# Study of Short-Range Correlations using Inclusive Electron Scattering

**Zhihong Ye**
**Argonne National Lab**

**Jefferson Lab User Group Meeting, 06/21~06/23, 2016**

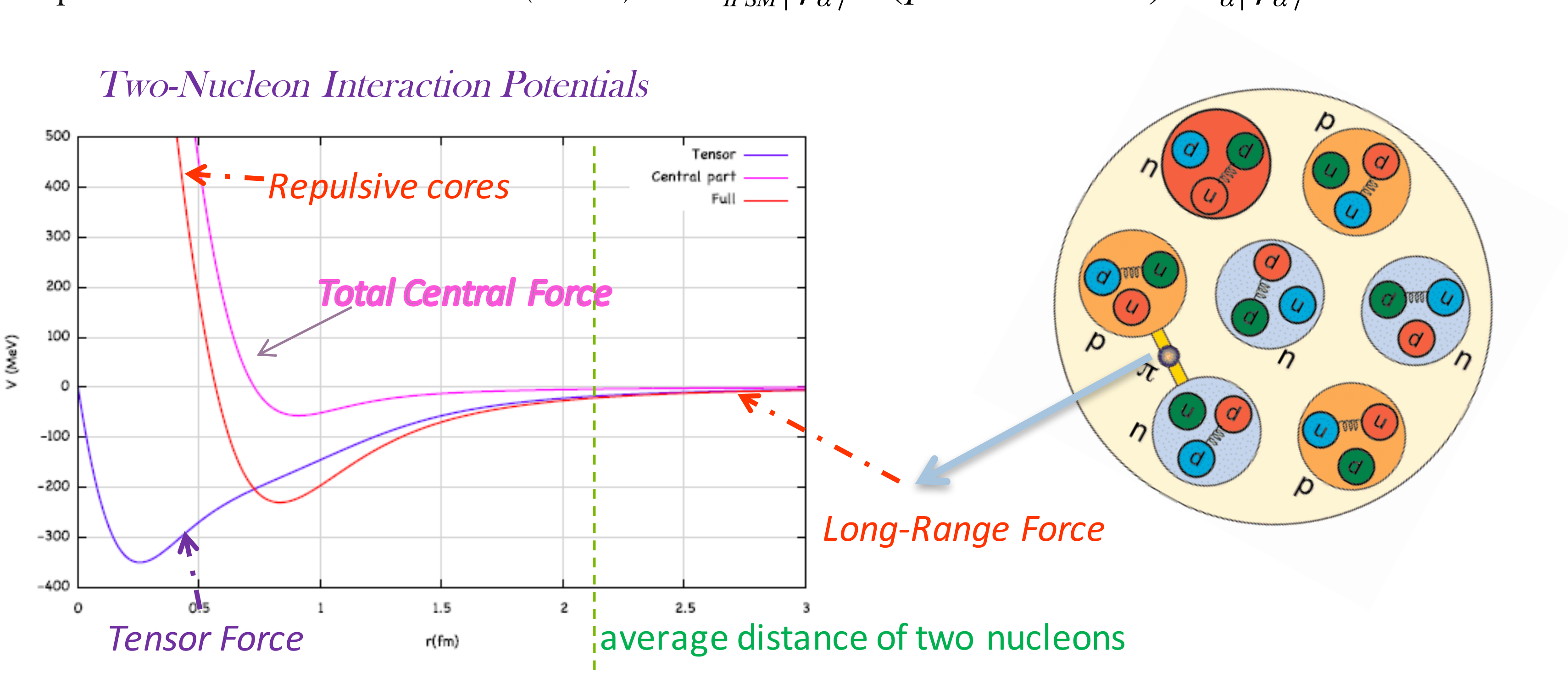
# Short-Range Correlations

➢ **Realistic Nucleon-Nucleon Interactions:**

No NN interaction Terms!

- Independent Particle Shell Model (IPSM): $h_{IPSM}|\varphi_\alpha\rangle \approx (p^2/2m + \bar{V} + \ldots) = \varepsilon_\alpha|\varphi_\alpha\rangle$

*Two-Nucleon Interaction Potentials*

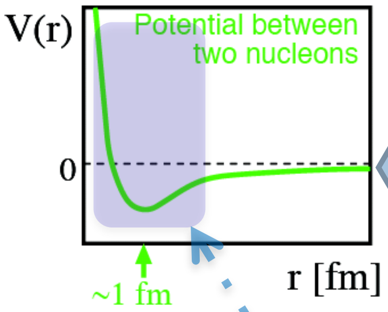



- ab initio calculations: many-body system + special potential: $H = \sum_i T(i) + \sum_{i<j} V^{(2)}(i,j) + \sum_{i<j<k} V^{(3)}(i,j,k) + \ldots,$

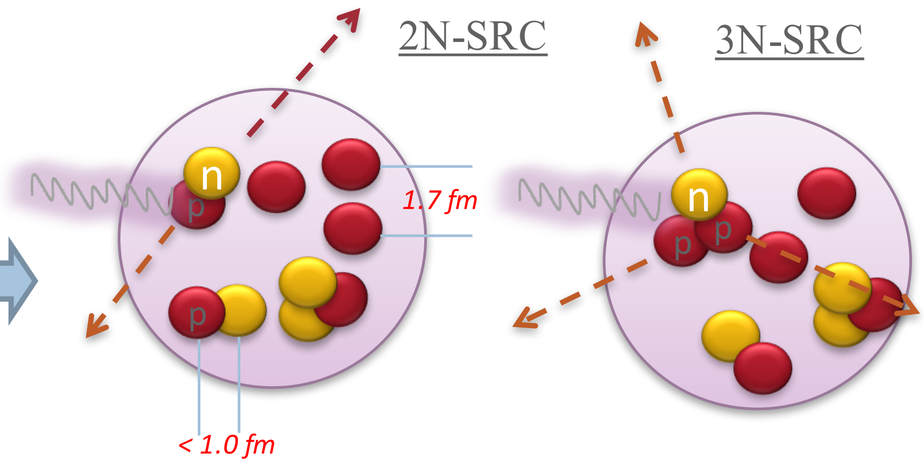
solved nucleus wave-functions for A<=12; beyond that, need approximation + experiments

# Short-Range Correlations

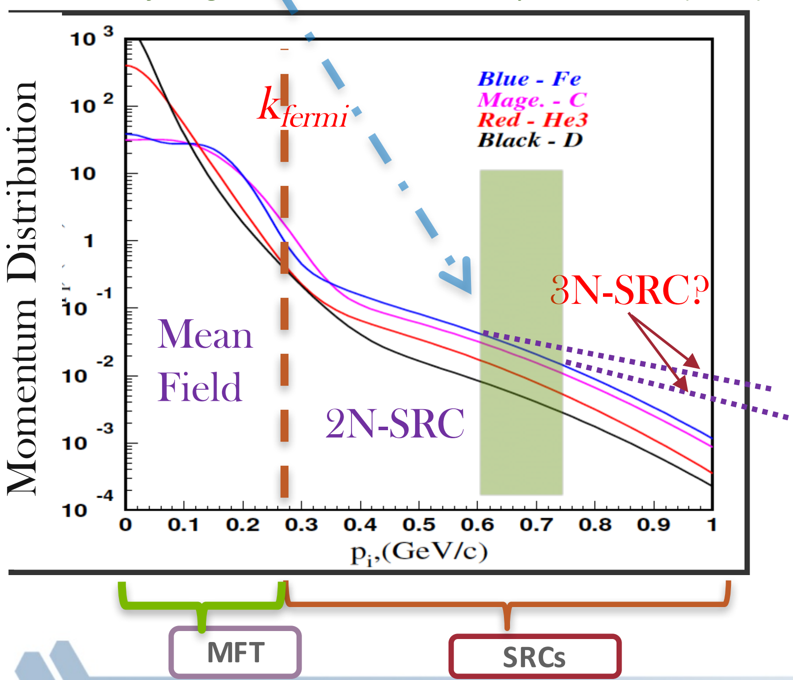
- **Main Features of SRCs:**




A dynamic balance between repulsive and attractive forces




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




- Involve 2-nucleons (2N-SRC), 3-nucleons (3N-SRC) …
- 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 for 2N-SRC
  *similar behavior for 3N-SRC?*
- Extremely high density configurations:
  connect to EMC effect, quark degrees of freedom, etc.

# Quasi-Elastic (e, e')

## ➤ Inclusive QE Electron-Nucleus Scattering:

- At Quasielastic (QE) Region, the Inclusive Cross Section has y-Scaling behavior :

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

$\bar{\sigma}(Q^2, x) \propto$ sum of free protons and neutrons

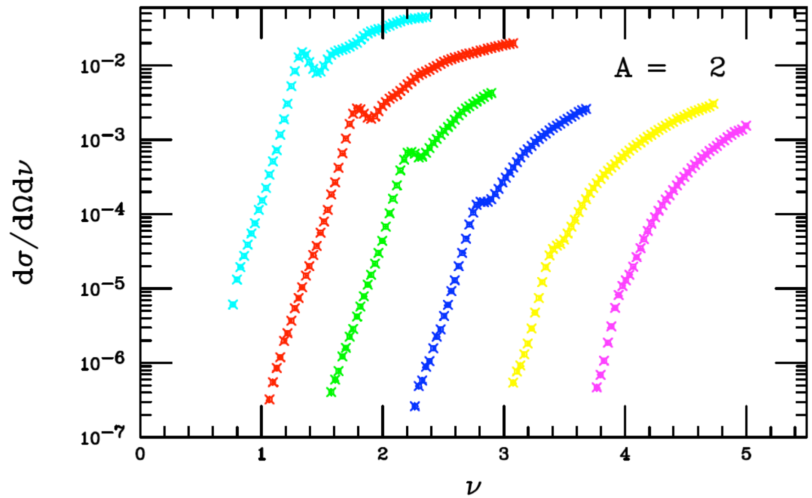
y→ the minimum accessible nucleon momentum

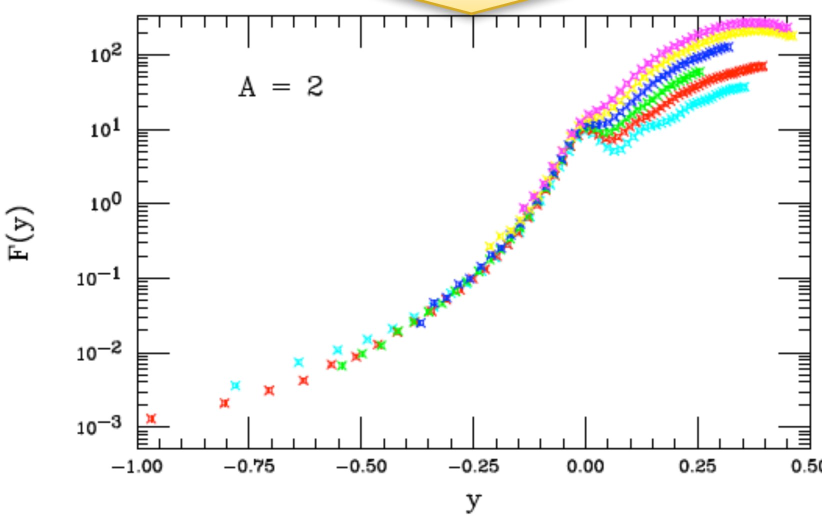
F(y)→ very small dependence on $Q^2$.

- F(y) is linked to Momentum Distribution of a nu inside a nucleus:

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

[N. Fomin et al., Phys. Rev. Lett. 108, 092502 (2012).



# Quasi-Elastic (e, e')

- **How to cleanly probe SRC:**

  - Isolate QES:

    → above the broad QE peak (x>1.3 )

  - Suppress FSI and MEC:

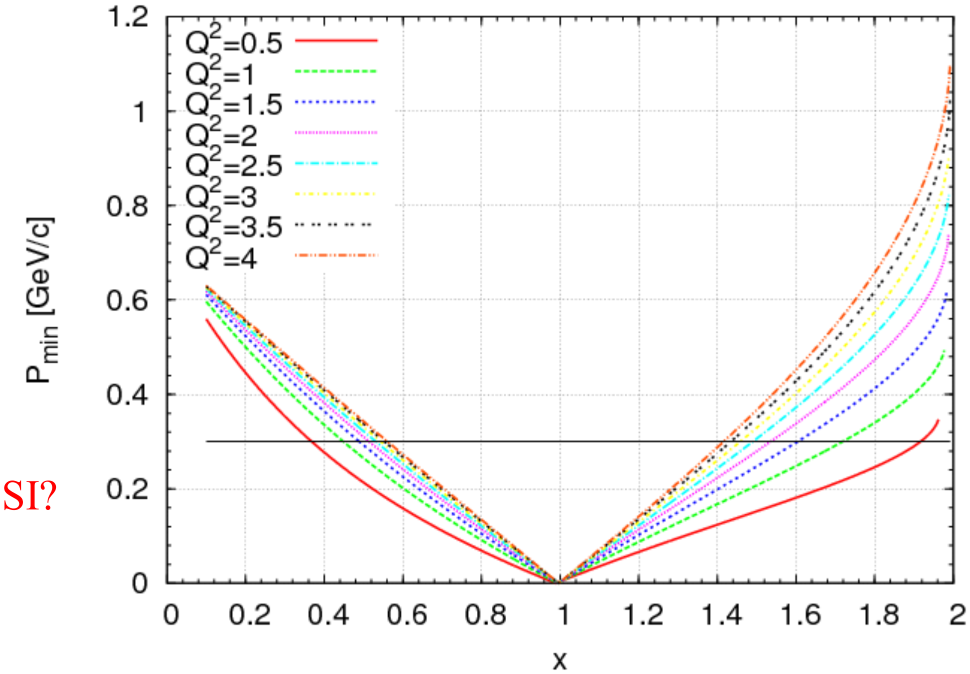
    → $Q^2>1\ GeV^2$

  or need to be higher for fully suppress FSI?

  - Remove Mean Field contributions

    → only detect struck nucleon with large momentum ($k>k_{Fermi}$).

Assuming a stationary D2-like 2N-SRC




✓ Large momentum transfer ($q_0 >> V_{NN}$, $q >> m_N/c$) to instantly remove SRCs from intact nucleus;

✓ Sufficiently high $x_{bj}$ and $Q^2$ to detect nucleons with minimum momenta.

# Quasi-Elastic (e, e')

## ➢ Inclusive QE cross section in SRC:

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

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

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

- Decompose the QE cross section in a SRC picture:

One nucleon: (x~1) . Two nucleons: (1.3<x<2) Three nucleons: (x>2)

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

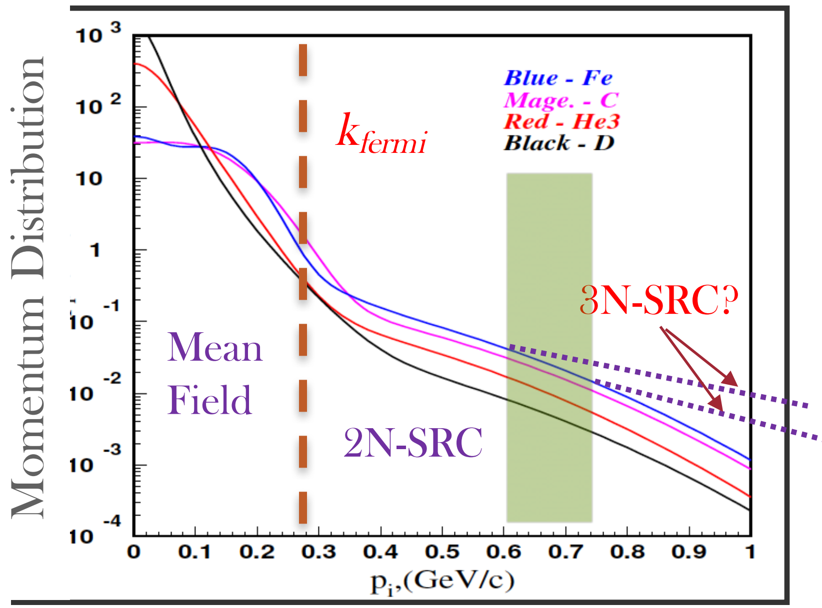
- QE cross sections are linked to momentum distributions by y-Scaling:

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)

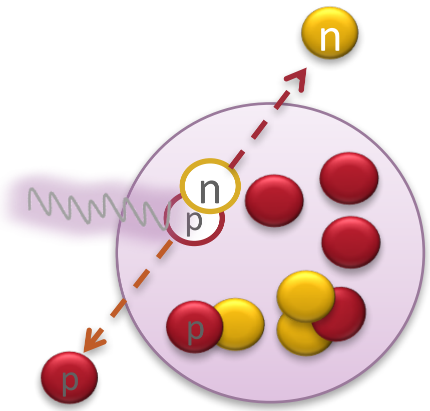
$$a_3(A,{}^3He) = K \cdot \frac{3\sigma_A}{A\sigma_{{}^3He}}$$




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

# 2N-SRC

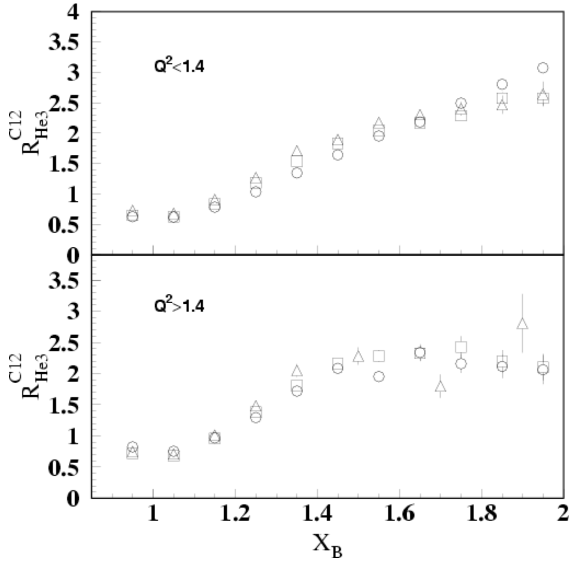
- Previous results from (e, e'):



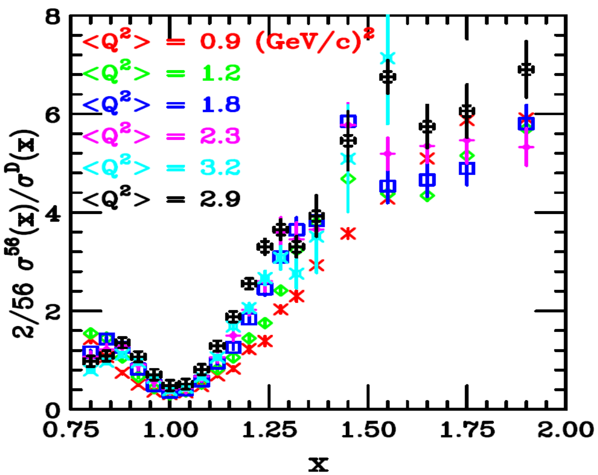

*2N-SRC (1.3<x<2)*

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

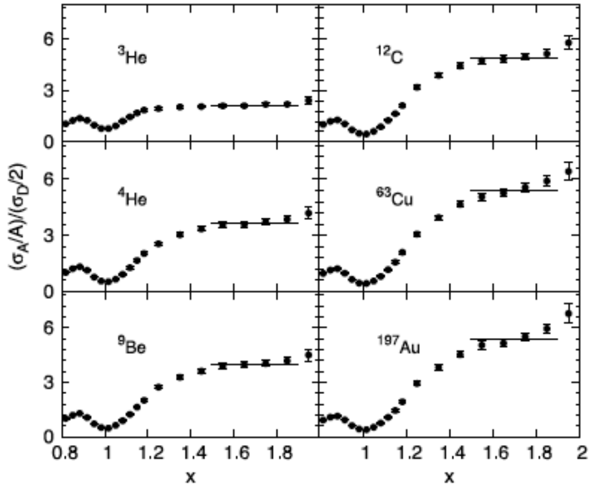
K. Egiyan et. al. PRC68, 014313 (2003)




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

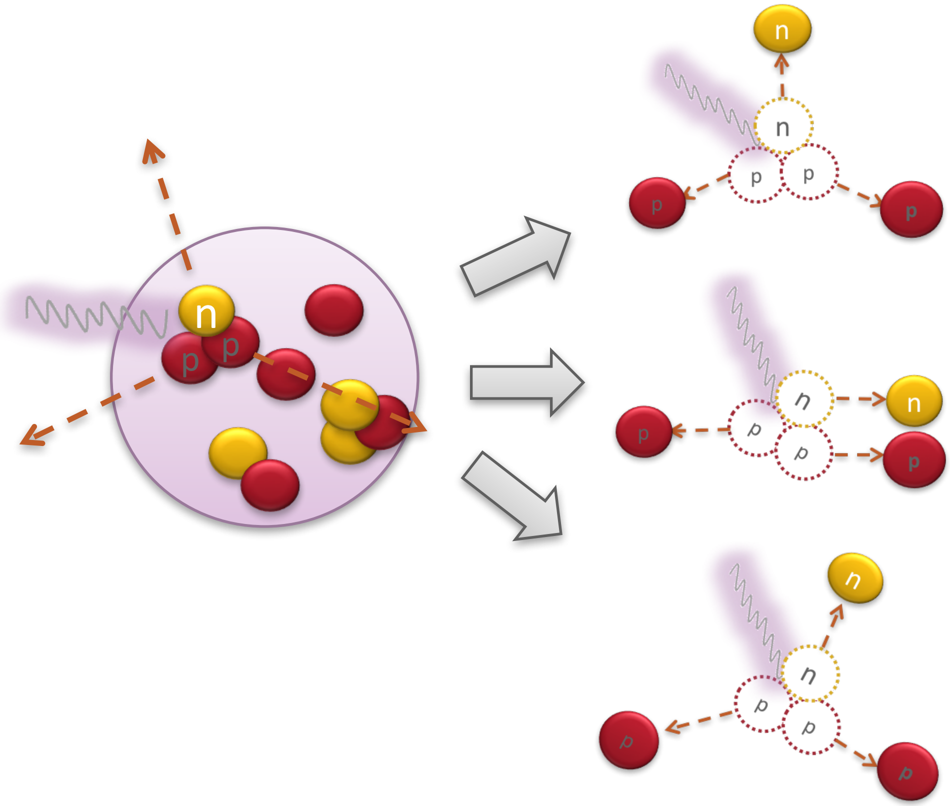



N. Fomin, E02-019 resutls, arXiv:0812:2144



# 3N-SRC

- **A more complicated study:**




**Symmetry:** 3 nucleons carry similar momentum values

**Back-to-Back:** 1 leading nucleons carries a large momentum while other 2 nucleons carry half of the momentum and go backward

**Random:** 3 nucleons carry arbitrary momentum values

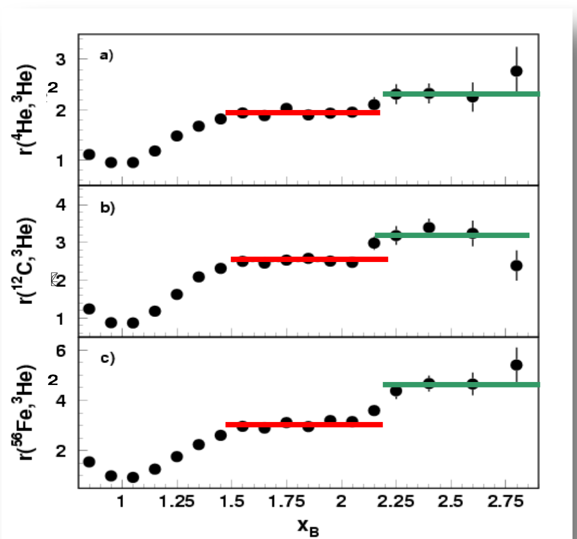
- The configurations of nucleons in 3N-SRC are far more complicated
- Inclusive measurement is currently the only way to study 3N-SRC

# 3N-SRC

- **Previous results from (e, e'):**

  An idea 3N-SRC picture:

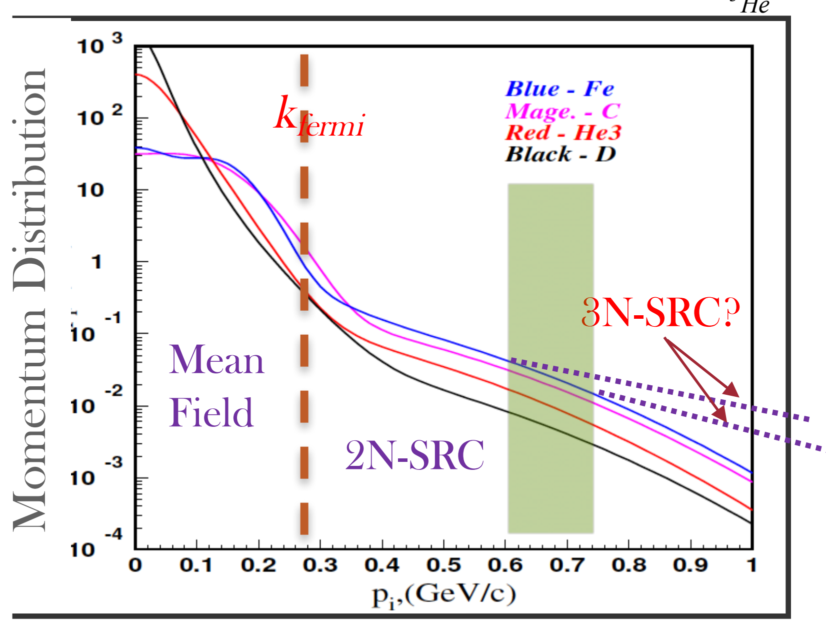
  - A smooth transition from 2N-SRC to 3N-SRC (like x~2)
  - A scaling behavior, like 2N-SRC, for momentum distributions of different nuclei
  - Small central momentum of 3N-SRC cluster, like pairs in 2N-SRC.




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

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

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



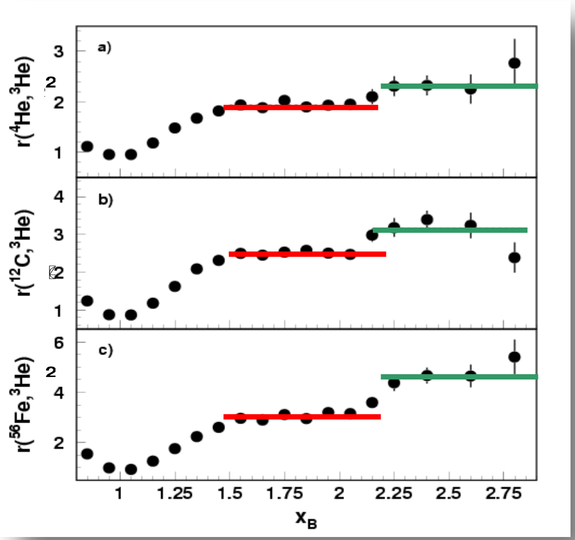
# 3N-SRC

- **Previous results from (e, e'):**

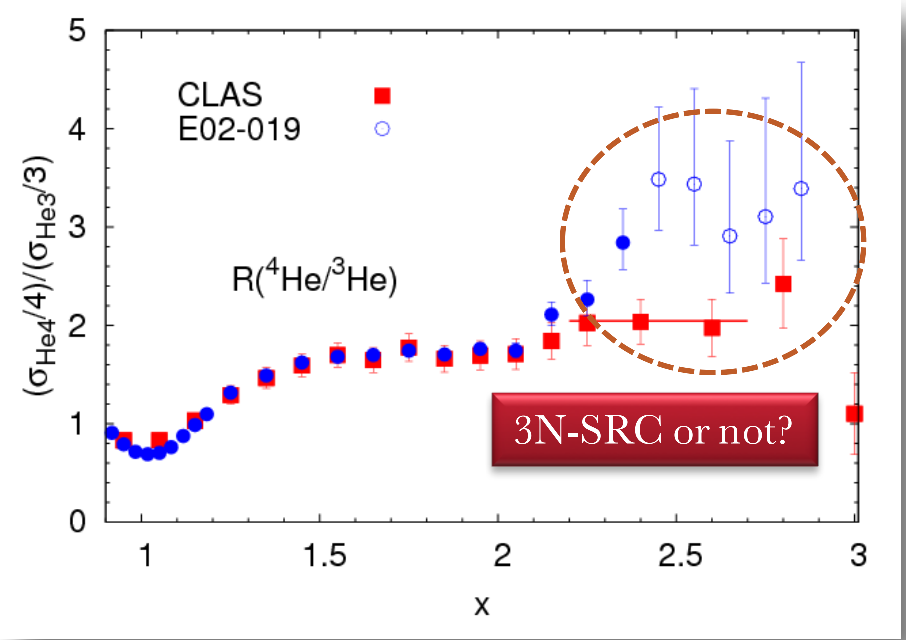
CLAS & E02-019 don't agree in the 3N-SRC region:

- CLAS shows 3N-SRC at x>2.2
- E02-019 doesn't have a clear plateau (or different onset if there is one)
- CLAS: $Q^2 \approx 1.6\ GeV^2$, E02-019: $Q^2 \approx 2.7\ GeV^2$

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



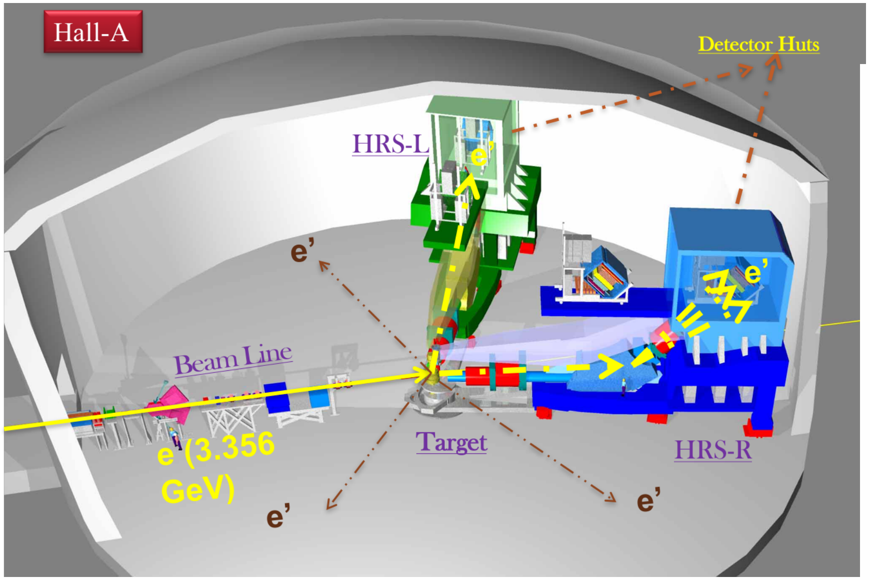

K. Egiyan et al, PRL96, 082501 (2006)



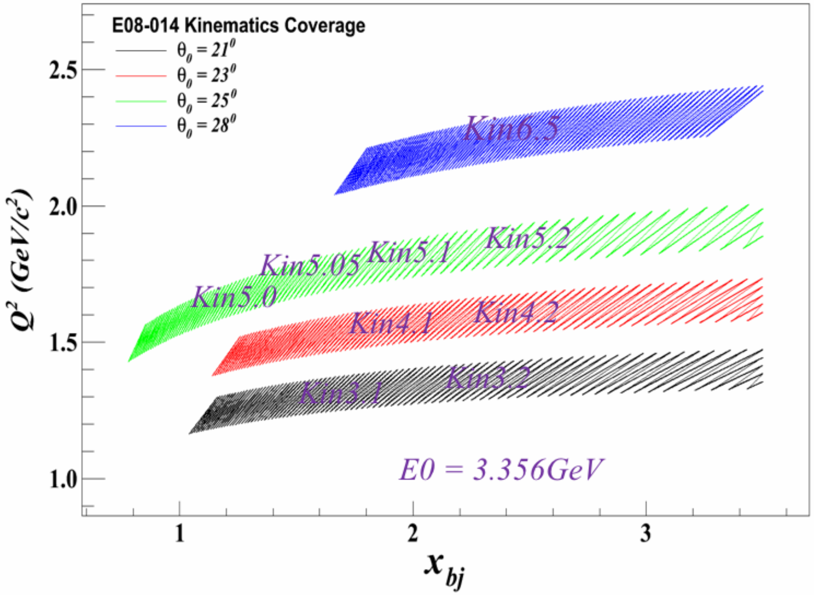
# E08-014 Experiment

- Study the onset of 3N-SRC scaling plateau at x>2
- Measure inclusive cross sections
- Isospin effect at SRCs (Ca40 & Ca48)

Spokespeople: Patricia Solvignon-Slifer*, John Arrington, Donal Day, Doug Higinbotham
Thesis Student: Zhihong Ye (UVa)



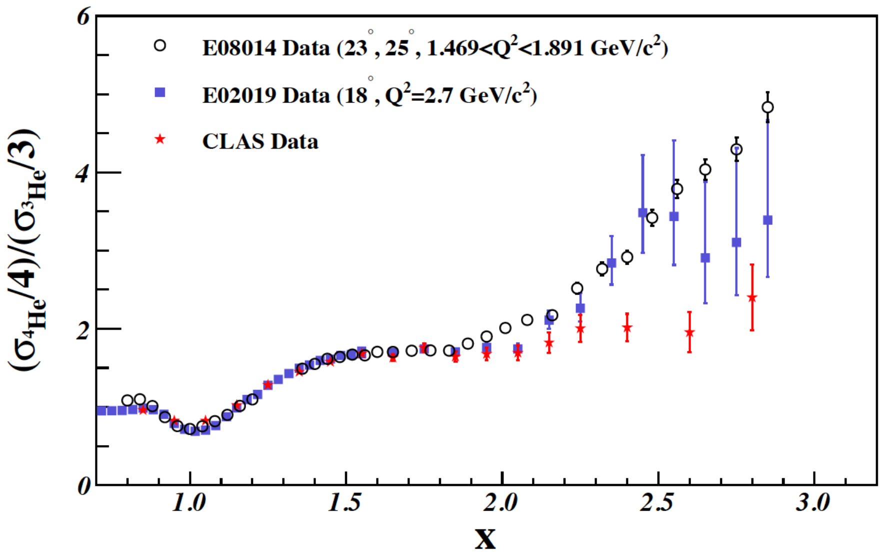

Data was taken in 2011




- **Configurations:** Unpolarized Beam; Two HRSs taking data Simultaneously; Standard Setup
- **Targets:** LH2, $^3$He, $^4$He, $^{12}$C, $^{40}$Ca, $^{48}$Ca, and other calibration targets.

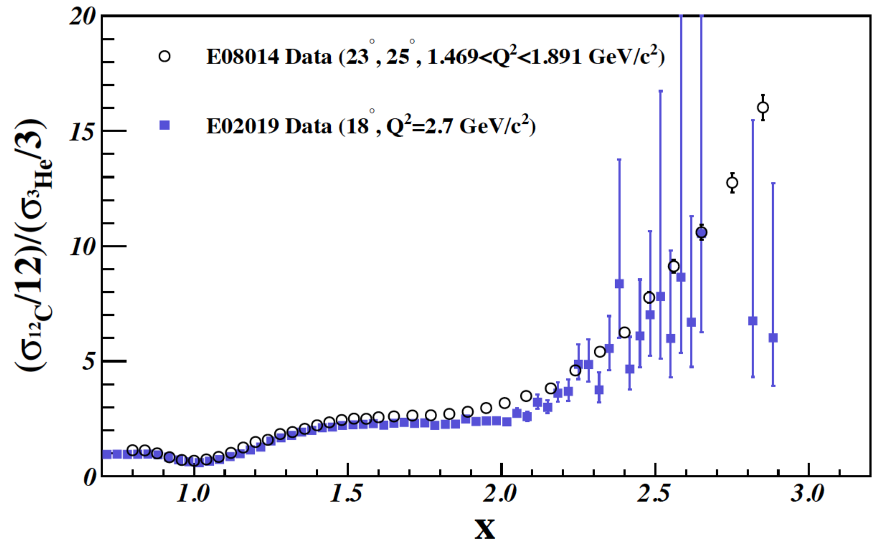
# E08-014 Results

- **3N-SRC:**




Absolute Cross Section Ratio:

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

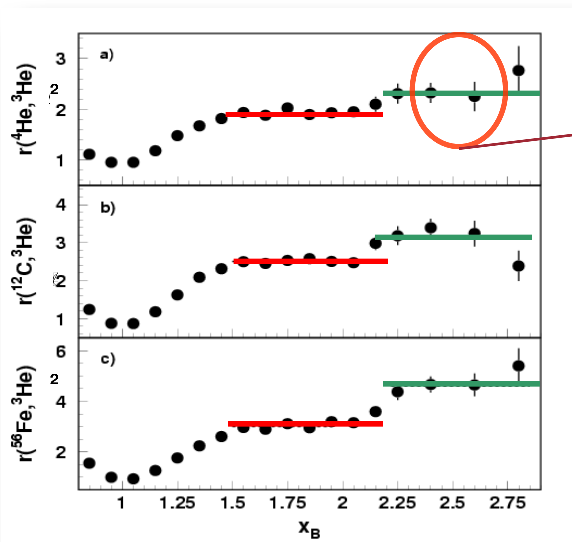


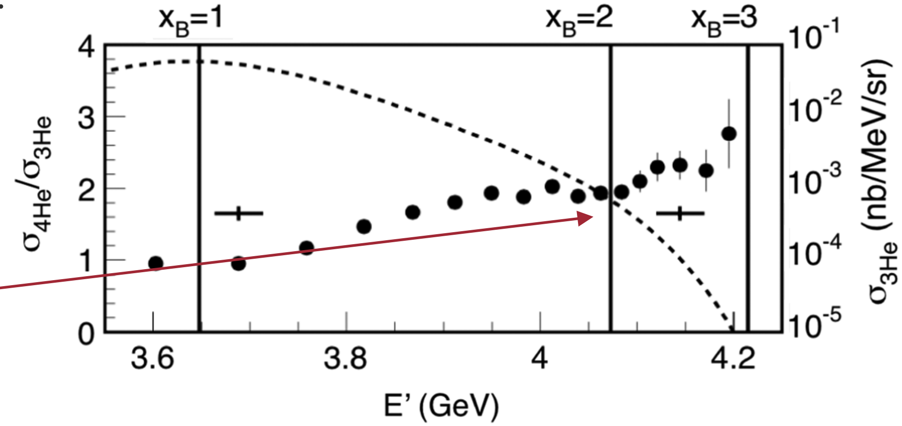

- ✓ Consistent results in 2N-SRC region
- ✓ Fast rise-up at x>2, and no indication of 3N-SRC plateau
- ✓ Agree with E02-019 data (within errors), and disagree with CLAS results

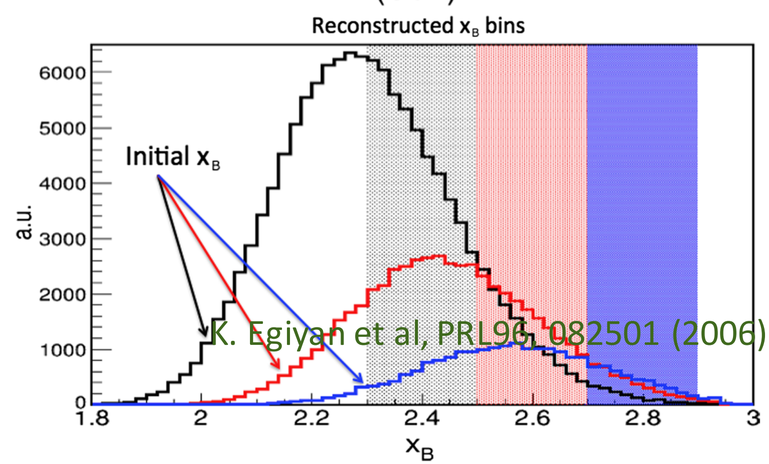
# E08-014 Results

➢ **CLAS's 3N-SRC Results:**

(Doug Higinbotham and Or Hen, PRL 114,169201 2015):



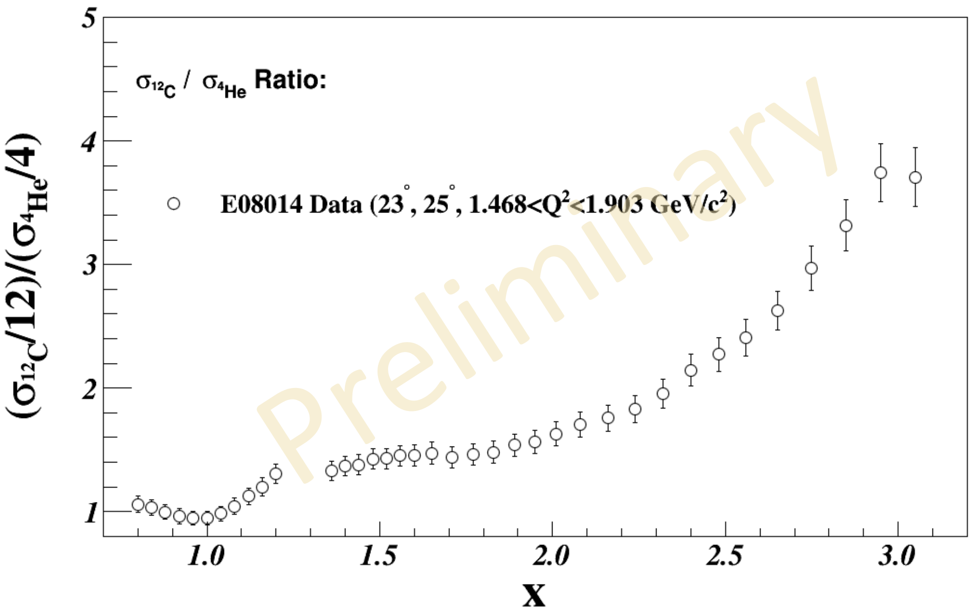

- ❖ Large bin migration due to the limited momentum resolution of CLAS
- ❖ For He3 at x→3, the elastic peak leaks in to the QE tail when resolution is poor.

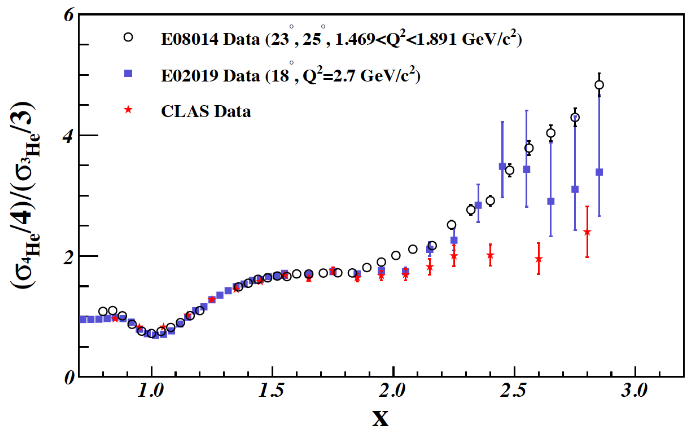
# E08-014 Results

- **3N-SRC:**

Bin-smearing effects become a more important issue for fast falling cross sections

this effect should be cancelled in the ratio (like foil .vs. foil, or long .vs. long), but it is not entirely true for foil-target .vs. long-target.



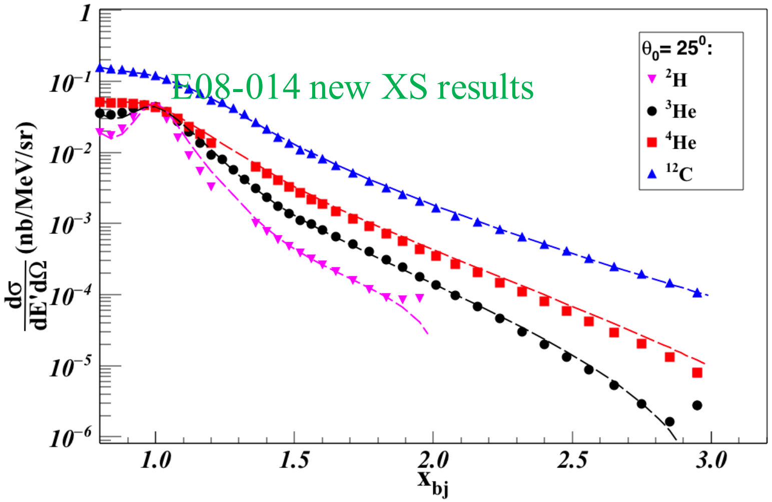



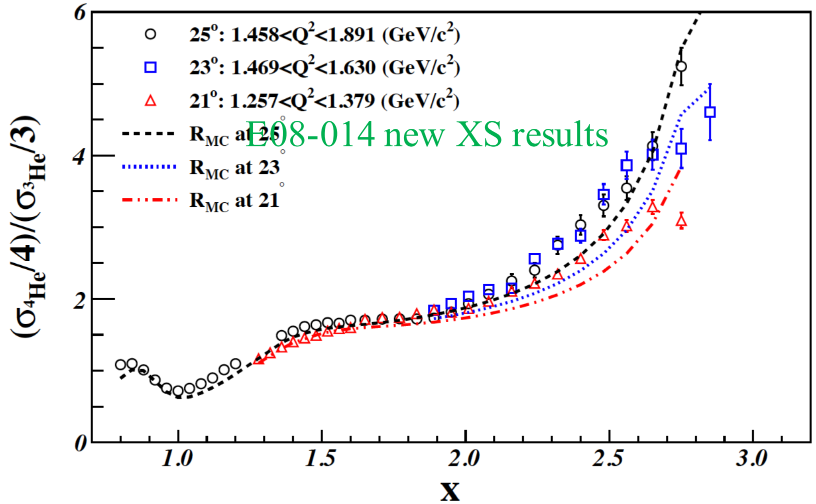

$^{12}C$ to $^4He$ ratio can be a better way to check 3N-SRC

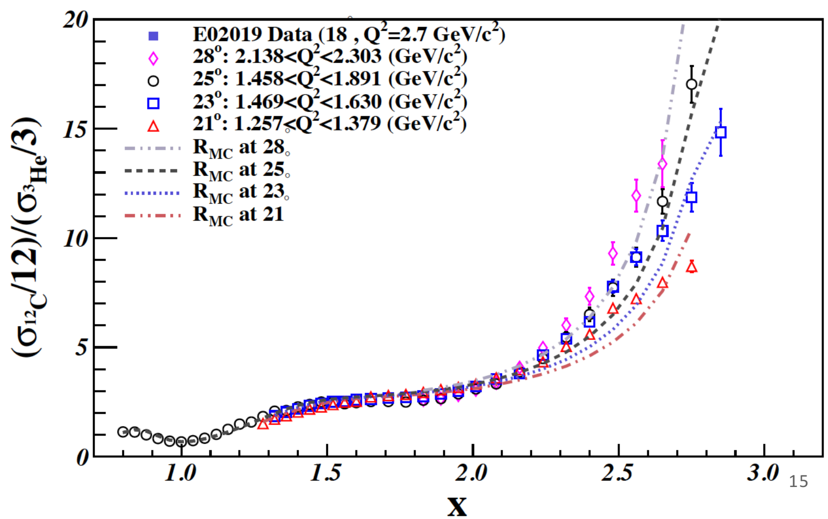
✓ $^3He$ cross sections don't drops too quickly when x→3, unlike $^3He$

# E08-014 Results

- **3N-SRC:**
  - ✓ $^3$He cross sections fall more rapidly than heavier nuclei when x→3 (until hit the elastic peak)



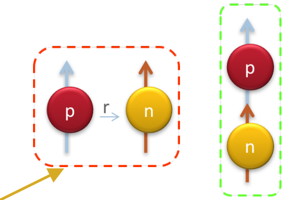

- ✓ New results at different $Q^2$ indicate that ratios raise even faster when $Q^2$ increase

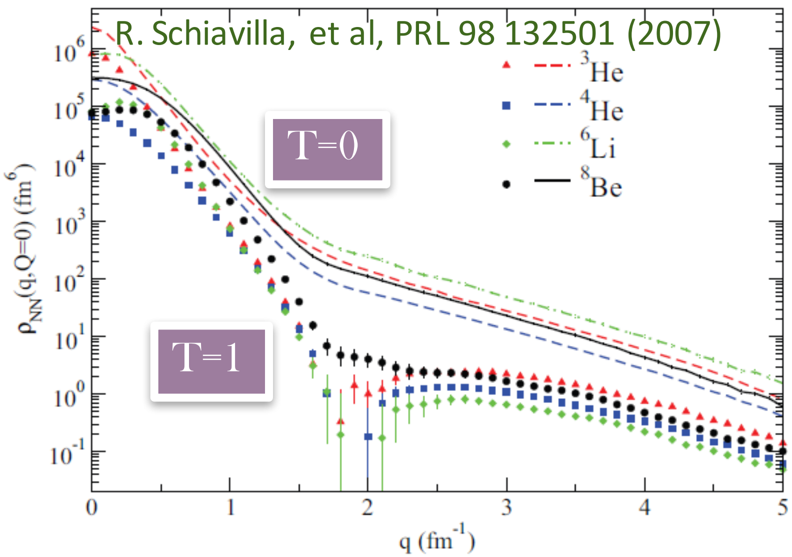
**Our Conclusions:**

- ✓ 2N-SRC & 3N-SRC in heavy nuclei are not stationary
- ✓ Larger $Q^2$ values may not necessarily help
- ✓ Require more careful investigation to isolate 3N-SRC

# Isospin Dependence

➢ **From (e, e'p) data:** *(see Or Hen's talk)*




<u>Proton → T= 1/2, Neutron→ T= -1/2</u>

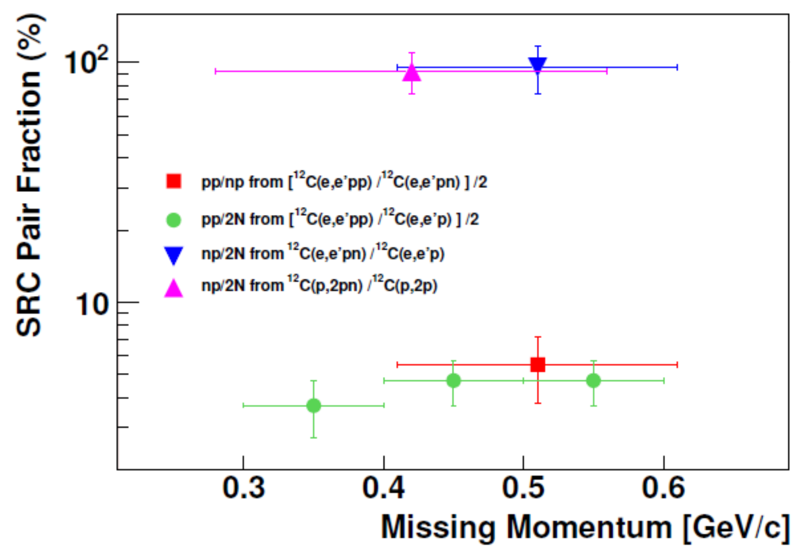
Isospin Singlet: T = 0, n-p pairs

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

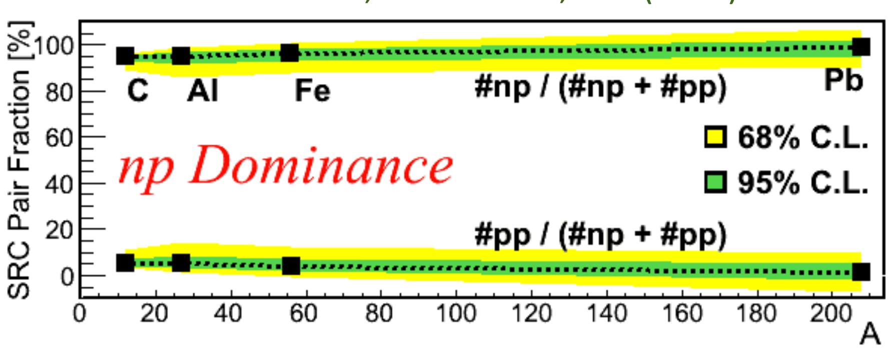
✓ Theoretical calculation shows n-p pairs have stronger strength

✓ (e,e'p) experiments reveal that np pairs are 90%

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




O. Hen et al., Science 346, 614 (2014)



# Isospin Dependence

## ➢ From Inclusive Measurements:

- Measuring two isotope targets, e.g. Ca40 and Ca48 in E08-014
- Assuming Isospin-Independent in inclusive measurement:

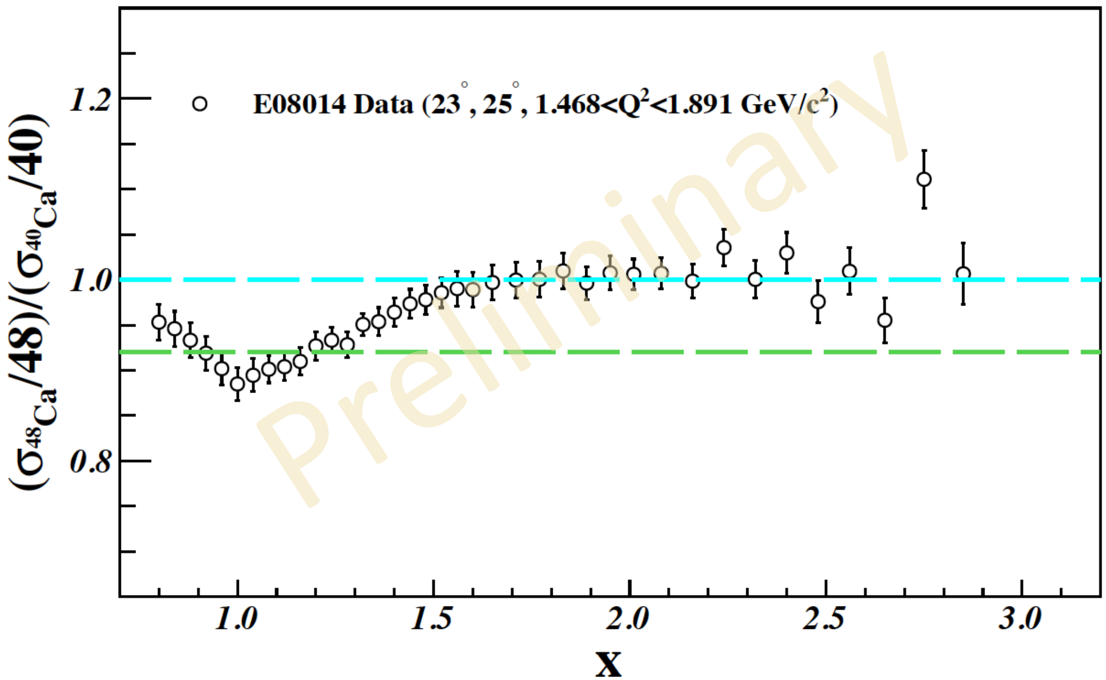
$$R = \frac{\sigma_{Ca48}/48}{\sigma_{Ca40}/40} = \frac{(20\sigma_p + 28\sigma_n)/48}{(20\sigma_p + 20\sigma_n)/40} \xrightarrow{\sigma_p \approx 3\sigma_n} 0.92$$

- Assuming n-p pairs dominance in 2N-SRC: R ≈1

- ✓ Much smaller FSI in the inclusive measurements
- ✓ A 5% difference between two cases
- ✓ A qualitative measurement
- ✓ New experiment → E12-11-112 using H3/He3: 40% difference

# Isospin Dependence

➢ **Calcium Ratio from E08-014 Results:**




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)*

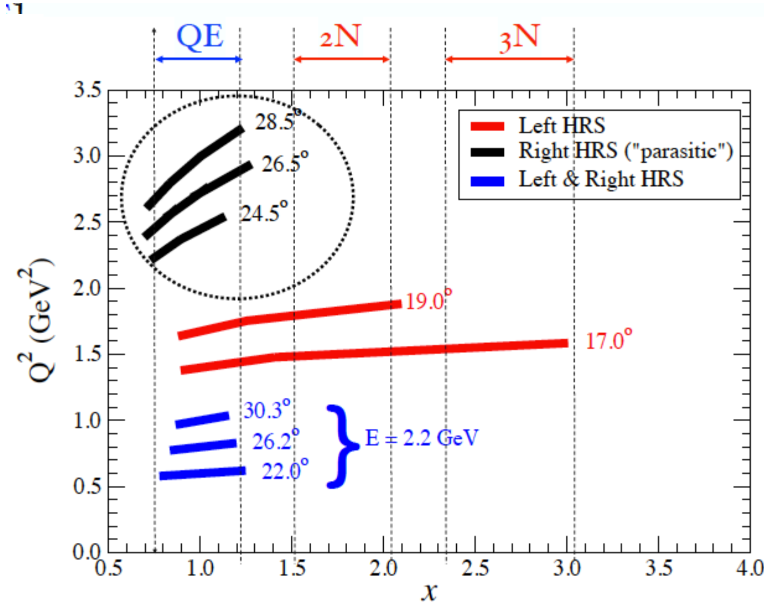
# Isospin Dependence

- **Future Experiments:**

  **<u>E12-11-112 using H3/He3</u>**

  <u>Spokespeople:</u> Patricia Solvignon-Slifer*, John Arrington, Donal Day and Doug Higinbotham

  <u>Thesis Students:</u> Shujie Li, and Dien Nguyen




- ✓ 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

Passed readiness review in March 2016; Ready for data taking in 2017

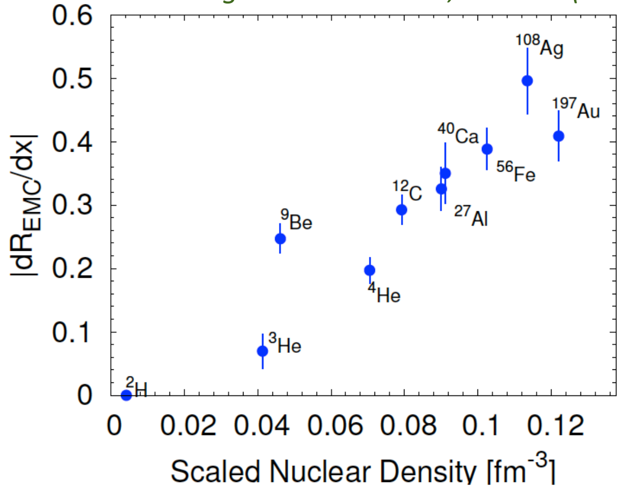
# SRC vs. EMC

- **Connection?**

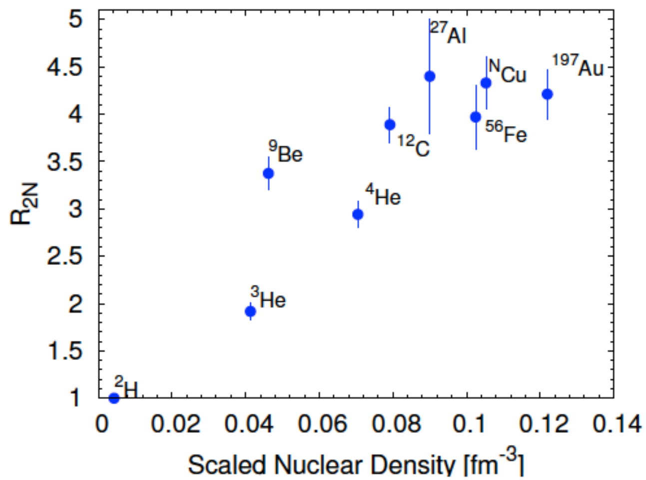
<u>EMC Effect:</u>
→A nucleon has different structures placed in different nuclei.

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

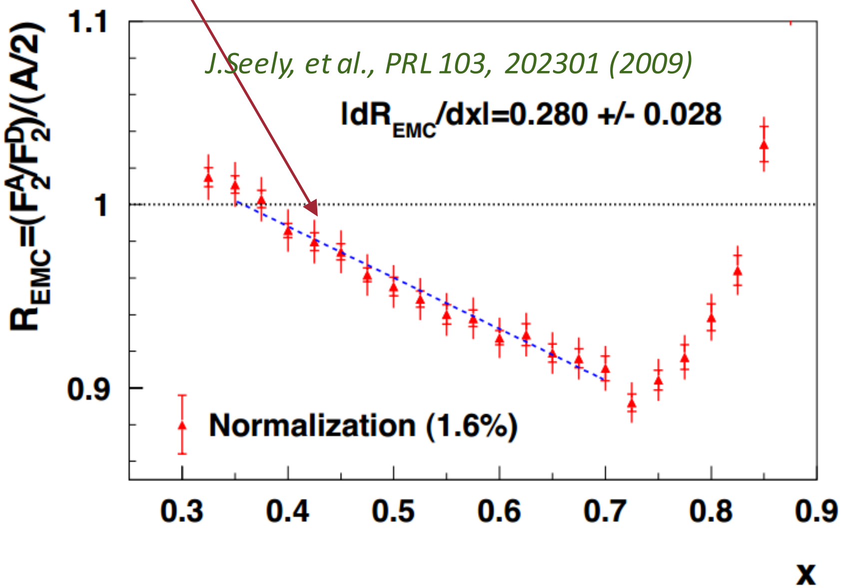
*J. Arrington et al. PRC 86, 065204 (2012)*




slope




a2

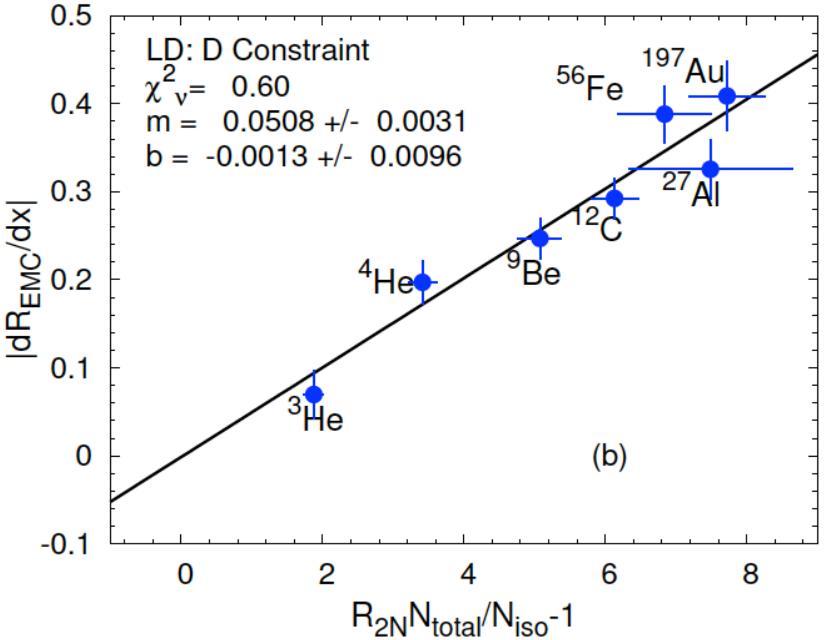



<u>$a_2$ in 2N-SRC:</u>
→ Probability of two nucleons to be correlated.

# SRC vs. EMC

➢ **Linear correlation:**

**D.O.F: Nucleus → Nucleon →Quarks & Gluons ?**




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

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

✓ EMC and SRC are linked to different degree of freedom in nuclei
 **EMC:** 0.3<xbj<0.7 → How quarks&gluons form nucleons
 **SRC:** xbj > 1.3 → How nucleons form nuclei
✓ Connections could be due to high density of the configurations in SRCs

# Future SRC&EMC Experiments

## ❑ Hall-A: (Tritium experiments)

- E12-11-112: Precision Measurement of the Isospin Dependence in the 2N- and 3N-SRC region.
  Spokespersons: J. Arrington, D. Day, D. Higinbotham, P. Solvignon*

- 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.
  Spokespersons: J. Annand, G. Petratos, J. Holt, J. Gomez, R. Ransome

- And so on …

## ❑ Hall-C:

- E12-06-105: Inclusive Scattering for Nuclei at x>1 in the Quasielastic and deeply inelastic regimes.
  Spokespersons: J. Arrington, D. Day, .N. Fomin, P. Solviginon*

- E12-10-008: Detailed studies of the nuclear dependence of F2 in light nuclei.
  Spokespersons: J. Arrington, A. Daniel, D. Gaskell

- E12-11-107: In Medium Nucleon Structure Functions, SRC, and the EMC Effect.
  Spokespersons: O. Hen, L. Weinstein, S. Gilad, S. Woods

- E12-10-003: W. Boeglin, M. Jones; E12-06-107: D. Dutta. R. Ent.

- And so on …

# Summary

- Study of Short Range Correlations (SRCs) will help us to understand the nuclear structure and properties of highly correlated nucleons
- Inclusive electron scattering in the Quasi-elastic region provides a powerful tool to study SRCs
- 2N-SRC has been observed in the exclusive reactions and inclusive reactions with good agreements
- E08014 results show no indication of 3N-SRC plateau; agree with Hall-C data and disagree with CLAS data.

  the plateau showed in CLAS data may be due to the bin-migration effect.
- Isospin dependence effects have been observed in both (e,e'p) and (e,e') data; good agreements;

  new Hall-A experiment will do further investigations with H3/He3.
- SRCs are linked to the EMC effects, indicating the highly localized density could cause the EMC effect.

  Many experiments in Hall-A/C have been approved to study both effects

## In memory of our dear friend:
## Patricia Solvignon-Slifer

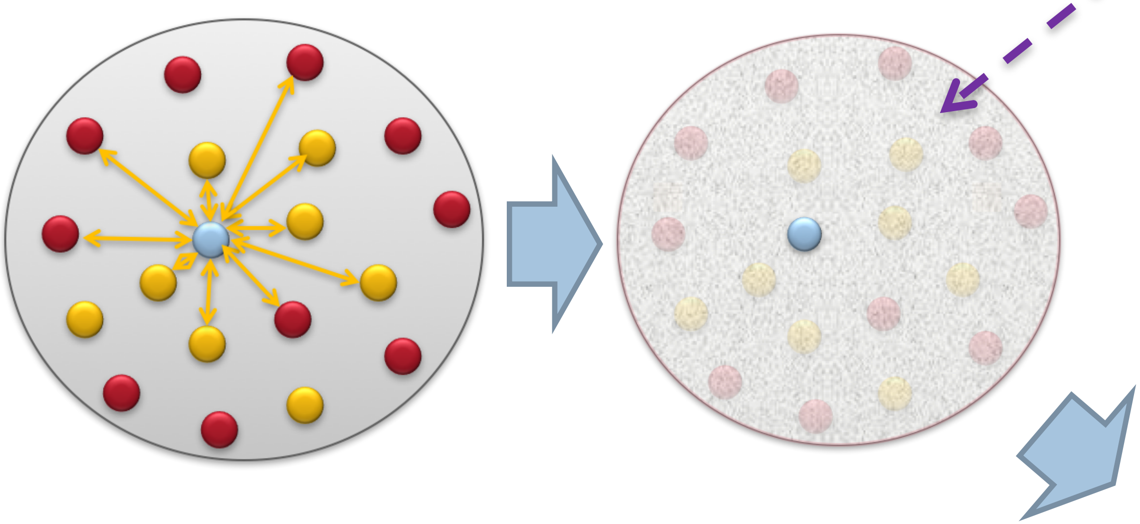
# Short-Range Correlations

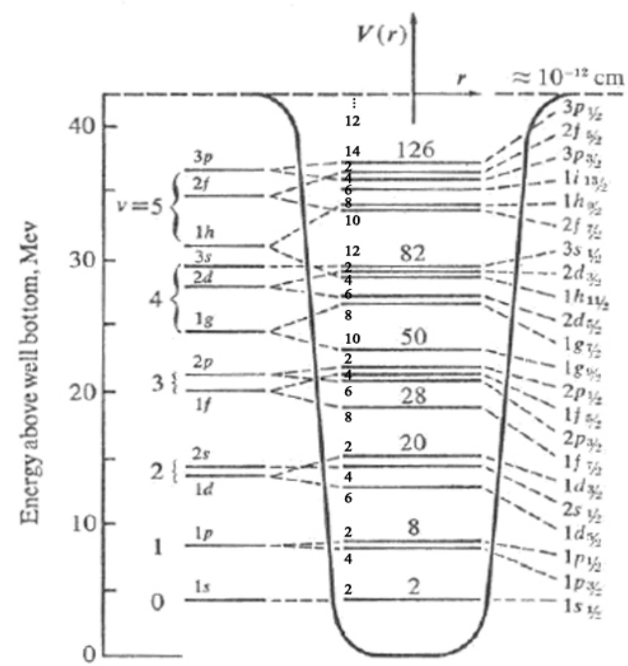
## ➢ Realistic Nucleon-Nucleon Interactions:

*No NN interaction Terms!*

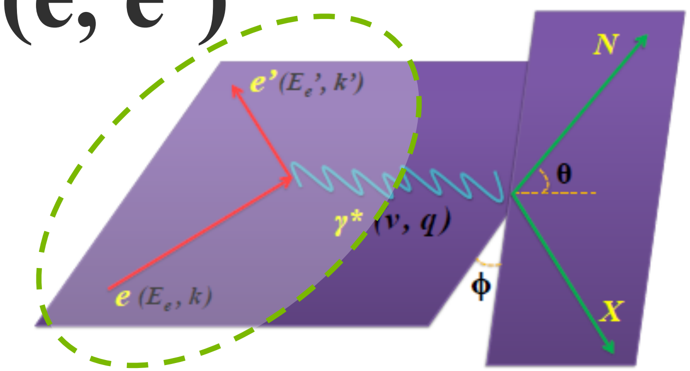
- Independent Particle Shell Model (IPSM): $h_{IPSM}|\varphi_\alpha\rangle \approx (p^2/2m + \overline{V} + \ldots) = \varepsilon_\alpha|\varphi_\alpha\rangle$

*The Mean Field*





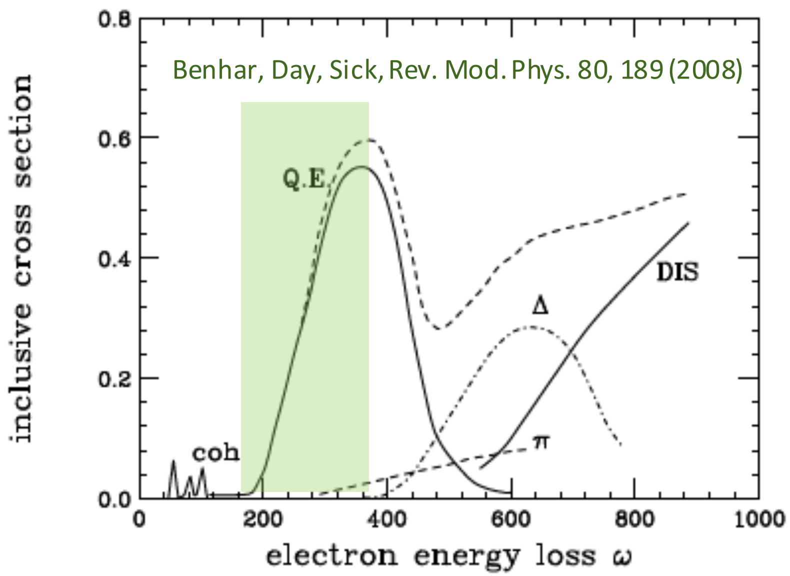
# Quasi-Elastic (e, e')




## ➤ Inclusive Electron-Nucleus Scattering:

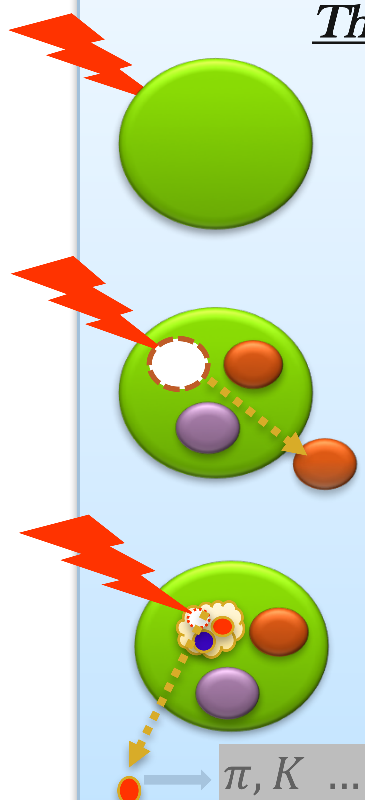
<u>To Probe SRC:</u> *(momentum distributions are not an observables)*

- (e, e'p/n): Measure knocked-out p/n and spectators
- (e, e'): Only measure scattered electrons after incoming electrons scatter on targets




Probe SRCs on the Quasi-Elastic (QE) tails!

### *Three Degree of Freedoms*




Elastic Scattering → probe nucleus (or free nucleon) as a bulk

*Form Factors, etc.*

Quasi-Elastic Scattering → probe protons & neutrons bounded in a nucleus; knock out nucleons

*Nuclear Structure, etc.*

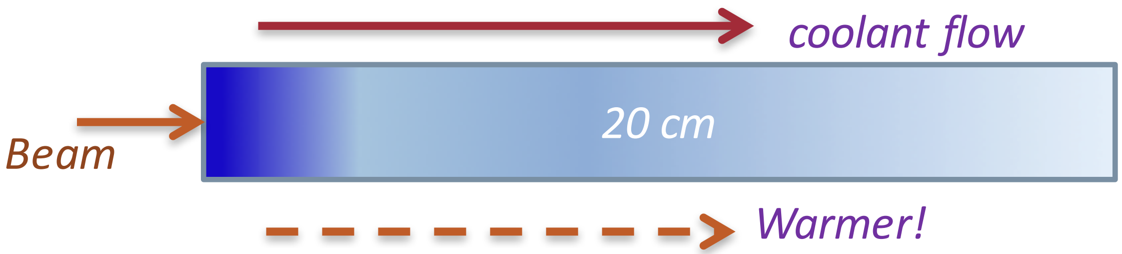
Inelastic Scattering → probe quarks & gluons in protons and neutrons; excited or break nucleons

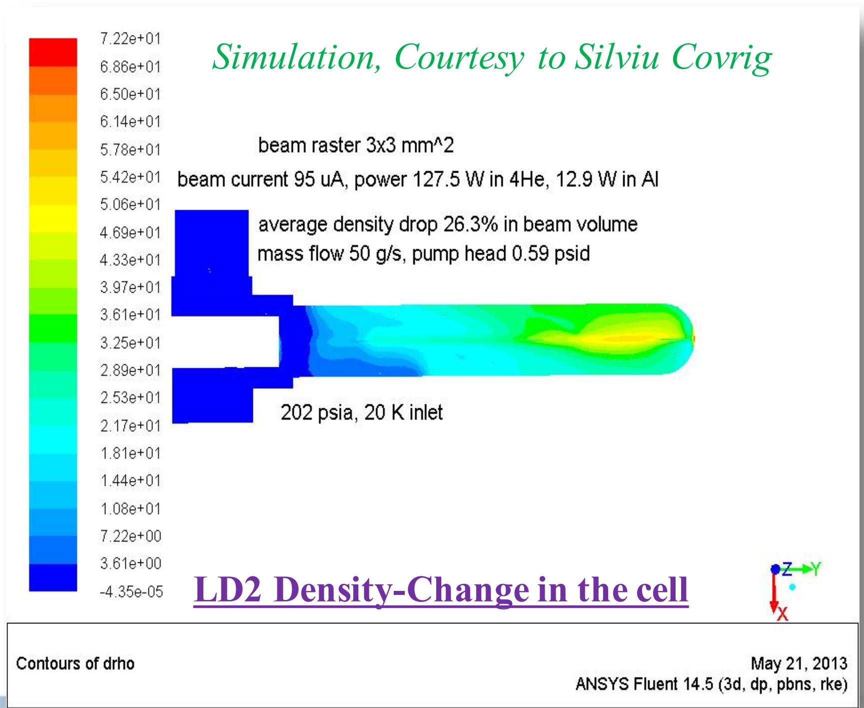
*Parton Distribution Functions, etc.*

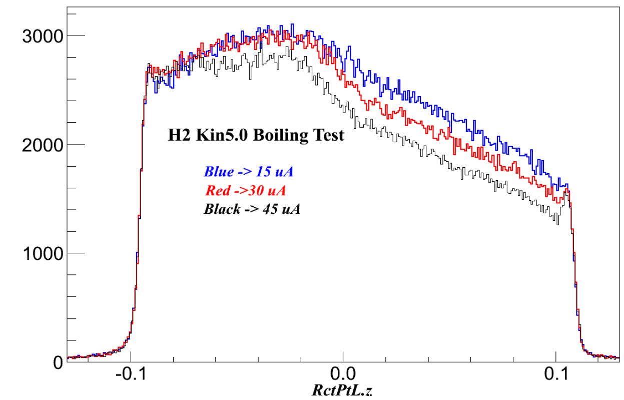
# E08-014 Experiment

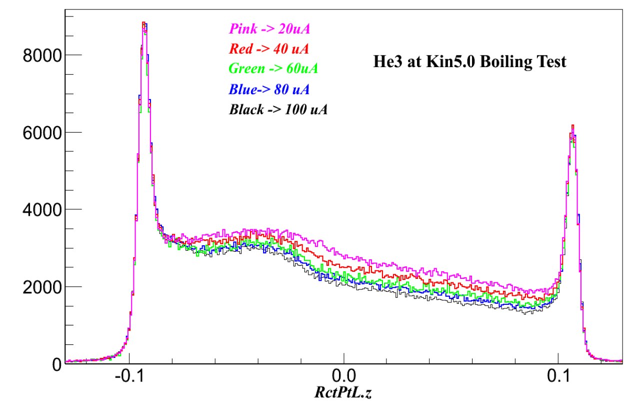
- **Cryo-Target Density Non-Uniformity**

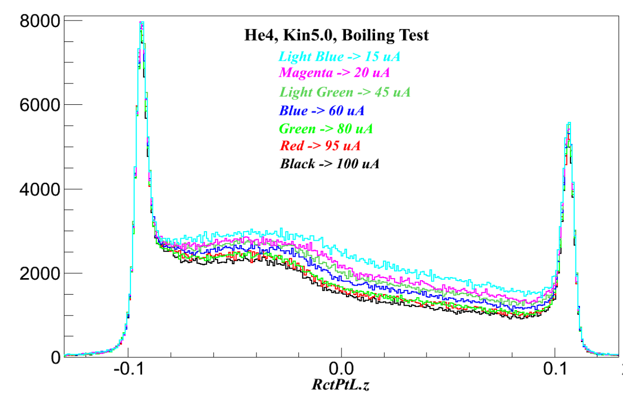
For LH2 (20 K), $^{3}$He (22 K), and $^{4}$He (19 K)



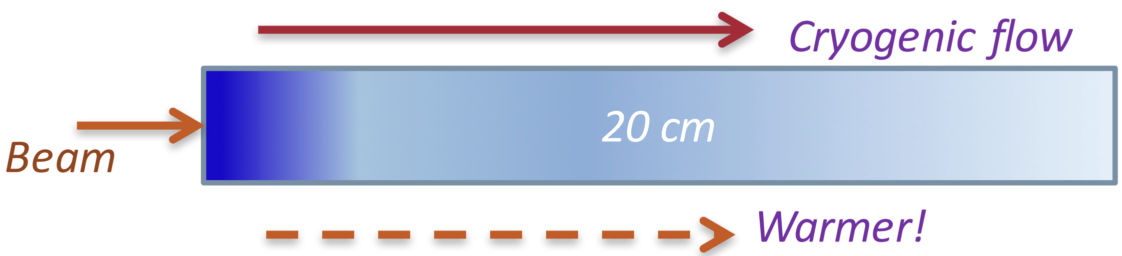



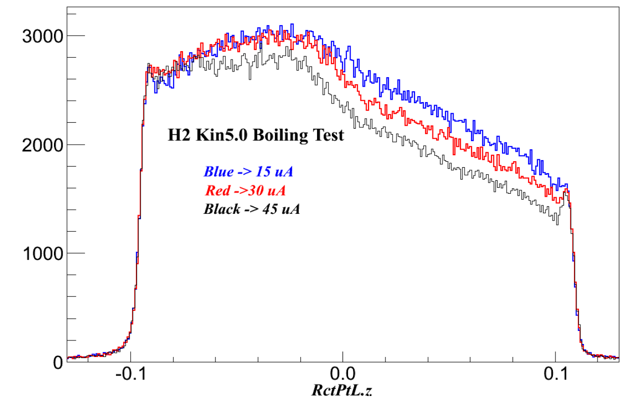



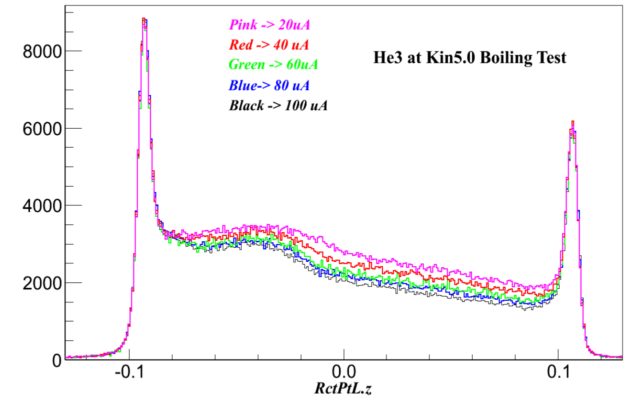
# E08-014 Experiment

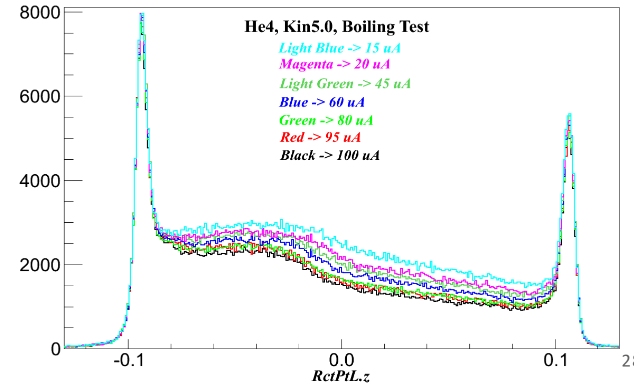
➢ **Cryo-Target Density Uniformity**

For LH2 (20 K), $^3$He (22 K), and $^4$He (19 K)




**Problems:**

- Hard to evaluate absolute target luminosity;

  Larger uncertainty (we assigned 5%)

- Complicated boiling effect correction;

  Z-dependent boiling study

- Complicated radiative corrections.

  Z-dependent radiative correction and multiple scattering

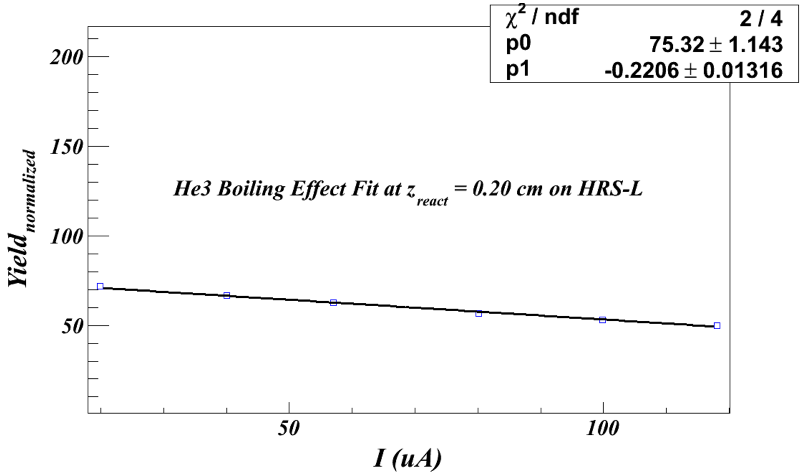
A valuable lesson learned for future high luminosity experiments with long targets

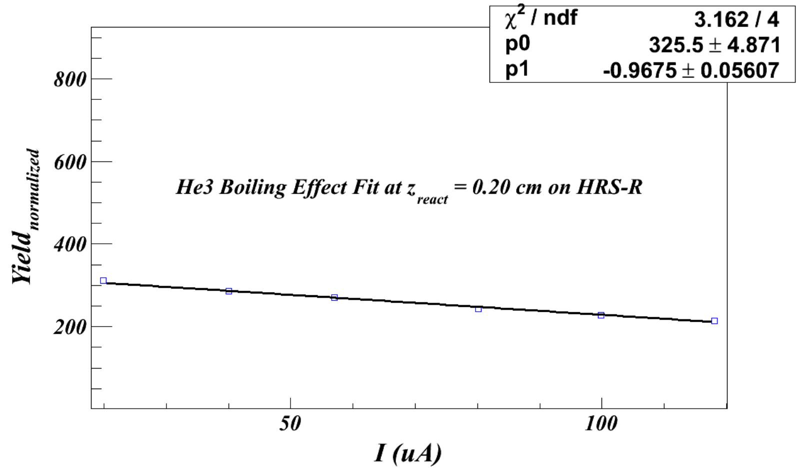
# E08-014 Experiment

## ➢ Boiling Effect Study:

1) Taking data with different currents.
2) Calculating yields and correlating them with currents.
3) Binning VZ into 60 bin and fitting the boiling factors in each bin.
4) Fitting the slops and constants for both arm.
5) Distribution of $Y_0$ denotes the relative density distribution.

$$\rho(I) = \rho(I=0)\cdot(1-BF\cdot I), BF = \frac{slope}{Y_0}$$



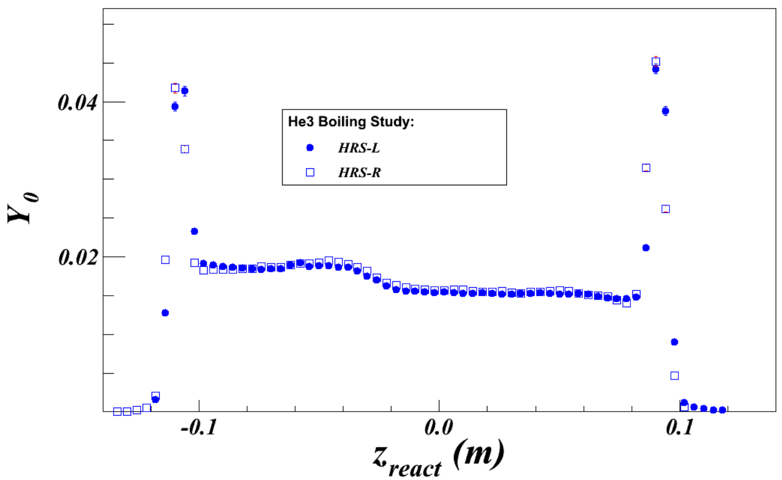

A z-dependent boiling effect

# E08-014 Experiment

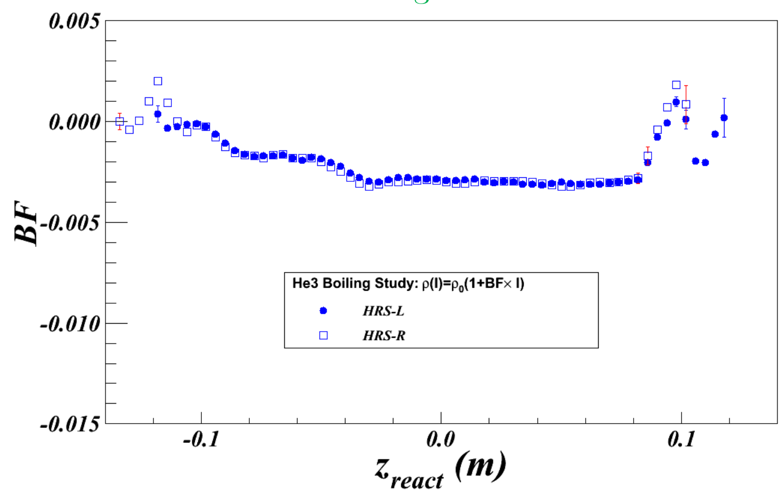
- **Boiling Effect Study:**

1) Taking data with different currents.
2) Calculating yields and correlating them with currents.
3) Binning VZ into 60 bin and fitting the boiling factors in each bin.
4) Fitting the slops and constants for both arm.
5) Distribution of $Y_0$ denotes the relative density distribution.

Relative Target Density Distribution w/o Boiling




Boiling Factors




- ✓ Obtained the real density distributions by comparing with the target survey report
- ✓ Used MC method to conform the study
- ✓ Extracted elastic cross sections to double-check (by Dien Nguyen)