



清华大学
Tsinghua University

Short-Range Correlations Study w/ Inverse pA Collision

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➤ Strong Force vs Nuclear Force

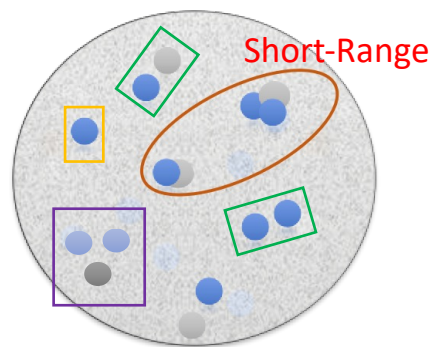
❑ Nuclear force is a “weak” strong force, but too complicated for QCD in description of Nuclei

❑ Surprisingly, shell-models work very well

✓ Sum of nucleon-nucleon(NN) Interactions → mean field

✓ Modern NN potentials, e.g. AV18

$$V = \sum_i \bar{V}(i) + \sum_{i<j} V^{(2)}(i,j) + \sum_{i<j<k} V^{(3)}(i,j,k) + \dots$$



- NN terms fitted from data
- Too hard for NNN and beyond
- Short range part (non-nucleonic)?

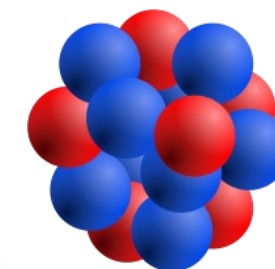
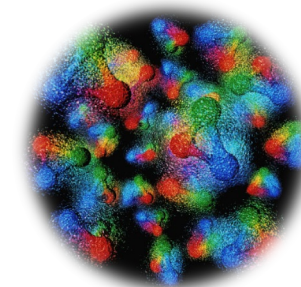
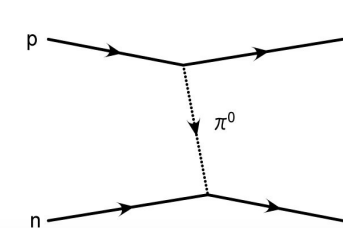
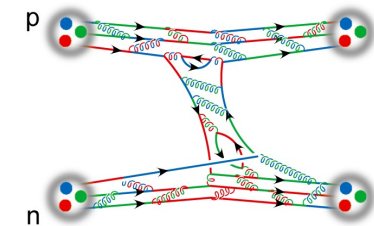
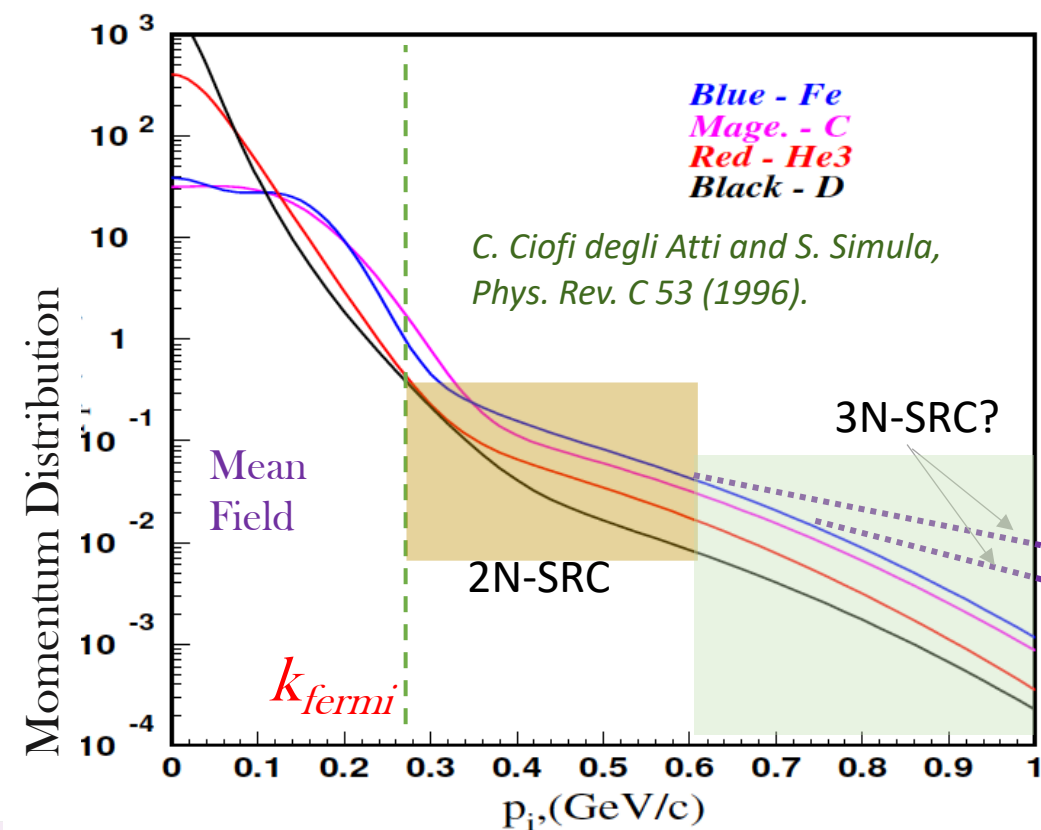
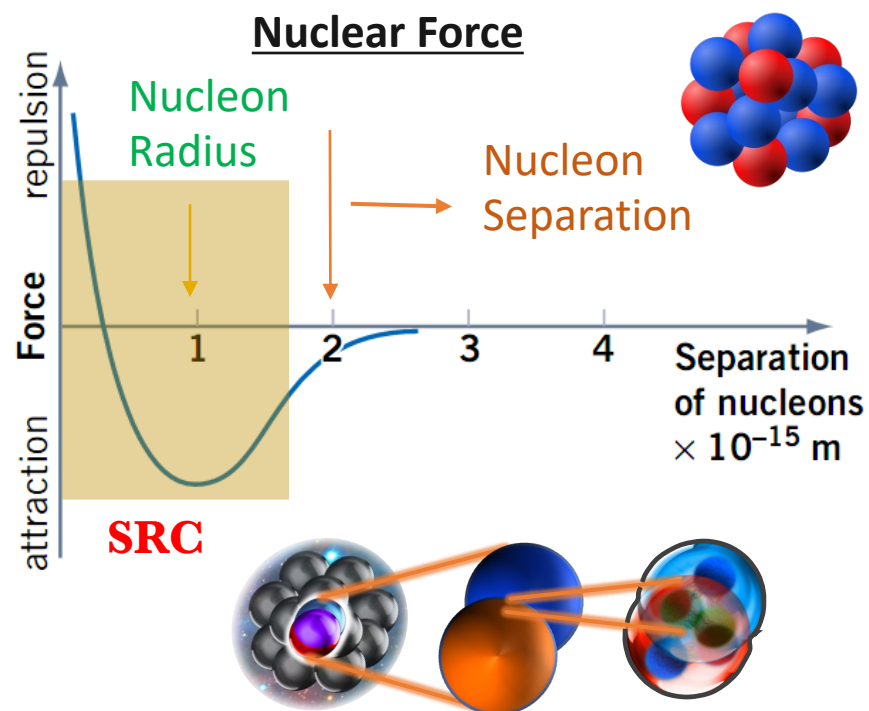
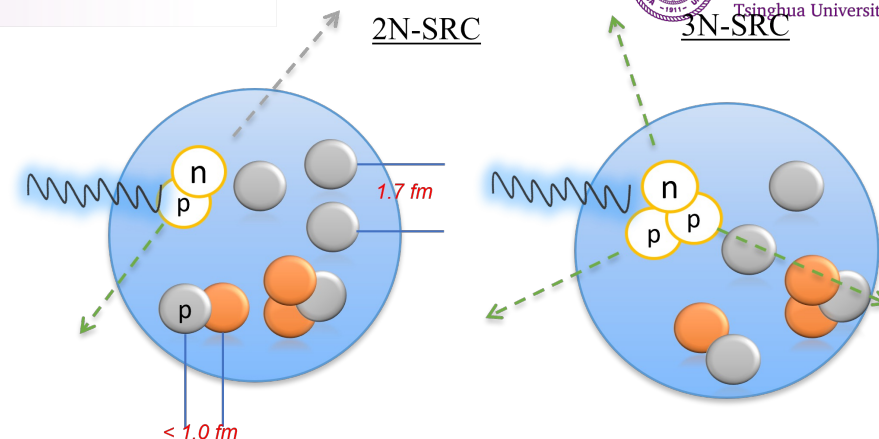


TABLE I. Argonne V18 spin-isospin operators in coordinate space.

Term	Spin-isospin operator in r space
O_1	\mathbf{I}
O_2	$(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$
O_3	$(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)$
O_4	$(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$
O_5	$S_{12} = 3(\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{r}})(\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{r}}) - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$
O_6	$S_{12}(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$
O_7	$(\mathbf{L} \cdot \mathbf{S})$
O_8	$(\mathbf{L} \cdot \mathbf{S})(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$
O_9	$(\mathbf{L} \cdot \mathbf{L})$
O_{10}	$(\mathbf{L} \cdot \mathbf{L})(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$
O_{11}	$(\mathbf{L} \cdot \mathbf{L})(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)$
O_{12}	$(\mathbf{L} \cdot \mathbf{L})(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$
O_{13}	$(\mathbf{L} \cdot \mathbf{S})^2$
O_{14}	$(\mathbf{L} \cdot \mathbf{S})^2(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$
O_{15}	$T_{12} = (3\tau_{1z}\tau_{2z} - \boldsymbol{\tau} \cdot \boldsymbol{\tau})$
O_{16}	$(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)T_{12}$
O_{17}	$S_{12}T_{12}$
O_{18}	$(\tau_{1z} + \tau_{2z})$

➤ Short Range Correlations (SRC)

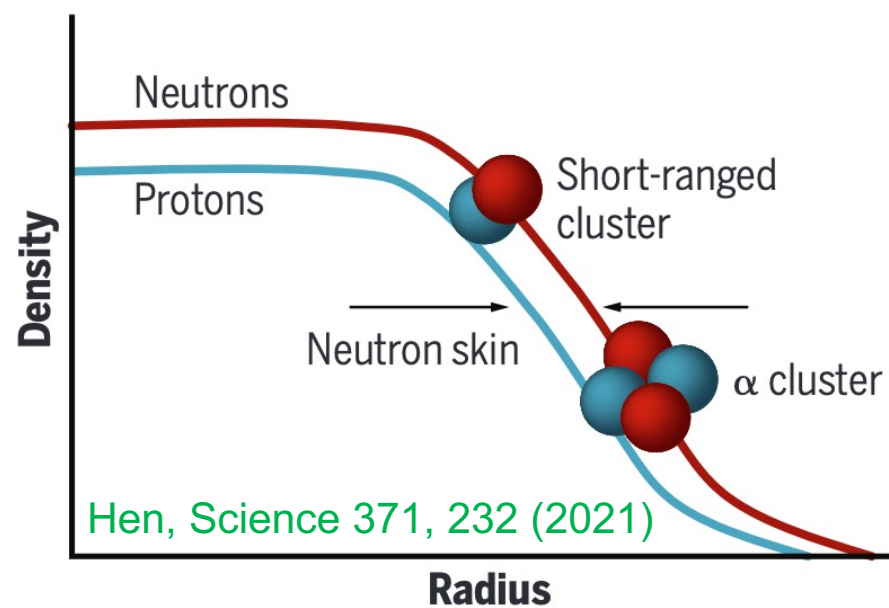
- ❑ 2 or more nucleons highly overlapped → high-density **but cold!**
- ❑ SRC nucleons carry high relative momenta (A-independent)
- ❑ Experimental signals:
 - ✓ Look for back-to-back nucleons after breaking up SRC



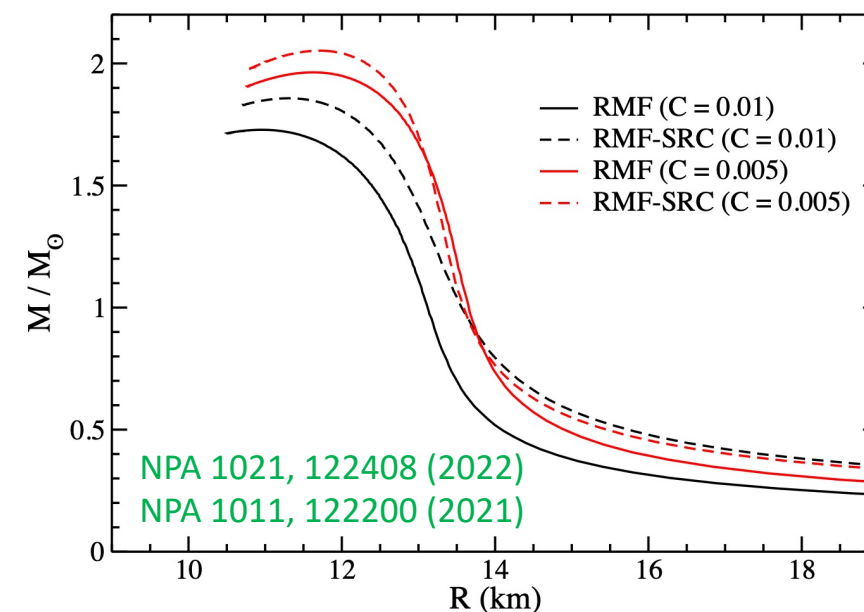
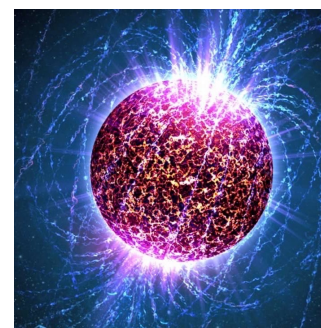
➤ Studying SRC is important

- ❑ Short-Range forces are the extreme cases of NN & NNN forces
- ❑ SRC could be important in forming neutron-rich nuclei

Nucleon density in neutron-rich nuclei



❑ SRC in forming ultra-heavy neutron stars?

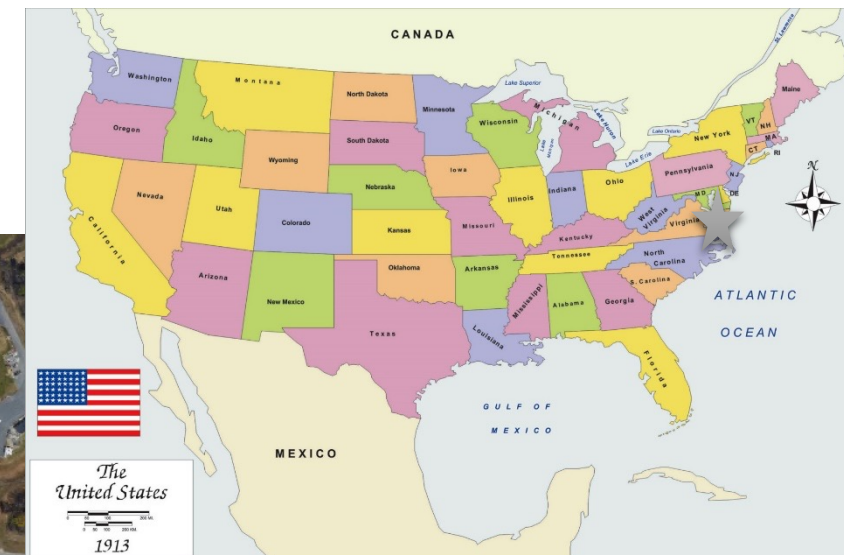
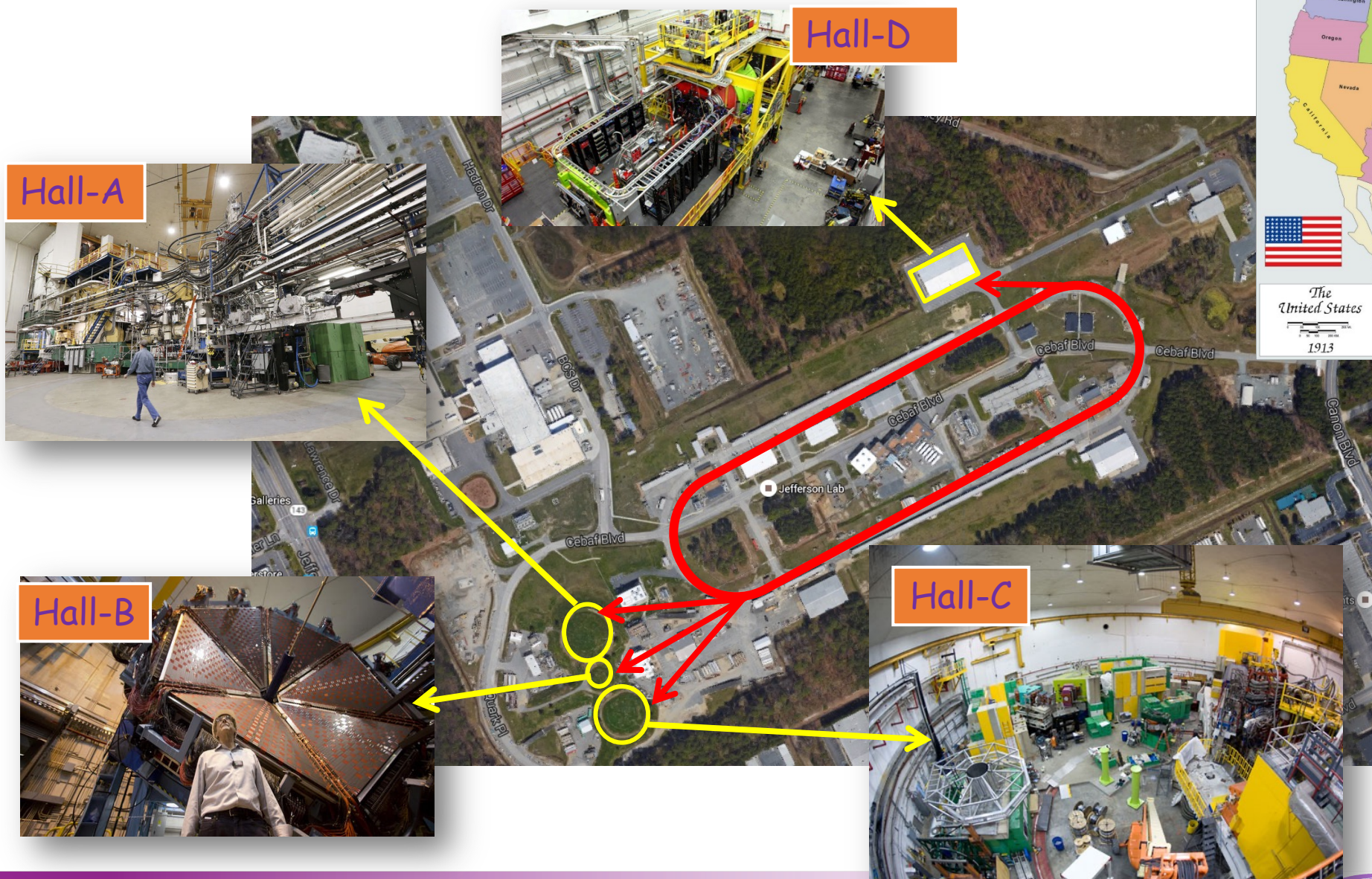


❑ SRC in the mass matrix for neutrino-less double beta decay?

Wang, Zhao, Meng, arXiv: 2304.12009, Song, Yao, Ring, Meng, Phys. Rev. C **95**, 024305



➤ Thomas Jefferson Lab



Jefferson Lab
Thomas Jefferson National Accelerator Facility

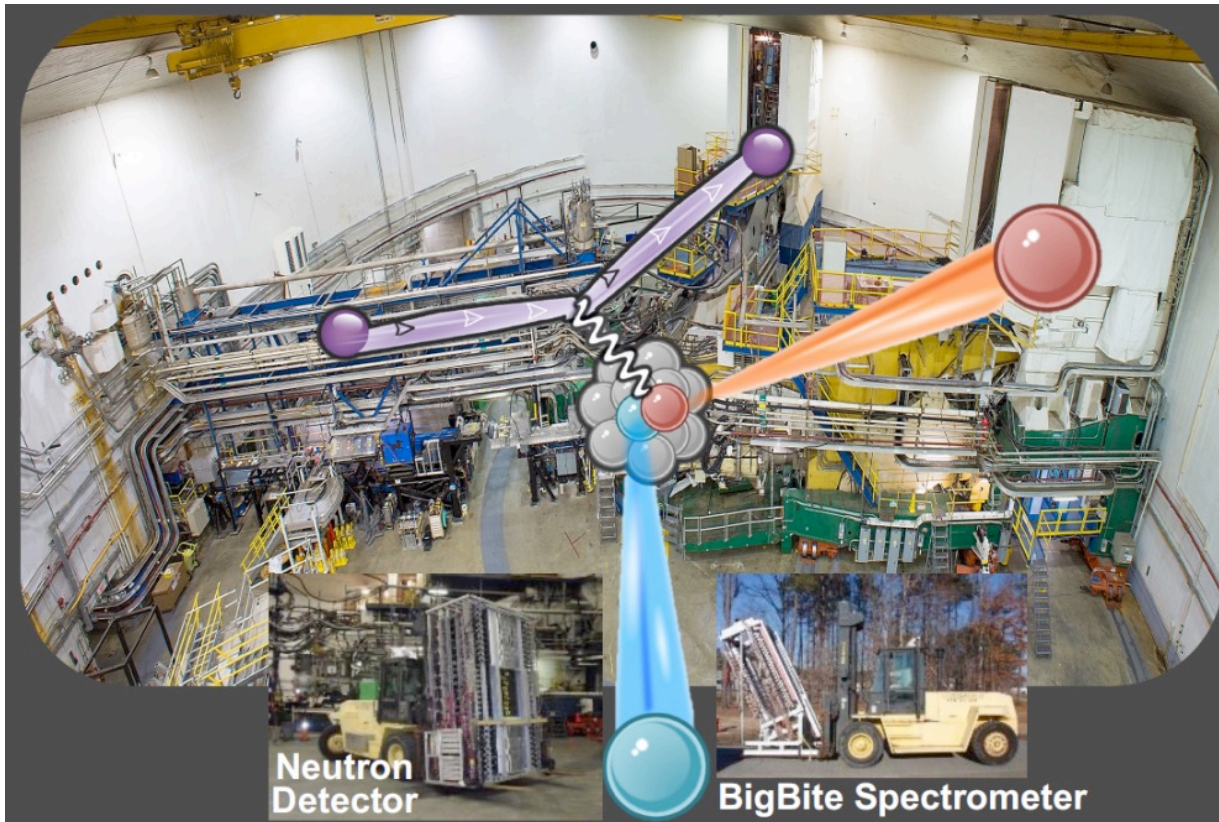


➤ Two Types of Detector Systems

- SRC has small reaction rates → Precision vs. Coverage

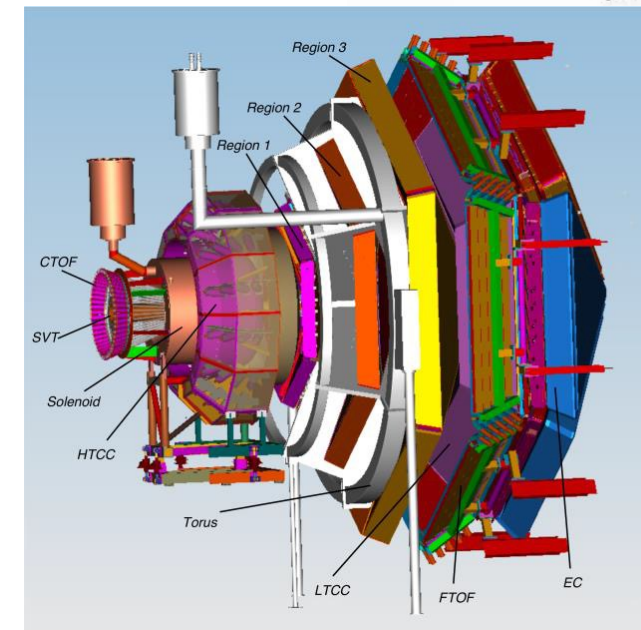
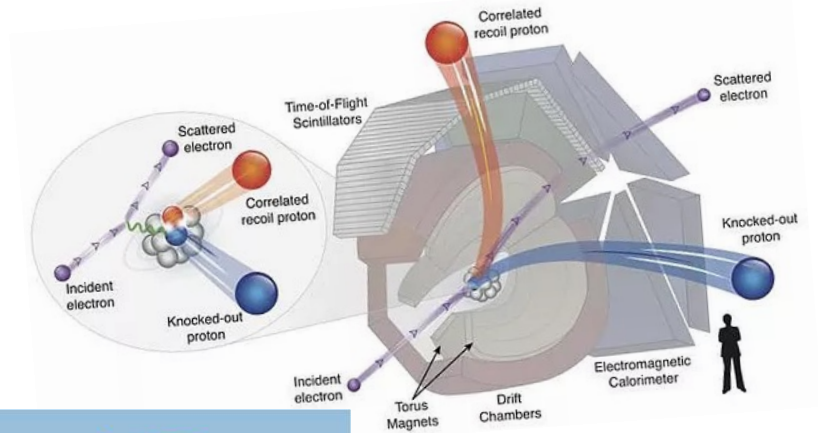
Hall-A HRS / Hall-C HMS

(High-Precision, Limited Acceptance);



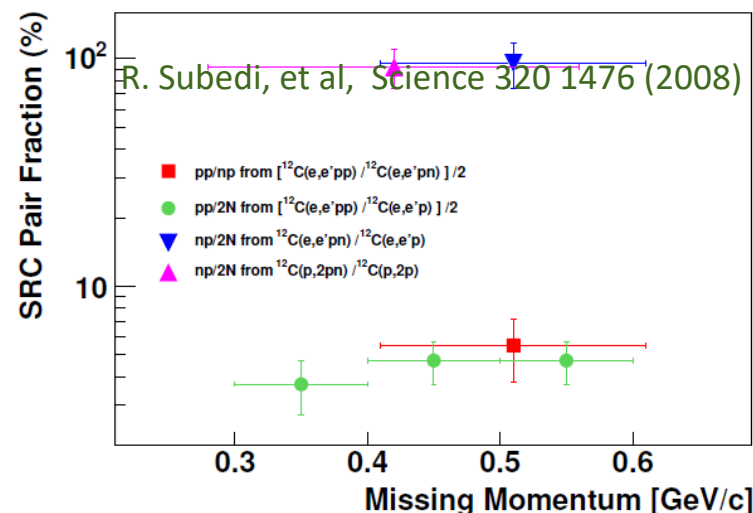
Add third-arm to detector p/n

Hall-B CLAS6/CLAS12 (Low-Precision, Full Acceptation)

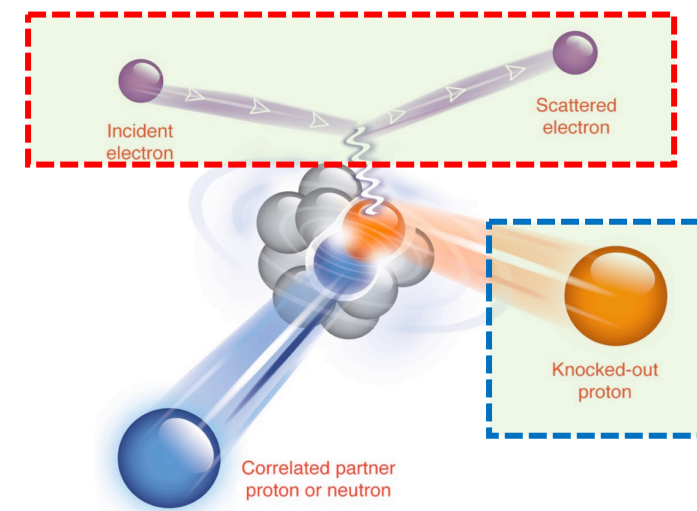
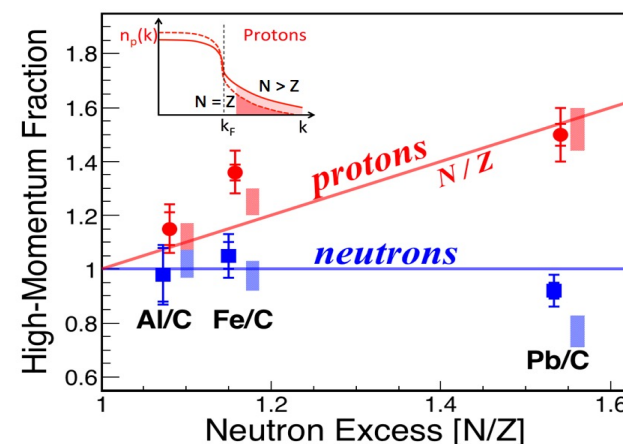


➤ Exclusive SRC Results

❑ Exclusively count np-/pp-/nn-SRC pairs → np make up 90% of SRC pairs

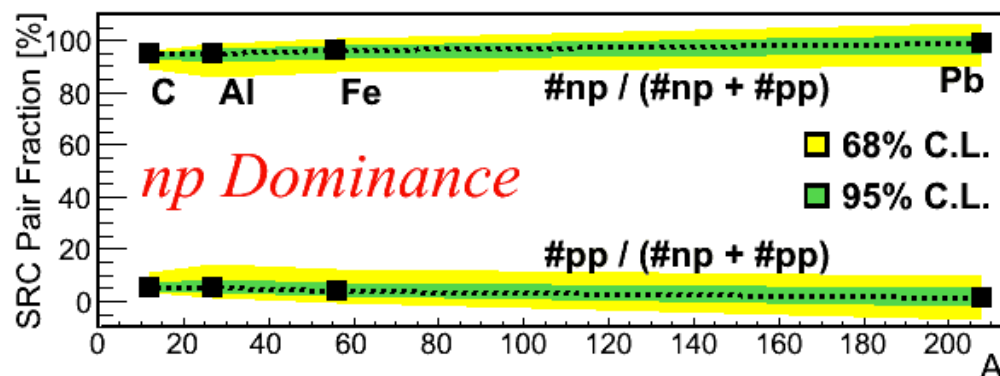


proton “speed up” with neutron excess



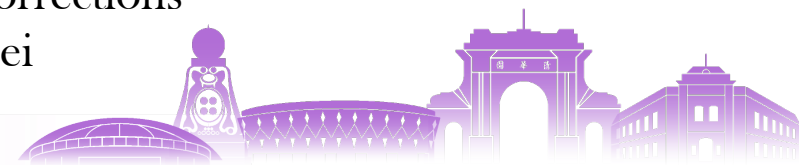
❑ Similar np-dominances in heavy nuclei → universality?

O. Hen et al., Science (2014), M. Duer et. al., Nature (2018), B. Schmookler et. al. Nature (2019), A. Schmidt et. al Nature (2020) + many others



❑ Cautions:

- Exclusive results are statistics limited
- Mixed with mean-field and long-range NN signals
- Complicated FSI corrections
- Limited stable nuclei



➤ Isospin Dependence

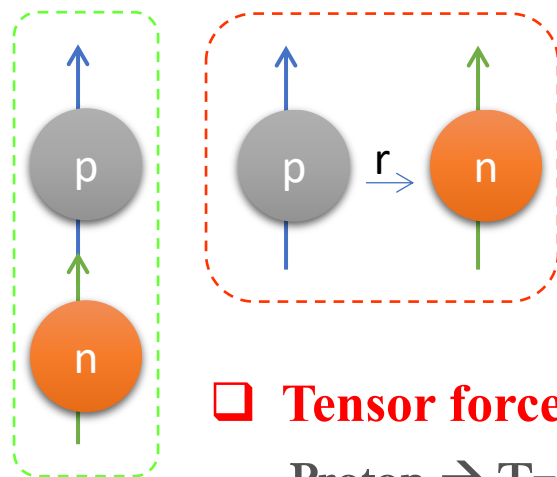
- Tensor Force is strongly attractive

$$-S_{12} = -3(\vec{\sigma}_1 \cdot \hat{r})(\vec{\sigma}_2 \cdot \hat{r}) + (\vec{\sigma}_1 \cdot \vec{\sigma}_2)$$

$$= -3 \sigma_1 \sigma_2$$

Attractive

$\Rightarrow 0 \rightarrow \text{Repulsive}$



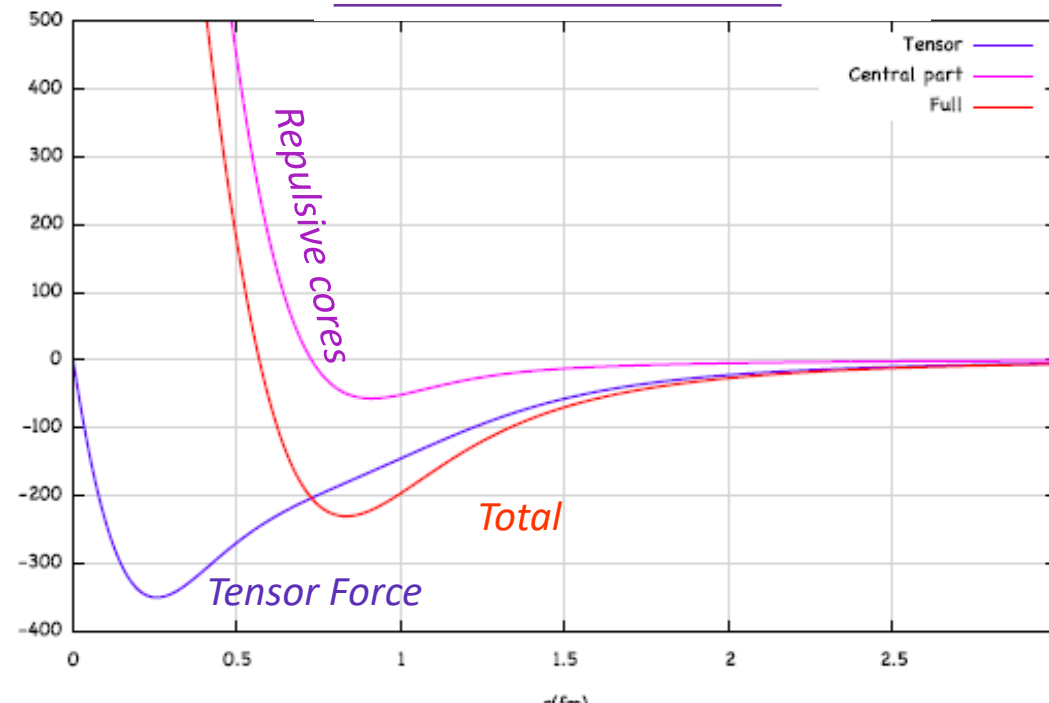
- **Tensor force favor neutron-proton pairs**

Proton $\rightarrow T = 1/2$, Neutron $\rightarrow T = -1/2$

Isospin Singlet: $T = 0$, n-p pairs ✓ *Stable! due to Pauli Principle*

Isospin Triplet: $T = 1$, p-p ($T_z=1$), n-p ($T_z=0$), and n-n ($T_z=-1$)

NN Interaction Forces



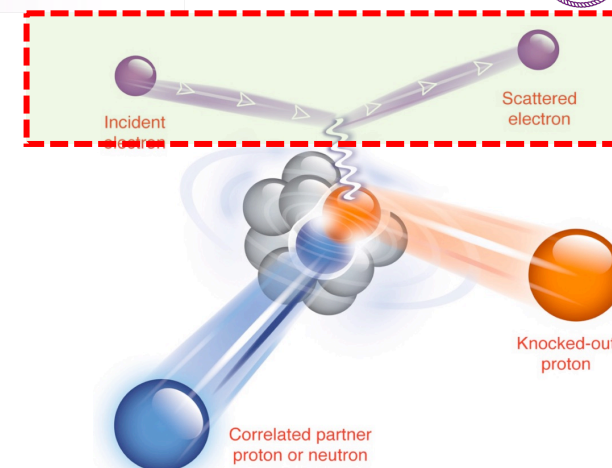
➤ Inclusive SRC Measurements:

❑ QES inclusive cross-sections:

$$\frac{d\sigma_{QE}}{dE' d\Omega}(Q^2, x_{bj}) = 2\pi\sigma_{eN} \int_{p_{min}}^{p_{max}} k dk \int_{E_S^{min}}^{E_S^{max}} S(k, E_S) dE_S$$

“links” to momentum distribution

Nucleon momentum distribution



❑ Heavy to light nuclei have similar high-P tails

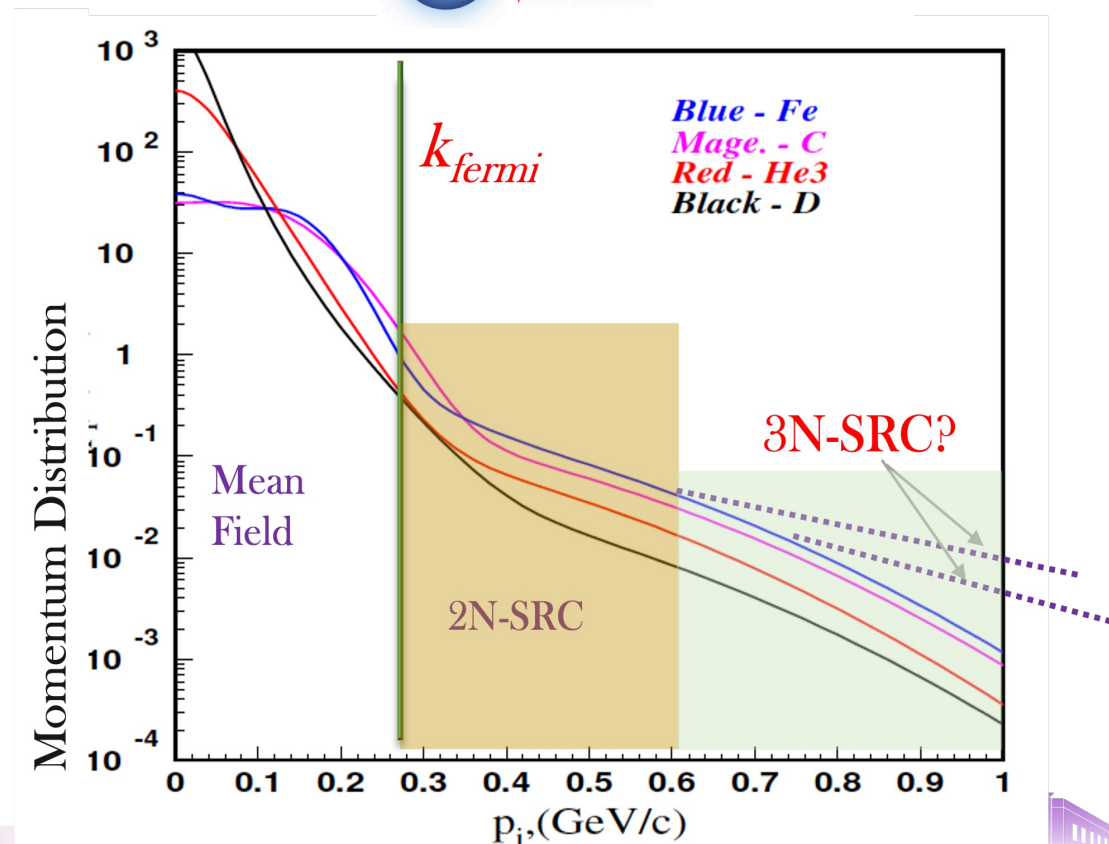
→ look for a plateau

✓ 2N-SRC ($1.3 < x_{bj} < 2$): $a_2(A, D) = \frac{2}{A} \frac{\sigma_A(x, Q^2)}{\sigma_D(x, Q^2)},$

✓ 3N-SRC ($2 < x_{bj} < 3$): $a_3(A, {}^3\text{He}) = \frac{3\sigma_A}{A\sigma_{{}^3\text{He}}}$

❑ Inclusive vs Exclusive:

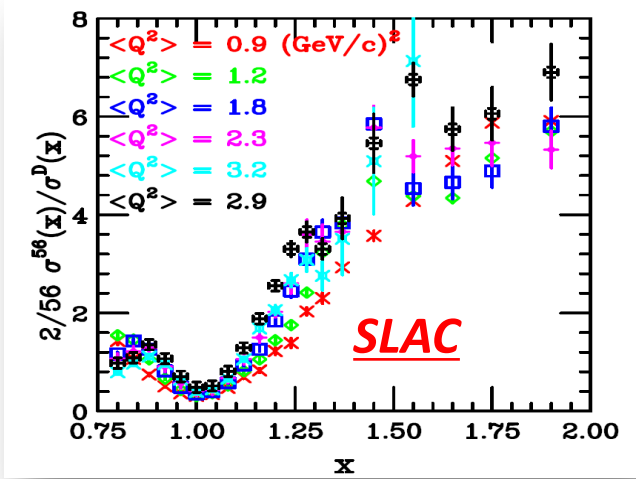
- High precision, small FSI
- Not direct probing SRC internal info



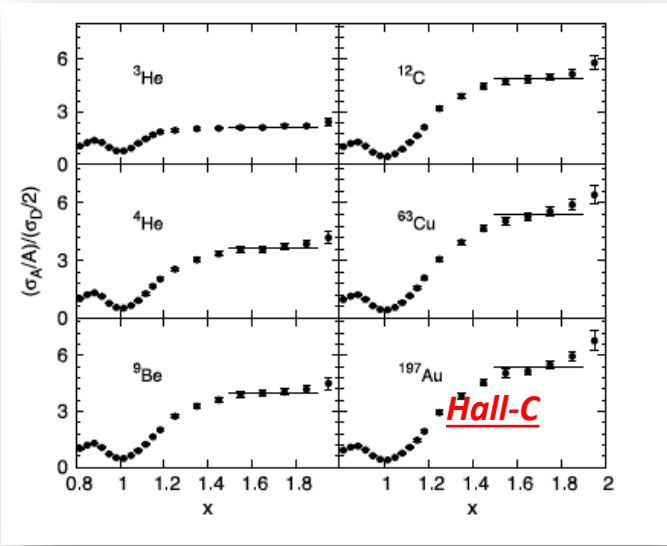
Measuring SRC w/ eA

➤ 2N-SRC

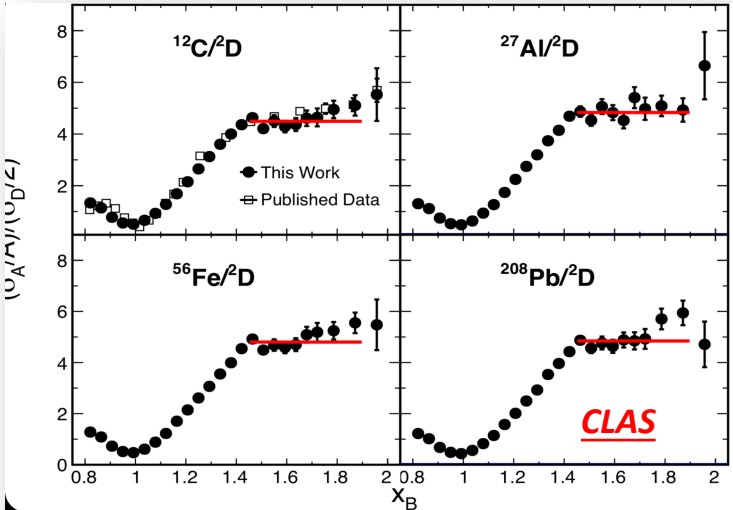
❑ SRC plateau at $Q^2 > 1.4 \text{ GeV}/c$



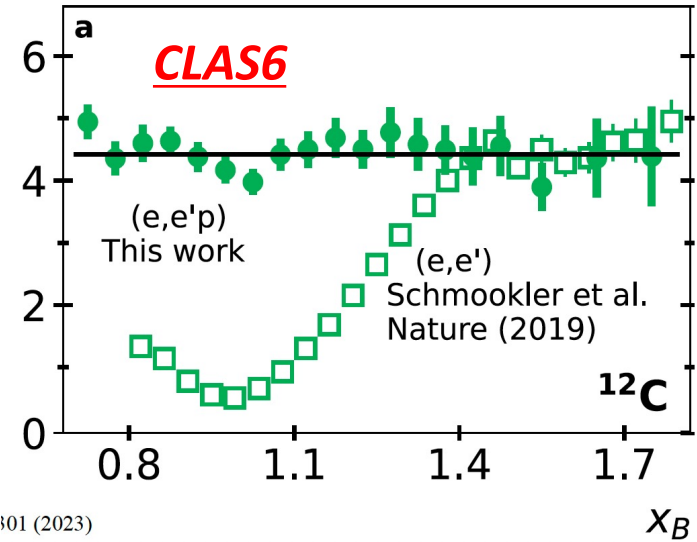
N. Fomin *et al*, PRL 108,092502 (2012)



Schmookler *et al.*, Nature (2019)



Frankfurt, Strikman, Day, Sargsian, PRC48, 2451 (1993)

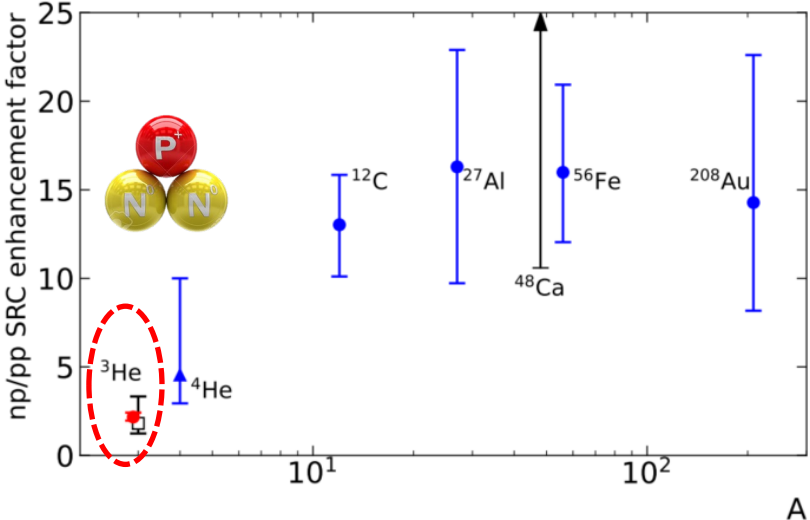


❑ Compared with exclusive SRC

Korover and Denniston *et al.*, CLAS, PRC 107, L061301 (2023) 27

❑ Non-Universal in light nuclei?

S. Li, R. Cruz-Torres, N. Santiesteban, Z. Ye, *et. al*, Nature, 2022, 609: 41

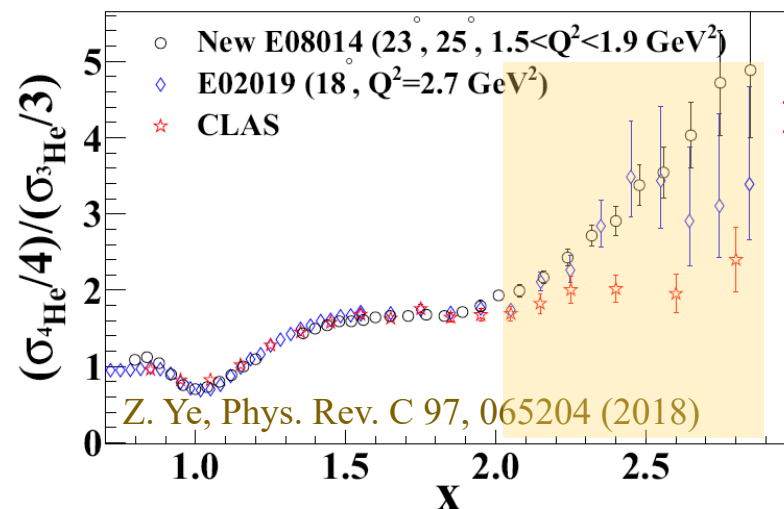


➤ 3N-SRC

- ❑ Much higher relative momenta
- ❑ Much denser cluster (Neutron-Star, Nuclear Matter)
- Bi-neutron-stars merger: neutron star > 2.4 solar mass
→ Short-Range 3-body force?

- ❑ Inclusive Measurement: XS links to the 3N-SRC tails

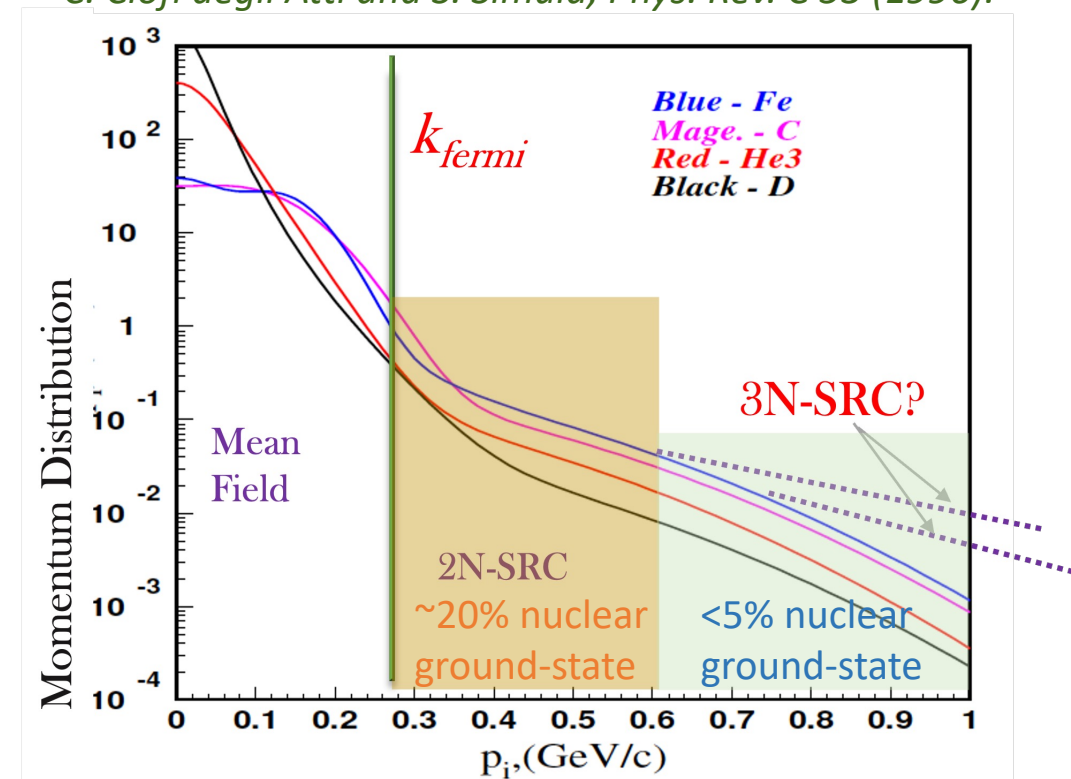
$$3\text{N-SRC } (2 < x < 3) \quad a_3(A, {}^3\text{He}) = K \cdot \frac{3\sigma_A}{A\sigma_{{}^3\text{He}}}$$



Missing 3N-SRC?

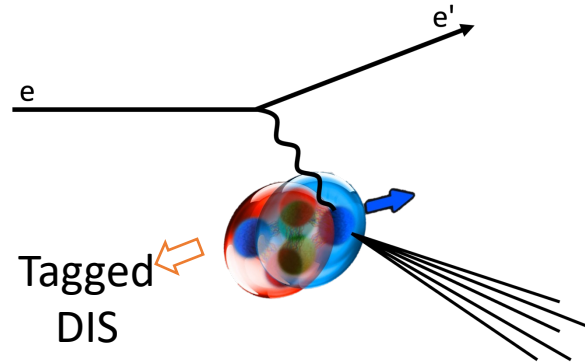
- CLAS result has big background
Higinbotham & Hen, PRL 114,169201 2015)
- Q^2 too low to see 3N-SRC?
- Much bigger FSI?

C. Ciofi degli Atti and S. Simula, Phys. Rev. C 53 (1996).



➤ Upcoming Jlab RC Experiments:

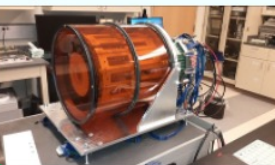
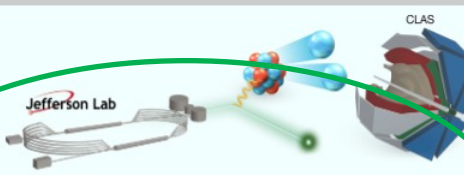
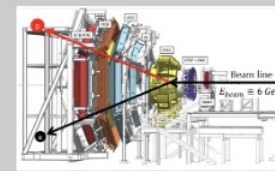
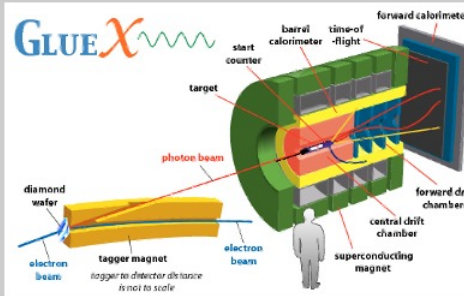
- ❑ ALERT- SRC: measure C.M motion of pairs (Mean-Field vs SRC)
- ❑ Real photon scattering (check universality)
- ❑ Future EIC with much higher energy: SRC in J/Psi, tagged DIS



- ❑ Precision Frontier of SRC: pA reaction!

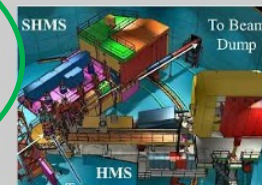
SRC studies with leptons

Jefferson Lab Hall D

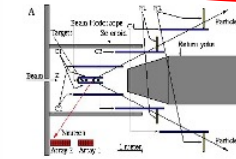


ALERT

Jefferson Lab Halls A, B, C



SRC studies with hadrons



EVA/BNL

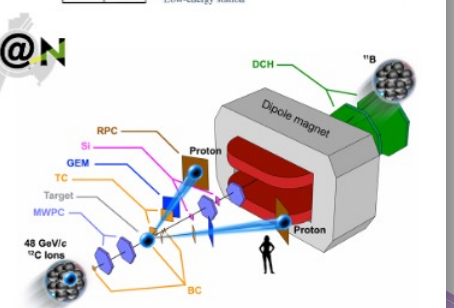
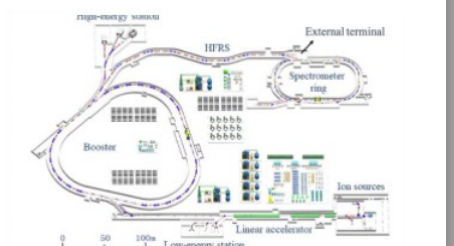
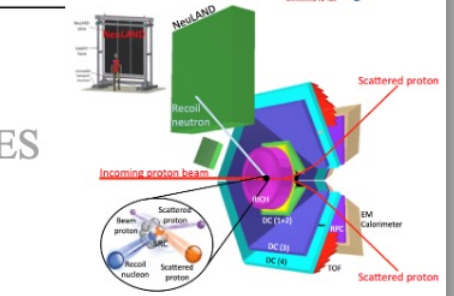
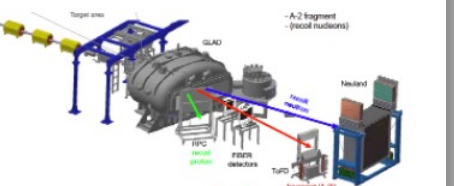
R3B

HADES

HIAF

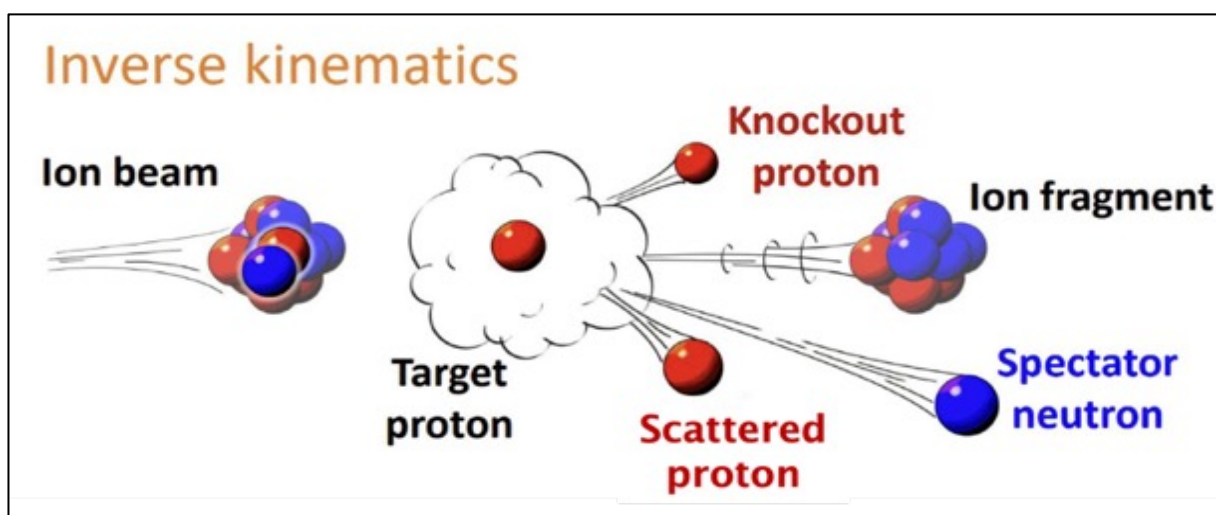
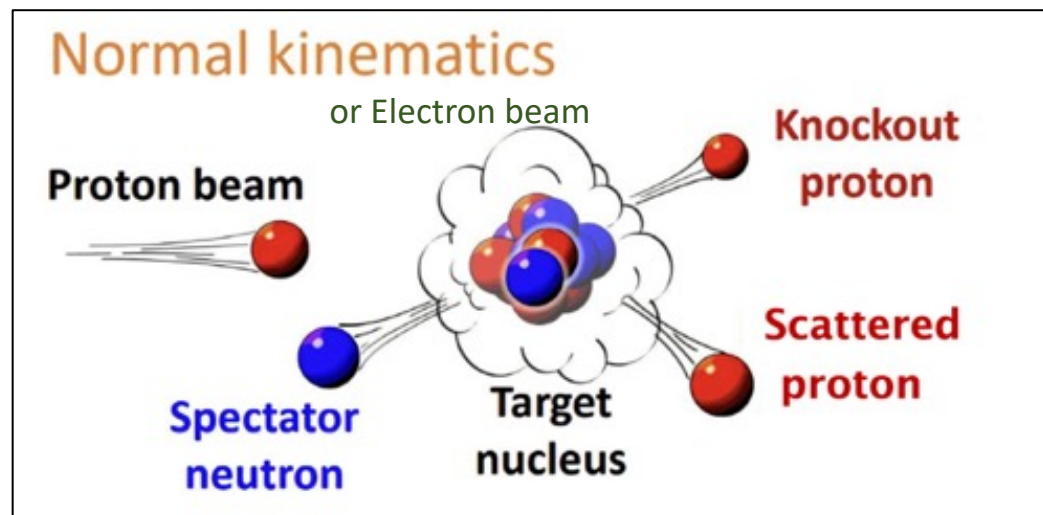
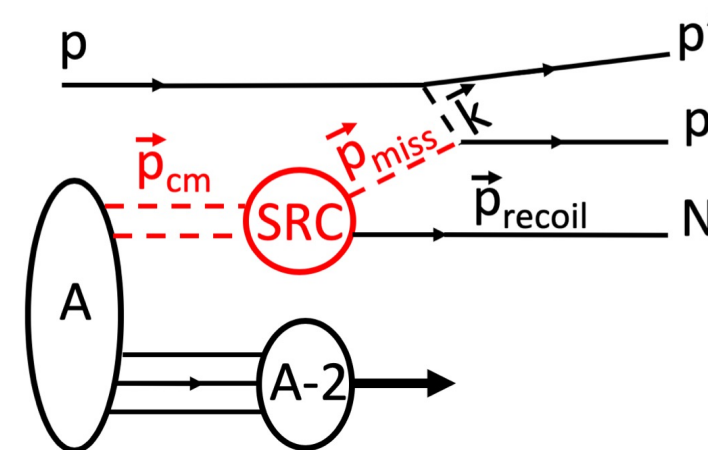
BM@N

JINR



➤ Advantage vs eA Scattering

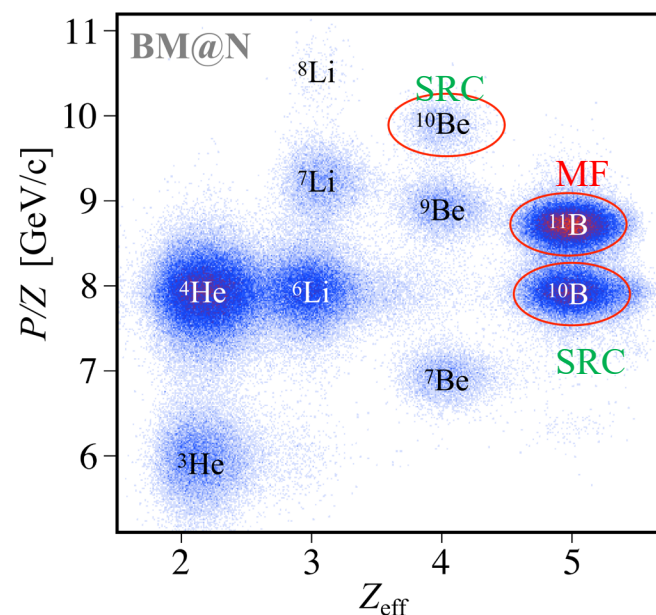
- ❑ Bigger cross-sections → Precision and discovery
- ❑ Easier detection of fragments → Suppress mean field contribution
- ❑ Better controlled FSI → Reduce theoretical systematic errors
- ❑ Secondary ion beams → Large asymmetric nuclei, radioactive isotopes



➤ JINR BM@N SRC Experiments

❑ Pioneer experiment at BM@N

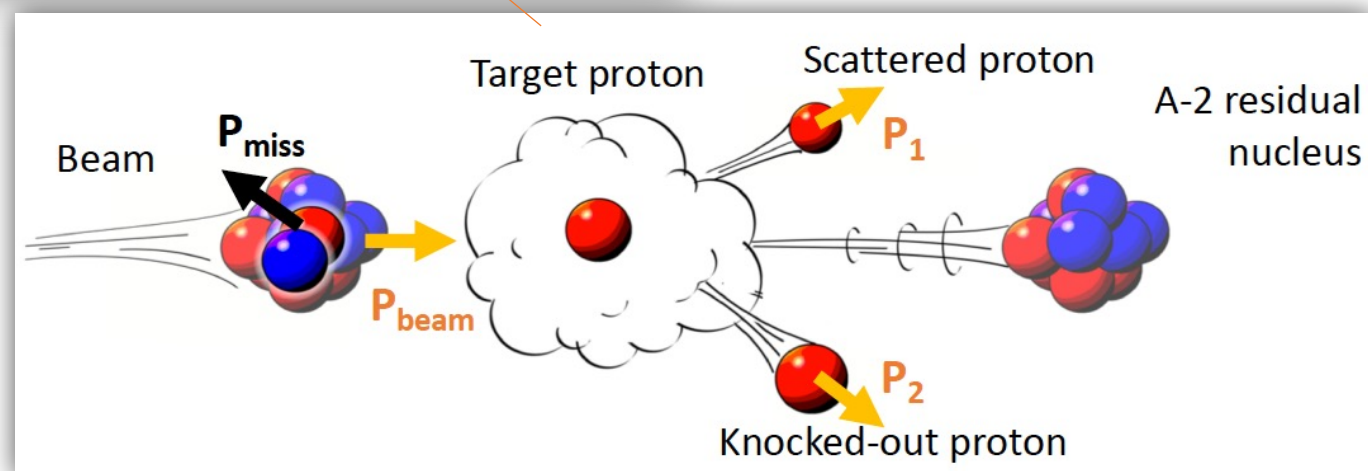
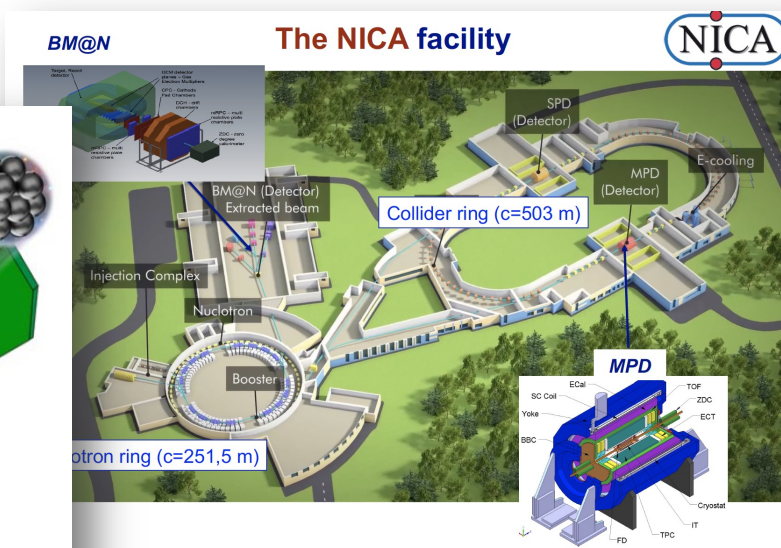
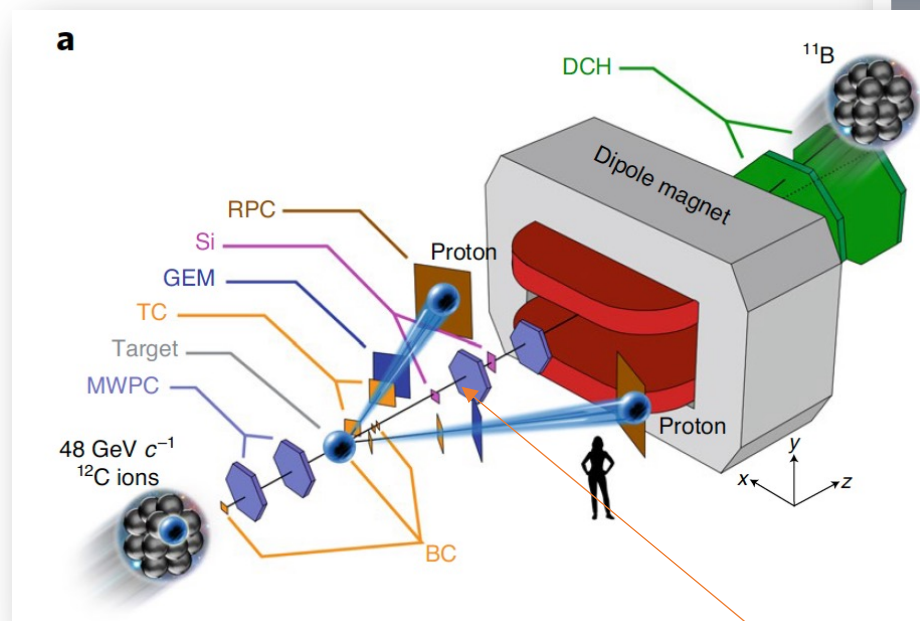
- Test run in 2018, results published
- ^{12}C beam, 3.5 – 4 GeV/c/nucleon
- Identify fragments:



- Detection of two outgoing nucleons
- Reconstruct initial nucleon momentum:

$$\mathbf{P}_{\text{miss}} = \mathbf{P}_1 + \mathbf{P}_2 - \mathbf{P}_{\text{beam}}$$

M. Patsyuk et al. Nature Physics 17, 693 (2021)

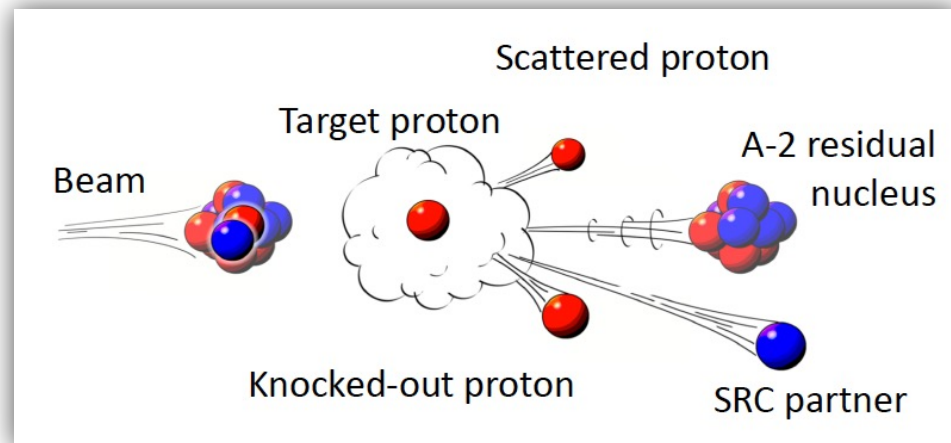


➤ JINR BM@N SRC Experiments

❑ Single nucleon quasi-free knock-out

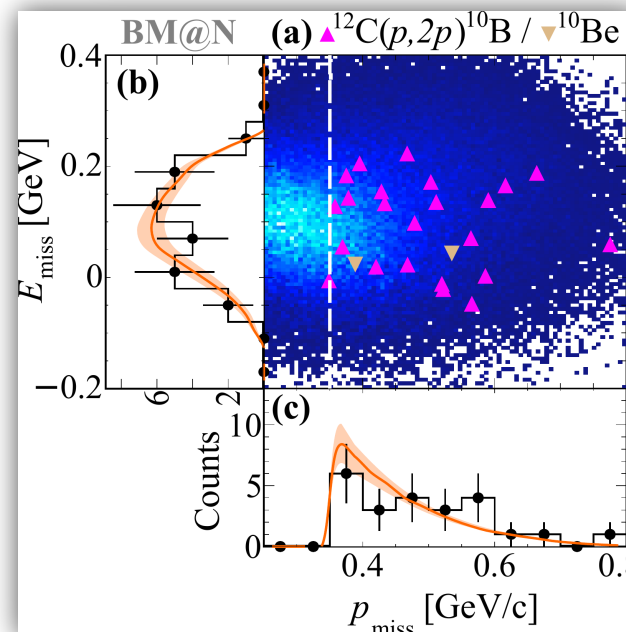
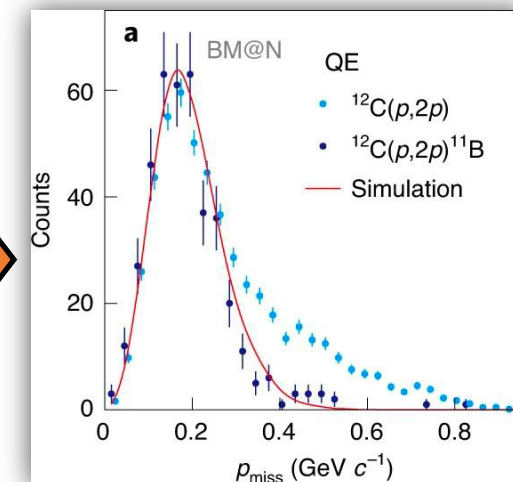
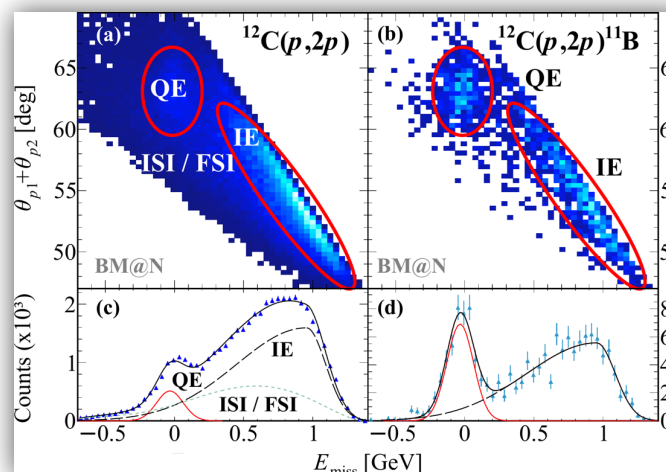
- Select bound ^{11}B
- Large momentum tails mixed with SRC w/o tagging $^{11}\text{B} \rightarrow$ Suppress Initial-&Final-State Interaction

❑ Selection of 2N-SRC Pairs

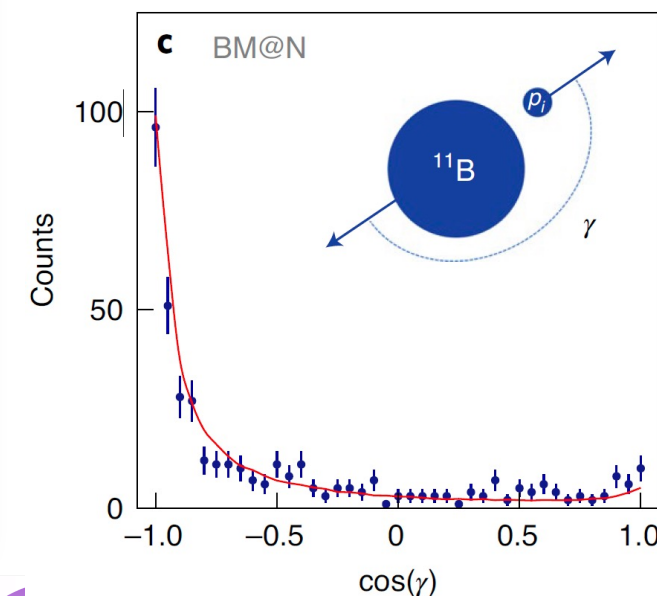


np pair: $^{12}\text{C}(p,2p) \ ^{10}\text{B}$
pp pair: $^{12}\text{C}(p,2p) \ ^{10}\text{Be}$

M. Patsyuk et al. Nature Physics 17, 693 (2021)



23 np & 2 pp SRC-pairs



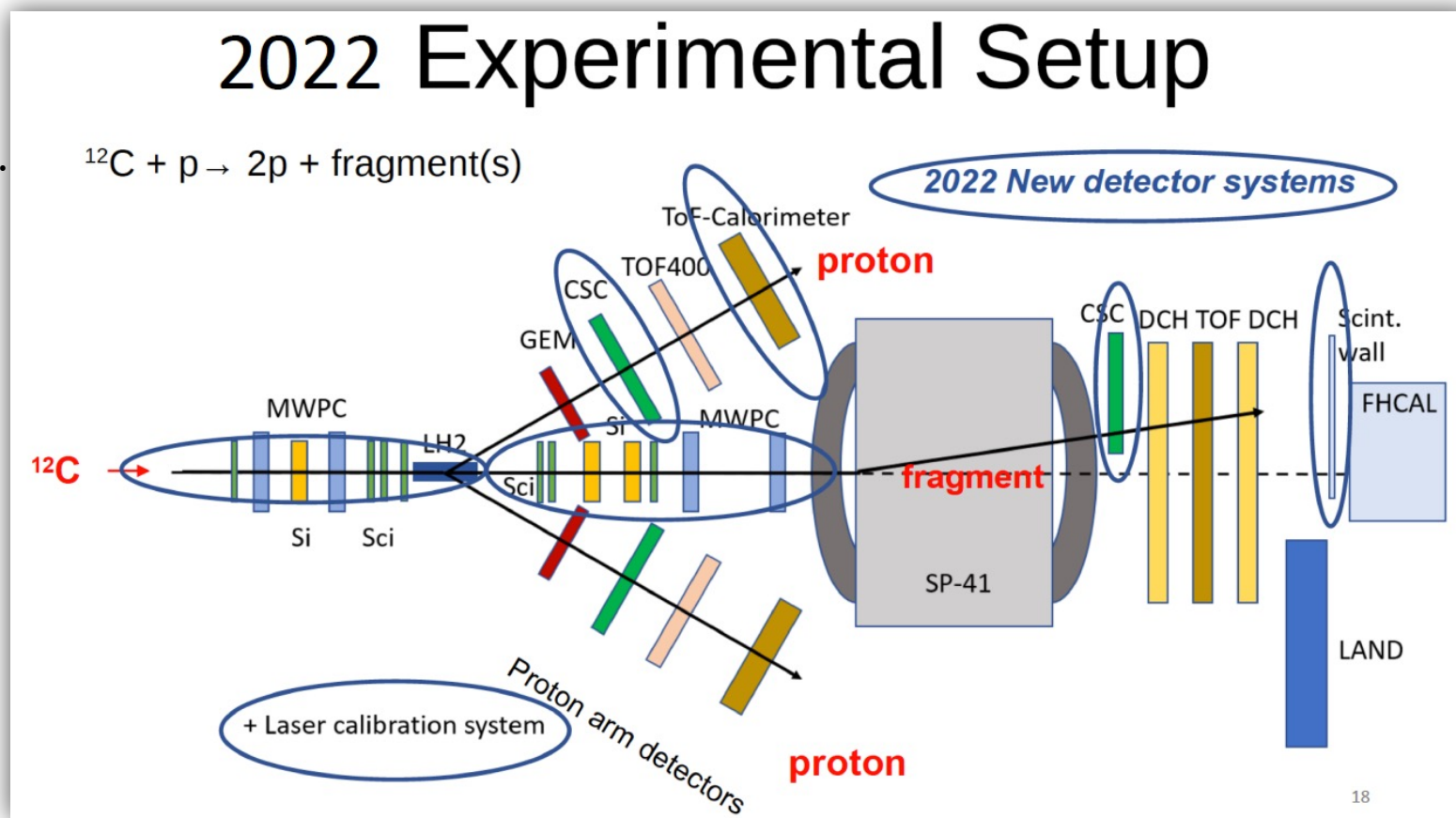
➤ JINR BM@N SRC Experiments

- ❑ 2018 run firstly demonstrated advantage of inverse-pA reaction in SRC study

M. Patsyuk et al. Nature Physics 17, 693 (2021)

- ❑ 2022 run completed

- ✓ JINR, GSI, MIT, Tel Aviv, Tsinghua ..
- ✓ Improve statics x100
- ✓ Detection of n & p recoils
- ✓ Multi-fragment reconstruction
- ✓ Absolute cross-section (in preparing)



➤ JINR BM@N SRC Experiments

❑ Preliminary results of 2022 run, under analysis by:



Göran
Johansson
(TAU)



Timur
Atovuallev
(JINR)



Sergey
Nepochatykh
(JINR)



Yaopeng
Zhang
(Tsinghua U)



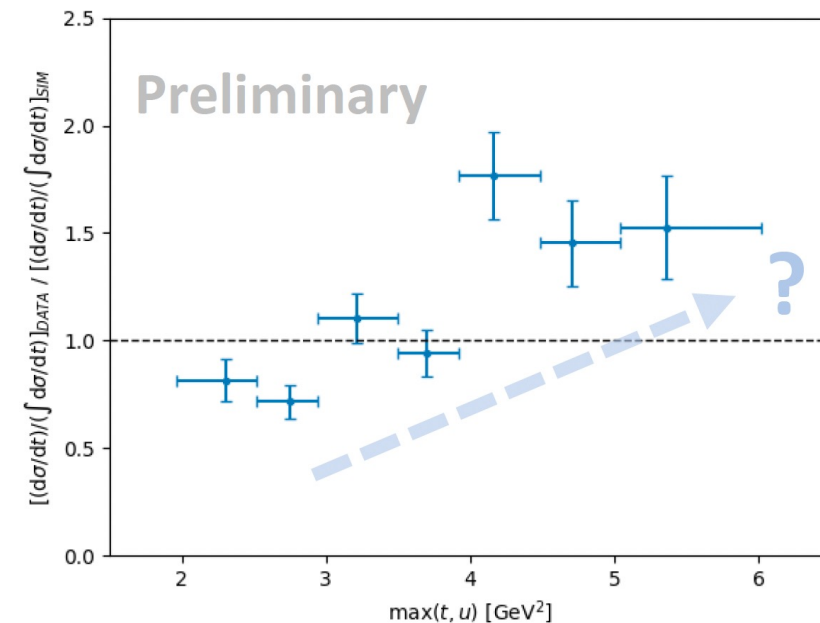
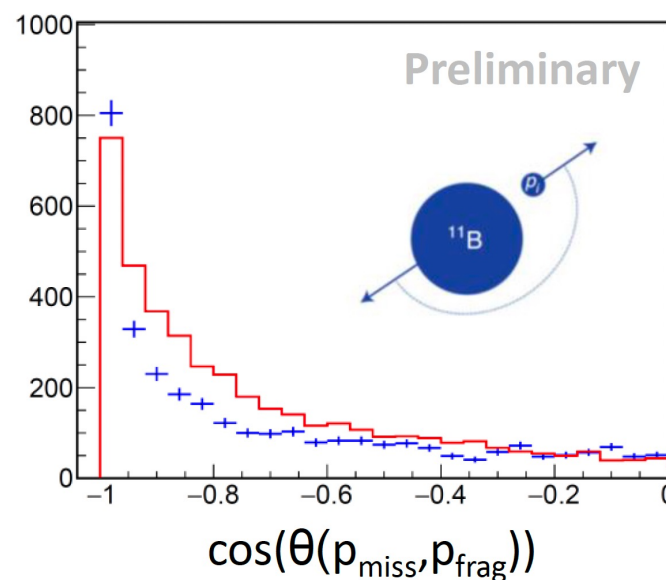
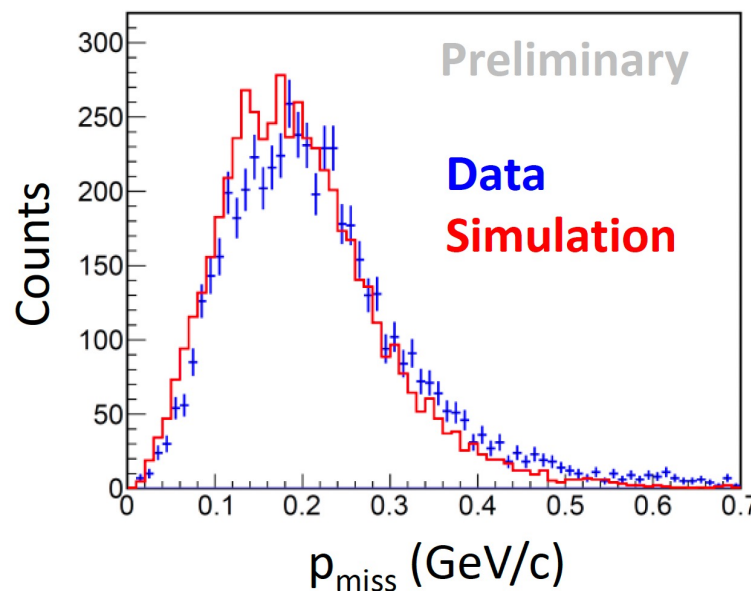
Vasilisa
Lenivenko
(JINR)



Maria Patsyuk
(JINR)



Julian Kahlbow
(MIT)



- ✓ X10 more statistics vs 2018 run
- ✓ First extraction of absolute XS

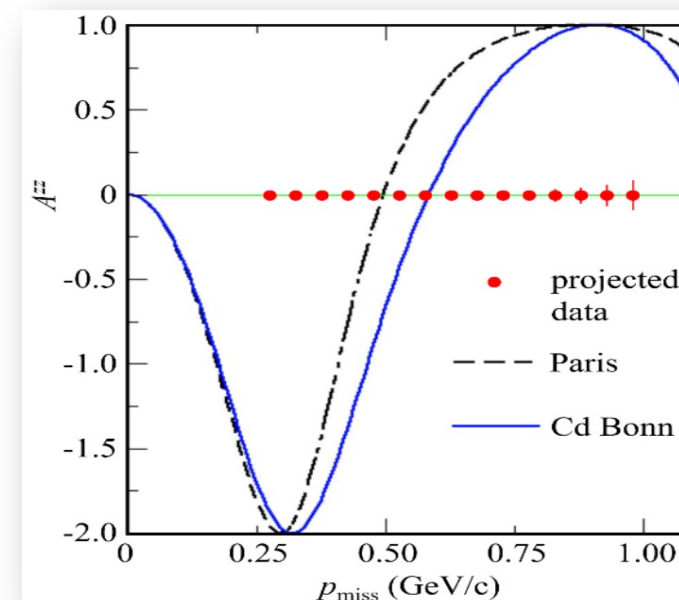
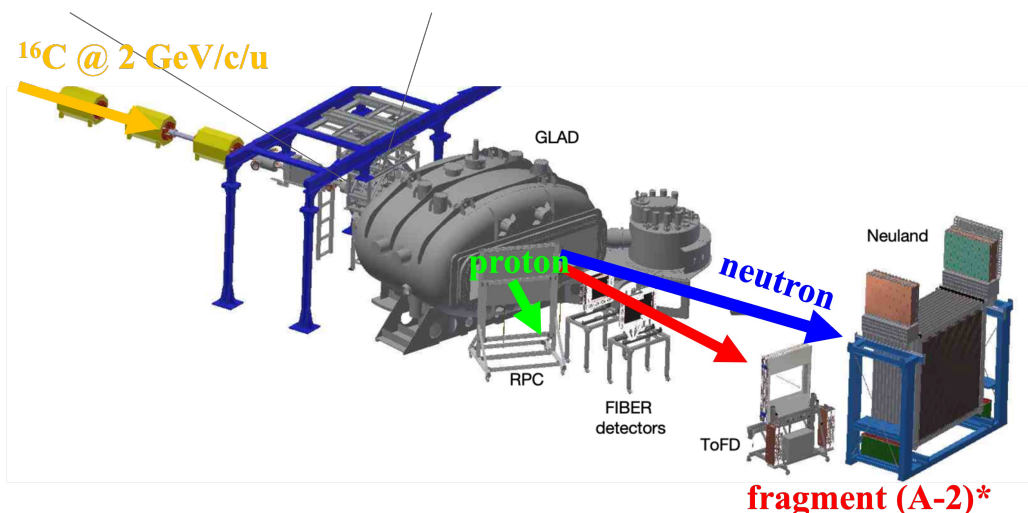
➤ Other ongoing/future Experiments

- ❑ 3rd Gen experiment in **HyperNIS@JINR**: non-nucleonic d.o.f in Deuteron (Tel Aviv, FIU, MIT, ODU, PSU, BNU, Tsinghua)

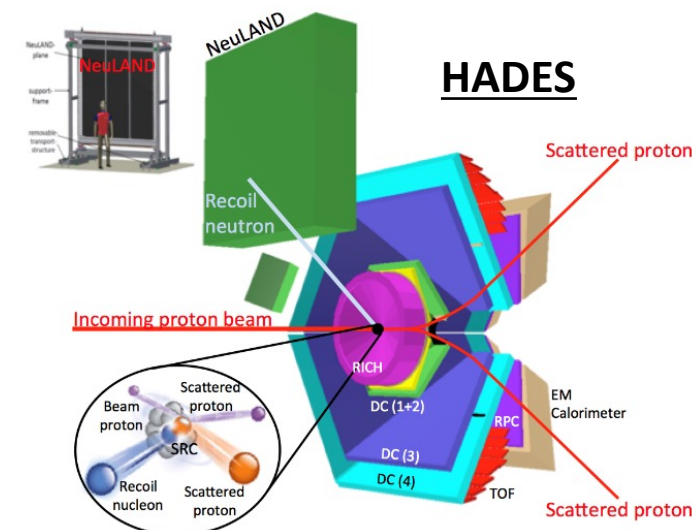
$$A_{zz} = \frac{(\sigma_- + \sigma_+ - 2\sigma_0)}{\sigma_{unpol}}$$

- ❑ SRC w/ rare radioactive isotope at **R³B@GSI**

- ¹⁶C(p,2pN)A-2* in 2022.
- Future: ^{110,120,132}Sn (N/Z = 1.20, 1.40, 1.64)



- ❑ SRC at **HADES@GSI**
 - 4.5 GeV p on fixed nuclear targets
 - Search for 3N-SRC signals in A(p,2pNN)



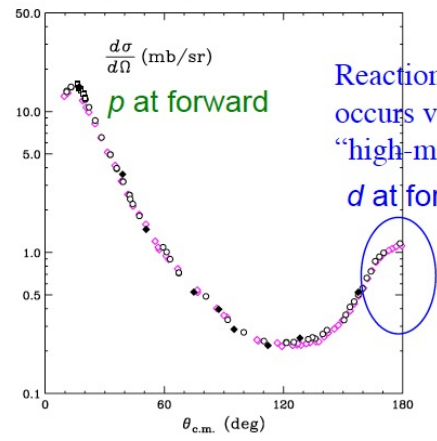
➤ Other ongoing/future Experiments

- ❑ (p, d) pickup reaction (slides from Hooi-Jin Ong@IMP)

Probe for high-momentum nucleons

(p,d)-type reaction: nucleon's internal momentum selectivity

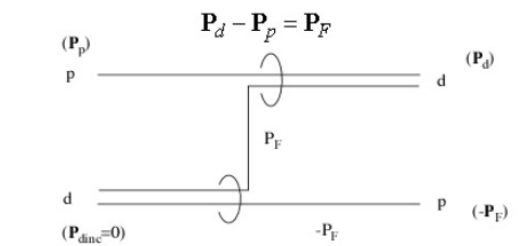
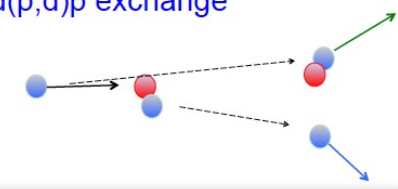
Forward deuteron in (p,d) reaction is equivalent to backward elastic scattering of p+d, which is dominated by a neutron pick-up.



K. Sekiguchi et al., PRL95, 162301(2004)

Reaction at "backward" angle occurs via the pickup of a "high-momentum" neutron

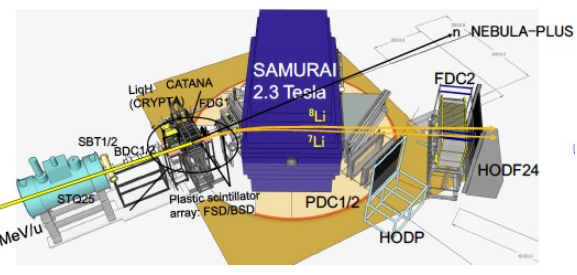
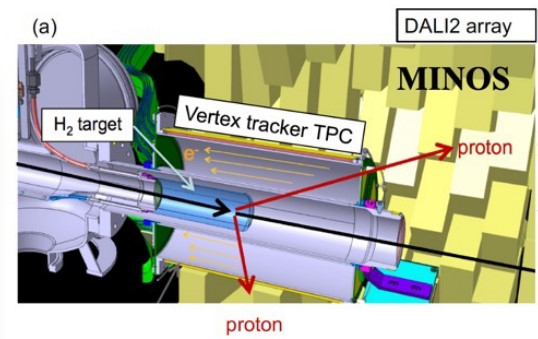
d(p,d)p exchange



$$\sigma_F = K \frac{P_d}{P} N(P_F) \left[B_D + \frac{\hbar^2}{M} (\mathbf{p} - \mathbf{P}_d/2)^2 \right]^2 \left| \langle \varphi(r), e^{i(\mathbf{p} - \mathbf{P}_d/2) \cdot \mathbf{r}} \rangle \right|^2$$

K: phase space constant, B_D : deuteron binding energy, M: nucleon mass by G. F Chew and M.L. Goldberger Phys. Rev. 77 (1950) 470.

by Hooi-Jin Ong



by Hooi-Jin Ong

Near Future: Secondary-Reaction Spectrometer

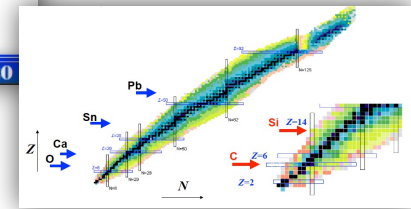
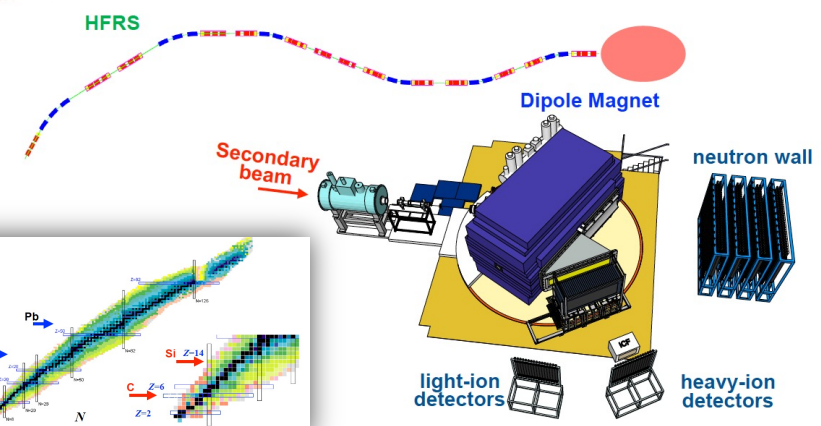


Image: RIKEN-SAMURAI spectrometer

- ❑ Bremsstrahlung γ generated from SRC (Y.H. Qin & Z.G. Xiao, Physics Letters B 850, 138514 (2024))

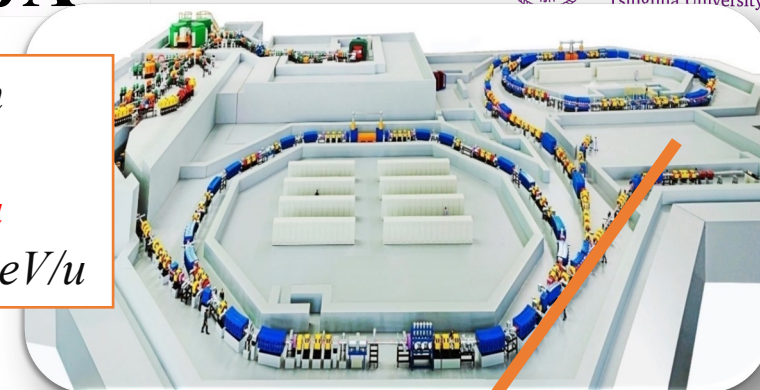
➤ CEE@HIRFL-CSR

❑ Comparable with GSI:

✓ 1.0 GeV/u @ 10^5 pps vs 1.25 GeV/u @ $1 \times 10^5 \text{ pps}$

HIRFL-CSR beam

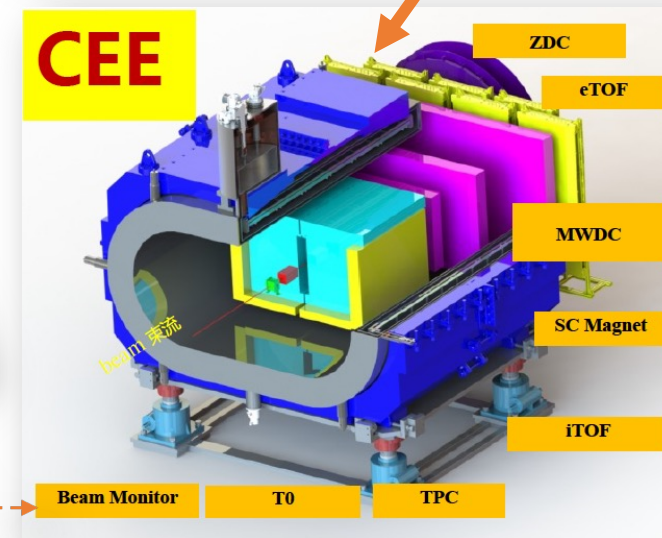
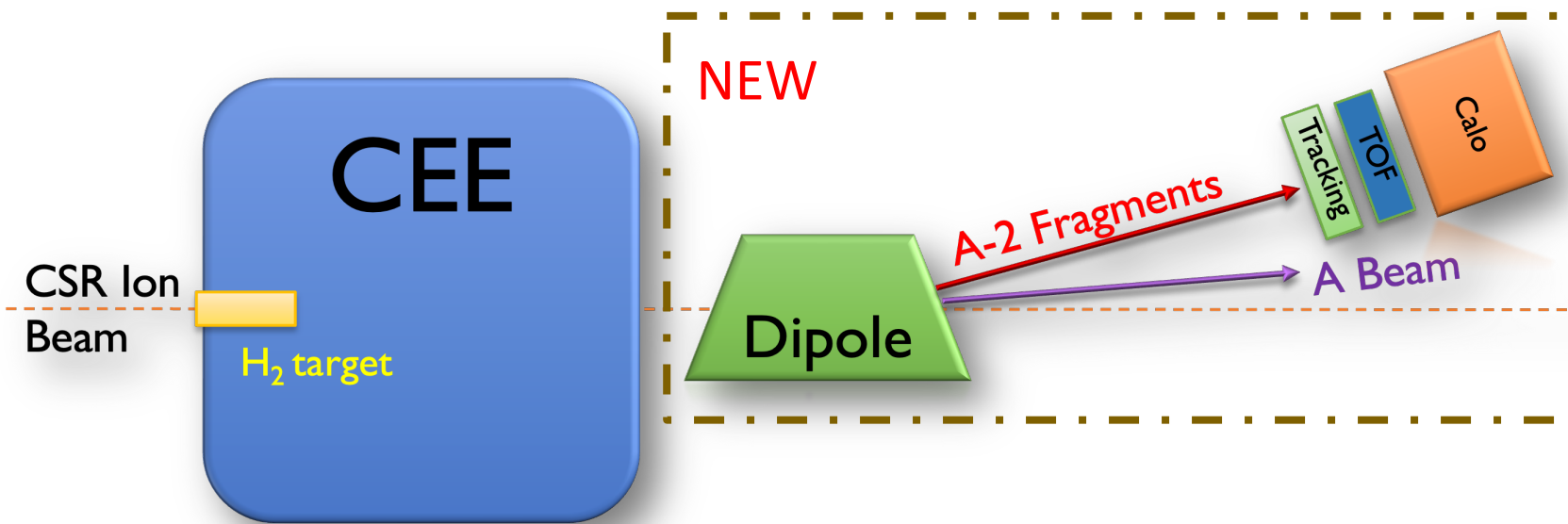
- P : 2.8 GeV
- $^{12}\text{C}^+$: 1 GeV/u
- $^{238}\text{U}^+$: 0.5 GeV/u



❑ Using CEE (see Yapeng Zhang's talk (July 14th) w/ changes:

✓ Liquid hydrogen (LH2) target

✓ a new ZDC (maybe also a new dipole) for A-2 fragments

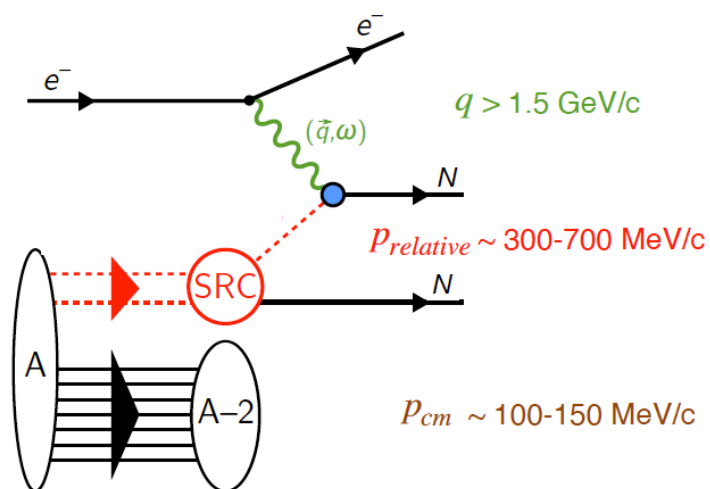


➤ CEE@HIRFL-CSR

□ Goals:

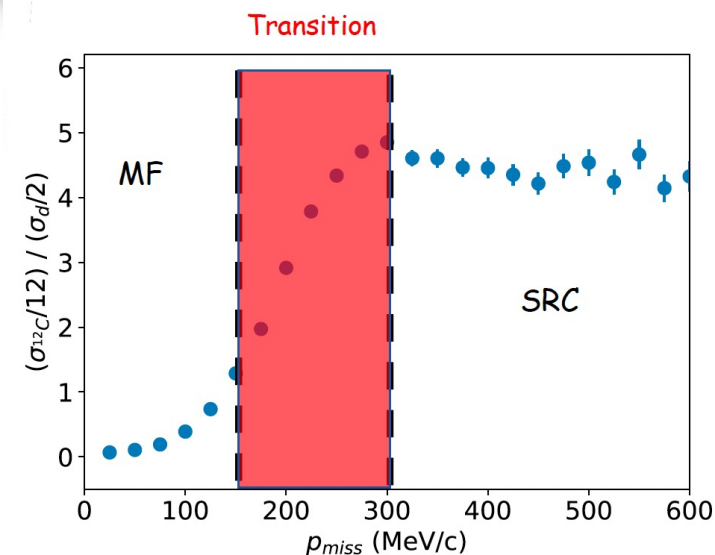
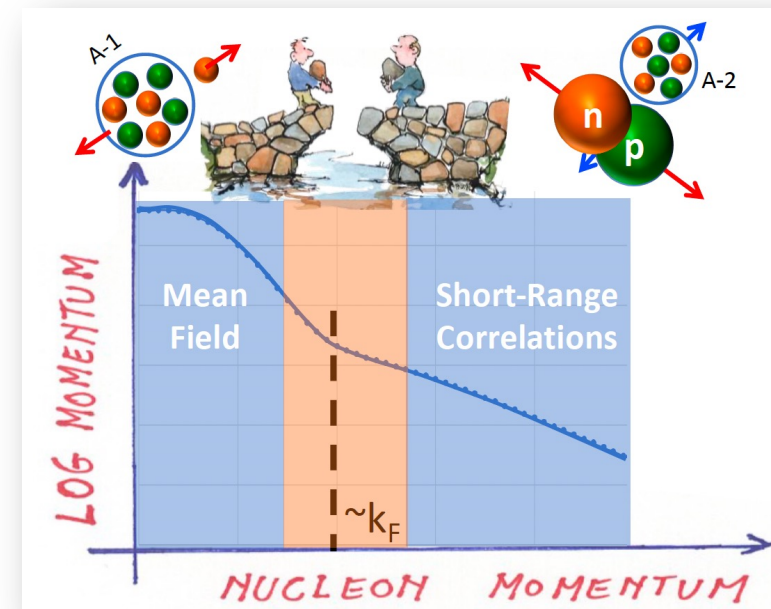
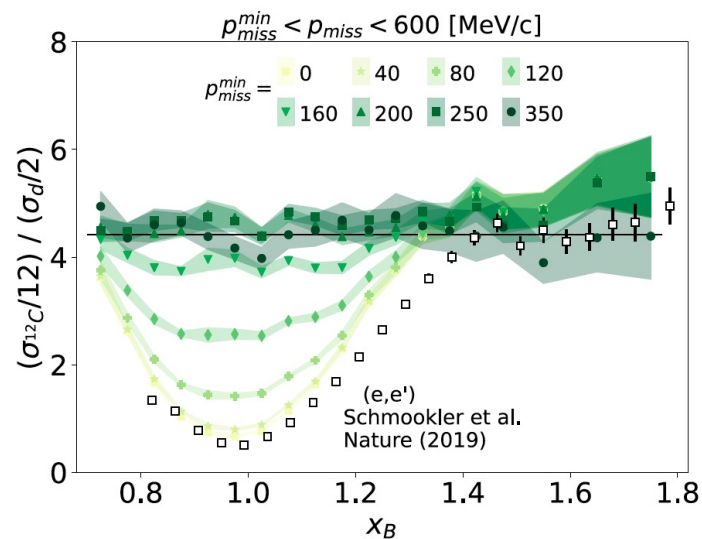
- ✓ Precision nuclear wave functions
- ✓ Define MF & SRC transition regions
- ✓ Check FSI corrections
- ✓ Other quasi-free knockout & pickup reactions

Scale Separation: $q \gg p_{\text{relative}} \gg p_{\text{cm}}$



PRC 92 (2015), PLB 780 (2018), PLB 791 (2019), PLB 792 (2019), JPG 47 (2020), Nature Physics 17 (2021), PRC 104 (2021), PRC 53 (1996), PRL 119 (2017)

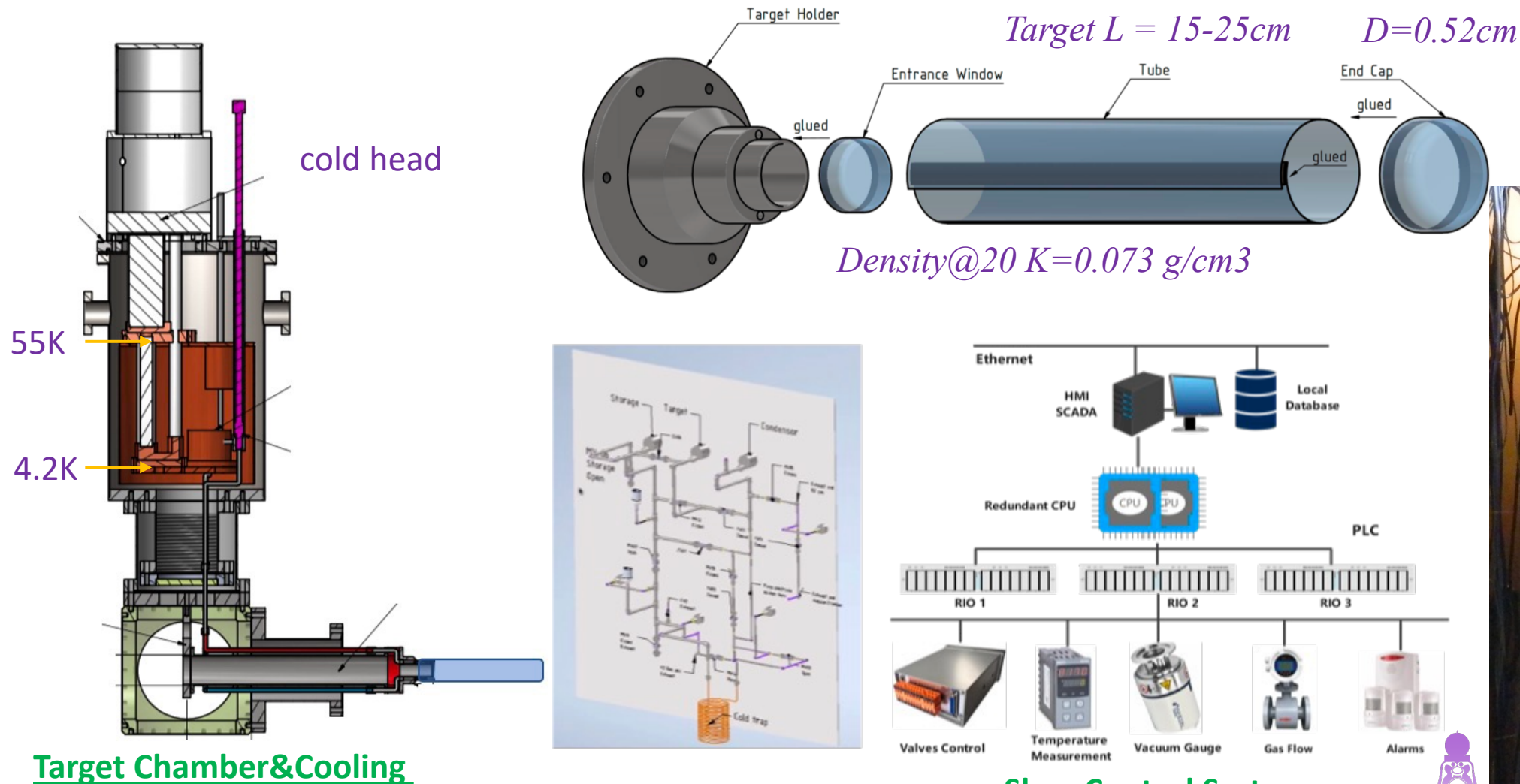
Korover PRC 107, L061301 (2023)



Measuring SRC w/ Inverse-pA

➤ LH2 Target:

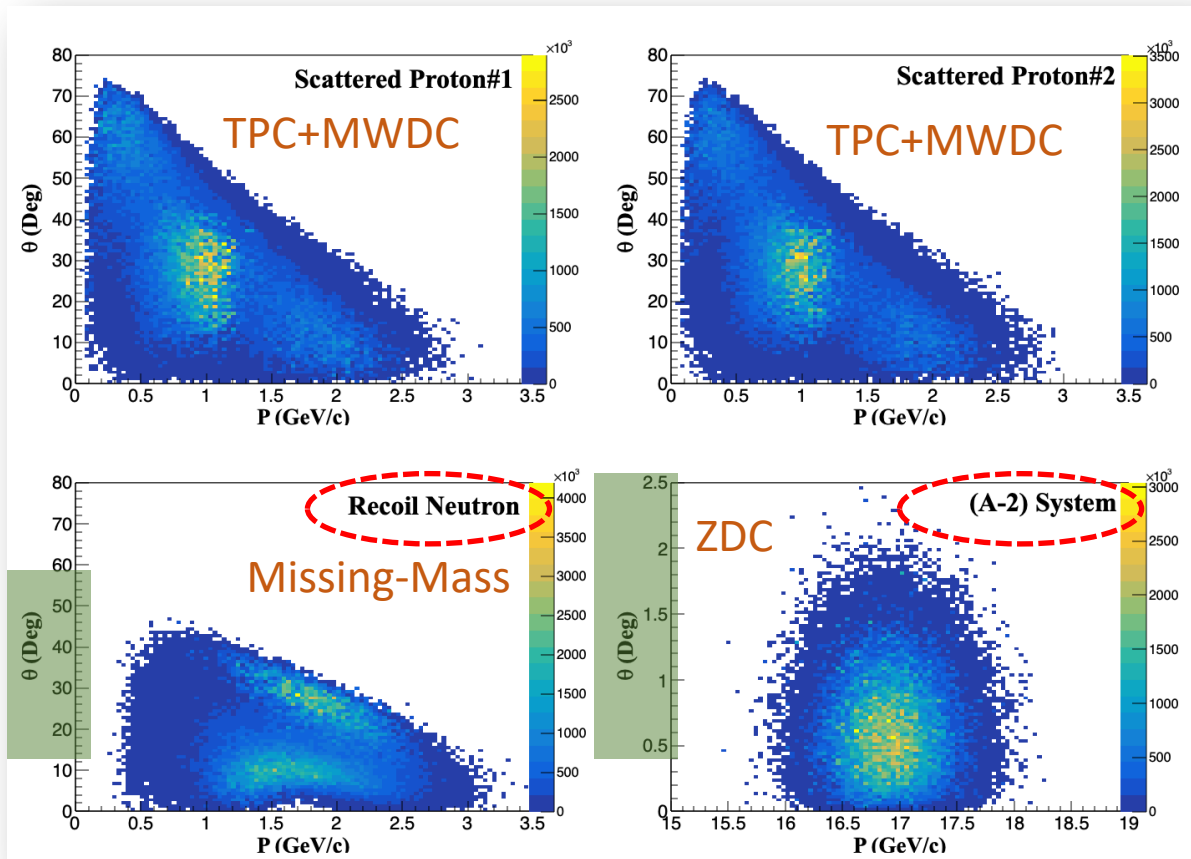
❑ Under development by Hongna Liu, Beijing Normal University (BNU)



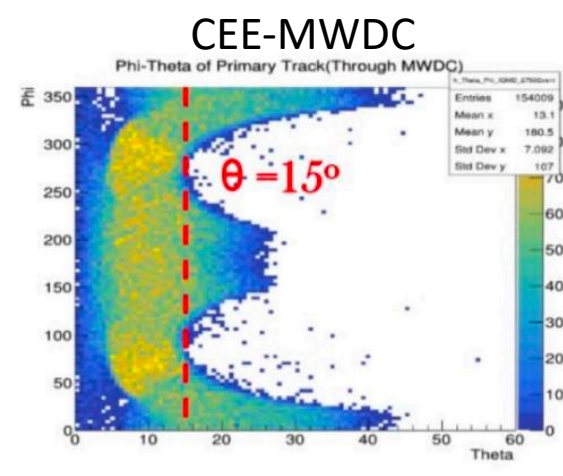
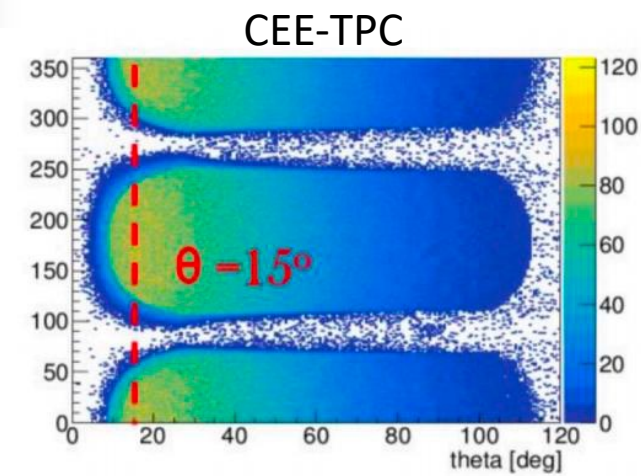
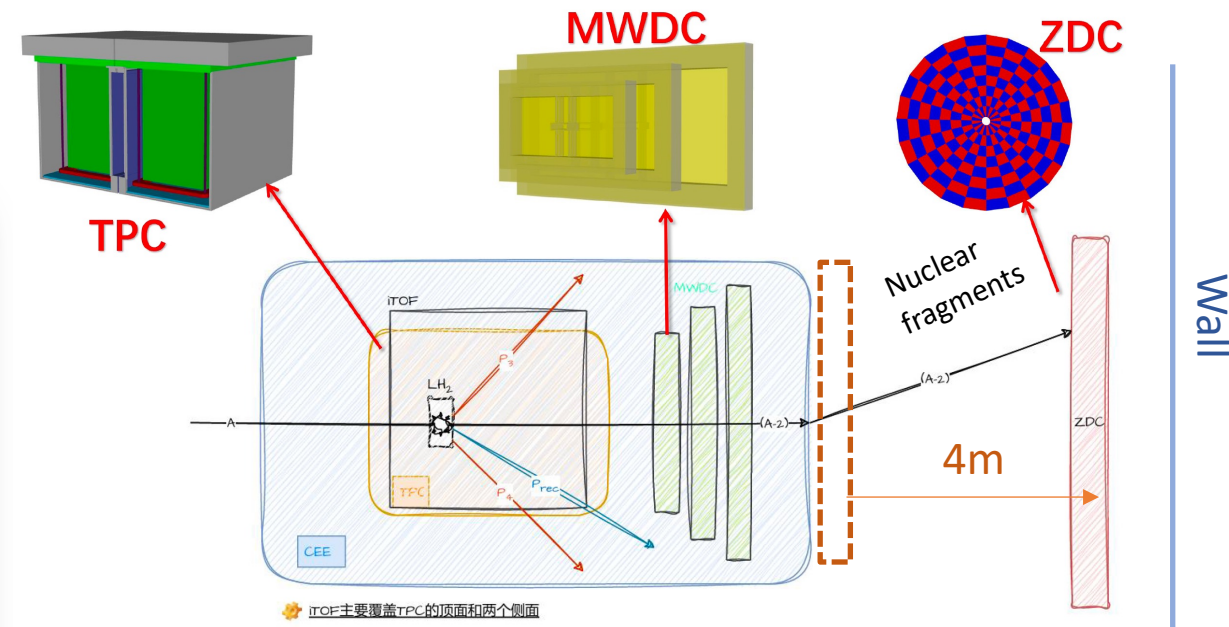
Slow Control System

➤ CEE@HIRFL-CSR

❑ Monte-Carlo simulation of SRC w/ CEE@HIRFL



$^{12}\text{C}^+ (p, ppn) ^{10}\text{B}^+$



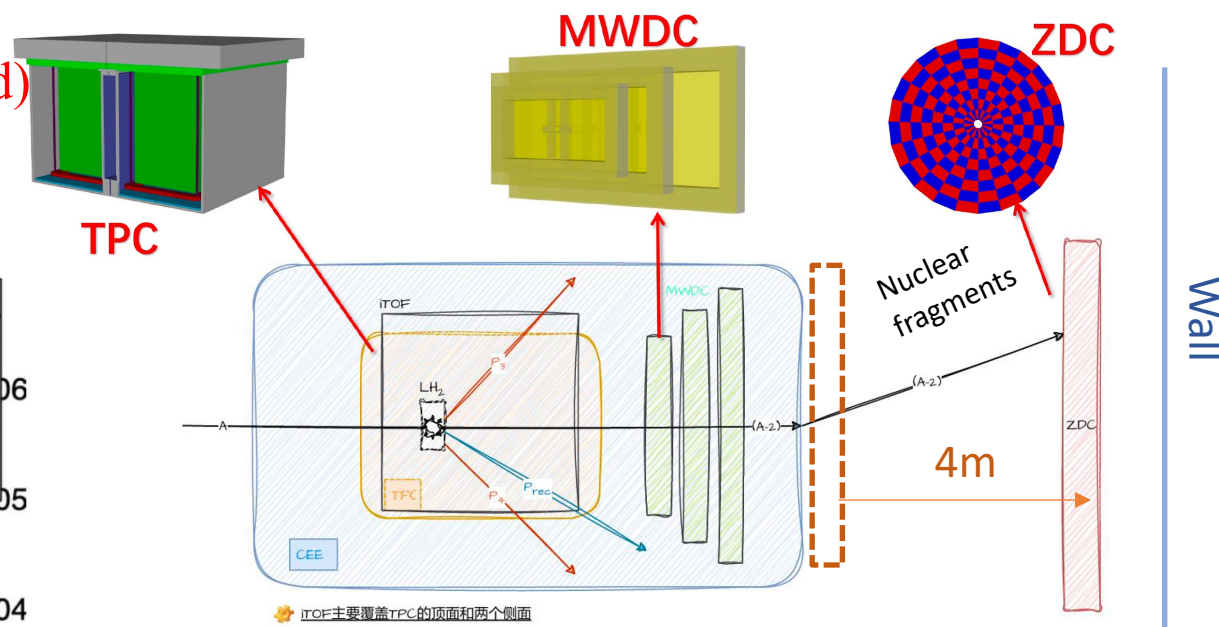
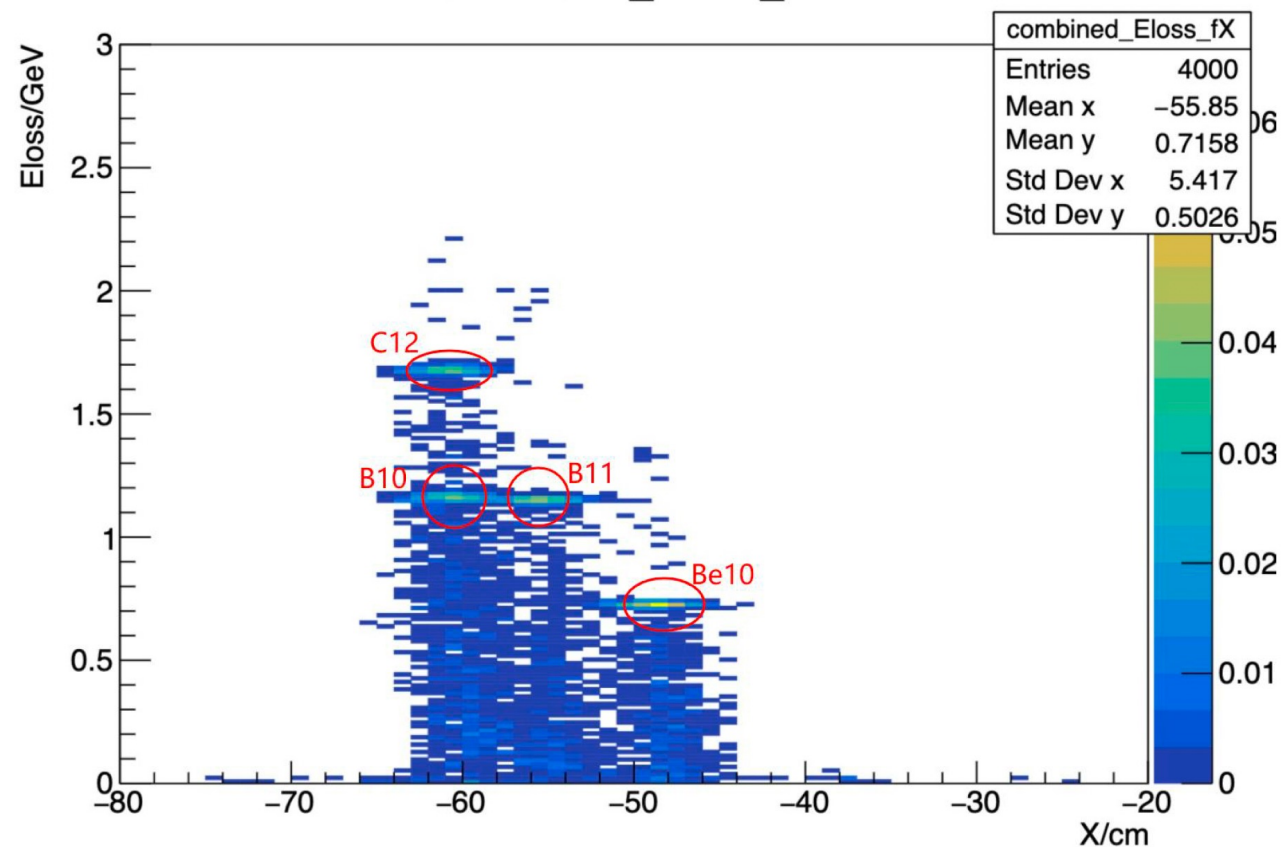
Measuring SRC w/ Inverse-pA

➤ CEE@HIRFL-CSR

❑ Fragment detection w/ CEE@HIRFL (no dipole added)

✓ Minimum modification, same 0.5T field

✓ New high-precision ZDC at 4m downstream



❑ Not yet considered:

- LH2 target should be outside CEE magnet
- Detector resolution & efficiencies
- Background

❑ Continue Improvement

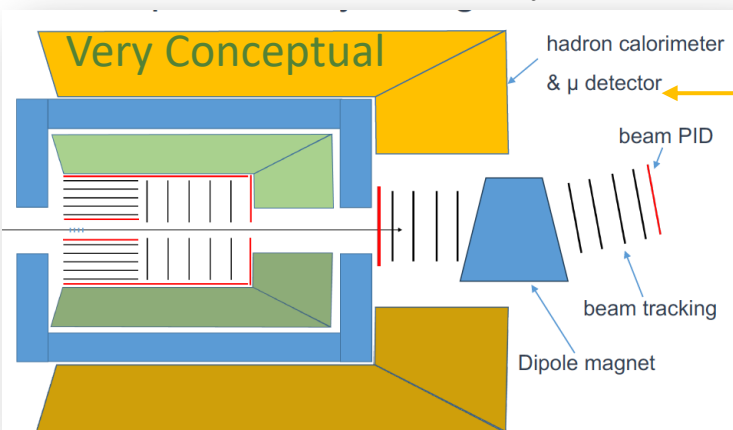
- ✓ Increase CEE magnet field to 1.0 T
- ✓ A new dipole between CEE & ZDC
- ✓ Neutron Detector?



➤ HIAF-High-Energy Station

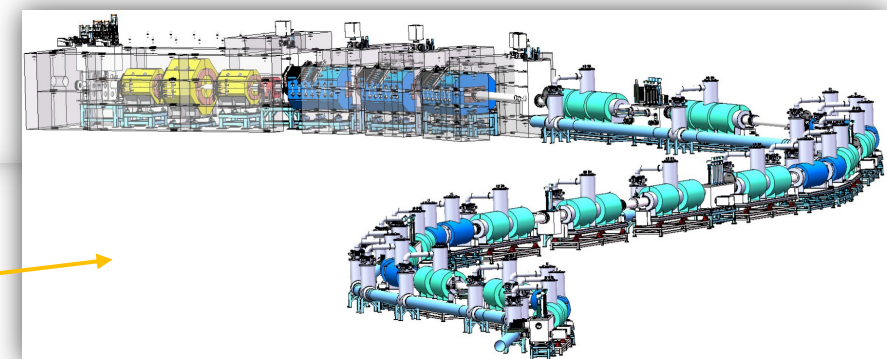
❑ HIAF construction to be completed in 2025 (see Aiqiang Guo's talk on July 14th) :

- C12, $E=51 \text{ GeV/c}$ (4.25 GeV/c/u) \rightarrow similar to NICA
- $1.8 \times 10^{12} \text{ pps}$ (fast extr.), $4.5 \times 10^{11} \text{ pps}$ (slow extr.) vs. $3.5 \times 10^4 \text{ pps}$ at JINR
- $\text{LH2} = 0.073 \text{ g/cm}^3 \times 15 \text{ cm}$
- Total Luminosity = $3 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ (slow ext)



High-Energy Station (HES):

- CEE+, CHNS, ...
- A general-purpose full acceptance detector?



High Energy Fragment Separator (HFRS):

- Secondary radioactive beam



Measuring SRC w/ Inverse-pA

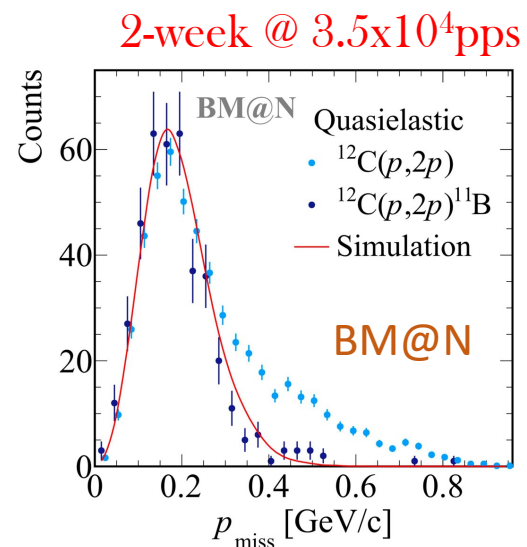
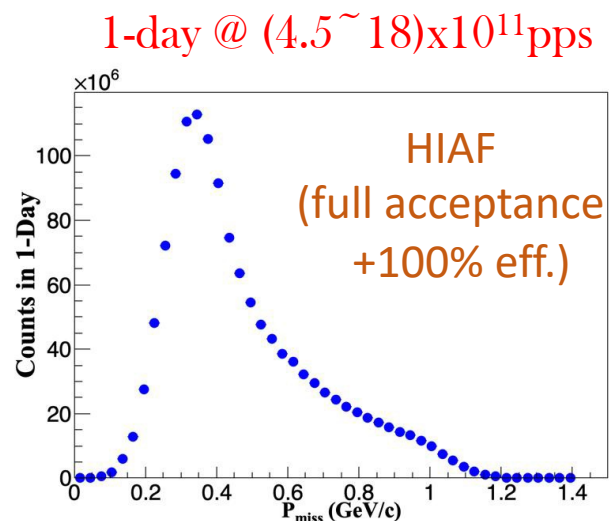
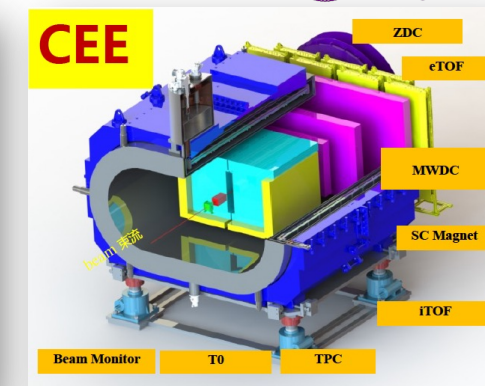
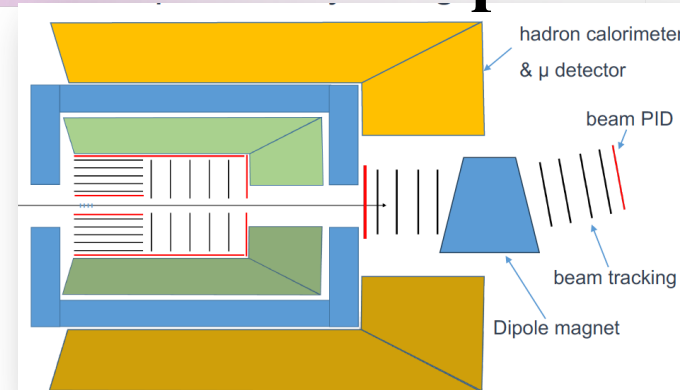
➤ HIAF-High-Energy Station

❑ Precision frontier for SRC in HES:

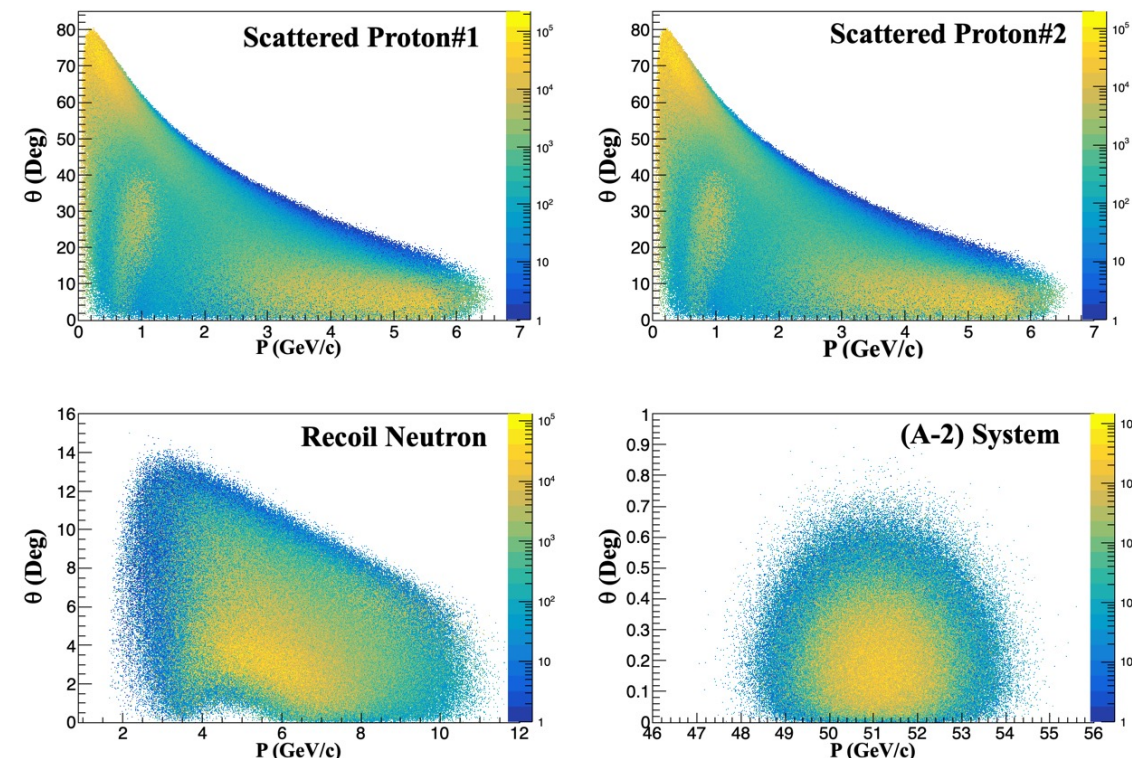
- Mapping 2N-SRC at all kinematic
- Search 3N-SRC

❑ Challenges:

- Detector efficiency at small angles \rightarrow upgrade needed!
- Target performance at high luminosity
- FEE, DAQ

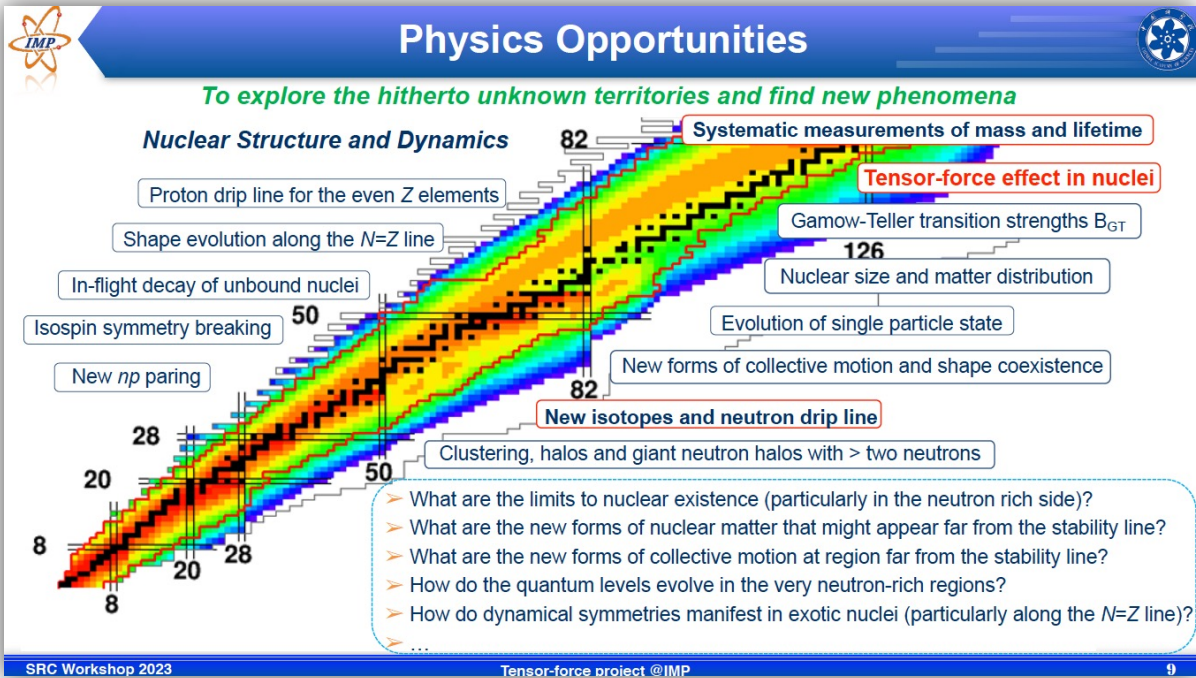


Monte-Carlo Simulation ($^{12}\text{C}^{6+}$ at 51 GeV/c)



➤ HIAF-HFRS

❑ Radioactive ion beams are produced at HFRS



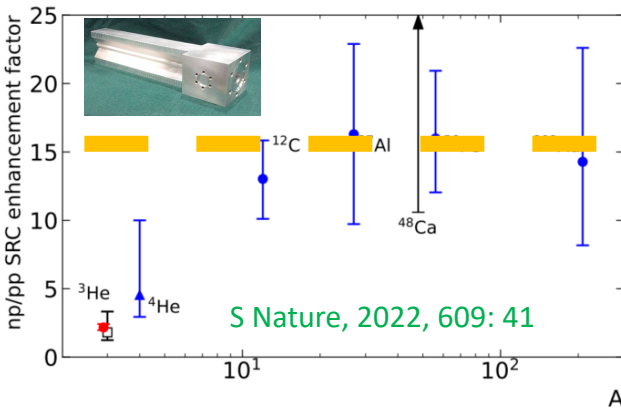
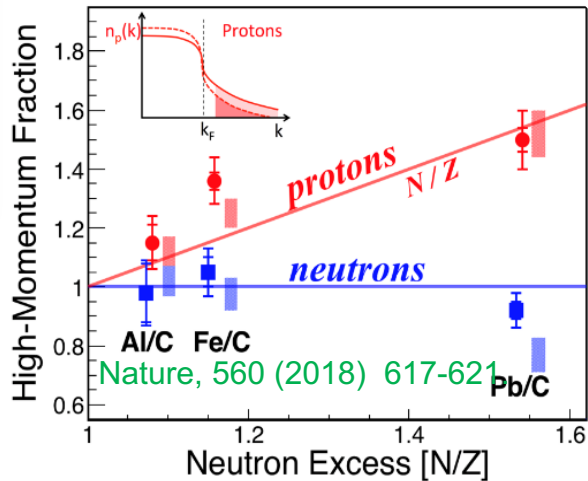
by Hooi-Jin Ong

Maximum rigidity	25 Tm
Resolving power	800, 700, 1100
Momentum acceptance	$\pm 2.0\%$
Angular acceptance	± 30 mrad (x) ± 15 mrad (y)
Beam size	± 1 mm (x) ± 2 mm (y)
Total length	192 m



❑ Study 2N-SRC w/ radioactive isotopes from HFRS

✓ Neutron-rich nuclei vs fixed “isoscaler” nuclei



- SRC allows fully studies of nuclear force, quark & gluon in nuclei, neutron stars, etc.
 - 2N-SRC well studied (np-dominate); 3N-SRC remains unseen
 - Inverse kinematic pA reaction → Precisely study SRC
 - Initial exploration with JINR & GSI & CEE@HIRFL, future high-precision study with HIAF
- ❑ Most of work done by TMEG graduate students: Haocen Zhao, Haojie Zhang, Yaopeng Zhang
- ❑ In close collaboration with: Eli Piasetzky (Telv Aviv), Maria Patsyuk (Dubna), Hongna Liu (BNU),
Or Hen&Julian Kahlbow & Hang Qi (MIT), Xionghong He & Hao Qiu & Yapeng Zhang (IMP), ...
- ❖ Supported by NSFC “Joint NSFC-ISF Research Grant” under funding#12361141822



Backup Slides



- Nucleus-scattering with high momenta

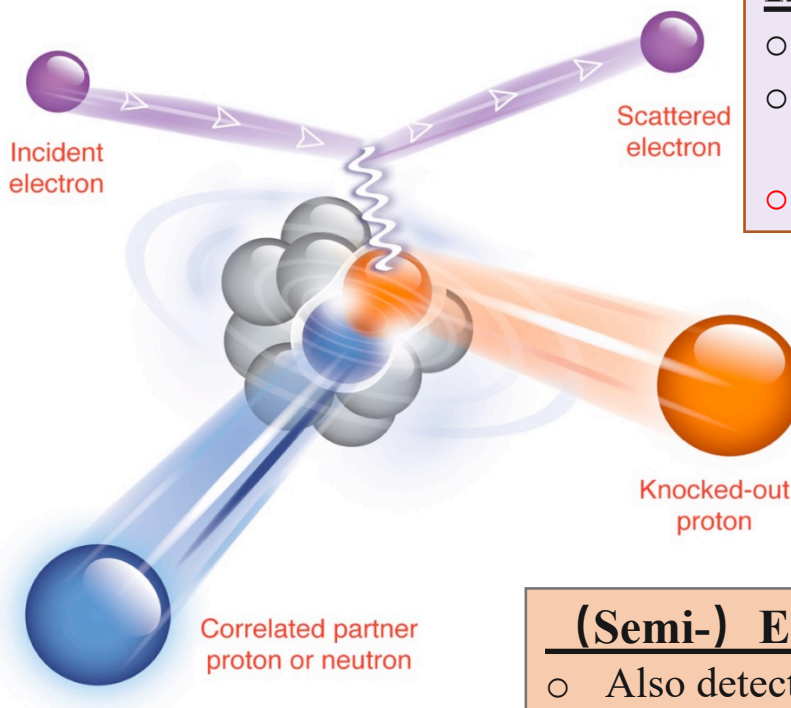
❑ **Quasi-Elastic Scattering (QES):** Knock out a nucleon but not breaking it

Beam Particle:

- Electron
 - Pro: Precise, low background
 - Con: small cross-section (EM)
- Proton:
 - Pro: large cross-section (Strong)
 - Con: Less precise, high background

“Target”:

- Fixed (Gas, Liquid, Solid)
 - Pro: Luminosity=Density, most of stable nuclei (atoms) available
 - Con: Knocked-out nucleon, residuals hard to escape
- Ion Beam:
 - Pro: detector final state particles w/ high momenta
 - Con: Luminosity=current, limited ion beams



Inclusive Measurement:

- Only detect scattered electrons, $A(e, e')$
- Measuring response of internal structure to the momentum-transfer
- **Less (not zero) Final State Interaction (FSI)**

(Semi-) Exclusive Measurement :

- Also detect knocked-out high-momentum nucleon, $A(e, e'pN)A-2$
- Can detect paired nucleon in opposite direction
- Strong FSI (experimental & theory corrections)
- **$A-2$ system in ground state**

• SRC Event Selection

□ Conditions: Knock-out nucleons, initial and final nuclear systems both in ground state \rightarrow QES tail on the low-E side

□ Quantities:

Momentum Fractions: $x = \frac{Q^2}{2m_p v}$

Four Momentum Transfer: $Q^2 = 4E_0 E' \sin^2(\theta/2)$

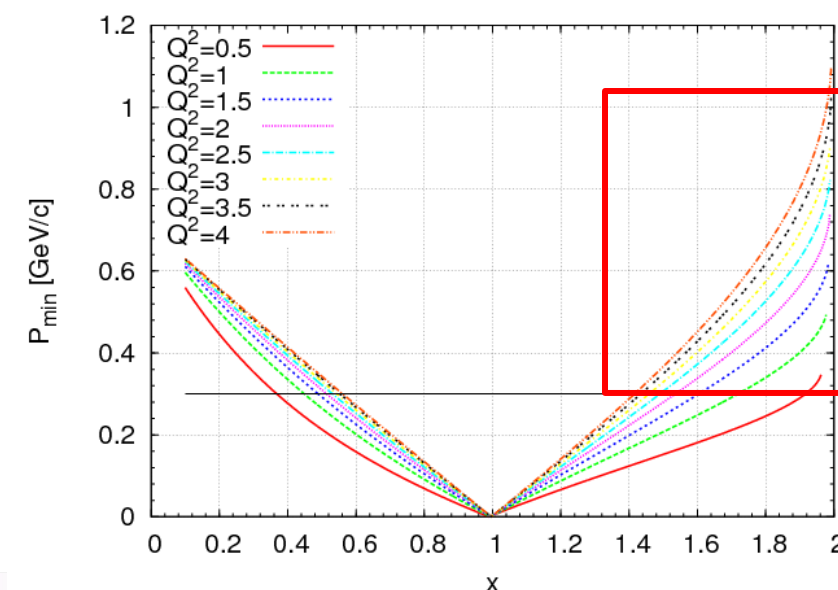
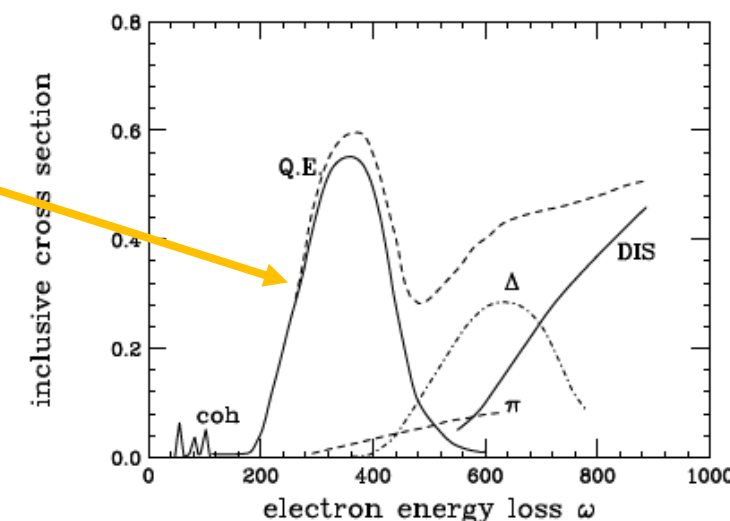
□ Remove mean-field contribution $\rightarrow k > k_{\text{Fermi}}$

- Directly measure high-P knock-out nucleons \rightarrow strong FSI
- $1 < x < A \rightarrow$ "quark" takes addition momenta from nucleon-motion

□ Control FSI in semi-(exclusive) measurements (**very hard!**):

- High- Q^2 to minimum the time of escaping \rightarrow less re-scattering
- Measure knocked out nucleons at special kinematics with min/max FSI
- Combine with theories models for additional corrections

Benhar, Day, Sick, Rev. Mod. Phys. 80, 189 (2008)



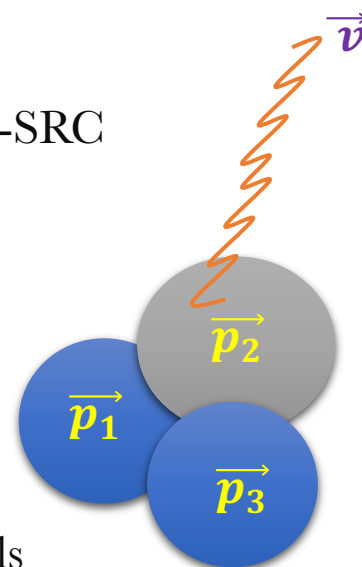
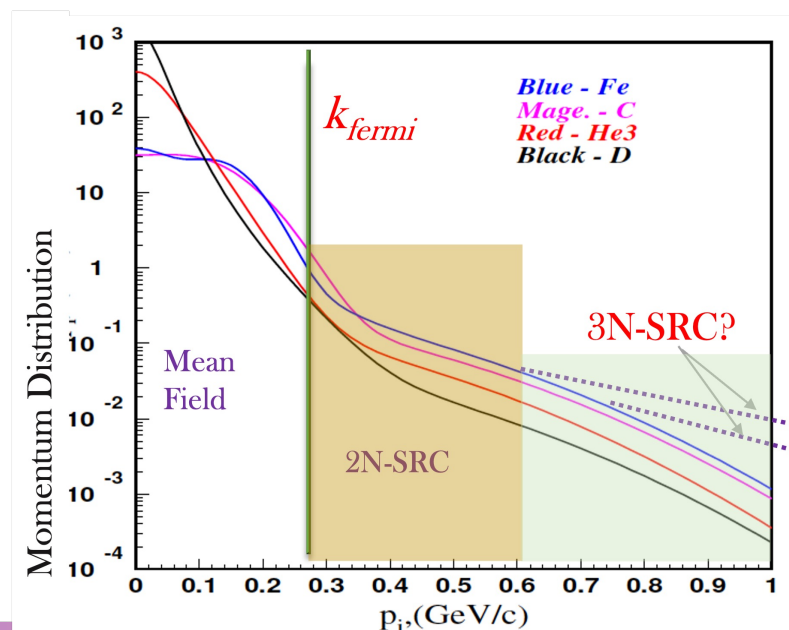
• Much Harder to Measure

- ❑ Many final-state combinations after breaking up 3N-SRC
- ❑ Impossible w/ eA exclusive measurement → need detect 3 high-P nucleons at all possible momenta
- ❑ Inclusive Measurement: XS links to the 3N-SRC tails

3N-SRC ($2 < x < 3$)

$$a_3(A, {}^3\text{He}) = K \cdot \frac{3\sigma_A}{A\sigma_{{}^3\text{He}}}$$

○ **2nd plateau?**



Center of Mass Frame

