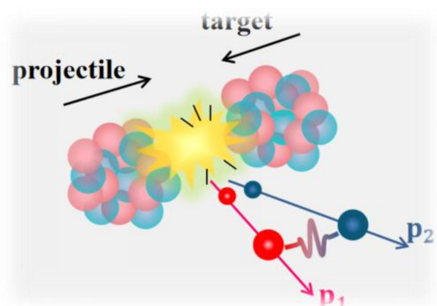
The 2nd International Workshop on Physics at High Baryon Density (PHD2025)

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



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Experimental Nuclear Physics Group
Department of Physics, Tsinghua University

Outline

1. Introduction: Motivation of the study

2. Experimental setup: CSHINE

3. Results and Discussions

   ✓ n-n correlation function and (f_0^{nn}, d_0^{nn})

   ✓ Preliminary p-p correlation function

4. Summary

Heavy Ion collisions and nuclear matter equation of state

01 Neutron Star

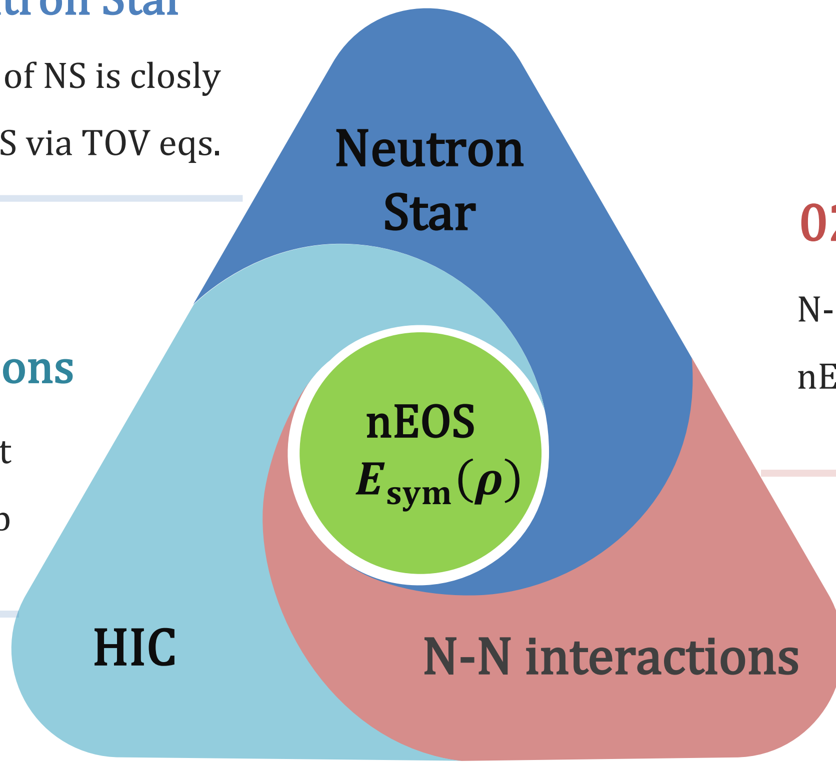
Properties, merging of NS is closly related to nEOS via TOV eqs.

02 N-N Interactions

N-N interactions is the base of nEOS

03 Heavy Ion Collisions

HIC is the unique way to creat dense nuclear matter in lab



Complication of HIC

#Measurement of N-N Interactions

Introduction

Two questions:

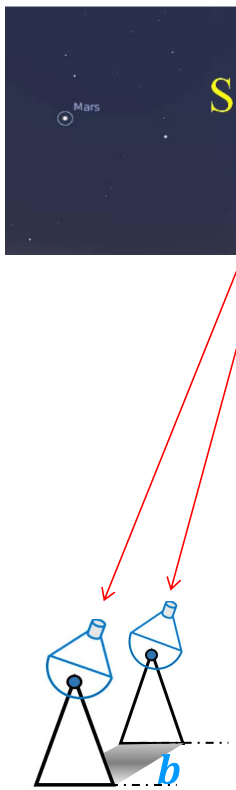
① Known from quantum mechanics, the interaction strength (scattering length and effective range) between particles can be measured by scattering experiment. **But what if the particles are not stable?**

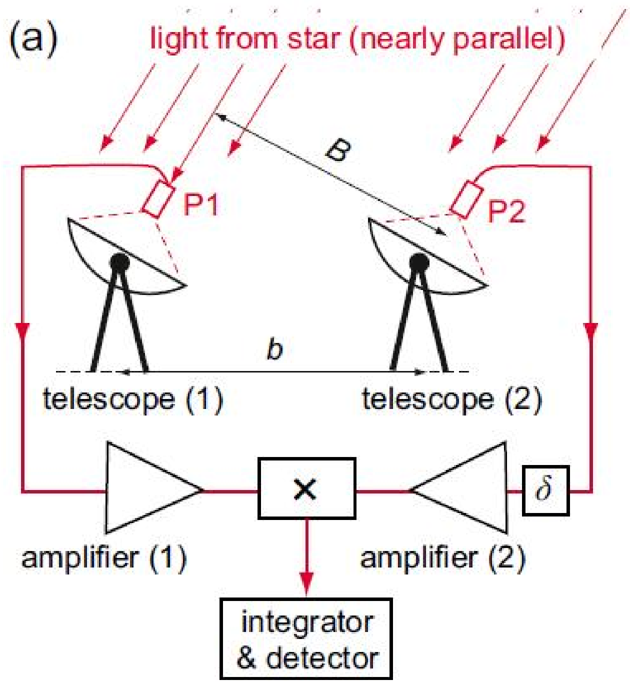
② Heavy ion reaction is a violent femtoscopic process lasting for zeptoseconds, **how can one measure the temporal-spatial size of such a process?**

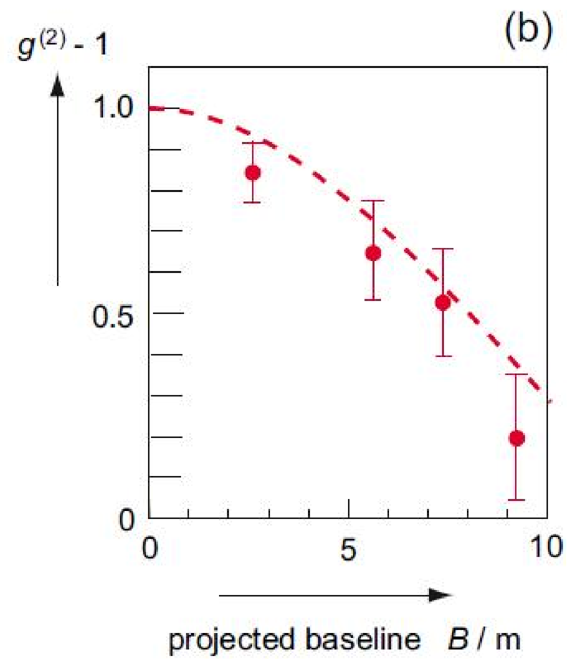
The answers to these two questions point to intensity inteferometry!

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

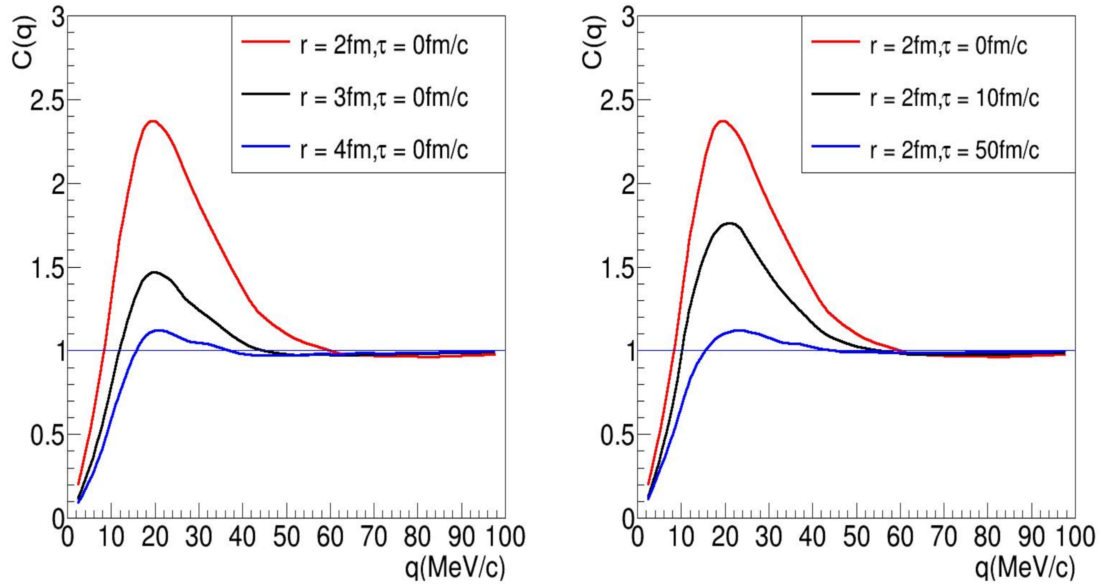
Formation the p-p correlation

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 distribution

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

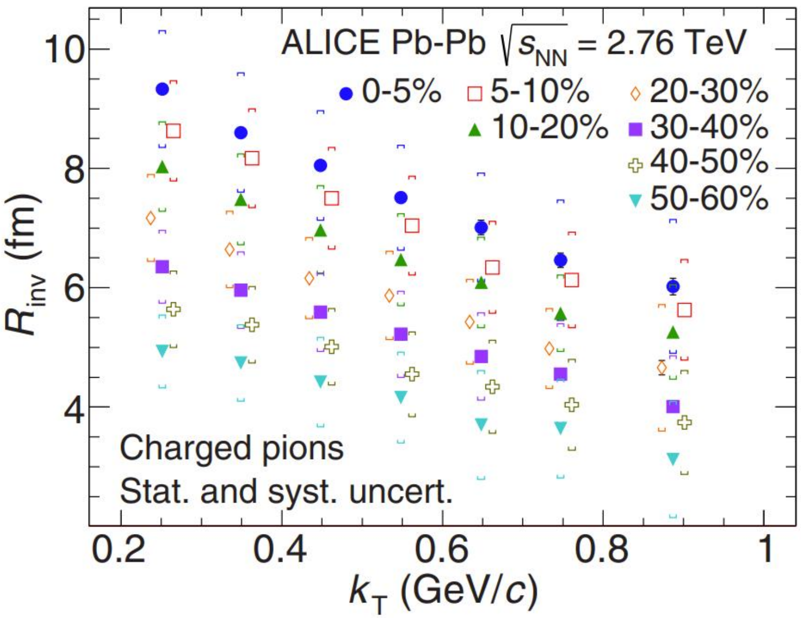
Propagation and p-p wave function of relative motion

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

Correlation Function — To visualize the dynamic evolution of HIC

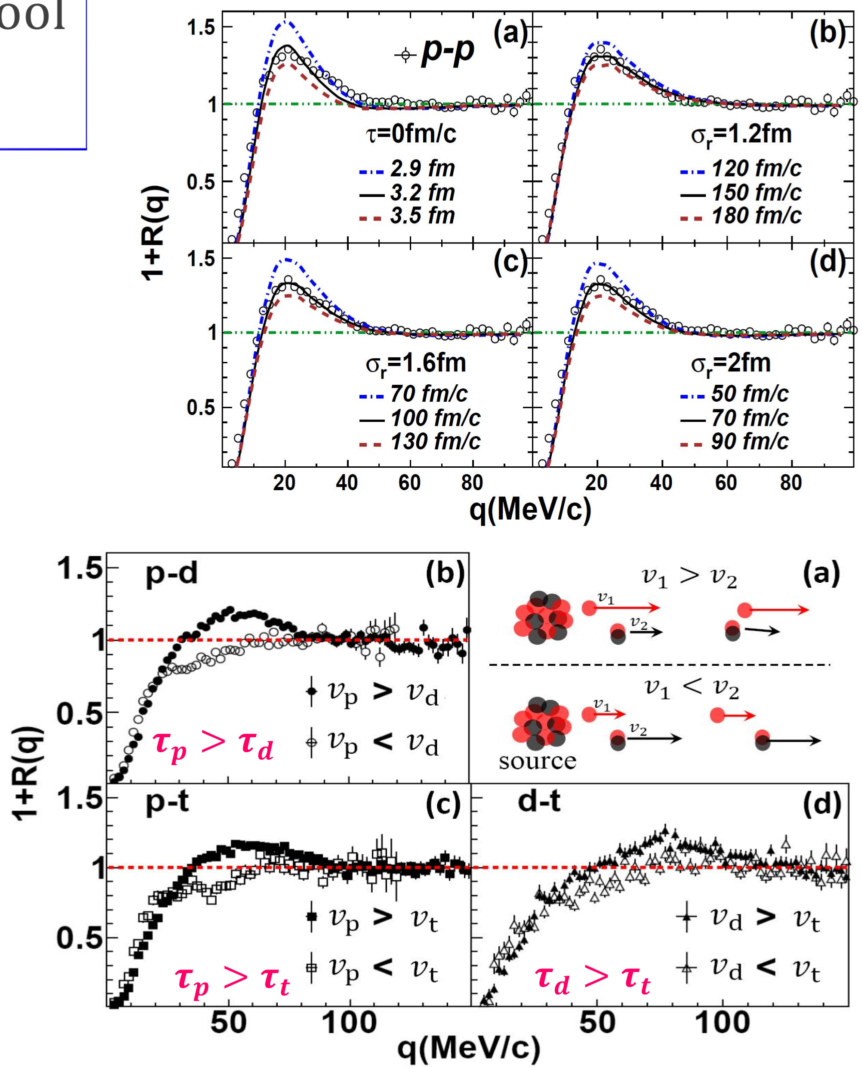
➤CF carries the spatial-temporal information of the emission source, providing a good tool to constrain transport model as well.

ALICE: Pb+Pb at √s= 2.76 TeV



Phys. Rev. C 93,024905(2016)

CSHINE: Ar+Au at 30 MeV/u



Y. J. Wang et al., **Phys. Lett. B** 825, 136856 (2022)

Correlation Function — To measure the final state interaction of the particle pair

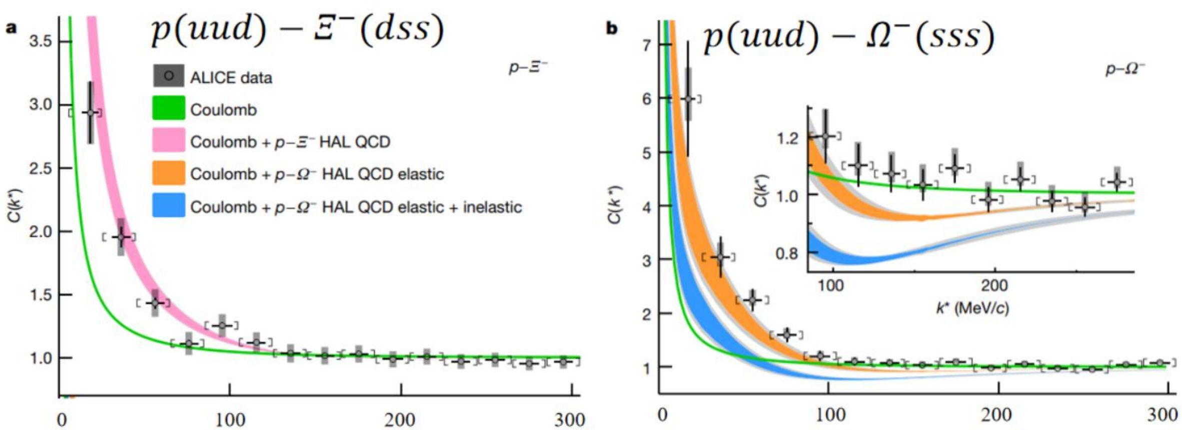
➤ CF measures the scattering length and effective range (f_0, d_0) of particle pair

Solving the Schrodinger equations at low energy(only s-wave), one get two constants (f_0, d_0)

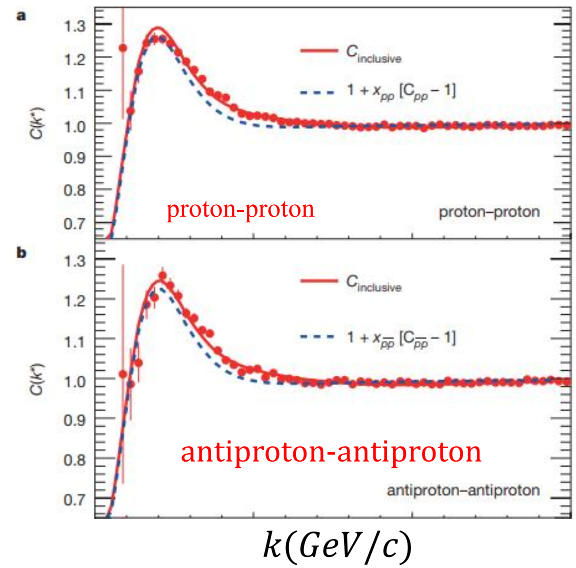
$$\Psi(\vec{k}^*,\vec{r}) \approx e^{-i\vec{k}^*\vec{r}^*} + f_{k^*}(\theta)\frac{e^{ik^*r^*}}{r^*}$$

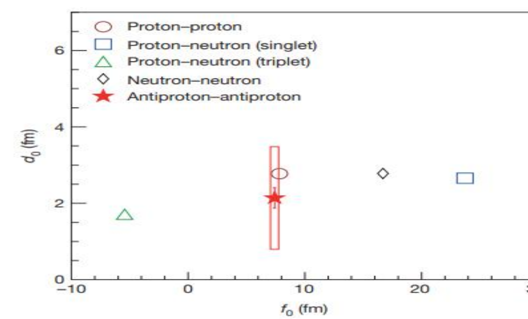
$$k\cot(\delta(k^*)) \approx \frac{1}{f_0} + \frac{1}{2}d_0k^{*2} + O(k^{*4})$$

$$f_{k^*}(\theta) \approx \frac{1}{2k^*i}(e^{2i\delta} - 1) \approx (\frac{1}{f_0} + \frac{1}{2}d_0k^{*2} - ik^*)^{-1}$$



ALICE Collaboration Nature, 588,232(2020)





Matter and antimatter Symmetry of the strong interaction

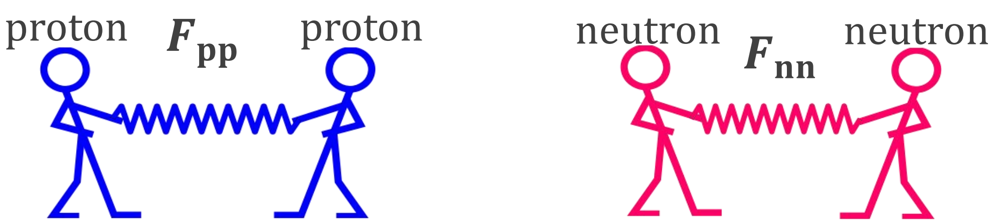
STAR Collaboration Nature, 527,345(2015)

Why neutron-neutron correlation so special

❶ reveal the collision dynamics in terms of the Isospin DOF

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

p-p: $(f_0^{pp} = -17.3 \pm 0.4, d_0^{pp} = 2.85 \pm 0.04)$
n-n: $(f_0^{nn} = -18.9 \pm 0.4, d_0^{nn} = 2.75 \pm 0.11)$
R. Machleidt., PRC 63, 024001 (2001)



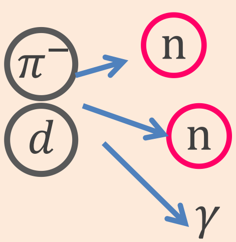
$$\Delta a_{CSB} = f_0^{pp} - f_0^{nn}$$

nuclear force CSB

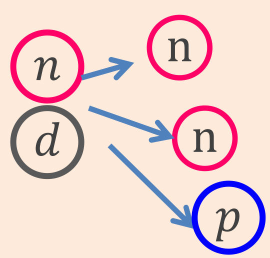
However, no n-n scattering data due to the unavailablity of neutron target!

Indirect Scattering:

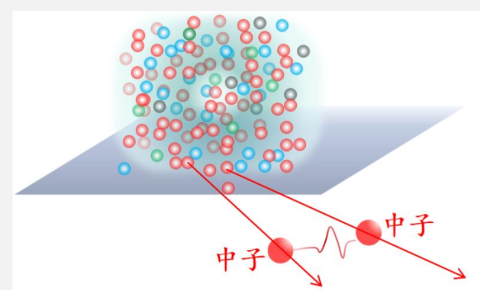
$d(\pi^-, \gamma)2n$



$d(n, p)2n$



Heavy Ion Collisions:

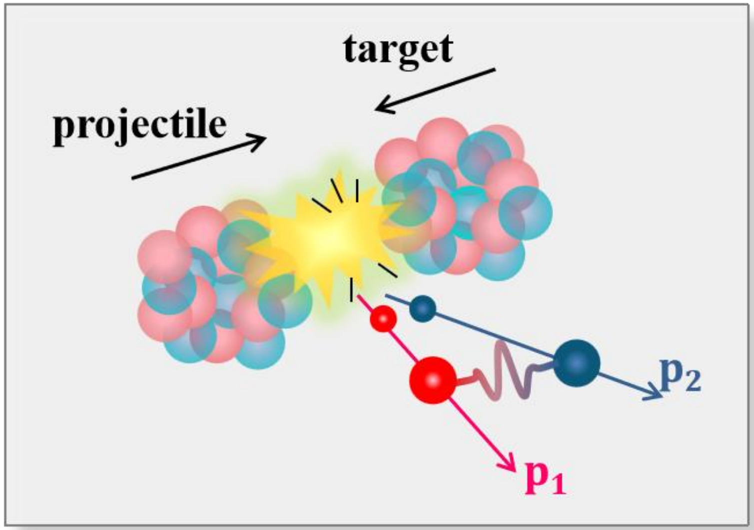


Lednicky and Lyuboshitz propose to extract (f_0^{nn}, d_0^{nn}) via the n-n CF in HIC

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:

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

Source function

Relative wave function of the particle pair

Experiment

Experimentally using mixture event method to subtract the background:

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

Signal

Background

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

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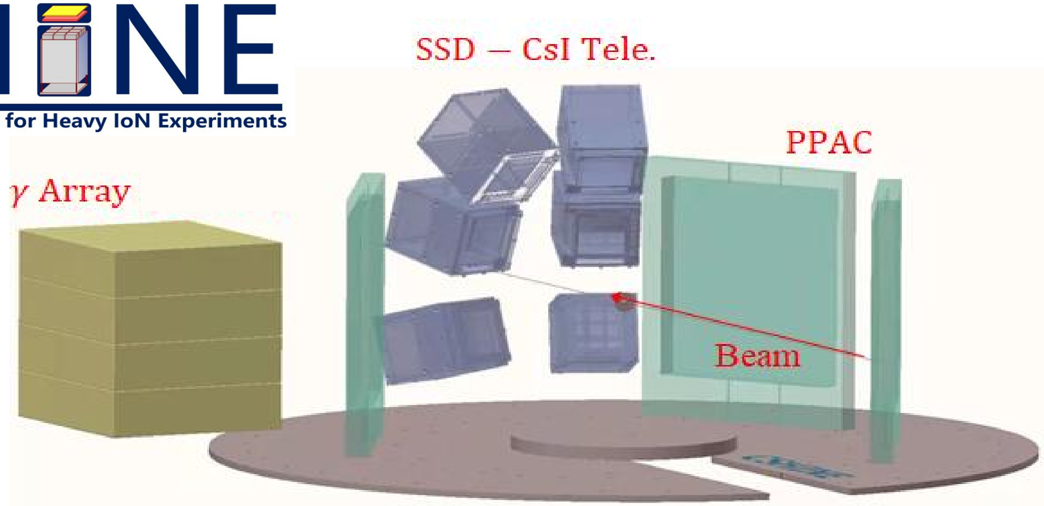
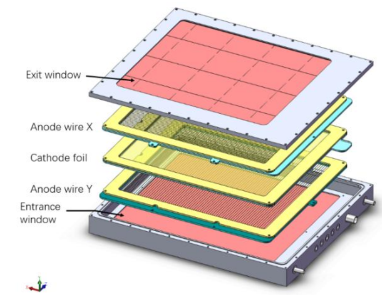
2. Experiment Setup and data analysis

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

CSHINE
Compact Spectrometer for Heavy IoN Experiments

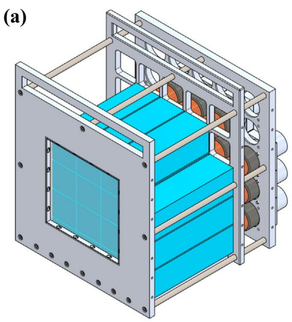




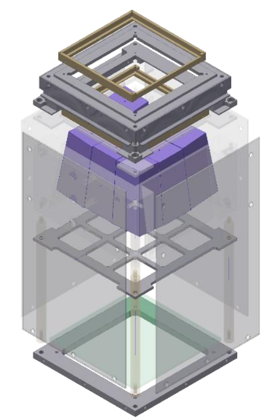
PPAC for fission fragments

Total channels: ~400, starting from 2014

(a)



CsI hodoscope for high energy γ



SSDT for LCP and IMFs

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

Operation of CSHINE

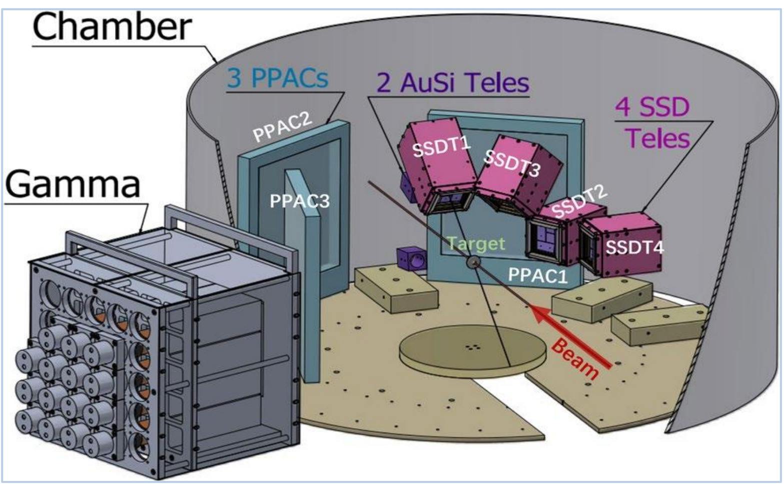
01 2014
30 MeV/u* $^{40}Ar+^{197}Au$

02 2018
30 MeV/u $^{40}Ar+^{197}Au$

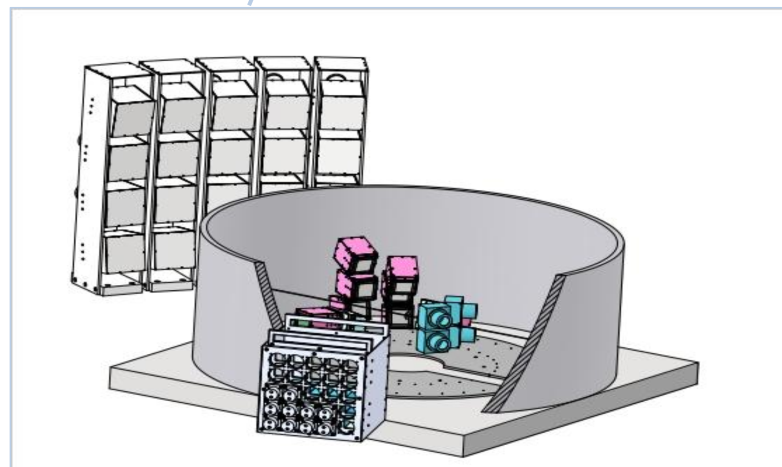
03 2019
25 MeV/u $^{86}Kr+^{208}Pb$

04 2022
25 MeV/u $^{86}Kr+^{124}Sn$

05 2024
25 MeV/u $^{124}Sn+^{124}Sn$



4th run： 2022 CSHINE-Gamma



5th run： 2024 CSHINE-Neutron Wall

Technique and Physics Programs of CSHINE

Detection Techniques:

Neutron Wall Construction

NIMA 1070,170055 (2025)

High Energy γ array

NIMA 1053 168330 (2023) ,
NIMA 1080, 170787 (2025)

FPGA Trigger System

NST 33, 162(2022)

PPACs for Fission Fragments

NST 33, 40 (2022)

Silicon Strip Detectors for LCPs

NIMA 1029, 166461 (2022),
NIMA 1011, 165592 (2021) ,
NST 32, 4 (2021), NST 36, 132 (2025)

Physics Studies:

Bremsstrahlung γ and SRC

PLB 850,138514 (2024)
PLB 857,139009 (2025)
arXiv 2504.13929; arXiv 2508.04550

n-n CF and (f_0^{nn}, d_0^{nn})

PRL 134,222301 (2025)

t/^{3}He ratio and ^{3}He-puzzle

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

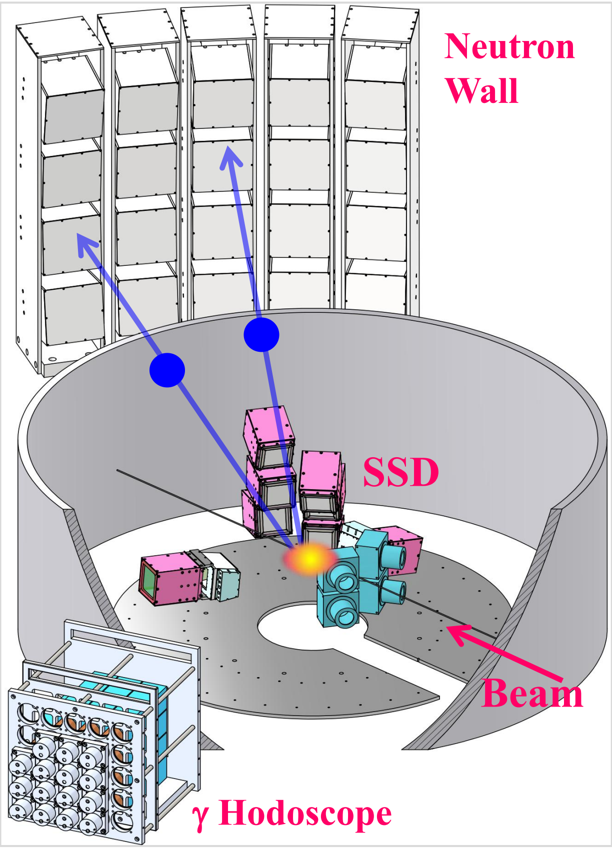
Isospin Choronology

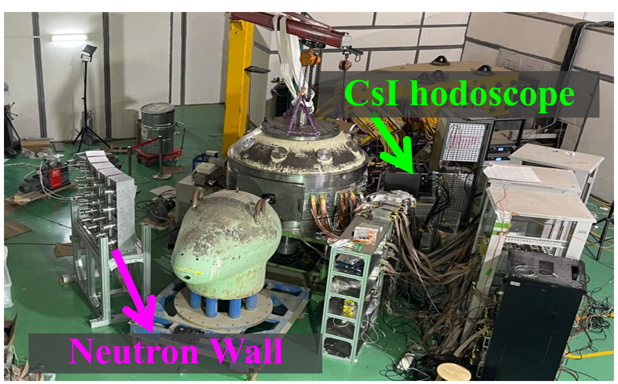
PLB 825, 136856 (2022)

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

PRC 95, 041602R (2017)

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



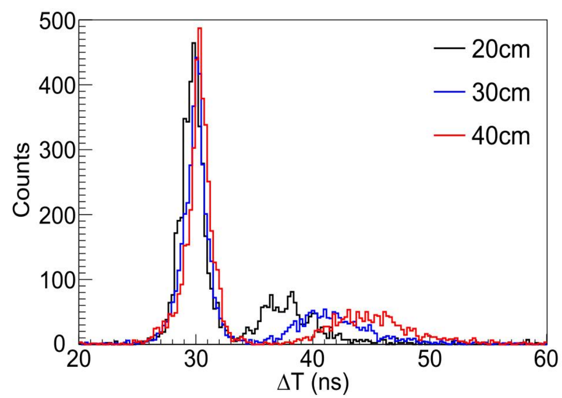


Detector Setup:

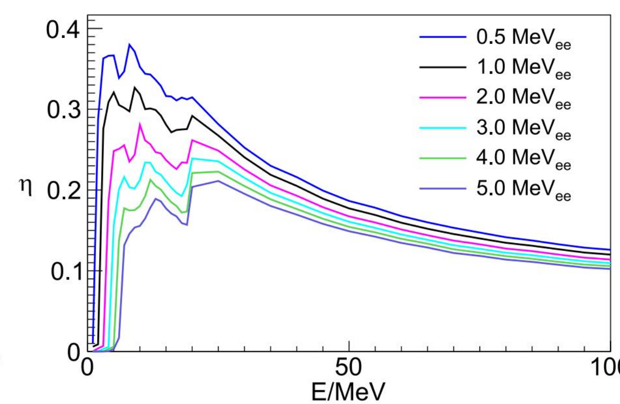
- A 4×5 array for neutrons
- 6 SSD telescopes for LCPs
- A 15-unit CsI(Tl) hodoscope for Bremstrahlung γ rays
- A small CsI wall for centrality determinaiton

Neutron Wall Parameters and Performance:

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



n-γ coincidence in ^{252}Cf test



Efficiency curve in G4 simulatoin

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

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- ✓ **n-n correlation function and (f_0^{nn}, d_0^{nn})**
- ✓ **Preliminary p-p correlation function**

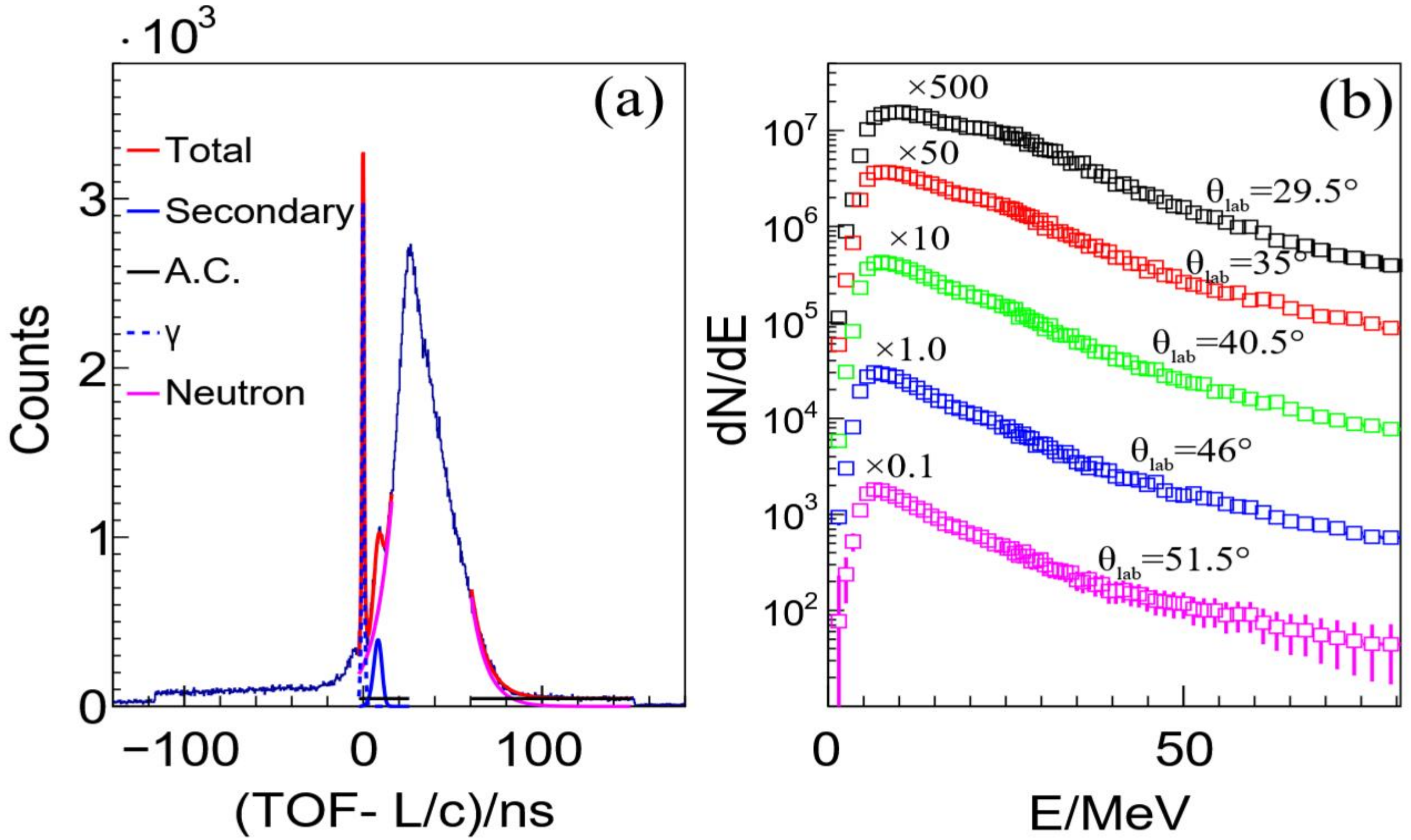
4. Summary

n-n correlation function and (f_0^{nn}, d_0^{nn})

Neutron spectra:

n-γ discrimination by TOF method

Neutrons, γ-rays, secondaries and backgrounds are distinguished.

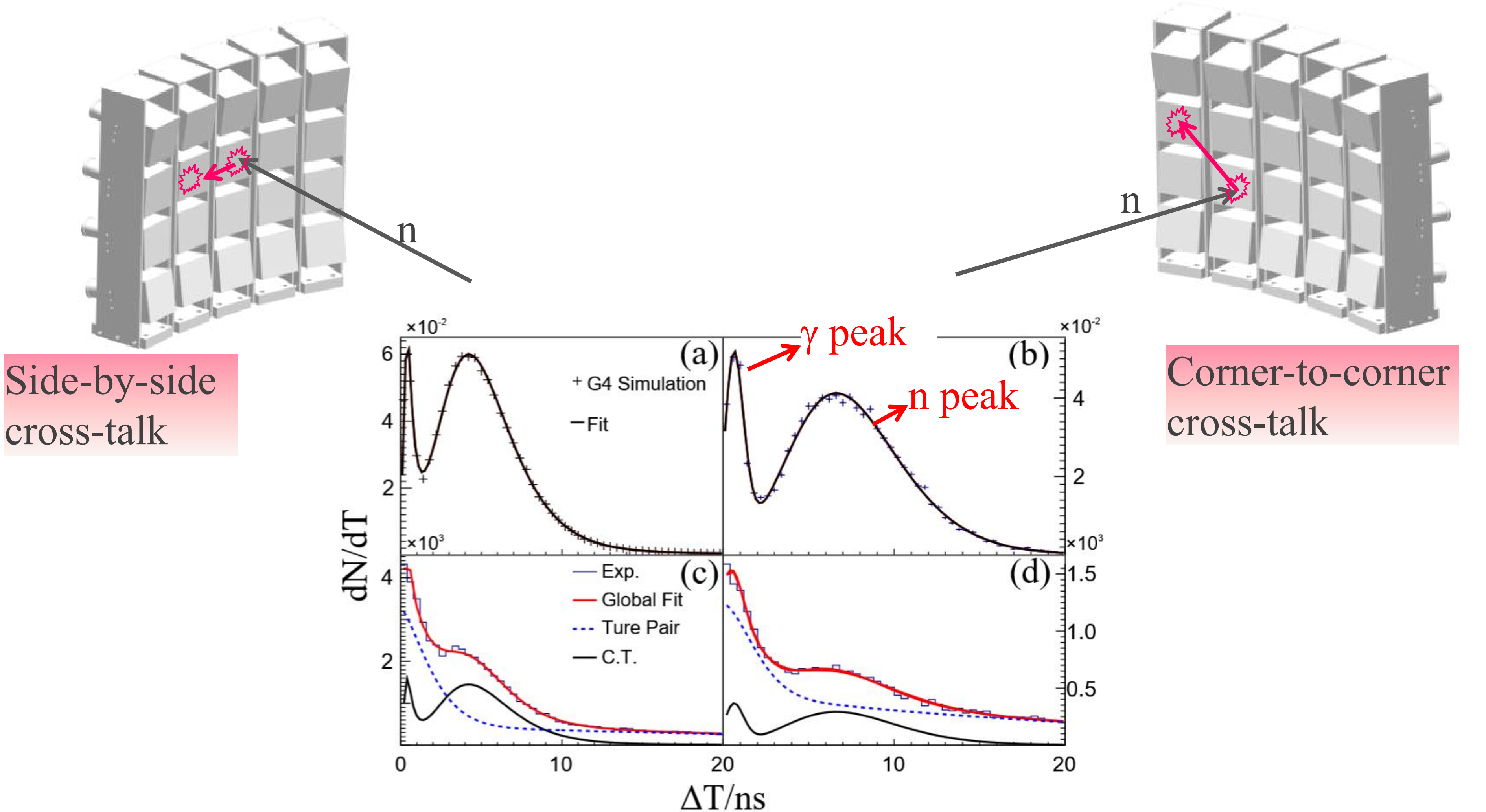


D. W. Si et al., **Nucl. Inst. Meth. A**1070,170055 (2025)

Cross-talk corrections and systematic uncertainties

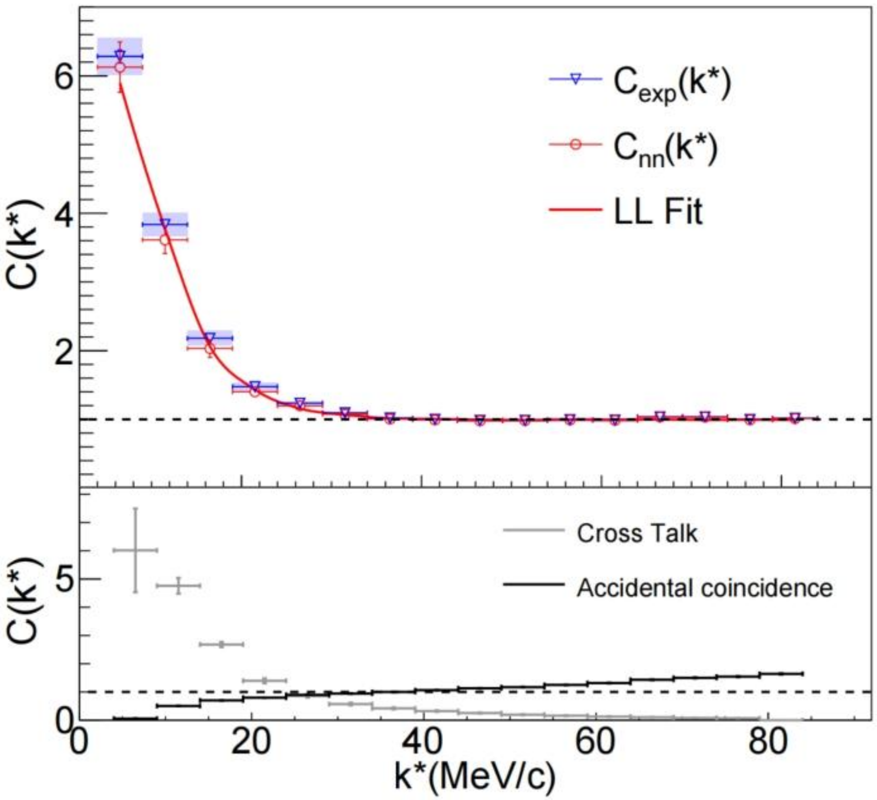
Cross-talk is the most influencial effect to be corrected!

- Using Geant 4 simulation to reproduce the cross-talk pattern
- Doing global fit to decompose and subtract the cross-talk



n-n correlation function and (f_0^{nn}, d_0^{nn})

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

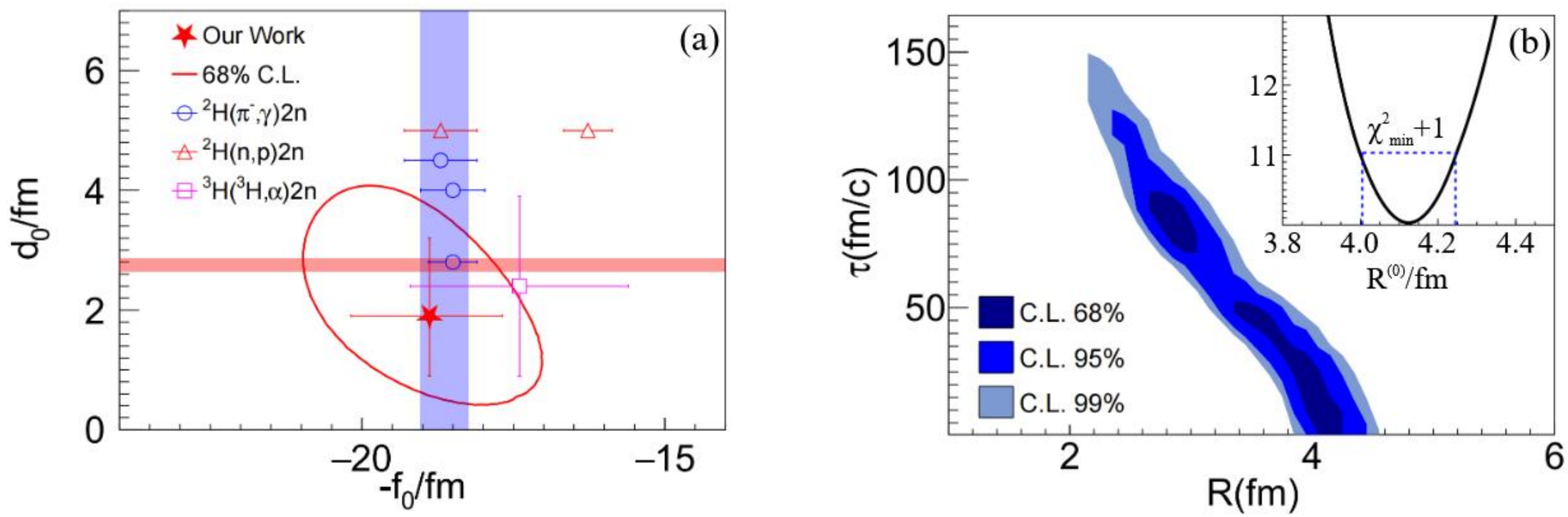


$$C_{\mathrm{nn}}(k^*) = A_{nn}\frac{N^{\mathrm{same}}_{\mathrm{nn}}(k^*)}{N^{\mathrm{mix}}_{\mathrm{exp}}(k^*)} = \frac{A_{\mathrm{nn}}}{1-\lambda_{\mathrm{ct}}-\lambda_{\mathrm{ac}}}\left(\frac{C_{\mathrm{exp}}(k^*)}{A_{\mathrm{exp}}} - \underbrace{\boxed{\lambda_{\mathrm{ct}}}}_{\Delta\text{TOF Fit}}\overbrace{\boxed{\frac{N^{\mathrm{mix}}_{\mathrm{ct}}(k^*)}{N^{\mathrm{mix}}_{\mathrm{exp}}(k^*)}} - \underbrace{\boxed{\lambda_{\mathrm{ac}}}}_{\text{TOF Fit}}\boxed{\frac{N^{\mathrm{same}}_{\mathrm{ac}}(k^*)}{N^{\mathrm{mix}}_{\mathrm{exp}}(k^*)}}}^{\text{G4 Simulation}}\right)$$

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

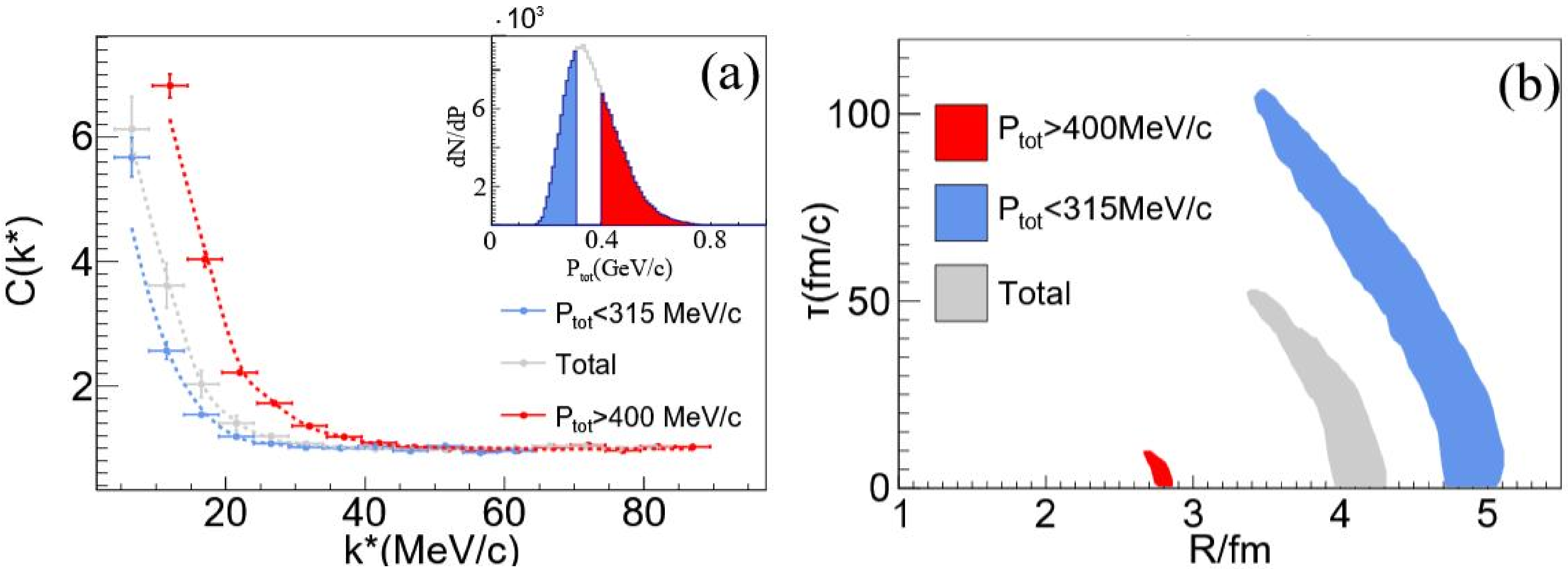


Here we assume a Gaussian source function：

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

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

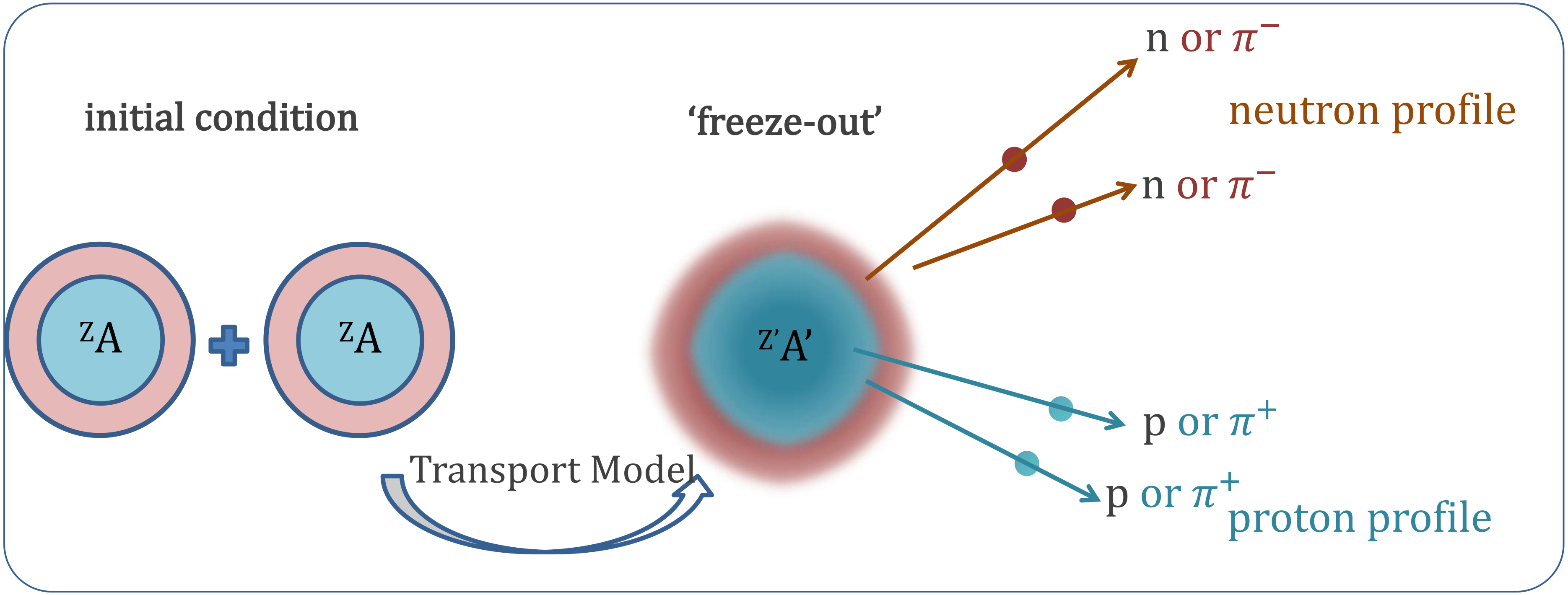
3.2 Preliminary p-p correlation function

Apparently, in order to

❶ reveal the collision dynamics in terms of the Isospin DOF

❷ investigate the CSB of nuclear force

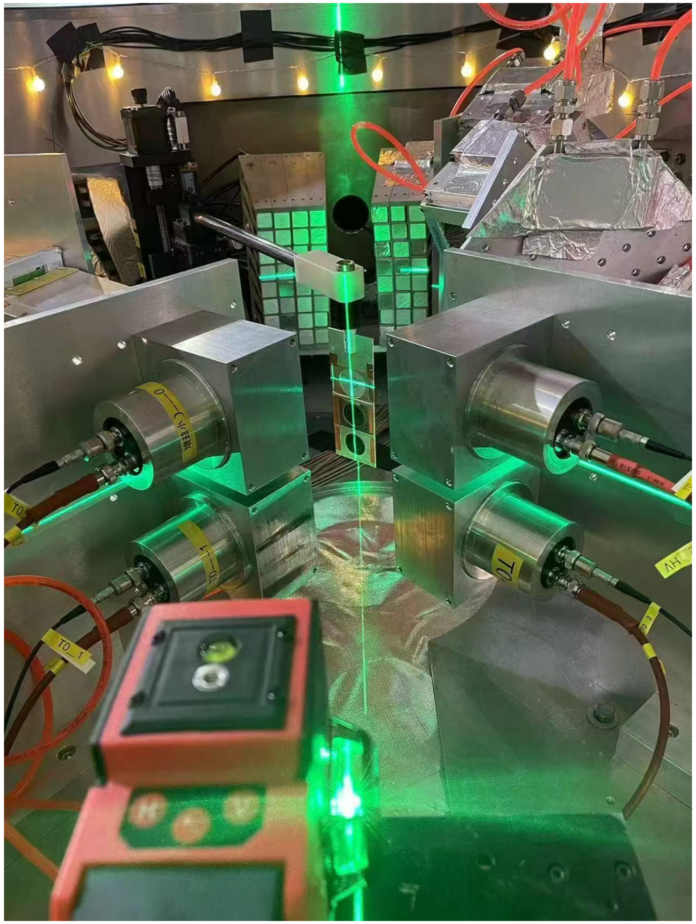
One need measuring n-n and p-p correlation functions simultaneously

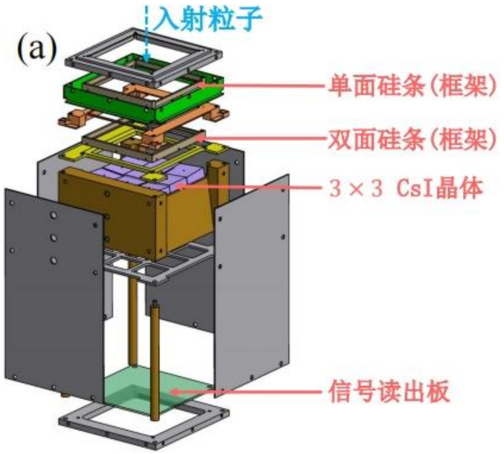


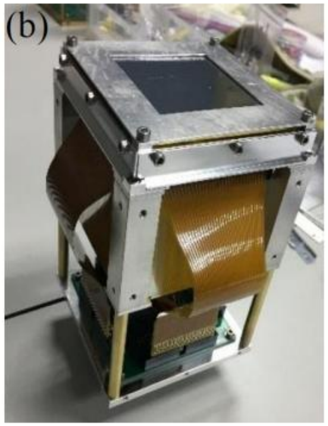
P. C. Li et al., Unlocking the initial neutron density distribution from two-pion HBT correlation function in HICs, **Phys. Lett. B, accepted.**

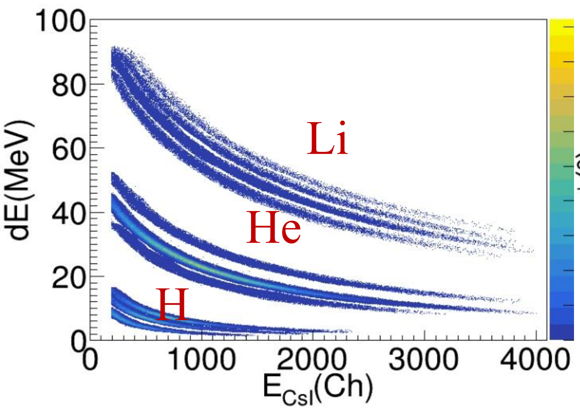
Ongoing activitiesn: p-p correlations

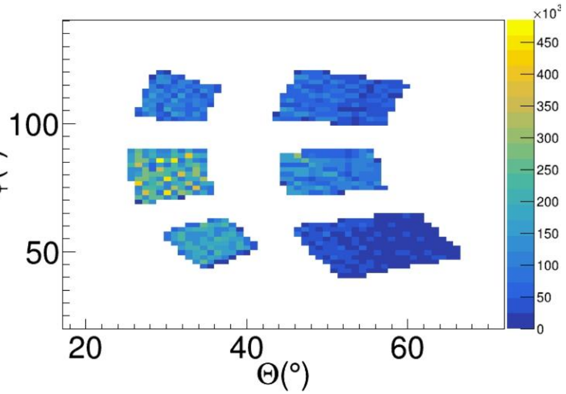
Protons are measured by the silicon strip detector telescopes (SSDT).







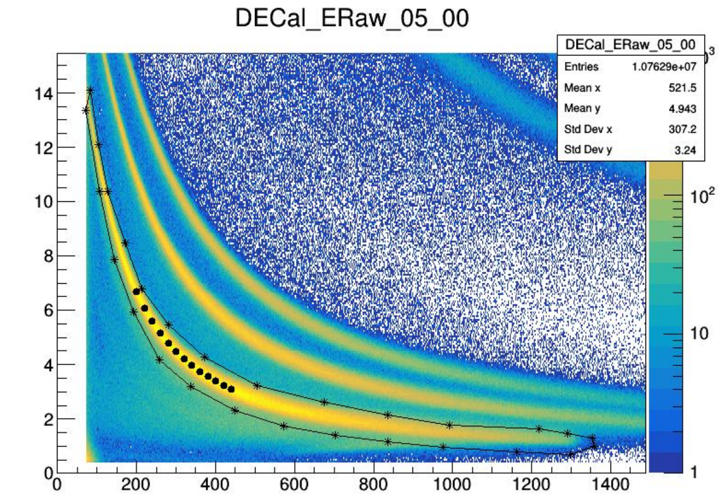


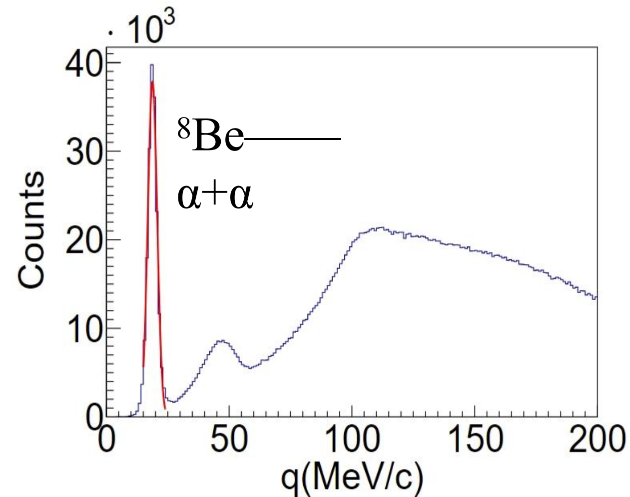


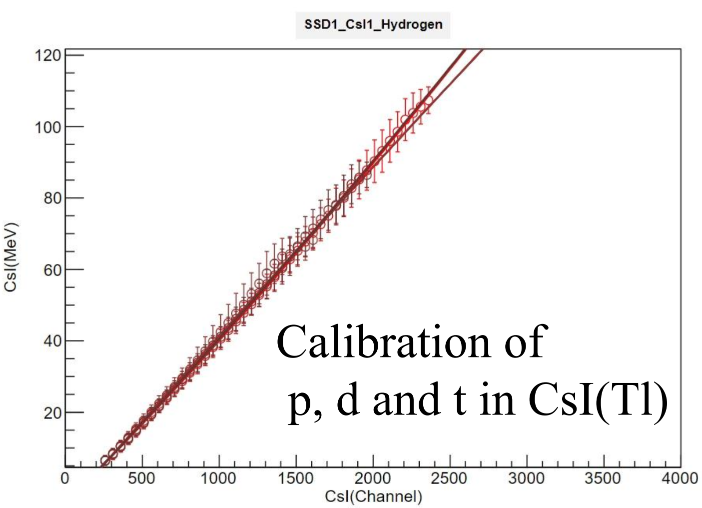
F.H.Guan et al., **NIMA** 1011, 165592 (2021) ,
Y. J. Wang et al., NST 32, 4 (2021), cover story
X. B. Wei et al., **NST** 36, 132 (2025), cover story

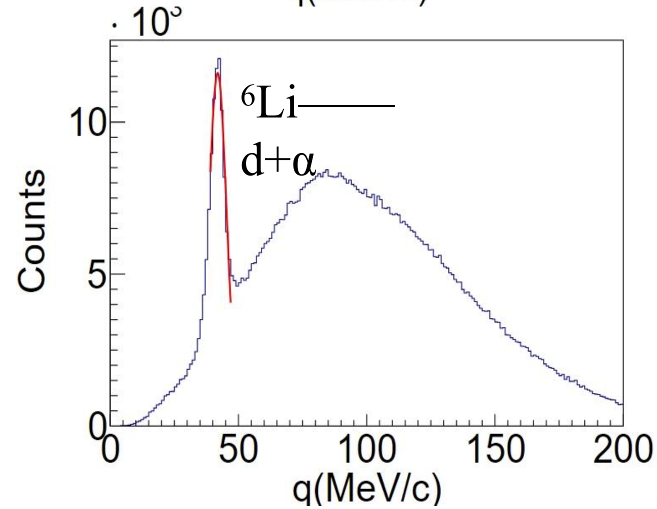
Calibration check for 25 MeV/u $^{124}Sn+^{124}Sn$

- SSD calibration by α source+pulser
- CsI calibration by enegy loss match
- Calibration check by the know correlation peaks



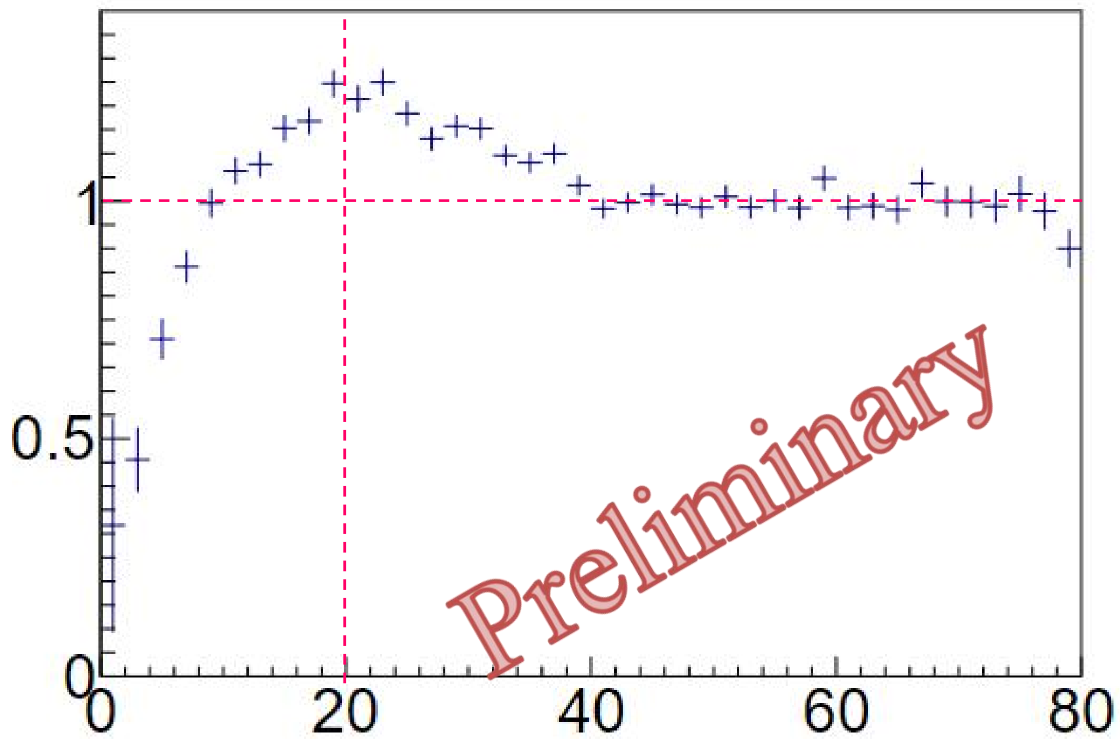






Preliminary p-p correlation function

- p-p correlation functions obtained preliminarily
  -- correlation peak well located!
  -- Due to insufficient statistics, no selection on impact parameteris done



Efficiency curve optimization and systematics analysis on going, stay tuned!

4 Summary

❶With 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 CF has been fitted by LL model assuming a Gaussian source.

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

❷ p-p correlation function analysis is ongoing ...

❸The 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 tunned . . .

Thank you for your attention!