



32nd Nuclear Physics Workshop

28-30 September 2026
Lublin, Poland



Femосcopy: its concept and selected applications in heavy ion collisions

Zhigang Xiao Tsinghua University

E-mail: xiaozg@tsinghua.edu.cn <http://info.phys.tsinghua.edu.cn/enpg>



Experimental Nuclear Physics Group
Department of Physics, Tsinghua University

Outline

1. Introduction: Femoscopy in HIC
2. CSHINE Experiment
3. nn and pp correlations in $^{124}\text{Sn}+^{124}\text{Sn}$
 - 3.1 nn correlation function results
 - 3.2 Comparison of n-n and p-p correlation functions
4. Summary and Outlook

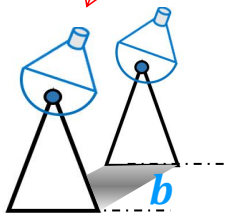
Introduction of intensity interferometry

- Introduced by Hanbury Brown and Twiss to measure the angular size of SIRIUS

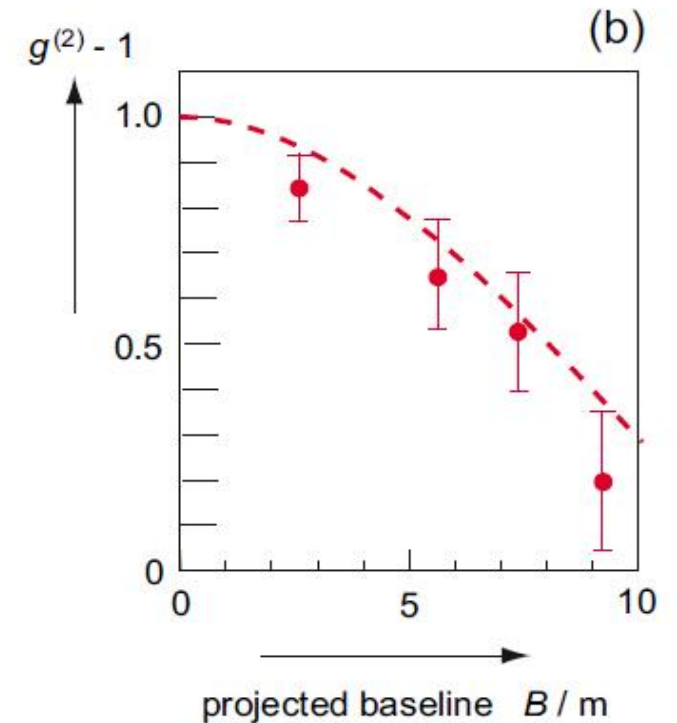
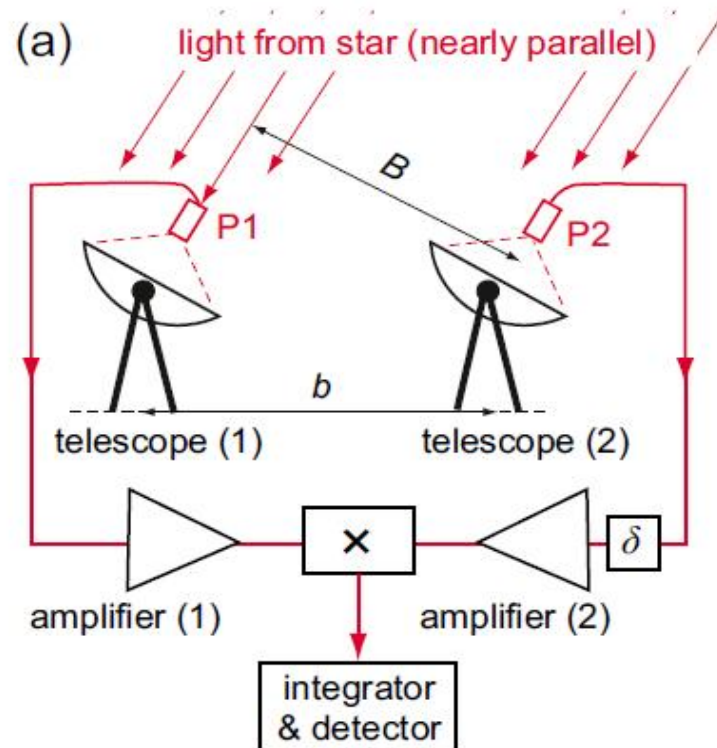


$$L/d \approx b/\lambda = 10^{7-9}$$

-incoherent
-intensity correlation



$$\frac{\text{Distance } L}{\text{Object size } d} = \frac{\text{Baseline } B}{\lambda} = 10^{7-9}$$



$$C(q) = \frac{P(\mathbf{p}_1, \mathbf{p}_2)}{P(\mathbf{p}_1)P(\mathbf{p}_2)} = 1 + R(\mathbf{p}_1, \mathbf{p}_2)$$

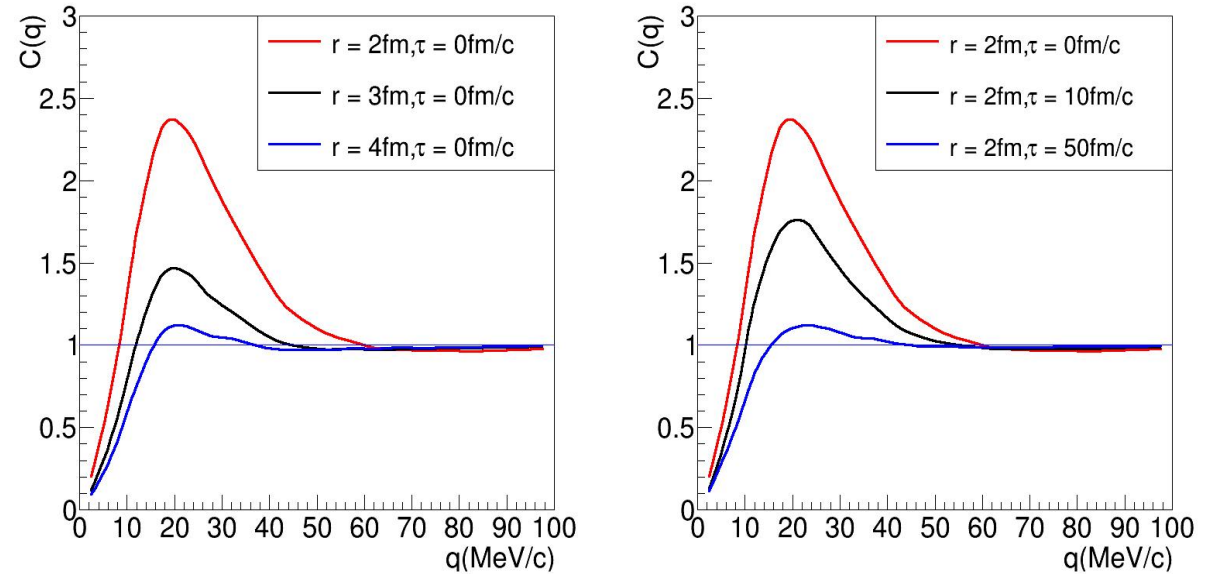
Hanbury Brown and Twiss, Nature **177**, 27 (1956)

Hanbury Brown and Twiss, Nature **178**, 1046 (1956)

Its Application in Heavy Ion Collisions

- 1960s, Goldhaber
 π - π correlations
- 1977, S Koonin
Formulate the p-p correlation
- 1990s, enormous application in HIC

S. Koonin, Phys. Lett. B70, 43 (1977)



What makes it different in heavy ion collisions? **Dynamic evolution** and **FSI between p-p pair**.

Source function

$$\frac{1}{\sigma} \frac{d\sigma}{d\mathbf{p}_1 d\mathbf{p}_2} = \int dt_1 dt_2 \int d\mathbf{r}_1 d\mathbf{r}_2 \boxed{D(\mathbf{r}_1 t_1, \mathbf{p}) D(\mathbf{r}_2 t_2, \mathbf{p})} \times \left\{ \frac{1}{4} |{}^1\Psi_{\mathbf{p}_1 \mathbf{p}_2}(\mathbf{r}'_1, \mathbf{r}_2)|^2 + \frac{3}{4} |{}^3\Psi_{\mathbf{p}_1 \mathbf{p}_2}(\mathbf{r}'_1, \mathbf{r}_2)|^2 \right\}$$

Propagation and p-p wave function of relative motion

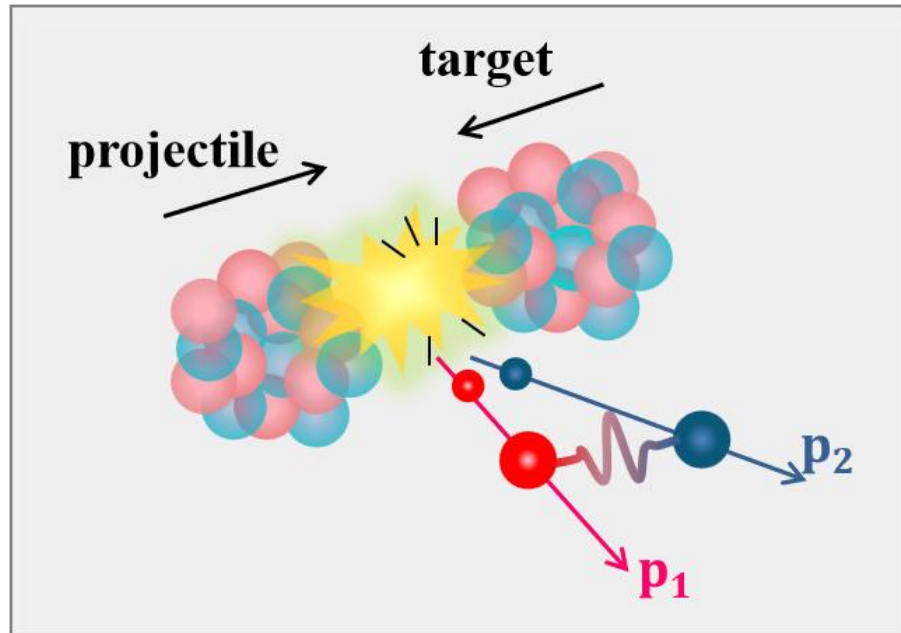
$$D(\mathbf{r}, t, \mathbf{p}) = \frac{1}{\sigma} \frac{d\sigma}{d\mathbf{p}} \left[\frac{1}{\pi^{3/2} r_0^3} \exp(- (r - V_0 t)^2 / r_0^2) \right] \left[\frac{1}{\pi^{1/2} \tau} \exp(- t^2 / \tau^2) \right]$$

Lednický and Lyuboshitz method

Lednický 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. Lednický, et al. Sov. J. Nucl. Phys. 35 (1982) 770

Definition

Original momentum CF definition

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

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

Modeling

Describing the CF using K-P formula:

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

Source
function

Relative wave function
of the particle pair

Experiment

Experimentally using mixture event method to subtract the background:

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

Signal
Background

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

Potential applications of CF method

Applications	Else Ref.
1. Spatial-Temporal distribution of emission source	FOPI Collab. EPJA05
2. Final State Interaction (f^0, d^0) ✓	STAR collab. Nature15
3. Femtoscopic imaging and non-Gaussian source	Kincses et al., Comm. Phys.25
4. Probe the Neutron Skin Structure ✓	X. G. Cao et al., PRC 12'
5. Isospin Chronology and $E_{\text{sym}}(\rho)$ inference	L. W. Chen et al, PRL03 Y. J. Wang et al., PLB 22
6. Potential probe of the SRC in nuclei	arxiv: 2604.25107
7. Properties of resonance/hypernuclei	STAR Collab., PRL26

2 CSHINE Experiment

HIRFL: Heavy Ion Research Facility at Lanzhou

RIBLL: Radioactive Ion Beam Line at Lanzhou

CSR: Cooling Storage Ring

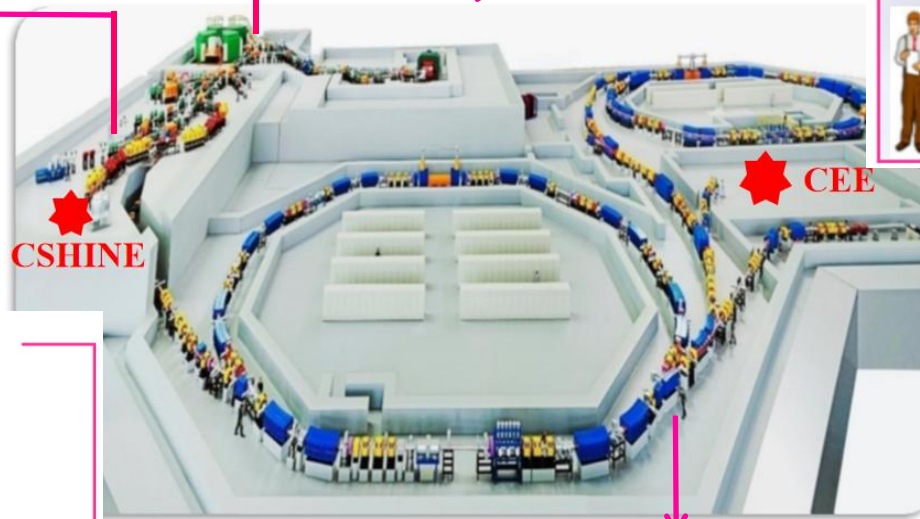
SSC:

Kr: ~ 40 MeV/u

Sn: ~ 30 MeV/u

RIBLL1

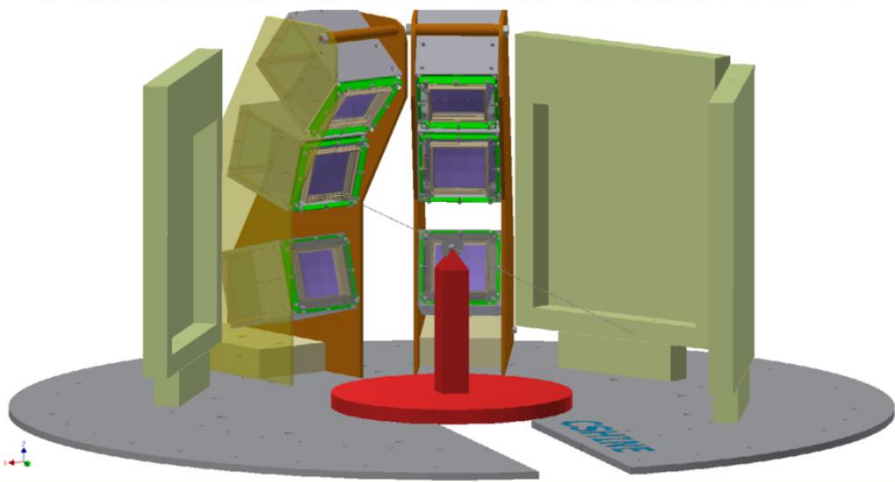
HIRFL-CSR Complex



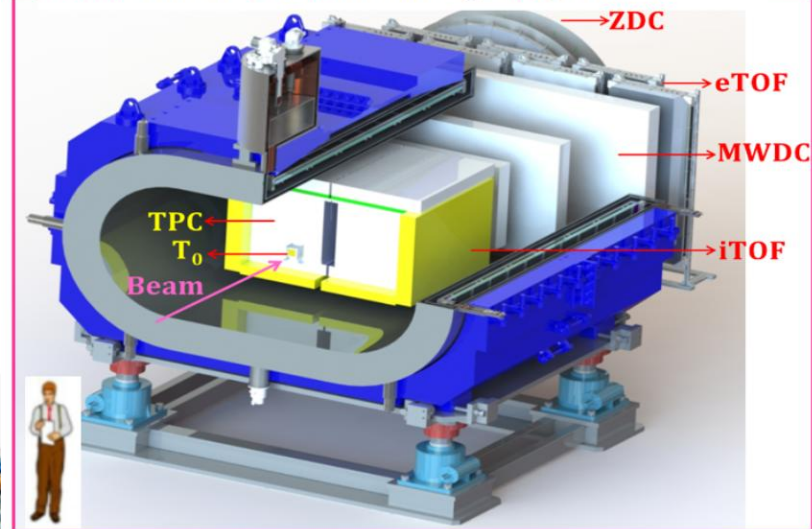
CSHINE

CEE

CSHINE: Compact Spectrometer for Heavy Ion Experiment



CEE: HIRFL-CSR External-target Experiment



CSR:

p: 2.8 GeV

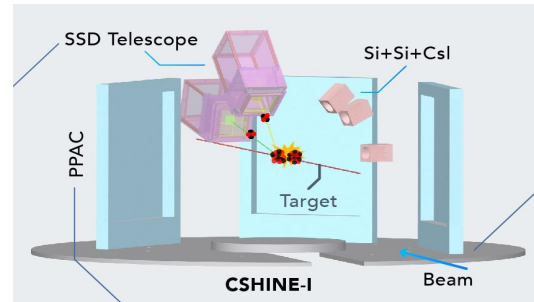
C: 1.0 GeV/u

U: 0.5 GeV/u

CSHINE experiment

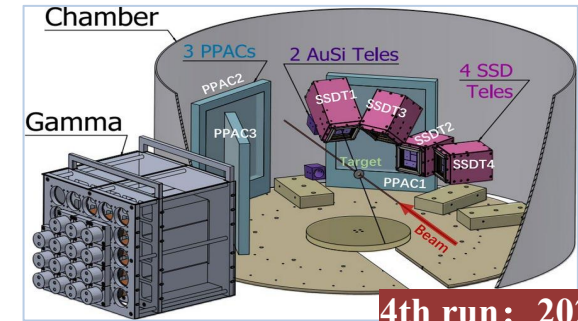
Compact Spectrometer for Heavy Ion Experiment

CSHINE
Compact Spectrometer for Heavy Ion Experiments



2nd run: 2019

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



4th run: 2022

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

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

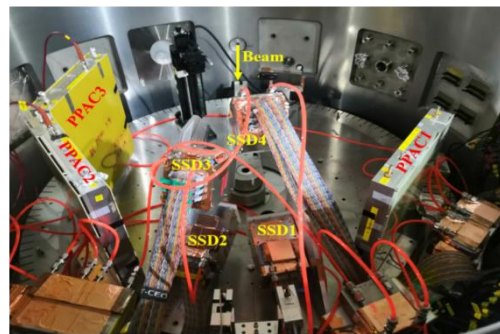
01 2014



1st run: 2014

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

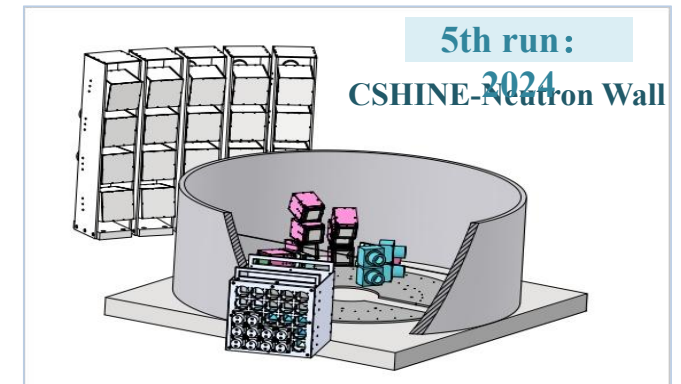
03 2019



3rd run: 2019

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

05 2024



5th run:

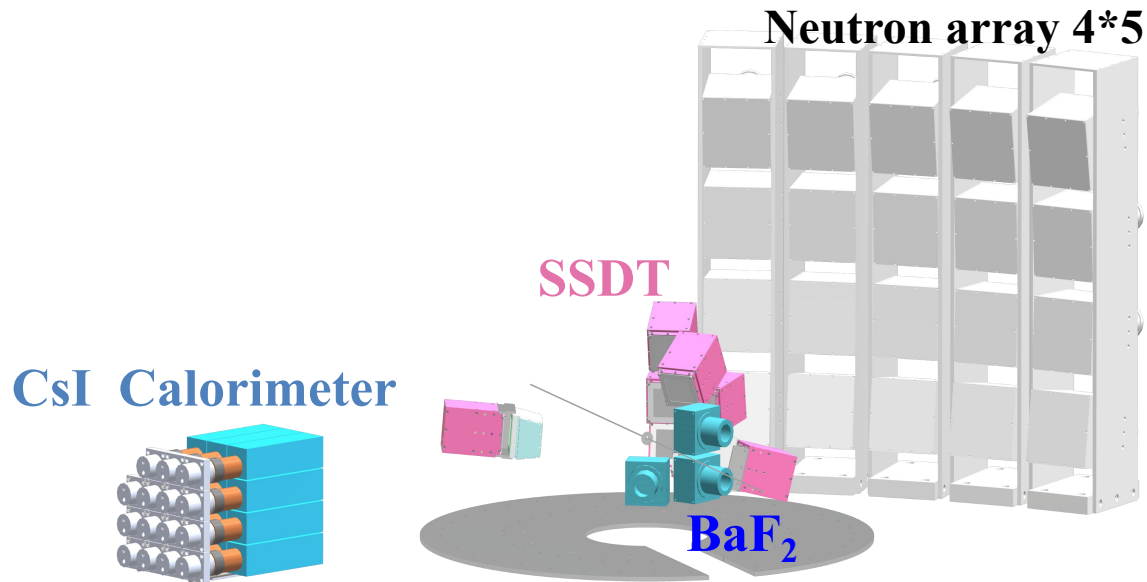
2024

CSHINE-Neutron Wall

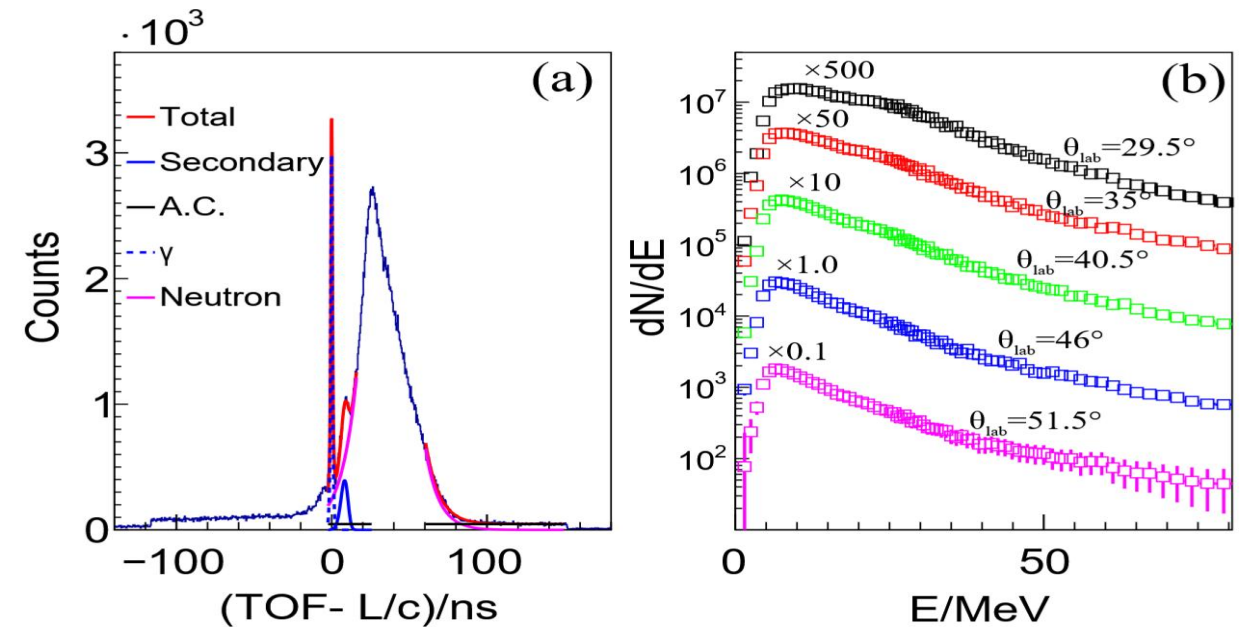
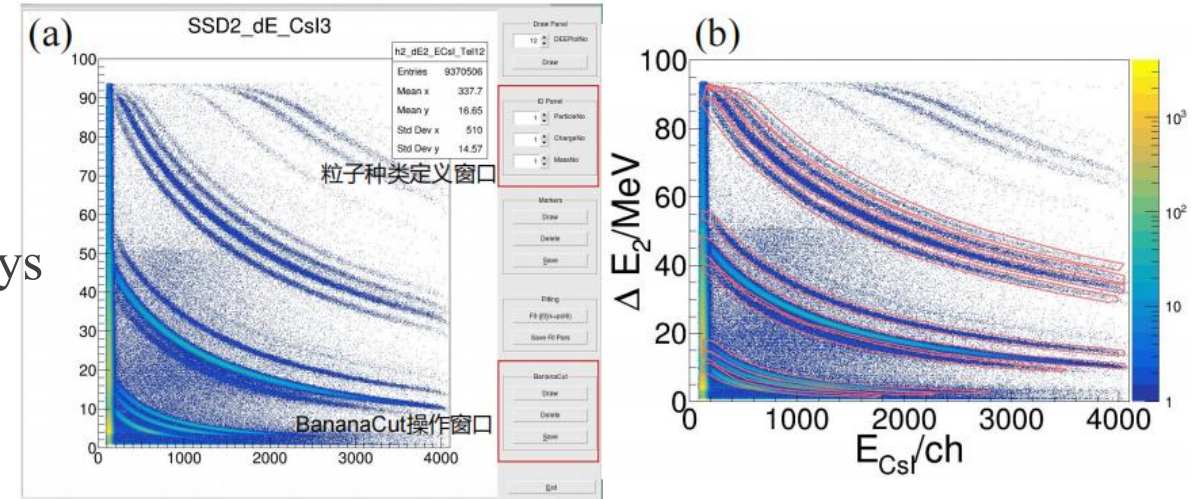
25 MeV/u $^{124}\text{Sn}+^{124}\text{Sn}$ Experiment (in April 2024)

Detector Setup:

- A 4×5 array for neutrons
- 6 SSD telescopes for LCPs
- A 15-unit CsI(Tl) hodoscope for Bremstrahlung γ rays
- A 64-unit CsI wall for centrality determination



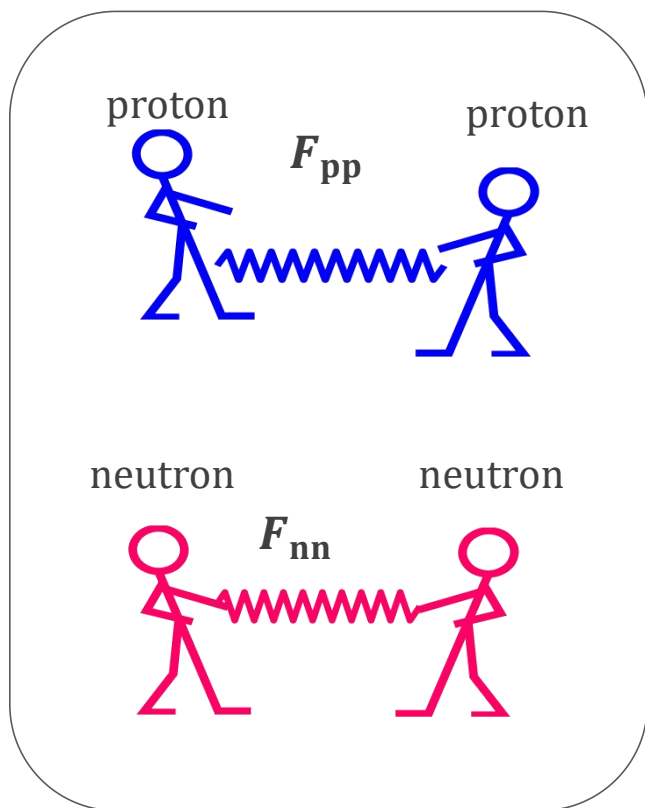
Neutron Wall unit size: 15cm $\times$ 15cm $\times$ 15cm



3. n-n and p-p correlation functions

Why we measure them ?

- ❶ Unravel the isospin dynamics in HIC
- ❷ Measure n-n (f_0, d_0) — related to CSB
- ❸ Can we probe the neutron-skin?



p-p: ($f_0^{pp} = -17.3 \pm 0.4$ fm, $d_0^{pp} = 2.85 \pm 0.04$ fm)

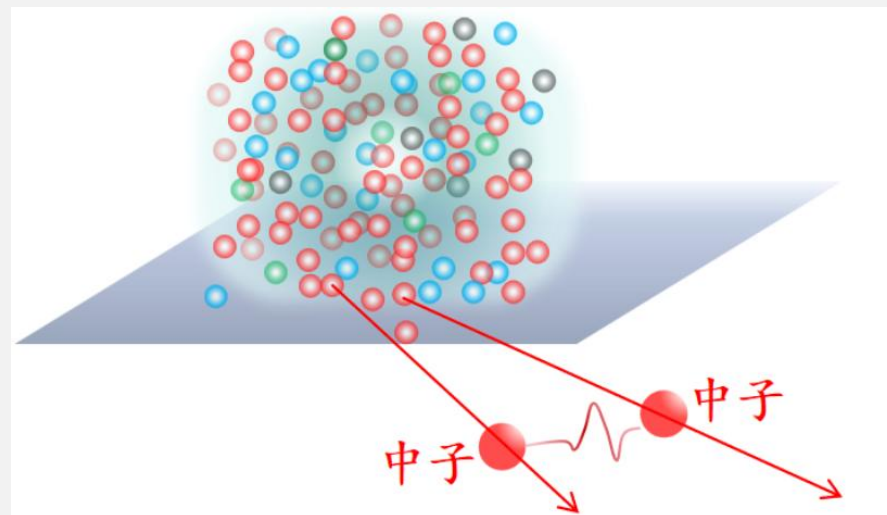
n-n: ($f_0^{nn} = -18.9 \pm 0.4$ fm, $d_0^{nn} = 2.75 \pm 0.11$ fm)

R. Machleidt., PRC 63, 024001 (2001)

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

CSB of nuclear force

via CF in HIC :



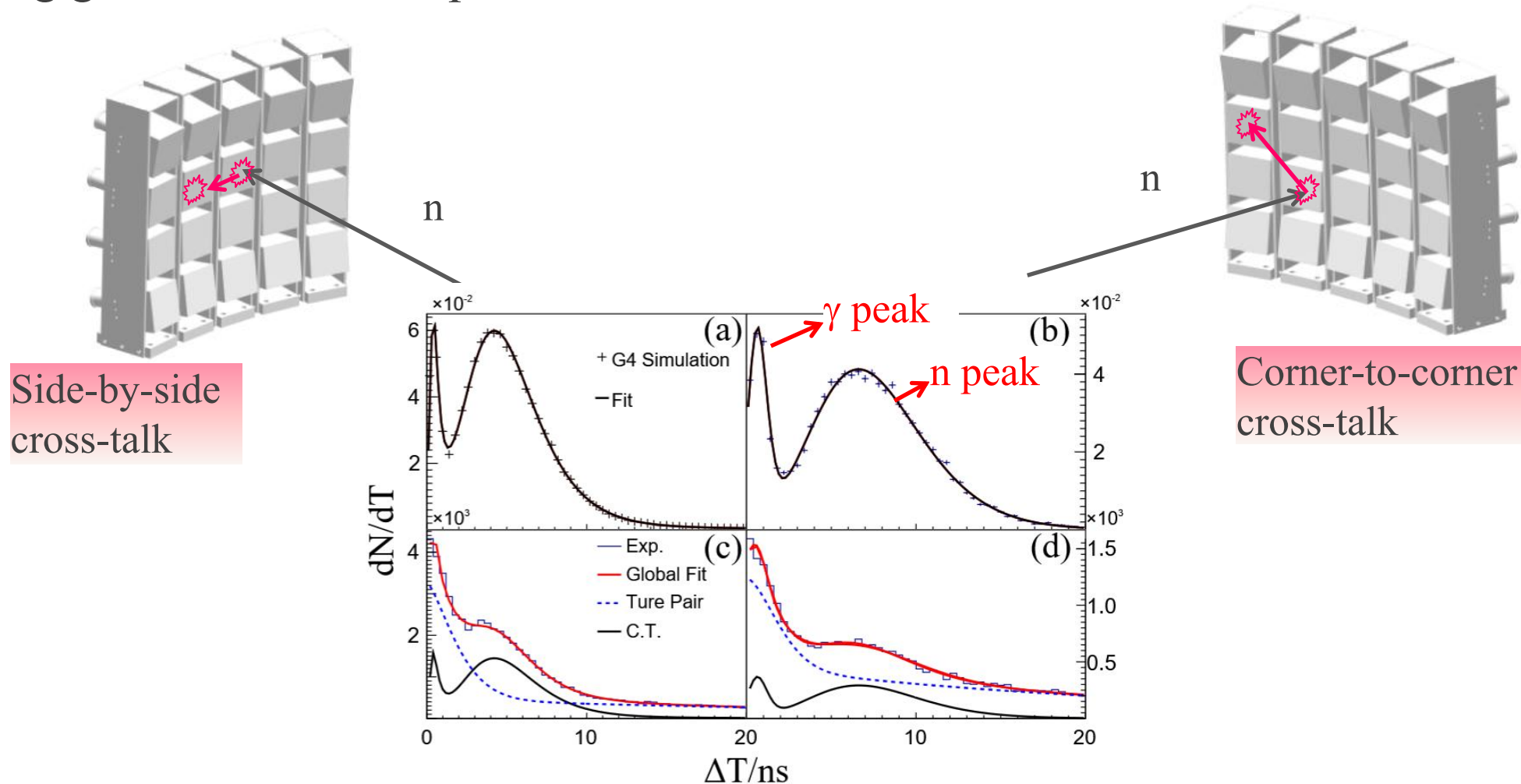
Lednicky and Lyuboshitz proposed to extract (f_0^{nn}, d_0^{nn}) by n-n CF

3.1 n-n correlation function

Cross-talk is the most influential effect to be corrected!

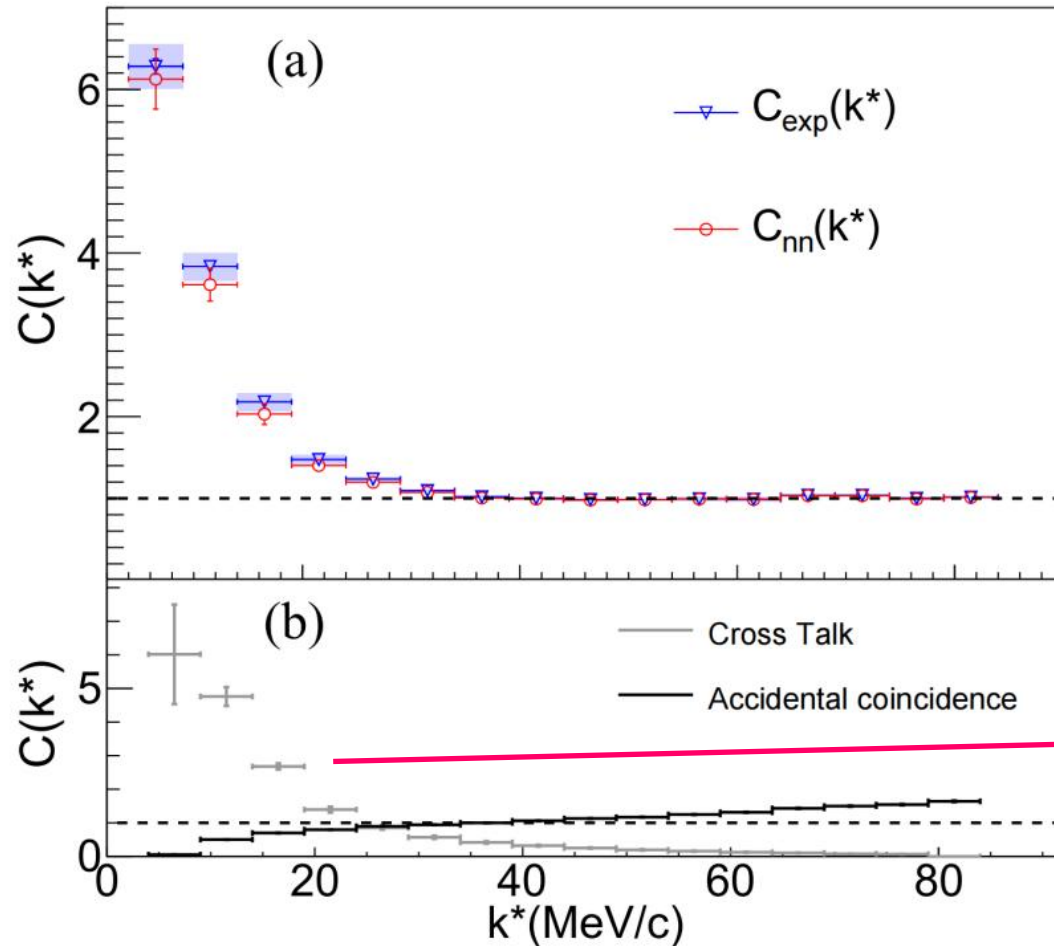
Using Geant 4 simulation to reproduce the cross-talk pattern

Doing global fit to decompose and subtract the cross-talk



n-n correlation function and LL fit

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



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

Cross-talk and accidental coincidence partly cancel each other.

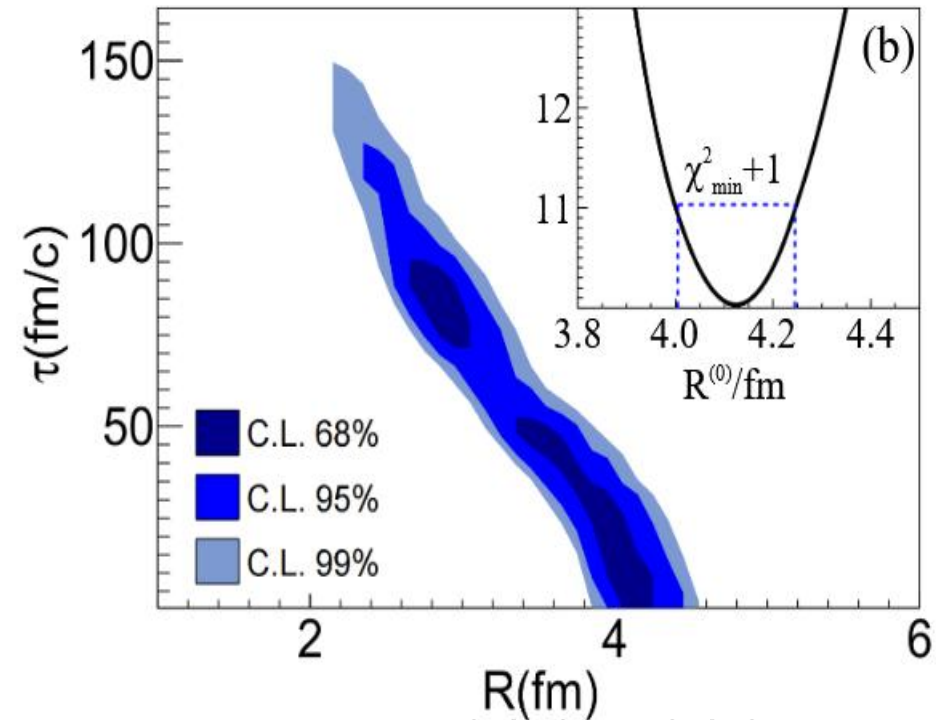
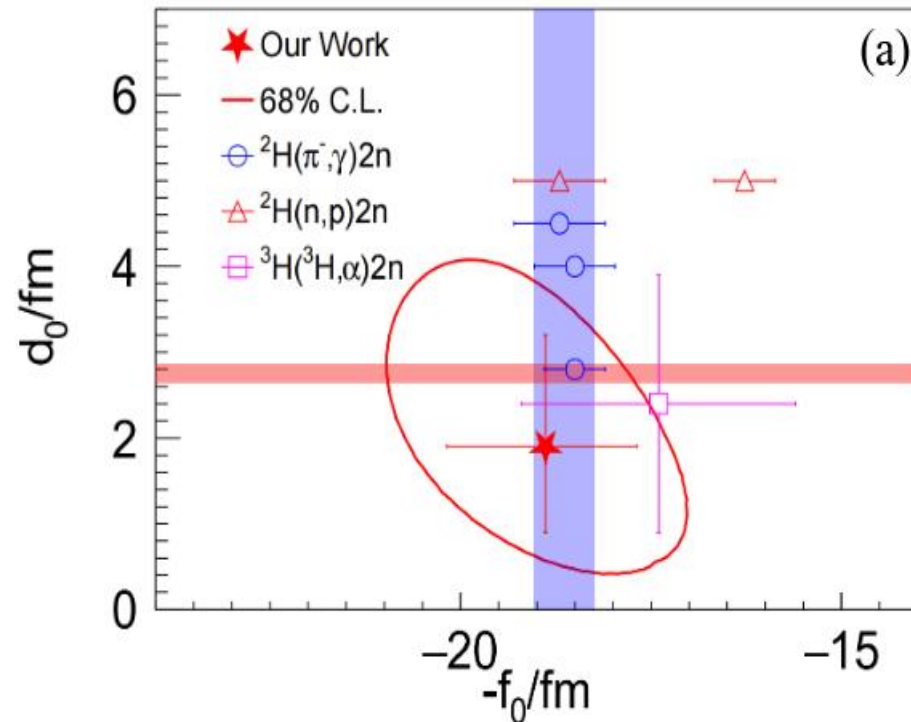
Extraction of (f_0^{nn}, d_0^{nn})

✓ (f_0^{nn}, d_0^{nn}) is extracted from 25 MeV/u $^{124}\text{Sn} + ^{124}\text{Sn}$ reactions:

$$f_0^{nn} = 18.9_{-1.2}^{+1.3} \text{ fm}, d_0^{nn} = 1.9_{-1.0}^{+1.3} \text{ fm}$$

[Better control of the uncertainty still demanded for CSB studies.]

✓ Simultaneously, the temporal-spatial source size is extracted: $R^{(0)} = 4.1 \pm 0.1 \text{ fm}$

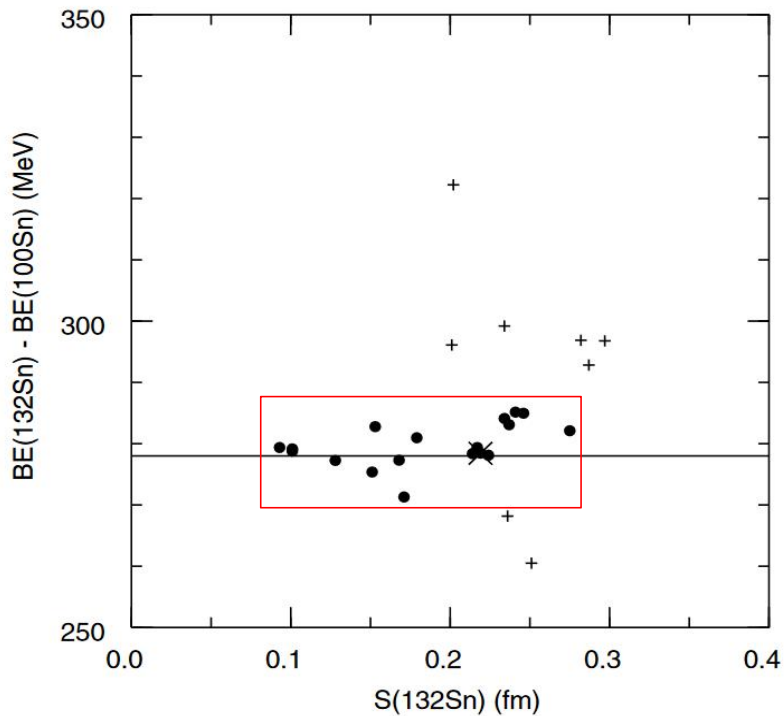


Here we assume a Gaussian source function: $S \propto \exp(-r^2/R^2 - t^2/\tau^2)$

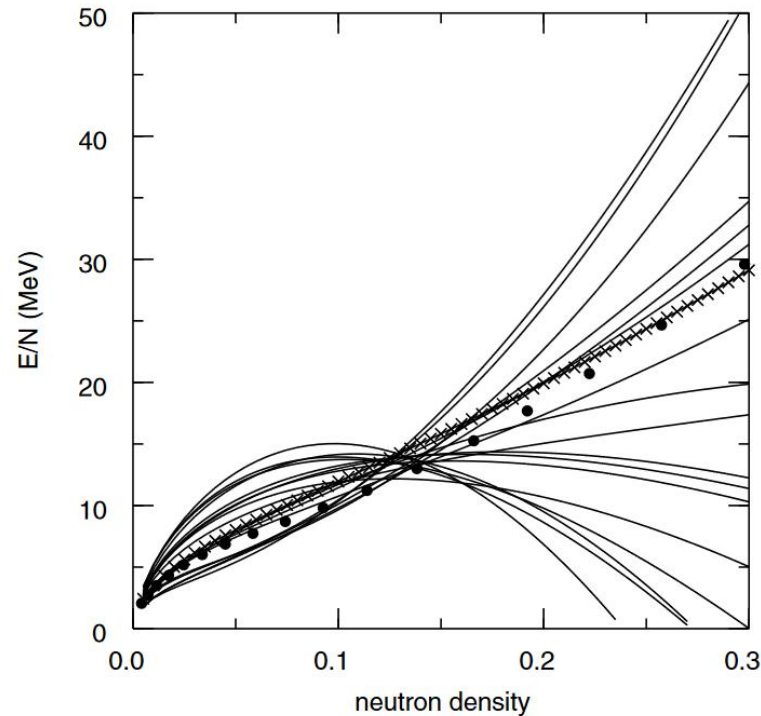
3.2 p-p and n-n correlation functions

Motivation: Neutron skin thickness (n-p rms radius difference) is correlated to $E_{\text{sym}}(\rho)$

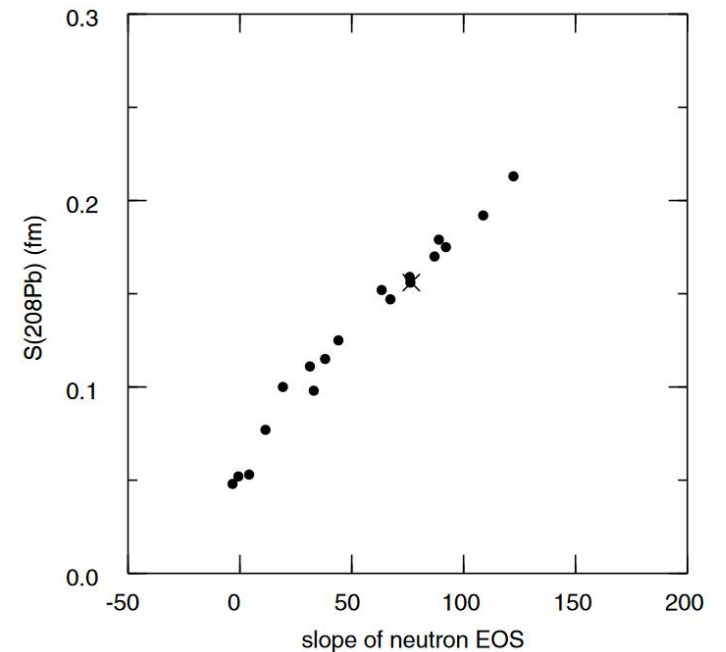
$$\Delta r_{np} \equiv \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$



26 sets of Skyrin potential parameters to calculate the ^{132}Sn binding energy



18 sets of the Skyrin potential

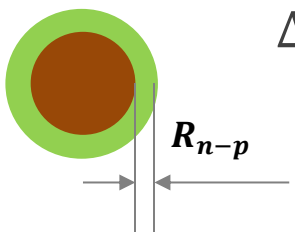


Correlation between Δr_{np} and $E_{\text{sym}}(\rho)$ slope parameter.

A. Brown., Phys. Rev. Lett. 85, 5296 (2000)

Tension between PREX and CREX results

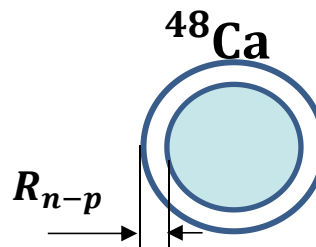
^{208}Pb



$$\Delta r_{np}(^{208}\text{Pb}) = 0.283 \pm 0.071 \text{ fm}$$

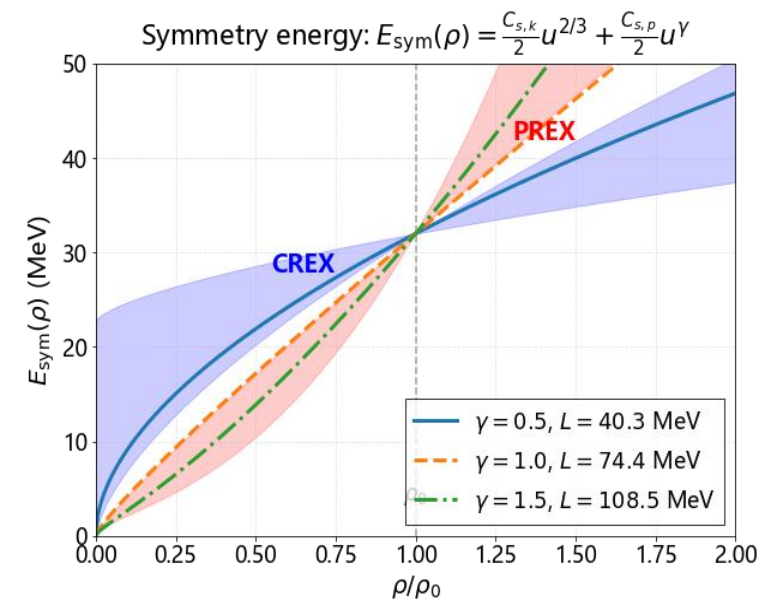
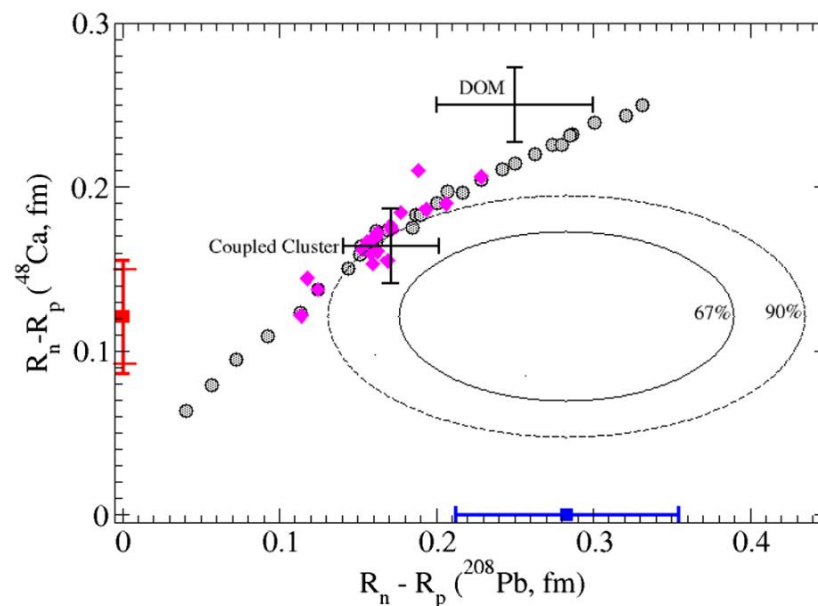
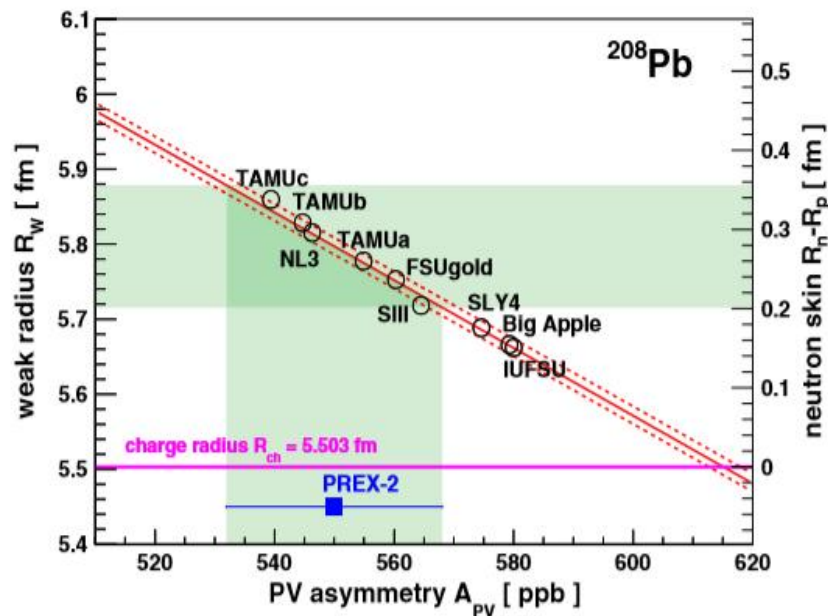
$$L = 106 \pm 37 \text{ MeV}$$

^{48}Ca



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

$$L \sim 10 \text{ MeV}$$



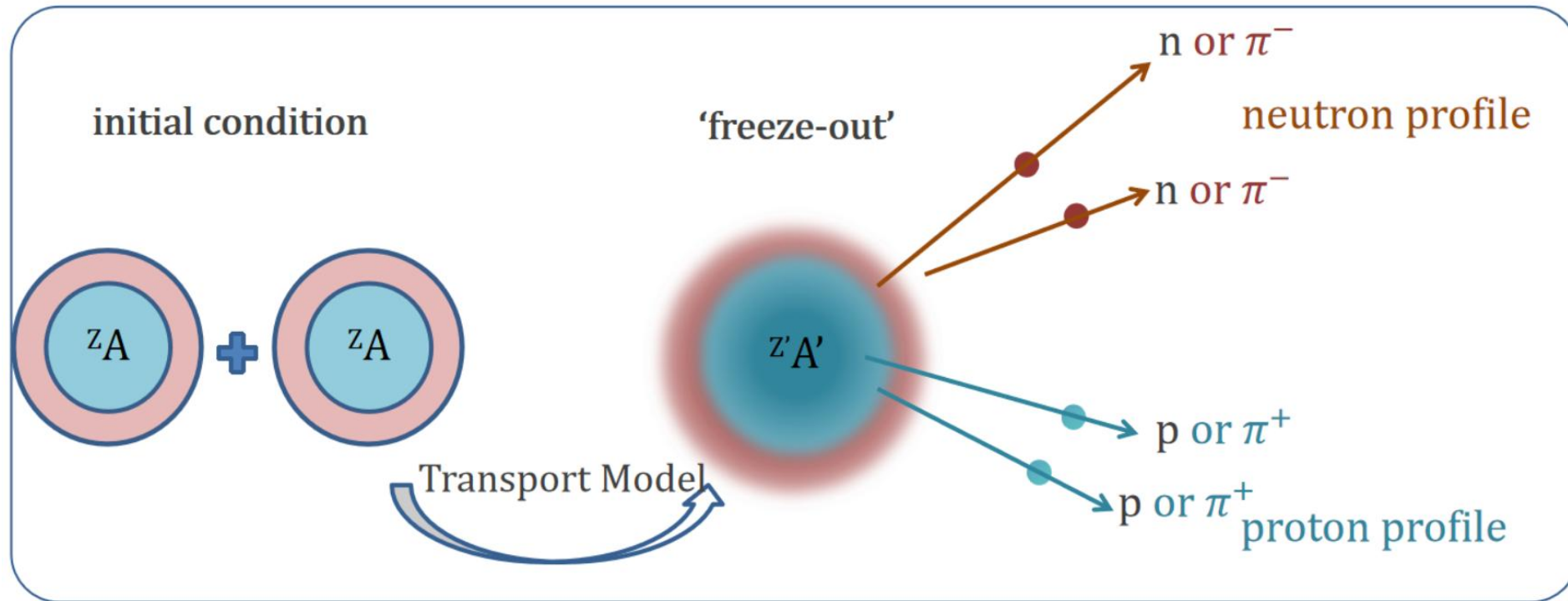
PREX collaboration., PRL 126, 172502 (2021)
B. T. Reed et al, PRL 126, 172503 (2021)

D. Adhikari et al (CREX collab.) PRL 129, 042501 (2022)
P. Reinhard et al PRL 129, 232501 (2022)

Our motivation: Seeking the potential probe of neutron skin via femtoscopy

Probe neutron skin thickness by correlation function

Is it possible to clarify the tension between PREX2 and CREX results using the **CF method** ?



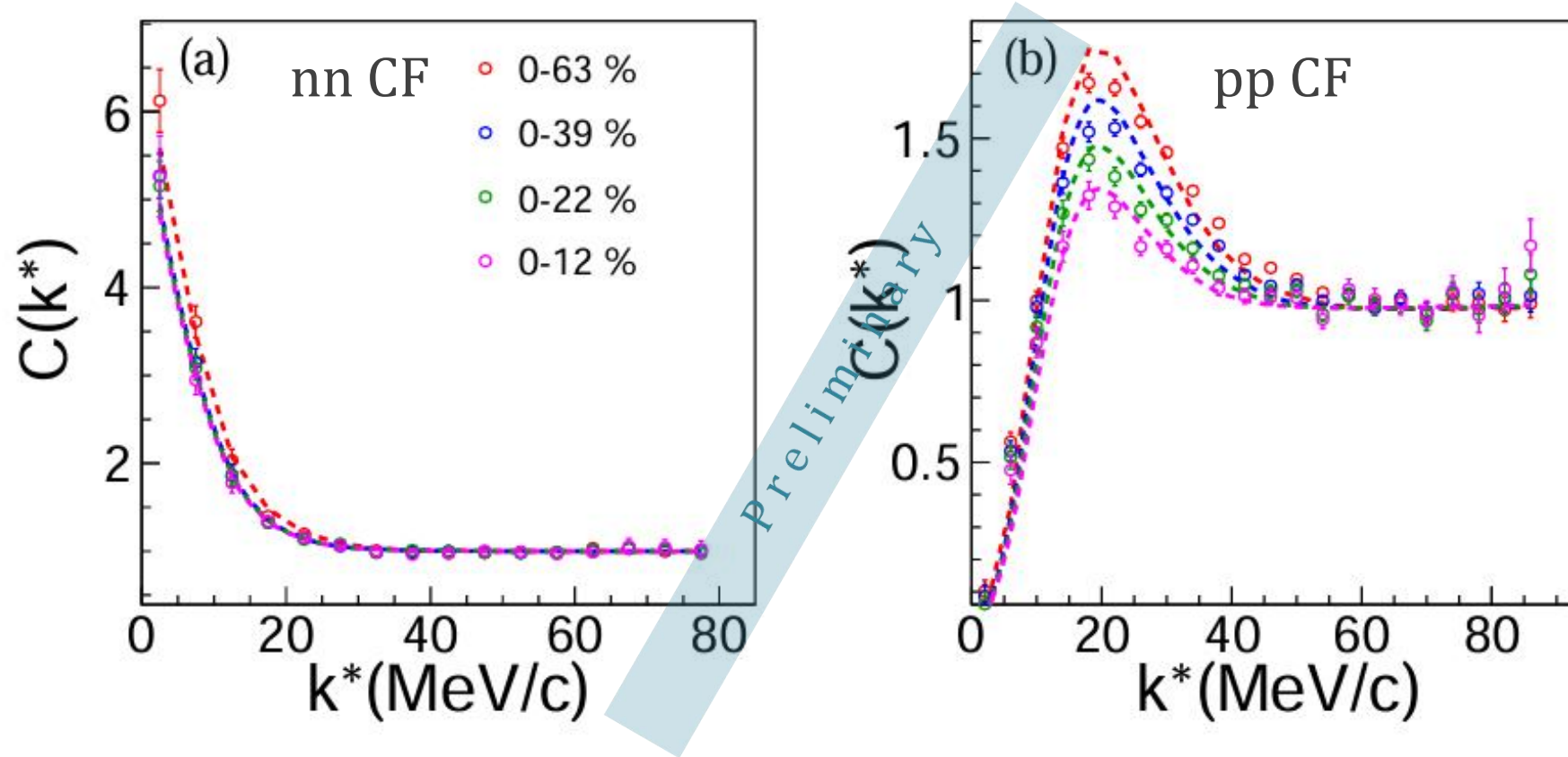
n-n and p-p CF at CSHINE

J. H. Xu et al., *Chin. Phys. Lett.* **42**, 031401 (2025) (Express)

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

H. J. Zhang et al., *Phys. Rev. C* **113**, 034904

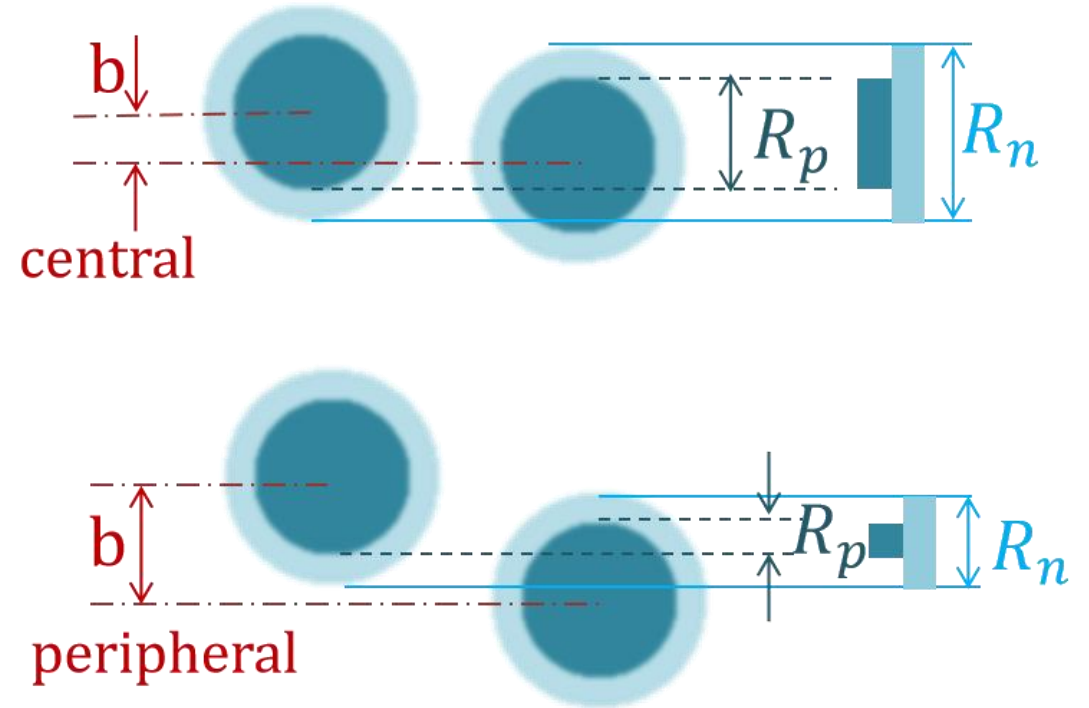
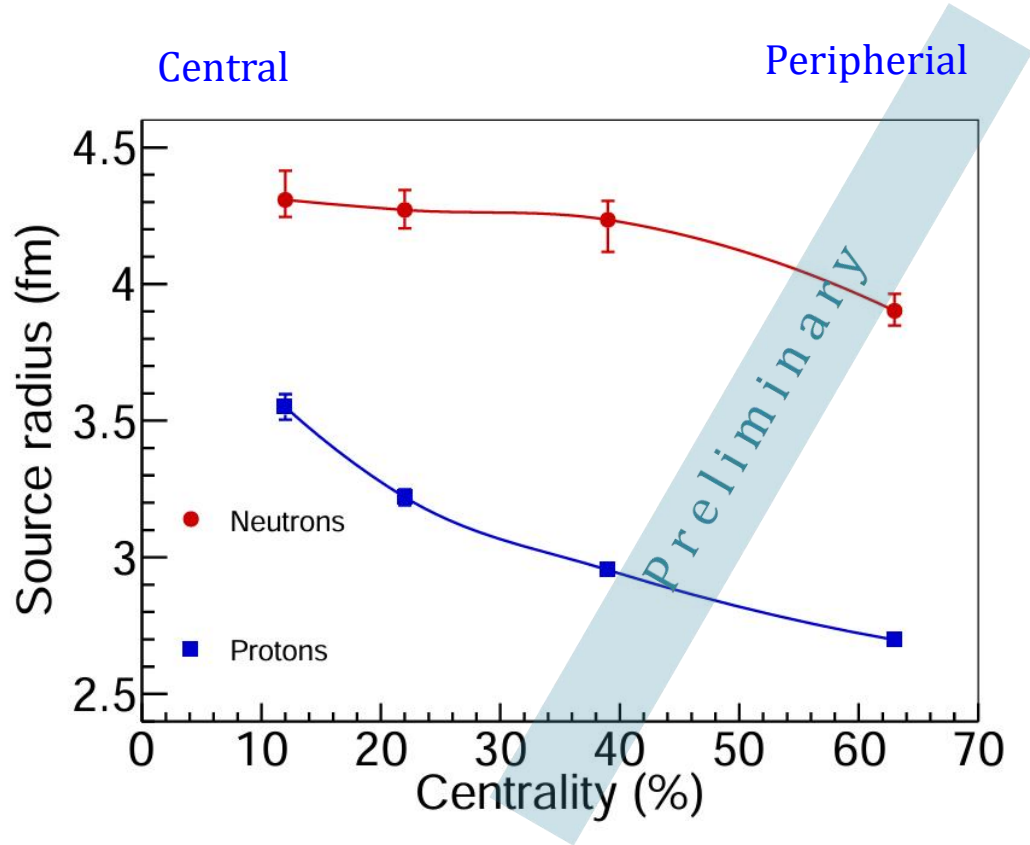
n-n and p-p CFs in $^{124}\text{Sn}+^{124}\text{Sn}$ at 25 MeV/u



Curves are LL
Fittings

- › Going to central collisions, nn and pp correlation strengths reduce, indicating the source sizes increase;
- › variation of nn CF strength is less pronounced, compared to pp CF.

n-n and p-p correlation functions in $^{124}\text{Sn}+^{124}\text{Sn}$ at 25 MeV/u

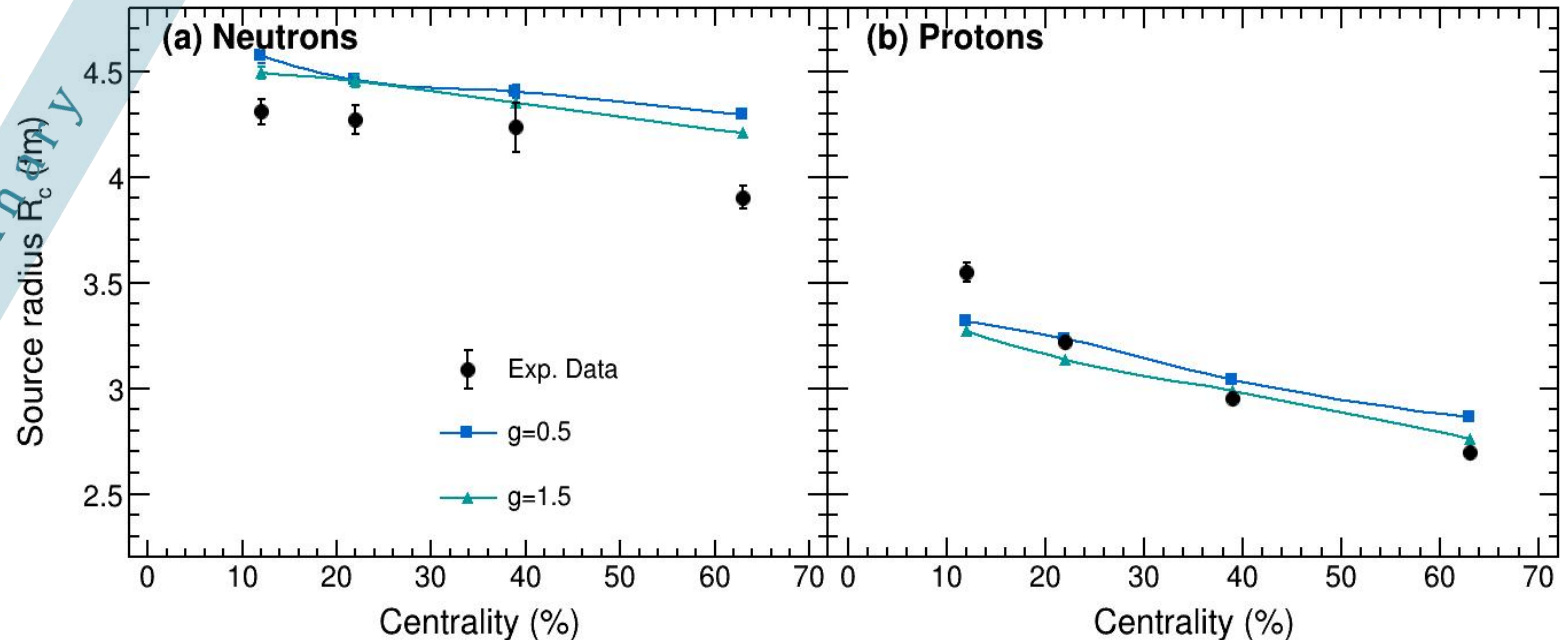
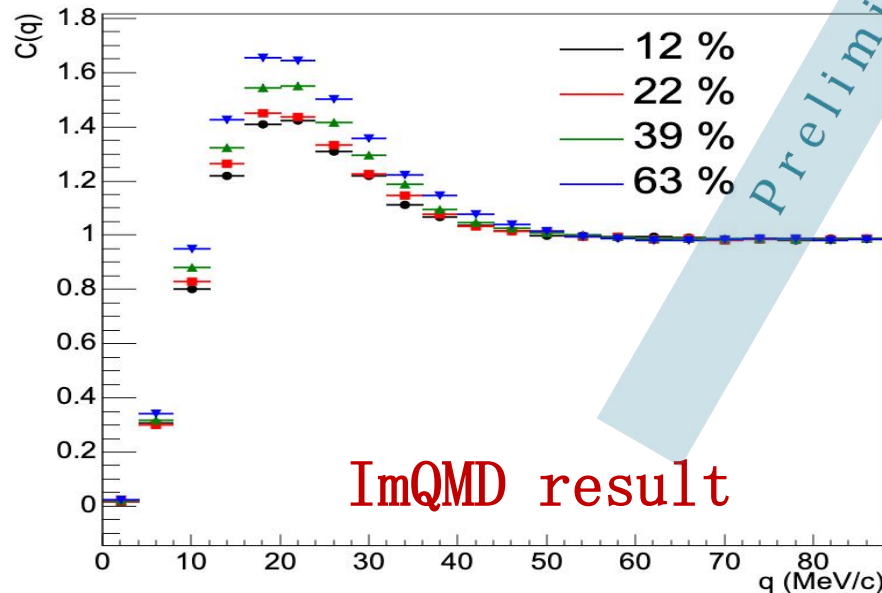
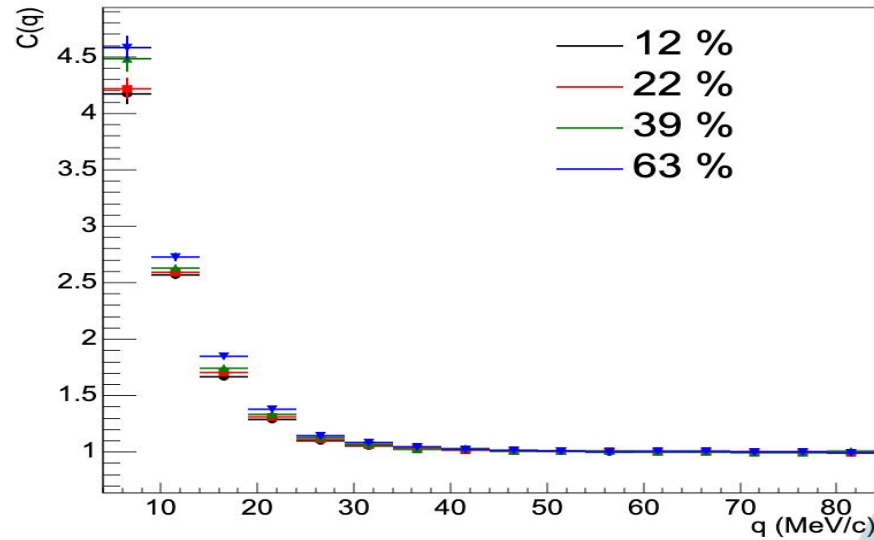


- Source size is larger for neutron emission than for proton emission
- Going more peripheral collisions, their difference becomes more pronounced

ImQMD Model Simulations

Symmetry energy in ImQMD model:

$$S(\rho, T) = \frac{C_{s,k}}{2} \left(\frac{\rho}{\rho_0} \right)^{2/3} + \frac{C_{s,p}}{2} \left(\frac{\rho}{\rho_0} \right)^{\gamma}$$



The model qualitatively reproduce the experimental trend, but not quantitatively.

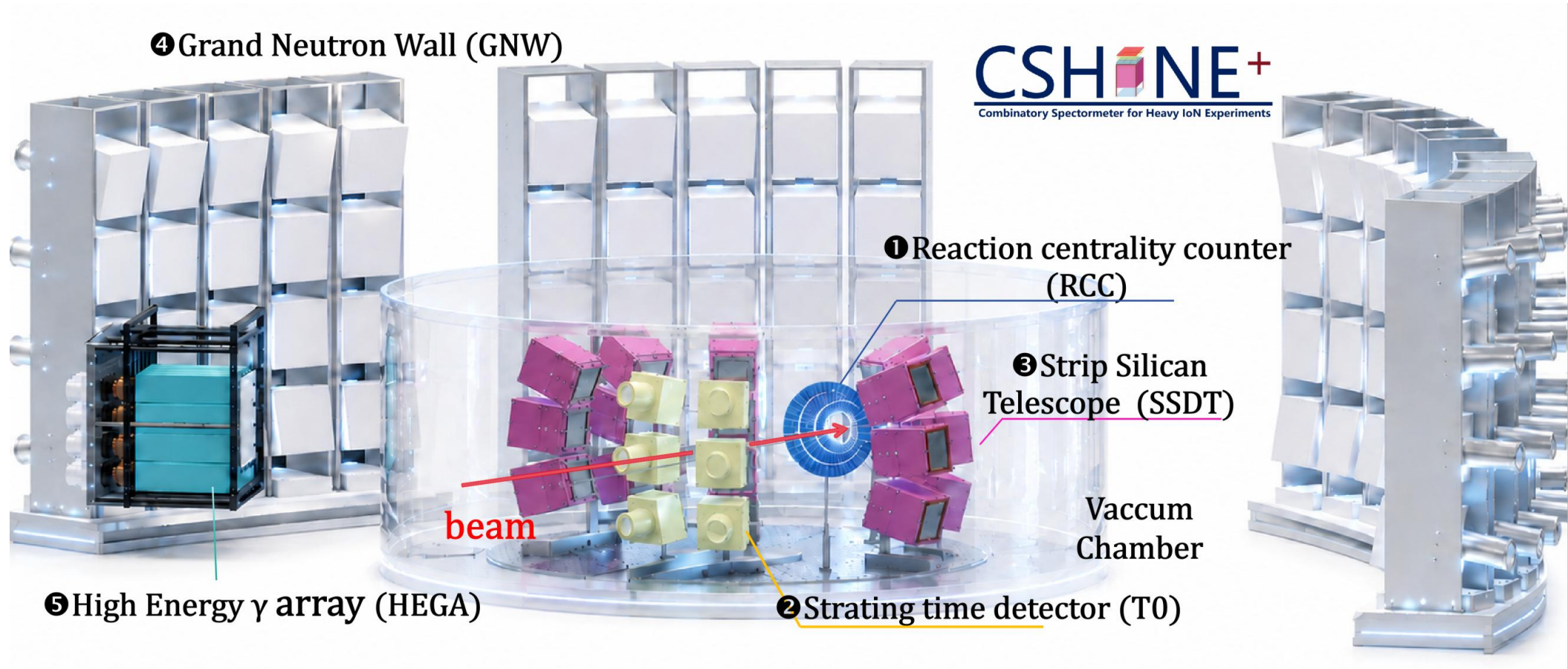
4. Summary and outlook

— Femtoscopy sees increasing applications in Heavy ion collision experiments:

✓ In 25 MeV/u $^{124}\text{Sn}+^{124}\text{Sn}$, the n-n CFs are measured. The n-n scattering length and effective range ($f_0^{nn} = 18.9_{-1.2}^{+1.3}\text{fm}$, $d_0^{nn} = 1.9_{-1.0}^{+1.3}\text{fm}$) has been extracted, indicating the potential feasibility to study the CSB of nuclear force using CF. The neutron emission source size $R^{(0)} = 4.1 \pm 0.1 \text{ fm}$ is also inferred.

✓ The p-p and n-n CFs are measured simultaneously. The source size of proton emission is smaller than neutron emission, and their difference increases towards peripheral collisions. It is consistent with the picture accommodating the neutron skin feature in ^{124}Sn . The femtoscopy might be a potential probe to the n-skin thickness.

Outlook



CSHINE⁺ is coming, with larger coverage of charged particles, neutrons and better centrality counter . HEGA will also be upgraded. It will provide better CF measurement. Stay tuned.

Thank you for your attention !