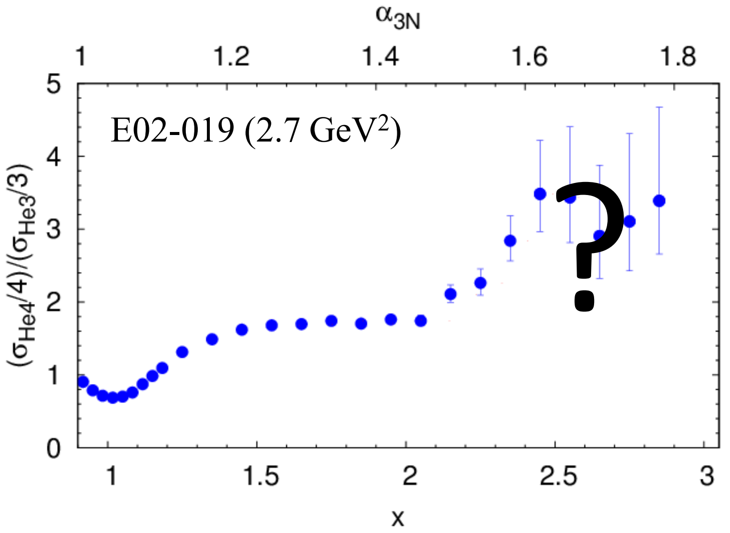
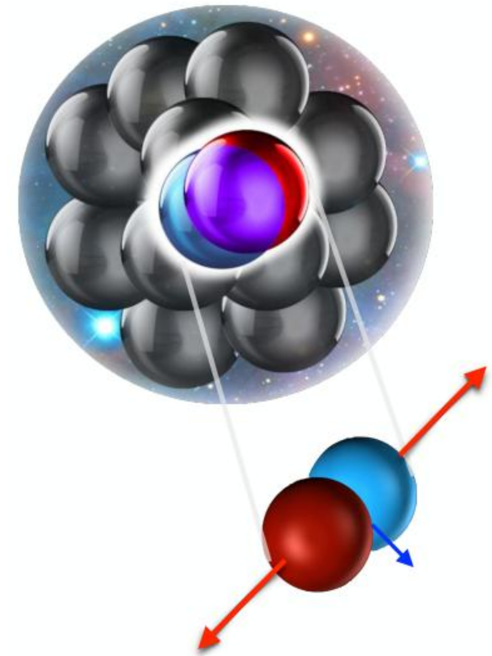
PR12-26-005: A definitive measurement of 3N correlations scaling plateau in inclusive scattering



N. Fomin (UTK) with B. Duran (NMSU) and N. Santiesteban (UNH)

PAC 52 and the SRC White Paper



Long Range Outlook for Short-Range Correlations

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S. Regmi,[17] M. Rinaldi,[28] J. L. Rodriguez-Sánchez,[47] D. Romanov,[9] G. Salmè,[48] A. Schmidt,[18] M. H. Shabestari,[49]
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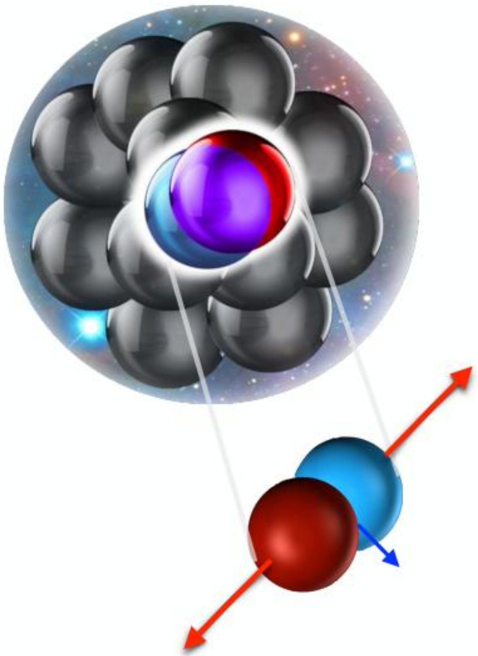
https://arxiv.org/pdf/2601.09568
To be published in Progress in Particle and Nuclear Physics

SRC White Paper – What we know

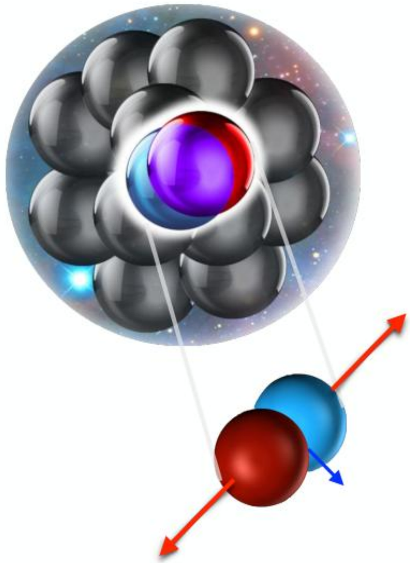


- Inclusive A(e,e')
  - Shows SRC dominance at $k > k_{fermi}$
  - Observed scaling of A/D cross sections at $x > 1.5$, $Q^2 > 1.5$ GeV$^2/c^2$
  - a_2 across many nuclei
  - Direct comparison to theory for light nuclei

- Single Nucleon Knockout A(e,e'p|n)
  - Proportional to abundance of high-momentum of protons and neutron
    - Which nucleons pair (pairing mechanisms)
  - Narrow transition region (mean field → SRC)
  - Direct comparison to theory for light nuclei

- Two-nucleon knock out A(e,e'NN)
  - *pn* pair dominance
  - All* high momentum nucleons belong in SRC pairs
  - pp/pn ratio increases with missing momentum
    - Tensor → scalar transitions

SRC White Paper – 2N SRC discovery



PHYSICAL REVIEW C VOLUME 48, NUMBER 5 NOVEMBER 199

Evidence for short-range correlations from high Q^2 (e,e') reactions

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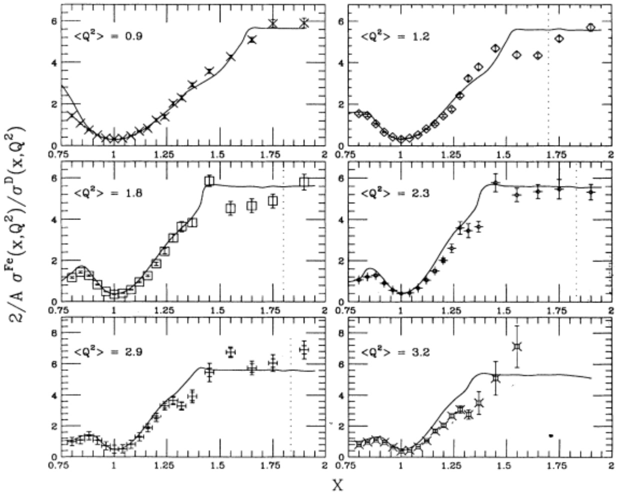
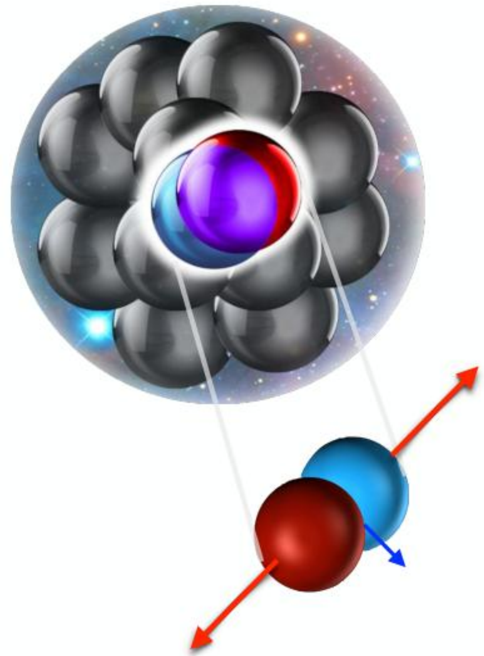
(Received 20 April 1992)

We argue that the ratio of cross sections of quasielastic electron scattering for heavy and light nuclei at $x>1$ and $Q^2>1$ $(\mathrm{GeV}/c)^2$ should exhibit simple scaling relations which are ultimately expressed through the ratio of the light-cone nucleon distributions in nuclei. We extract these cross section ratios from existing data in a practically model independent way. The results are found to be in reasonable agreement with our x-scaling relations for the region of $2>x\geq 1.4$ where the contribution of two-nucleon short-range correlations are expected to dominate. The ratios exhibit scaling in the light-cone fraction, α, of the struck nucleon for the range $2>x\geq 0.9$. The α scaling is in agreement with the expectations of the light-cone quantum mechanics of nuclei, providing further evidence for the dominance of short-range correlations in nuclei at $k>0.3$ GeV/c. An extension of this analysis to the interpretation of color transparency experiments is discussed.

PACS number(s): 25.30.Fj



SRC White Paper – Experimental Priorities (4)

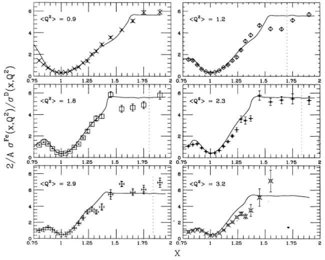


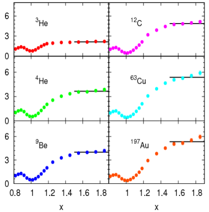
1. Opportunity to discover short-range 3N correlations through analysis **of high-Q^2 inclusive cross-sections at $x>2$** and exclusive three-nucleon knockout reactions
   a) If observed, extract triplet characteristics (isospin structure, angular kinematics and momentum distributions)
   b) If observed, measure 3N SRC abundances and characteristics over a range of nuclear mass and asymmetry

Inclusive SRC Milestone timeline

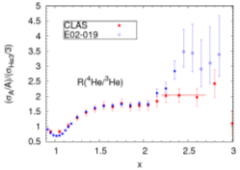
QCD and short-range nuclear phenomena
(FS 1980)

Evidence for SRCs
(Phys.Rev.C 48 1993)

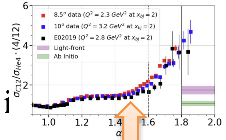




Precision 2N SRCS
2011 (data in 2004, prop 2002)

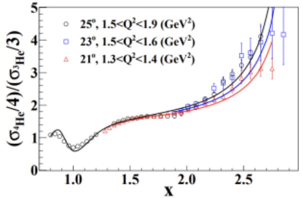


E12-06-105 data taking
(2N nuclear dep, 3N SRCs. SFQs, etc)
(2022-2023)
3N Manuscript i
preparation

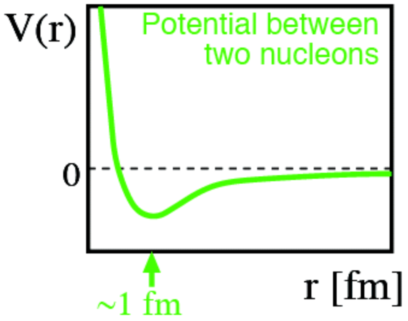


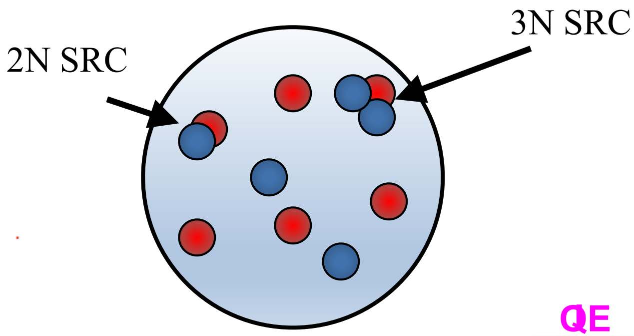
<< 13 years >> *<< 18 years >>* *<< 7 years >>*

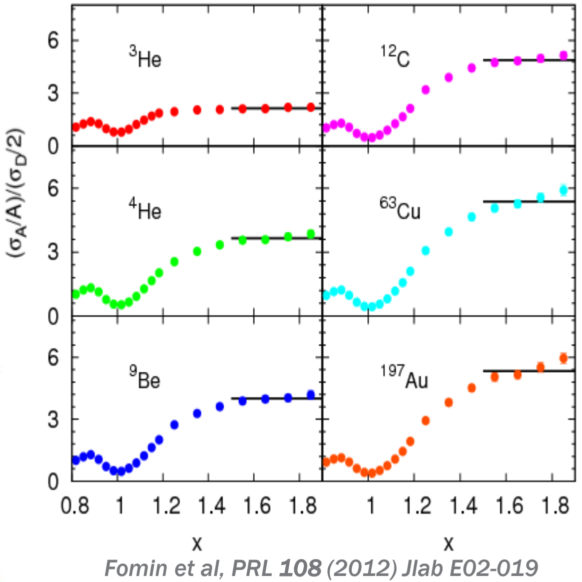
Hall A 3N search
Phys.Rev.C 97
(**2018**) Proposed 2008

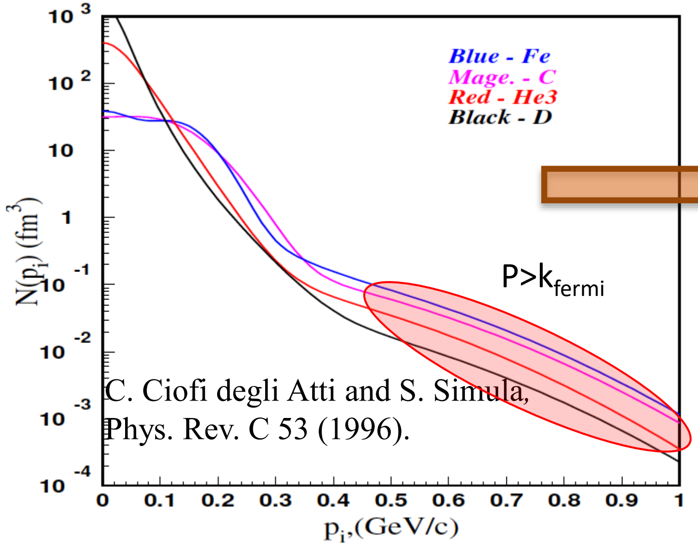


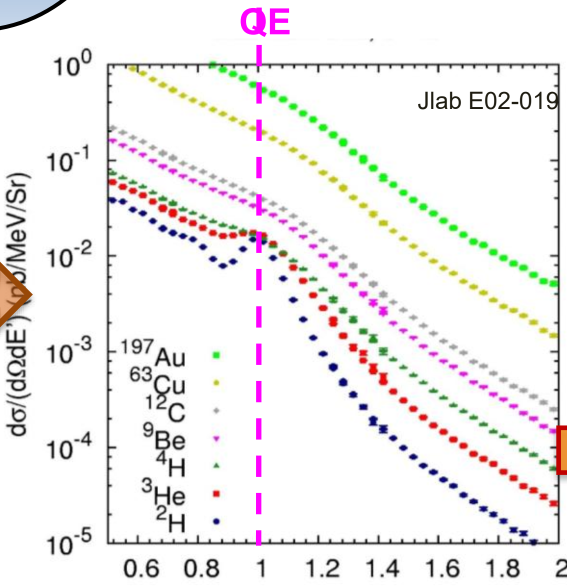
Today
(2026)





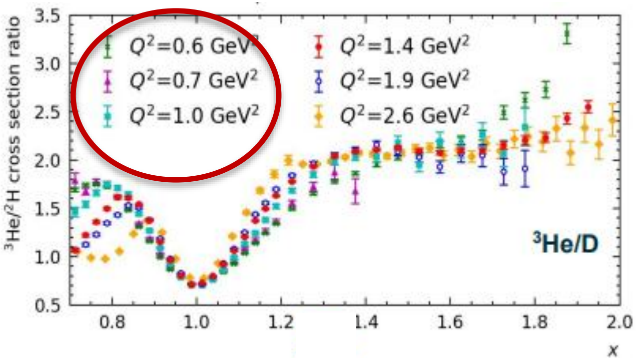




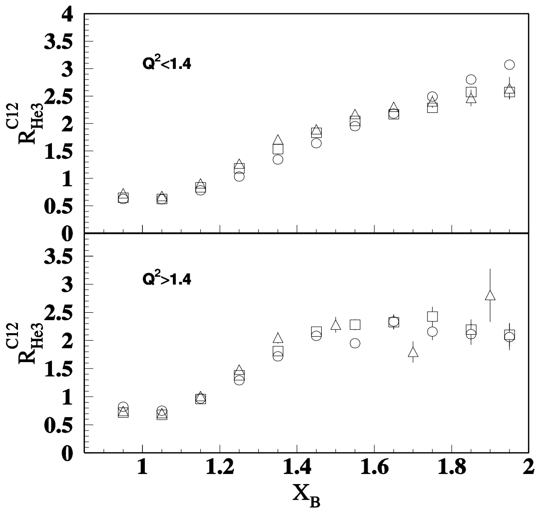


1.4<x<2 => 2 nucleon correlation

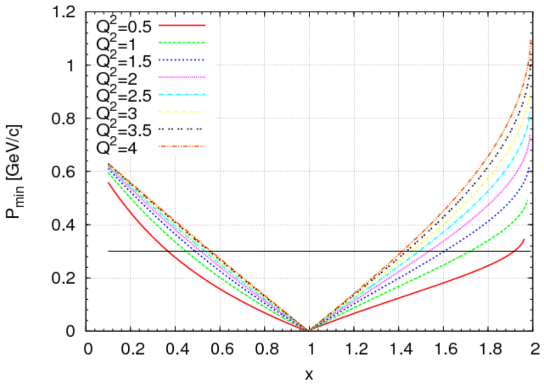
What does it look like at the wrong kinematics?



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

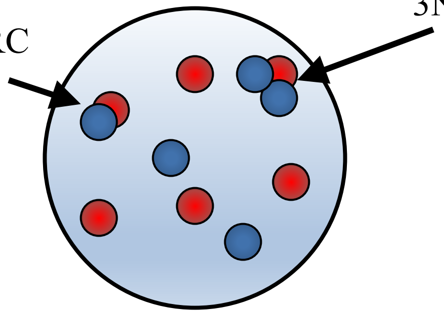


Egiyan et al (2003)



Need right kinematics and suppression
of center of mass motion contribution

More nucleons in a correlation



$1.4 < x < 2$ => 2 nucleon correlation

$2.4 < x < 3$ => 3 nucleon correlation

$$\sigma(x, Q^2) = \sum_{j=1}^{A} A \frac{1}{j} a_j(A)\sigma_j(x, Q^2)$$

$$= \frac{A}{2} a_2(A)\sigma_2(x, Q^2) +$$

$$\frac{A}{3} a_3(A)\sigma_3(x, Q^2) + ...$$

Go to x>2 to see a second, 3N SRC plateau in $\frac{\sigma_{A1}}{\sigma_{A2}}$

Global 3N Inclusive Data Set

Light Front Dynamics

Light cone variables:

$$p_+ = E + p_z; \;\; p_- = E - p_z$$

(z → direction of propagation)

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

Light-cone nuclear momentum fraction carried by the struck nucleon

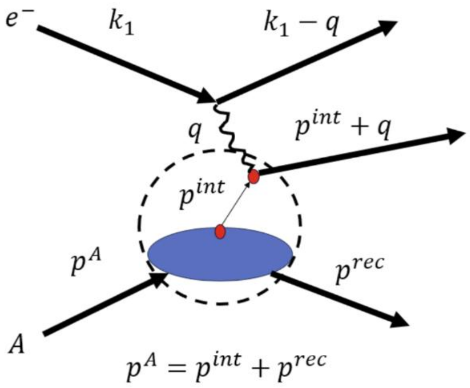


Figure 2: A conceptual diagram of the short-range correlations scattering proces
represents the nucleon with momentum p^{int} being probed by the virtual photon, p
nucleus, p^{rec} is the recoiling nucleus, and the rest are the usual variables.

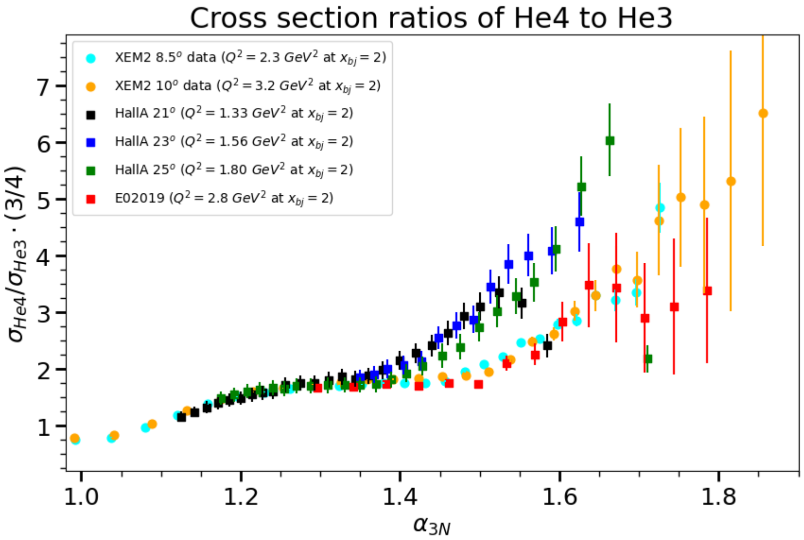
$$\alpha_{3N} = 3 - \frac{q_- + 3m}{2m}\left[1 + \frac{m_s^2 - m^2}{W_{3N}^2} + \sqrt{\left(1 - \frac{(m_s+m)^2}{W_{3N}^2}\right)\left(1 - \frac{(m_s-m)^2}{W_{3N}^2}\right)}\right]$$

with:

$$\begin{aligned} W_{3N}^2 &= Q^2\frac{3-x}{x} + 9m^2 \\ p_s = \sqrt{E_s^2 - m_s^2} \text{ and } E_s &= \frac{W_{3N}^2 - m^2 + m_s^2}{2W_{3N}} \\ m_s^2 &= 4\frac{m^2 + k_t^2}{\beta(2-\beta)} \\ q_- &= \nu - \sqrt{(Q^2 + \nu^2)} \end{aligned}$$

Inclusive 3N SRC data so far

Experiment	Q^2 range (GeV^2)	Max α_{3N}	Note
E02019	~2.7	1.8	XEM (6 GeV)
E08014	1.3-1.9	1.7	Hall A 6 GeV
CLAS	1.6 (ave)	1.4	Resolution Limited
XEM2	2.2, 3.1	1.85	Publication in preparation

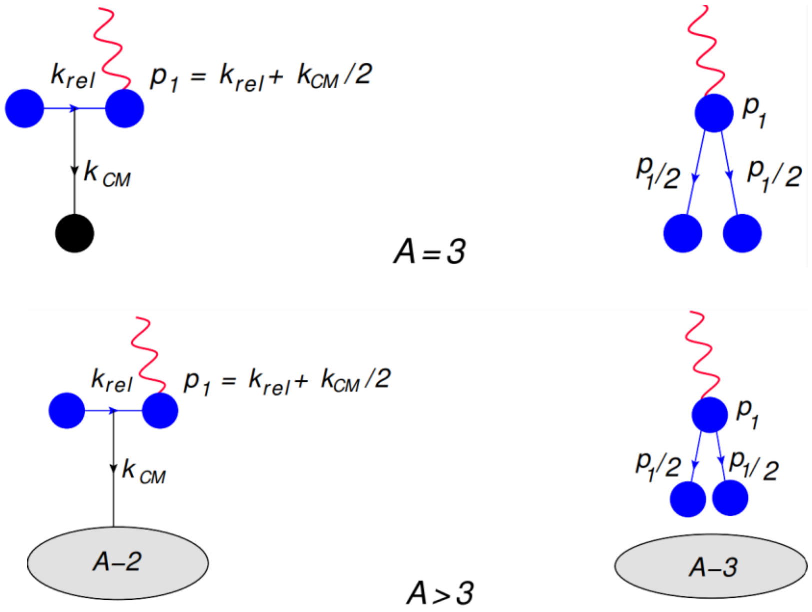


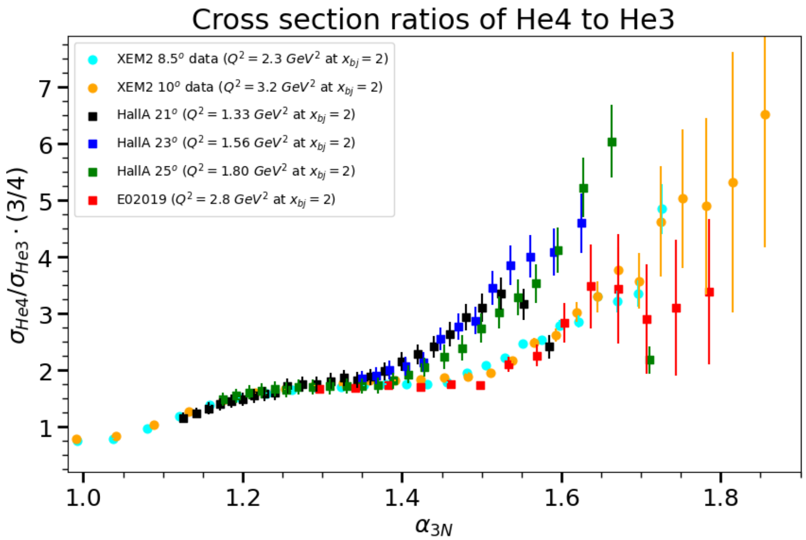
Analogy to x and 2N SRCs:

Q^2-dependence → wrong kinematics

Saturation but no plateau → CoM motion of the pair

Inclusive 3N SRC data so far





Analogy to x and 2N SRCs:

Q²-dependence → wrong kinematics

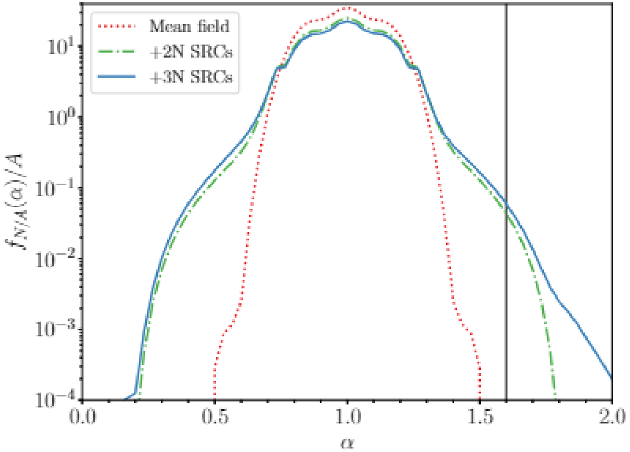
Saturation but no plateau → CoM motion of the pair

Cartoons from Misak Sargsian

Onset of 3N Dominance

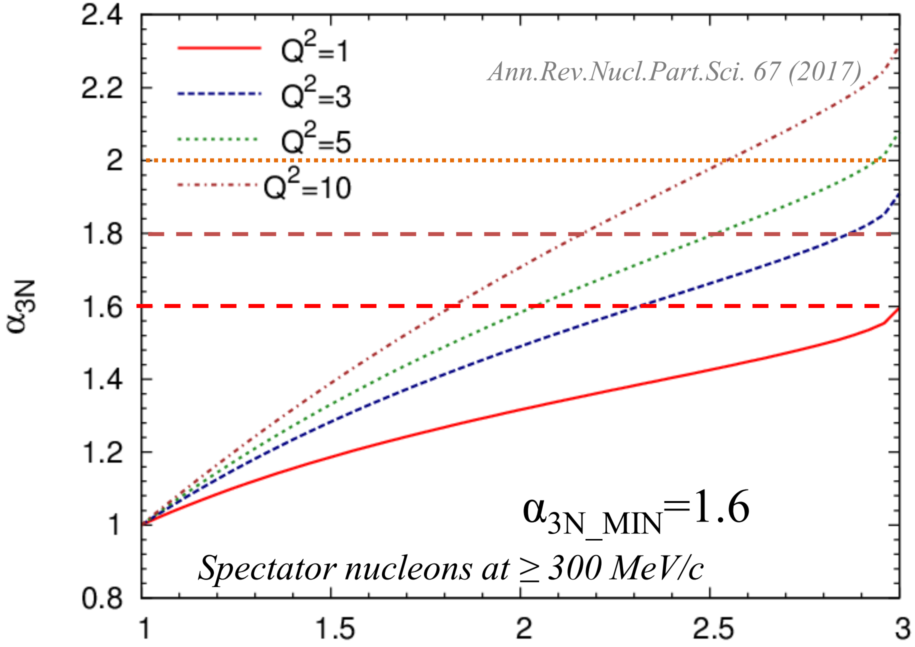
Light cone momentum fraction in a 3N system →

$$\alpha_{3N} = 3 - \frac{q_- + 3m_N}{2m_N}\left[1 + \frac{m_S^2 - m_N^2}{W_{3N}^2} + \sqrt{\left(1 - \frac{(m_S^2 + m_N^2)^2}{W_{3N}^2}\right)\left(1 - \frac{(m_S^2 - m_N^2)^2}{W_{3N}^2}\right)}\right]$$

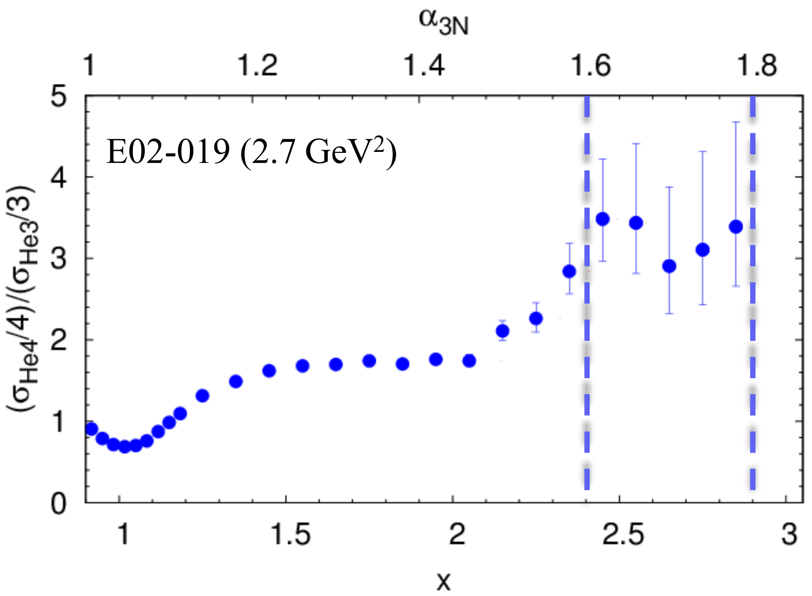


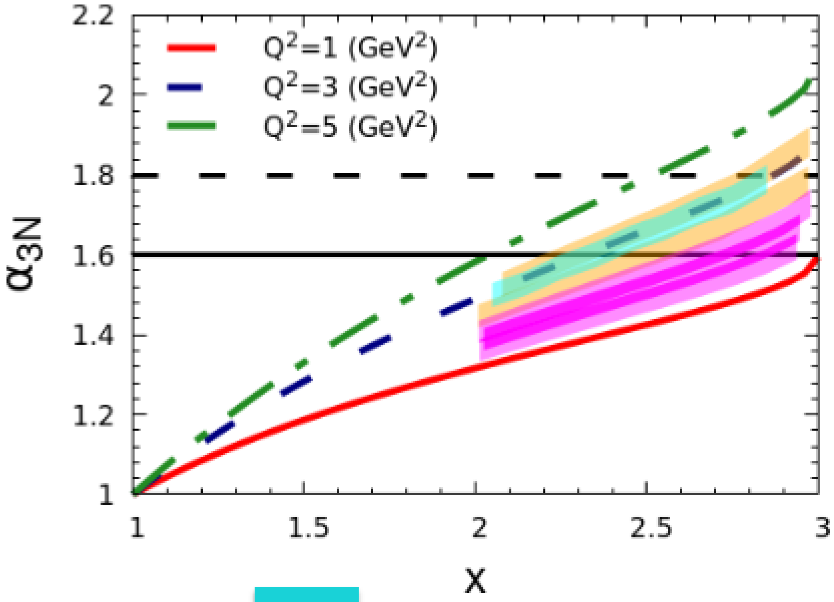
$$\rho_{3N}(\alpha_1) = \int \frac{1}{4}\left[\frac{3-\alpha_3}{(2-\alpha_3)^3}\rho_{pn}(\alpha_3, p_{3\perp})\,\rho_{pn}\left(\frac{2\alpha_2}{3-\alpha_3}, p_{2\perp} + \frac{\alpha_1}{3-\alpha_3}p_{3\perp}\right) + \frac{3-\alpha_2}{(2-\alpha_2)^3}\rho_{pn}(\alpha_2, p_{2\perp})\,\rho_{pn}\left(\frac{2\alpha_3}{3-\alpha_2}, p_{3\perp} + \frac{\alpha_1}{3-\alpha_2}p_{2\perp}\right)\right]\delta\left(\sum_{i=1}^{3}\alpha_i - 3\right) d\alpha_2 d^2p_{2\perp} d\alpha_3 d^2p_{3\perp},$$

Artiles, Phys. Rev. C94 06431 8(2016)



Hall C XEM data from 6 GeV





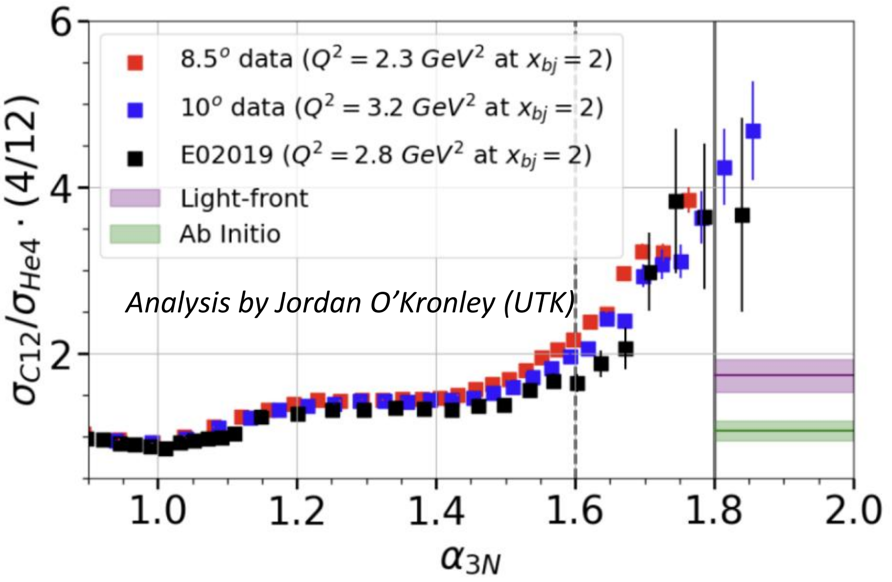
6 GeV XEM

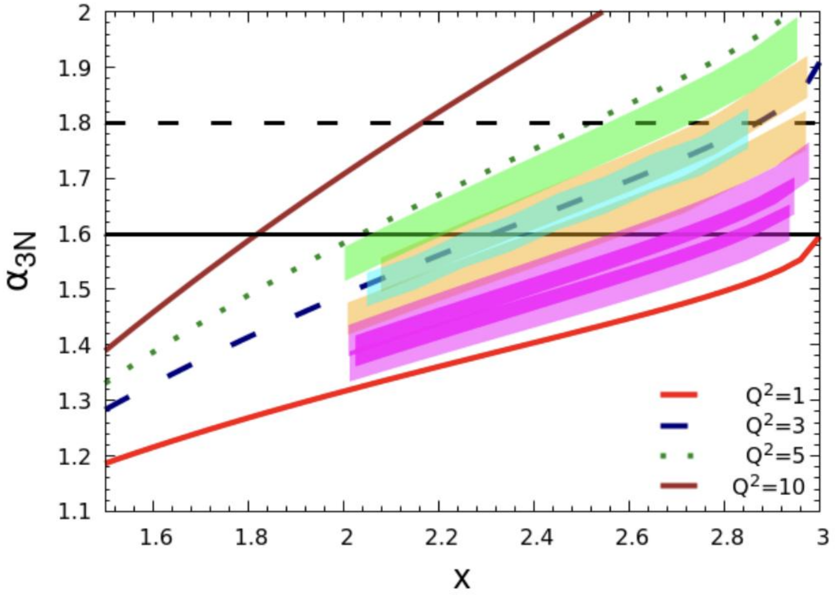
12 GeV XEM2 (Under Analysis)

Hall A at 6 GeV

THE UNIVERSITY OF TENNESSEE KNOXVILLE

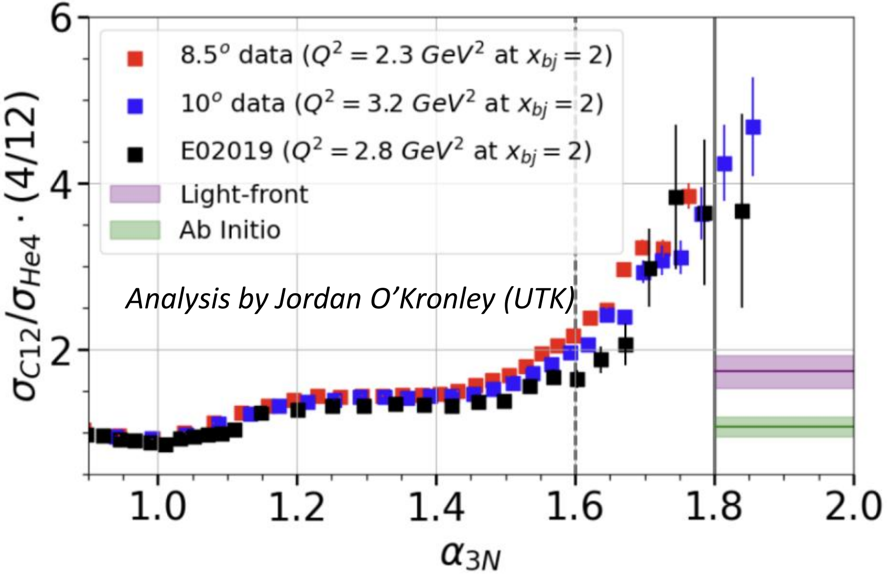
P12-26-005: Pushing to highest Q^2

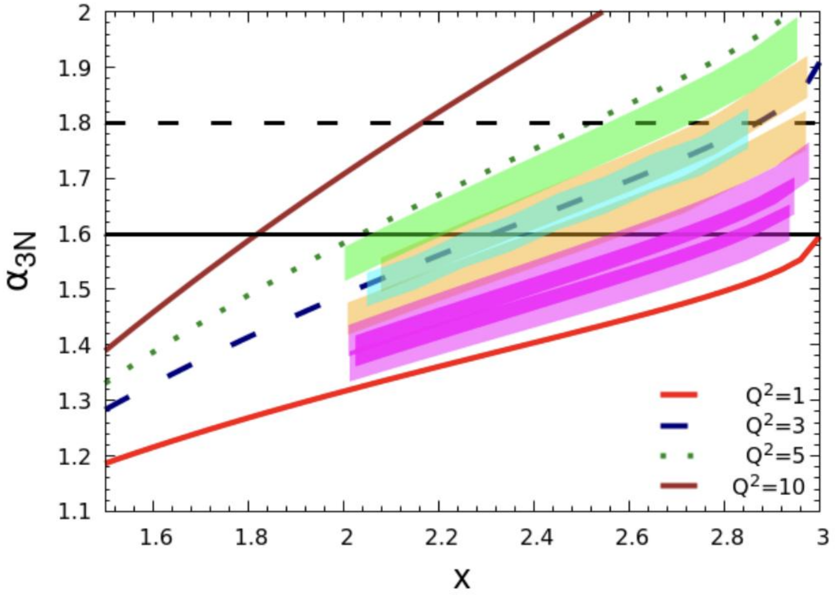




Proposed Kinematics
6 GeV XEM
12 GeV XEM2 (Under Analysis)
Hall A at 6 GeV

P12-26-005: Pushing to highest Q²

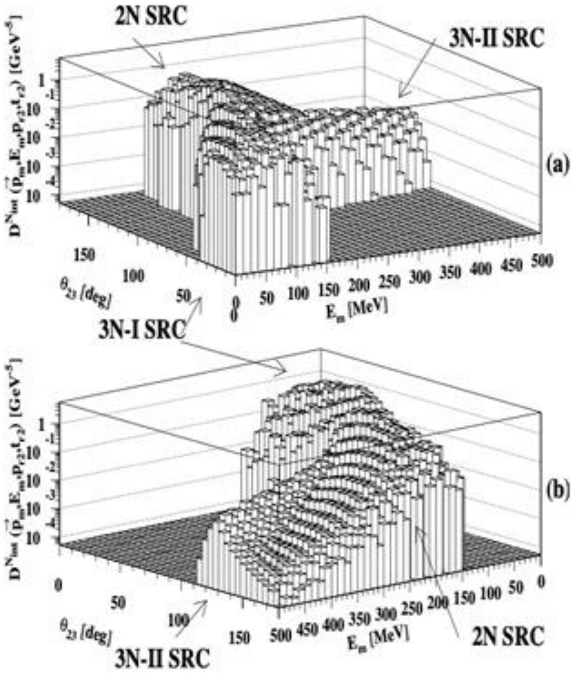




Let's talk about those predictions

Light Front Dynamics (Misak Sargsian)

Phys. Rev. C 71, 044615 (2005)

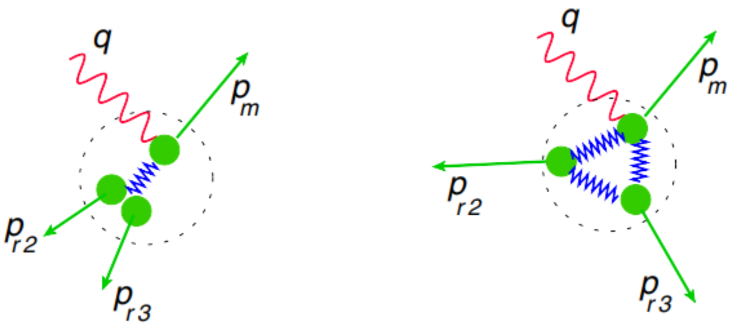


Type I

(rocketship)

Type II

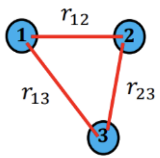
(star)



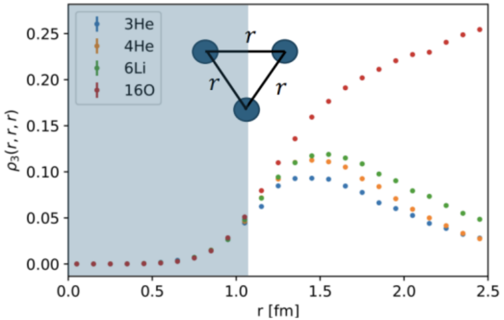
- Jlab inclusive kinematics will be rocketship (energy and momentum conservation)
- Formulated as 2 subsequent 2N SRC interactions
    - Strength goes as $a_3 \sim a_2^2$

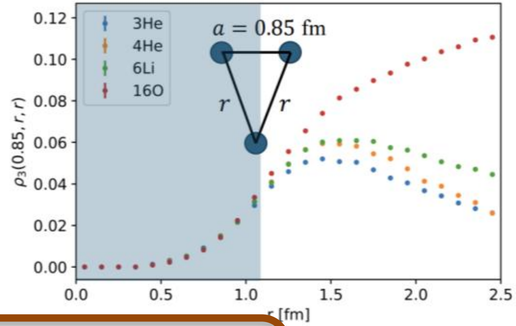
Ab-Initio Calculations (Ronen Weis...)

- Calculations based on exact solutions of the Schrodinger Equation
- Calculate ground state with QMC method (AFDMC)
  - N2LO (R=1.0 fm) E1 local chiral interaction
- Integrate over all configurations
  - Universal scaling



$$\rho_3(r_{12}, r_{13}, r_{23}) \equiv \binom{A}{3} \langle \Psi | \delta(|\boldsymbol{r}_1 - \boldsymbol{r}_2| - r_{12}) \delta(|\boldsymbol{r}_1 - \boldsymbol{r}_3| - r_{13}) \delta(|\boldsymbol{r}_2 - \boldsymbol{r}_3| - r_{23}) | \Psi \rangle$$

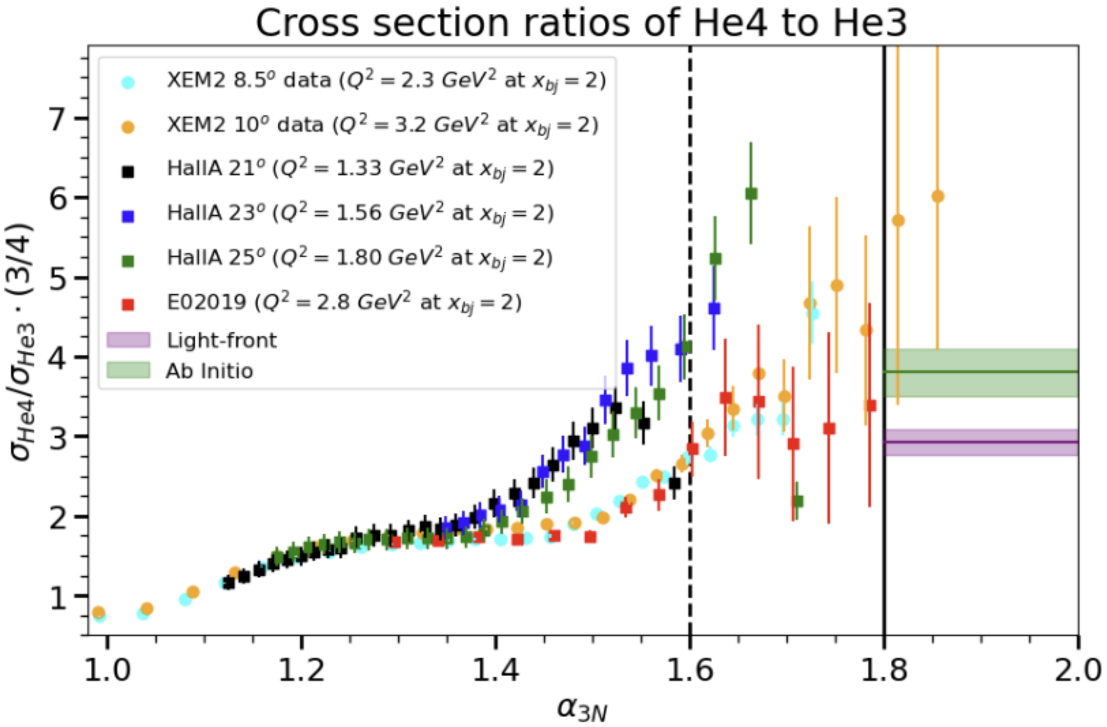




$$\frac{C(\,^4\mathrm{He})}{C(\,^3\mathrm{He})} \times \frac{3}{4} = 3.8 \pm 0.3 \qquad \frac{C(\,^6\mathrm{Li})}{C(\,^4\mathrm{He})} \times \frac{4}{6} = 0.82 \pm 0.10 \qquad \frac{C(^{12}\mathrm{C})}{C(\,^4\mathrm{He})} \times \frac{4}{12} = 1.08 \pm 0.12$$

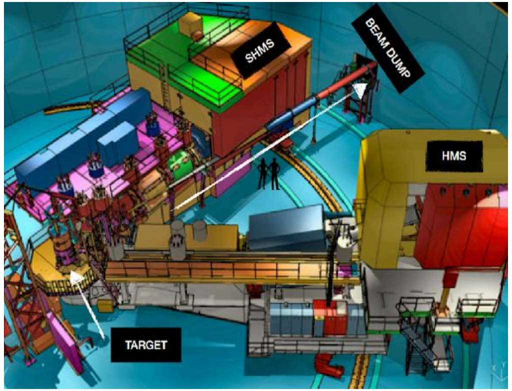
Phys. Rev. C 108 (2023)

Comparison to Existing Data



Experimental Details

PR12-26-005: Request

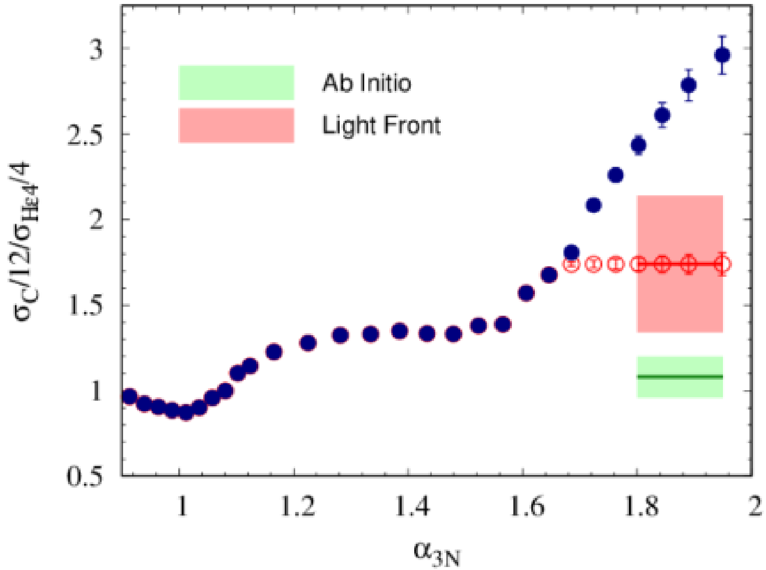


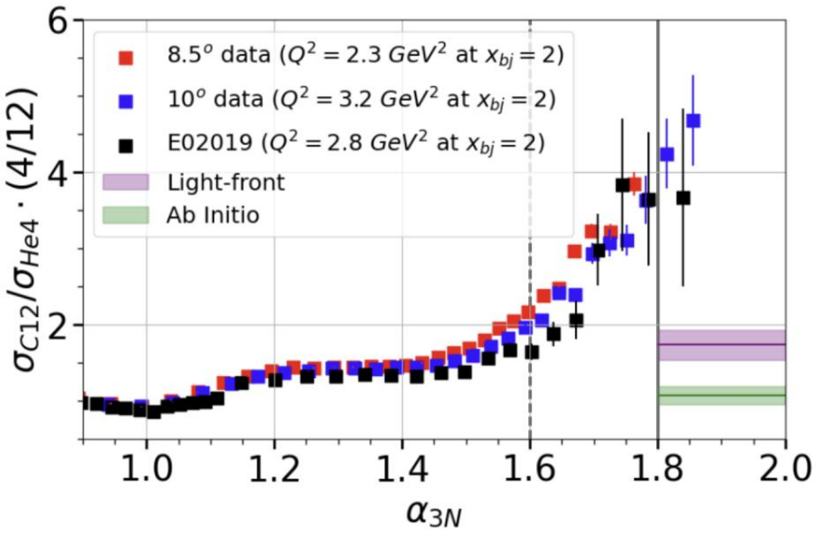
Target	Target thickness (g/cm^2)	P_{SHMS} (GeV)	Current (uA)	Production	non-production activities	total time
^{4}**He**	1.2927	9.2	60	213 hrs	-	213 hrs
^{6}**Li**	0.225	9.2	40	277 hrs	-	277 hrs
^{12}**C**	0.574	9.2	60	91 hours	6 hrs (calibration)	97 hrs
Al dummy	0.24/0.236	9.2	40	27 hrs	-	27 hrs
LD2	1.6698	9.2	60	-	4 hrs (trigger/hodoscope tests)	4 hrs
LH2	0.7247	-	60	-	12 hrs (hydrogen elastic)	12 hrs
-	-	-	-	-	kinematic and target changes	2 hrs
-	-	-	-	-	^{1,2}H to ^{4}He target changeover	48 hrs
						680 hrs (28.3 days)

- Standard Hall C equipment
- No new or exotic targets

PR12-26-005: Statistics Requested

$$\frac{\sigma_{12C}/12}{\sigma_{4He}/4}$$





- Statistics focused on 2.5 < x < 3.0 kinematic range: 3% [on the ratio]

PR12-26-005: Systematic Uncertainties

- **First**: in cross section ratios, many systematic effects cancel or have reduced uncertainties
- **Second**: Observation vs quoting a precise a3 value

Source	Scale	Point-to-Point
Trigger Eff	-	0.02%
Track Eff	0.5%	0.3%
τ_{He} (incl boiling)	1.5%**	-
τ_A	(0.5-1.0)%	-
PID cuts	-	0.2%
Ytar accep	0.5%	0.2%
Charge	0.5%	0.35%
Pion Contam.	-	N/A
Dummy sub	0.7%	0.3%
Model dependence	-	1%
Kine offsets	0.6%	0.7% (1.4% for x>1.7)
Rad Corr	0.5%	0.3%
Total	2.1 - 2.5 %	upto 2%

Strong Community Support (Theory and Exp)

"Thank you for sharing the proposal with me. Having read it now, ***I would like to say that I think it's a good measurement that I'm happy to support.***
I understand there are questions about the theoretical interpretation of the data, and as you know I think they are generally valid. That said, I also think this is a very sensible measurement that should be done. Inclusive scattering has proven to be an informative tool for SRC studies, and while interpreting it for 3N-SRCs may be less straightforward than it was for 2N-SRCs, that situation is unlikely to improve without new data. ***Measuring a minimal set of nuclei at the most extreme kinematics accessible at JLab is worthwhile. I don't know what the outcome will be, but I do think it's a measurement that should be done."***

Or Hen, MIT (leader of SRC exclusive program at JLab)

"Exploring the region of large x and large Q^2 is necessary to understand the remaining fundamental issues of nuclear physics. Knowledge of this kinematic region is related to quark degrees of freedom in nuclei, relativistic nuclear wave functions, the role of non-nucleonic components of nuclear wave functions and reaction mechanisms. It is very likely that the experiment would cause new responses from theorists that go beyond the existing calculations. ***I am very firmly in support of the proposed experiment becoming real."***

Jerry Miller, UW (former PAC member)

Strong Community Support (Theory and Exp)

"The proposed experiment has the potential to provide the first cross section measurements sensitive to three-body short-range correlations. This will allow us to test different existing theories for the formation of 3N SRCs, crucial for further developing a comprehensive theoretical description of short range nuclear physics, and for testing nuclear interaction models."

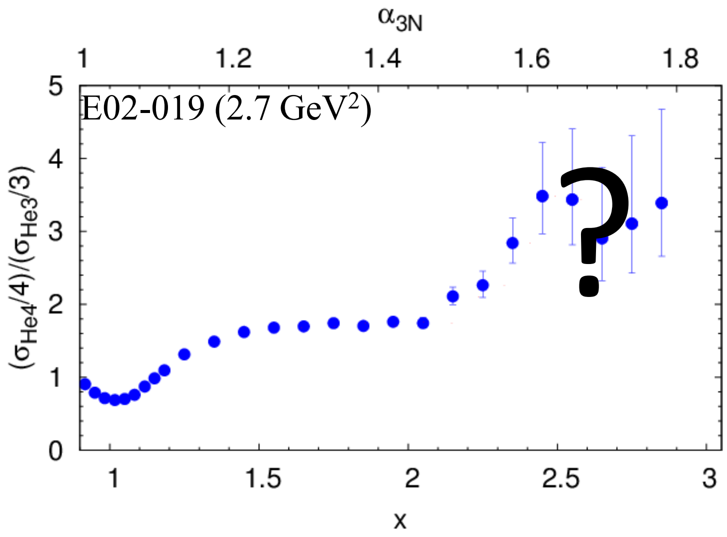
Ronen Weiss, Hebrew University of Jerusalem (Theory)

*"The proposed experiment has significant **discovery power** if 3N-SRCs exist. Discovery of 3N-SRCs will open up a new venue in high energy physics for investigation of dynamical structure of these correlations, identifying dominating interactions and their spin-isospin structure. The measurement carried at wide range of A will be significant for the extrapolation of the observed scaling parameters to infinite nuclear matter and constructing reliable equation of states based on solid phenomenology."*

Misak Sargsian, FIU (Theory)

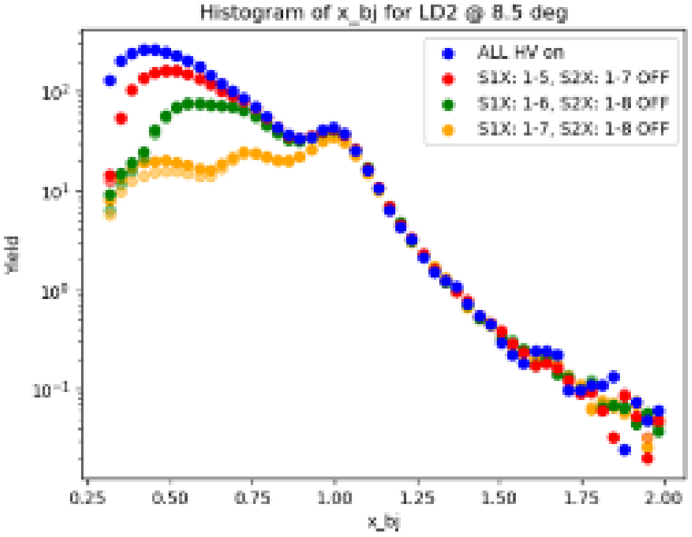
PR12-26-005: Summary

- Potential for a discovery measurement of 3N SRCs
- Hints that we are approaching the right kinematics – need last push
- If we don't see a scaling plateau in A/4He at these kinematics – we cannot access it at Jlab

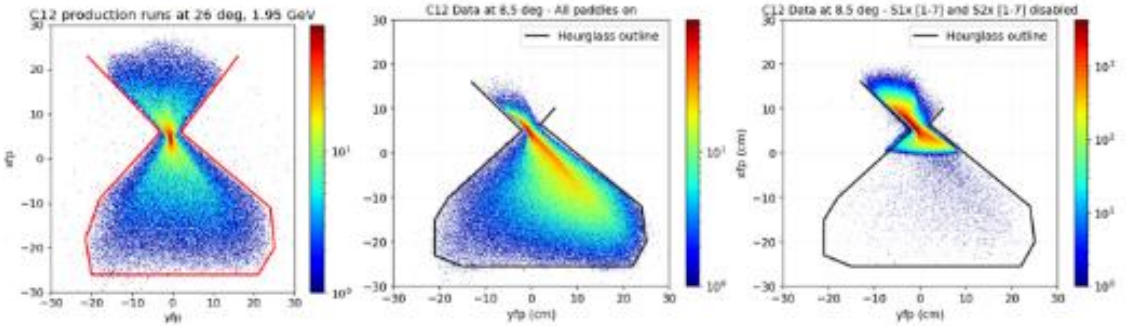


END

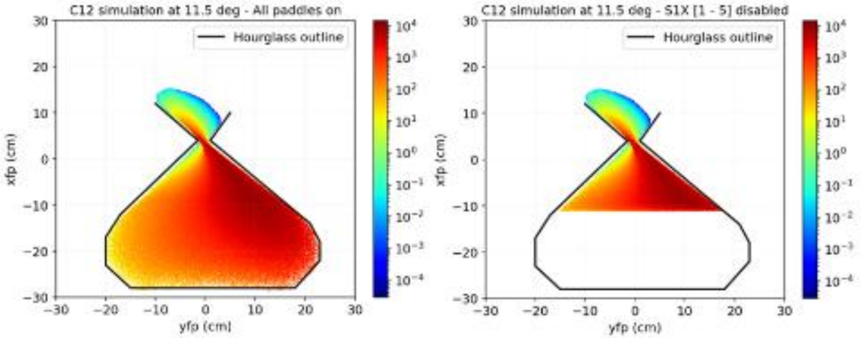
PR12-26-005: Acceptance Simulations



HallC 2023 – XEM2

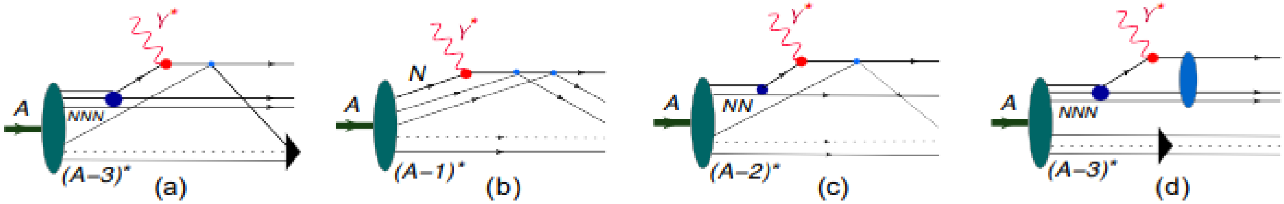


Proposed Kinematics



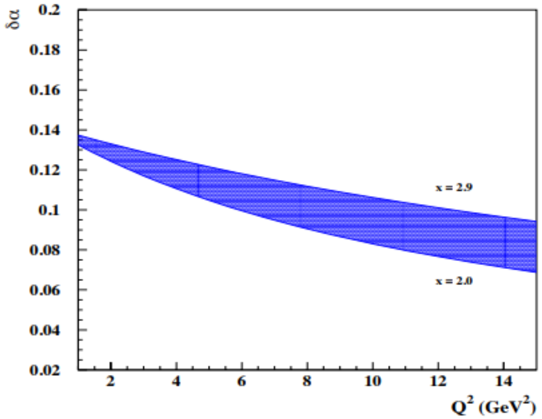
Work by Jordan O'Kronley

Final State Interactions



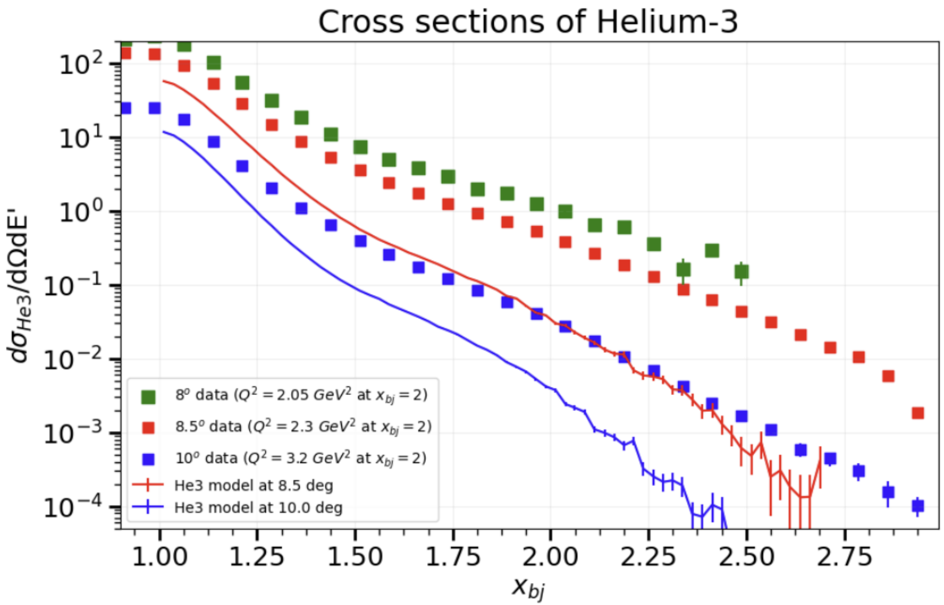
- Migration into the 3N-SRC region is suppressed
  - the approximate conservation of the LC momentum fraction in high energy (eikonal) regime
- Non-conservation estimated to be:

$$\delta\alpha \approx \frac{x^2}{Q^2}\frac{2m_N E_R}{(1+\frac{4m_N^2 x^2}{Q^2})},$$

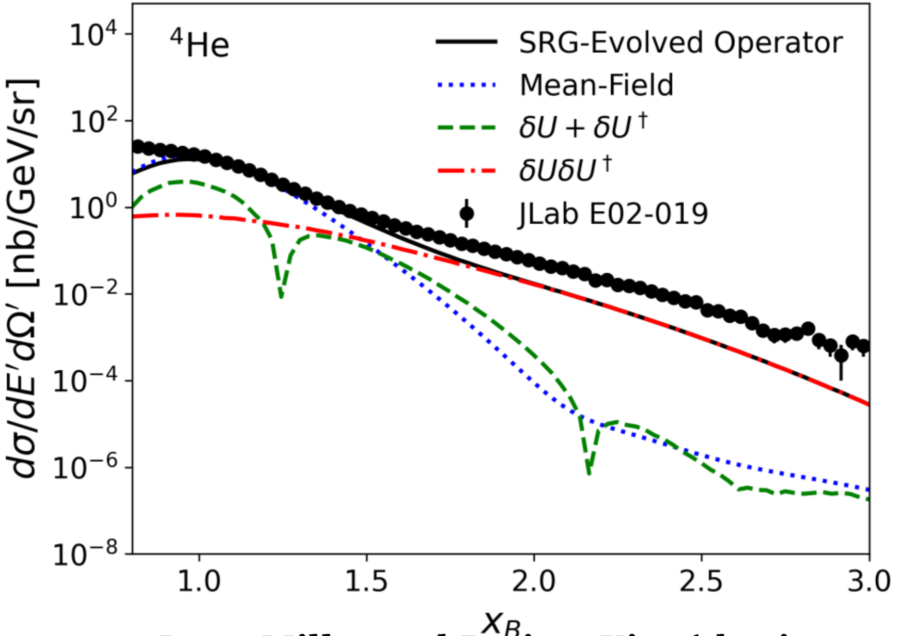


THE UNIVERSITY OF TENNESSEE KNOXVILLE

Inclusive cross section calculations



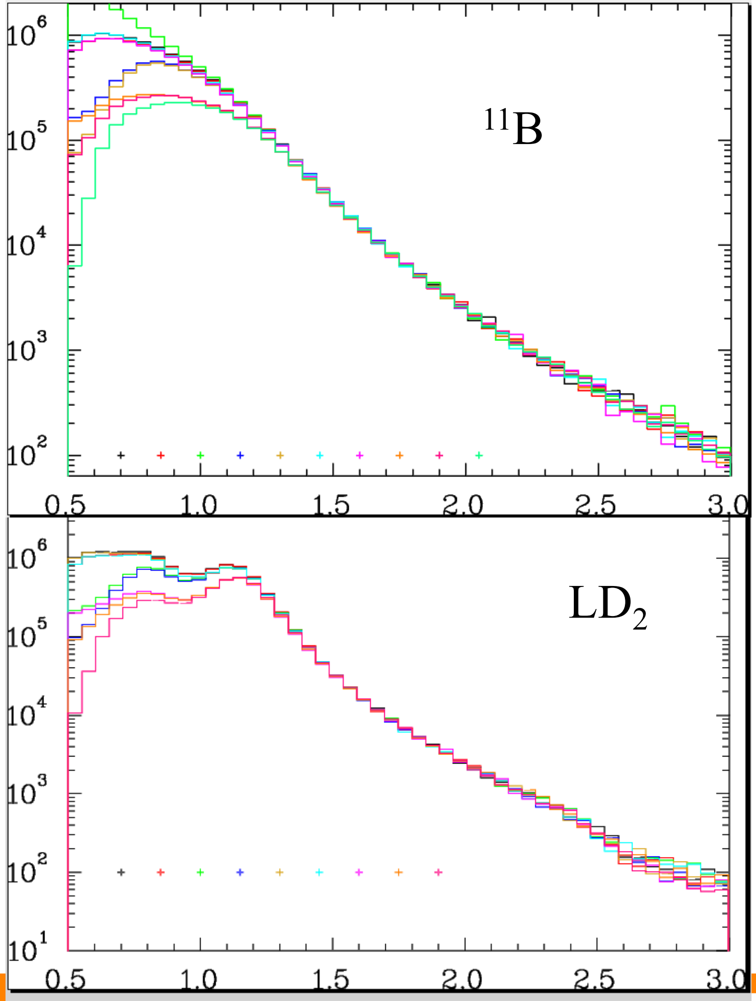
PWIA calculation by Axel Schmidt using Kaptari spectral function



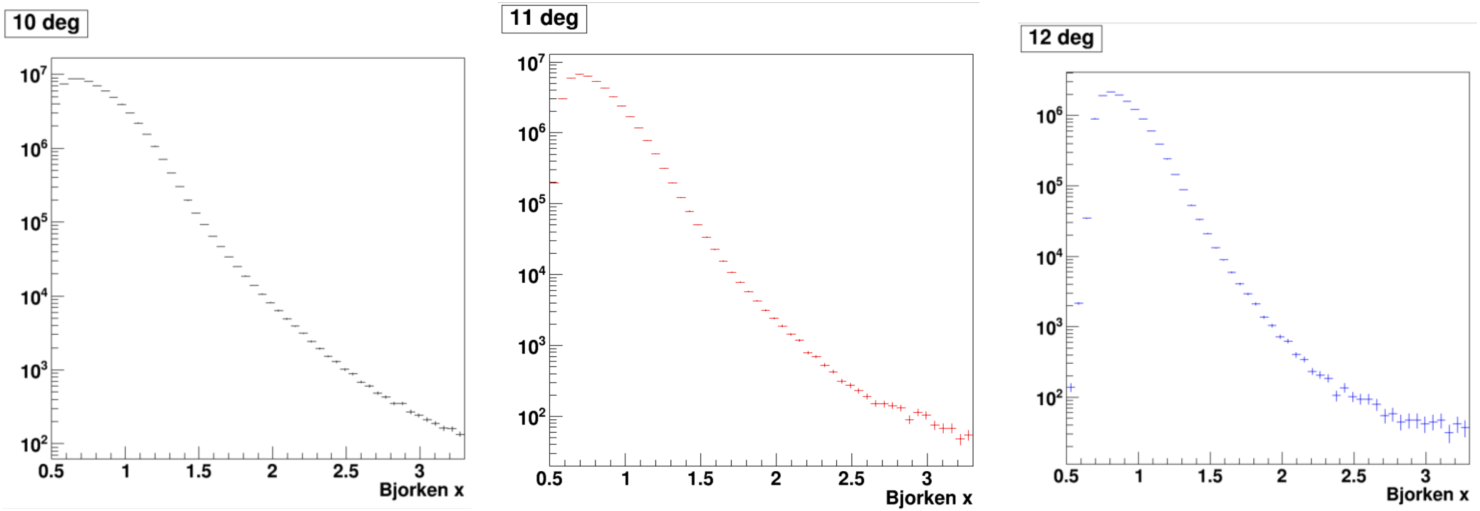
Jerry Miller and Dmitry Kim (thesis: https://arxiv.org/abs/2606.11458v1)

PR12-26-005: Non-production data

- Beam Checkout Procedure
- Trigger tests (LD2 target)
  - Rate Modification via Hodoscope/Preshower configuration change (see plots right)
- Calibrations
- Hydrogen Elastic Data taking
  - PID studies
  - Spectrometer offset studies
- Cryogen Loop Changeover
- Target/kinematic settings changes



PR12-26-005: Estimate of Runtimes (^{11}B)



- **Rates in the 2.5<x<3.0 region known from XEM2 for 10 degrees**
- **Relative scaling based on ^{11}B data for higher angles**

XEM2 (E12-06-105 uncertainties)