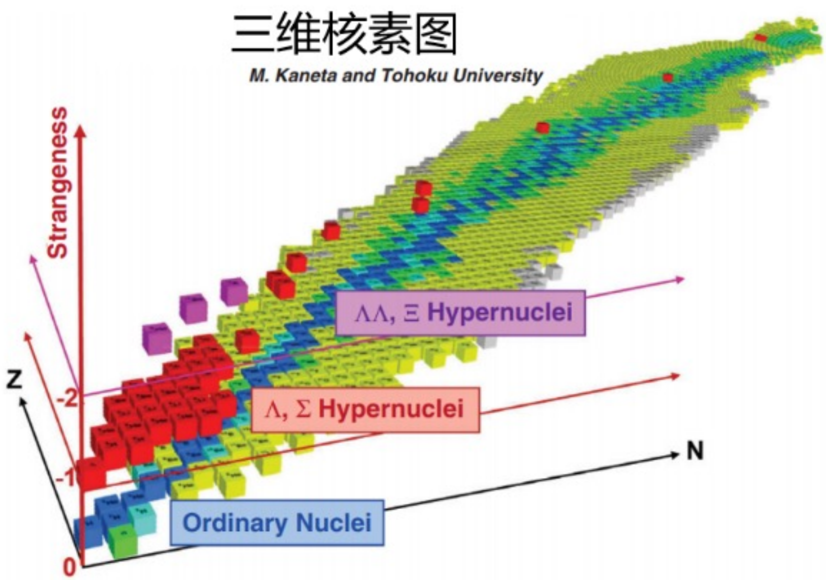
New spectrometer at HIAF - conceptual design

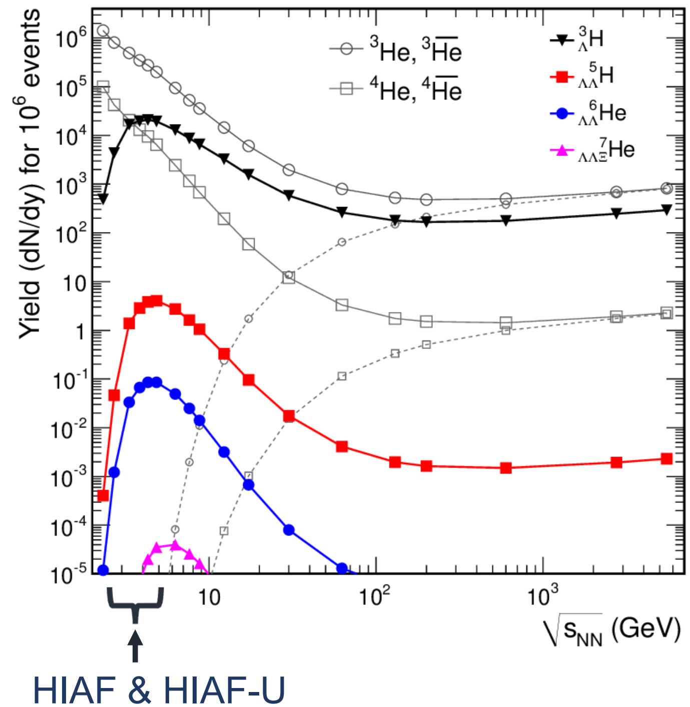


Feature of the spectrometer

- All-silicon tracker
  - Ultra-high event rate
    - η physics: >100MHz, statistics equal to current world η data within hours
    - Heavy ion collisions: >MHz (STAR 1kHz, ALICE 50kHz, CBM 10MHz)
  - Compact spectrometer
    - Tracker + TOF radius ~30cm, greatly reducing cost for calorimeter, magnet & μ detector
  - High position resolution
    - Meeting momentum resolution requirement with shorter track length
    - ~0 background for reconstructed particles with secondary vertices (Λ & hypernuclei)

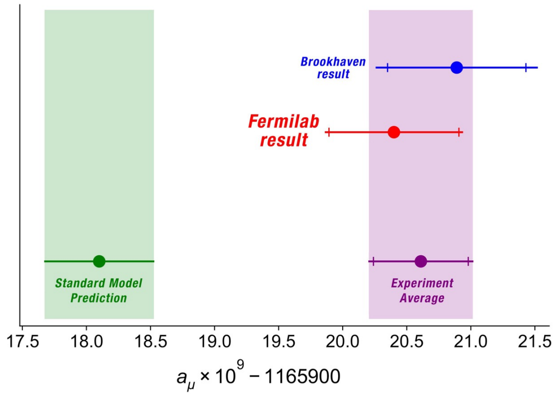
Hypernuclei

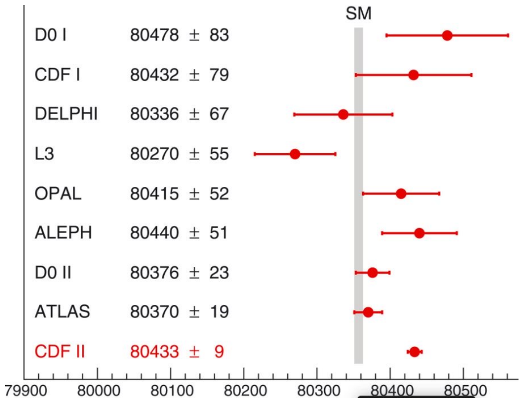




- Heavy ion collisions at HIAF & HIAF-U energies can produce hypernuclei, especially multi-strange hypernuclei ⇒ hyperon-nucleon & hyperon-hyperon interactions ⇒ structure and properties of neutron stars

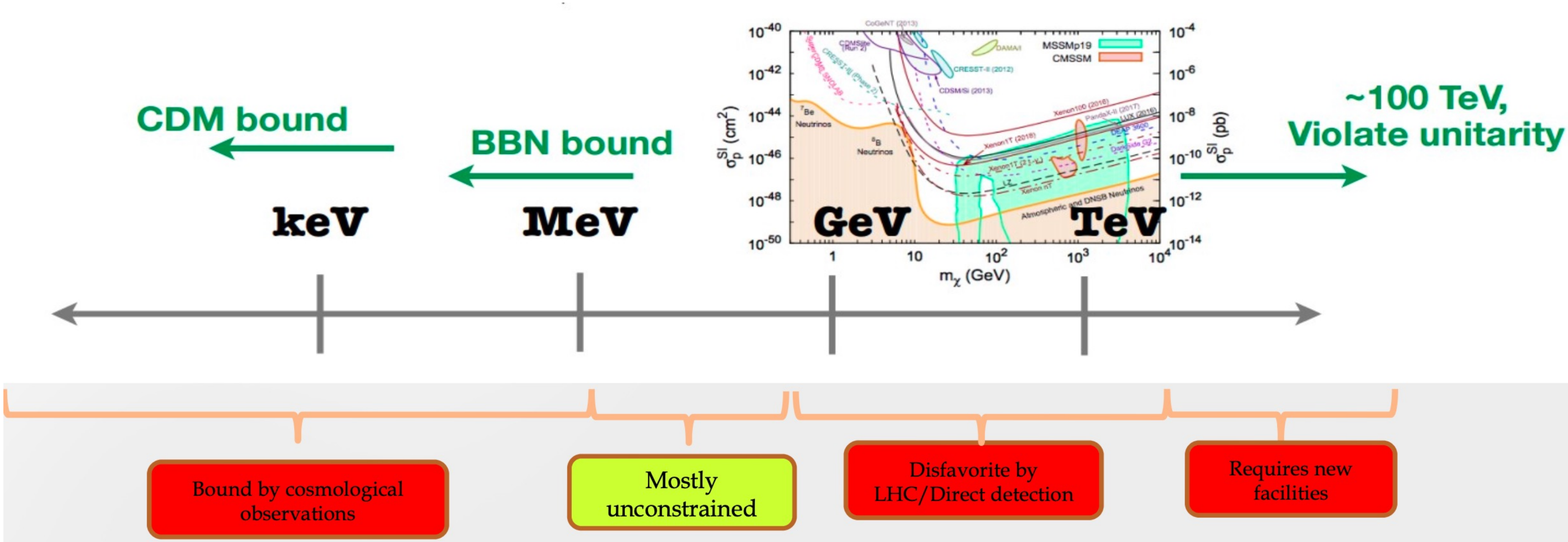
η meson physics





- The standard model of particle physics confronts several problems, calling for new physics beyond the current standard model
- At the high-energy frontier, LHC hasn't found any new particles / physics beyond the Higgs predicted by the standard model
- High-precision measurements is another important frontier for the discovery of new physics, e.g. abnormal magnet moment of μ (g-2), W mass

η meson physics



- In the search for dark matter particles, the parameter space for traditional WIMP (GeV~100TeV) is gradually being excluded by experiments
- Light dark matter particles (MeV~GeV) are currently less constrained by experiments

η meson physics

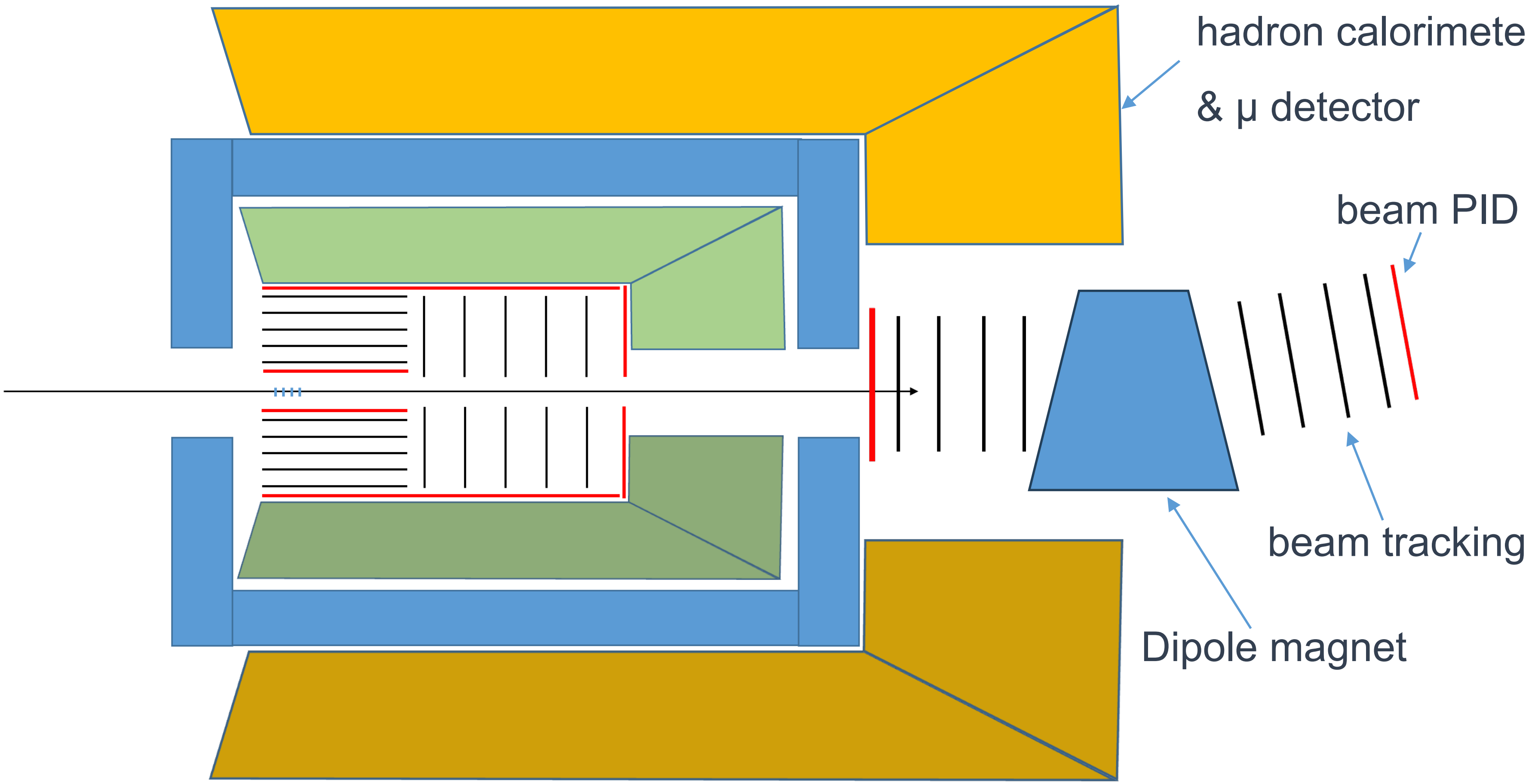
- η / η' mesons & Higgs are the only known particles with all-zero quantum numbers: $Q = I = J = S = B = L = 0$
  - Strong & EM decays forbidden in lowest order by various symmetry invariance.

  $\Rightarrow$ Branching ratio of processes from new physics are enhanced compared to SM

- Some examples:
  - Search for dark photon: $\eta \to \gamma A'$, $A' \to \mu^+\mu^-$, $A' \to e^+e^-$
  - Search for axion & axion like particles: $\eta \to \pi\pi a$, $a \to \gamma\gamma$, $a \to \mu^+\mu^-$, $a \to e^+e^-$
  - Search for dark scalar particles: $\eta \to \pi^0 H$, $H \to \mu^+\mu^-$, $H \to e^+e^-$
  - Test of CP invariance via Dalitz plot mirror asymmetry: $\eta \to \pi^0\pi^+\pi^-$
  - Lepton Flavor Universality studies: $\eta \to \mu^+\mu^- X$, $\eta \to e^+e^- X$

- These can be studied at the new spectrometer at HIAF

SRC with the new spectrometer – preliminary thoughts



- Since this spectrometer is very compact, hadron calorimeter with full coverage may be affordable

Summary

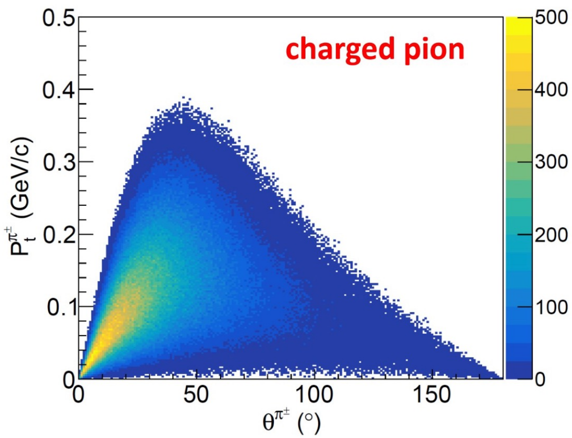
- CEE (@CSR & @HIAF) introduced,
  - QCD phase diagram & nuclear matter EOS
  - data taking next year
- SRC @ CEE is possible, with some upgrades
- New spectrometer at HIAF high energy terminal
  - + hypernuclear & light hadron physics & η meson physics
  - all silicon tracker, ultra-fast & compact
- SRC @ HIAF new spectrometer, possible with some new components added

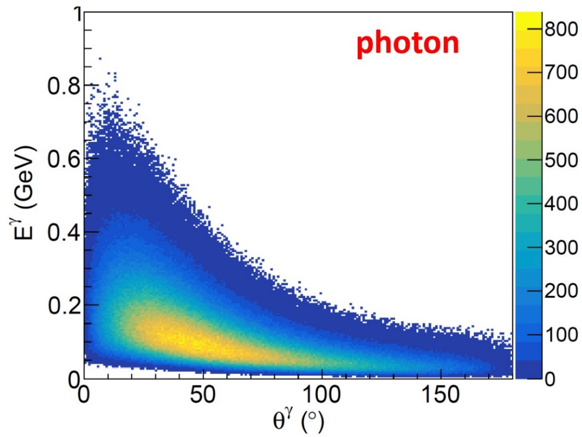
Thanks ☺

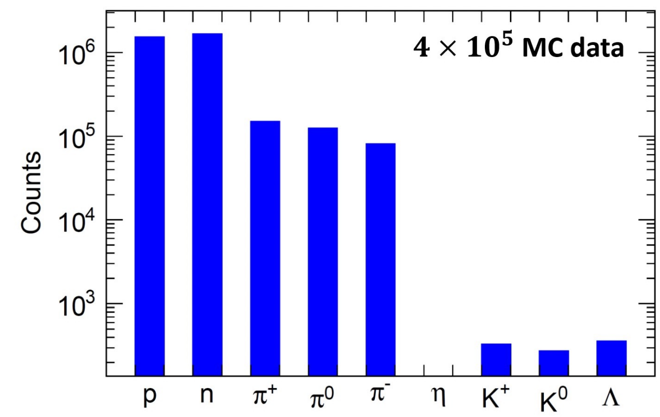
Back-up

Requirements – η meson physics

$\eta \rightarrow \pi^+\pi^-\pi^0(\gamma\gamma)$

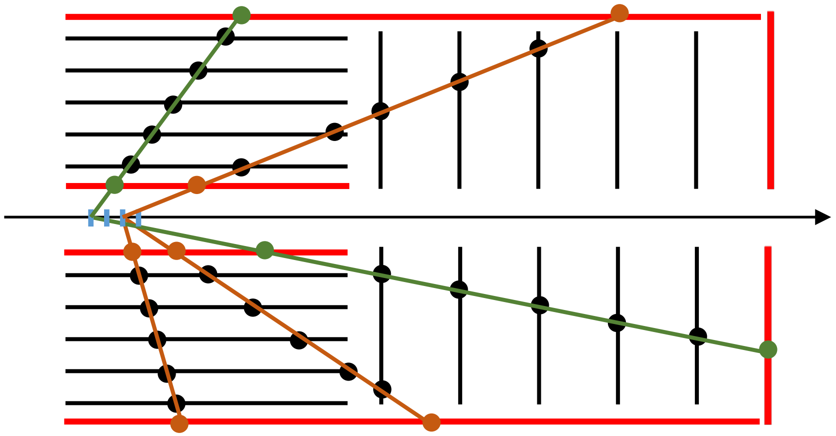






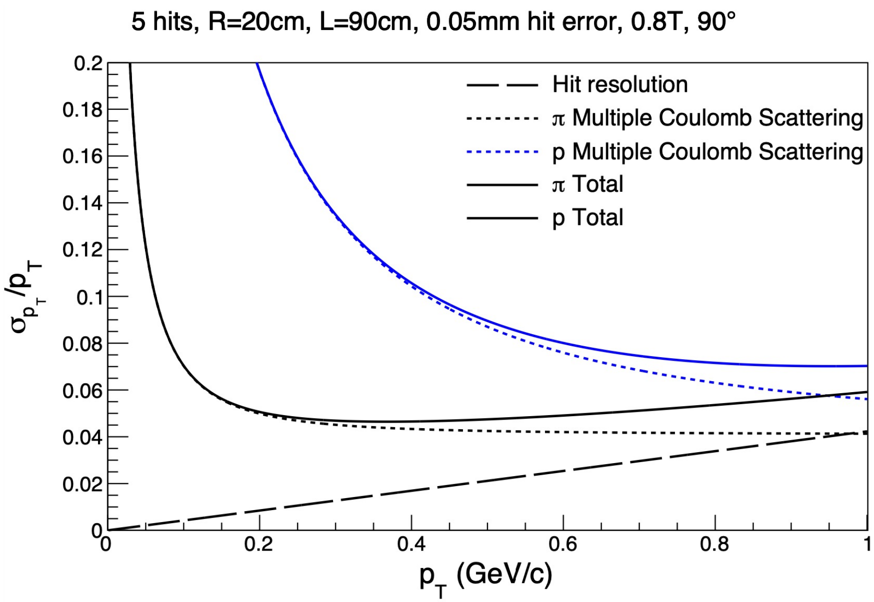
- 1.8 GeV p + ^{7}Li
- Measurement and identification of π^{+-}, e^{+-}, μ^{+-}, γ, acceptance as large as possible
  - Transverse momentum for charged particles: 50MeV-600MeV
  - γ energy: 50MeV-2GeV
  - To identify e^{+-} & μ^{+-}, π^{+-} background should be rejected with high efficiency, π^{+-}/e^{+-}~100 (e mainly from π^0)
  - To identify γ, neutron background should be rejected with high efficiency, n/γ~8 (γ mainly from π^0)
- Event rate >100MHz, to have statistics far beyond current data (REDTOP~500MHz)

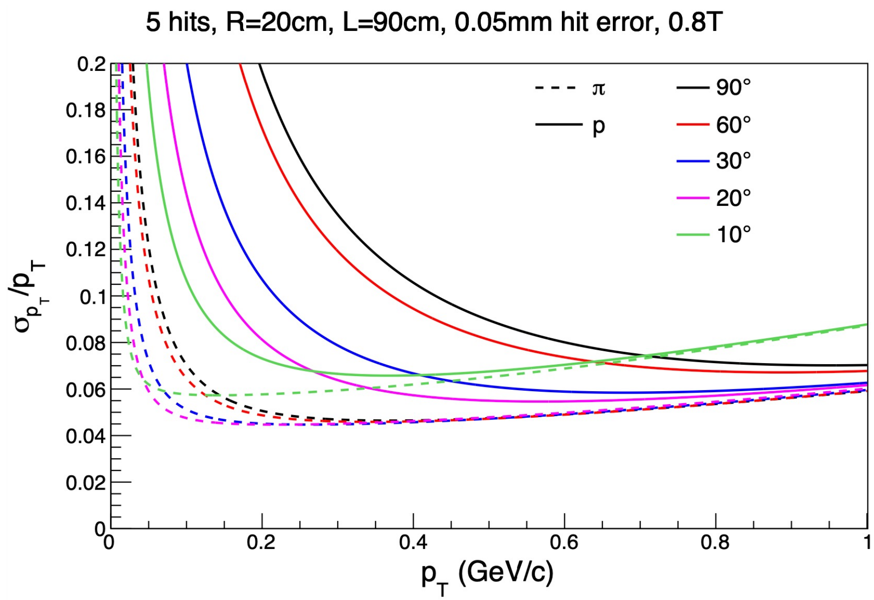
Pixel tracker



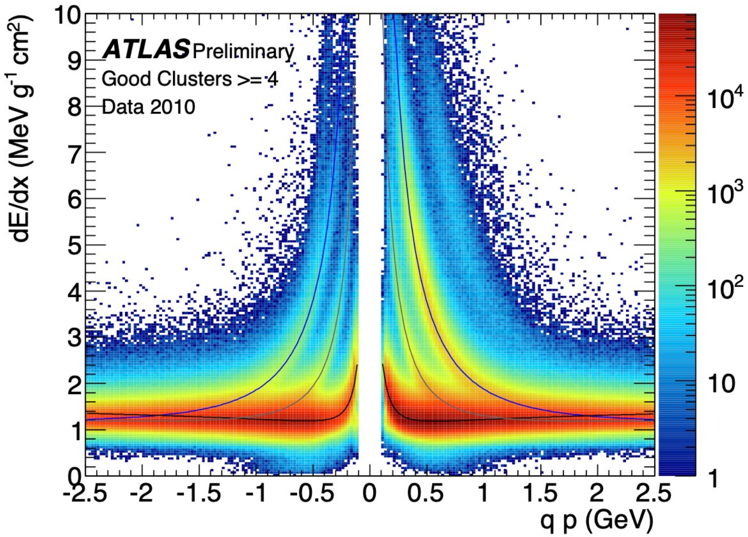
- 5 barrel layers + 5 disks
- Radius: 7.5-27.5cm, length~90cm
- 100μm pixel size
- Single pixel dead time ~1μs (1/MHz)
  - 100MHz event rate, 4 tracks (η physics)
  - ~10M pixels on the innermost layer, 4 pixel / hit
  - Chance of hit in dead time ~4*4/10M*100MHz/1MHz = 0.0002
- Energy & time dual readout, time resolutions <10ns (1/100MHz)
  - Can distinguish hits from different events with 100MHz event rate
  - For rare pile-up events, track-by-track separation with LGAD TOF hit
- Energy measurement dynamic range: 1-50 MIP
- Cluster reconstruction on sensor, to save DAQ band width and storage
- 2-3 yr for R&D needed for energy & time dual readout
- Area: 28000 cm^2 cost: 14M + 12M (R&D) Chinese yuan

Pixel tracker

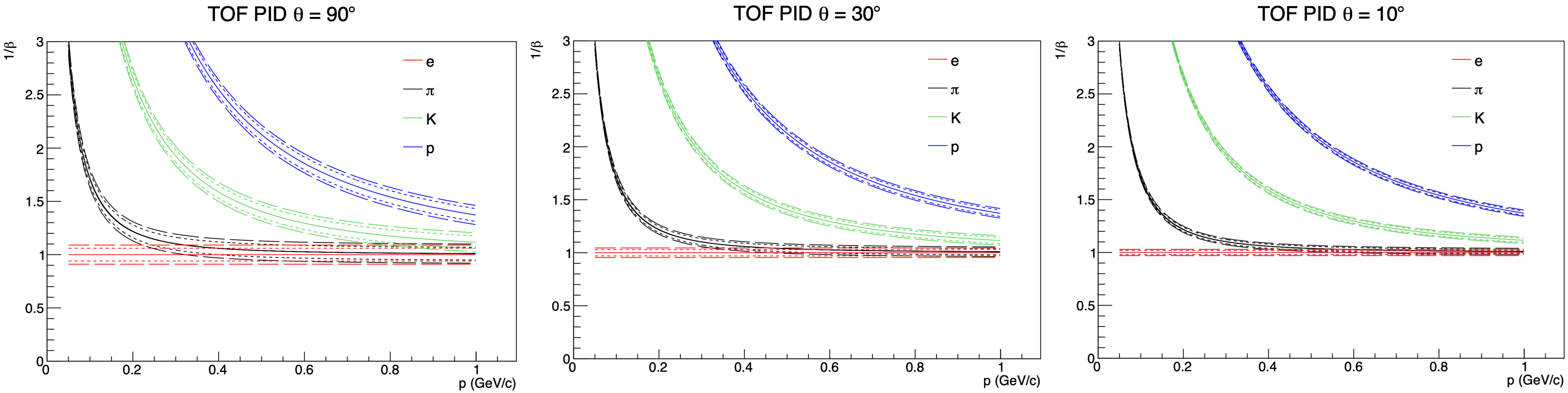




- With a magnetic field of 0.8 T, momentum resolution of 4-7% for most particles
- Particles with p_T as low as 50MeV can reach the outermost LGAD TOF layer, to ensure good efficiency at low p_T
- dE/dx measurement precise enough to identify light nuclei with different Z

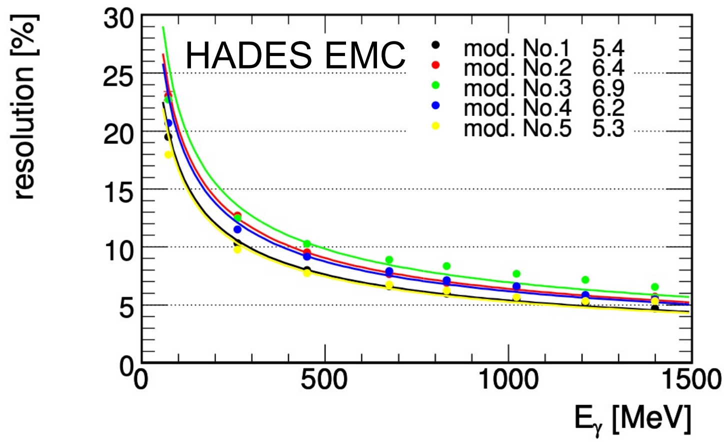


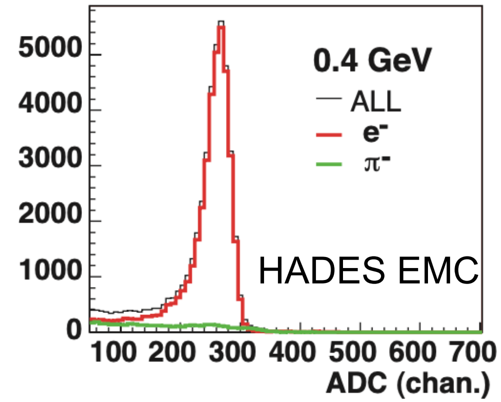
LGAD TOF



- Inner barrel + outer barrel + end cap
- Inner radius ~5cm, outer radius ~30cm, length ~100cm
- Time resolution ~30ps
- Good p, K identification; e / π separation (6σ) for p< 0.2 GeV/c for θ=90 degrees
- Smaller θ, longer track, better TOF PID ability
- Used by ATLAS
- Area: 22000 cm^2 cost: 33M Chinese yuan

Calorimeter

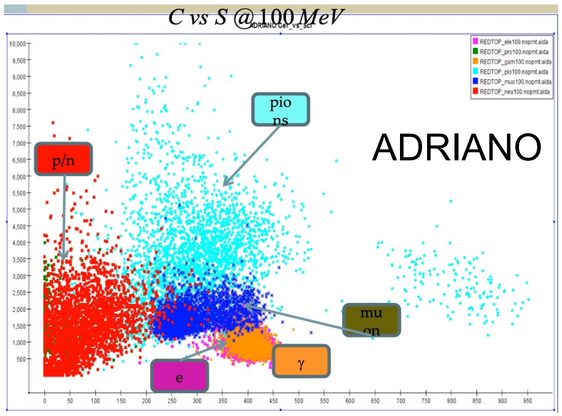


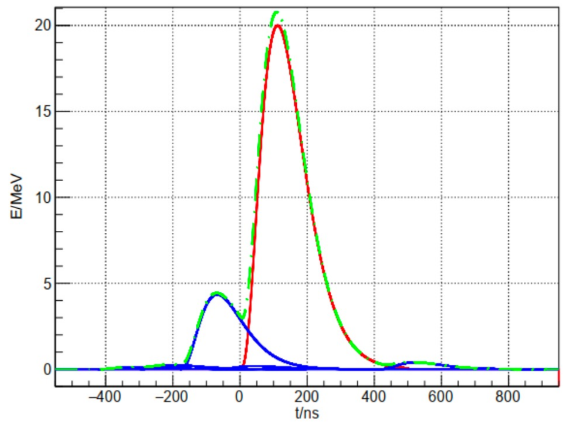


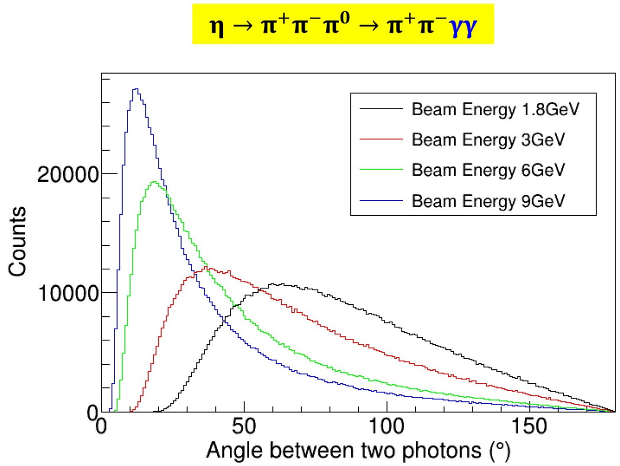
	ΔE/E @ 50MeV	ΔE/E @ 1GeV	Δt (ps)	Shaping time (ns)	reference	cost (M yuan)
Pb glass	~25%⇒	~6%⇒	215ps @ 0.8GeV	~500	HADES	~<10
Undoped CsI	~7%	~2%	600ps @ 1GeV⇒	~1000	STCF	~58
Pb + plastic scint.	~20%	~6%	~100ps @ 1GeV	?	NICA-MPD	~<10
ADRIANO2	~22%	~5%⇒3%	⇒80ps	?	REDTOP	167⇒

- Various techniques under consideration, detailed simulation going on to choose the best technique
- Pb glass: low energy hadrons in hadronic showers do not generate Cherenkov light. So n & π backgrounds will be suppressed comparing with γ & e.

Calorimeter

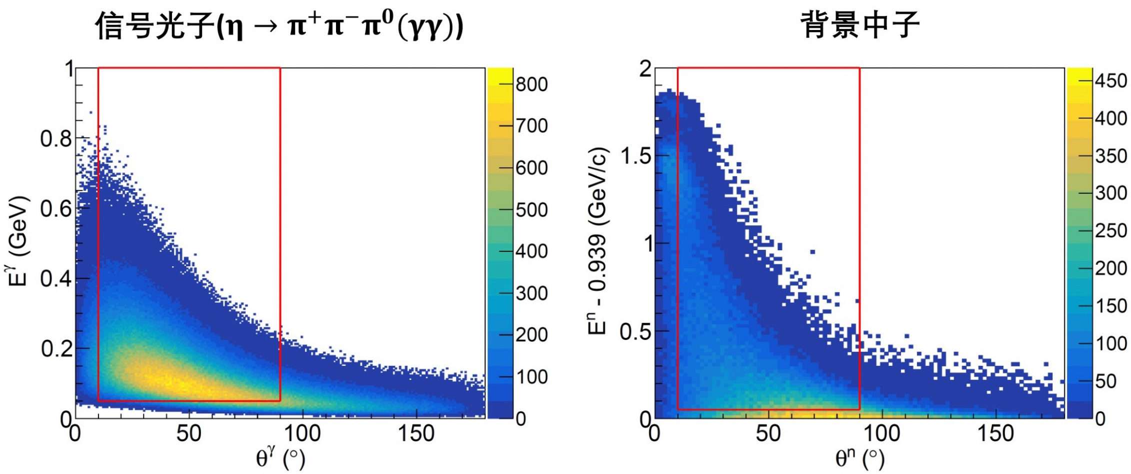


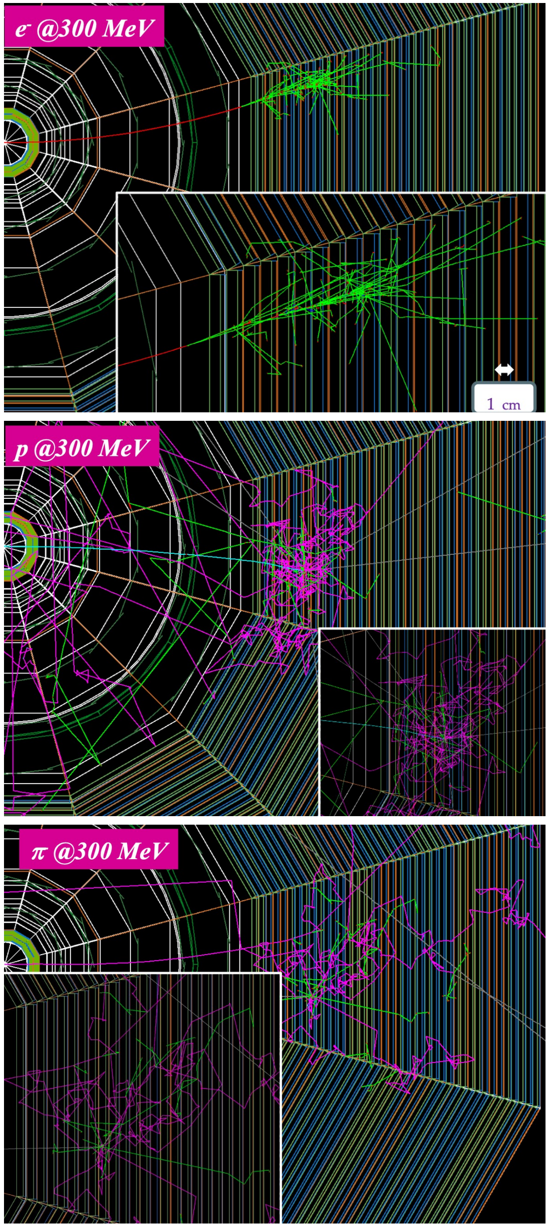




- ADRIANO2: Cherenkov light & scintillation light dual read out for PID
  - The 167M yuan cost include 40cm-thick EMC (high granularity) + 40cm-thick hadronic calorimeter (with stopping layers), EMC alone will be cheaper
- Sub-μs level module dead time (electronics shaping time) required, all the currently considered techniques should be OK
  - Event rate >100MHz, ~10 modules hit / event (4p+4n), ~1000 modules
  - Contributions from pile-up events can be obtained by fitting the signal shape
- The angle between 2 γ from π^0 is usually large, no high requirement for granularity
- Radiation dose (both ionization and neutron) are being estimated with simulation

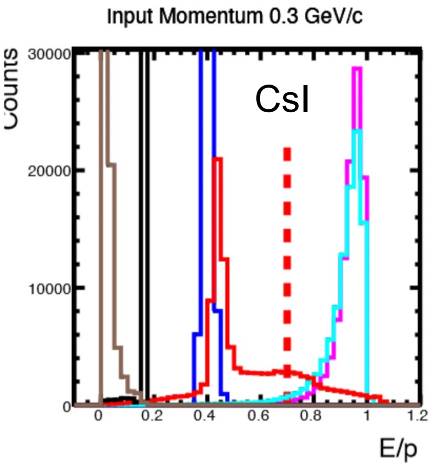
γ-n & e-π identification

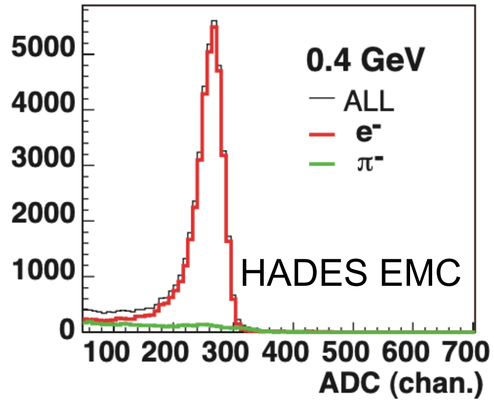


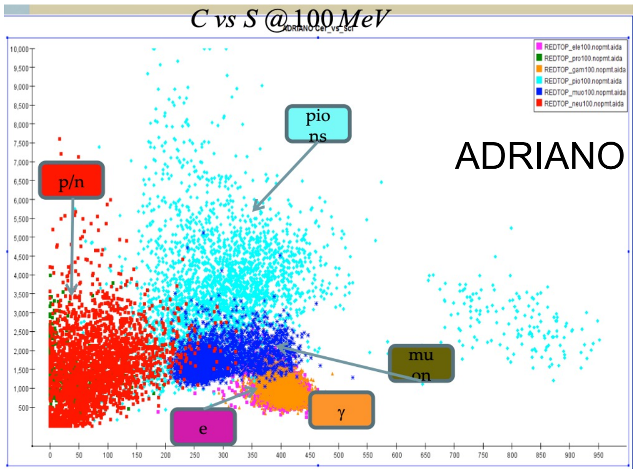


- n/γ~8   π/e~100
- Whether the shower happens
  - Pb glass radiation length 1.27cm, nuclear interaction length 24.5cm
  - For 12 radiation lengths, the chance that a neutron does not interact ~54%
- Dimension and shape of the shower
  - signal concentrated in 1 module vs. spread over many modules

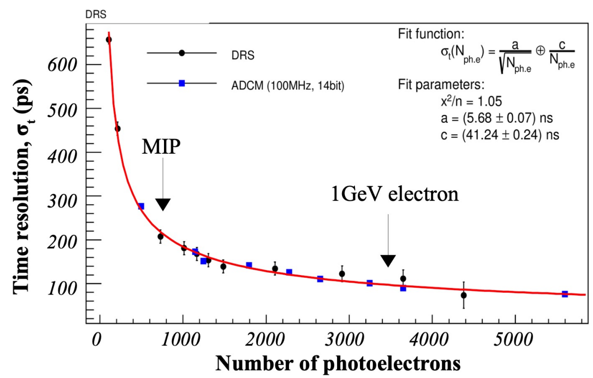
γ-n & e-π identification



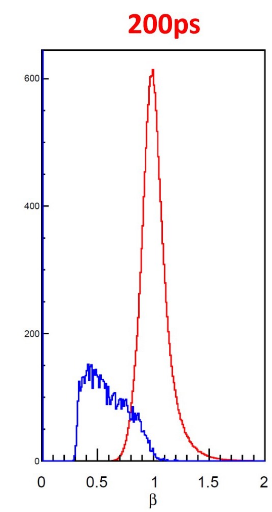




- Electron E/p~1 (only appliable to e-π)
- Low energy hadrons in hadronic showers do not generate Cherenkov light:
  - Pb glass: lower signal for hadrons
  - ADRIANO2: dual read out



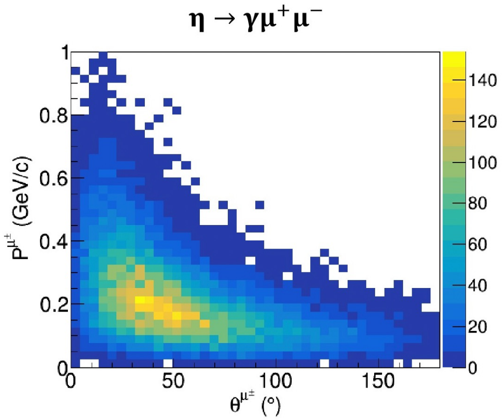
NICA-MPD EMC

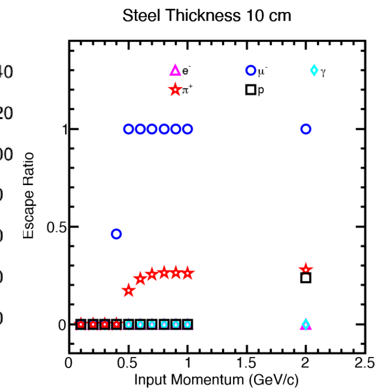


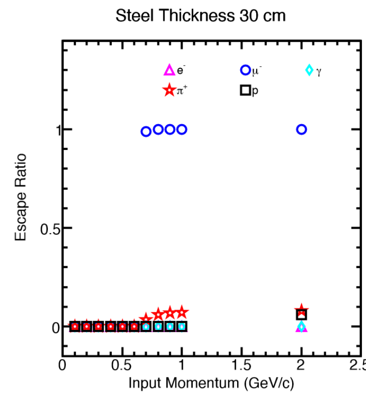
reconstructed γ/n velocity

- Time of flight
  - ~200ps time resolution will provide some γ-n separation
  - However, time resolution usually get worse for lower signals
- GEANT simulation on-going to study γ-n & e-π separation for different techniques

μ detector







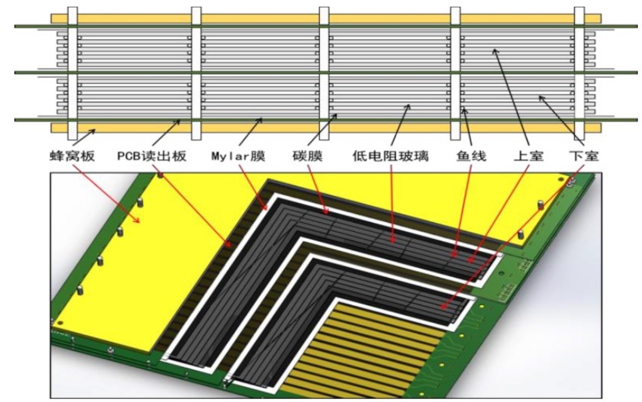


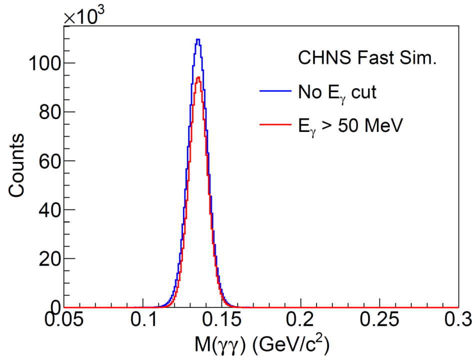
图 10 eTOF MRPC 结构示意图。

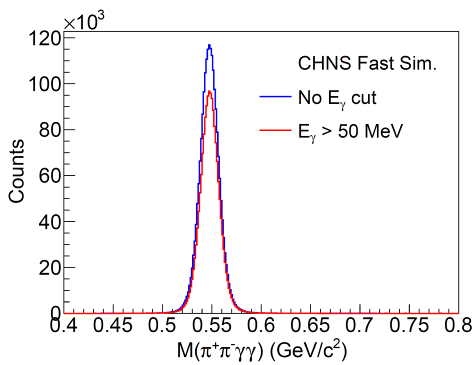
- MRPC, like CEE/STAR TOF
- With 25cm CsI + 30cm Fe stopping material, μ^{+-} with p>0.7GeV/c can be chosen, π^{+-} suppressed by 1 order of magnitude, other hadrons fully stopped
- Less stopping material, μ^{+-} with lower p can be detected, but lower π^{+-} suppression
- Read out strip pitch 25mm; 2-side readout provides position information along the strip: 100ps*c=30mm ⇒ 2D cm-level position resolution
- Time resolution ~70ps, 4D match to track
- Inside & outside the magnet yoke in the current design, can add more layers for different stopping material thicknesses
- Area ~11 m^2 cost: 5M yuan

Data rate

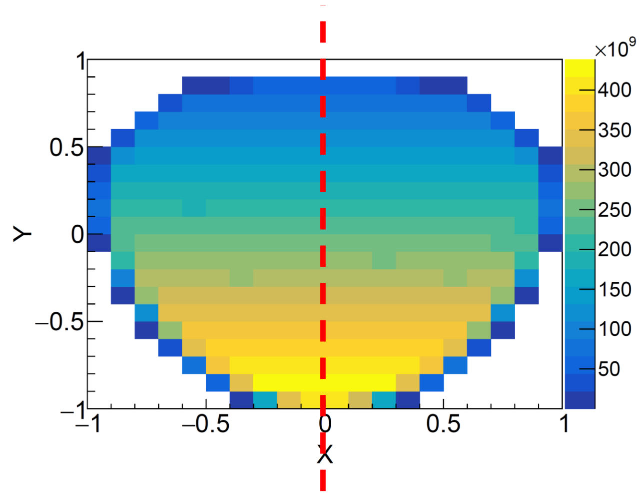
- Heavy ion physics:
  - 1MHz
  - ~100 track
  - 7 hits / track
  - 1M*100*6 = 700M hits / s
- η meson physics:
  - ~>100MHz
  - ~4 track
  - 6 hits / track
  - 100M*4*6 = 2400M hits / s
- If clusters (hits) reconstructed on pixel sensors, data rate on the same order of magnitude as CEE
- CEE for reference:
  - 10kHz
  - ~100 track
  - ~30 hits / track
  - ~20 digi / hit
  - 10k*100*30*20 = 600M digi / s

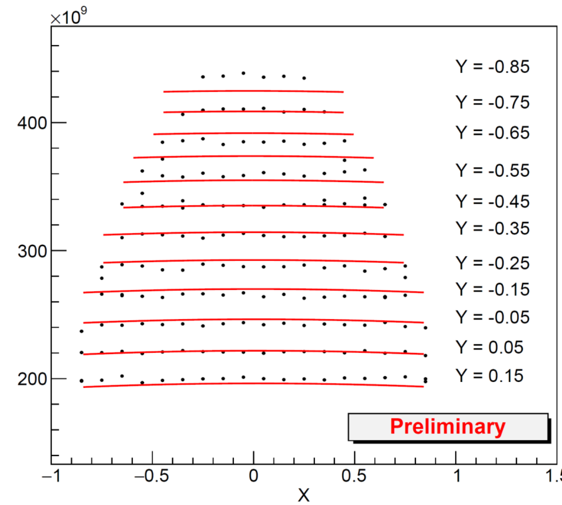
(Very preliminary) $\eta \rightarrow \pi^+ \pi^- \pi^0 (\gamma\gamma)$ fast simulation





$$|A(X,Y)|^2 \simeq N(1+aY+bY^2+cX+dX^2+eXY+fY^3+gX^2Y+hXY^2+lX^3+\ldots)$$





NO.	NAME	VALUE	ERROR
1	N	2.34197e+11	7.64137e+04
2	a	-1.04898e+00	1.49290e-06
3	b	-2.02919e-01	1.97655e-06
4	c	5.23094e-04	4.40604e-07
5	d	-1.63753e-02	9.30251e-07
6	e	1.49152e-03	1.69850e-06

$c = -0.007 \pm 0.009(\text{stat})$, **WASA@COSY**

$e = -0.020 \pm 0.023(\text{stat}) \pm 0.029(\text{syst})$

- Considering p & E resolution
- Background not considered yet (future work)
- Total reconstruction efficiency ~16%
- Assuming constant beam intensity
- ~6.4*10^{13} η with 1 month running
- 4 orders of magnitude more precise than COSY result

Budgets

子系统	所需经费（万元）
Topmetal-S 芯片	350
读出电子学及数据获取系统	120
TPC 场笼	74
高压气腔及铜屏蔽体	61
气路系统	44
外屏蔽体	260
气密洁净间	320
SeF_6 气体	350
总计	1579

表 7. 各子系统未来完成研制所需经费

项目名称	总经费（万元）	结余经费（万元）
国家重点研发计划 2022YFA1604703（支持 NνDEx 实验部分）	441.6	428.4
国家重点研发计划青年项目 2021YFA1601300（直接经费）	395	322
中国科学院从 0 到 1 原始创新计划 ZDBS-LY-SLH014	240	41.5
中国科学院国际合作伙伴计划 GJHZ2067	100	4.9
国家自然科学基金委青年科学基金项目 12105110	30	20.4
总计	1206.6	817.2

表 8. NνDEx-100 探测器研制经费来源