1st Workshop on Physics at High Baryon Density
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The opportunities of CEE in the studies of nuclear EOS

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Content

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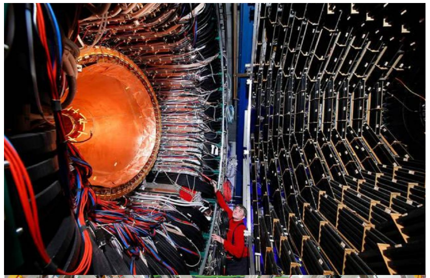
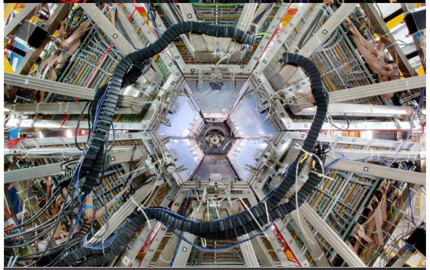
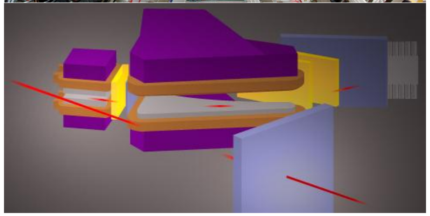
    - 2.1 CEE：Physical programs of EOS related studies
    - 2.2 HIAF：Towards higher density

3. Summary

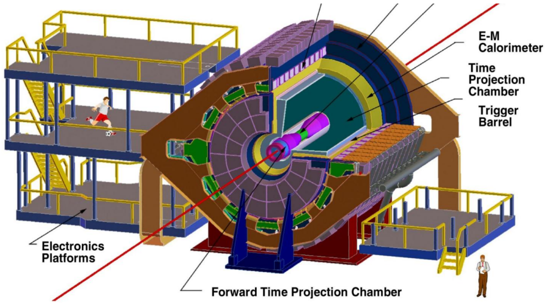
Main world experiments in GeV/u regime


One of the main goals of heavy ion collisions, is to infer the EOS of nuclear matter (NEOS).

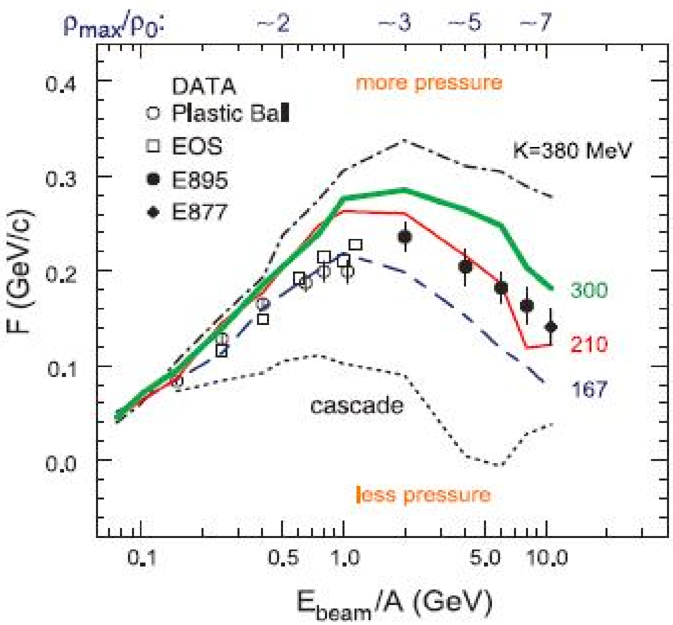
In the last decades, a lot world experiments did intensively studies on NEOS.

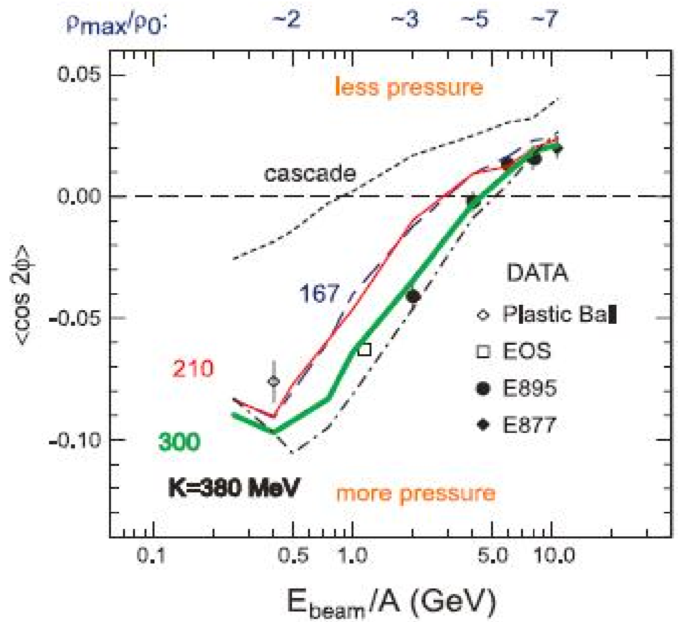
1. Plastic Ball at Bevalac
   PRC 42, 640 (1990) ...
2. EOS at Bevalac
   PRL 78, 2535 (1997); RPC 76, 3911 (1996); PRL 75, 2662 (1995) ...
3. FOPI at SIS
   NPA 876, 1 (2012); NPA 848, 366 (2010); NPA781, 459 (2007) ...
4. KAOS at SIS
   PRL 96, 072301 (2006); PRL 95, 012301 (2005) ; PRL 86, 1974 (2001)...
5. HADES at SIS
   PRL 125, 262301 (2020); PRL 123, 022002 (2019) ; PRC 102, 024914 (2020) ...
6. SπRIT at RIBF
   PRL 126, 162701 (2021); PLB 822, 136681(2021); PLB813, 136016 (2021)...
7. STAR-BES at RHIC
   PRL128, 202303 (2022); PLB827, 137503 (2022)...
8. LAMPS at RAON
   NIMB B 541 (2023) 260–263



and a lot more literatures...

Extract EOS from flow (v_1, v_2)



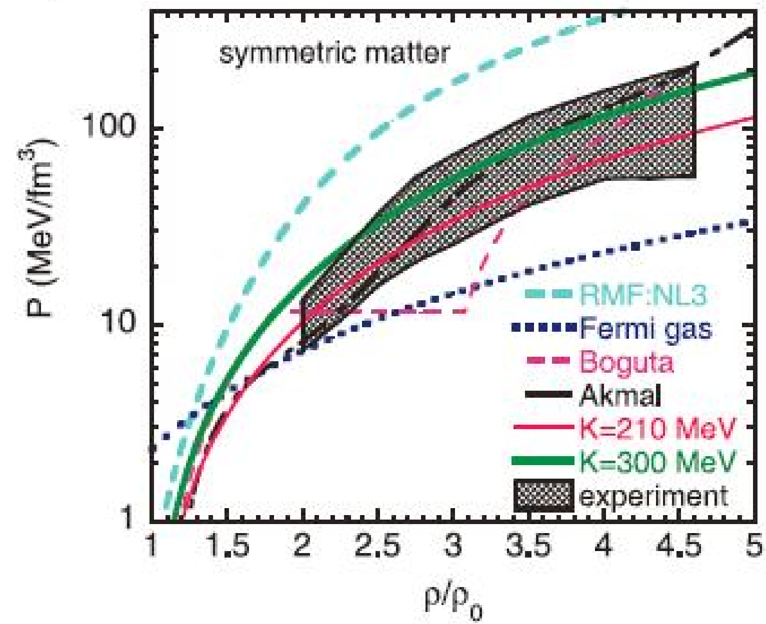


Matter compressions occur when two nuclei collide. Pressure gradient appears, leading to collective flow.

$$\frac{dN}{u_t du_t dy d\phi} = v_0[1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi)]$$

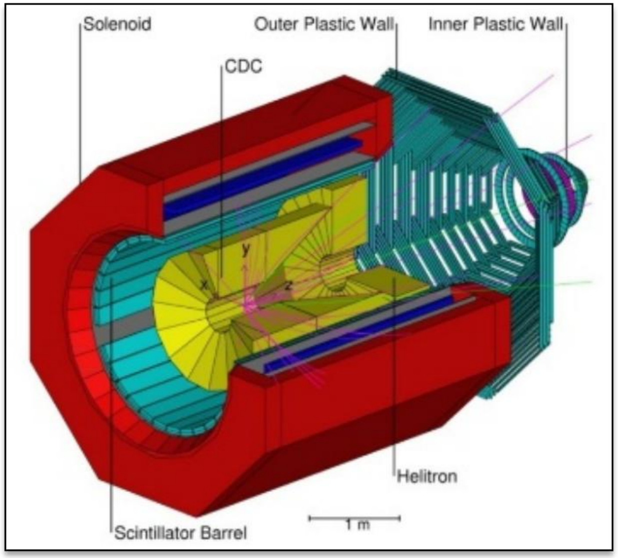
$$v_1 = \left\langle \frac{p_x}{p_t} \right\rangle = \langle \cos(\phi) \rangle,$$

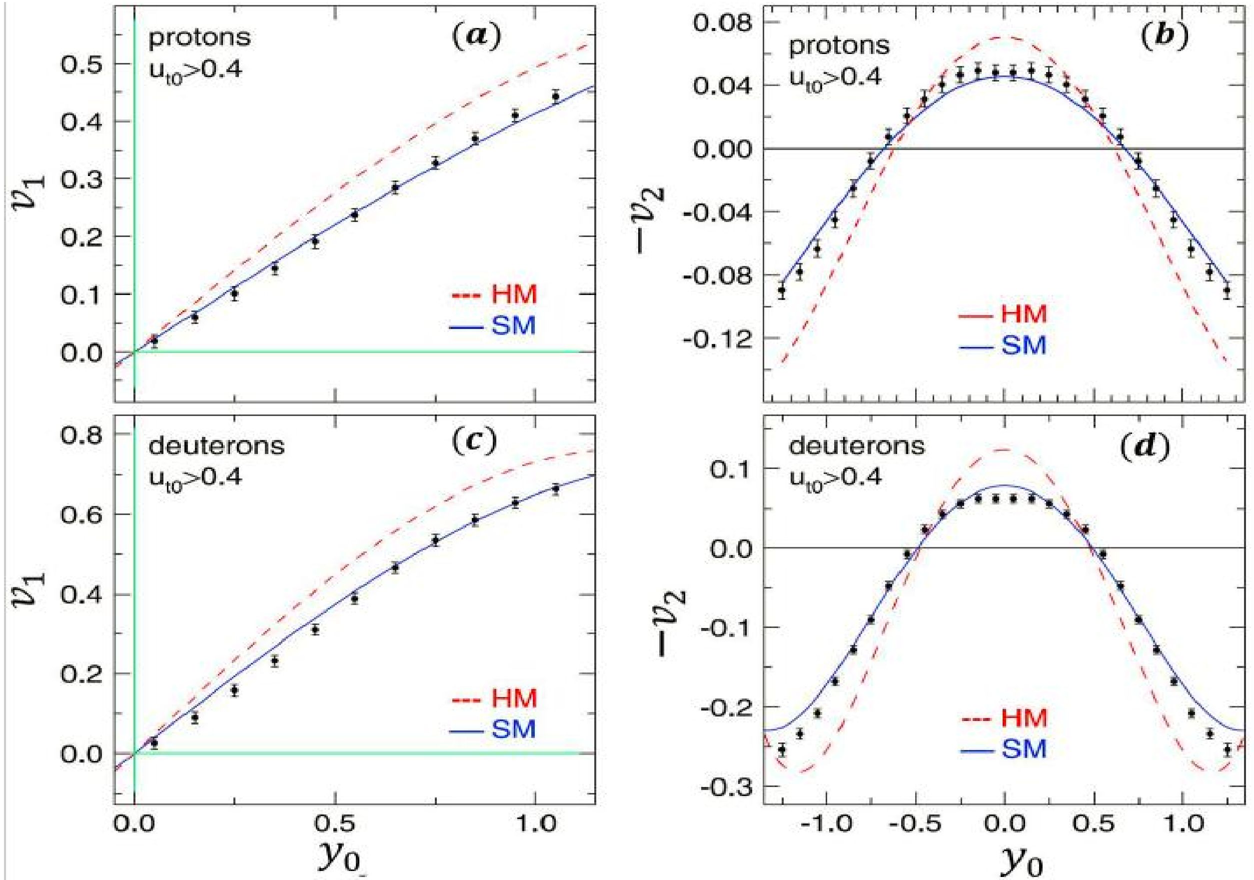
$$v_2 = \left\langle \left(\frac{p_x}{p_t}\right)^2 - \left(\frac{p_y}{p_t}\right)^2 \right\rangle = \langle \cos(2\phi) \rangle$$



P. Danielewicz, R. Lacey, and W. G. Lynch. Determination of the equation of state of dense matter. **Science**, 298,1592 (2002)

Extract EOS from flow (v_1, v_2)



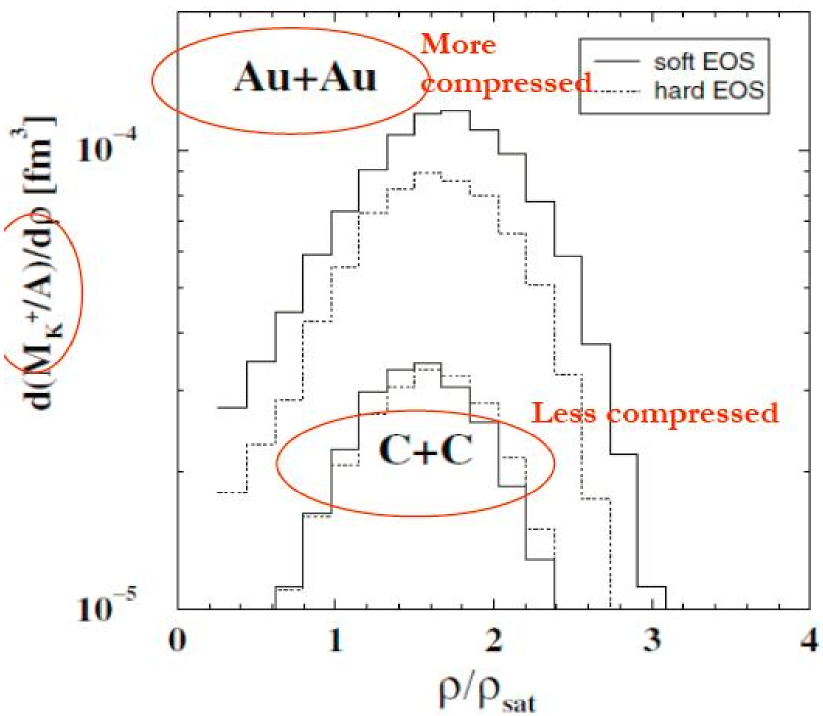


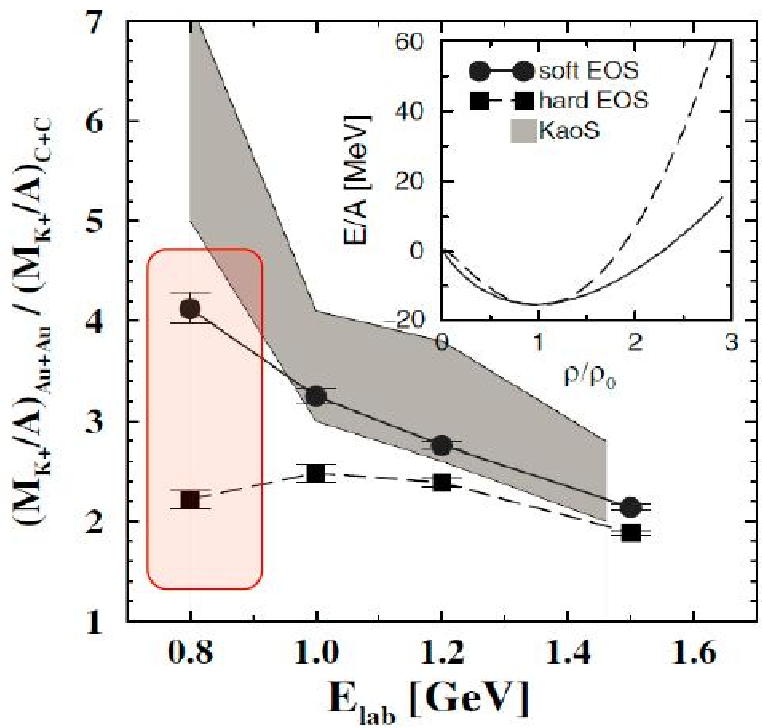
$$v_i = v_i(u_t, y)$$

Systematics of azimuthal asymmetries in heavy ion collisions in the 1 AGeV regime
W. Reisdorf et al for FOPI collaboration, **NPA 876**, 1 (2012)

Extract EOS from yield of K^+ meson

Extract EOS from near-threshold meson production





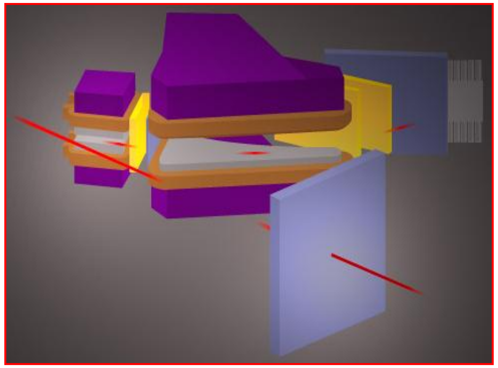
$B+B \rightarrow N+Y+K^+ \quad (Y = \Lambda \; or \; \Sigma)$

$\pi + B \rightarrow Y + K^+$

J. Aichelin and Che Ming Ko, **PRL** 55,2661 (1985)

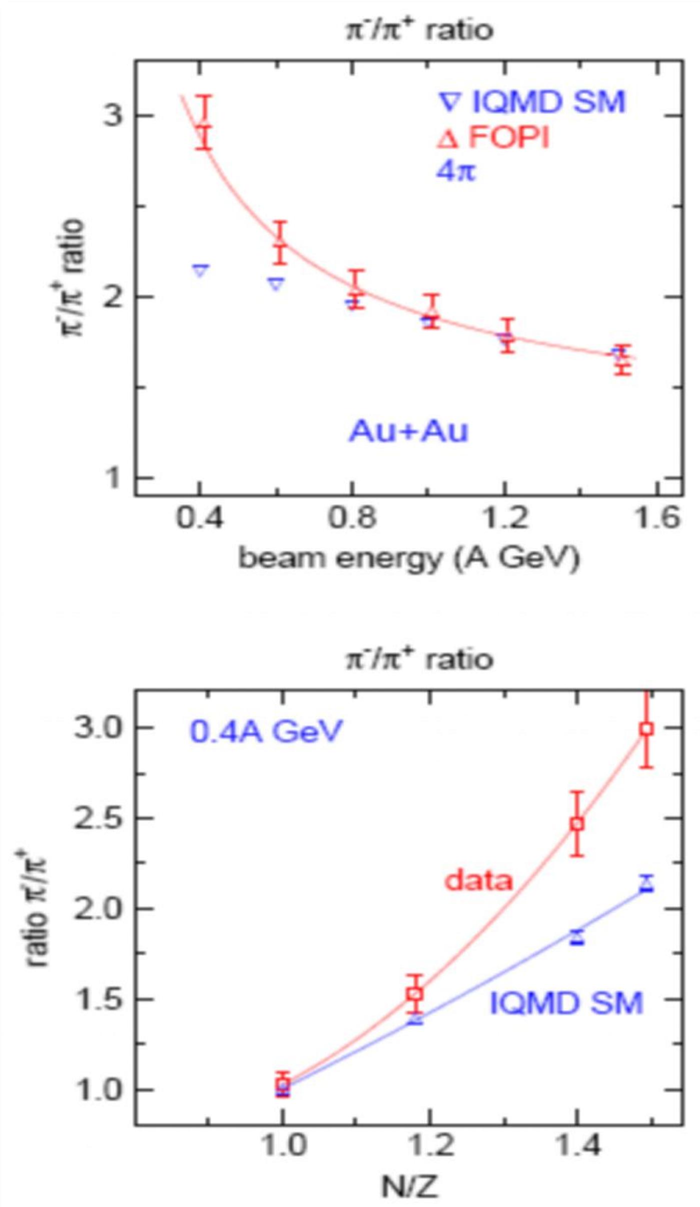
C. Fuchs et al., **PRL** 86, 1974 (2001)

Insensitive in light system C+C; Higher sensitivity found at lower energies



KaoS Collaboration

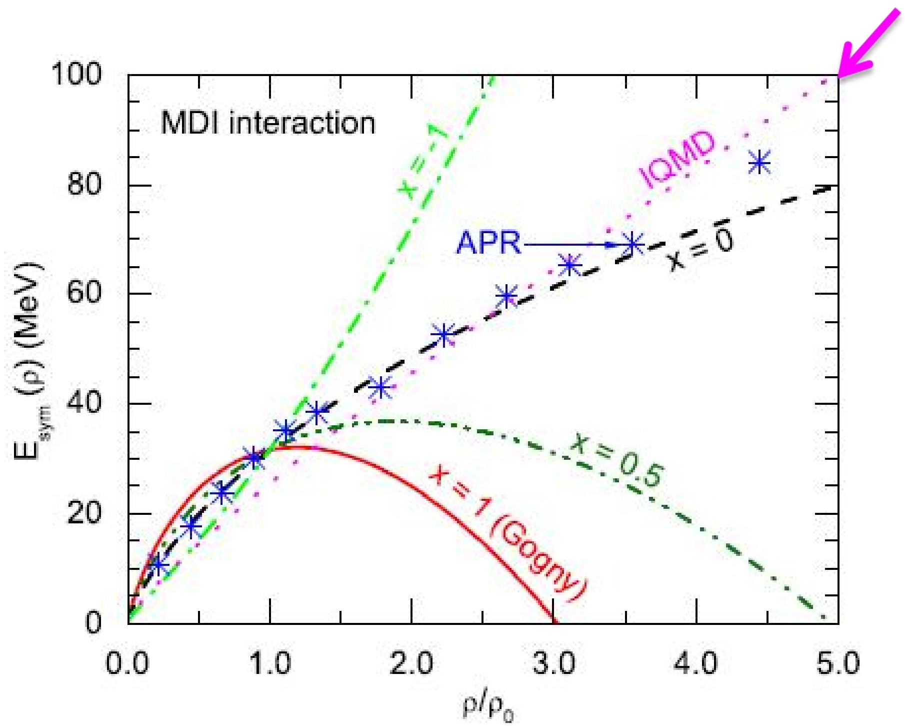
Extract $E_{\mathrm{sym}}(\rho)$ from π^-/π^+ yield ratio



IQMD: C. Hartnack et al, **EPJA** 1 (1998) 151

$$V_{sym}^{ij} = t_6 \frac{1}{\rho_0} T_{3i} T_{3j} \delta(\vec{r}_i - \vec{r}_j), \quad t_6 = 100 \text{ MeV}$$

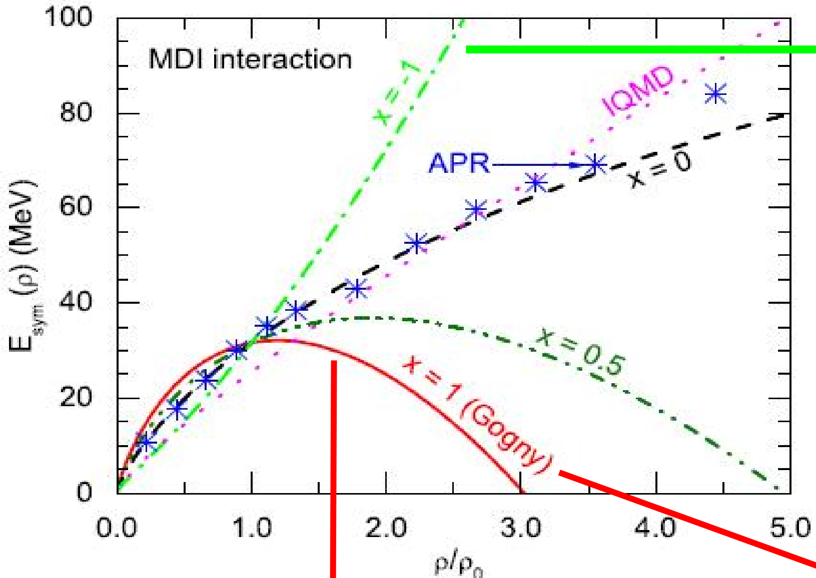
$$E_{\mathrm{sym}}(\rho) = \frac{25}{2}\frac{\rho}{\rho_0} + (2^{2/3} - 1)\frac{3}{5} E_{\mathrm{F}}^0 \left(\frac{\rho}{\rho_0}\right)^{2/3}$$

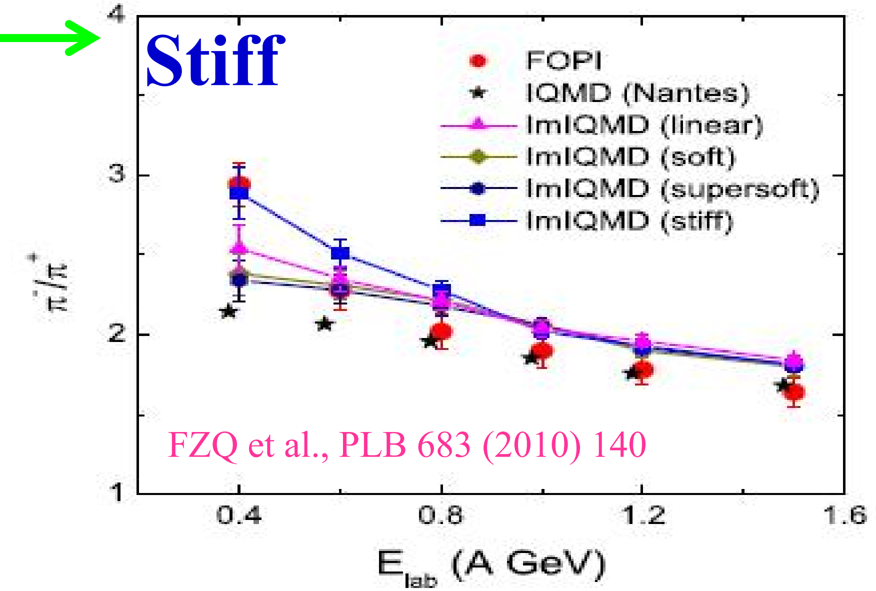


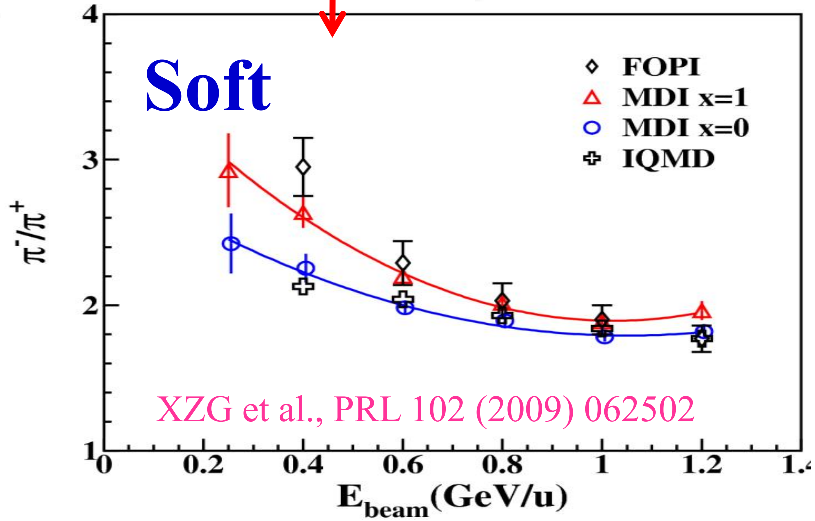
Need a softer symmetry energy to make the pion production region more neutron-rich!

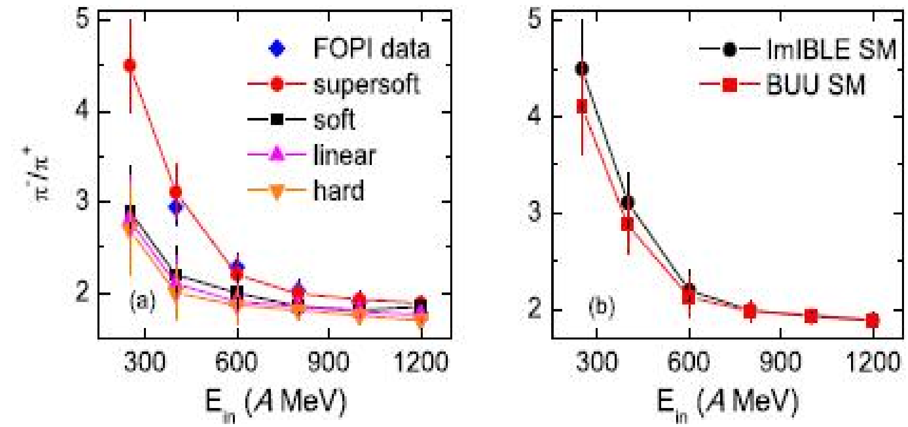
FOPI collaboration , NPA781 (2007) 459

Model dependence of the probe π^-/π^+ yield ratio









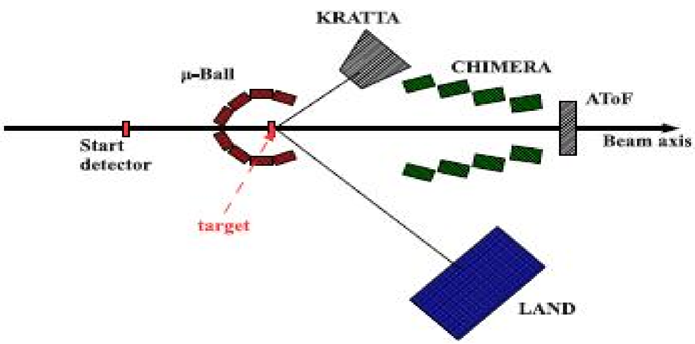
XWJ et al., PLB 718 (2013) 1510

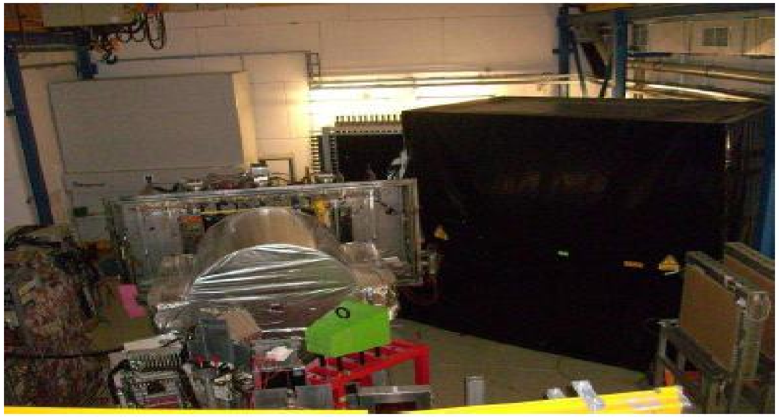
or insensitive on γ

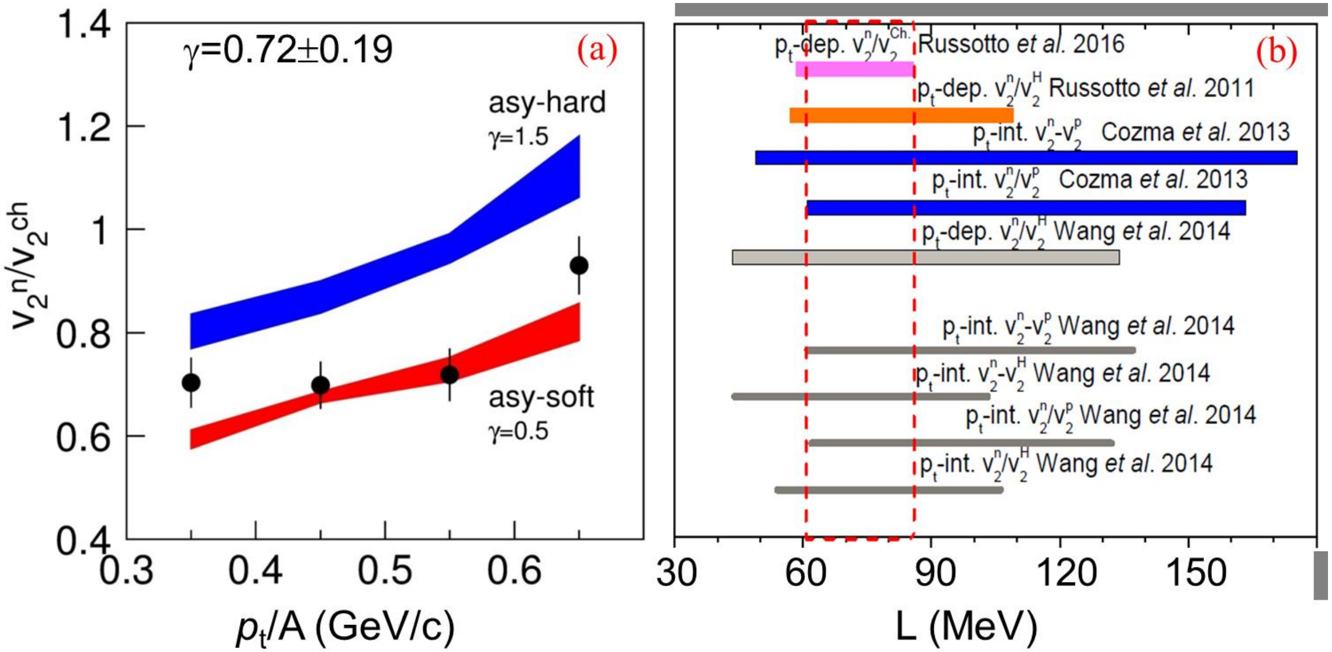
J. Hong et al, PRC 90,024605(2010)

Extract $E_{sym}(\rho)$ from n/p differential flow

AnSYS-EOS Collaboration







Y. Leifels et al
PRL71,963 (1993)

Russotto et al.,
PLB 697,471 (2011);
PRC 94, 034608 (2016)

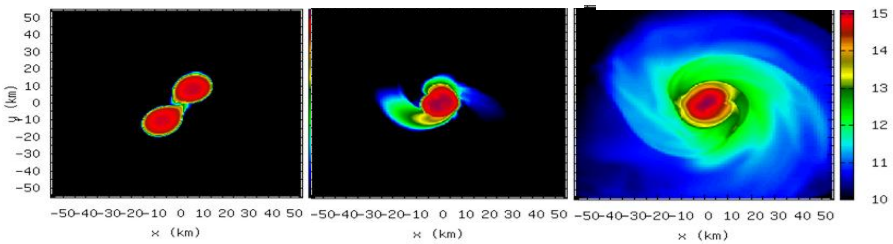
$$E_{sym}(\rho) = 12(\rho/\rho_0)^{2/3} + 22(\rho/\rho_0)^{\gamma}$$

Y. J. Wang et al, **Frontiers of Physics**, 15(4):1, 2020.

$E_{\mathrm{sym}}(\rho)$ constraint from Neutron star GW170817

The observation of GW170817 remarkablely stimulate the study of $E_{\mathrm{sym}}(\rho)$...

$t = 10$ ms $t = 11.2$ ms $t = 13.9$ ms



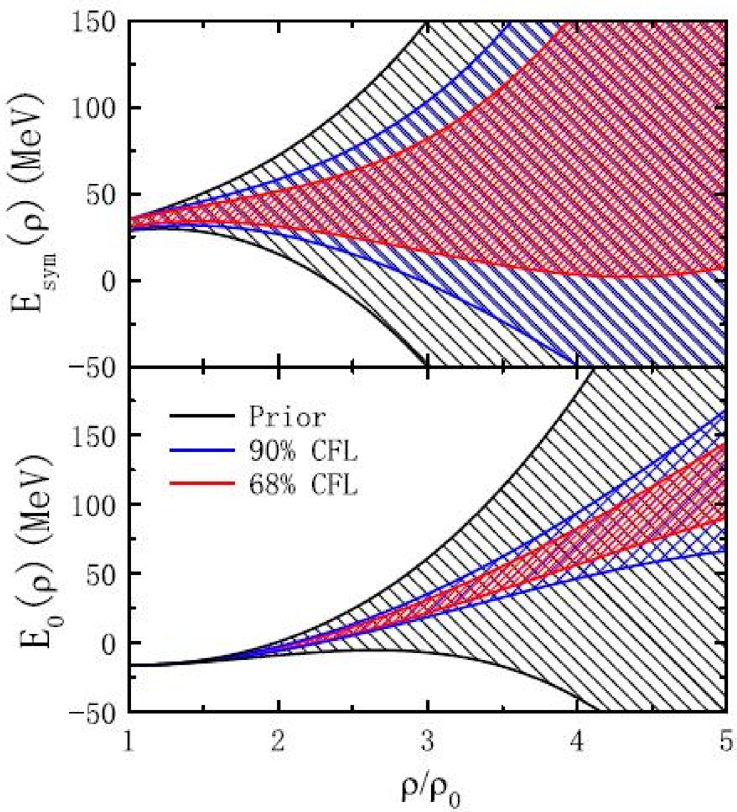
$R_{1.4} = 11.9^{+1.4}_{-1.4}\ km$, PRL, 121, 161101,2018; $R_{1.4} = 10.8^{+2.1}_{-1.6}\ km$, PRL, 121, 091102,2018

1. Bayersian analysis

$$E_{sym}(2\rho_0) = 39.1^{+12.1}_{-8.2}\ \mathrm{MeV}\ (1\sigma)$$

W. J. Xie et al., **APJ 883**,174 (2019)

N. B. Zhang et al., **APJ 879**, 99(2019)



Combining GW170817 /PSRJ0740+6620 and HICdata

2. Combine the GW1708 and nuclear data:
Y. Zhou et al., **PRD99** 121301(R) (2019)

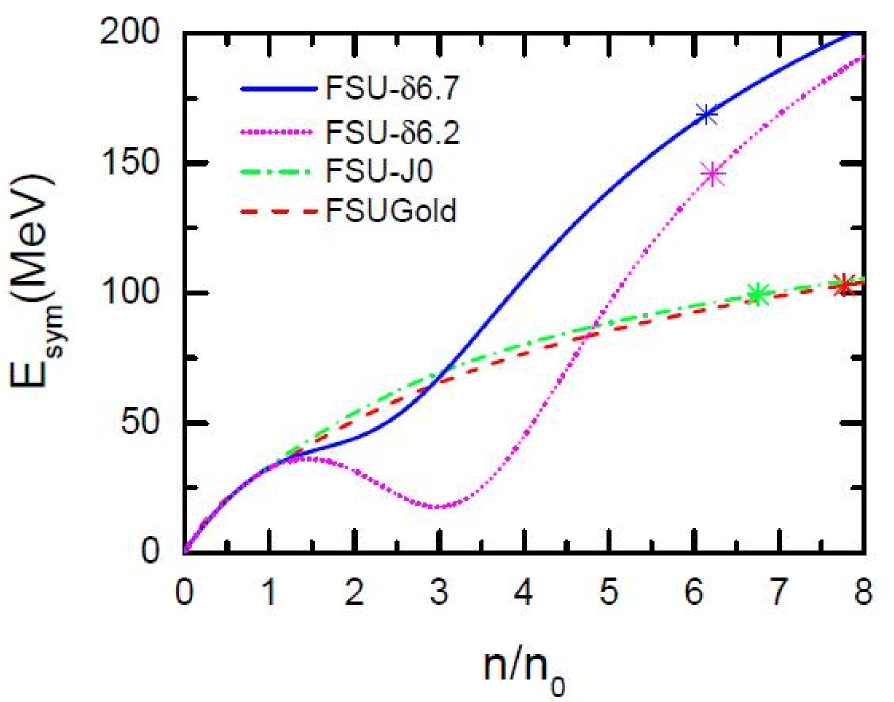
→ $L(N_c) = 47.3 \pm 7.8$ MeV
$E_{sym}(2\rho_0) = [39.4^{-6.4}_{+7.5}, 54.5^{-3.2}_{+3.1},]$MeV

3. Taking $\delta - \sigma$ coupling into account，two RMF parameter sets are suggested

FSU-δ6.7, FSU-δ6.2

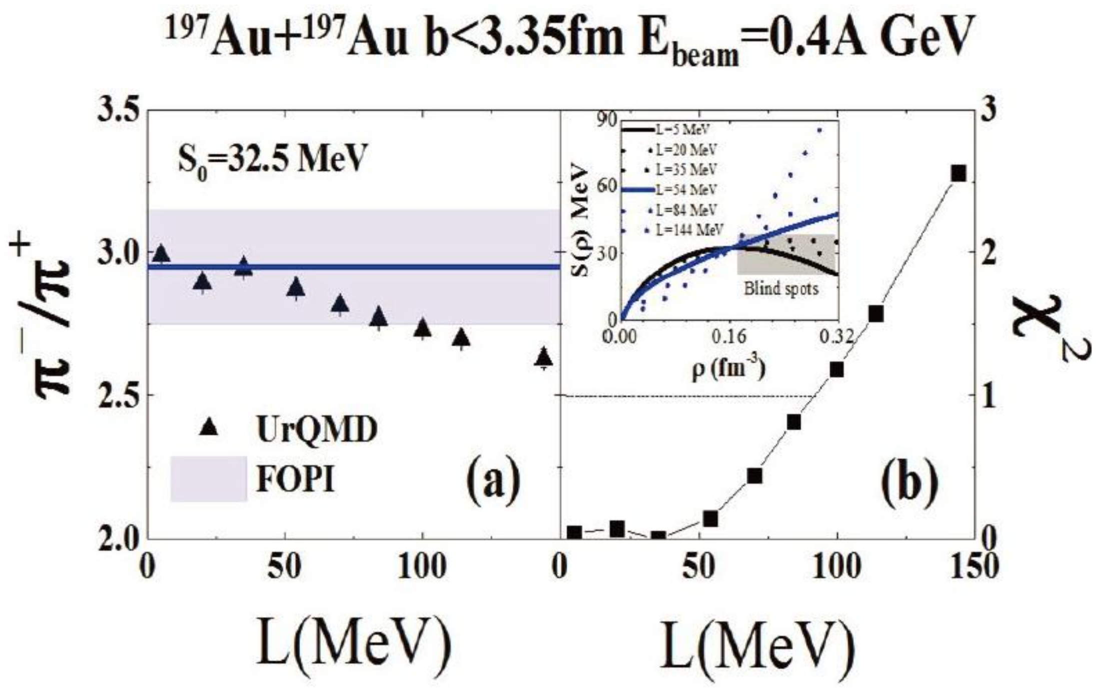
F. Li et al., ApJ 929, 183 (2022)

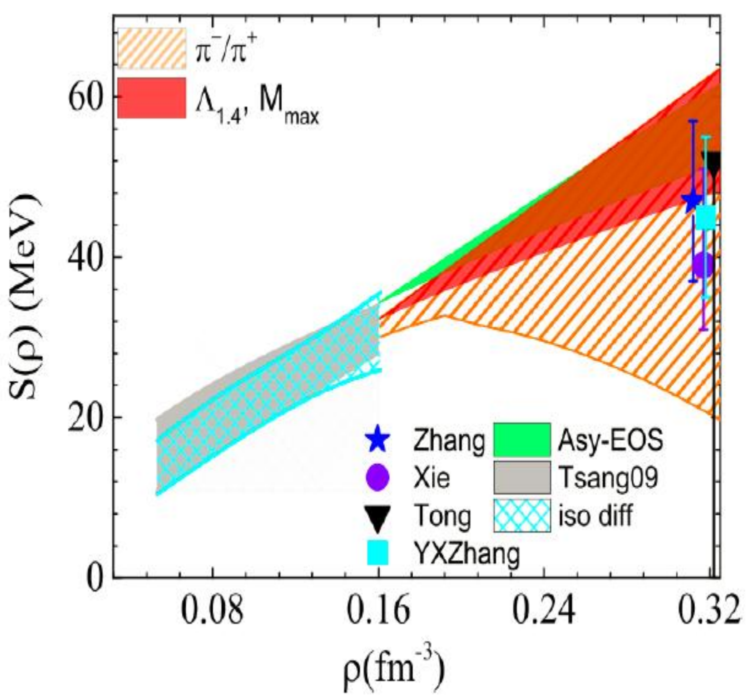
Slope parameter at ρ_0：
$L(\rho_0) = 53.5$ MeV， 48.2 MeV



Combining GW170817 and HICdata

π^-/π^+ yield ratio is complicated, for which enormous studies emerge on the production and transport of π mesons, including threshold effect, medium effect, π optical potential, π-Δ loops etc. Jun Xu, Yingxun Zhang, C-M Ko, Dan Cozma et al.

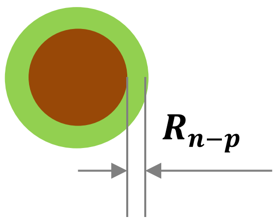




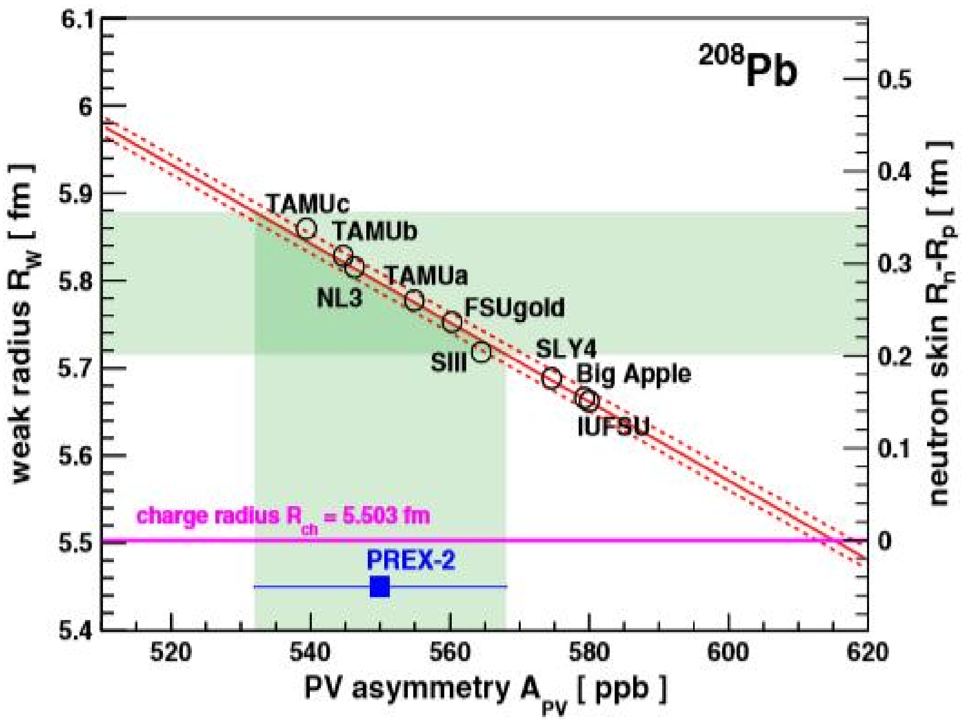
Combine GW170817/HIC: $54 < L < 91$ MeV 【Y.Y. Liu et al., **PRC 103**, 014616 (2021)】

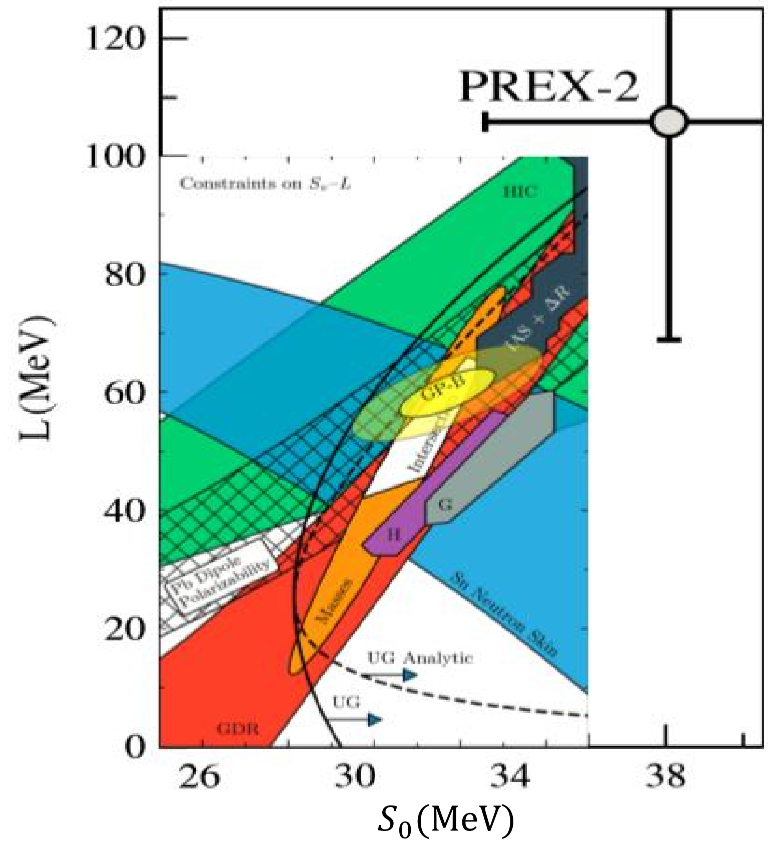
Progress of PREX experiment

^{208}Pb



PREX : PV scattering of $e + {}^{208}$Pb to determine the neutron skin thickness of ^{208}Pb





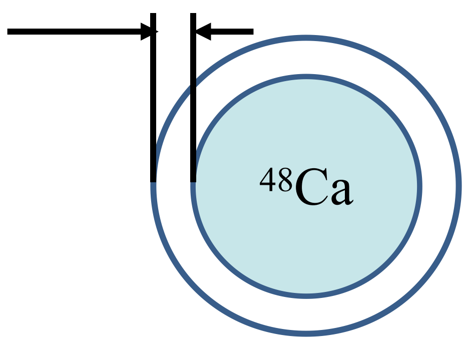
$R_{n-p} = 0.283 \pm 0.071$ fm
$L = 106 \pm 37$ MeV

PREX collaboration., PRL 126, 172502 (2021)
B. T. Reed et al, PRL 126, 172503 (2021)

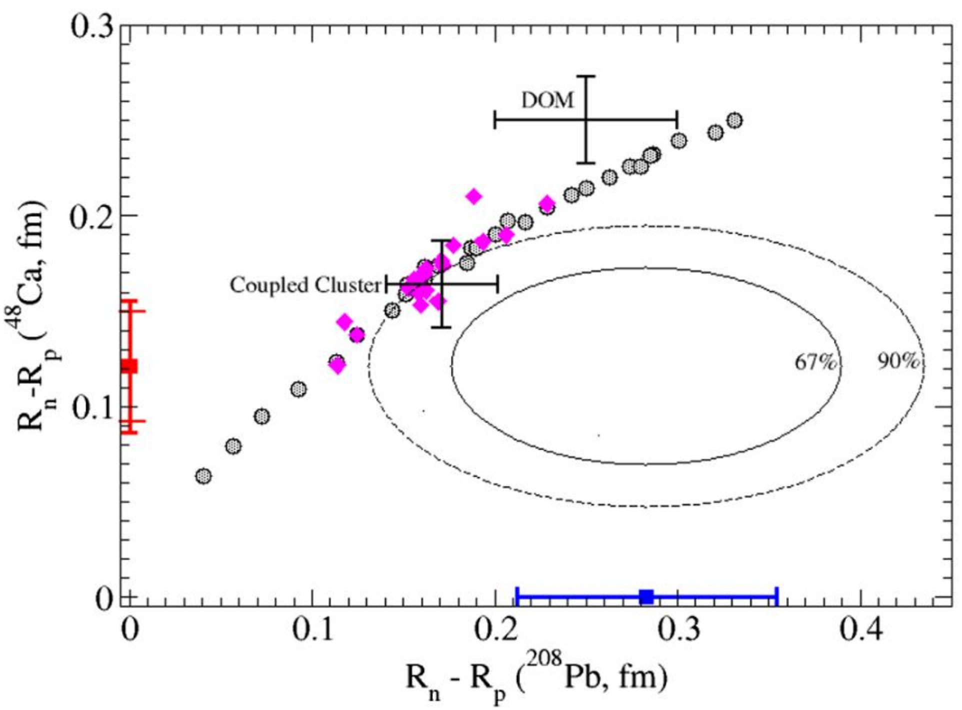
Conbined analysis of PREX-II and CREX

Based on the same scheme, Neutron skin thickness of ^{48}Ca is determined: $\Delta r_{np}(^{48}Ca) = 0.121 \pm 0.026(exp) \pm 0.024(model)$ fm

Results of PREX and CREXshow no consistence at 68% CL



D. Adhikari et al (CREX collab.) Phys. Rev. Lett. 129, 042501 (2022)

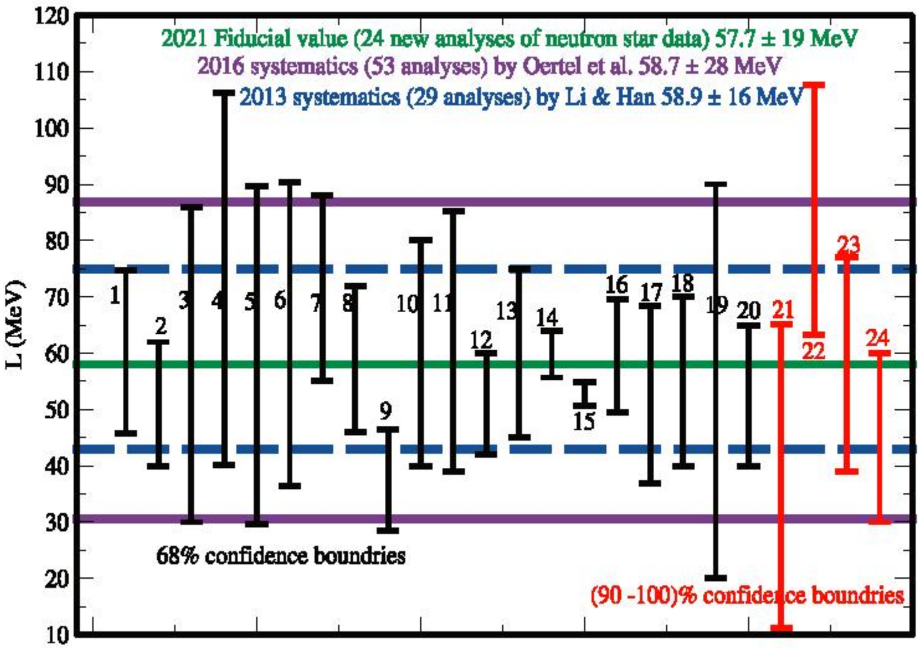


The inferred $E_{sym}(\rho)$ and Δr_{np} separately from CREX and PREX-2 are compatible with each other at 90% C.L., although they are inconsistent at 68.3% C.L., with CREX (PREX-2) favoring a very soft (stiff) $E_{sym}(\rho)$ and rather small (large) Δr_{np}.

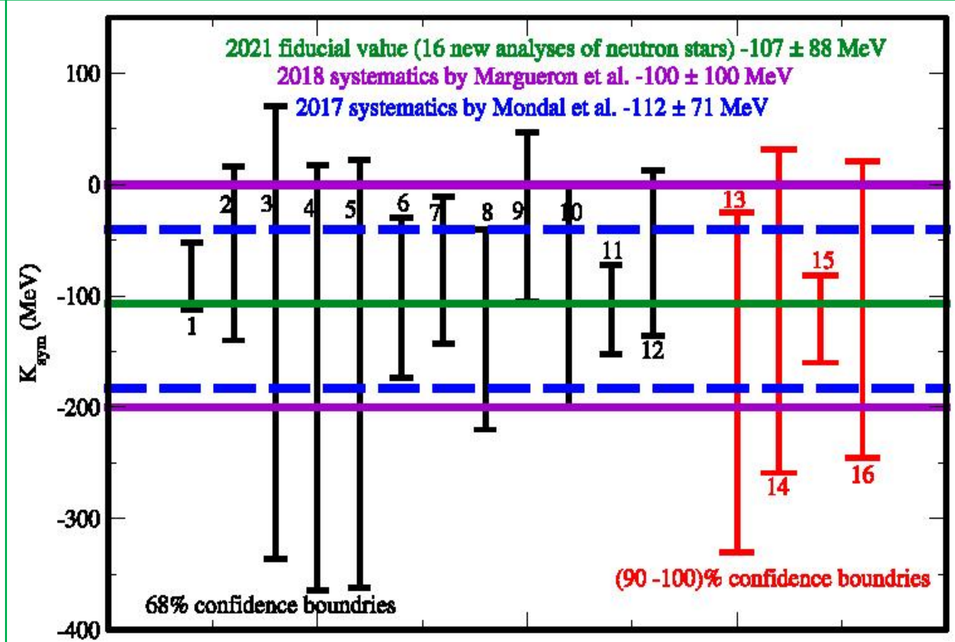
Paul-Gerhard Reinhard et al PRL. 129, 232501 (2022)
Z. Zhang, L. W. Chen et al., PRC 108, 024317 (2023)

Fiducial constraints of $E_{\mathrm{sym}}(\rho)$

Recent results on L



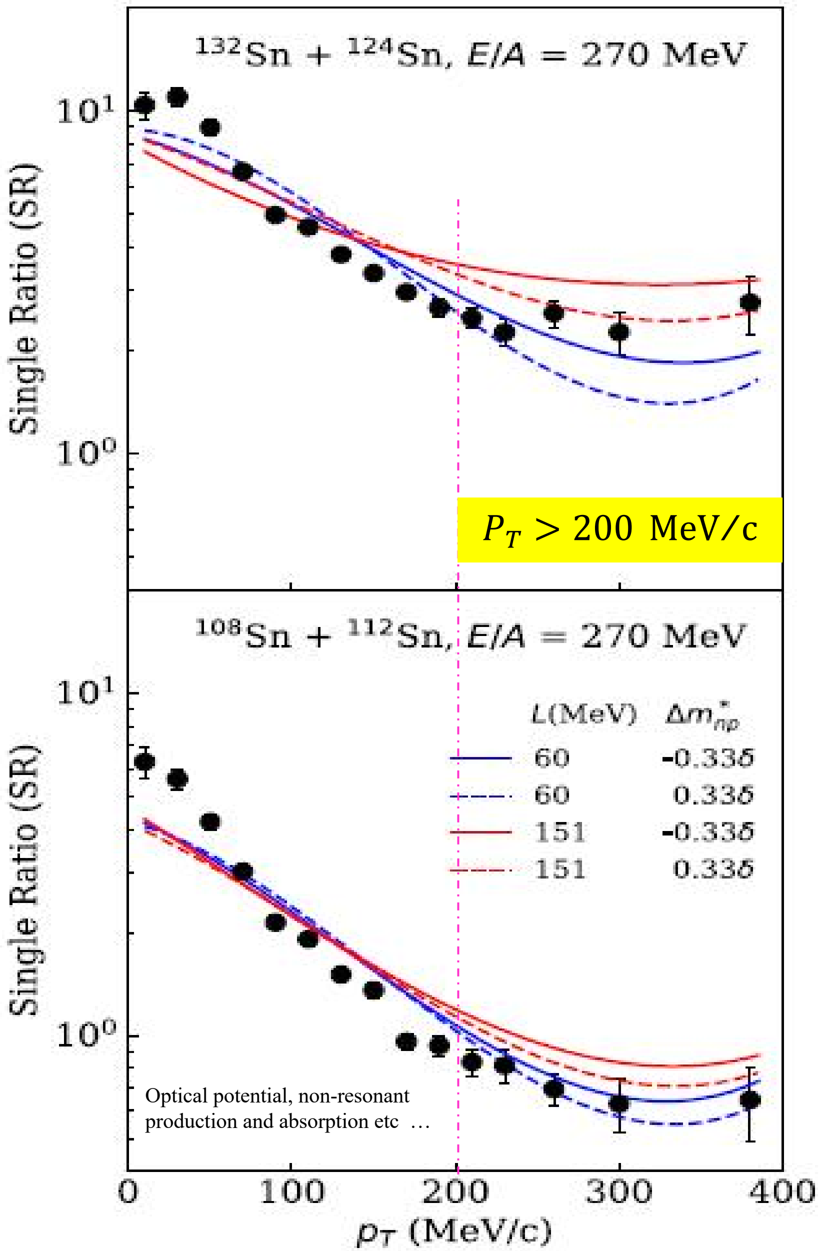
Recent results on K_{sym}

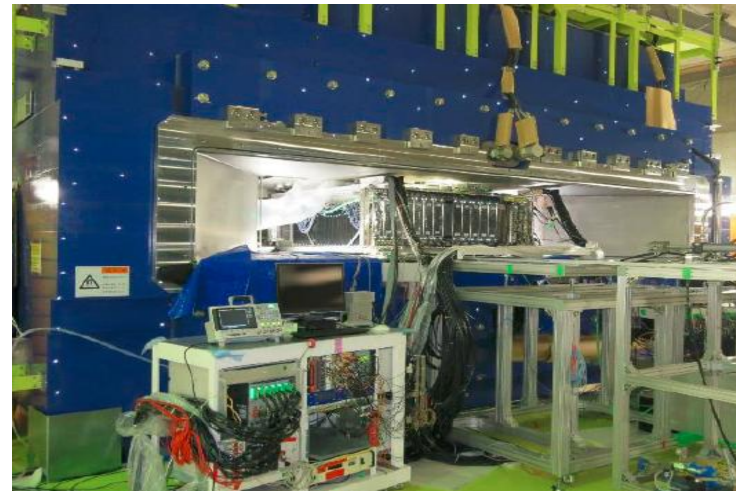


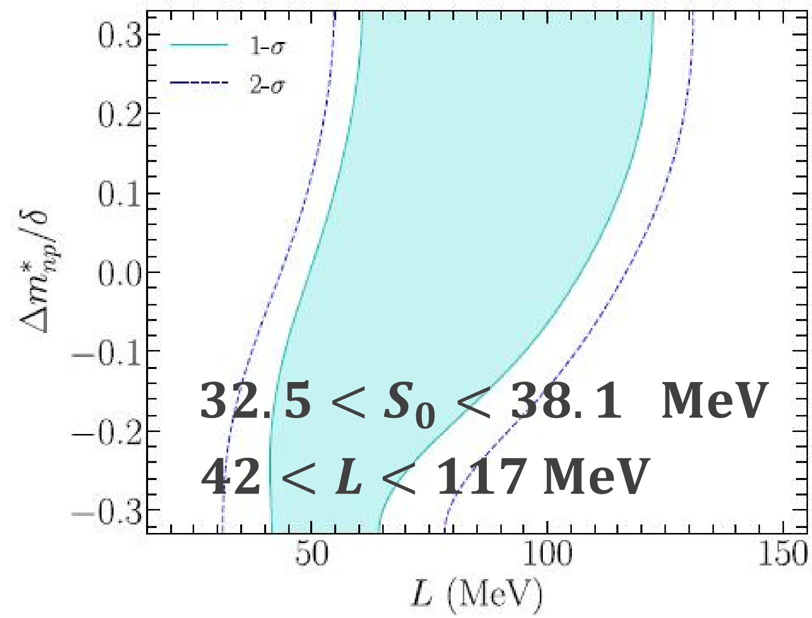
Bao-An Li et al., **Universe 7**, 182 (2021)

24 new analysis from the NS observables
In comparison to 2013 and 2016 survey.
In tention with the most recent PREX II results.

"SπRIT brings neutron star down to earth"







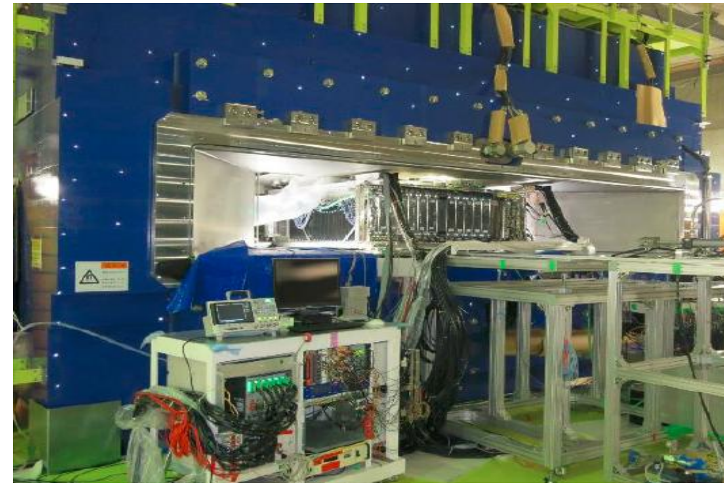
J. Estee et al., **PRL 126**, 162701 (2021)

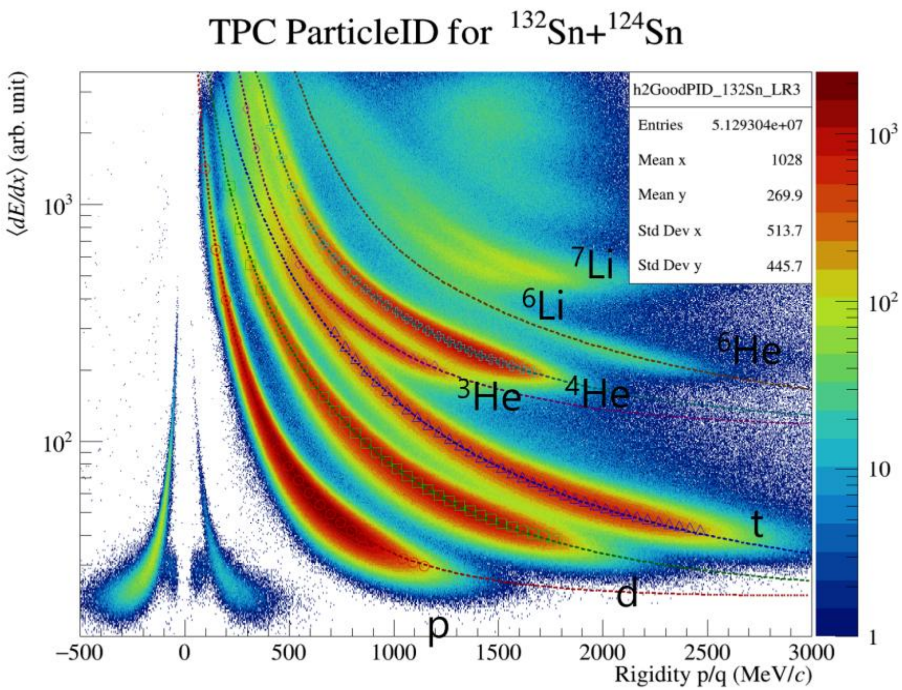
SπRIT Recent progress

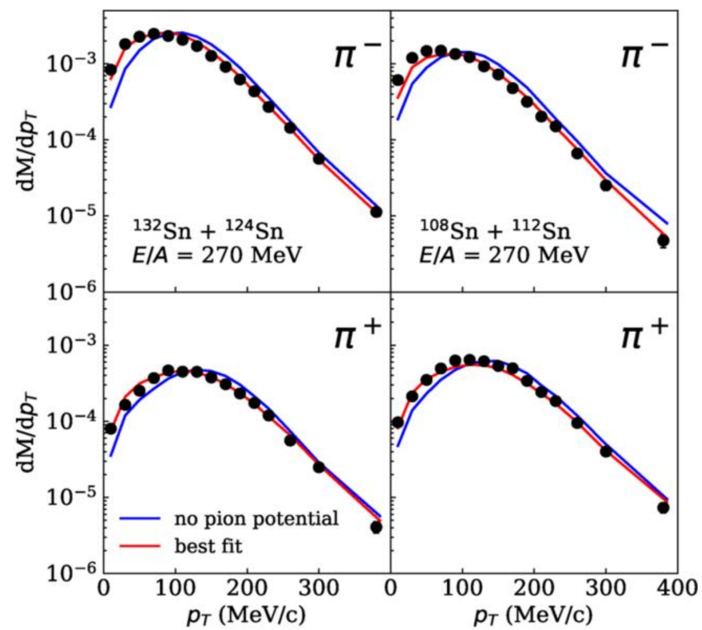
- 270 MeV/u $^{108,132}Sn + ^{112,124}Sn$: published

[π^-/π^+ ratio, Flow, LCP published: 1 PRL + 3 PLB]

- 345 MeV/u $^{136}Xe + ^{112,124}Sn$: Running

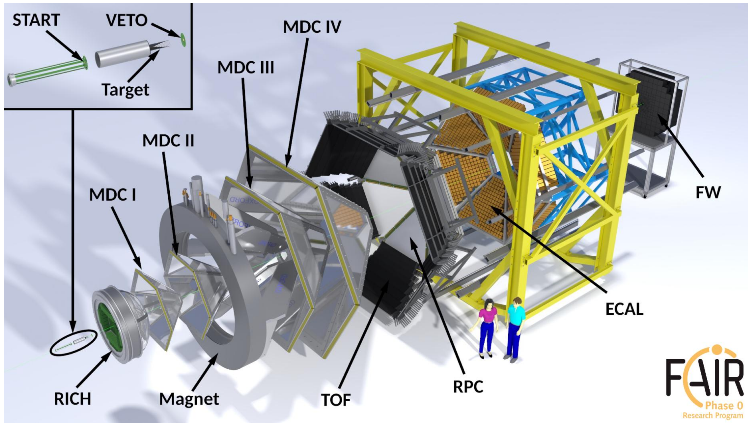






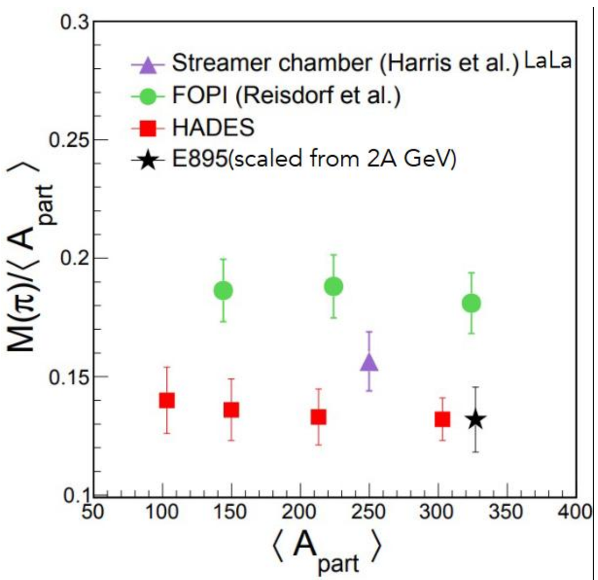
SπRIT at RIBF: PRL 126, 162701 (2021); PLB 822, 136681(2021); PLB813, 136016 (2021)...

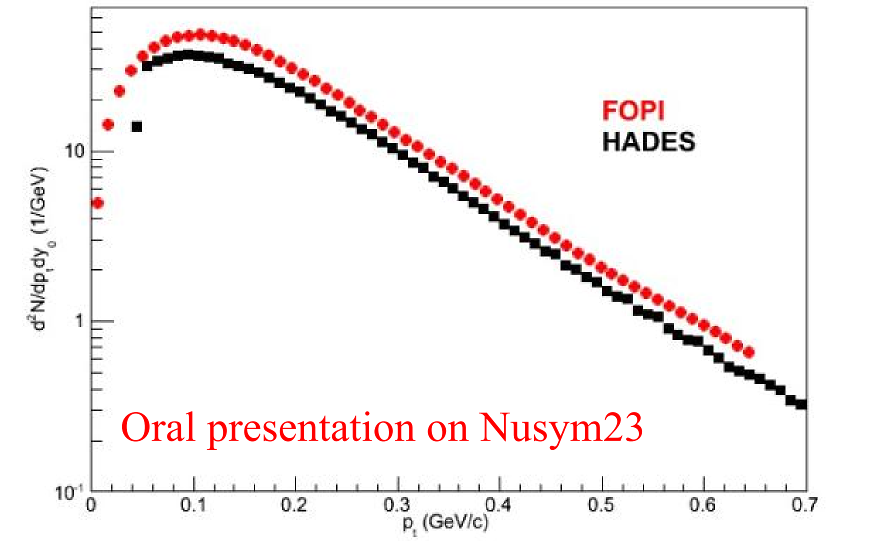
Recent progress from HADES



HADES energy scan 2024

System	Energy (A GeV)	Requested shifts	DAQ rate (kHz)	Estimated #events
Au+Au	0.8	30	10	3×10^9
Au+Au	0.6	30	10	3×10^9
Au+Au	0.4	9	10	1×10^9
Au+Au	0.2	9	10	1×10^9
C+C	0.8	6	30	2×10^9
C+C	0.6	6	30	2×10^9



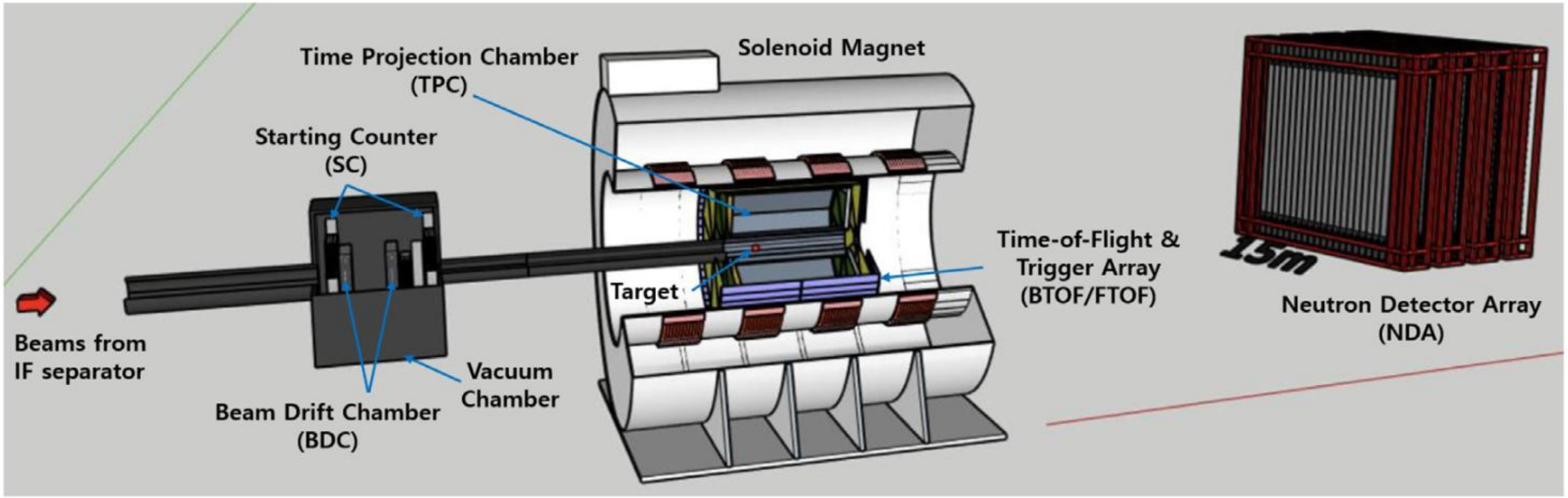


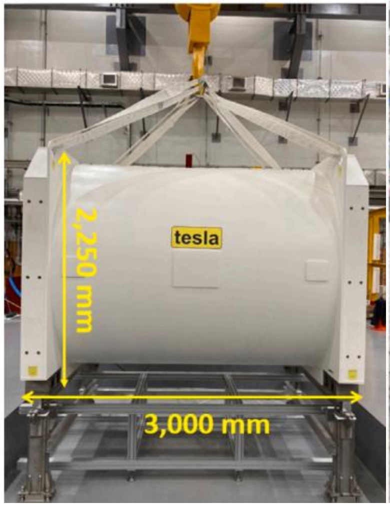
Cf. Joachim's Talk

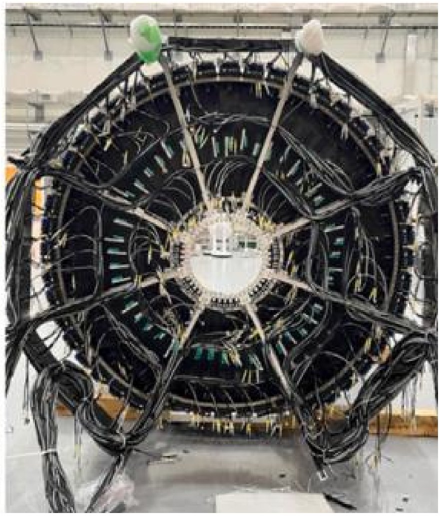
- Beam energy scan of Au+Au and C+C system;
- Flow and pion ratio analysis ongoing
- p-induced collisions planned for short range correlation studies

HADES at SIS: PRL 125, 262301 (2020); PRL 123, 022002 (2019) ; PRC 102, 024914 (2020) ...

LAMPS Progress





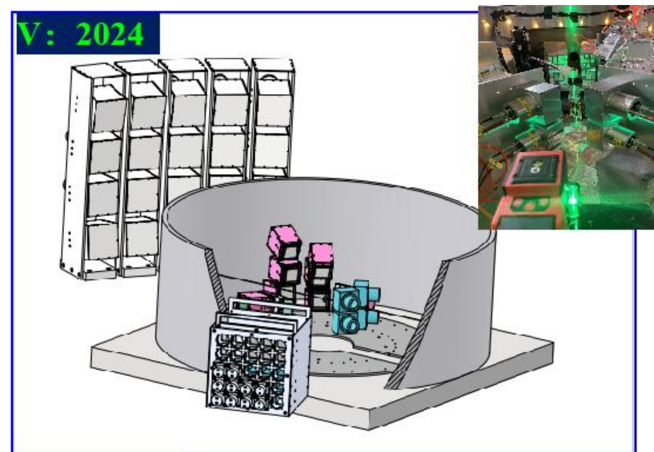


LAMPS at RAON is nearly constructed. [NIMB B 541 (2023) 260–263]

CSHINE： Compact Spectrometer for Heavy Ion Experiment

The Compact Spectrometer for Heavy IoN Experiment has been built at HIRFL,

- to studies the isospin dynamics of HICs at Fermi energies
- to infer the $E_{sym}(\rho)$ near saturation density



☐ Beam time statistics:

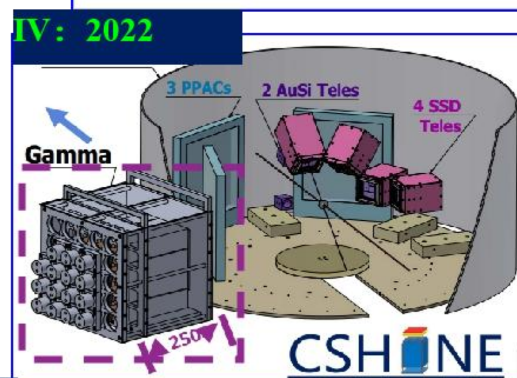
I： 30 MeV/u* ^{40}Ar+^{197}Au (2014)

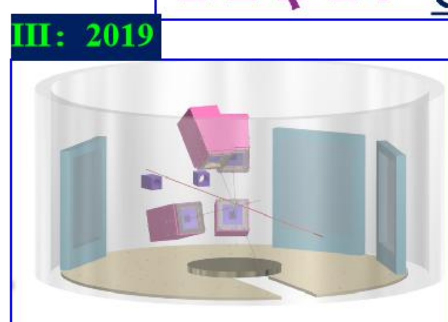
II： 30 MeV/u ^{40}Ar+^{197}Au (2018)

III： 25 MeV/u ^{86}Kr+^{208}Pb (2019)

IV： 25 MeV/u ^{86}Kr+^{124}Sn (2022)

V： 25 MeV/u ^{124}Sn+^{124}Sn (2024)

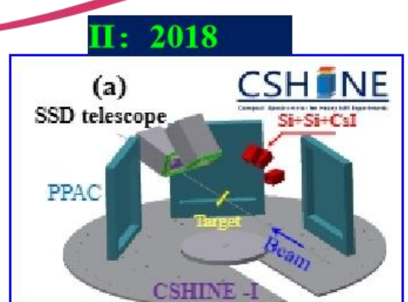


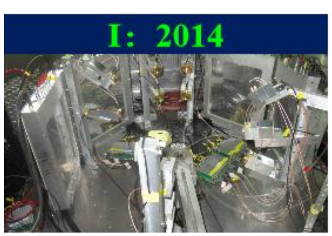


2024 → + neutron array

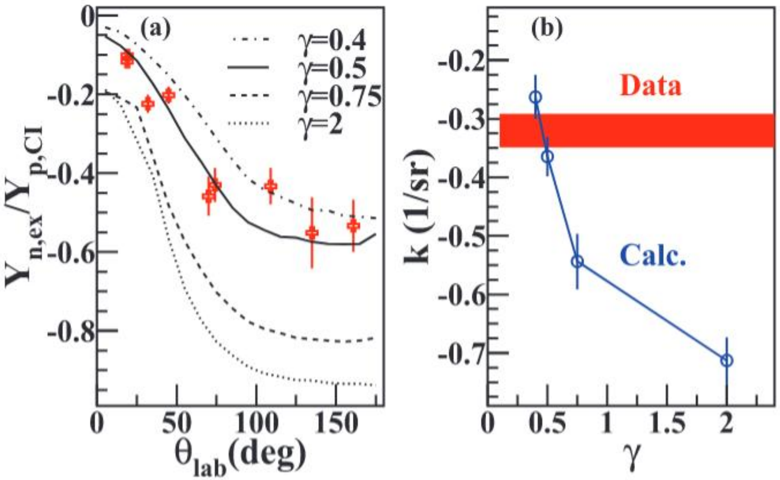
2022 → + γ Hodoscope

2018 → + SSDT

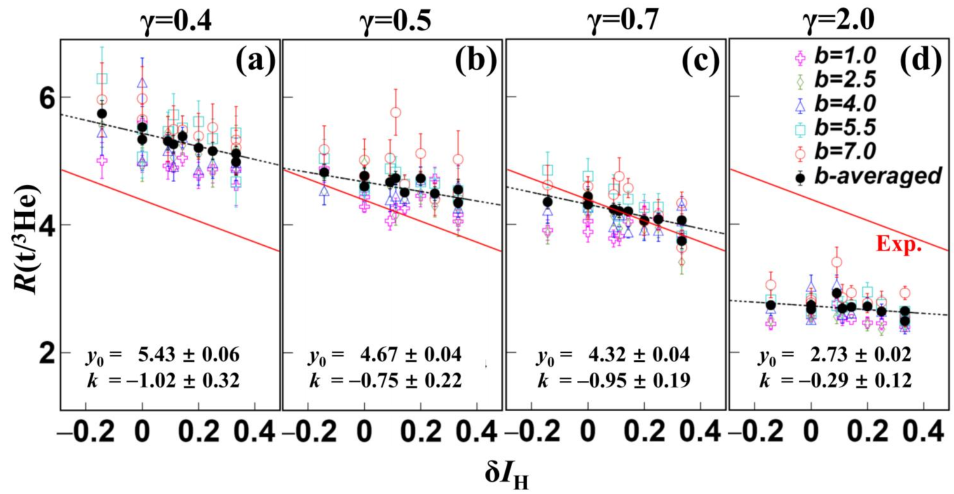




CSHINE contrains $E_{sym}(\rho)$ at saturation density



❶ Angular behavior of N/Z of LCPs



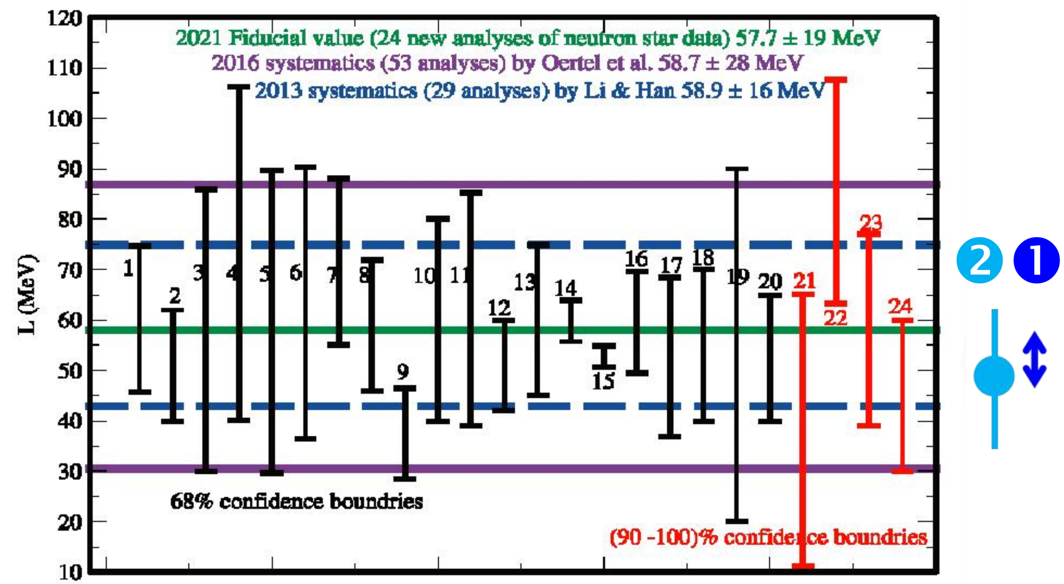
❷ $t/^3He$ yield ratio

$\gamma \approx 0.5$

$L = 47 \pm 14$ MeV

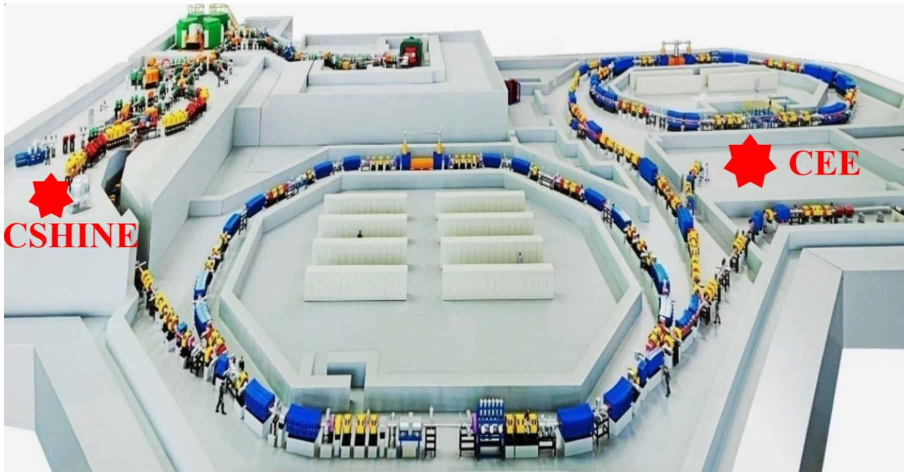
❶ Y. Zhang et al , **PRC** 95,041602(R) (2017)

❷ Y. J. Wang et al, **PRC** 107,L041601 (2023)



2、Opportunities of **CEE** (HIRFL-CSR) and **CEE**$^{+}$(HIAF)

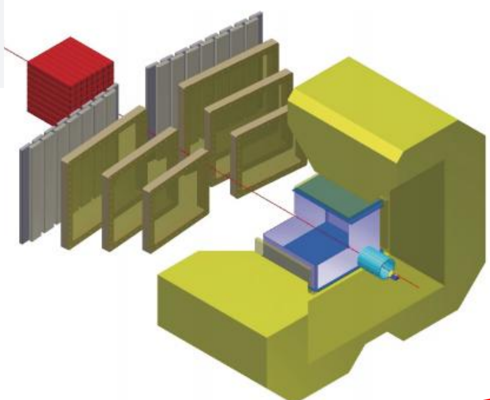
HIRFL-CSR accelerator complex



Cool Storage Ring

HIRFL-CSR:

P	2.8 GeV
C	1100 MeV/u
U	0.5 GeV/u



If equipped with an advance experiment:

→ Explore the phase boundary of QCD phase diagram at high net-baryon densities.

→EOS near $2\rho_0$

→ Production of hyperons and hypernuclei

CEE Detection System

- CEE：HIRFL-CSR Extermal-target Experiment

After ~10 years' hard R&D, construction started in Aug. 2019, by NSFC and CAS.

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**

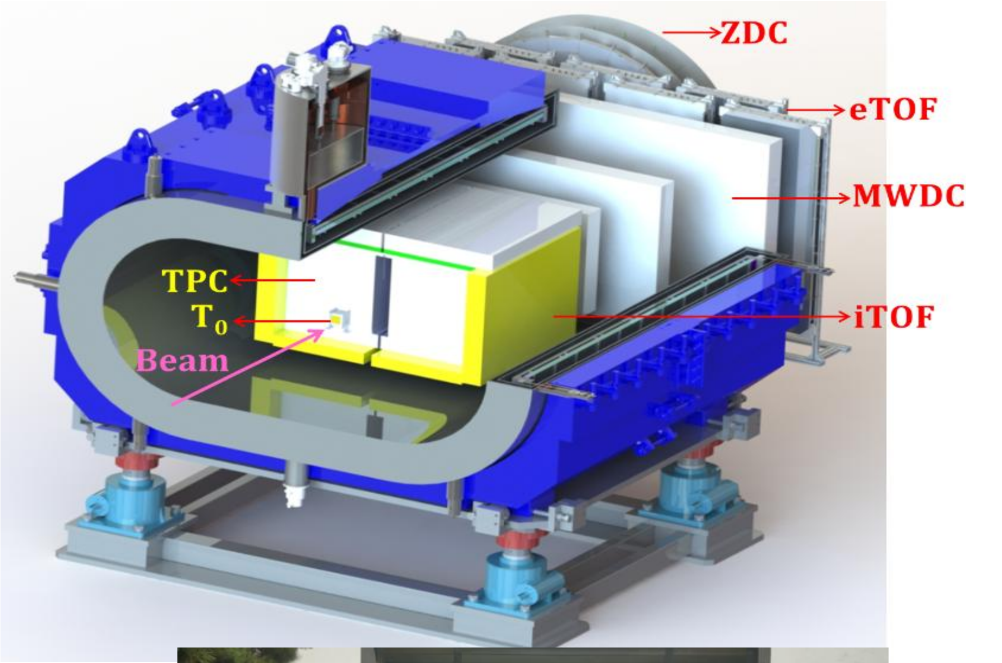


TABLE I. (Color online) Technical indicators of CEE.

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

Physical programs at **CEE** (HIRFL-CSR)

Given the enormous progress of the studies on nEOS, what opportunities do we have in HIC at hundreds MeV/u beam energies?

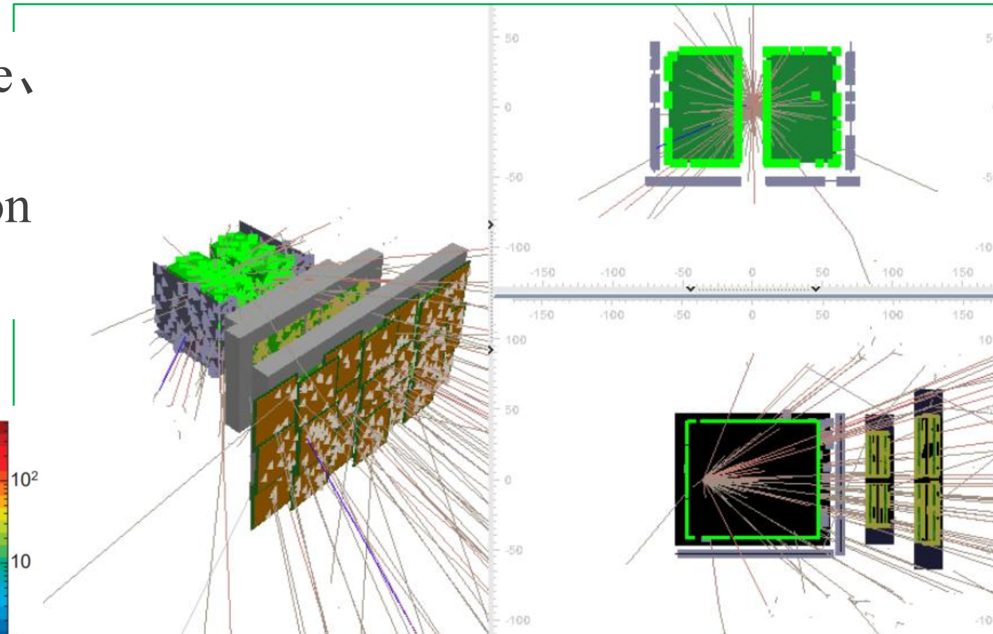
based on charged particle detection, CEE covers the following observables：

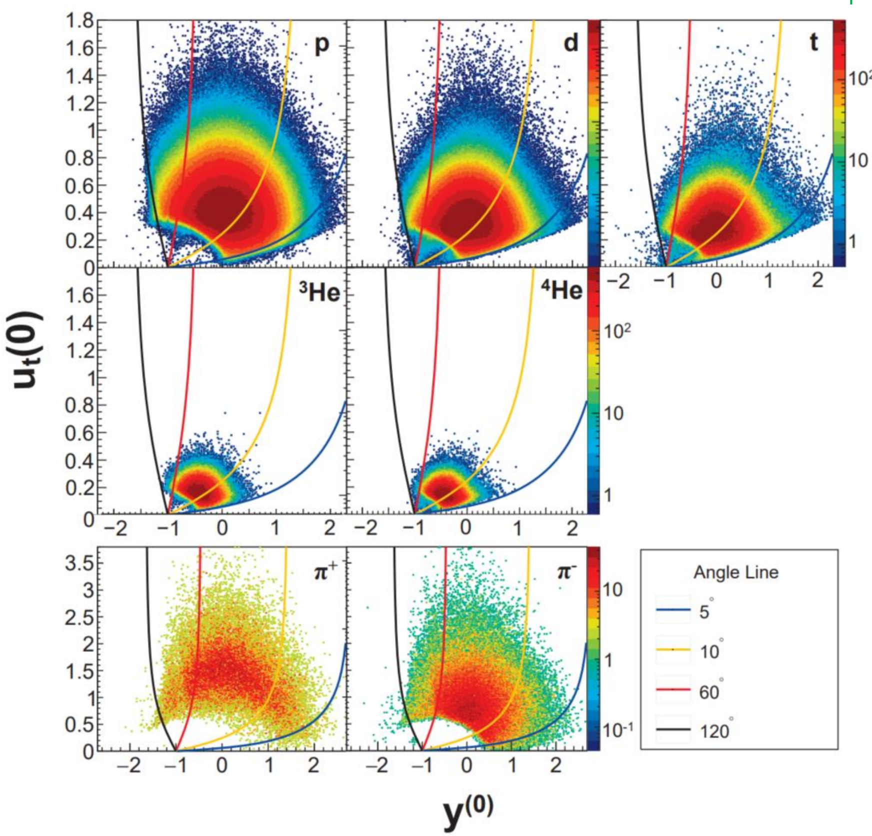
- t-^{3}He Puzzle and Clustering；
- π production, π^-/π^+ yield ratio and femtoscopic correlation
- p-p, cluster-cluster correlations
- K_s^0 production
- p+A fragmentation, short range correlations
- Flow、polarization of the colliding system

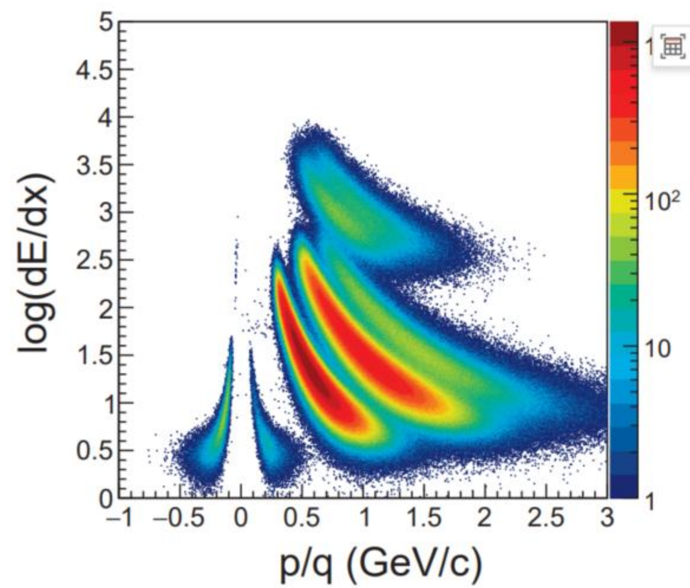
……

CEE provides new opportunities for $E_{sym}(\rho)$ studies

Simulations studies on π^-/π^+、t-^{3}He、radial flow and K_s^0 production has been started, in CEERoot Framework based on CBMRoot



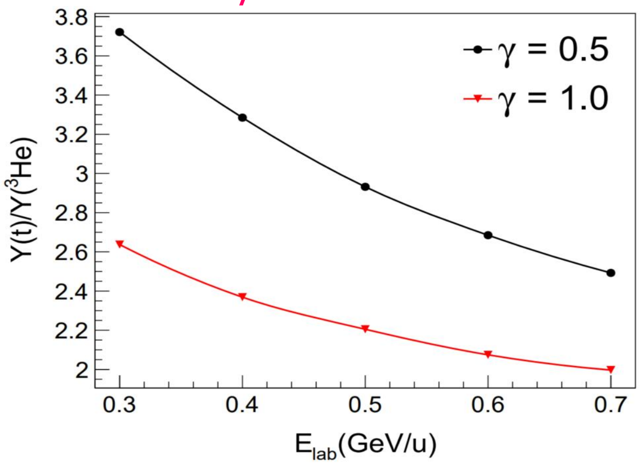




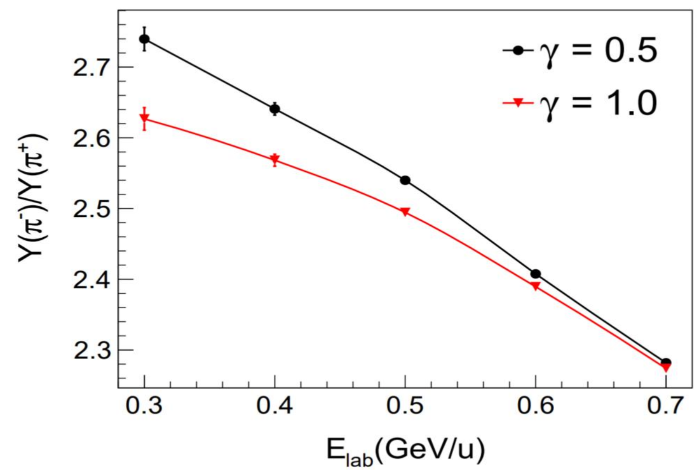
CEE provides new opportunities for NEOS studies

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

$t/{}^{3}\text{He}$ Ratio

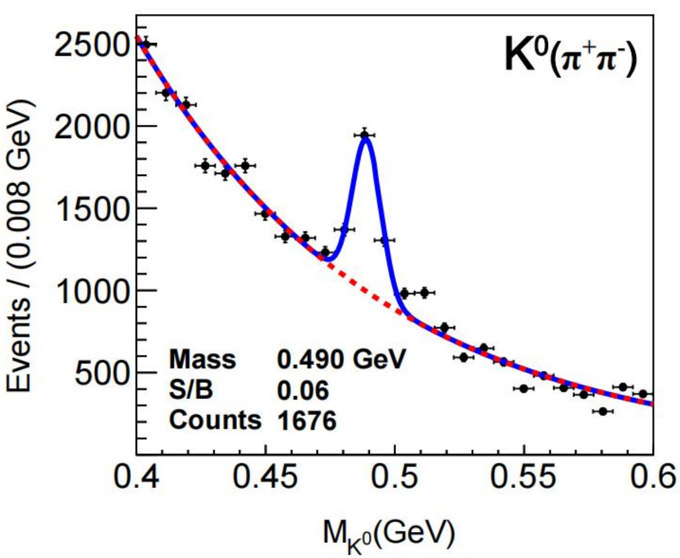


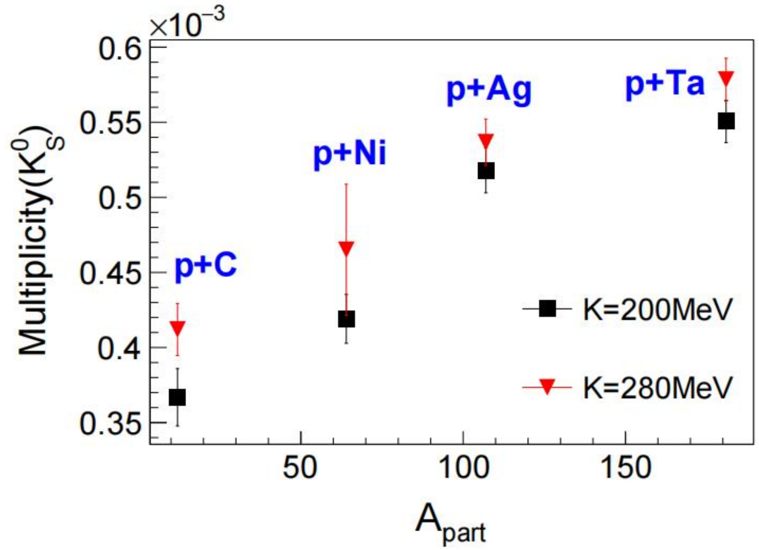
π^{-}/π^{+}Ratio



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

K_s^0 production





Dong Guo et al., **Euro. Phys. J. A 60,** 36 (2024) Studies of nuclear equation of state with the HIRFL-CSR external-target experiment

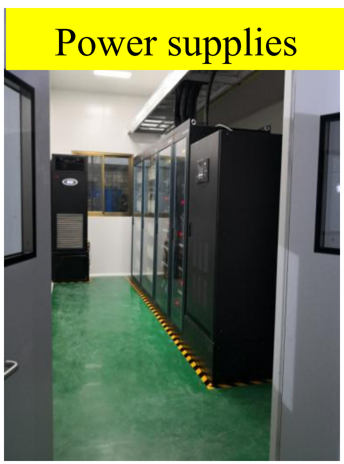
Current Status: Infrastructure

CEE Infrastructure nearly ready!


Gas System


Counting Roon


Grounding


Power supplies

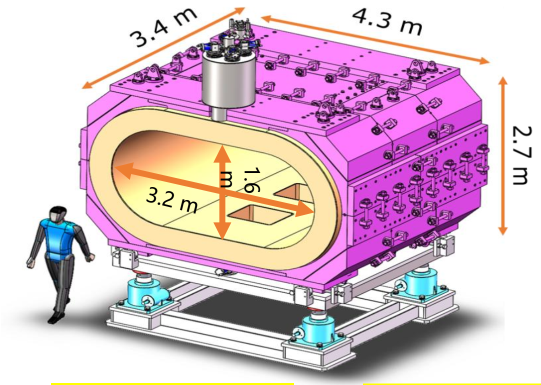

DAQ


Cage Gate


CEE Cave

Current Status: Subdetectors

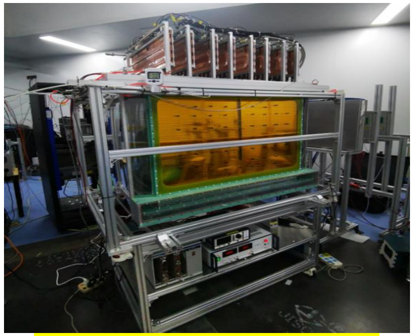
All the detector subsystems and slow control are in the stage of mass production



Yoke

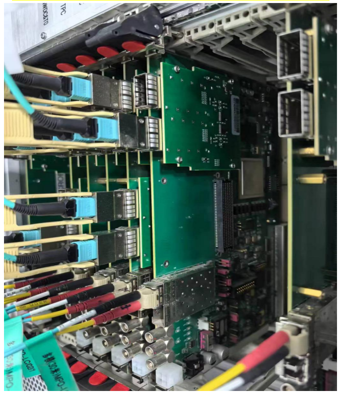
Helium Container

TPC Detector



Electronics

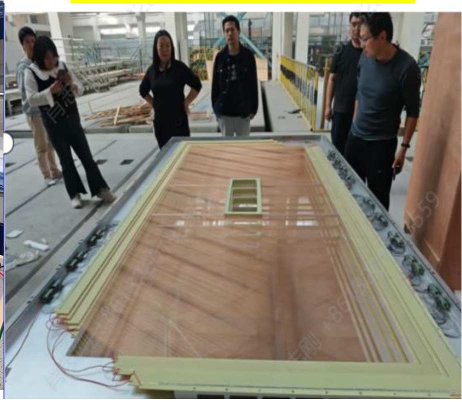
DAQ boards



ZDC modules

TOF modules

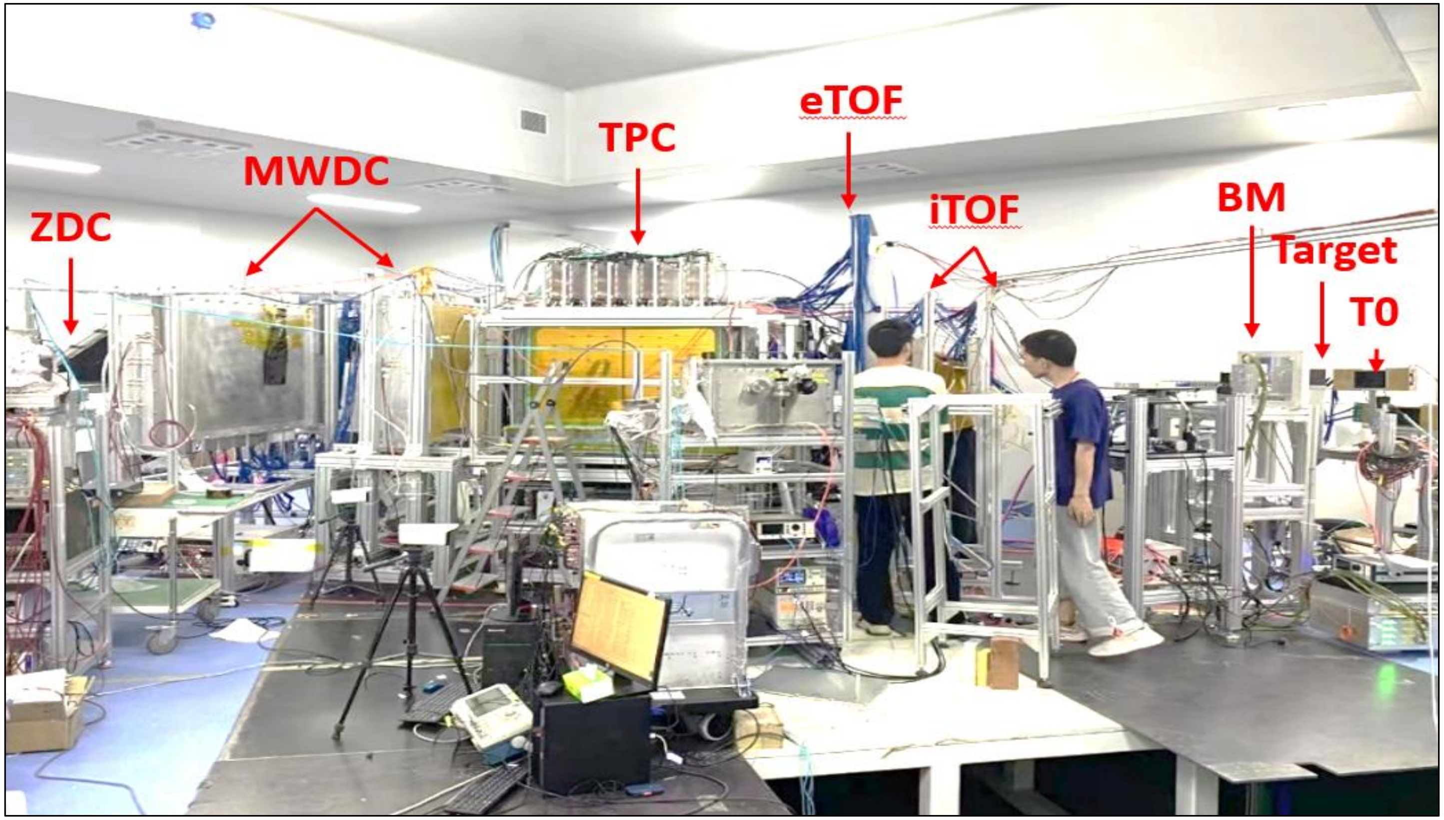
MWDC in manu.



- 4th beam test in Dec 2024
- Commissioning run is expected in 2025

Current Status: detector performance test

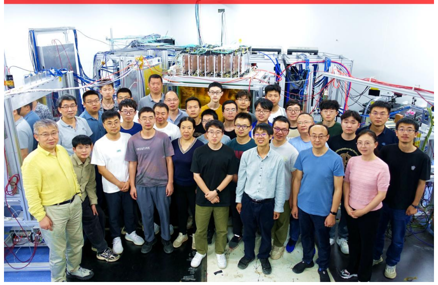
Integration beam tests conducted 3 times: Mar. /Dec. 2023, May. 2024



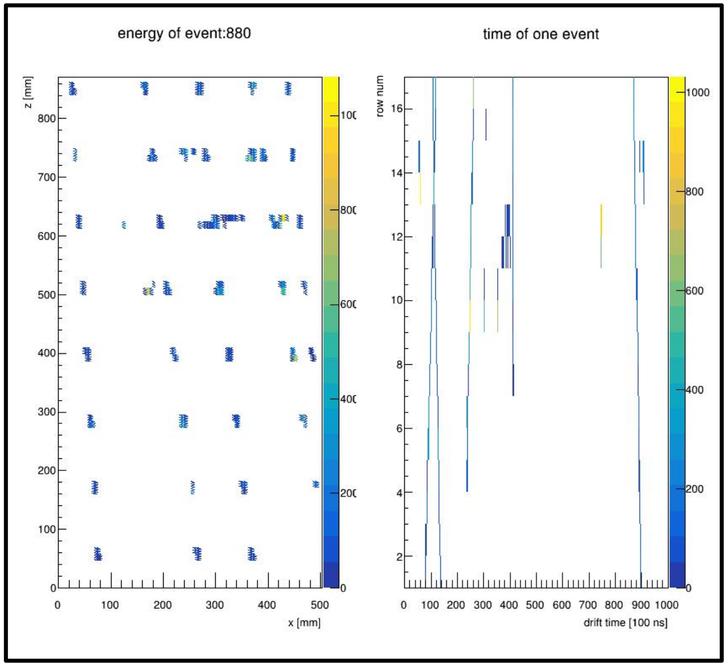
CEE谱仪第一次（模块级）束流联试

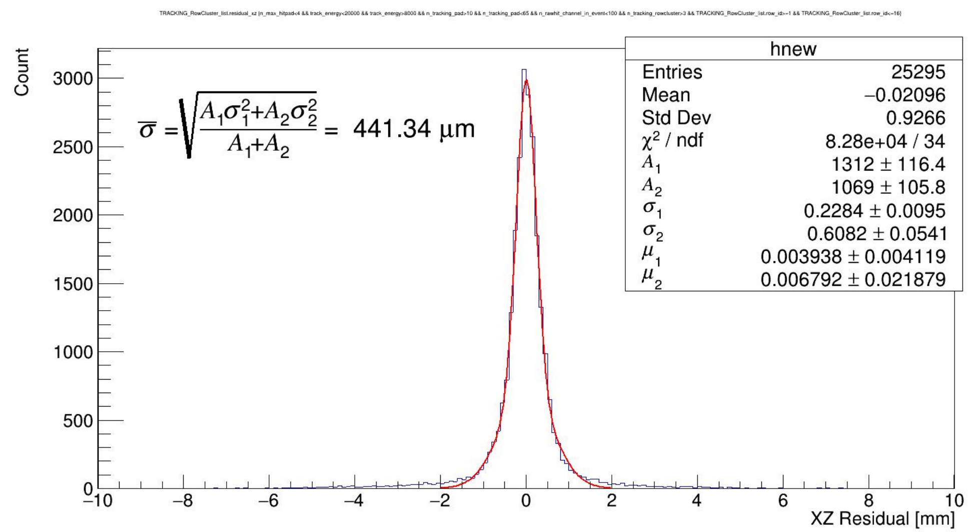
CEE谱仪第二次（模块级）束流集成联试

CEE谱仪第三次（模块级）束流联试



Tracking Detector Performance



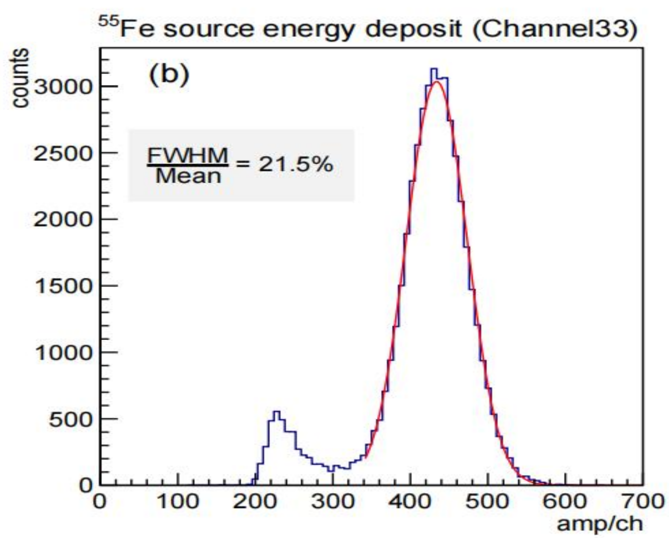


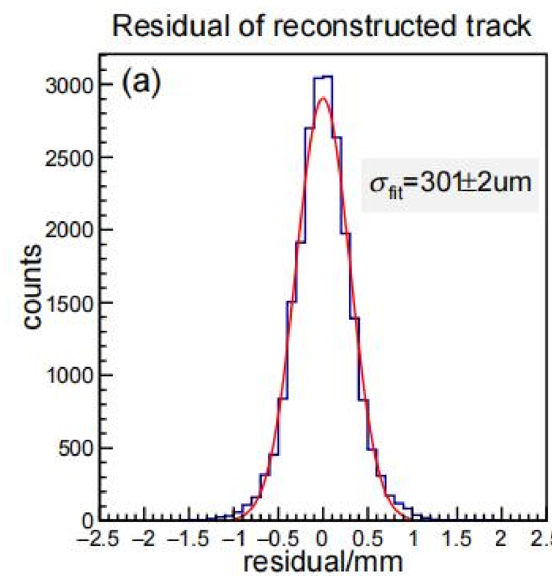
TPC: Residue $\sigma_{xy} = 441\ \mu m$

MWDC:

$\mathrm{FWHM_E} = 21.5\%$

$\sigma_r = 301\ \mu m$

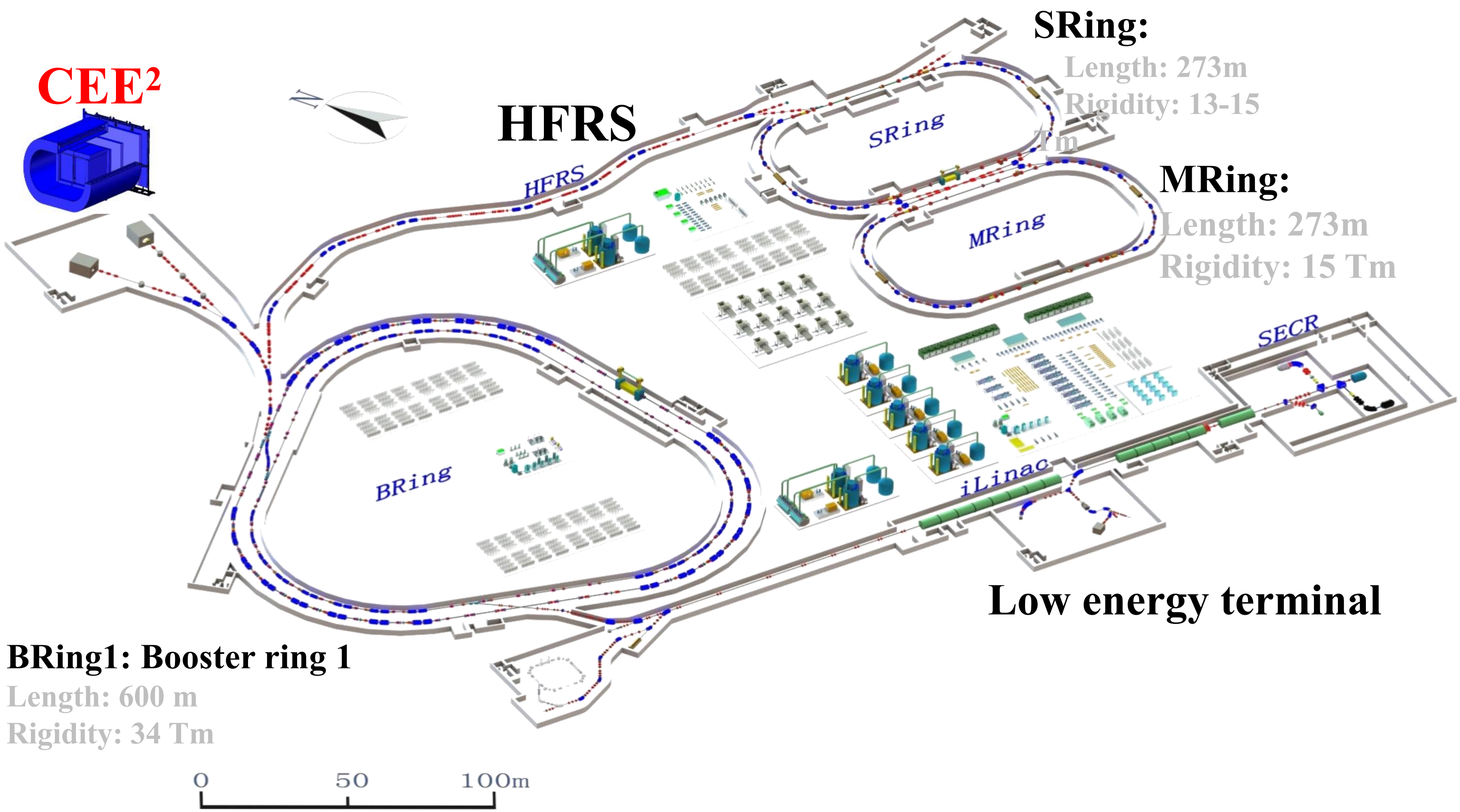




Towards to HIAF

Beam energy (A/Z=2) ~ 4.5 GeV/u <<>> Beam intensity HIAF/HIRFL: $10^3 - 10^4$

$$\rho \gtrsim 3 - 4\rho_0$$



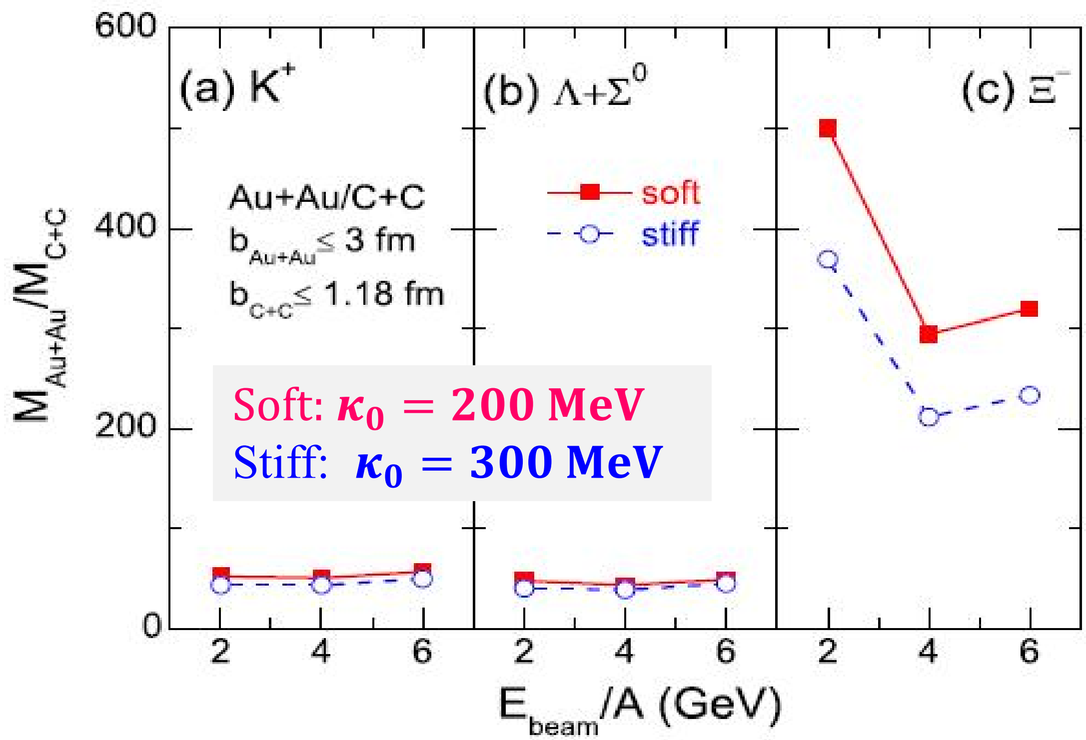
Probes of NEOS in HIAF energy range

At a few GeV/u beam energy, highly compressed baryon matter is formed.

According to simmulations, multi-strangeness baryon are created in secondary collisions in high density region, showing sensitivity to nEOS.

$\overline{K} + Y \rightarrow \pi + \Xi^- \quad (Y = \Lambda \; or \; \Sigma)$
$Y + N \rightarrow N + \Xi^- + K$
$Y + Y \rightarrow N + \Xi^-$

yield of the double strangeness Ξ^-, is sensitive on EOS



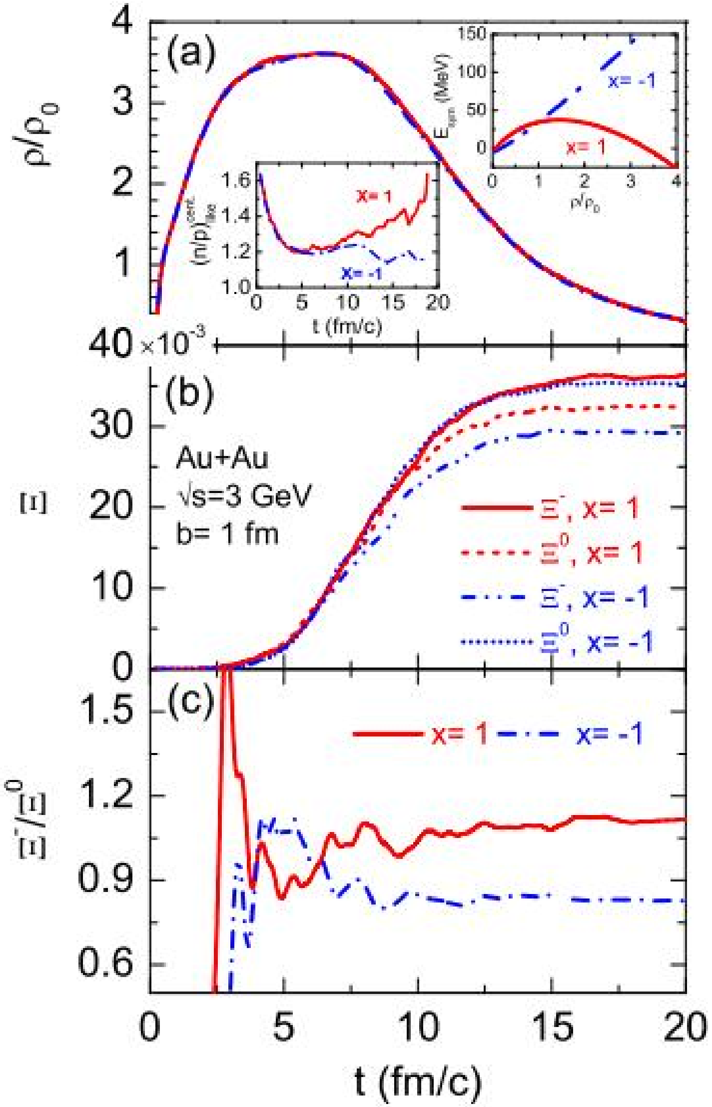
Soft: $\kappa_0 = 200$ MeV
Stiff: $\kappa_0 = 300$ MeV

G. C. Yong, ZGX, Y Gao and Z. W. Lin, PLB 820 (2021) 136521

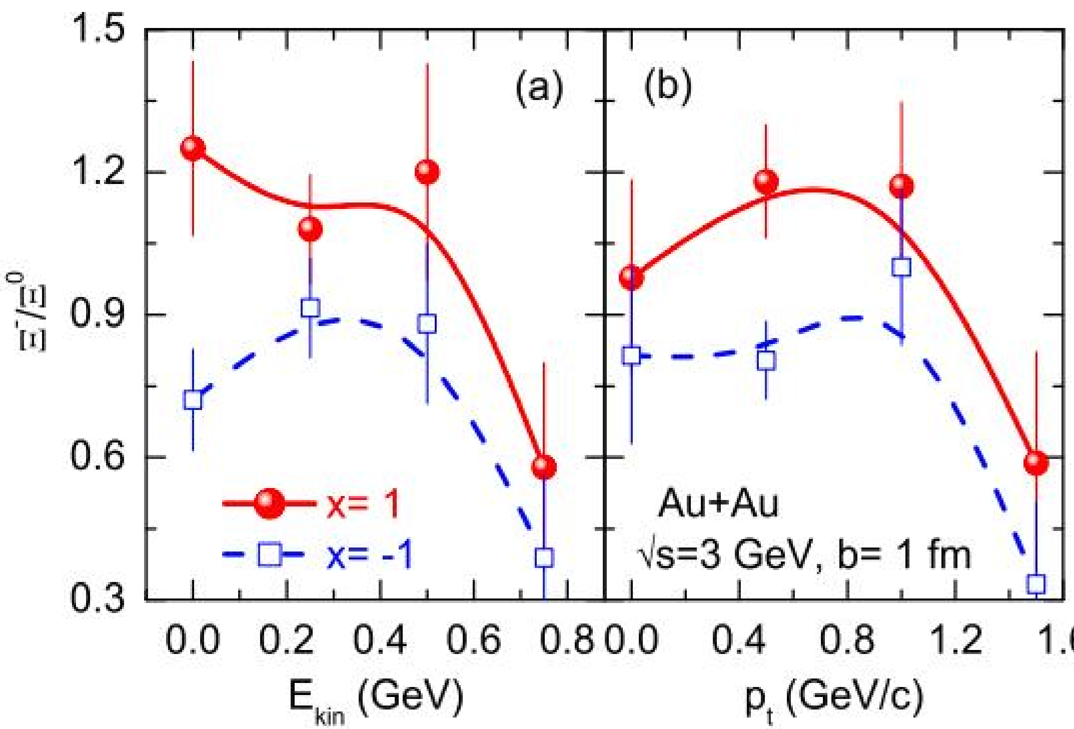
Probes of $E_{sym}(\rho)$ at higher density

isospin probes: $\frac{n}{p} \rightarrow \frac{\pi^-}{\pi^+} \rightarrow \frac{K^0(d\bar{s})}{K^+(u\bar{s})} \rightarrow \frac{\Sigma^-(dds)}{\Sigma^+(uus)} \rightarrow \frac{\Xi^-(dss)}{\Xi^0(uss)}$

with the increase of beam energy

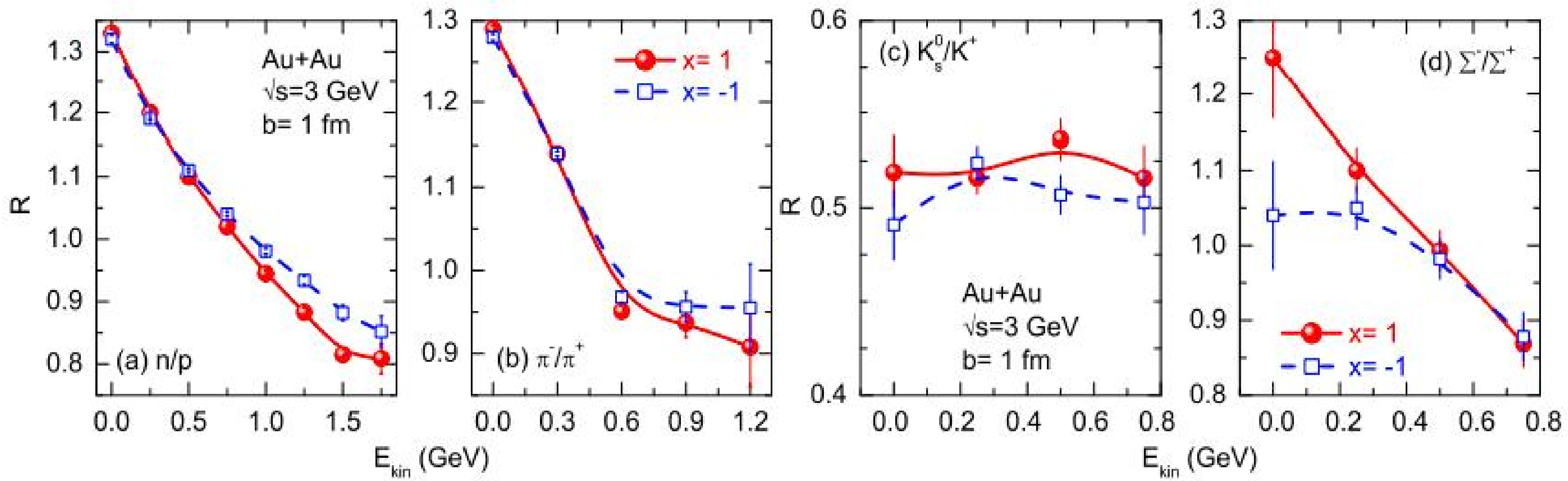


via $\pi + \mathrm{N} \rightarrow \Sigma$ secondly process, isospin effect carried by nucleons and pions are passed to strangeness.



Probes of $E_{sym}(\rho)$ at high densities

Isospin probes: $\frac{n}{p} \rightarrow \frac{\pi^-}{\pi^+} \rightarrow \frac{K^0(d\bar{s})}{K^+(u\bar{s})} \rightarrow \frac{\Sigma^-(dds)}{\Sigma^+(uus)} \rightarrow \frac{\Xi^-(dss)}{\Xi^0(uss)}$



Experimental challenge: To detect the neutral particles

$$\Sigma^- \rightarrow n + \pi^-, \;\; \Sigma^+ \rightarrow n + \pi^+ \; or \;\; p + \pi^0$$
$$\Xi^- \rightarrow \Lambda + \pi^-, \Xi^0 \rightarrow \Lambda + \pi^0$$

Gao-Chan Yong, Bao-An Li, ZGX, Zi-Wei Lin, **PRC 106**, 024902 (2022).

3. Summary

1. Heavy ion collisions creat compressed nuclear matter, and offer an effective means to probe the equation of state of nuclear matter. Enormous progress have been made so far, the $E_{\mathrm{sym}}(\rho)$ at suprasaturation density is less constrained.

2. To be operated at GeV/u energy regime, CEE foresees some new opportunities in the studies of $E_{\mathrm{sym}}(\rho)$ at about $\rho_0 \sim 2\rho_0$ via the observables ($t/^3$He)、π^-/π^+ ratio, production of K^0 mesons etc.

3. CEE construction is ongoing smoothly, Commisioning run is expected in 2025.

Stay tuned