Workshop on Non-equilibrium QCD and Transport
Dec 9-12, 2025, Southern China Nuclear Theory Center (SCNT), Huizhou, China.

Nuclear Matter Studies at HIRFL and HIAF
—an experimental review

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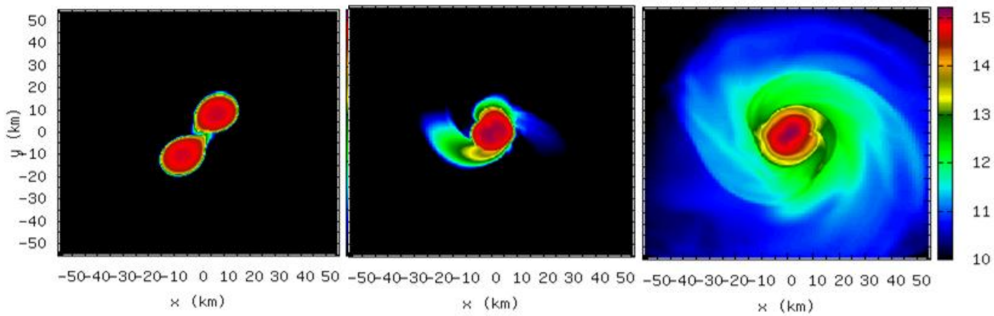
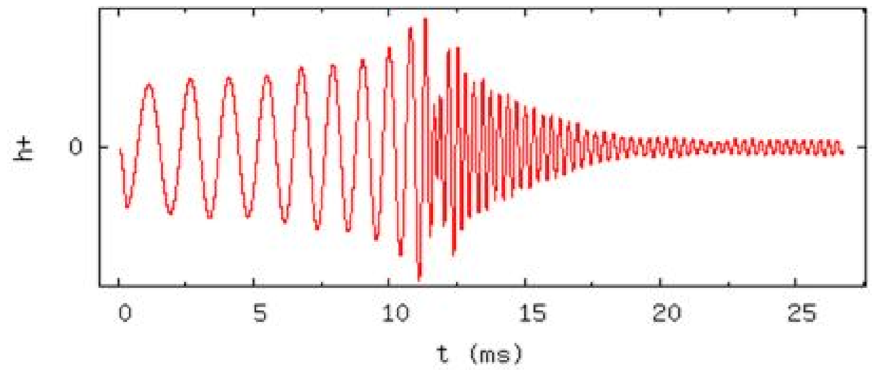
GW170817 and its relevance to nuclear EOS

GW170817 provides a new opportunities in the studies of nEOS

$t = 10$ ms $\quad t = 11.2$ ms $\quad t = 13.9$ ms





$E(\rho, \delta)$ ⟷ **R-M formular** ⟷ **GW**

TOV Eq. $\quad \Lambda \propto (R/M)^5$

TOV equations:

$$\frac{d\mathcal{M}(r)}{dr} = 4\pi r^2 \varepsilon(r), \quad -\frac{d\mathcal{P}(r)}{dr} = \frac{G\varepsilon\mathcal{M}}{r^2}\left(1 - \frac{2G\mathcal{M}}{r}\right)^{-1}\left(1 + \frac{\mathcal{P}}{\varepsilon}\right)\left(1 + \frac{4\pi r^3 \mathcal{P}}{\mathcal{M}}\right)$$

Nuclear Equation of State

The nucleon specific energy of nuclear matter formed in HIC or in neutron star is written as:

$$E(\rho,\delta) = E_0(\rho) + \delta^2 E_{sym}(\rho) + \mathcal{O}(\delta^4), \quad \delta = \frac{\rho_n-\rho_p}{\rho_n+\rho_p}$$

$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{J_0}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3 + \ldots$$

$$\boldsymbol{E}_{\mathbf{sym}}(\boldsymbol{\rho}) = \boldsymbol{S}_0 + \boldsymbol{L}\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K_{\mathrm{sym}}}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{J_{\mathrm{sym}}}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3 + \ldots$$

symmetry energy

The $\boldsymbol{E}_{\mathbf{sym}}(\boldsymbol{\rho})$ is yet poorly known, but it is important to understand dense asymmetric nuclear matter.

For npe matter, the pressure :

$$P(\rho,\delta) = \rho^2\frac{\partial E(\rho,\delta)}{\partial\rho} + \frac{1}{4}\rho_e\mu_e = \rho^2\left[\frac{\partial E_0}{\partial\rho} + \delta^2\frac{\partial E_{\mathrm{sym}}}{\partial\rho}\right] + \frac{1}{2}\delta(1-\delta)\rho E_{\mathrm{sym}}(\rho)$$

Siemens's $\rho^{2/3}$ scaling for nuclear symmetry energy

Lane potential reads

$U_\tau(k,\rho,\tau) = U_0(k,\rho) + \tau_3 U_{\rm sym}(k,\rho)$ where τ is isospin, $\tau_3 = \pm 1$ for p and n.

In the Hugenholtz-Van Hove (HVH) threme, the $E_{\rm sym}(\rho)$ can be written as (kinetic term + potential term)

$$E_{\rm sym}(\rho) = \frac{1}{3}\frac{k_{\rm F}^2}{2m_0^*(\rho,k_{\rm F})} + \frac{1}{2}U_{\rm sym}(k_{\rm F},\rho)$$

In non-relativistic region, the potential term is also protional to $k_{\rm F}^2$ [*] thus, the total $E_{\rm sym}(\rho)$ is propotional to $k_{\rm F}^2$, or $\rho^{2/3}$.

[*] Bruekner, Coon and Dabrowski PR 168, 1184 (1968)

NUCLEAR-MATTER REACTION MATRIX

PHILIP J. SIEMENS †

Laboratory of Nuclear Studies, Cornell University, Ithaca, New York ††

Received 11 September 1969

P. J. Siemens, Nucl. Phys. A 141, 225 (1970)

If the average binding energy per particle is expanded in powers of α^2,

$$E = E_0(k_{\rm F}) + \tfrac{1}{2}\varepsilon(k_{\rm F})\alpha^2(1+\varepsilon'\alpha^2+\ldots), \tag{2.13}$$

then at $k_{\rm F} = 1.4\ {\rm fm}^{-1}$, $\varepsilon = 31$ MeV and $\varepsilon' = -1.7$. The value of ε at $k_{\rm F} = 1.0\ {\rm fm}^{-1}$ suggests setting $\varepsilon(k_{\rm F})$ proportional to $k_{\rm F}^2$; this is of course the form of the kinetic part of ε, and since the potential energy is nearly quadratic in the single-particle momentum, it is not surprising that all of ε scales quite well with $\rho^{\frac{2}{3}}$. The value of ε found here is in

$\rho^{2/3}$ scaling law of $E_{\rm sym}(\rho)$ as a benchmark

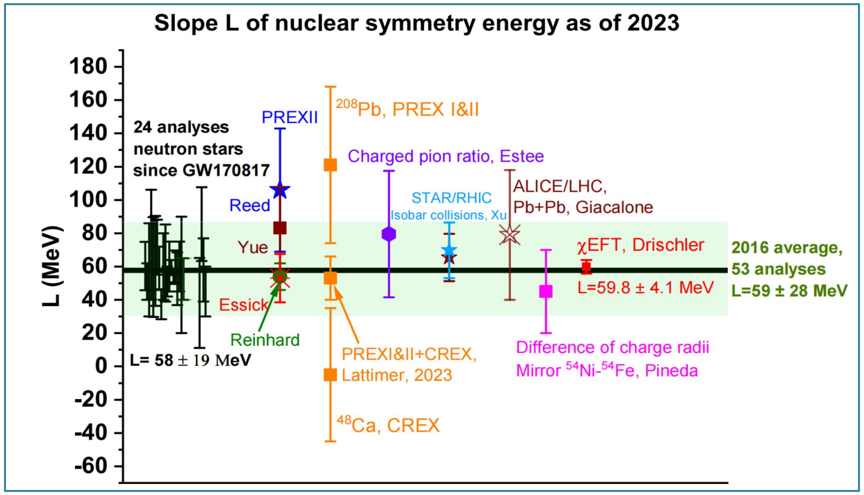
From Taylor expension $E_{\rm sym}(\rho) = \boldsymbol{S_0} + \boldsymbol{L}\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{\boldsymbol{K_{\rm sym}}}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{\boldsymbol{J_{\rm sym}}}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3 + \sigma$, and compare to $E_{\rm sym}(\rho) \propto \rho^{2/3}$, if assuming $S_0 = 31 \pm 3$ MeV, it reads:

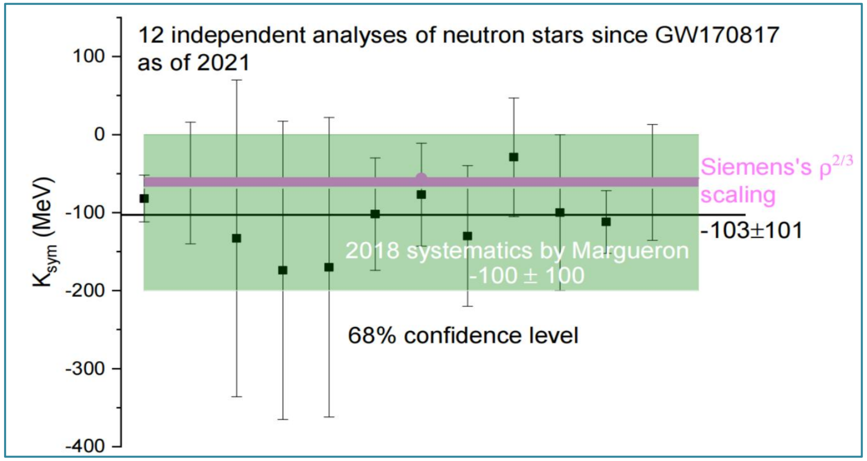
$$L = 2S_0 \approx 62 \pm 6 \text{ MeV}$$

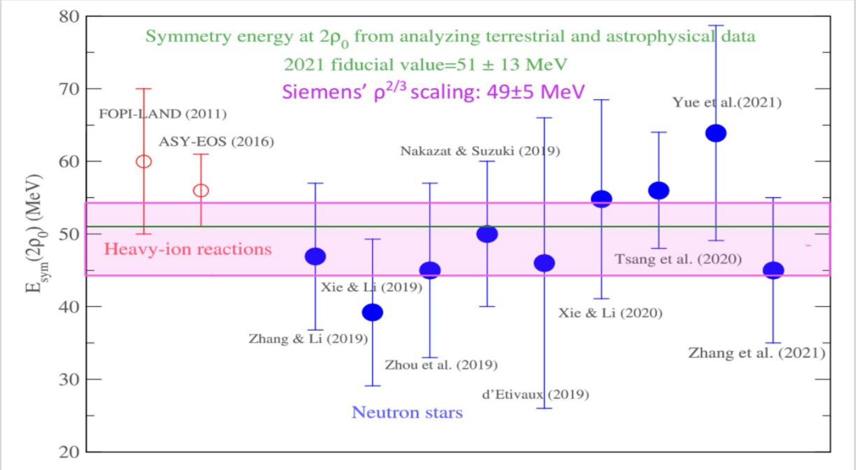
$$K_{\rm sym} = -2S_0 \approx -62 \pm 6\text{MeV}$$

$$J_{\rm sym} = 8S_0 \approx 248 \pm 24 \text{ MeV}$$

$$E_{\rm sym}(2\rho_0) = 1.58S_0 \approx 50 \pm 5 \text{ MeV}$$







B. A. Li, arXiv: 2510.05508v1

Is the story satisfying?

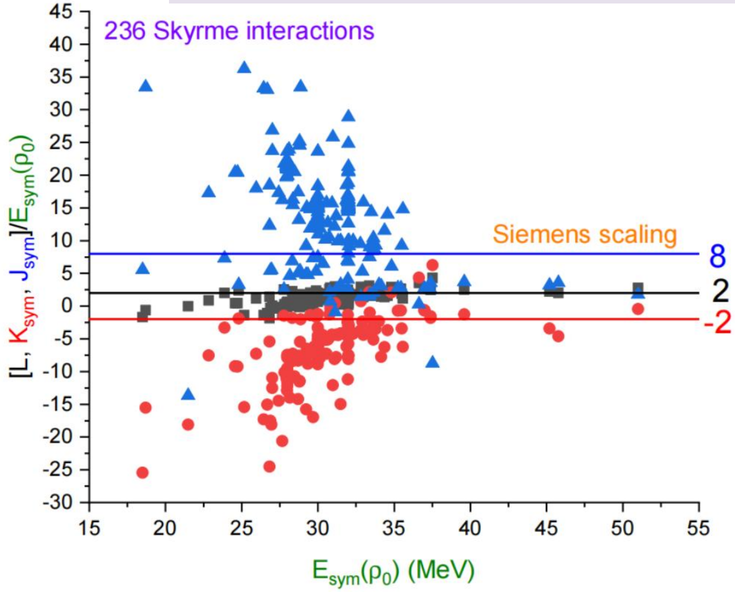
Siemens's $\rho^{2/3}$ scaling law is based on non relativistic theory and it may break down.

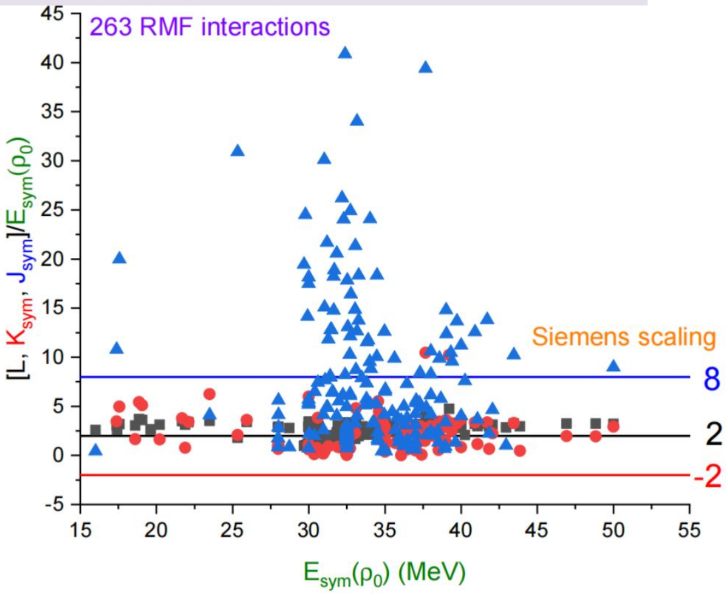
So far the behavior of $E_{\text{sym}}(\rho)$ at high density is poorly constrained.

Break-down of $\rho^{2/3}$ scaling at high densities

Predictions of $E_{sym}(\rho)$ coefficients based on Skyrme Hartree-Fock (SHF) and Relativistic Mean Field (RMF) energy density functionals：

K_{sym} and J_{sym}, exhibit obvious deviation from the $\rho^{2/3}$ scaling.





1) Siemens's $\rho^{2/3}$ scaling law is based on non-relativisitc theory anyway.
2) The uncertainty of the constraint of L is still large.
3) High order terms K_{sym} and J_{sym} not yet constrained.

Deviation from $\rho^{2/3}$ scaling unravels physical reasons

Siemens's $\rho^{2/3}$ scaling near ρ_0 emerges under two key assumptions: (i) the isoscalar mean-field potential is quadratic in momentum； (ii) the isovector potential is only weakly density dependent.

It may break down at high density for the following possible reasons:

1) The nucleon single-particle potential acquires higher-order momentum dependence due to finite-range interactions at high densities;

2) The symmetry potential can vary strongly with density, especially with contributions from ρ- and δ-mesons or density-dependent couplings, breaking (ii);

***3) The presence of spin-isospin dependent tensor forces, Short Range Correlation, and three-body forces, which become increasingly pronounced at high density.**

***4) Large isospin splitting of nucleon effective masses at high deisities.**

5) Relativistic self-energies and Lorentz structure;

6) Emergence of new degrees of freedom including , hyperons, Δ resonances, meson condensates etc.

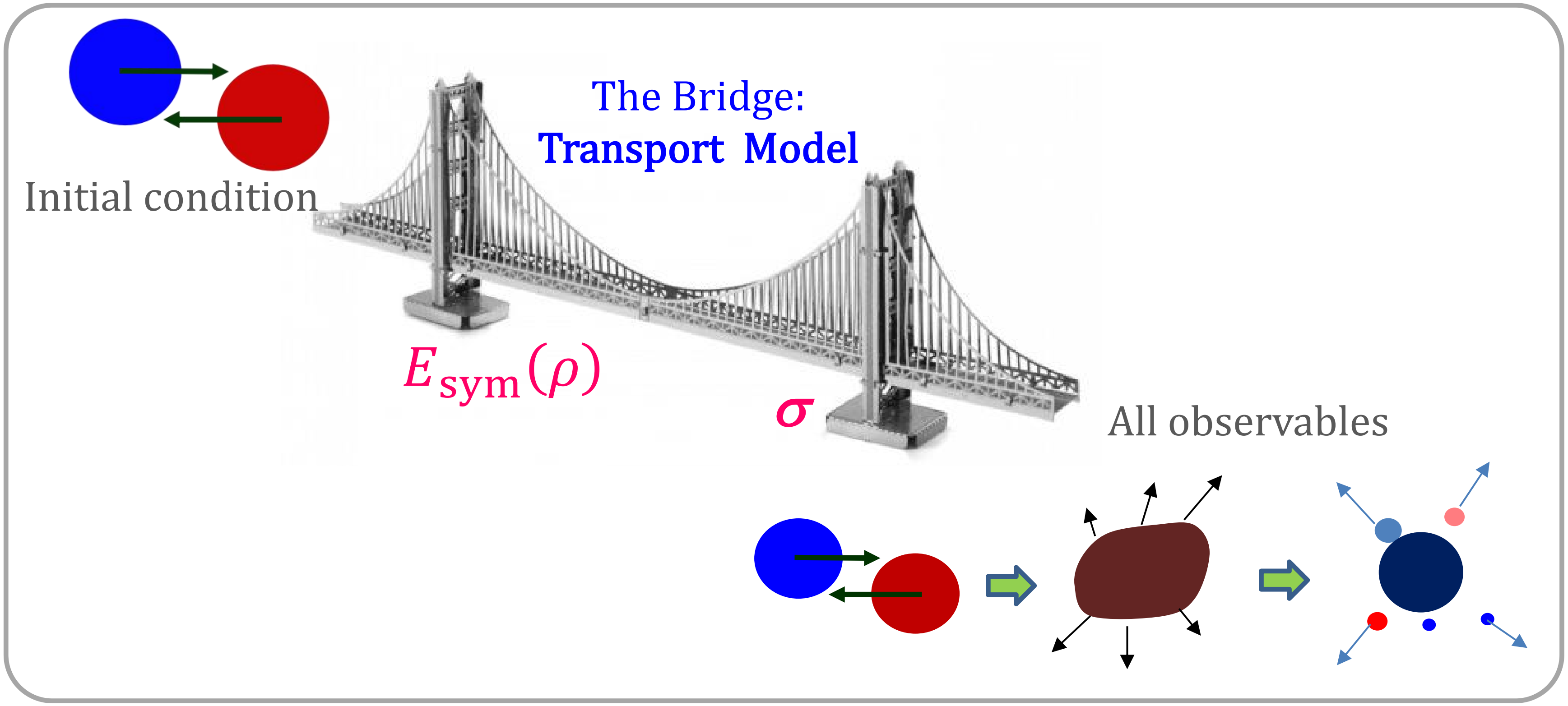
7) In-medium modifications of nucleon quasiparticles.

Penetrating studies on any of the above points help to understand the large uncertainty of $E_{\mathrm{sym}}(\rho)$ at high density!

Probe $E_{sym}(\rho)$ using heavy ion collisions

› HIC is a unique means to creat denst nuclear matter in lab. But $E_{sym}(\rho)$ is not directly detectable!

› Relying solely on transport model， one can extract $E_{sym}(\rho)$ from various observables.



What are the challenges ?

- **Identify good** (and often updated) **isospin observables,**
  Isovector potential effect, quite small

- **Model the underlining physics related to the observable,**

- **Understand well the collision dynamics, particularly of the isospin DOF,**
  (spatial-temporal behavior of the collision ...)

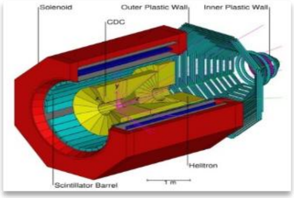
- **Conduct the systematic studies**
  (beam energy scan, multi observables ....)

- **Reduce model dependence, observable dependence ...**
  (HIC is extremely complicated: medium effect, production/progation, Pauli blocking)

Some world HIC experiments for $E_{sym}(\rho)$

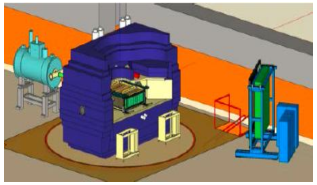
\# Measure chemistry/collectivity to extract $E_{sym}(\rho)$ by comparing to transport model.

\# One of the key fronties absorbing investment in many world-class laboratories.



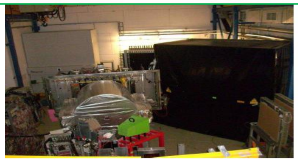
FOPI Experiment: π^-/π^+ ratio, Flow, Stopping

XZG et al., PRL 102 (2009) 062502; FZQ et al., PLB 683 (2010) 140
XWJ et al., PLB 718 (2013) 1510; J. Hong et al, PRC 90,024605(2010)



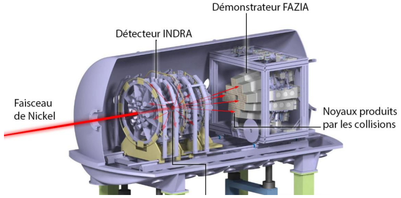
SπRIT : π^-/π^+ ratio, Radial flow of p, d and t

SpRIT collaboration , **PRL 126**, 162701 (2021)
SpRIT collaboration, **PLB** 822,136681(2021)



AnsysEOS: n/p differential flow

AnsysEOS Collaboration, **PRC** 034608 (2016)
Y.J.Wang **Frontiers of Physics**, 15(4):1, 2020

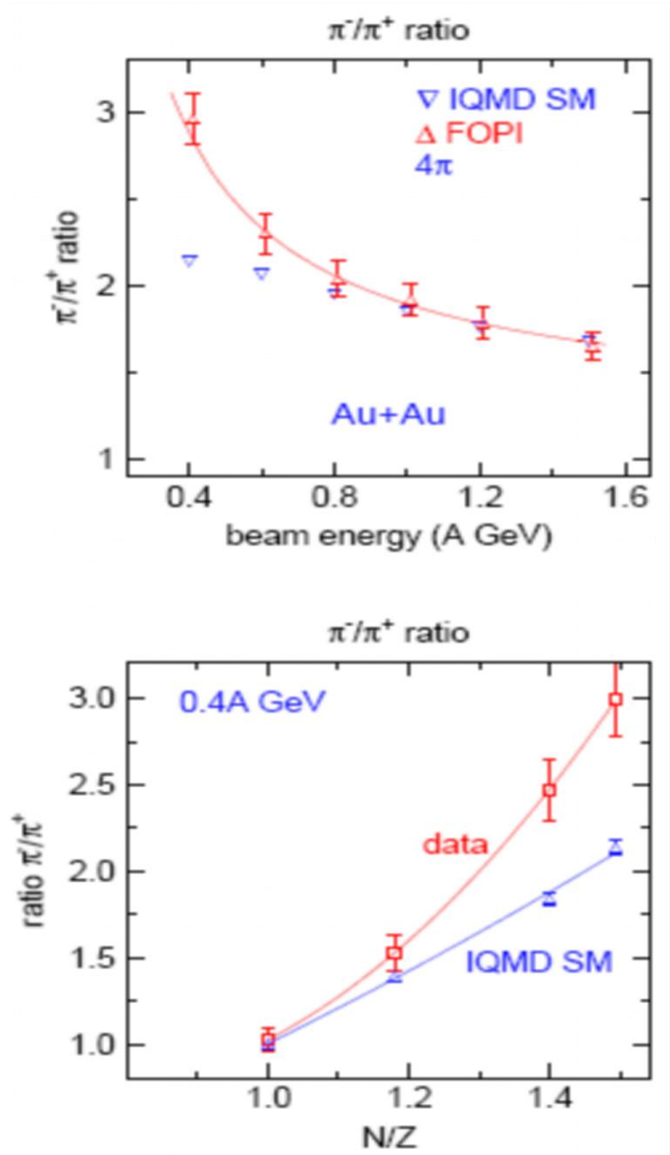


FAZIA-INDRA: $E_{sym}(\rho)$ at saturation densities

C. Ciampi et al., **PLB** 868, 139815 (2025)

and HADES(GsI), LAMPS(IBS), HIRA(MSU) and other experiments...

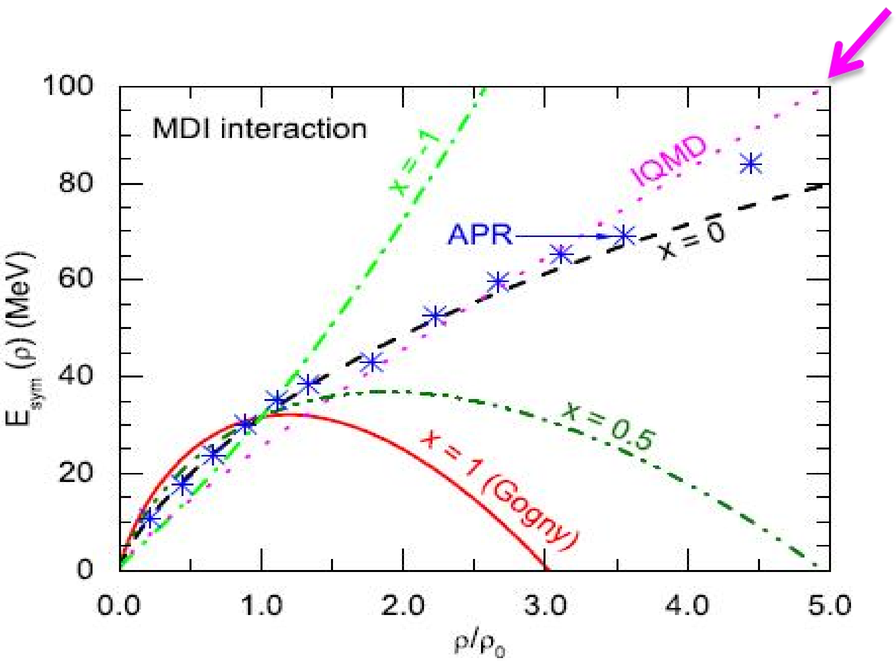
Extract the $E_{\mathrm{sym}}(\rho)$ from π^-/π^+ ratio



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

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

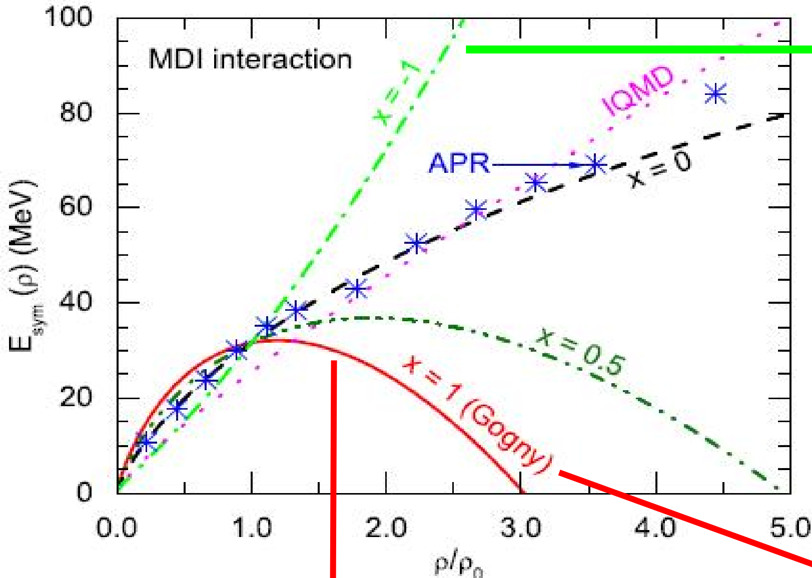
here, $E_{\mathrm{sym}}(\rho) = \frac{25}{2}\frac{\rho}{\rho_0} + (2^{2/3} - 1)\frac{3}{5} E_{\mathrm{F}}^0 \left(\frac{\rho}{\rho_0}\right)^{2/3}$

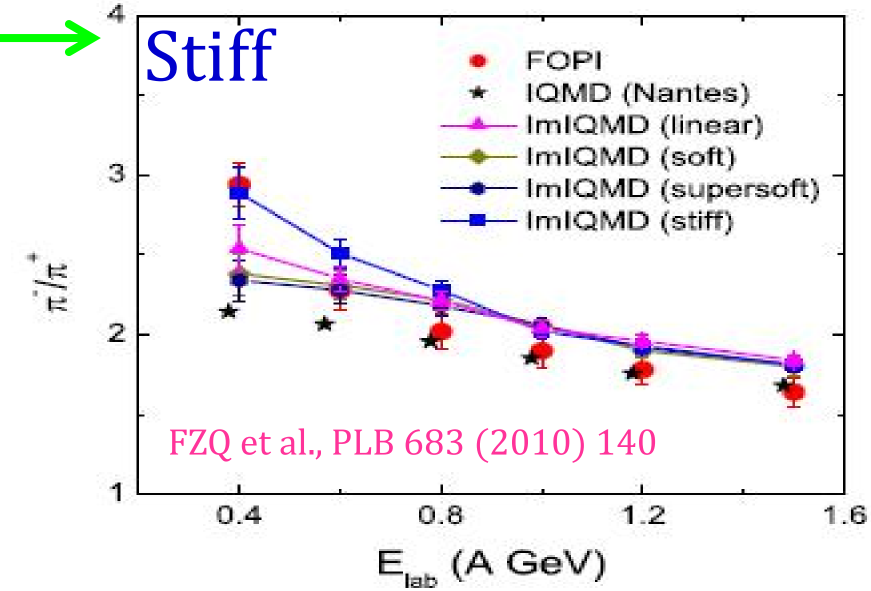


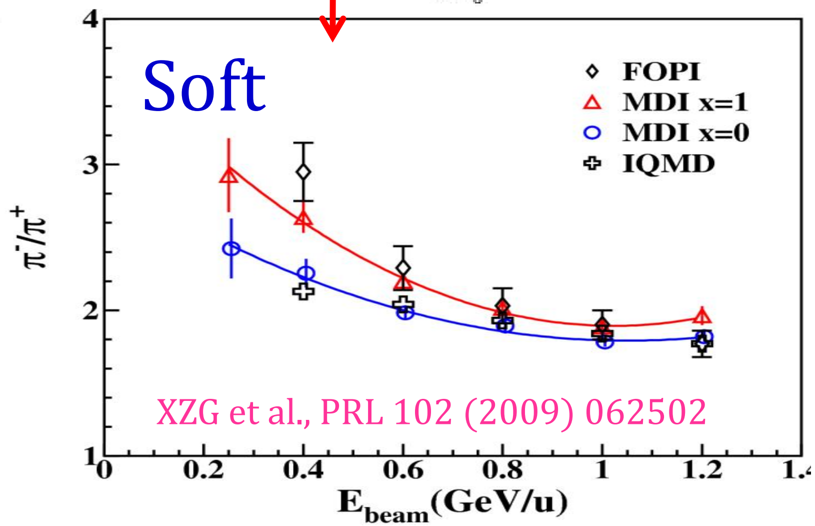
Need a softer symmetry energy to make the pion production region more neutron-rich!

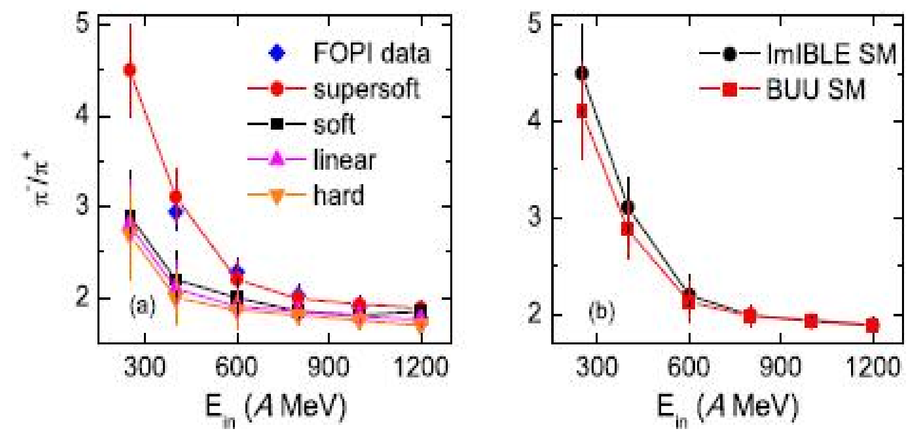
FOPI collaboration , NPA781 (2007) 459

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





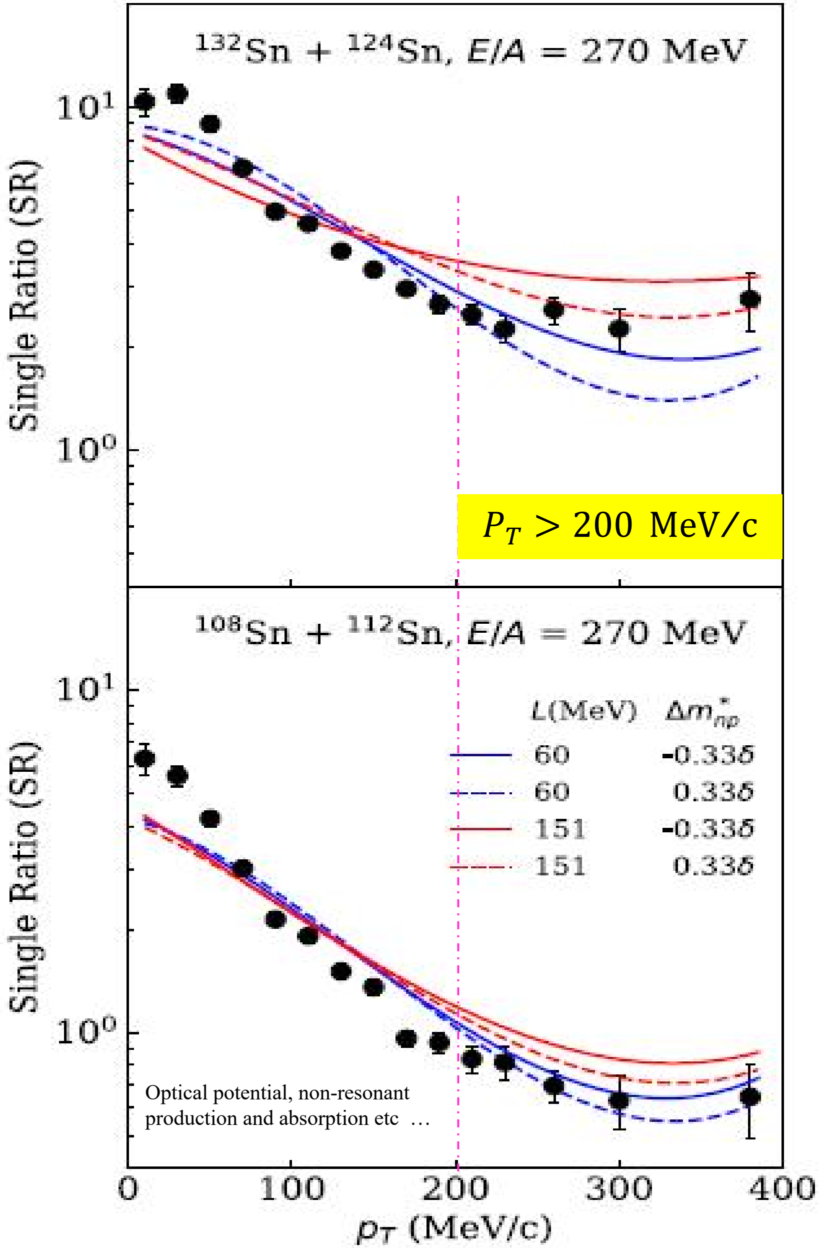


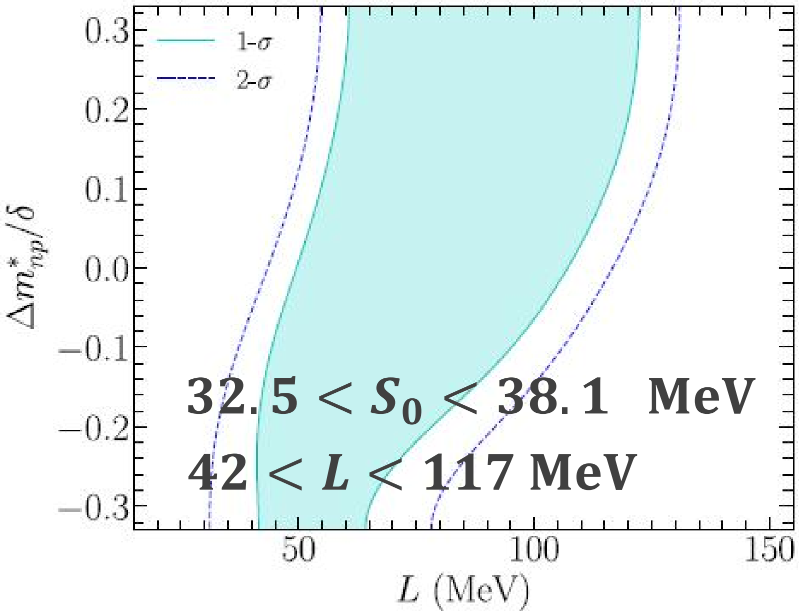


XWJ et al., PLB 718 (2013) 1510

or loss sensitivity on γ J. Hong et al, PRC 90,024605(2010)

Update π^-/π^+ results by SπRIT experiment





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

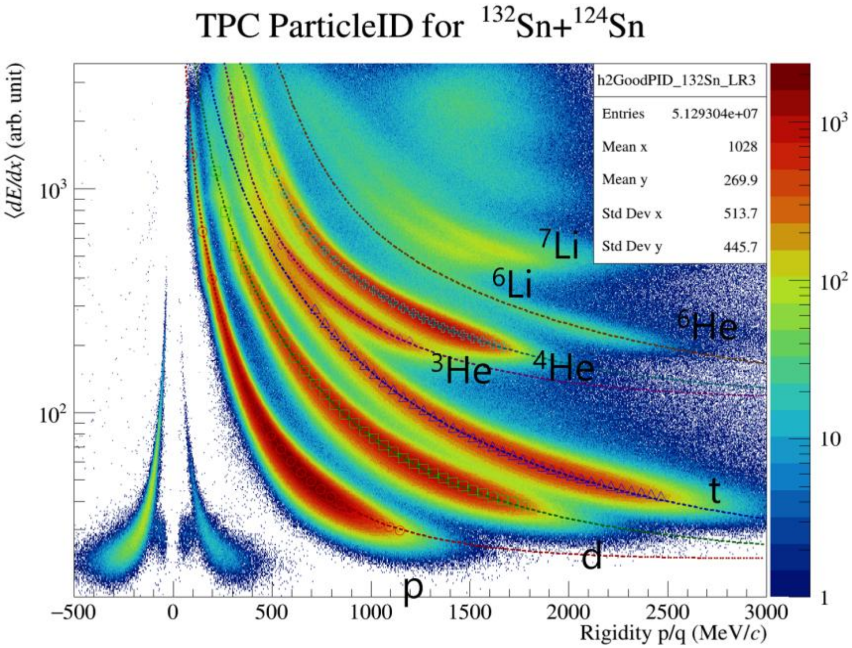
Some perspectives of near future: SπRIT Experiemnts

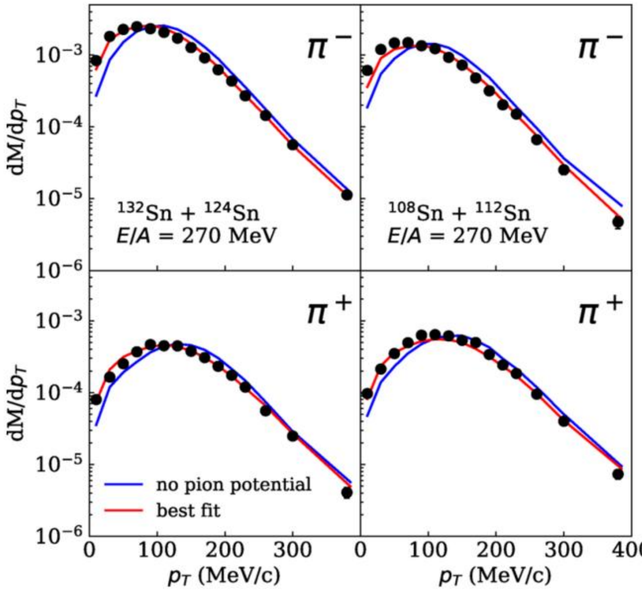
PRL 126, 162701 (2021); PLB 822, 136681(2021); PLB813, 136016 (2021)...

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

  [π^-/π^+ ratio， Flow， Light charged particles published]

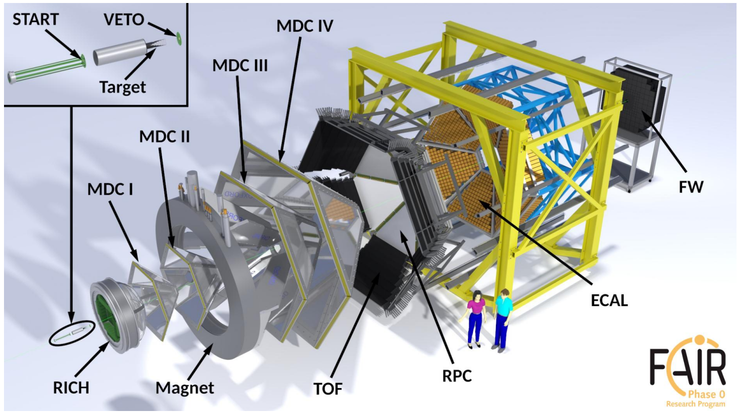
- ☐ 345 MeV/u ^{136}Xe + ^{112,124}Sn： June 2024
- ☐ 270 MeV/u $^{186，208}$Pb + ^{208}Pb： in plan





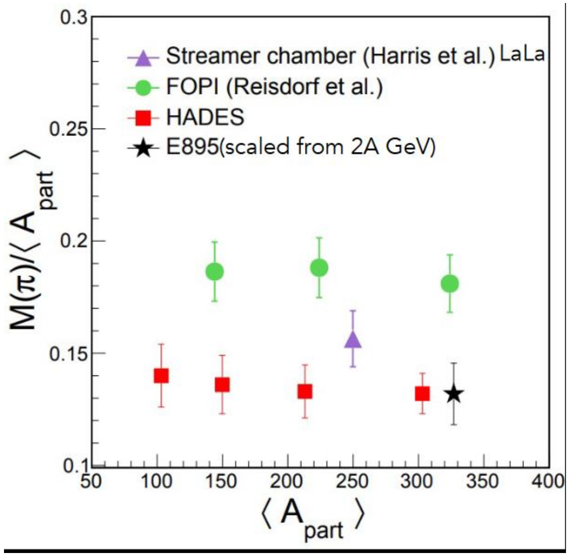
Some perspectives of near future: HADES experiment

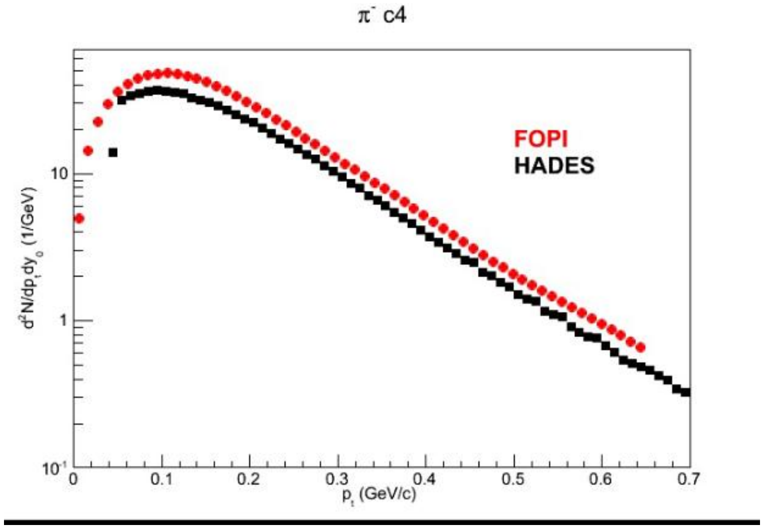
PRL 125, 262301 (2020); PRL 123, 022002 (2019) ; PRC 102, 024914 (2020)



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





M. Lorenz presentation on Nusym23

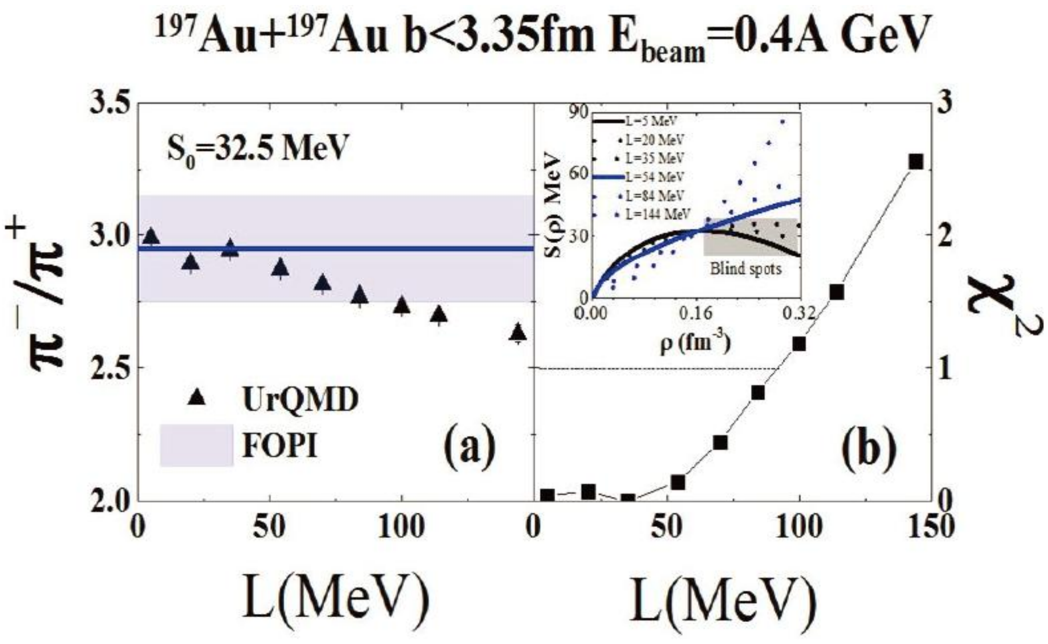
- Beam energy scan of Au+Au and C+C system;
- Flow and pion ratio analysis ongoing
- p-induced collisions planned for short range correlation studies

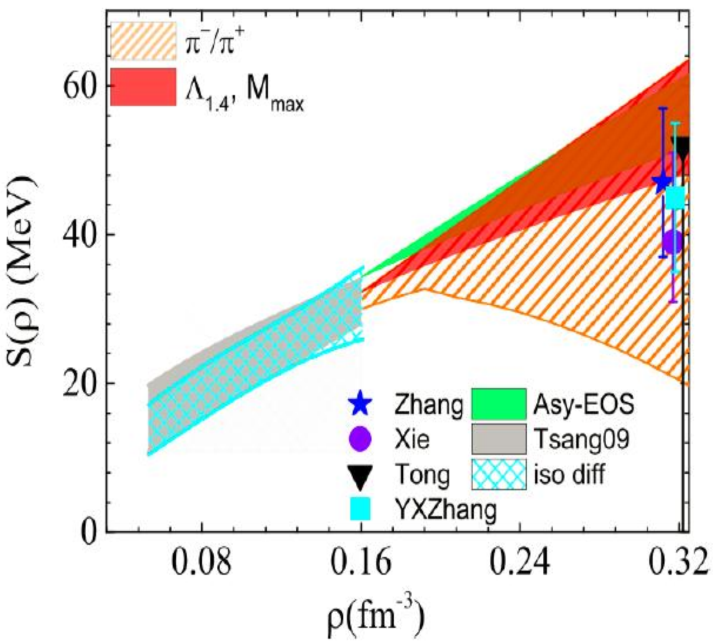
Revisit the π^-/π^+ in combination with GW170817

π^-/π^+ is complicated, for the convolution of threshold effect, medium effect, pion optical potential and $\pi-\Delta$ loop etc.

More studies have been conducted on the production of pions and transport in HIC.

J. Xu, Y. X. Zhang, Q. F. Li, C. M. Ko, Dan Cozma and A. Ono etc...

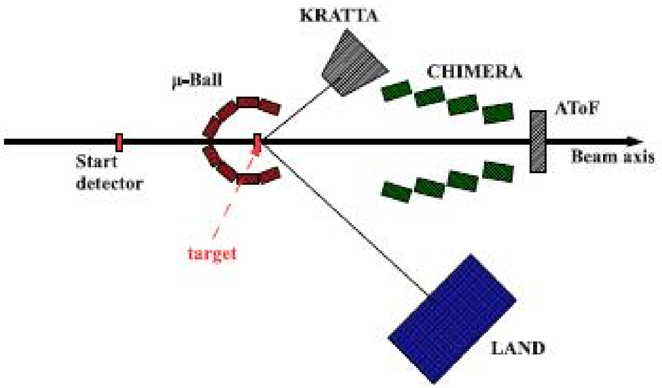


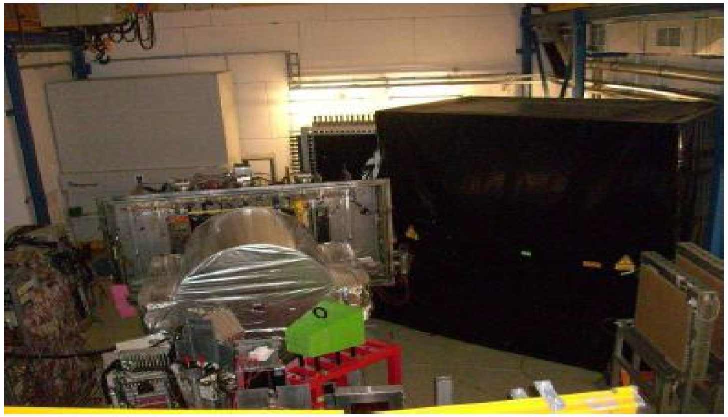


Combine GW170817/HIC: $54 < L < 91$ MeV 【Y.Y. Liu et al., **PRC 103**, 014616 (2021)】

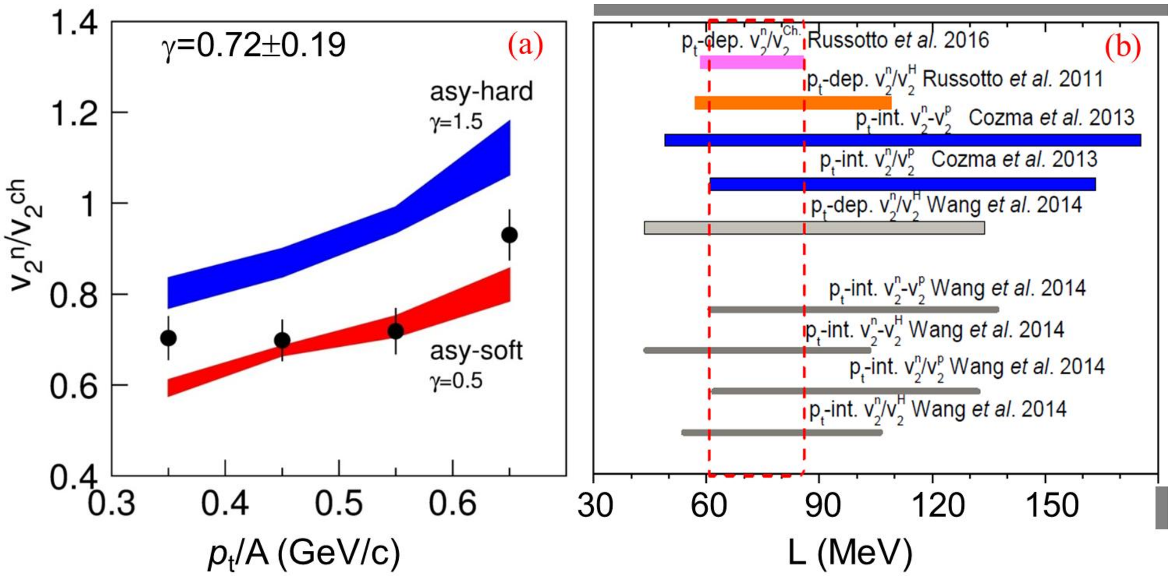
Extract the $E_{sym}(\rho)$ from n/p differential flow

AnSYS-EOS collaboration





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



Y. Leifels et al
PRL71,963 (1993)

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

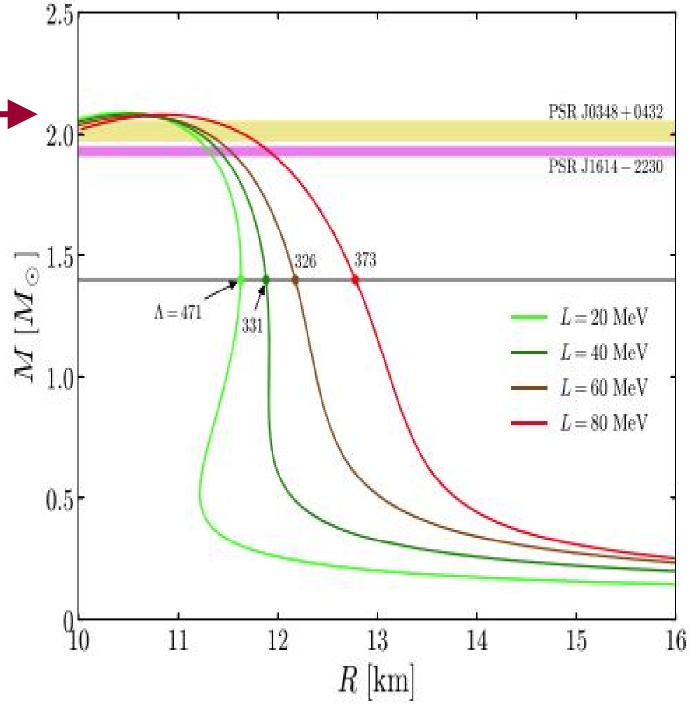
Yongjia Wang et al., **Frontiers of Physics**, 15(4):1, 2020.

Combining GW170817 /PSRJ0740+6620 and HIC

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

1. **QMF18:** $L = 40$ MeV

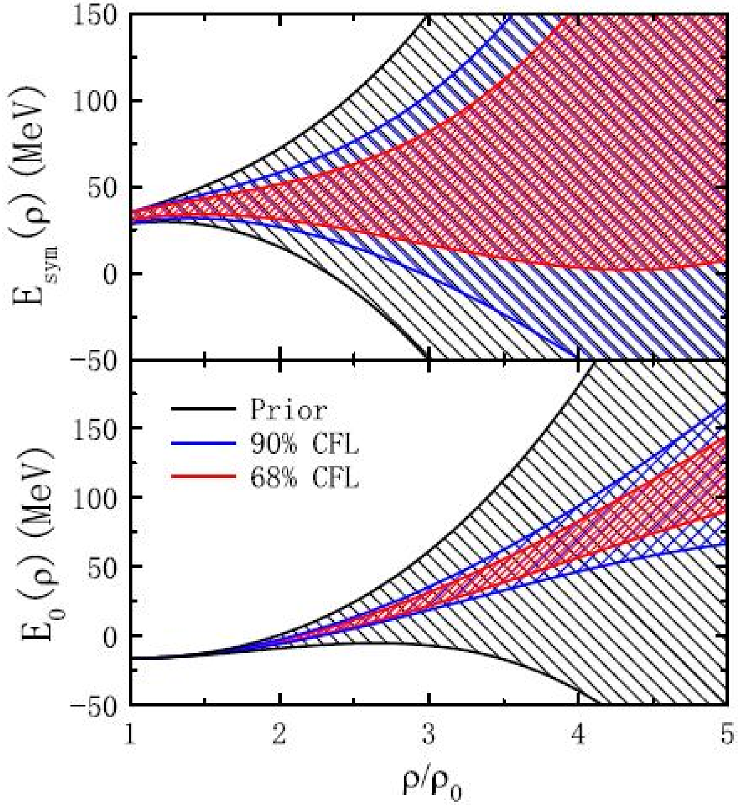
Z. Y. Zhu et al., **APJ 862**,98 (2018)



2. **Bayesian analysis,**

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

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



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

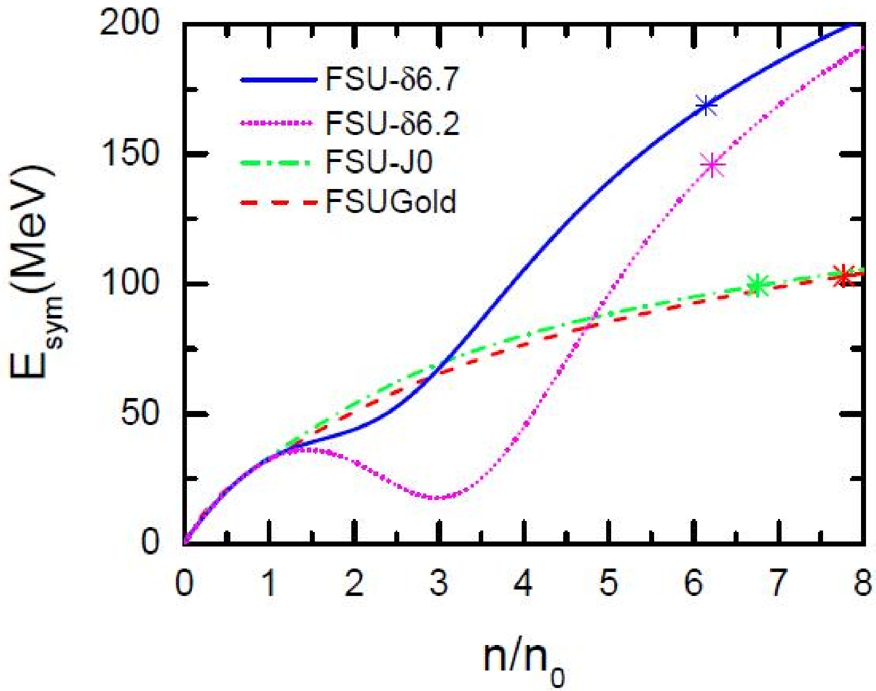
Combining GW170817 /PSRJ0740+6620 and HIC

3. Combing the neutron star merging and nuclear data
   Y. Zhou et al., **PRD99** 121301(R) (2019)

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

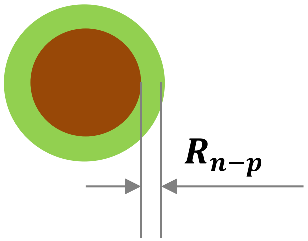
4. Including $\delta-\sigma$ coupling, one get two parameter sets **FSU-δ6.7, FSU-δ6.2**
F. Li et al., ApJ 929, 183 (2022)

Slope parameters are:
$L(\rho_0) = 53.5$ MeV, 48.2 MeV

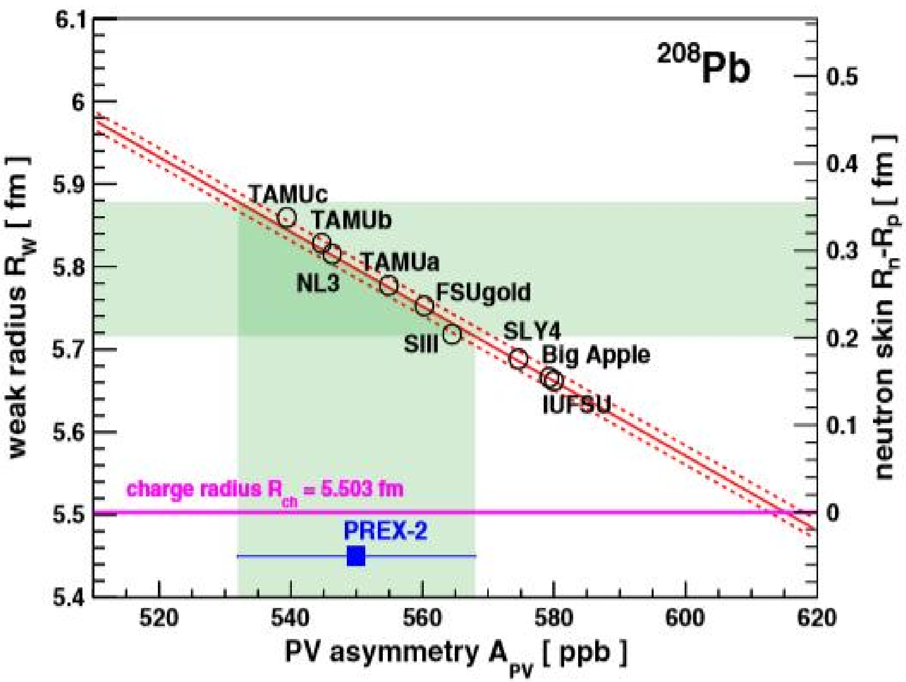


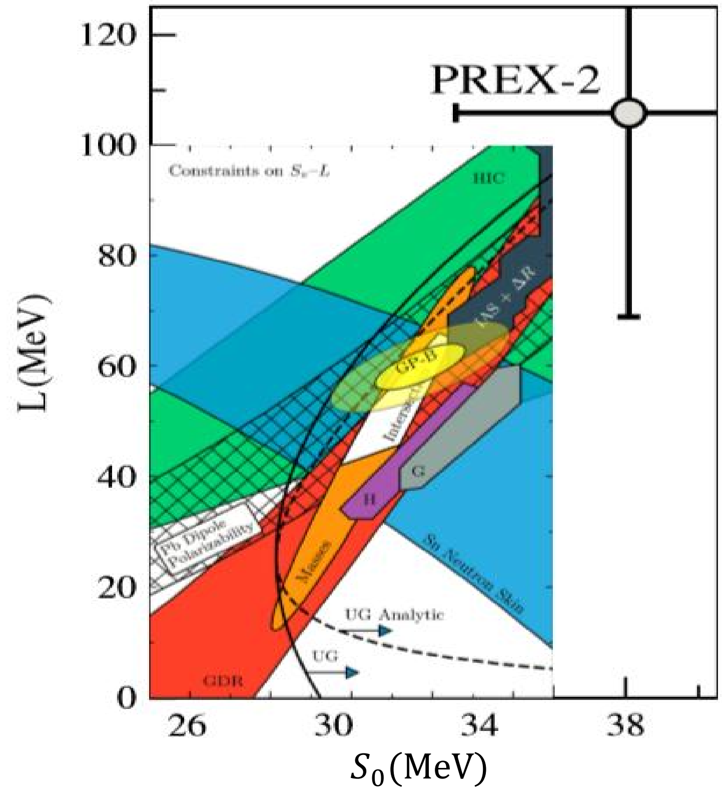
Recent progress of PREX2 experiment

^{208}Pb



PREX masures the parity violation scattering of $e + {}^{208}$Pb to infer the neutron skin thickness of ^{208}Pb .





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

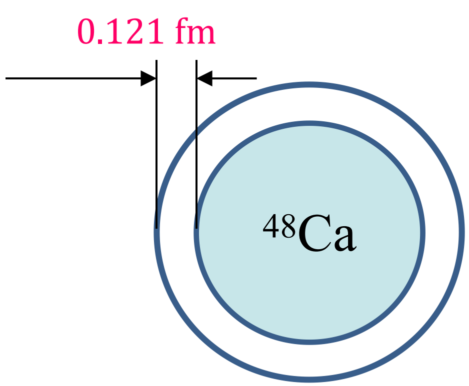
PREX collaboration., PRL 126, 172502 (2021)
B. T. Reed et al, PRL 126, 172503 (2021)

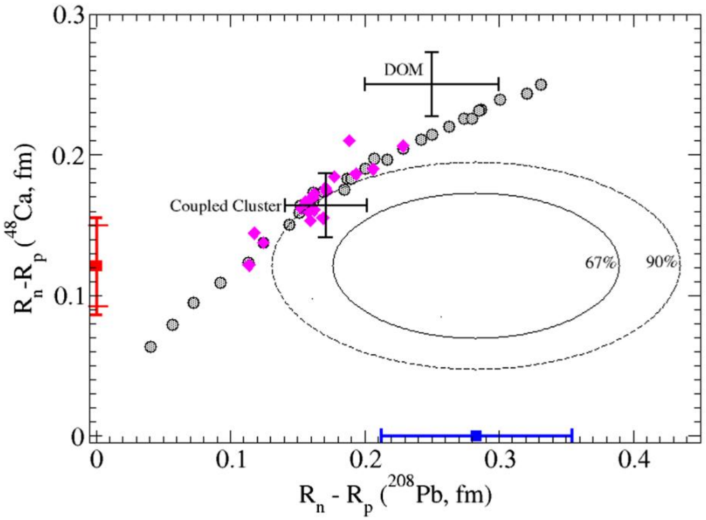
Conbined analysis of PREX-2 and CREX

Based on the same method, ^{48}Ca has been measured:

$$\Delta r_{np}(^{48}\mathrm{Ca}) = 0.121 \pm 0.026(\mathrm{exp}) \pm 0.024(\mathrm{model})\ \mathrm{fm}$$

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.

CREX: small Δr_{np}, very soft $E_{sym}(\rho)$;
PREX-2: large Δr_{np}, rather hard $E_{sym}(\rho)$

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

So, a few words to sumarize the introduction

- The $E_{\mathrm{sym}}(\rho)$ is of significance, attracting theoretical and experimental efforts continuously...
- Despite of the large progress of constraining $E_{\mathrm{sym}}(\rho)$, there is still long way to go before arriving at an accurate and convincing results ,
- In heavy ion collisions, it always comes together with the complicated collision dynamics, particularly of the different transport of neutron and proton,
- Further studies are required, and opportunities with HIRFL/HIAF are expected.

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2.2 CSHINE in Fermi energy domain

3. $E_{\text{sym}}(\rho)$ related studies at Fermi energies

3.1 Isospin dynamics and new probes of $E_{\text{sym}}(\rho)$

3.2 Short range correlations using bremsstralung γ rays

3.3 Direct probe to nuclear force by correlation functions

4. Opportunities towards GeV/u region

4.1 Isospin chemistry with CEE

4.2 Probe neutron skin thickness by correlation function

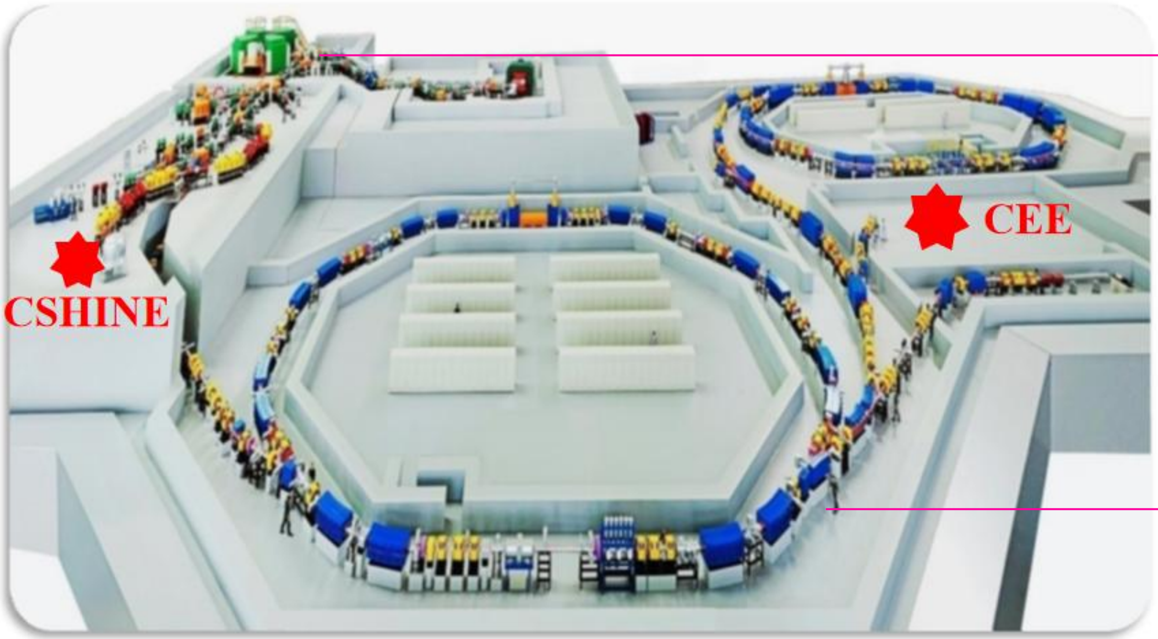
*4.3 Isovector reorientation effect of deuteron

5. Summary and outlook

Opportunies with HIRFL

HIRFL： Heavy Ion Research Facility at Lanzhou
CSR： Cooling Storage Ring

HIRFL-CSR Complex



SSC：
Kr： ~ 40 MeV/u
Sn： ~ 30 MeV/u

→Collisions dynamics and nEOS near ρ_0

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

If equipped with an advance spectrometer：

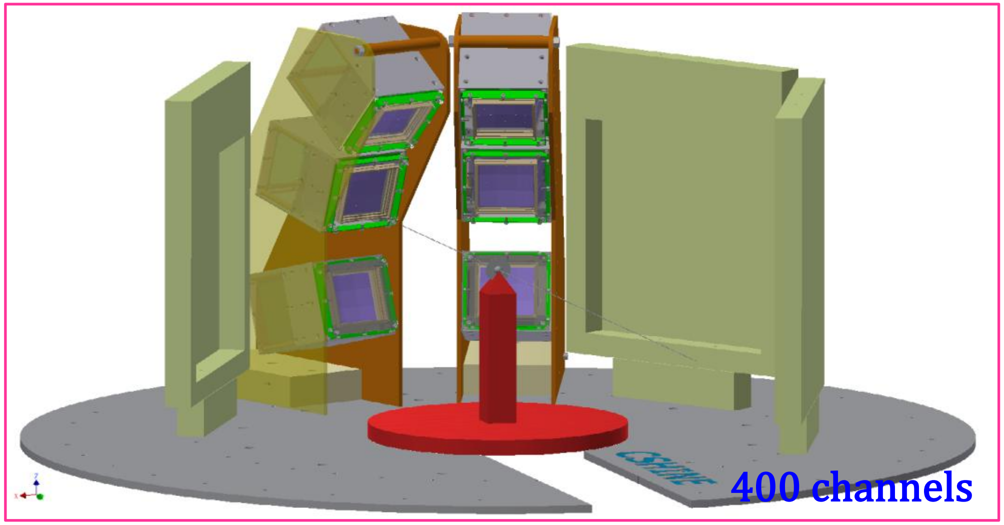
→Collision dynamics, QCD phase diagram and nEOS near $2\rho_0$

→ Hyperon-N interactions

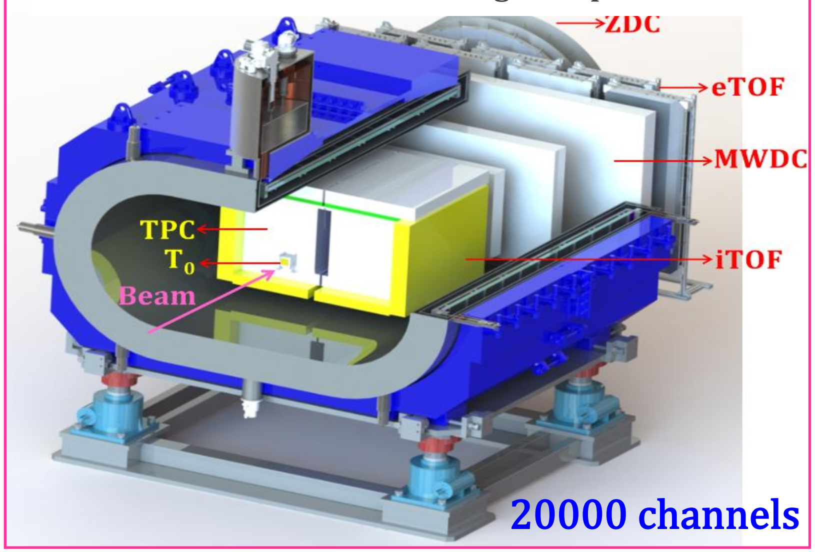
CSHINE and CEE experiments

- Two experiments at HIRFL:
  CSHINE: Running, on RIBLL for HIC at Fermi energies
  CEE: Under construction, on HIRFL-CSR in GeV/u energy region

CSHINE: Compact Spectrometer for Heavy IoN Experiment



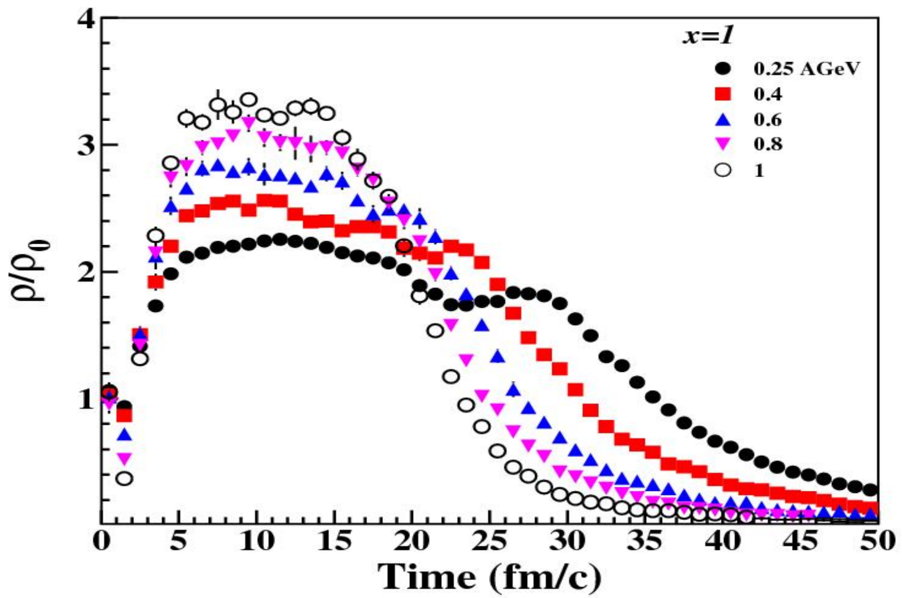
CEE: HIRFL-CSR External-taget Experiment

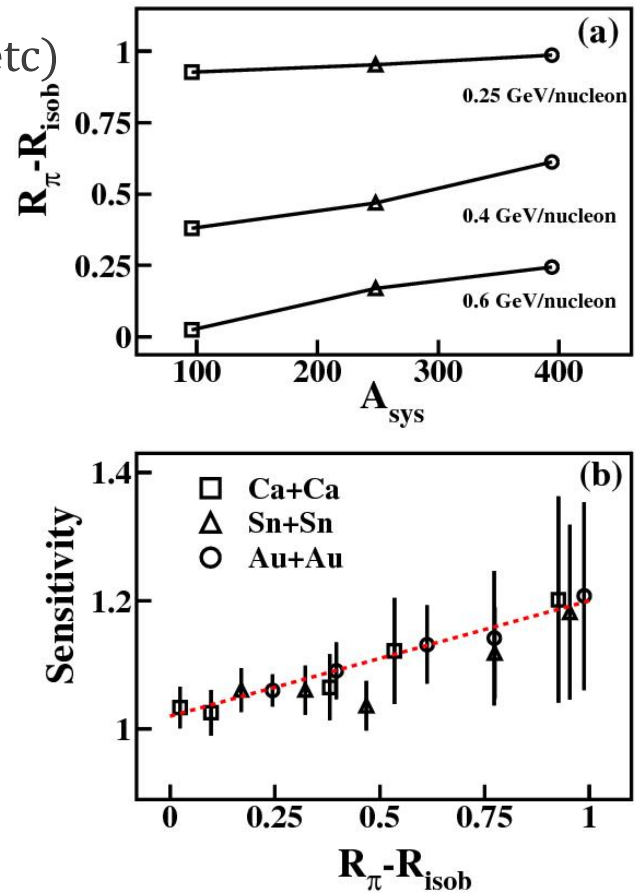


2.1 CEE at GeV/u energy domain

Why is HIRFL-CSR energy region is favorable for $E_{sym}(\rho)$ studies?

- Nuclear matter at $2\rho_0$ can be produced at E_{beam}=0.5 GeV/u.
- The sensitivity of the observable on $E_{sym}(\rho)$ reaches maximum (correlated with Finite size effect, nuclear transparency etc)

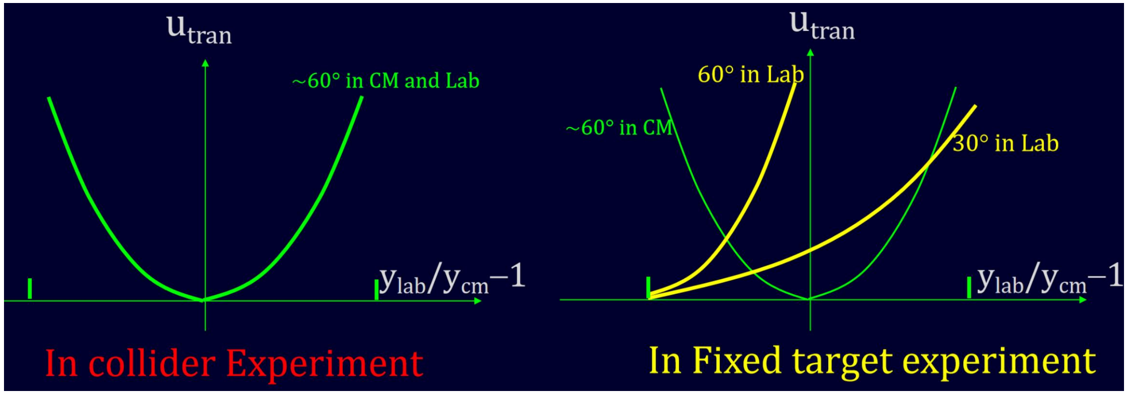




F. Fu, ZGX et al, Phys. Lett. B 666 (2008) 359
M. Zhang, ZGX et al., Phys. Rev. C 80 (2009) 034616

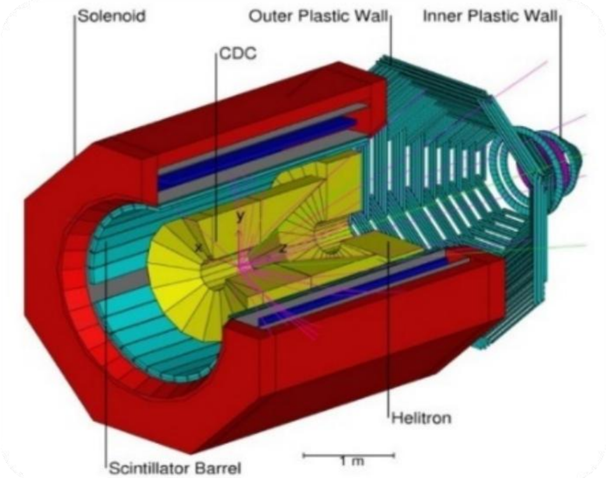
What do we need for a detector?

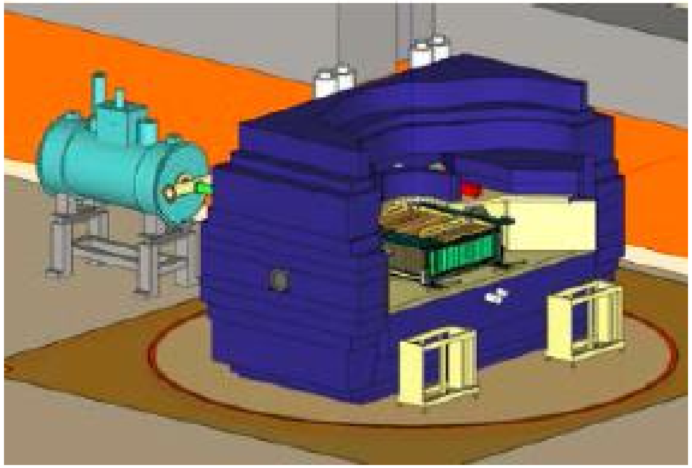
In order to improve both the mid-rapidity and the forward rapidity region, we preferred a large-acceptance dipole type spectrometer for CEE.

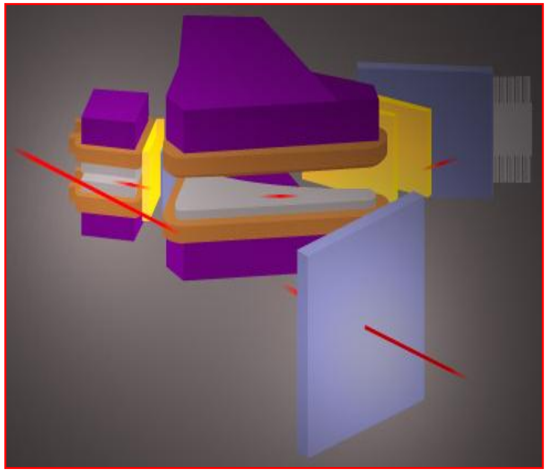


Less powerful forward rapidity (P//Beam) ability

Powerful forward rapidity (P//Beam) ability





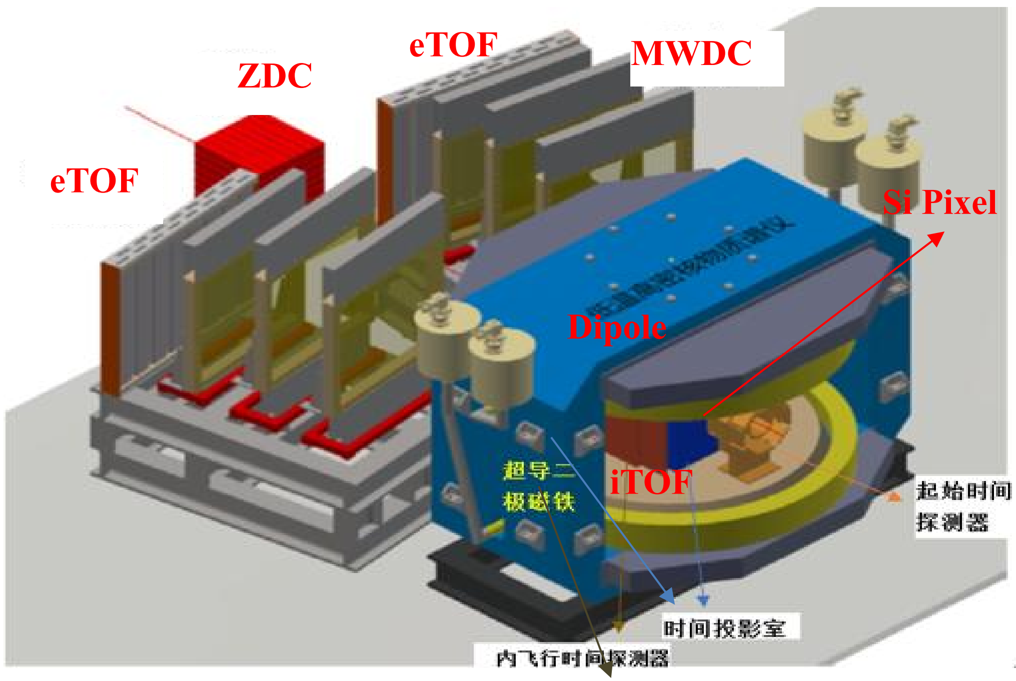


Solenoid Type, FOPI, GSI

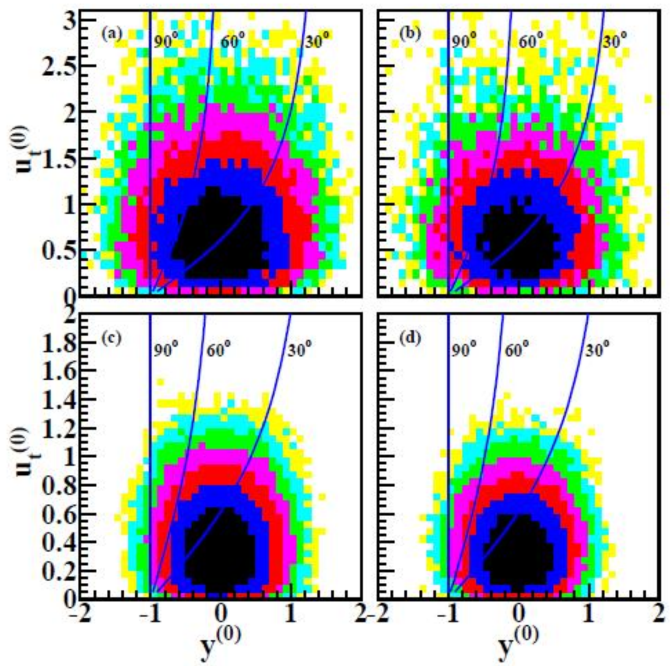
Dipole Type（SAMURAI@RIKEN； KAOS@ GSI)

Preliminary Design for CEE

In order to improve both the mid-rapidity and the forward rapidity region, we preferred a large-acceptance dipole type spectrometer for CEE.



$$E\frac{d^3\sigma}{dp^3}=\frac{1}{p_t}\frac{d^3\sigma}{dydp_td\varphi}$$



L. M. Lv, ZGX, M. Shao, S. Zhang, G. Q. Xiao and N Xu, SCPMA 60, 012021 (2017)

Conceptual design of the HIRFL-CSR external-target experiment

LiMing Lü[1], Han Yi[1], ZhiGang Xiao[1,2*], Ming Shao[3], Song Zhang[4], GuoQing Xiao[5], and Nu Xu[6]

CEE Detection System

- CEE： HIRFL-CSR Extermal-target Experiment

After 10 years pre R&D,

- Project approved in Aug. 2019
- Scheduled to Dec. 2024, extended to Dec. 2026
- Support from both NSFC and CAS

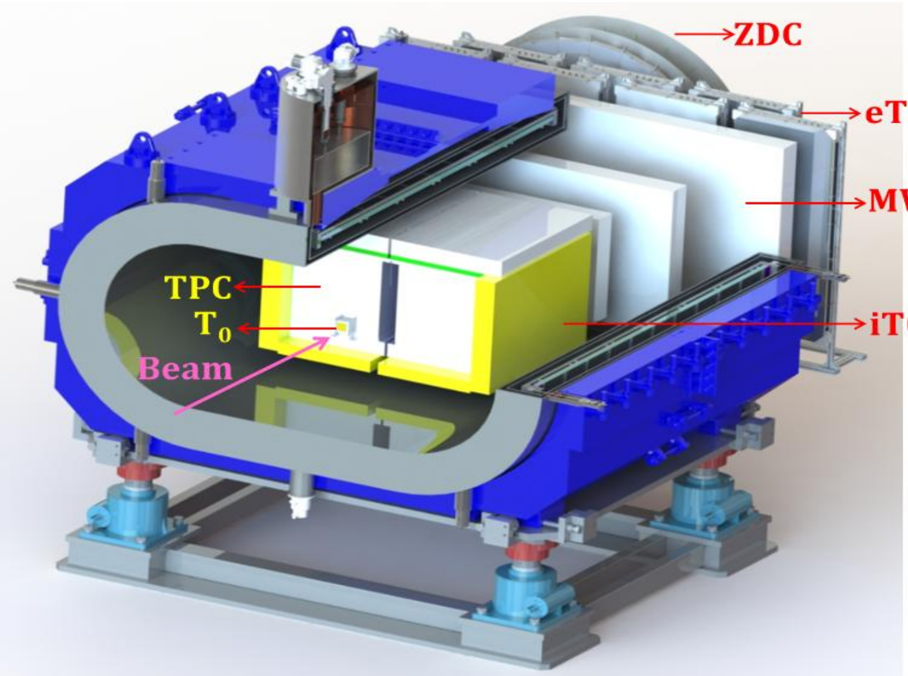


TABLE I. (Color online) Technical indicators of CEE.

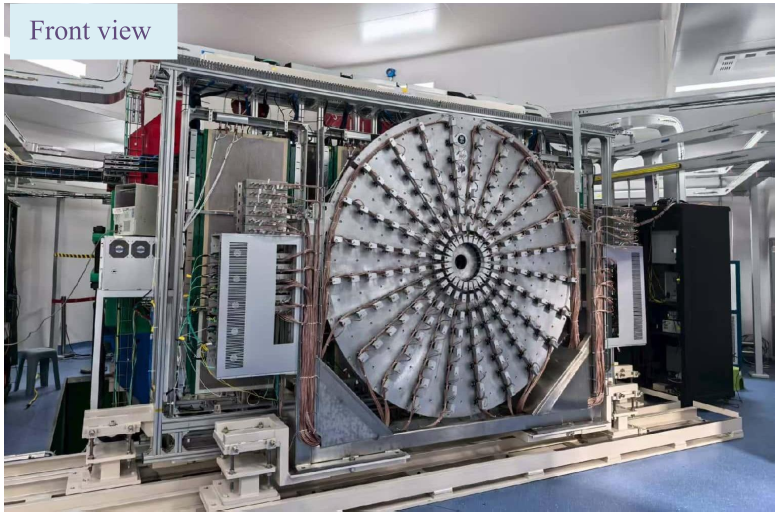
Item	value
Maximum beam energy	0.5GeV/u(U) – 2.8GeV(p)
Bean type	$p \sim U$
Maximum event rate	10 kHz
Acceptance	$> 50\%$
Total channel number	20k

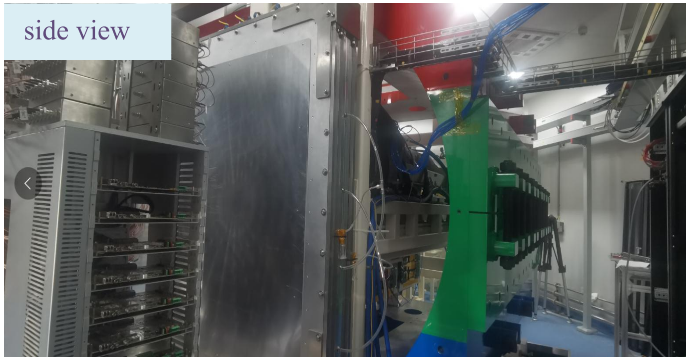
2019.8.15, 1st CEE collaboration meeting

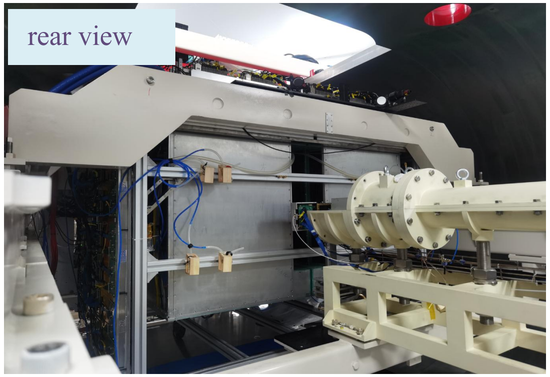
Current Status: Test runs without magnetic field

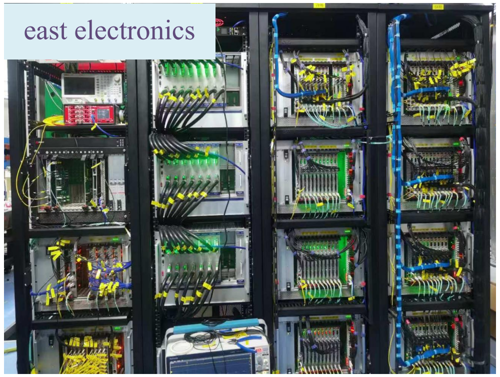
Contributions from Tsinghua ENPG group: MWDC tracking hardware & software

Trigger system design & intergration









ENPG Group publication list on CEE R&D

NIMA 701,54 (2013) ; **CPC**38, 126002 (2014); **CPC** 40, 116102, (2016); **SCPMA** 60,012021 (2017); **NST** 31, 11 (2020) ; **JINST** 19, T02018 (2024) ; **EPJA** 60, 36 (2024); **NST** 35,174 (2024); **NST** 36, 67 (2025)

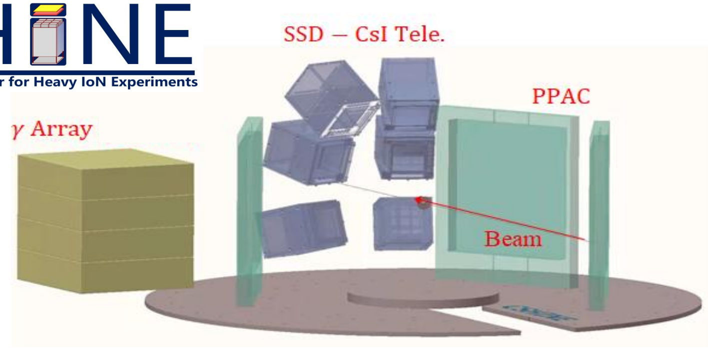
2.2 CSHINE in Fermi energy domain

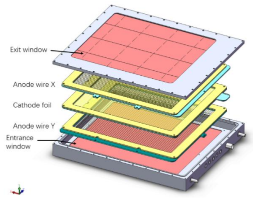
▶Why CSHINE? To better know HD, precise result at ρ_0 is required; some related studies are favored at low energy!

▶Isospin-dependent emission hierarchy is observed in fission process of 35 MeV/u Ar+Au [*] [**]

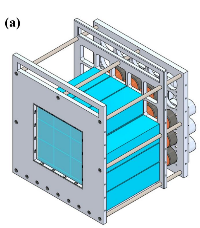
[*] R. S. Wang et al., **Phys. Rev. C** 89, 064613 (2014)
[**] Q. H. Wu et al., **Phys. Lett. B** 797, 134808(2019); **Phys. Lett. B** 811,135865 (2020)

CSHINE
Compact Spectrometer for Heavy IoN Experiments



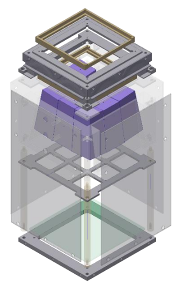


PPAC for Fission



CsI γ hodoscope

Total Channels: ~400, Starting 2014



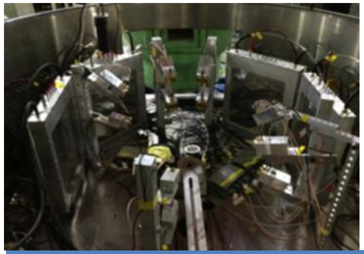
SSDT for LCPs

Exp. Site: HIRFL-RIBLL1

A 4π-coverage experiment is not affordable!

We want a **compact, flexible, less costly but specific** detector!

Construction and 5 runs of CSHINE



02 2018

30 MeV/u $^{40}Ar+^{197}Au$

04 2022

25 MeV/u $^{86}Kr+^{124}Sn$

30 MeV/u* $^{40}Ar+^{197}Au$

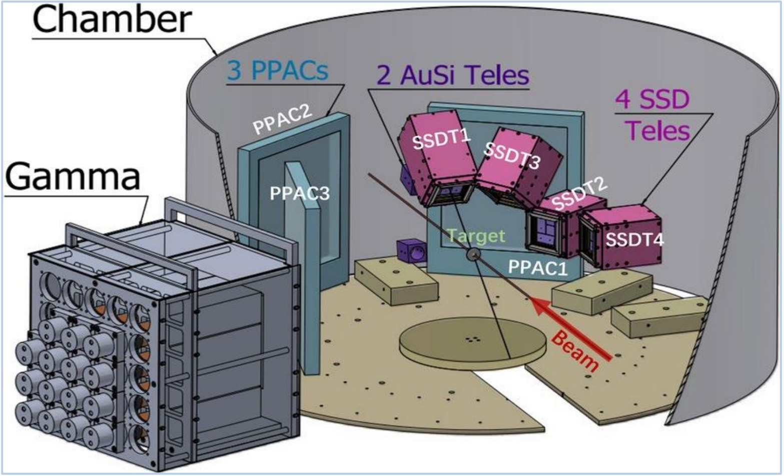
01 2014

25 MeV/u $^{86}Kr+^{208}Pb$

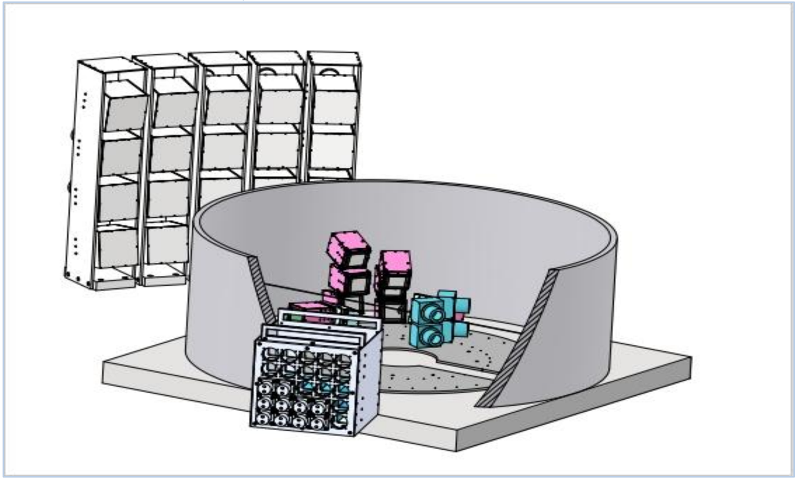
03 2019

25 MeV/u $^{124}Sn+^{124}Sn$

05 2024



4th run: 2022 CSHINE-Gamma



5th run: 2024 CSHINE-Neutron Wall

CSHINE techniques and physical programs

Detector R&D：

›Technique Publications

NIMA 1070,170055 (2025)
NIMA 1053, 168330 (2023) ,
NIMA 1080, 170787 (2025)
NST 33, 162 (2022)
NST 33, 40 (2022)
NIMA 1029, 166461 (2022),
NIMA 1011, 165592 (2021) ,
NST 32, 4 (2021),
NST 36, 132 (2025)

On the cover of Nucl. Sci. Tech.
Jan. 2021 July 2025

Physical Studies:

›n-n CF and (f_0^{nn}, d_0^{nn})

PRL 134,222301 (2025)

› Bremsstrahlung γ and SRC

PLB 850,138514 (2024)
PLB 857,139009 (2025)
PRResearch 7,043174 (2025)
arXiv2508.04550 (PRC, under review);

›t/^{3}He ratio and ^{3}He-puzzle

PRC 107, L041601 (2023)
NST 36,155 (2025)

›Isospin Choronology

PLB 825, 136856 (2022)

›Constraint of $E_{sym}(\rho)$ near $\rho \approx \rho_0$

PRC 95, 041602R (2017)

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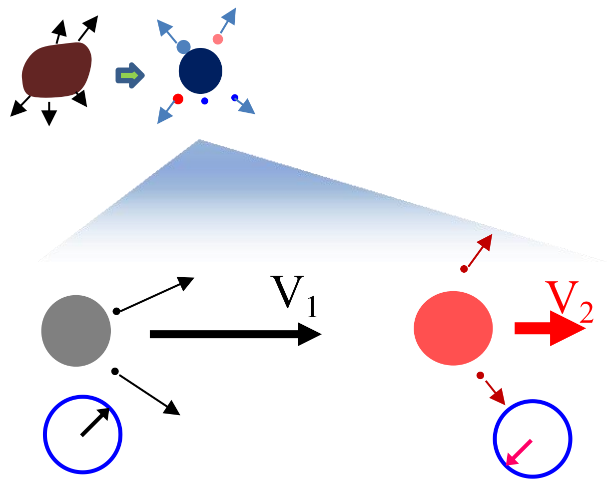
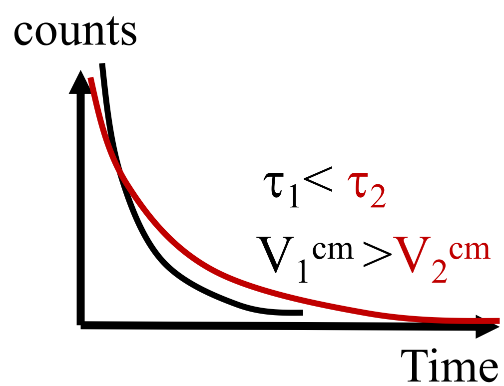
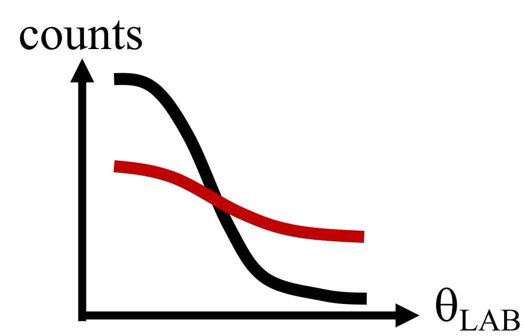
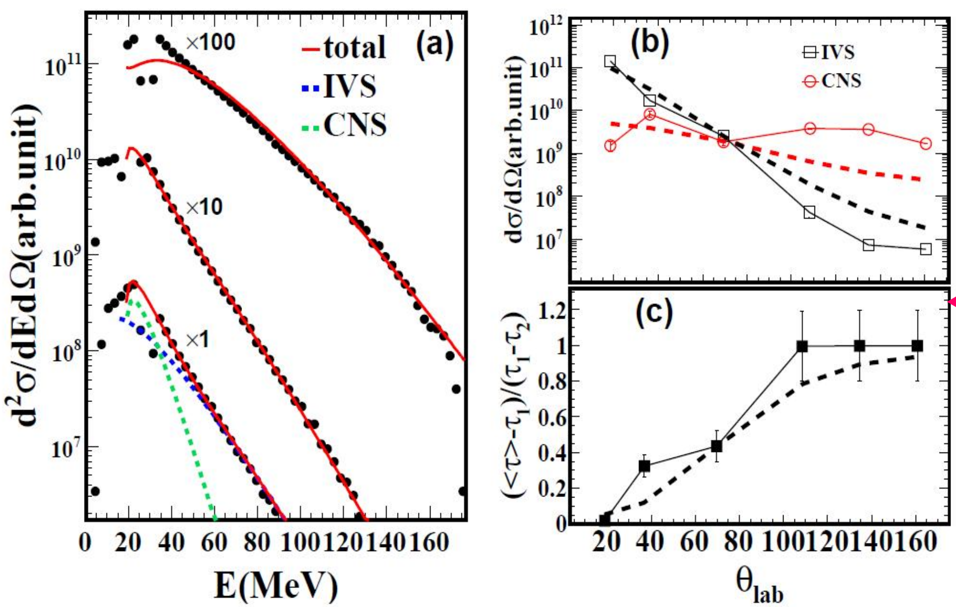
3.1 Isospin dynamics and new probes of $E_{sym}(\rho)$

Translate the angular distribution to time evolution:



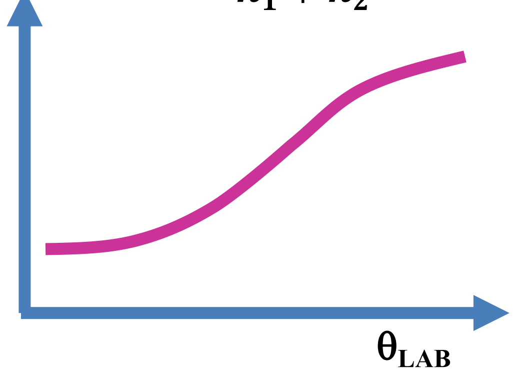






30 MeV/u Ar+Au

$$< \tau > = \frac{n_1\tau_1 + n_2\tau_2}{n_1 + n_2}$$

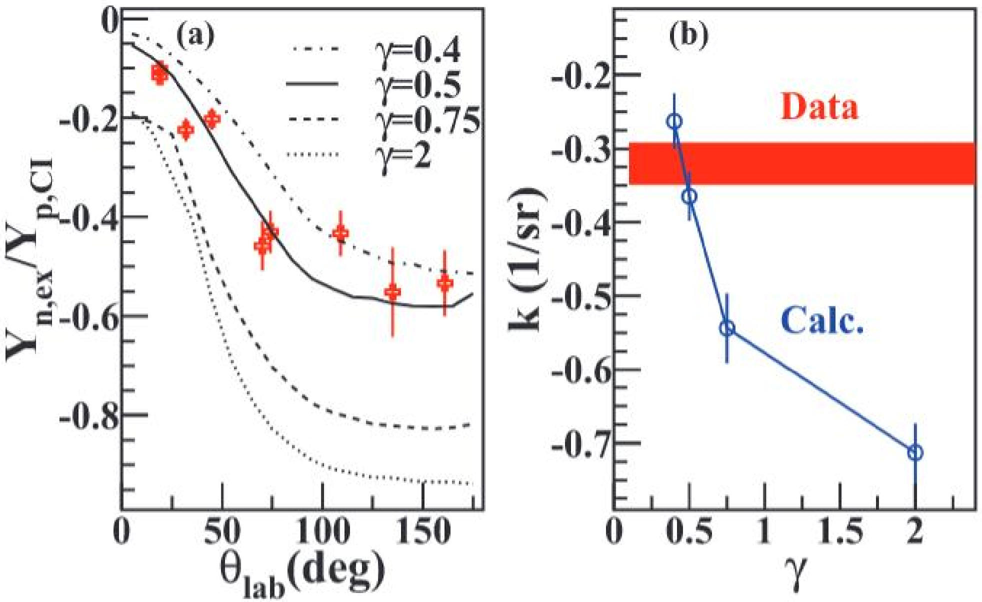


Constraining $E_{sym}(\rho)$ near $\rho \approx \rho_0$

1. Isospin drift persist to long time;

2. Comparing to the transport model: $\gamma_{\mathrm{i}} = 0.46 \pm 0.025$ **or** $L = \mathbf{47} \pm \mathbf{14}$ MeV (CL = 95%) ($S_0 = 28.3$MeV)

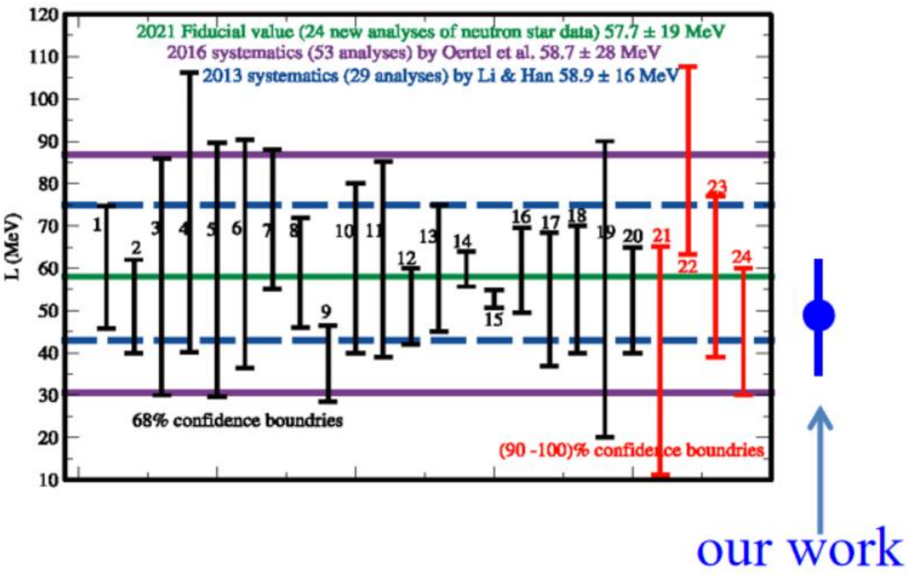
$$\frac{Y_{\mathrm{n,ex}}}{Y_{\mathrm{p,CI}}} = \frac{\sum y_i (N_i - Z_i)}{\sum y_i Z_i}$$



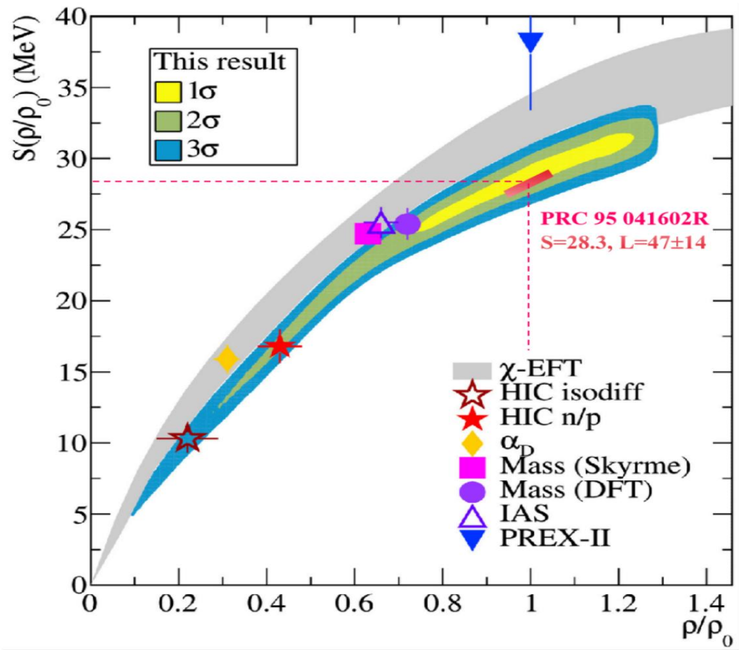
Y. Zhang et al., **Phys. Rev. C** 95,041602(R) (2017)

Comparing with recent world data

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



PLB 868, 139815 (2025)



In accordance with most recent world data：

INDRA-FAZIA： **PLB** 868, 139815 (2025)

Analysys from neutron star merge： **PRC** 112, 015805(2025) L≈48

Y. Cui et al., **NST** 36, 141 (2025) L=49±20 (better constraint at $2\rho_0$)

SπRIT Collaboration： **PLB** 822,136681(2021) L=46

Isospin Chronology results

Using CRAB model to fit the correlation function $C_{12}\,[1+R(q)] = \frac{\Sigma Y_{12}(\vec{p}_1,\vec{p}_2)}{\Sigma Y_1(\vec{p}_1)\, Y_2(\vec{p}_2)}$

Source function:

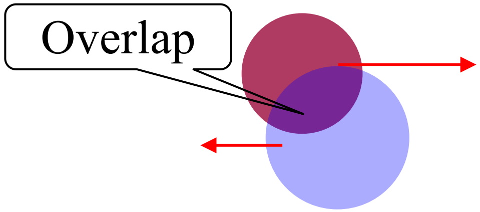
$$S(r,t) = c\exp\left(-\frac{r^2}{2\sigma_r^2} - \frac{t^2}{2\tau^2}\right)$$

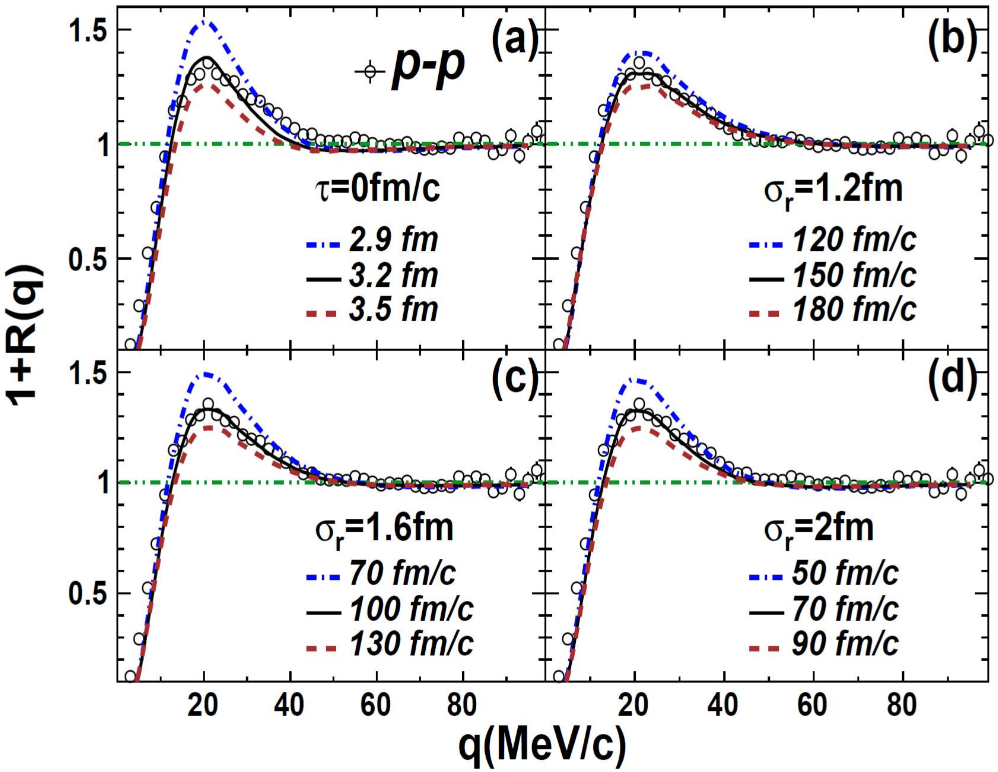
$\boldsymbol{\tau_p} \approx 100\ \mathrm{fm/c}$

$\sigma_r \approx 1.6\ \mathrm{fm}$

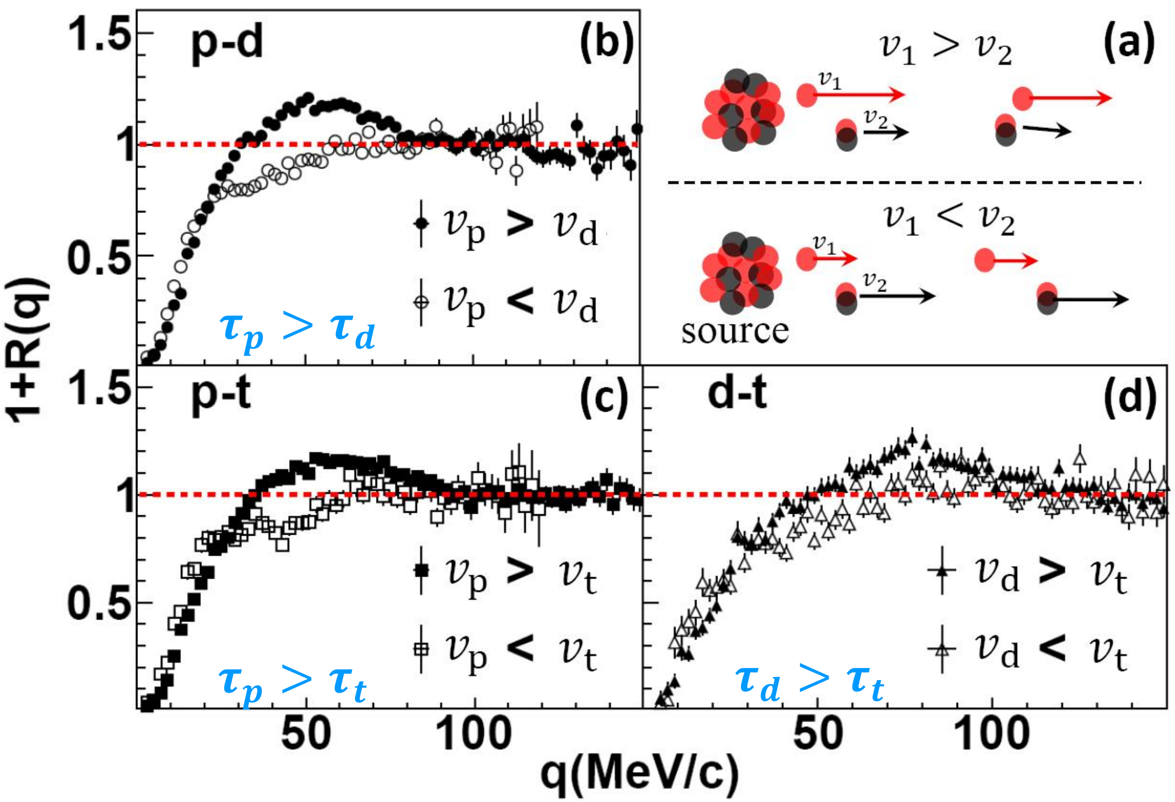
Size of overlape region

$\approx 2 \times 0.75 A_{\mathrm{pro}}$





Isospin Chronology results



By velocity-cut analysis, we obtain the emission order of two unlike particles:

$\boldsymbol{\tau_p > \tau_d > \tau_t}$

Consistent with :
$\tau_p > \tau_d > \tau_n$

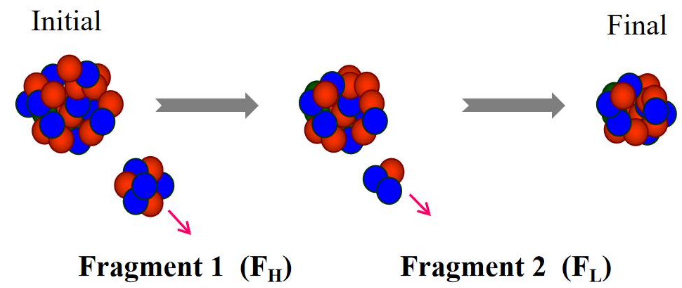
R. Ghetti et al., PRL 91, 092701 (2003).

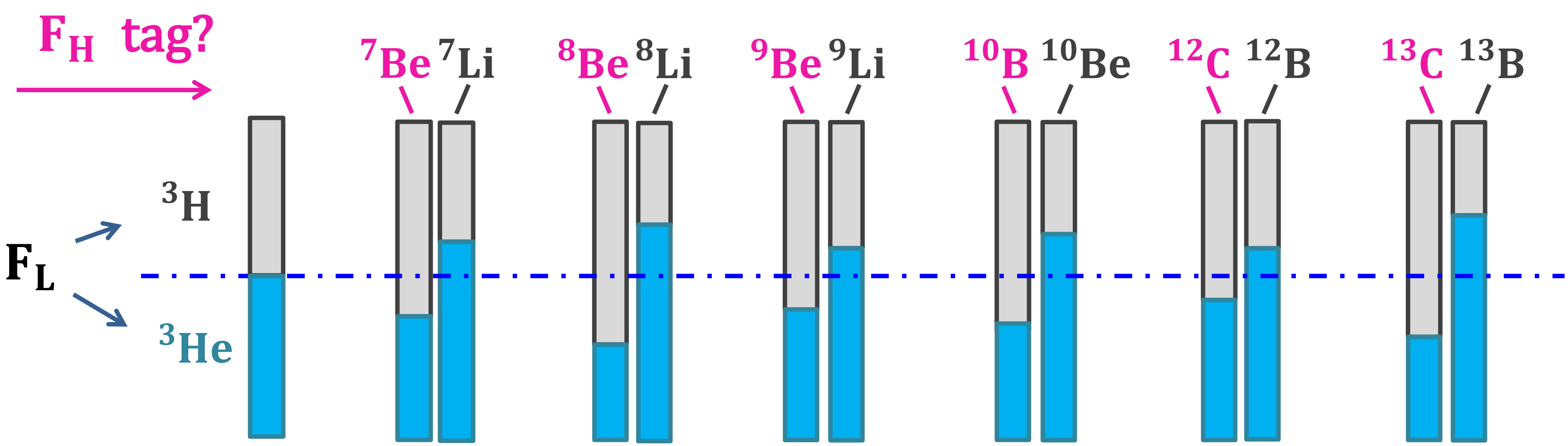
- ImQMD simulations reveals $E_{sym}(\rho)$ influences the time constant of ci-n and ci-p ;

The emission order of hydrogen isotopes via correlation functions in 30 MeV/u Ar+Au reactions
Y. J. Wang et al., Phys. Lett. B 825, 136856 (2022)

Anticorrelation of N/Z of the two emitted fragments

$\frac{^{3}H}{^{3}He}$ yield ratio is a probe of $E_{sym}(\rho)$, it shall be correlated with the relaxation of the isospin DOF, how can we view the correlation?

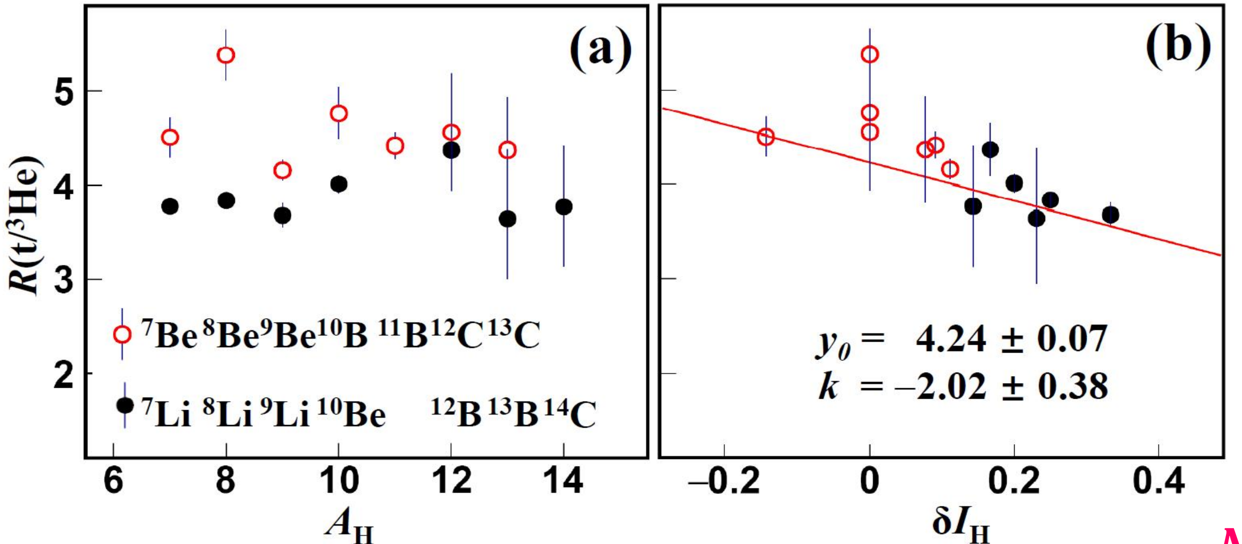




- The N/Z of the light fragment is anti-correlated with that of the tagging heavy fragment, demonstrating a ping-pong modality of emission in isospin!

Anticorrelation between $R(\mathrm{t}/^3\mathrm{He})$ and the heavy fragment N/Z

- $R(\mathrm{t}/^3\mathrm{He})$ splitted in two groups according to the N/Z of the heavy tagging fragment;
- Ping-pong modality: F_H is neutron-rich, $R(\mathrm{t}/^3\mathrm{He})$ is smaller, and *vise versa.*

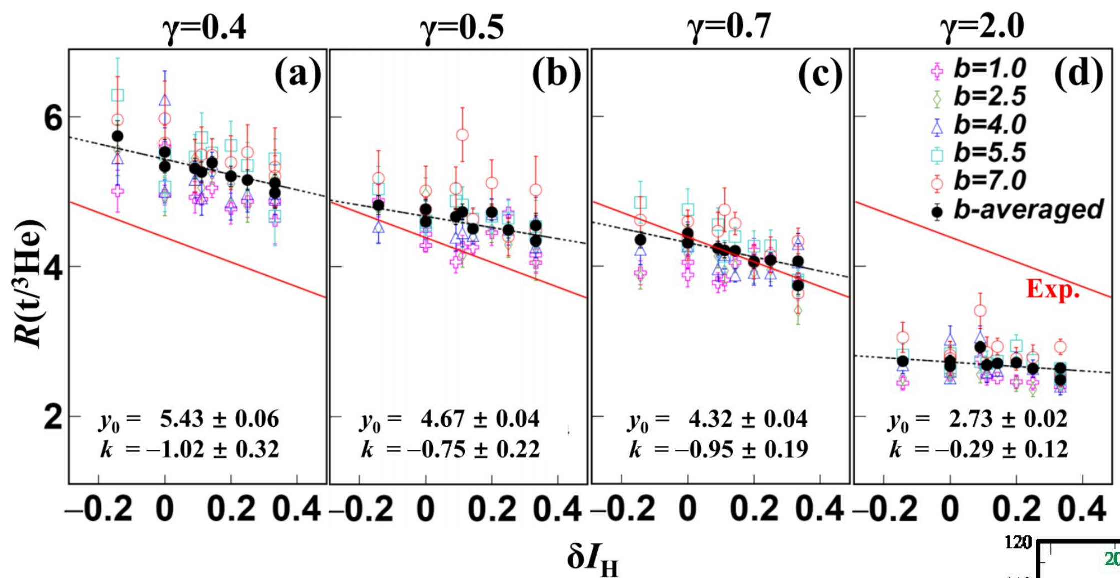


$$\delta I_H = \frac{N_H - Z_H}{A_H}$$

- $R(\mathrm{t}/^3\mathrm{He})$ anti-correlated with δI_H, partly due to N、Zconservation of a finite system.

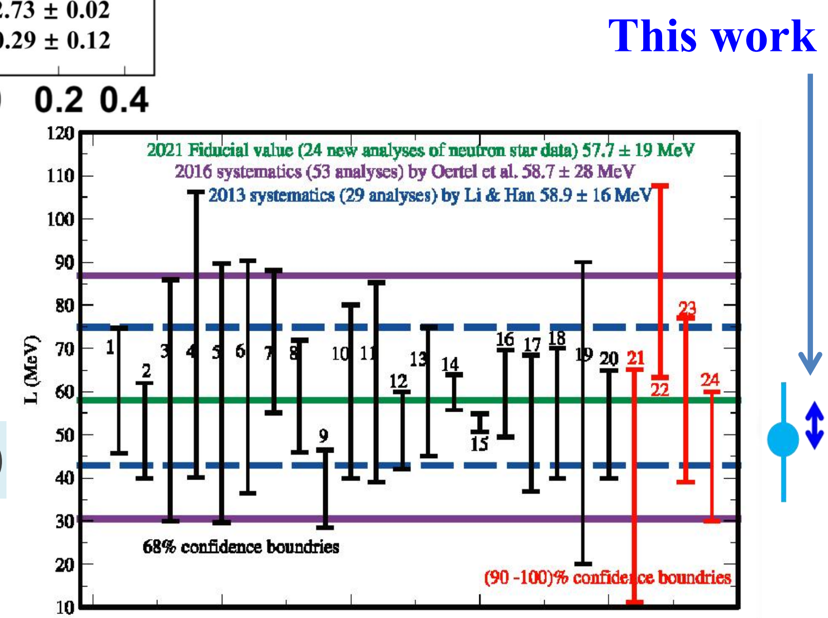
Compare with ImQMD calculations to constrain $E_{\mathrm{sym}}(\rho)$

- $R(t/{}^3He)$ depends weakly on b, strongly on slope parameter of $E_{\mathrm{sym}}(\rho)$;
- $R - \delta I_H$ anti-correlation provides a sensitive probe to $E_{\mathrm{sym}}(\rho)$.



A soft symmetry energy with $\gamma = 0.5$ - 0.7 ($L = 49 - 60$ MeV) is supported

Y. J. Wang et al., **Phys. Rev. C** 107, L041601 (2023)

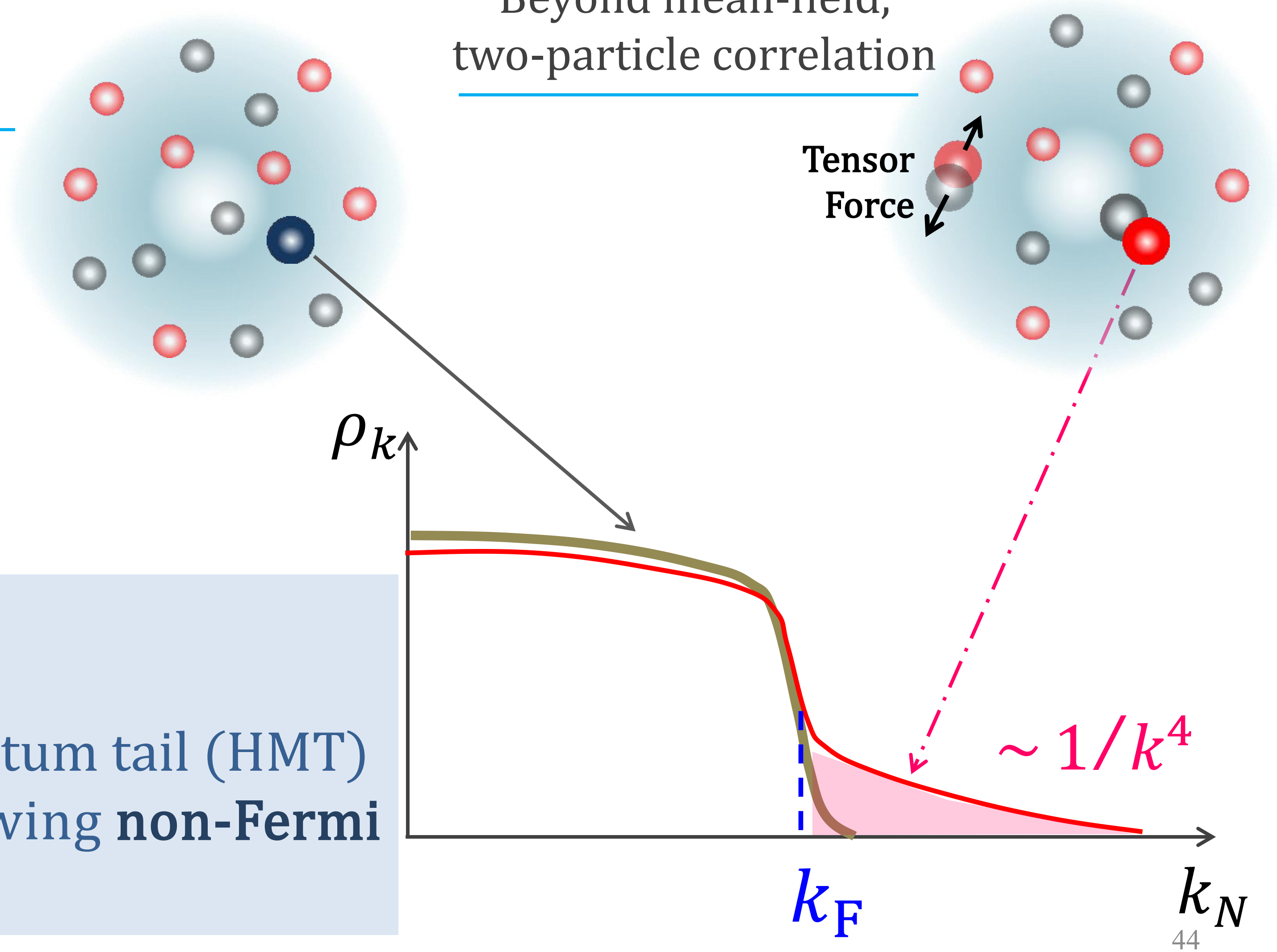


3.2 Short Range Correlations using bremsstralung γ rays

- **SRC: Nucleons form temporally correlated pairs in close proximity.**

mean-field,
Single particle

Beyond mean-field,
two-particle correlation

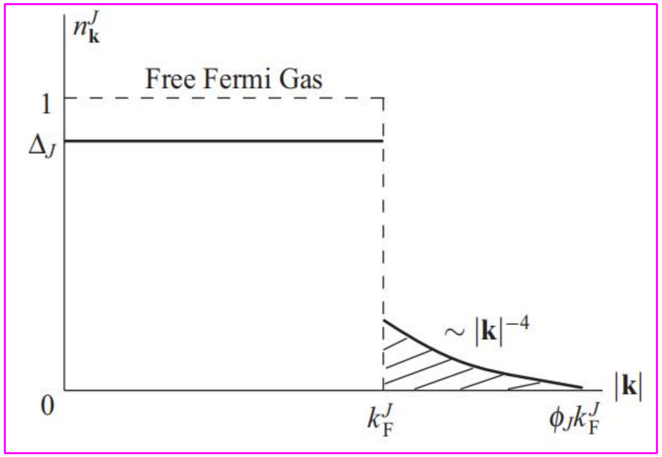


Consequence:

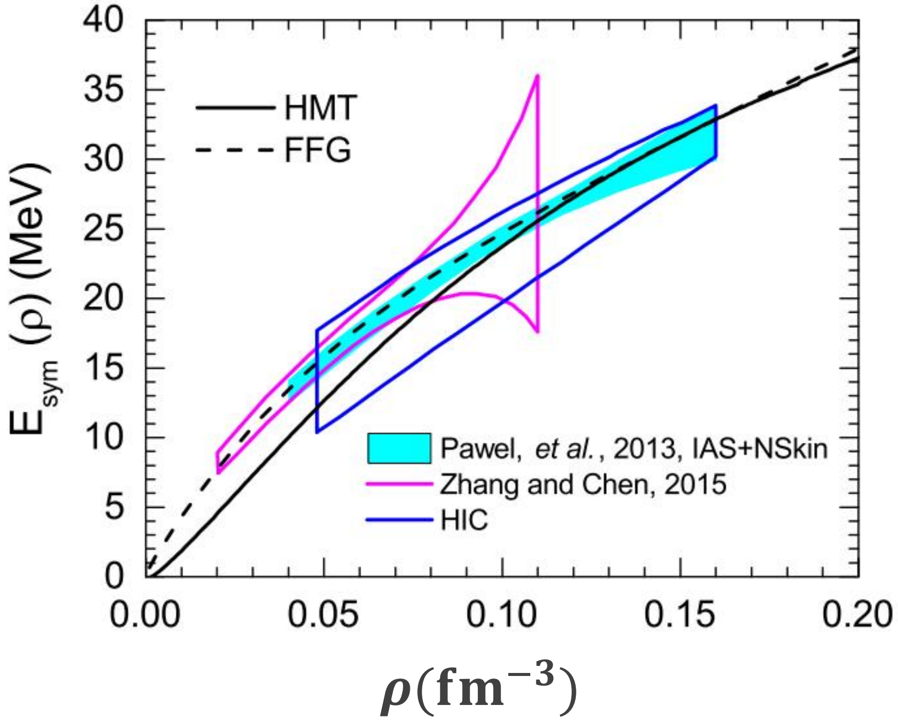
High momentum tail (HMT) appears, showing **non-Fermi** behavior!

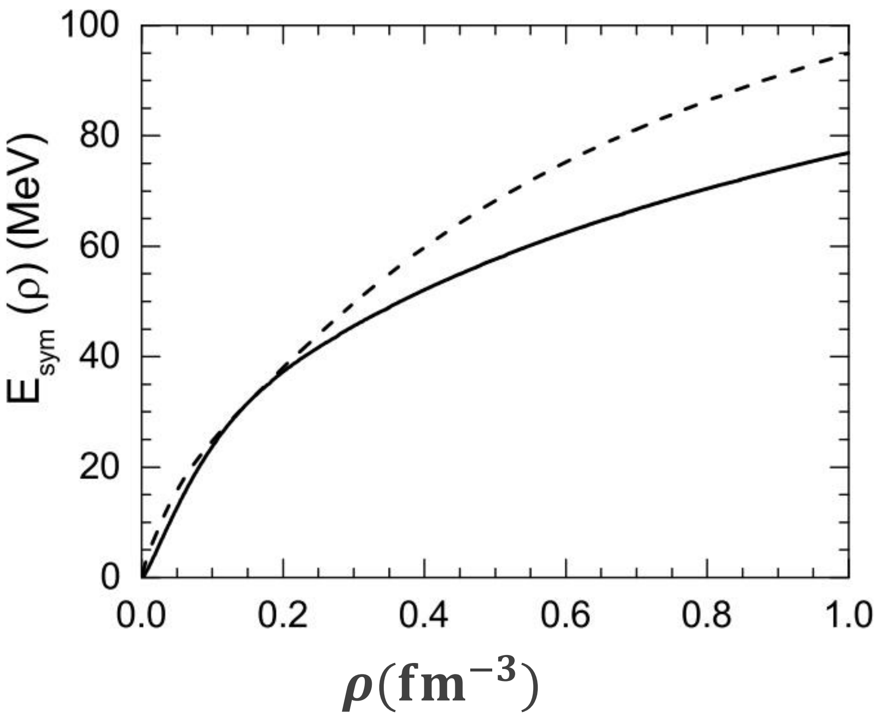
SRC and nuclear EOS

SRC caused by short-range tensor force is one of the reasons making $E_{\mathrm{sym}}(\rho)$ uncertain at $\rho > \rho_0$.



SRC-modified single-nucleon momentum distribution soften the $E_{\mathrm{sym}}(\rho)$ significantly at both $\rho > \rho_0$ and $\rho < \rho_0$ regimes!





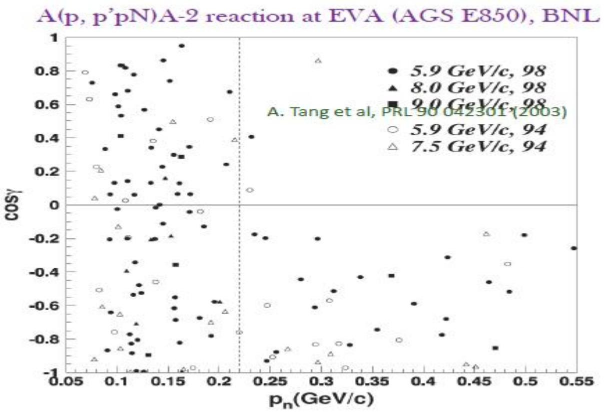
B. J. Cai and Bao-An Li, **PRC** 93, 014619(2016)

Current means to measure SRC in nuclei

1： p-A knockout reaction： $^{12}C(p, p'pn)^{10}B$

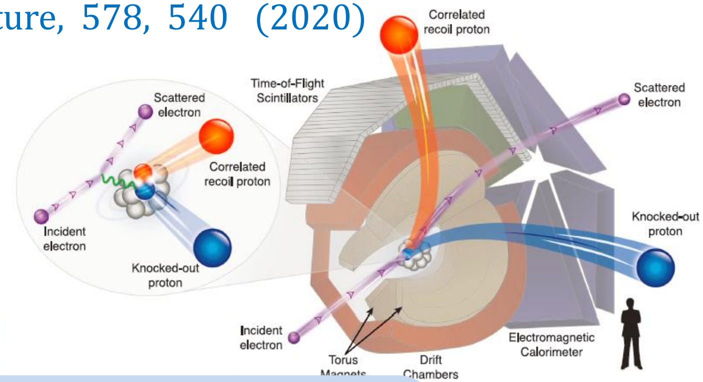
PRL 90 (2003) 042301; PRL97 (2006) 162504

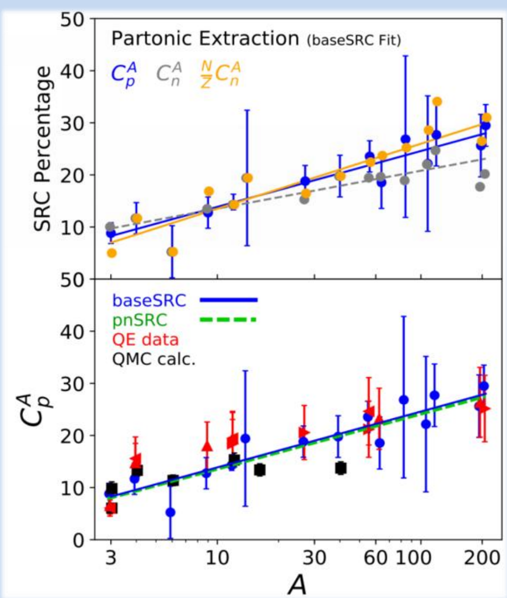
Nat. Phys. 17 (2021) 693.



2： e-A DIS process

Science, 320, 1476 (2008)
Science, 346, 614 (2014)
Nature, 560, 617 (2018)
Nature, 566, 354 (2019)
Nature, 578, 540 (2020)





SRC contains of nucleon PDF in nuclear medium！

$$f_i^A(x,Q) = \frac{Z}{A}\left[(1 - C_p^A) f_i^p(x,Q) + C_p^A f_i^{SRCp}(x,Q)\right] + \frac{N}{A}\left[(1 - C_n^A) f_i^n(x,Q) + C_n^A f_i^{SRCn}(x,Q)\right]$$

A. W. Denniston et al.,
PRL, 133, 152502 (2024)

SRC in heavy ion reactions

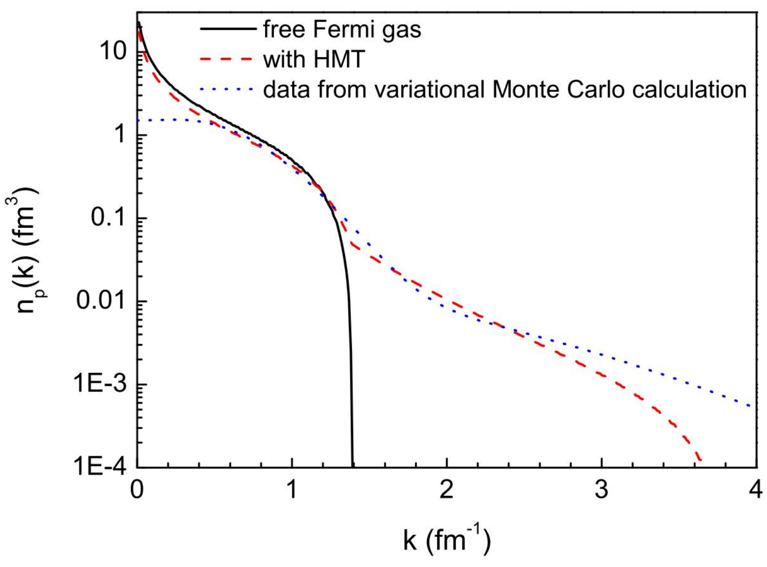
- HICs offer a unique way to probe SRC in dense matter that none of the other experiments can do!

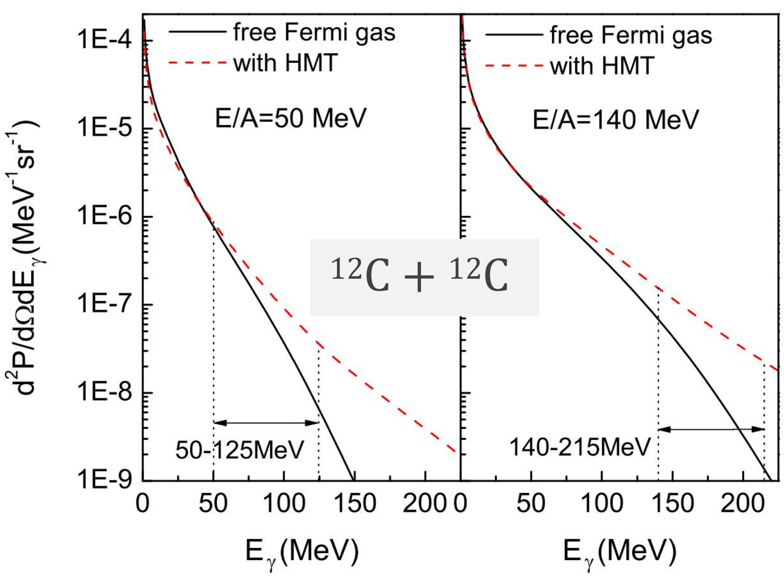
But How? ——via $n + p \rightarrow n + p + \gamma$ in HIC

HMT arising from SRC hardens the bremsstrahlung γ spectrum.

- Bremsstrahlung photon produced in **np** collision**

$$d^2P/(d\Omega dE_\gamma) = 1.6 \times 10^{-7}\left[1 - (E_\gamma/E_{\max})^2\right]^\alpha/(E_\gamma/E_{\max})$$

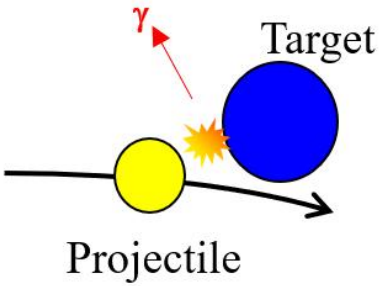


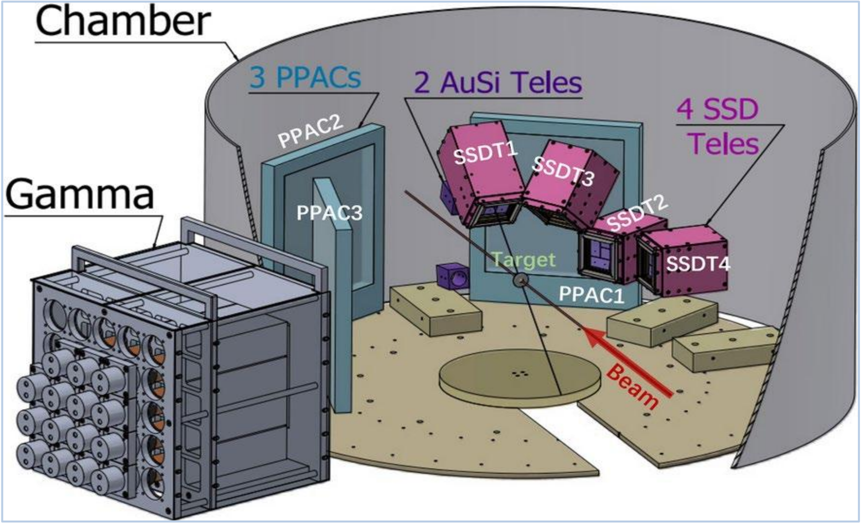


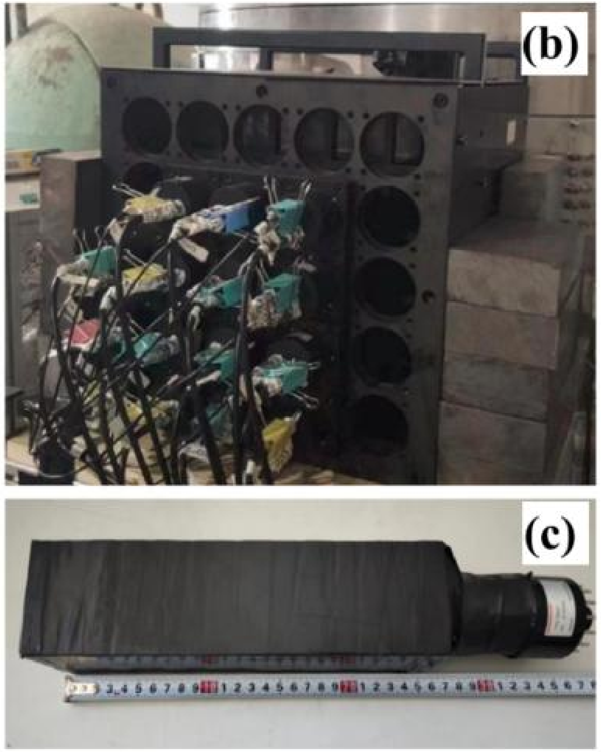
H.Xue, C. Xu et al. PLB 755, 486 (2016); ** N. Gan et al., PRC 49, 298 (1994).

Detection of Bremsstrahlung γ rays with CSHINE

- 2022， 25 MeV/u $^{86}Kr+^{124}Sn$ experiment





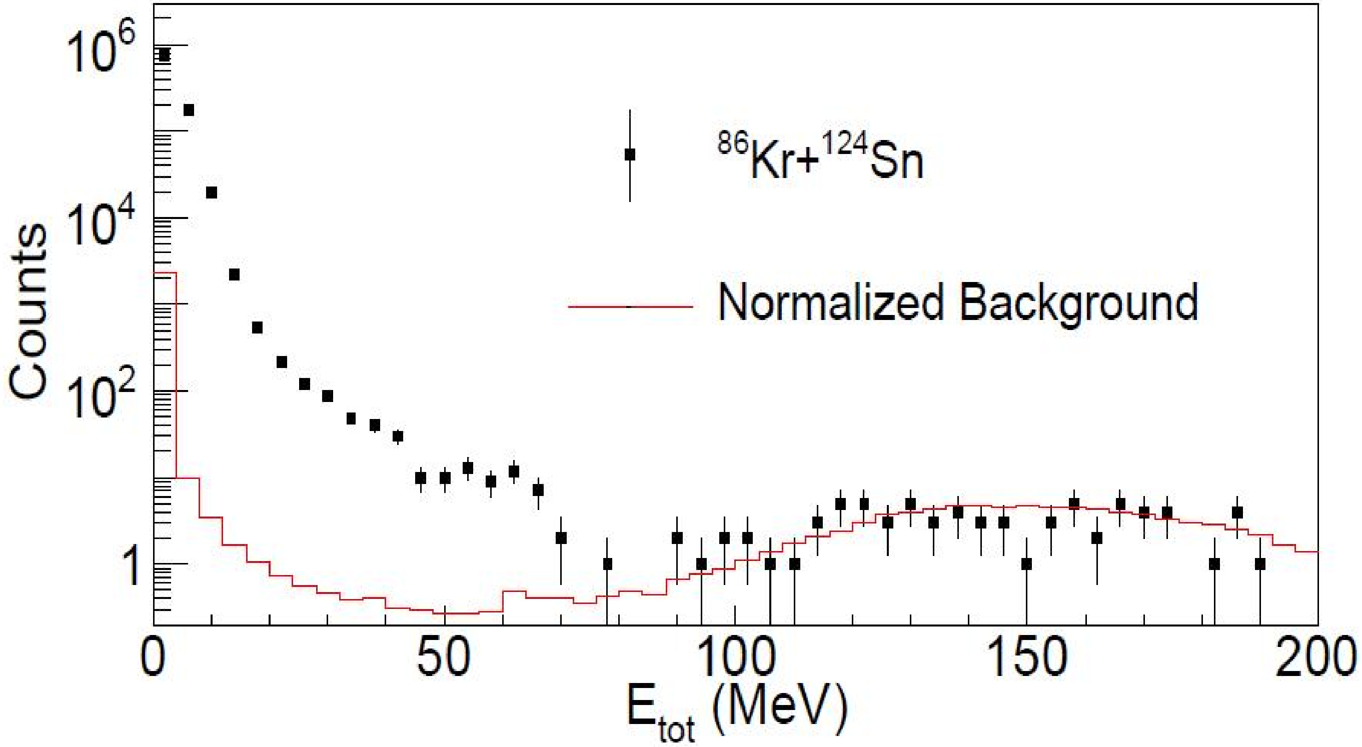


15-unit CsI(Tl) hodoscope：
each: 7cm × 7cm × 25cm

Y. H. Qin et al., **Nucl. Inst. Meth. A** 1053 168330 (2023)
J. H. Xu et al., **Nucl. Inst. Meth.** 1080, 170787 (2025)

The total energy spectrum and background subtraction

Experimental energy spectrum： The off-beam measurement perfectly follows the cosmic ray background.

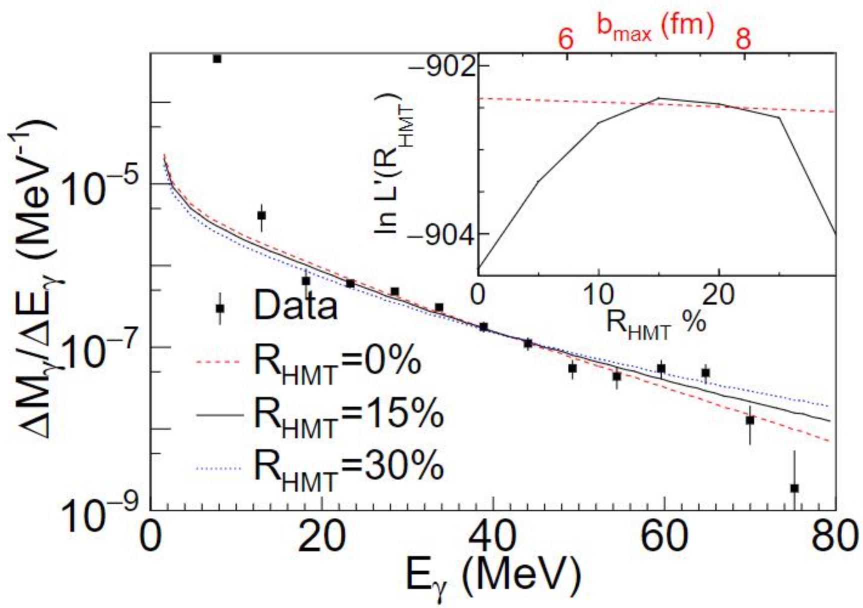


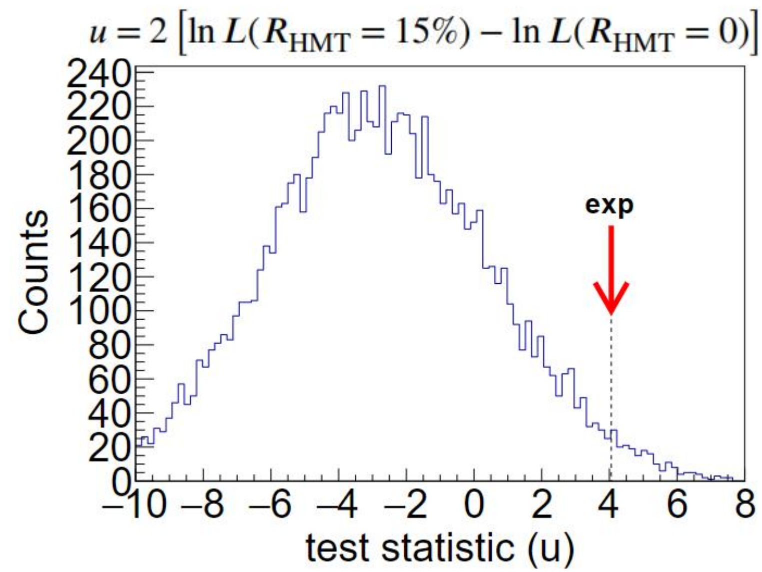
Comparison between data and BUUsimulations

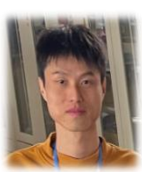
- BUU simulations follows the data, without any normalization
- $\mathrm{R_{HMT}} = 15\%$, 2σ C.L. to exclude zero $\mathrm{R_{HMT}}$.

$$L(R_{\mathrm{HMT}}) = \qquad n! \prod_i^{\mathrm{range}} \frac{1}{n_i!} p_i^{n_i}(R_{\mathrm{HMT}}),$$

$$\ln L(R_{\mathrm{HMT}}) = \sum_i^{\mathrm{range}} n_i \ln p_i(R_{\mathrm{HMT}}) - \sum_i^{\mathrm{range}} \ln n_i! + \ln n!,$$





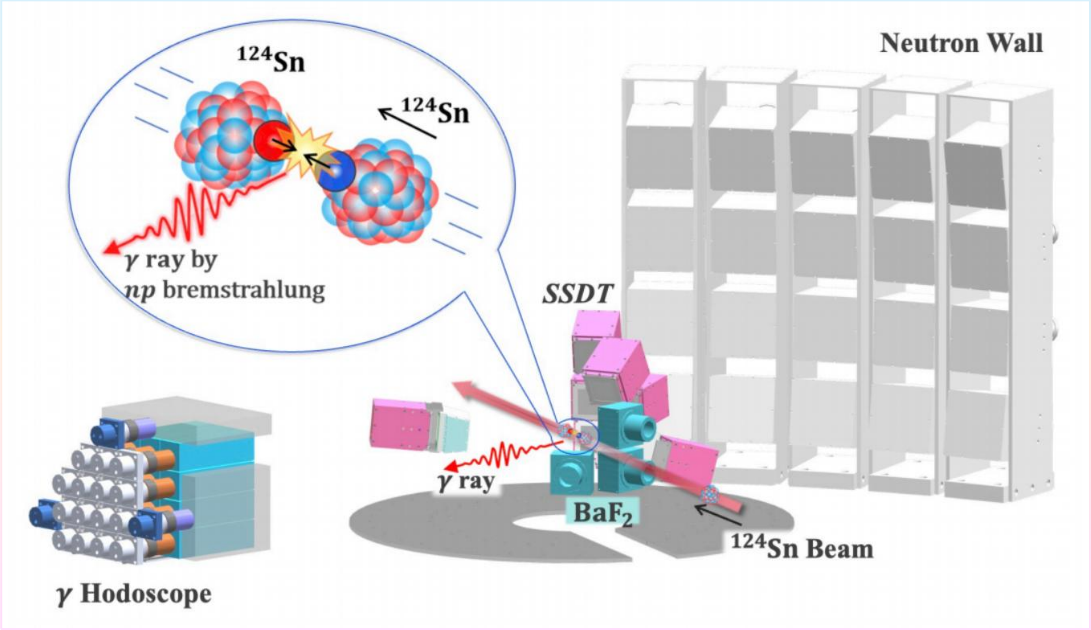


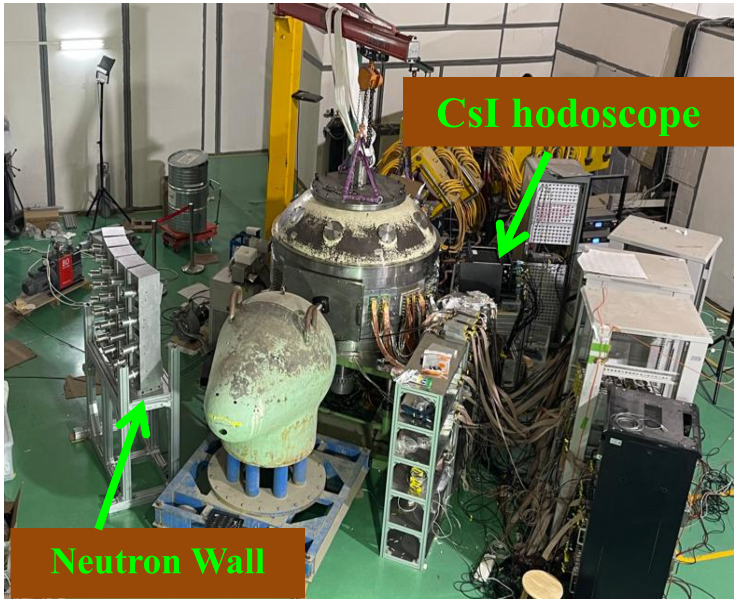
Y.H.Qin et al., **Phys. Lett. B** 850,138514 (2024)
J.H. Xu et al., **Phys. Lett. B** 857,139009 (2024)

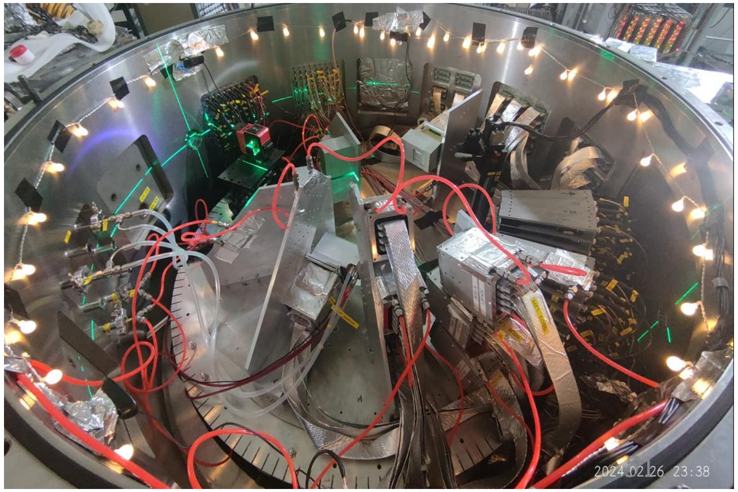
The new Experiment: 25 MeV/u $^{124}Sn+^{124}Sn$

Experimental Improvements:

- Symmetric system **$^{124}Sn+^{124}Sn$**
- SCHINE-Gamma is surrounded by scintillators to veto the cosmic ray muons
- γ statistics improved by 5^+ times
- Detection Range extended to 100 MeV

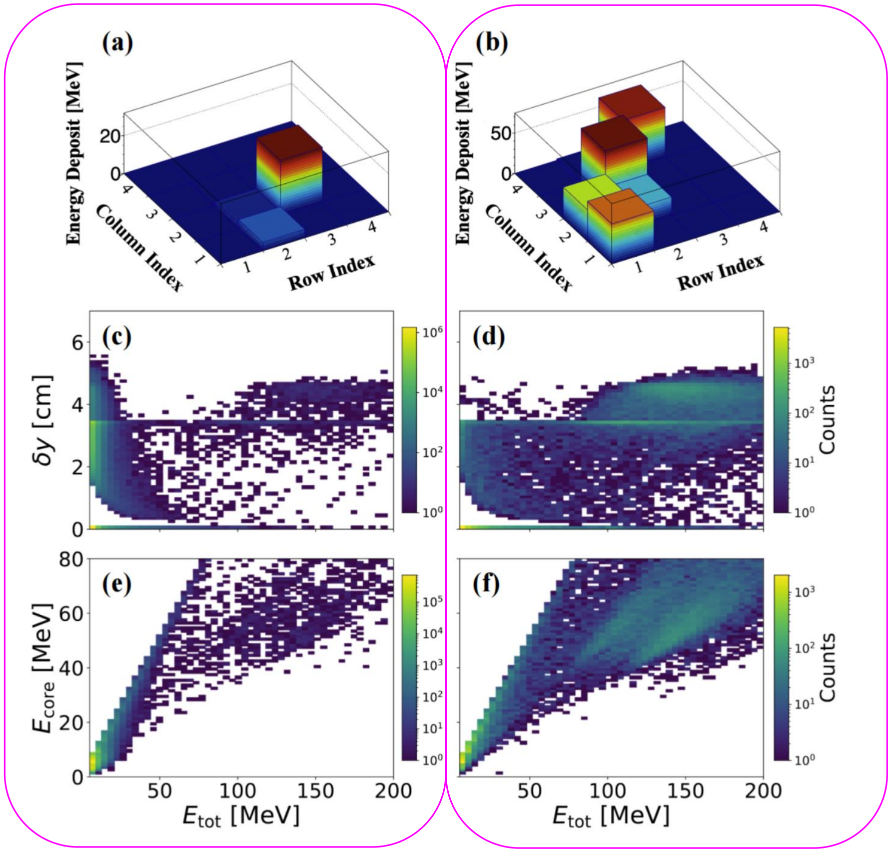






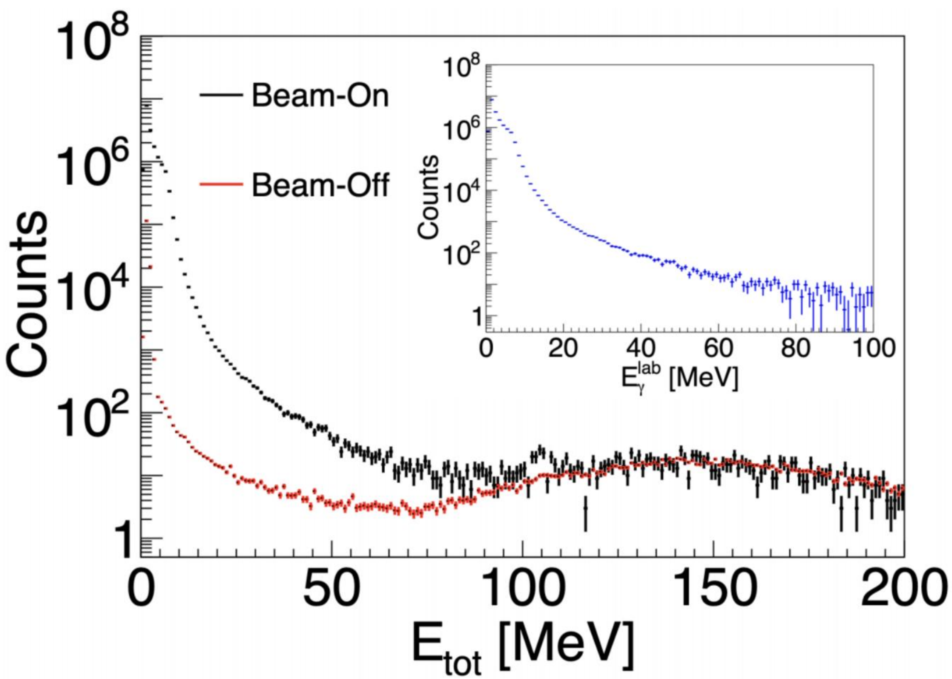
Data analysis and checks

- Same scheme to substract the beam-off background



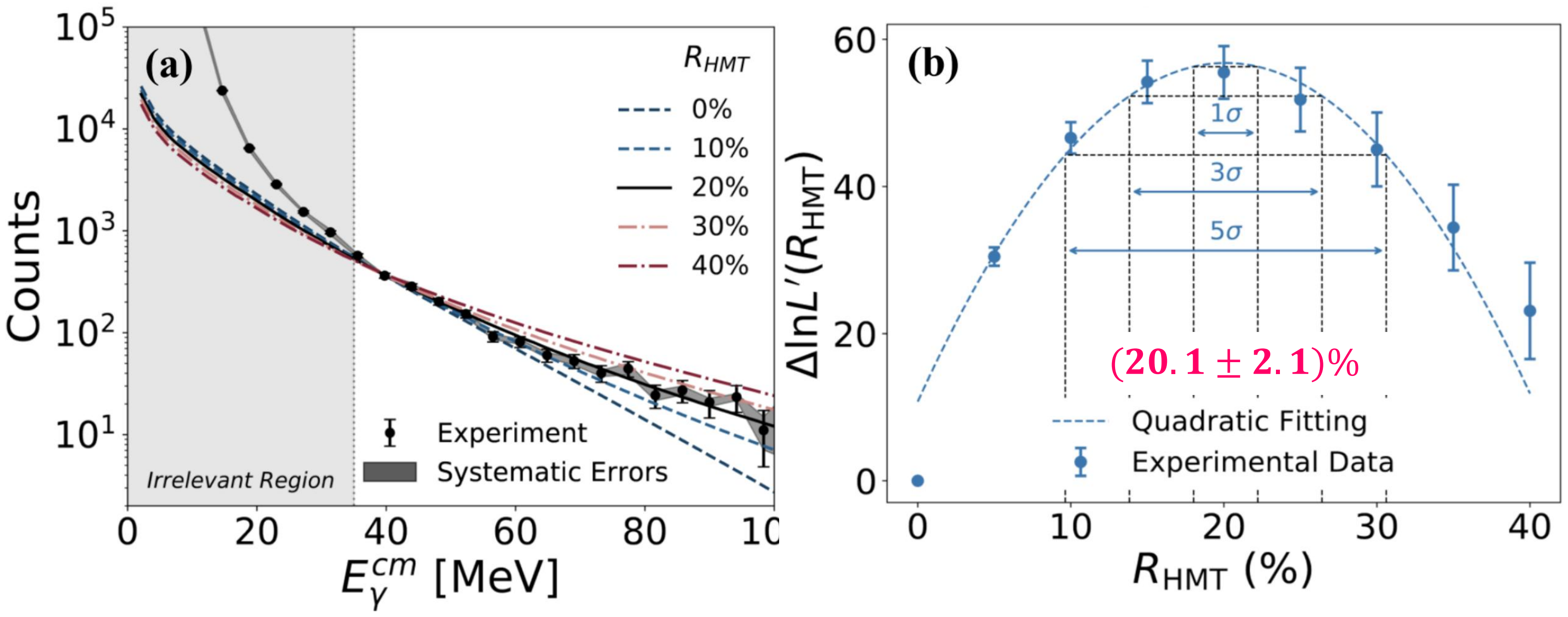
Beam-on

Beam-off



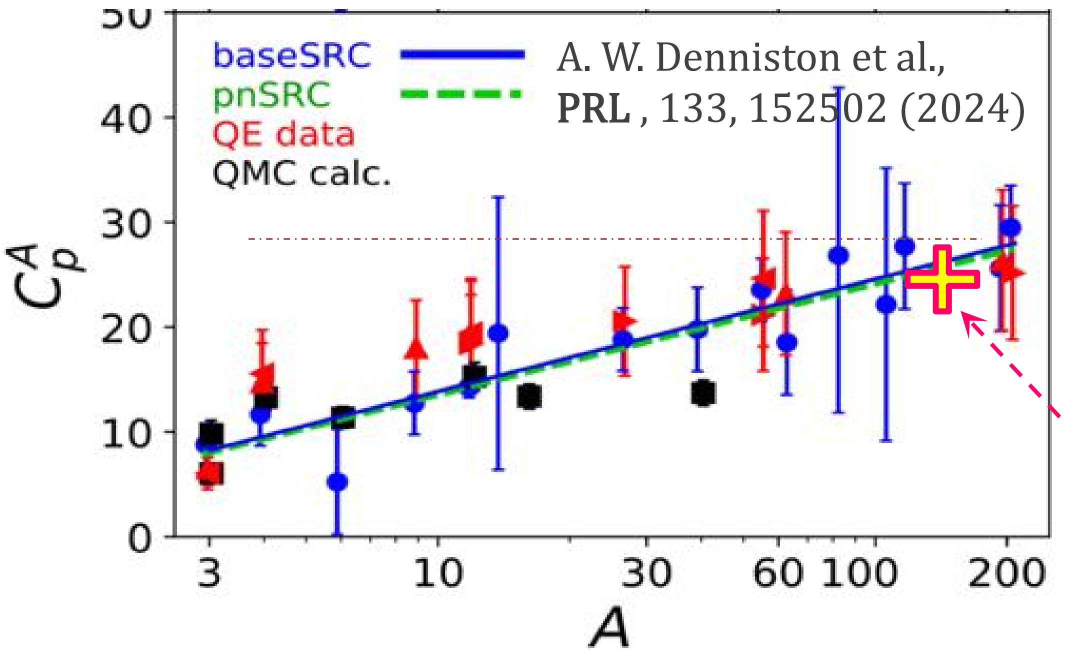
Comparison between data and BUUsimulations

- Likelihood analysis infers a nonzero R_{HMT}: over 5σ： $\mathbf{(20.1 \pm 2.1)\%}$



In line with high-energy data compliation

- Uncertainty combining: $\sigma_{tot} = \sqrt{2.1^2 + 0.4^2 + 2^2}$
  - Liklihood (2.1^2), Fitting (0.4^2), Method diff. (2^2)
- Final: $\mathbf{R_{HMT} = (20 \pm 3)\%}$



Will be very interesting to do a systematic measurement in ^{112}Sn and ^{124}Sn reactions

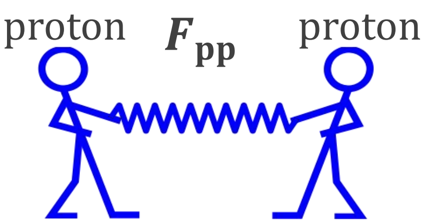
Stay tuned

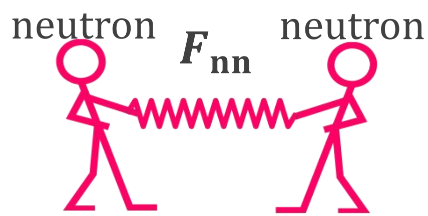
- In ^{124}Sn ($A = 124, \delta = 0.194$), $C_n^{124} = 16\%$, $\mathbf{C_p^{124} = 24\%}$, respectively!

J. H. Xu et al., **Phys. Rev. Research** 7, 043174 (2025) ;
J. H. Xu et al., arXiv 2508.04550, **Phys. Rev. C**, under review

3.3 Direct probe to nuclear force by correlation functions

Above all, the underlying physics of $E_{sym}(\rho)$ is the isospin-dependence of nuclear force.





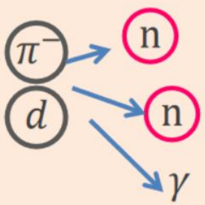
$$\Delta a_{CSB} = f_0^{pp} - f_0^{nn}$$

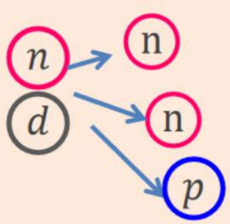
nuclear force CSB

However, no n-n scattering data due to the unavailablity of neutron target!

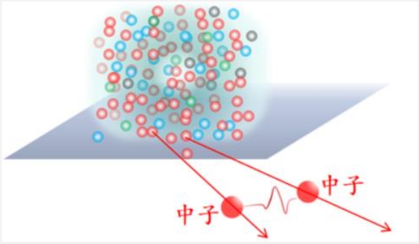
Indirect Scattering:

$d(\pi^-, \gamma)2n$ $\quad$ $d(n, p)2n$





Heavy Ion Collisions:



Lednicky and Lyuboshitz propose to extract (f_0^{nn}, d_0^{nn}) via the n-n CF in HIC

So, by n-n CF, one can

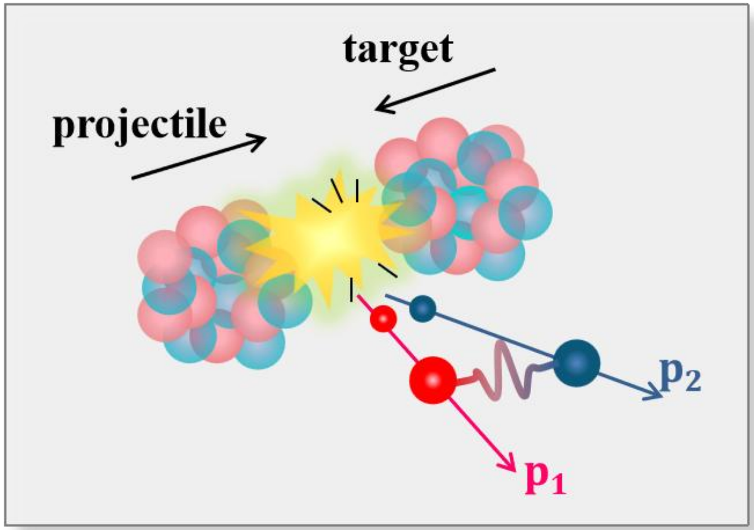
❶ determine the n-n (f_0, d_0) — CSB of nuclear force

❷ reveal the collision dynamics in terms of the Isospin DOF

Lednicky and Lyuboshitz method

Lednicky and Lyuboshitz proposed to extract n-n FSI by measuring the n-n correlation function in heavy ion collisions.

Assuming:
- Incoherent emission source
- A smooth emission source
- Correlation beyond 3 bodies negligible



R. Lednicky, et al. Sov. J. Nucl.Phys. 35 (1982) 770
Ann. Rev. Nucl. Part. Sci. 55 (2005) 357-402
Phys. Rev. C 102 (2020) 3, 034001

Definition

Original momentum CF definition

$$C(\boldsymbol{p}_1, \boldsymbol{p}_2) \equiv \frac{P(\boldsymbol{p}_1, \boldsymbol{p}_2)}{P(\boldsymbol{p}_1)P(\boldsymbol{p}_2)}$$

$\boldsymbol{p}_1, \boldsymbol{p}_2$ are the single particle momentum

Modeling

Describing the CF using K-P fomula:

$$C(\boldsymbol{k}^*) = \int d^3r S(\boldsymbol{r}^*) |\boldsymbol{\psi}(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2$$

Source function

Relative wave function of the particle pair

Experiment

Experimentally using mixture event method to subtract the background:

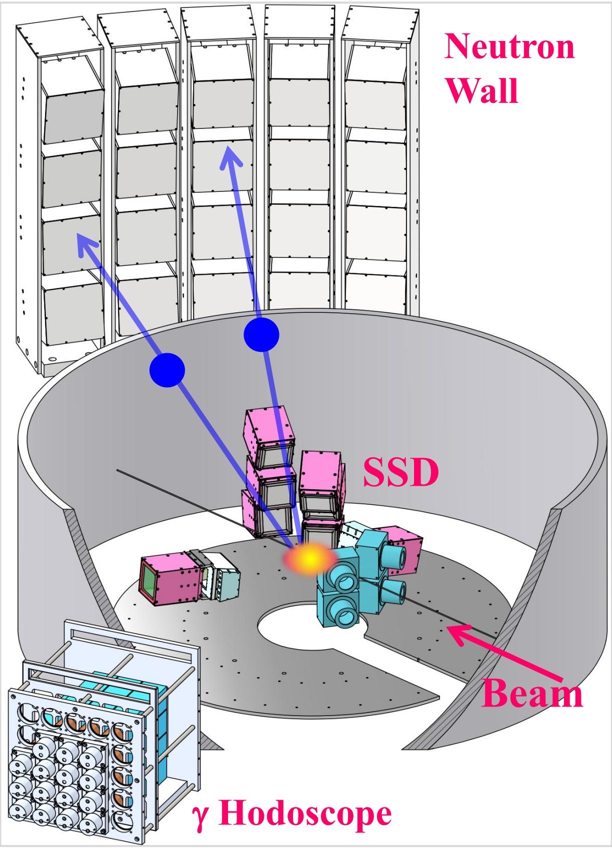
$$C(\boldsymbol{k}^*) = \mathcal{N} \frac{A(\boldsymbol{k}^*)}{B(\boldsymbol{k}^*)}$$

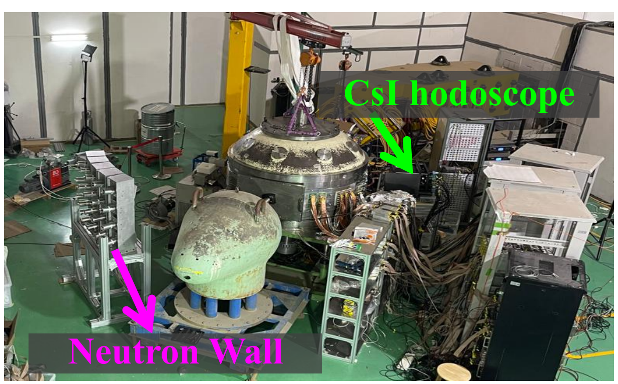
Signal

Background

$\boldsymbol{k}^*$: Relative momentum in pair rest frame

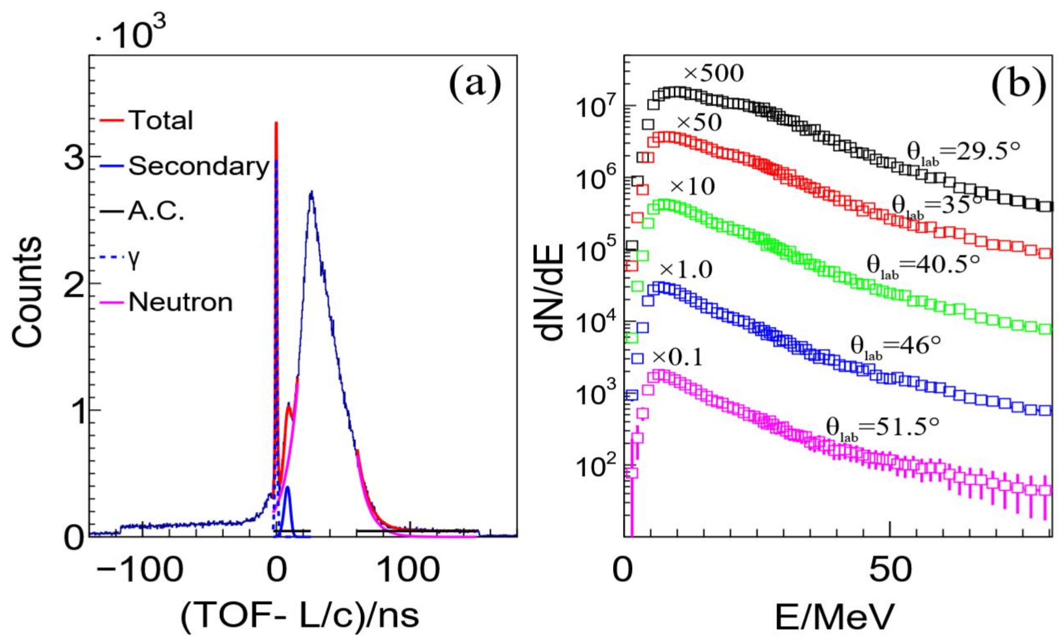
25 MeV/u $^{124}Sn+^{124}Sn$ Experiment (in April 2024)





Neutron Wall Parameters and Performance:

- unit size: 15cm × 15cm × 15cm
- Intrinsic time resolution 200 ps, $L \approx 220cm$
- 20 units: Covering $21° < \theta_{lab} < 53°$ in Lab



D. W. Si et al., **Nucl. Inst. Meth. A** 1070,170055 (2025)

n-n correlation function LL fit

After the corretion of TOF resolution, cross-talk and accidental coincidence, one obtains the n-n correlation function.

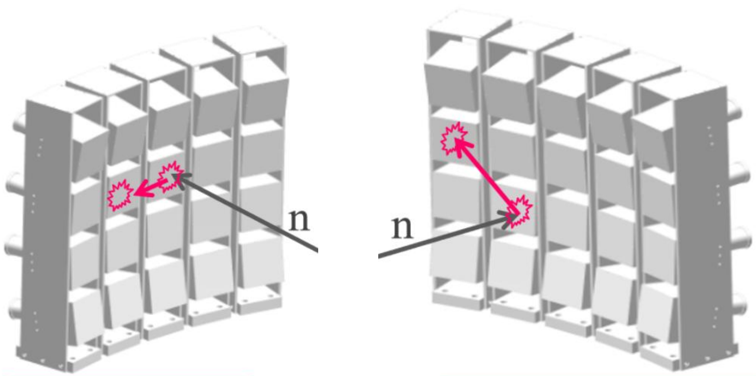
$$C_{\rm nn}(k^*) = A_{nn}\frac{N^{\rm same}_{\rm nn}(k^*)}{N^{\rm mix}_{\rm exp}(k^*)}$$

$$= \frac{A_{\rm nn}}{1-\lambda_{\rm ct}-\lambda_{\rm ac}}\left(\frac{C_{\rm exp}(k^*)}{A_{\rm exp}} - \lambda_{\rm ct}\frac{N^{\rm mix}_{\rm ct}(k^*)}{N^{\rm mix}_{\rm exp}(k^*)} - \lambda_{\rm ac}\frac{N^{\rm same}_{\rm ac}(k^*)}{N^{\rm mix}_{\rm exp}(k^*)}\right)$$

G4 Simulation

ΔTOF Fit

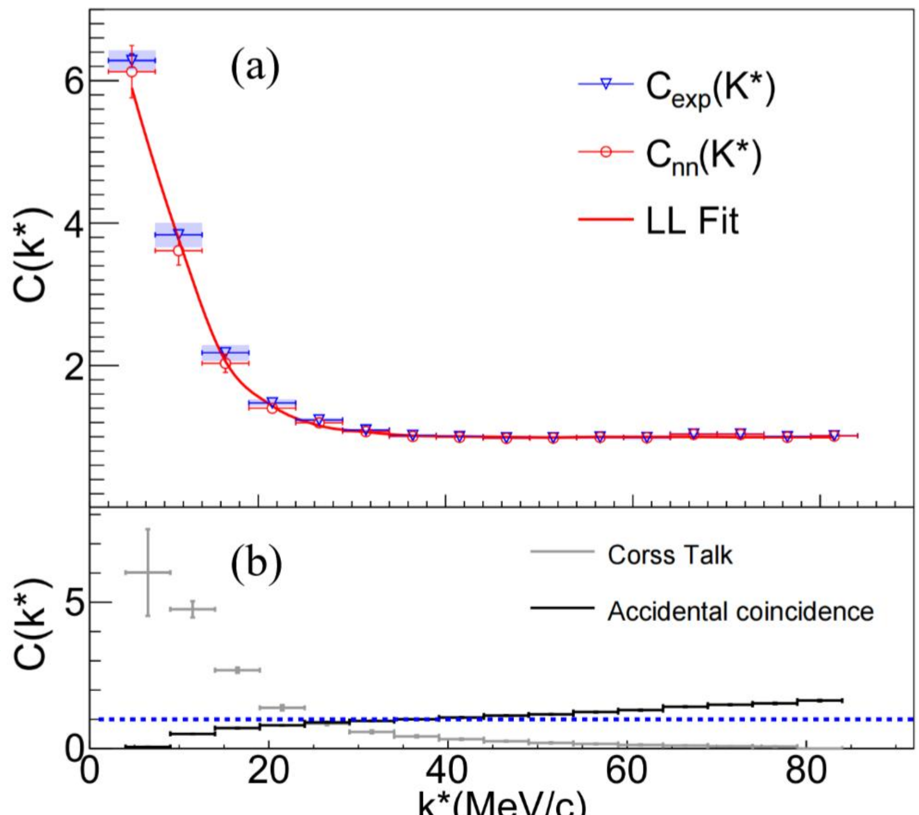
TOF Fit



Side-by-side cross-talk

Corner-to-corner cross-talk

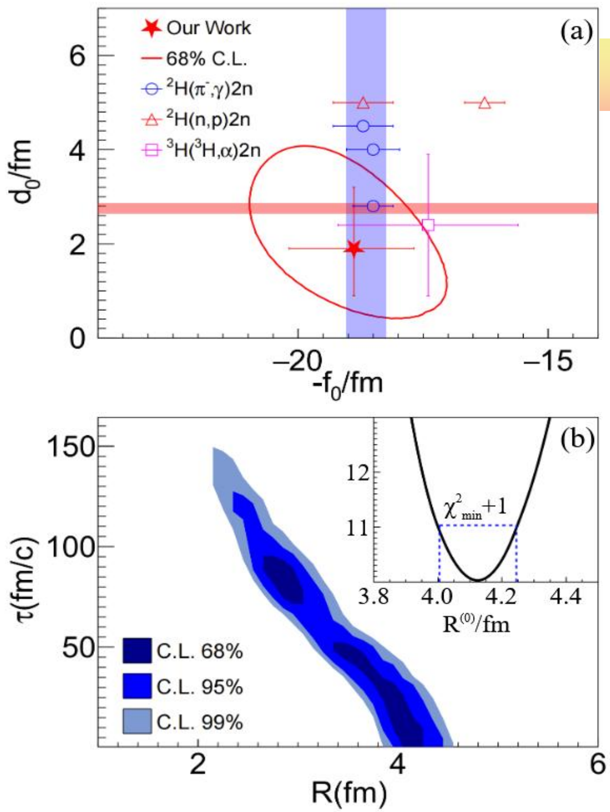
Correction of cross talk



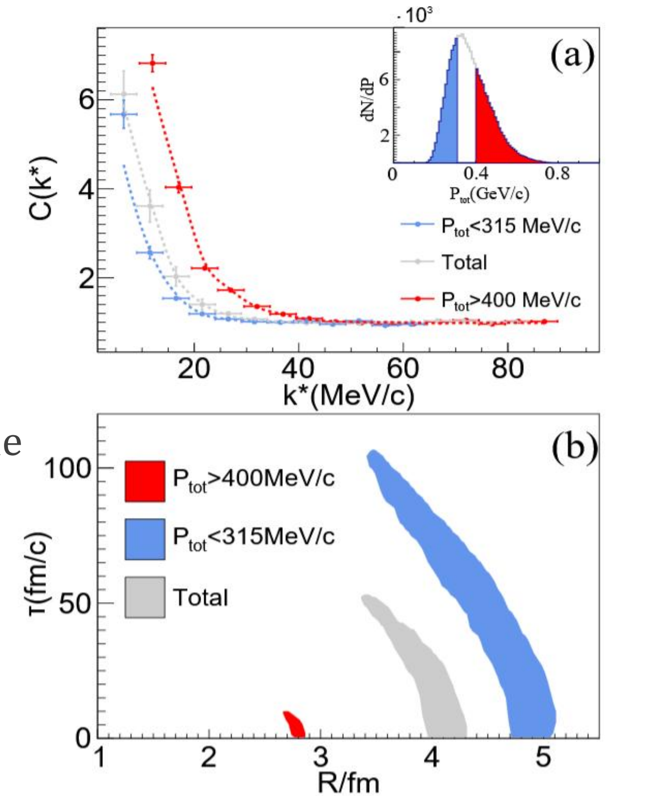
Cross-talk and accidental coincidence partly cancel each other.

Extraction of (f_0^{nn}, d_0^{nn}) and the emission source size

- ✓ (f_0^{nn}, d_0^{nn}) is extracted from 25 MeV/u ^{124}Sn + ^{124}Sn reactions:
  $f_0^{nn} = 18.9^{+1.3}_{-1.2}$fm , $d_0^{nn} = 1.9^{+1.3}_{-1.0}$fm
- ✓ Simultaneously, the temporal-spatial source size is extracted: $R^{(0)} = 4.1 \pm 0.1$ fm



$$S \propto \exp(-r^2/R^2 - t^2/\tau^2)$$



- ✓ n-n CF Showing dependence on the pair-momentum

Plan to measure n-n and p-p CF in one exp, and infer the CSB and isospin dynamics simultaneously!

D.W.Si et al., **Phys. Rev. Lett.** 134, 222301 (2025)

Outline

1. Introduction: $E_{\text{sym}}(\rho)$ and current status

2. Experiments CSHINE and CEE: the stories behind constructions

2.1 CEE at GeV/u energy domain

2.2 CSHINE in Fermi energy domain

3. $E_{\text{sym}}(\rho)$ related studies at Fermi energies

3.1 Isospin dynamics and new probes of $E_{\text{sym}}(\rho)$

3.2 Short range correlations using bremsstralung γ rays

3.3 Direct probe to nuclear force by correlation functions

4. Opportunities towards GeV/u region

4.1 Isospin chemistry with CEE and at HIAF

4.2 Probe neutron skin thickness by correlation function

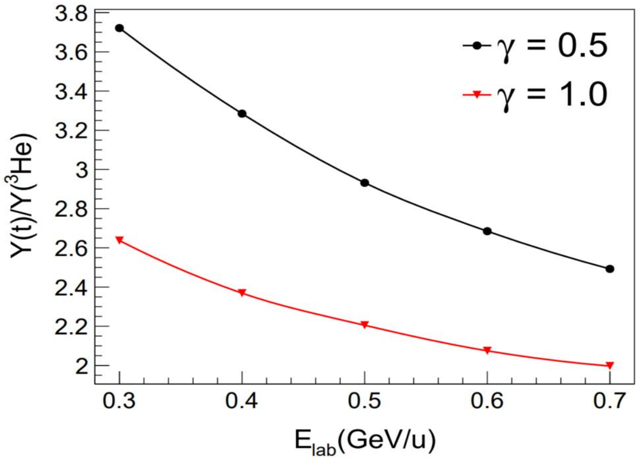
*4.3 Isovector reorientation effect of deuteron

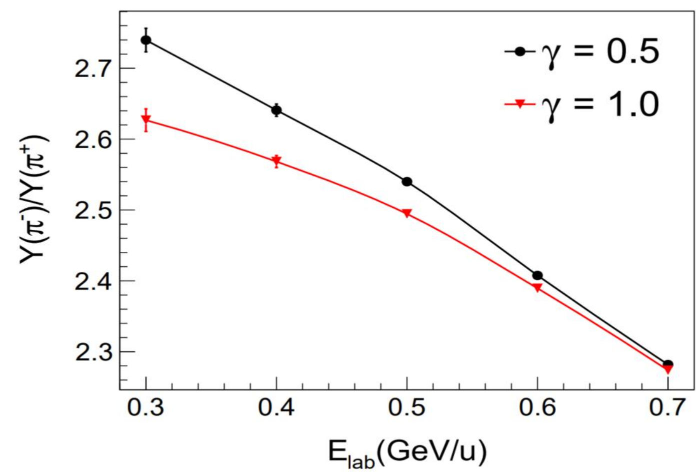
5. Summary and outlook

4.1 Isospin chemistry with CEE and at HIAF

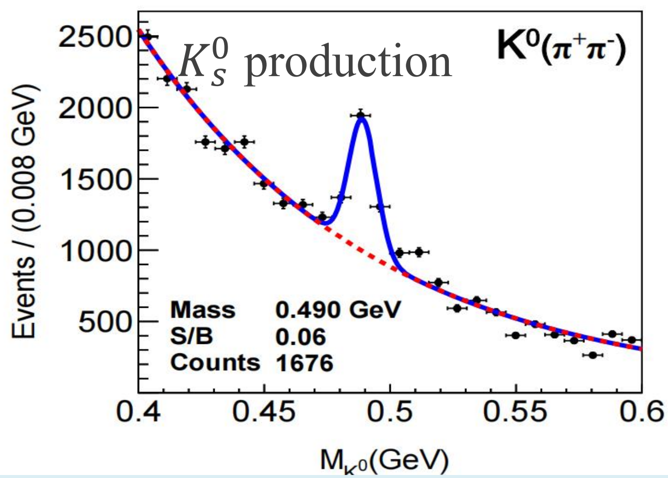
(i) Potential observables on CEE

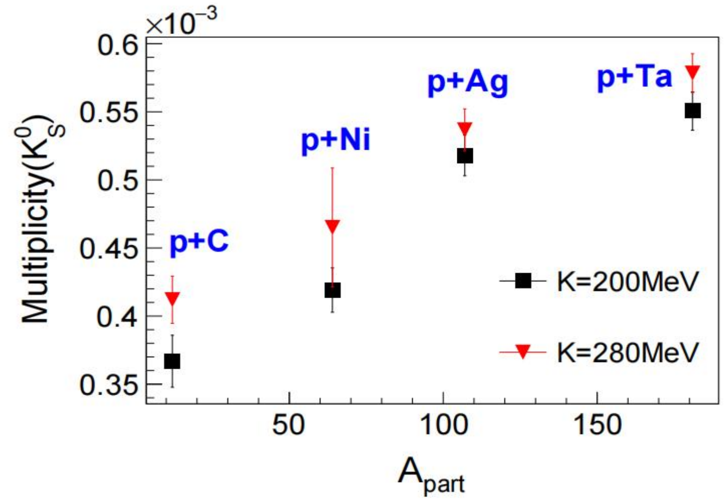
$t/{}^{3}$He Ratio **0.5 GeV/u ^{208}Pb+ ^{208}Pb:** π^{-}/π^{+}Ratio





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



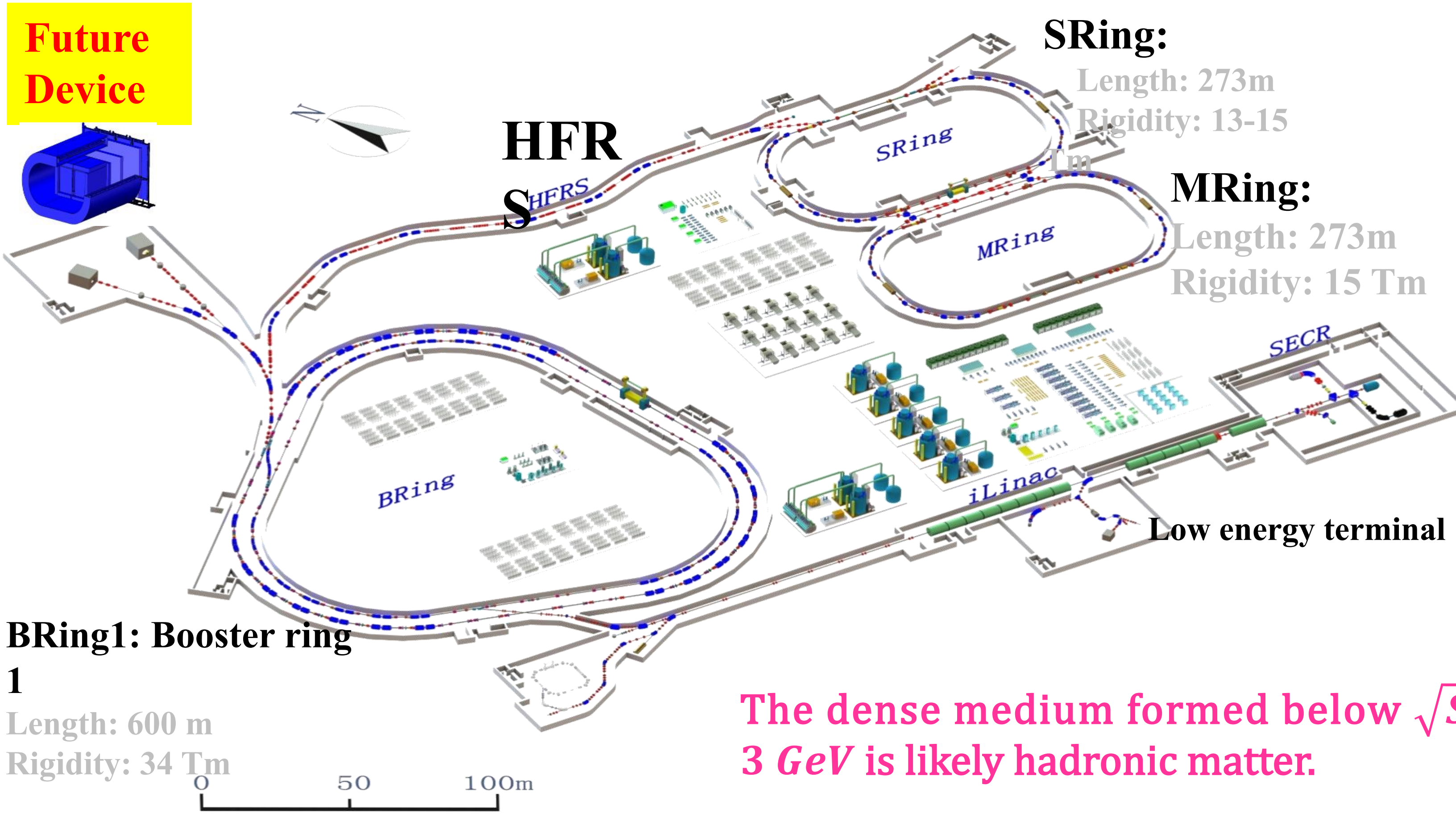


Dong Guo et al., Studies of nuclear equation of state with the HIRFL-CSR external-target experiment
Euro. Phys. J. A 60, 36 (2024)

(ii) Future opportunities at HIAF

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

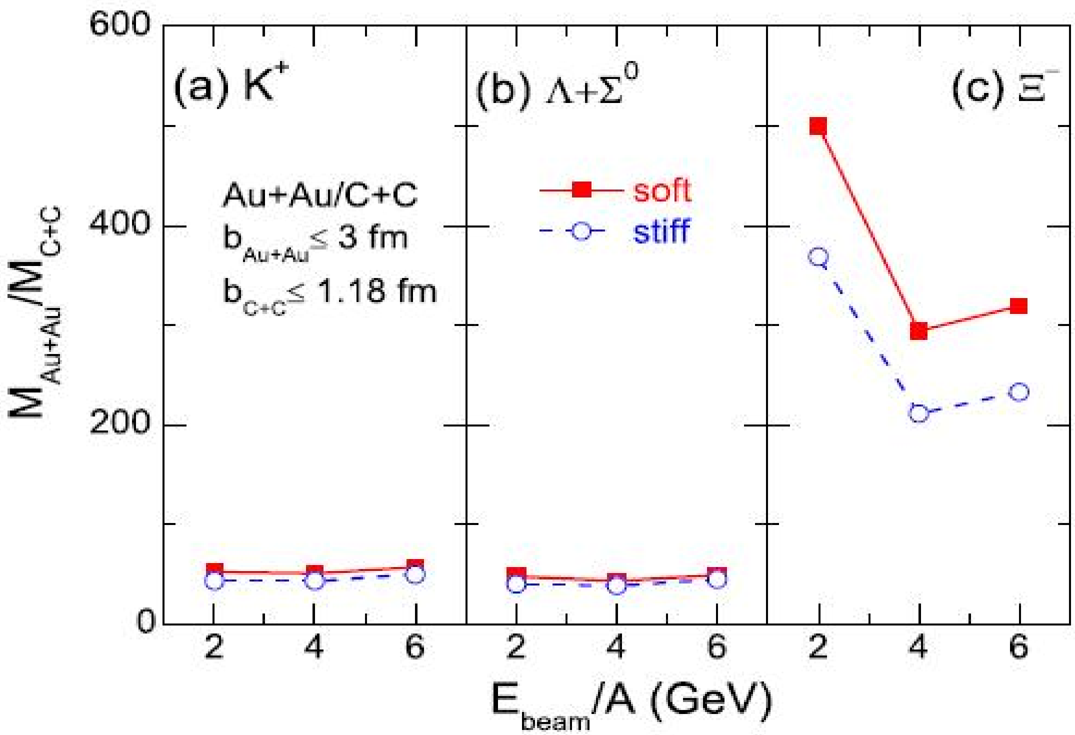
Nuclear matter compressed: $\rho \gtrsim 3 - 4\rho_0$



The dense medium formed below $\sqrt{S_{NN}} = 3\ GeV$ is likely hadronic matter.

STAR Collab., PLB827, 136941 (2022)

Probe of symmetric nuclear matter: Implications



With the increase of E_{beam}, the sensitivity of single strangeness on EOS is reduced . But the yield of double strangeness Ξ^- , enhances the sensiticity on EOS.

in accordance with
[G. Ferini et al., PRL97, 202301 (2006)]
[M. Zhang et al., PRC, 80,034616 (2009)]

One shall consider:

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

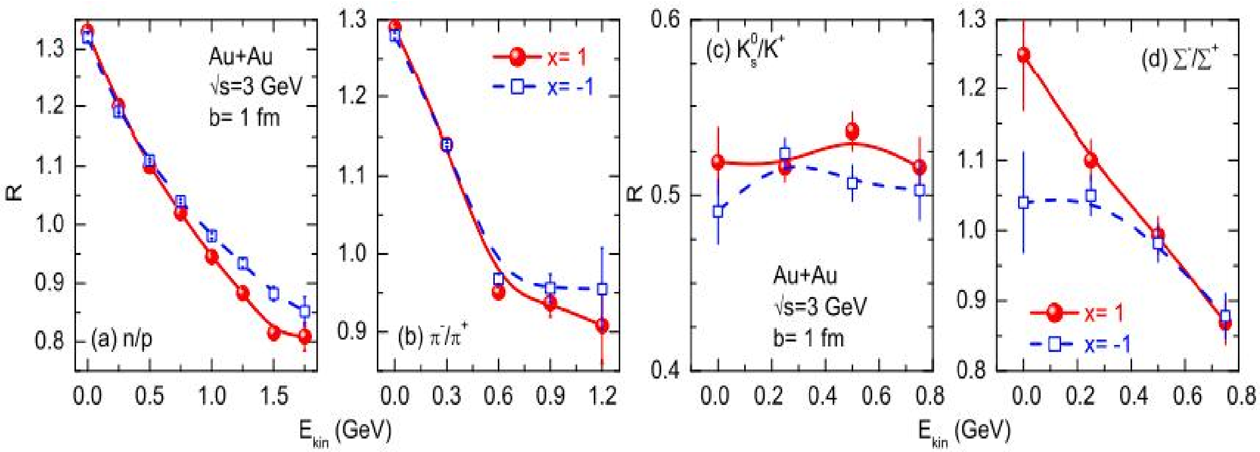
G. C. Yong, ZGX, Y Gao and Z. W. Lin, **Phys. Lett. B** 820 (2021) 136521

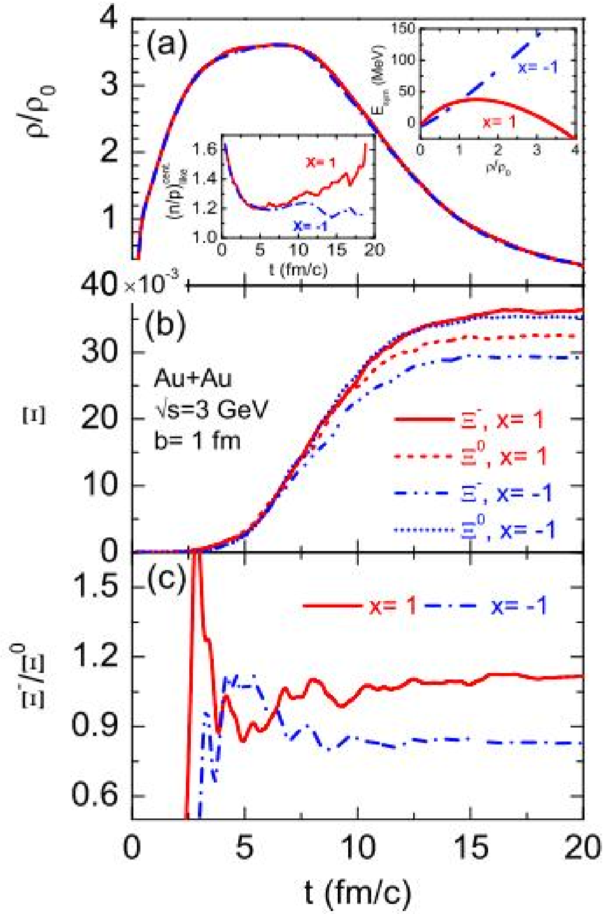
Comstrain $E_{\mathrm{sym}}(\rho)$ at higher density

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 increasing beam energy →

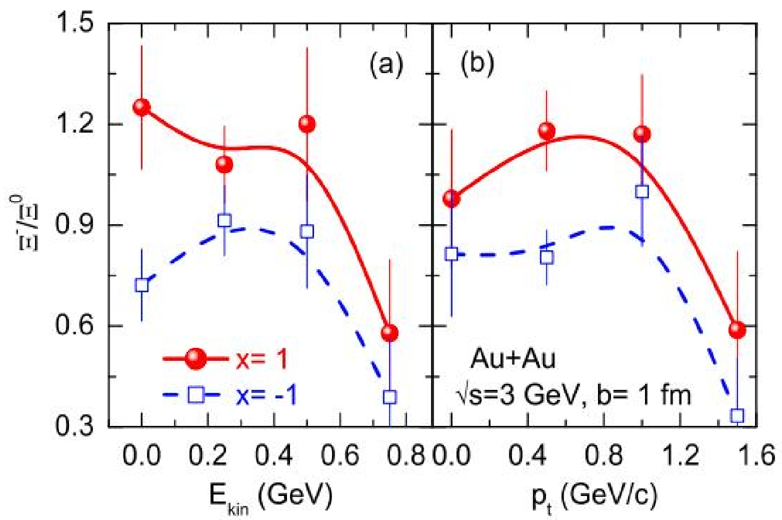
via $\pi + \mathrm{N} \rightarrow \Sigma$ secondly process， isospin effect carried by pions are passed to strangeness.





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

Opportunity and challenge at HIAF

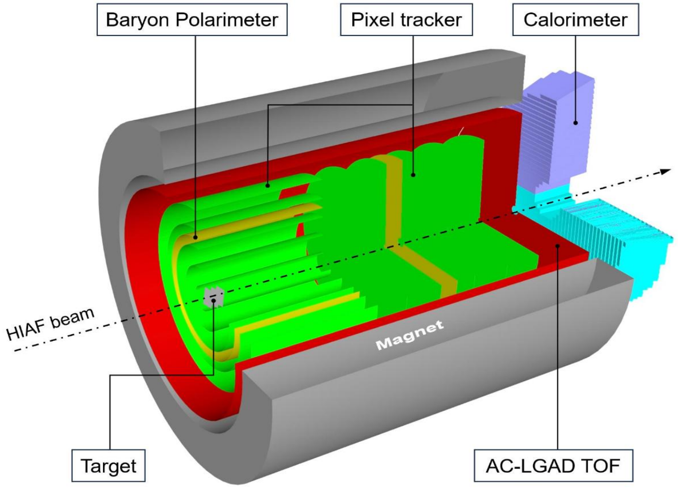


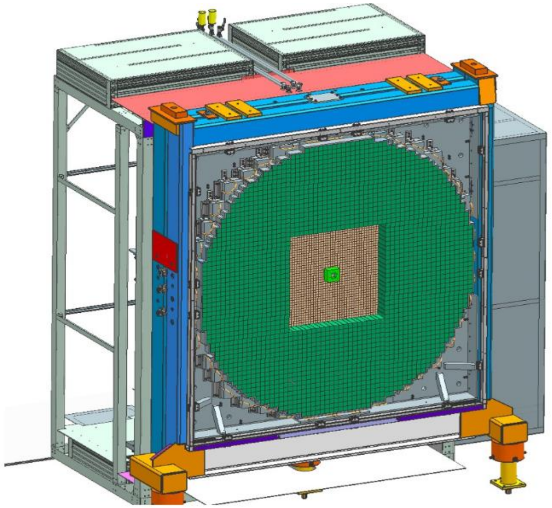
Necessary： Reconstruction and PID for neutral particles

$\Sigma^- \rightarrow n + \pi^-$,

$\Sigma^+ \rightarrow n + \pi^+ \; or \;\; p + \pi^0$

$\Xi^- \rightarrow \Lambda + \pi^-, \Xi^0 \rightarrow \Lambda + \pi^0$



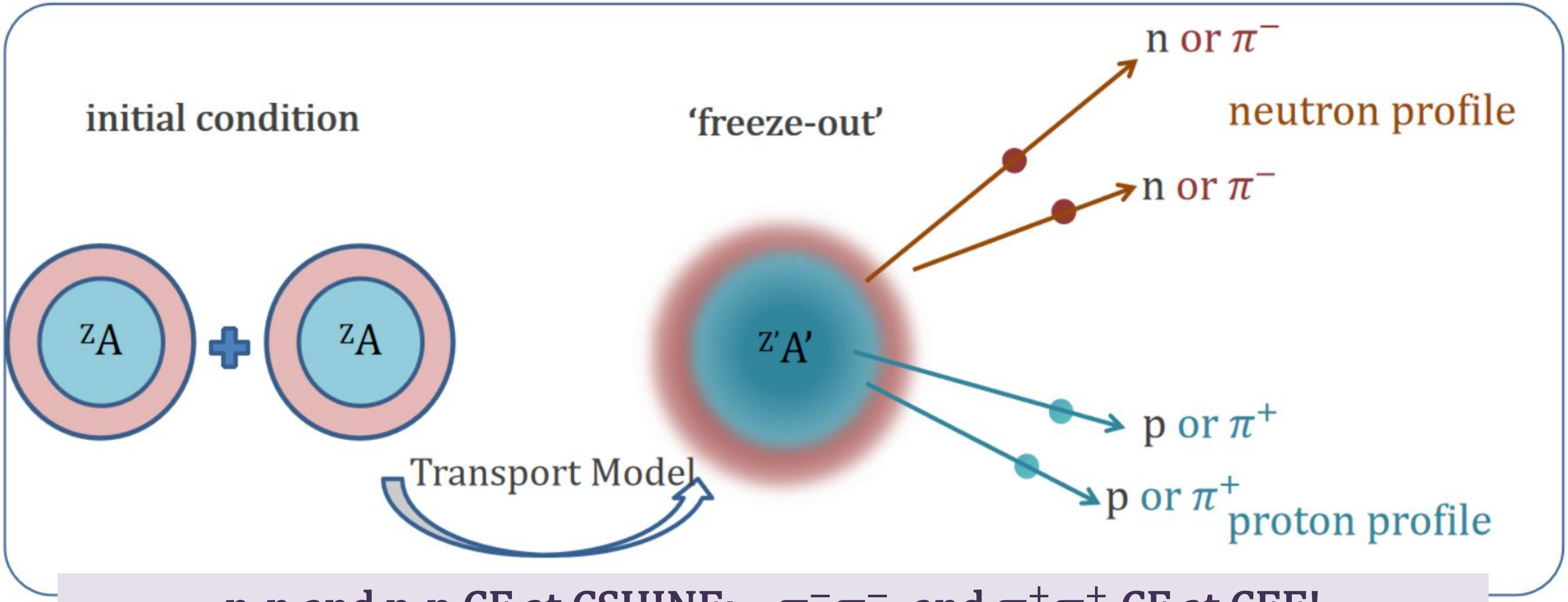


In the design of future large-scale spectrometer at HIAF, eg. H-NS, an end-cap EM calorimeter is highly demanded! —— Tsinghua's contribution is expected!

4.2 Probe neutron skin thickness by correlation function

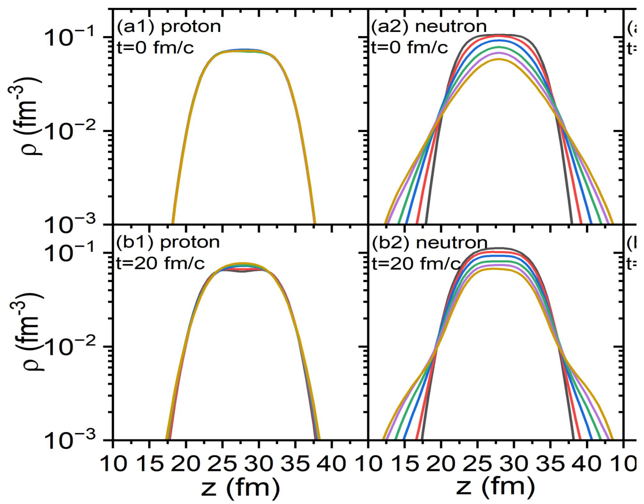
Its it possible to clarify the tension between PREX2 and CREX results by the third way?

Yes, Extract the spatial-temporal information of emission source via HBT CF method!

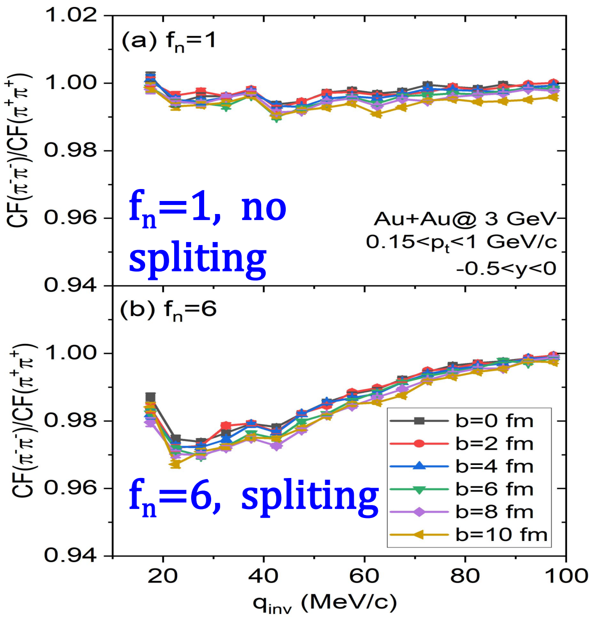


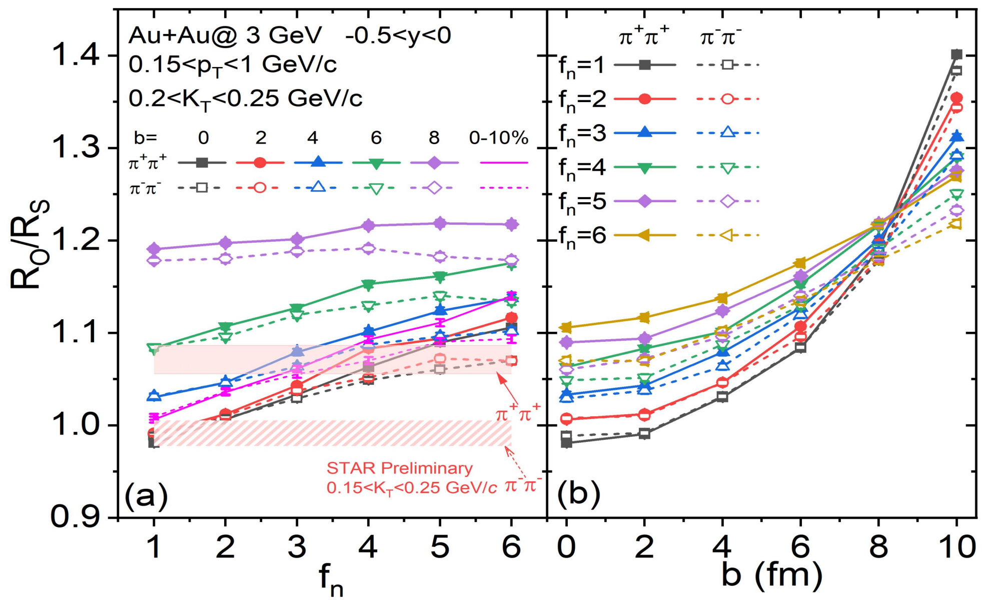
n-n and p-p CF at CSHINE; $\pi^-\pi^-$ and $\pi^+\pi^+$ CF at CEE!

Probe the initial n and p distribution via CF method



First question: Can we expect any **splitting effect on the $\pi^-\pi^-$ and $\pi^+\pi^+$ correlation function** caused by the neutron skin!

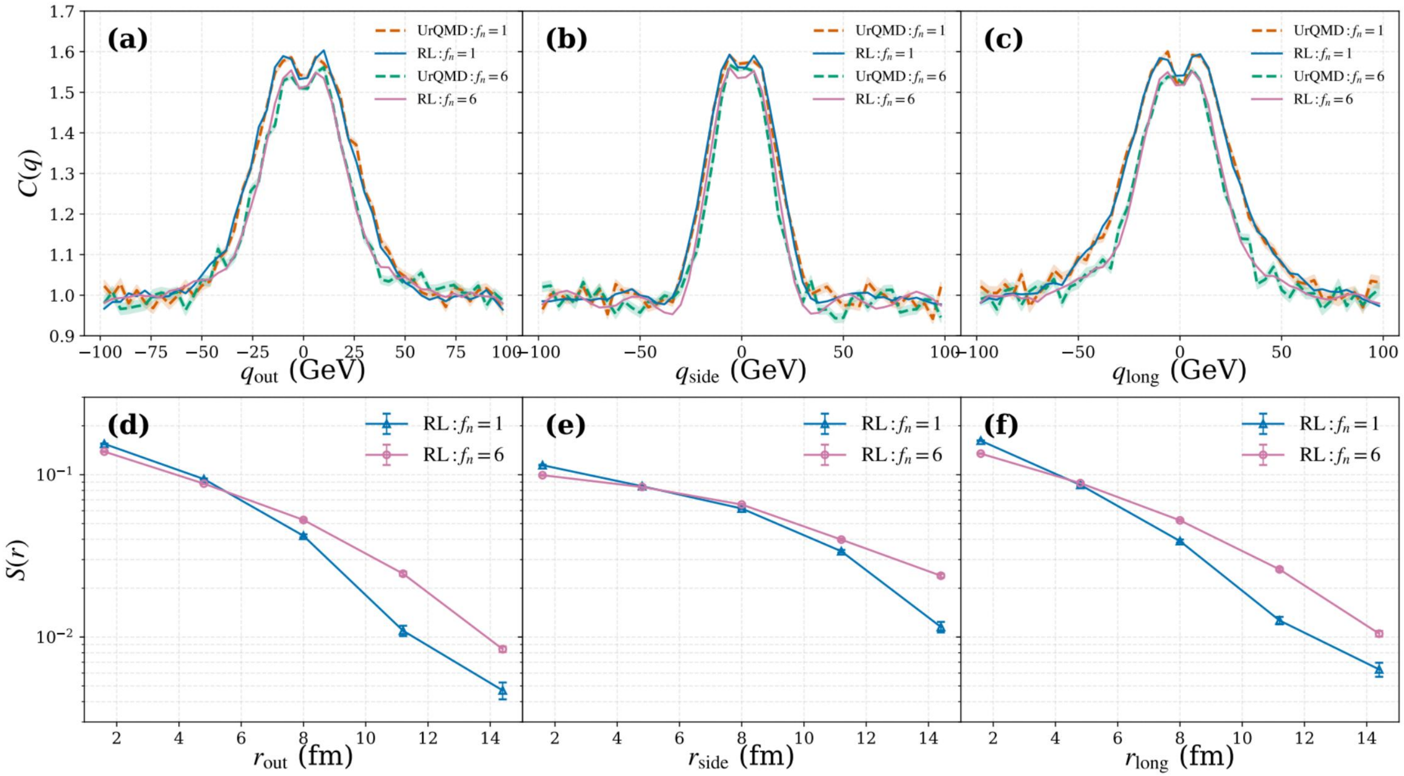




P. C. Li et al.， **Phys. Lett. B** 870 (2025) 139963.

Application of the 3d imaging technique

Combine UrQMD simulation and Richardson-Lucy deblurring algorithm, an enhanced neutron skin has effect on the 3-D CF， and exhibits a different neutron profile at freezeout, which can be imaged! **—— An opportunity for CEE at HIRFL-CSR!**



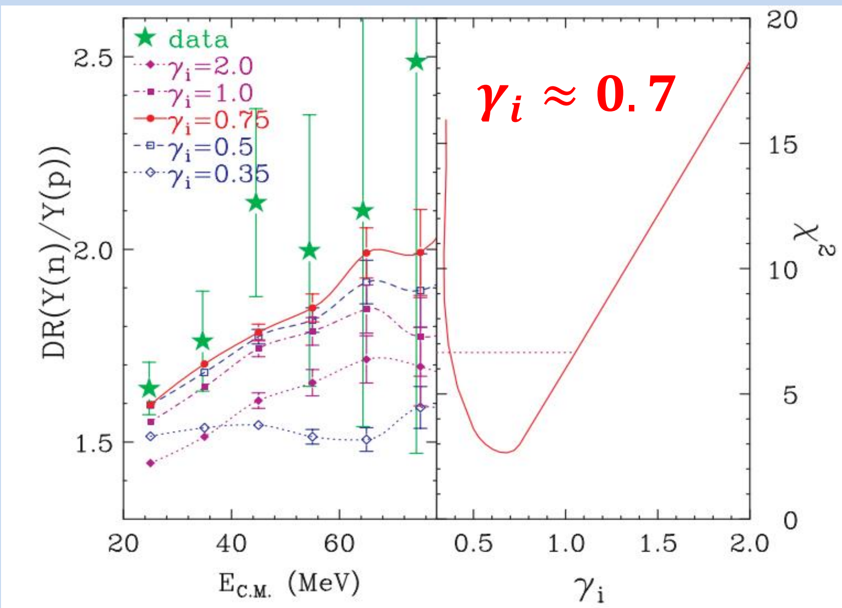
J. H. Xu et al., **Chin. Phys. Lett. 42**, 031401 (2025) (Express)
H. J. Zhang et al.， **Phys. Rev. C**, under review

An upcoming chance: **nucleon effective mass splitting**

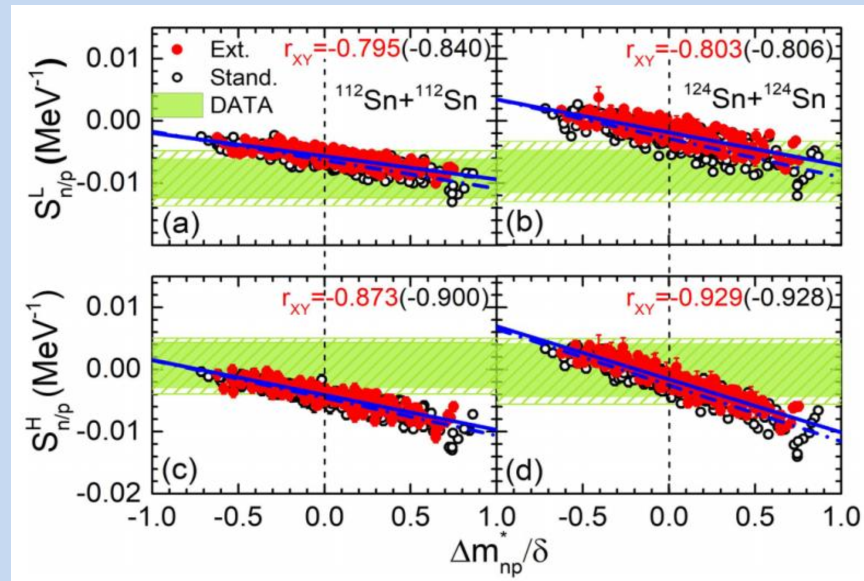
Measuring both n and p provides good opportunities to study the $E_{\text{sym}}(\rho)$ and $\Delta m_{n-p}/\delta$!

50 AMeV $^{124}Sn + ^{124}Sn$, $^{112}Sn + ^{112}Sn$

$$\boldsymbol{E_{\text{sym}}(\rho) = 12.5\left(\frac{\rho}{\rho_0}\right)^{2/3} + 17.6\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}}$$



$$S_{\text{n/p}} = \frac{\ln R_{n/p}(E_2) - \ln R_{n/p}(E_1)}{E_2 - E_1}$$



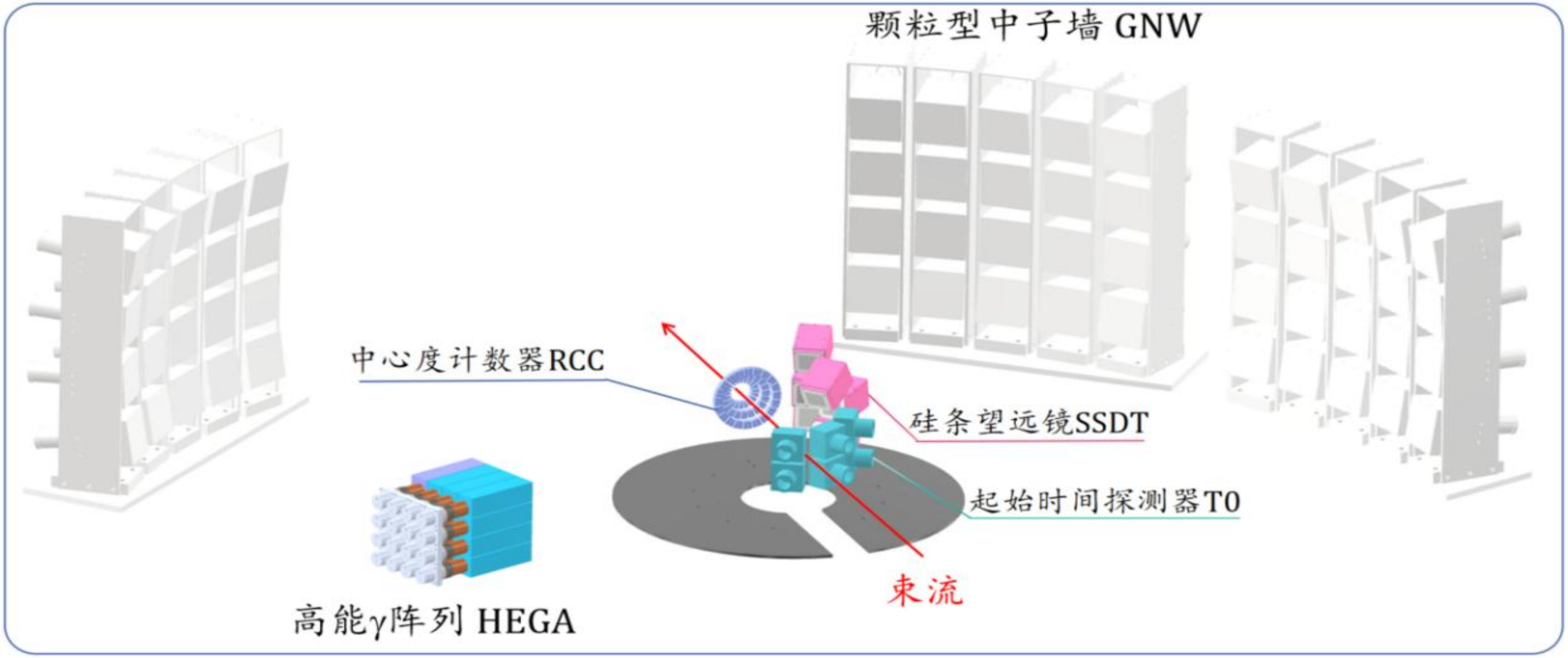
1. Single effective Skyrme interaction fails;
2. Δm_{n-p} depends on E_{kin} or momentum

M. B. Tsang et al., PRL 102, 122701 (2009)

J. P. Yang et al., PRC 112, 044604 (2025)

Opportunities with CSHINE$^+$

CSHINE$^+$： Combinatory Spectrometer for Heavy IoN Experiment



1) measure p-p and n-n correlation function simultaneously, inferring neutron skin thickness.

2) high-quality measurement of the n/p differenital yield helps to decode the nucleon effective mass splitting, as well as check the constraint of $E_{\mathrm{sym}}(\rho)$.

3) Upgraded high-energy gamma hodoscope for systematic studies of SRC in HIC.

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Collaboration Groups (The.):

IMP-CAS: Gaochan Yong

CIAE: Yingxun Zhang

Nanjing U: Chang Xu

HZU: Qingfeng Li

GXNU: Li Ou

and ENPG group members

Summary

1. $E_{\mathrm{sym}}(\rho)$ -related studies underline profound physics — of the isospin- and momentum dependent nuclear force — and remains the hot frontiers in heavy ion research.

2. While high-density $E_{\mathrm{sym}}(\rho)$ is poorly known, the uncertainty of $E_{\mathrm{sym}}(\rho)$ constraint at ρ_0 is yet large, despite that large progress has been made.

3. With CSHINE, some experimental progress have been reported. i.e., isospin dynamics in HI reactions, n-n correlation functions and precise SRC determination.

4. More opportunities can be emerged with the **CSHINE**$^+$ and **CEE**, including the neutron skin determination, nucleon effective mass splitting as well as systematic SRC investigations in HIC.

Thank you for your attention!