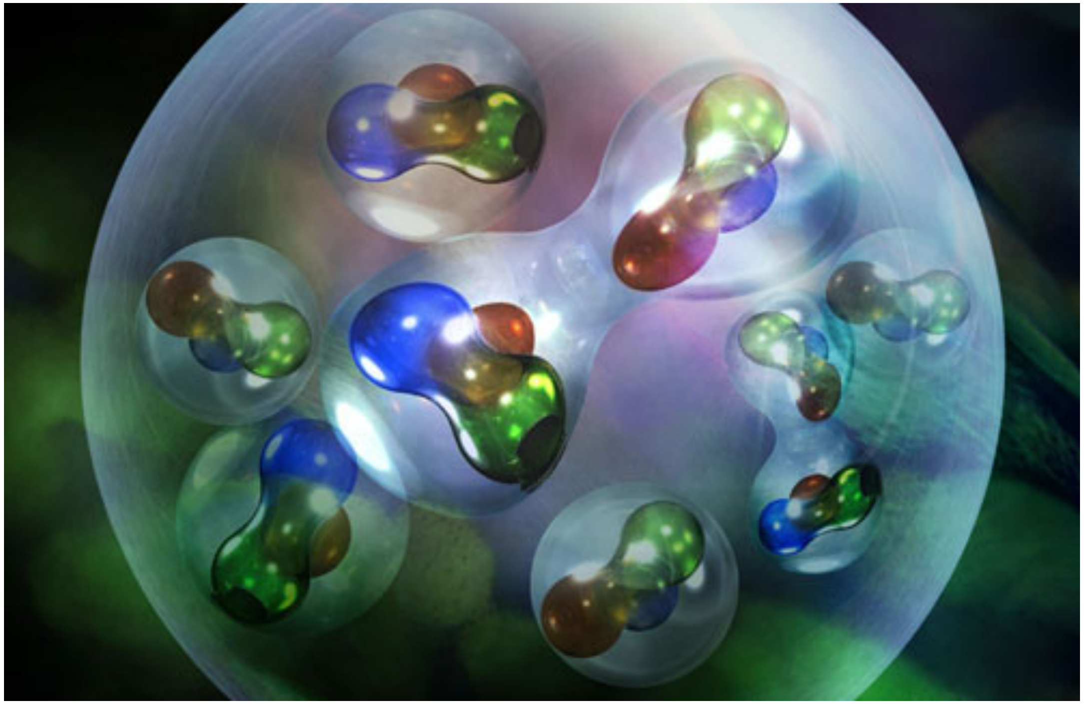
Nucleon-Nucleon Short Range Correlations



Zhihong Ye (叶志鸿）

Medium Energy Group, Argonne National Lab

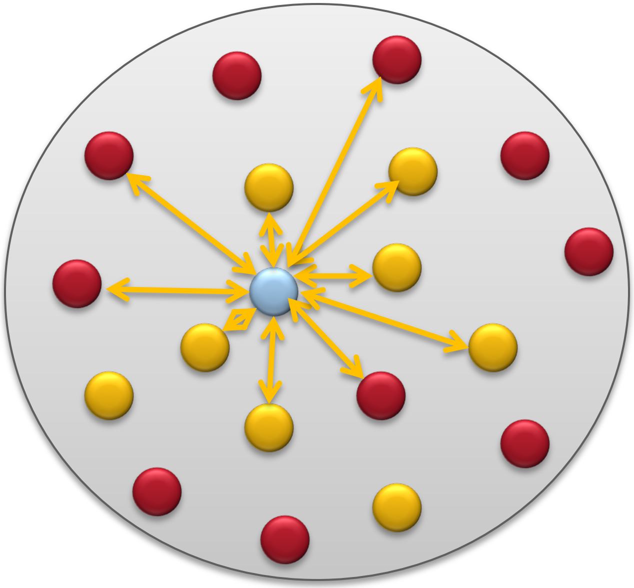
iHIC2018, Tsinghua University, 04/08/2018 – 04/10/2018

Outline

- **Nucleon-Nucleon Interaction**
- **Short Range Correlations (SRC)**
- **Measuring SRC**
- **SRC vs EMC**
- **Future Opportunities**
- **Summary**

Nucleon-Nucleon Interaction

- **Mean Field Theory (Shell Model):**
  - Nucleons move independently in an average field induced by the surrounding nucleons;



Nucleon-Nucleon Interaction

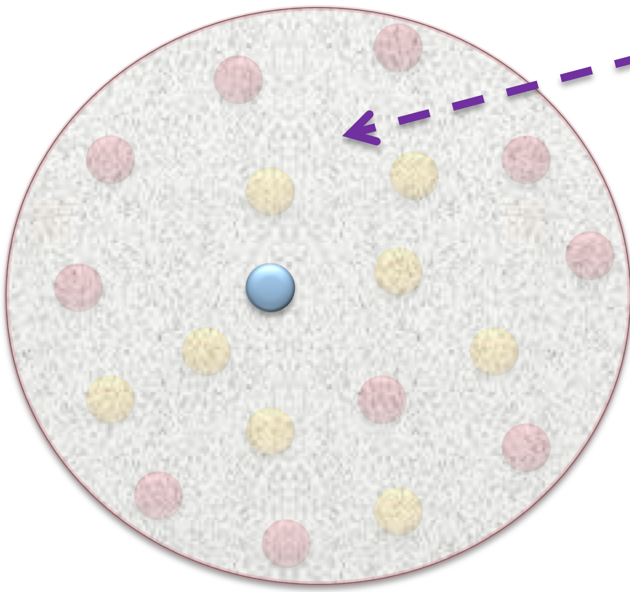
- **Mean Field Theory (Shell Model):**
  - Nucleons move independently in an average field induced by the surrounding nucleons;
  - Independent Particle Shell Model **(IPSM):**

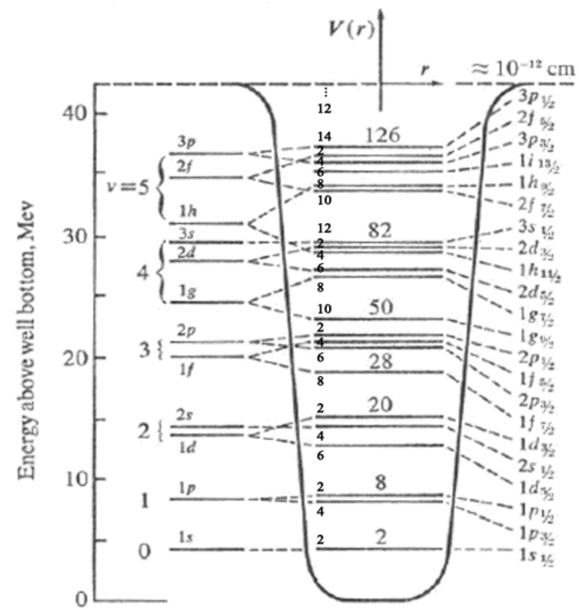
$$h_{IPSM}\left|\varphi_\alpha\right\rangle \approx (p^2/2m+\overline{V}+\ldots)=\varepsilon_\alpha\left|\varphi_\alpha\right\rangle$$

No NN interaction Terms!

  - Occupying energy shells below Fermi Momentum (k_F) and Energy (ε_F).

The Mean Field



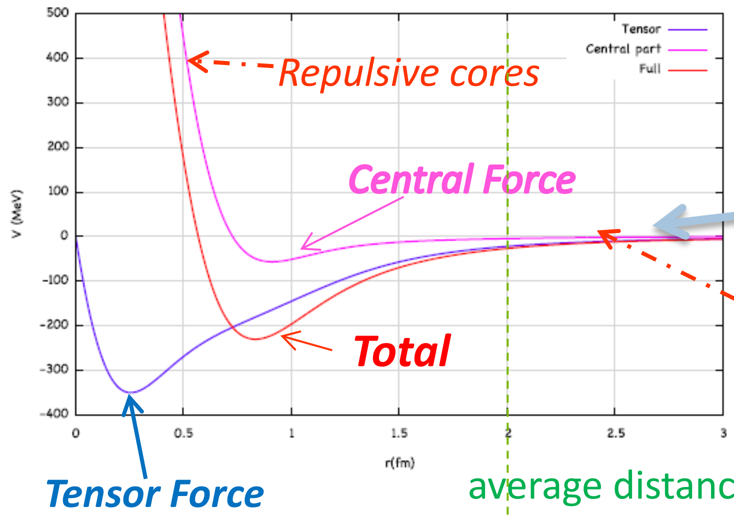


However, IPSM has its limitations, such as NN interaction at short distance, Nuclear magnetic moments, Highly Excitation States, High Density Nuclear Matter.

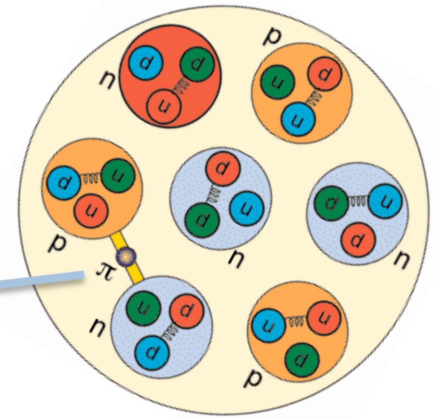
Nucleon-Nucleon Interaction

➢ Realistic Nucleon-Nucleon Interactions:

Two-Nucleon Interaction Potentials



average distance of two nucleons



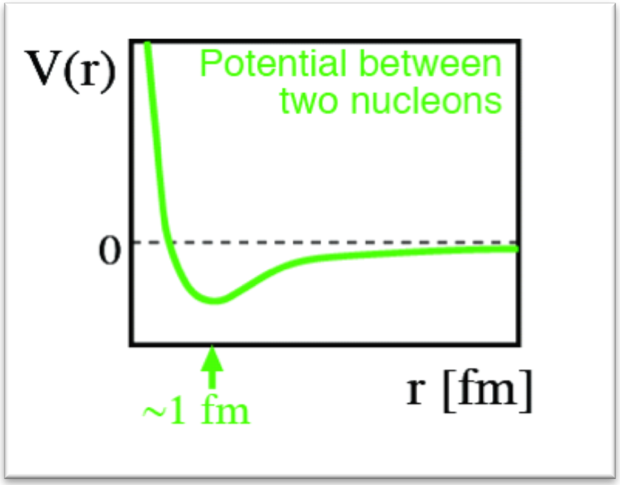
Long-Range Weak Attraction
by exchanging pions

- Nucleons are weakly interacting in their normal distances
- Far more complicated interactions at short distance (both strong attractive and strong repulsive)
- *ab initio* calculations: many-body system + special potential:

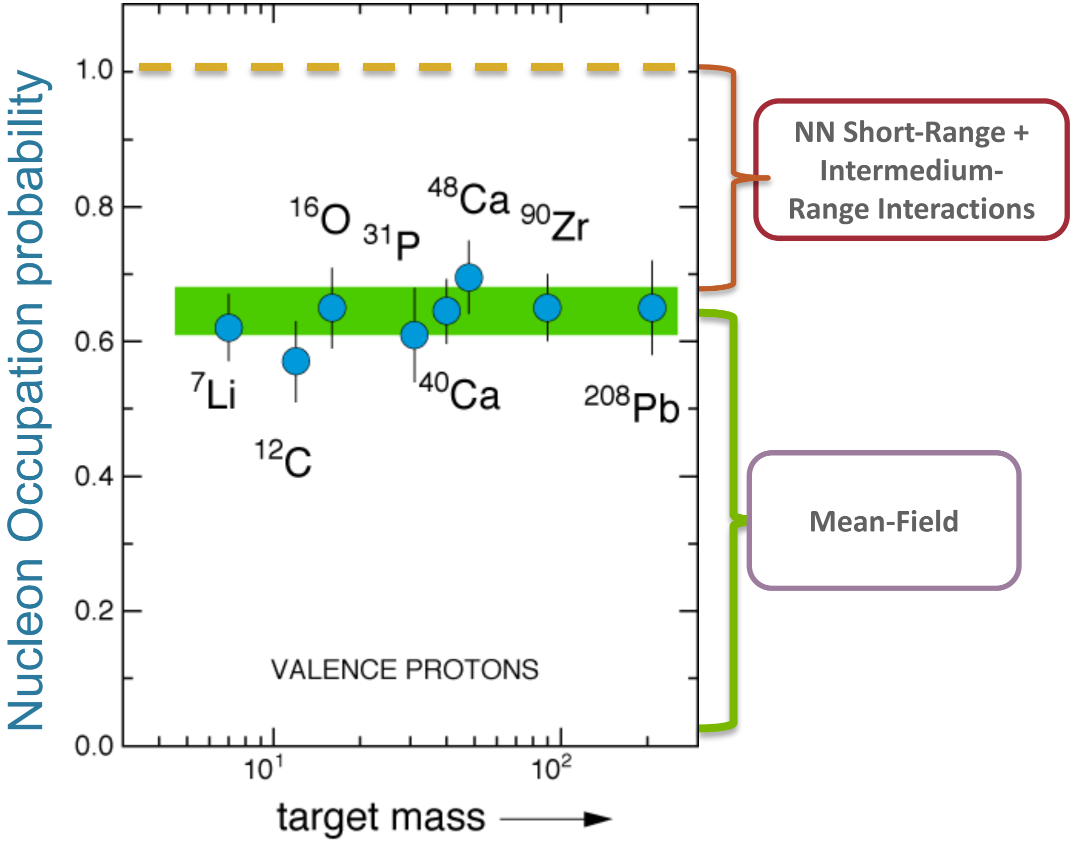
$$H=\sum_{i}T(i)+\sum_{i<j}V^{(2)}(i,j)+\sum_{i<j<k}V^{(3)}(i,j,k)+\ldots,\qquad H\psi_A=E\psi_A$$

Nucleon-Nucleon Interaction

- **Missing Strength:**



Proton knocked out experiments showed that nucleons with momenta lower then k_F (~200MeV/c) don't occupy all the nuclear orbits.



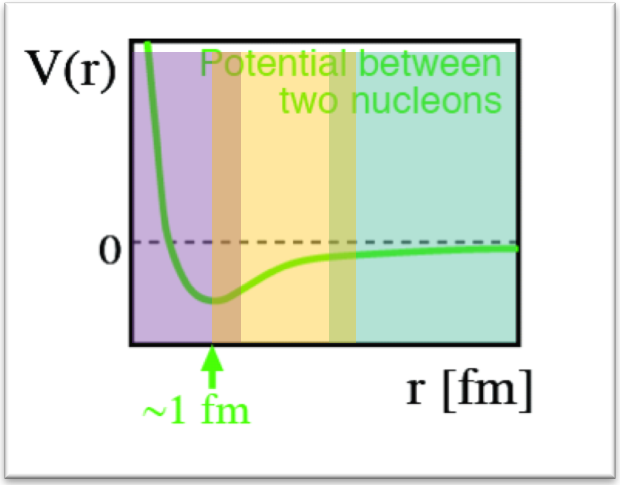
L. Lapiks, Nuclear Physics A 553, 297 (1993)

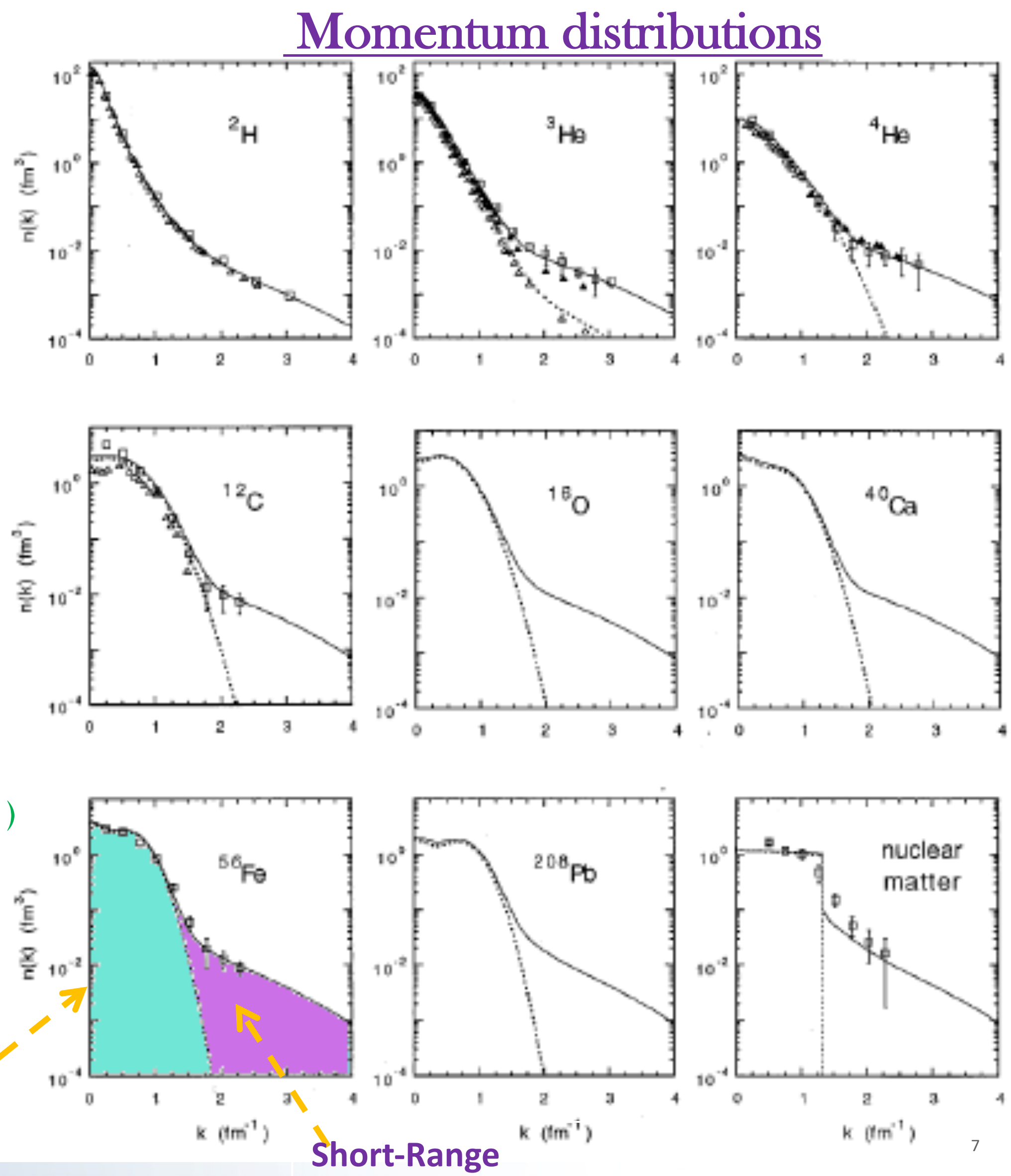
Nucleons can live at $k>k_F$ (~20% of them are from SRC)

Nucleon-Nucleon Interaction

C. Ciofi degli Atti, et al, PRC 53 1689 (1996)

➢ **Missing Strength:**





- Nucleon-nucleon (NN) distance can be small

  Strong attraction and repulsion at <1 fm

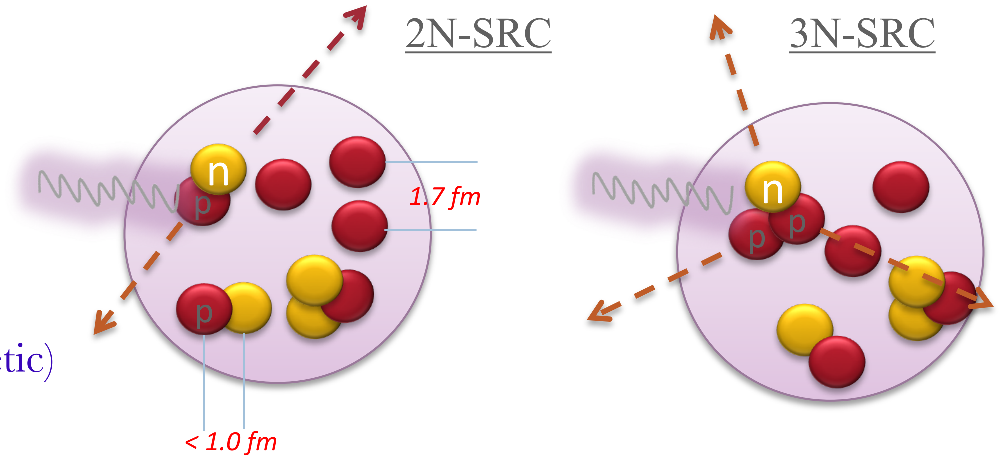
- Nucleons can carry much higher momenta ($k>k_F$)
- Zero (or tiny) total momentum for NN pairs:

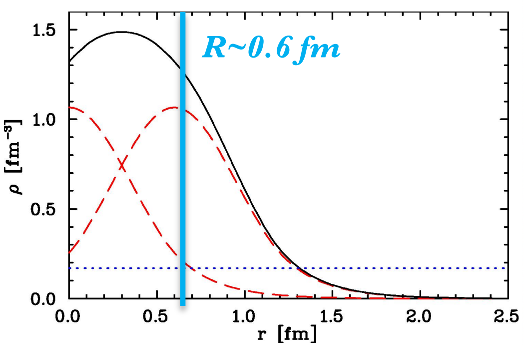
  A real ground state, not an excited state.

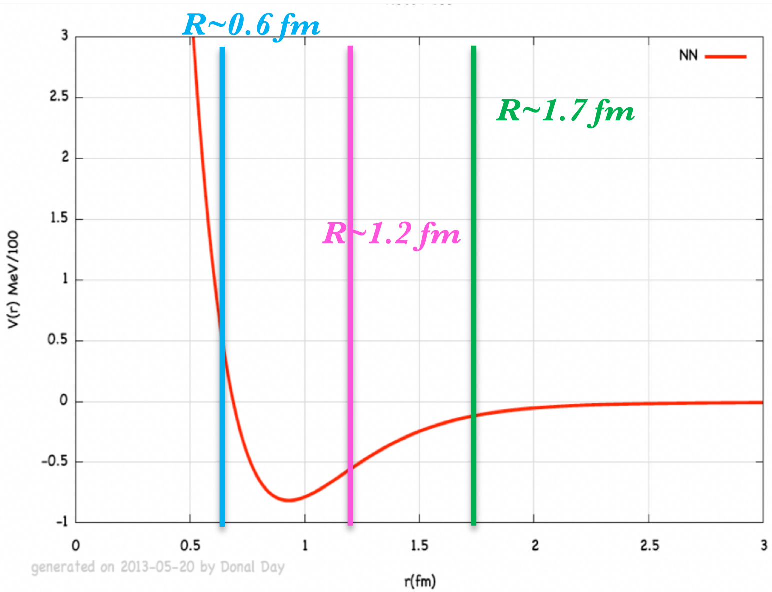
Short Range Correlations (SRC)

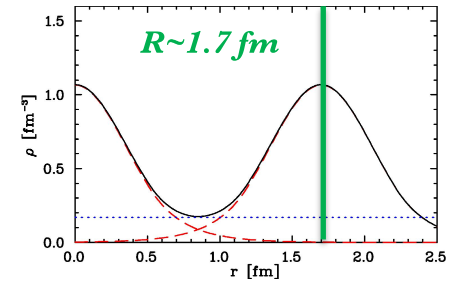
- **Key Features:**
  - Involve 2-nucleons (2N-SRC),
    3-nucleons (3N-SRC) and more;
  - The nucleons are largely overlapped

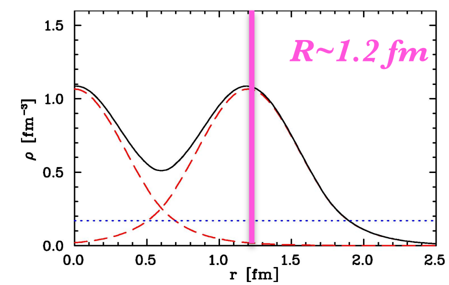
✓ Proton radius ~ 0.85 fm (charged & magnetic)
✓ Neutron radius ~ 0.86 fm (magnetic)
✓ Inter-nucleon separation in nuclear matter (A->infinity) ~1.6 fm





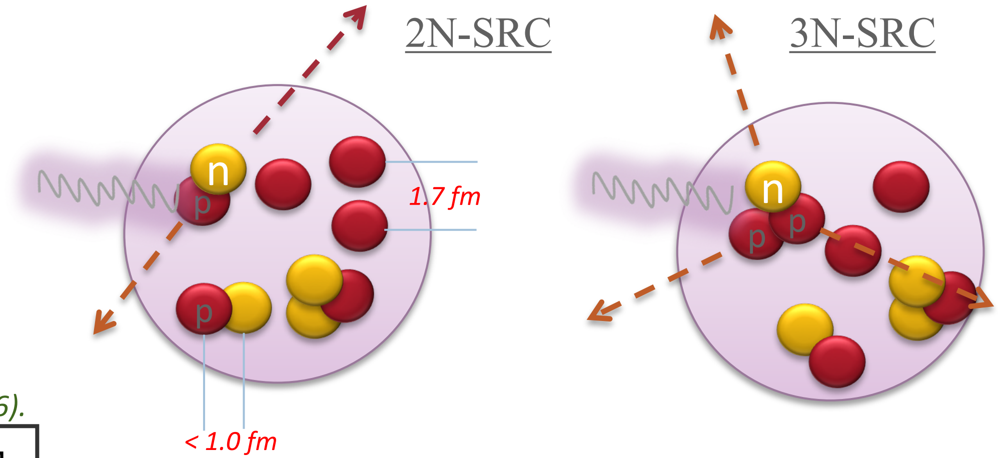




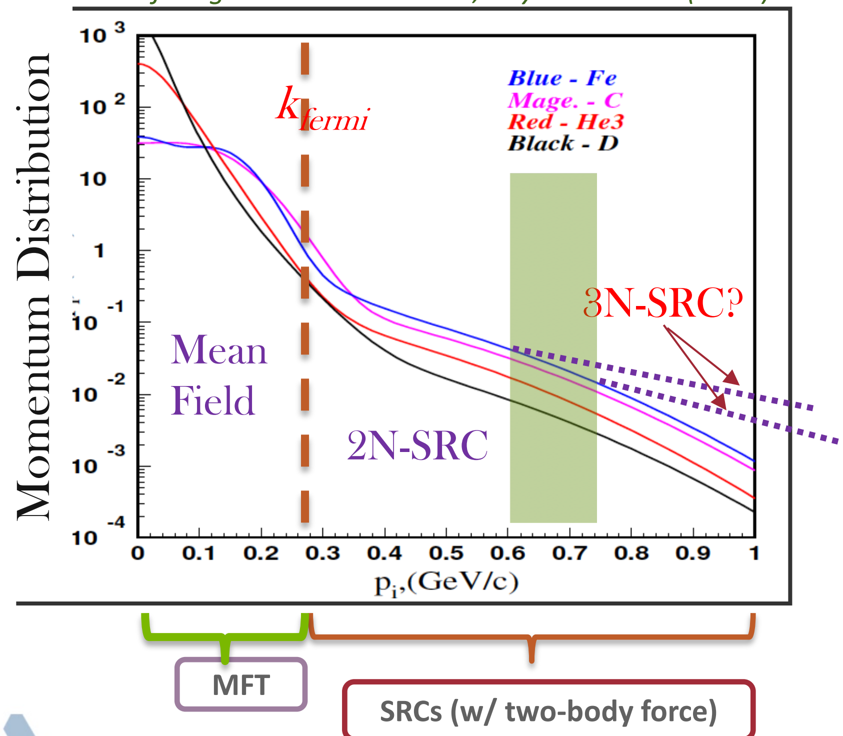


Short Range Correlations (SRC)

- **Key Features:**
  - Involve 2-nucleons (2N-SRC), 3-nucleons (3N-SRC) and more;
  - The nucleons are largely overlapped



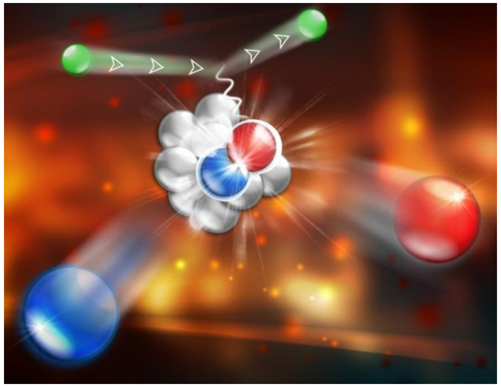
C. Ciofi degli Atti and S. Simula, Phys. Rev. C 53 (1996).



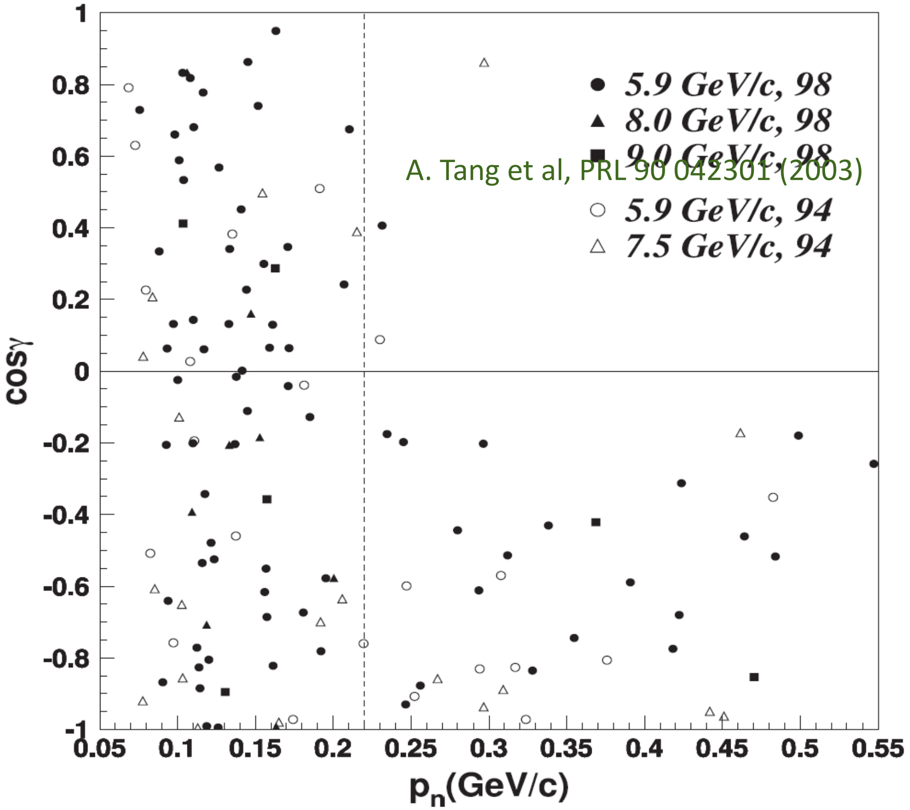
- 2N-SRC and 3N-SRC in heavy nuclei:
  similar to ^{2}D and ^{3}H/ ^{3}He.
- Similar shape for High momentum tails:
  scaling behavior at k>kF
- Extremely high density configurations:
  connect to EMC effect, quark degrees of freedom, Inner Structure of Neutron Stars, etc.

Measuring SRC

- **From Exclusive Measurements:**
  - ✓ Back-to-back scattering between the knocked-out nucleon and the spectator nucleon

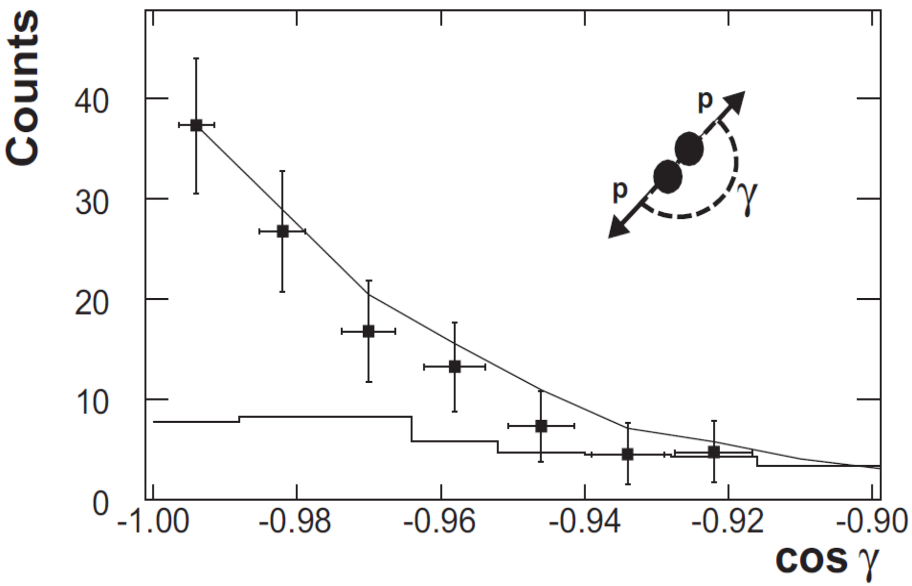


A(p, p'pN)A-2 reaction at EVA (AGS E850), BNL



A. Tang et al, PRL 90 042301 (2003)

A(e,e'pN)A-2 reaction in Hall-A, JLab

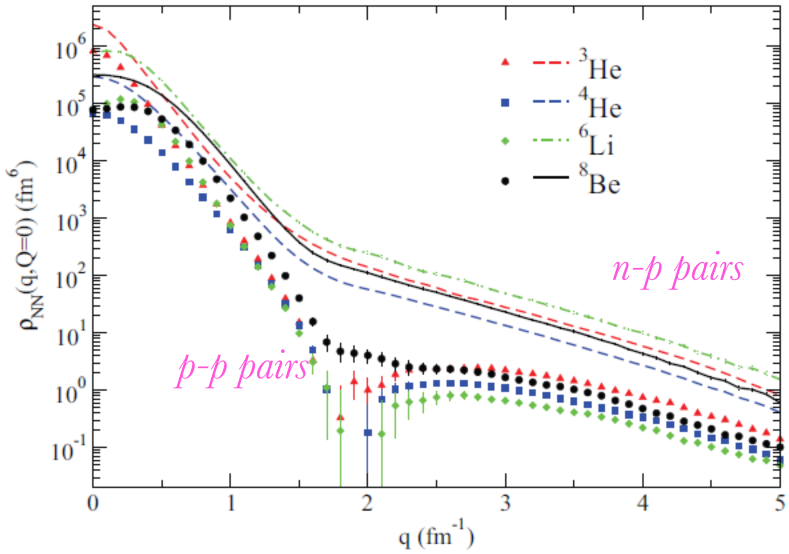


R. Shneor et al, PRL 99 072501 (2007)

Measuring SRC

- **From Exclusive Measurements:**
  - ✓ Theoretical calculation shows n-p pairs have stronger strength.

R. Schiavilla, et al, PRL 98 132501 (2007)



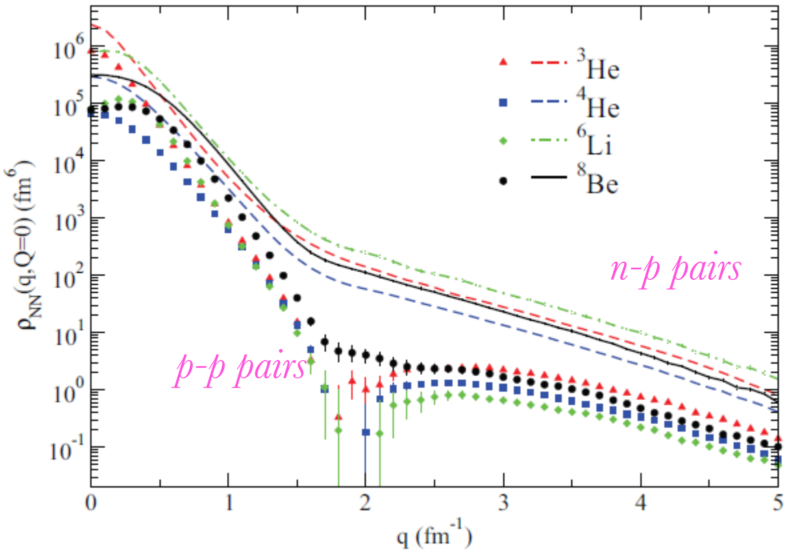
O. Hen et al., CLAS Collaboration @ JLab, Science 346, 614 (2014)

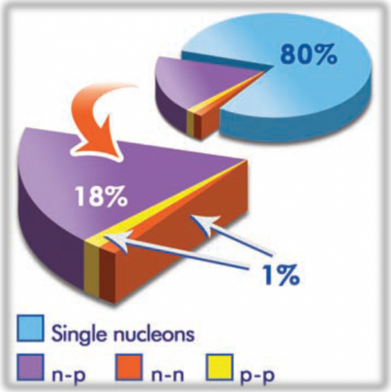
Measuring SRC

➢ **From Exclusive Measurements:**

✓ Theoretical calculation shows n-p pairs have stronger strength.

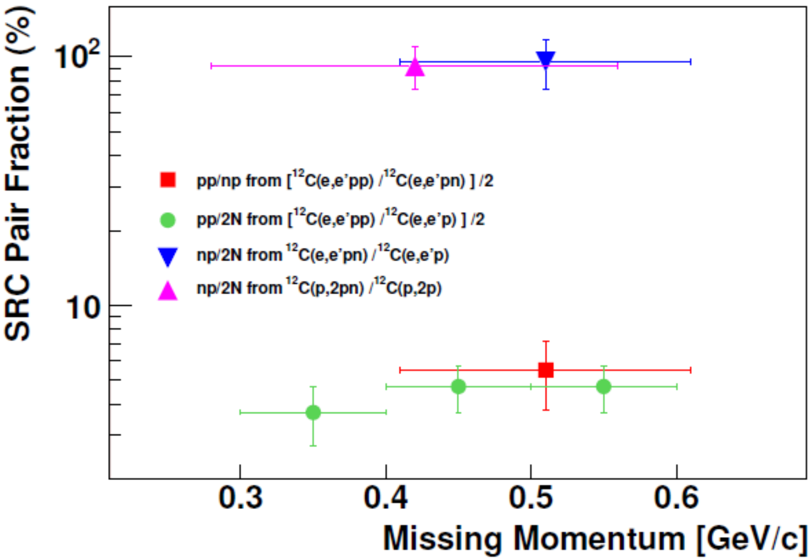
R. Schiavilla, et al, PRL 98 132501 (2007)





✓ Experiment discovered that np pairs are 90% in 2N-SRC

R. Subedi, et al, Hall-A Collaboration @ JLab Science 320 1476 (2008)



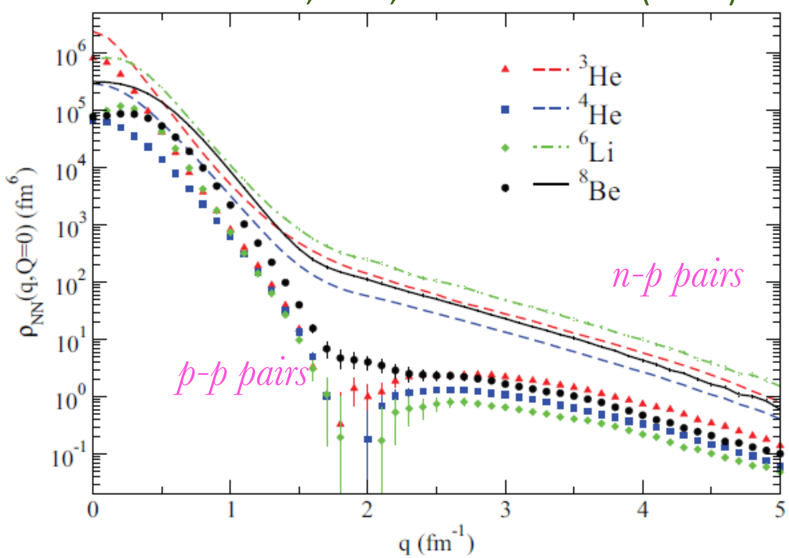
O. Hen et al., CLAS Collaboration @ JLab, Science 346, 614 (2014)

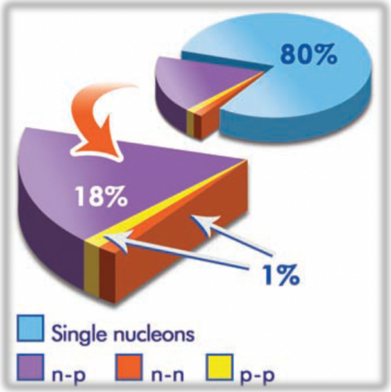
Measuring SRC

➢ **From Exclusive Measurements:**

✓ Theoretical calculation shows n-p pairs have stronger strength.

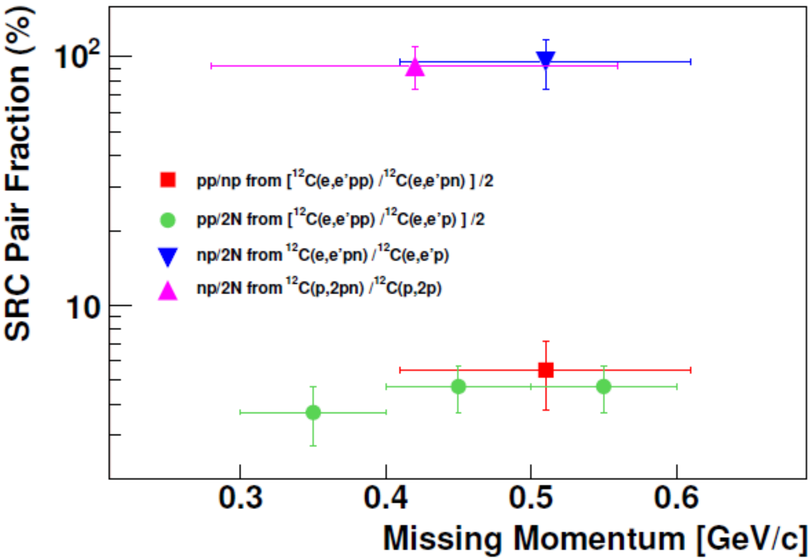
R. Schiavilla, et al, PRL 98 132501 (2007)

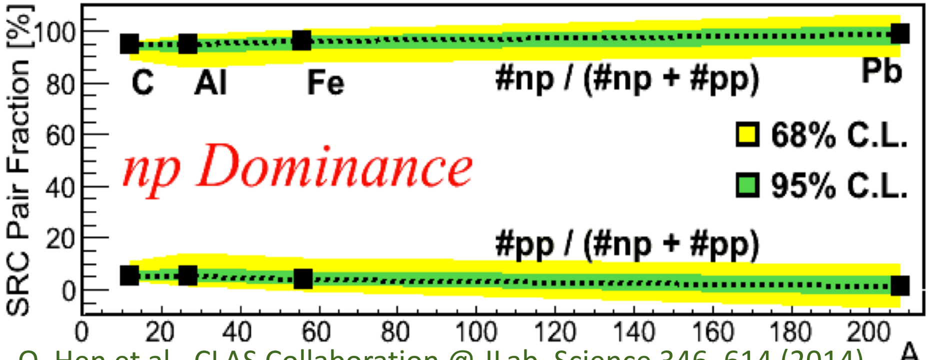




✓ Experiment discovered that np pairs are 90% in 2N-SRC

R. Subedi, et al, Hall-A Collaboration @ JLab Science 320 1476 (2008)





O. Hen et al., CLAS Collaboration @ JLab, Science 346, 614 (2014)

✓In Neutron-Rich matter, a protons is more likely to be above Fermi-Sea than a neutron.

Measuring SRC

➢ From Inclusive Electron-Nucleus Scattering:

- Incoming electrons scatter on nuclei and only measure the scattered electrons.

- Important quantities:

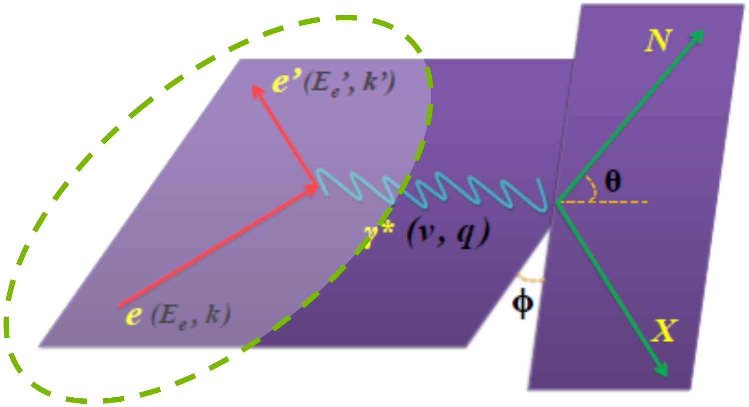
Four Momentum Transfer of the virtual photon.

$$Q^2 = 4E_0E'sin^2(\theta/2)$$

Borrow and extend the definition of x_{bj} in DIS:

$$x = \frac{Q^2}{2m_p\upsilon}$$

(x>1 if more than one nucleon involve in the interaction)



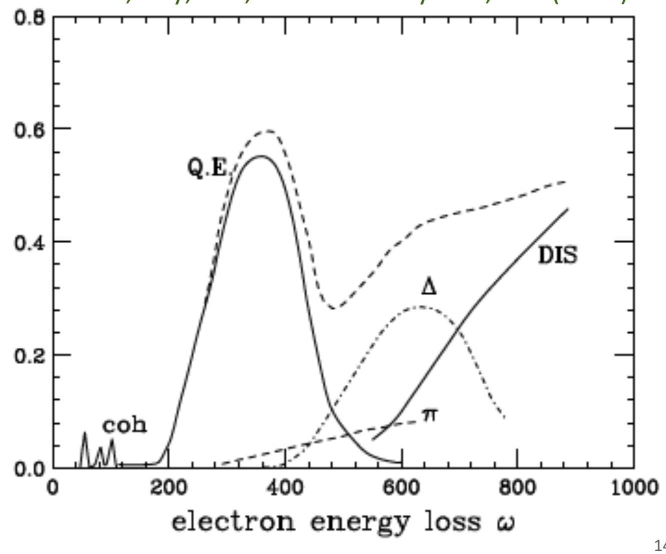
- Three processes →Three type of D.O.F.

(1) $x = \frac{Q^2}{2m_A\upsilon} \equiv 1$: "Elastic"→Interact with the whole nucleus,

(2) $1 < x = \frac{Q^2}{2m_p\upsilon} < A$: "Quaselastic"→Interact with a nucleon moving inside the nucleus

(3) $x = \frac{Q^2}{2m_p\upsilon} < 1$: "Inelastic"→ Interact with components inside a nucleon

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



Measuring SRC

- **From Inclusive Electron-Nucleus Scattering:**

Momentum Distribution is not a direct observable but links to the inclusive cross sections.

- At Quasielastic (QE) Region, the Inclusive Cross Section:

Spectral Function → Link to the nuclear structure

$$\frac{d\sigma}{dE'd\Omega}(Q^2, x_{bj}) = \int \sum_{nucleons} \sigma_{eN} S_N'(E_0, \vec{p}_0) d^3\vec{p}',$$

Integral accounting for all electron-nucleon reactions

- y-Scaling:

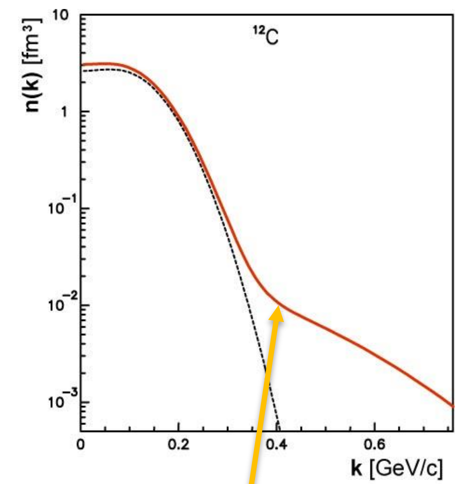
y→ the minimum accessible nucleon momentum

$$\frac{d\sigma}{dE'd\Omega}(Q^2, x_{bj}) = 2\pi\bar{\sigma} \cdot F(y),$$

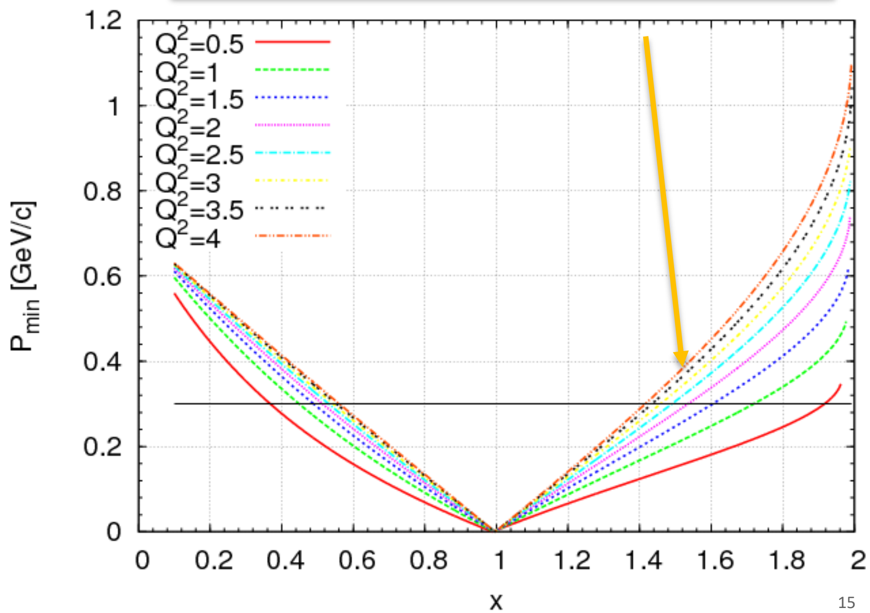
F(y)→ very small dependence on Q^2.

- Momentum Distribution of a nucleon inside a nucleus:

$$n(p_0) = \frac{-1}{2\pi p_0} \frac{dF(p_0)}{dp_0}\bigg|_{p_0 = y}$$



QE cross sections get access to the high momentum tail at x>1.4 and Q2=4GeV²



Measuring SRC

➢ From Inclusive Electron-Nucleus Scattering:

- Decompose the QE cross section in a SRC picture:

One nucleon: $(x\sim 1)$. Two nucleons: $(1.3<x<2)$ Three nucleons: $(x>2)$

$$\sigma_A(x,Q^2) = \sum_{j=1}^{A}\frac{A}{j}\sigma_j(x,Q^2) = A\sigma_{1N}(x,Q^2) + \frac{A}{2}a_2(A)\sigma_{2N}(x,Q^2) + \frac{A}{3}a_3(A)\sigma_{3N}(x,Q^2)\ldots$$

a_j (A) ---the probability of a nucleon in a jN-SRC.

σ_j (A) --- the cross section of an electron scattering on a nucleon in jN-SRC.

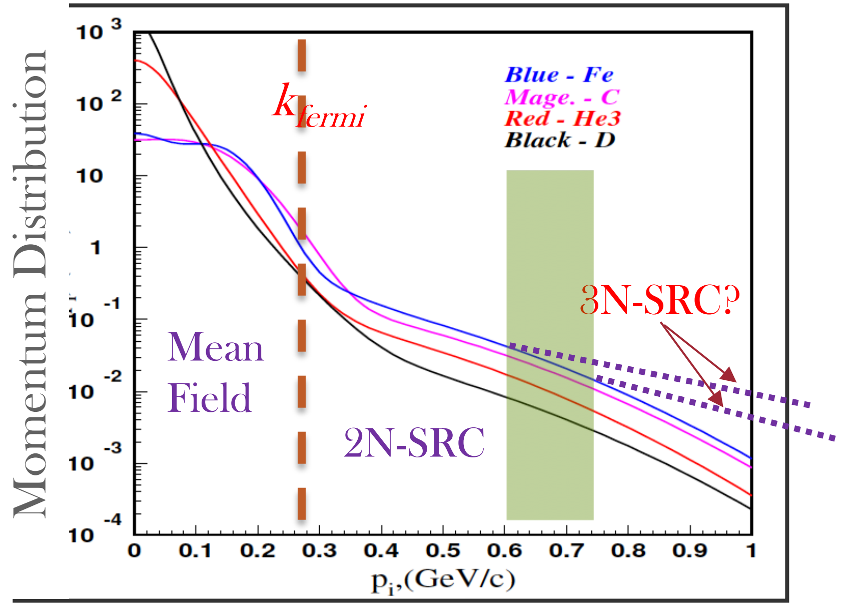
- QE cross sections are linked to momentum distributions by y-Scaling:

2N-SRC $(1.3<x<2)$

$$a_2(A,D) = \frac{2}{A}\frac{\sigma_A(x,Q^2)}{\sigma_D(x,Q^2)},$$

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

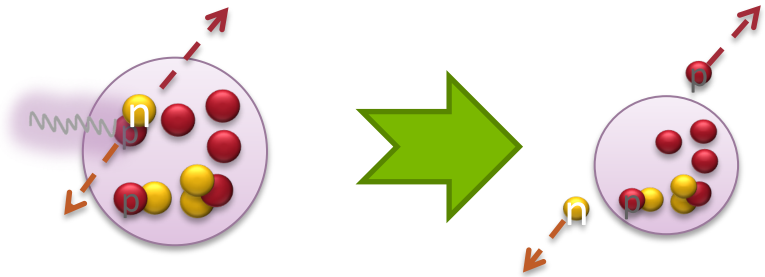
$$a_3(A,{}^3He) = K\cdot\frac{3\sigma_A}{A\sigma_{^3He}}$$



An open question: Where (in x, or in p) do 2N-SRCs lose dominance and give way to 3N-SRCs?

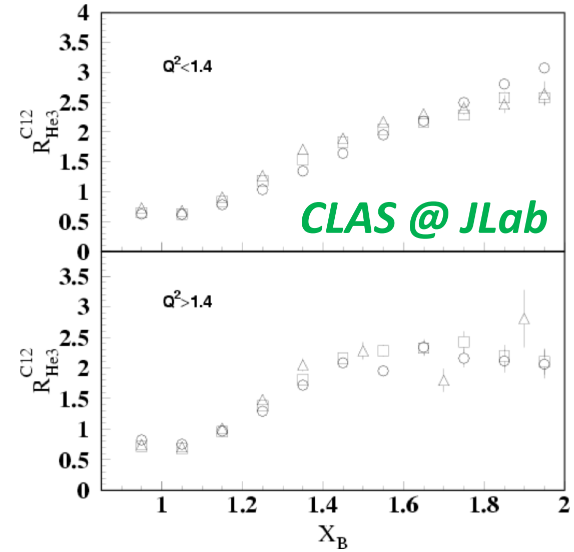
Measuring SRC

➢ **Previous Results (2N-SRC):**

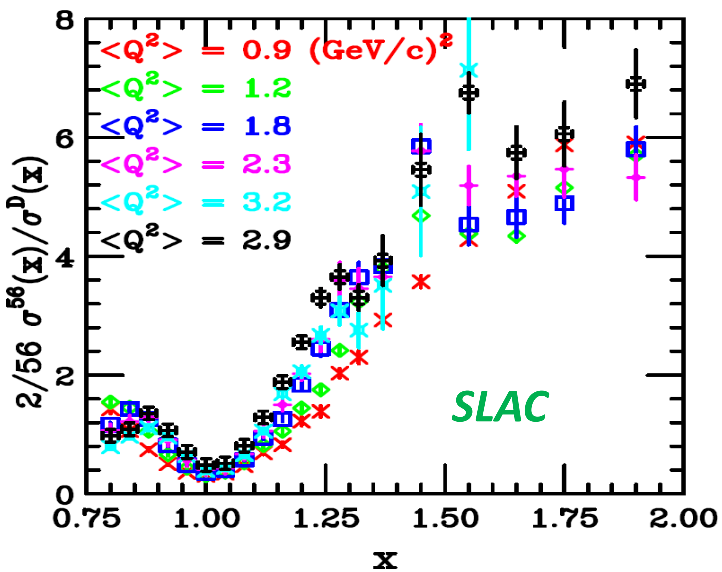


2N-SRC plateau for heavy nuclei to D2 or He3 have been observed by multiple experiments.

K. Egiyan et. al. PRC68, 014313 (2003)

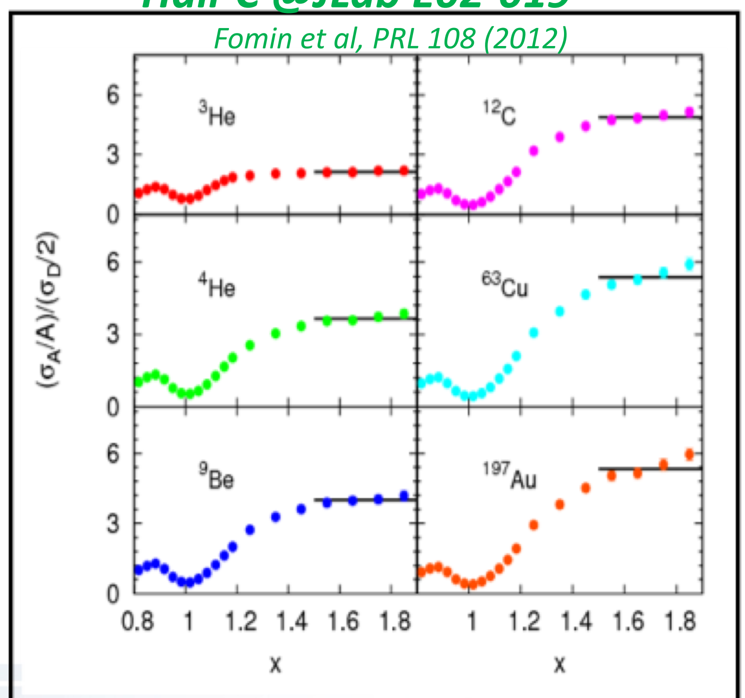


Frankfurt, Strikman, Day, Sargsian, PRC48, 2451 (1993)



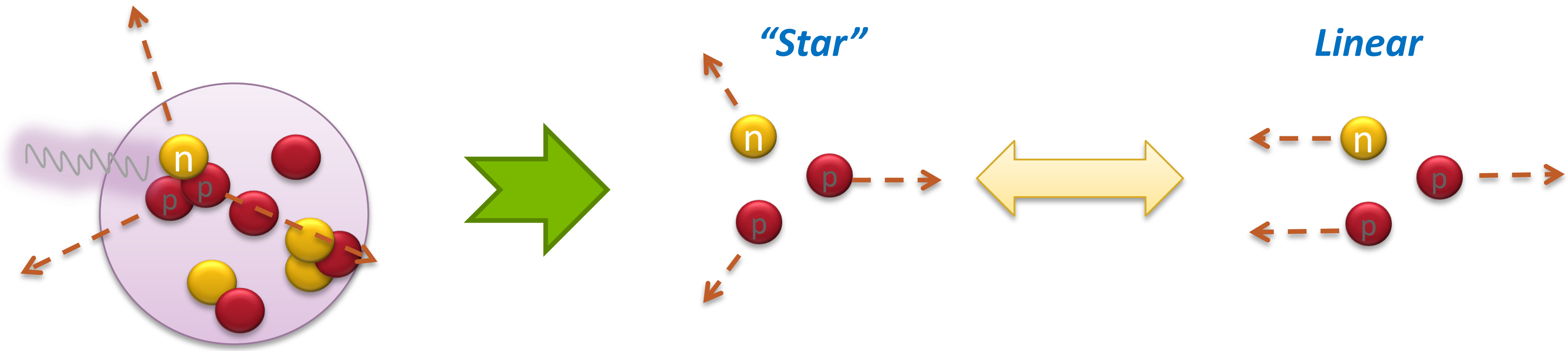
Hall-C @JLab E02-019

Fomin et al, PRL 108 (2012)



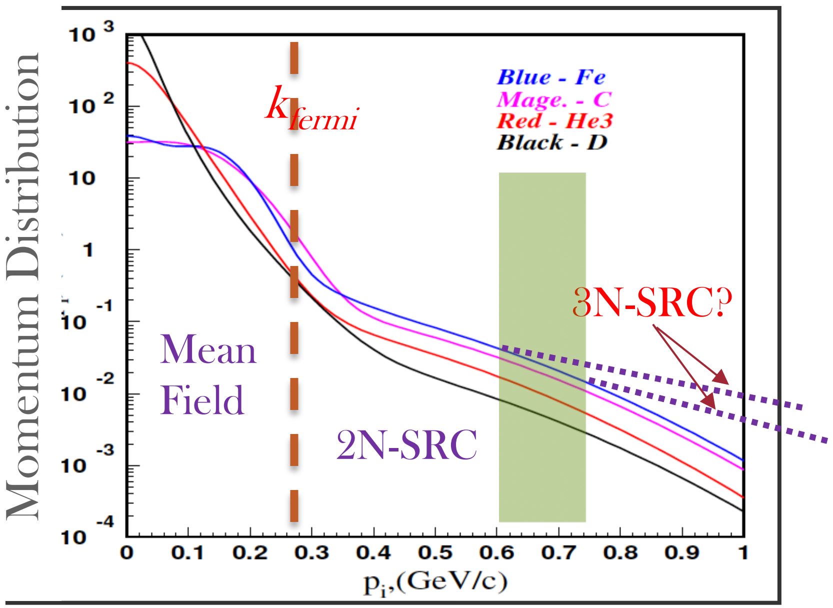
Measuring SRC

- **Previous Results (3N-SRC):**



Some questions related to 3N-SRC yet to be answered:

- A smooth transition from 2N-SRC to 3N-SRC?
- A scaling behavior, like 2N-SRC, for momentum distributions of different nuclei?
- A small central momentum of 3N-SRC cluster, like pairs in 2N-SRC?

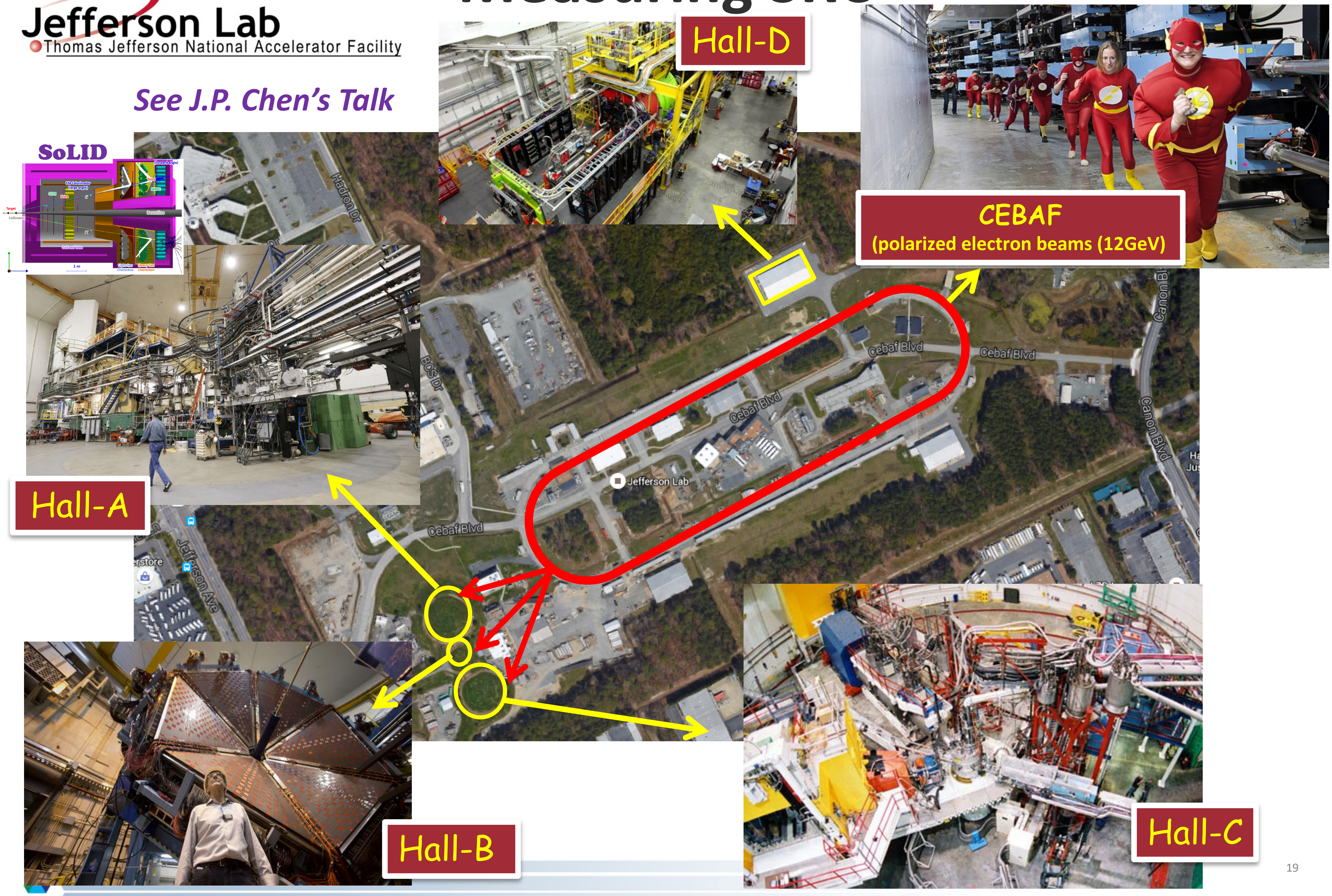


Need very high yield experiments to measure 3N-SRC; Only inclusive measurements at JLab so far!

Measuring SRC

Jefferson Lab
Thomas Jefferson National Accelerator Facility

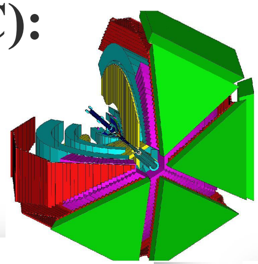
See J.P. Chen's Talk



Measuring SRC

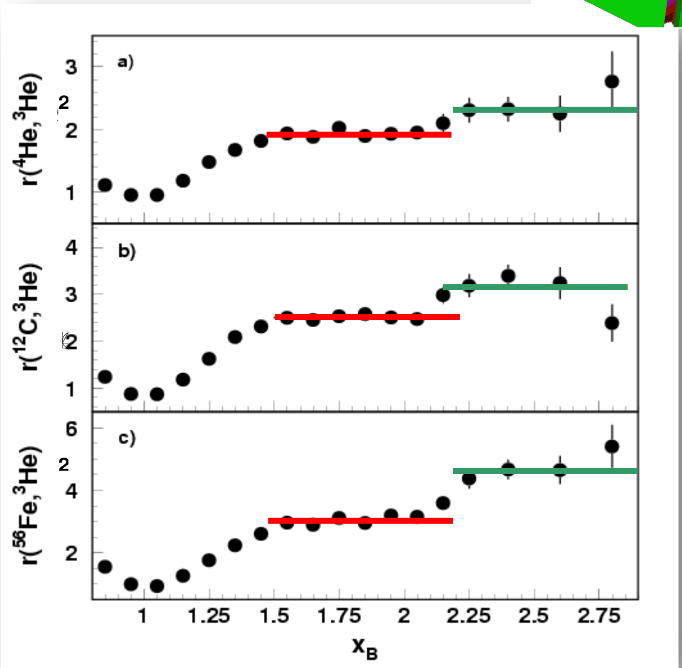
- **Previous Results (3N-SRC):**

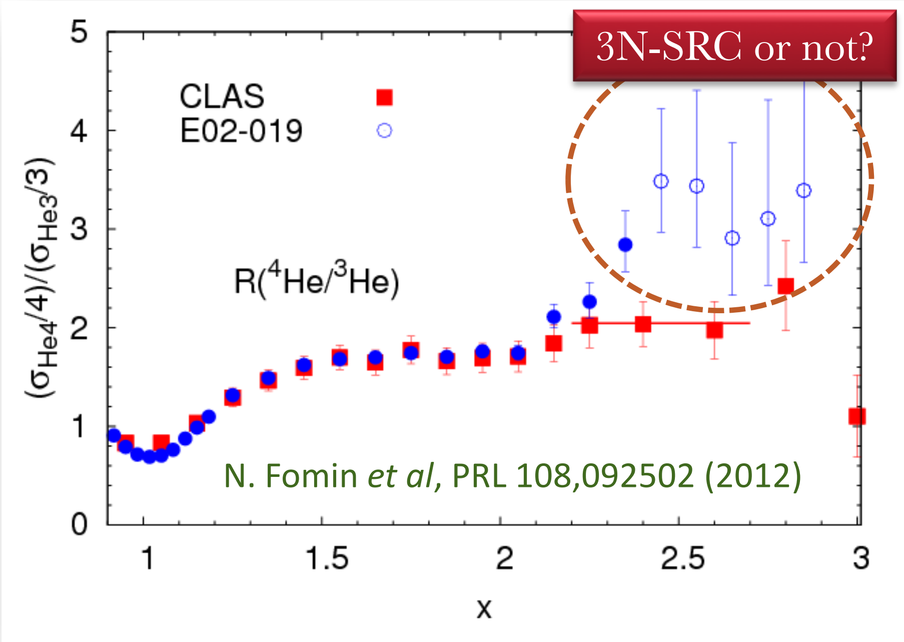
CLAS



Hall-C

K. Egiyan et al, PRL96, 082501 (2006)



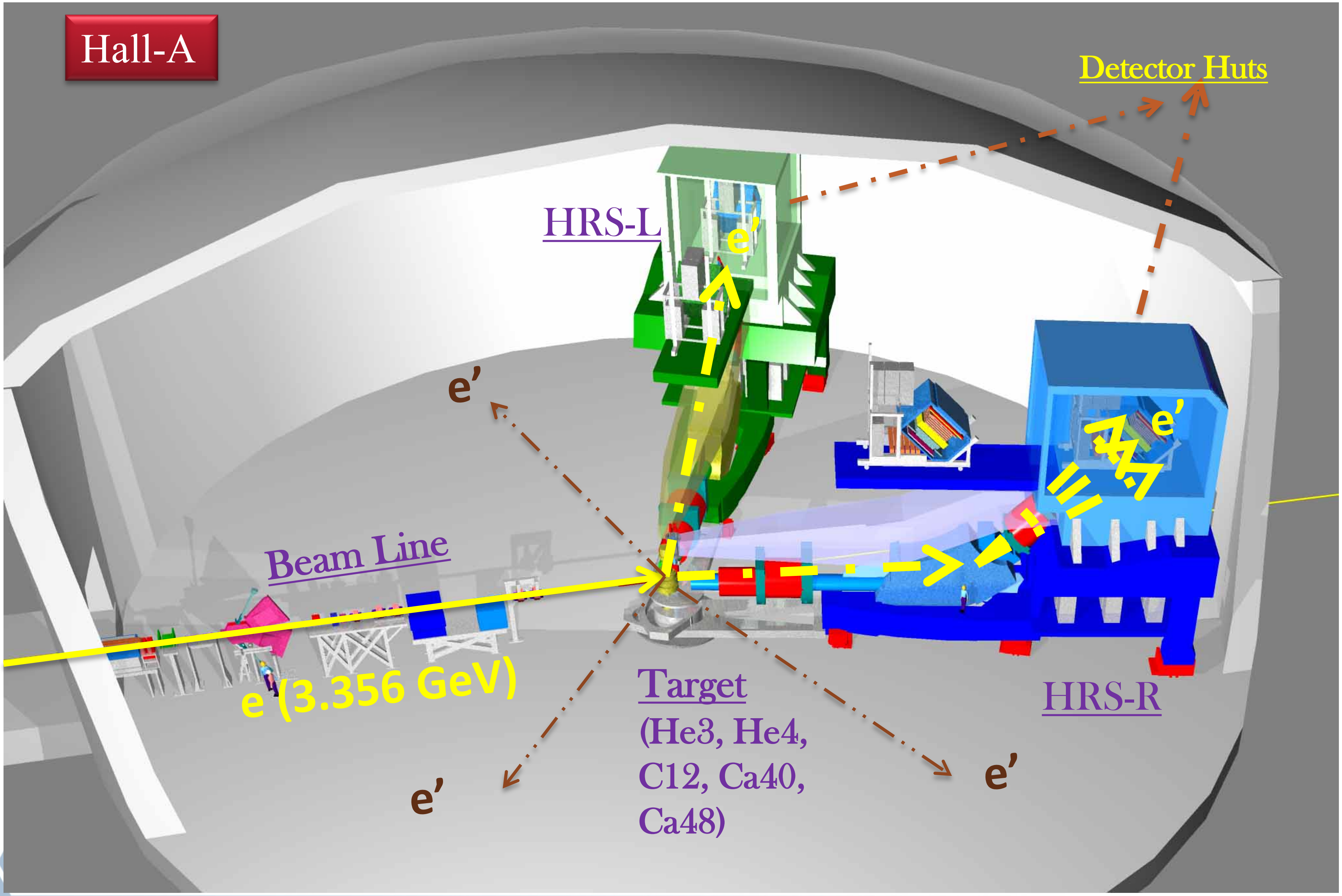


CLAS & Hall-C (E02-019) don't agree in the 3N-SRC region:

- CLAS shows 3N-SRC at x>2.2
- E02-019 doesn't have a clear plateau
- CLAS: *$Q^2 \approx 1.6$ GeV^2*, E02-019: *$Q^2 \approx 2.7$ GeV^2*
- Large error bars at 3N-SRCs for E02-019

Measuring SRC

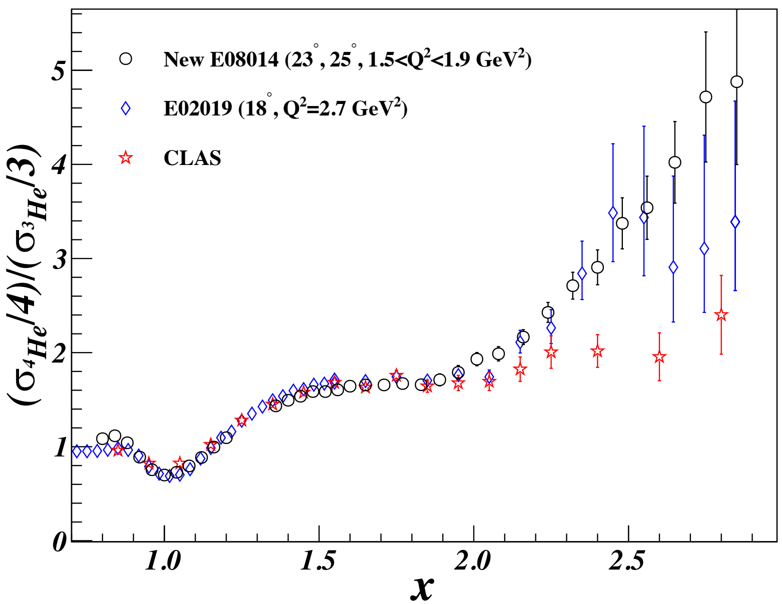
- E08-014 Experiment in Hall-A using HRS (2011)

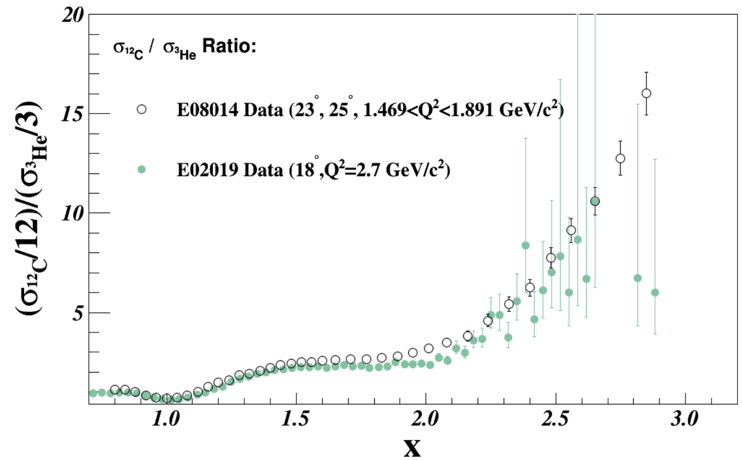


Measuring SRC

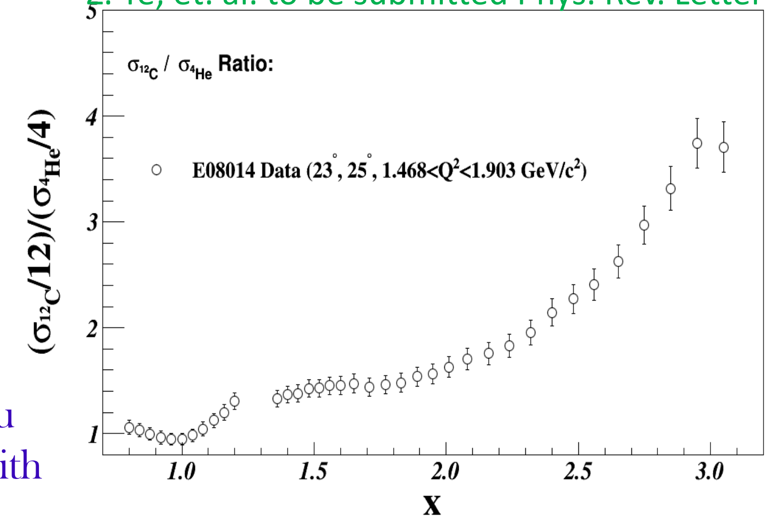
- **E08014 Results:** $R(x_i) = \left(\frac{\sigma_{A_1}(x_i)}{A_1}\right) / \left(\frac{\sigma_{A_2}(x_i)}{A_2}\right)$

Z. Ye, et. al. arXiv1712.07009, appear on Phys. Rev. Letter soon





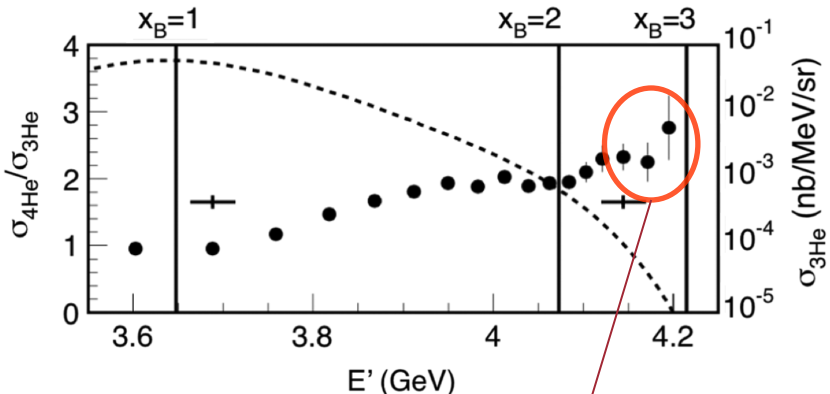
Z. Ye, et. al. to be submitted Phys. Rev. Letter soon

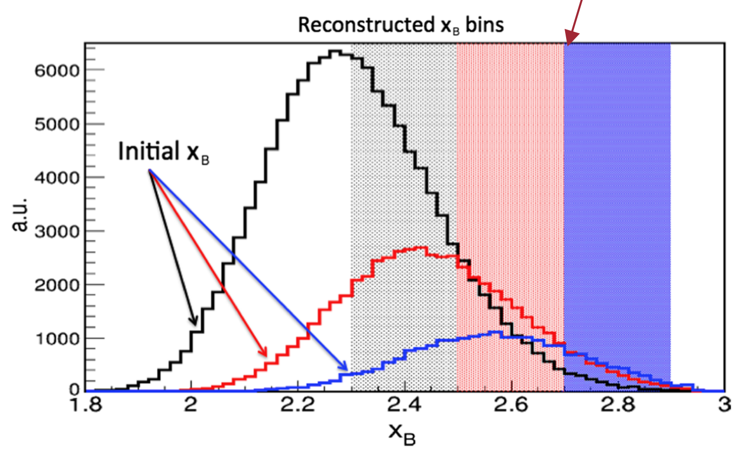


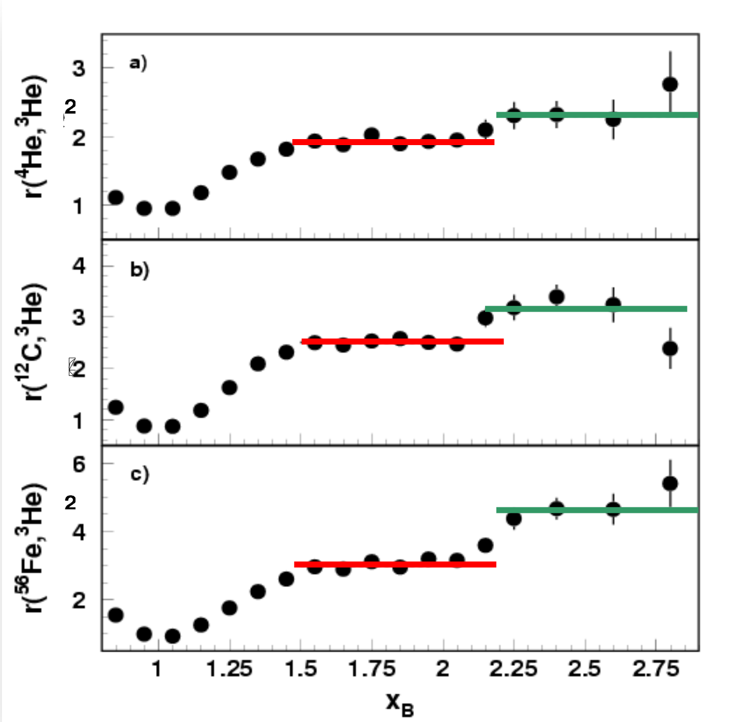
- ✓ Consistent results in 2N-SRC region
- ✓ Fast rise-up at x>2, and no indication of 3N-SRC plateau
- ✓ Agree with E02-019 data (within errors), and disagree with CLAS results

Measuring SRC

- **3N-SRC or not?**
  - About CLAS's 3N-SRC plateau (PRL 114,169201 2015):







K. Egiyan et al, PRL96, 082501 (2006)

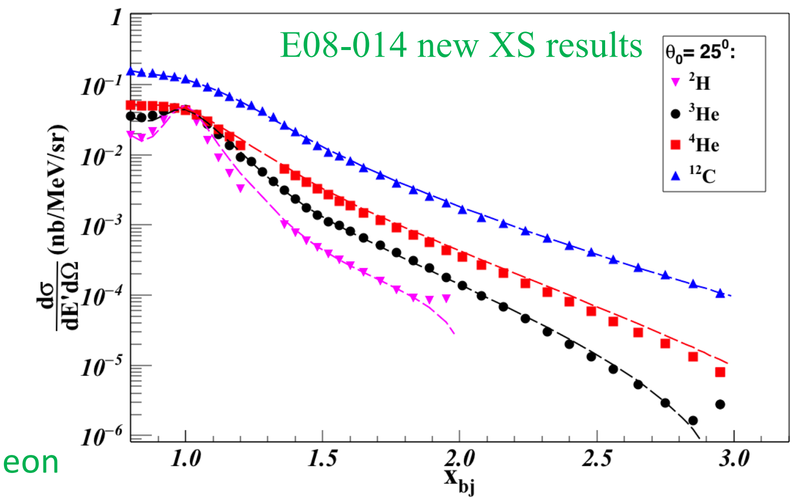
The 3N-SRC "plateau" is due to the large bin migration because the CLAS's poor momentum resolution.

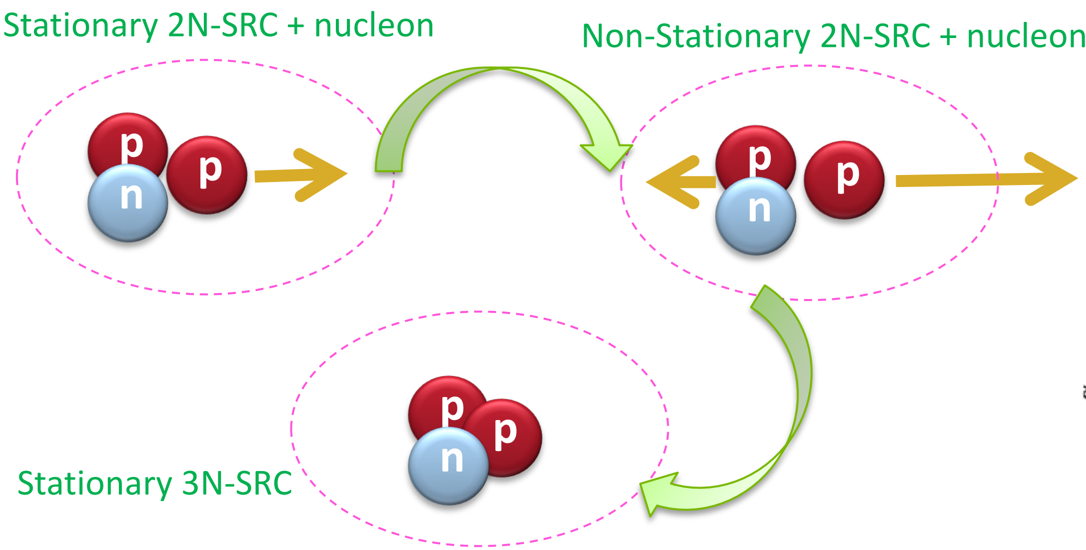
Measuring SRC

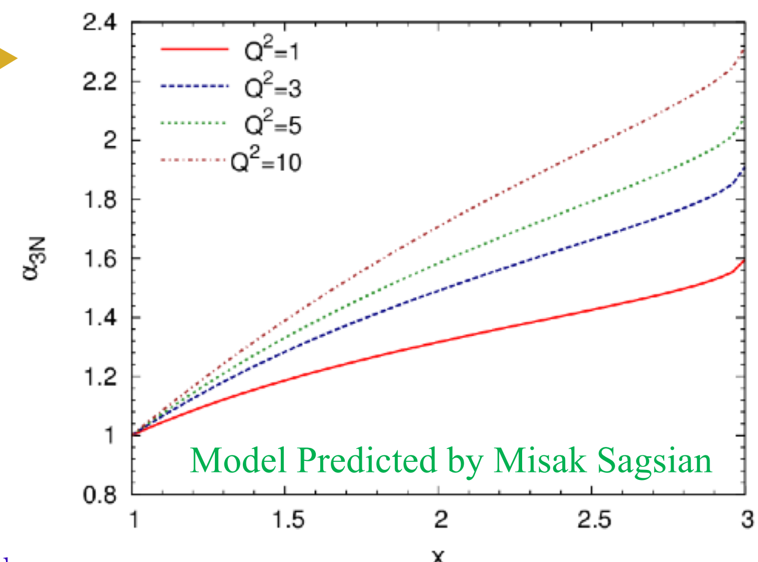
➢ **3N-SRC or not?**

✓ ^{3}He cross sections fall more rapidly than heavier nuclei when x→3 (until hit the elastic peak)

✓ ^{4}He cross sections fall more slowly but still don't scale with ^{12}C cross sections







✓ Scaling of 2N-SRC (3N-SRC) assume a stationary configuration like ^{2}H (^{3}He)

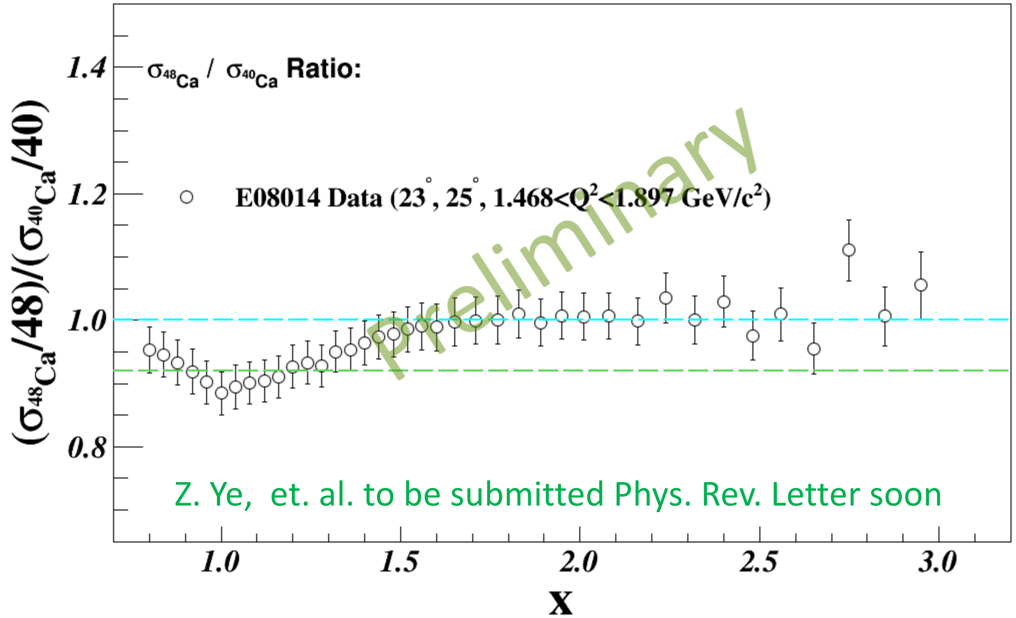
✓ 2N-SRC & 3N-SRC in heavy nuclei may be not stationary

✓ May need larger Q^2 values to isolate 3N-SRC

Measuring SRC

➢ **Isospin Dependence of SRC from Inclusive Scattering:**

^{48}Ca to ^{40}Ca Cross Section Ratio from E08-014



$$R(x_i) = \left(\frac{\sigma_{A_1}(x_i)}{A_1}\right) \Big/ \left(\frac{\sigma_{A_2}(x_i)}{A_2}\right)$$

Preliminary→ More precise absolute thickness of Ca40 needed

- Naïve prediction: R= 0.92 if isospin-independent, or R ≈ 1 if n-p pairs dominated.
- Consistent with a recent theoretical calculation ($R \approx 1$)

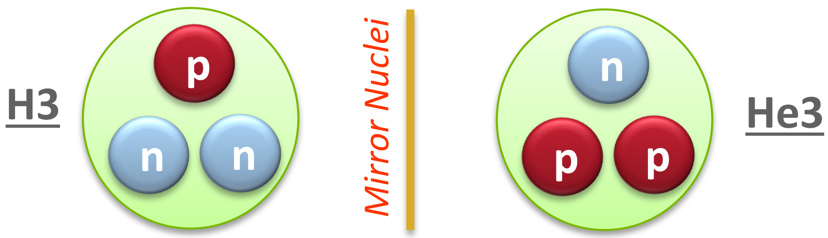
(M. Vanhalst, et. al., PRC 84, 031302 (2011), PRC 86, 044619 (2012)

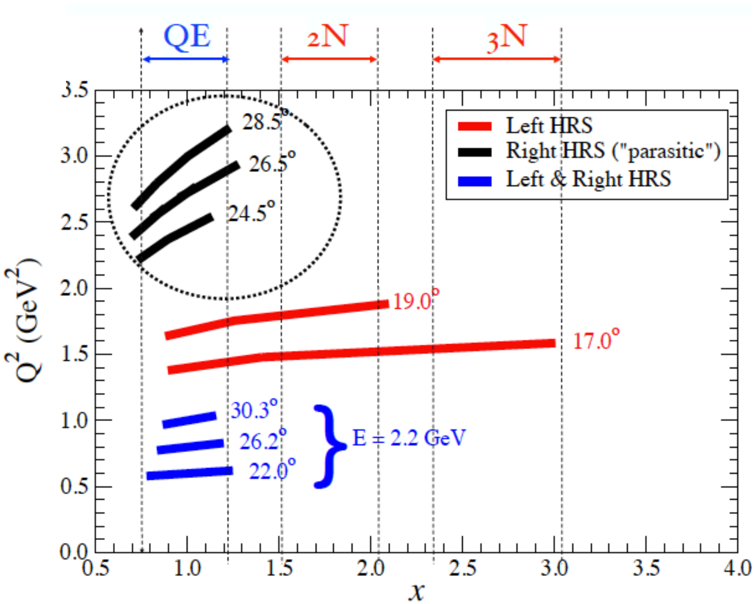
- ***New experiment → E12-11-112 using H3/He3: 40% difference***

Measuring SRC

➤ **Tritium Experiments:** E12-11-112: using inclusive electron quasi-elastic scattering on H3/He3

Spokespeople: John Arrington, Donal Day
Doug Higinbotham, Zhihong Ye
Thesis Students: Shujie Li, and Nathaly
(University of New Hampshire)





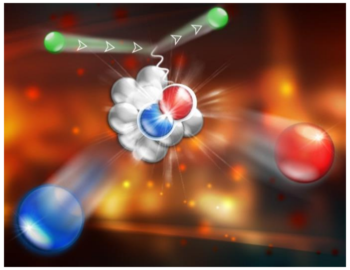
- ✓ Isospin dependence:
  - ✓ Better precision: extract ratio $R(T=1/T=0)$
  - ✓ Much smaller FSI (inclusive)
  - ✓ Larger difference (40%) between two assumptions

if np dominance: $R \approx 1$ if isospin independent: $R = \frac{\sigma_{He3}/3}{\sigma_{H3}/3} = \frac{(2\sigma_p+\sigma_n)/3}{(\sigma_p+2\sigma_n)/3} \xrightarrow{\sigma_p\approx 3\sigma_n} 1.4$

- ✓ Determine isospin dependence for A>3 nuclear corrections
- ✓ Absolute cross sections and ratios; Test *ab initio* calculations

Took first part (QE) of the data in December 2017; Will take rest of data in Fall 2018.

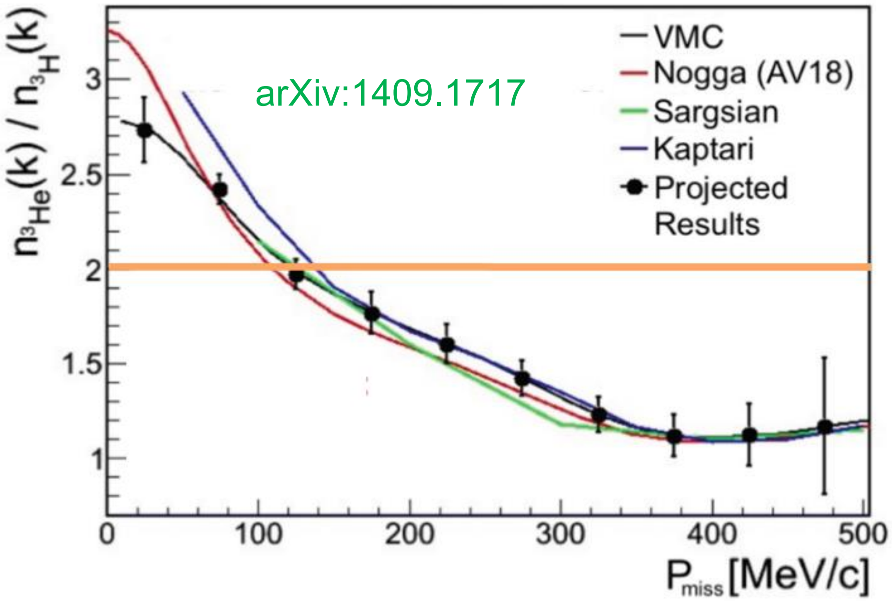
Measuring SRC



- **Tritium Experiments:**

E12-14-011: Exclusive SRC

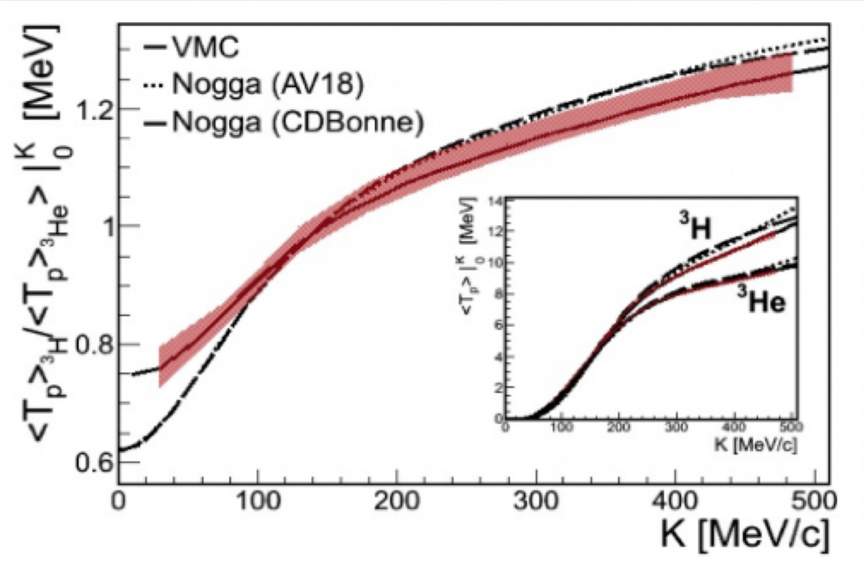
Spokespeople: L. Weinstein, O.Hen,
W. Boeglin, S. Gilad



- He3/H3 ratio for proton knockout

→ n/p ratio in 3H (No neutron detection Required)

- np-dominance at high-Pm implies n/p ratio →1
- n/p at low Pm enhanced



- Map out difference between proton and neutron distribution up to (and slightly beyond) Fermi momentum

- Start data-taking in few days (April 2018)!

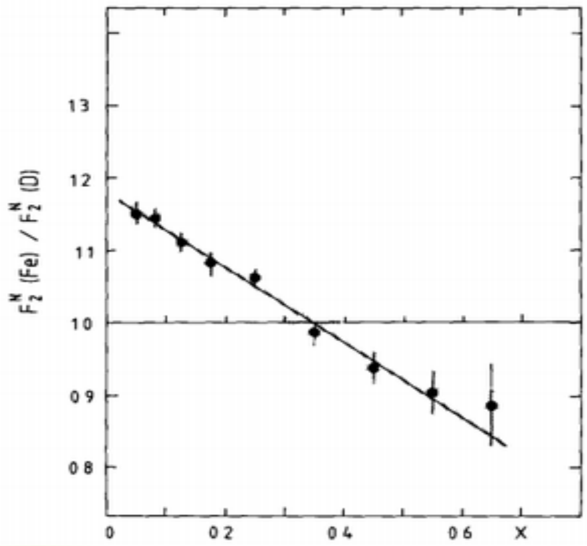
Measuring SRC

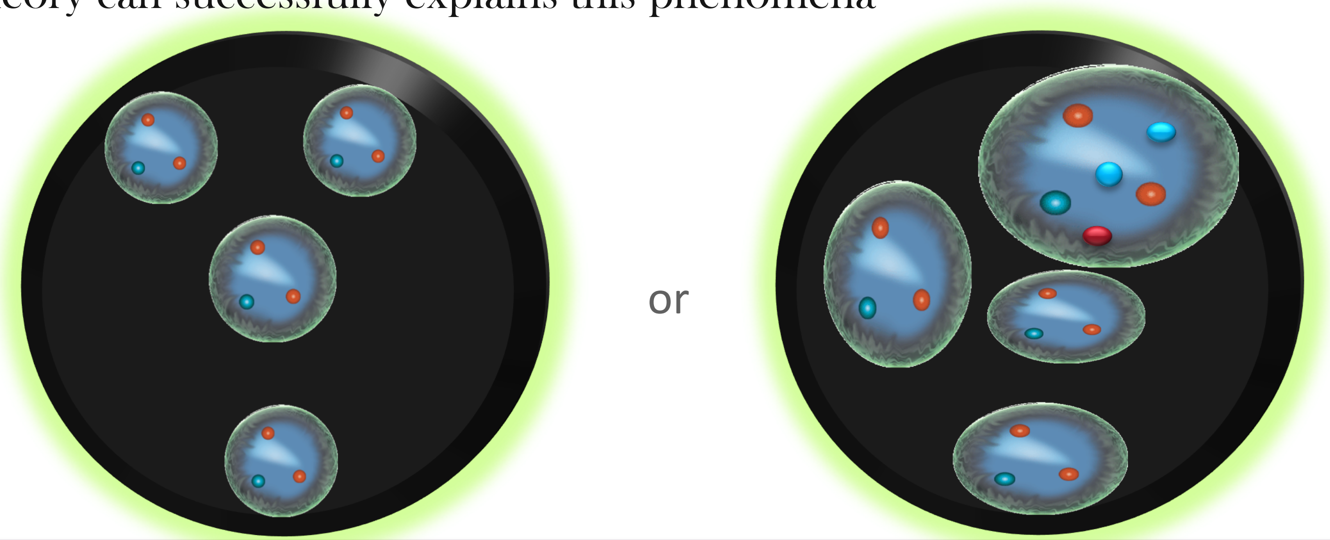
➢ **Tritium Experiments:**

The Tritium Experiments in Hall-A at Jefferson Lab (Dec. 2017- Dec. 2018)

SRC vs EMC

- **What is EMC Effect?**
  - <u>EMC Effect:</u> is the surprising observation by European Muon Collaboration (EMC) that: The DIS cross section ratios (or F2 ratio) of heavy nuclei to Deuteron show a linear slope in the range of 0.3<x<0.7.
  - It indicates that the quark density functions in a free nucleon is different from one in heavy nuclei (strong A-dependence)
  - No theory can successfully explains this phenomena

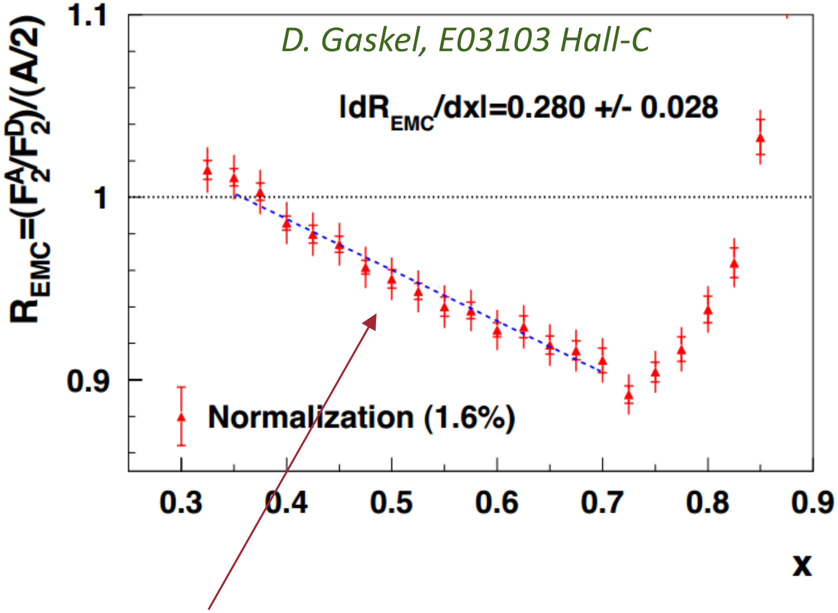




Is there a Medium Modification Effect? Does a nucleon change its shape when it is placed in different nuclei?

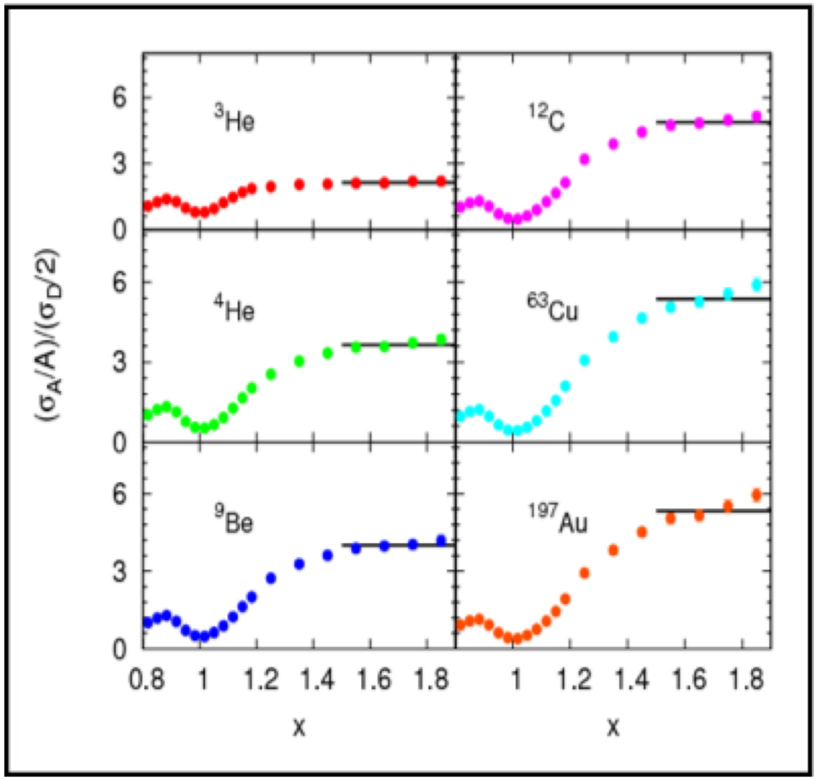
SRC vs EMC

➢ **Connection?**



"slope" in EMC:
→ how difference a nucleon in a nucleus compared with one in the Deuterium.

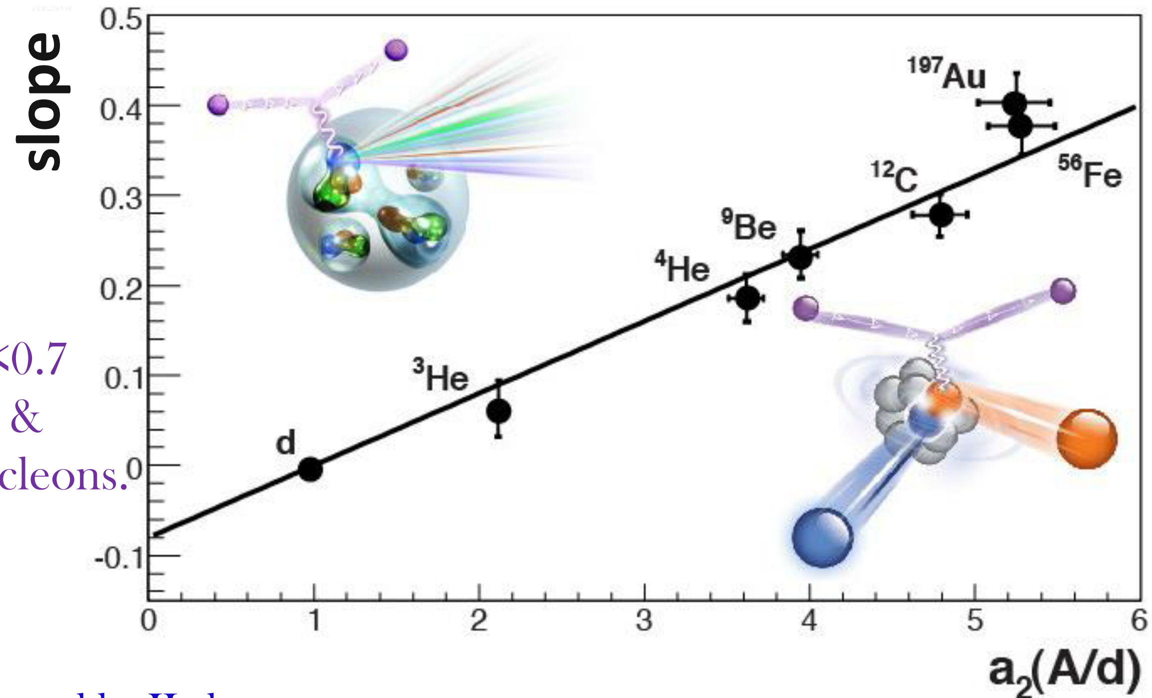
<u>a_2 in SRC:</u>
→ Probability of two nucleons to be correlated.



Fomin et al, PRL 108 (2012) Jlab E02-019

SRC vs EMC

➤ **Linear correlation!** **D.O.F: Nucleus → Nucleon →Quarks & Gluons ?**



EMC: 0.3<xbj<0.7
→ How quarks & gluons form nucleons.

SRC: xbj > 1.3
→ How nucleons form nuclei.

Data contributed by JLab:

- Egiyan, *et al.* (2006 PRL, Hall B)
- J. Seely, *et al.* (2009, Hall C)
- N. Fomin, *et al.* (2012, Hall C)

And SLAC data

L. Weinstein et al, PRL 106, 052301 (2011)
J. Arrington et al., PRC 86, 065204 (2012)
O. Hen et al, PRC 85, 047301 (2012)

Understanding how EMC connects to SRCs will be one of the major studies in 12 GeV.

Future Opportunities

➢ **More New SRC & EMC Experiments at 12GeV@JLab:**

❑ **Hall-A: (MARATHON experiment using Tritium)**

- E12-10-103: Measurement of the F2n/F2p, d/u Ratios and A=3 EMC effect in Deep Inelastic Scattering off the Tritium and Helium Mirror Nuclei.
- **Finished data takin in early April 2018!**

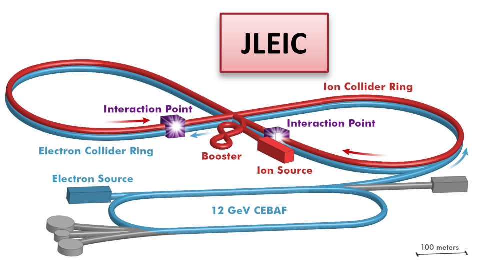
❑ **Hall-C:**

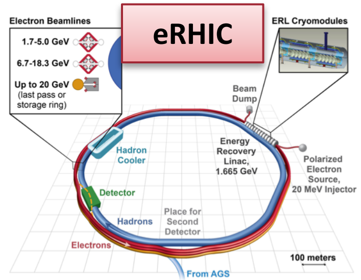
- E12-06-105: Inclusive Scattering for Nuclei at x>1 in the Quasielastic and deeply inelastic regimes.
- E12-10-008: Detailed studies of the nuclear dependence of F2 in light nuclei.
- E12-11-107: In Medium Nucleon Structure Functions, SRC, and the EMC Effect.
- E12-10-003; E12-06-107. etc…

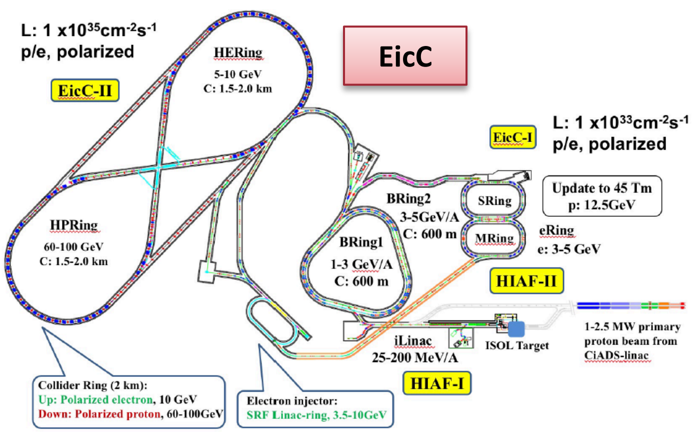
Future Opportunities

- **More New SRC & EMC Experiments at 12GeV@JLab:**
  - **Hall-A: (MARATHON experiment using Tritium)**
    - E12-10-103: Measurement of the F2n/F2p, d/u Ratios and A=3 EMC effect in Deep Inelastic Scattering off the Tritium and Helium Mirror Nuclei.
    - **Finished data takin in early April 2018!**
  - **Hall-C:**
    - E12-06-105: Inclusive Scattering for Nuclei at x>1 in the Quasielastic and deeply inelastic regimes.
    - E12-10-008: Detailed studies of the nuclear dependence of F2 in light nuclei.
    - E12-11-107: In Medium Nucleon Structure Functions, SRC, and the EMC Effect.
    - E12-10-003; E12-06-107. etc…

- **EIC(C) will also provide a powerful tool:**







- ✓ Open up new channels to study the Nucleon-Nucleon force at the Quark level, such as SIDIS.
- ✓ Will reach much higher Q2 (to isolate 3N-SRC)
- ✓ Direct exclusive measurement of high momentum nucleons from 3N-SRC breakup
- ✖ However, Full detector coverage and high luminosity needed! Rate could be an issue

Summary

- Mean-Field Theory only explains 80% of the nucleon strength in a nucleus; 20% are from strong N-N interaction at short-distance.
- SRCs are important to understand high momentum components of the nucleon momentum distribution
- Study the property of high density matter from the 2N–SRC and 3N-SRC clusters
- Experimental study with electron-scattering learns a lot on 2N-SRC but little on 3N-SRC.
- The Connection to the EMC effect provides a new way to learn the NN interaction at the quark-gluon level
- Many new experiments at 12GeV JLab, and EIC;
- Possible opportunities using high energy proton beam to perform quasi-elastic scattering on nuclei

Backup Slides

Measuring SRC

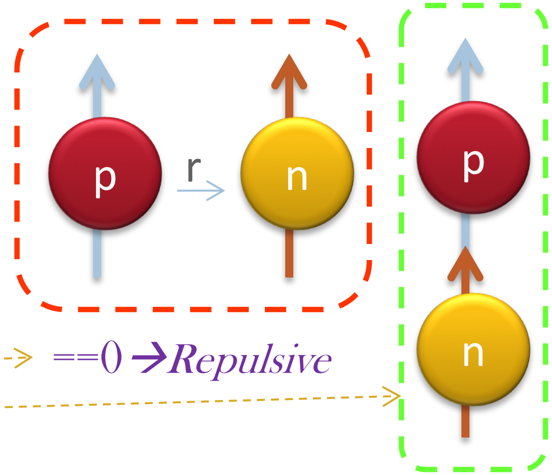
➢ Isospin Dependence:

- Nucleons interact thought exchanging one pion:

  Parity = 1 → lowest state, L= 0, S = 1/2 +1/2 =1.

- The force at <*1 fm* is from the tensor component:

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



==0 →*Repulsive*

= -3 $\sigma_1\sigma_2$ →*Attractive*

= $\sigma_1\sigma_2 > 0$ →*Always repulsive*

- Proton and Neutron carry different isospin (T):

  Proton → T= 1/2, Neutron→ T= -1/2

  Isospin Singlet: T = 0, n-p pairs → *Stable!*

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

So the nature of the attractive tensor force favor the n-p pairs!

Future Opportunities

➢ Using pA scattering to study Nucleon-Nucleon Interaction

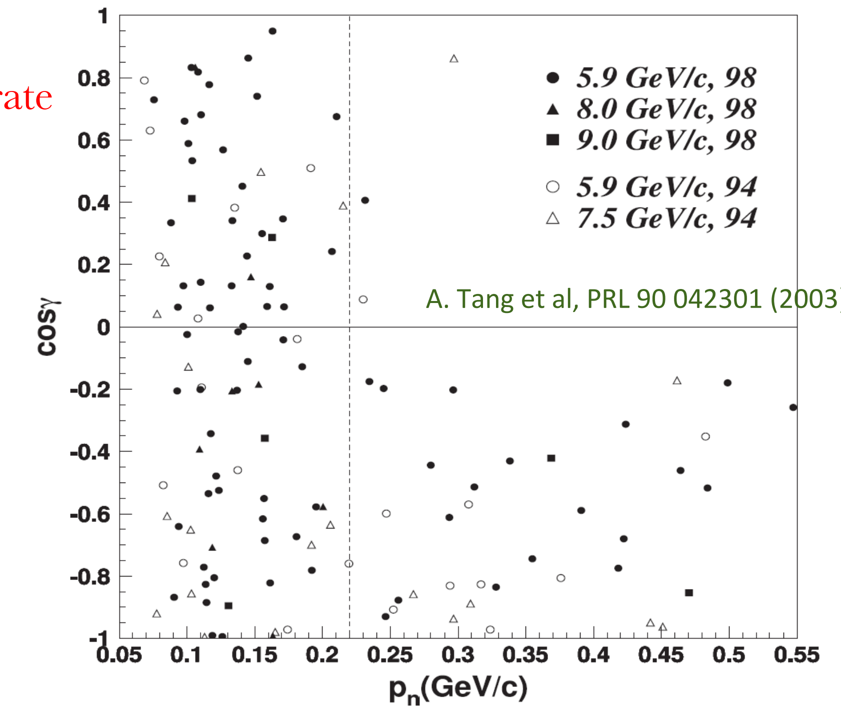
- The pA data firstly showed the direct back-to-back np scattering after breaking up 2N-SRC
- However, at low CM energy (0.15 GeV/c), the count rate was very low (one count per week, 18 counts in total)

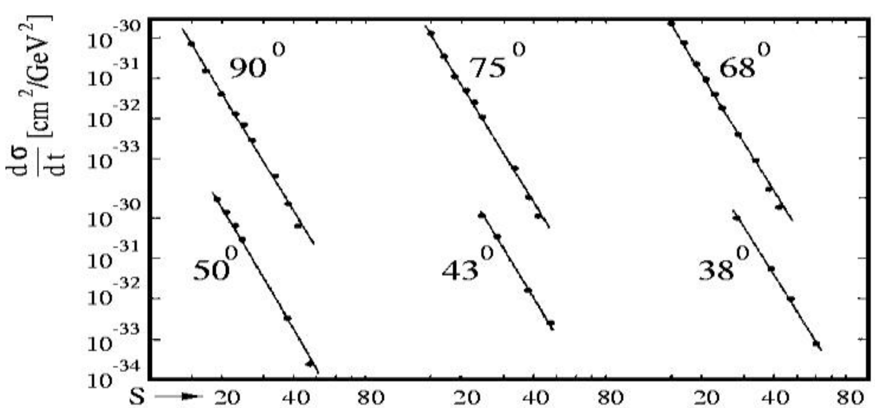
- Beam protons have Small deBroglie wavelength:

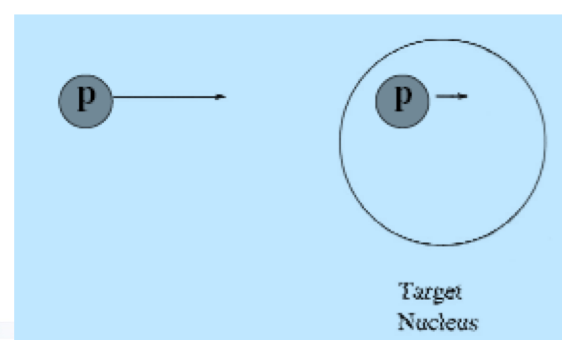
$$\lambda = \frac{hc}{pc} = 2\pi \times 0.197\ GeV \cdot \frac{fm}{5GeV} \sim 0.2 fm$$

Hence, large momentum transfer is possible with wide angle scattering Cross section is large

A(p, p'pN)A-2 reaction at EVA/BNL







- QE pp scattering have a very strong preference for reacting with forward high momentum protons
- With 5 GeV/c proton, the Cross-Section becomes larger.