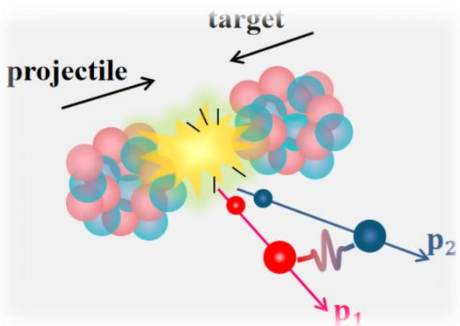

Extract the n-n interaction strength and the space-time size of neutron emission using femtoscopic method

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Outline

1. Introduction: Motivation of the study
2. Experimental setup: CSHINE
3. Results and Discussions
4. Summary

Introduction

Two questions:

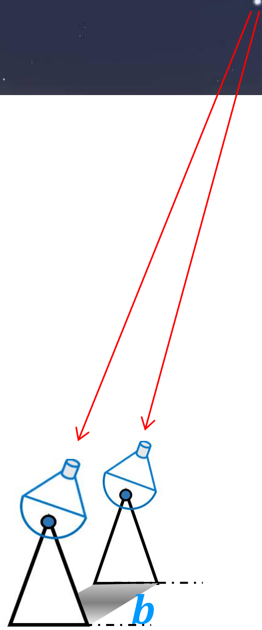
① Known from quantum mechanics, the interaction strength (scattering length and effective range) between particles can be measured by scattering experiment. But what if the particles are not stable?

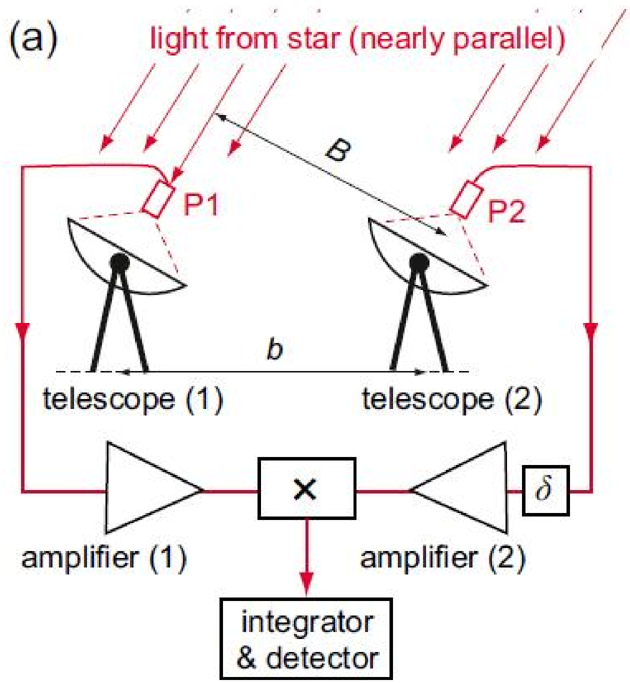
② Heavy ion reaction is a violent femtoscopic process lasting for zeptoseconds, how can one measure the temporal-spatial size of such a process?

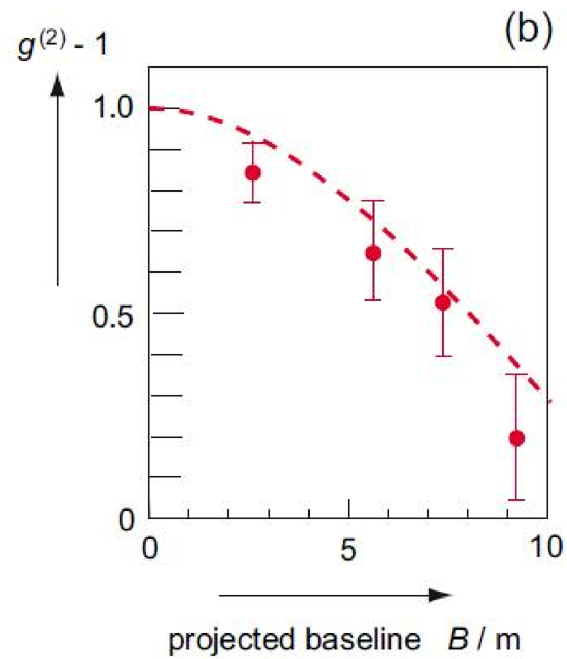
The answers to these two questions point to intensity inteferometry!

What is the intensity interfrometry (femtoscopic method)

- Invented by Hanbury Brown and Twiss in 1950s to determine the angular radius of Siris.







$$C(q) = 1 + \frac{P(\mathbf{p_1}, \mathbf{p_2})}{P(\mathbf{p_1})P(\mathbf{p_2})}$$

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

Hanbury Brown and Twiss, Nature **177**, 27 (1956)
Hanbury Brown and Twiss, Nature **178**, 1046 (1956)

Application extends to nuclear physics

1960s, Goldhaber

π-π correlations

1977, S Koonin

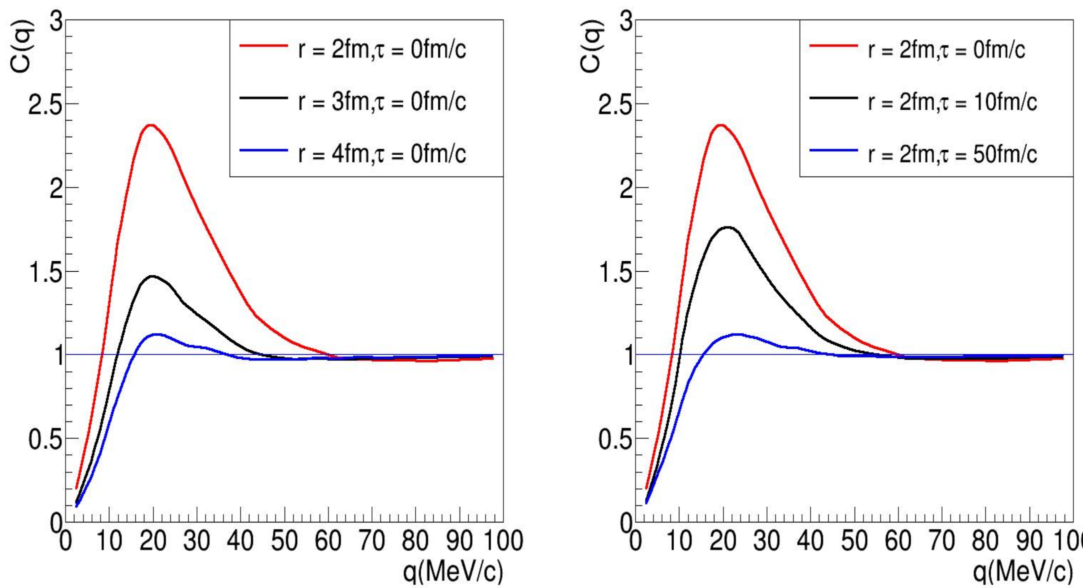
Formation the p-p correlation

1990s, enormously applied in HIC

IMF-IMF correlation functions

2000s, Imaging technique explored using pi-pi and p-p in relativistic HIC

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



Soure function

$$\frac{1}{\sigma}\frac{d\sigma}{d\mathbf{p}_1 d\mathbf{p}_2} = \int dt_1 dt_2 \int d\mathbf{r}_1 d\mathbf{r}_2 \boxed{D(\mathbf{r_1}t_1,\mathbf{p})D(\mathbf{r_2}\boldsymbol{t_2},\mathbf{p})} \times \left\{\frac{1}{4}\left|{}^1\Psi_{\mathbf{p}_1\mathbf{p}_2}(\mathbf{r}'_1,\mathbf{r}_2)\right|^2 + \frac{3}{4}\left|{}^3\Psi_{\mathbf{p}_1\mathbf{p}_2}(\mathbf{r}'_1,\mathbf{r}_2)\right|^2\right\}$$

Propagation and p-p wave function of relative motion

$$D(\mathbf{r},\mathrm{t},\mathbf{p}) = \frac{1}{\sigma}\frac{d\sigma}{d\mathbf{p}}\left[\frac{1}{\pi^{3/2}r_0^3}\exp(-(r-V_0t)^2/r_0^2)\right]\left[\frac{1}{\pi^{1/2}\tau}exp(-t^2/\boldsymbol{\tau}^2)\right]$$

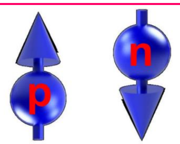
Why neutron-neutron correlation so special

Via n-n correlation function, one can

❶ reveal the collision dynamics in terms of the Isospin DOF

❷ determine the n-n (f_0, d_0) — related to CSB of nuclear force

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



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

Directly Observations for CSB

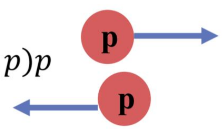
In scattering experiment:

$f_0^{pp} =- 17.4 \pm 0.4 fm$

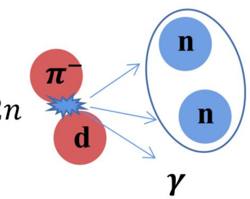
$f_0^{nn} =- 18.5 \pm 0.5 fm$

$f_0^{nn} =- 18.7 \pm 0.6 fm$

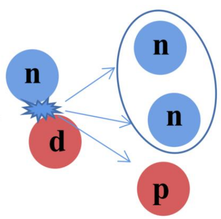
$p(p,p)p$



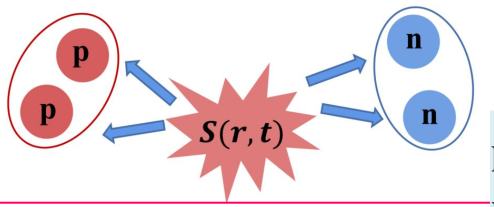
$d(\pi^-,\gamma)2n$



$d(n,p)2n$



In HIC experiment:



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

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

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

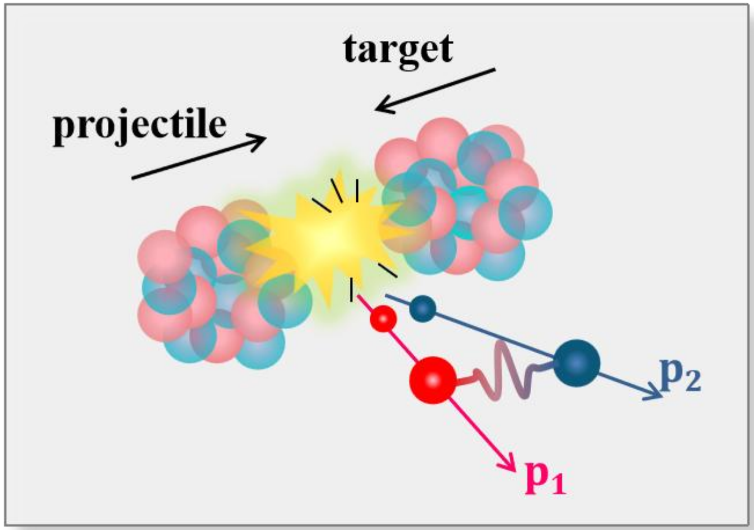
Motivation: To measure n-n correlation function and extract n-n (f_0, d_0) inHIC.

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:

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

Source function

Relative wave function of the particle pair

Experiment

Experimentally using mixture event method to subtract the background:

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

Signal

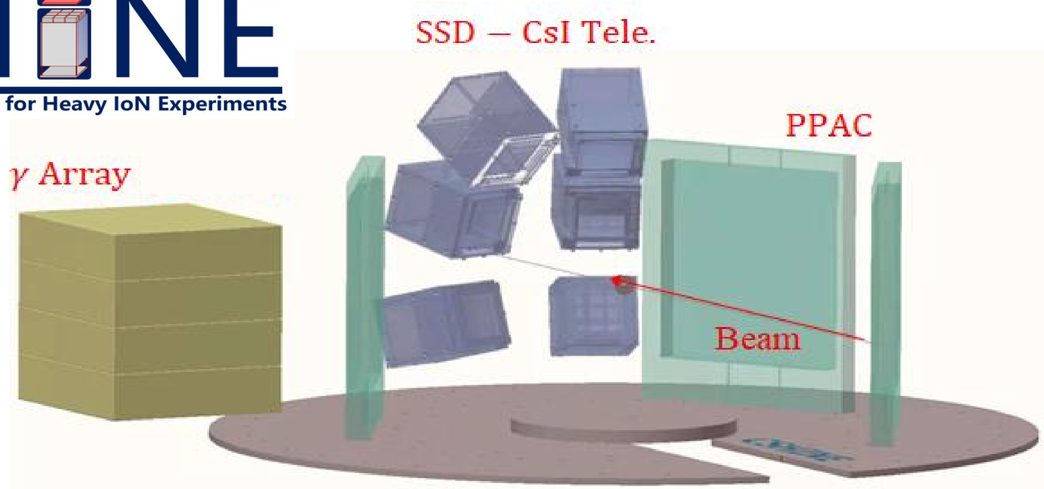
Background

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

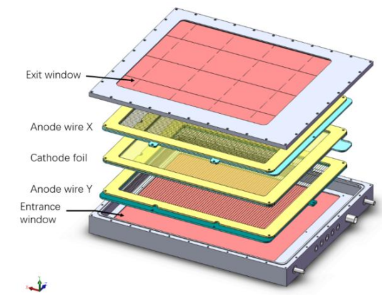
2. Experiment Setup and data analysis

Compact Spectrometer for Heavy IoN Experiment
installed at the Radioactive Ion Beam Line at Lanzhou, HIRFL

CSHINE
Compact Spectrometer for Heavy IoN Experiments

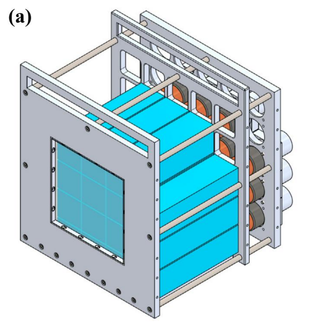


Total channels: ~400, starting from 2014

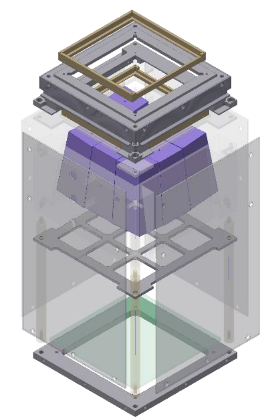


PPAC for fission fragments

(a)



CsI hodoscope for high energy γ



SSDT for LCP and IMFs

F. H. Guan et al., **NIMA** 1011, 165592 (2021)

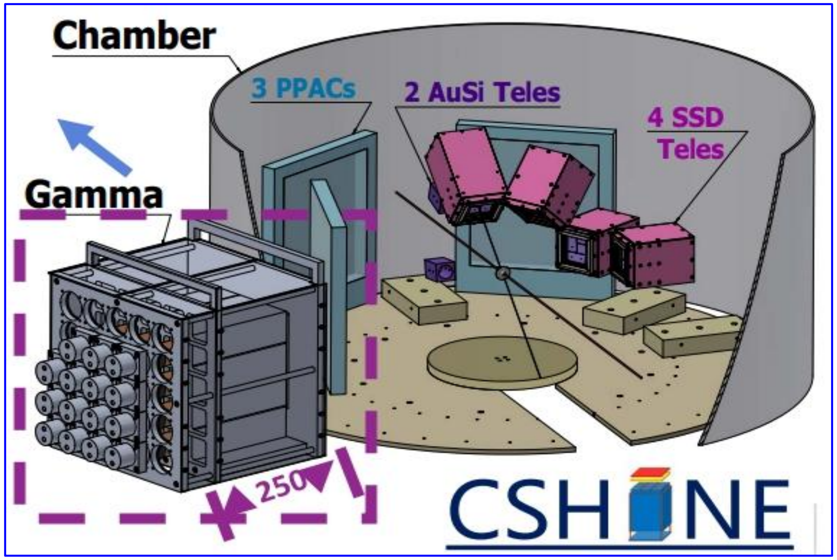
Building-up of CSHINE

5 Beam Runs：

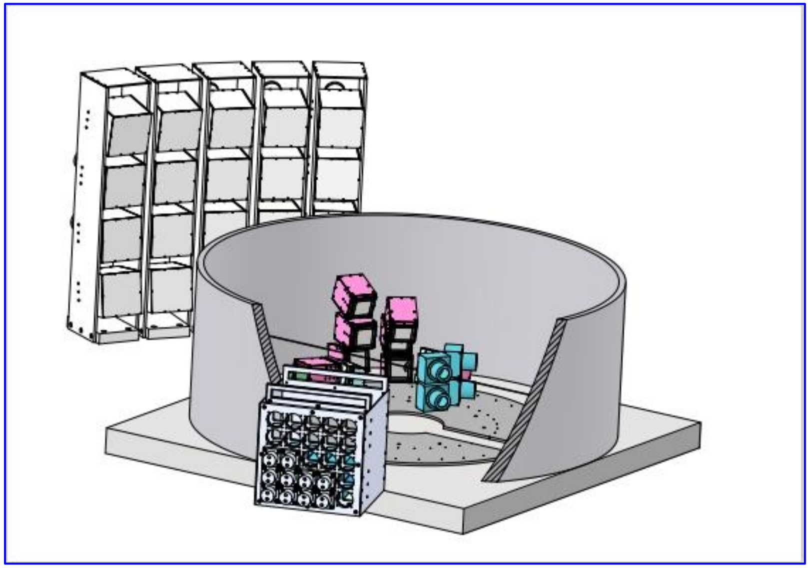
I： 30 MeV/u* ^{40}Ar+^{197}Au (2014)
II： 30 MeV/u ^{40}Ar+^{197}Au (2018)
III： 25 MeV/u ^{86}Kr+^{208}Pb (2019)
IV： 25 MeV/u ^{86}Kr+^{124}Sn (2022)
V： 25 MeV/u ^{124}Sn+^{124}Sn (2024)

Goal of CSHINE:

- Isospin Dynamics of heavy ion reactions
- $E_{\mathrm{sym}}(\rho)$ at $\rho \approx \rho_0$

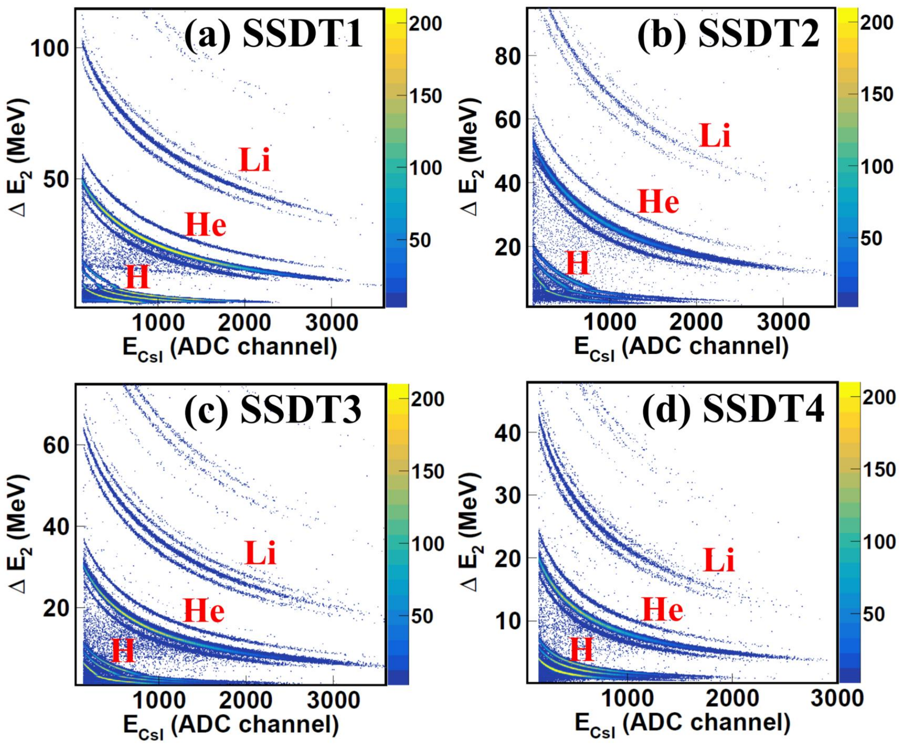


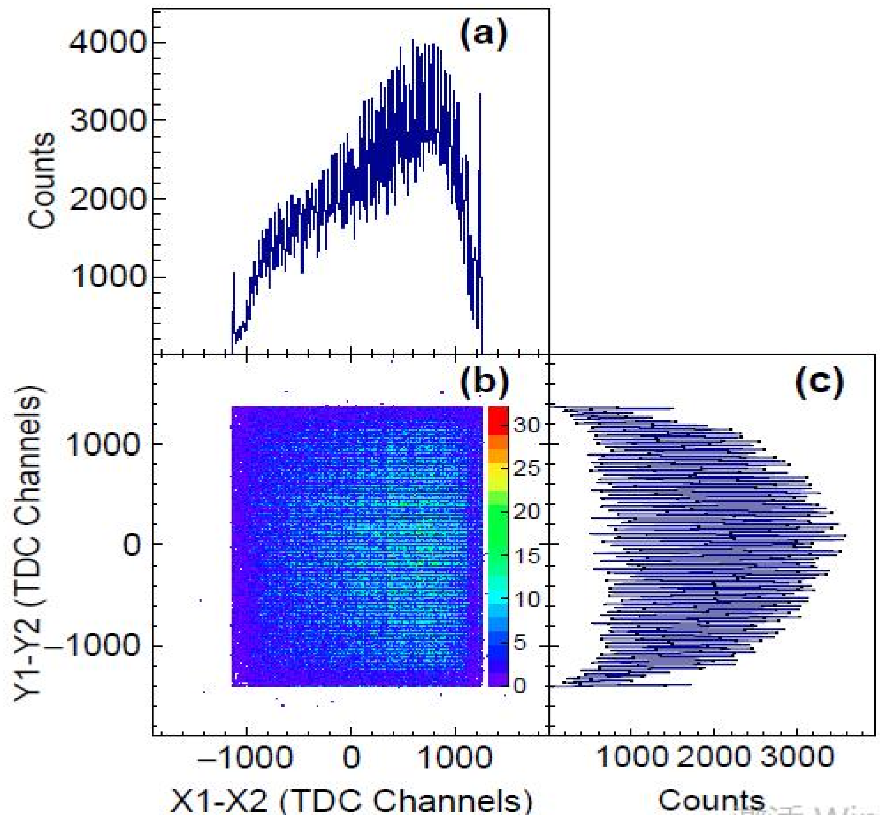
4th run： 2022 + High energy γ hodoscope



5th run： 2024 + Neutron Wall

Detector Developement of CSHINE





Development of detector technologies with CSHINE:

Neutron Wall: **NIMA** 1070,170055 (2025) ; High energy γ hodoscope: **NIMA** 1053 168330 (2023)

Silicon Strip Detector Telescopes: **NIMA** 1029, 166461 (2022), **NIMA** 1011, 165592 (2021) , **Nucl. Sci. Tech.** 32, 4 (2021)

FPGA based Trigger System: **Nucl. Sci. Tech.** 33, 162(2022);

PPAC for fission fragments: **Nucl. Sci. Tech.** 33, 40 (2022)

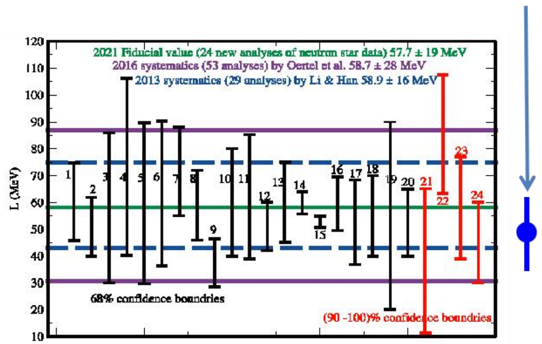
Physics Programs of CSHINE

一 Isospin Dynamics via N/Z ratio、CF and bremsstrahlung γ emission

1. Constraining L of $E_{\mathrm{sym}}(\rho)$ at $\rho \approx \rho_0$

PRC 95, 041602R (2017)

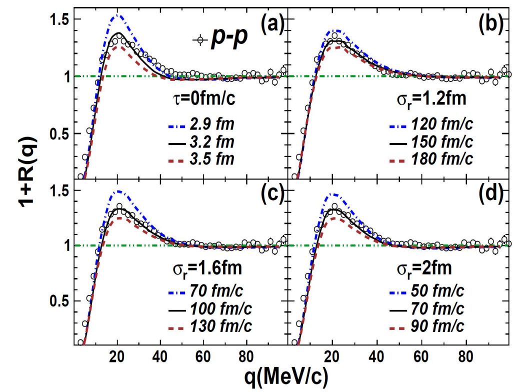
our work



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

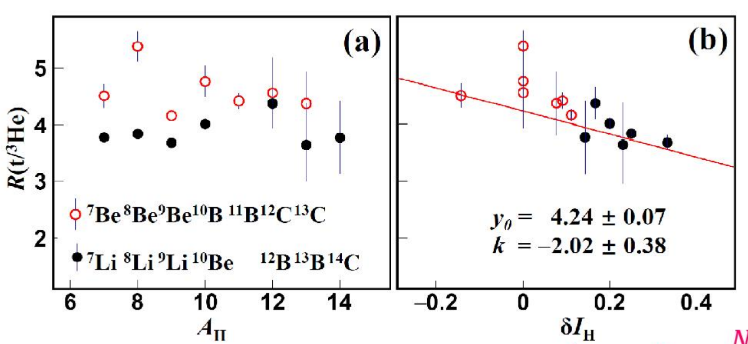
2. Isospin Chronology of p, d, and t

PLB 825, 136856 (2022)



3. Isospin Dynamics by Triton/^{3}He

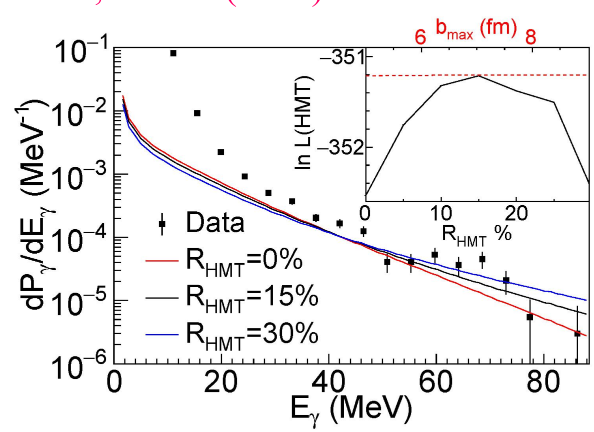
PRC 107, L041601 (2023); **NST** (2025)



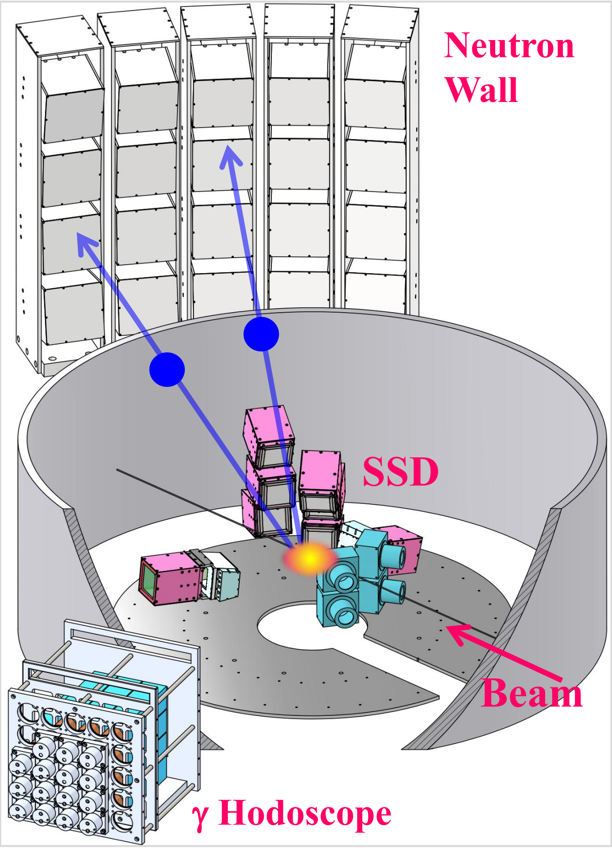
$$\delta I_{\mathrm{H}} = \frac{N_{\mathrm{H}} - Z_{\mathrm{H}}}{A_{\mathrm{H}}}$$

4. Bremstrahlung γ emission and SRC

PLB 857,139009 (2024)



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

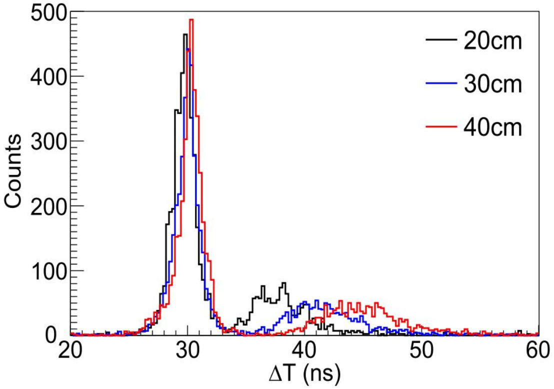


Detector Setup:

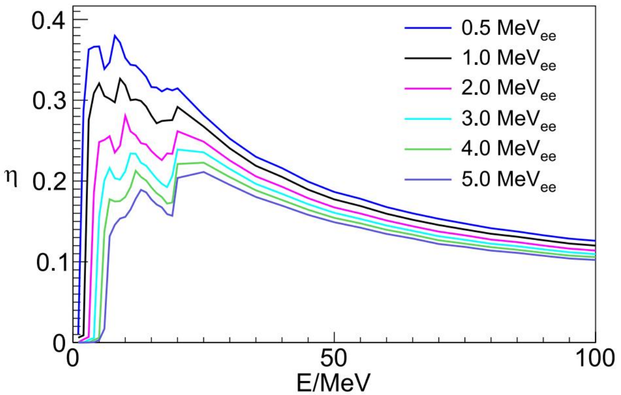
- A 4 × 5 array for neutrons
- 6 SSD telescopes for LCPs
- A 15-unit CsI(Tl) hodoscope for Bremstrahlung γ rays
- A small CsI wall for centrality determinaiton

Neutron Wall Parameters and Performance:

- unit size: 15cm × 15cm × 15cm
- Intrinsic time resolution 200 ps



n-γ coincidence in ^{252}Cf test



Efficiency curve in G4 simulatoin

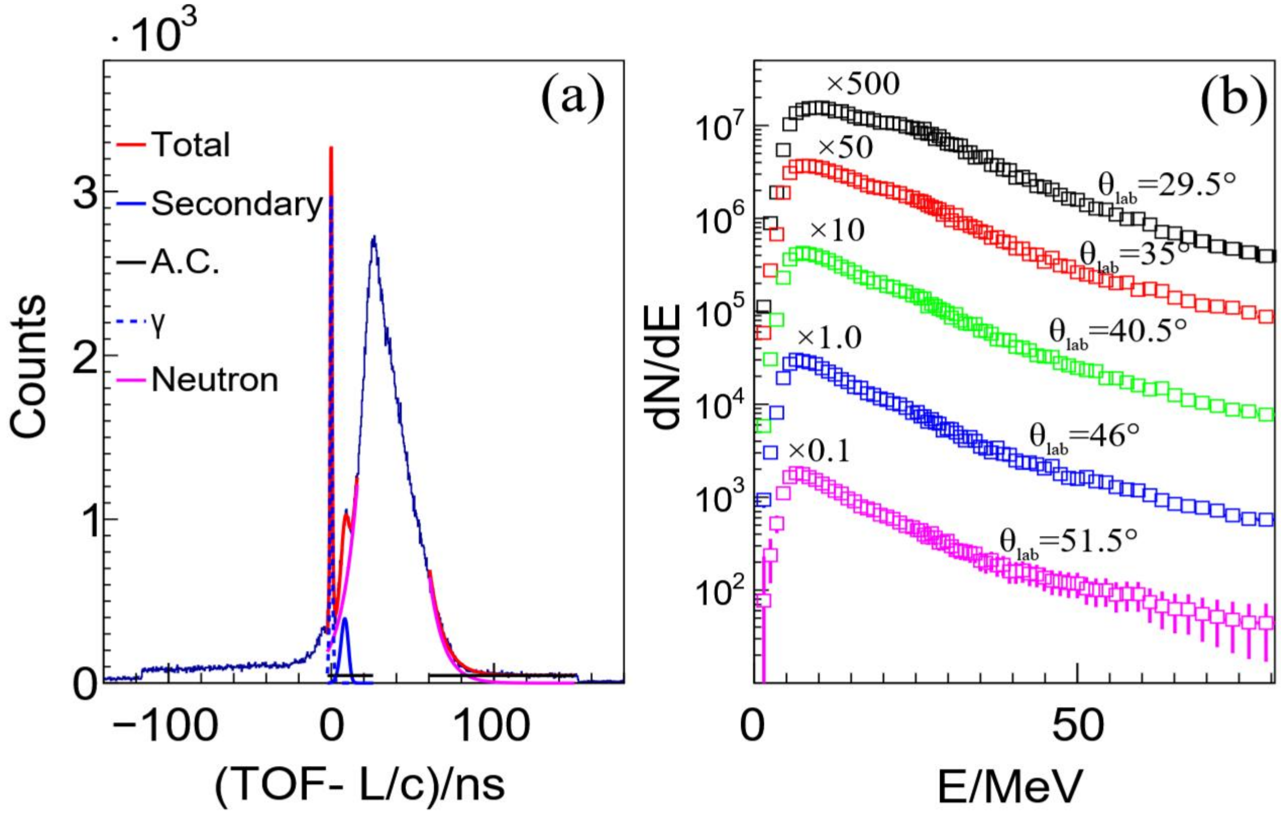
D. W. Si et al., **Nucl. Inst. Meth. A**1070,170055 (2025)

3 Results and Discussions

Distance to target: L ≈ 220cm

Covering $21° < \theta_{\mathrm{lab}} < 53°$ in Lab

n-γ discrimination by TOF method.

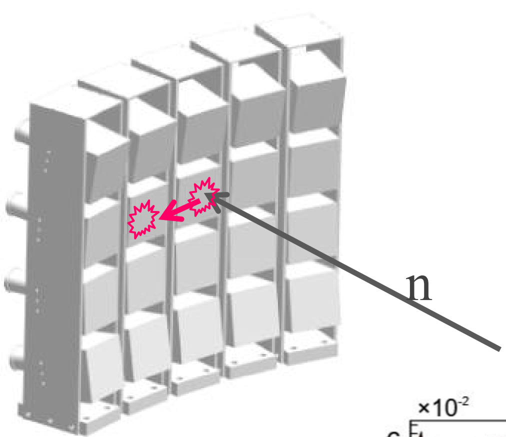


Cross-talk corrections and systematic uncertainties

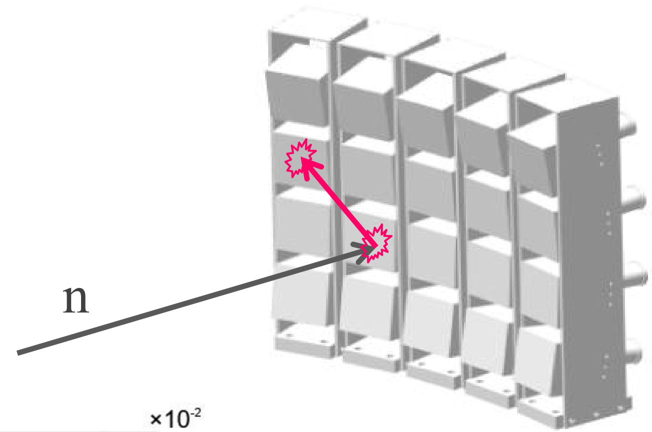
Cross-talk is the most influencial effect to be corrected!

Using Geant 4 simulation to reproduce the cross-talk pattern

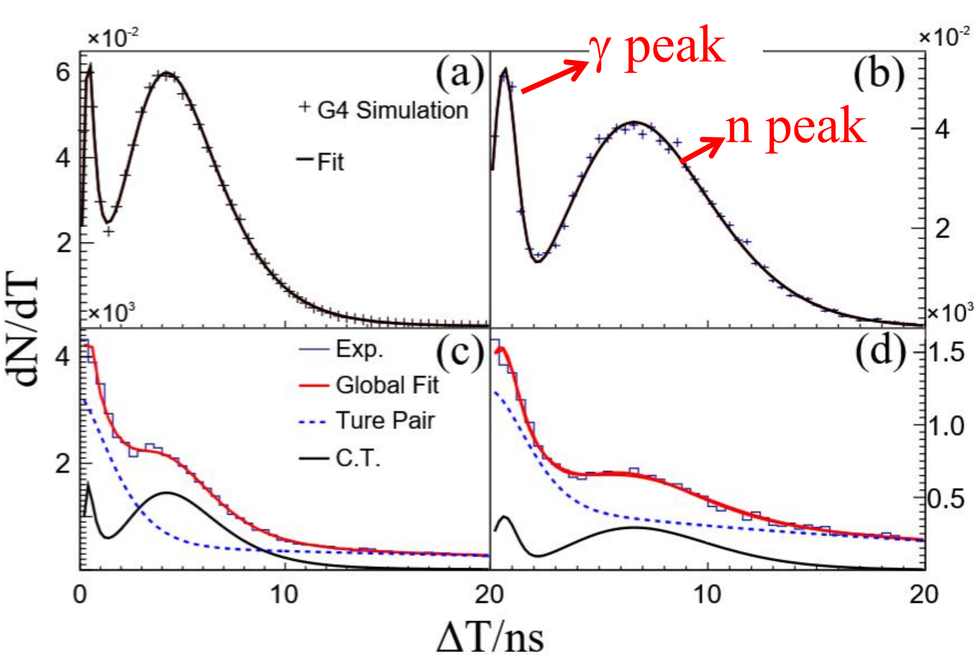
Doing global fit to decompose and subtract the cross-talk



Side-by-side cross-talk

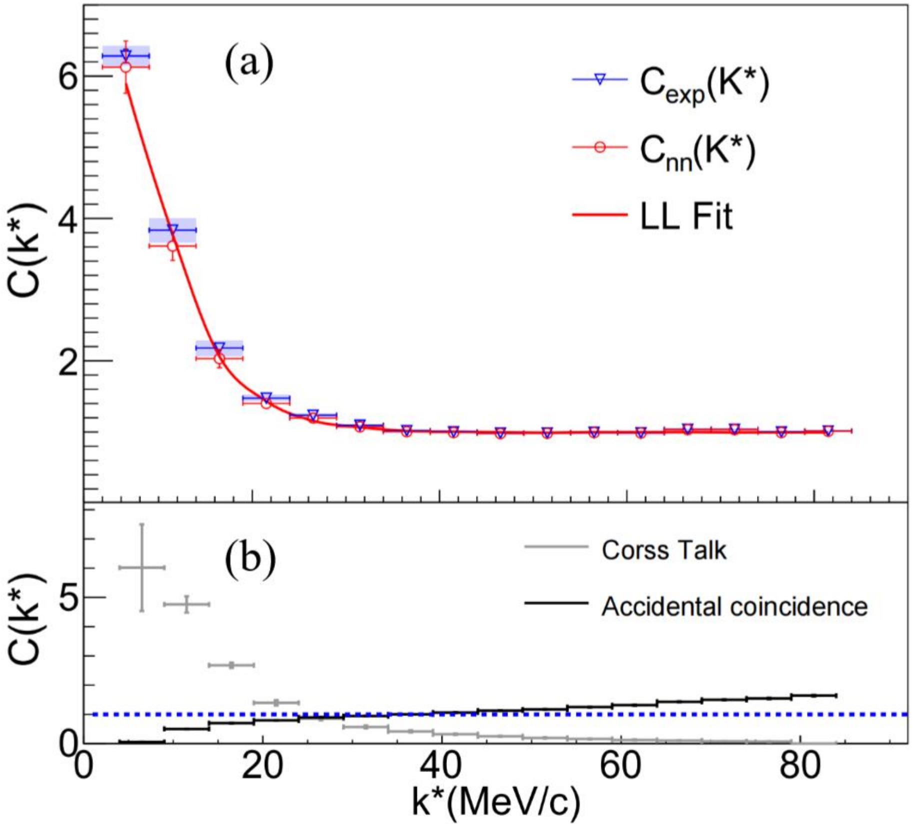


Coner-to-coner cross-talk



n-n correlation function and LL fit

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

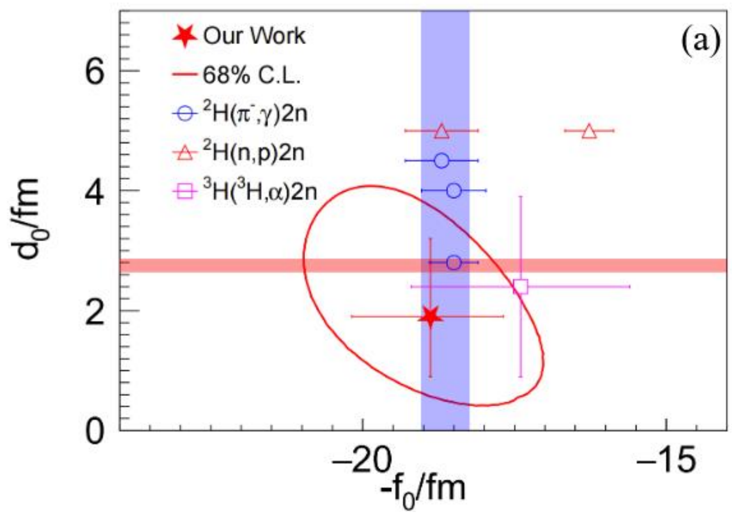


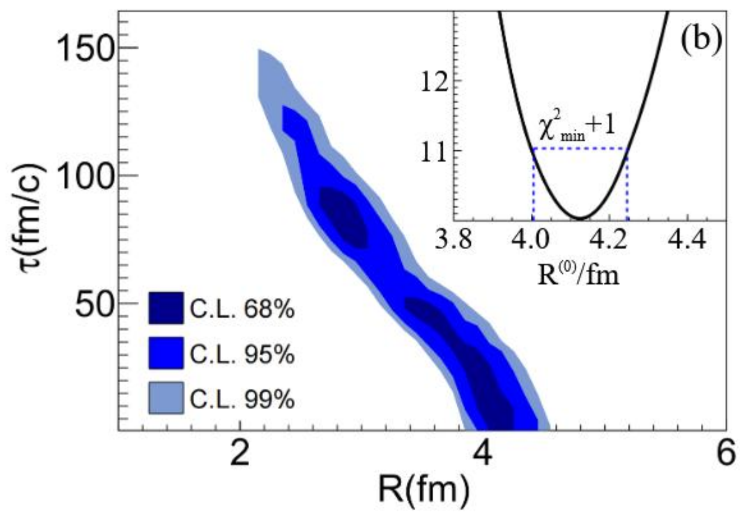
$$C_{\mathrm{nn}}(k^*) = A_{nn}\frac{N_{\mathrm{nn}}^{\mathrm{same}}(k^*)}{N_{\mathrm{exp}}^{\mathrm{mix}}(k^*)}$$
$$= \frac{A_{\mathrm{nn}}}{1-\lambda_{\mathrm{ct}}-\lambda_{\mathrm{ac}}}\left(\frac{C_{\mathrm{exp}}(k^*)}{A_{\mathrm{exp}}} - \lambda_{\mathrm{ct}}\frac{N_{\mathrm{ct}}^{\mathrm{mix}}(k^*)}{N_{\mathrm{exp}}^{\mathrm{mix}}(k^*)}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

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}Sn + ^{124}Sn reactions:
  $f_0^{nn} = 18.9^{+1.3}_{-1.2}$fm , $d_0^{nn} = 1.9^{+1.3}_{-1.0}$fm
  [Better control of the uncertainty still demanded for CSB studies.]
- ✓ Simultaneously, the temporal-spatial source size is extracted: $R^{(0)} = 4.1 \pm 0.1$ fm



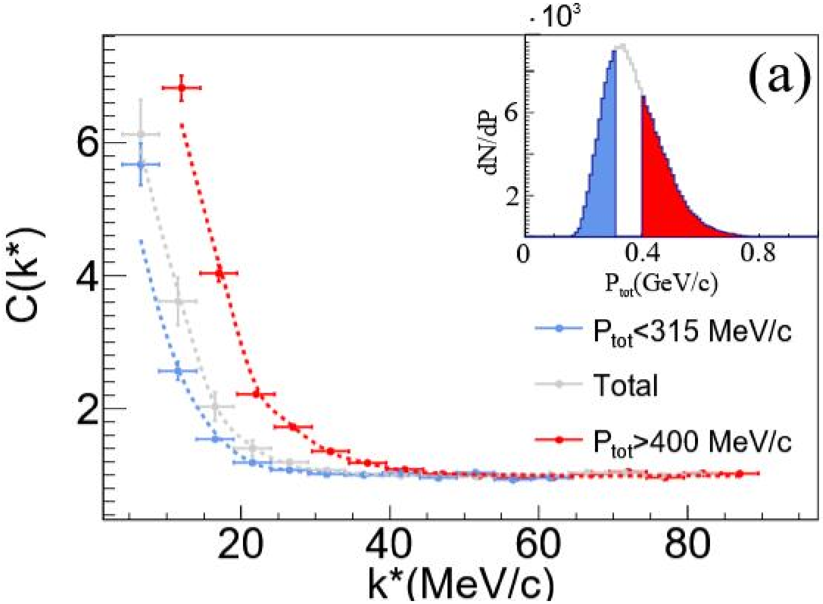


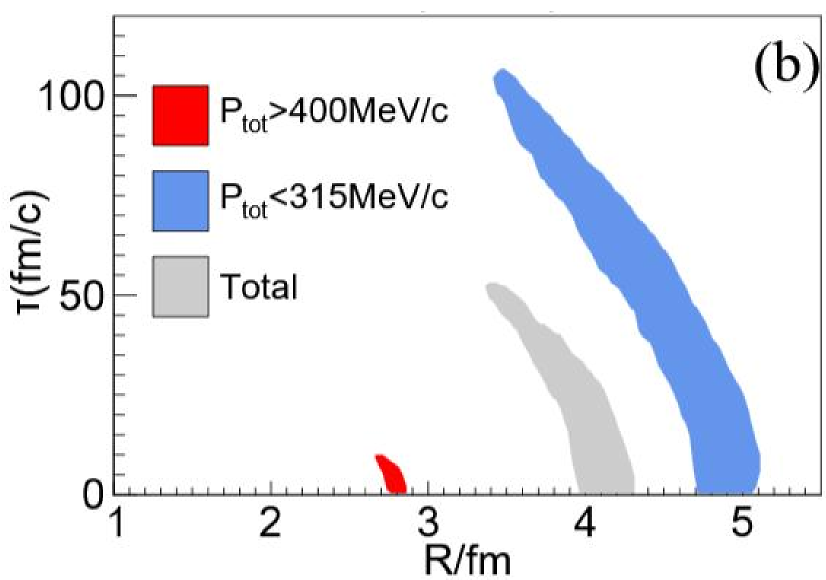
Here we assume a Gaussian source function：

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

Dependence of souce size on nn pair momentum

- ✓ n-n CF Showing dependence on the pair-momentum
- ✓ For the low momentum, space-volume is larger (larger space, longer time), correlation becomes weaker.





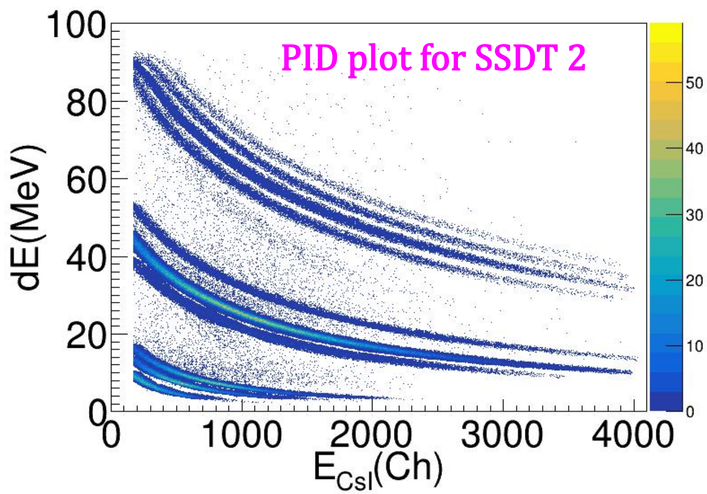
D.W.Si et al., **Phys. Rev. Lett.** (2025), accepted

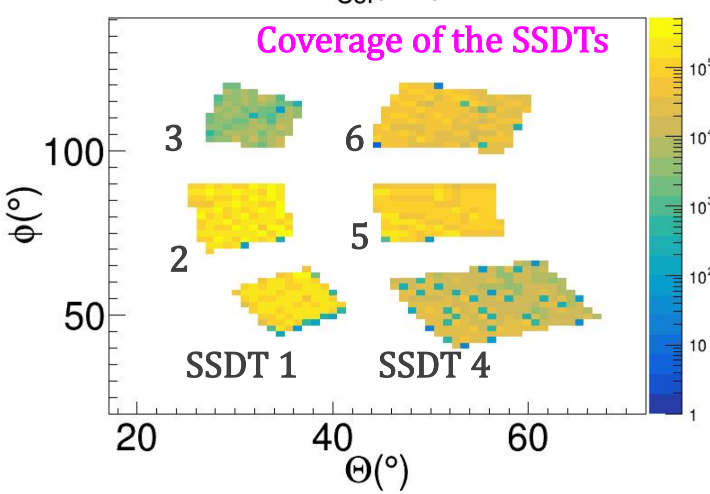
Future Plan

1) Analyze n-n, p-p and n-p correlation functions in the same experiment.

→ Charge Independence of nuclear force

→ Isopin Chronology

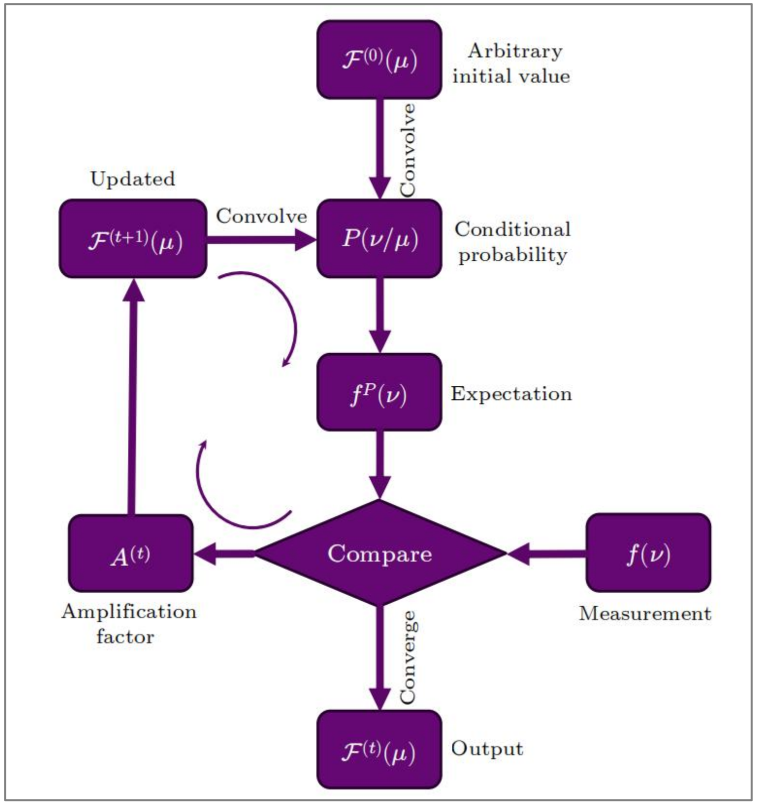




2) Do the source imaging without assuming a Gaussian source.

→ Inverse problem solution

$$C(\boldsymbol{q}) = \int d^3r|\Psi_{\boldsymbol{q}}(\boldsymbol{r}')|^2 S(\boldsymbol{r})$$



J. H. Xu et al., **CPL 42**, 031401 (2025)

4 Summary

❶ With the newly built neutron wall on CSHINE, the n-n correlation function in the reactions of $^{124}Sn + ^{124}Sn$ at 25 MeV/u has been measured.

— Geant 4 simulation is applied to do the cross talk correction.

— The nn correlation function has been fitted by LL model assuming a Gaussian source.

$$f_0^{nn} = 18.9^{+1.3}_{-1.2}\text{fm}\,,\ d_0^{nn} = 1.9^{+1.3}_{-1.0}\text{fm},\quad R^{(0)} = 4.1 \pm 0.1\ \text{fm}$$

❷ The results demonstrate the feasibility to pin down the CSB with femtoscopy correlation at improved resolution, and highlight the perspective of the future studies on isospin dynamics and CIB, using n-n, p-p and n-p correlation functions with better uncertainty control.

Stay tuned . . .

Thank you for your attention!