New Results on SRC from Inclusive Measurements at JLab

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Jefferson Lab

Nuclear Structure and Dynamics at Short Distances
Institute of Nuclear Theory
February 13, 2013

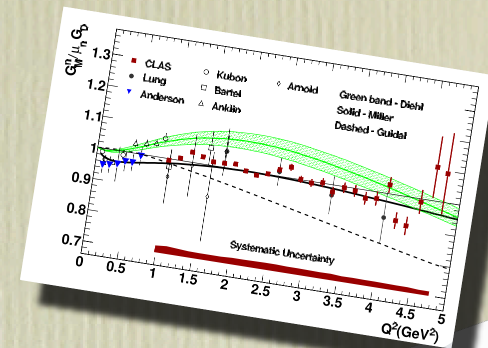
Outline

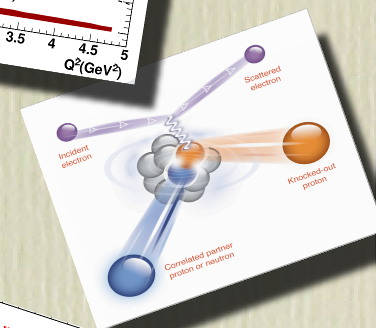
Motivations

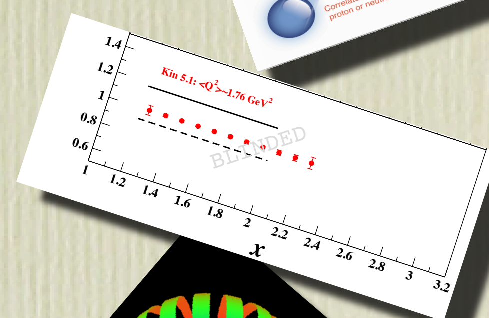
E08-014: the *x*>2 experiment

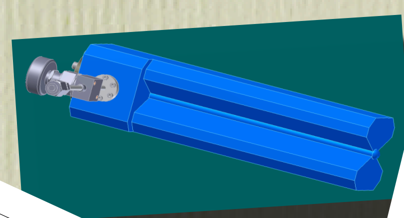
Future measurements planned at JLab 12 GeV

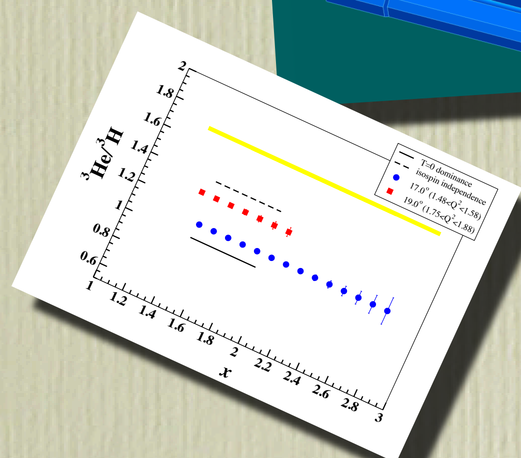
Summary

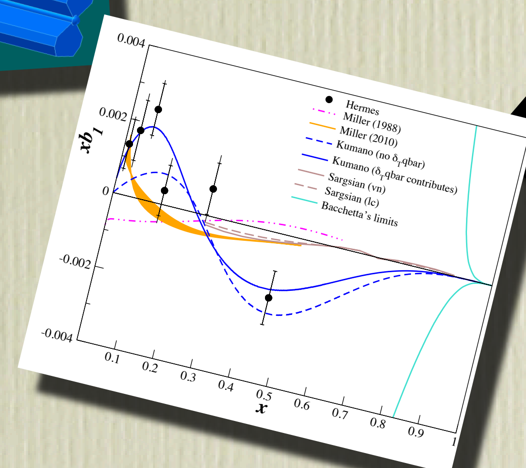


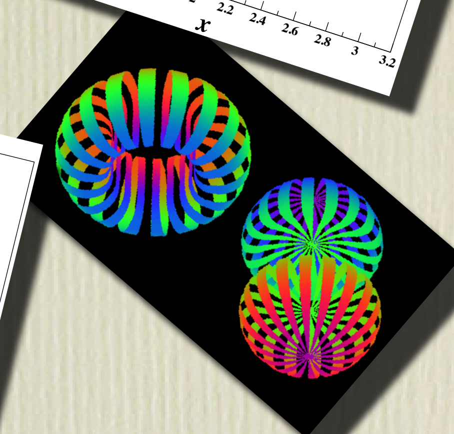






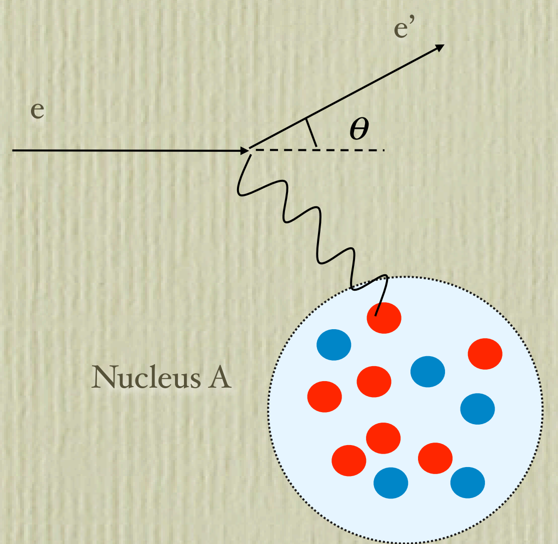




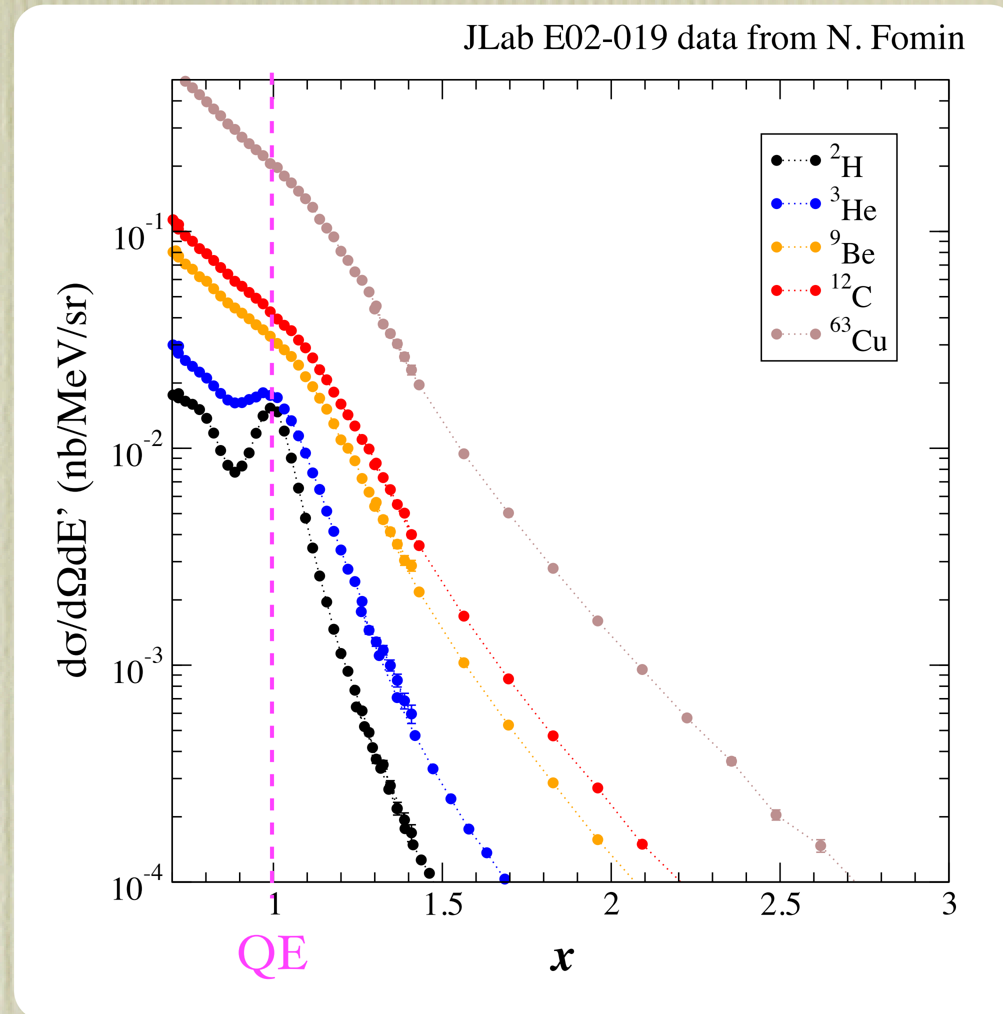


Inclusive scattering at large x

At $x \approx 1$



Quasi-Elastic Scattering



➡ Motion of nucleon in the nucleus broadens the peak.

➡ little strength from QE above $x \approx 1.3$.

Inclusive scattering at large x

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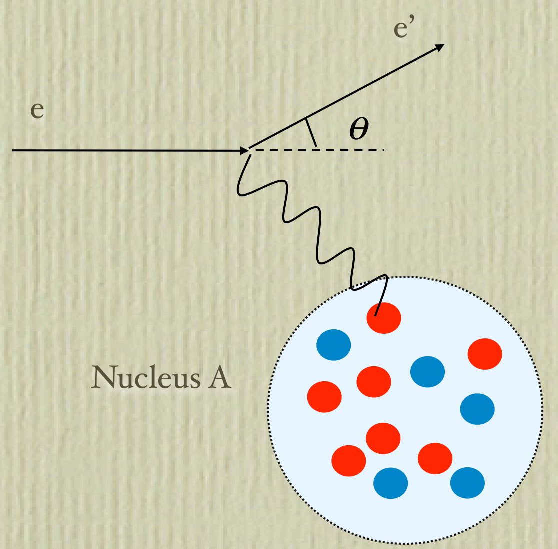

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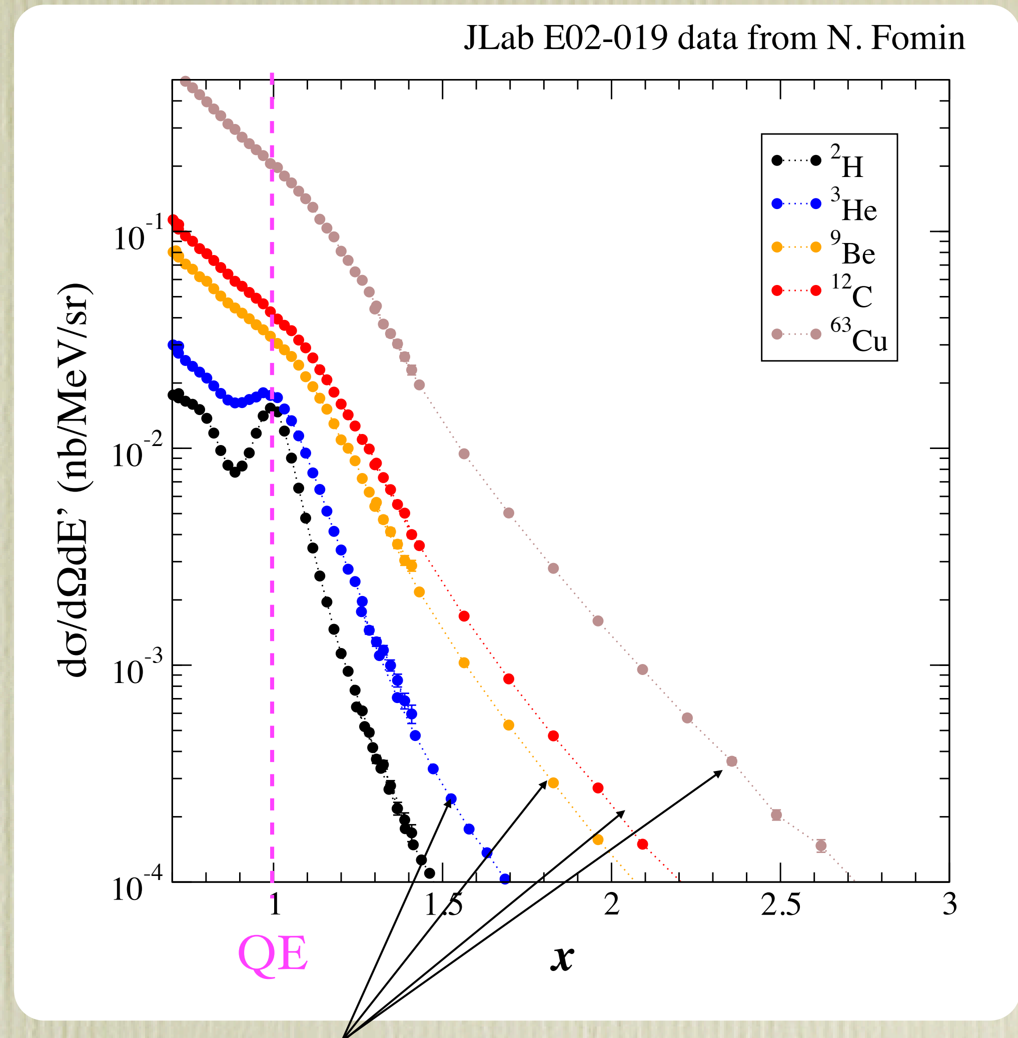
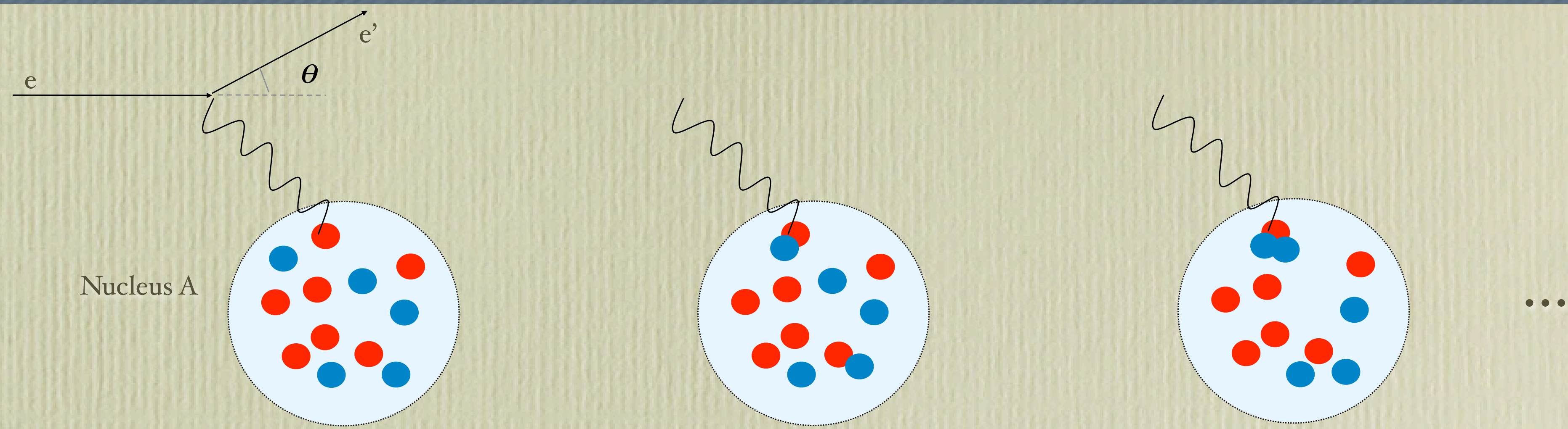


High momentum tails should yield constant ratio if seeing SRC

Short Range Correlations



QES
$x=1$

2N-SRC
$1<x<2$

3N-SRC
$2<x<3$

For $x \geq 1.3$:

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

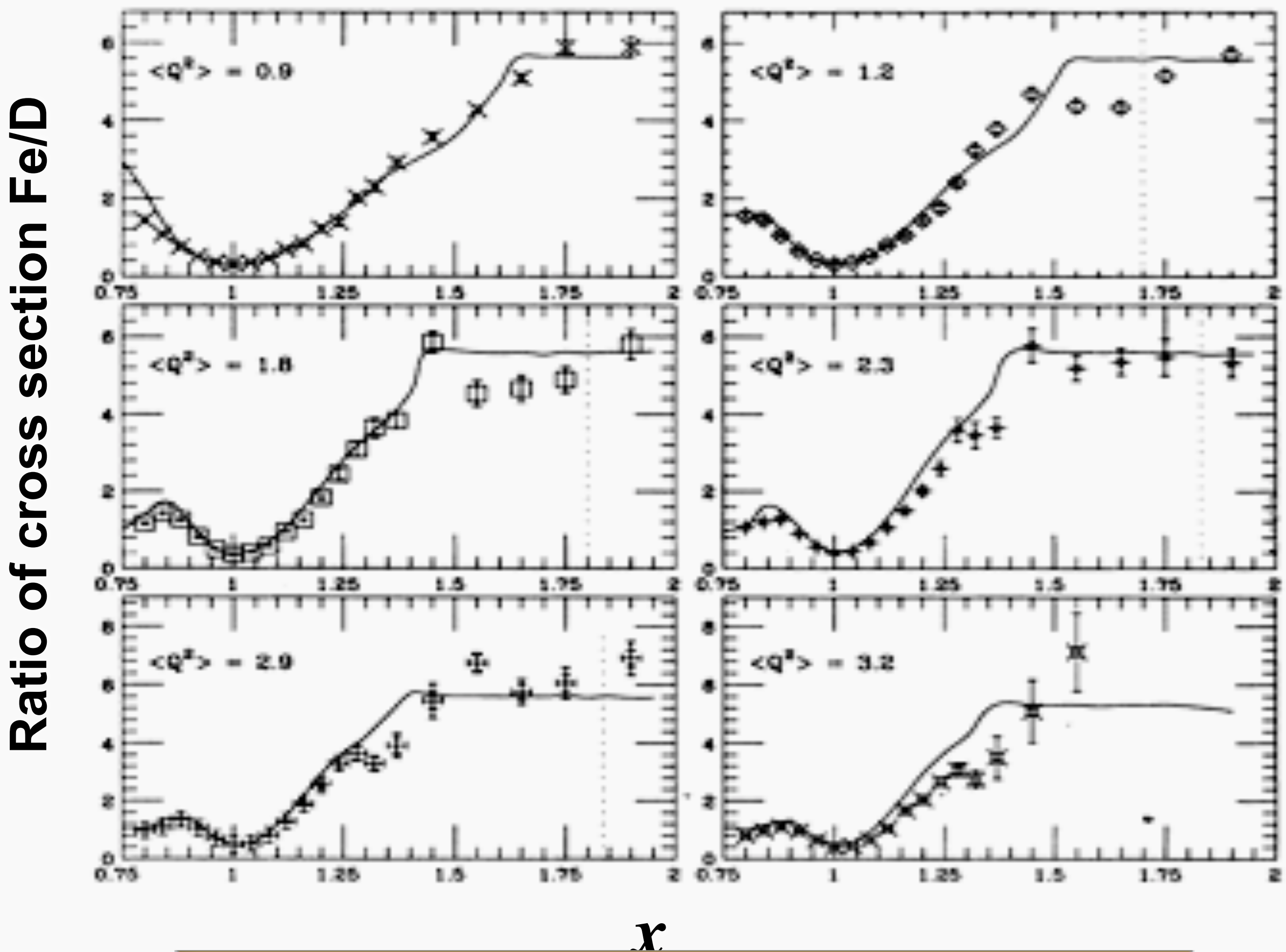
$$= \frac{A}{2} a_2(A)\sigma_2(x,Q^2) + \frac{A}{3} a_3(A)\sigma_3(x,Q^2) + \ldots$$

$\sigma_j \rightarrow$ cross section from a j-nucleon correlation

$a_j(A) \propto$ probability of finding a nucleon in a j-nucleon correlation

SRC evidence at SLAC

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



Ratio in plateau, proportional to the number of 2N SRCs

$a_2(^3He)=1.7\pm0.3$

$a_2(^4He)=3.3\pm0.5$

$a_2(^{12}C)=5.0\pm0.5$

$a_2(^{27}Al)=5.3\pm0.6$

$a_2(^{56}Fe)=5.2\pm0.9$

Evidence of 2N-SRC at x>1.5

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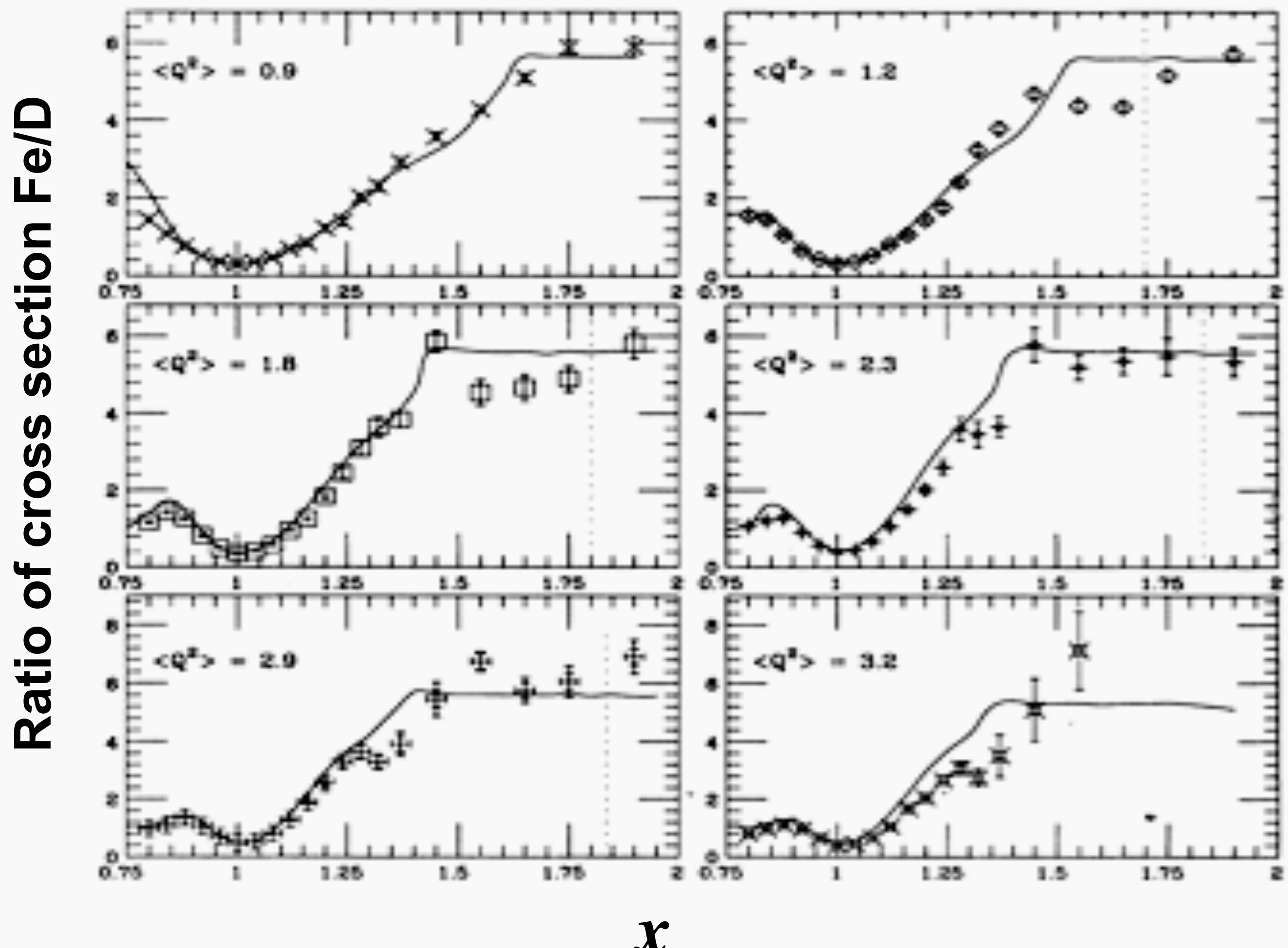

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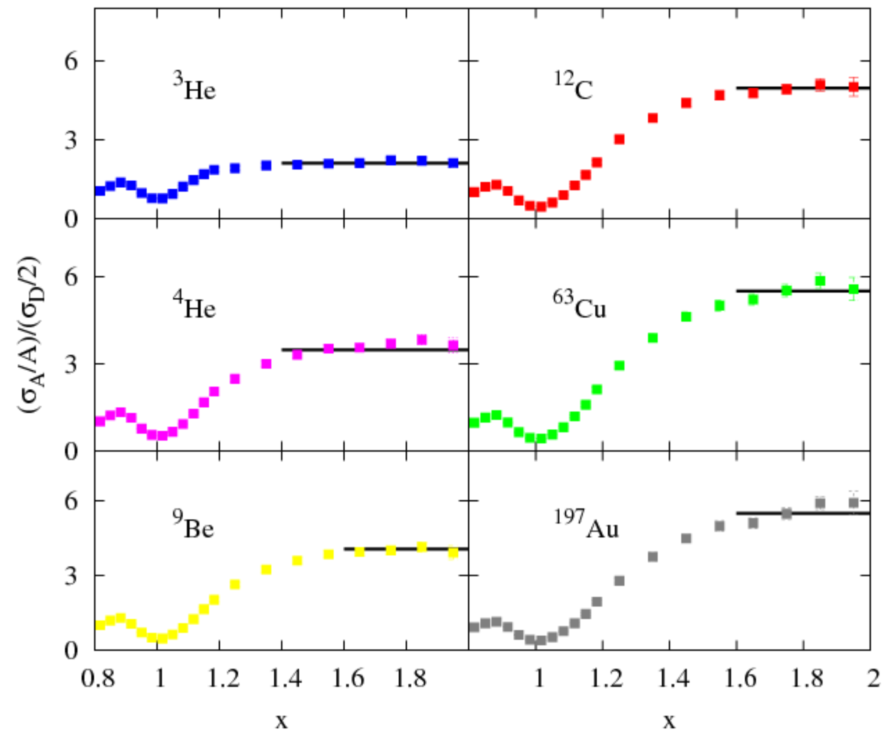
Saturation

SRC evidence at JLab

A	R_{2N} (E02-019)	SLAC
^{3}He	1.93 ± 0.10	1.8 ± 0.3
^{4}He	3.02 ± 0.17	2.8 ± 0.4
Be	3.37 ± 0.17	⋯
C	4.00 ± 0.24	4.2 ± 0.5
Cu(Fe)	4.33 ± 0.28	(4.3 ± 0.8)
Au	4.26 ± 0.29	4.0 ± 0.6
$\langle Q^2 \rangle$	$\sim$2.7 GeV^2	$\sim$1.2 GeV^2
x_{min}	1.5	⋯
α_{min}	1.275	1.25

Hall C

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



Evidence of 2N-SRC at x>1.5

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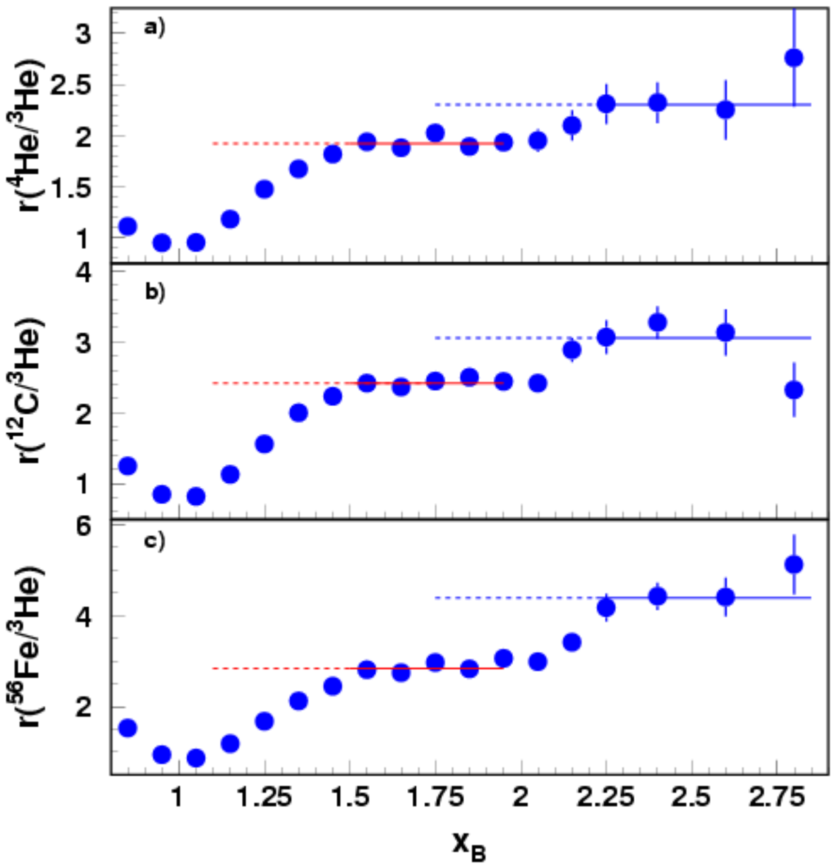
K. S. Egiyan et al., Phys. Rev. Lett. 96, 082501 (2006)



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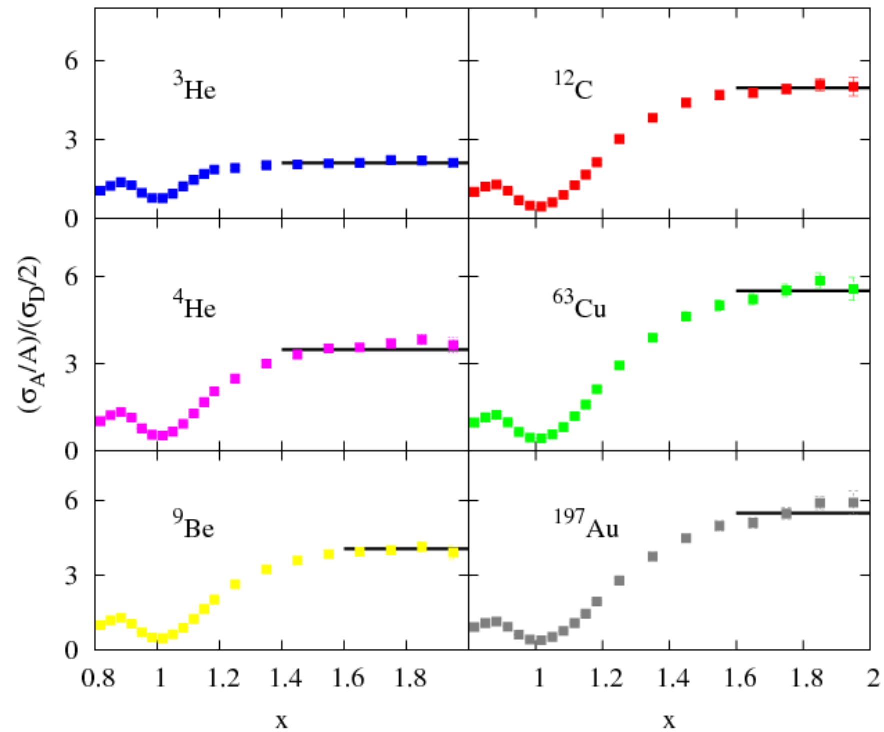

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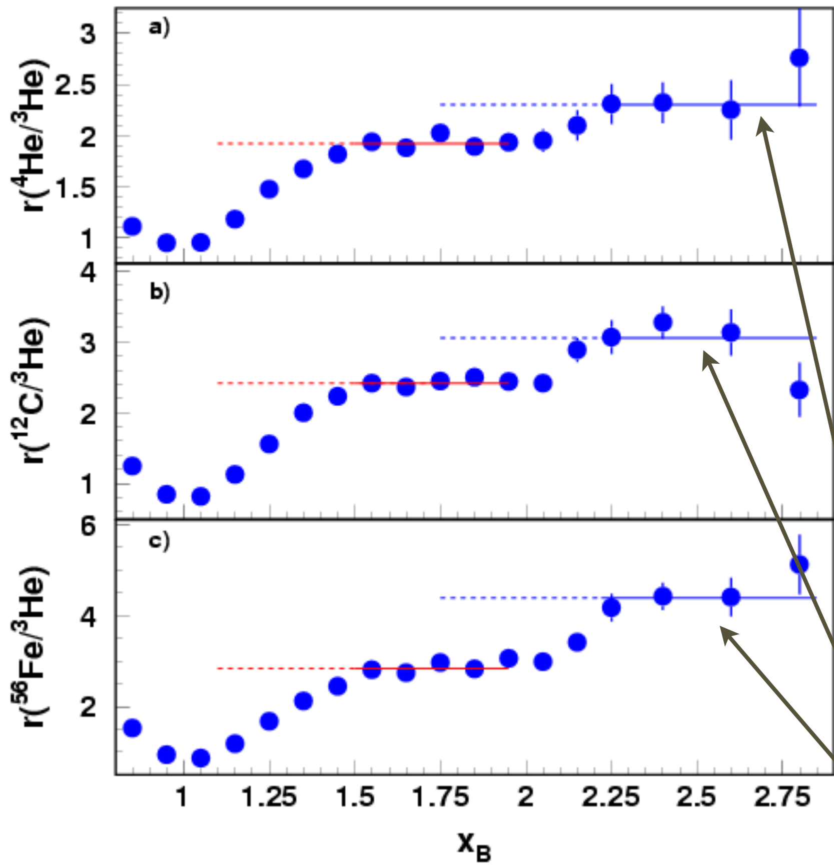

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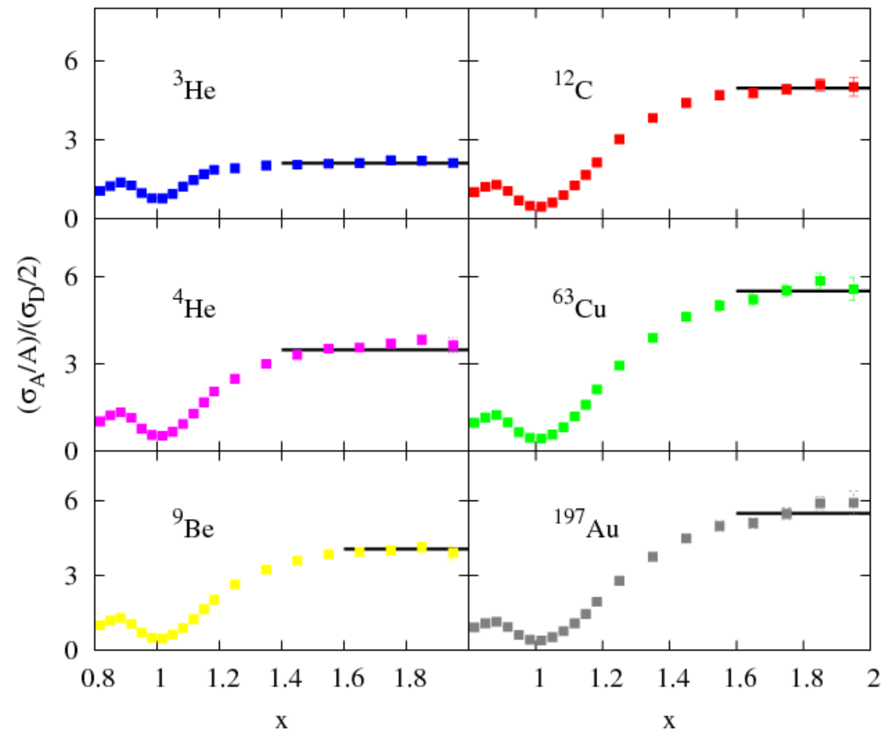
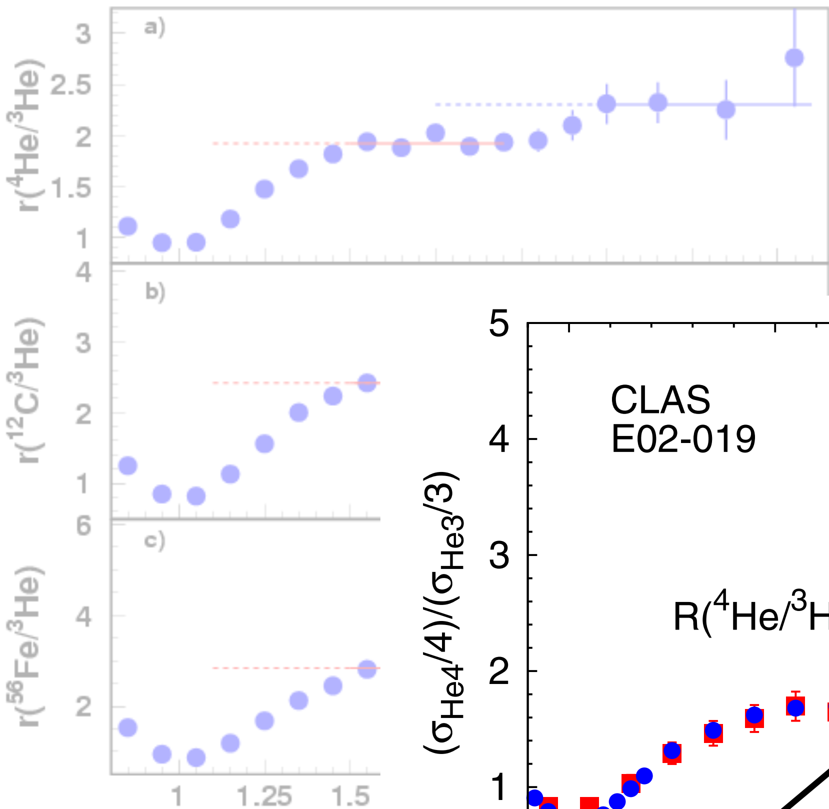


Hint of 3N-SRC at x>2 ?

SRC evidence at JLab

Hall B

K. S. Egiyan et al., Phys. Rev. Lett. 96, 082501 (2006)



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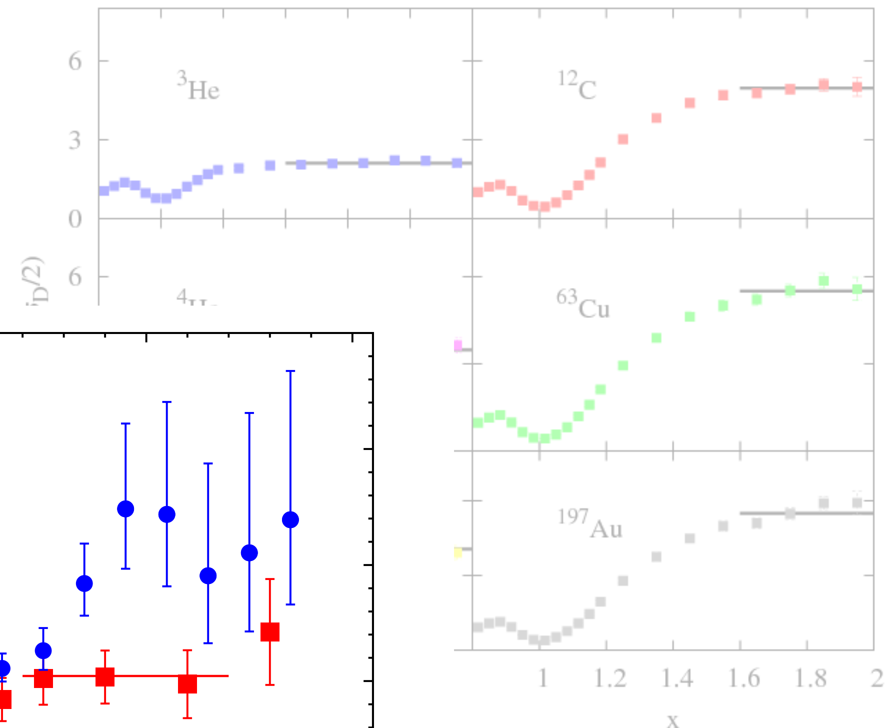
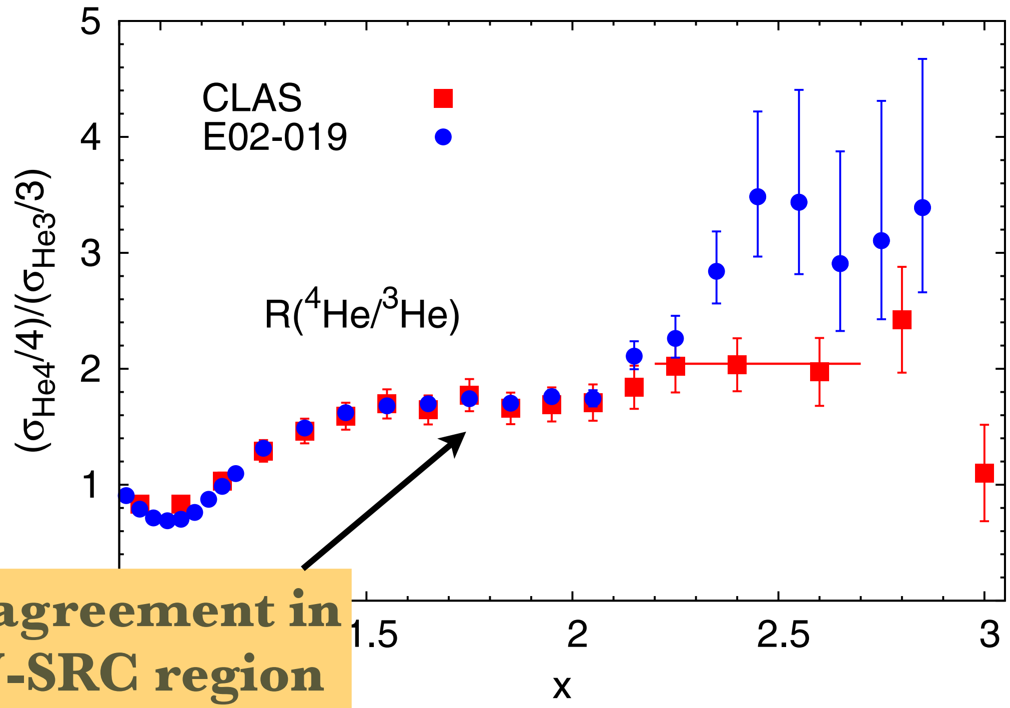
N. Fomin et al., Phys. Rev. Lett. 108, 092502 (2012)





Good agreement in the 2N-SRC region

SRC evidence at JLab

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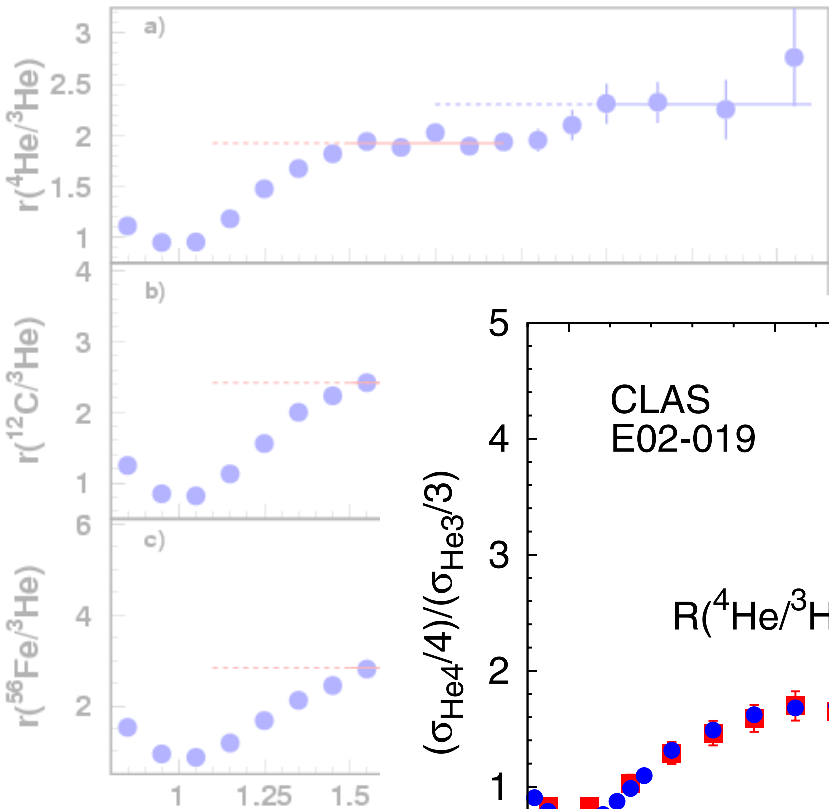

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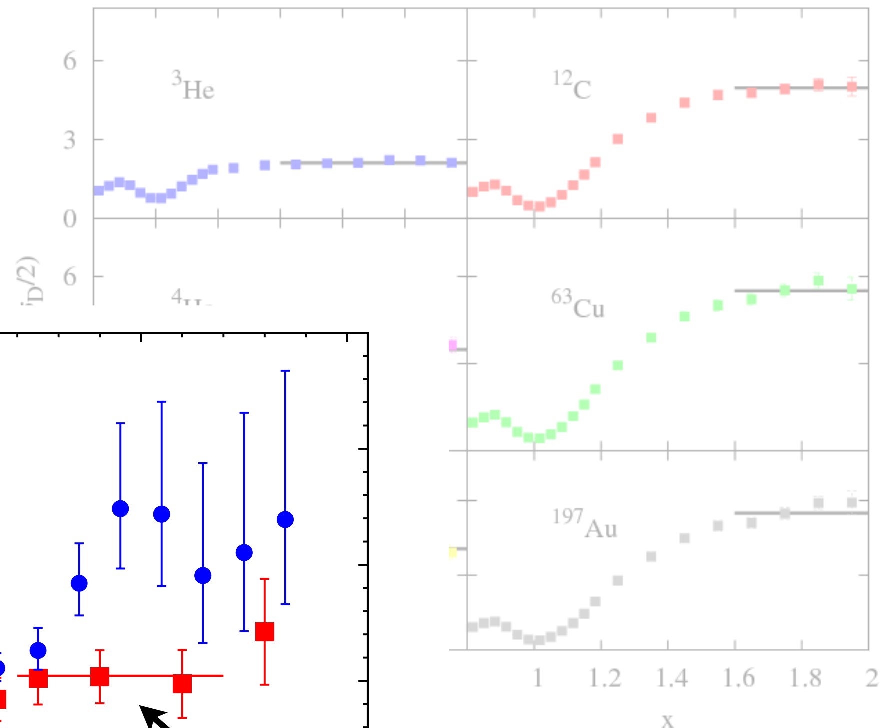
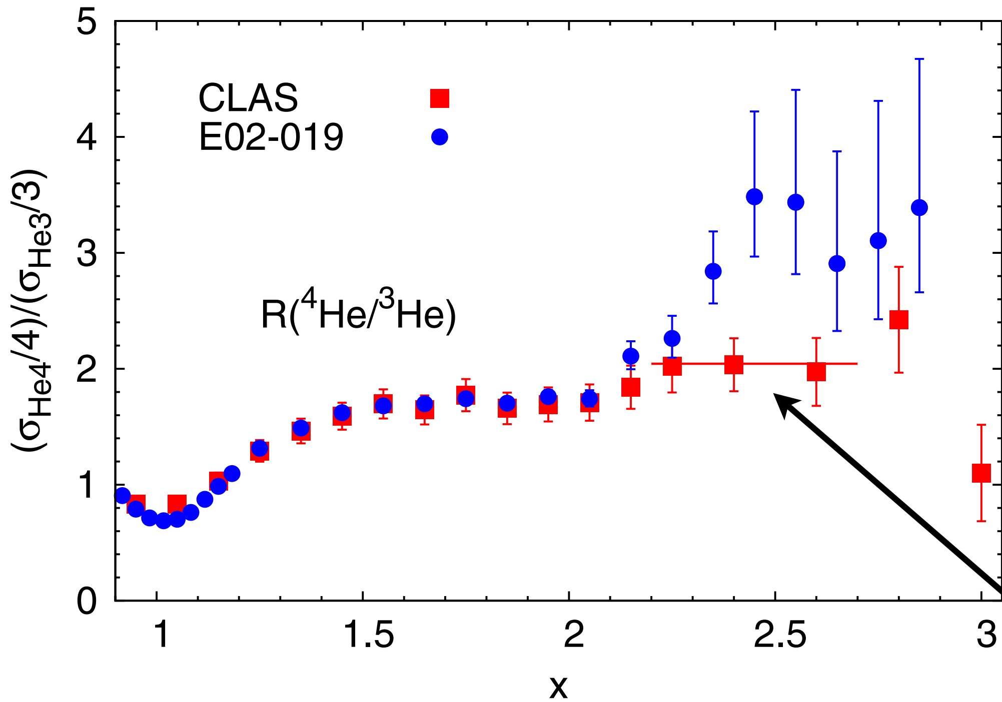




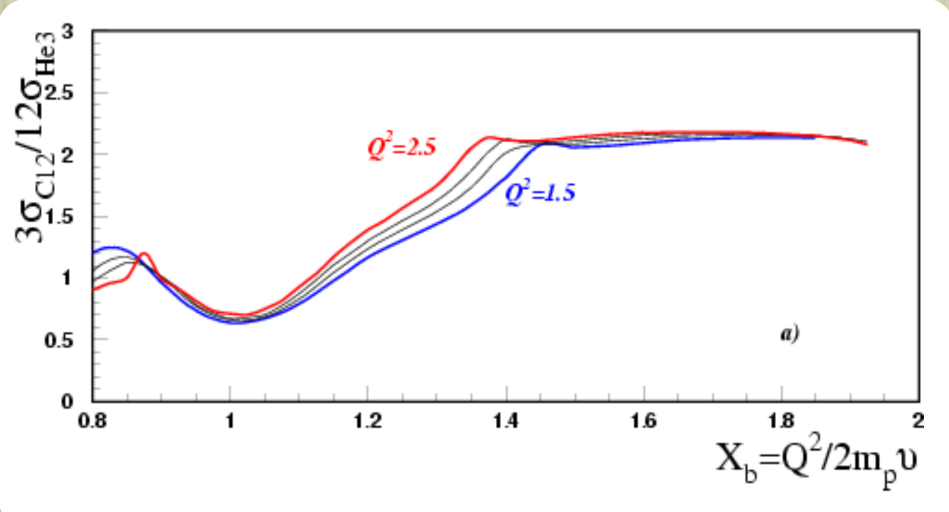
but
potential difference in the 3N-SRC region

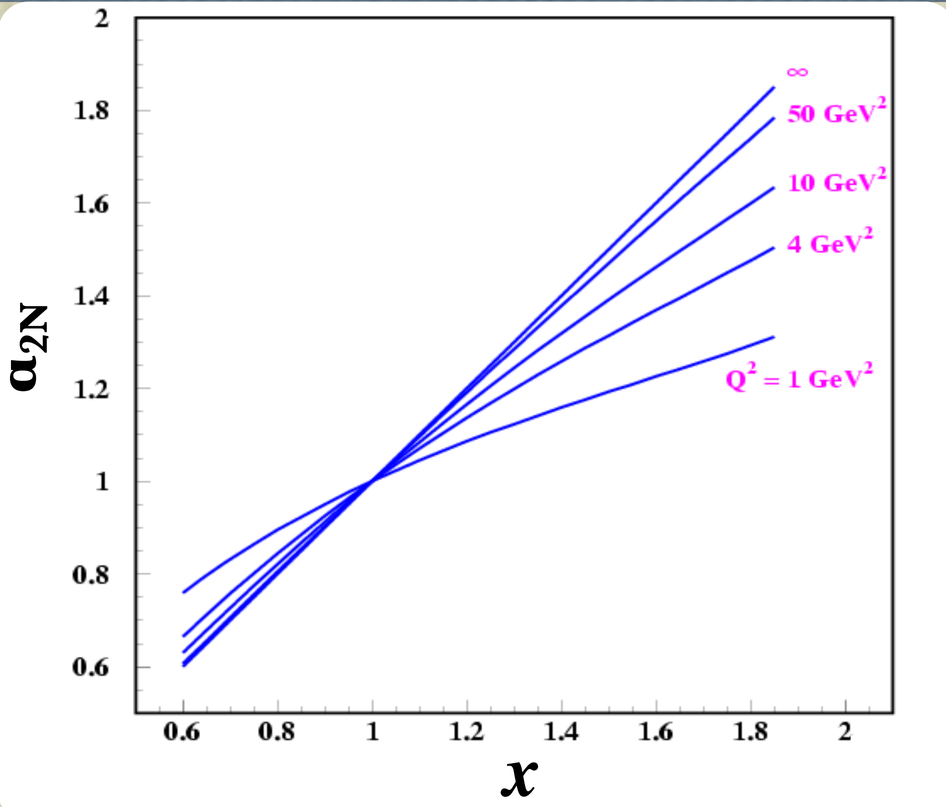
Light-cone fraction: α_{2N}

SRC model: 1N, 2N, 3N, …, contributions at x≤1,2,3,…

Motion of SRCs: broaden the range of contribution

$$\alpha_{2N} = 2 - \frac{q_- + 2m}{2m}\left(1 + \frac{\sqrt{W^2 - 4m^2}}{W}\right)$$





α_{2N} is the light-cone variable for the interacting nucleon of the correlated nucleon pair.

Light-cone fraction: α_{2N}

Ratios versus:

x α_{2N}

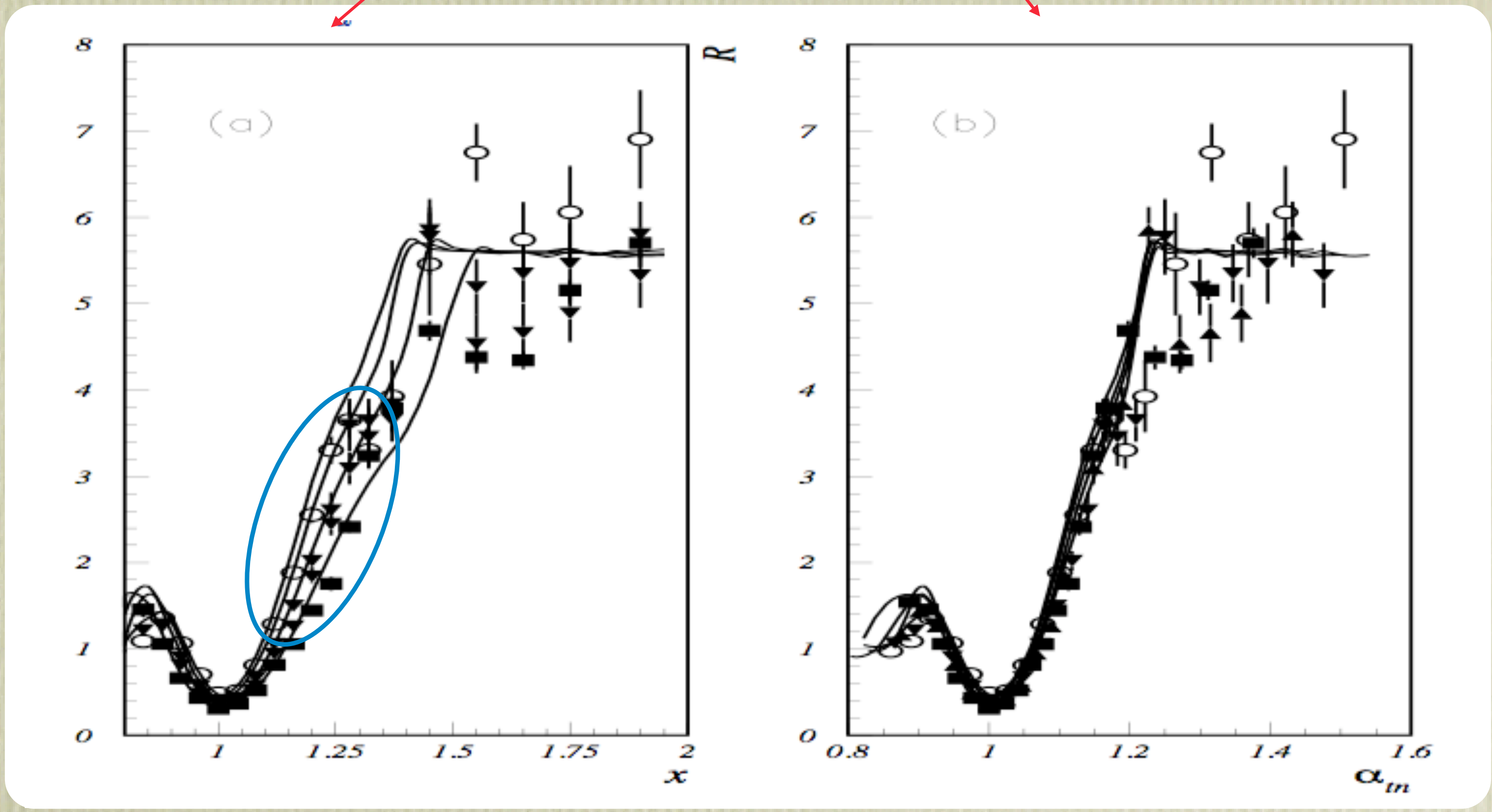
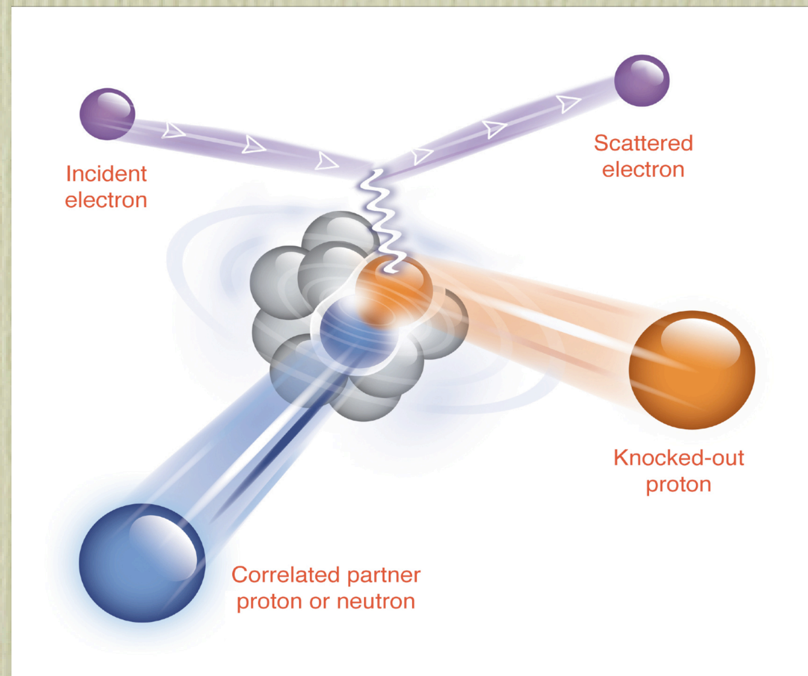


Figure from M. Sargsian

Isospin Symmetry of SRCs ?

Two-nucleon knock-out experiment



Simple SRC model assumes isospin independence

Isospin Symmetry of SRCs ?

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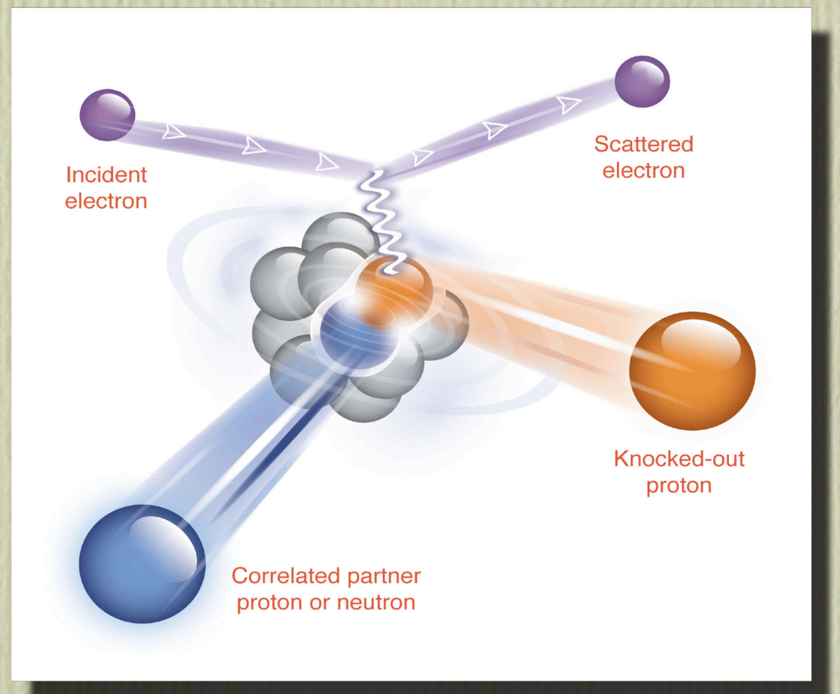
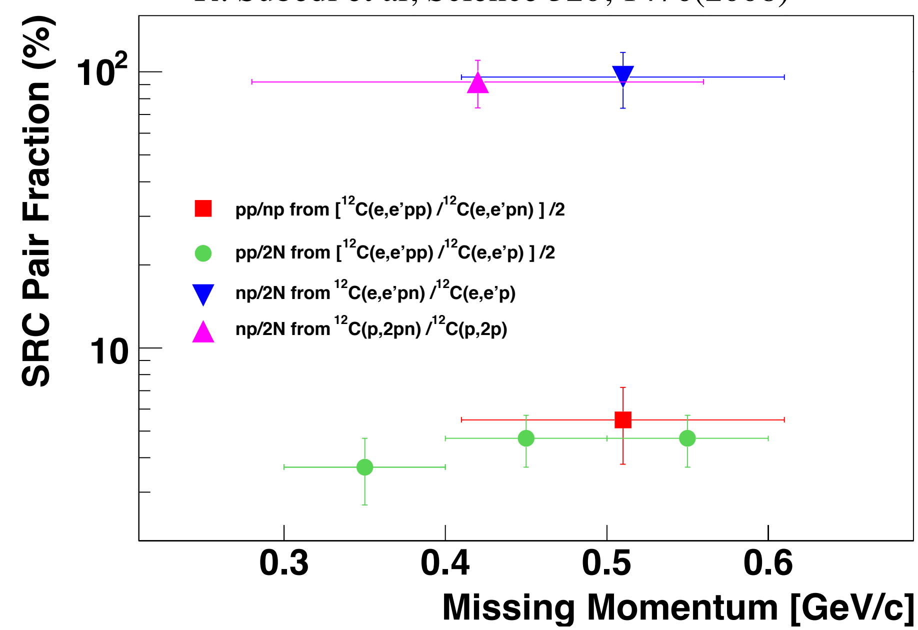


R. Subedi et al, Science 320, 1476(2008)



Simple SRC model assumes isospin independence

Data show large asymmetry between np, pp pairs:

Qualitative agreement with calculations; effect of tensor force

Huge violation of often assumed isospin symmetry

Isospin Symmetry Violation

PRL **98,** 132501 (2007) PHYSICAL REVIEW LETTERS week ending 30 MARCH 2007

Tensor Forces and the Ground-State Structure of Nuclei

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[2]*Department of Physics, Old Dominion University, Norfolk, Virginia 23529, USA*
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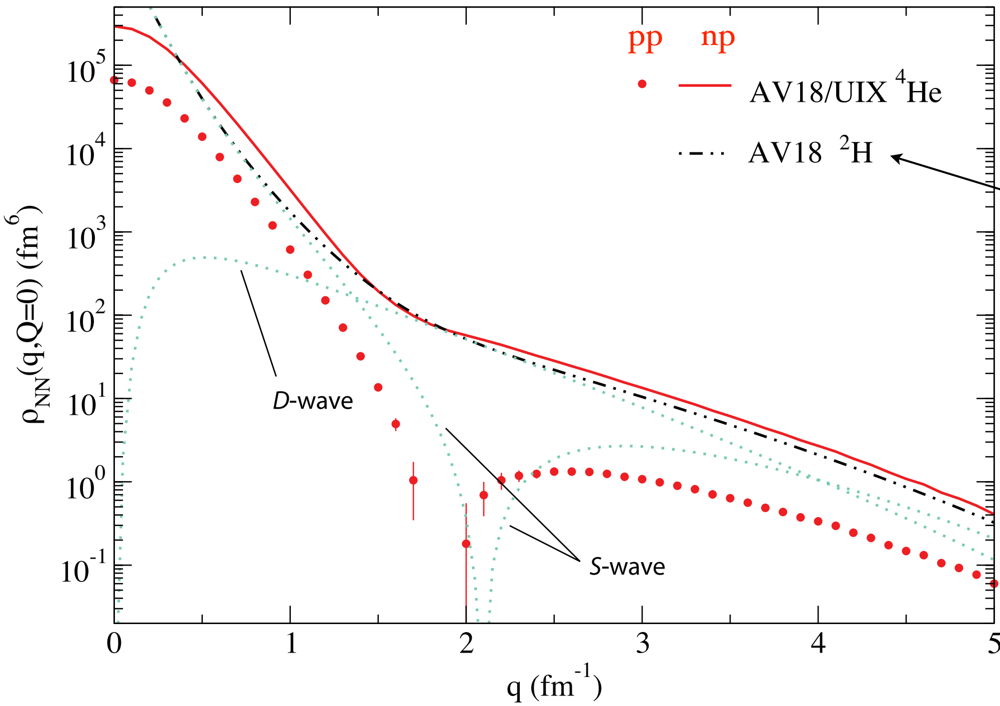
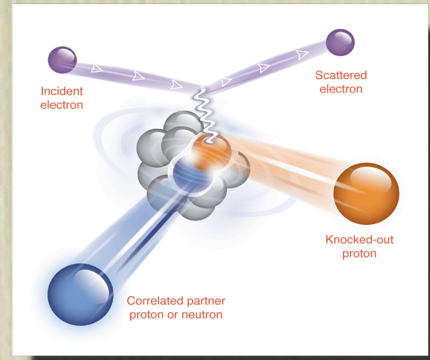
(Received 10 November 2006; published 27 March 2007)



Scaled momentum distribution of the deuteron

Two-Nucleon Knockout Experiments

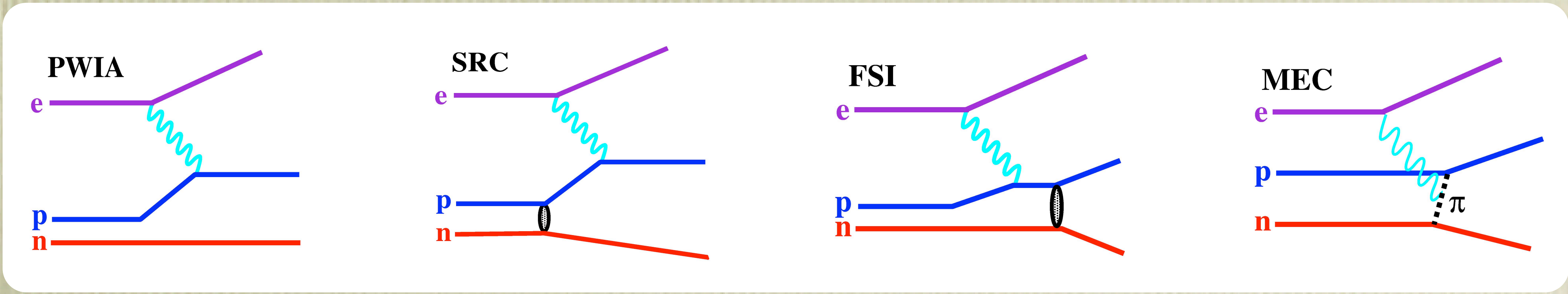


Problem: ^{12}C(e,e'p) data is dominated by FSI/MEC

FSI should conserve total pair momentum, isospin dependence

MEC mainly act to amplify signal of existing SRCs

Really want a ***cleaner,*** *quantitative* measure of isospin dependence



SRC Isospin from Inclusive Scattering

Inclusive ratio is 'isospin-blind' (sum of n and p)

Target **can be isospin sensitive**

➡ Compare ^{40}Ca to ^{48}Ca – JLab experiment E08-014

ran in Spring 2011

➡ Compare ^{3}H to ^{3}He – JLab experiment E12-11-112

scheduled to run in Spring 2015

n-p pair dominance
↓
equal number of high momentum proton and neutron

or

Isospin-independent correlations
↓
Z protons and N neutrons at high momentum

Isospin study of SRC

Simple mean field estimates for 2N SRC

Isospin independent: $$\frac{\sigma_{48}/48}{\sigma_{40}/40} = \frac{(20\sigma_p + 28\sigma_n)/48}{(20\sigma_p + 20\sigma_n)/40} \xrightarrow{\sigma_p \approx 3\sigma_n} 0.92$$

n-p (T=0) dominance: $$\frac{\sigma_{48}/48}{\sigma_{40}/40} = \frac{(20 * 28)/48}{(20 * 20)/40} = 1.17$$

25% difference isospin indep. vs.pn-only (compare to 40% for $^3He/^3H$)

For no extra T=0 pairs with $f_{7/2}$ neutron: $$\frac{\sigma_{48}/48}{\sigma_{40}/40} = \frac{\sigma_{40}/48}{\sigma_{40}/40} = 0.83$$

Experiment E08-014

Spokespeople: P. Solvignon (JLab), J. Arrington (ANL), D. Day (UVa), D. Higinbotham (JLab)
Ph.D student: Zhihong Ye (UVa)

Verify and define scaling regime for 3N-SRC:

3N-SRC over a range of density

Test α_{3n} for x> 2

Isospin effects on SRCs:

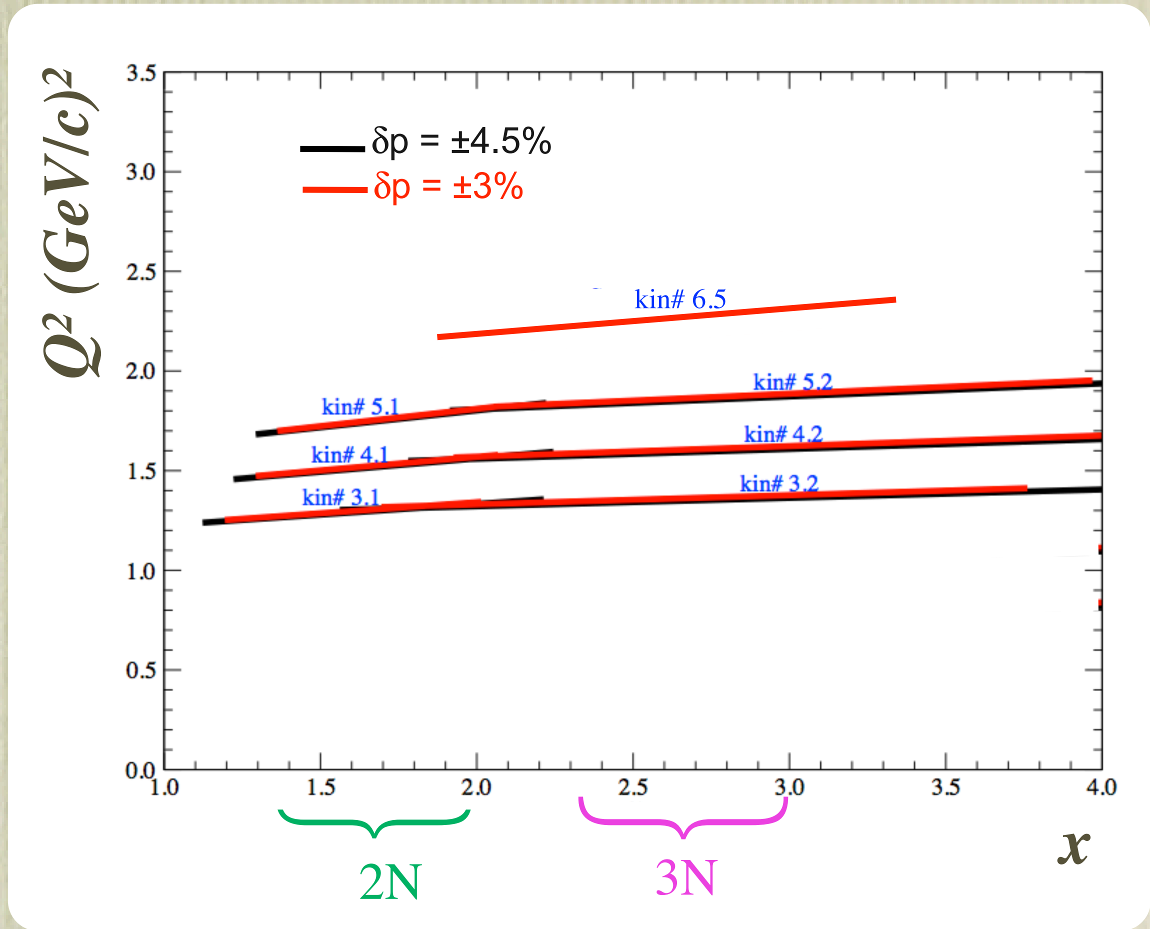
^{48}Ca vs. ^{40}Ca

Study onset of scaling:

ratios as a function of α_{2n} for 1<x<2

First precise data on ^{3}He and ^{4}He for x>2 to test FSI, and examine IMF distribution $\rho_A(\alpha)$

needed for $q_A(x)$ convolution
(EMC, hard processes in A-A collisions, ...)



Experimental setup

Standard Hall A configuration

^{2}H, ^{3}He, ^{4}He cryo-target

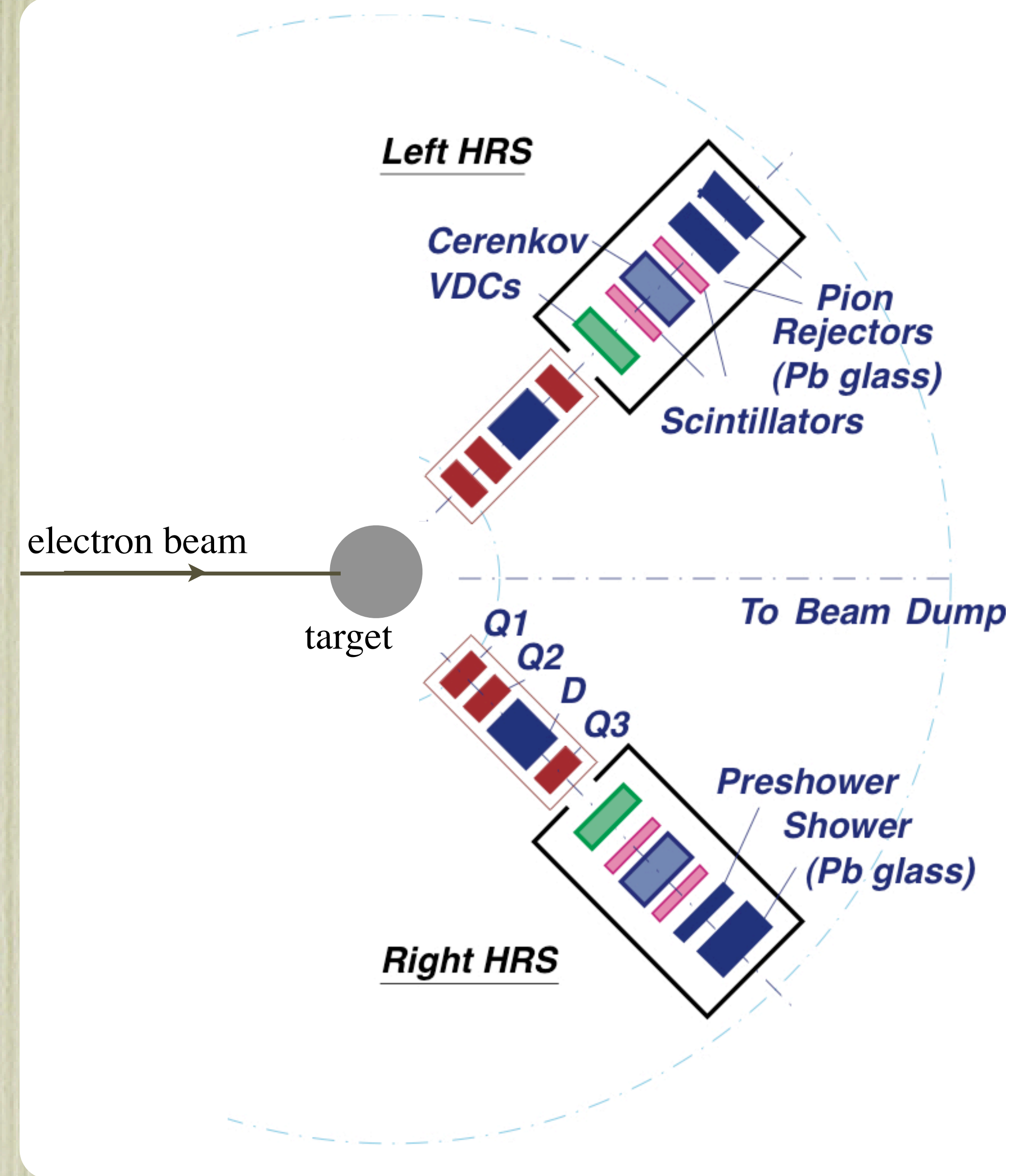
^{12}C, ^{40}Ca, ^{48}Ca

Empty Al cell for cryo-window subtraction

Carbon foils for optics

Gas Cerenkov + Calorimeter for PID

Beam energy: 3.356 GeV



E08-014 Analysis Status

Detectors --> performed very well, no issues

Spectrometer magnet --> RQ3 mismatch

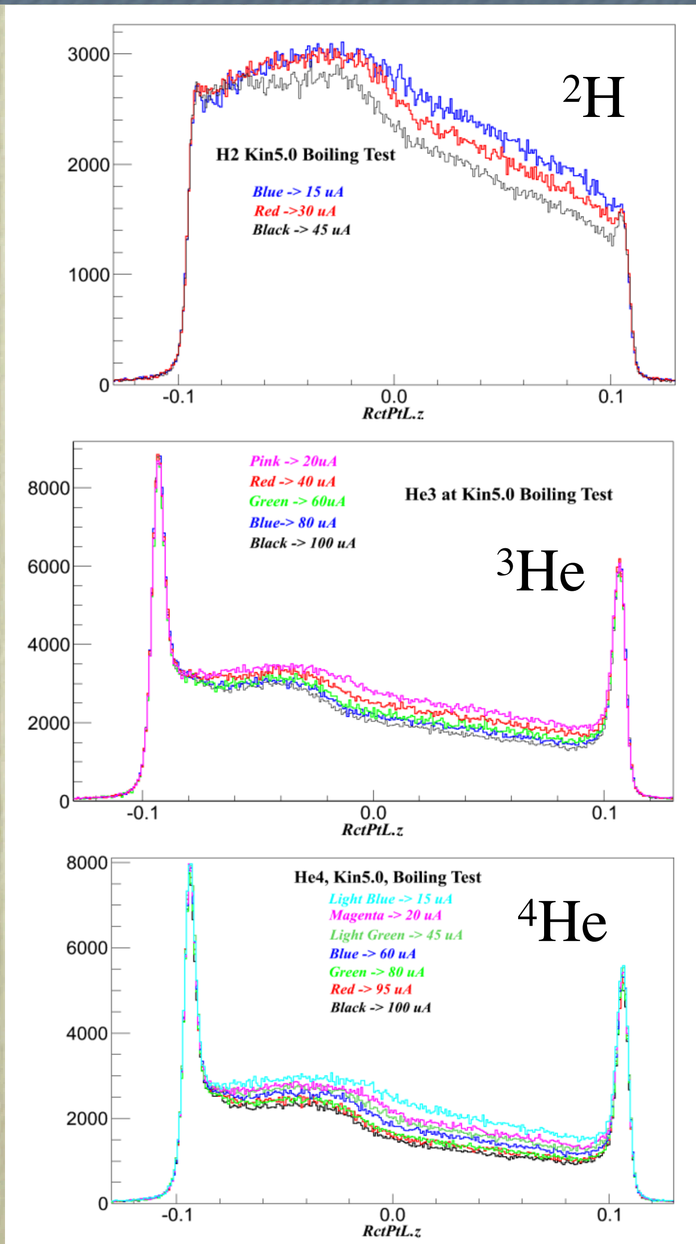
Target --> large density fluctuation along the cell

Beam --> a short glitch of 3MeV at the beginning of the experiment

Cross section model --> have to deal with the vanishing of the ^{3}He cross section at x close to 3.

Ratio --> special attention to be paid on the ratio from short to long targets

Target density non-uniformity



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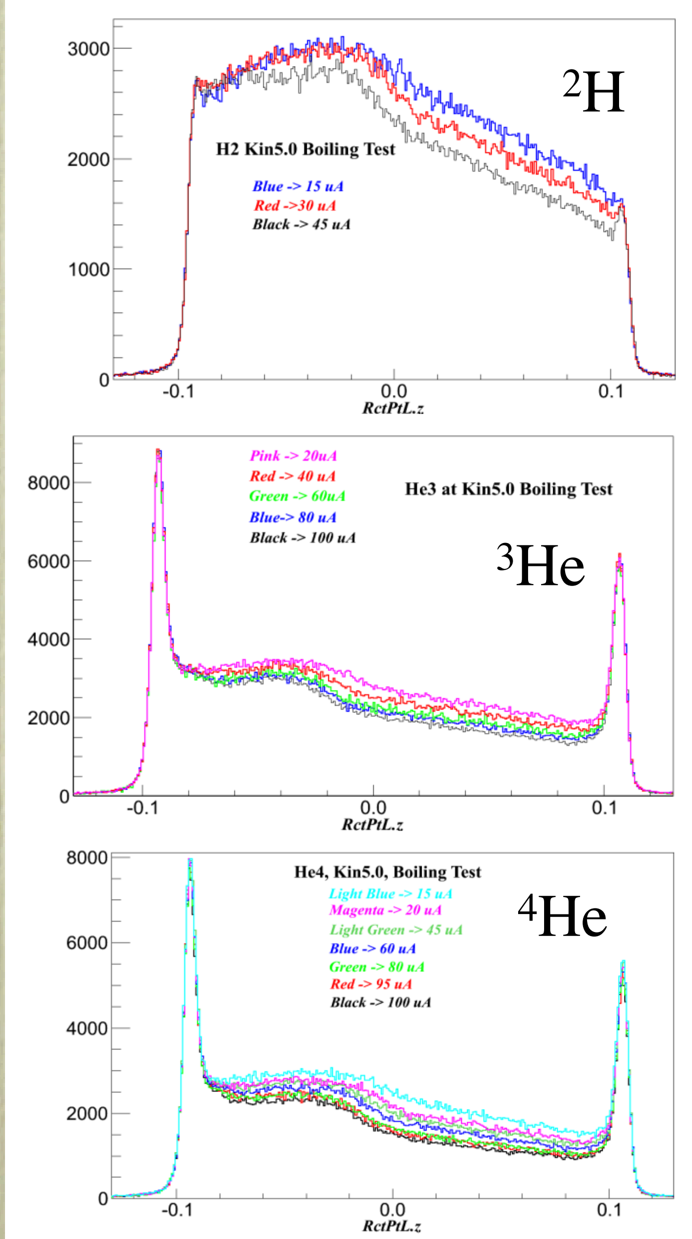
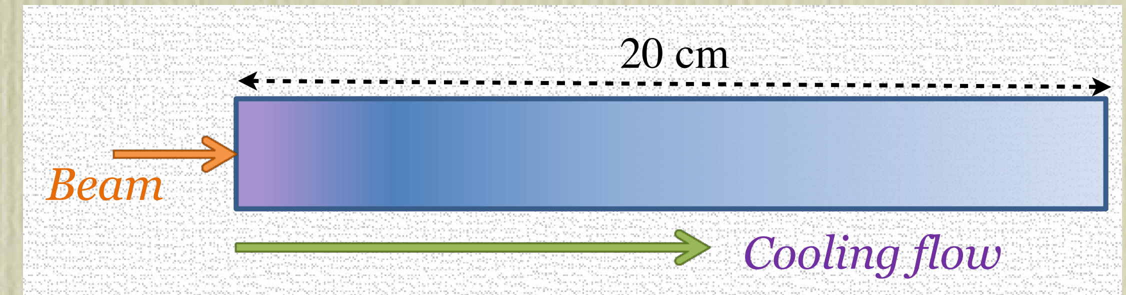
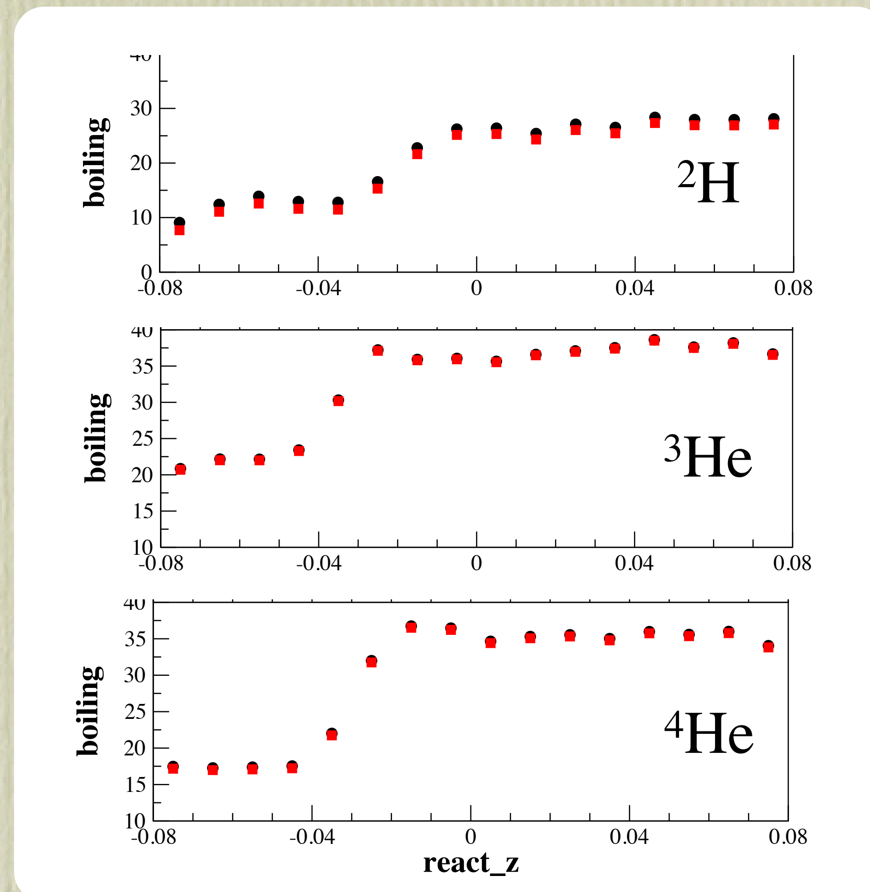
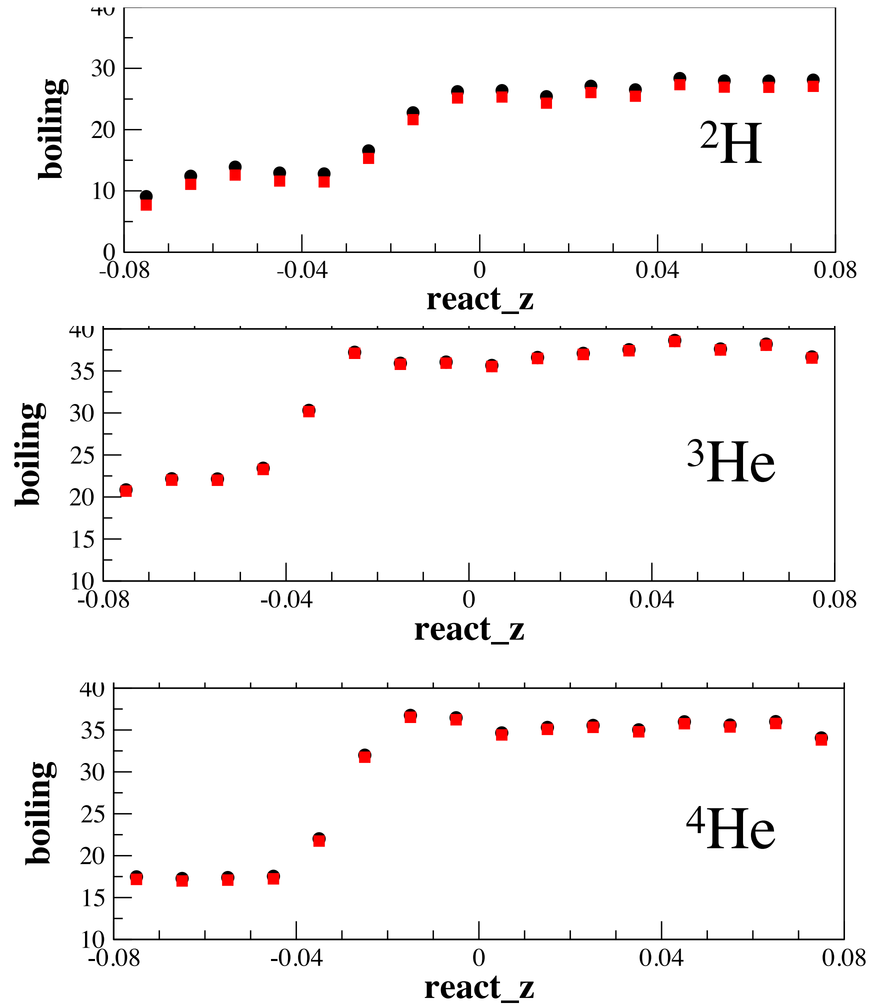


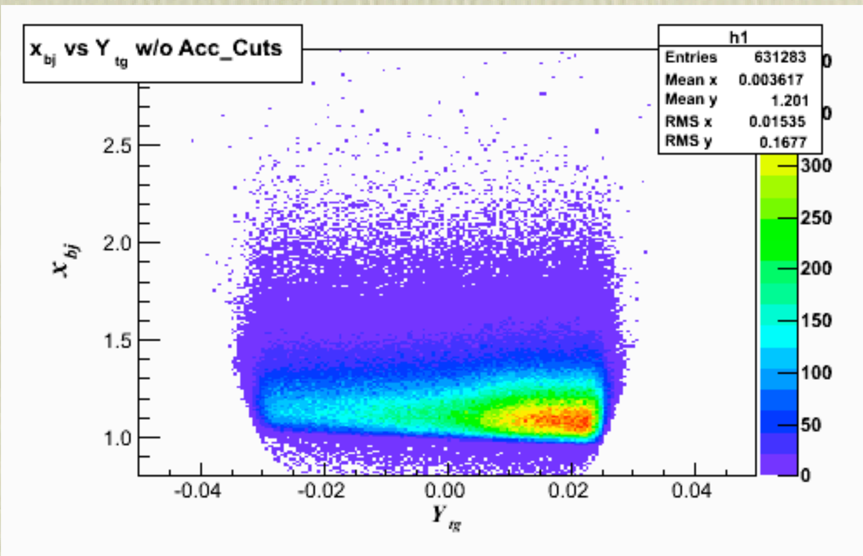




Boiling study



Each x-bin corresponds to an average over the target length.



The density non-uniformity is mostly an issue for radiative corrections.

E08-014 Analysis

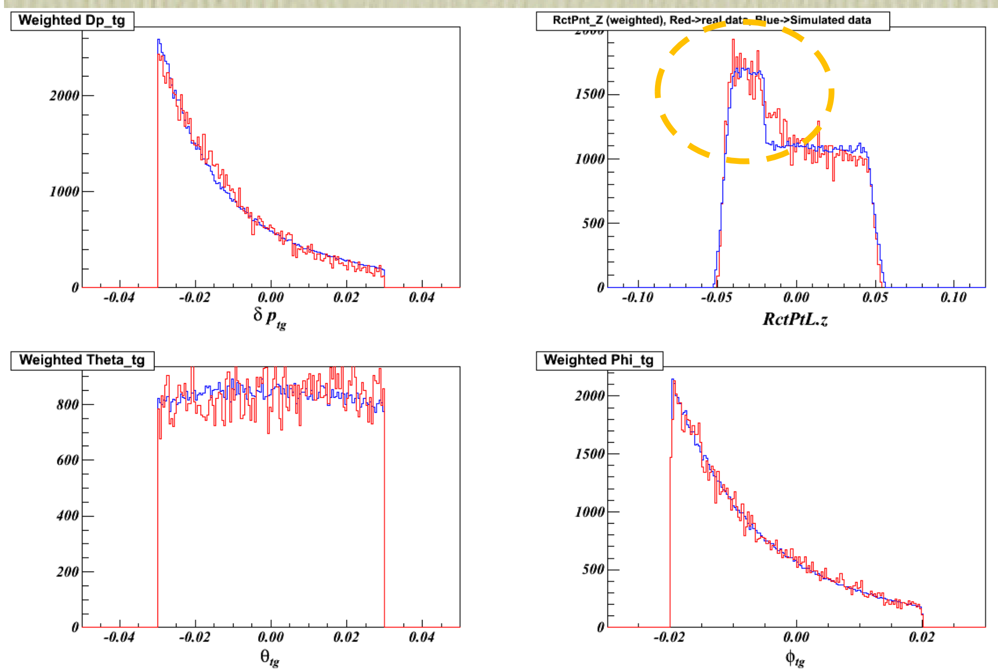
Correcting for the boiling effect is not straightforward.

"Boiling function" is added in the Monte Carlo

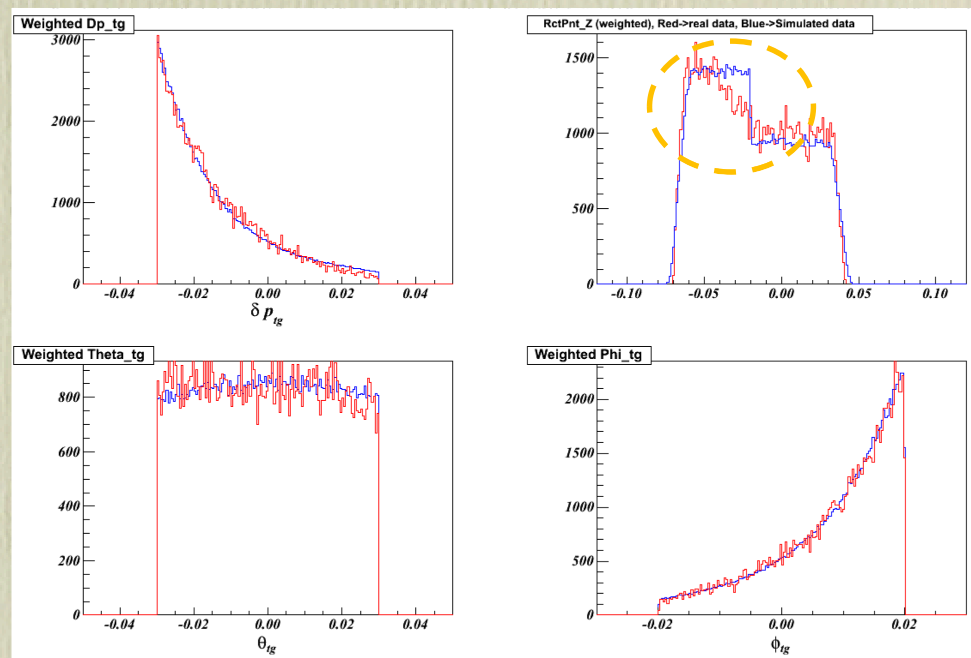
Histograms are weighted by Cross Sections from XEMC model

(QE part from y-scaling + inelastic part from F1F2IN09)

Left HRS



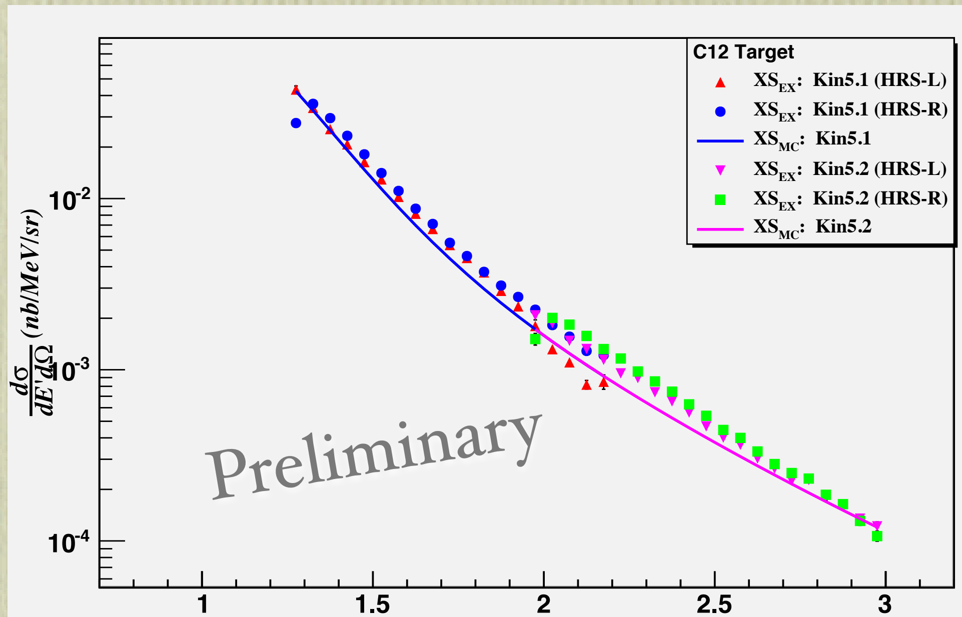
Right HRS

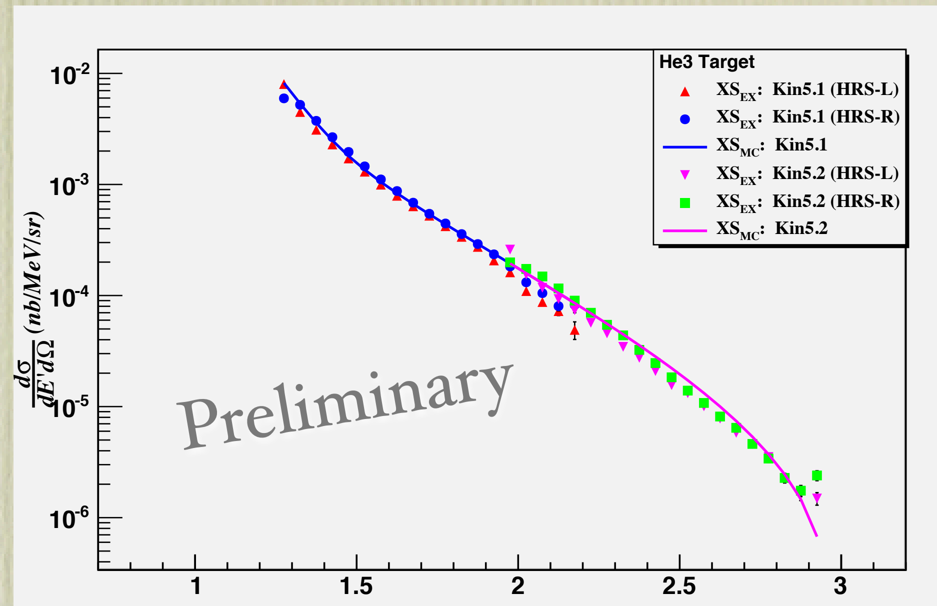


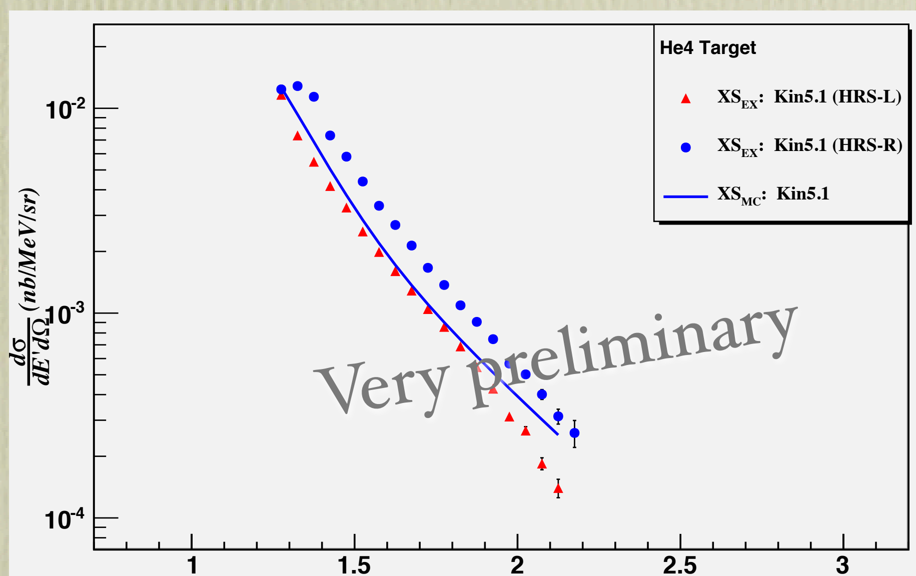
Blue -> Simulation Data

Red -> E08-014 Data

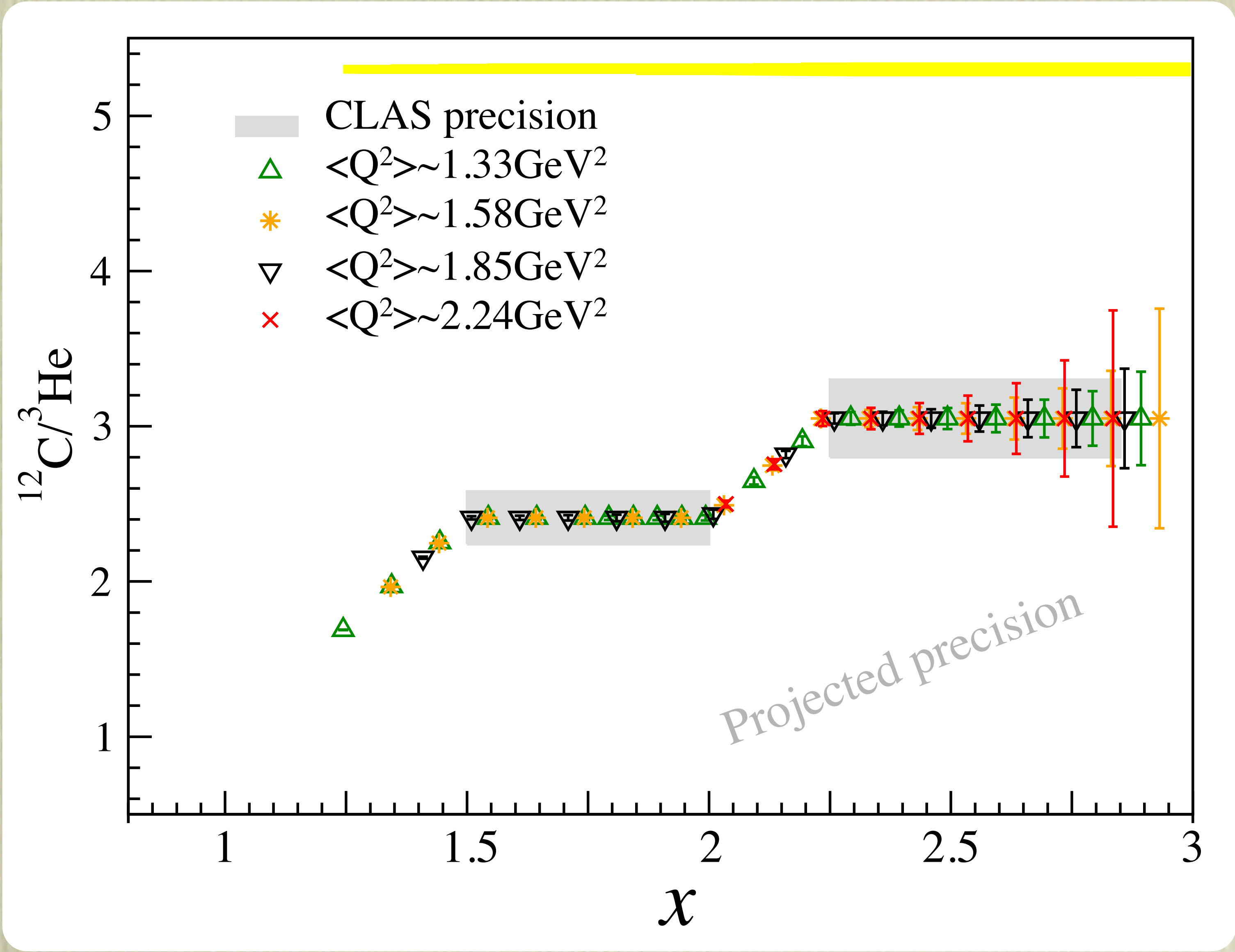
E08-014: Preliminary cross sections



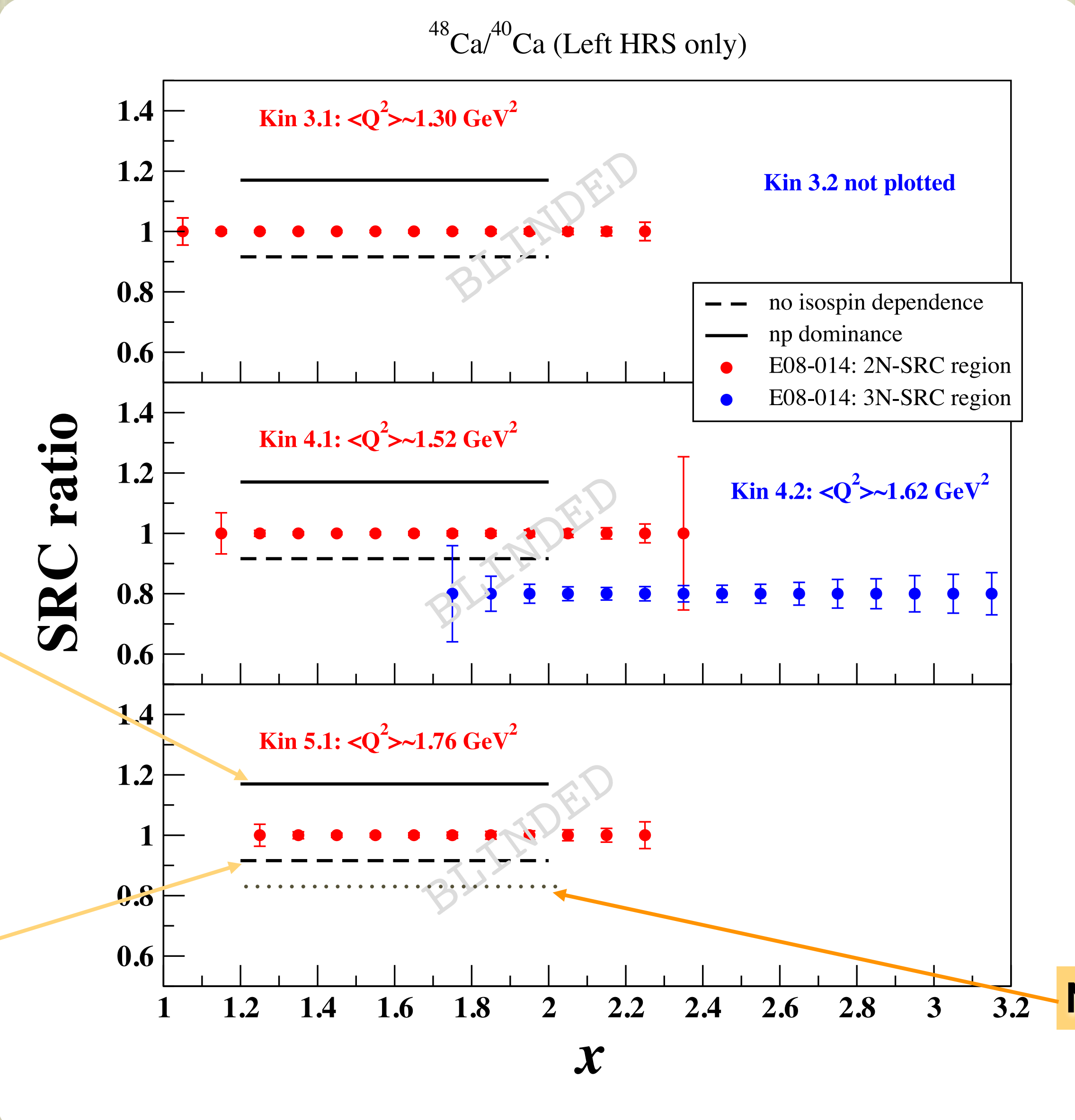




E08-014: Projected precision



E08-014: Isospin dependence study

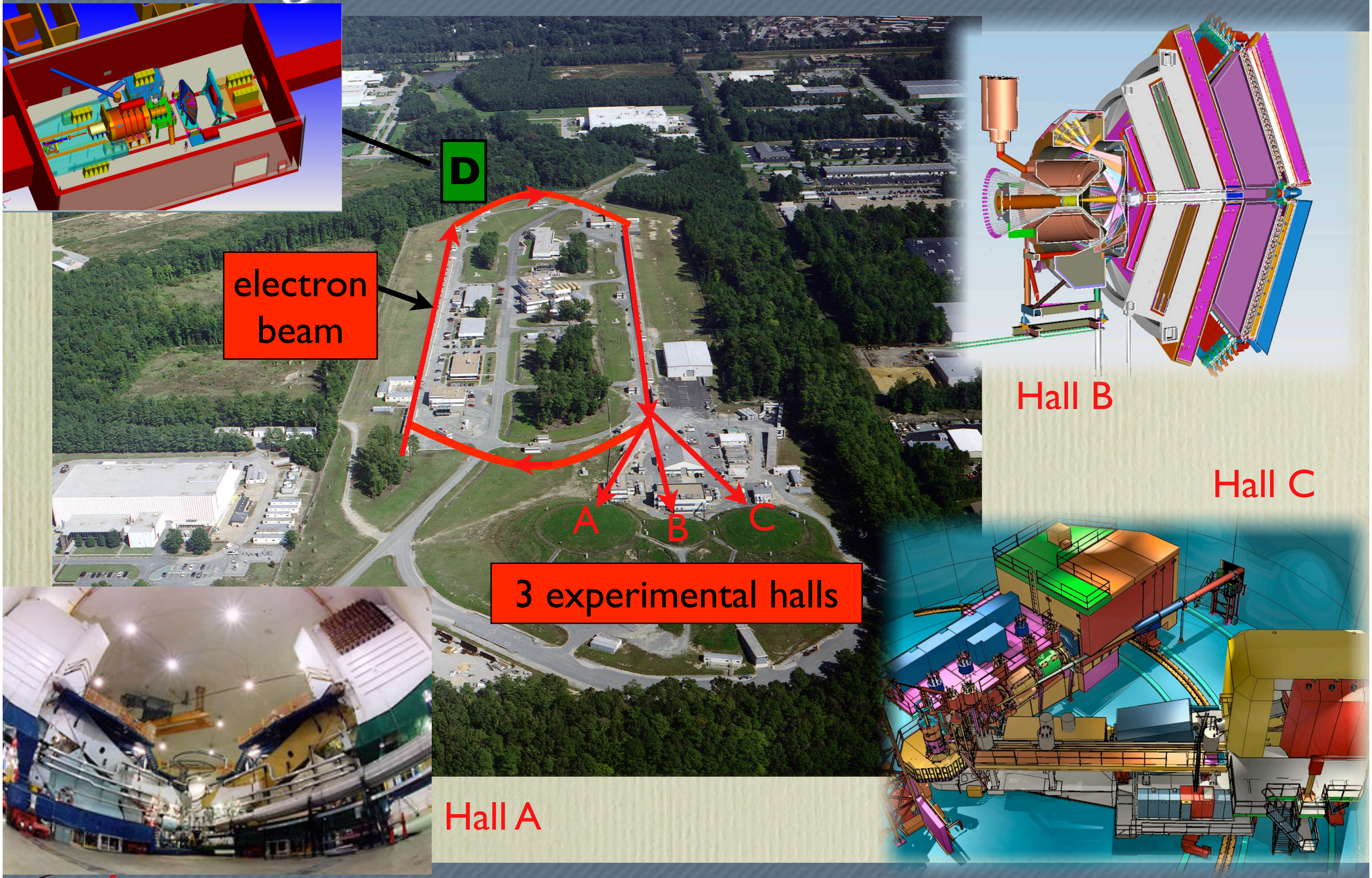


n-p pair dominance
↓
equal number of high momentum proton and neutron

Isospin-independent correlations
↓
Z protons and N neutrons at high momentum

No extra n-p pair

Jefferson Lab at 12 GeV



Experiment E12-11-112

Precision measurement of the isospin dependence in the 2N and 3N short range correlation region

Spokespeople

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Experiment E12-11-112

Precision measurement of the isospin dependence in the 2N and 3N short range correlation region

Main physics goals

Isospin-dependence

✓ Improved precision: extract R(T=1/T=0) to 3.8%

✓ FSI much smaller (inclusive) and expected to cancel in ratio

3N SRCs structure (momentum-sharing and isospin)

Improved A-dependence in light and heavy nuclei

✓ Average of ^{3}H, ^{3}He --> A=3 "isoscalar" nucleus

✓Determine isospin dependence --> improved correction for N>Z nuclei, extrapolation to nuclear matter

Absolute cross sections (and ratios) for ^{2}H, ^{3}H, ^{3}He: test calculations of FSI for simple, well-understood nuclei

Isospin study from ^{3}He/^{3}H ratio

Simple mean field estimates for 2N-SRC

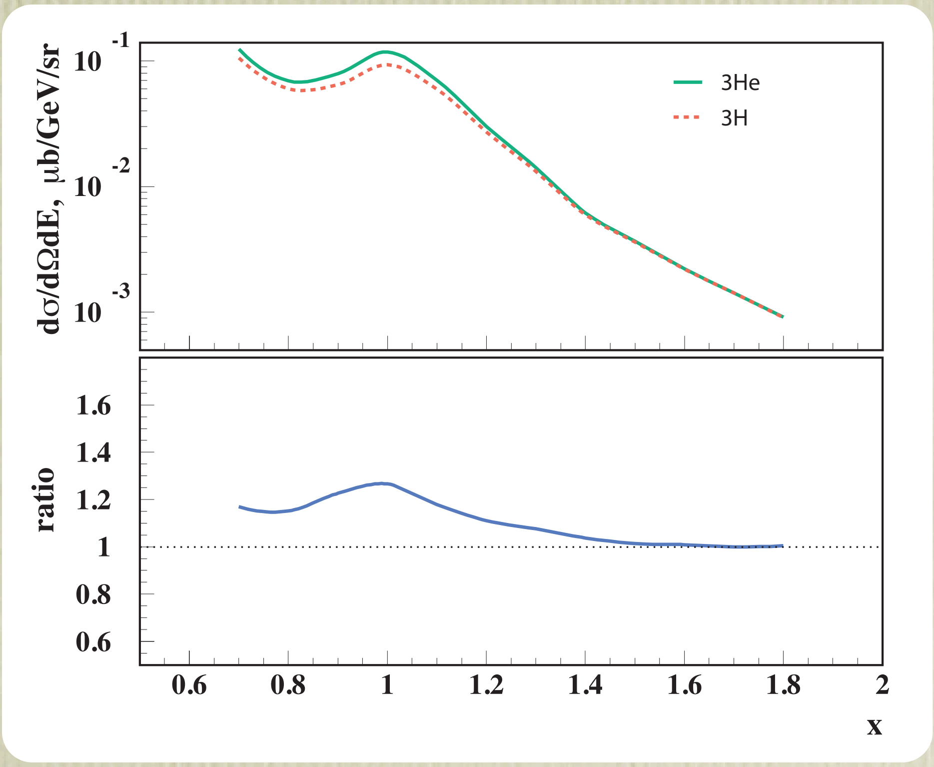
Isospin independent:

$$\frac{\sigma_{^3He}/3}{\sigma_{^3H}/3} = \frac{(2\sigma_p + 1\sigma_n)/3}{(1\sigma_p + 2\sigma_n)/3} \xrightarrow{\sigma_p \approx 3\sigma_n} 1.40$$

n-p (T=0) dominance:

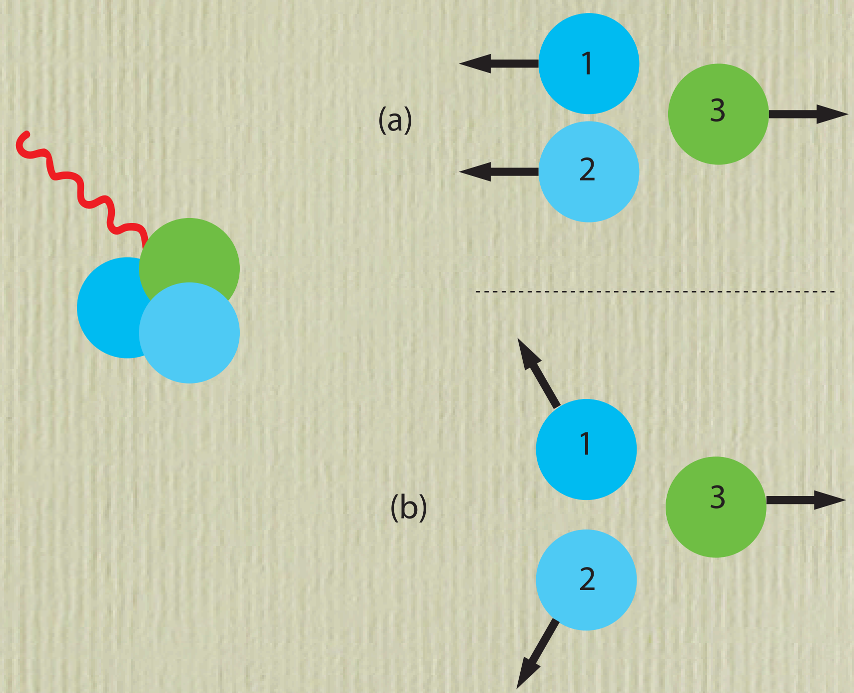
$$\frac{\sigma_{^3H}/3}{\sigma_{^3He}/3} = \frac{(2pn + 1\cancel{nn})/3}{(2pn + 1\cancel{pp})/3} = 1.0$$

Inclusive cross section calculation from M. Sargsian using AV18/UIX



M. Sargsian, private com.

3N-SRC Configurations



extremely large momentum

$p_3 = p_1 + p_2$

“Star-configuration”

$p_1 = p_2 = p_3$

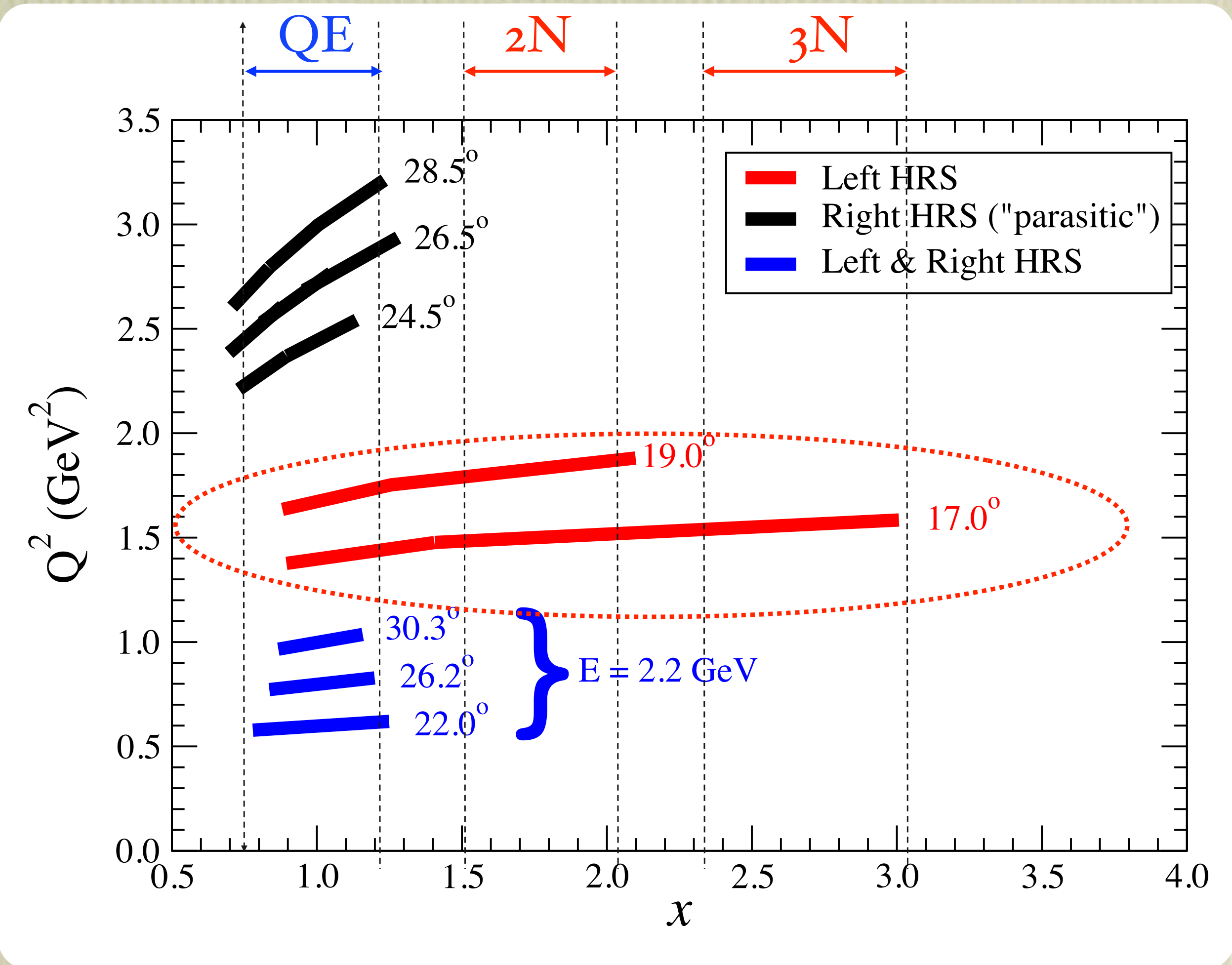
(a) yields $R(^3He/^3H) \approx 3.0$ if nucleon #3 is always the doubly-occurring nucleon
(a) yields $R(^3He/^3H) \approx 0.3$ if nucleon #3 is always the singly-occurring nucleon
(a) yields $R(^3He/^3H) \approx 1.4$ if configuration is isospin-dependent, as does (b)

$R \neq 1.4$ implies isospin dependence AND non-symmetric momentum sharing

E12-11-112: Kinematic coverage

Beam current: 25 μA, unpolarized, Raster interlock
Beam energy:
17.5 Days 4.4 GeV [main production]

Left HRS running
(380 hours)

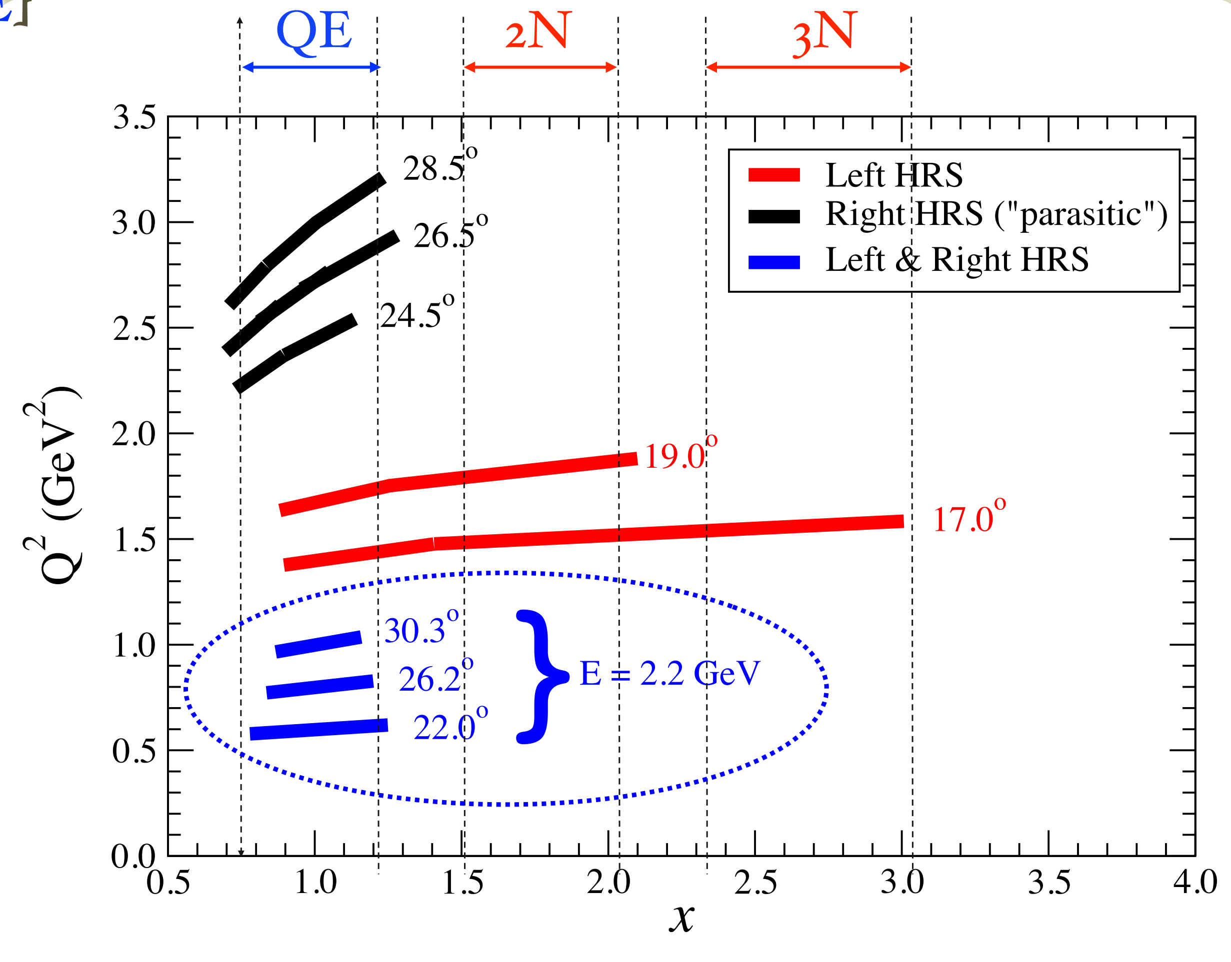


E12-11-112: Kinematic coverage

Beam current: 25 μA, unpolarized, Raster interlock
Beam energy:
17.5 Days 4.4 GeV [main production]
1.5 days 2.2 GeV [checkout+QE]

Left HRS running (380 hours)

Left+Right HRS running (about 1 day)



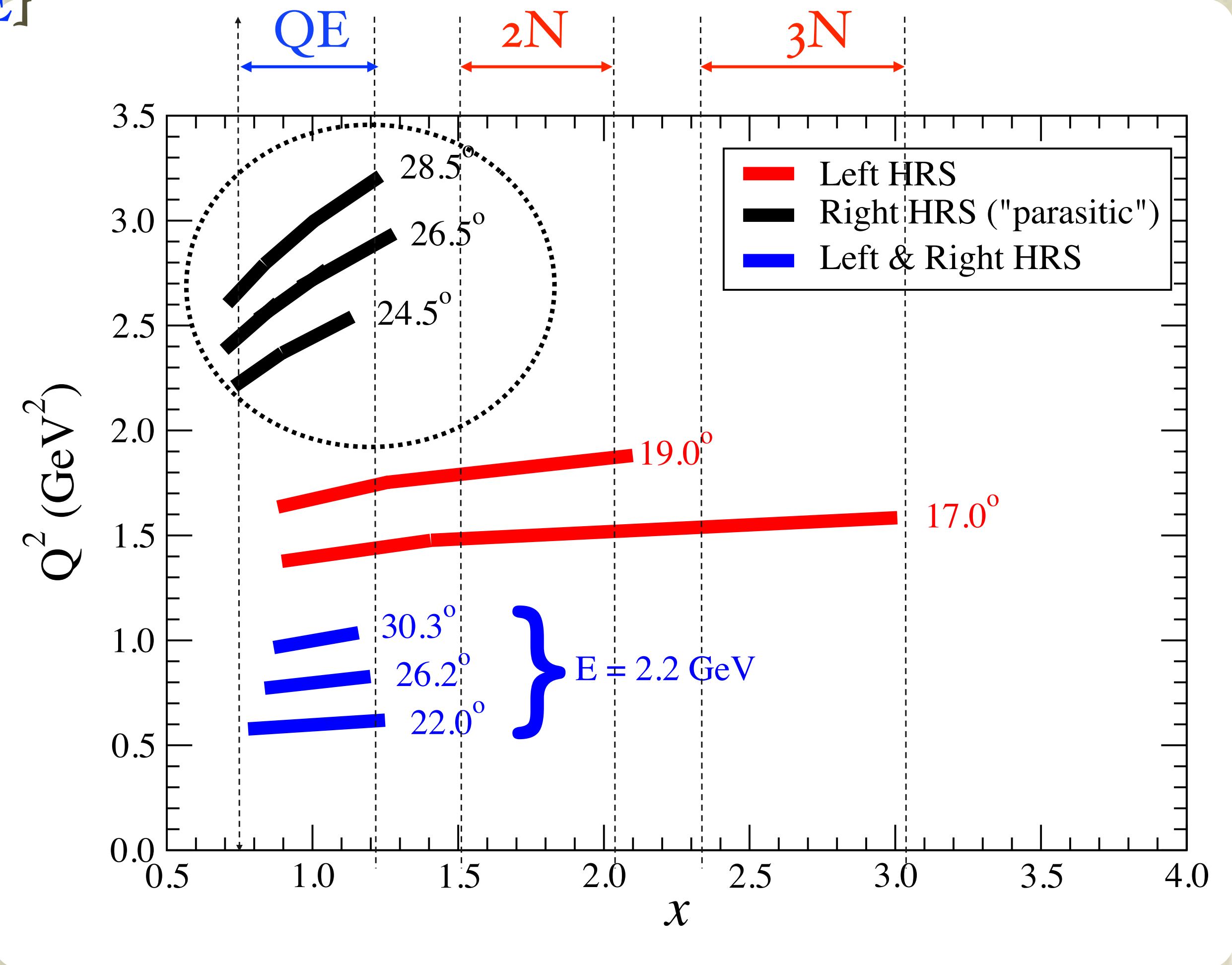
E12-11-112: Kinematic coverage

Beam current: 25 μA, unpolarized, Raster interlock
Beam energy:
17.5 Days 4.4 GeV [main production]
1.5 days 2.2 GeV [checkout+QE]

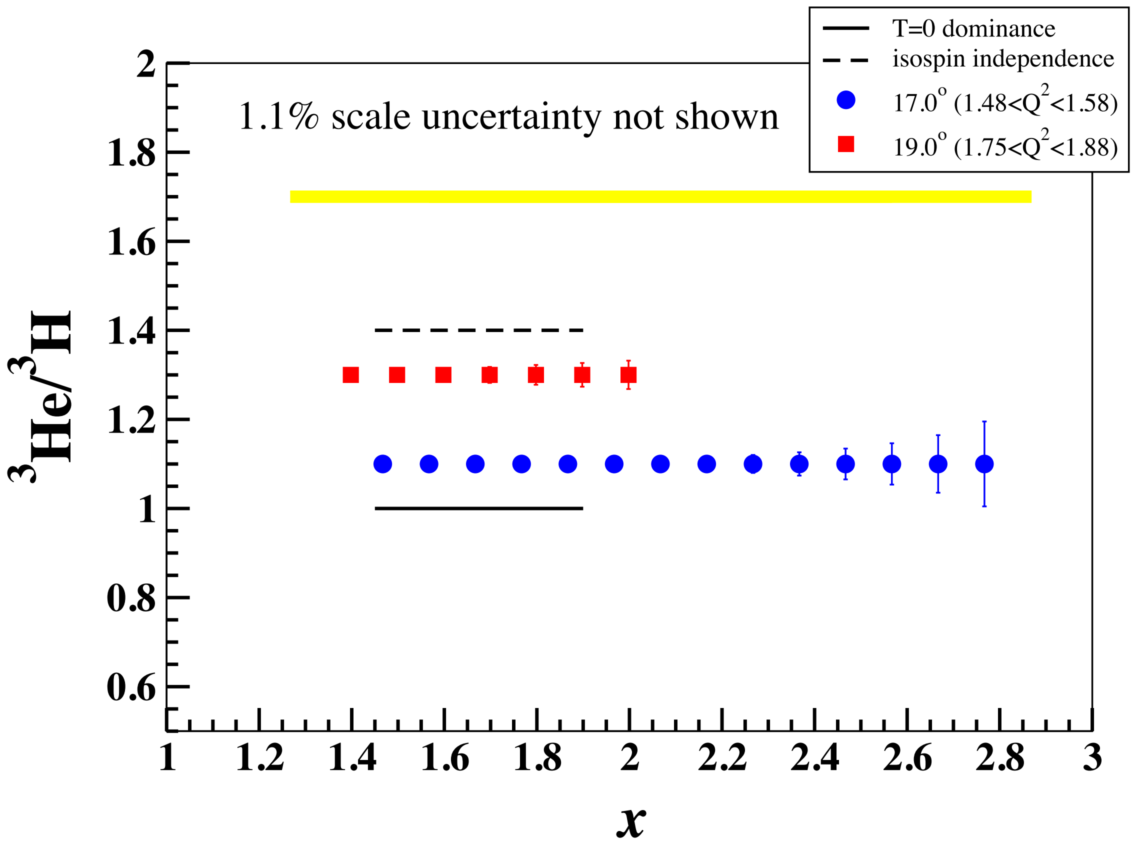
Right HRS running (“parasitic”)
Existing ^3H QE data limited $Q^2 \leq 0.9$ GeV^2

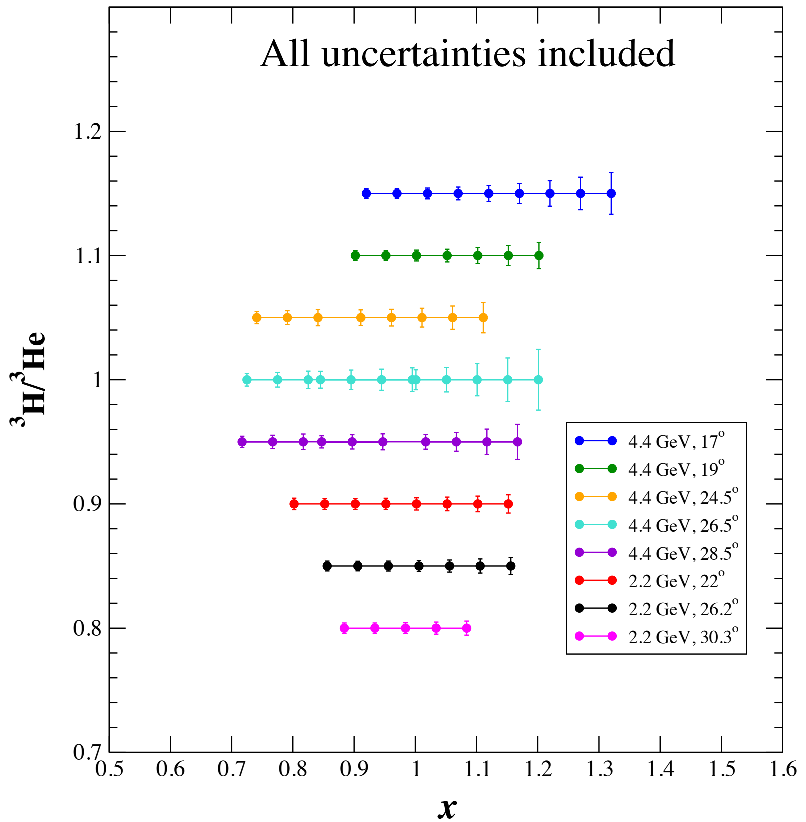
Left HRS running (380 hours)

Left+Right HRS running (about 1 day)



E12-11-112: Isospin study from $^3He/^3H$

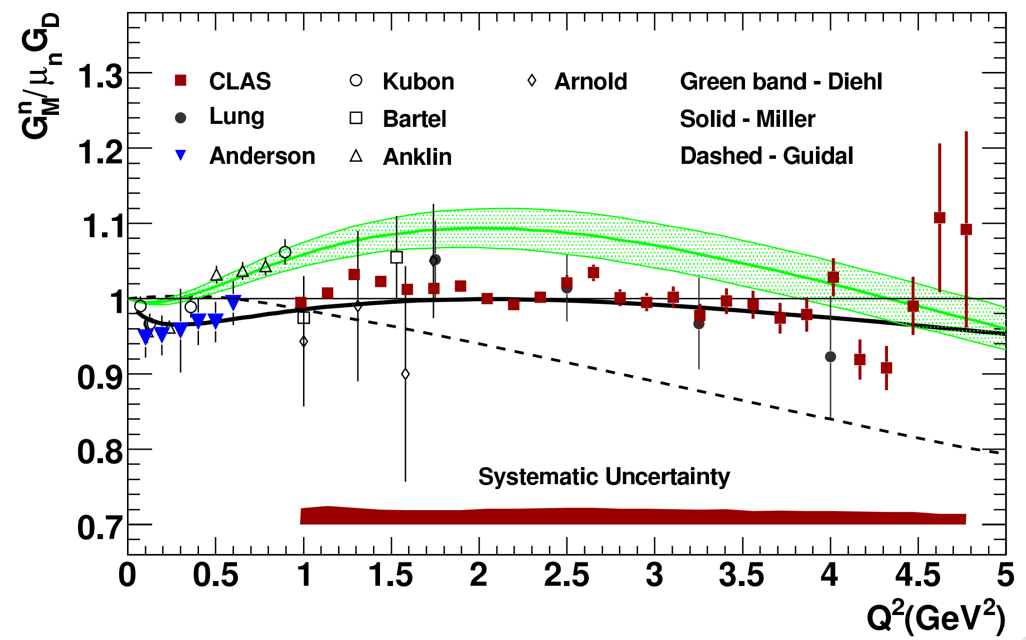




QE data and Neutron Magnetic FF

World ^3H QE data:
$Q^2 \leq 0.9 GeV^2$

This experiment:
0.6, 0.8, 1.0, 1.4, 1.7, 2.4, 2.7 and 3.0 GeV^2

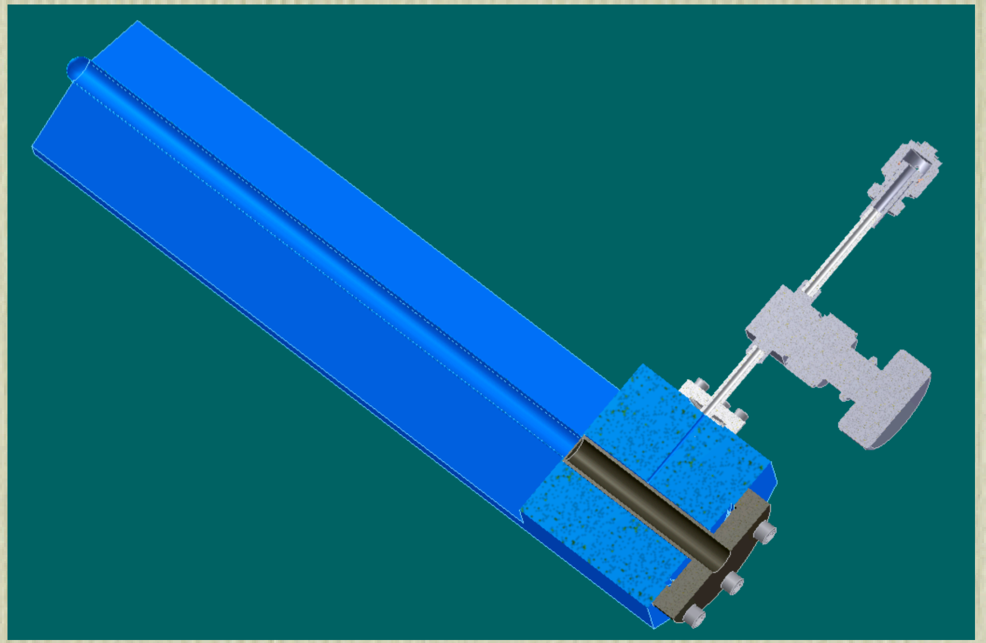


In PWIA, $^3He/^3H$ with 1.5% uncertainty corresponds to 3% on G_M^n

- Limited to $Q^2 \leq 1 GeV^2$, where QE peak has minimal inelastic contribution
- This is the region with ~8% discrepancy between the Ankin, Kubon data and the CLAS ratio and the Hall A polarized ^3He extraction.

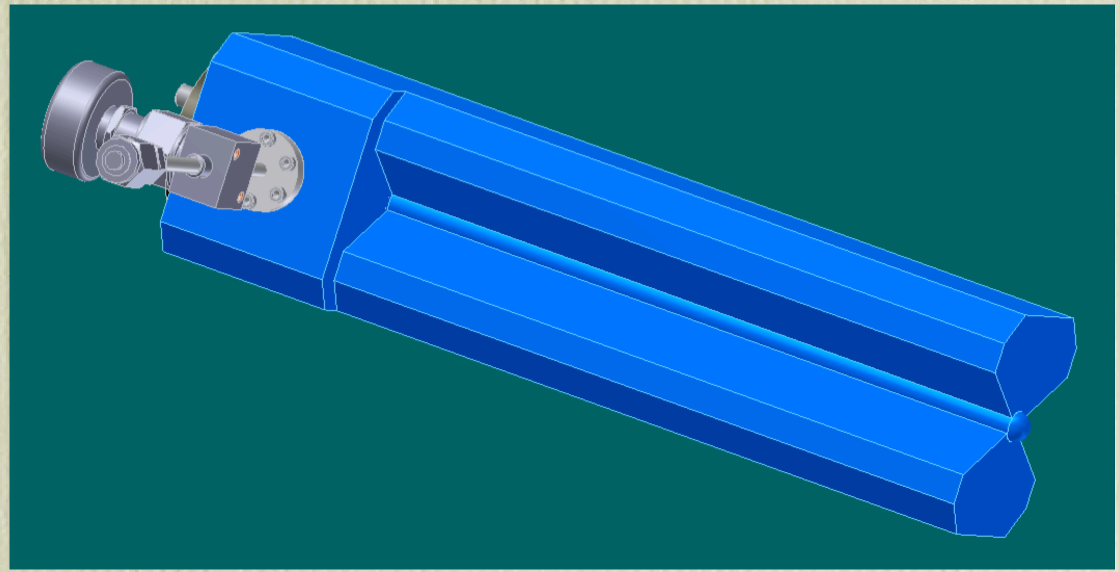
Nuclear effects expected to be small, largely cancel in ratio

Tritium target: updated design



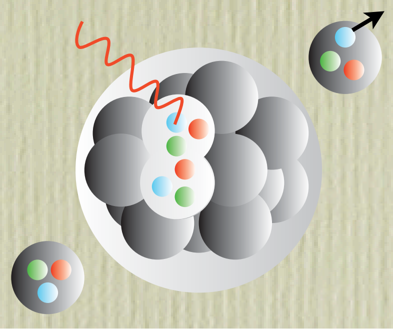
- Four identical cells: ^{1}H, ^{2}H, ^{3}He at 25 atm., ^{3}H at 13 atm.
- Operate at room temperature
- Length: 25cm, Diameter: 1.25cm
- 18 mils walls and 10 mils entrance windows

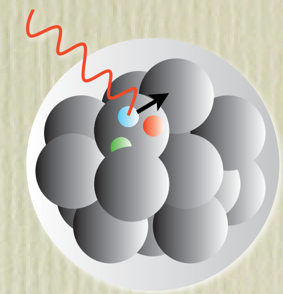
design from D. Meekins (JLab)

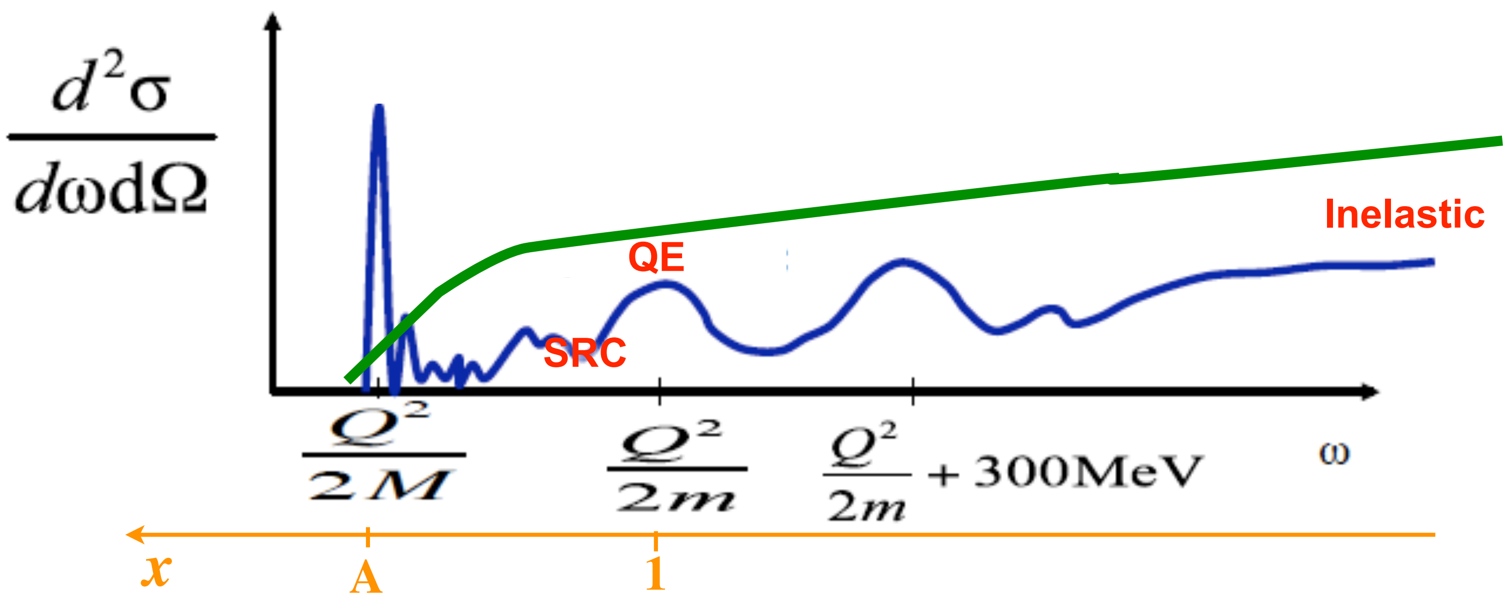


E12-06-105: Quark distributions of SRC

Spokespeople: J. Arrington (ANL), D. Day (UVa), N. Fomin (LANL), P. Solvignon (JLab)



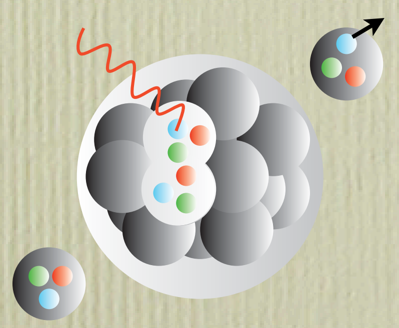


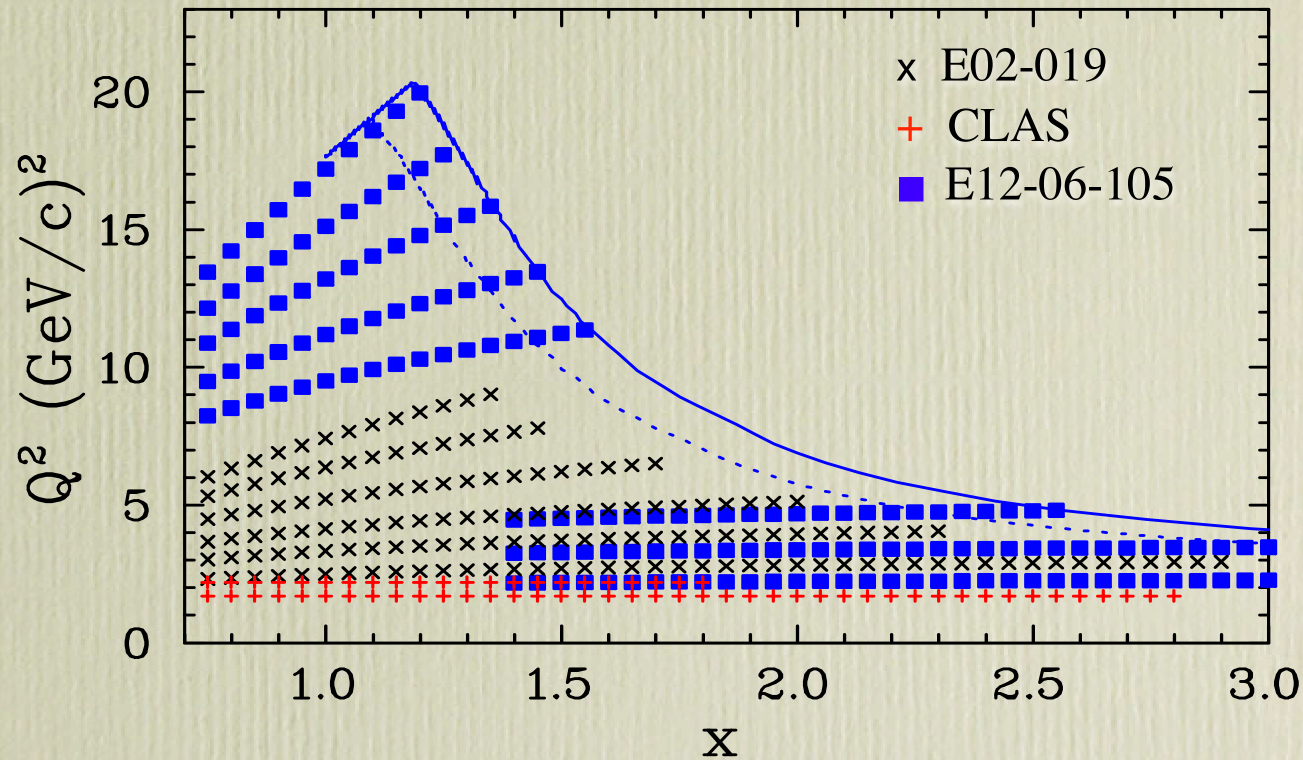


E12-06-105: Quark distributions of SRC

Inclusive scattering at x > 1 on several light and heavy nuclei:

- ✓ A-dependence of 2N and 3N-SRCs at moderate Q^2 values for large x
- ✓ First studies of the size and importance of α-clusters in nuclei
- ✓ Distribution of superfast quarks in nuclei: high sensitivity to non-hadronic components (6-q bags)

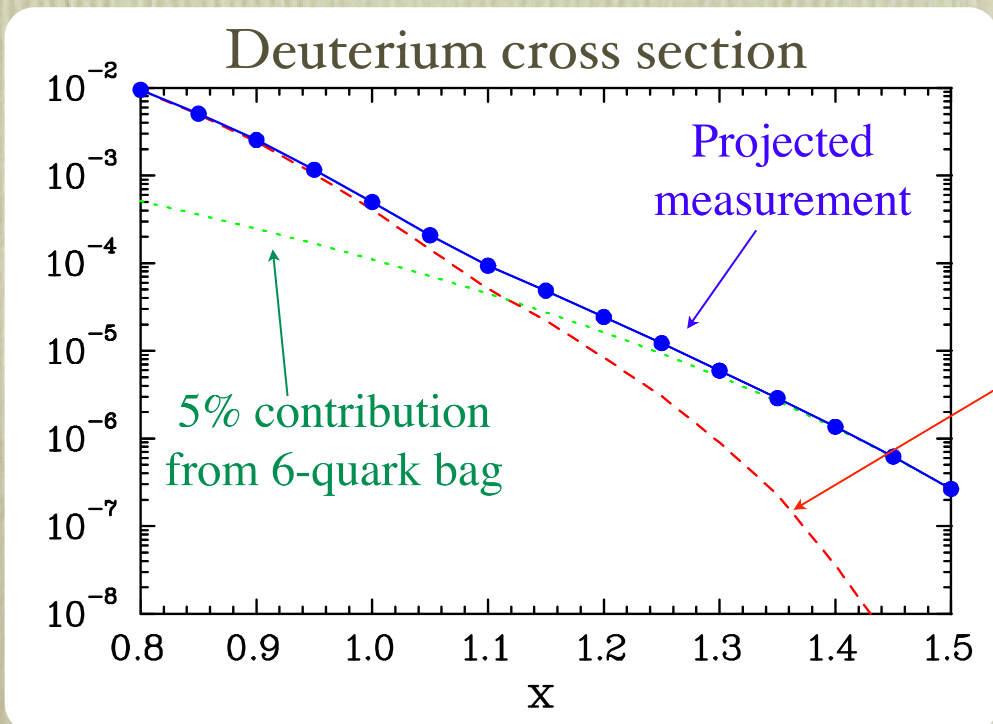




E12-06-105: Quark distributions of SRC

Six-quark bag contribution = break down of the individual identities of the two nucleons:

- ➡ greater sharing of momentum between the quarks in the two nucleons
- ➡ enhancement of the distribution of high-momentum quarks



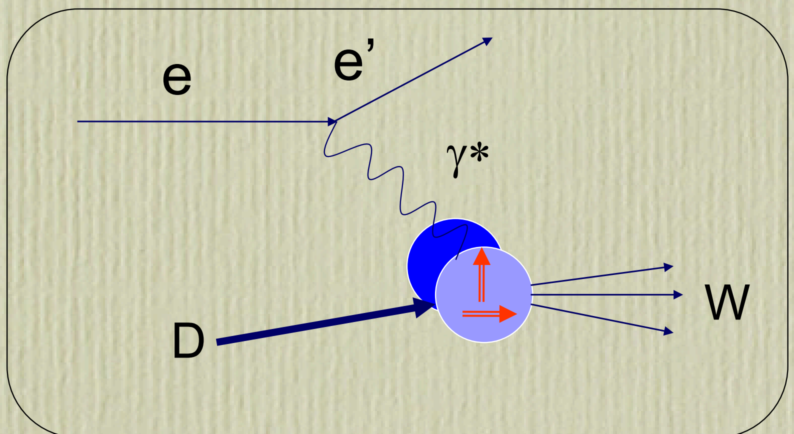
convolution of proton and neutron quark distributions

6-quark bag calculation from P. Mulders and A. Thomas, Phys. Rev. Lett. 52, 1199 (1984)

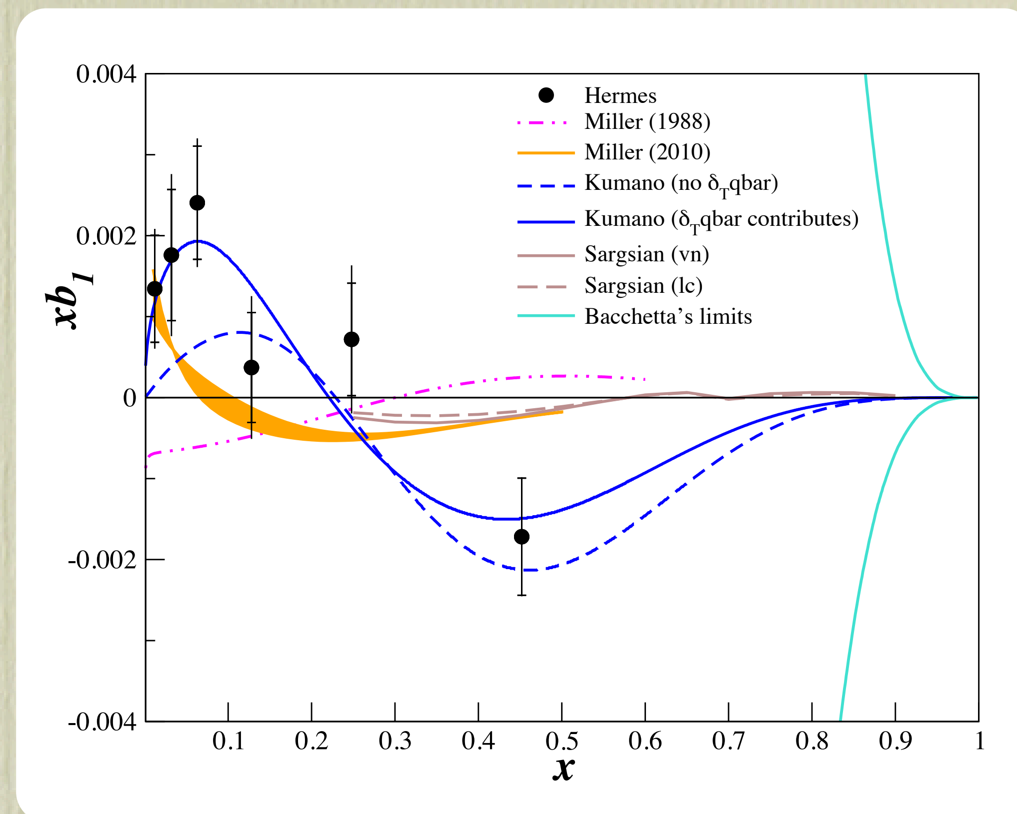
Note: for heavier nuclei, one needs a quantitative understanding of the distribution of high momentum nucleons to provide a reliable “baseline” calculation for the purely hadronic picture.

Deuteron Tensor Structure Function

Spokespeople: K. Slifer (UNH), J.P. Chen (JLab), N. Kalatarians (HU), O. Rondon (UVa), P. Solvignon (JLab)



$$
\begin{aligned}
W_{\mu\nu} &= -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P\nu}{\nu} \\
&\quad - b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) \\
&\quad + \frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu}) \\
&\quad + i \frac{g_1}{\nu} \epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i \frac{g_2}{\nu^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q s^\sigma - s \cdot q p^\sigma)
\end{aligned}
$$



Need unpolarized electron beam and polarized target

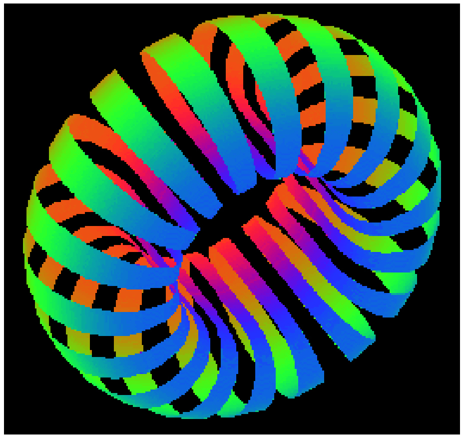
b_1 Structure Function

slide from K. Slifer (UNH)

$$b_1(x) = \frac{q^0(x) - q^1(x)}{2}$$

q^0 : Probability to scatter from a quark (any flavor) carrying momentum fraction x while the *Deuteron* is in state m=0

q^1 : Probability to scatter from a quark (any flavor) carrying momentum fraction x while the *Deuteron* is in state |m| = 1



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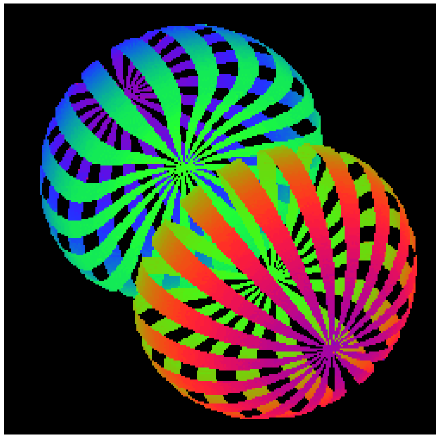


Nice mix of nuclear and quark physics

measured in DIS (so probing quarks), but depends solely on the deuteron spin state

Investigate nuclear effects at the level of partons!

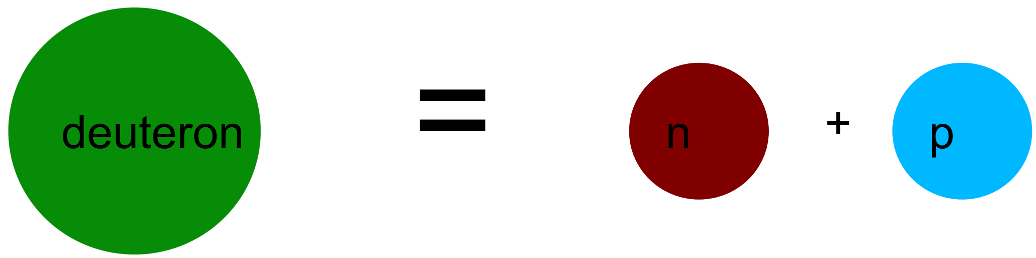
b_1 Structure Function

slide from K. Slifer (UNH)

Hoodbhoy, Jaffe and Manohar (1989)

b_1 vanishes in the absence of nuclear effects

i.e. if...



Proton Neutron in relative S-state

Even accounting for D-State admixture b_1 expected to be vanishingly small

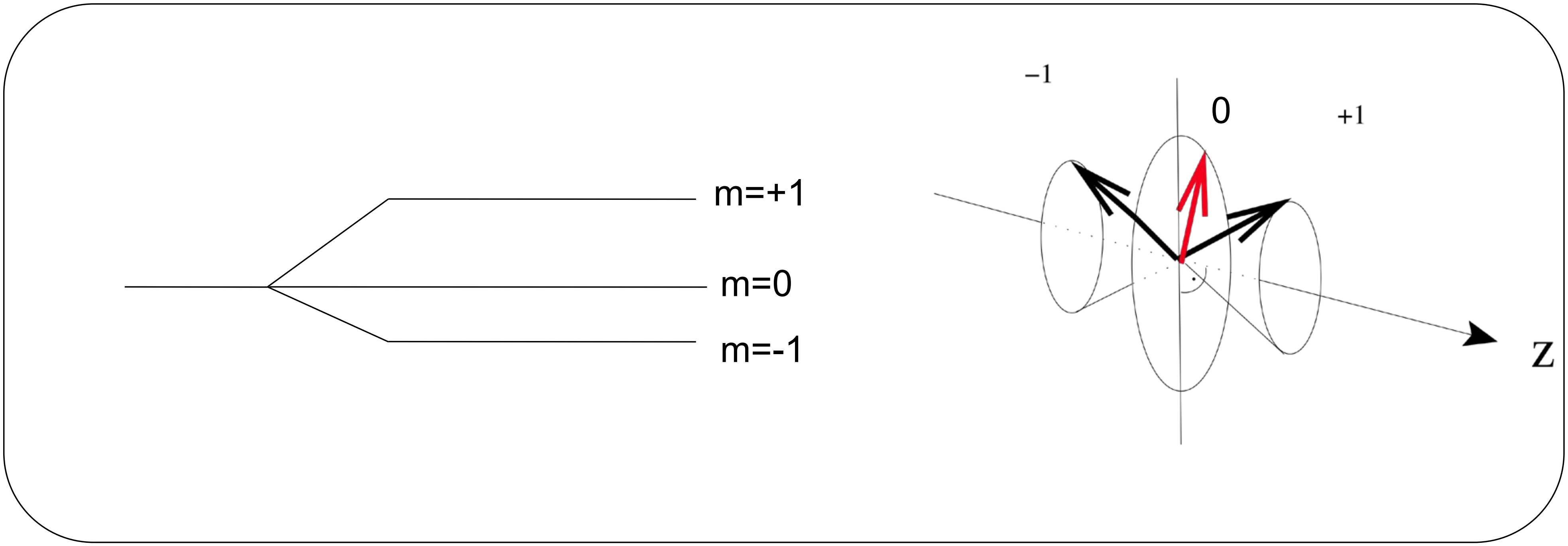
Khan & Hoodbhoy, PRC 44 ,1219 (1991) : $b_1 \approx O(10^{-4})$
Relativistic convolution model with binding

Umnikov, PLB 391, 177 (1997) : $b_1 \approx O(10^{-3})$
Relativistic convolution with Bethe-Salpeter formalism

Spin-1 System

slide from K. Slifer (UNH)

Spin-1 in B-field leads to 3 Zeeman sublevels



Vector Polarization P_z : $(n^+ - n^-)$ $(-1 < P_z < +1)$

and

Tensor polarization P_{zz} : $(n^+ - n^0) - (n^0 - n^-)$ $(-2 < P_{zz} < +1)$

Normalization

$(n^+ + n^- + n^0) = 1$

Summary

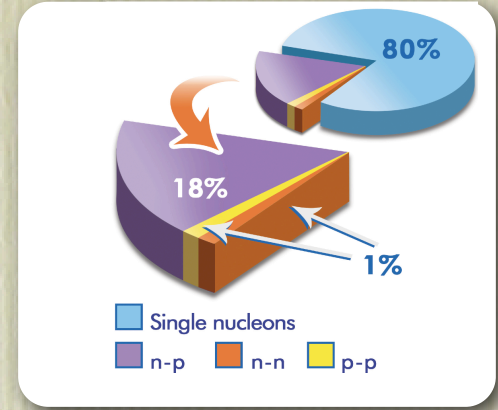
SRCs are an important component to nuclear structure:

~20% of nucleons in SRC

Very few (~1%) p-p, n-n pairs

Limited room for other things: 3N, 4N SRCs,

more exotic configurations (6q bag)



Inclusive scattering measurements from E08-014 and E12-11-112 will map out the 2N- and 3N-SRCs and produce a detailed study of their isospin dependence

--> E12-11-112 is scheduled to run in February 2015

E12-06-105 will probe quark distribution in SRC = EMC effect in SRCs

--> A part of the experiment is scheduled to run in 2016

Several other experiments at 12 GeV to look at SRC and EMC and their possible link.

Deuteron tensor structure function: investigation of nuclear effects at the quark level. Proposal to be re-submitted next PAC.