Tag! You're It!
Bound Nucleon Structure at JLab

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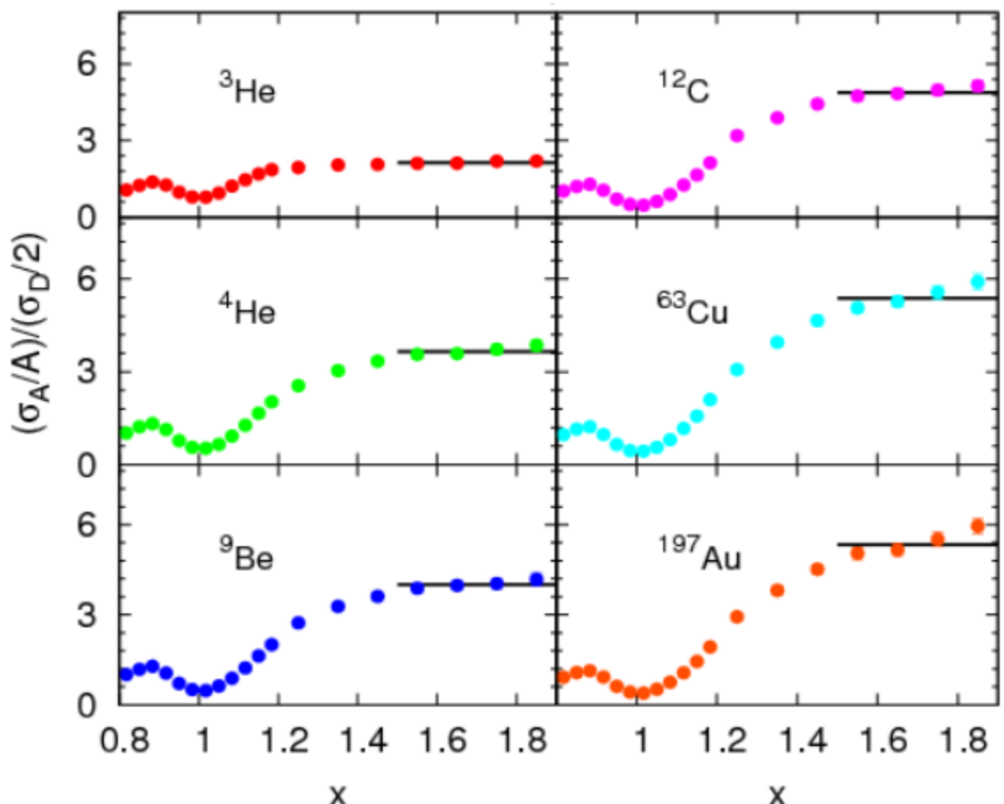
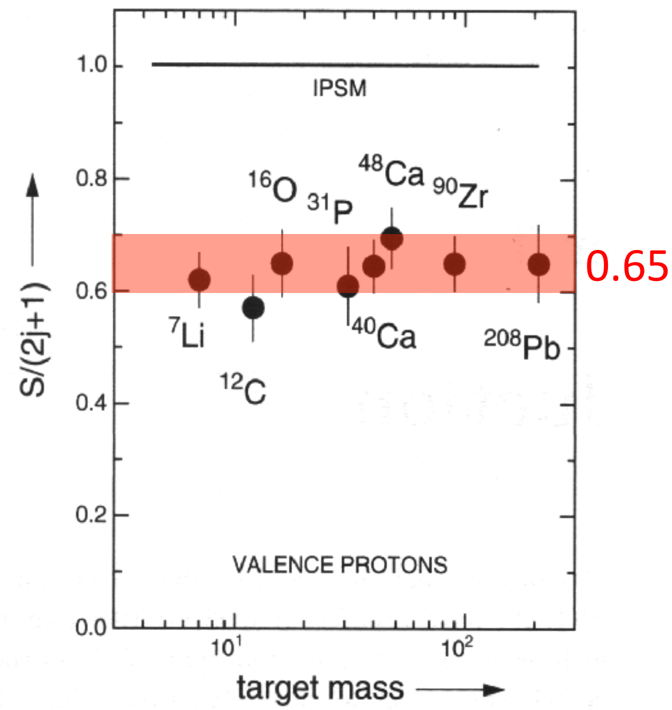
Brief Tour of Nuclear Structure

Nucleons:

- ~65% in single particle orbitals
- ~25% in NN correlations
  - Almost all high momentum nucleons





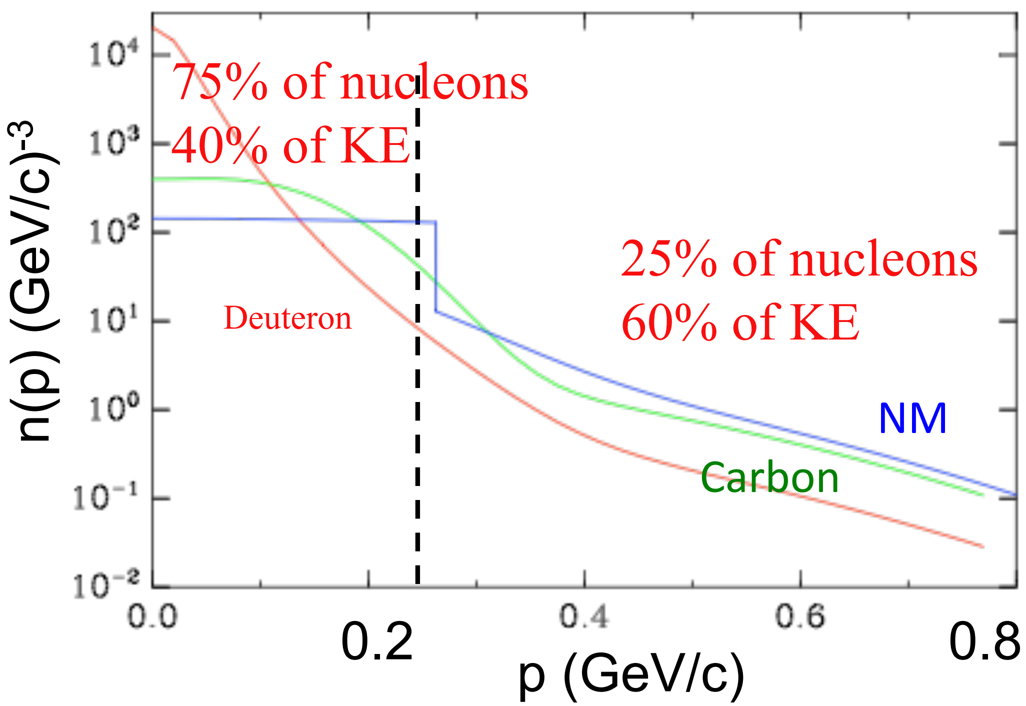
L. Lapikas, NP **A553** (1993) 297c

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

Short Range Correlations (SRCs)

➔High momentum tails: $k > k_F$

Calculable for $A \leq 12$
Not well constrained at $k >> k_f$

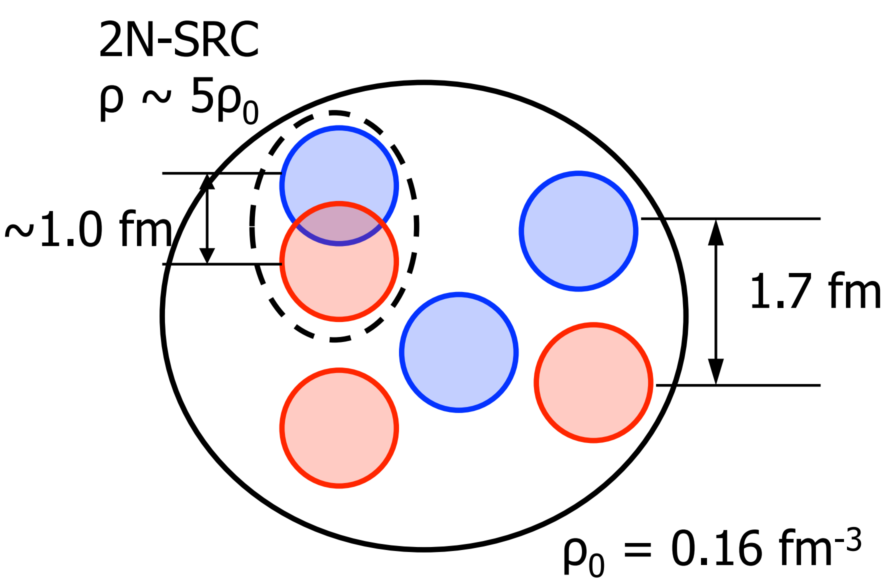


Effects:

- High momentum part of the nuclear wave function
- Short distance behavior of nucleons -

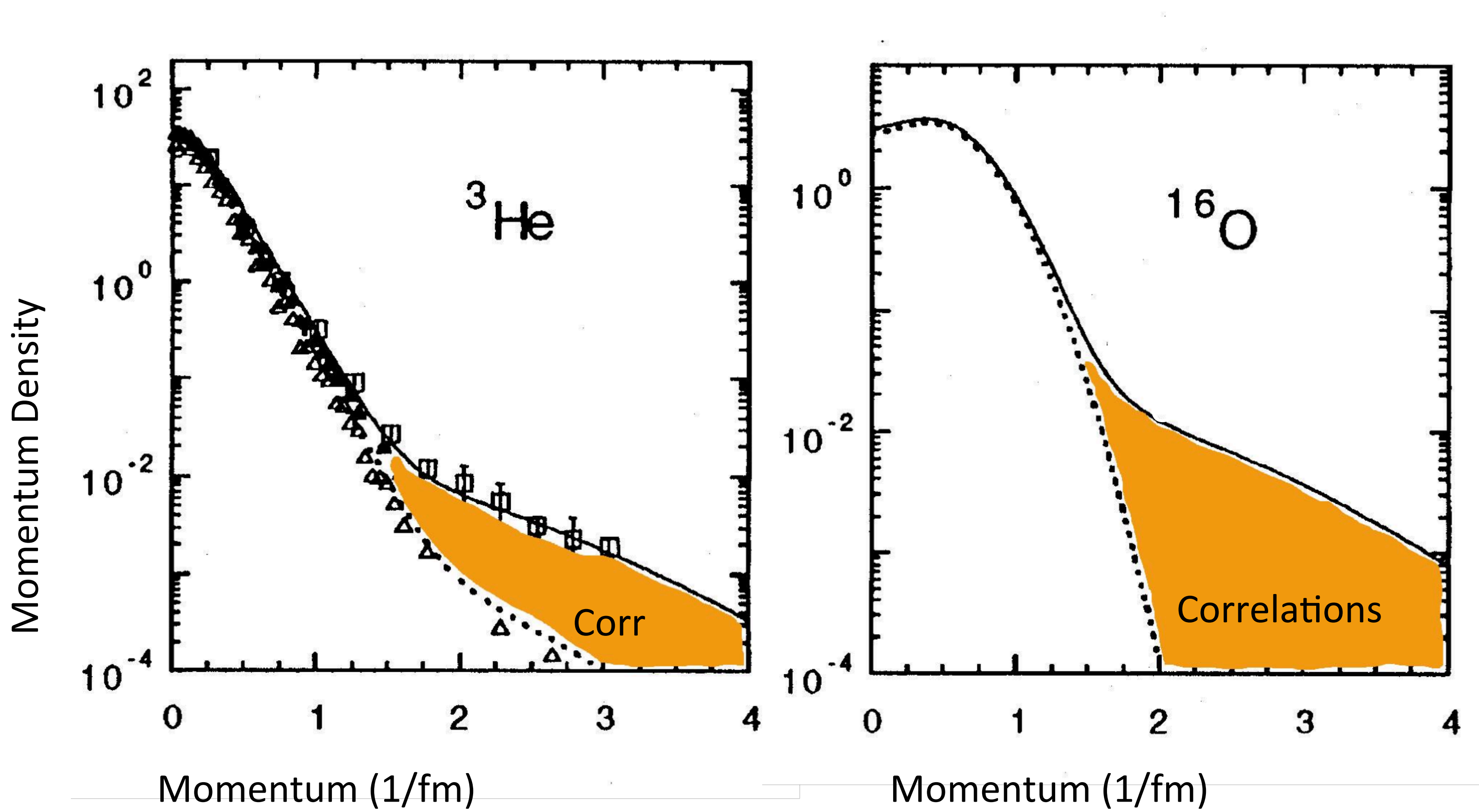
modification??

- Cold dense nuclear matter
- Neutron Stars



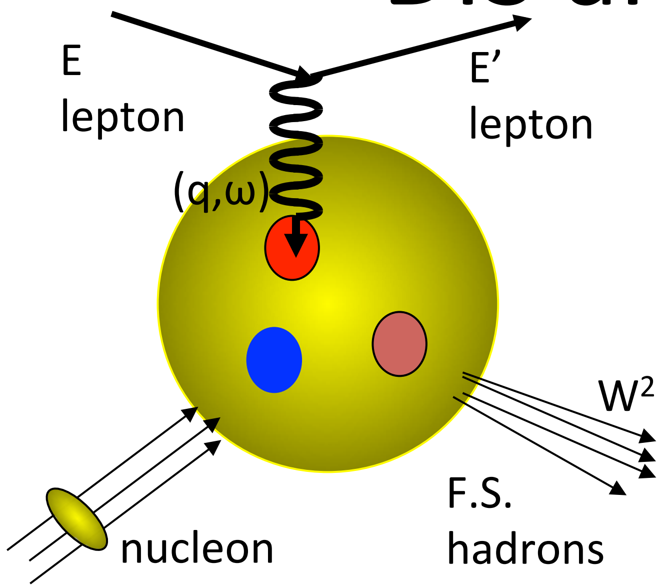
Nucleons are like people …

Correlations and High Momentum



Ciofi degli Atti, PRC **53** (1996) 1689

DIS and the EMC Effect



$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

$$\omega = E' - E$$

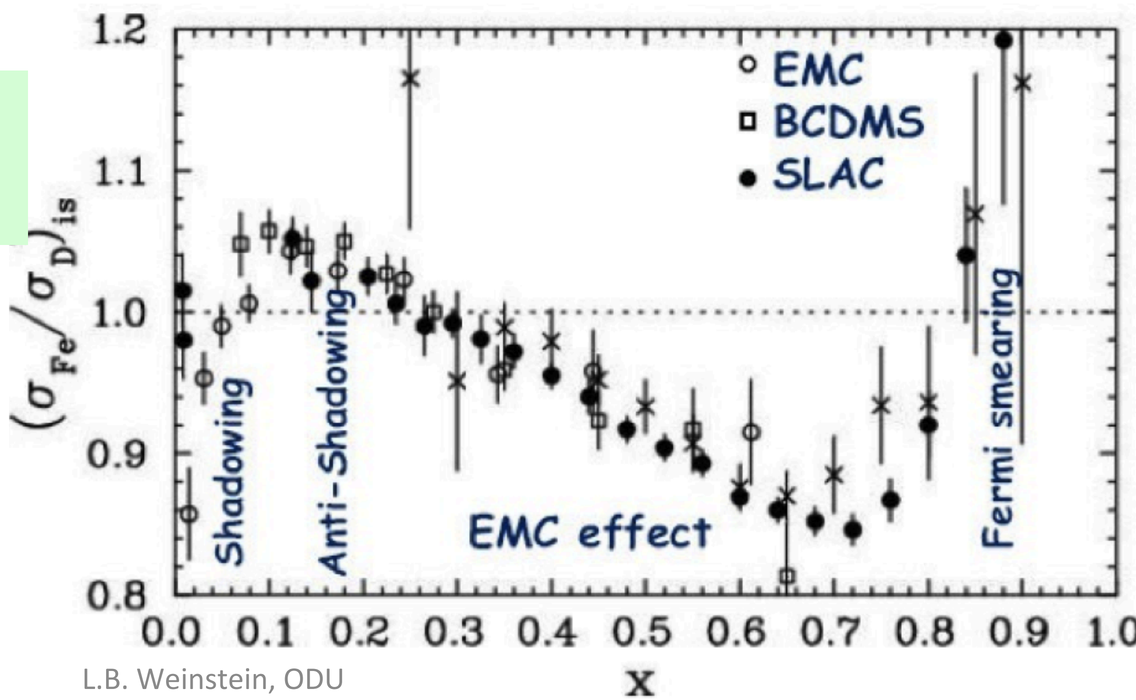
$$0 < x_B = \frac{Q^2}{2m_N\omega} < 1$$

- EMC Scale: several GeV
- Nuclear binding energy scale: several MeV

Expectation: DIS off bound nucleons equals DIS of a free nucleons

Reality: Bound nucleon DIS **does not equal** free DIS

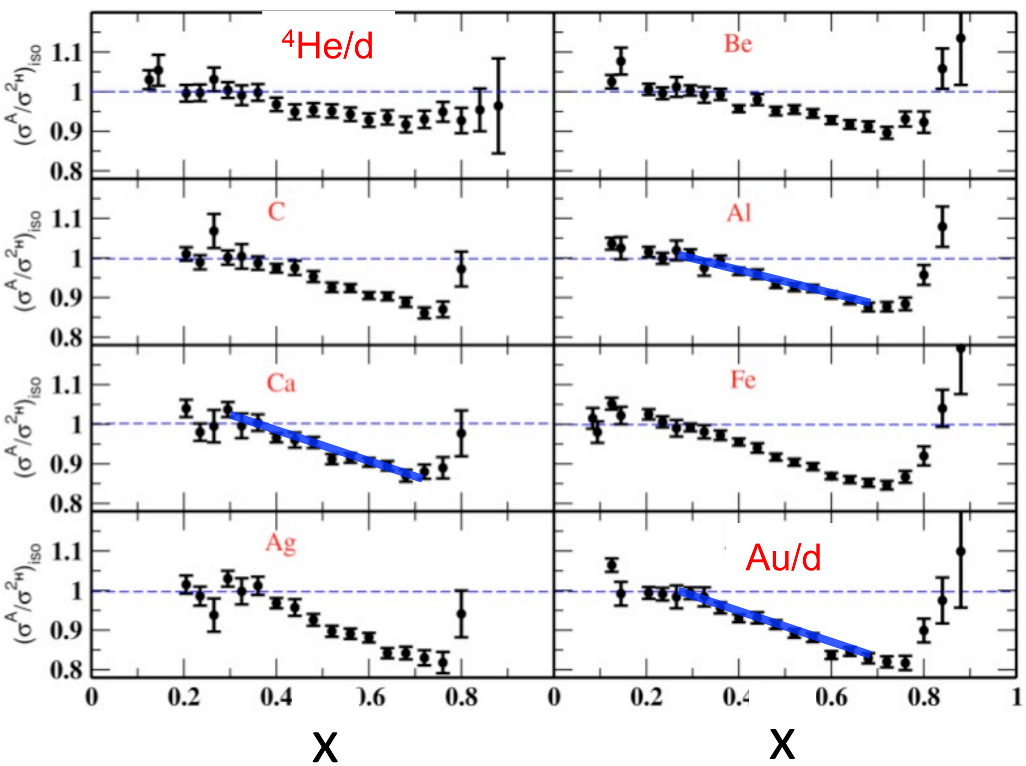
Origin of EMC effect unknown.
Nucleon modification needed.
≈10^3 publications



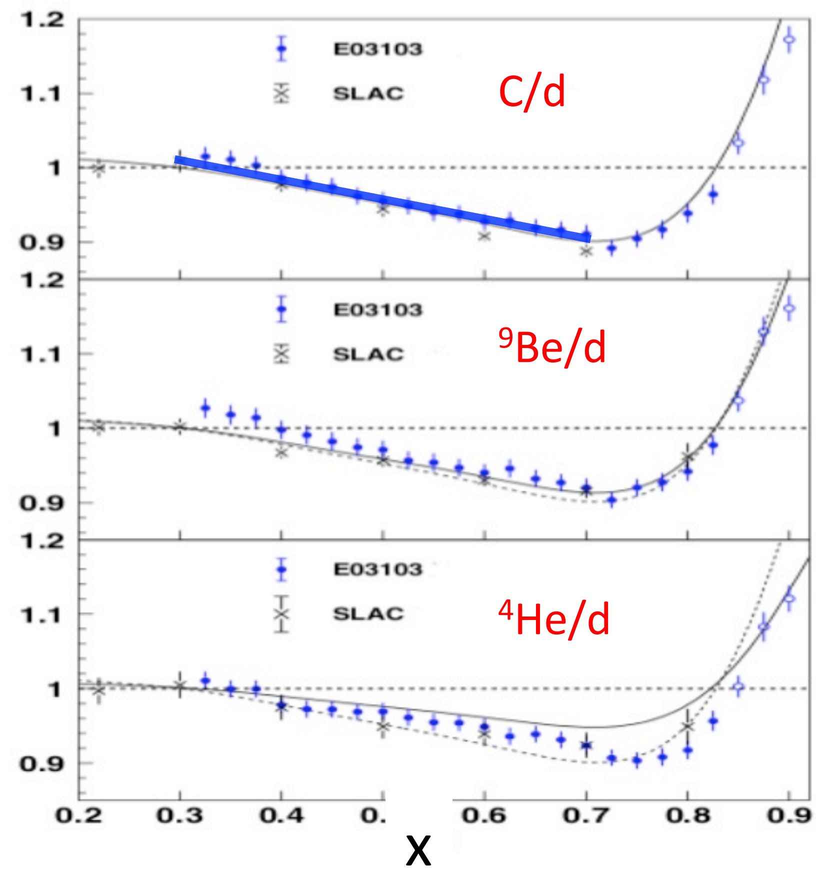
EMC Effect: Universal

$$\frac{2}{A} \cdot \frac{\sigma^A}{\sigma^d}$$

SLAC



Hall C



Very linear for $0.3 < x_B < 0.7$
(the lines shown are not fits)

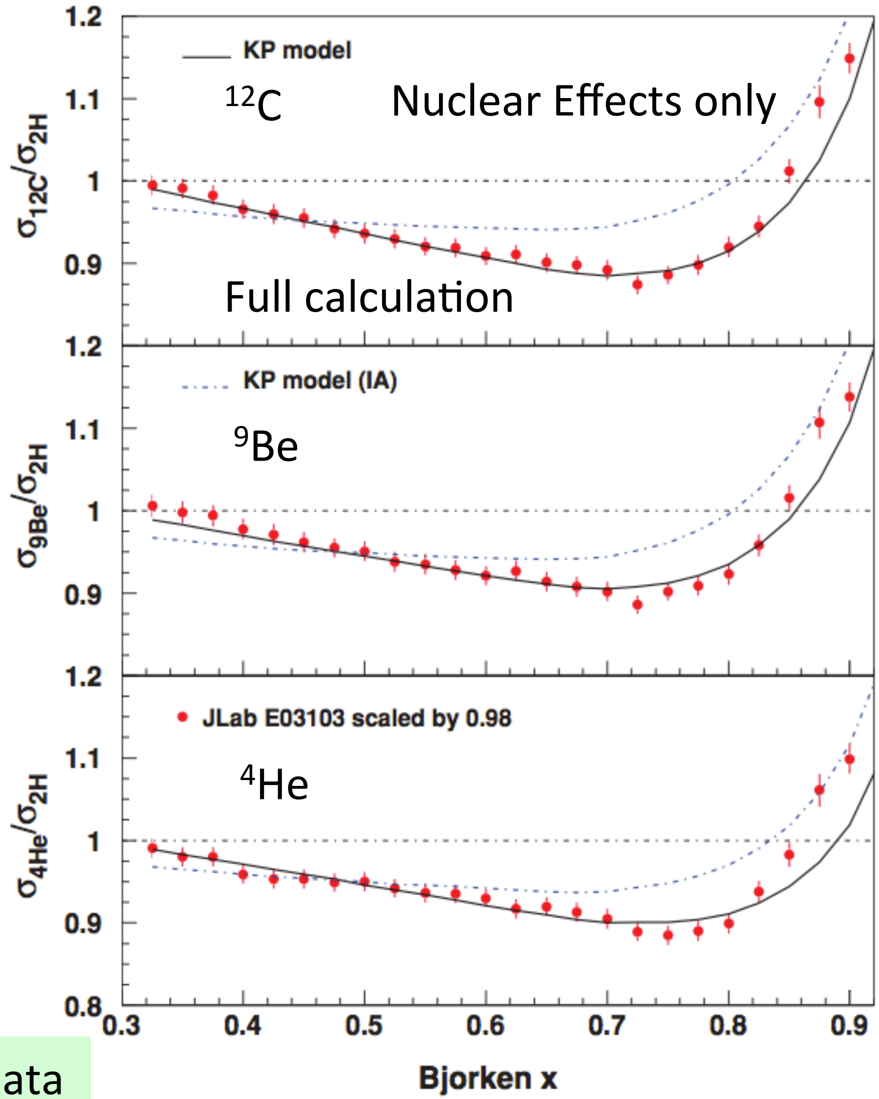
J. Seely, PRL 103, 202301 (2009)
J. Gomez, PRD **49**, 4348 (1994).

Size of effect ("depth" or slope) grows with A

EMC Effect: Theory

- Nuclear Effects:
  - Fermi motion
  - Binding energy
- Full Calculation
  - Nucleon modification
  - Nuclear pions
  - shadowing

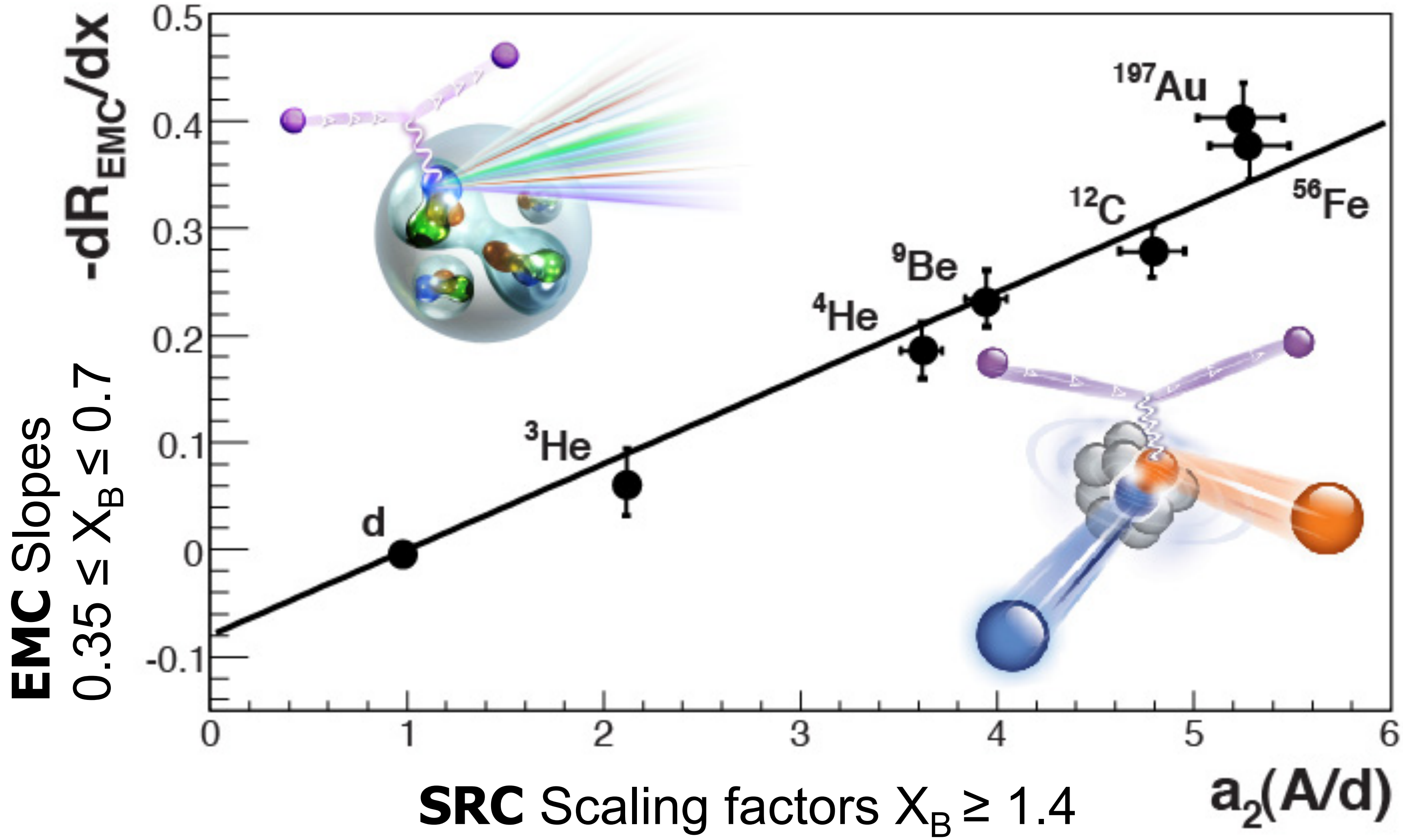
Nucleon modification:
Phenomenological change to bound nucleon structure functions, change proportional to virtuality $v = (p^2 - M^2)/M^2$



Nucleon modification needed to describe data

Kulagin and Petty, PRC 82, 054614 (2010)

EMC Effect and Correlations



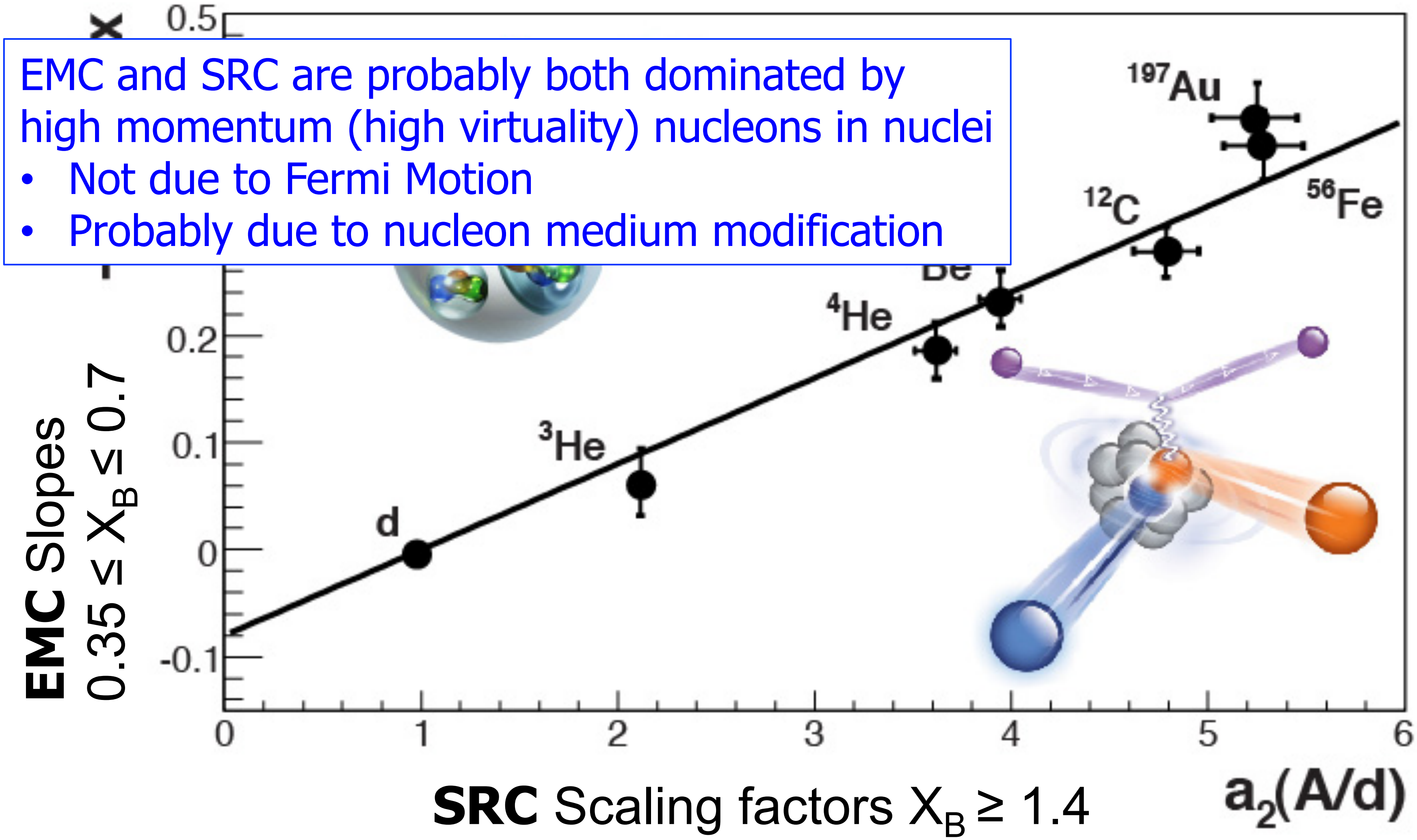
SRC data from Fomin et al
EMC data from Gomez et al and Seely et al

Weinstein et al, PRL**106**, 052301 (2011)
Hen et al, PRC**85**, 047301 (2012)

EMC Effect and Correlations

EMC and SRC are probably both dominated by high momentum (high virtuality) nucleons in nuclei

- Not due to Fermi Motion
- Probably due to nucleon medium modification



SRC data from Fomin et al
EMC data from Gomez et al and Seely et al

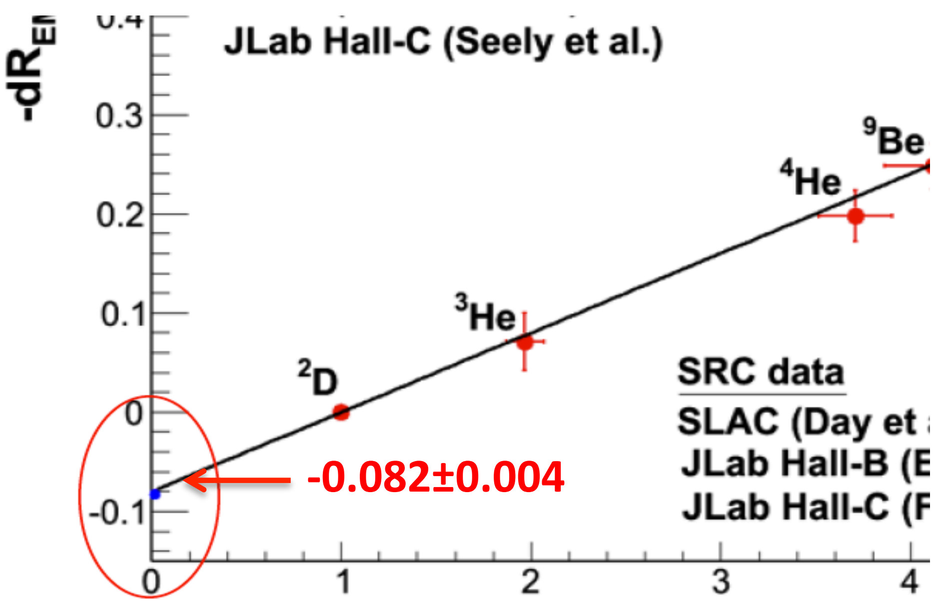
Weinstein et al, PRL**106**, 052301 (2011)
Hen et al, PRC**85**, 047301 (2012)

EMC-SRC Connection

If we are right, we should measure a large EMC effect by selecting high-momentum nucleons!?

Deuteron

- Is there an “EMC” effect in the deuteron?
- Is it bigger at high-momentum?
- Does the structure function F_2 depend on nucleon momentum (virtuality)?



$$\sigma_d^{DIS} \neq \sigma_p^{DIS} + \sigma_n^{DIS}$$

$$\frac{\sigma_d}{\sigma_p + \sigma_n} = 1 - (0.082 \pm 0.004)(0.6 - 0.31 \pm 0.04) \approx 0.976$$

$$\frac{\sigma_d}{\sigma_p + \sigma_n}(x_B = 0.6) \approx 0.976$$

$$\frac{\sigma_p^*}{\sigma_p} \approx \frac{\sigma_n^*}{\sigma_n} \approx \frac{2.4\%}{5\%} \approx 0.5$$

Suggested Explanation of Correlation between SRC and EMC

- EMC effect does not occur (or is very small) for mean-field nucleons
- Both SRC and EMC are related to high-momentum (high virtuality) nucleons
- High momentum (high virtuality) nucleons in the medium are modified

Hmm..

- Let's measure the in-medium modified(?) structure function F_2 in DIS

$$\frac{d^3\sigma}{d\Omega dE'} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[\frac{1}{\omega}F_2(x_B,Q^2) + \frac{2}{M}F_1(x_B,Q^2)\cdot\tan^2\left(\frac{\theta_e}{2}\right)\right]$$

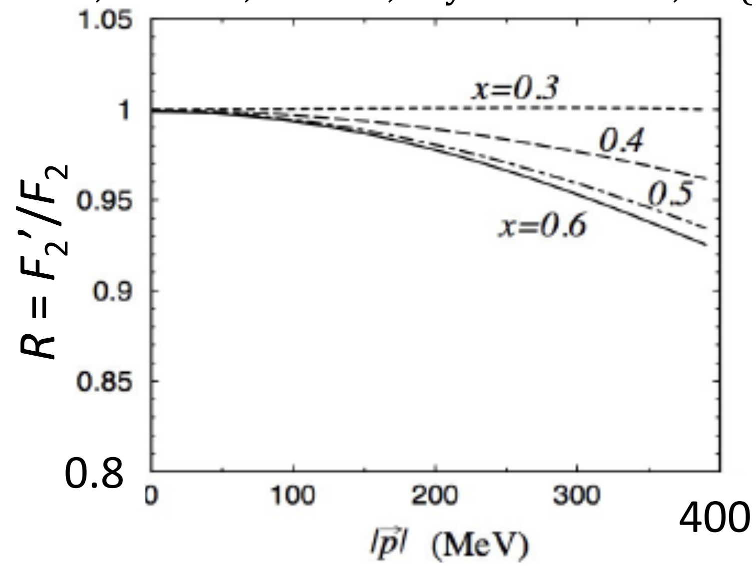
(F_1 and F_2 are related by R, the measured ratio of longitudinal and transverse cross sections. Thus measuring the cross section yields F_2.)

F_2 Momentum Dependence

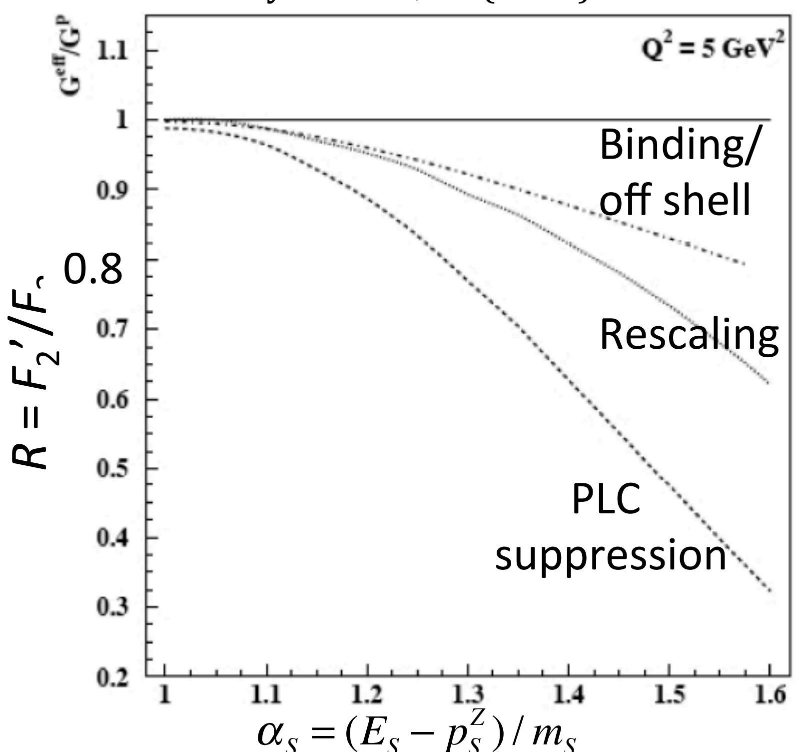
Dependence on:

- Models
- Nucleon's momentum and x_B
- Nucleon's momentum, not x_B

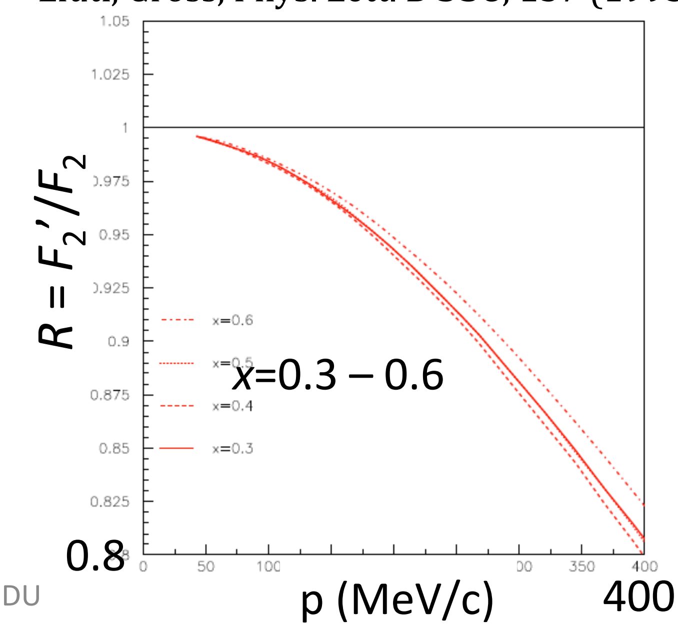
Melnitchouk, Screiber, Thomas, Phys. Lett. B **335**, 11 (1994)



Melnitchouk, Sargsian, Strikman,
Z. Phys. A **359**, 99 (1997)



Liuti, Gross, Phys. Lett. B **356**, 157 (1995)

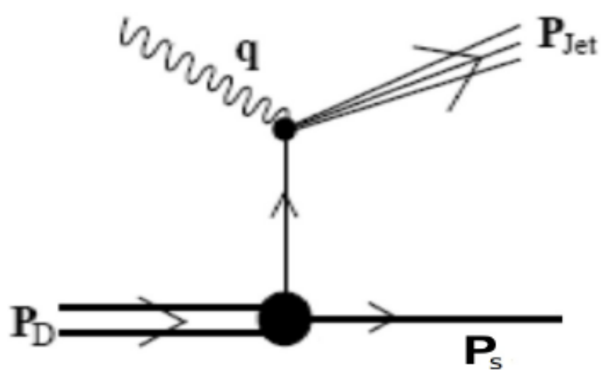


Tagging Nucleon Structure Functions

- 6 GeV: $d(e,e'p_s)$ Hall B (Kuhn, Griffeon)
- 12 GeV: E12-11-107 Hall C (Hen, Weinstein, Gilad, Wood)

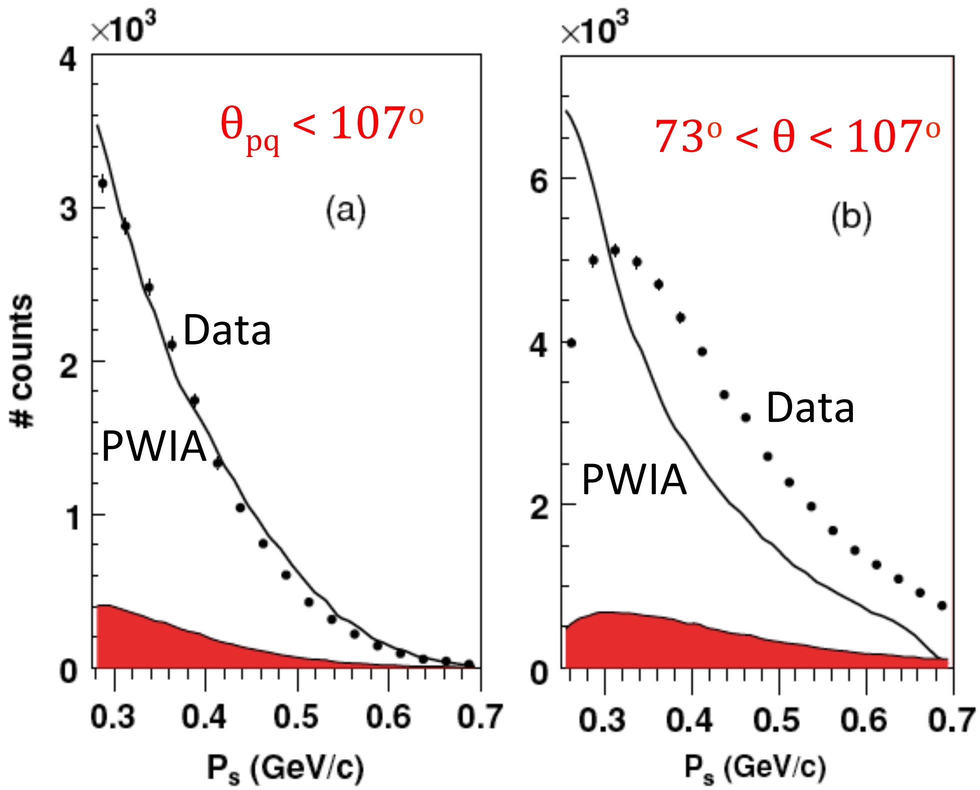
Experimental method

- DIS on a deuteron target
- Tag high-momentum nucleons with high-momentum backward-recoiling ("spectator") partner nucleon $d(e,e'N_S)$
- Recalculate struck nucleon kinematics (x', W')



Minimize nucleon rescattering (FSI)

$D(e,e'p_S)$

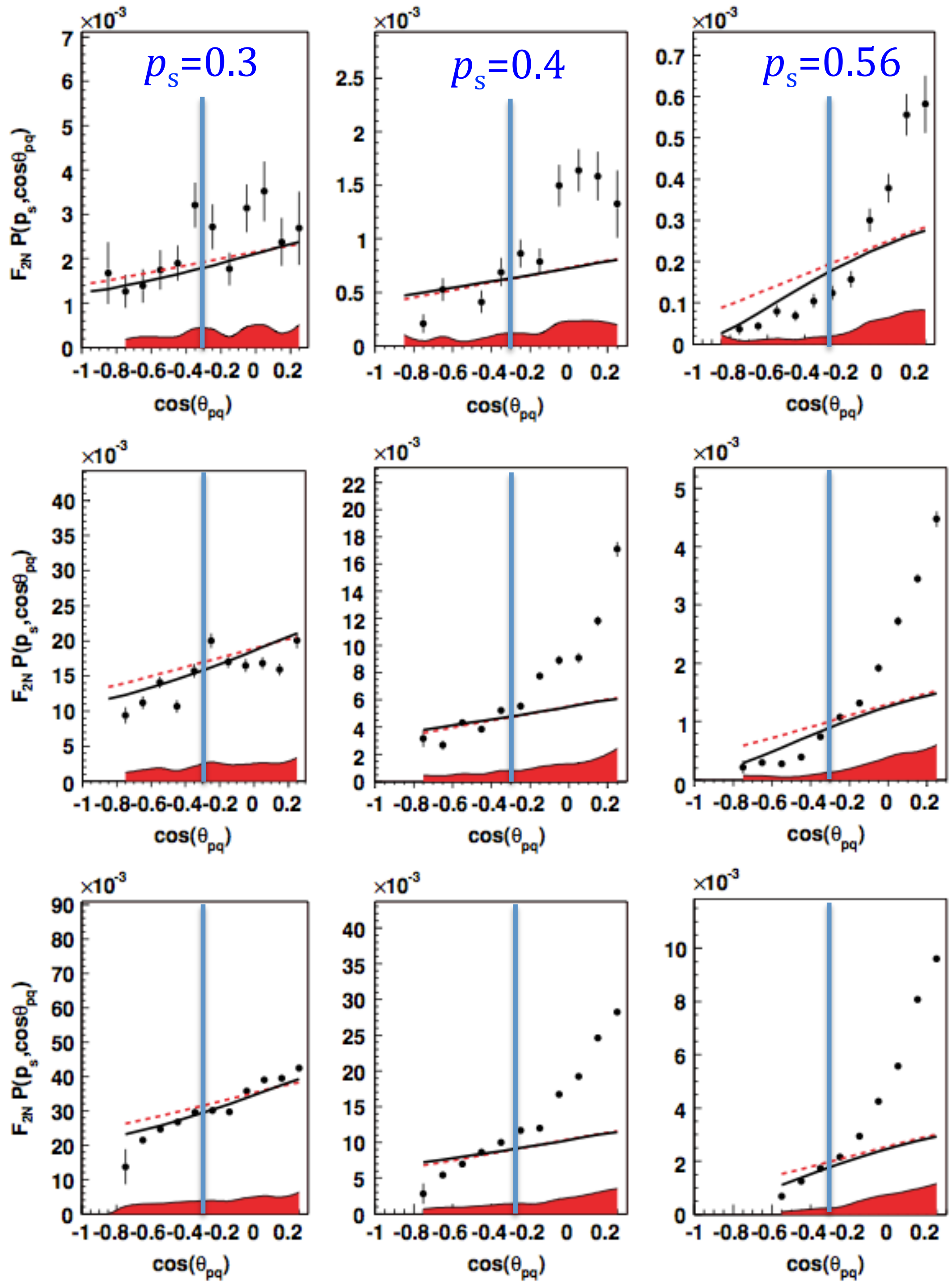


A. V. Klimenko *et al.*, PRC **73**, 035212 (2006)

FSI:

- Decrease with Q^2
- Increase with W'
- Not sensitive to x'
- Small for $\theta_{pq} > 107°$

Minimize nucleon rescattering (FSI)



A. V. Klimenko *et al.*, PRC **73**, 035212 (2006)

Experimental Method

$d(e,e'N_S)$ cross section Factorizes into the cross section ($\sigma \sim F_2$) times the distorted momentum distribution.

Cross section ratio at fixed nucleon momentum ➔ distorted spectral function cancels:

$$F_2^*(x_1', \alpha_S, p_T, Q_1^2) \Big/ F_2^*(x_2', \alpha_S, p_T, Q_1^2) = \left(\frac{d^4\sigma}{dx_1' dQ^2 d\vec{p}_S} / K_1 \right) \Big/ \left(\frac{d^4\sigma}{dx_2' dQ^2 d\vec{p}_S} / K_2 \right)$$

Measure α_s dependence at $\theta_{pq} > 107°$ (small FSI)

$$x' = \frac{Q^2}{2 p_\mu q^\mu} = \frac{Q^2}{2[(M_d - E_S)\omega + \vec{p}_S \cdot \vec{q}]}$$

x' is x-Bjorken for the moving struck nucleon

$$\alpha_s = (E_s - p_s^z) / m_s$$

$\vec{p}_s$ maps to (α_s, p_T)

Experimental Method (cont.)

- Minimize experimental and theoretical uncertainties by measuring cross-section ratios

$$\frac{\sigma_{DIS}(x'_{high}, Q_1^2, \vec{p}_s)}{\sigma_{DIS}(x'_{low}, Q_2^2, \vec{p}_s)} \cdot \frac{\sigma_{DIS}^{free}(x_{low}, Q_2^2)}{\sigma_{DIS}^{free}(x_{high}, Q_1^2)} \cdot R_{FSI} = \frac{F_2^{bound}(x'_{high}, Q_1^2, \vec{p}_s)}{F_2^{free}(x_{high}, Q_1^2)}$$

FSI correction factor

x' = x from a moving nucleon

$$x'_{high} \geq 0.45$$

$$0.25 \geq x'_{low} \geq 0.35$$

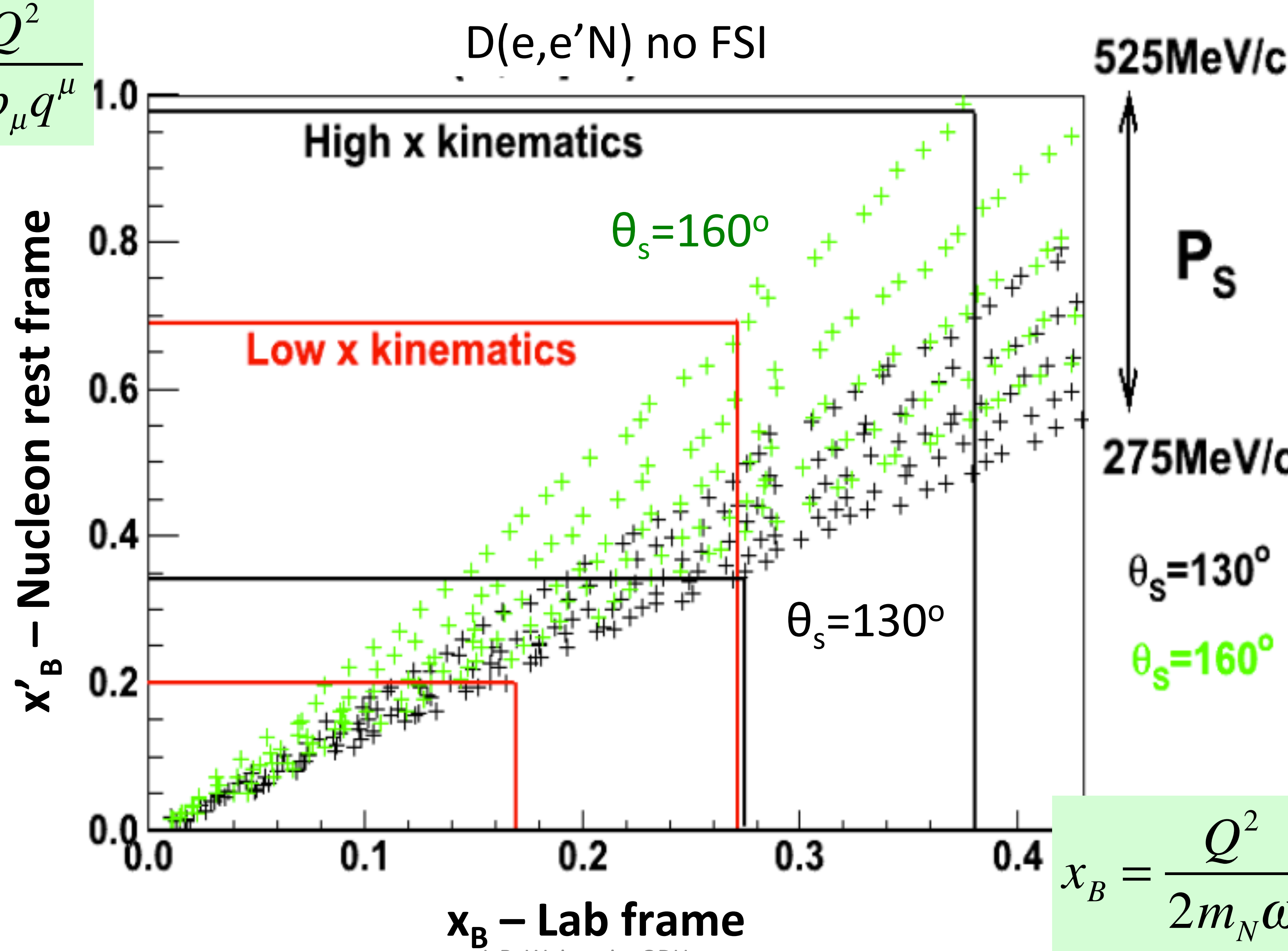
No EMC effect is expected

$$x'_B = \frac{Q^2}{2p_\mu q^\mu} \overset{\text{(For d)}}{=} \frac{Q^2}{2[(M_d - E_S)\omega + \vec{p}_S \cdot \vec{q}]}$$

$$x_B = \frac{Q^2}{2m_N\omega}$$

x_B' vs. x_B

$$x'_B = \frac{Q^2}{2p_\mu q^\mu}$$

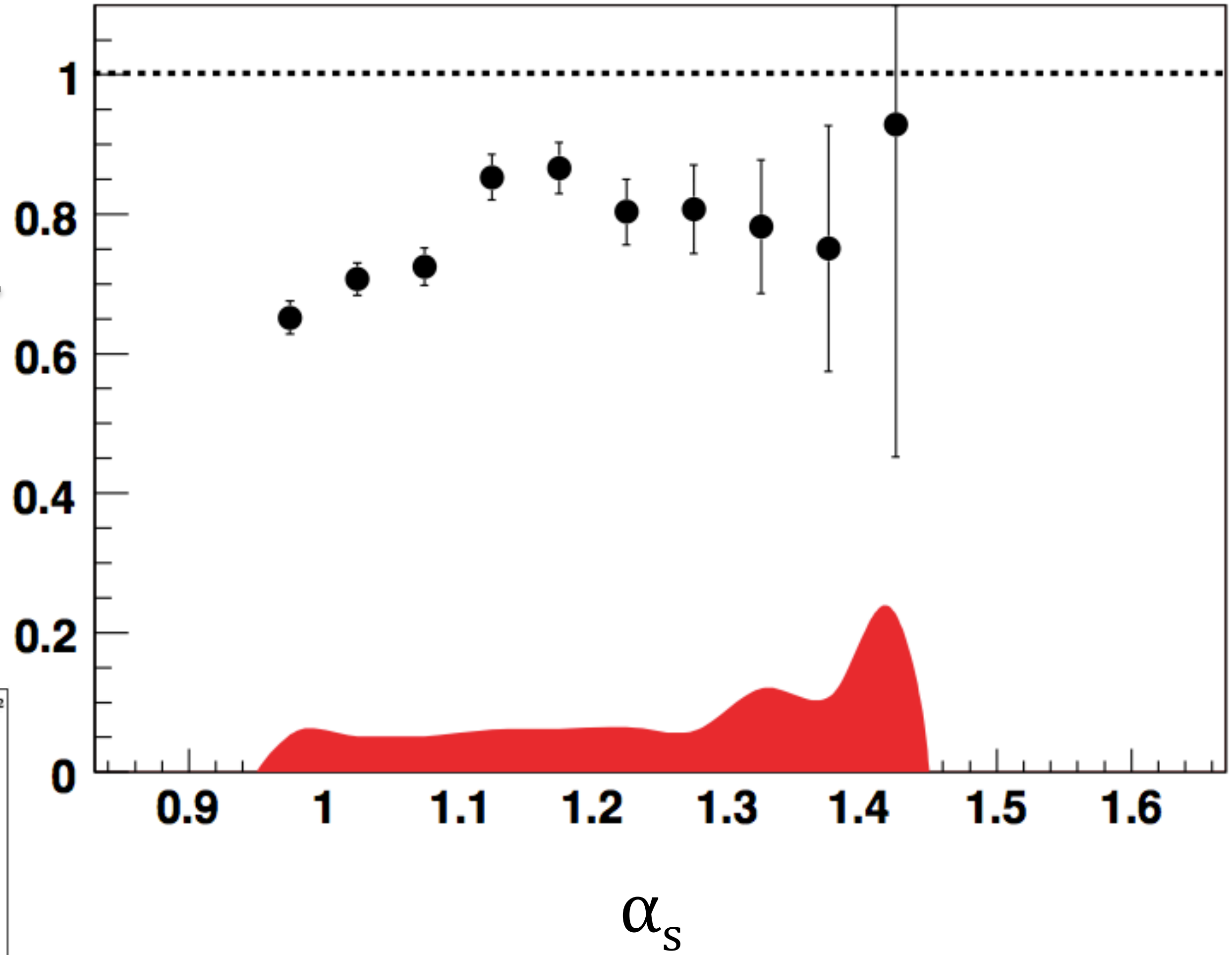


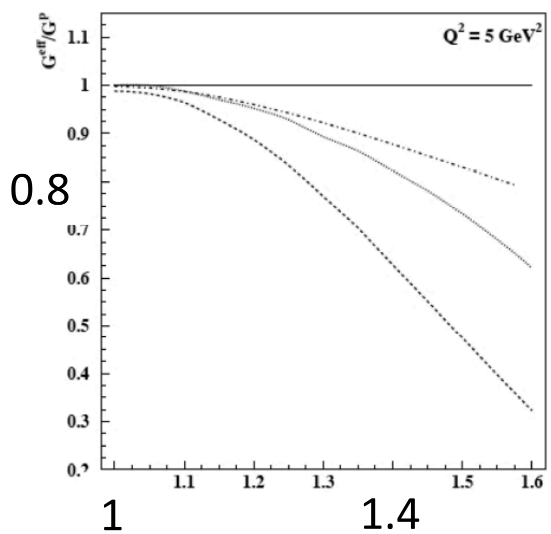
$$x_B = \frac{Q^2}{2m_N\omega}$$

CLAS6 Results: $d(e,e'p_s)$

$$\frac{\left.\dfrac{F_2(x'=0.55,Q^2=2.8)}{F_2(x'=0.25,Q^2=1.8)}\right|_{\text{data}}}{\left.\dfrac{F_2(x'=0.55,Q^2=2.8)}{F_2(x'=0.25,Q^2=1.8)}\right|_{\text{free}}}$$

$p_T \sim 0.3$ GeV/c





Inconclusive

Klimenko et al, PRC **73**, 035212 (2006)

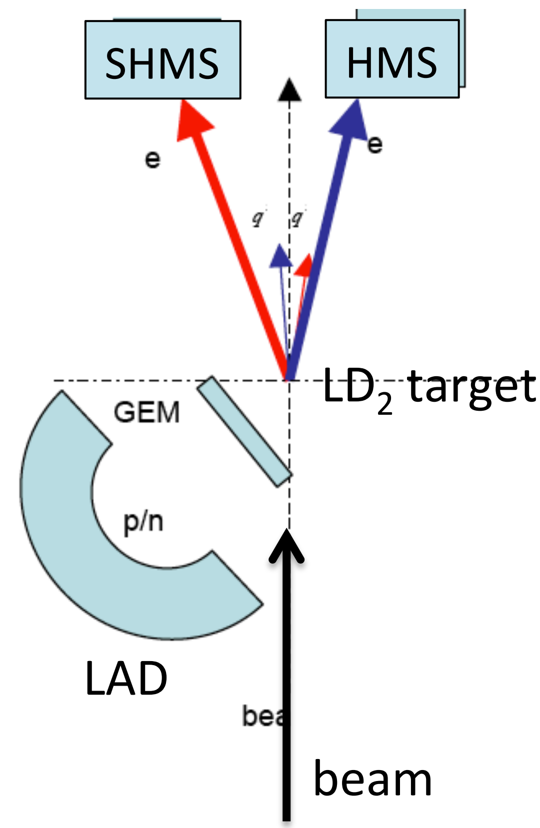
12 GeV – Hall C

E12-11-107: Hen, Weinstein, Gilad and Wood

HMS and SHMS detect electrons

LAD (132 reused CLAS6 TOF detectors, 1.5 sr, 20% neutron efficiency) detects recoiling nucleon

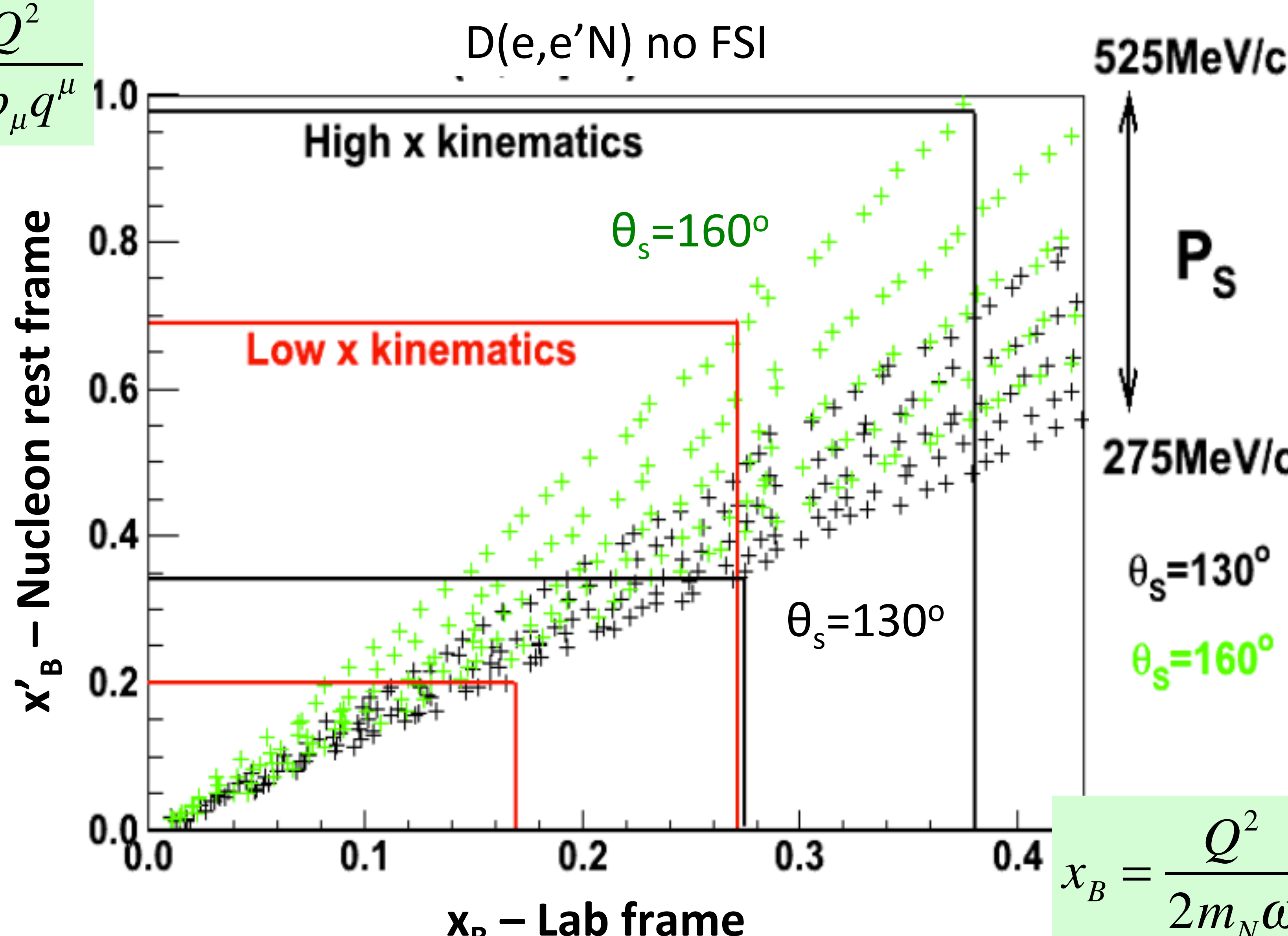
Low x'	High x'
$E_{in} = 10.9$ GeV	$E_{in} = 10.9$ GeV
$E' = 4.4$ GeV	$E' = 4.4$ GeV
$\theta_e = 13.5^o$	$\theta_e = -17^0$
$Q^2 = 2.65$ GeV^2	$Q^2 = 4.19$ GeV^2
$\lvert \vec{q} \rvert = 6.7$ GeV/c	$\lvert \vec{q} \rvert = 6.8$ GeV/c
$\theta_q = -8.8^0$	$\theta_q = 10.8^0$
$x = 0.217$	$x = 0.34$



Collect both LAD-HMS and LAD-SHMS coincidences

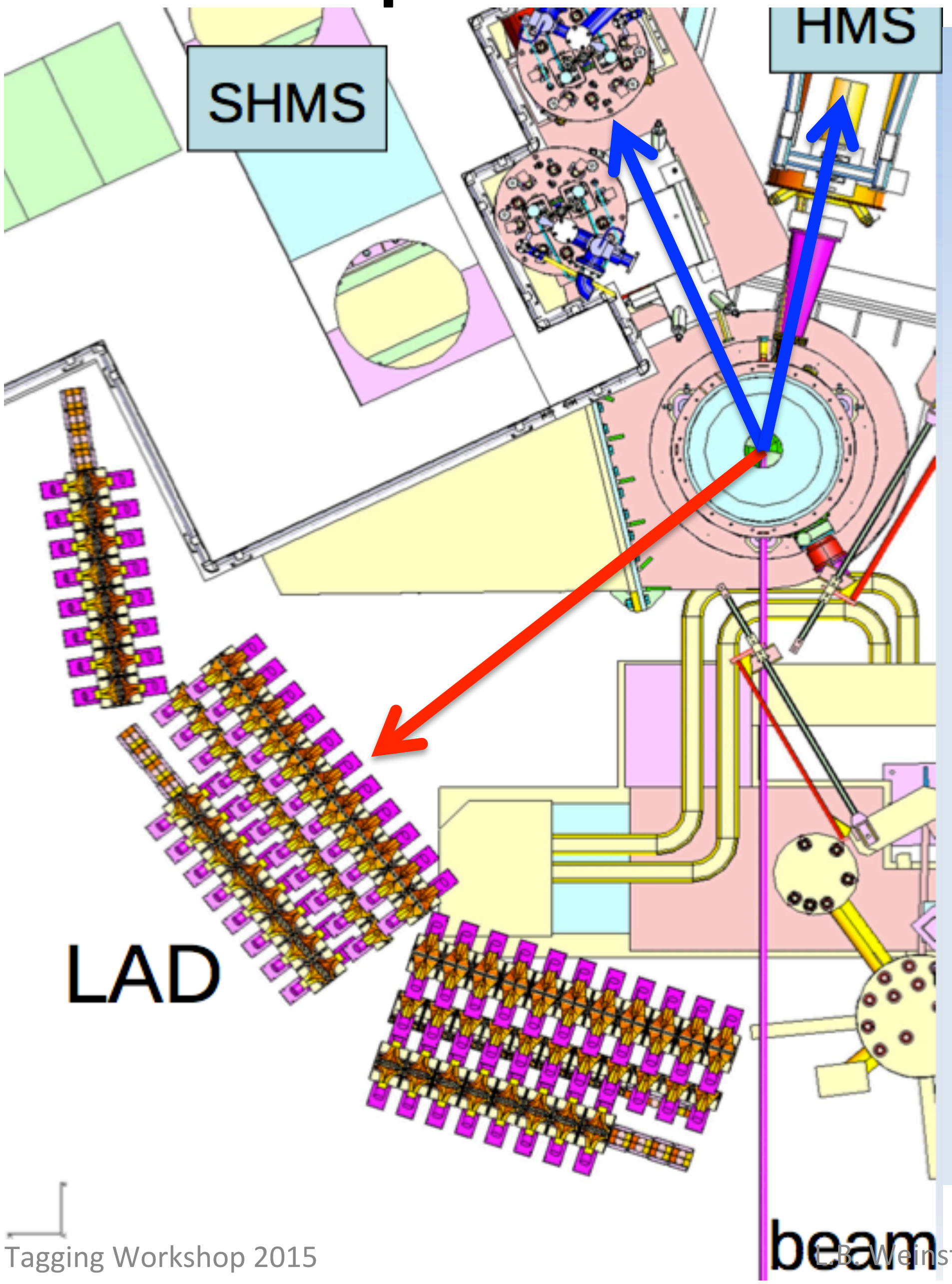
x_B' vs. x_B (Why x'?)

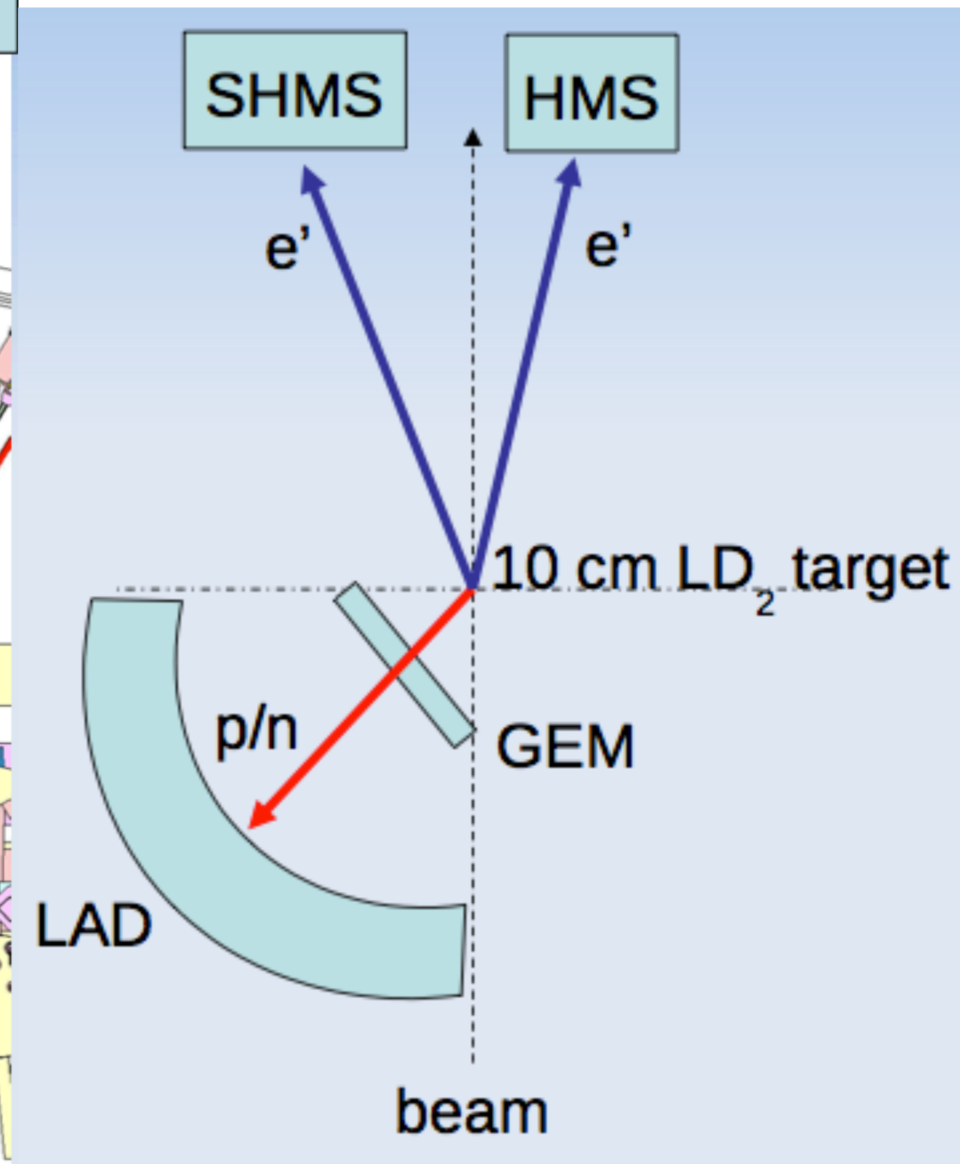
$$x_B' = \frac{Q^2}{2p_\mu q^\mu}$$



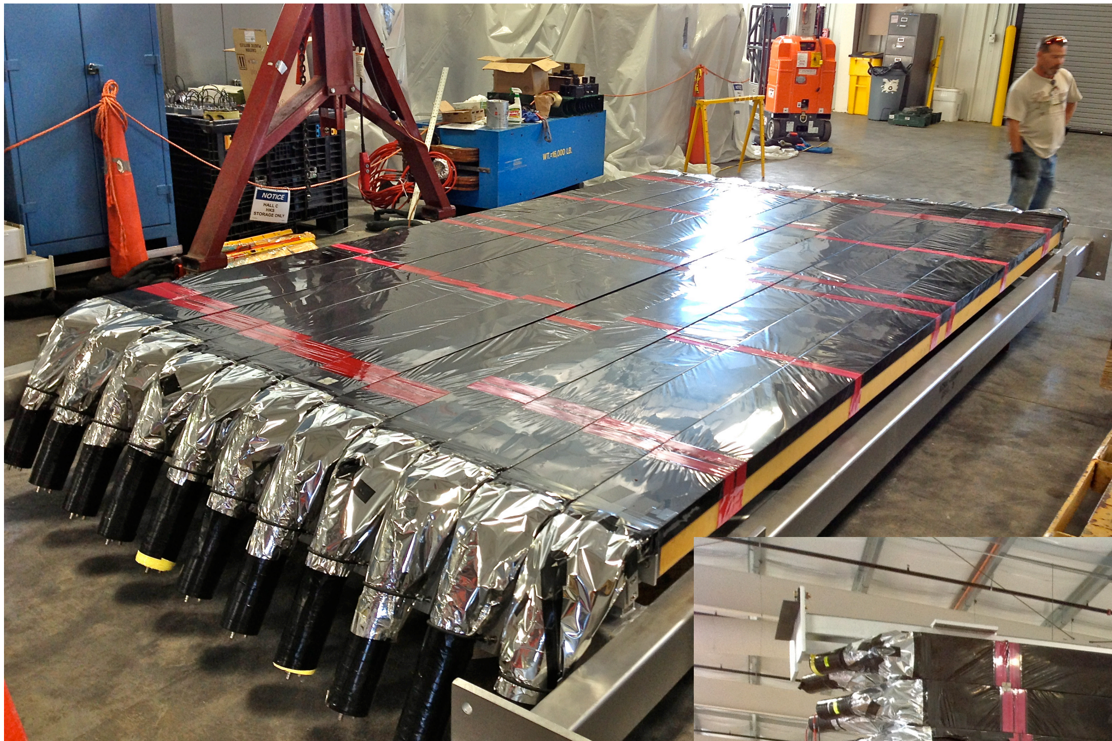
$$x_B = \frac{Q^2}{2m_N\omega}$$

Experimental Set Up – Hall C





CLAS6 TOF → LAD

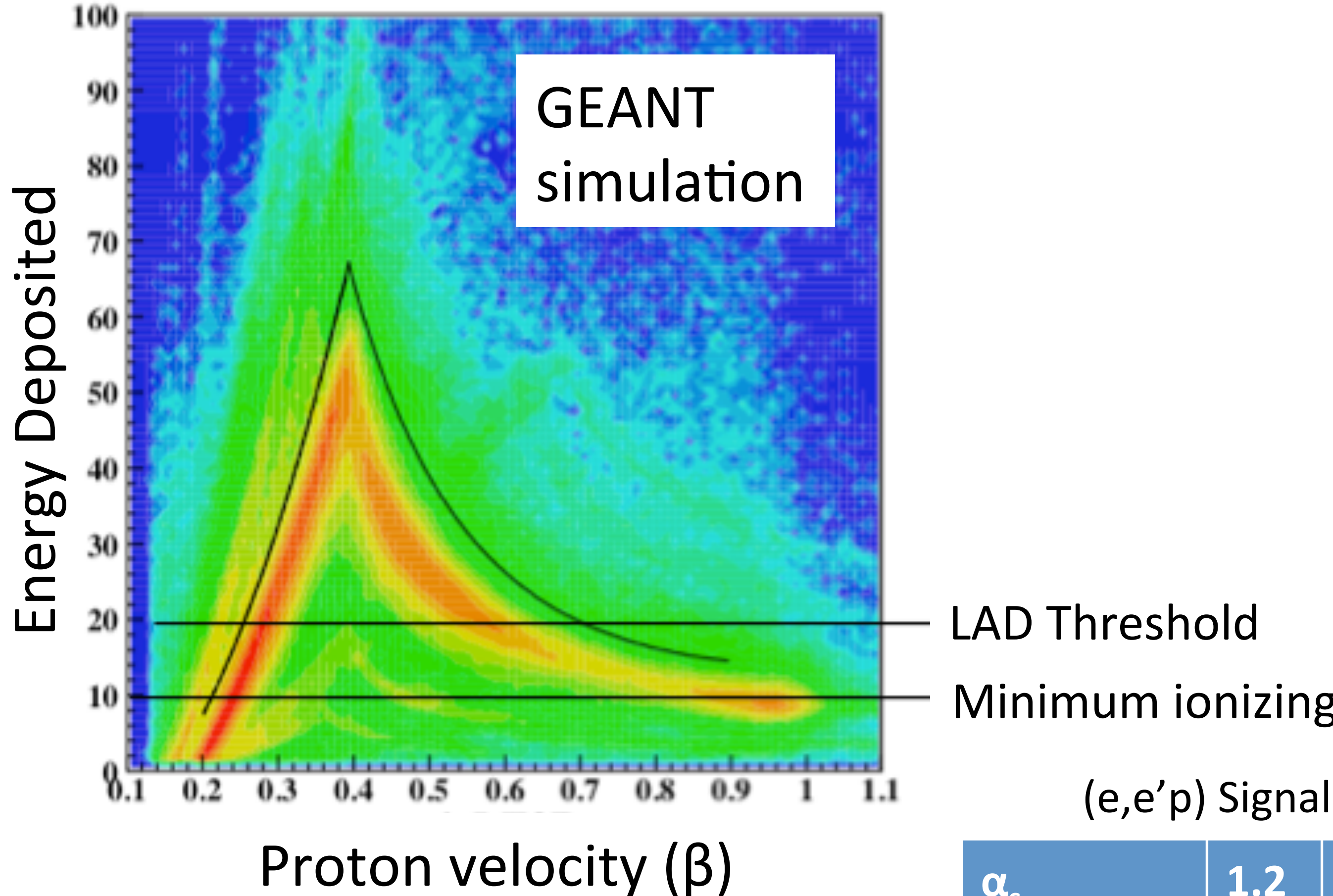


Refurbishing next door in the ODU high bay area.

Come see!

Tel Aviv, Kent State, MIT, JLab, ODU

LAD Performance



Momentum resolution (300 < p < 500 MeV/c) ≈ 0.7%

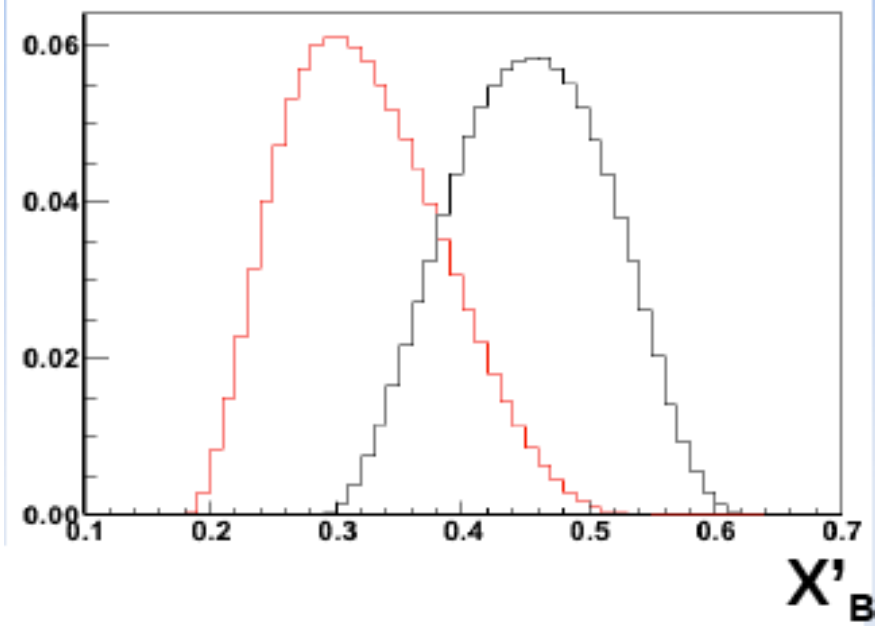
(e,e'p) Signal:Background

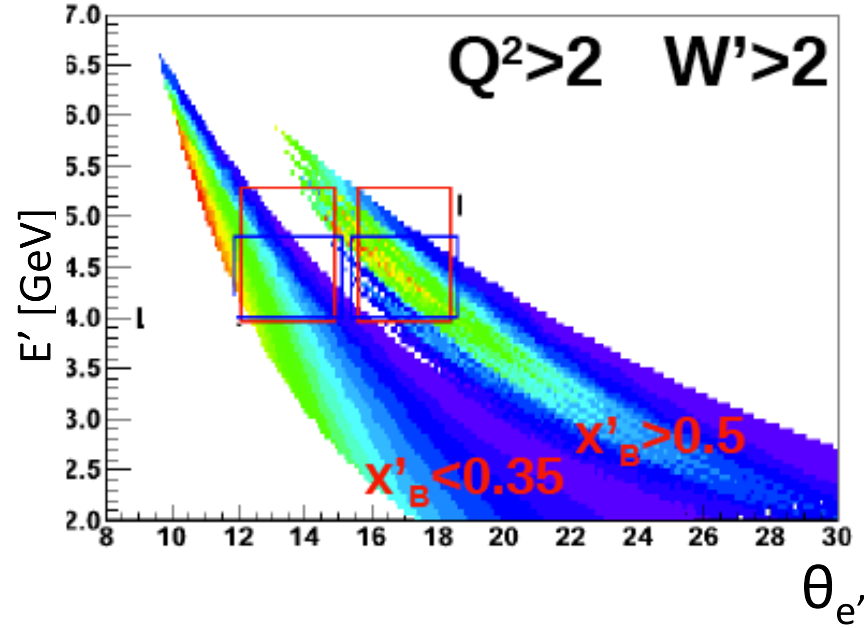
α_s	1.2	1.3	1.4	1.5
$x'_B > 0.45$	1:1	1:2	1:2	1:2
$x'_B \approx 0.3$	3:1	1:1	1:1	1:1

(The neutron is much worse)

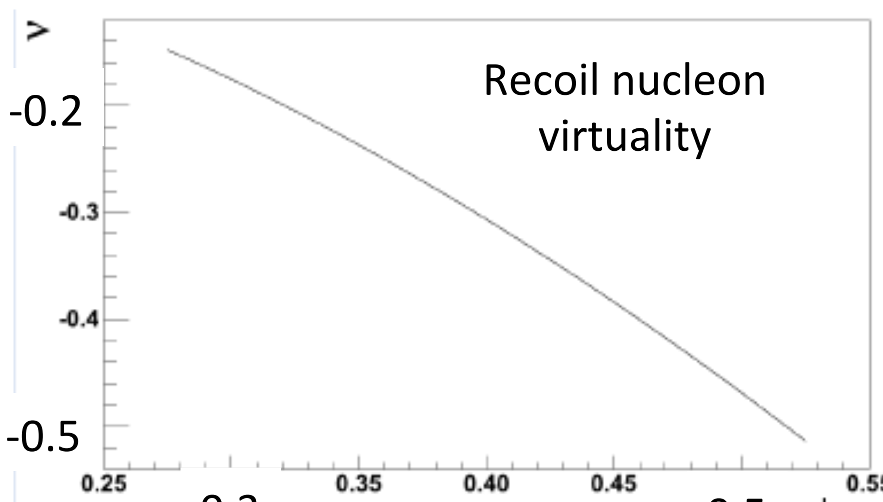
Kinematic Coverage

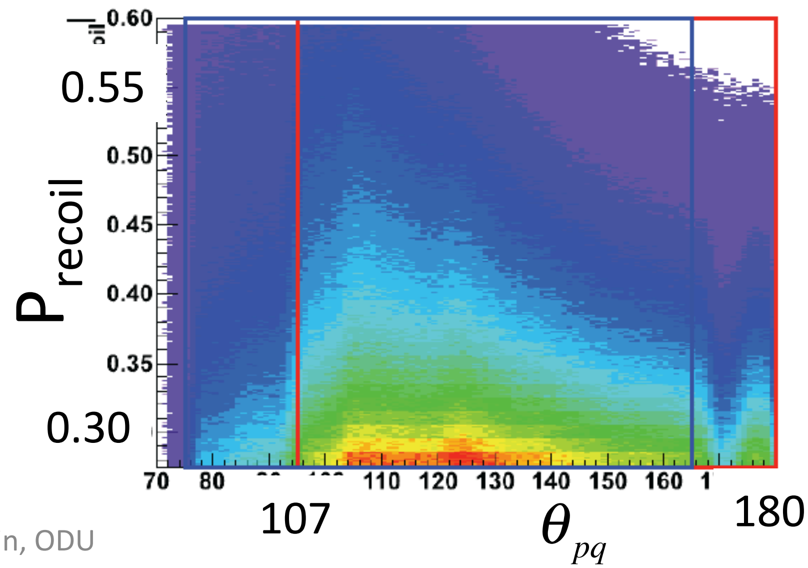
Scattered electrons



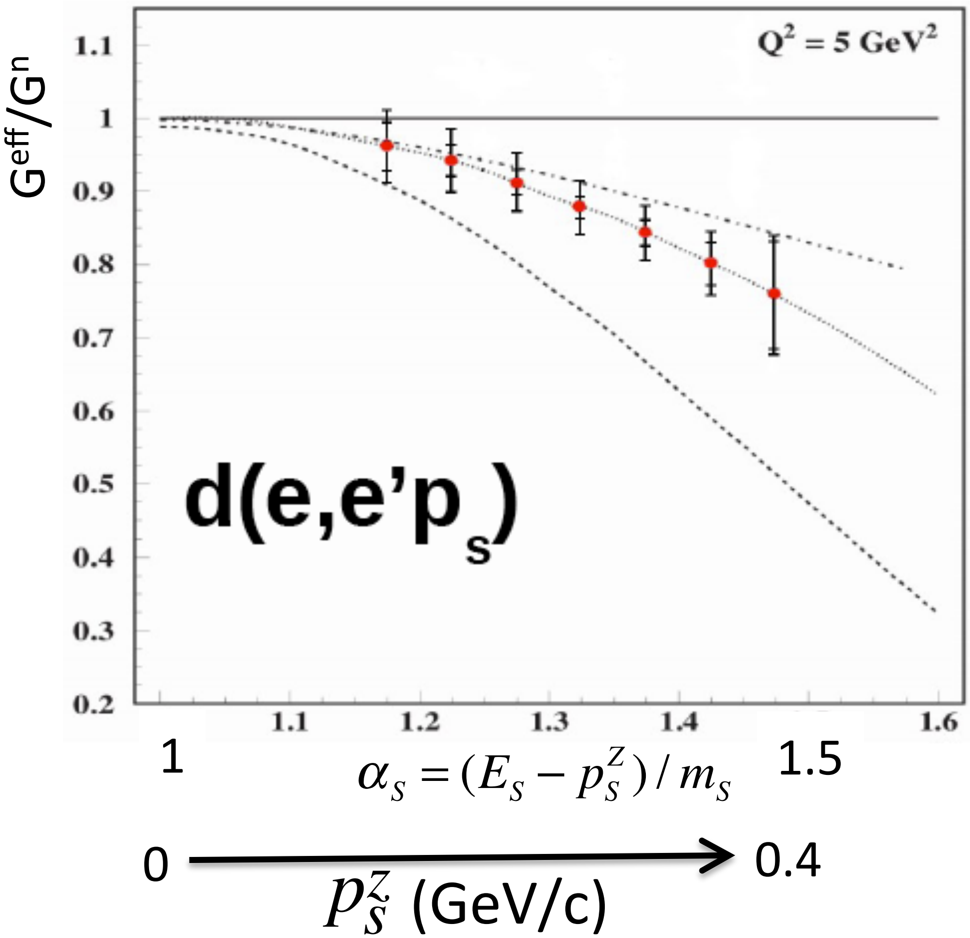


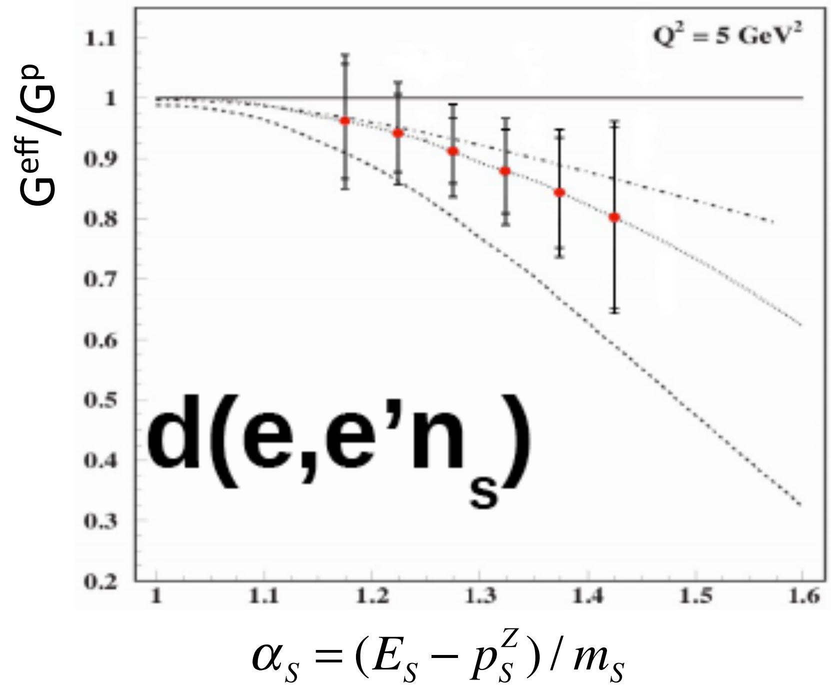
Recoiling nucleons

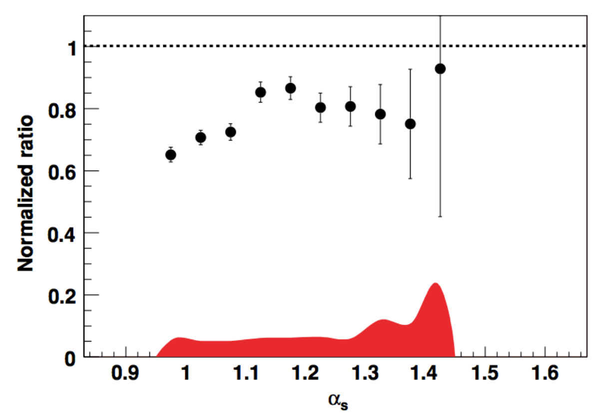




JLab12: Expected Results







Collider Tagging Kinematics

Spectator Momentum

100 GeV d: $\gamma = 50$

Center of Mass		Lab	
P_z (CM) GeV/c	P_perp (CM) GeV/c	P_z (Lab) GeV/c	θ_p (Lab)
0	0	50	0
0.2	0	41	0
0.4	0	34	0
0.6	0	28	0
0.6	0.2	29	0.007
0.6	0.6	36	0.02

Summary

- Bound neutron structure is probably modified, even in the deuteron
  – Modification should increase with momentum
- Measure with $d(e,e'N_s)$ spectator tagging
  – Ratio of cross sections
  – Inconclusive measurement at 6 GeV
  – Upcoming measurement at 12 GeV
  – Exciting possibilities at a collider (see Kijun's Monday talk)