Searching for Three-nucleon Short-range Correlations

Shujie Li

APS-GHP workshop 2025 @ Anaheim, CA

March 14, 2025

Nucleons in Nuclei:

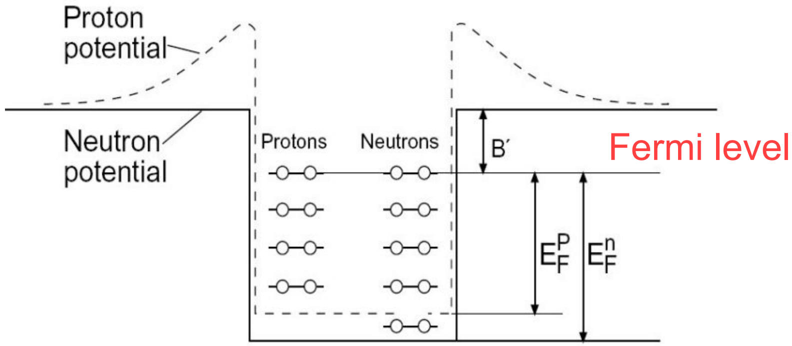
Independent Particle Shell Model(IPSM)

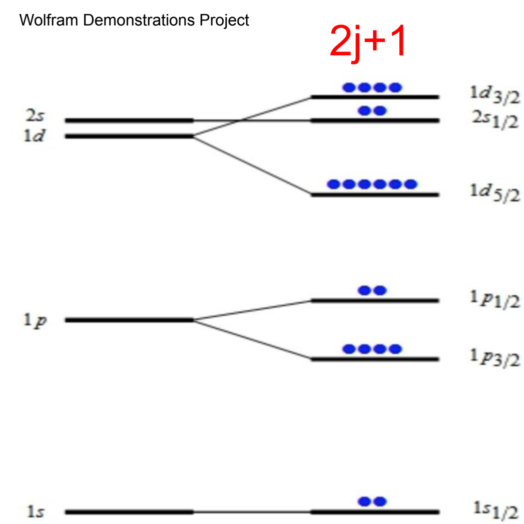
- Low energy, non-relativistic:

$$[\sum_i -\frac{\hbar^2}{2m_N}\nabla_i^2 + \sum_{i<j} v_2(\boldsymbol{x}_i,\boldsymbol{x}_j) + \sum_{i<j<k} v_3(\boldsymbol{x}_i,\boldsymbol{x}_j,\boldsymbol{x}_k) + ...]\Psi_A = E_A\Psi_A$$

- Nucleons move independently in an averaged potential (mean field) induced by the rest of the nucleus system:

$$[-\frac{\hbar^2}{2m_N}\nabla_i^2 + U(\boldsymbol{x})]\phi_\alpha(\boldsymbol{x}_i) = \epsilon_\alpha\phi_\alpha(\boldsymbol{x}_i).$$

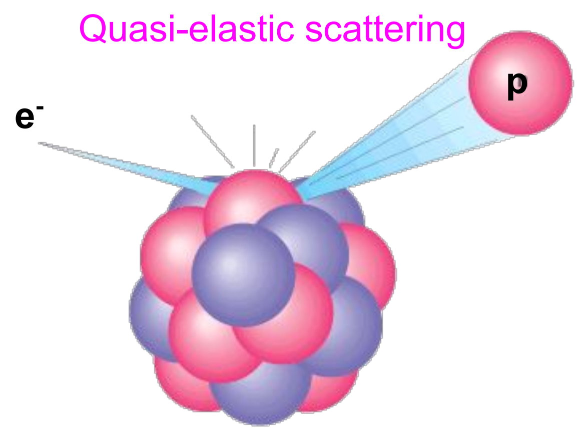




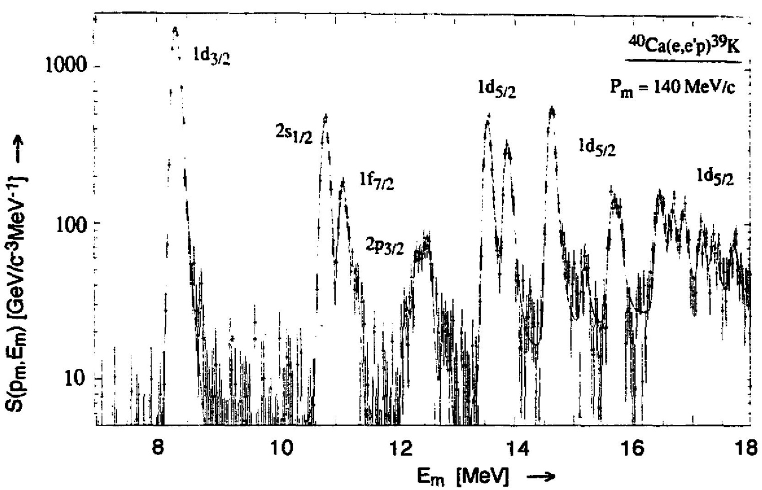
Nucleons on shells

Nucleons in Nuclei

Independent Particle Shell Model(IPSM)



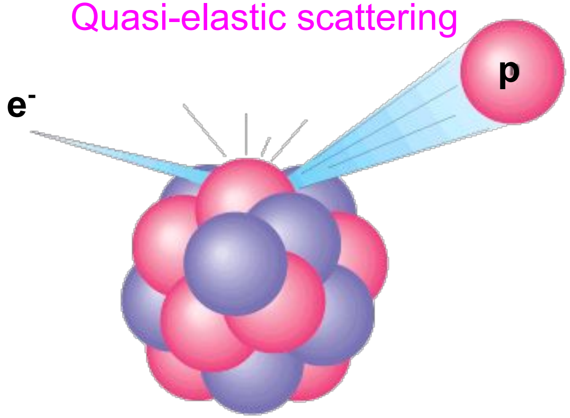
Lapikas1993 @ NIKHEF: (e,e'p)



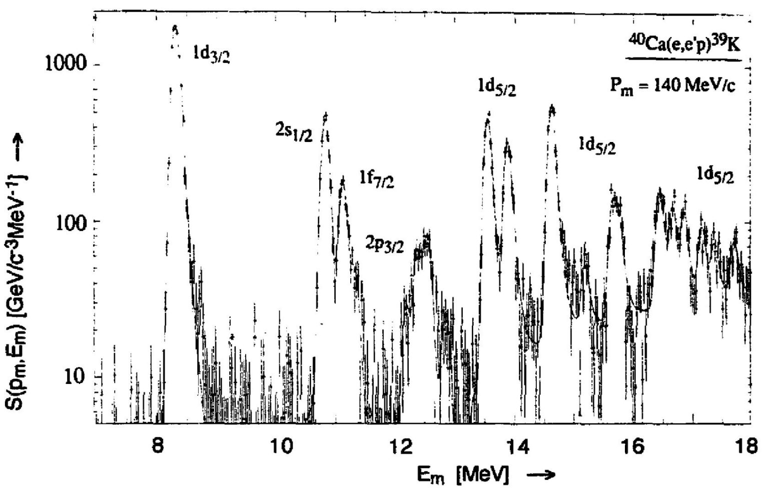
Nucleons in Nuclei

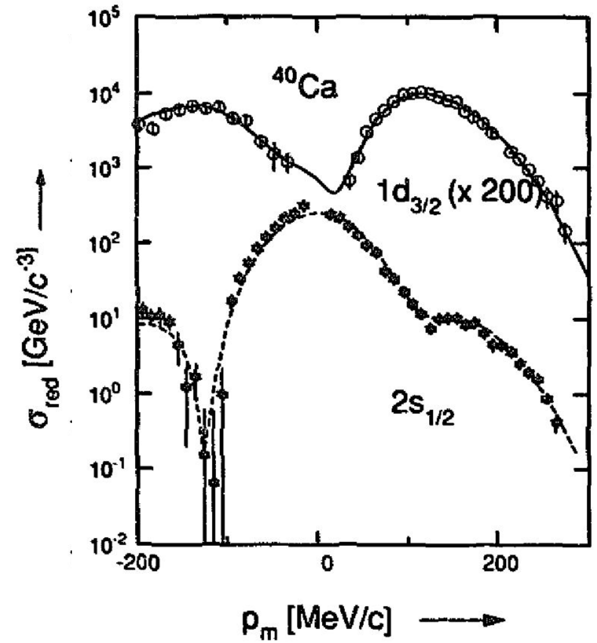
Independent Particle Shell Model(IPSM)

Quasi-elastic scattering



Lapikas1993 @ NIKHEF: (e,e'p)





valence (outmost) shell

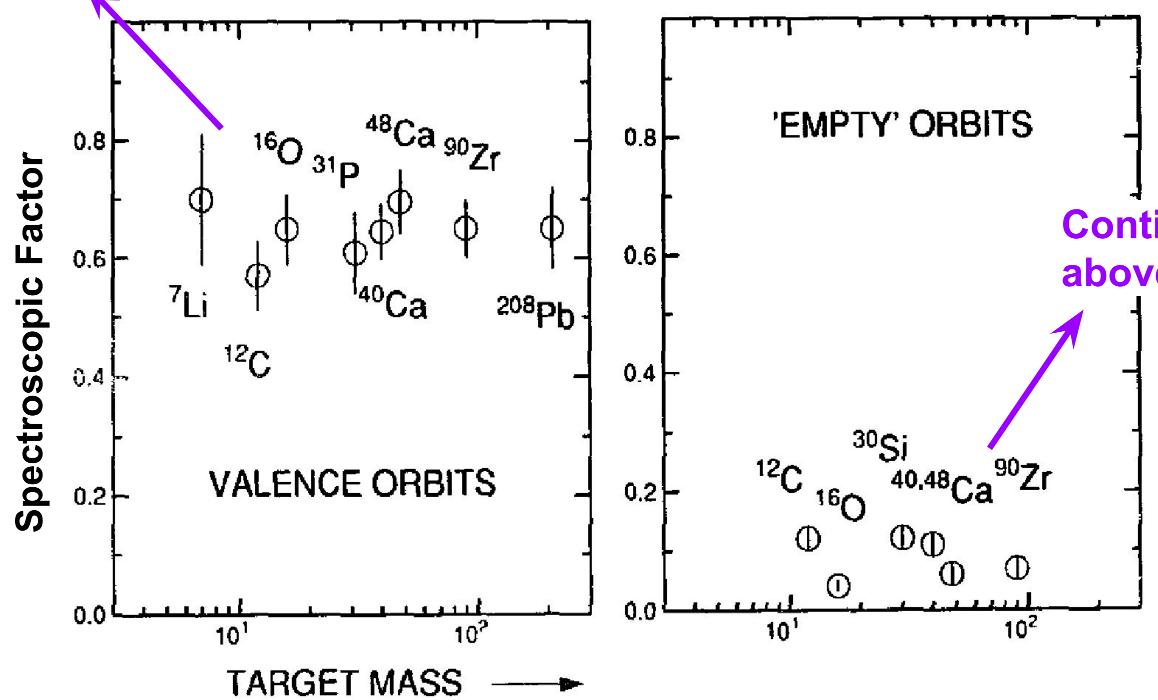
next deeper shell

Curves: Bound state wave functions evaluated in a mean-field potential with **fitted** spectroscopic strength

Nucleons in Nuclei

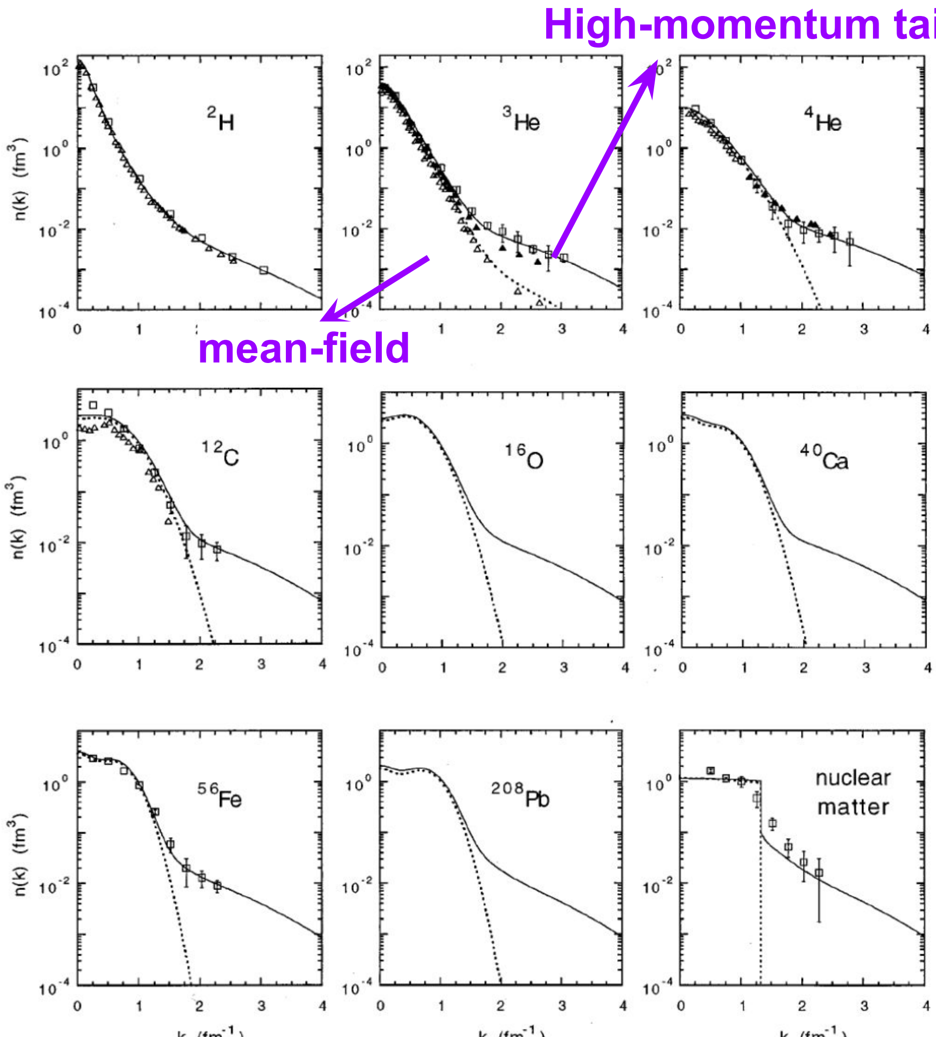
Independent Particle Shell Model(IPSM)

Valence shells are NOT filled:
strength < 1



Continuous spectrum
above Fermi level

Nucleon Momentum Distribution

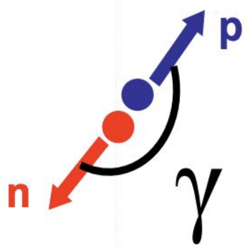


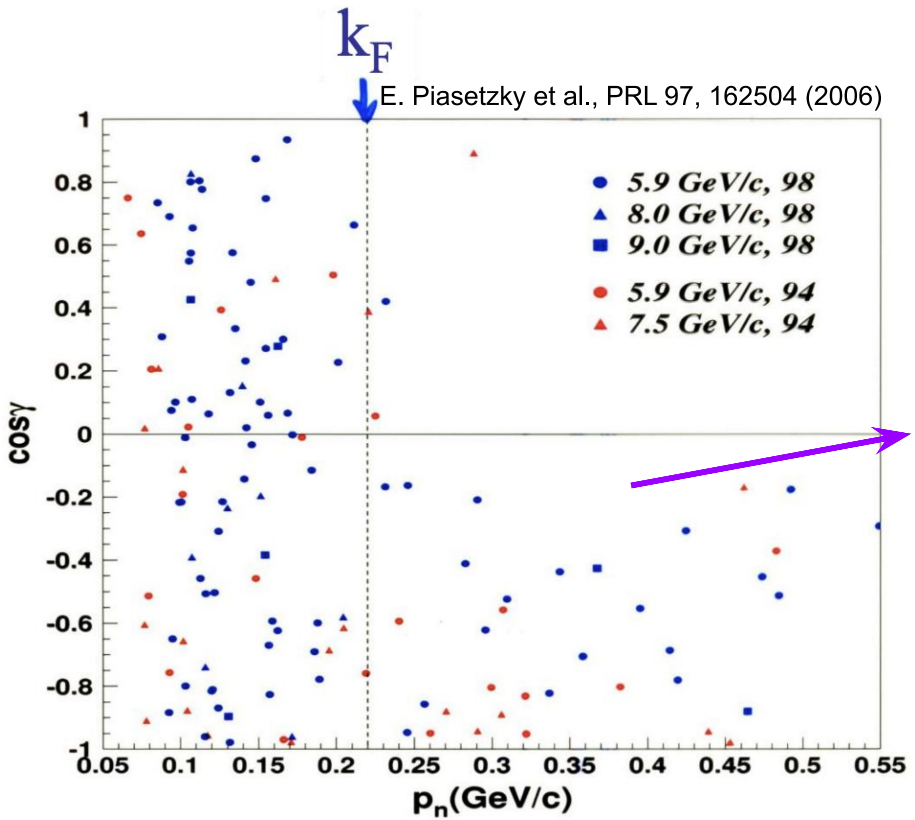
"The main effects of **NN correlations** is to generate **high momentum** and high removal energy components"

C. Atti and S. Simula, PRC 53. 1689 (1996)

High Momentum Nucleons are Correlated Pairs

C(p,p'pn)X at BNL:
Coincidence measurement to reconstruct the initial states of correlated nucleons





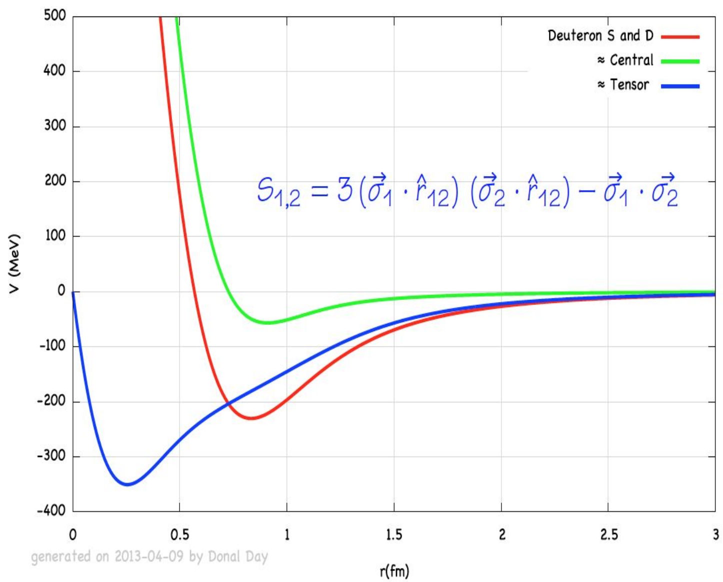
most high momentum nucleon pairs have strong **back-to-back** initial angle correlation.

2N Isospin Configuration

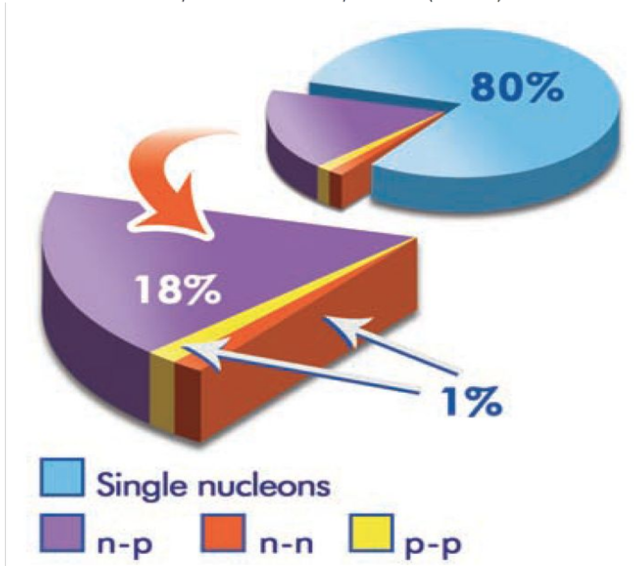
Free nucleon-nucleon potential = **Repulsive core** + **attractive tensor force**

S (spin) = 0, T (isospin) = 1: np, pp, nn pairs. The **tensor operator** $S_{1,2}$= 0 , no attractive tensor force

S (spin) =1, T (isospin) = 0: Deuteron-like np pair. → Enhanced by tensor force, dominate in 2N SRC



Subedi et al, Science 320, 1476 (2008)

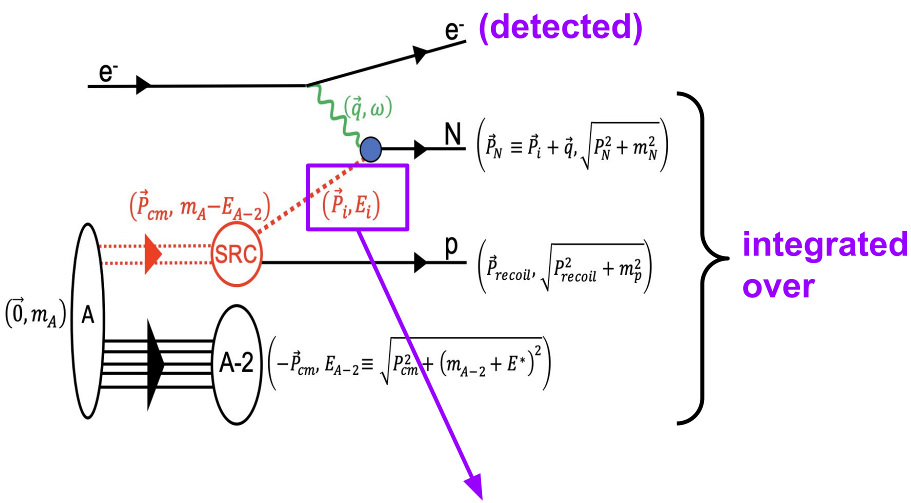


Isolate high momentum nucleons in (e,e') Kinematically

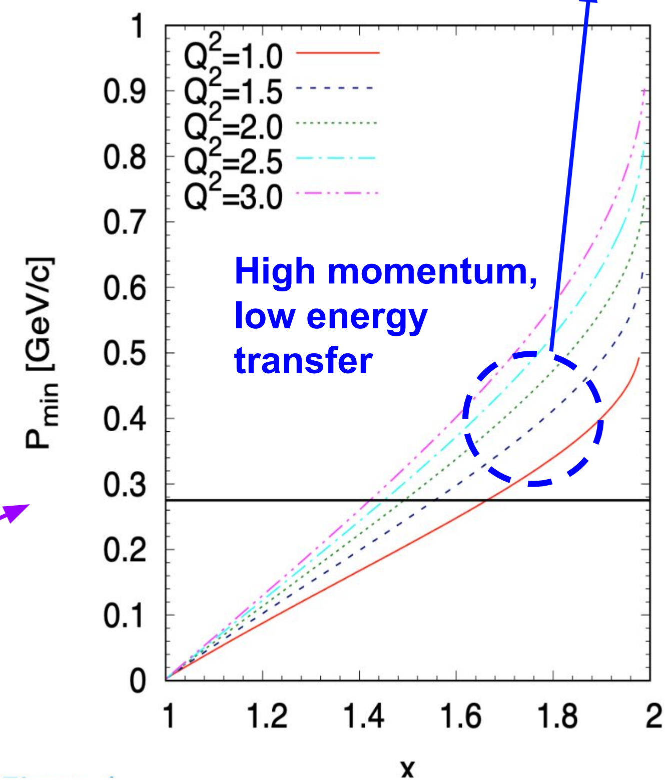
Inclusive QE scattering on 2N SRC:

- High statistics
- Competing processes are kinematically suppressed at high x, high Q^2

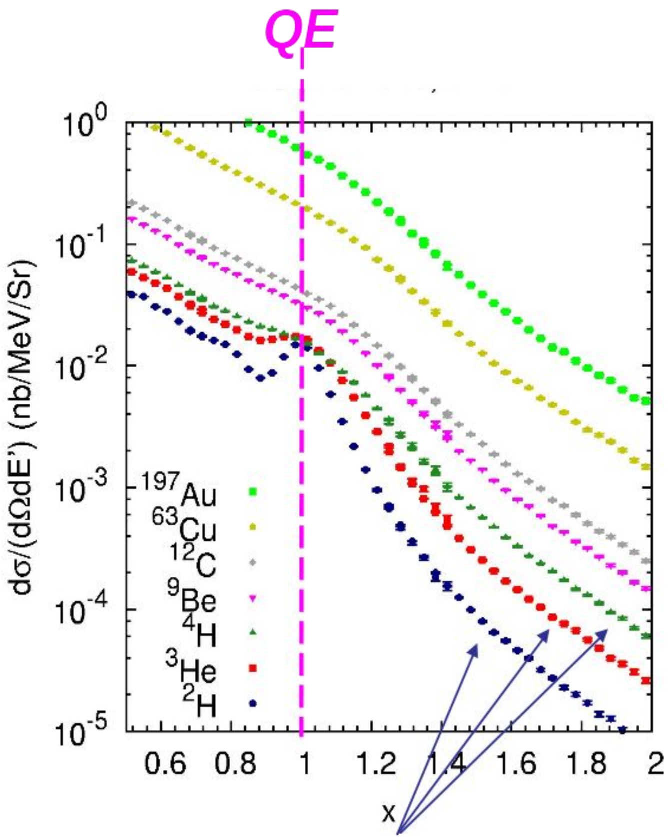
Experimental cut:
$Q^2>1.4$ GeV^2, $x>1.4$ ⇒
$p_{min} > k_F$ ⇒ 2N SRC dominant



Kinematic constraints on the minimum initial momentum



SRC Plateau / Bjorken x-scaling



High momentum tails should yield ***constant ratio*** ***if SRC-dominated***

N. Fomin, et al., PRL 108 (2012) 092052

prob. of finding 2N SRC in nucleus A

$$\sigma_A = \cancelto{0}{\sigma_{QE}} + a_2(A)\sigma_2 + a_3(A)\cancelto{0}{\sigma_3} + \dots$$

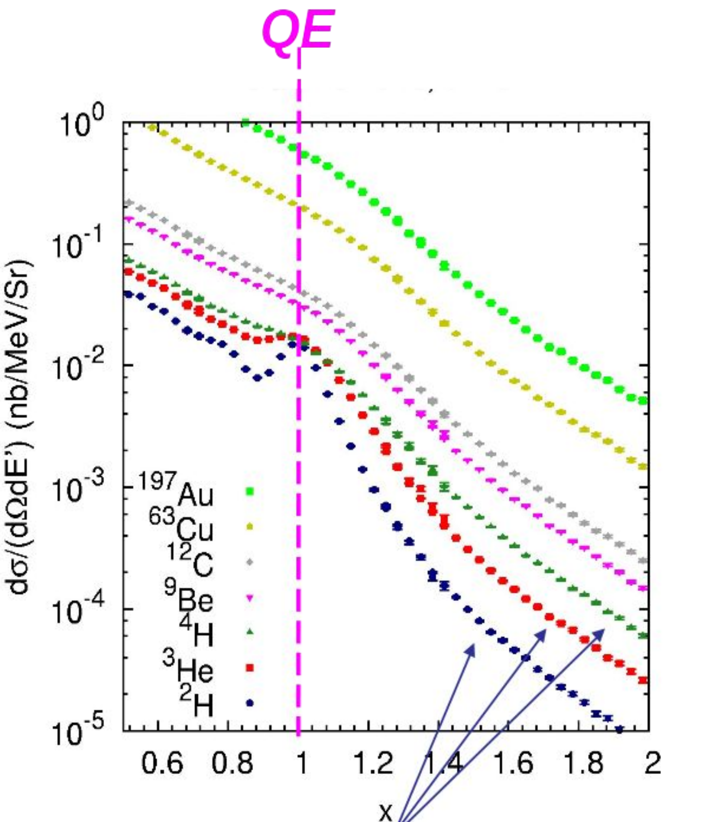
cross section from 2N SRC

$$\frac{\sigma_A}{\sigma_{^2H}} \approx a_2(A) = const$$

** up to center-of-mass motion corrections

4% high momentum component in deuteron wave function

SRC Plateau / Bjorken x-scaling



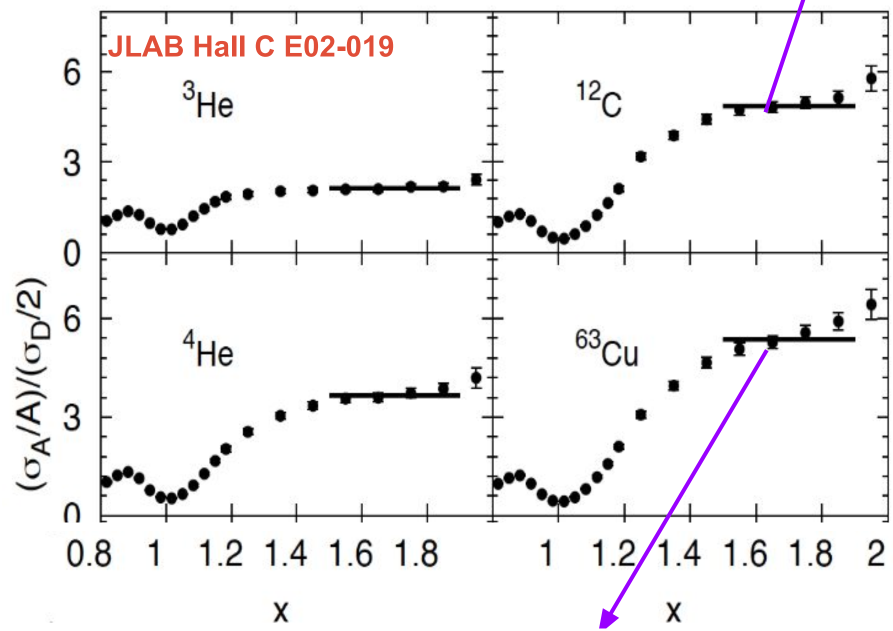
High momentum tails should yield constant ratio *if SRC-dominated*

N. Fomin, et al., PRL 108 (2012) 092052

$a_2(^{12}C) = 5$

$\Rightarrow$ 5 x 4% = 20% SRC pairs in ^{12}C

Plateaus in A/D cross section ratio

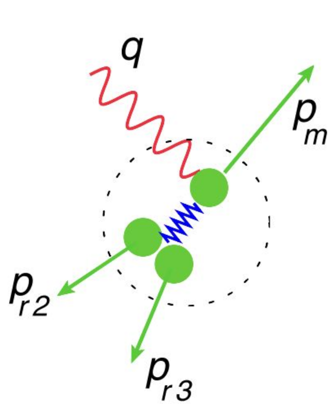


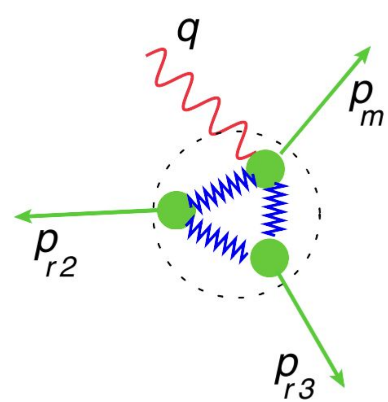
Smeared plateau due to center-of-mass motion, non-ground state configuration etc

3N SRC

Three nucleon configuration with ultra high nucleon momentum and small center-of-mass motion.

Two extreme cases of momentum-sharing:





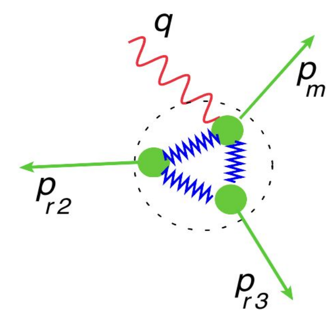
- 3N type I: Linear configuration
  The large momentum of a leading nucleon is balanced by two nucleons going backwards. Generated by two consecutive 2N SRC.

- 3N type II: Star configuration
  Total symmetric momentum sharing between three nucleons. Irreducible, with intermediate delta states.

3N configuration

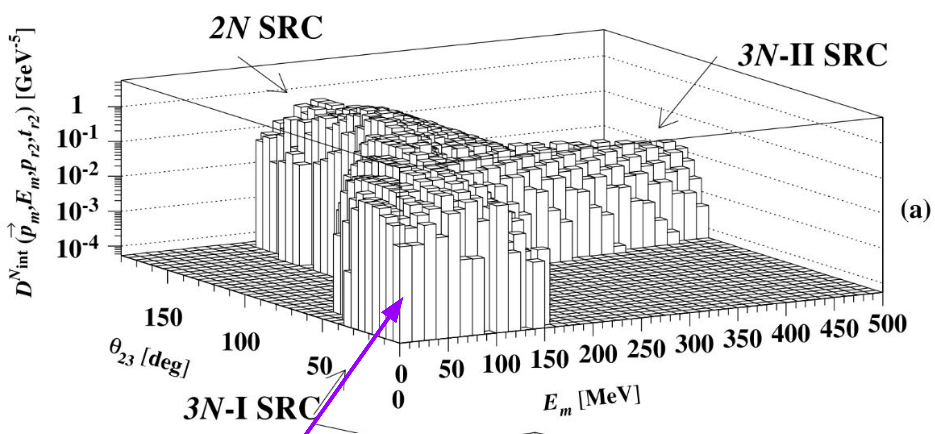
3He Photon-disintegration eA → e + p + p + n:

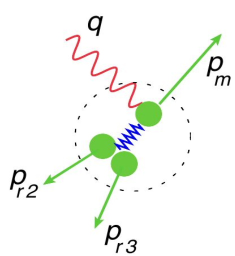
- Very difficult coincidence measurement at large momentum.
- Critical to validate the decay function calculation



Type II: large angle between recoils, high Emiss, lower probability

Sargsian, Abrahamyan, Strikman, Frankfurt, PRC 71, 044615 (2005)





Type I: small angle between recoils, small Emiss, higher probability

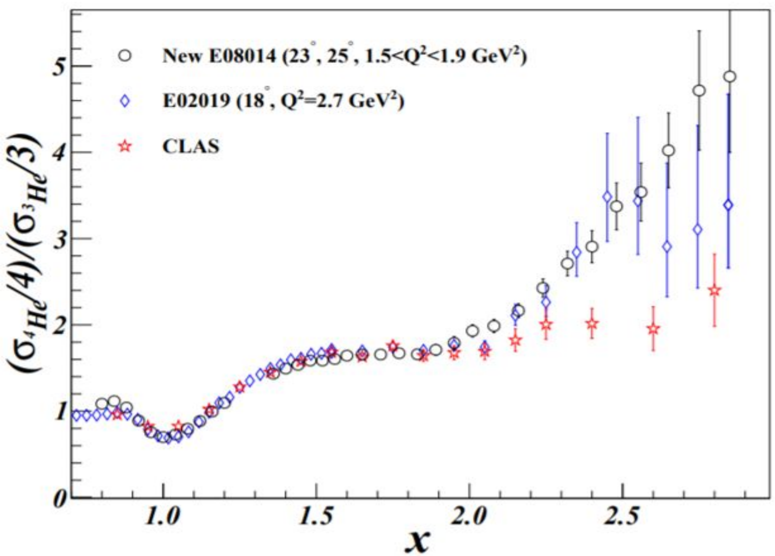
Focus of 3N SRC search

3N SRC scaling search

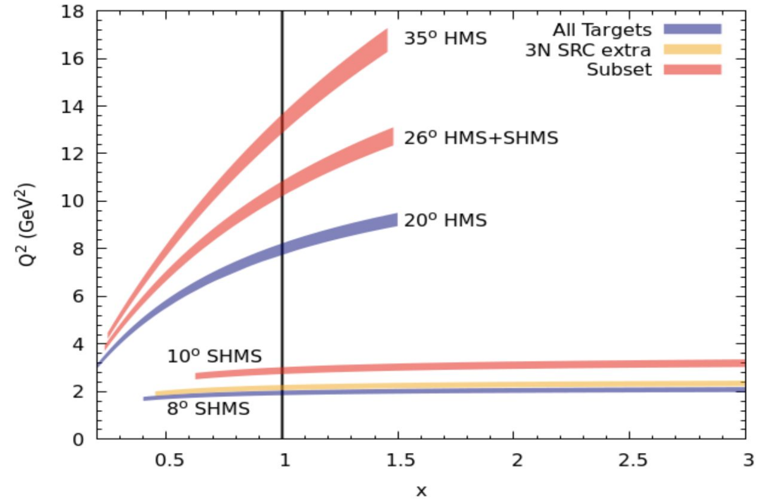
In (e,e'), isolate 3N SRC contribution at very high p_m → higher x and Q^2

$$\sigma_A = \cancelto{0}{\sigma_{QE}} + a_2(A)\cancelto{0}{\sigma_2} + a_3(A)\sigma_3 + \ldots$$

- **Past: Inconsistent results from early experiments**



- **Current: XEM2 @ JLab Hall C, 2022:**
  - **higher Q2, better resolution**
  - **Data under analysis**

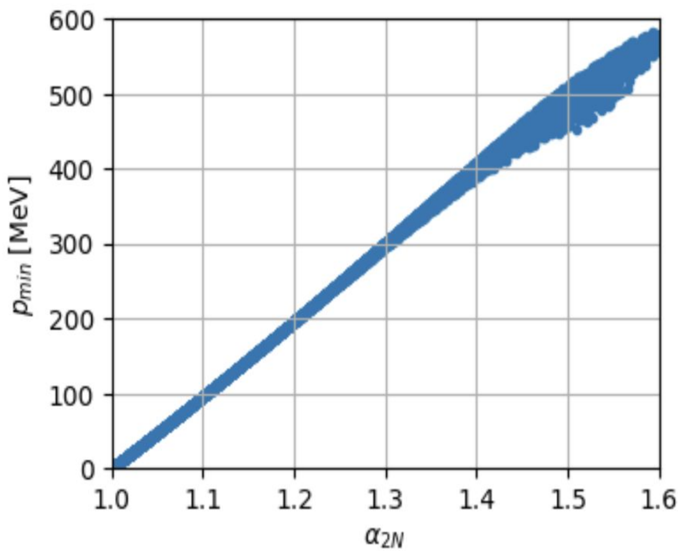


- **Future: new proposal to probe 3N SRC at higher Q^2**
  - **JLab PR-12-24-008, plan to re-submit to PAC**

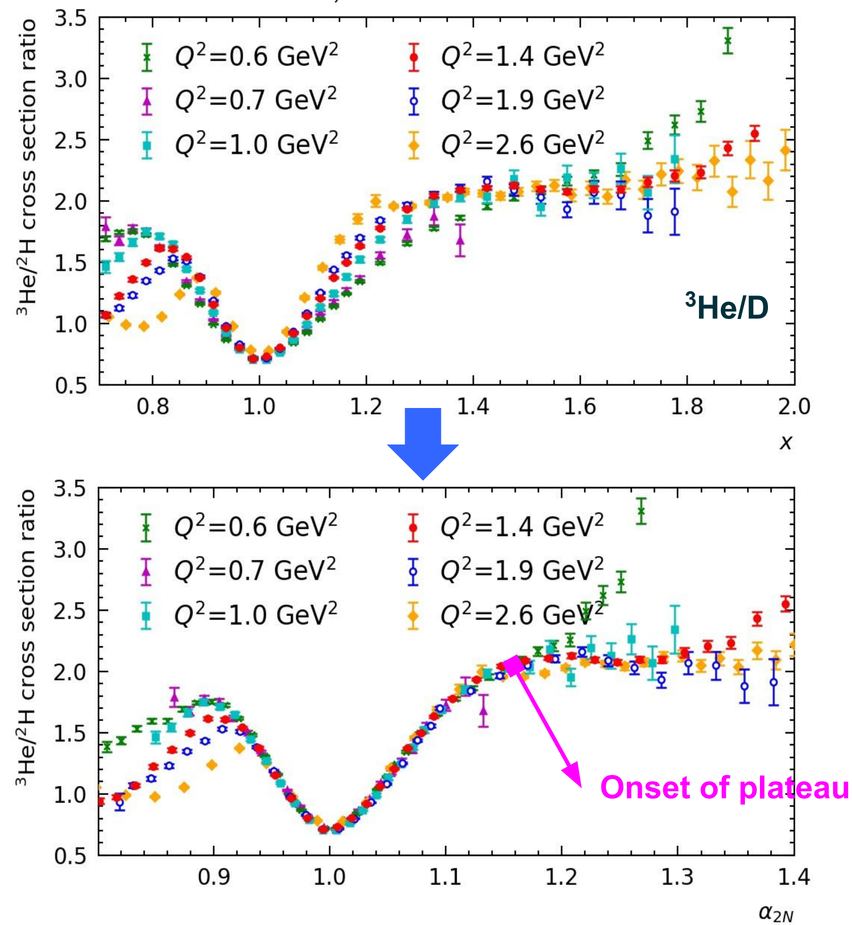
2N SRC revisit: scaling in light cone

light-cone momentum fraction of the nucleus carried by the interacting bound nucleon:

$$\alpha = A\frac{E_N - k_{N,z}}{E_A - k_{A,z}}$$



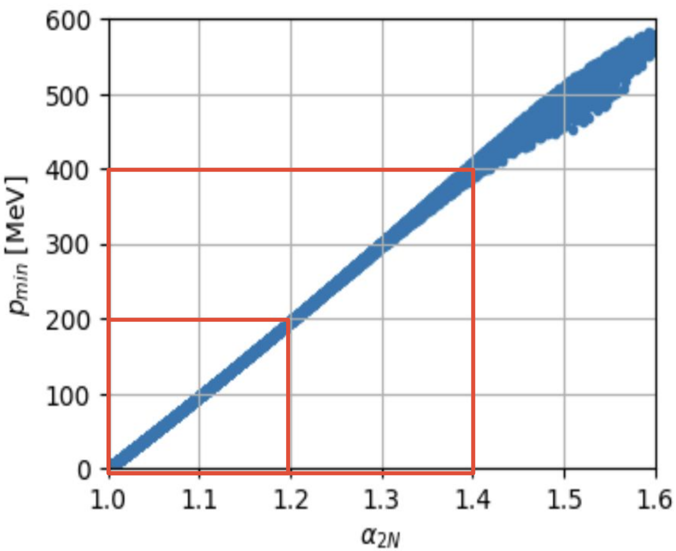
Example of alpha scaling:
arxiv 2404.16235, submitted to PLB



2N SRC revisit: scaling in light cone

light-cone momentum fraction of the nucleus carried by the interacting bound nucleon:

$$\alpha = A\frac{E_N - k_{N,z}}{E_A - k_{A,z}}$$



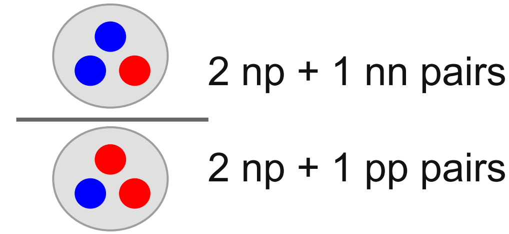
Observation from 2N SRC in ^{3}He/D :

- **Scaling down to $Q^2 = 1$ GeV^2 :**
  - More cancellation between FSI, CM motion
  -
- **Onset at $\alpha_{2N} < 1.2 \rightarrow$ pmin ~ 200 MeV**
  - Earlier onset in α_{2N} due to lower mean-field momenta: **k_F <100 MeV in A=3**

Implication on possible 3N SRC in ^{3}H/^{3}He :

- **Scaling at low Q^2 :**
  - FSI, COM etc. cancellations should be nearly complete in ^{3}H/^{3}He
- **3N onset at $\alpha_{2N} > 1.4 \rightarrow$ pmin ~ 400 MeV**
  - Doubled the 2N SRC pmin to allow generation of two consecutive 2N SRC in linear configuration

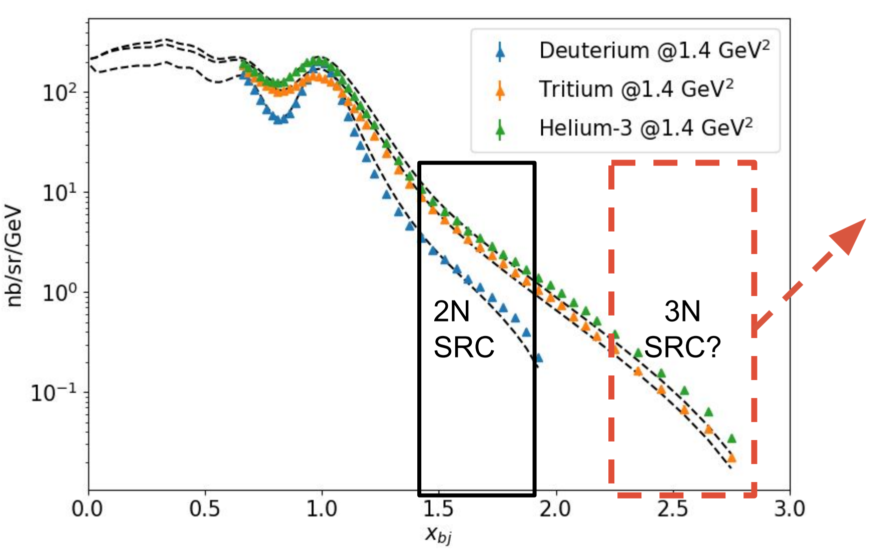
3N SRC scaling in A=3?



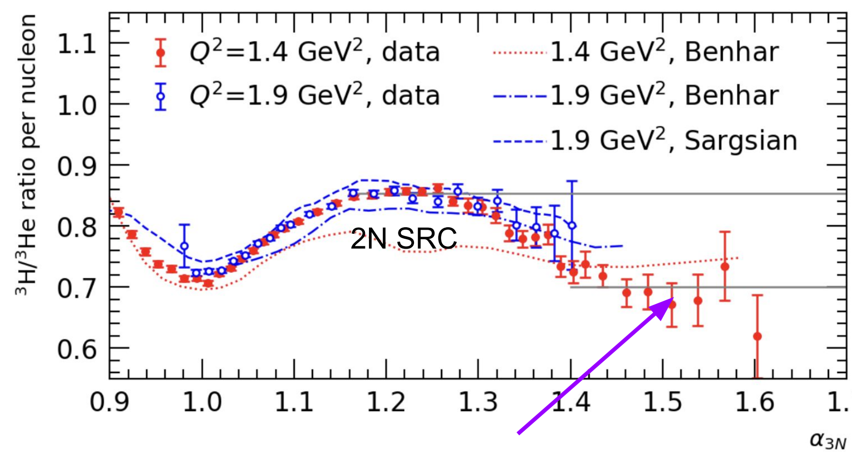
$^3H/^3He$ Data from JLab E12-11-112:

SL et al, Nature 609, 41-45 (2022)

- Only tritium target for high energy electron scattering in the past 30 years
- Mirror nuclei comparison to maximize isospin asymmetry



arxiv 2404.16235, submitted to PLB



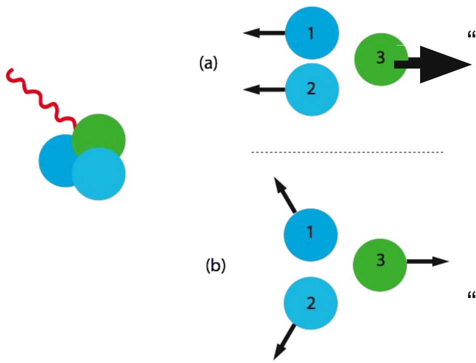
Possible 3N SRC with the expected strength ~ (2N SRC) ^2

Next step:

Need more data at higher alpha, multiple Q2 to confirm the scaling. PR12-24-012, resubmission planned

Why we need more ^{3}H/^{3}He data:

- Nuclear effect, competing processes etc largely canceled for a clean comparison of nnp v.s. Npp
- Pair with A/3 data for iso-scalar ratio A/(^{3}H +^{3}He)
- Extract 3N momentum sharing and isospin configurations for energetic nucleons:



"Line" configuration

$p_3 = p_1 + p_2$

R(^{3}H/^{3}He) ≈ σ_p/σ_n ≈ 2.5 if nucleon #3 is always the singly-occurring nucleon

R(^{3}H/^{3}He) ≈ σ_n/σ_p ≈ 0.4 if nucleon #3 is always the doubly-occurring nucleon

R(^{3}H/^{3}He) ≈ 0.7 if configuration is isospin-independent

"STAR" configuration

$p_1 = p_2 = p_3$

→ **Kinematically forbidden**

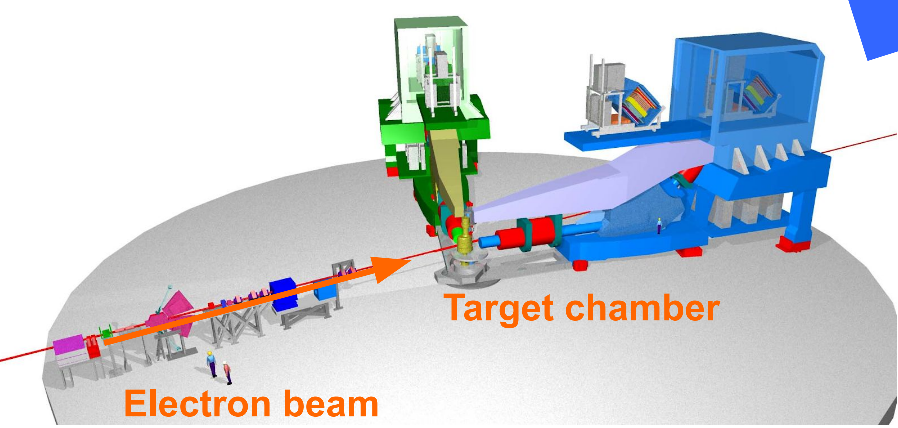
- Compare with few-body calculations to test the boundary of non-rel wave function, and provide unique access to ultra-high momentum nucleons.
- Sensitive to isospin-dependent nuclear effect

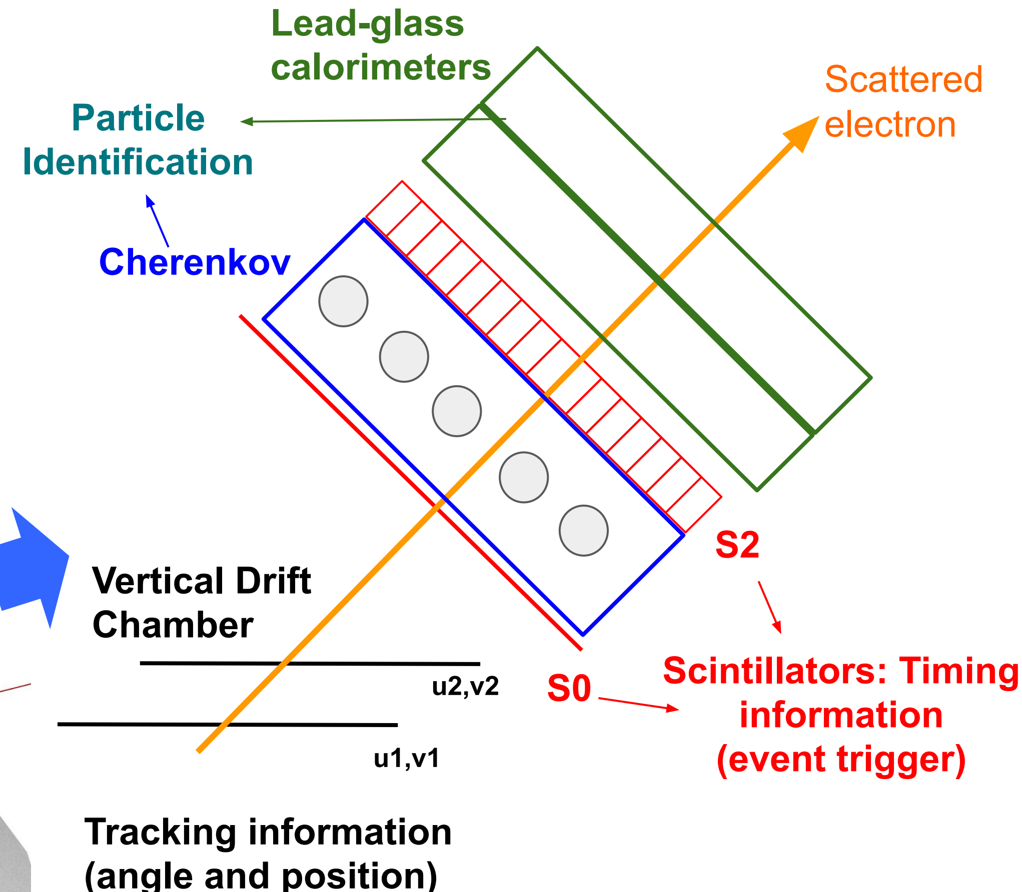
Backup

Electron Detection

- **High resolution spectrometer**
  - Magnets to “zoom in” the scattered electrons
  - Reconstruct charged particle tracks
  - Particle identification through time-of-flight, energy deposit, and threshold detectors

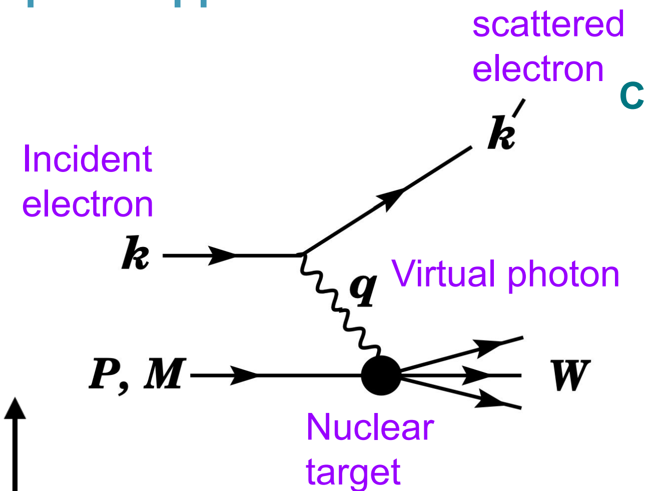
Detector Package





Quasi-elastic (QE) Scattering Kinematics

Impulse approximation

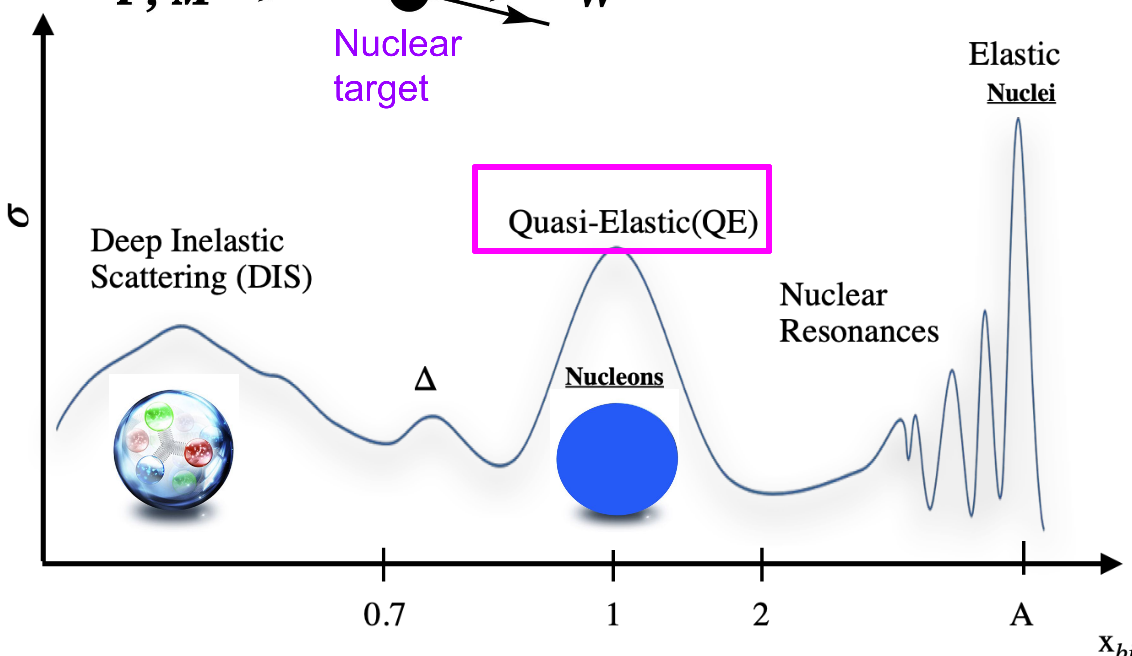


Cross section ~ probability of scattering

$$\frac{d^2\sigma}{dxdy} = \frac{2\pi y\alpha^2}{Q^4}\sum_j \eta_j L_j^{\mu\nu} W_{\mu\nu}^j$$

Leptonic tensor (QED)
Point-like electron

hadronic tensor
Nuclear structure:
(nucleonic / partonic)

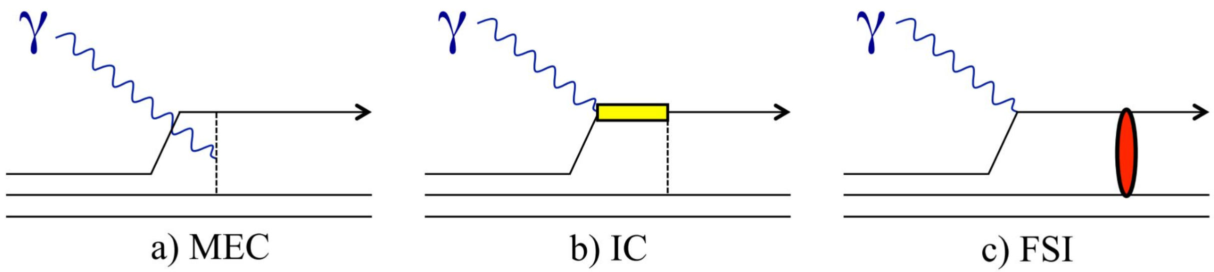


$Q^2 = -q^2$ four-momentum transfer squared

$x = \frac{Q^2}{2M\nu}$ Bjorken x: the fraction of nucleon momentum carried by the struck quark in parton model.

Quasi-elastic Scattering

Competing processes



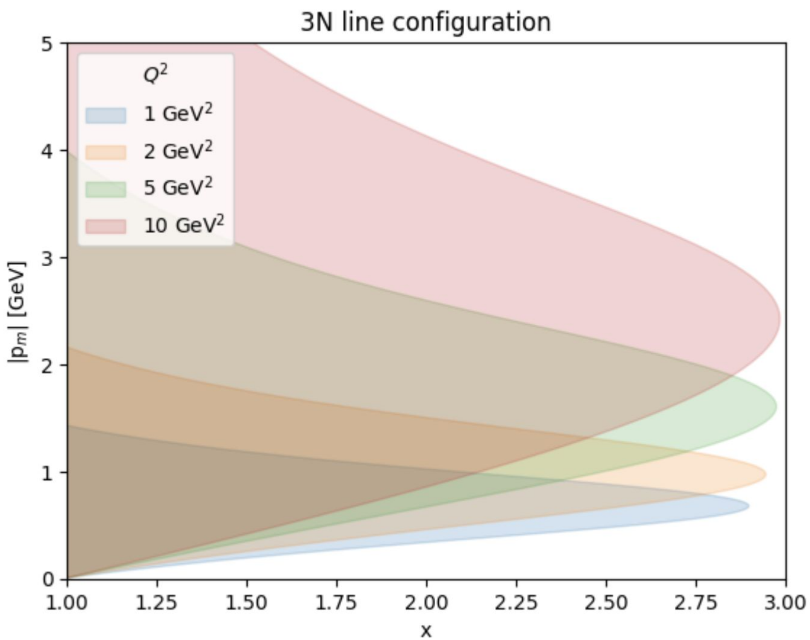
- a) Meson-exchange current (MEC):
  - $1/Q^2$ suppression
- b) Isobar Current (IC):
  - $1/Q^2$ and $x>1$ suppression
- c) Final State Interactions (FSI):
  - **(e, e'p)**:
    - kinematics (recoil angle etc.) pre-selection
    - model-dependent corrections
  - **(e, e')**: contained within the SRC pair at large Q^2

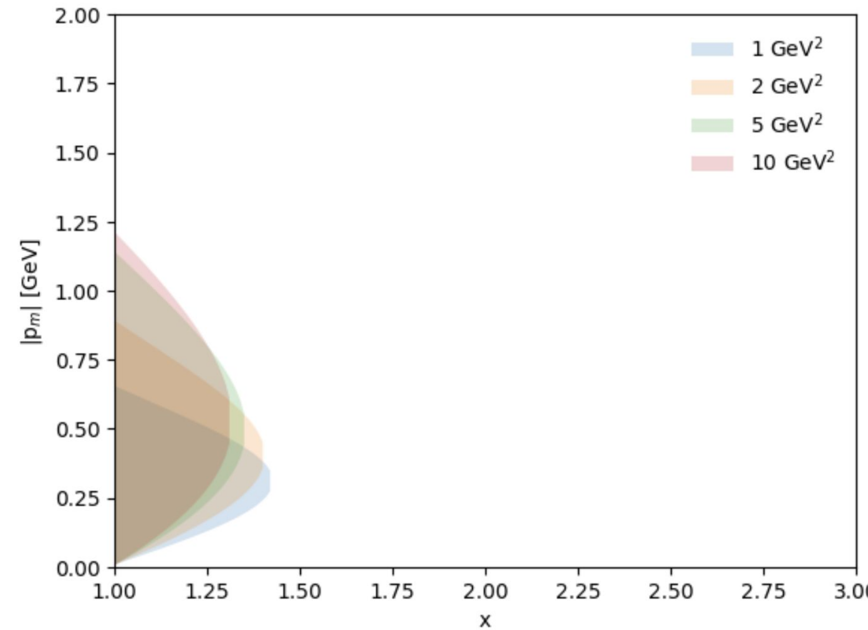
Pmin for ground state 3N system

m_3: 3H or 3He mass

Line: $m_3 + v = 2\sqrt{m_N^2 + 0.25p_m^2} + \sqrt{m_N^2 + (p_m + q)^2}$

Star: $m_3 + v = 2\sqrt{m_N^2 + p_m^2} + \sqrt{m_N^2 + (p_m + q)^2}$

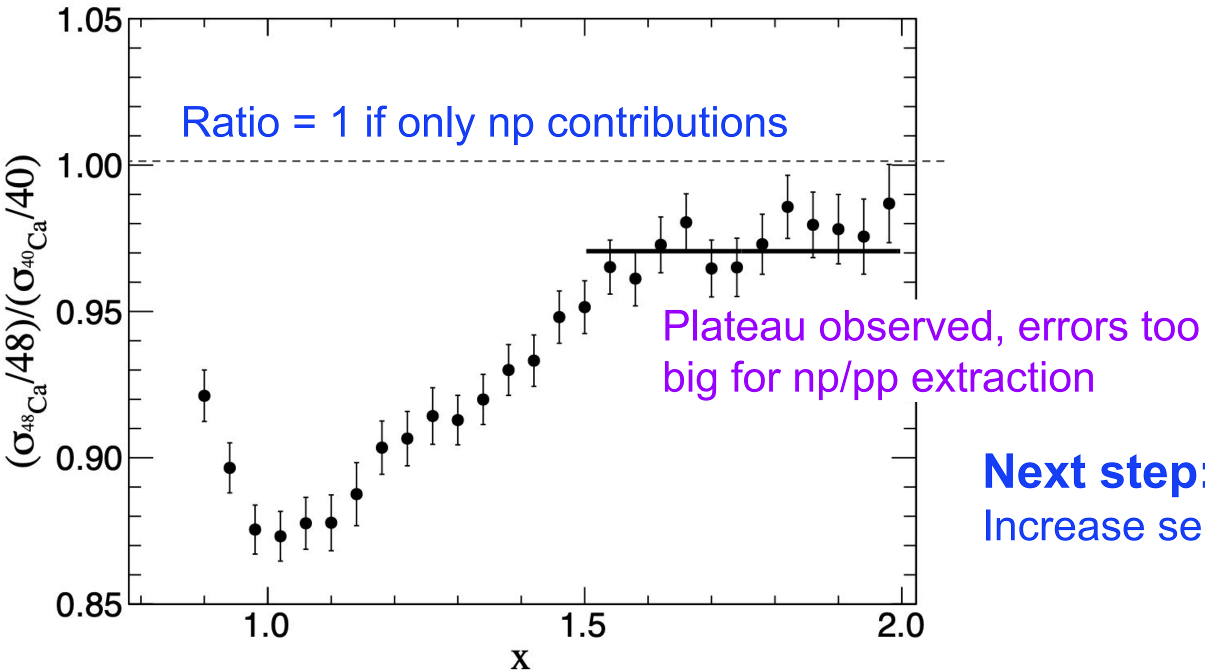




Extracting np/pp ratio with Isotopes?

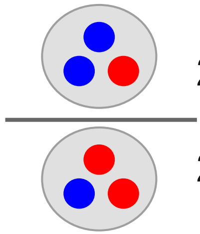
- (e,e’): higher stats, higher precision
- Ca40 vs Ca48: large isospin asymmetry

D. Nguyen, Phys. Rev. C 102, 064004 (2020)



Next step:
Increase sensitivity

Extracting np/pp ratio with A=3 “mirror” nuclei



2 np + 1 nn pairs

2 np + 1 pp pairs

- Only tritium target for high energy electron scattering in the past 30 years
- Low-density, 1000 Ci of tritium gas for safety concern

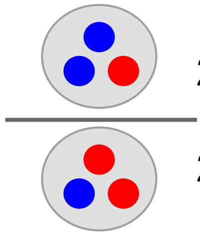
Tritium v.s. Helium-3:

- Large isospin (neutron-proton) asymmetry
- Similar separation energy: 6.26 MeV v.s. 5.49 MeV
- Similar center-of-mass motion of the pair
- Similar FSI
- Calculable* few-body systems

Inclusive cross section ratio:

- High statistics
- Systematic uncertainties canceled in the ratio

Extracting np/pp ratio with A=3 "mirror" nuclei

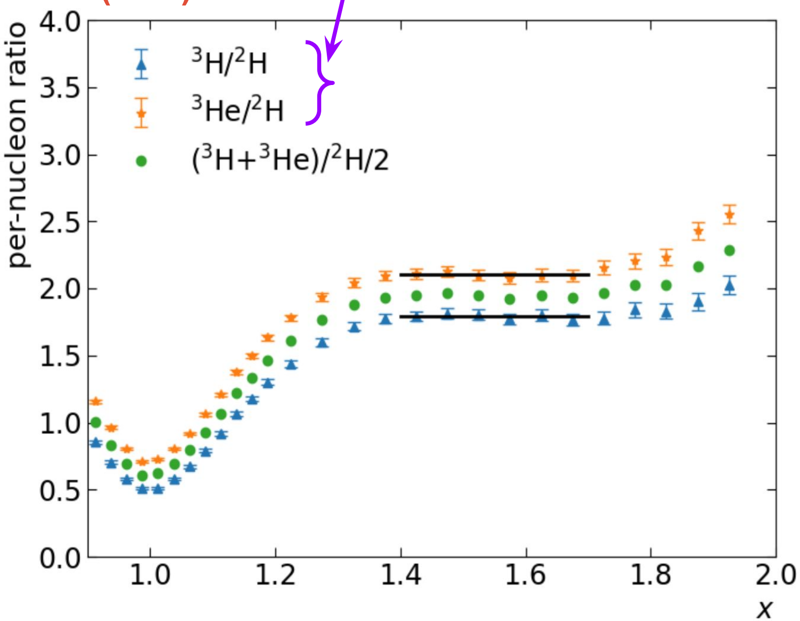


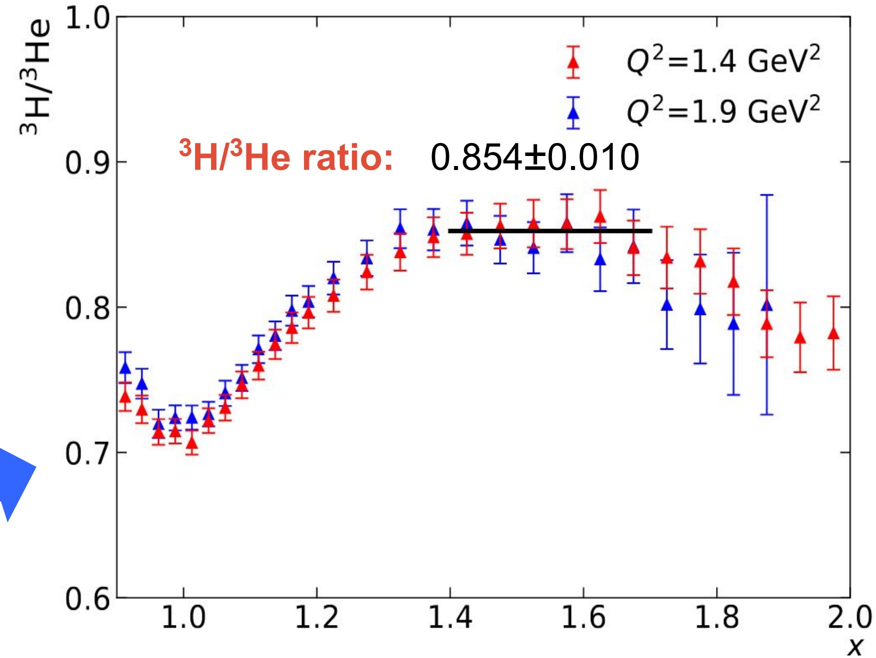
2 np + 1 nn pairs

2 np + 1 pp pairs

would have given the same plateau height if 100% np dominant

(A=3)/D ratio



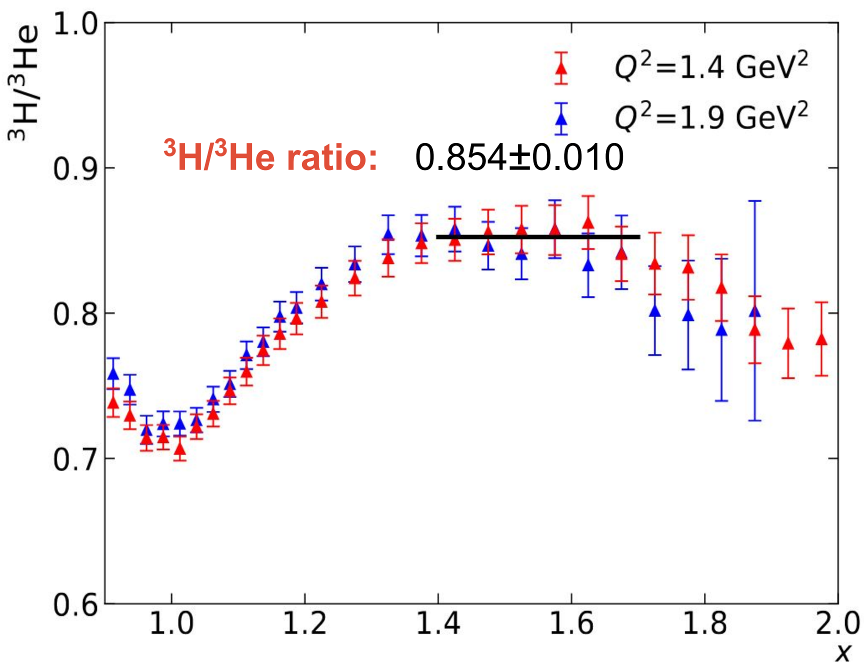


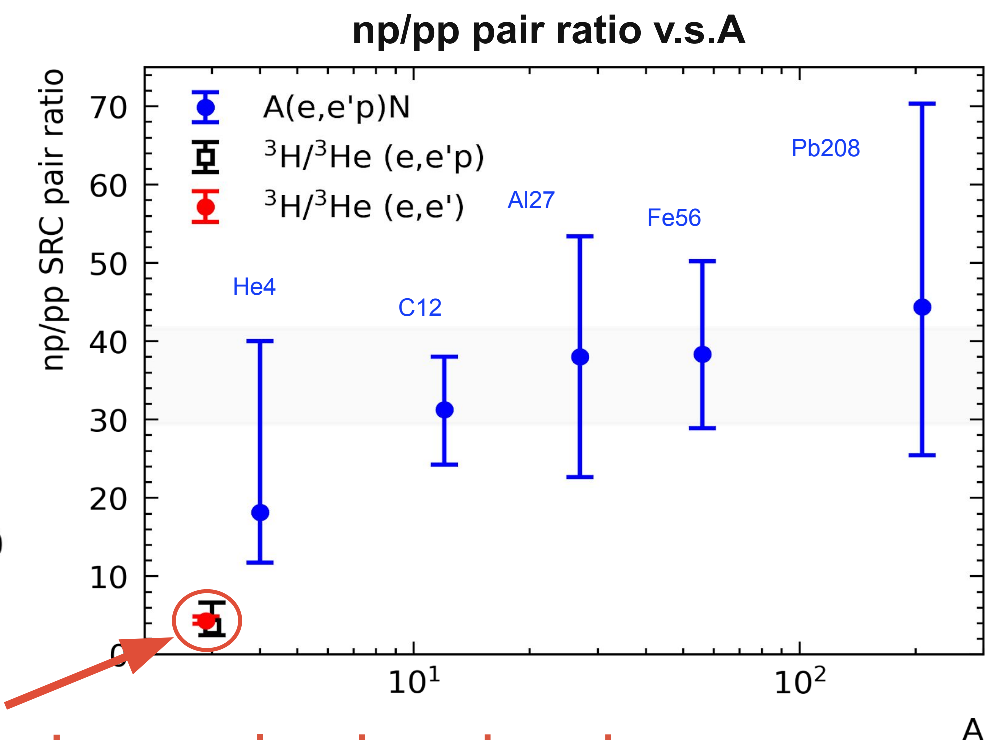
Ratio of np/pp SRC pairs in A=3 nuclei:

$R_{np/pp} = 4.3 \pm 0.4$

SL et al, Nature 609, 41-45 (2022)

Extracting np/pp ratio with A=3 "mirror" nuclei





Ratio of np/pp SRC pairs in A=3 nuclei:

$R_{np/pp}$ =4.3 ± 0.4

Large nuclear dependence in np/pp SRC

SL et al, Nature 609, 41-45 (2022)