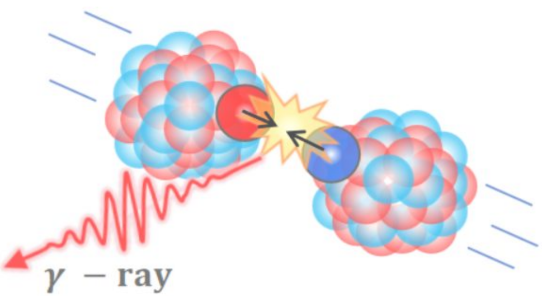
Probing Nucleon-Nucleon Short Range Correlations by Bremsstrahlung γ-rays in Heavy Ion Collisions



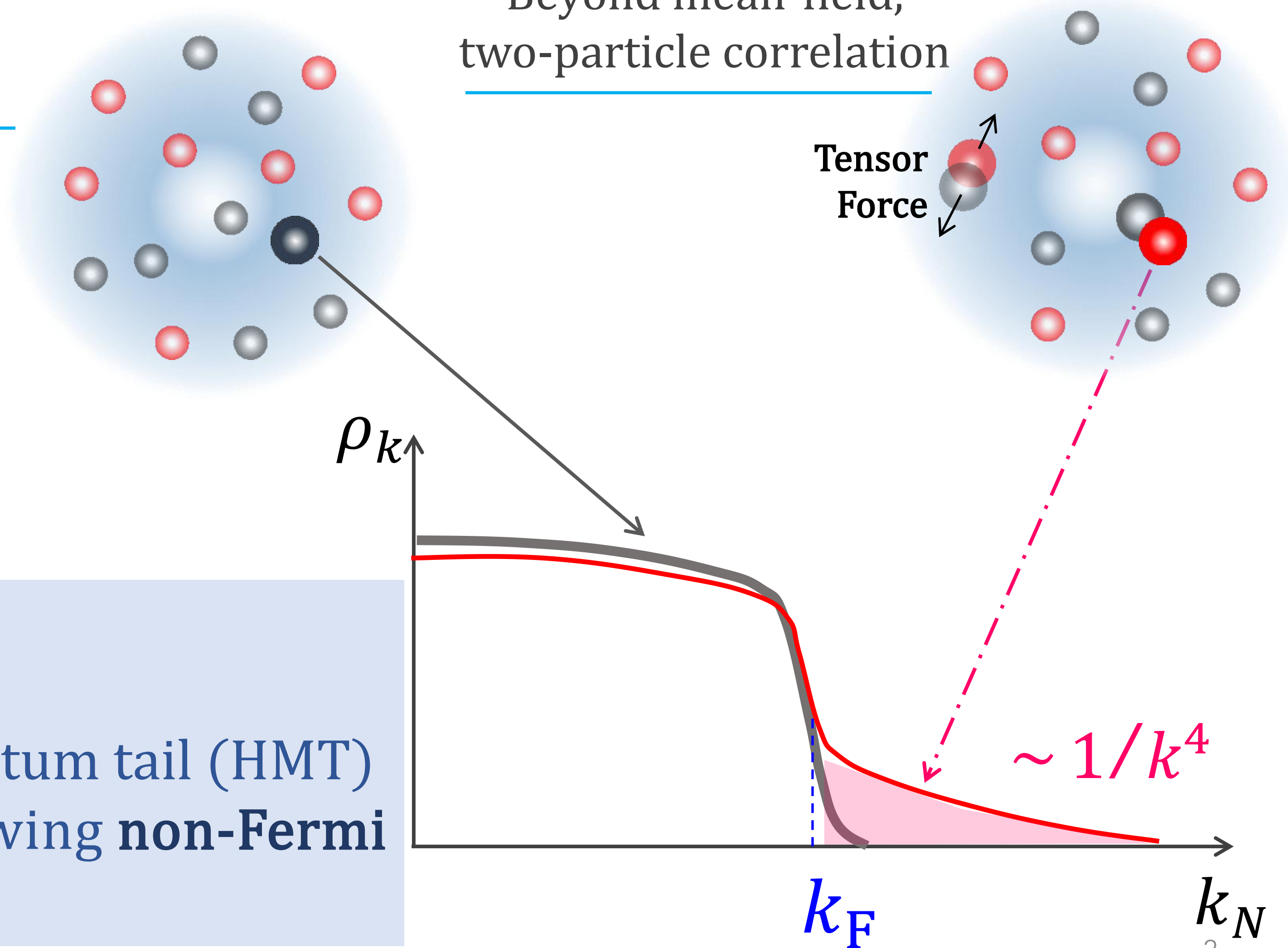
Zhigang Xiao Tsinghua University
E-mail: xiaozg@tsinghua.edu.cn http://info.phys.tsinghua.edu.cn/enpg

What is Short-Range Correlation

- **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 quark level structure of nuclei

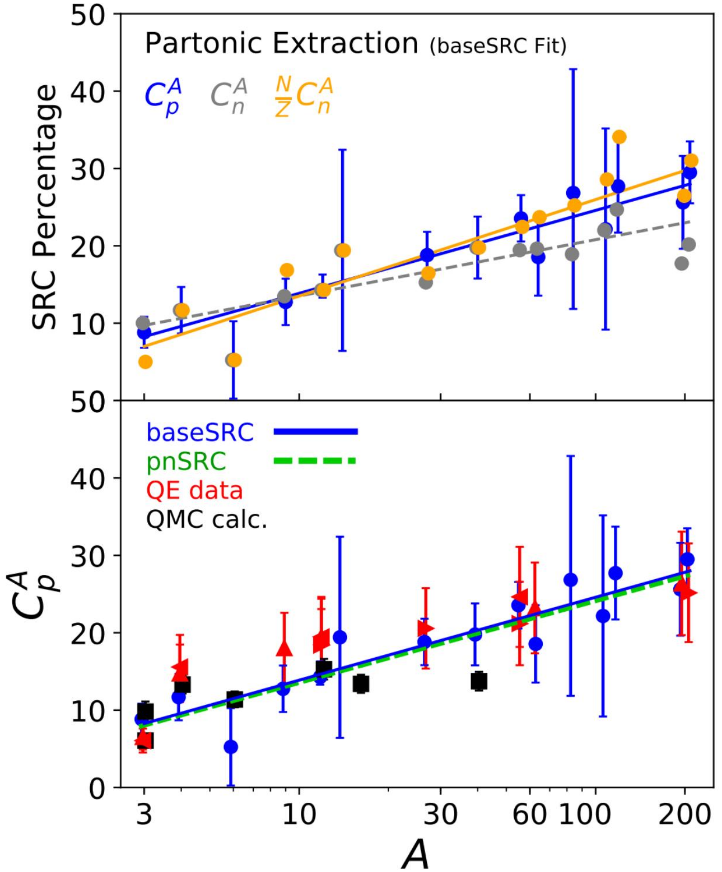
SRCs are primarily characterized by ***np*** pairs in T=0 channel at short distances, favoring [***ud***] diquark isosinglet and spin-singlet configurations

J. Rittenhouse West, **NPA** 1029, 122563 (2023).

nPDF is composed of a linnear combination of free nucleon PDF and SRC PDFs, which describe the universal quark and gluon distribution inside an SRC pair:

$$f_i^A(x,Q) = \frac{Z}{A}[(1-C_p^A)\times f_i^p(x,Q) + C_p^A \times f_i^{\mathrm{SRC}p}(x,Q)] + \frac{N}{A}[(1-C_n^A)\times f_i^n(x,Q) + C_n^A \times f_i^{\mathrm{SRC}n}(x,Q)].$$

f_i^A: PDF of parton i as a function of x and Q
C_n^A: fraction of neutron in the correlated pair
C_p^A: fraction of proton in the correlated pair



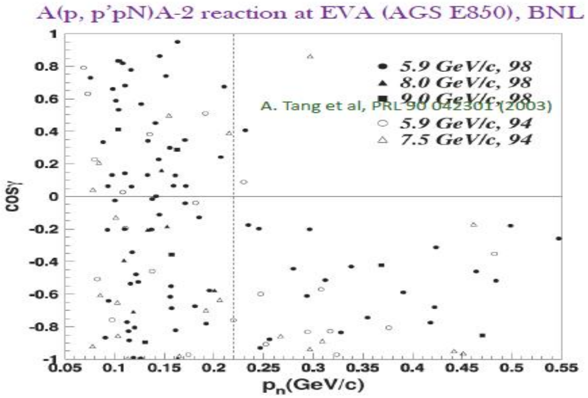
A. W. Denniston et al., **PRL** , 133, 152502 (2024)

SRC encodes the parton distribution function of nucleons in nuclei (nPDF) !

Experimental observations of SRC since decades

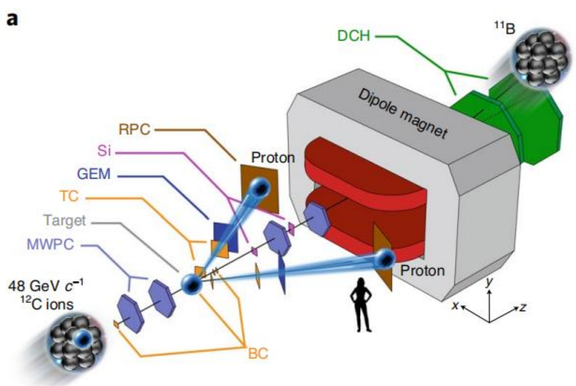
Early report in $^{12}C(p, p'pn)^{10}B$ reactions

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



More studies come out at RIKEN and BM@N

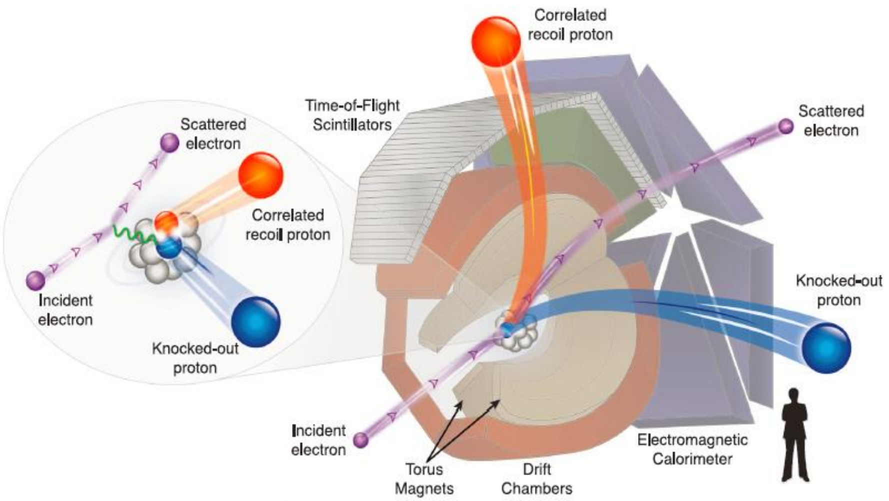
Nat. Phys. 17 (2021) 693.



By further detecting residual ^{10}B and ^{10}Be nuclei, one identifies SRC n–n pairs, providing direct experimental evidence for separation of the pair wavefunction from that of the residual many-body nuclear system.

Series of papers by CLAS experiment at JLab

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

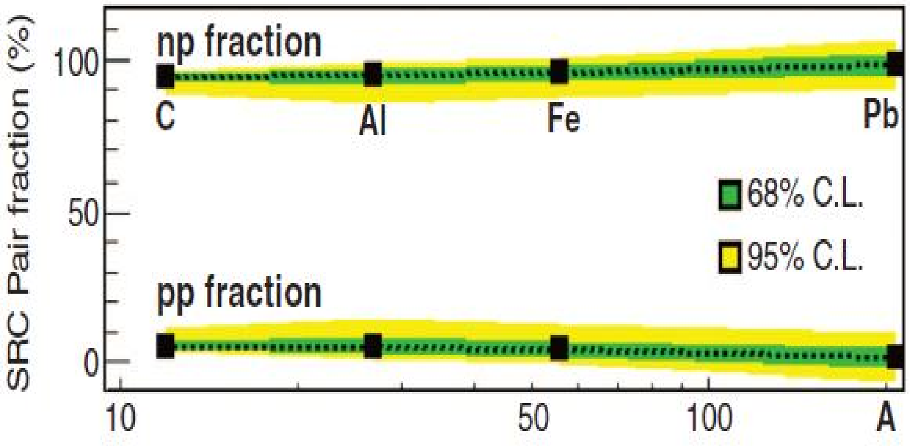


More about SRC

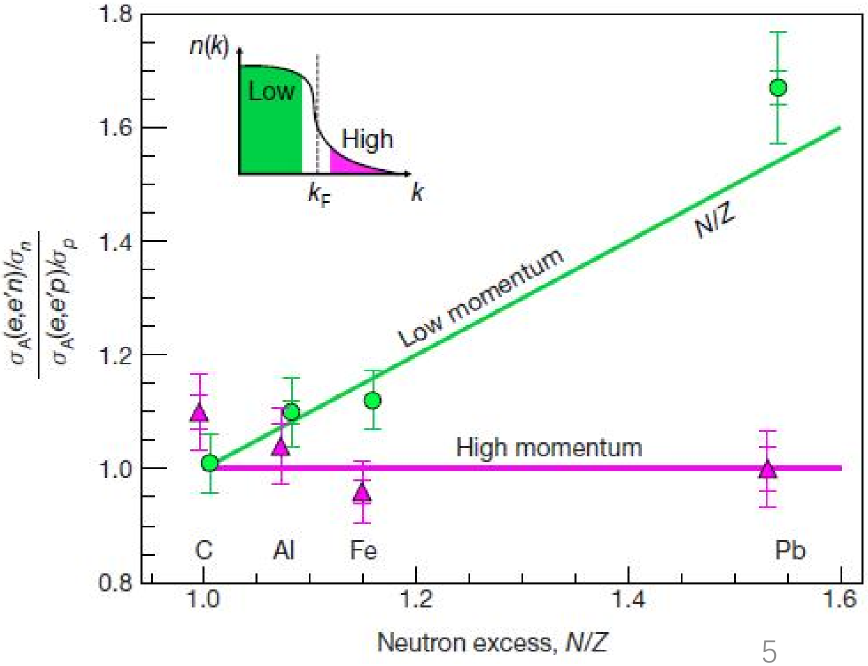
- SRC is isophoibic: ***np*** SRC dominates over ***nn*** or ***pp*** SRC, same for all nuclei;

- High momentum n and p in same number; on average protons move faster than neutrons in neutron-rich nuclei

Science, 346 , 614, (2014)



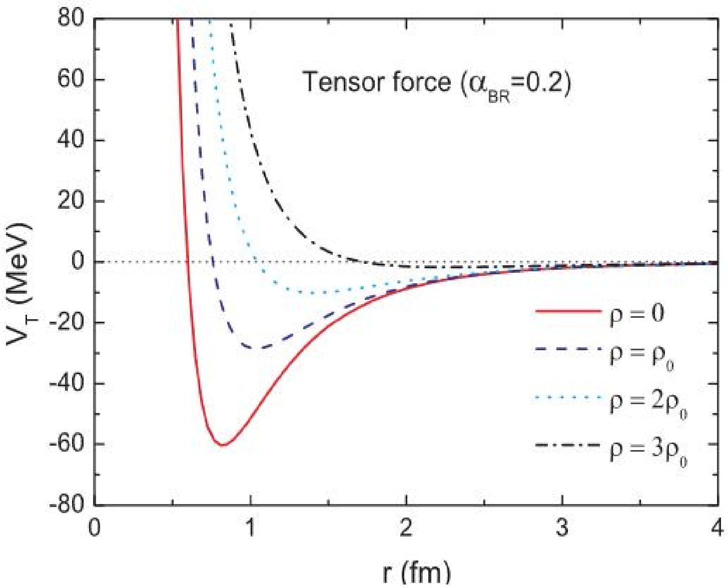
Nature, 560 , 617, (2018)

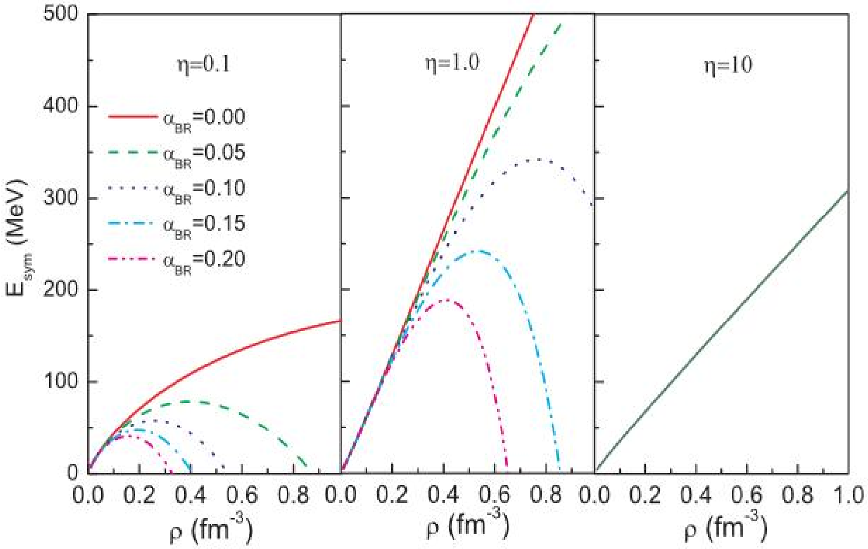


Why SRC? It possibly causes $E_{sym}(\rho)$ uncertain

Three possible reasons making $E_{sym}(\rho)$ uncertain:

- in-medium three-body interaction
- two-body short-range tensor force
- **short-range nucleon correlation**

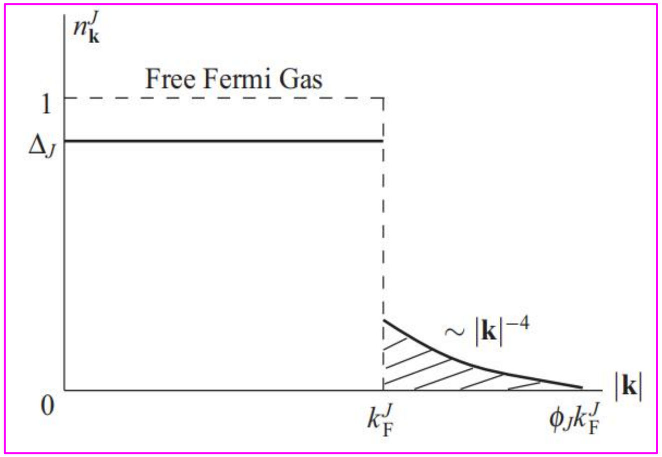


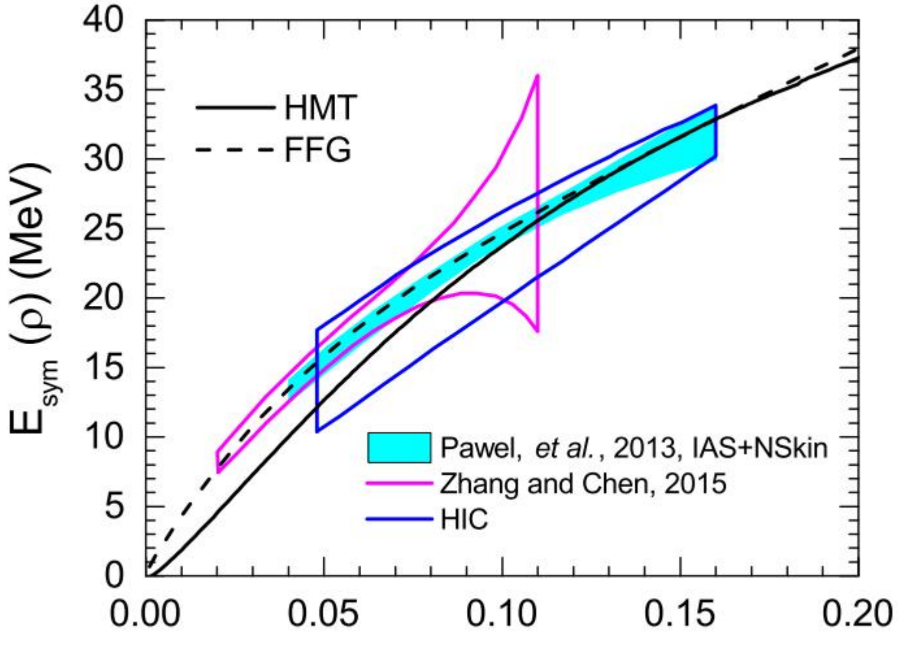


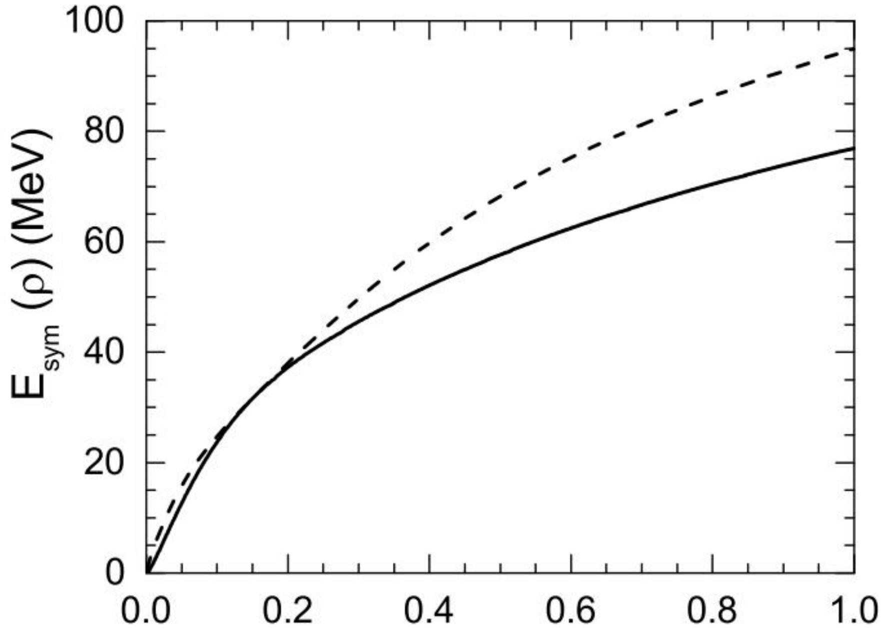
C. Xu and Bao-An Li, **PRC** 81, 064612 (2010)

SRC and nuclear EOS

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



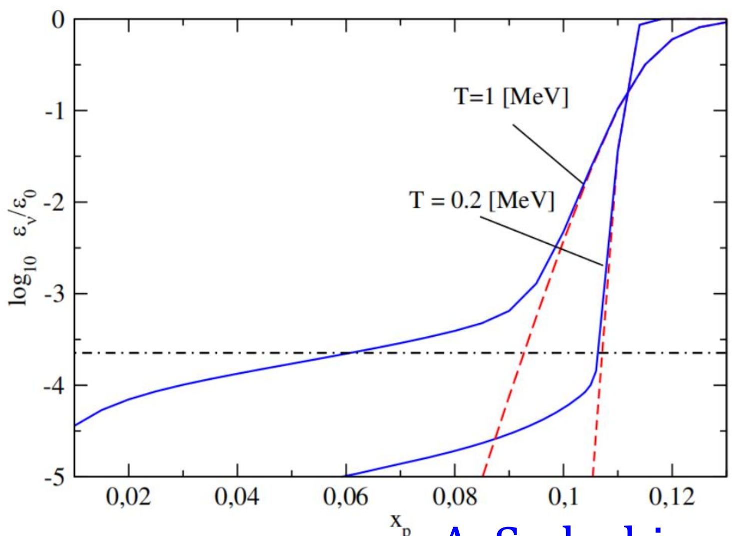


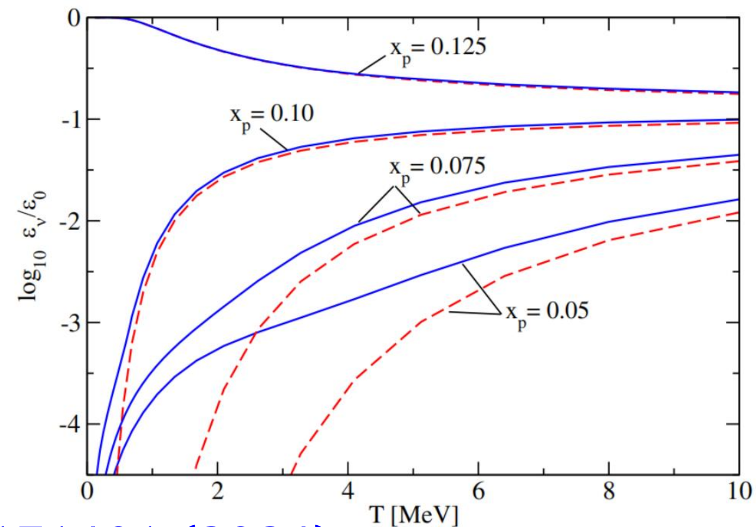


B. J. Cai and Bao-An Li, **PRC** 93, 014619(2016)

SRC and URCA cooling of neutronproton stars

SRC modifies the cooling process of protoneutron stars!





A. Sedrakian **PRL** 133, 171401 (2024)

Neutrino emissivities of protoneutron stars as a function of proton fraction

Neutrino emissivities of protoneutron stars as a function of Temperature

SRC in dense matter is as important as that in atomic nuclei!

How to bridge SRC and dense nuclear matter exp.?

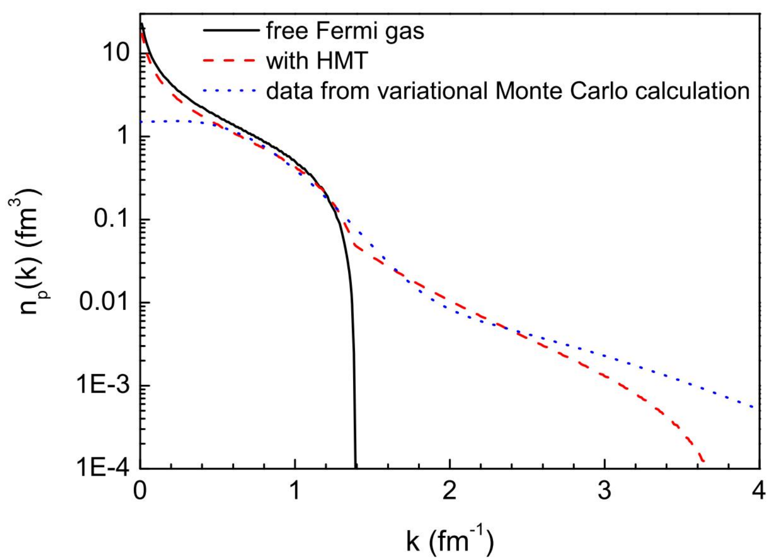
SRC in heavy ion reactions

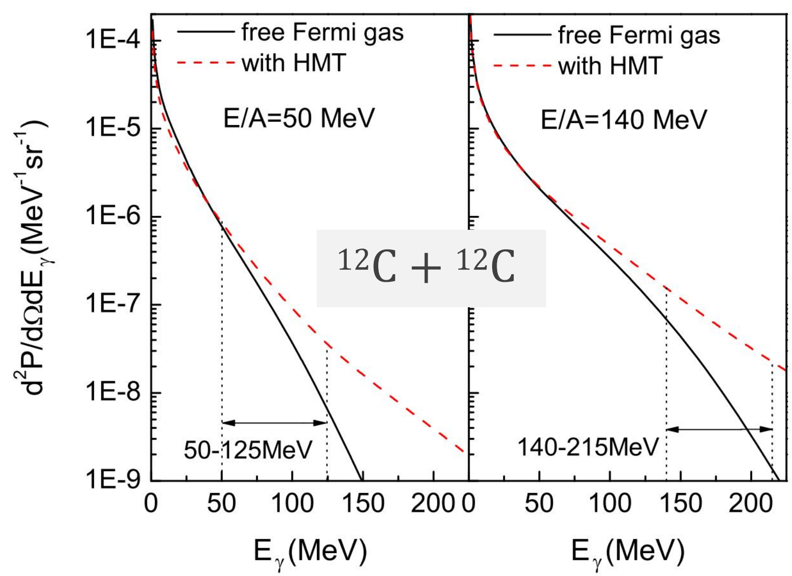
- The information from HICs about SRC is valuable to understand the dense nuclear matter.

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

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

HMT arising from SRC hardens the bremsstrahlung $\boldsymbol{\gamma}$ spectrum.





H.Xue, C. Xu et al. PLB 755, 486 (2016)

Motivation

to probe the **HMT** of nucleons associated with **SRC** in nuclei

by

measuring the Bremsstrahlung γ rays

from

heavy ion reactions at Fermi energies!

New Results: **ArXiv:** 2504.13929 & **ArXiv:** 2508.04550

Test Results: **PLB** 850 (2024) 138514 & **PLB** 857(2024) 139009

Detector Tech: **NIMA** 1053 (2023) 168330 & **NIMA** 1080 (2025) 170787

Outline

1. Introduction
2. Experimental setup
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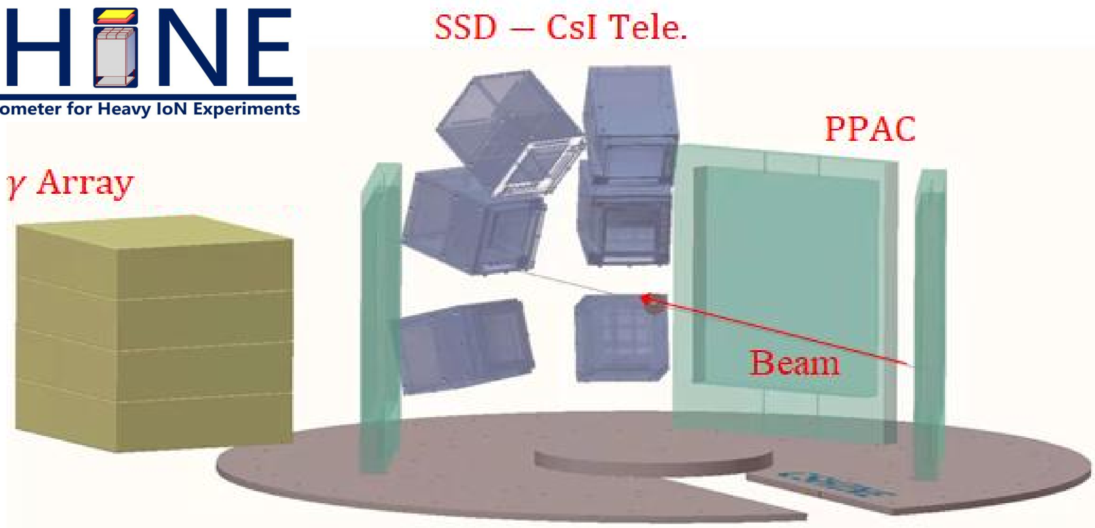
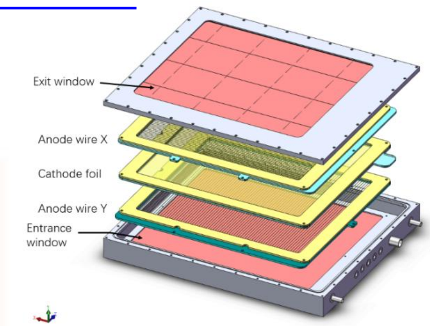
Introduction to CSHINE

Space-time volume of HIC： 10^{-14}m / 10^{-21}s， we need a super camera ——
a Compact Spectrometer for Heavy IoN Experiment

Initial goal is to study the EOS and isospin physics in heavy ion reactions

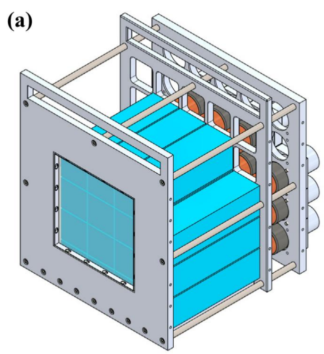
CSHINE
Compact Spectrometer for Heavy IoN Experiments





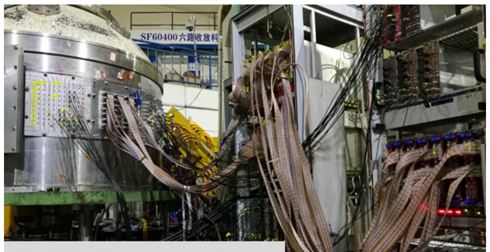
PPAC for fission fragments

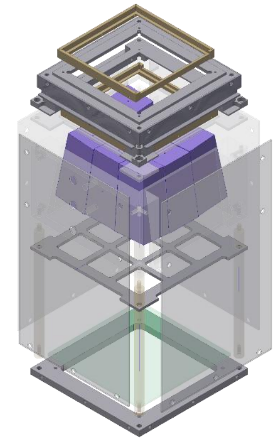
Total channels： ~400， starting from 2014



CsI hodoscope for high energy γ
— CSHINE-gamma


CSHINE in chamber


CSHINE out chamber



SSDT for
LCP and IMFs

Operation of CSHINE

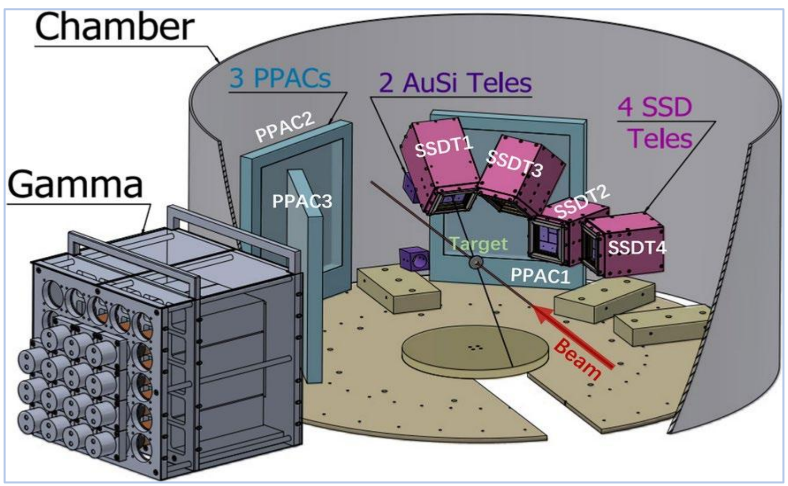
02 2018
30 MeV/u $^{40}Ar+^{197}Au$

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

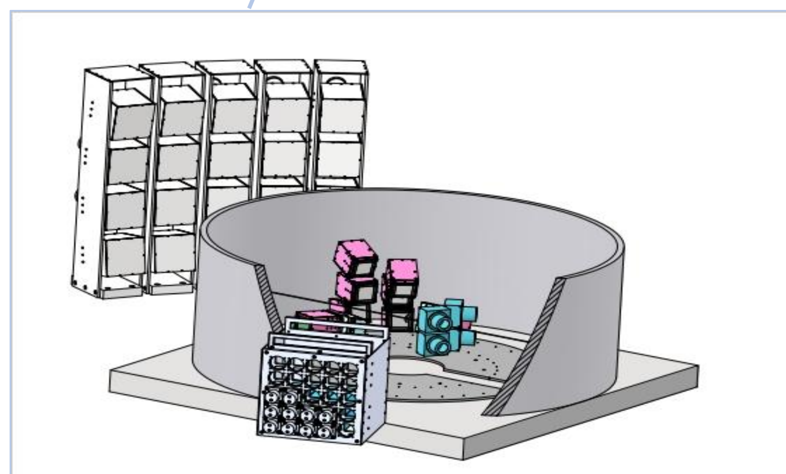
30 MeV/u* $^{40}Ar+^{197}Au$
01 2014

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

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)

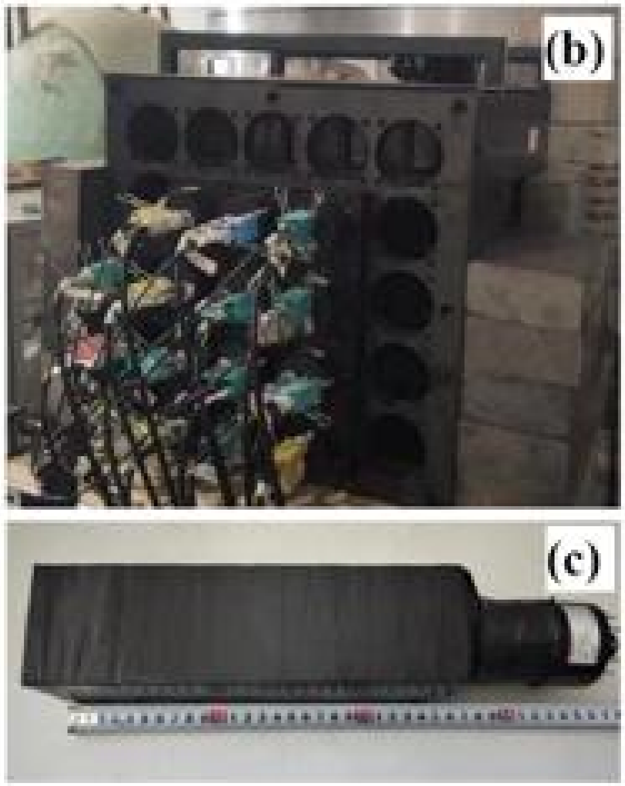
Isospin Choronology

PLB 825, 136856 (2022)

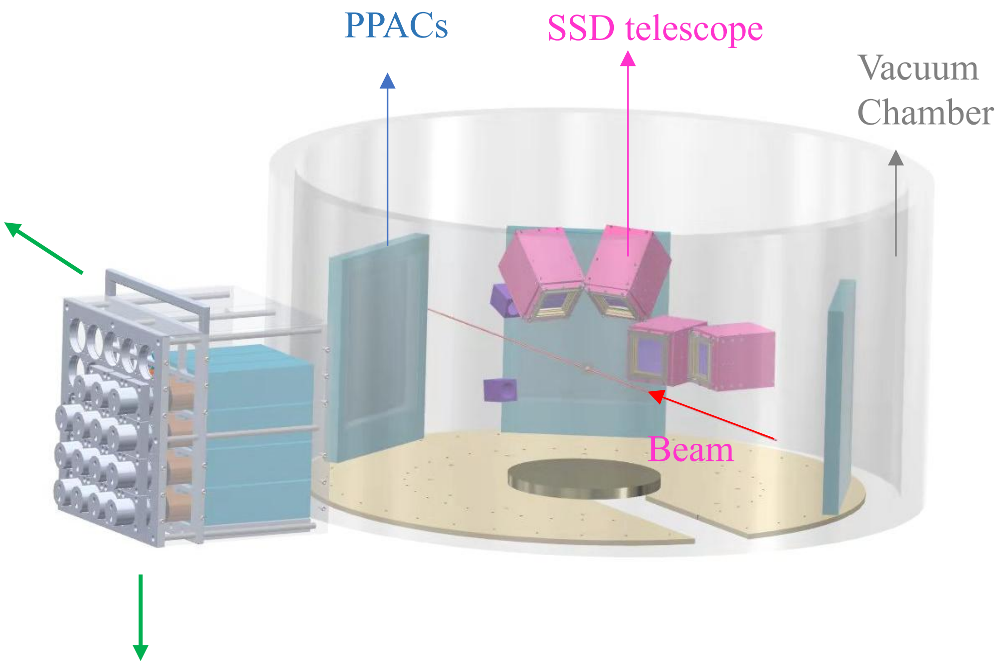
Constraint of $E_{\rm sym}(\rho)$ near $\rho \approx \rho_0$

PRC 95, 041602R (2017)

The SCHINE-GAMMA hodoscope -architecture



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

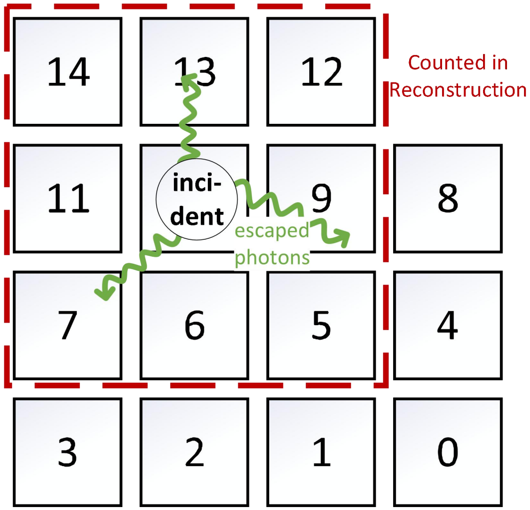


25-unit CsI(Tl) hodoscope (15 available first)：

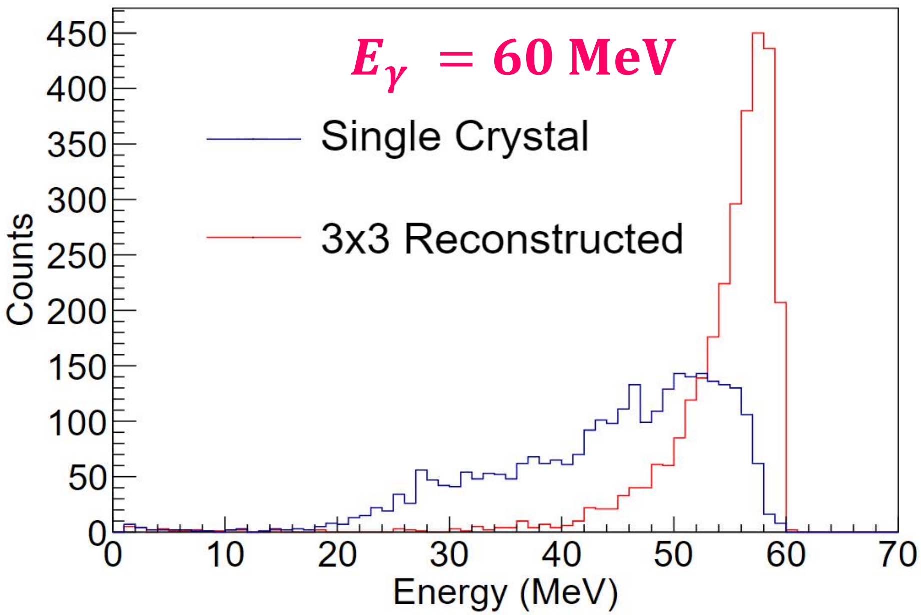
each: 7cm × 7cm × 25cm $[d\sim7.92\ R_M,\ \ L\sim13.4\ x_0]$

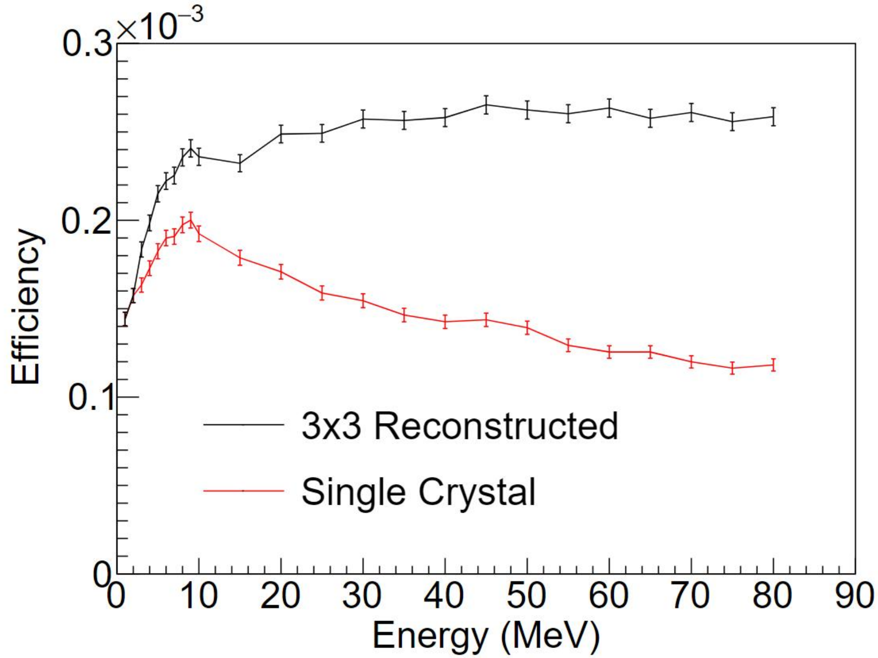
Y. H. Qin et al., Nucl. Inst. Meth. A **1053** 168330 (2023)

The SCHINE-GAMMA hodoscope - simulation



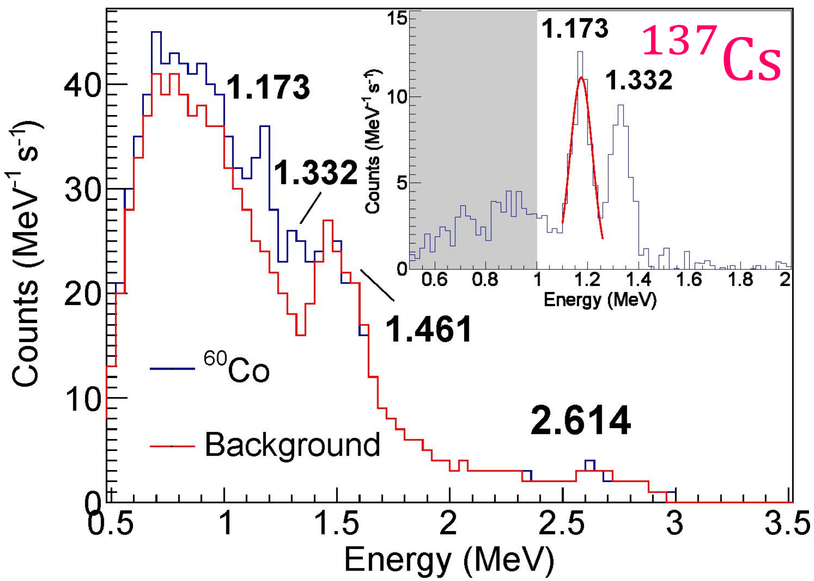
- Detector Response Filter simulated by Geant4
- Reconstruct the total energy from neighboring units
- Efficiency becomes nearly constant ~80%

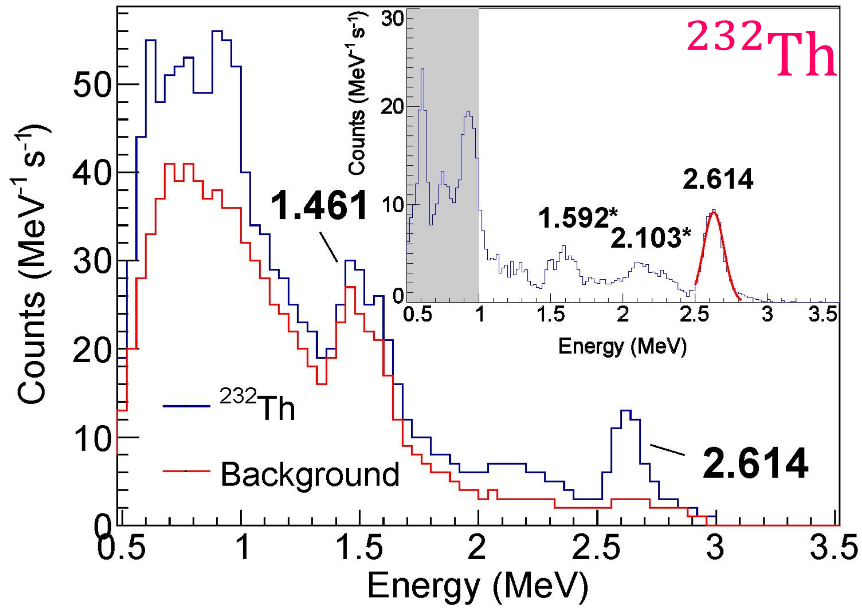


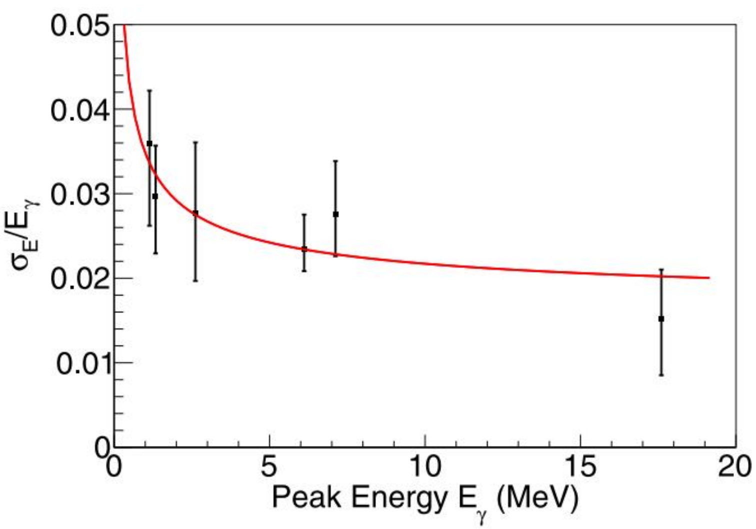


Y. H. Qin et al., Nucl. Inst. Meth. A **1053** 168330 (2023)

Calibration using source







Energy resolution:

$$\sigma_E / E_\gamma = 1.6\% + 2\% / E_\gamma^{1/2}$$

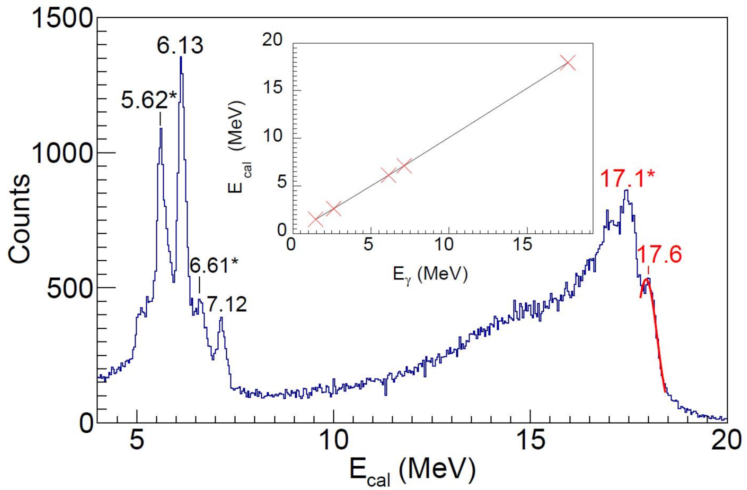
Y. H. Qin et al., Nucl. Inst. Meth. A **1053** 168330 (2023)

Calibration using pLi reaction and γ beam

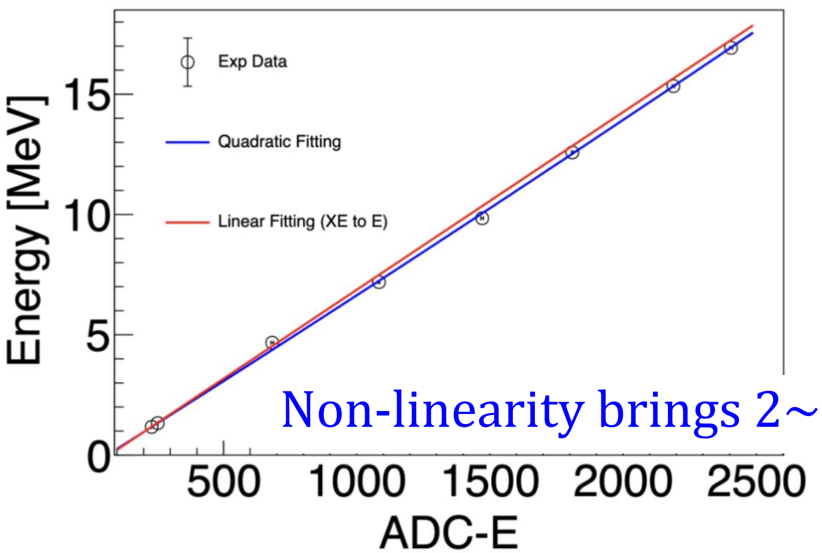
1. 506 keV p+LiF at CIAE

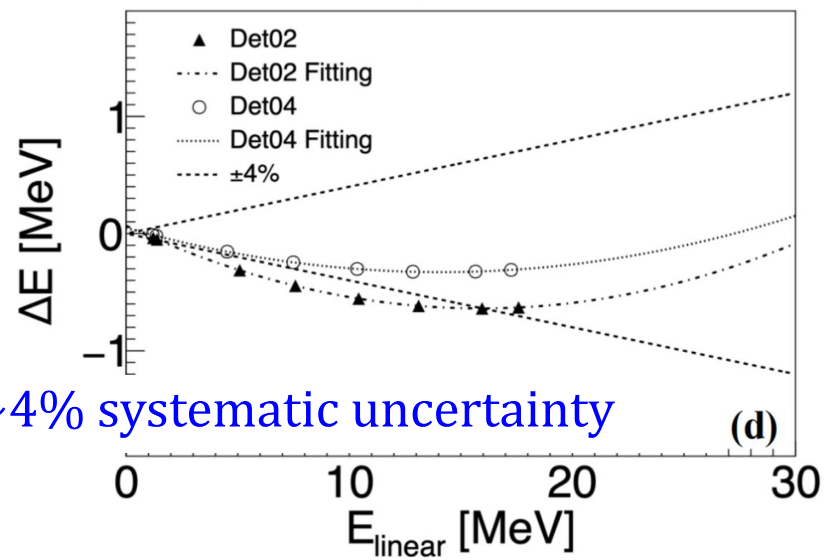
Table 1
Proton capture reactions on LiF target.

Reaction	$E_{\gamma 1}$ (MeV)	$E_{\gamma 2}$ (MeV)
$^{19}F(p,\alpha\gamma)^{16}O$	6.13	7.12
$^{7}Li(p,\gamma)^{8}Be$	17.6	/



2. Monochromatic γ beam calibration at SLEGS





Non-linearity brings 2~4% systematic uncertainty

Y. H. Qin et al.,NIMA **1053** 168330 (2023)； J. H. Xu et al., NIMA 1080, 170787 (2025)

IBUU-MDI model

IBUU-MDI transport model simulations (by C. Xu's group*)

- NN collisions simulated by the transport model

- All the SRC effect is included in the initialization of the single nucleon momentum distrobution!

  R_{HMT} is a parameter initializing $\rho_N(k)$!

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

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

* H.Xue, C. Xu et al. PLB 755, 486 (2016)

** N. Gan et al., PRC 49, 298 (1994).

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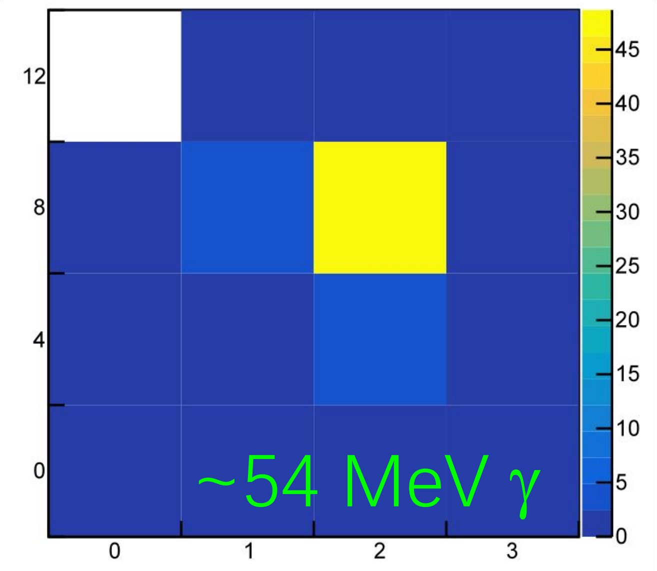
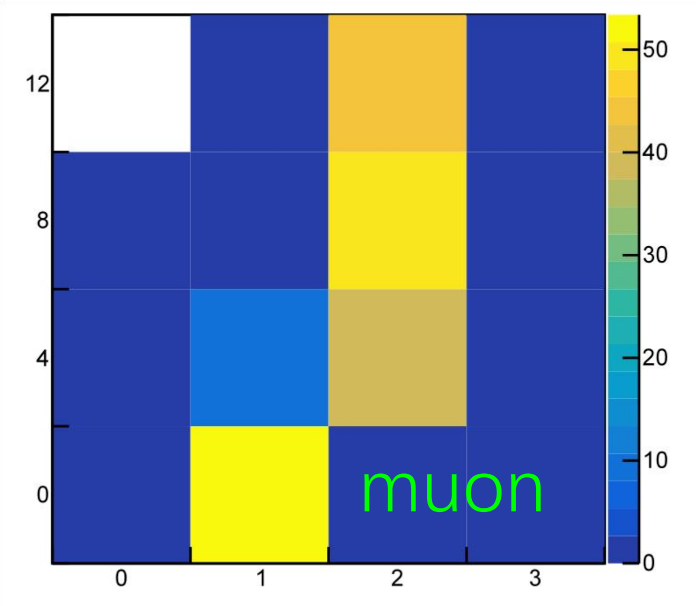
A test Experiment: 25 MeV/u ^{86}Kr+^{124}Sn



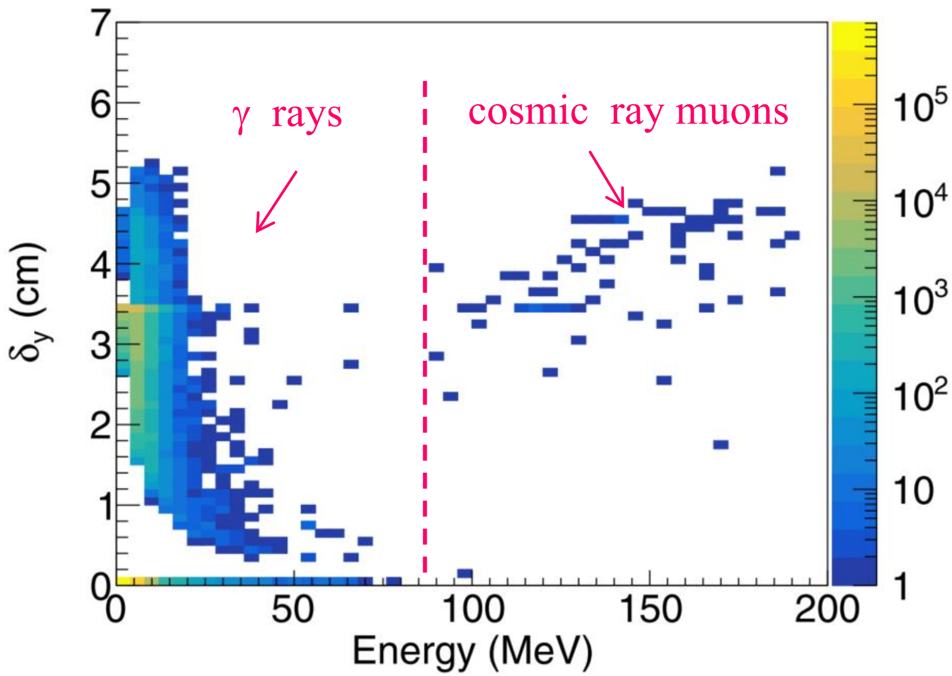


On the event topology:

high energy γ: an event center

cosmic ray muons: a long track

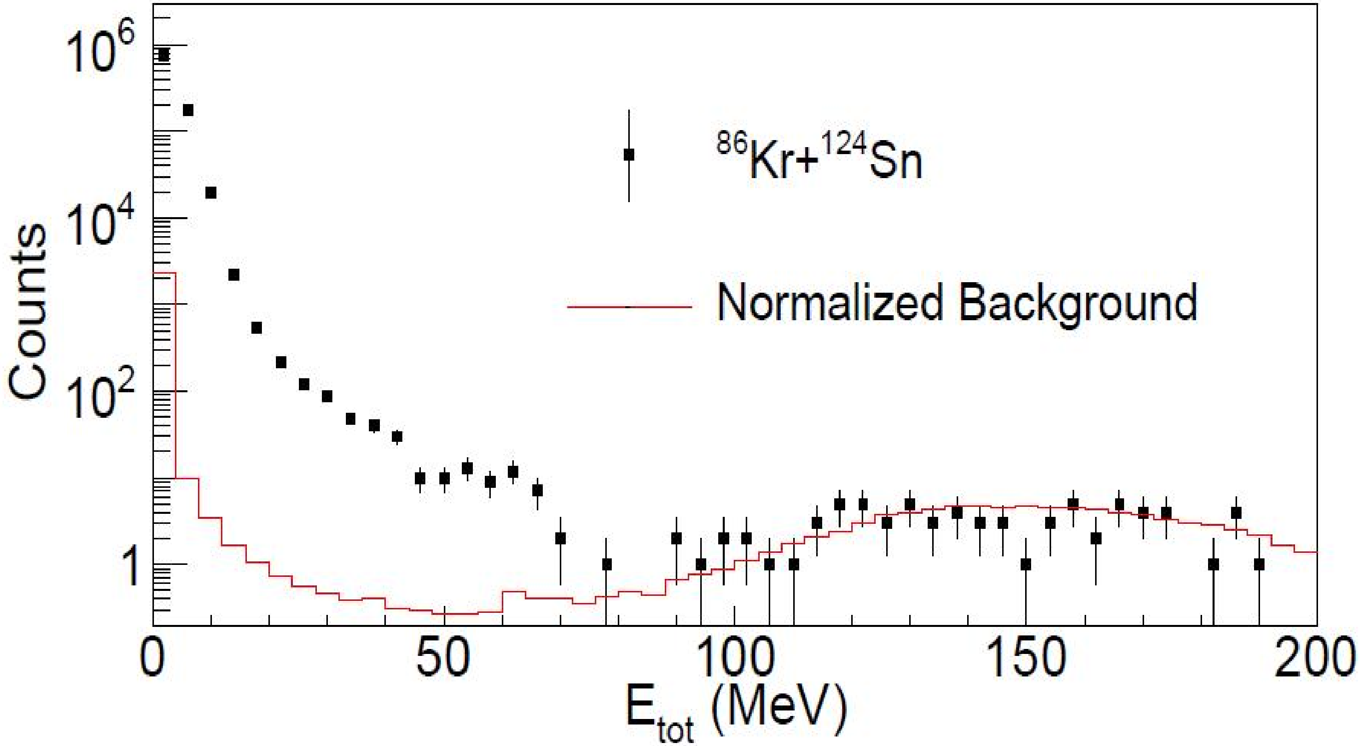
Distinguishable!



Y. H. Qin et al., Nucl. Inst. Meth. A **1053** 168330 (2023)

The total energy spectrum and background subtraction

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

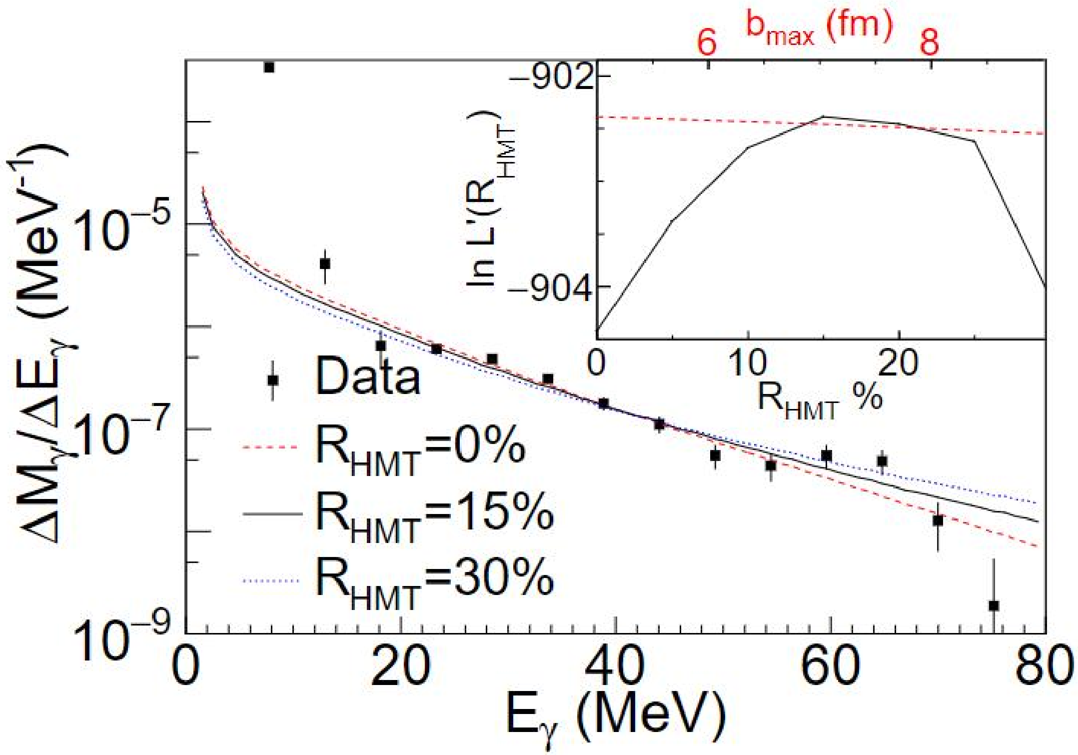


Comparison between data and BUUsimulations

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

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

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

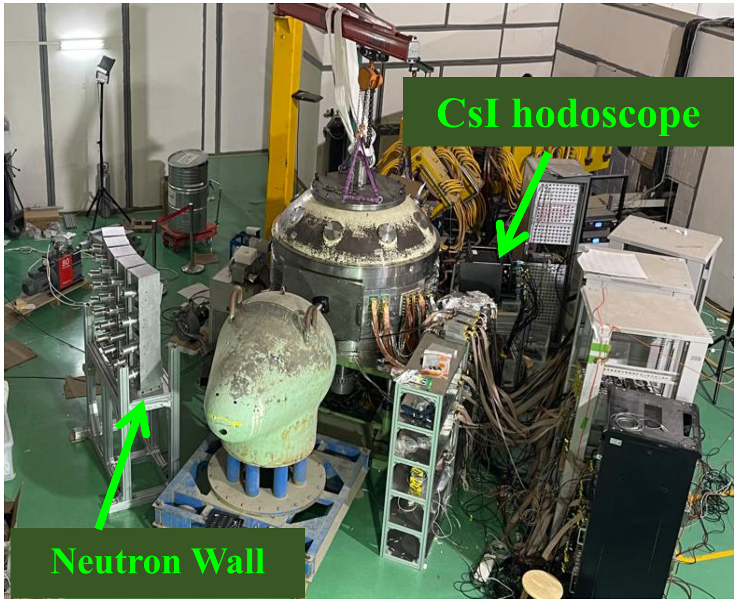


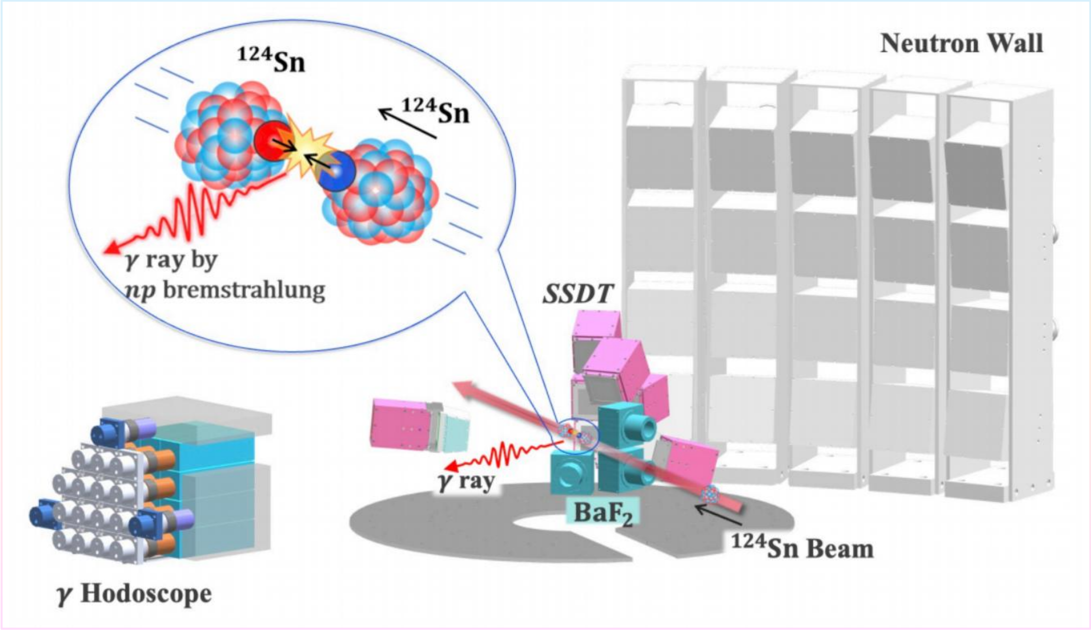
Y.H.Qin, Q. L. Niu et al., **PLB850,**138514 (2024); Erratum: **PLB** 857,138984

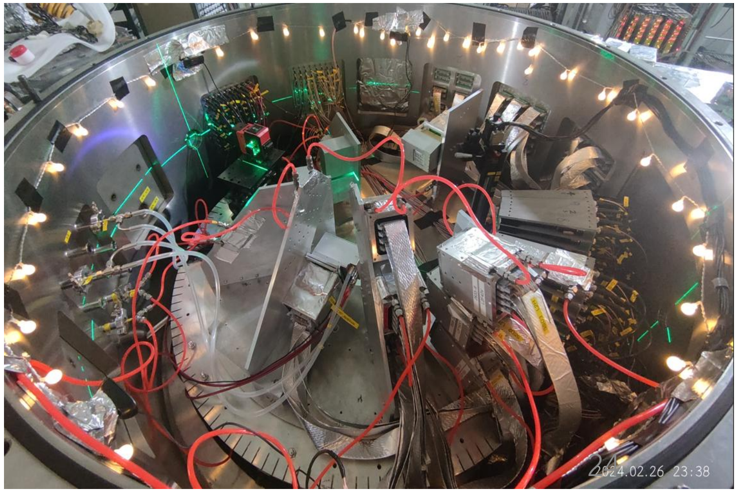
The new Experiment: 25 MeV/u $^{124}Sn+^{124}Sn$

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

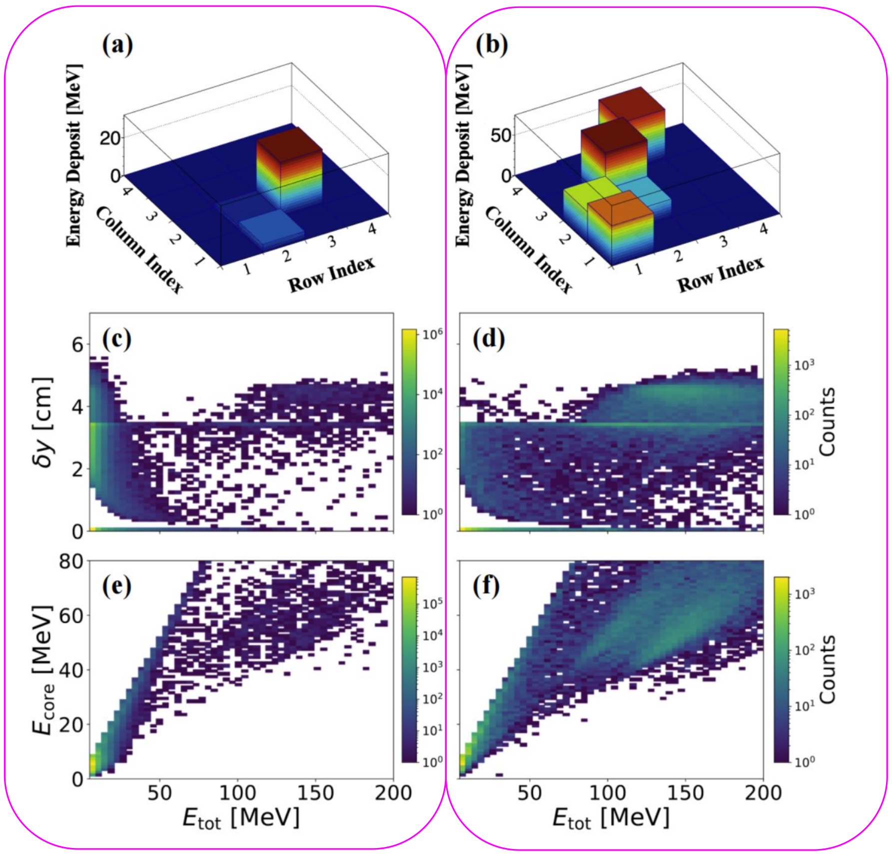




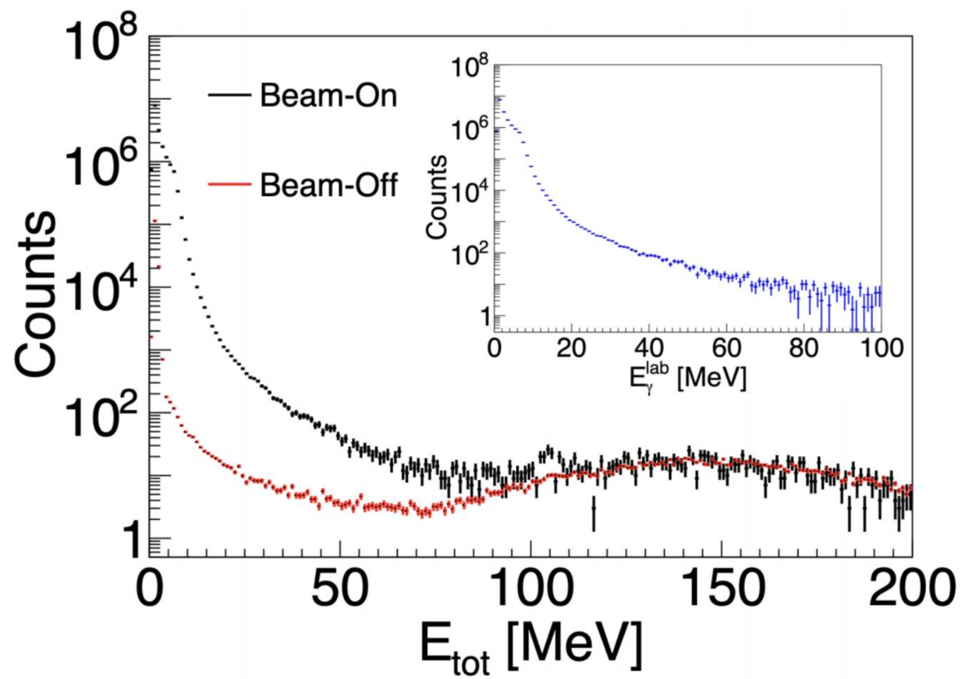


Data analysis and checks

- Same scheme to substract the beam-off background

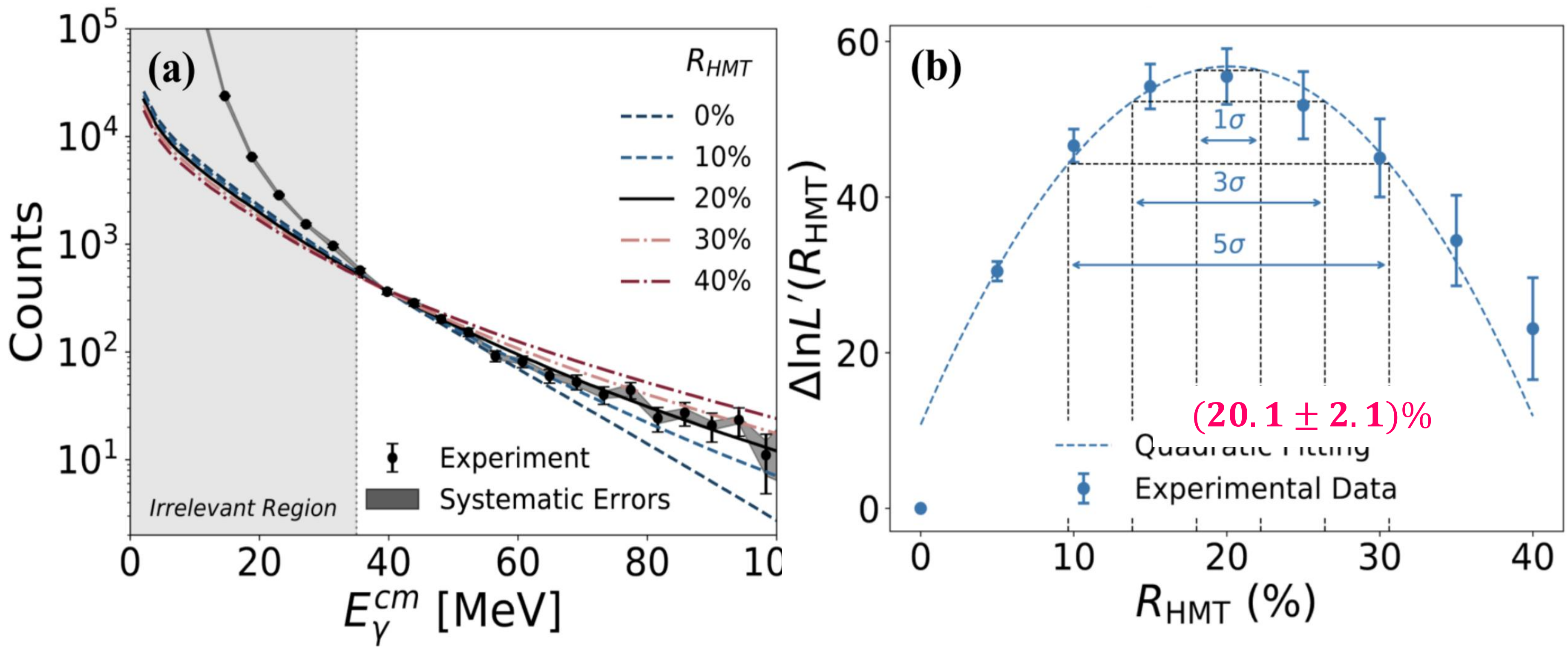


Beam-on
Beam-off



J. H. Xu et al., **arXiv** 2504.13929; J. H. Xu et al., **arXiv** 2508.04550

Comparison between data and BUUsimulations



- Likelihood analysis infers a nonzero R_{HMT}

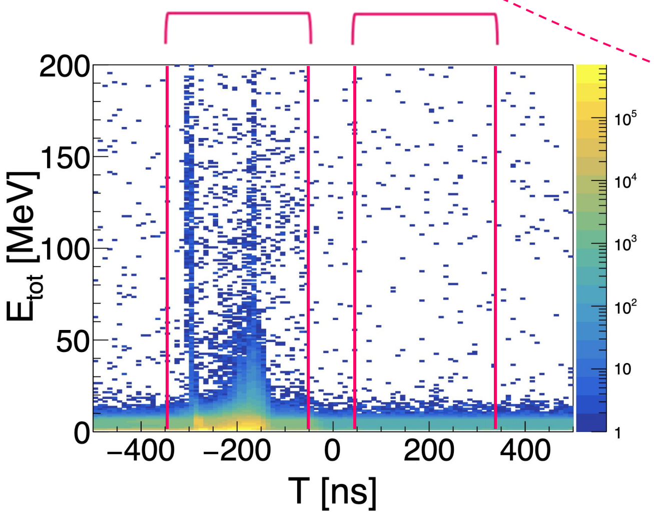
  over 5σ:　$\mathbf{(20.1 \pm 2.1)\%}$

J. H. Xu et al., **arXiv** 2504.13929 [submitted];　J. H. Xu et al., **arXiv** 2508.04550

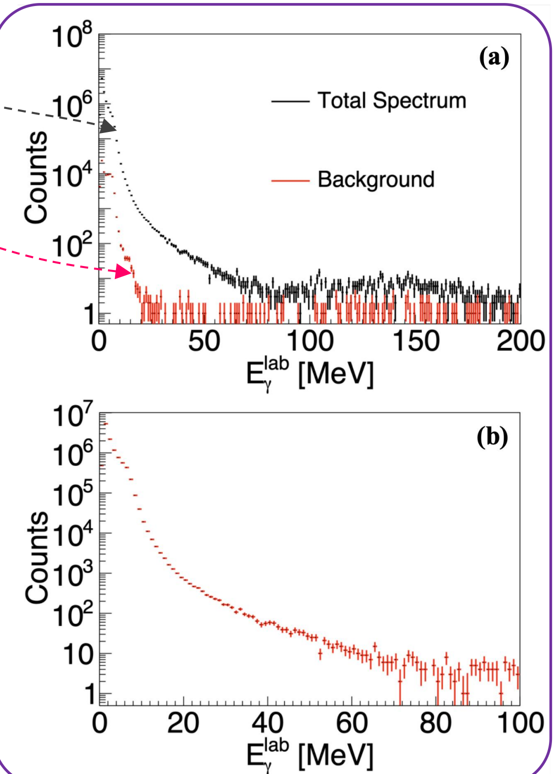
Cross check with different bkg-subtraction method

Subtract background by timing gates

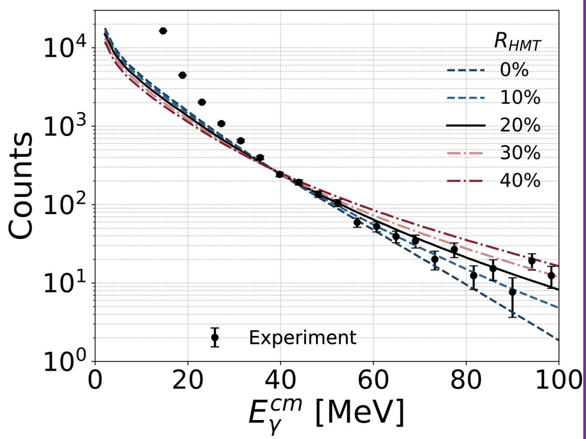
signal gate bkg gate



SSD M2 Trigger excluded



Comparison twith IBUU model



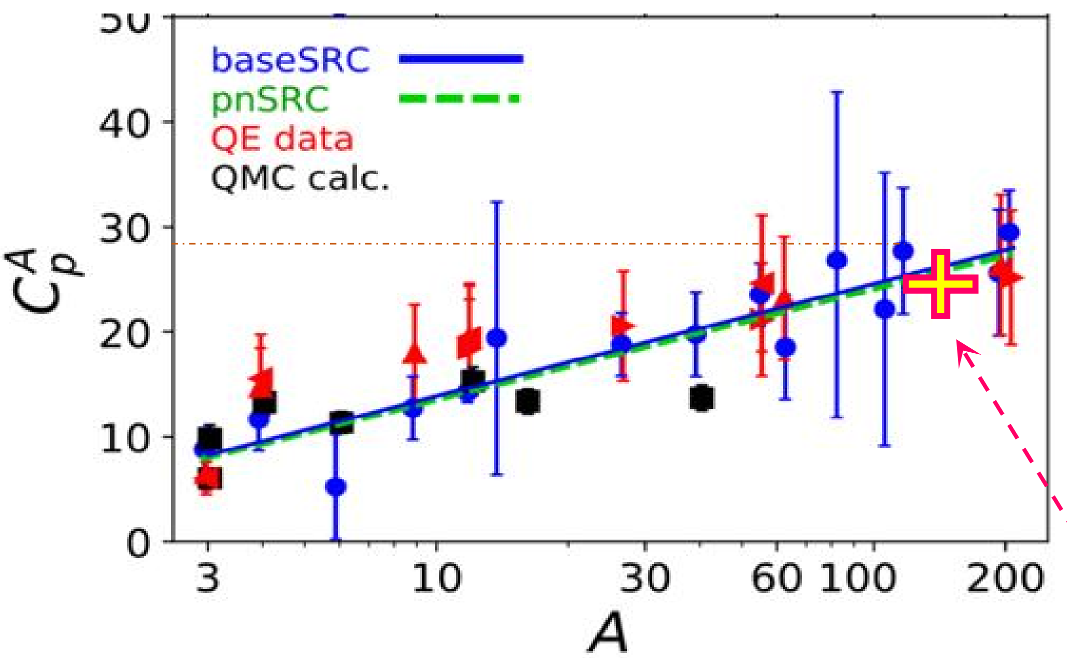
$\mathbf{R_{HMT} = (18.0 \pm 2.8)\%}$

- $\mathbf{R_{HMT} = (18.0 \pm 2.8)\%}$, in accordance with the previous method! (2% difference is treated as a systematic error!)
- Robust against using different bkg-subtraction scheme.

J. H. Xu et al., **arXiv** 2508.04550

In line with high-energy data compliation

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



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

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

J. H. Xu et al., **arXiv** 2508.04550

Summary

> **Motivation:** SRC gives rise to the correlated nucleons with high momentum tail (HMT) beyond the Fermi surface. In heavy ion reactions, the HMT tends to harden the Bremsstrahlung γ spectrum produced by incoherent n-p process.

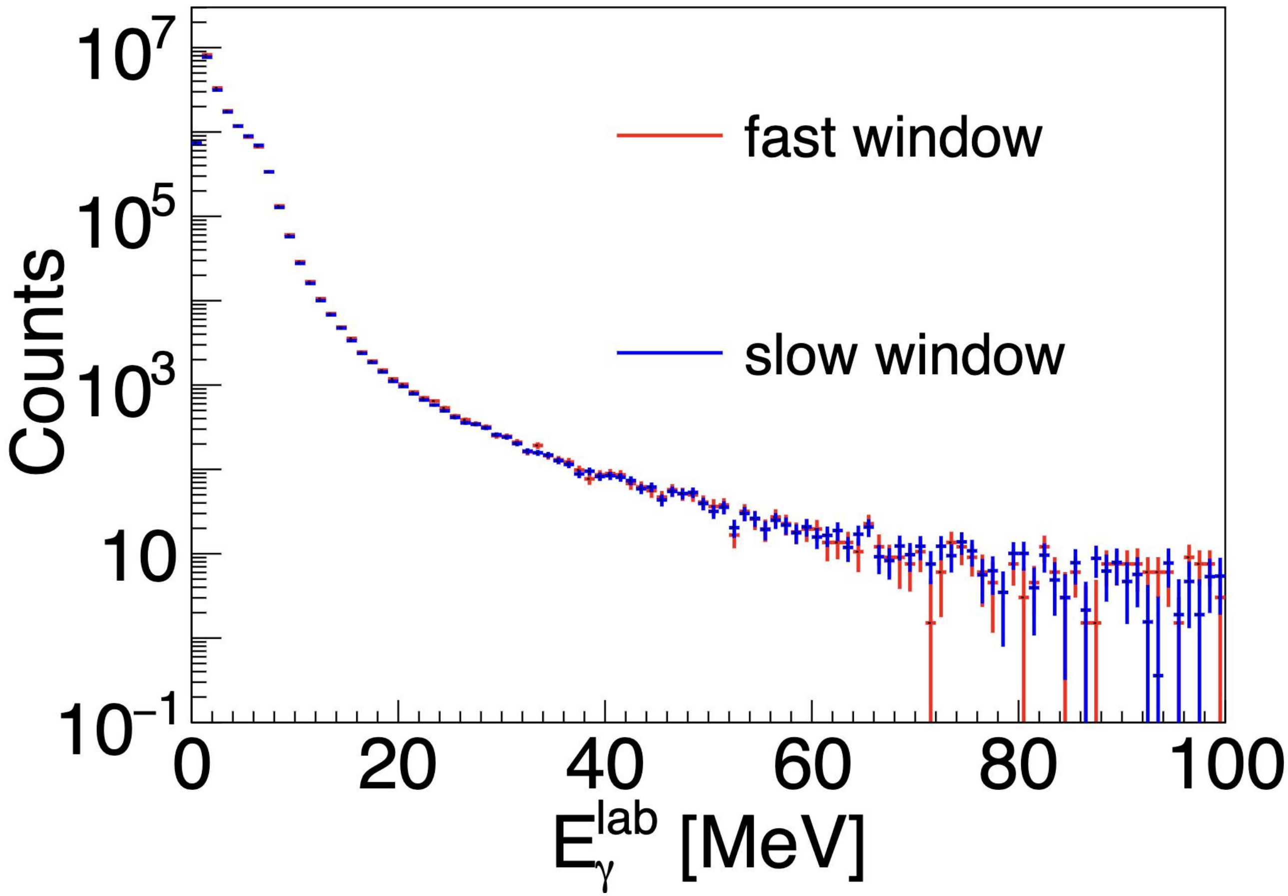
> **Experiments and Results:** Two experiments results show that

$^{86}Kr+^{124}Sn$ at 25 MeV/u, a nonzero HMT ratio (CL=2σ) is indicated.

$^{124}Sn+^{124}Sn$ at 25 MeV/u, $R_{\mathrm{HMT}} = (20 \pm 3)\%$ is derived, providing an unambiguous evidence of SRCs.

> **Significance:** Our results demonstrate that low-energy HIC offers a new approach to studying SRC in connection with quark-level dynamics. Meanwhile, a transport model able to treat correlation in collision process is called for!

Thank you for your attention!



Comparison of the background-subtracted spectrum between fast coincidence and slow coincidence windows. ---- They are consistent.