Study Short-Range Correlations with Multiple Probes

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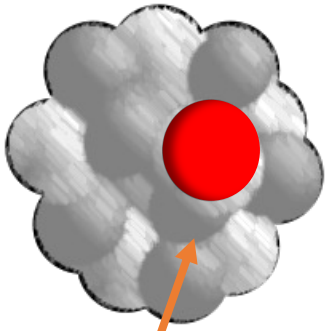
Workshop of “Nuclear Physics across Energy Scales”

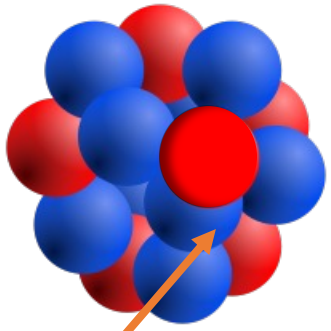
CCNU, Wuhan, 2025-09-21

What is a Nucleus?

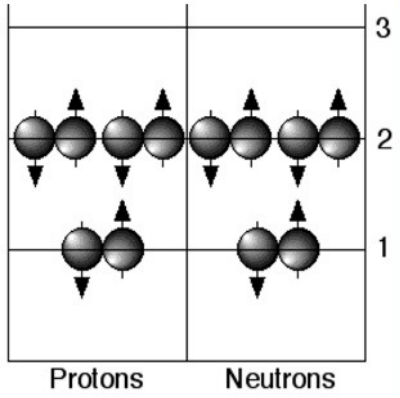
Mean-Field (Shells)

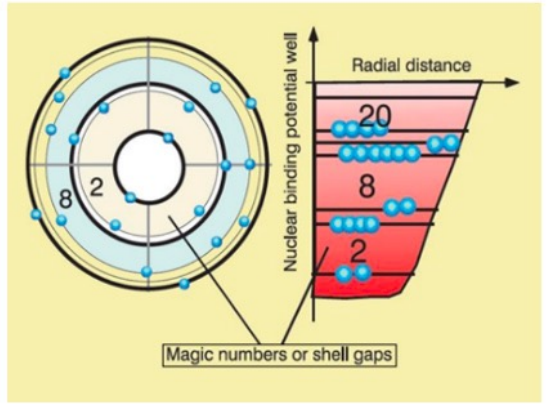


Many-Body Nuclear Forces

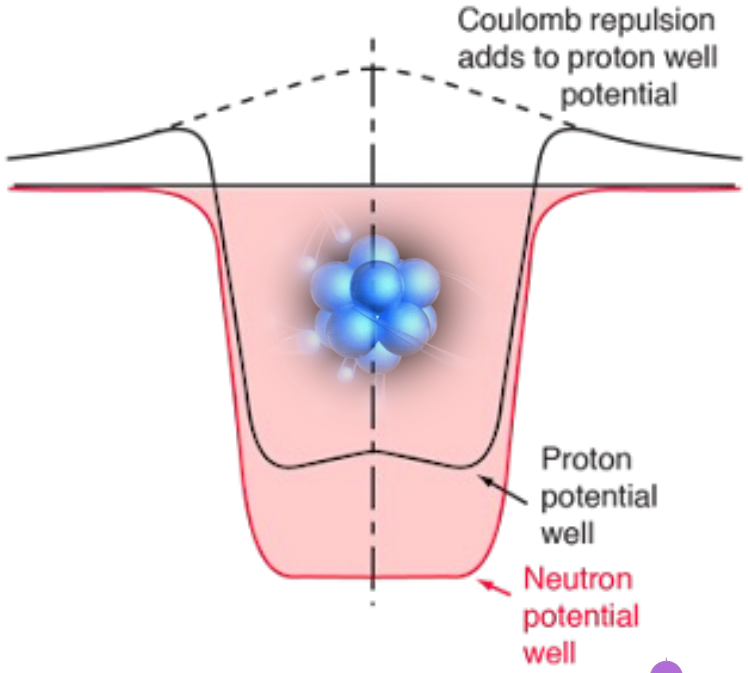


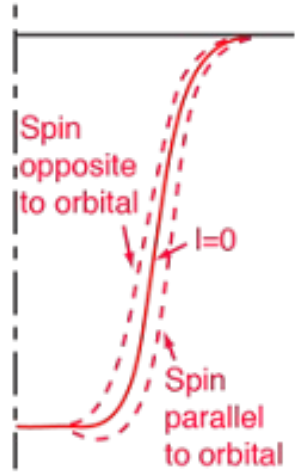
$$V = \sum_i \bar{V}(i) + \sum_{i<j} V^{(2)}(i,j) + \sum_{i<j<k} V^{(3)}(i,j,k) + \ldots$$





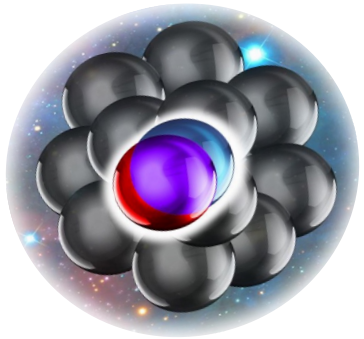
- A nucleus is compact, but not too much!
- Nucleons occupy “shells” , and point-like
- Yukawa Potential → Modern Potentials (AV18)
- Succesful (supprisely), but not very



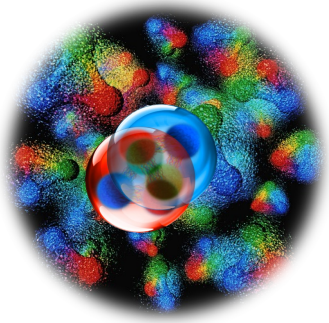


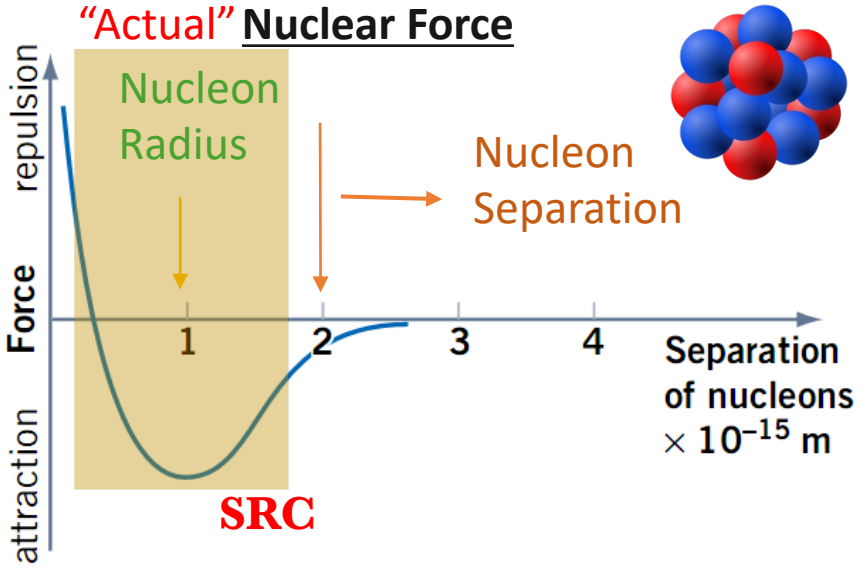
Short-Range Correlations

Short-Range Correlations(SRC)



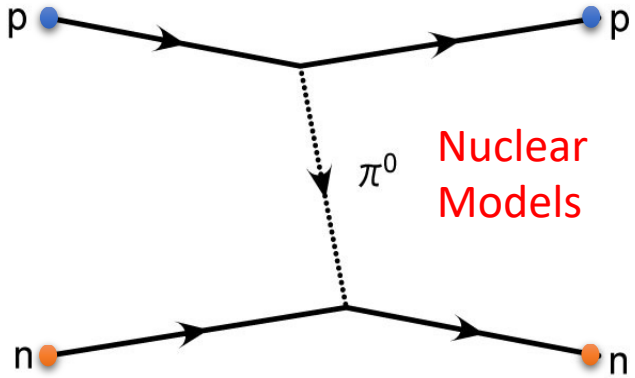
Quarks in Nucleus

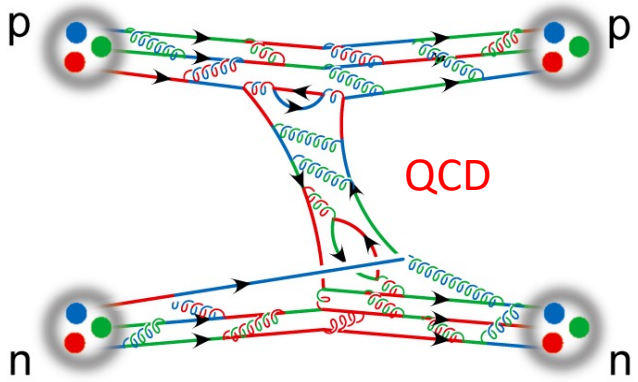




- Nucleosn overlapped due to tensor forces, then pushed away
  → 20% nucleons offshells!
- Dynamic balance leads to SRC
- Nucleons largely overlapped (much dense vs. alpha clusters)

- All mena-field models fail for SRC, but hard to use QCD
- Heavily rely on measurements





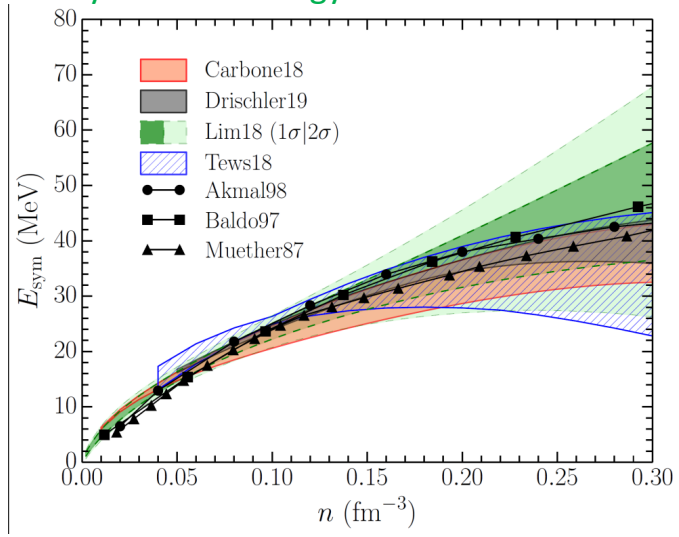
“Cross Energy Scales”

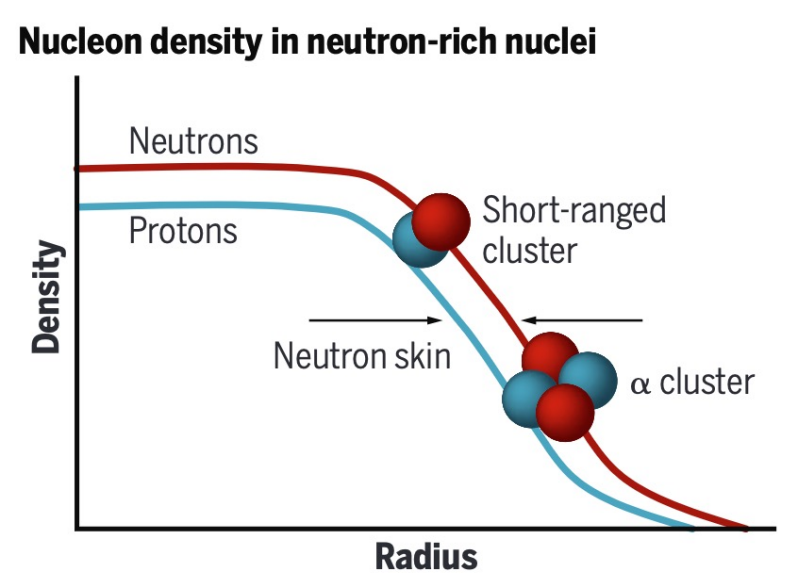
- NN & NNN forces, nuclear structure, cold nuclear matter
- Nuclear structure in QCD (nuclear PDF, EMC, heavy-ion, …)
- Mass matrix for neutrino-less double beta decay?

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

- Important in forming neutron-rich nuclei

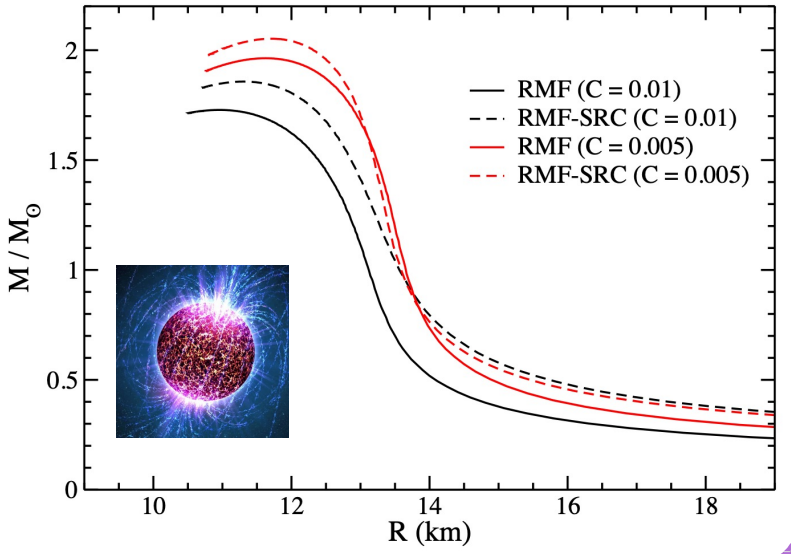
Symmetric Energy in Neutron Star





Hen, Science 371, 232 (2021)

- Forming ultra-heavy neutron stars?

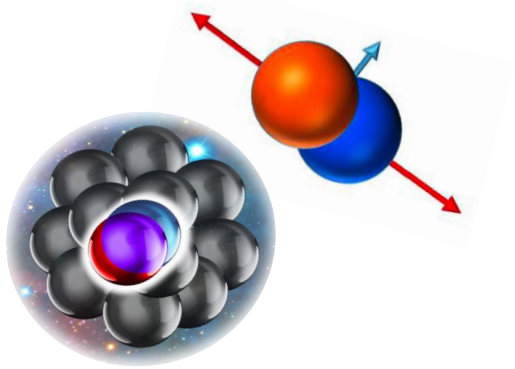


NPA 1021, 122408 (2022)
NPA 1011, 122200 (2021)

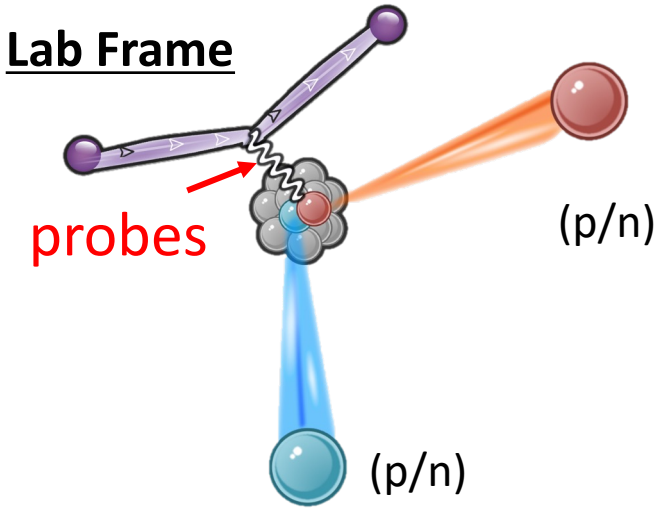
Short-Range Correlations

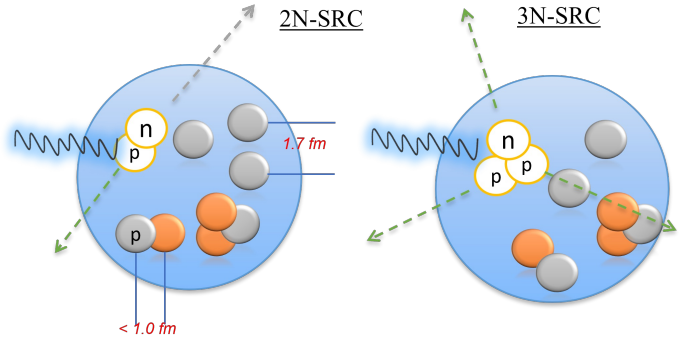
How to probe?

Center-of-Mass Frame



Lab Frame

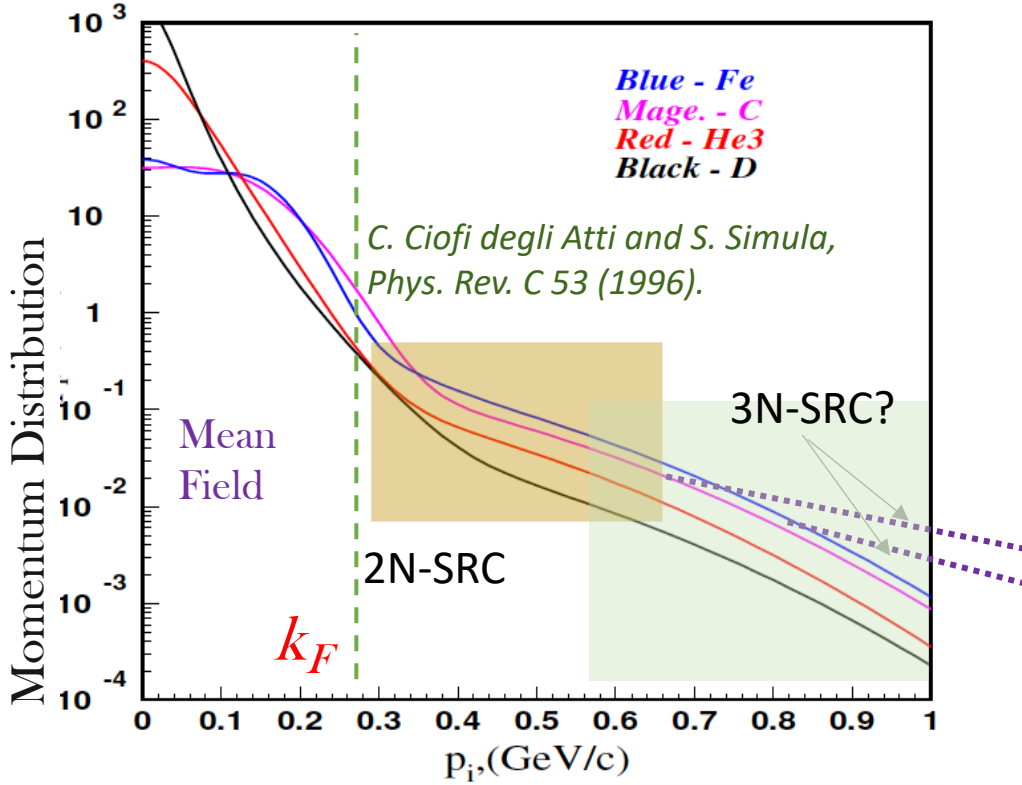




- C.M. frame, SRC pairs move in opposite direction, with high momentum (>300MeV/c)

- In Lab frame, probes "kick" out one nucleon, then measure:
  1. response to the "kick", e.g. (e,e')
  2. high-P proton (>k_F), e.g. (e,e'p)
  3. high-P nucleon in opposite direction (C.M.), e.g. (e,e'pN)
  4. % of np-SRC vs. pp-SRC vs. nn-SRC?

- Key idea: Nuclear system → 2- or 3-body system

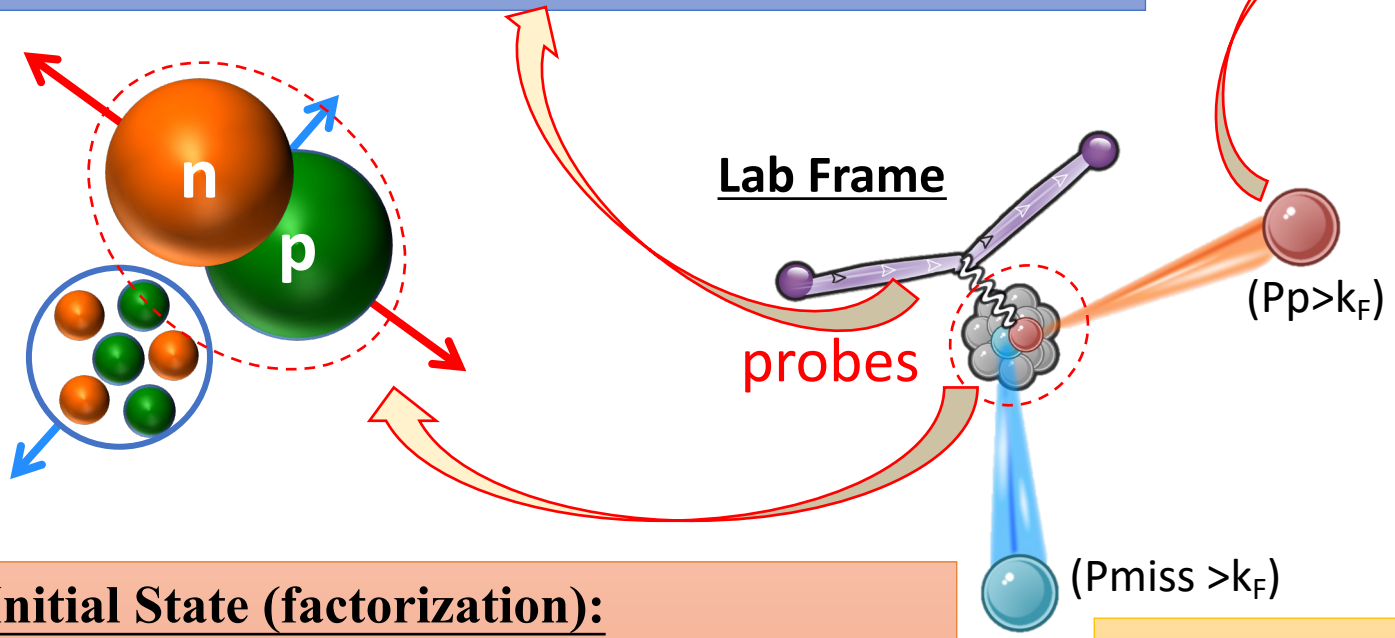


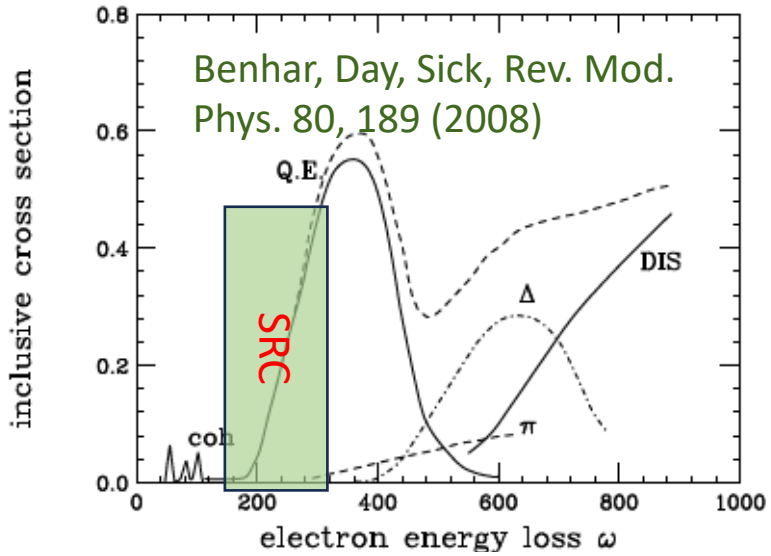
Short-Range Correlations

Experimental Method (2N-SRC case)

➢ **Probe (electrons, photons, protons, ions):**
- ✓ High resolution (<0.84fm, ~r_p)
- ✓ "Snapshot" of initial state
- ✓ Knock out but not break nucleons (clean!)

➢ **Final State:**
- ✓ SRC nucleons leave (A-2) w/o re-scattering, back-to-back (in CM)
- ✓ (A-2) fragment is intact, not excited
- ✓ Reject non-SRC back-to-back signals





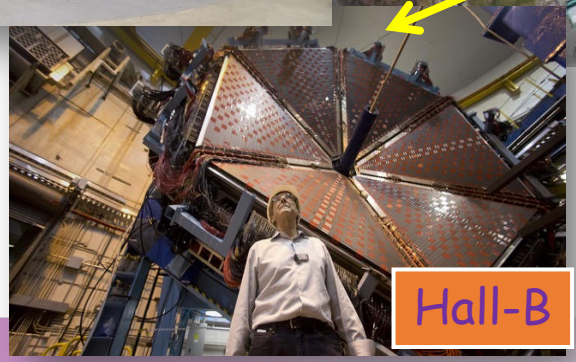
➢ **Initial State (factorization):**
- ✓ SRC nucleons large relative momenta (P_1=-P_2), small total momentum (P_{total})
- ✓ (A-2) momentum=-P_{total} (<<k_F)

❑ Select SRC events (roughly!):
1. Q^2 >1GeV^2, x>1.2 (Quasi-elastic scattering, Q.E.)
2. Pp & Pmiss >> k_F (~>300MeV/c), back-to-back
3. Tagging (A-2), very hard for fixed targets

Electron-Scattering Experiments

Thomas Jefferson Lab (JLab)

Hall-D



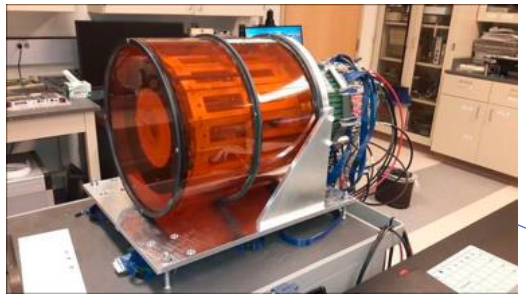
Hall-B

Hall-C

Electron-Scattering Experiments

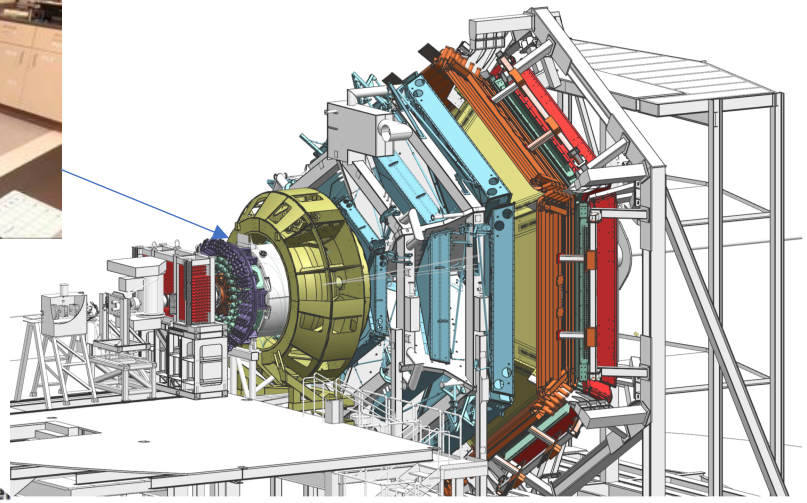
- **Detector Systems (Precision vs Acceptance)**

Vacuum Chambers for Targets



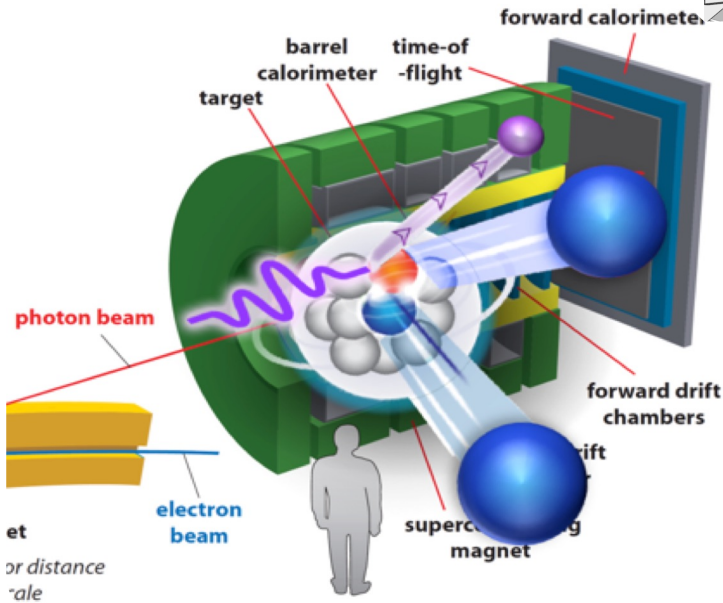
ALERT Recoil Detector

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



Hall-A HRS / Hall-C HMS
(High-Precision, Limited Acceptance);

Third-arm to detector p/n



Hall-D GlueX
(photon-beam, Full Acceptation)

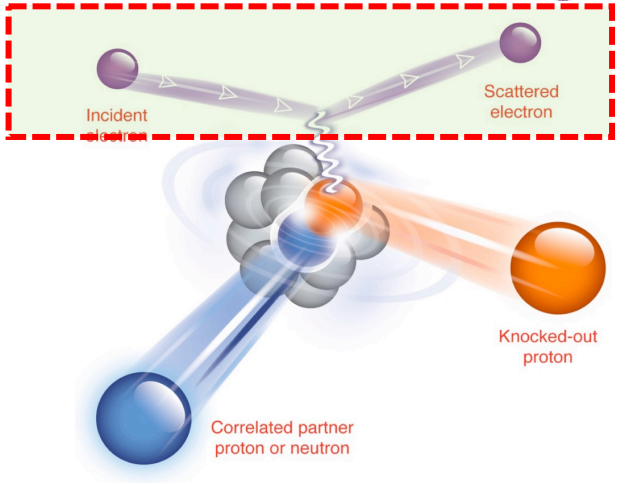
Electron-Scattering Experiments

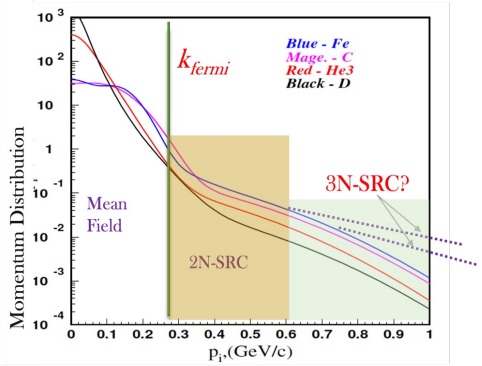
- **Inclusive cross-sections in Q.E:**

Nucleon momentum distribution

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

"links" to momentum distribution

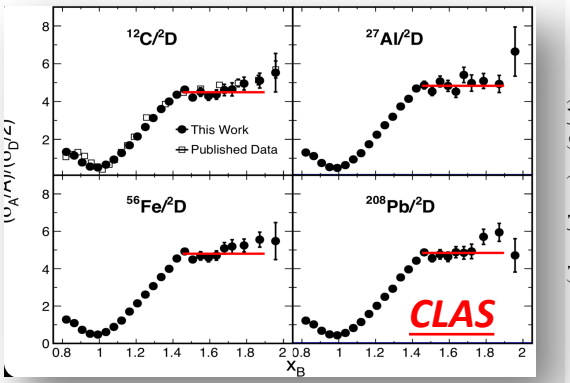




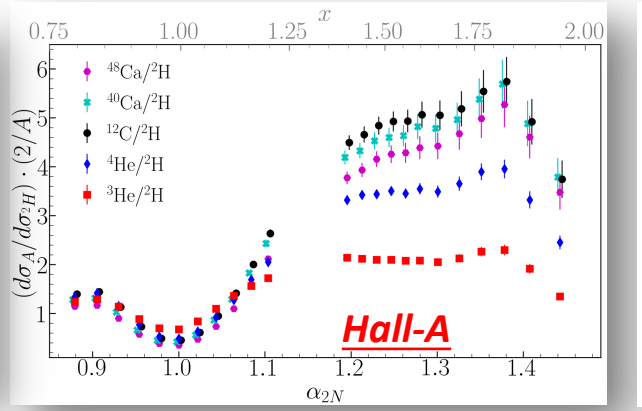
- ❑ Similar high-P tails → look for a plateau
- ✓ *2N-SRC* ($1.3<x_{bj}<2$): $a_2(A,D) = \frac{2}{A}\frac{\sigma_A(x,Q^2)}{\sigma_D(x,Q^2)}$,

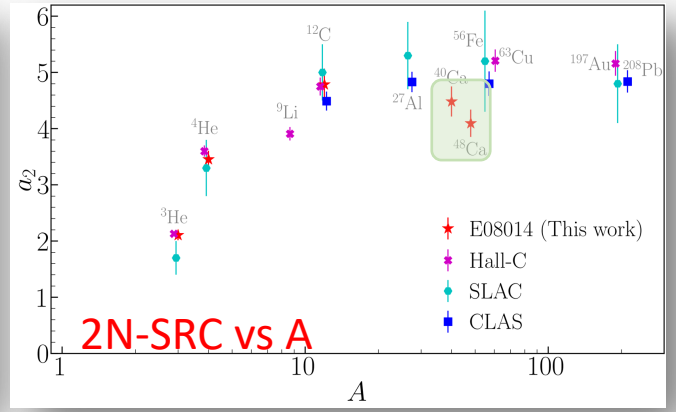
a_2 → probability of 2N-SRC in A

Schmookler et al., Nature (2019)

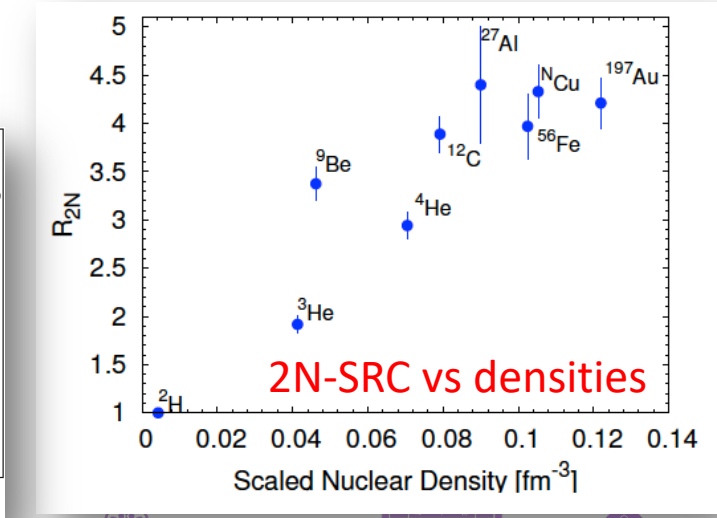


Y.P. Zhang, Z. Ye, et. al, arXiv:2504.17462 , submitted



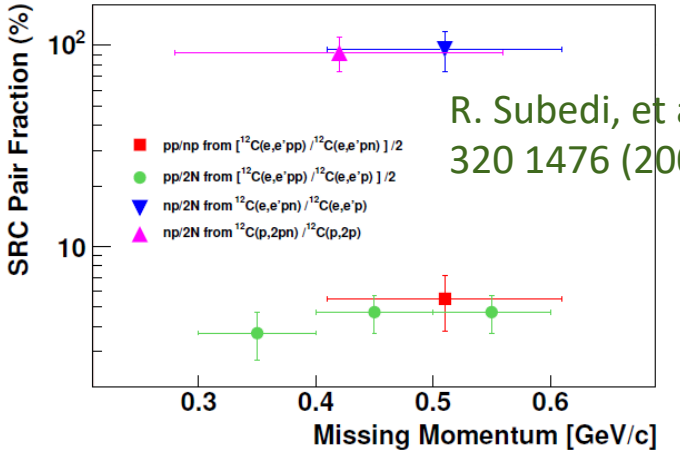


Arrington et al. PRC 86, 065204 (2012)

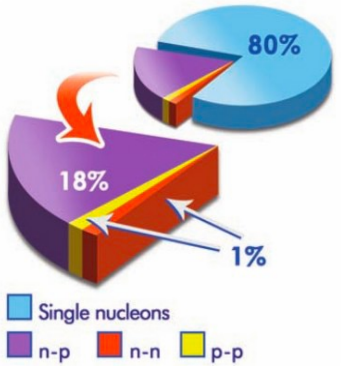


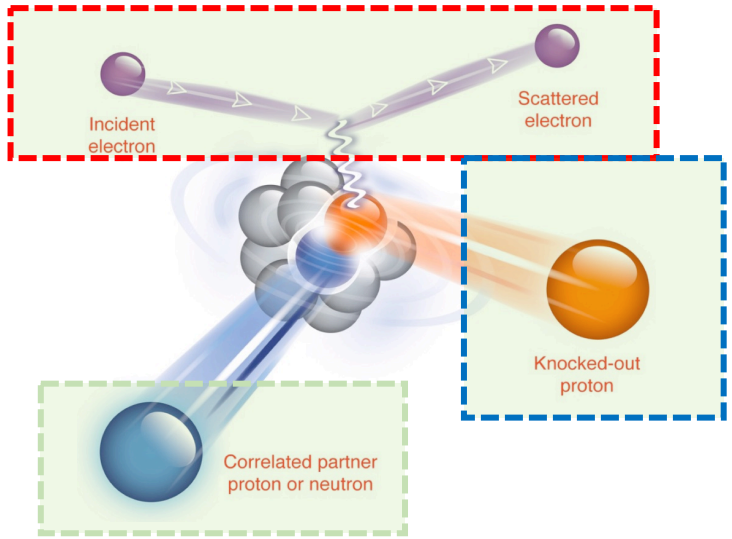
Isospin-Dependence

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

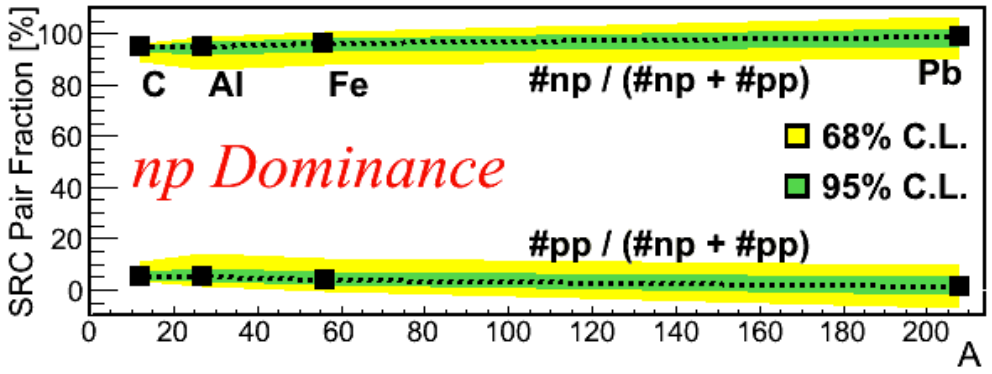


R. Subedi, et al, Science 320 1476 (2008)

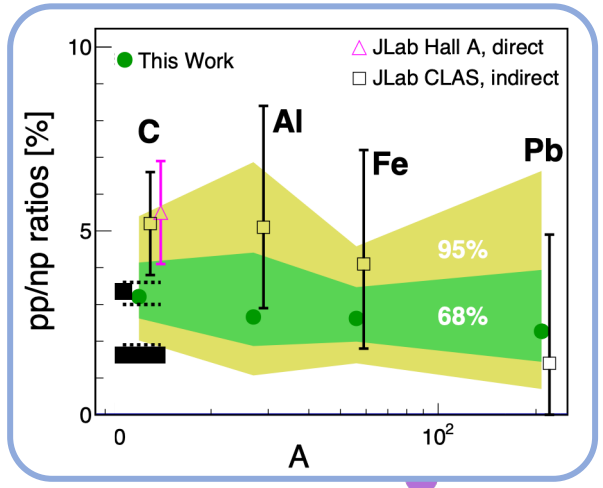




- Similar np-dominances in heavy nuclei → universality?



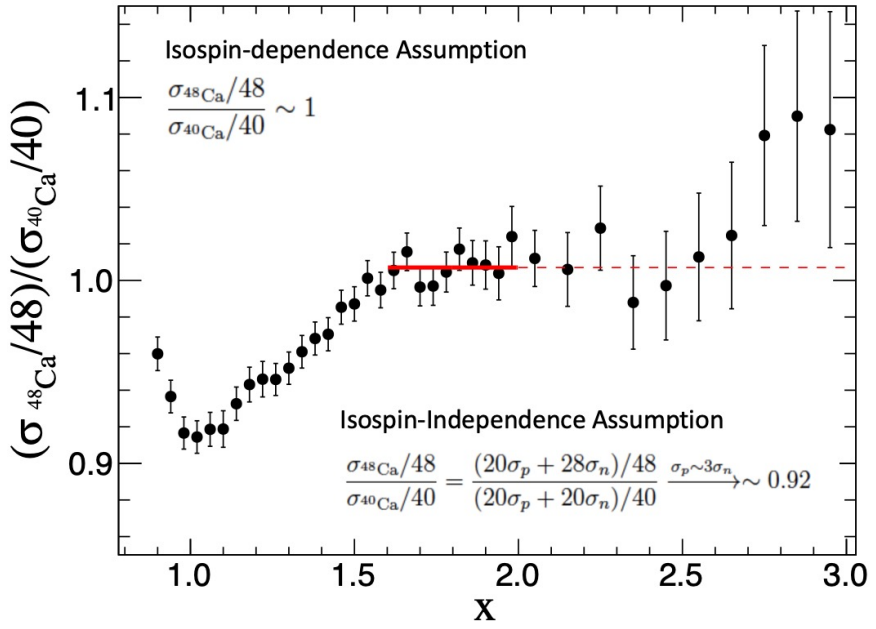
Review: Hen RMP '17;



Isospin-Dependence

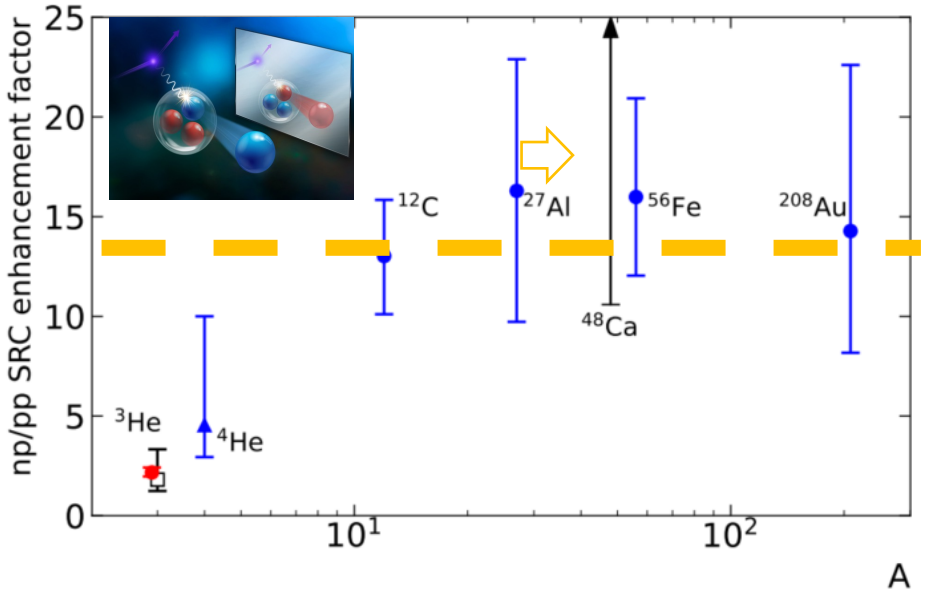
- First inclusive measurement w/ Ca48 & Ca40 isotopes → not clear!

  D. Nguyen, Z. Ye, et al, RPC **102**, 064004 (2020)



- Using Tritium and Helium-3 isotopes (E12-11-112)

$$\frac{\sigma_{H3}}{\sigma_{He3}} = \frac{2R_{pp/np} + 1 + \frac{\sigma_{ep}}{\sigma_{en}}}{(2R_{pp/np}+1)\frac{\sigma_{ep}}{\sigma_{en}} + 1} \qquad R_{pp/np} = \frac{\left(1 + \frac{\sigma_{ep}}{\sigma_{en}}\right)\left(1 - \frac{\sigma_{H3}}{\sigma_{He3}}\right)}{2\left(\frac{\sigma_{H3}}{\sigma_{He3}} \cdot \frac{\sigma_{ep}}{\sigma_{en}} - 1\right)}$$

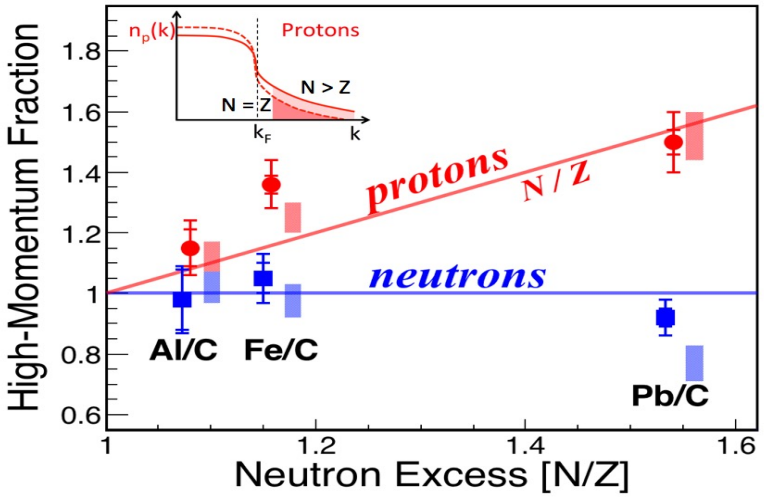


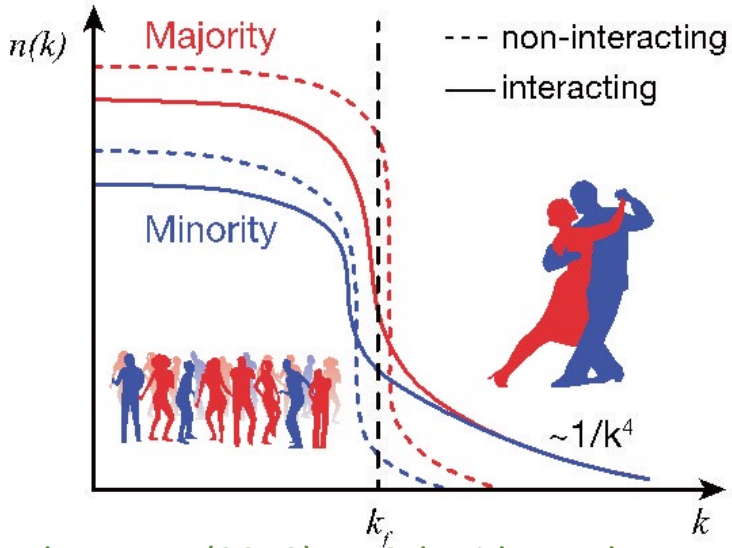
Li, Torres, Sentiestaben, ZYe, et. al, Nature, 2022, 609: 41

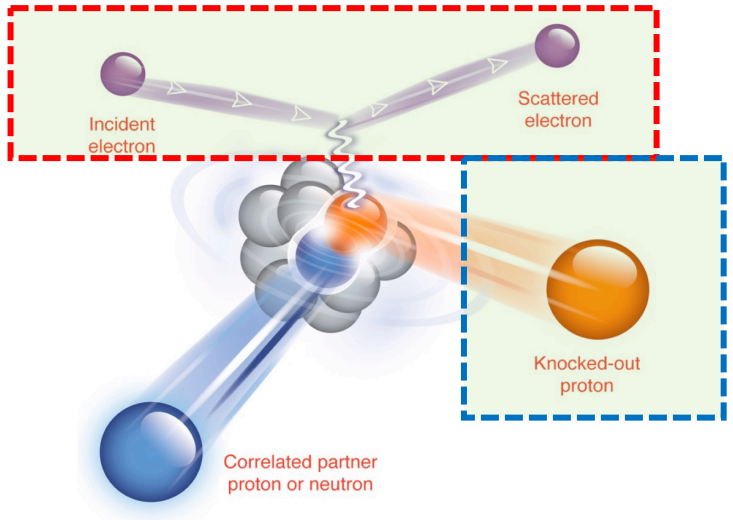
- Small np-dominances in A=3 nuclei → Why?
  - Few-body nuclei vs heavy ones?
  - **Neutron-rich nuclei vs. Isoscaler?**
- Need more neutron-rich radio-active isotopes!

Isospin-Dependence

❑ Proton "speed up" with neutron excess







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

❑ Many problems:

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

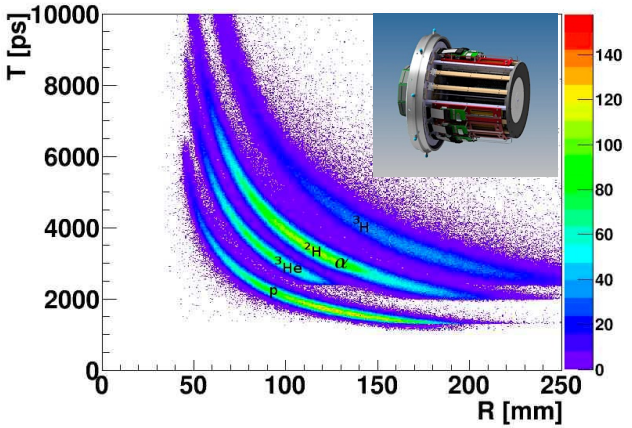
New method!

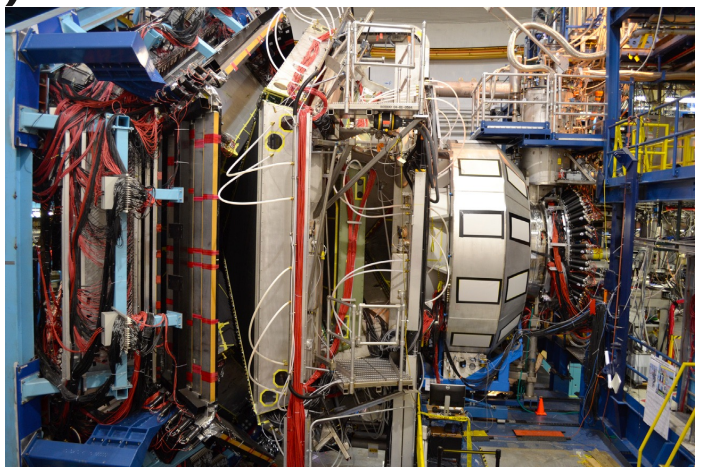
New ALERT-SRC experiment!

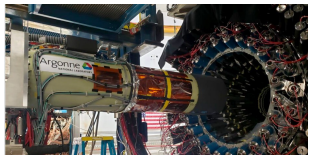
Mean-Field vs SRC

❑ NEW: ALERT-SRC w/ CLAS12 in Hall-B (finished on Sep. 3rd 2025)

- 6.6 GeV electron beam on He4
- CLAS12 measured e' and p
- ALERT recoil detector measure fragments (^{3}He & ^{3}H & ^{2}H)



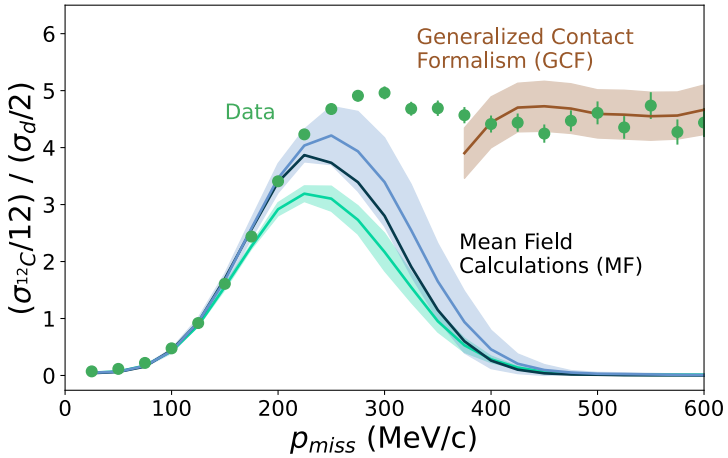




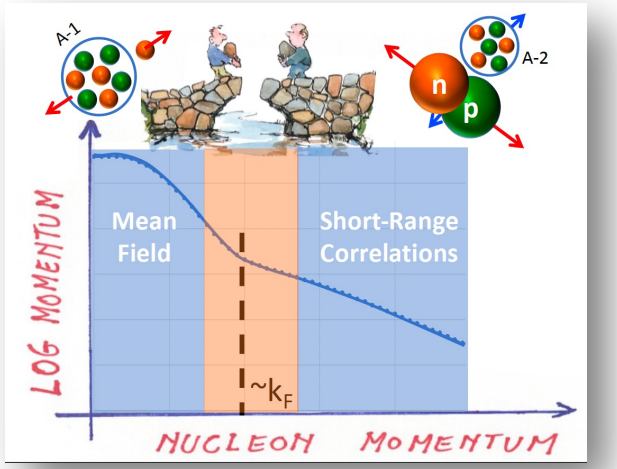
✓ Goal#1: Test factorization

Elementary eN cross section | Nuclear Contacts | Two-body wave function | Center of mass motion

$$\sigma_{eA} = \sigma_{eN}(q) \cdot \sum_{NN-pairs} \cdot C_A^{NN} \cdot |\phi(p_{relative})|^2 \cdot n(p_{cm})$$



✓ Goal#2: Transition from Mean-field to SRC?



Zeyu Zhang, Ph.D thesis students from Tsinghua

SRC vs EMC

Tsinghua University

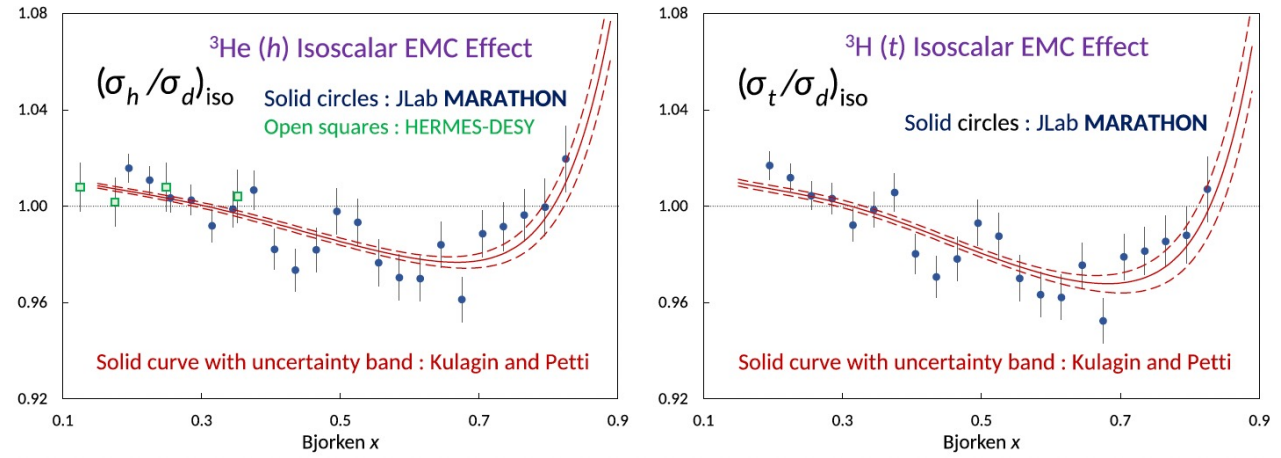
➢ EMC Effect:

- ❑ EMC: Inclusive DIS cross-section ratio of A to D drops linearly in 0.3<x<0.7

  Phys.Lett.B 123 (1983) 275-278

- ❑ Even modified in A=3 (likely D2 as well)

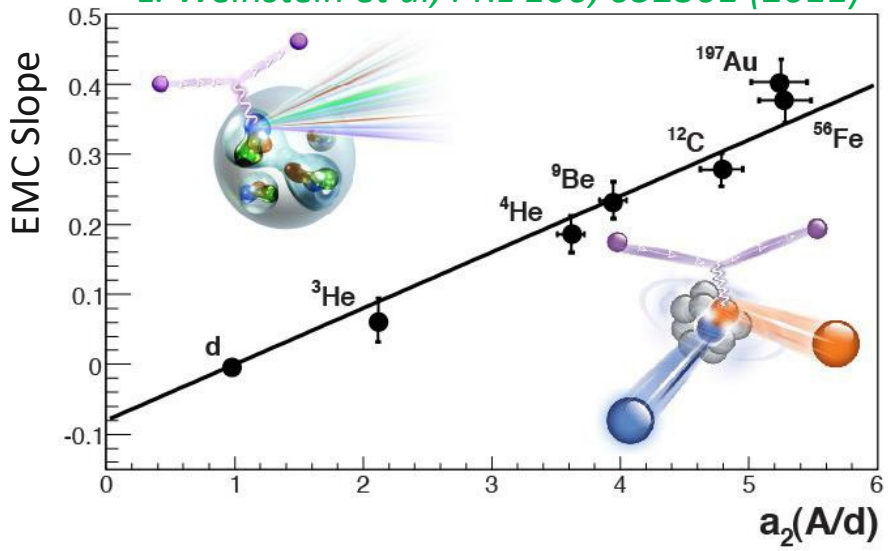
  MARATHON Phy. Rev. Lett. 135, 062502 (2025), editor suggested



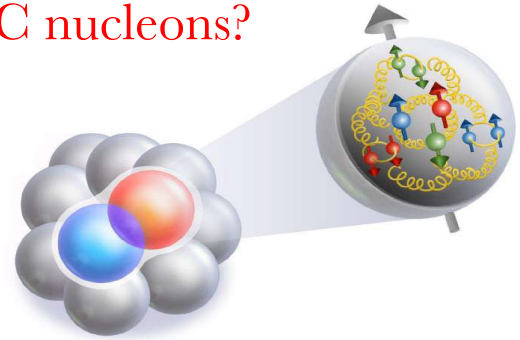
- ❑ 40 years after discovery, still unknown!

- ❑ Connection with SRC?

L. Weinstein et al, PRL 106, 052301 (2011)



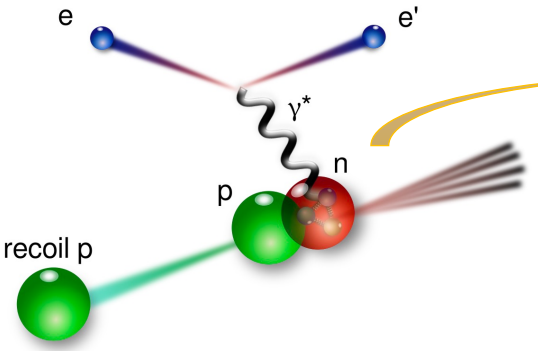
- ❑ Modification in all nucleons or only SRC nucleons?

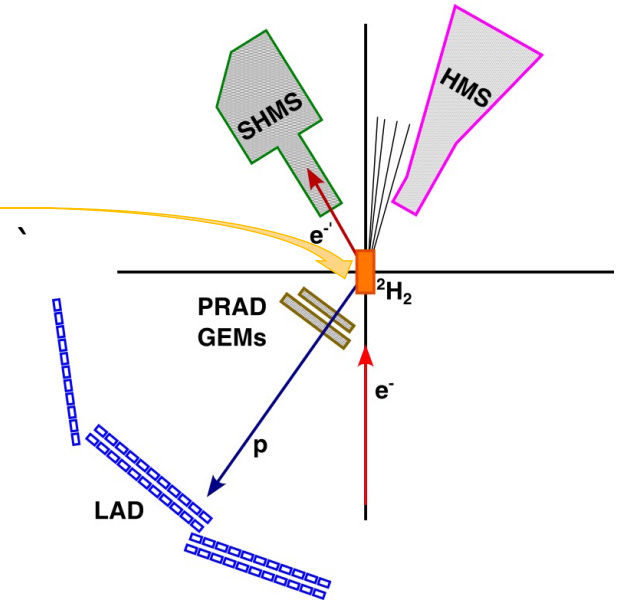


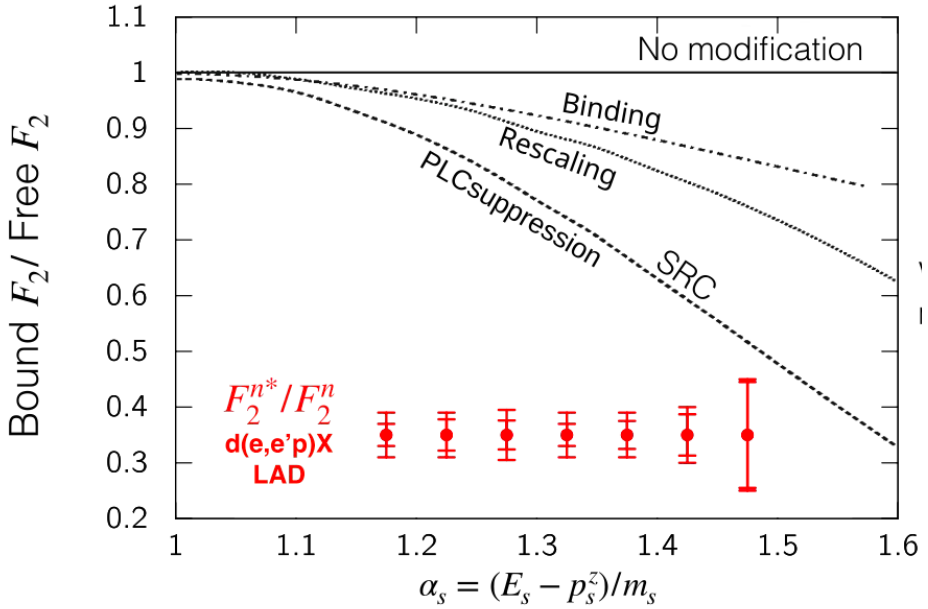
SRC vs EMC

❑ NEW: LAD Experiment in Hall-C (finished on August 2025)

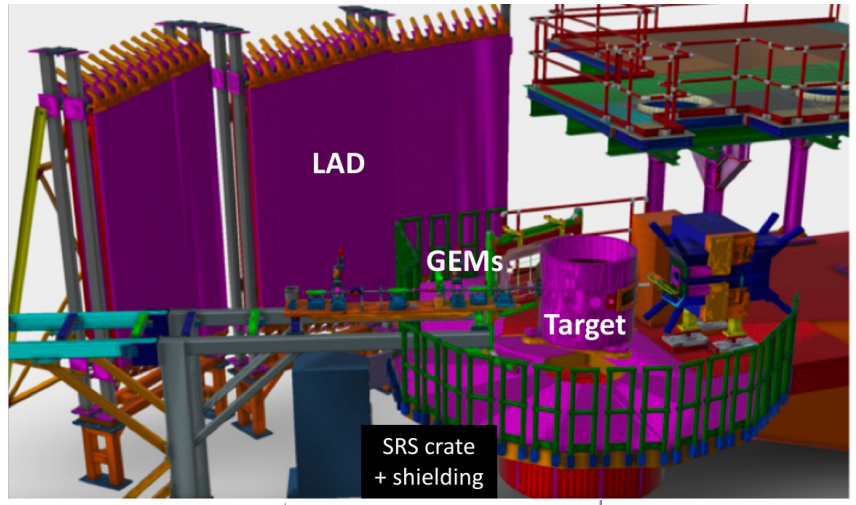
- ✓ 11 GeV e-beam on 20 cm liquid D2 (DIS)
- ✓ Standard HMS & SHMS for electrons
- ✓ LAD detector for recoil protons
- ✓ PRAD GEMs for tracking
- ✓ Duration: 34 PAC days





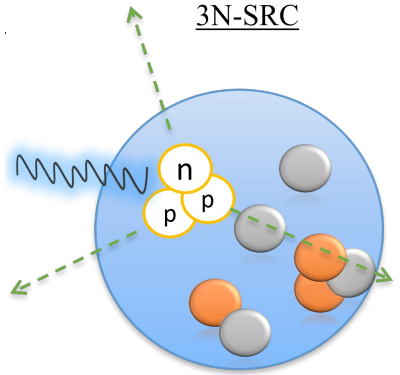


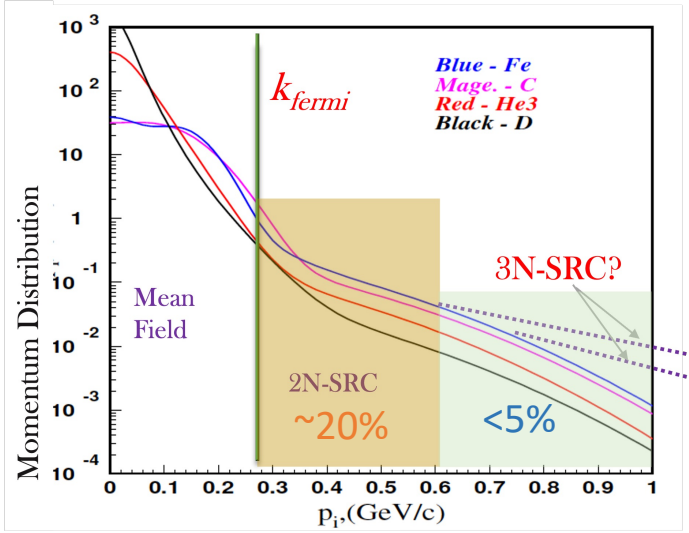
Haocen Zhao, Ph.D thesis student from THU



3N-SRC (still missing)

- Higher P & densities → neutron stars
- Link to unknown 3-body forces
- Complicated initial and final states



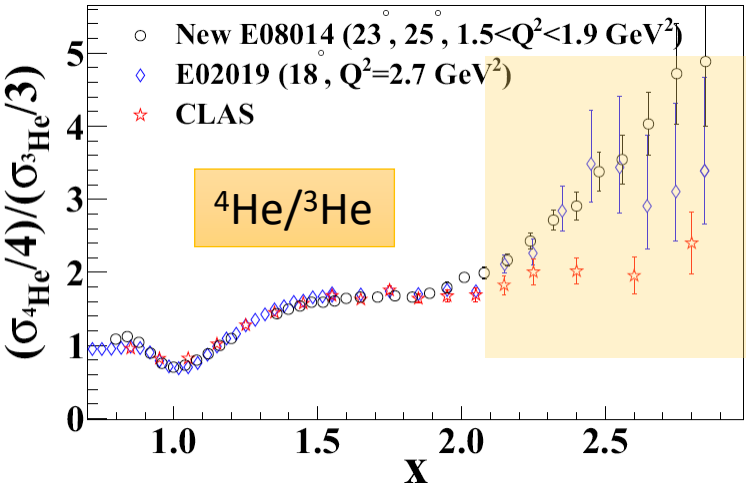


- Only can assess via inclusive method (so far)

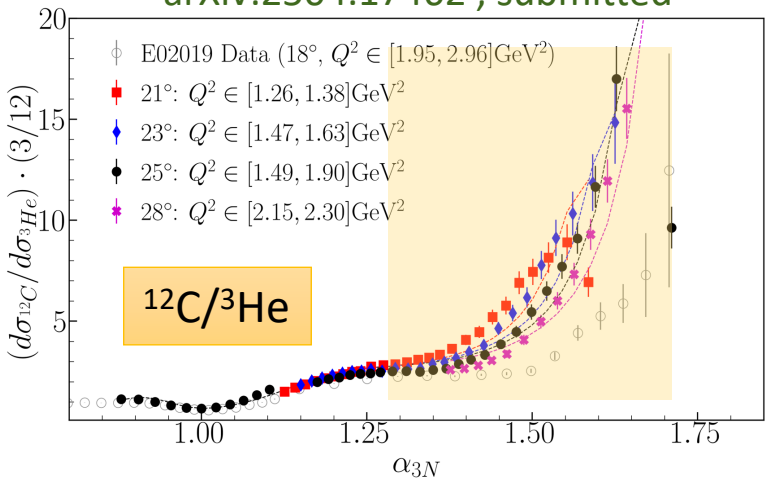
3N-SRC (2<x<3) $\quad a_3(A,^3He) = K \cdot \frac{3\sigma_A}{A\sigma_{^3He}}$

- No 3N-SRC plateau seen so far

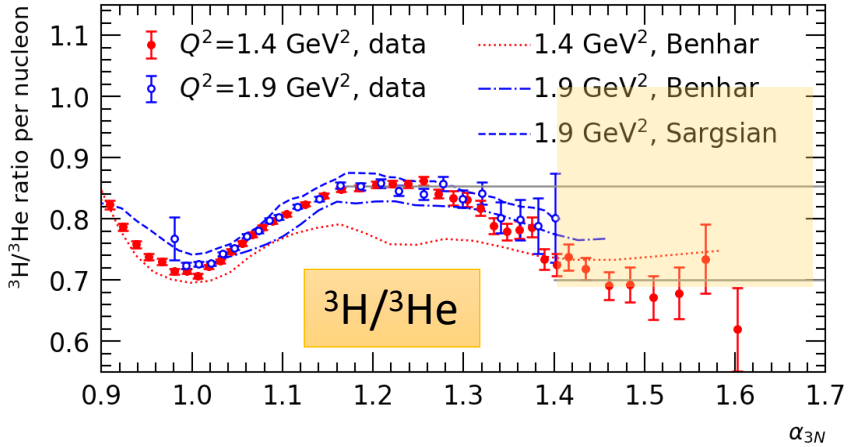
Z. Ye, Phys. Rev. C 97, 065204 (2018)



Y.P. Zhang, Z. Ye, et. al, arXiv:2504.17462 , submitted

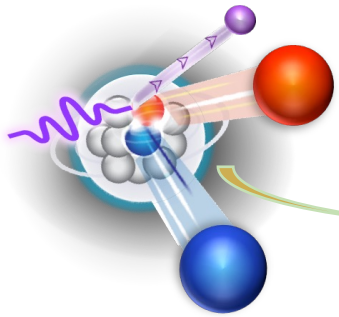


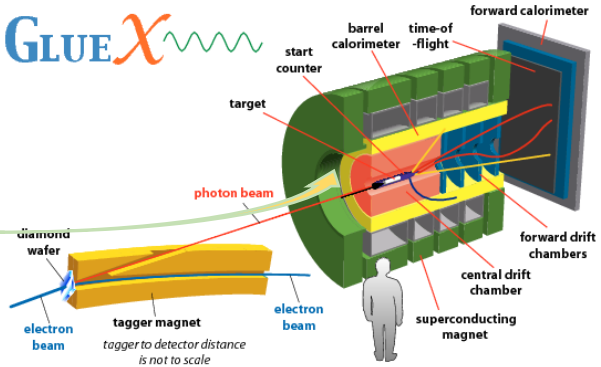
S. Li, et. al. Phys. Lett. B 868 (2025) 139734



SRC w/ Photons (new probe)

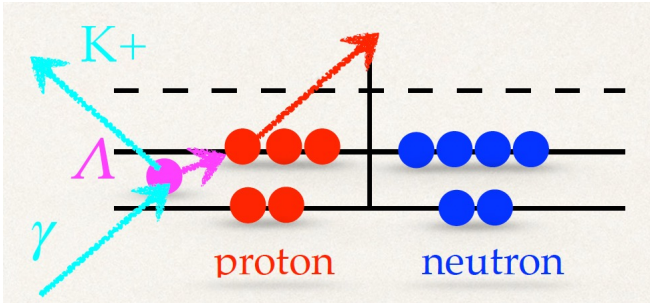
- A(γ, J/ψ p)X reaction below threshold (Haiyan Gao & Or Hen):
  - ✓ ~8GeV photons scatter on He4&C12 near threshold J/ψ ~ (8.2GeV)
    J.R. Pybus, et. al. PRL 134 (2025) 201903, w/ editor suggest.
  - ✓ Another approved GLUX SRC experiment in 2025



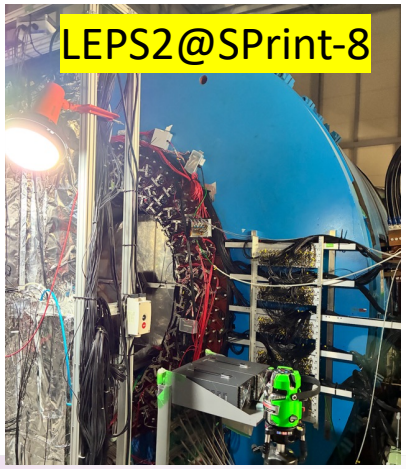


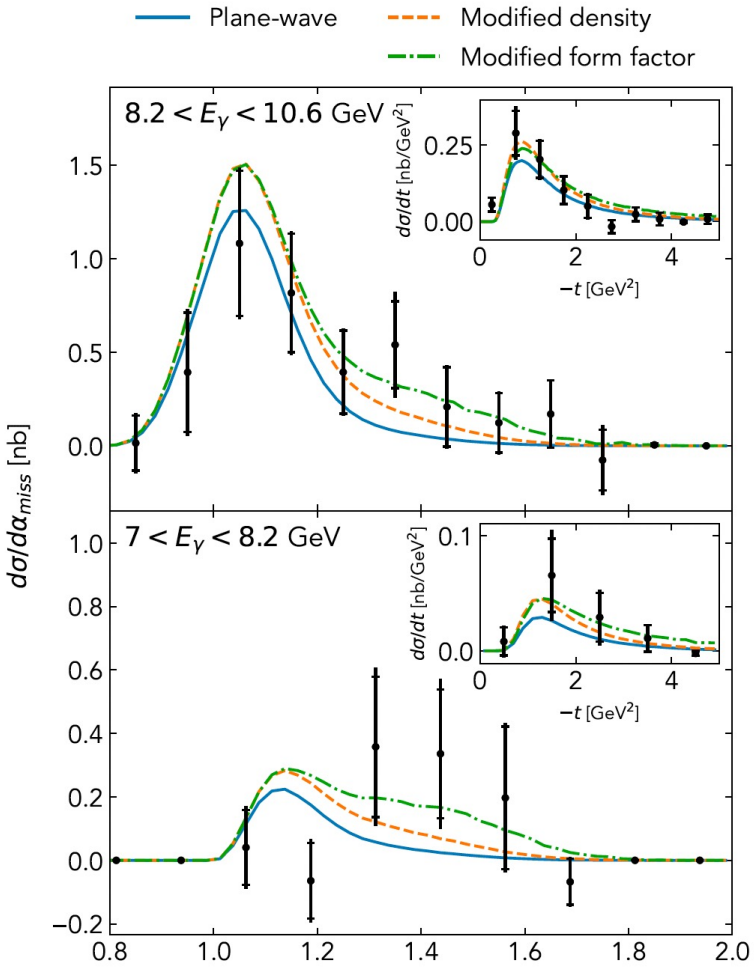
$$\vec{P}_{p-recoil} = -\vec{P}_{p\to J/\psi}$$

- Near-threshold Λ-Production (LEPS2, SHINE?)



Credit to Yue Ma (RIKEN)



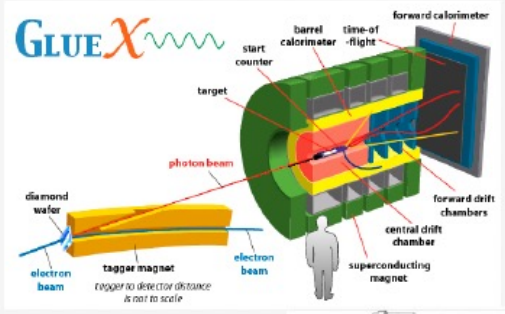


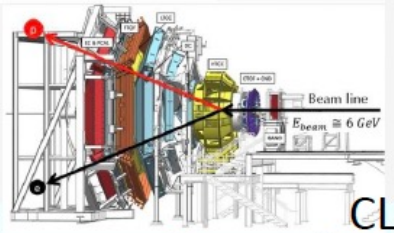
$$\alpha_{\mathrm{miss}} = \frac{E_{\mathrm{miss}} - p_{z,\mathrm{miss}}}{m_A/A}$$

”Muti-messenger” era

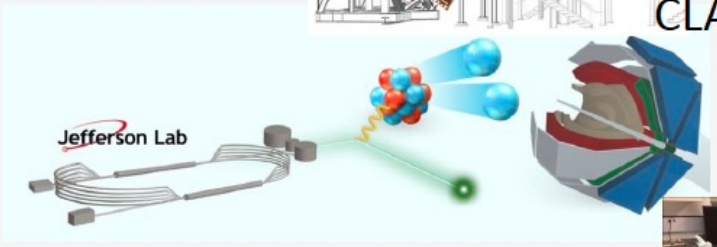
SRC studies with leptons

Jefferson Lab Hall D GlueX

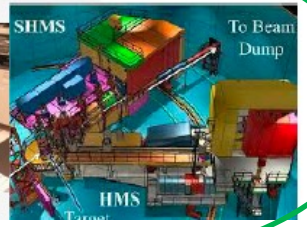




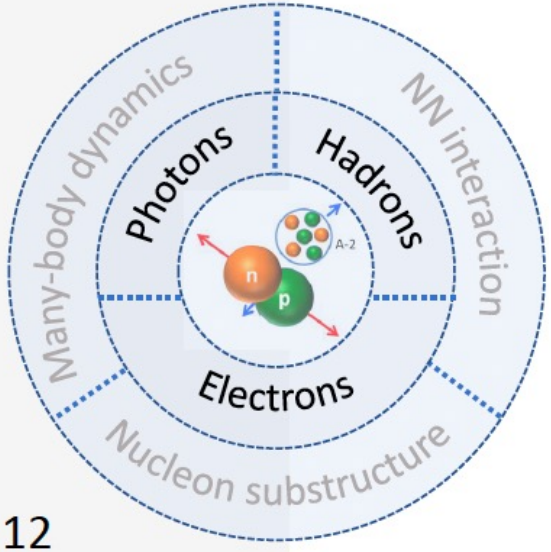
CLAS 12

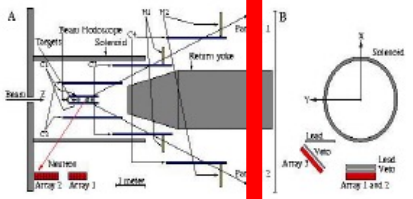


Jefferson Lab Halls A, B, C

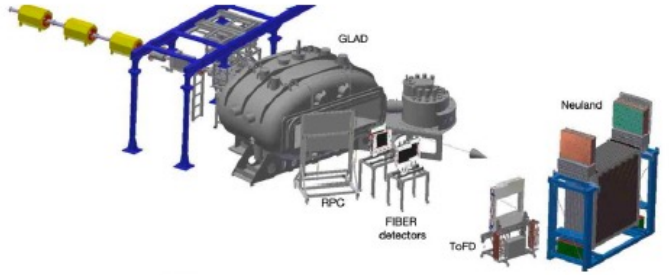


ALERT

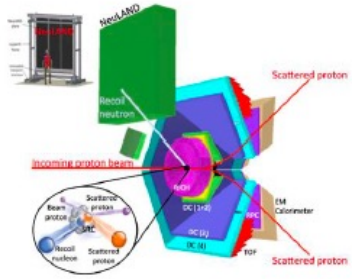




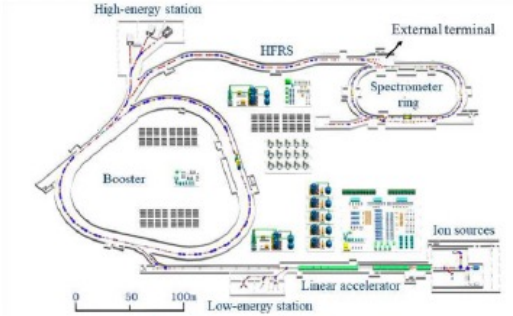
EVA/BNL



R3B



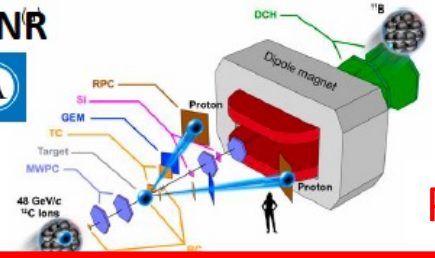
HADES



HIAF

JINR

NICA

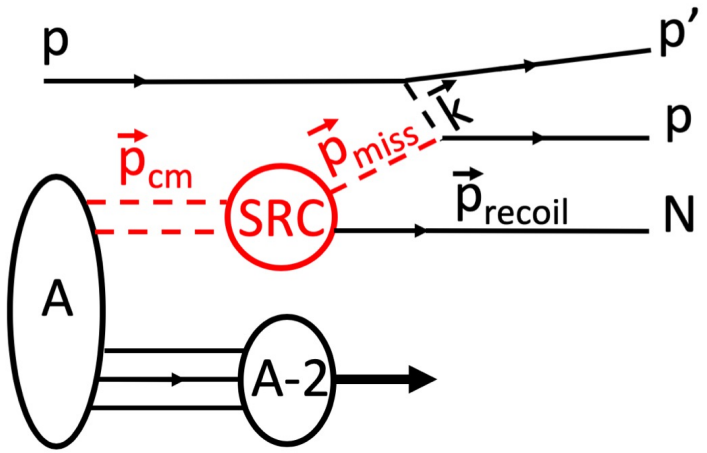


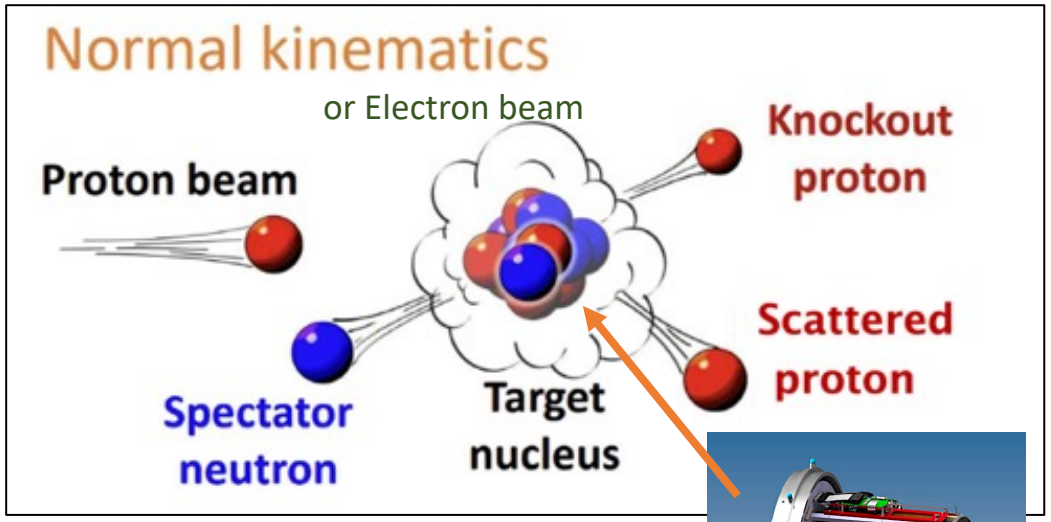
Precision Frontier!

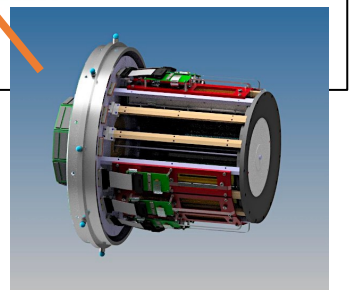
SRC Study w/ Inverse-pA

❑ Could solve issues remained w/ eA Scattering

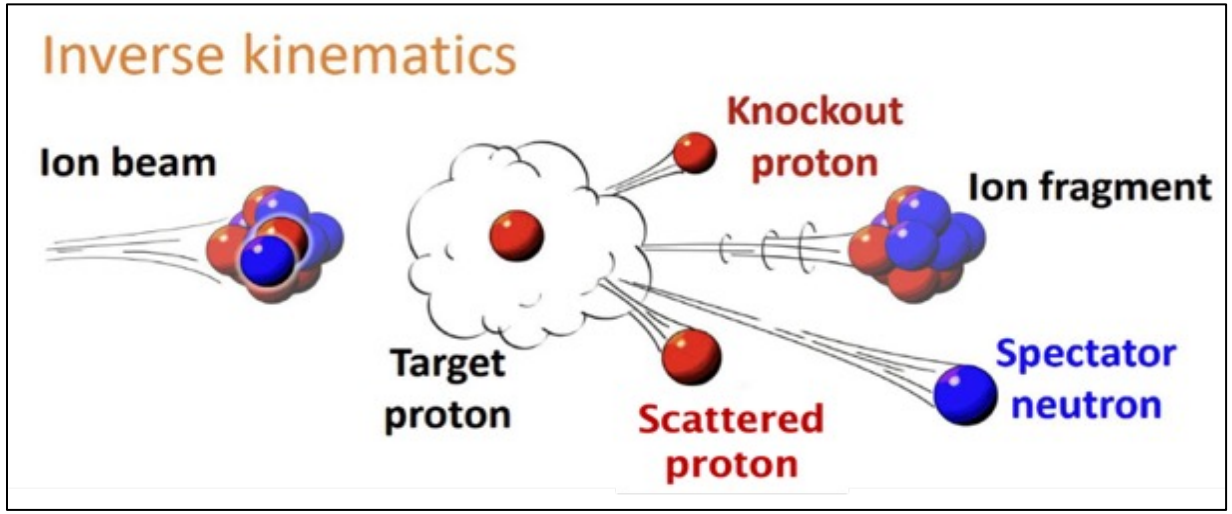
- ✓ Larger cross-sections → map 2N-SRC & search 3N-SRC
- ✓ Easier to detect fragments → Mean-field vs SRC
- ✓ Better controlled FSI → Reduce theoretical systematic errors
- ✓ **Large asymmetric nuclei, radioactive isotopes**







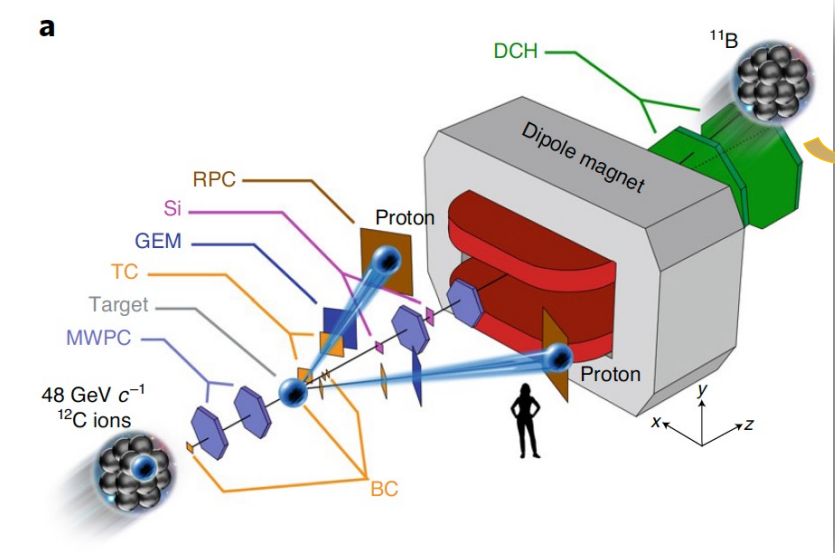
Recoil detector (e.g. ALERT)

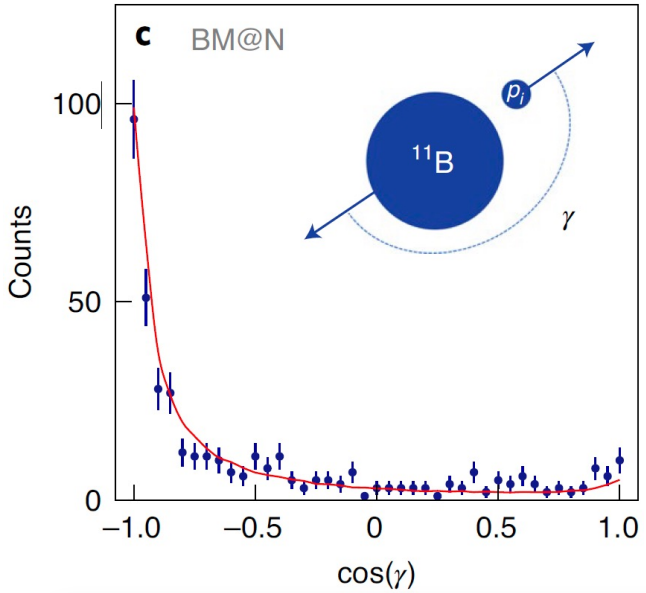


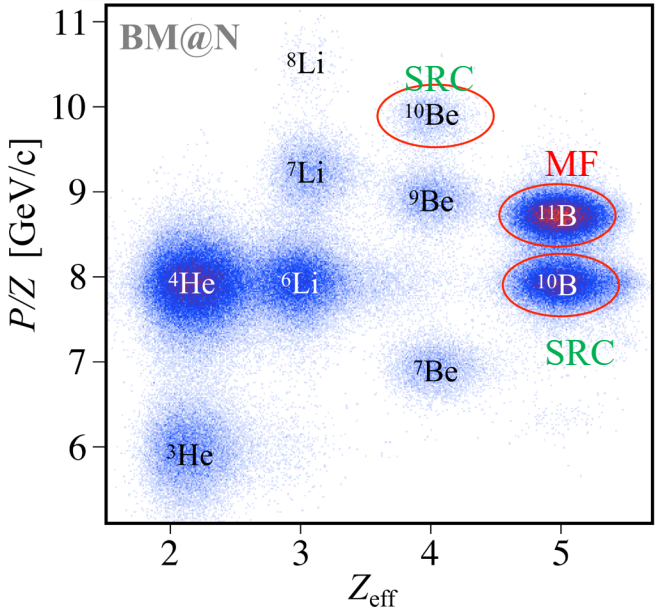
First Atemp at JINR BM@N

❑ Pioneer run in BM@N in 2018

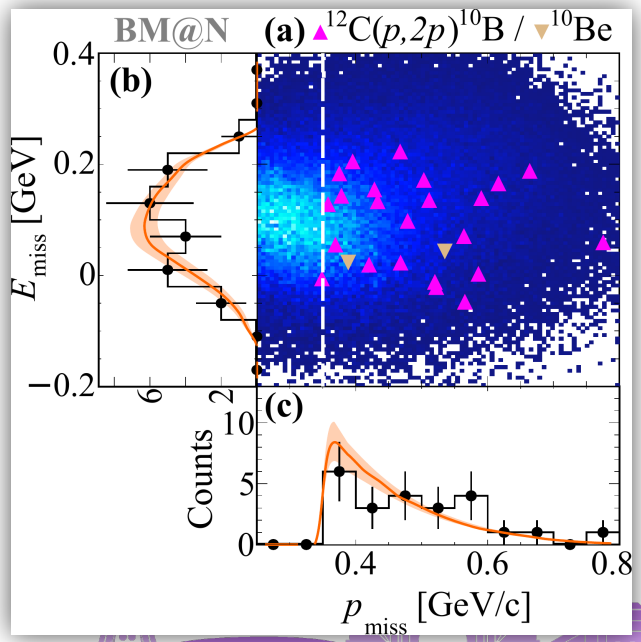
✓ ^{12}C beam, 4 GeV/c/nucleon







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



✓ Detect two outgoing nucleons & (A-2)

✓ Reconstruct initial nucleon momentum:

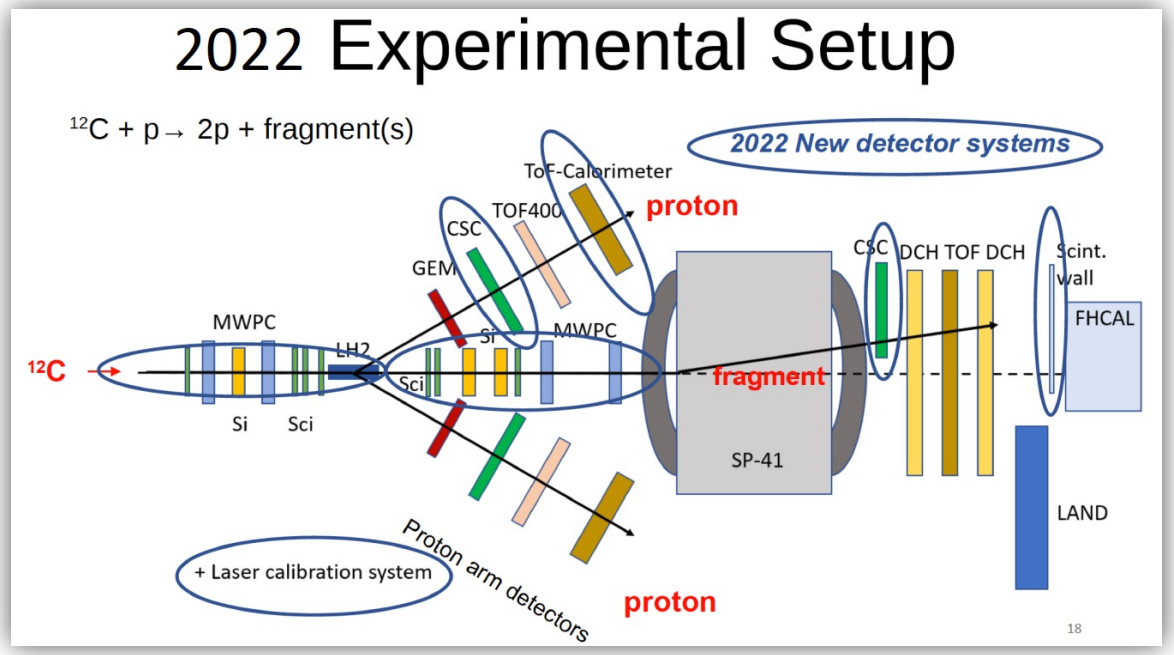
$$P_{miss} = P_1 + P_2 - P_{beam}$$

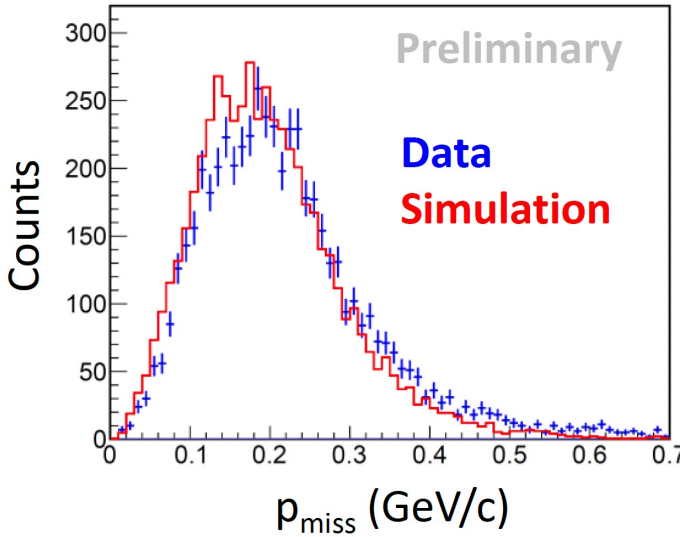
✓ Select2N-SRC: np pair: ^{12}C(p,2p) ^{10}B
pp pair: ^{12}C(p,2p) ^{10}Be

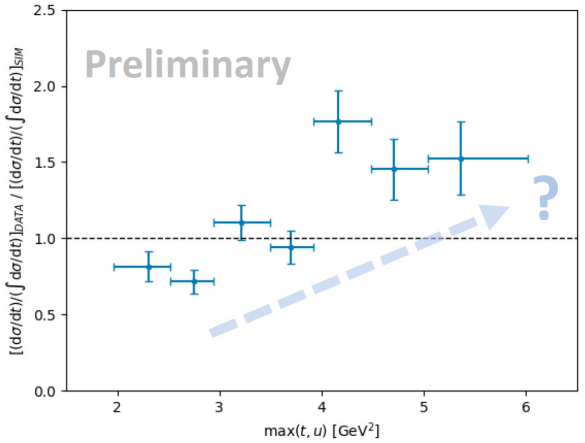
23 np & 2 pp SRC-pairs

Full BM@N SRC Run

- Full run completed in 2022
  - ✓ JINR,GSI, MIT, Tel Aviv, Tsinghua ...
  - ✓ Improve statics x100
  - ✓ Detect both n & p
  - ✓ Multi-fragment reconstruction
  - ✓ First extract absolute cross-section
  - ✓ Publishing soon







Maria Patsyuk (JINR)

Julian Kahlbow (MIT)

Göran Johansson (TAU)

Timur Atovuallev (JINR)

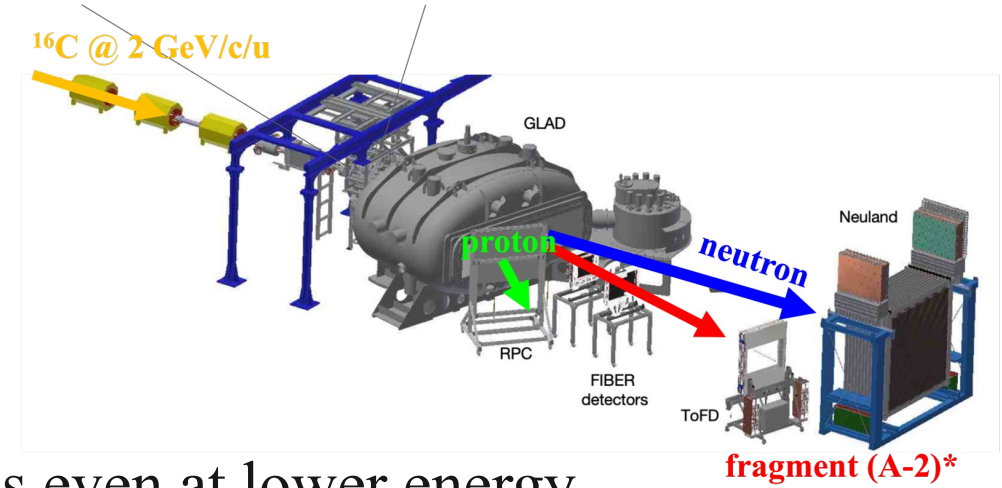
Sergey Nepochatykh (JINR)

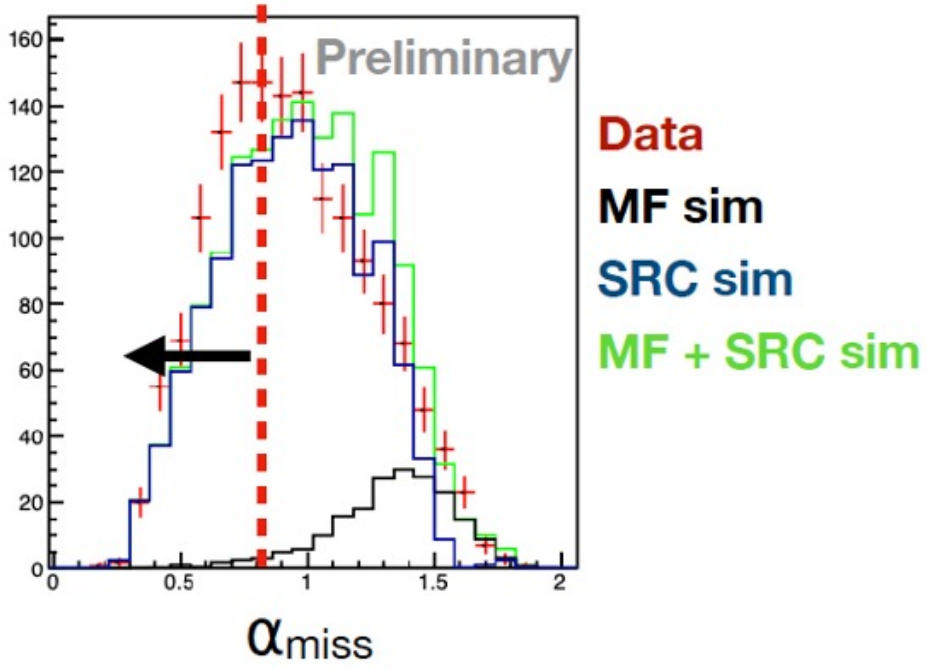
Yaopeng Zhang (Tsinghua U)

Vasilisa Lenivenko (JINR)

GSI SRC Run

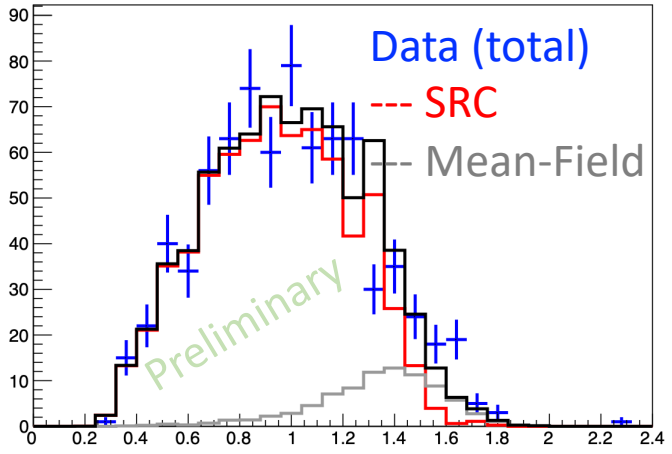
- SRC w/ rare radioactive isotope at R^3B@GSI (2022)
  - ~2 GeV/c beam, $^{16}C(p,2pN)A-2^*$
  - Future: $^{110,120,132}Sn$ (N/Z = 1.20, 1.40, 1.64)



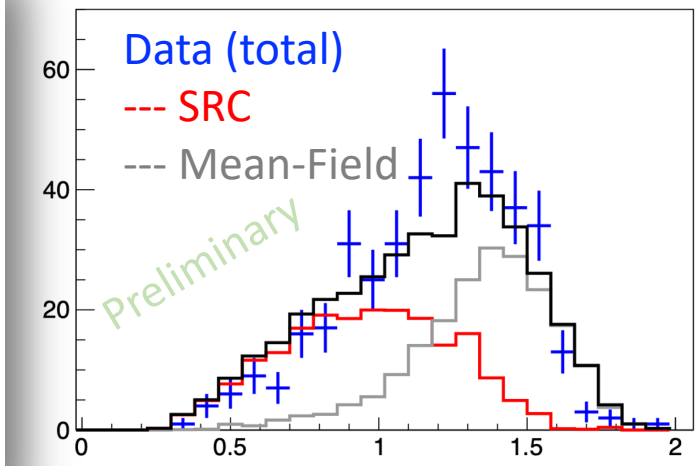


- See SRC signals even at lower energy
- Link to sub-nuclear structure?

$^{16}C + p \rightarrow$ np-SRC + ^{13}B+n

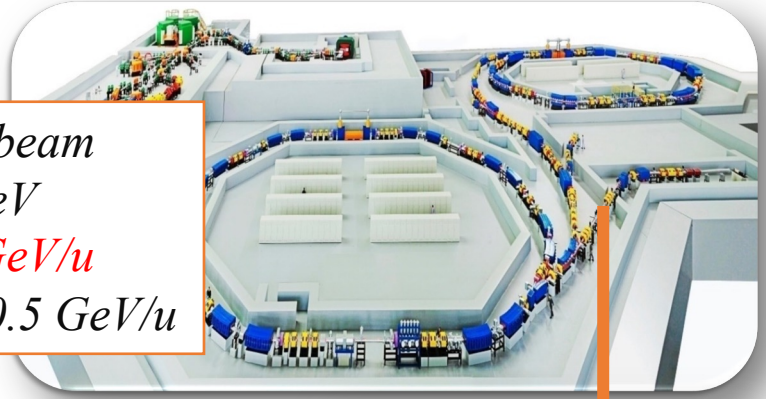


~~$^{16}C + p \rightarrow$ np-SRC + ^{14}B~~

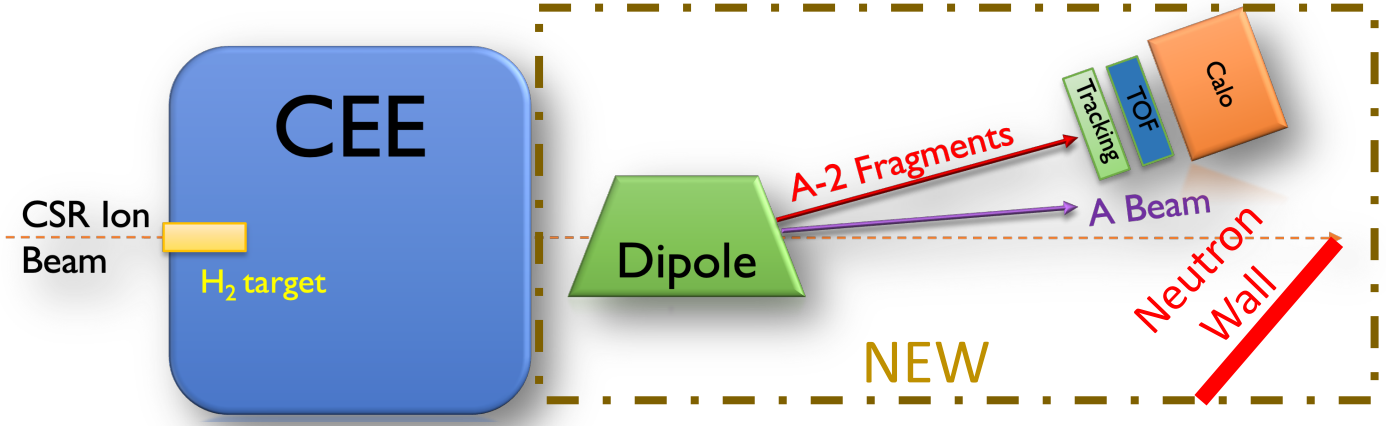


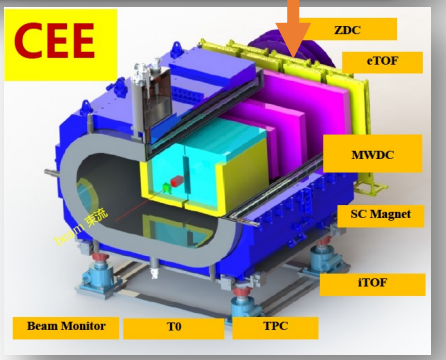
SRC Experiment @ HIRFL-CEE

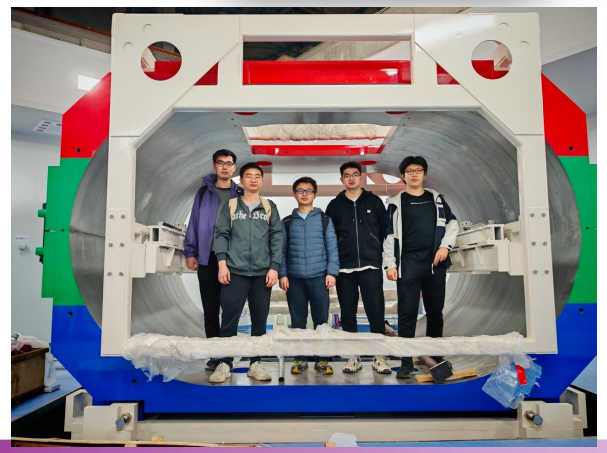
- CSR External-Target Experiment (CEE) device under commissioning
- Using CEE w/ additional changes/upgrades:
  - ✓ Liquid hydrogen (LH2) target
  - ✓ Replace ZDC w/ a new detectors for nuclear fragments
  - ✓ + new dipole + Neutron wall?



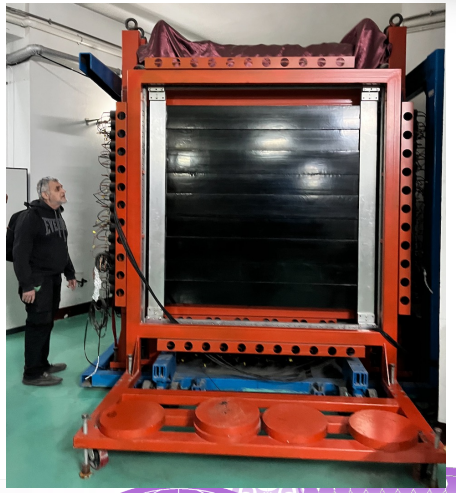
HIRFL-CSR beam
- *P*: *2.8 GeV*
- $^{12}C^{+}$: *1 GeV/u*
- $^{238}U^{+}$: *0.5 GeV/u*







THU Students in CEE magnet



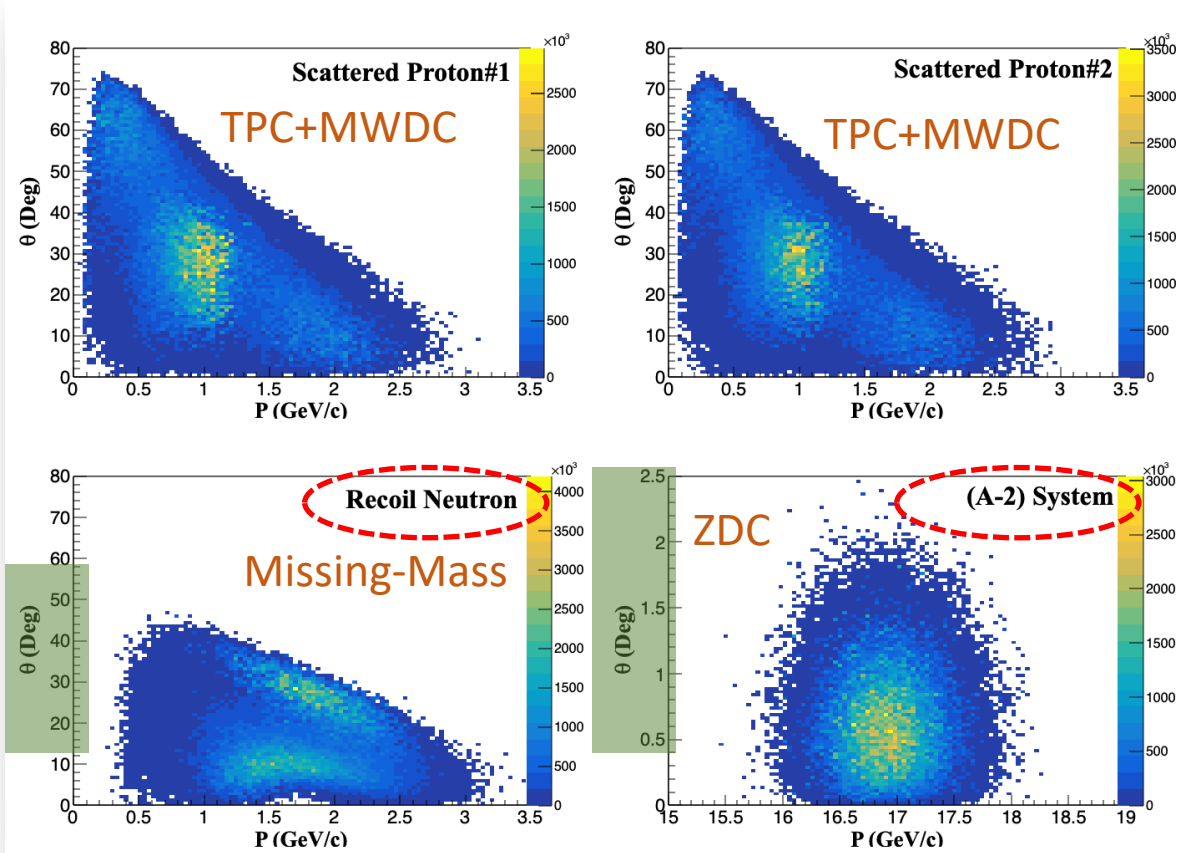
Eli Piasetzky @ IMP
neutron detector

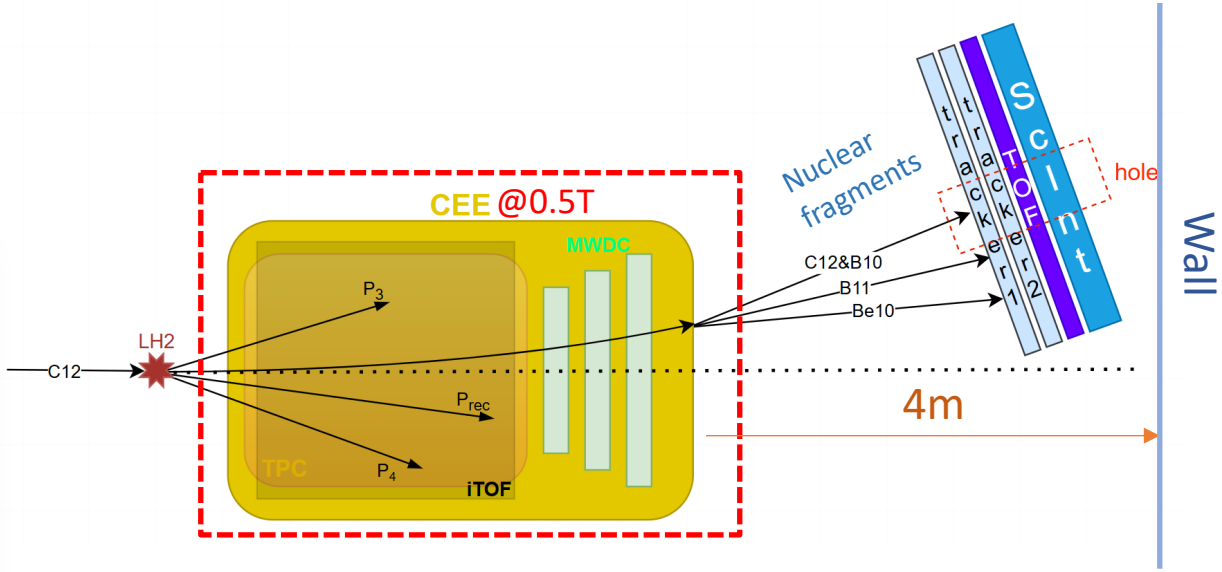
SRC Experiment @ HIRFL-CEE

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

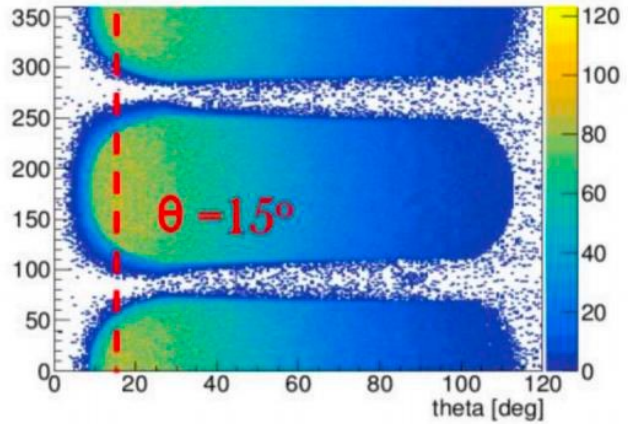
✓ Protons are within existing CEE detectors

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

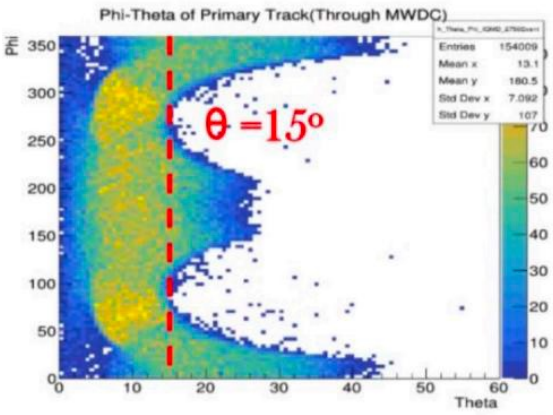




CEE-TPC

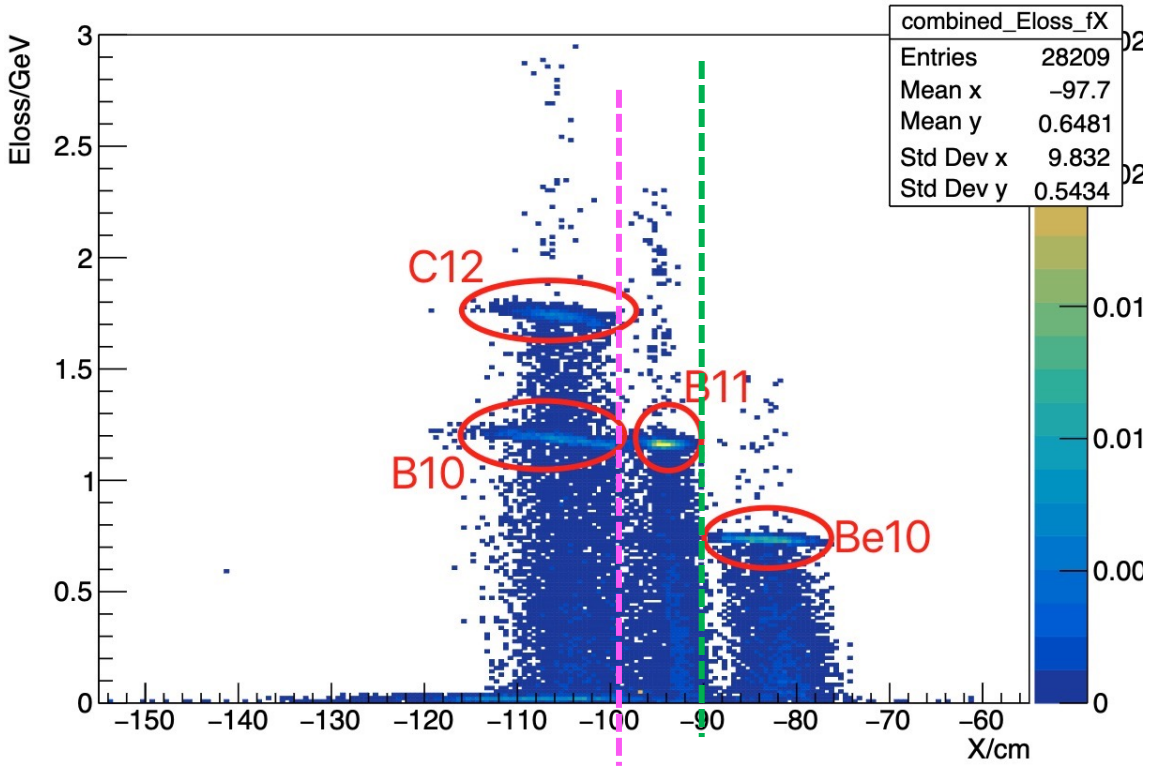


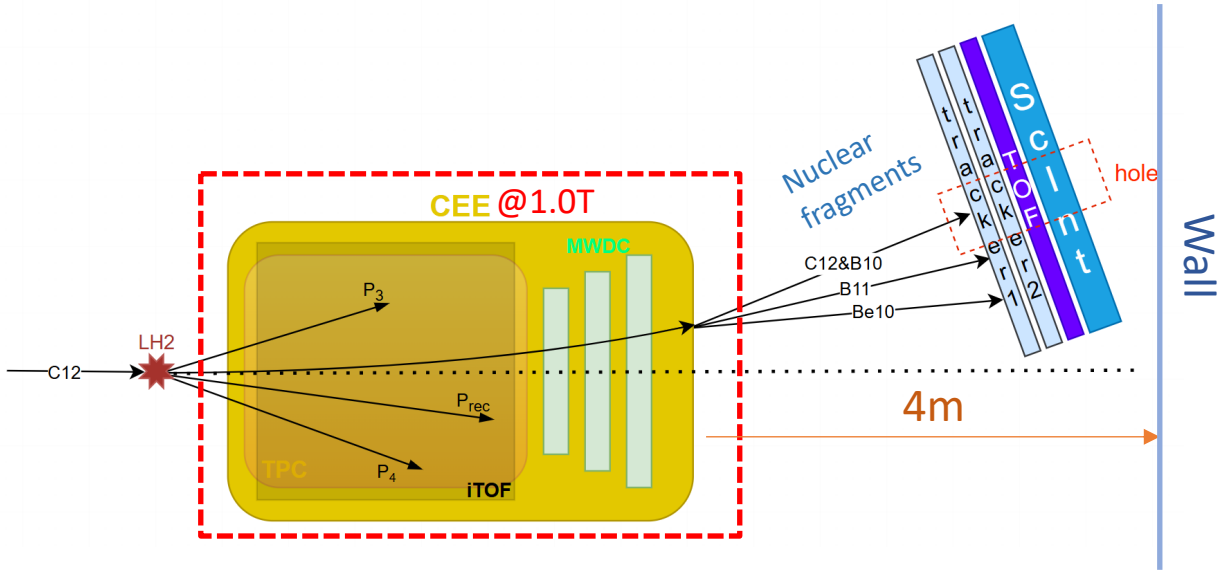
CEE-MWDC



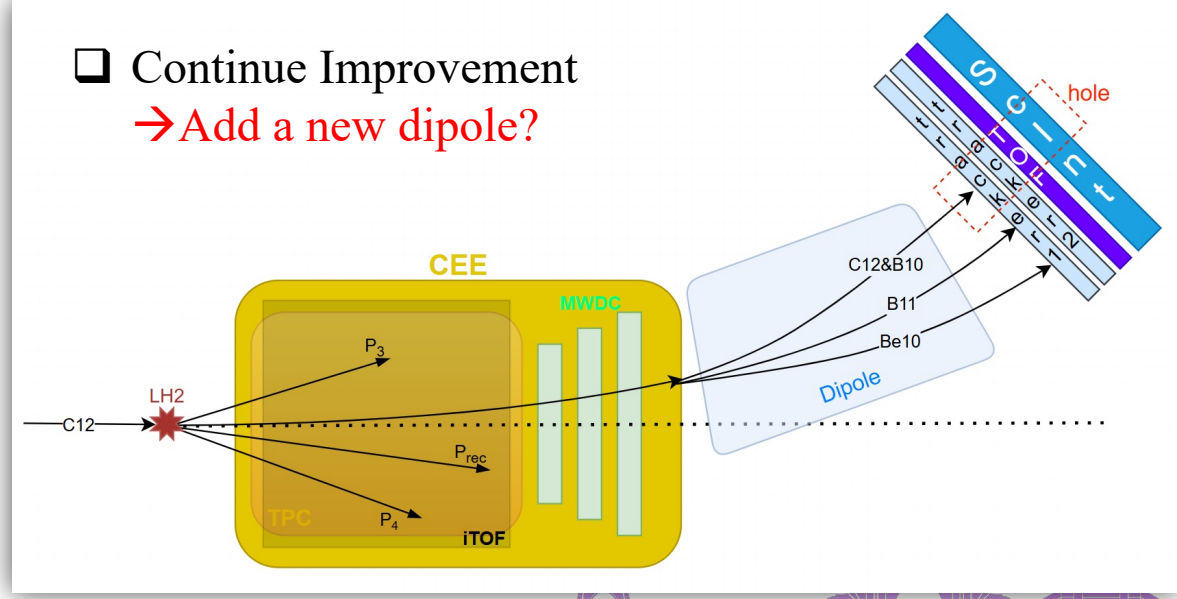
SRC Experiment @ HIRFL-CEE

- Fragment detection w/ standard CEE setup
  - ✓ Fragment-Detector at 4m downstream
  - ✓ Increase magnetic field to 1.0T





- Continue Improvement
  - →Add a new dipole?

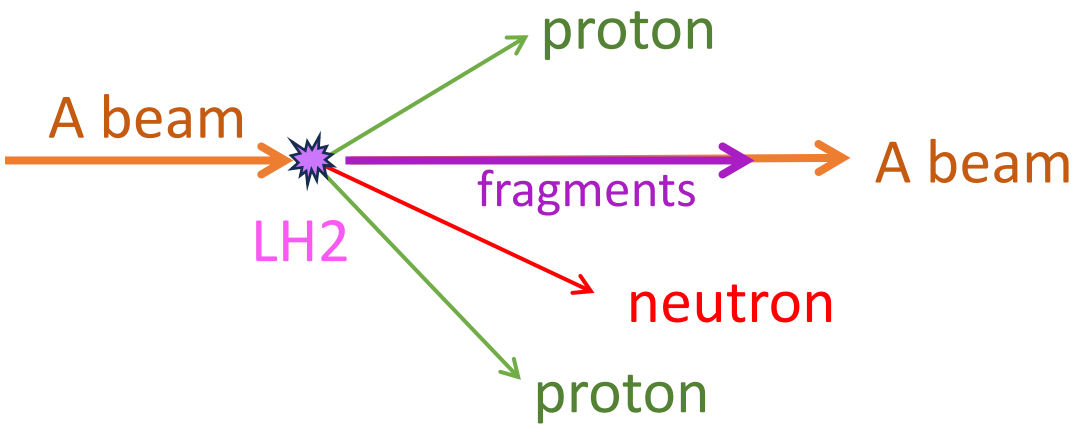


SRC Experiment @ HIRFL-CEE

❑ CEE will run with no magnet in 2025

❑ SRC study w/o B-field

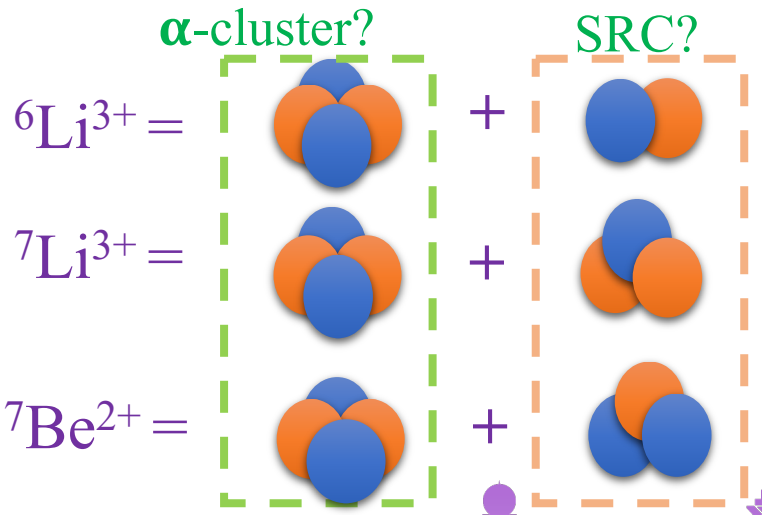
- ✓ Measure protons and neutrons (TOF method)
- ✓ Detect fragments (A-1) or (A-2) (suppress FSI)
- ✓ Find high momenta of protons & neutrons



❑ What are needed: Hydrogen target or CH2 & Neutron detector

❑ Light ions to study SRC in few-body nuclei?

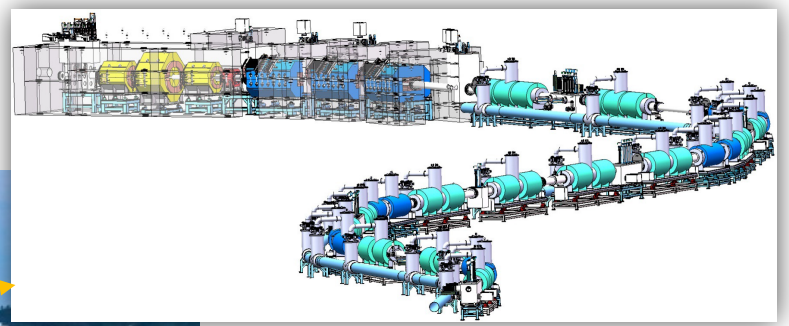
- ✓ **α** make final-state simpler, but prefer mostly in even-even N=Z nuclei, or excited states
- ✓ Alternatively, learn nuclear formation if no intact (A-2) or (A-3) fragments.

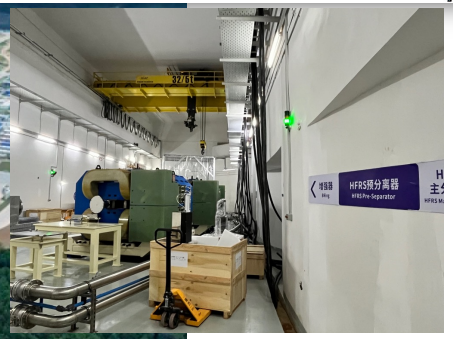


SRC Experiment @HIAF

- High-Intensity Heavy-Ion Accelerator Facility (Huizhou, Guandong):
  - C12, E=51 GeV/c (4.25GeV/c/u) → similar to NICA
  - 1.8×10^{12}pps (fast extr.), 4.5×10^{11}pps (slow extr.) vs. 3.5×10^{4} pps at JINR
  - First beam in end of 2025

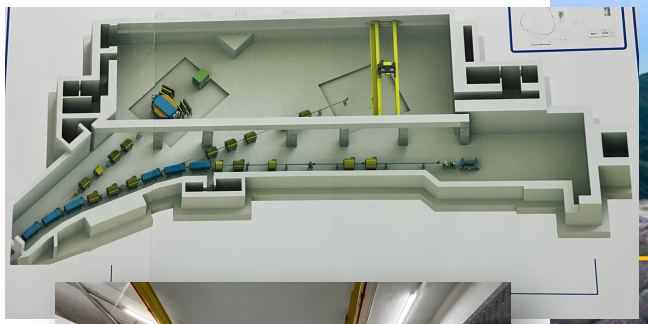
HRFS





Beam Direction

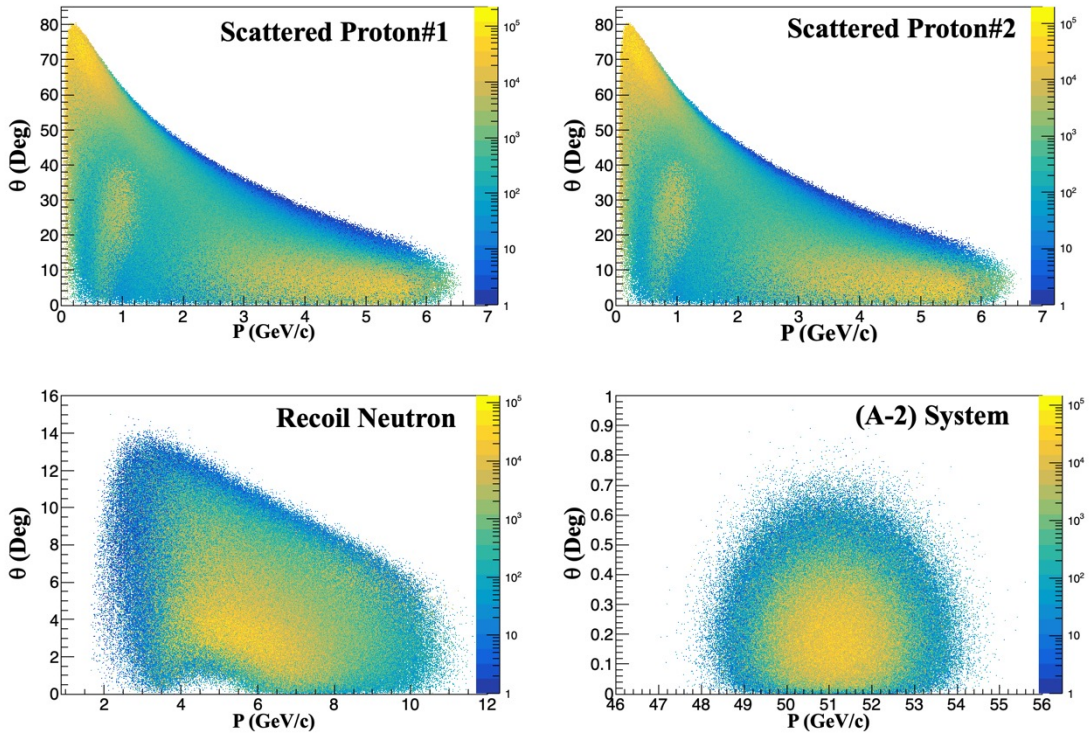
High-Energy Station (HES)



Beam Direction

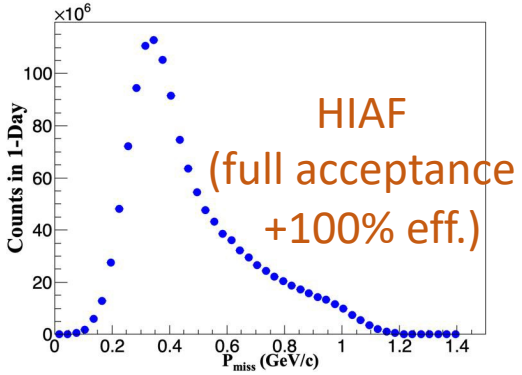
SRC Experiment @HIAF-HES

- Precision frontier for SRC in HES:
  - Mapping 2N-SRC at all kinematic, Search 3N-SRC
- Monte-Carlo Simulation ($^{12}C^{6+}$ at 51GeV/c)

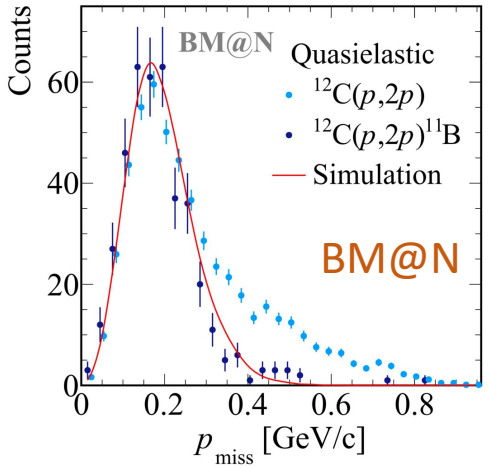


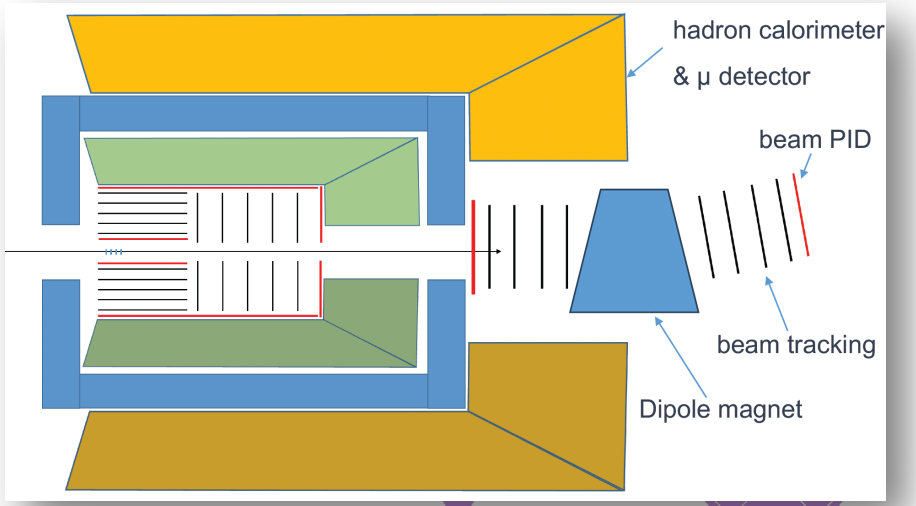
Z. Ye, et. al., Eur. Phys. J. A 60(6), 126 (2024).

1-day @ (4.5~18)x10^{11}pps



2-week @ 3.5x10^{4}pps

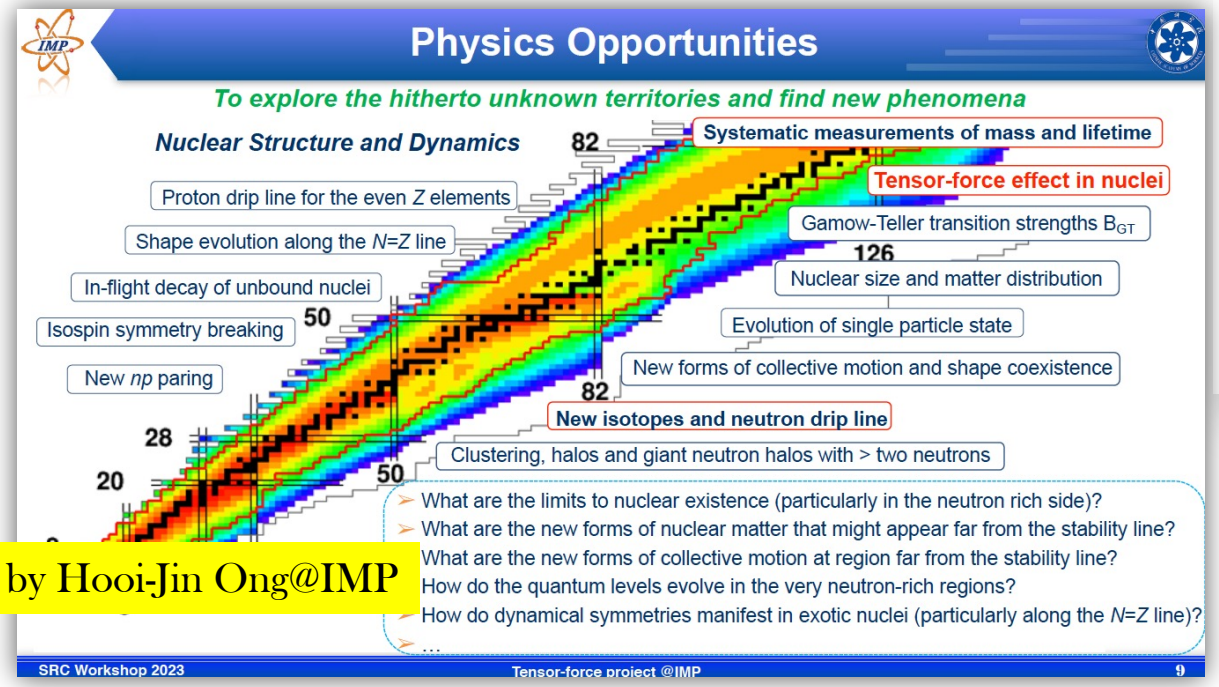




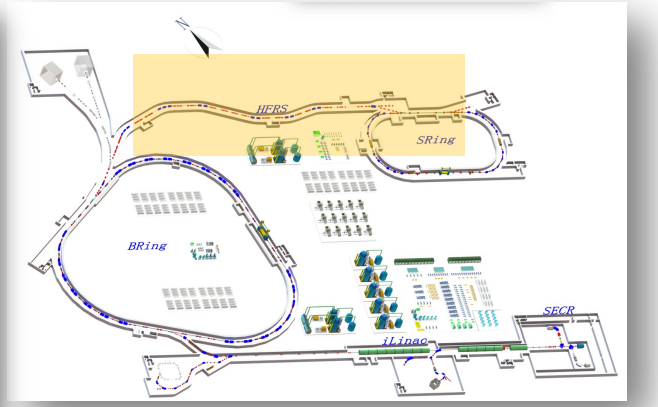
- Use full-acceptance spectrometer , e.g. H-NS (under discussio)

SRC Experiment @HIAF-HFRS

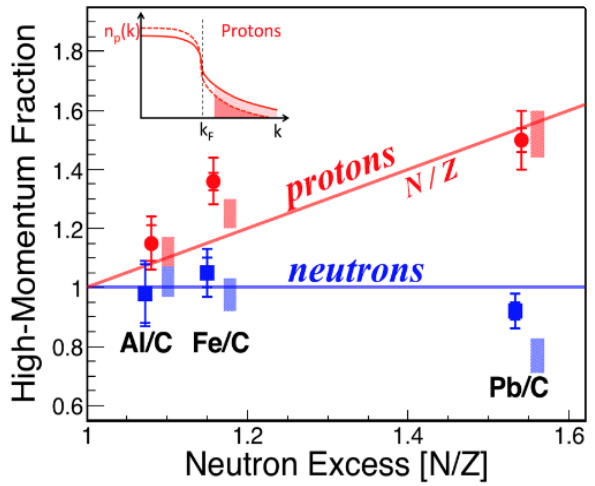
- Radioactive ion beams are produced at HFRS(HIRIBL)



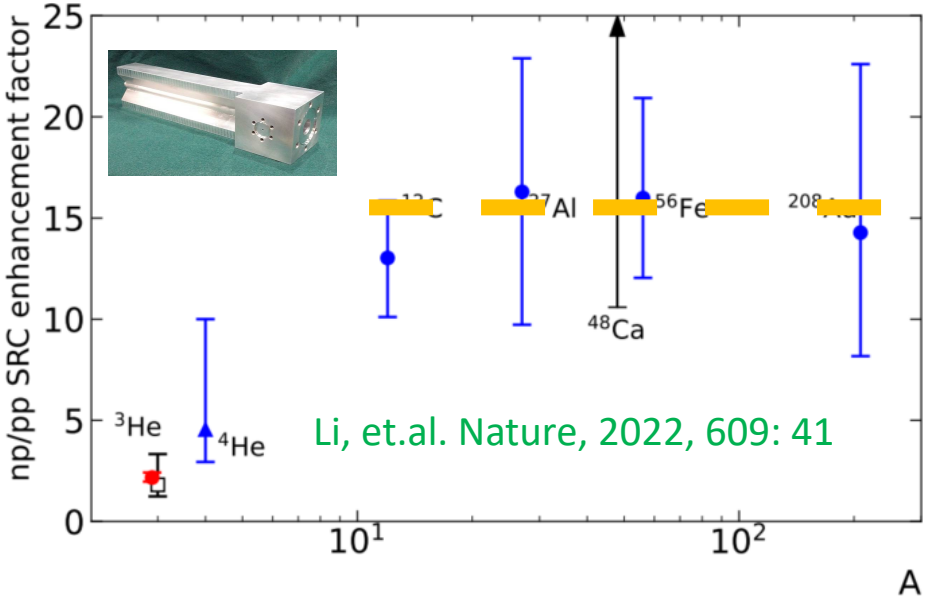
by Hooi-Jin Ong@IMP



Nature, 560 (2018) 617-621.



- Study 2N-SRC w/ radioactive isotopes from HIRIBL
  - ✓ Light to large neutron-rich nuclei
  - ✓ Cannot be done in fixed target experiments



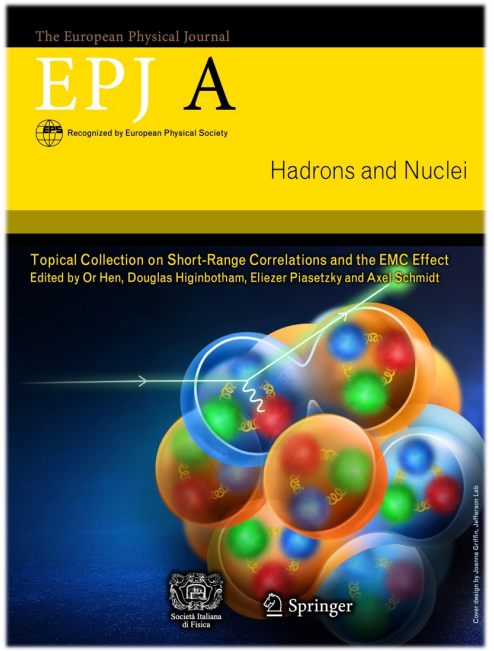
Li, et.al. Nature, 2022, 609: 41

Summary

- SRC helps us to understand nuclear structure & forces, neutron stars, quarks in nuclei ...

- Many progresses made at JLab
  - ✓ np-SRC dominated, universal in heavy nuclei, less in light nuclei
  - ✓ no 3N-SRC found
  - ✓ hard to isolate SRC (mean-field, initial & final state interaction)
  - ✓ NEW`: below-threshold production with photons

Topical issue on short-range correlations and the EMC effect, EPJA (2025) 61:109



- SRC study with inverse kinematic (ion beams on hydrogen):
  - First in BM@N (JINR) and R3B (GSI)
  - with CEE@HIRFL & small upgrades

- Precision frontier at HIAF→ Mean-Field vs SRC in few-body nuclei,

  2N-SRC in neutron-rich isotopes, 3N-SRC ...

- Many efforts made to realize SRC programs in China, welcome to join!

Works are supported by NSFC
(12275148 & 12361141822)

Thanks!

谢谢！

清華大學
Tsinghua University

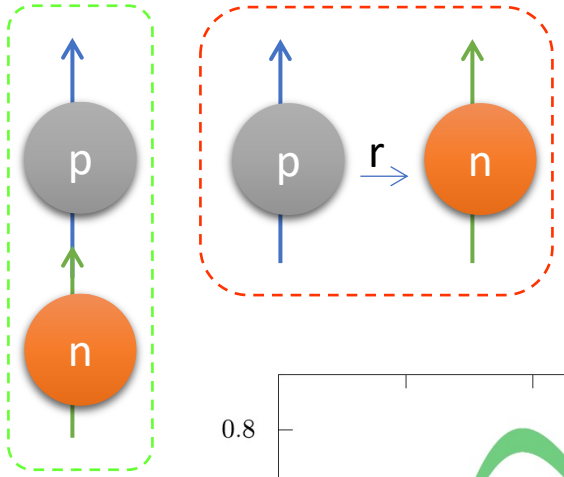
Isospin Dependence

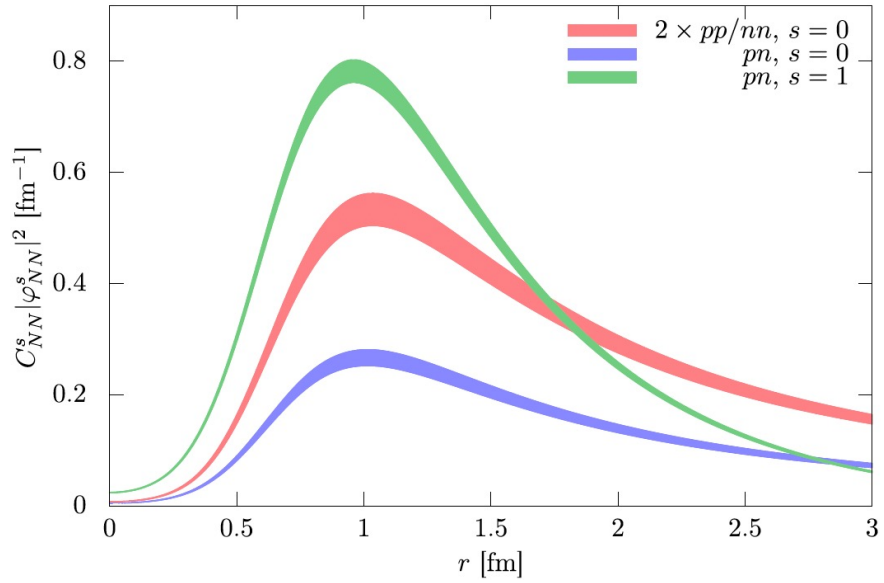
- Tensor Force is strongly attractive

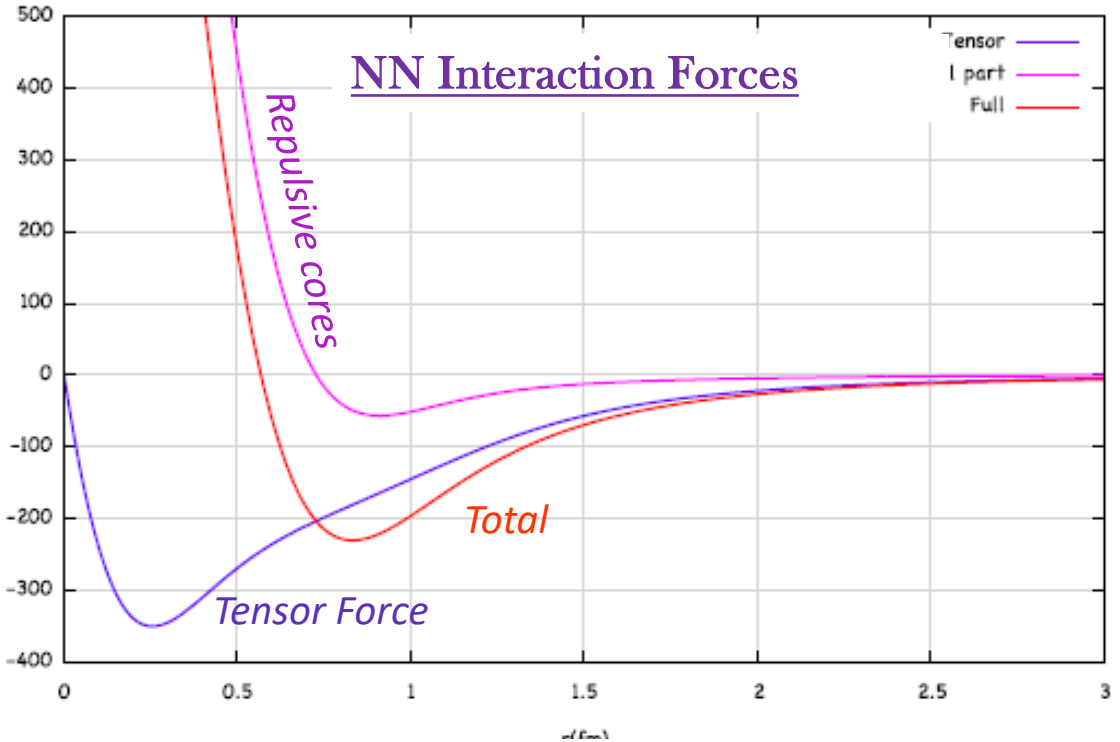
$$-S_{12} = -3(\vec{\sigma}_1 \cdot \hat{r})(\vec{\sigma}_2 \cdot \hat{r}) + (\vec{\sigma}_1 \cdot \vec{\sigma}_2)$$

$= -3\ \sigma_1\sigma_2$ *Attractive*

$==0 \rightarrow$ *Repulsive*







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

R. Cruz-Torres et al. / Physics Letters B 785 (2018) 304–308