The measurement and analysis of neutron-neutron correlation function in heavy ion experiment

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17th Workshop on Particle Correlations and Femtoscopy

November 4th-8th, 2024, Toulouse, France

outline

- **Research Background**
- **CSHINE detector system**
- **Result**

  1. TOF and neutron energy spectrum
  2. n-n correlation at 25MeV/u $^{124}Sn+^{124}Sn$
  3. Momentum-gated correlation function

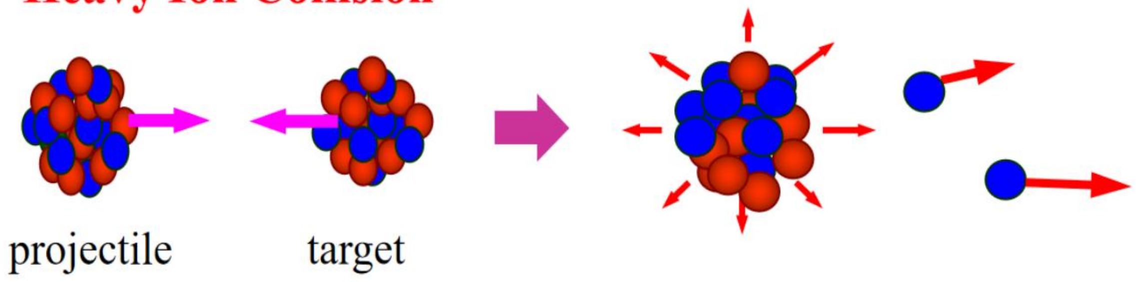
- **Summary**

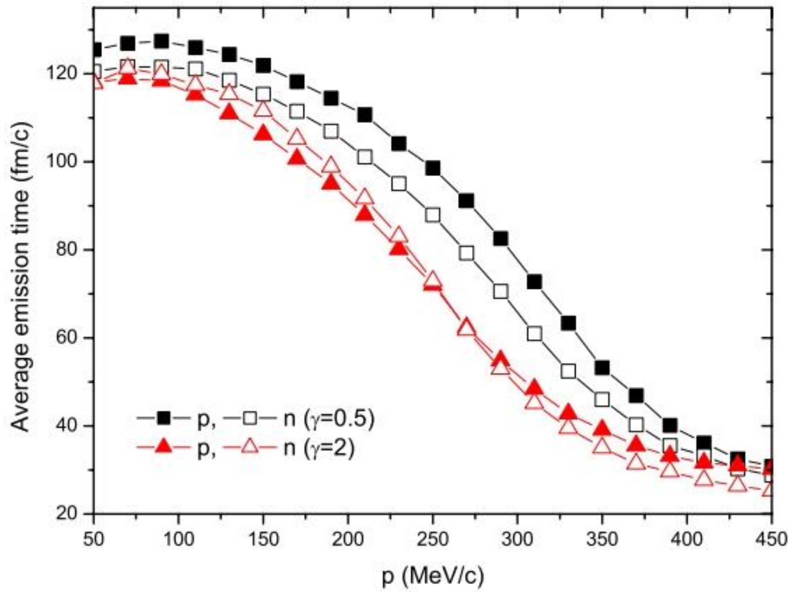
Isospin dynamics and $E_{sym}(\rho)$

☐What is isospin dynamics?

In the process of HIC ($\sim 10^{-21}s$), protons, neutrons and the fragments with varying N/Z, exhibit different behaviors in production and transport due to $E_{sym}(\rho)$ .....

Heavy Ion Collision





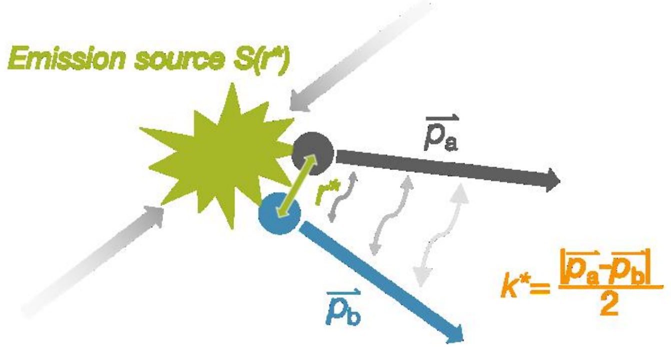
Phys. Rev. Lett 90, 162701

$E_{sym}(\rho) \Rightarrow \tau_p , \tau_n$

The emission timescale of neutrons and protons are important characteristics of isospin dynamics.

Question：How to measure the dynamic evolution in the ultra-fast process?

Correlation function and isospin chronology



Two particle correlation function:

Model **Experiment**

$$C(k^*) = \int S(\vec{r}, t)|\Psi(\vec{k}^*, \vec{r})|d^3\vec{r} = \frac{N_{same}(k^*)}{N_{mix}(k^*)}$$

$S(\vec{r}, t)$: Source function

$\Psi(\vec{k}^*, \vec{r})$:two particle wave function

Effective range expansion for $\Psi(\vec{k}^*, \vec{r})$
Smoothness approximation for source function $S(\vec{r}, t)$

$$S(\vec{r}, t) = \frac{1}{(4\pi)^2 r_0^3 \tau_0} exp(-\frac{r^2}{4r_0^2} - -\frac{t^2}{4\tau_0^2})$$

Experiment

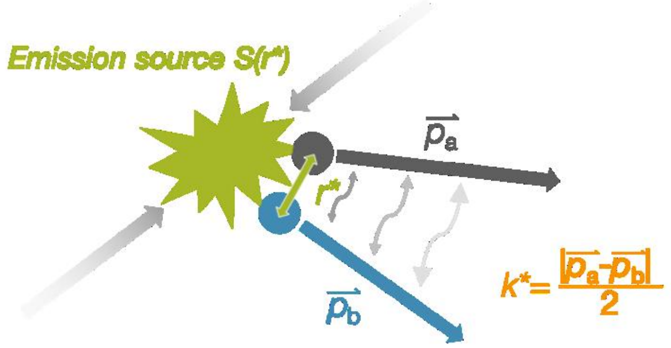
$$\frac{N_{same}(k^*)}{N_{mix}(k^*)}$$

L-L approach →

Physical quantity:

1. f_0: Scattering length
2. d_0: Effictive range
3. r_0: Source size
4. τ_0: Time scale

Correlation function and isospin chronology



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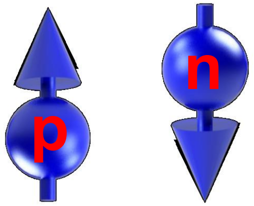
space-time information

Charge symetry breaking(CSB) measurement in HIC



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

Directly Observations for CSB

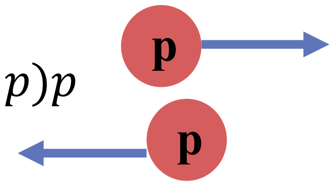
In scattering experiment:

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

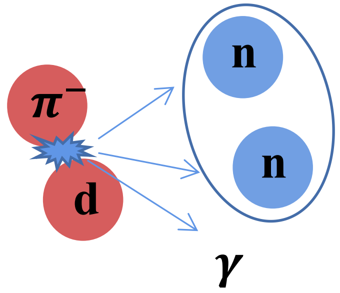
$f_0^{nn} = -18.5 \pm 0.5 fm$

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

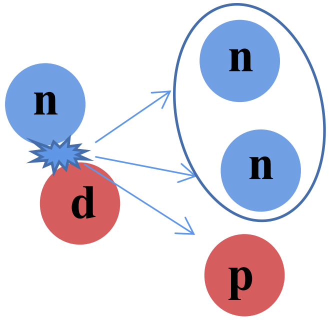
$p(p,p)p$



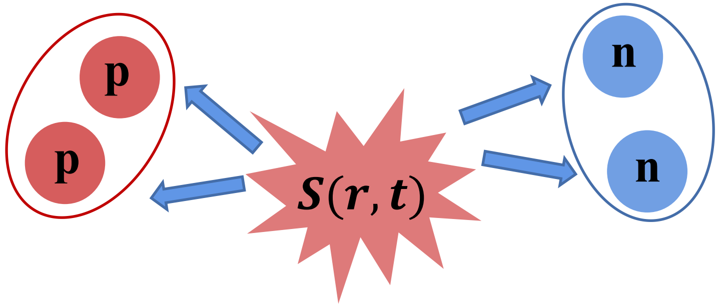
$d(\pi^-,\gamma)2n$



$d(n,p)2n$

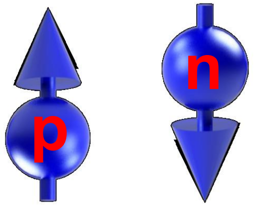


In HIC experiment:



Two-Nucleon CF can be a probe to get the Charge symmetry breaking in the same reaction system

Charge symetry breaking(CSB) measurement in HIC



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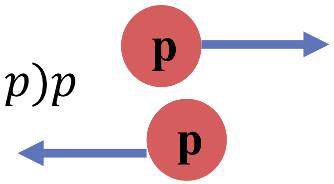
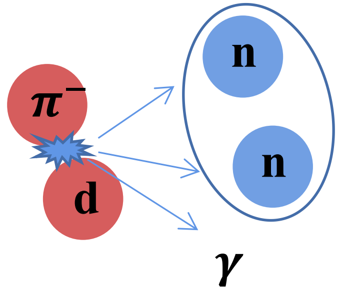
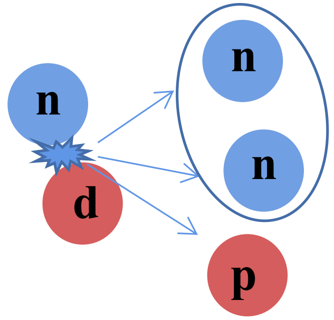


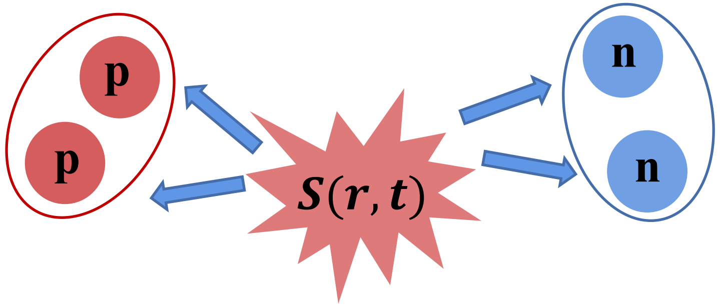
$d(\pi^-,\gamma)2n$



$d(n,p)2n$



In HIC experiment:



Require simultaneous measurement of neutrons and charged particles!

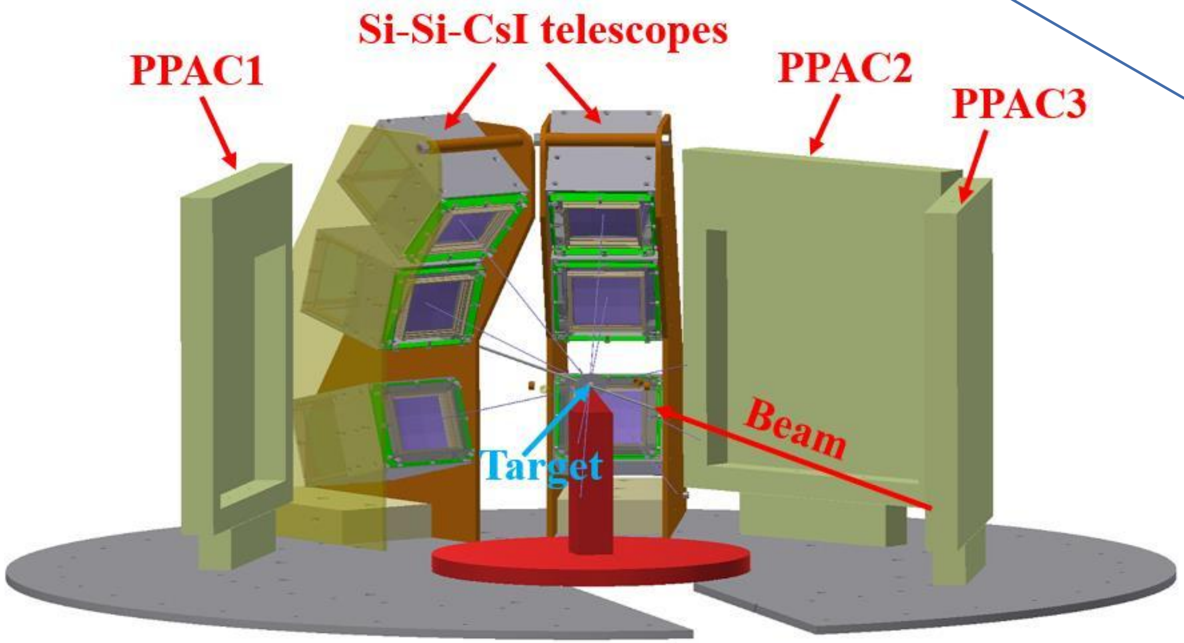
Two-Nucleon CF can be a probe to get the Charge symmetry breaking in the same reaction system

CSHINE detector system

HIRFL: Heavy Ion Research Facility at Lanzhou, China

Compact Spectrometer for Heavy IoN Experiments(CSHINE)

SSC:
Kr: ~40 MeV/u
Sn: ~30 MeV/u



CSHINE detector system

CSHINE
Compact Spectrometer for Heavy IoN Experiments

Beam time statistics:

I: 30 MeV/u* ^{40}Ar+^{197}Au (2014)

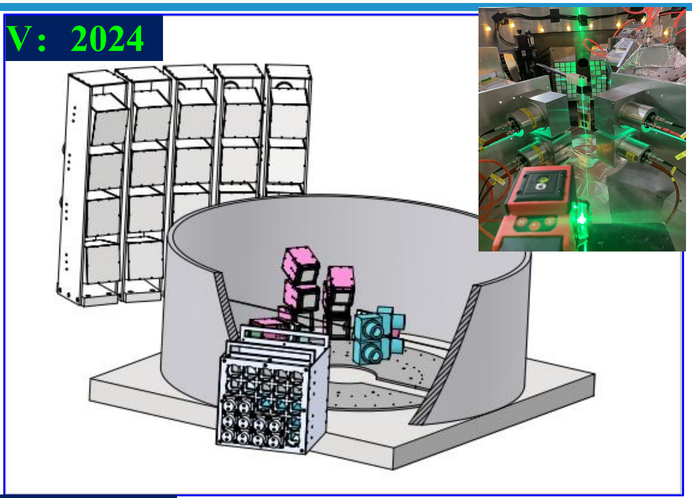
II: 30 MeV/u ^{40}Ar+^{197}Au (2018) **+ SSDT**

III: 25 MeV/u ^{86}Kr+^{208}Pb (2019)

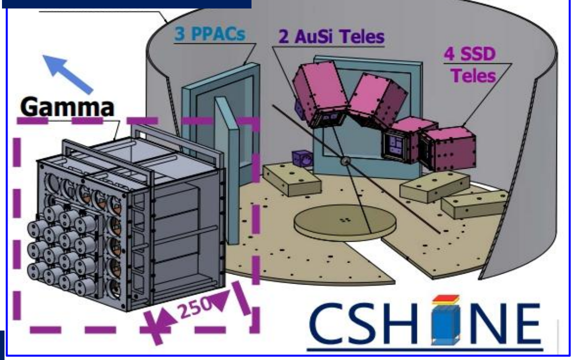
IV: 25 MeV/u ^{86}Kr+^{124}Sn (2022) **+ γ Hodoscope**

V: 25 MeV/u ^{124}Sn+^{124}Sn (2024) **+ Neutron Array**

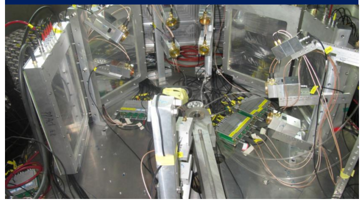
V: 2024



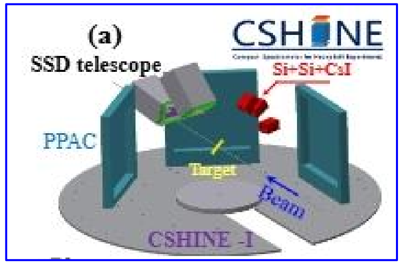
IV: 2022



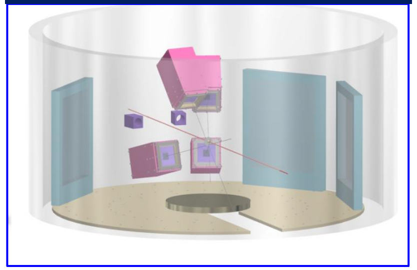
I: 2014



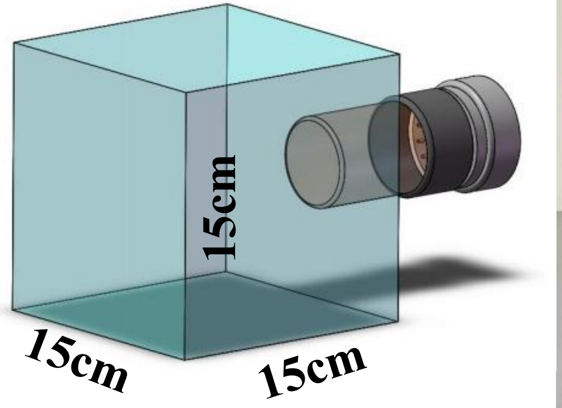
II: 2018

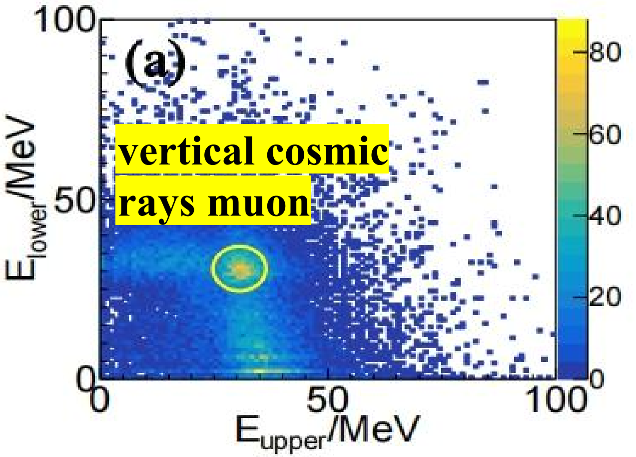


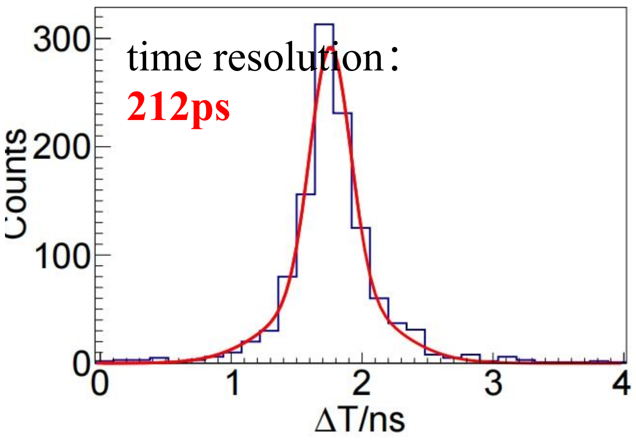
III: 2019



CSHINE detector system —— Neutron Array



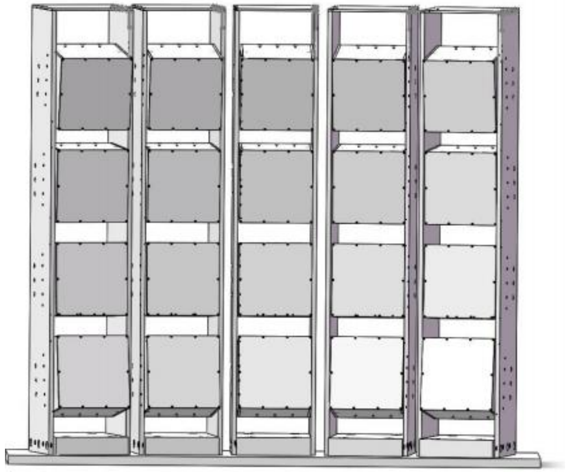


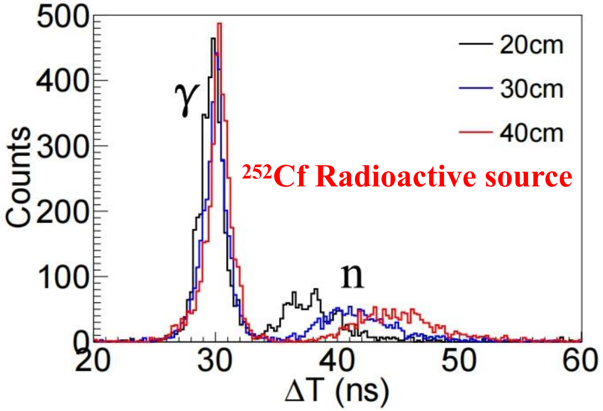


Plastic scintillator： HND-S2

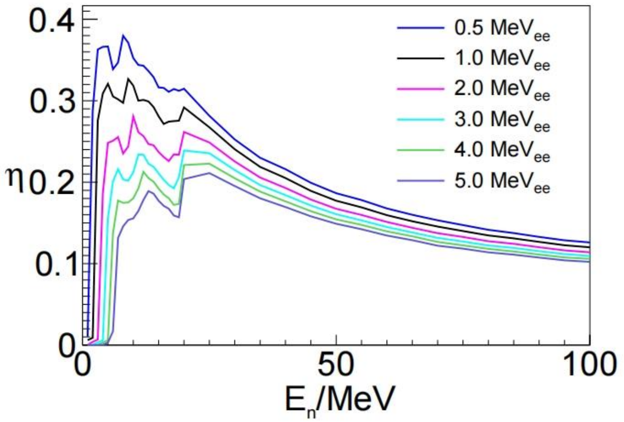
PMT： Hamamatsu R7724

The units are placed 6° apart on a sphere with a radius of 2m



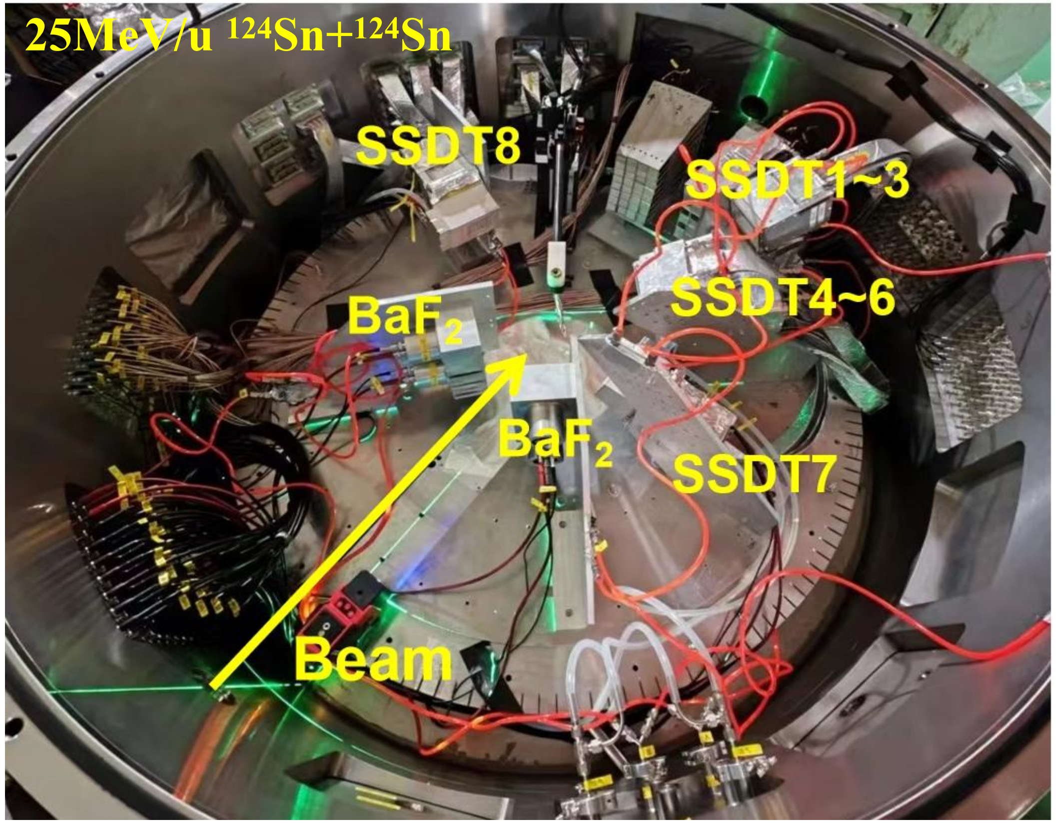


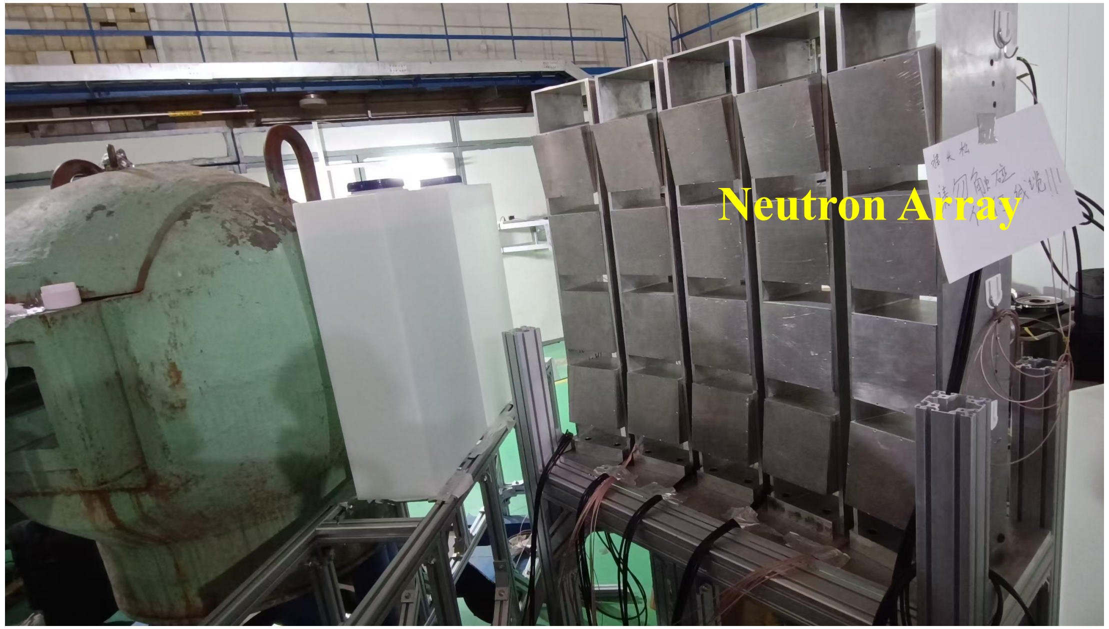
n γ discrimination test



Efficiency simulation by G4

CSHINE2024 Experiment





SSD1~6： 25°<θ<65°

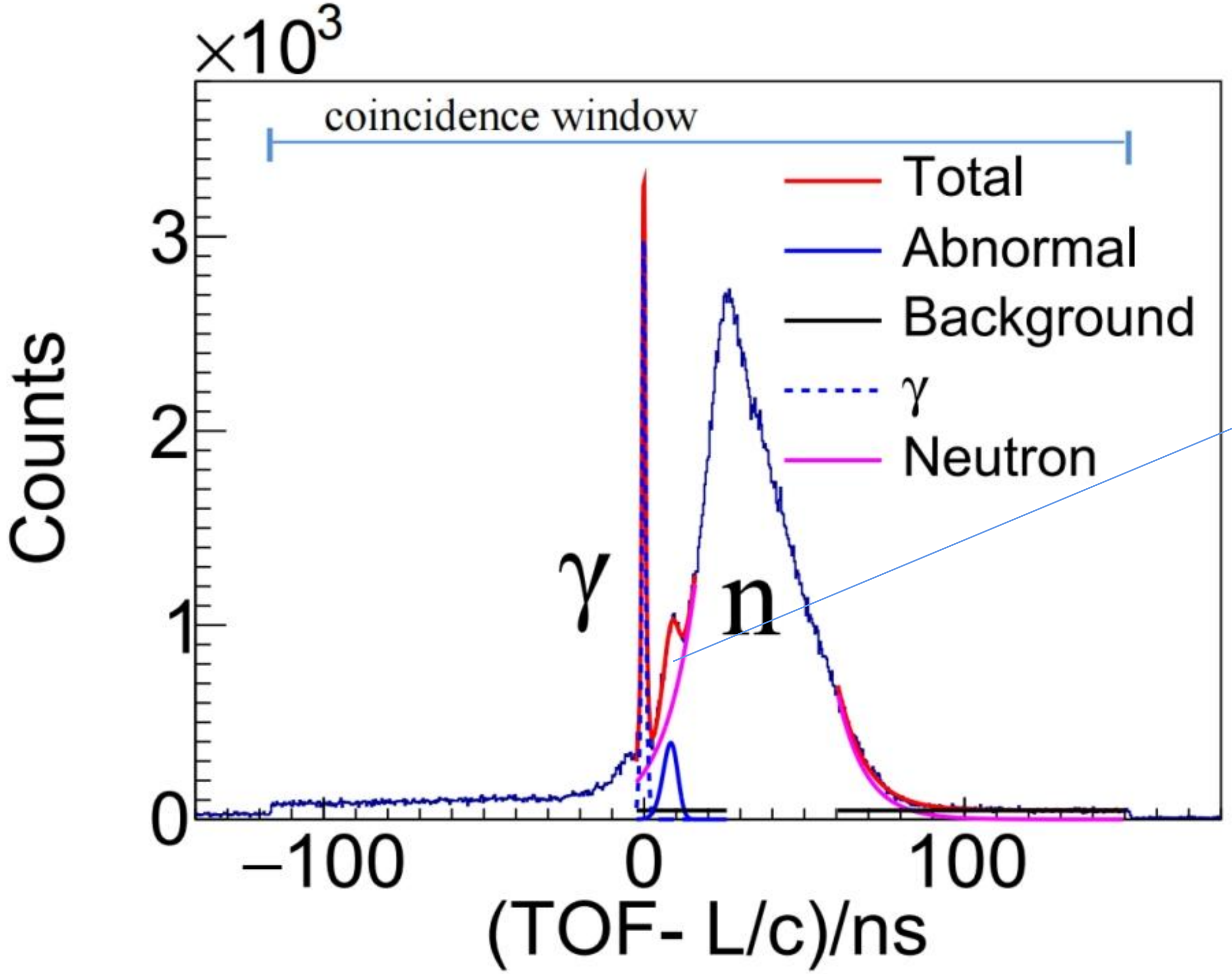
SSD7,8 : θ = 90° , -70°

BaF_2(T0): ±145°

Neutron Array: 27°<θ<53°

~500 Channel

Result——Time Of Flight(TOF) distribution



- A clear distinction between neutrons and γ
- A uniform background exists in the time window
- Abnormal peaks appeared between γ and n peaks

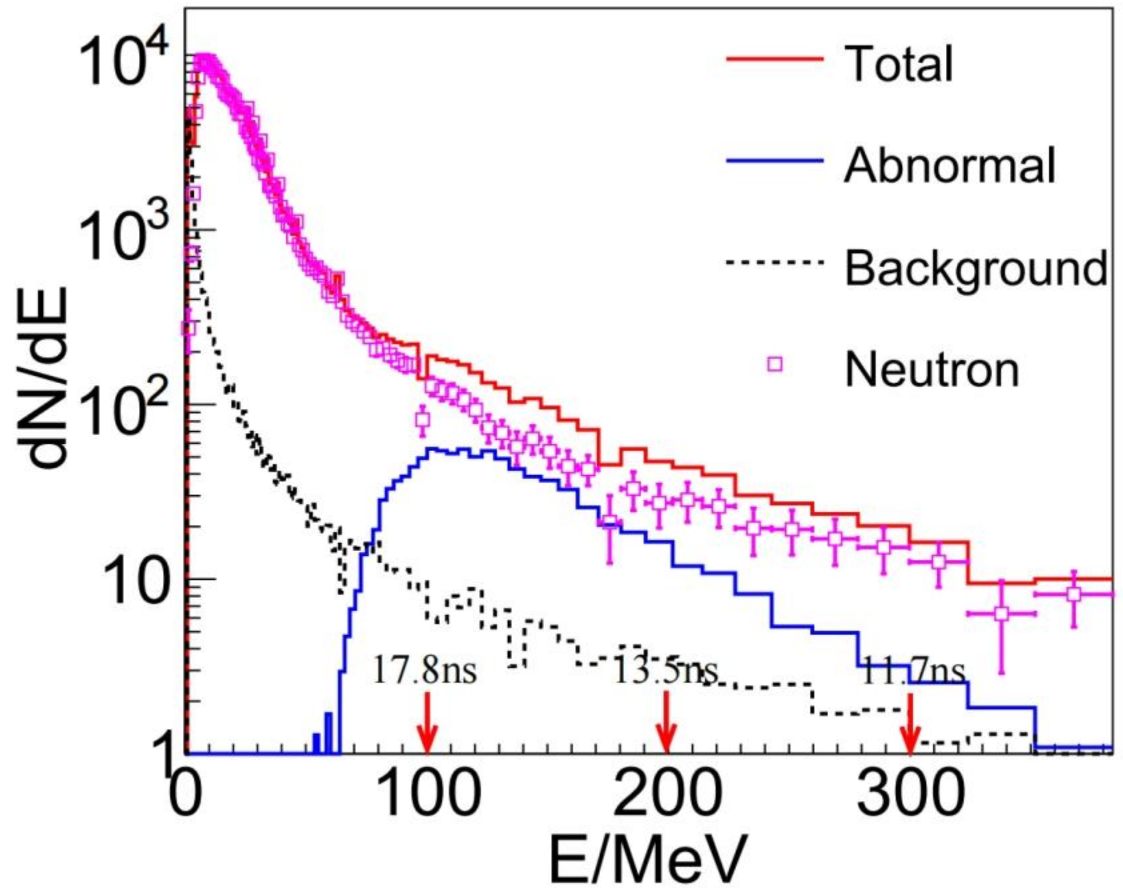
$M_{\gamma}=1$： neutron peak significantly decreased, decline of abnormal peak is not obvious

(abnormal peak may be the secondary products from target chamber)

$$\sigma_{\exp} = 744 \pm 40\,ps = \sqrt{212^2 + 713^2}\,ps$$

space effect of unit

Result——Energy spectrum



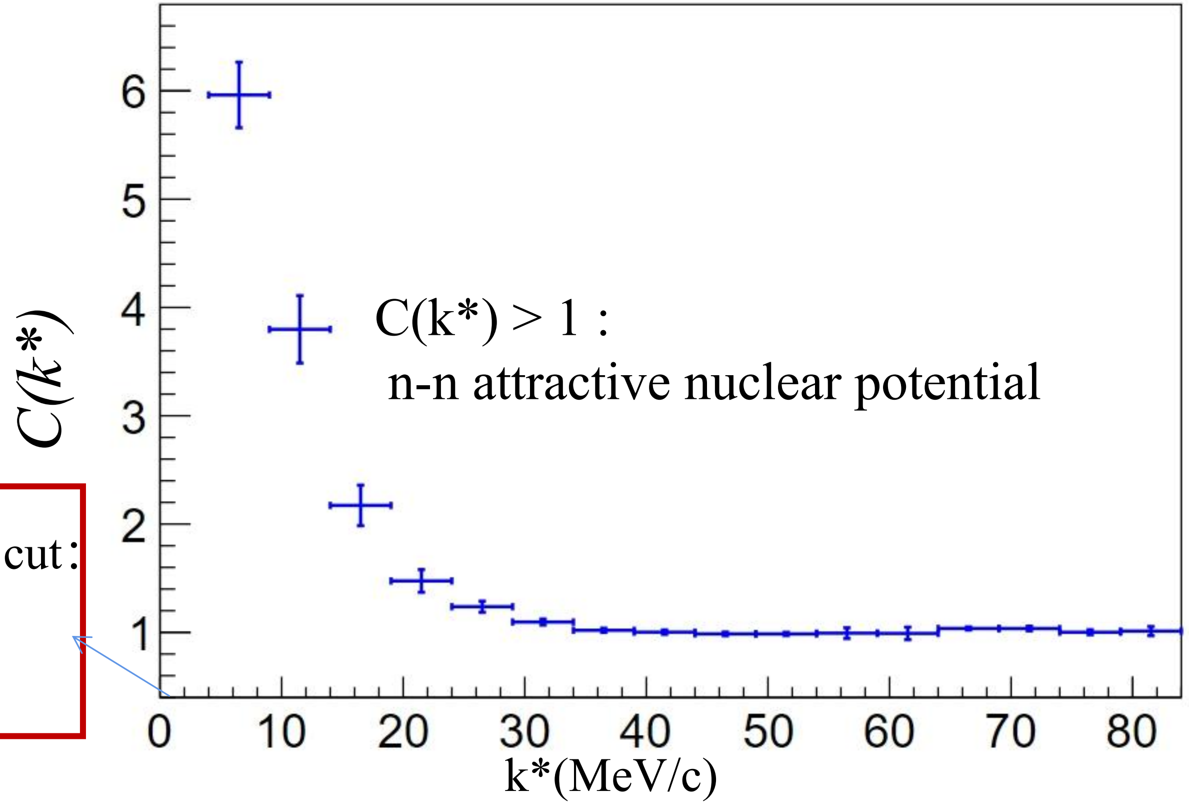
1. The component of background are converted from TOF to energy spectrum using Monte Carlo

2. Abnormal peaks have little effect on the energy spectrum below 100MeV.

The energy uncertainty of data above 100MeV is already large: 100(10)，200(30), 300(60)MeV for σ_{TOF} = 744ps

Result——Neutron-Neutron Correlation Function

~20w two neutron events(TOF:12.5~80ns、E:3~72MeV)) are used



Caused by the phase space cut：
Energy threshold
Angular resolution limit

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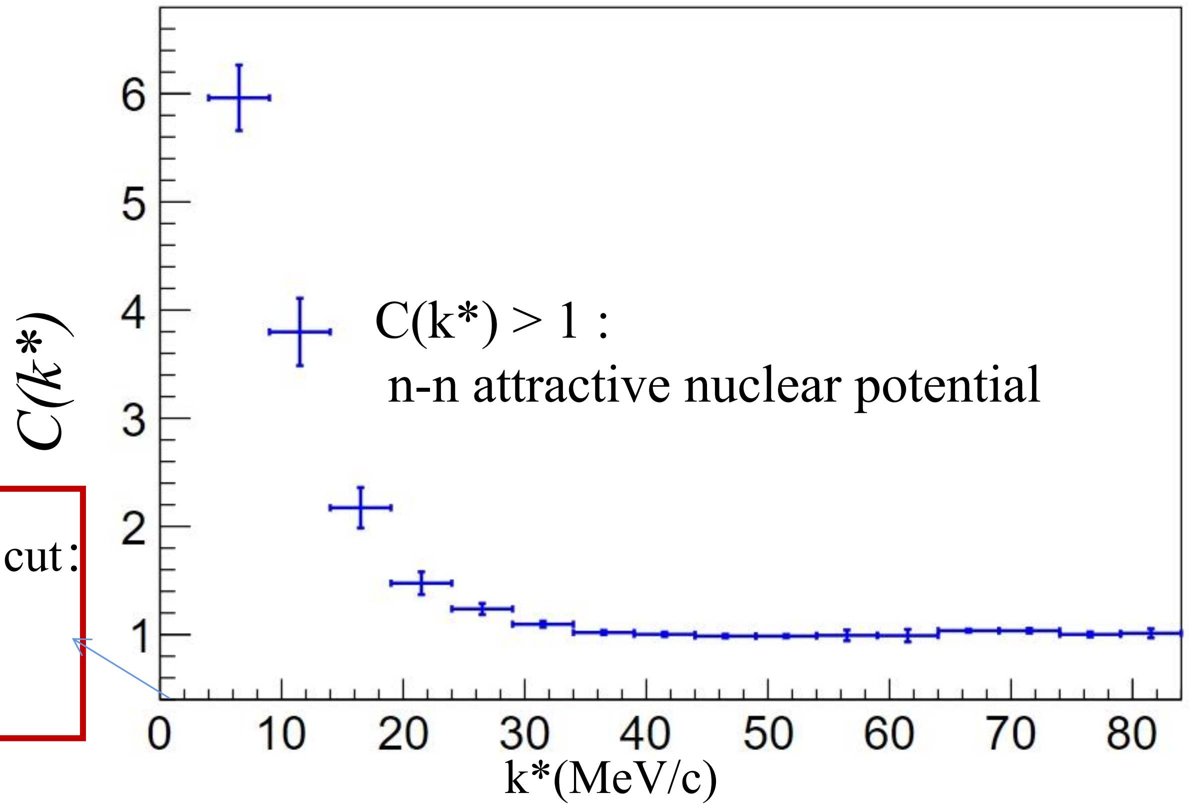
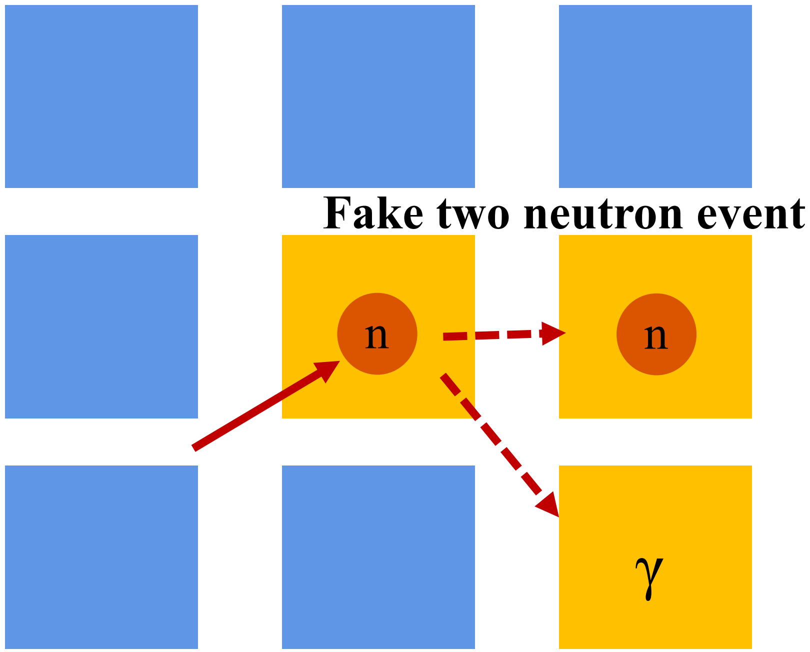


Caused by the phase space cut：
Energy threshold
Angular resolution limit

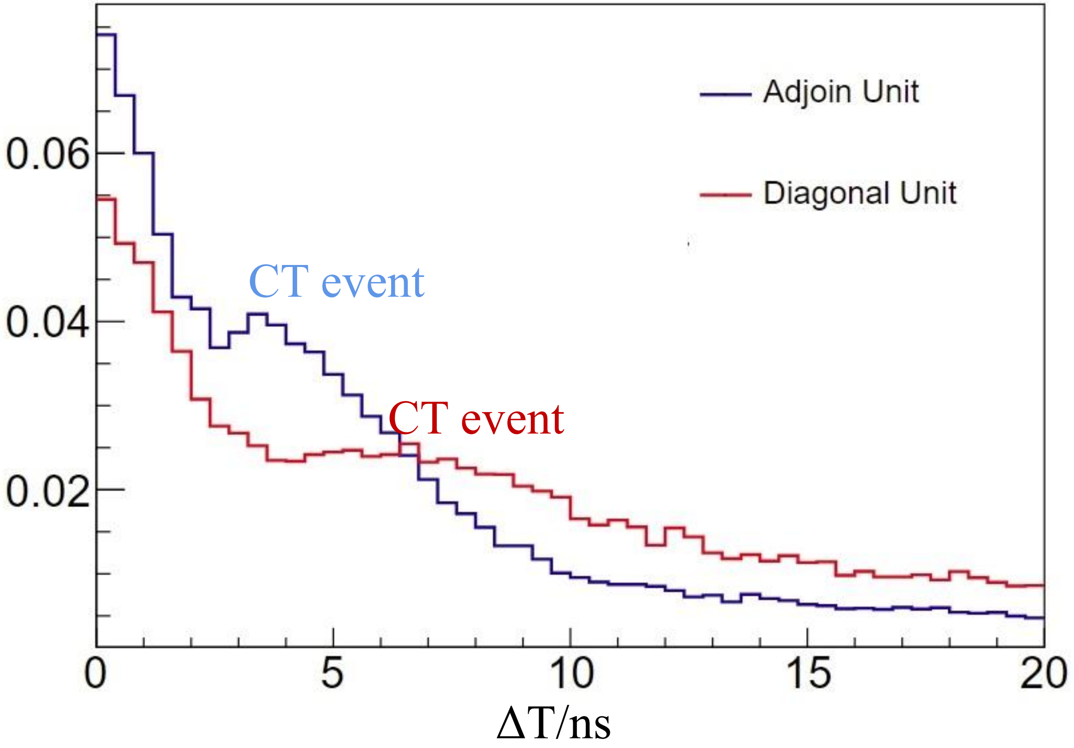
The effect of cross talk and uniform background has not been considered!

$$C_{nn} = \frac{F_{sam,nn}(Q)}{F_{mix}(Q)} = \frac{1}{\lambda_{nn}}\left[\frac{C_{\exp}(Q)}{A} - \lambda_{ct}\frac{F_{sam,ct}(Q)}{F_{mix}(Q)} - \lambda_{bkg}\frac{F_{sam,bkg}(Q)}{F_{mix}(Q)}\right]$$

Result—— Cross talk rejection



Cross talk: a single neutron scatters from a unit to another unit or the secondary γ emits to another unit.

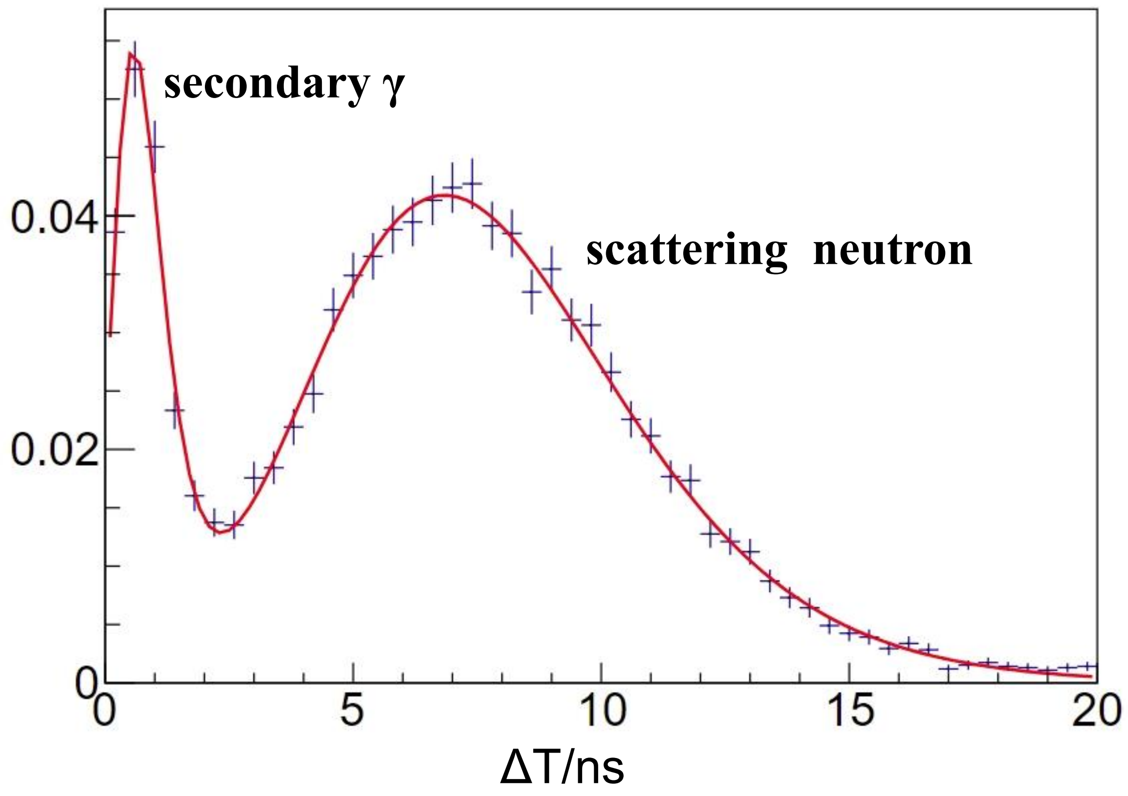


ΔT: TOF difference of the two neutron events

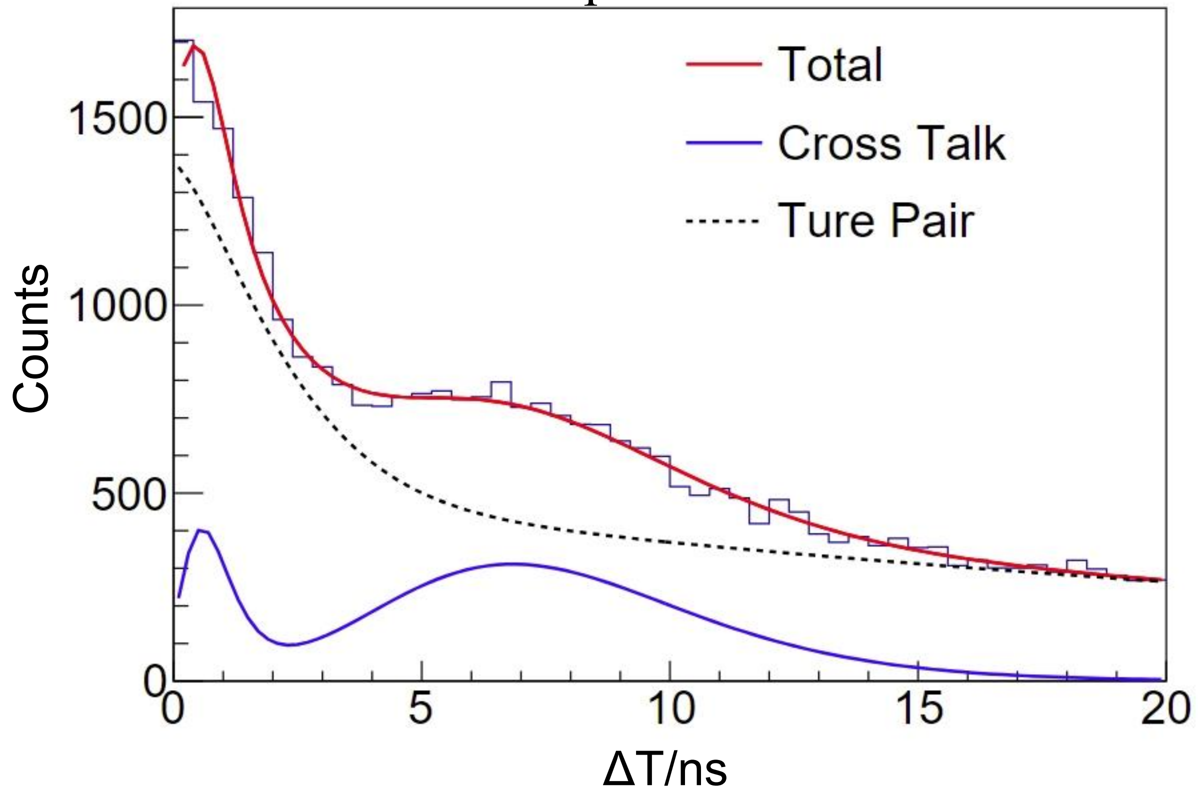
As the flight distance increases, the time difference becomes larger

Result—— Cross talk rejection

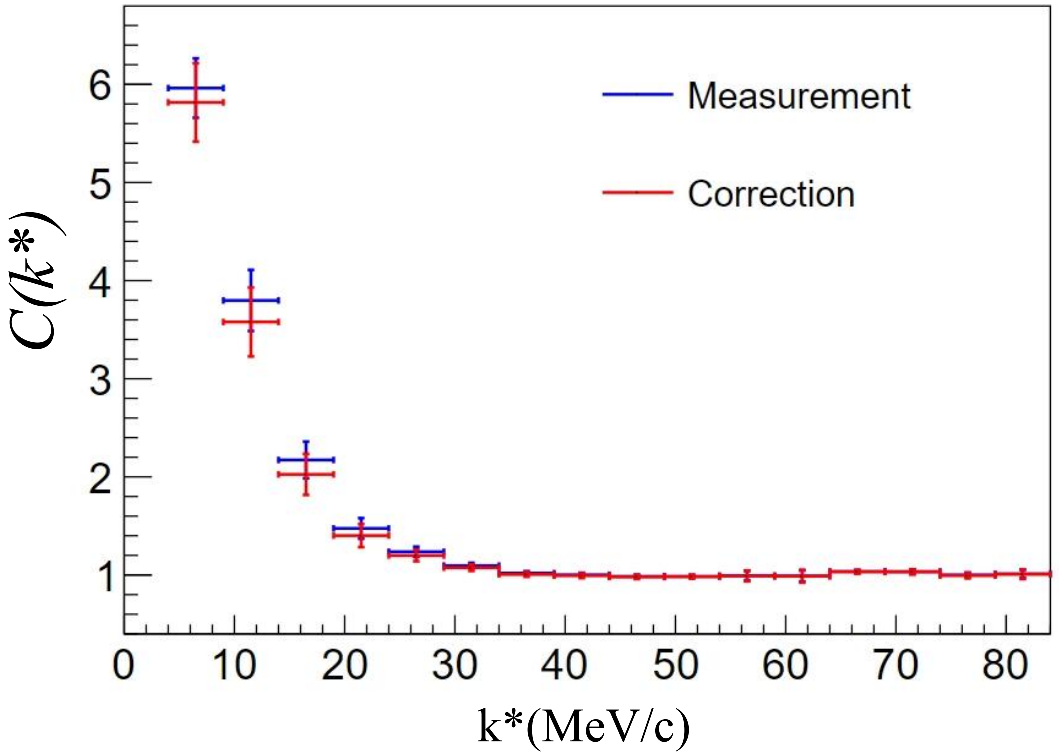
Time difference distribution of ct events(simulation)

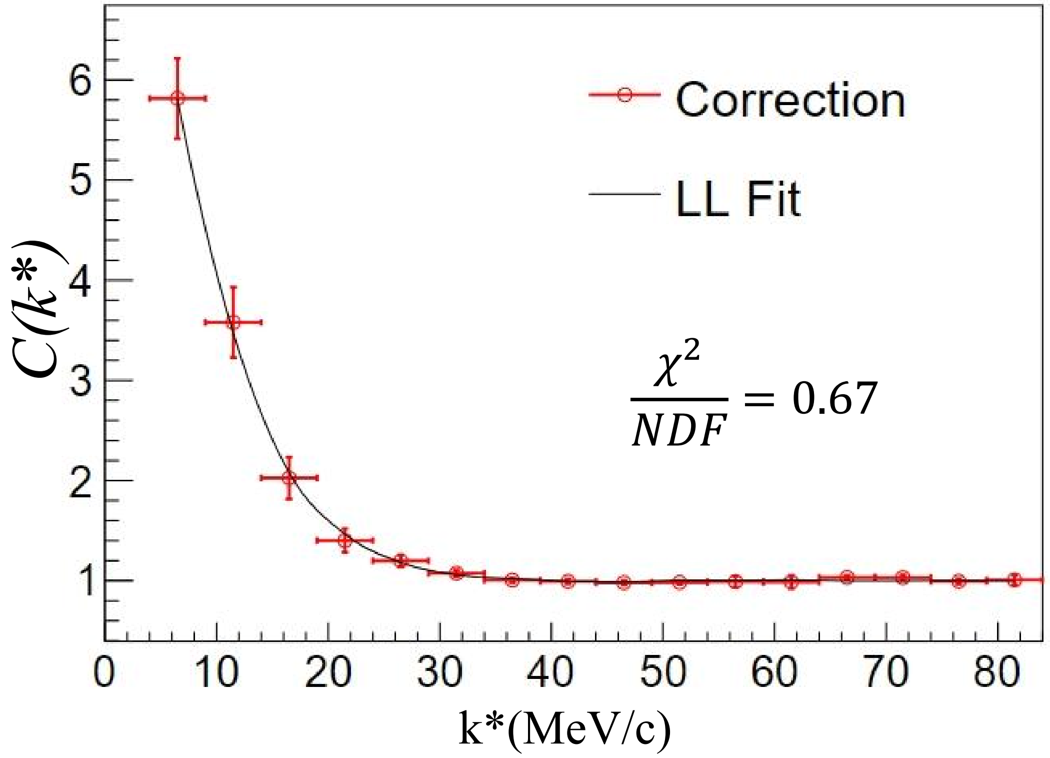


The number of ct events was obtained by fitting the experimental data



Result—— L-L Fitting

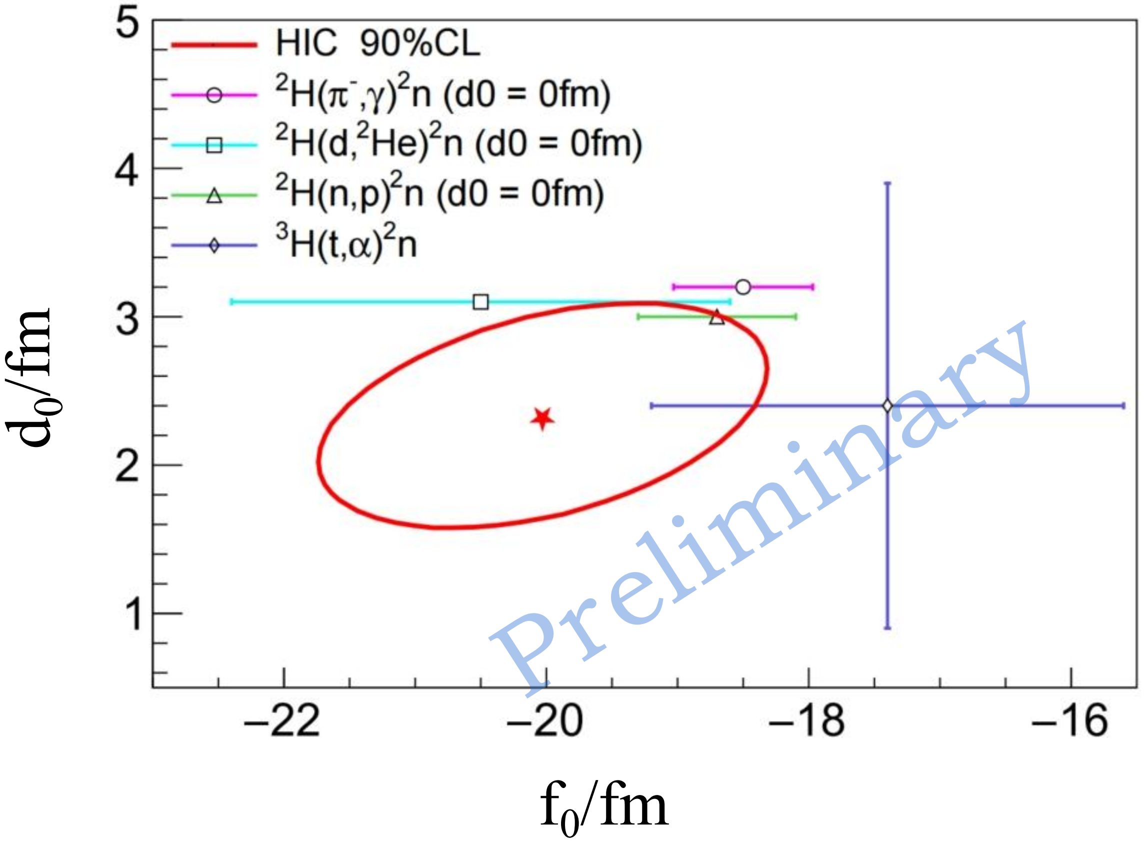


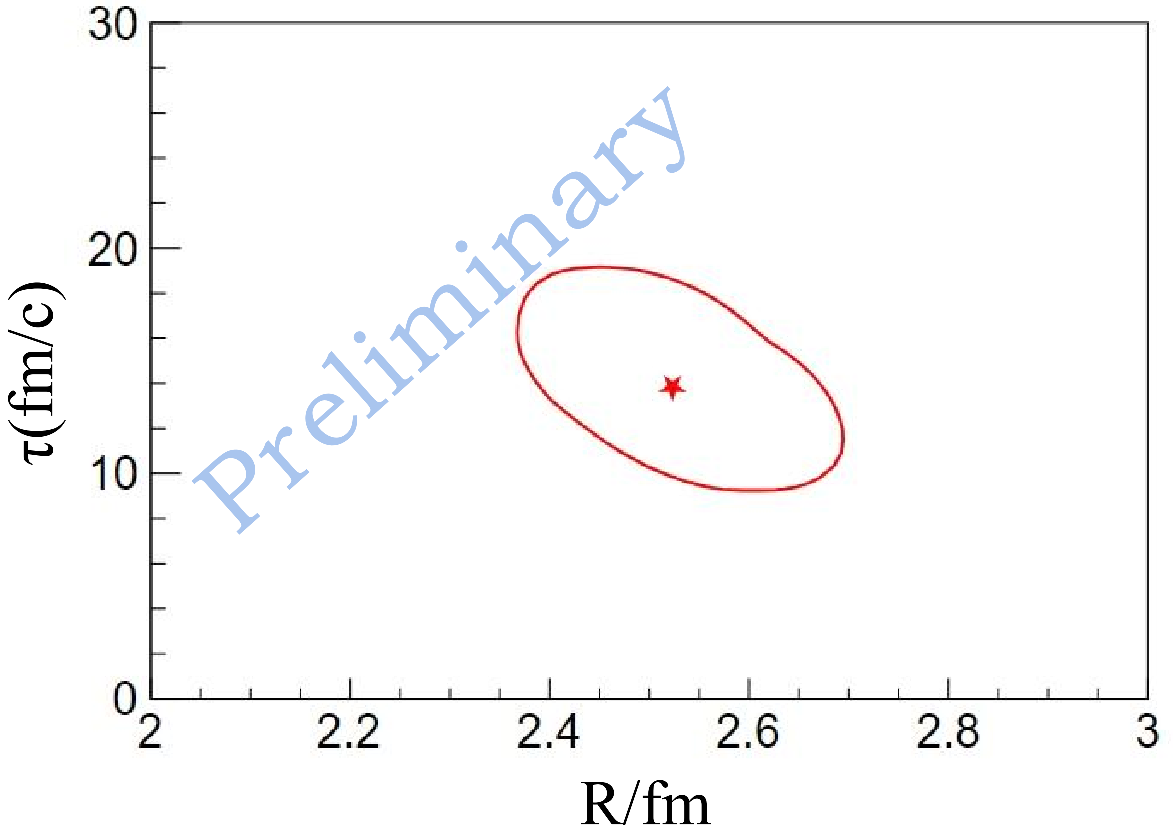


The main errors of data points come from flight distance uncertainty, statistical error and the threshold uncertainty in simulation.

We use the LL method to fit n-n correlation function after correction

Result—— L-L Fitting





The f0 and d0 measured by us in heavy ion collision agree with reference value(by scattering experiment)!

The single particle emission source size and emission timescale are also obtained here

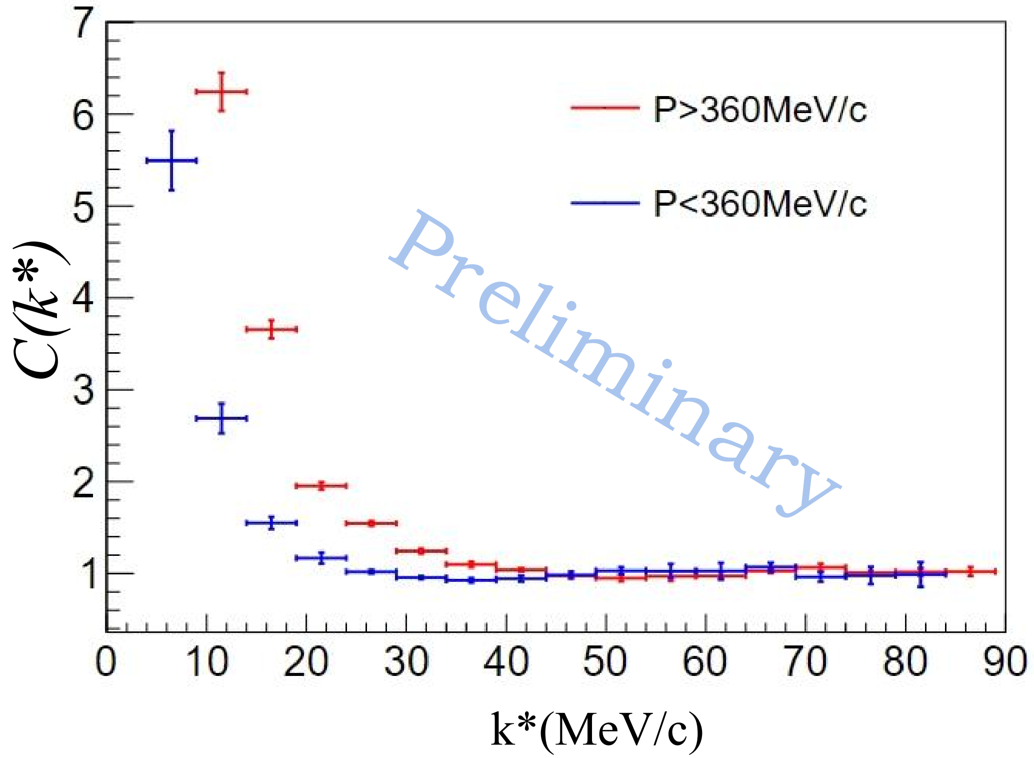
Result—— Momentum-gated correlation function

Multi-source picture in low energy HIC：

The characteristics of the emission source are inconsistent in different periods.

Pre-equilibrium emission ⟹ **Higher particle momentum**

Compound emission ⟹ **Lower particle momentum**



enhancement in the correlation function of high momemtum neutron pairs

Summary

- We make the neutron array and mounted it on CSHINE, and completed the beam experiment at HIRFL in Lanzhou.

- We calibrated the neutron data and obtained the neutron energy spectrum

- We obtain the correlation function and modify it, the f0 d0 τ R are preliminarily obtained by L-L method.

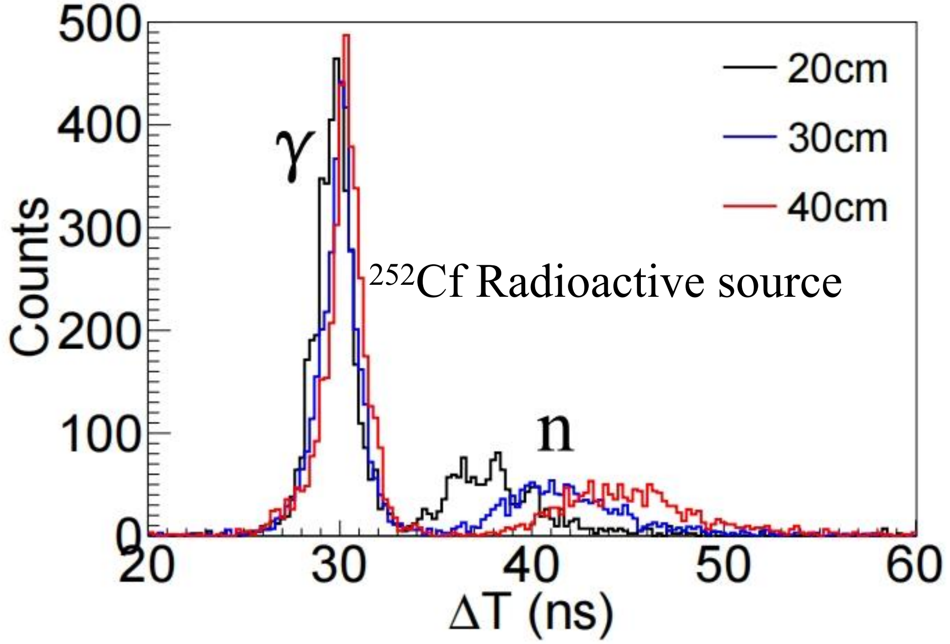
OutLook：

The analysis of momentum-gated correlation function and the calibration of SSD Telescope are on the way.

Thanks

Thank you to all the members of the CSHINE2024 experiment !

BACK UP

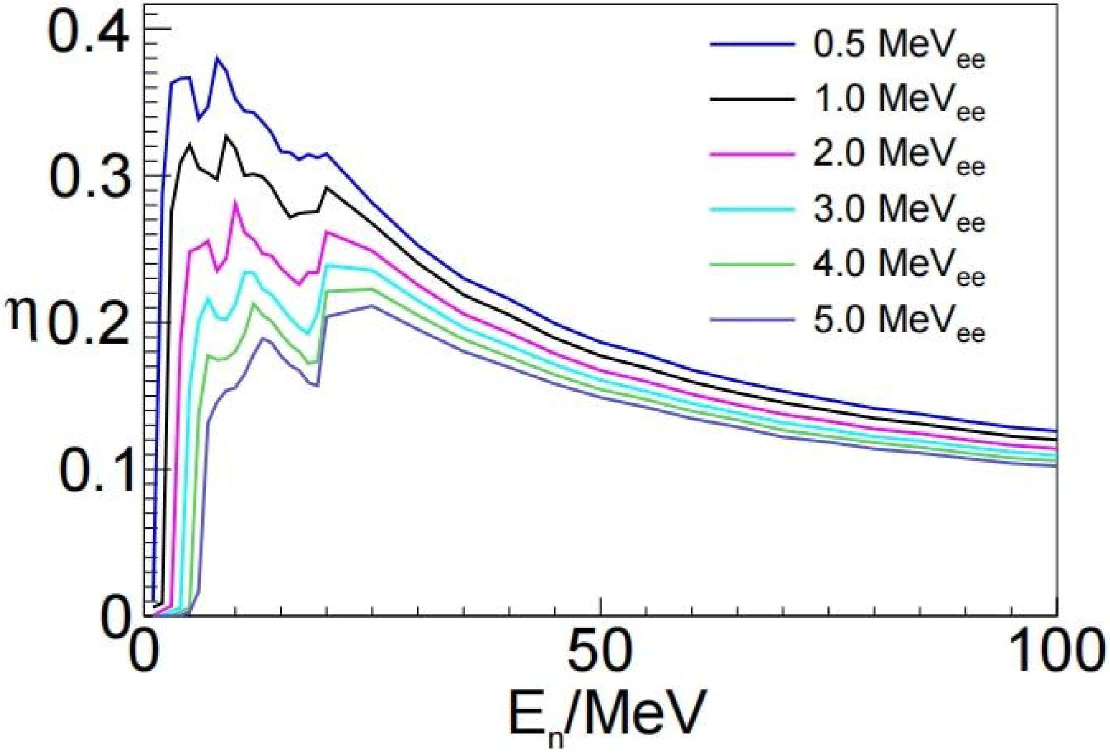


A clear distinction between neutrons and γ

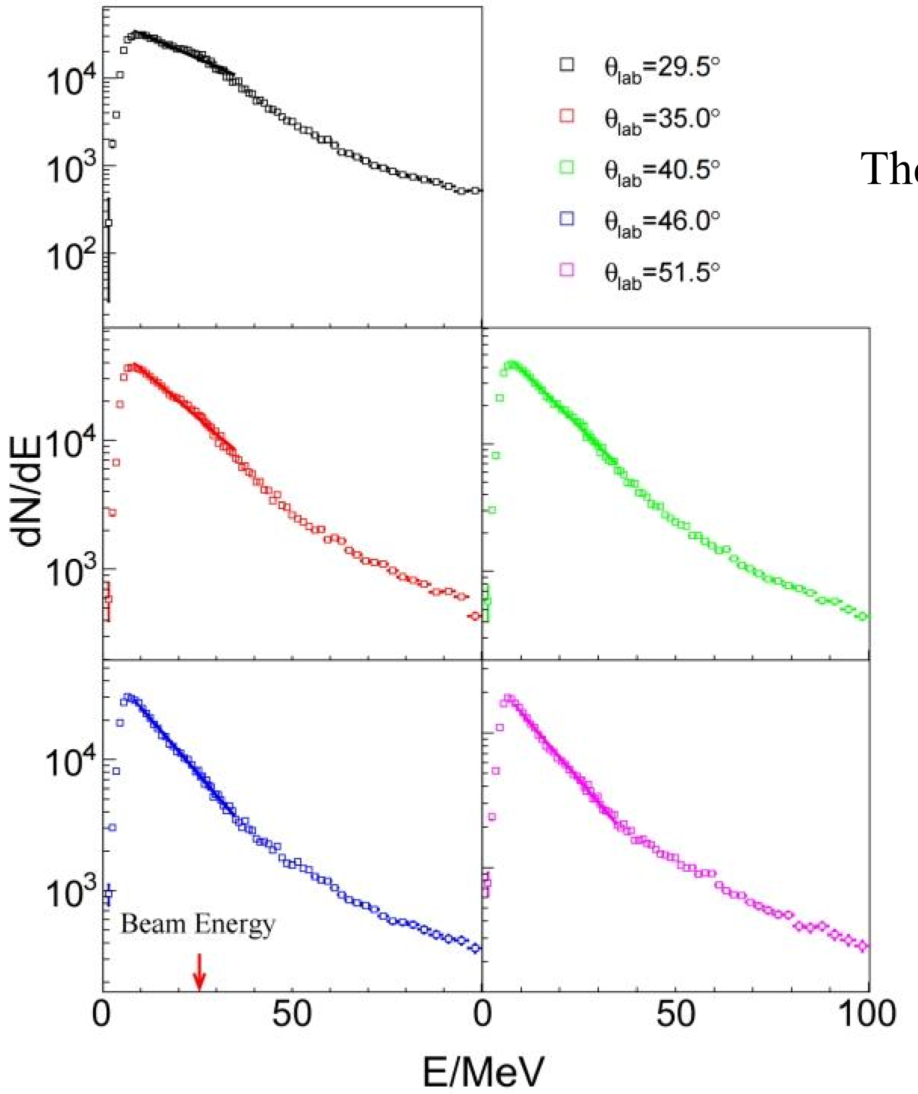
Neutron Unit efficiency Geant4 simulation

Neutron cross section packet: G4NDL4.5

Physical list: FTFP_BERT_HP



BACK UP



The statistical emission range(8~30MeV) is fitted exponentially(**$exp(-E_n/T)$**):

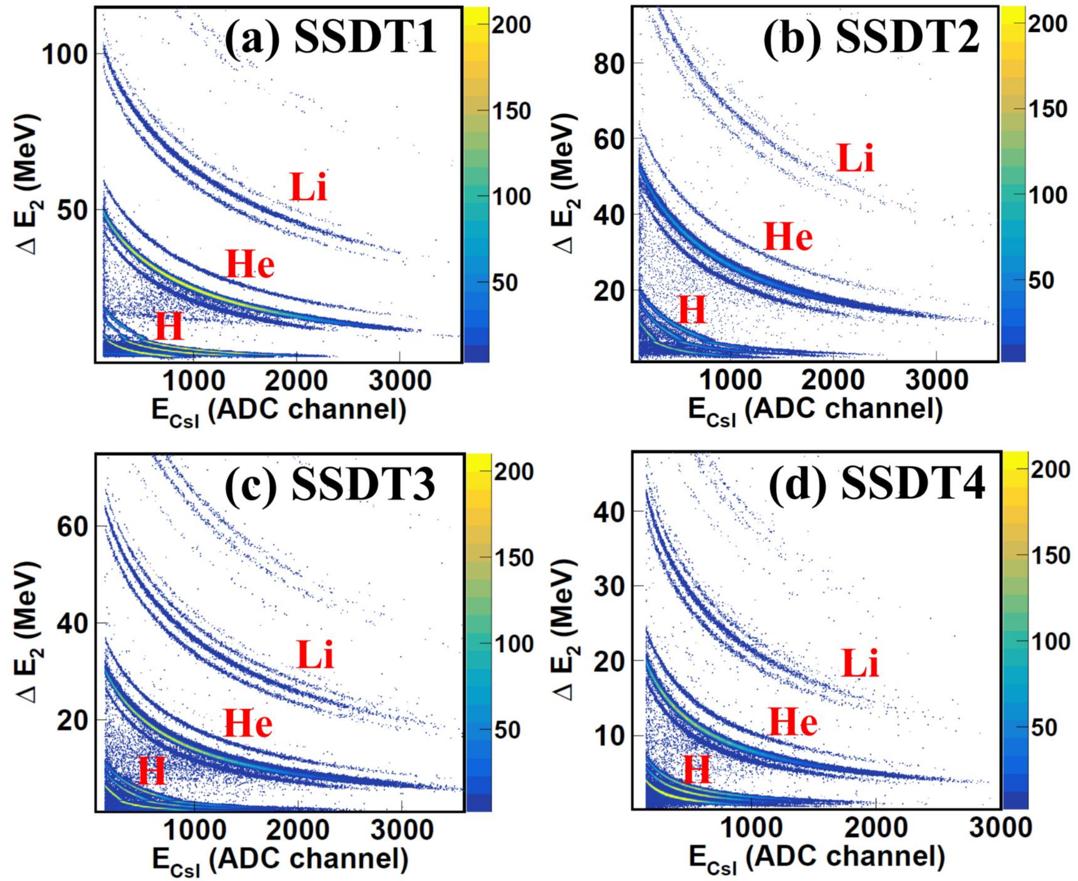
θ_{lab}(°)	29.5°	35.0°	40.5°	46°	51.5°
T(MeV)	22.87	17.11	14.43	12.98	12.99

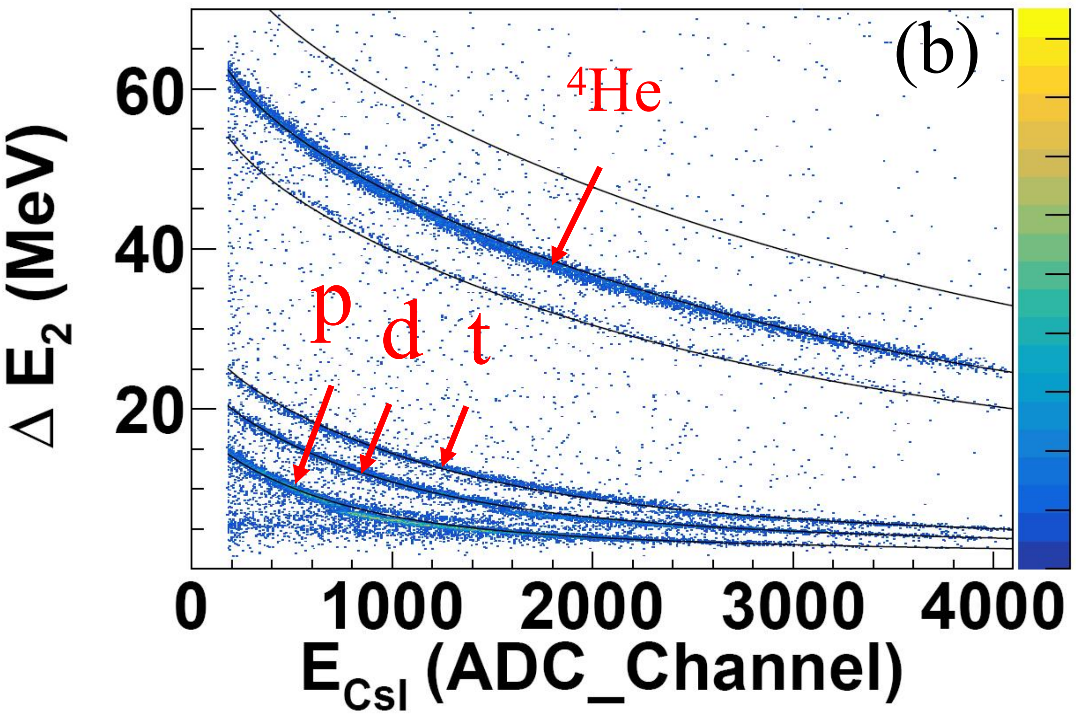
The nuclear temperature and statistics decrease with increasing θ_{lab}

The variation of energy spectrum with angle is consistent with the dynamics of HIC

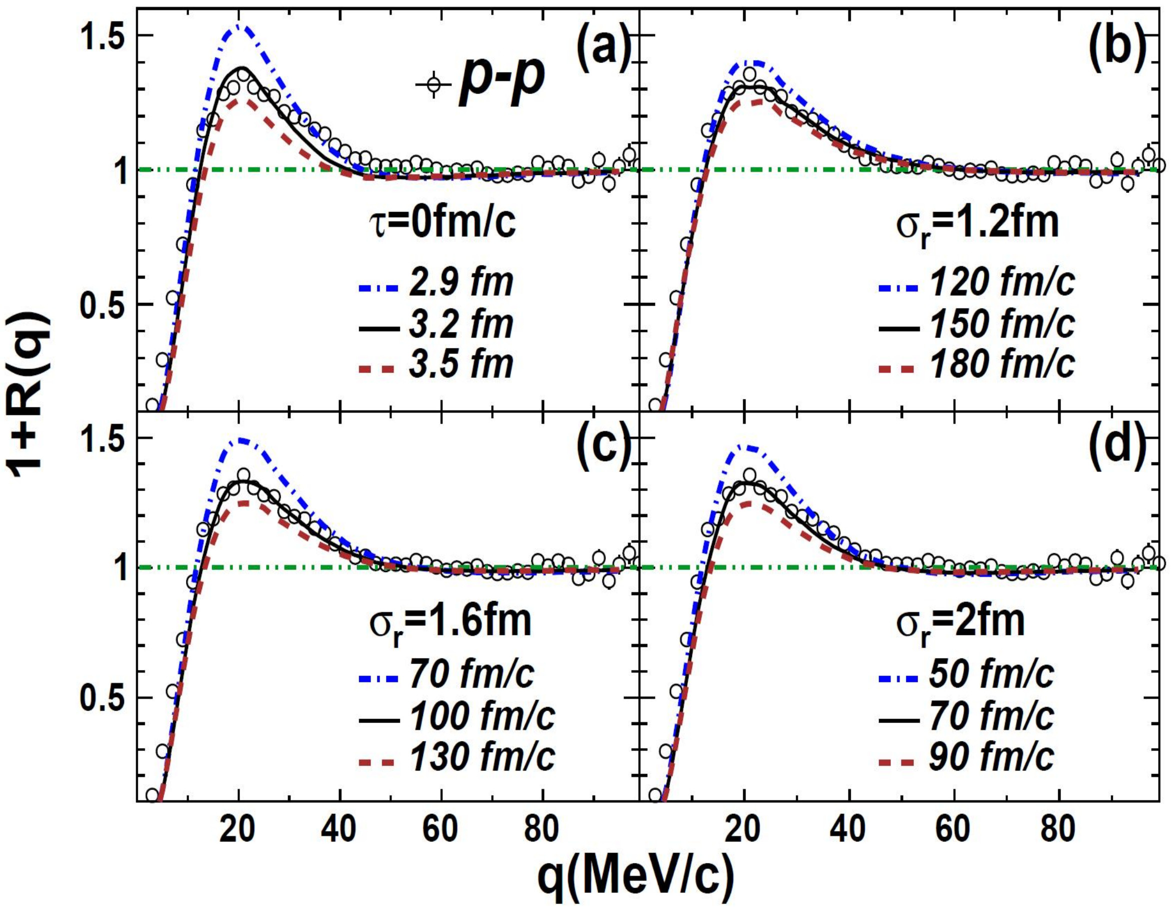
BACK UP

The PID in the CSHINE2019



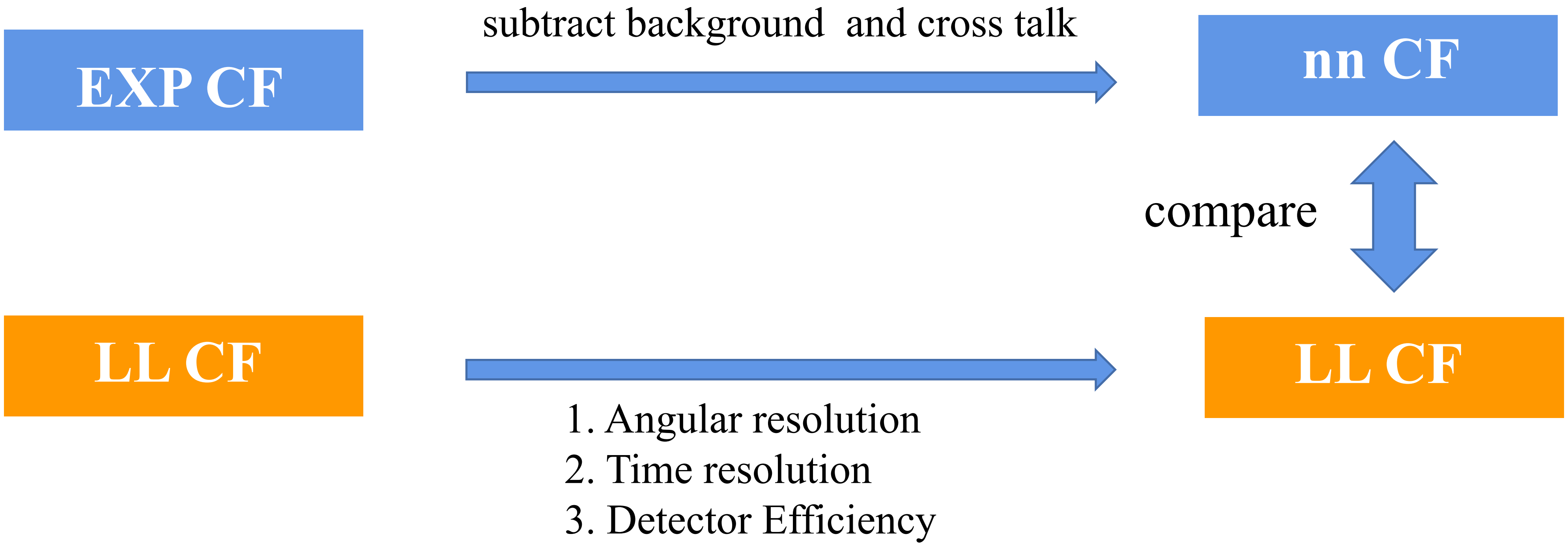


The proton-proton correlation function in the CSHINE2018



The line are the calculations of Crab with different source size and emission timescale

BACK UP


EXP CF
subtract background and cross talk
nn CF
compare
LL CF
LL CF
1. Angular resolution
2. Time resolution
3. Detector Efficiency

BACK UP

$$C_{\exp}(Q) = \frac{F_{mix}(Q_{big})}{F_{sam}(Q_{big})} \frac{N_{sam}(Q)/N_{sam}}{N_{mix}(Q)/N_{mix}}$$

N(Q) denote the count of pair in bin Q
F(Q) denote the Q distribution = N(Q)/N

$$= A[\frac{N_{sam,nn}}{N_{sam}} \frac{N_{sam,nn}(Q)}{N_{sam,nn}} + \frac{N_{sam,ct}}{N_{sam}} \frac{N_{sam,ct}(Q)}{N_{sam,ct}} + \frac{N_{sam,bkg}}{N_{sam}} \frac{N_{sam,bkg}(Q)}{N_{sam,bkg}}]/(N_{mix}(Q)/N_{mix})$$

$$= A[\lambda_{nn} \frac{F_{sam,nn}(Q)}{F_{mix}(Q)} + \lambda_{\mathrm{ct}} \frac{F_{sam,ct}(Q)}{F_{mix}(Q)} + \lambda_{\mathrm{bkg}} \frac{F_{sam,bkg}(Q)}{F_{mix}(Q)}]$$

λ_{nn}: **fraction of true nn pair**

λ_{ct}: **fraction of cross talk pair**

λ_{bkg}:**fraction of single neutron and background**

Assume: $F_{mix}(Q) = F_{mix,nn}(Q)$

$$C_{nn} = \frac{F_{sam,nn}(Q)}{F_{mix}(Q)} = \frac{1}{\lambda_{nn}}[\frac{C_{\exp}(Q)}{A} - \lambda_{ct} \frac{F_{sam,ct}(Q)}{F_{mix}(Q)} - \lambda_{bkg} \frac{F_{sam,bkg}(Q)}{F_{mix}(Q)}]$$

$F_{sam,ct}(Q)$ and $F_{sam,bkg}(Q)$ are obtained by MC simulation

λ_{bkg} is obtained from fitting of TOF spectrum, λ_{ct} is obtained from ΔT distribution + G4 simulation