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

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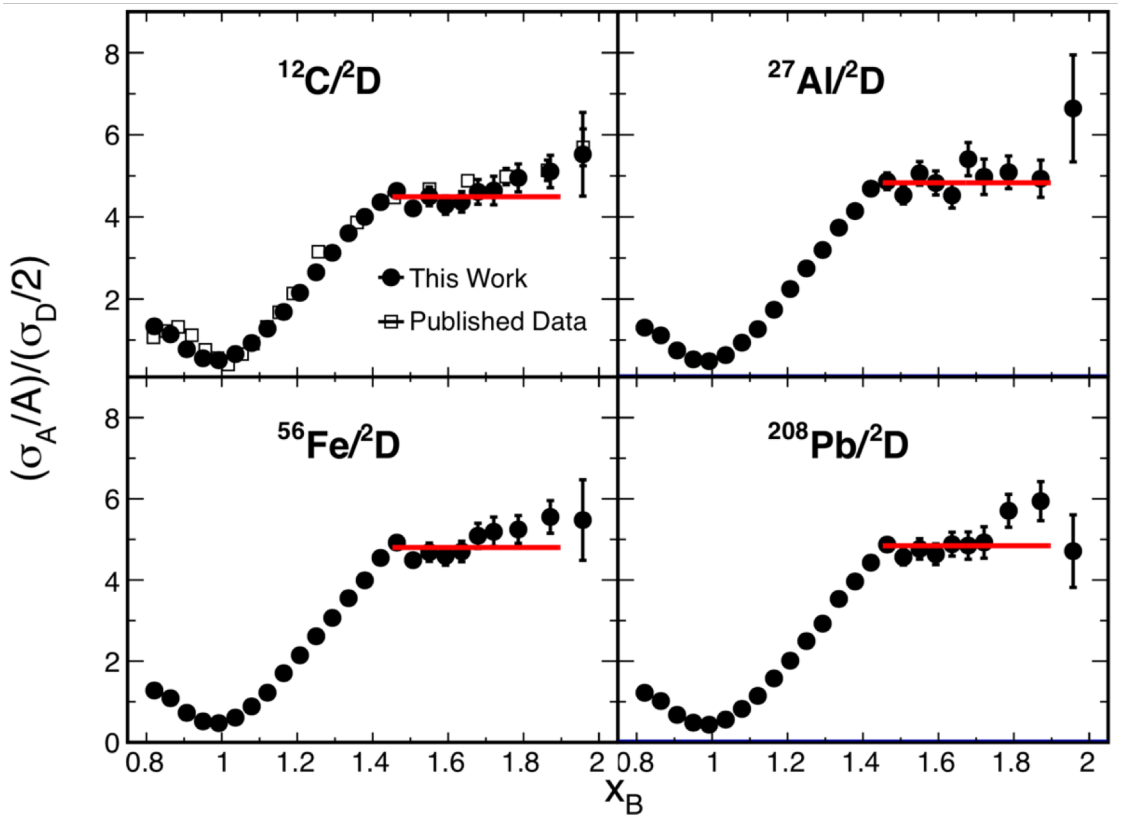
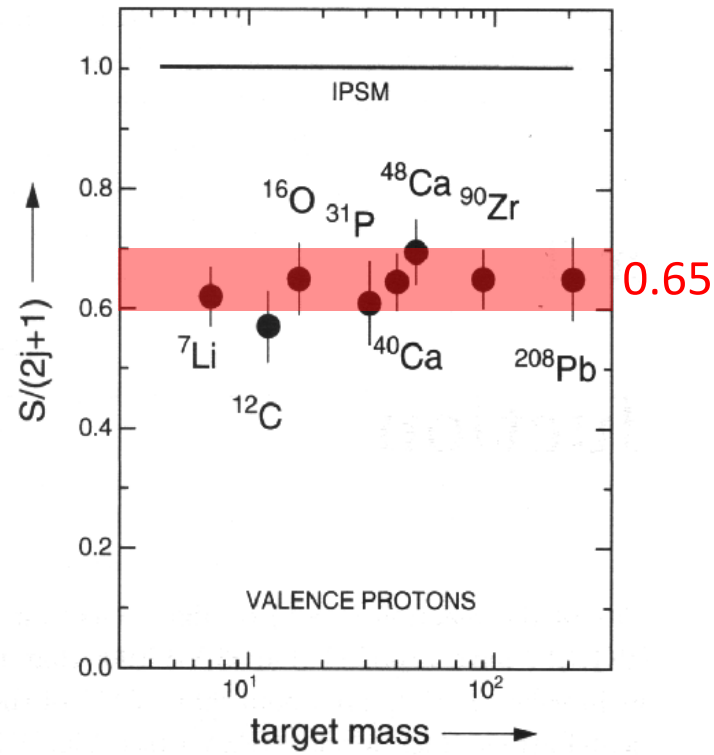
Old Dominion University

Brief Tour of Nuclear Structure

Nucleons:

- ~65% in single particle orbitals
- ~20% in NN correlations
  - Almost all high momentum nucleons



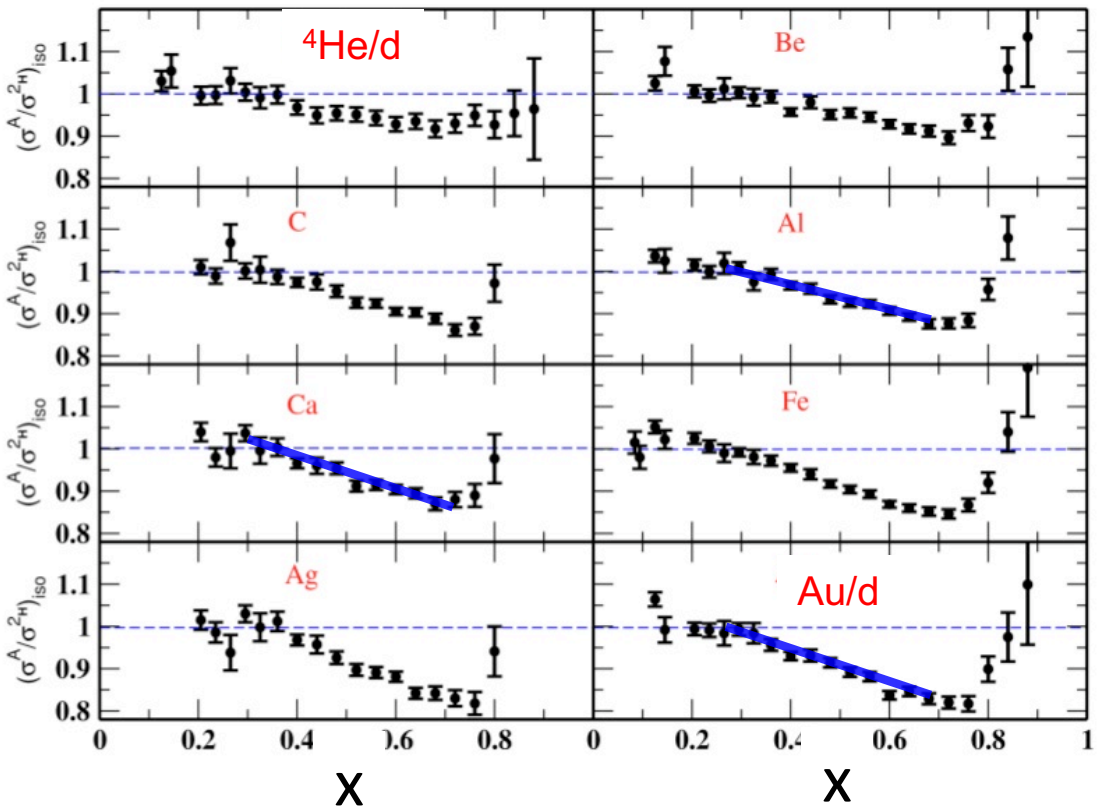


L. Lapikas, NP **A553** (1993) 297c
B. Schmookler, submitted
N. Fomin, PRL **108**, 092502 (2012)
K. Egiyan, PRL **96**, 082501 (2006)

EMC Effect: Universal

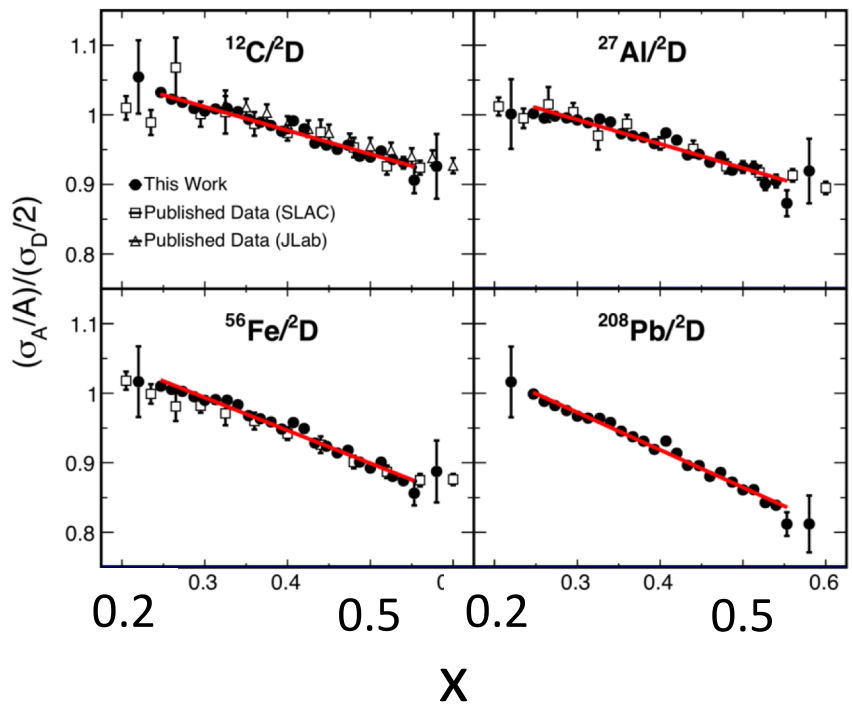
$$\frac{2}{A} \cdot \frac{\sigma^A}{\sigma^d}$$

SLAC



Very linear for $0.3 < x_B < 0.7$

CLAS/SLAC/Hall C



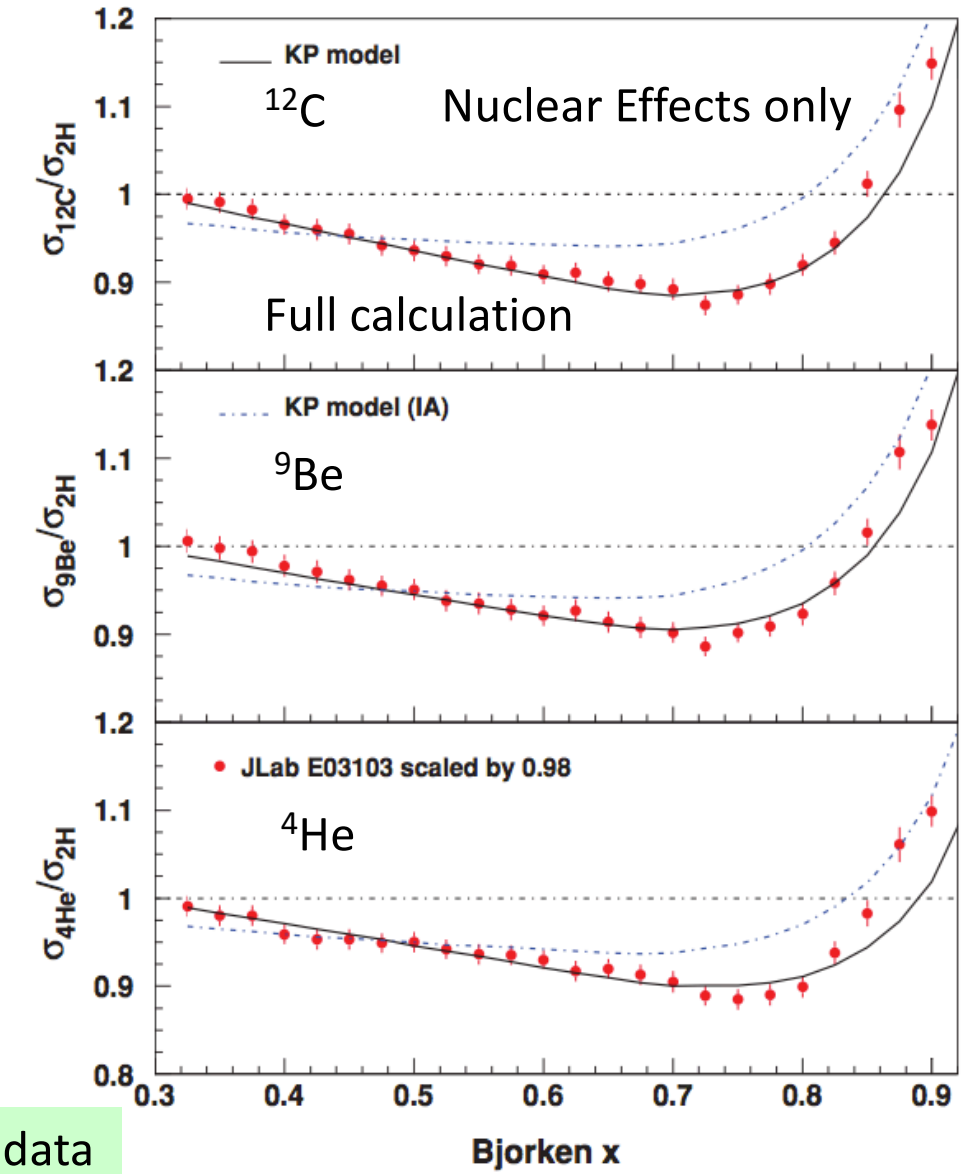
B. Schmookler, submitted
J. Gomez, PRD **49**, 4348 (1994).
J. Seely, PRL **103**, 202301 (2009)

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

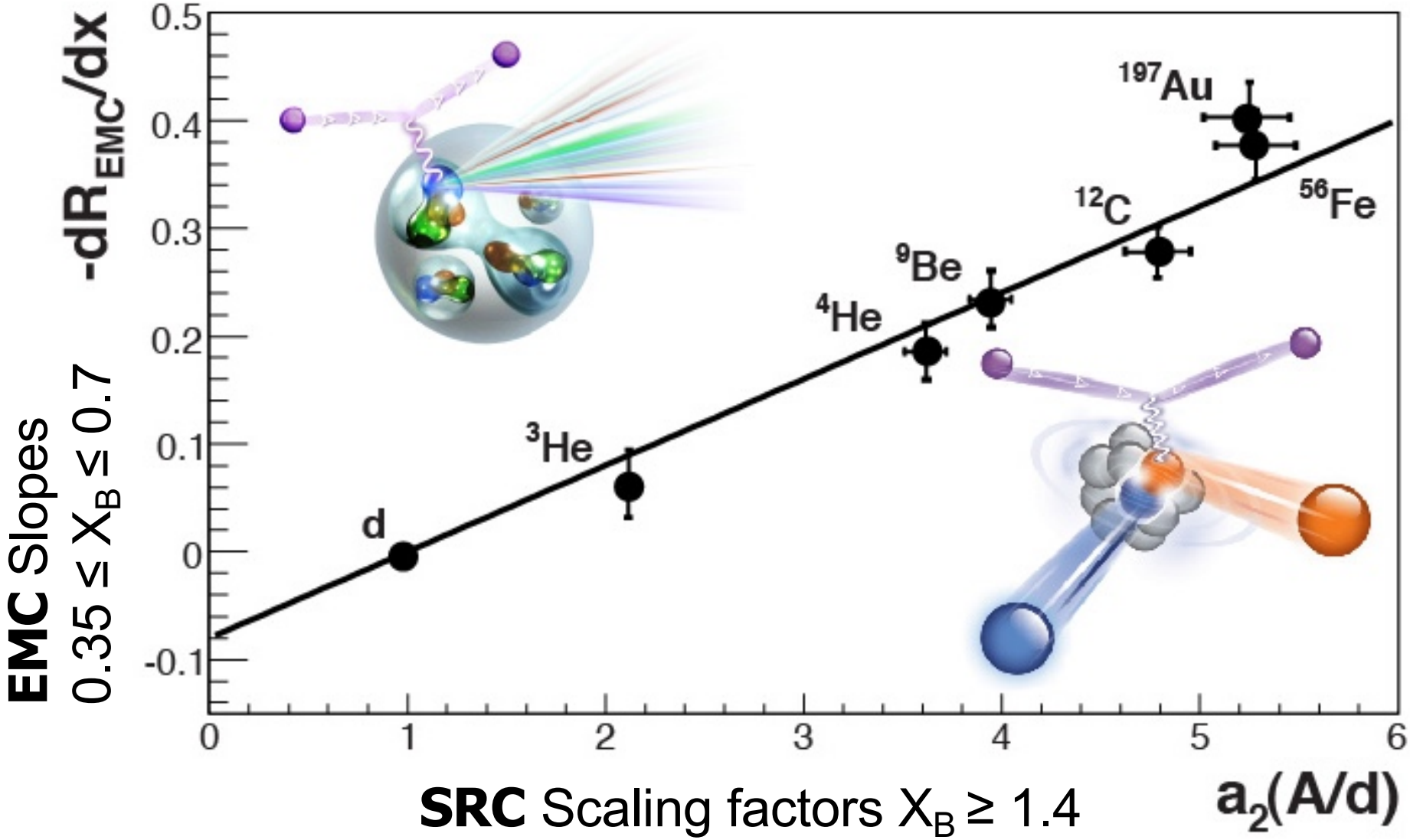
Nucleon modification:
Phenomenological change to bound nucleon structure functions, change proportional to virtuality $\nu = (p^2 - M^2)/M^2$



Nucleon modification needed to describe data

Kulagin and Petti, PRC 82, 054614 (2010)

EMC Effect and Correlations



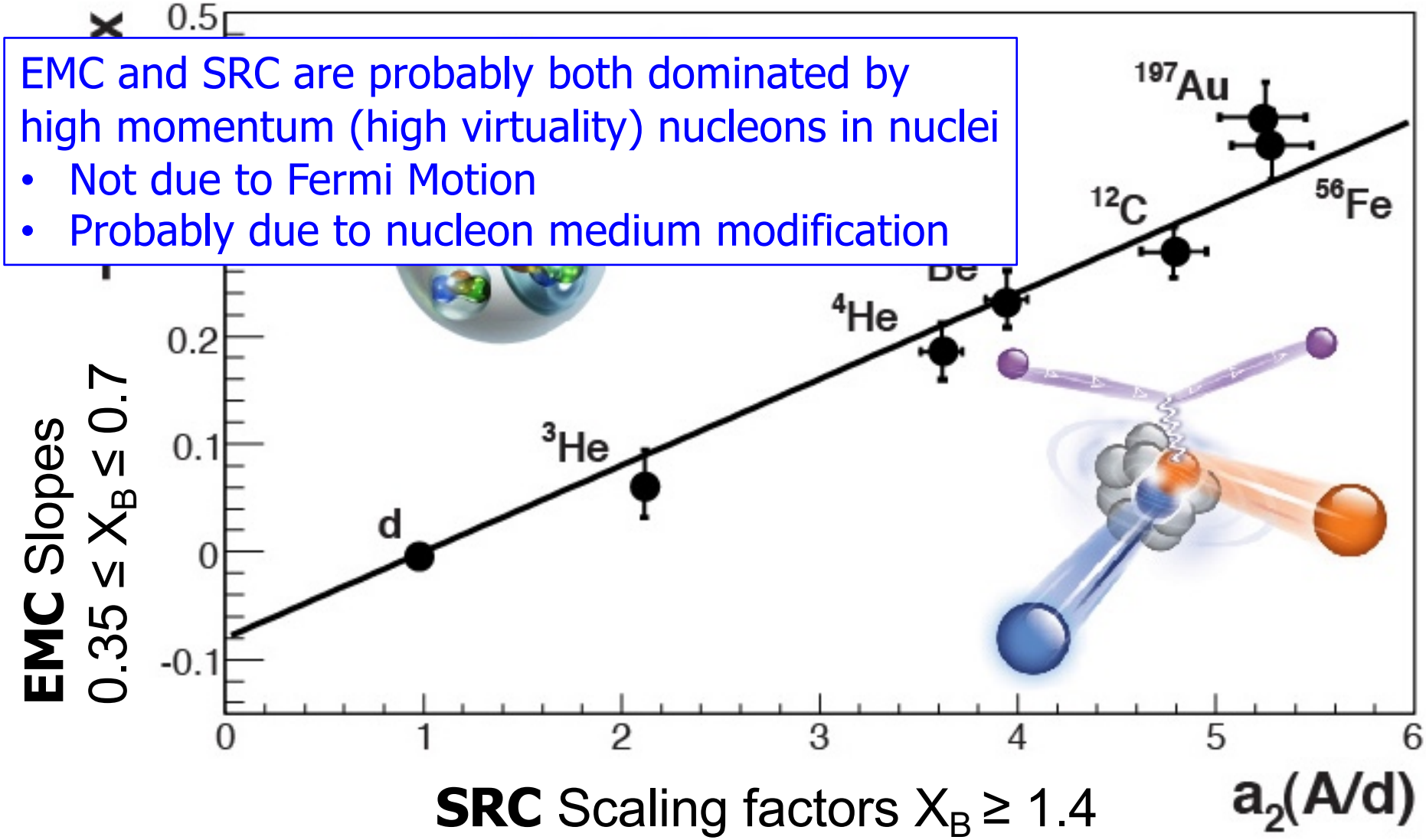
SRC data from Fomin et al
EMC data from Gomez et al and Seely et al

Weinstein et al, PRL**106**, 052301 (2011)
Hen et al, PRC**85**, 047301 (2012)
Hen et al, RMP **89**, 045002 (2017)

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

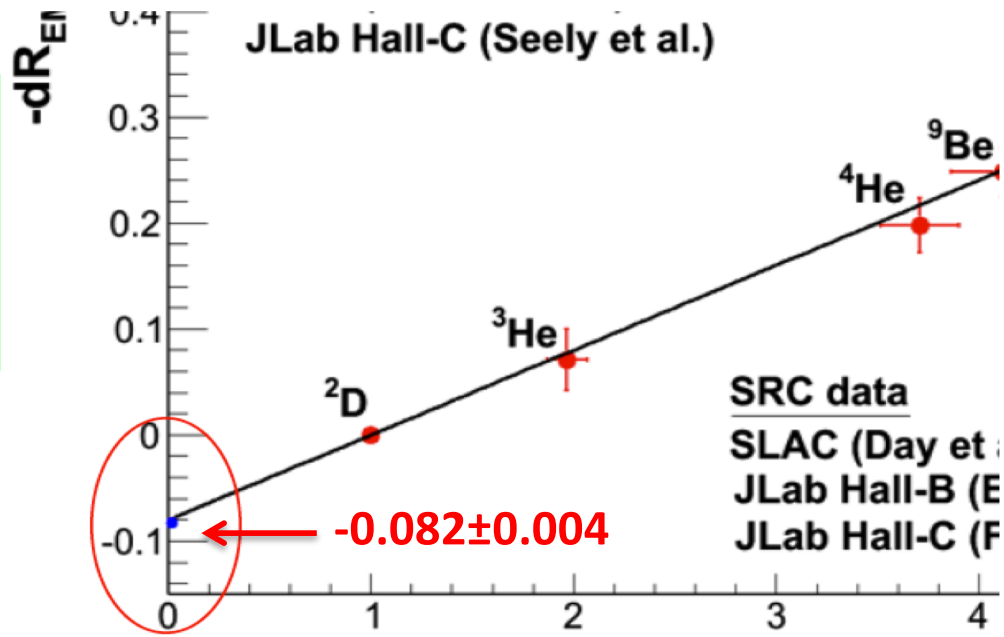


SRC data from Fomin et al
EMC data from Gomez et al and Seely et al

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)?

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

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

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

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

EMC Effect Explanations

- 1) all nucleons are slightly modified by the nuclear mean field (see Ian's talk)
  - or
- 2) nucleons in SRC pairs are strongly modified by their partners
  - High momentum (large virtuality) nucleons are much more modified

- EMC/SRC correlation points to #2

  Hmm… How do we test this?

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

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

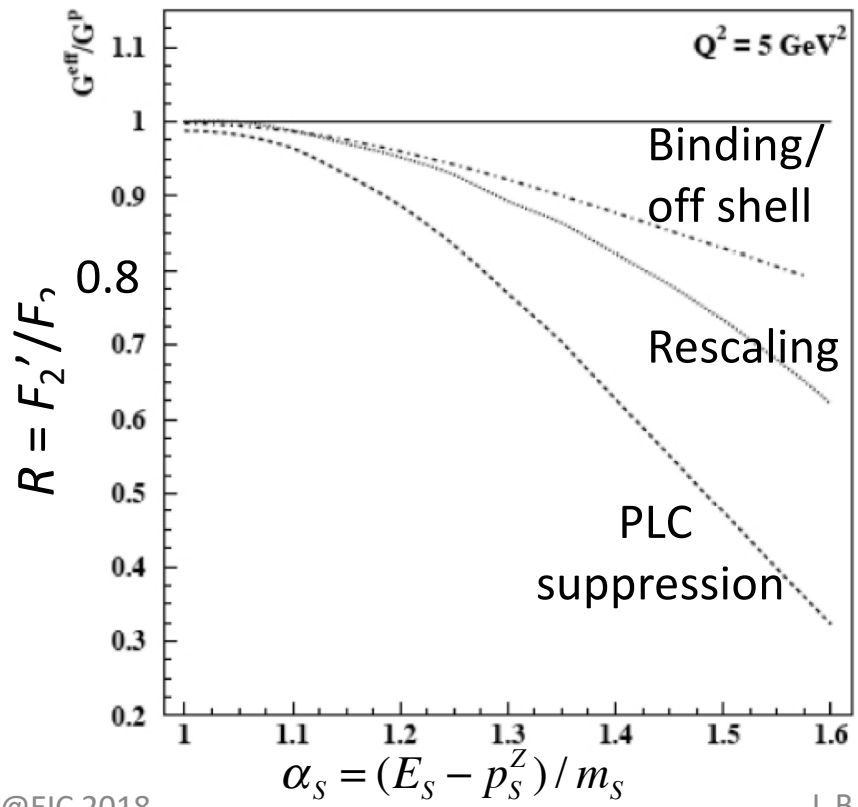
(F_1 and F_2 are related by R, the measured ratio of longitudinal and transverse cross sections. Thus measuring the cross section yields F_2.)

F_2 Momentum Dependence

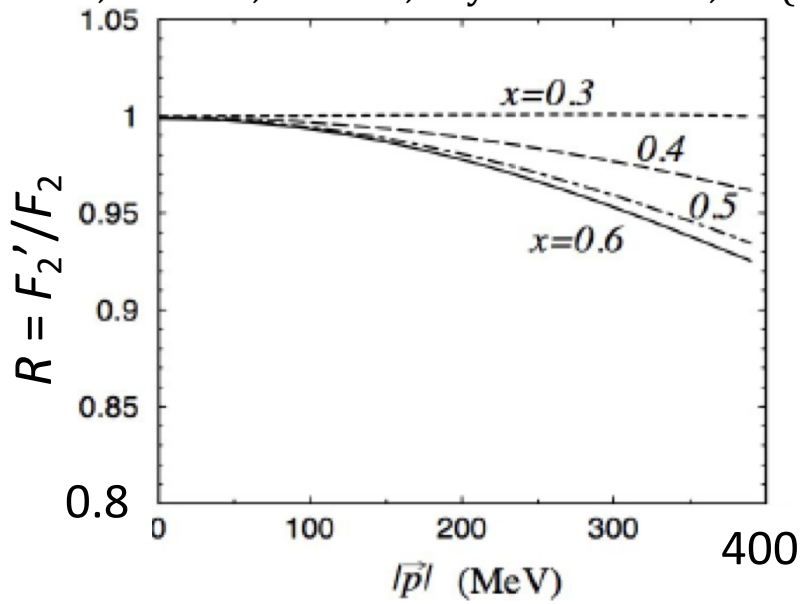
Dependence on:

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

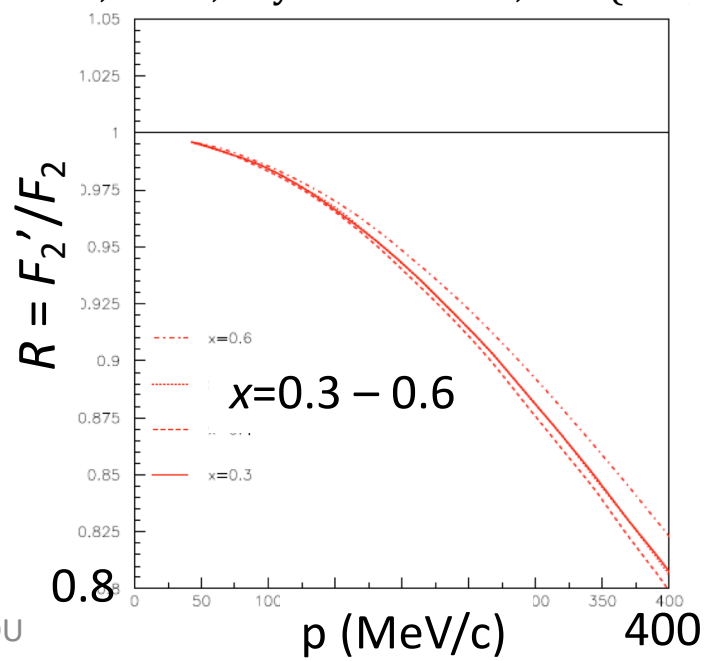
Melnitchouk, Sargsian, Strikman, Z. Phys. A **359**, 99 (1997)



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



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



What modification do we need?

- Assume $F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A(\Delta F_2^p + \Delta F_2^n)$
- Take the ratio to deuterium

$$\frac{F_2^A}{F_2^d} = \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right) n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} + (Z - N)\frac{F_2^p}{F_2^d} + N$$

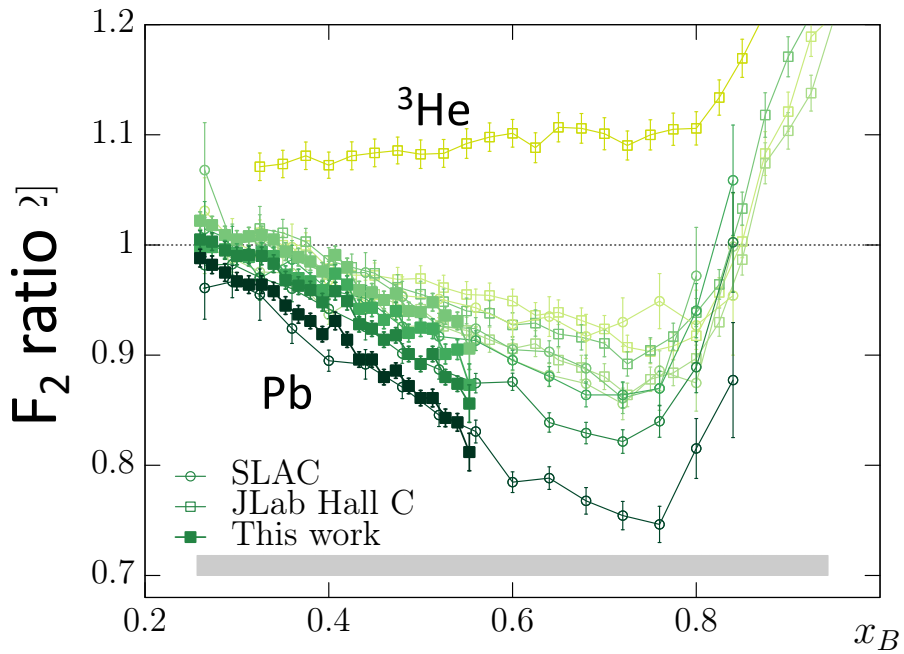
Previously Measured **Universal?** **Previously Measured**

- Use measured n_{SRC}^A from QE $A(e,e')$
- Fit $n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}$ for each nucleus
- Do we get a universal modification function?

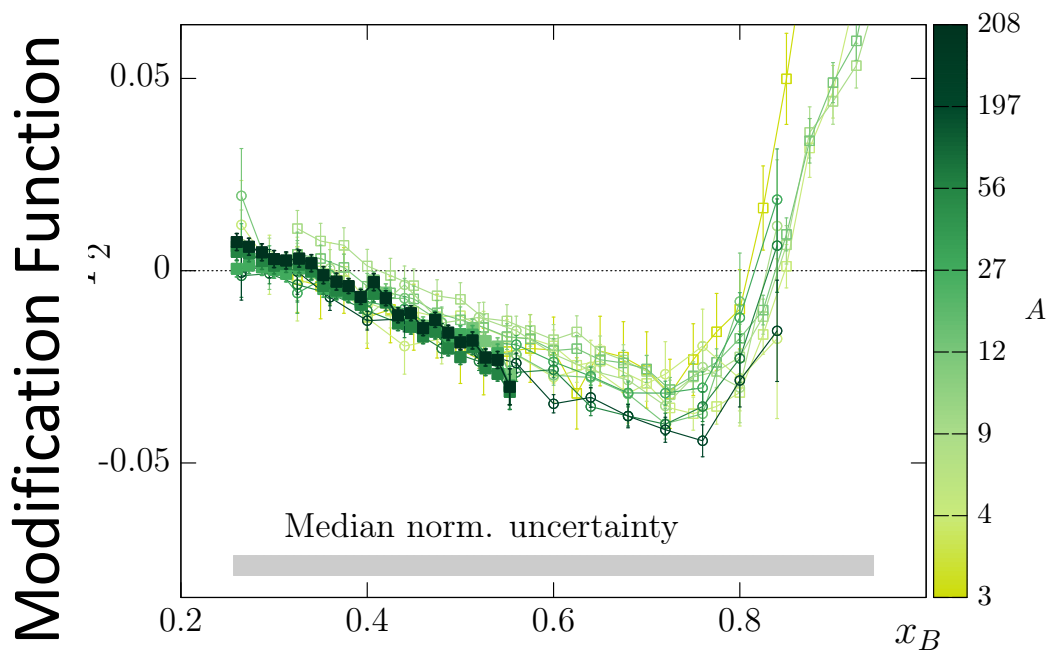
What modification do we need?

$$\frac{F_2^A}{F_2^d} = \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right) n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} + (Z - N)\frac{F_2^p}{F_2^d} + N$$

Previously Measured **Universal?** **Previously Measured**



EMC Ratios
No isospin corrections



Universal function within normalization uncertainty

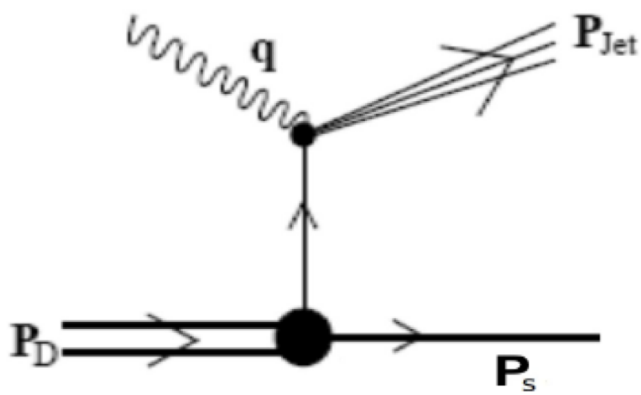
B. Schmookler, submitted

Tagging Nucleon Structure Functions

- 6 GeV: $d(e,e'p_s)$ Hall B (Kuhn, Griffeon)
- $d(e,e'n_s)$ Hall B, BAND detector, E12-11-003A
- $d(e,e'p_s)$ Hall C, LAD detector, E12-11-107

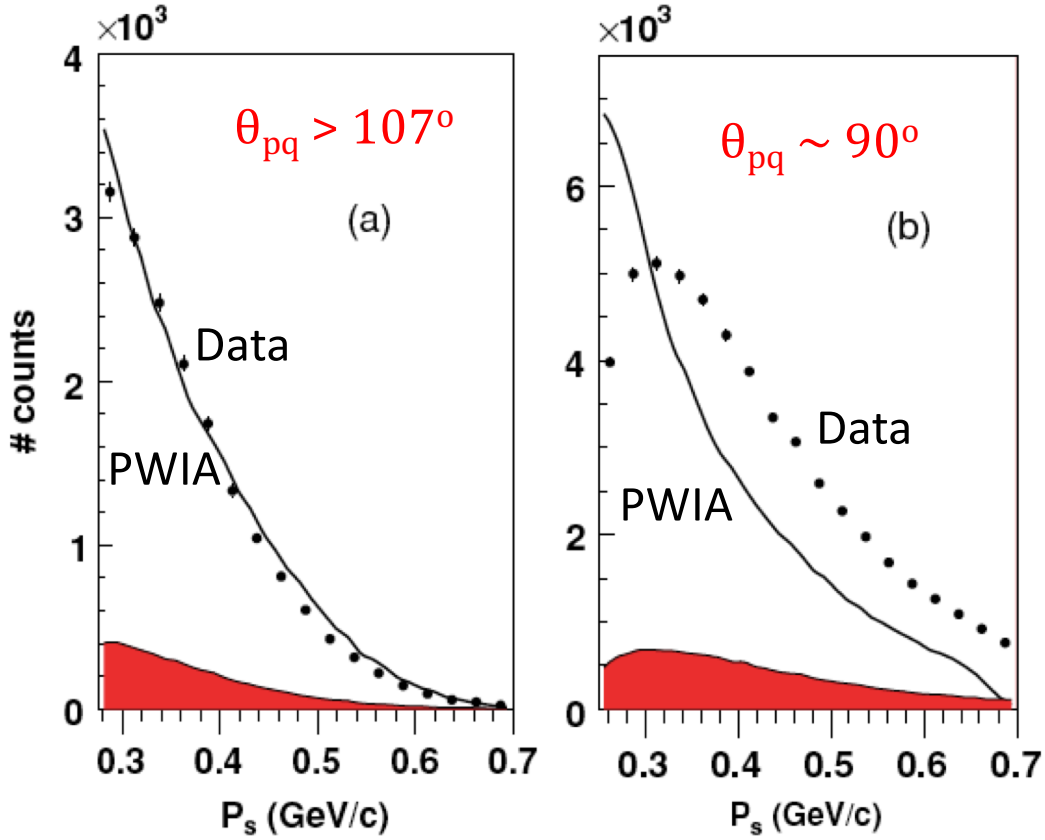
Experimental method

- 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)



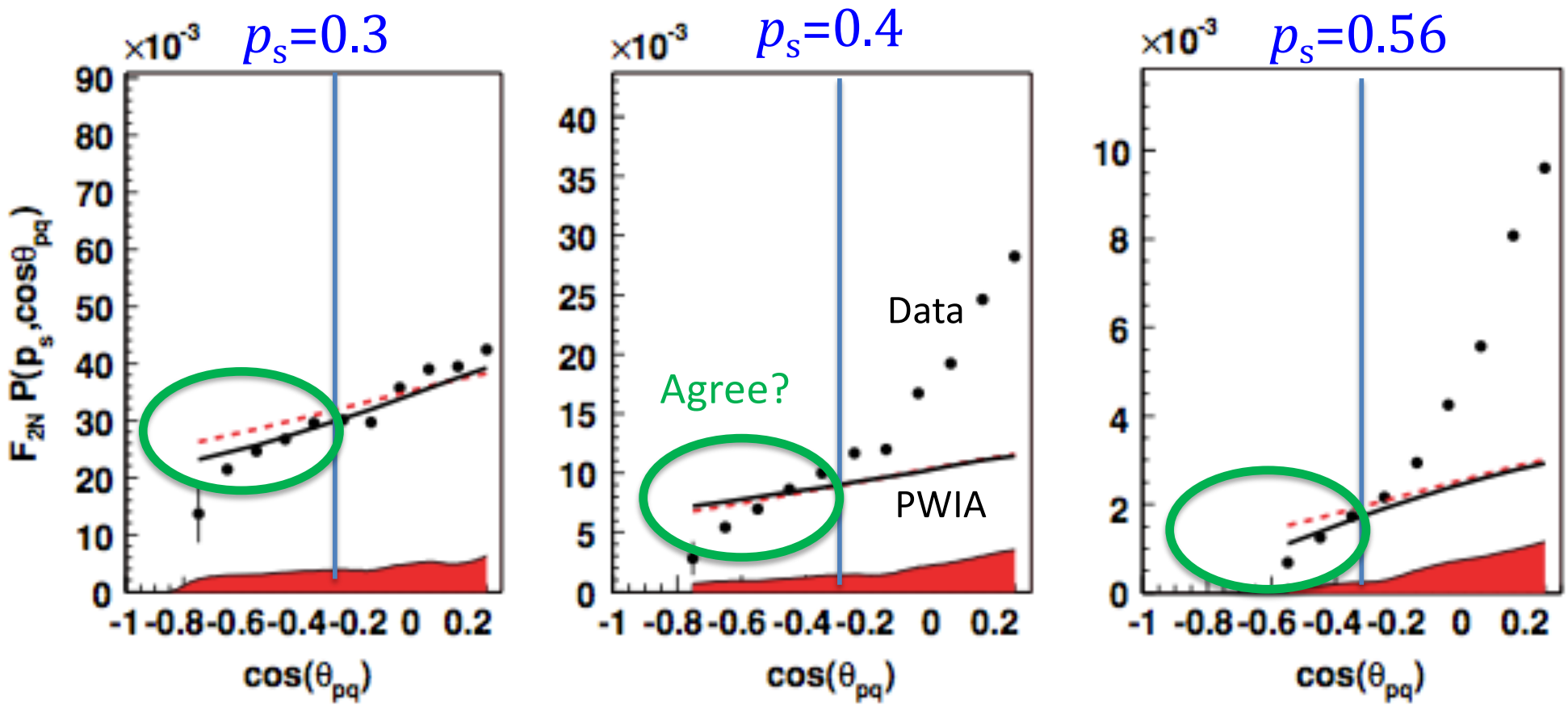
A. V. Klimenko *et al.*, PRC **73**, 035212 (2006)

FSI:

- Decrease with Q^2
- Increase with W'
- Not sensitive to x'
- Data = PWIA for $\theta_{pq} > 107°$
  - FSI small for $\theta_{pq} > 107°$

Minimize nucleon rescattering (FSI)

W'=2



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:

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

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

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

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

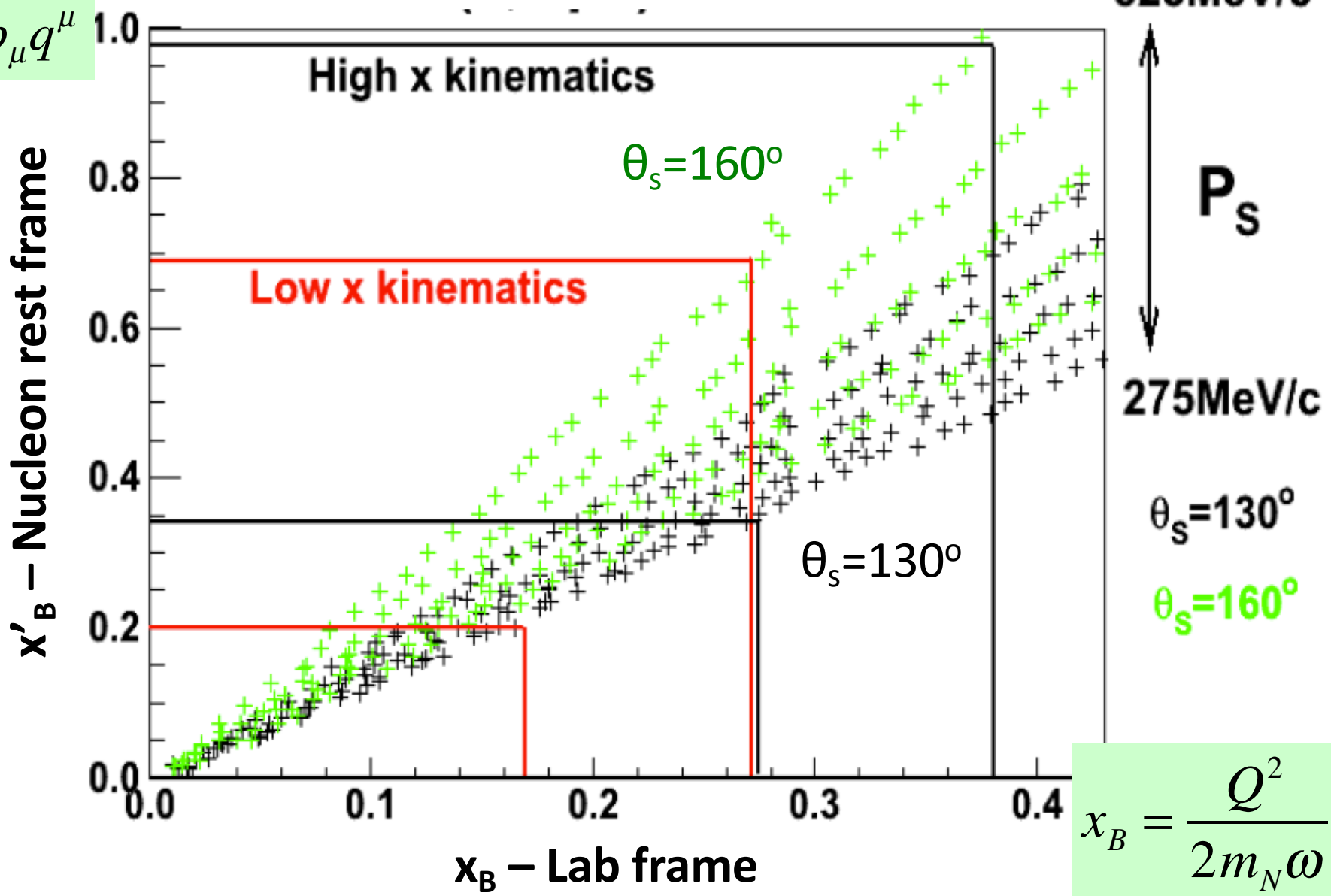
$$x'_B=\frac{Q^2}{2p_\mu q^\mu}\overset{\text{(For d)}}{=}\frac{Q^2}{2[(M_d-E_S)\omega+\vec{p}_S\cdot\vec{q}]}$$

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

x_B' vs. x_B

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

D(e,e'N) no FSI

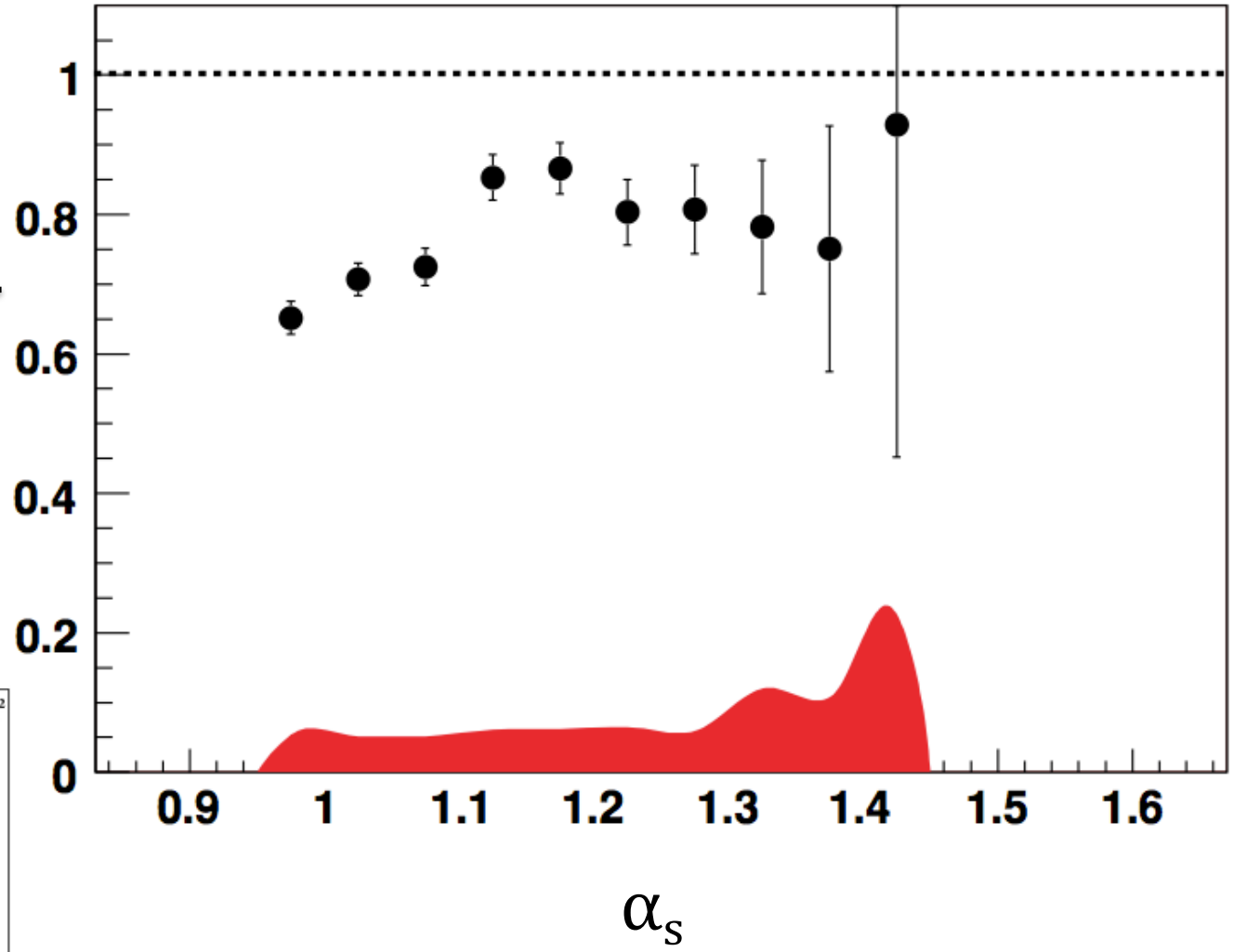


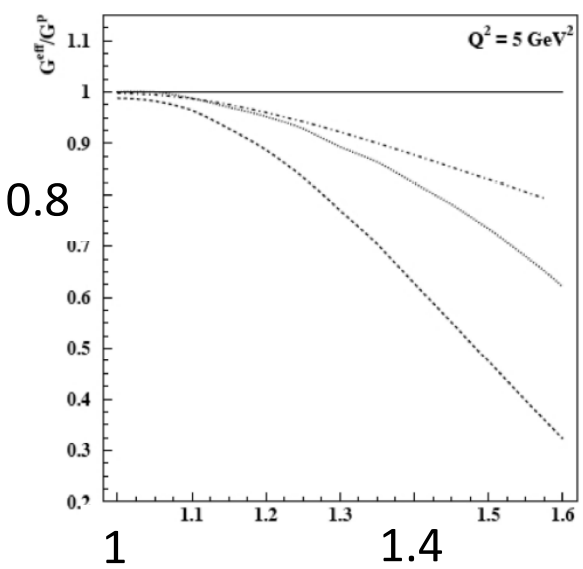
$$x_B = \frac{Q^2}{2m_N\omega}$$

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

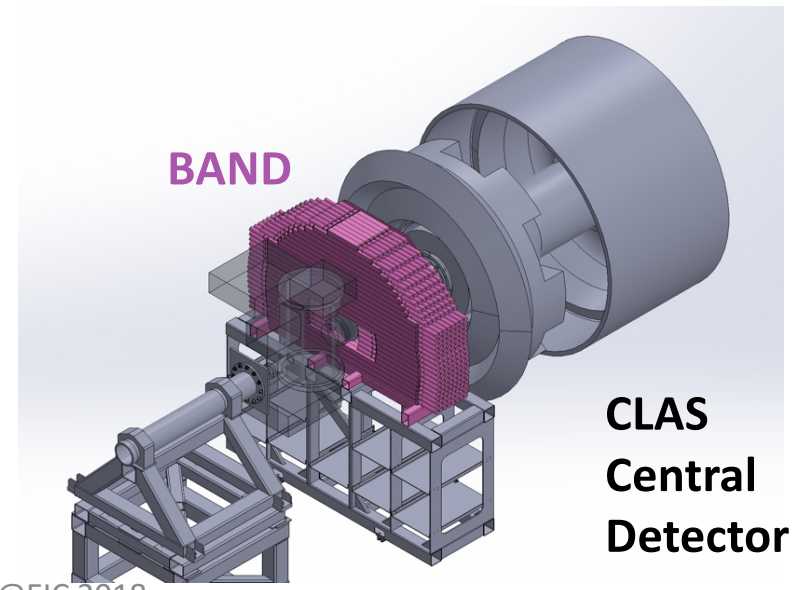
Klimenko, PRC **73**, 035212 (2006)

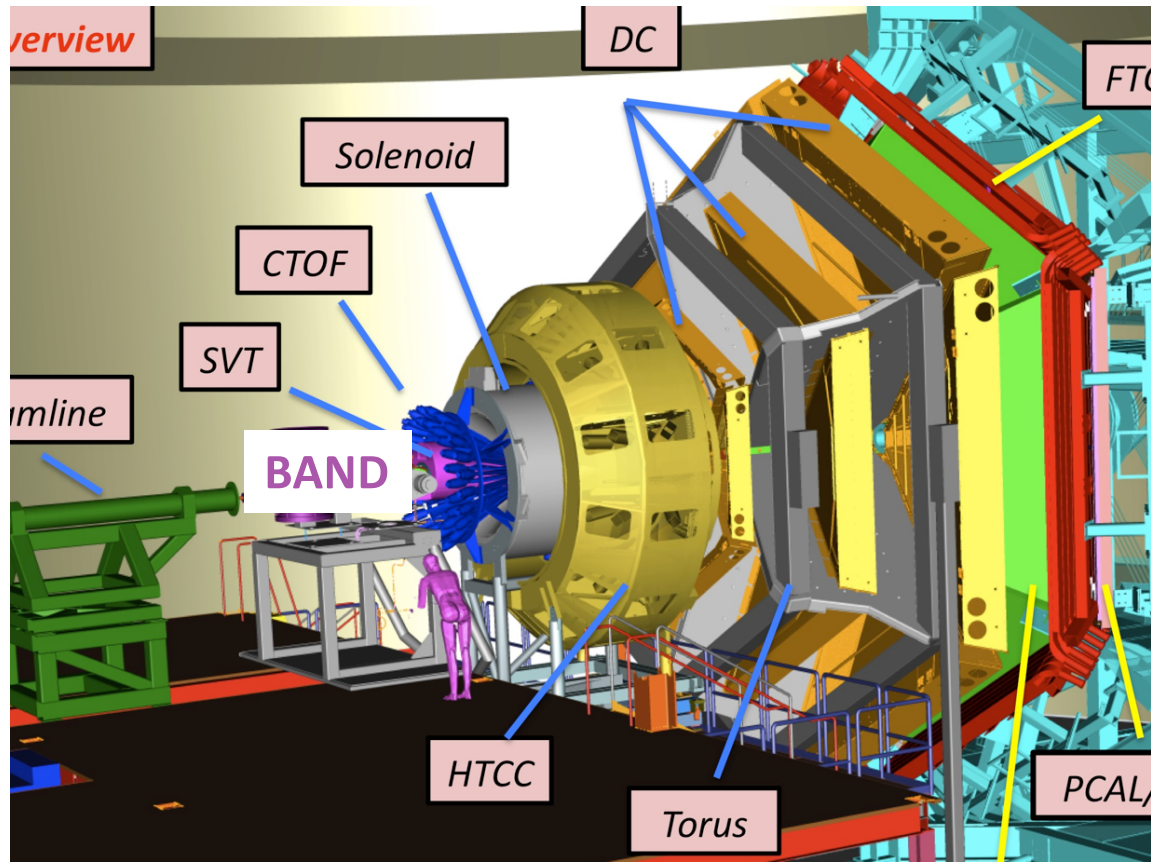
12 GeV – CLAS12 + BAND

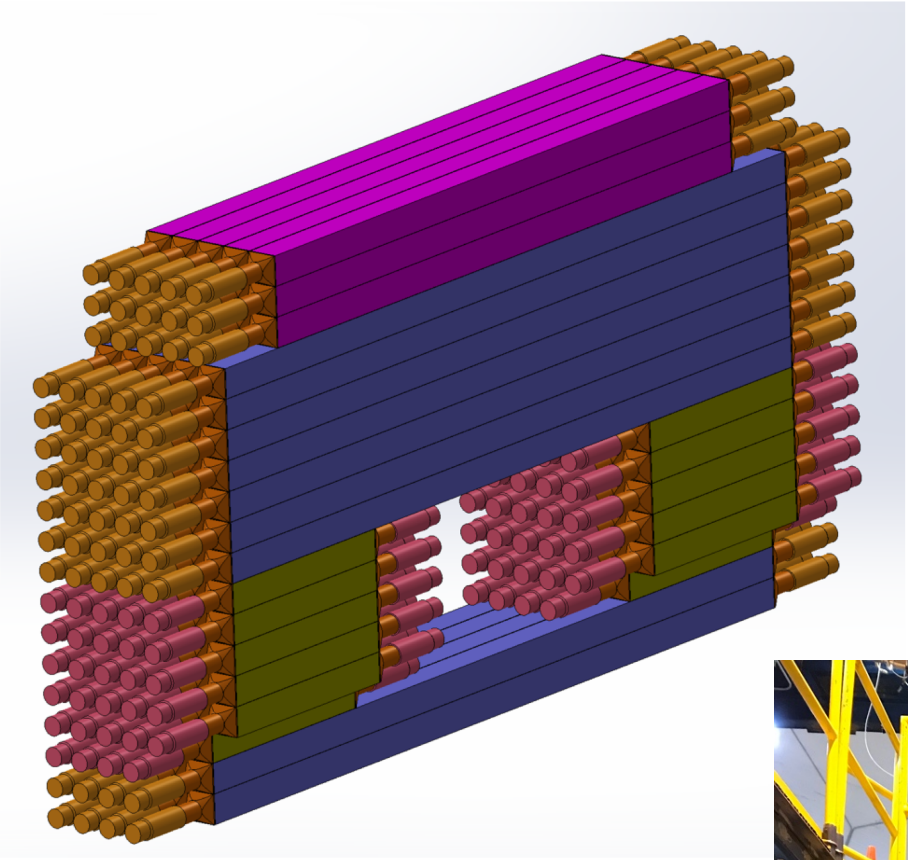
E12-11-003A : Hen, Weinstein, Piasetzky and Hakobyan

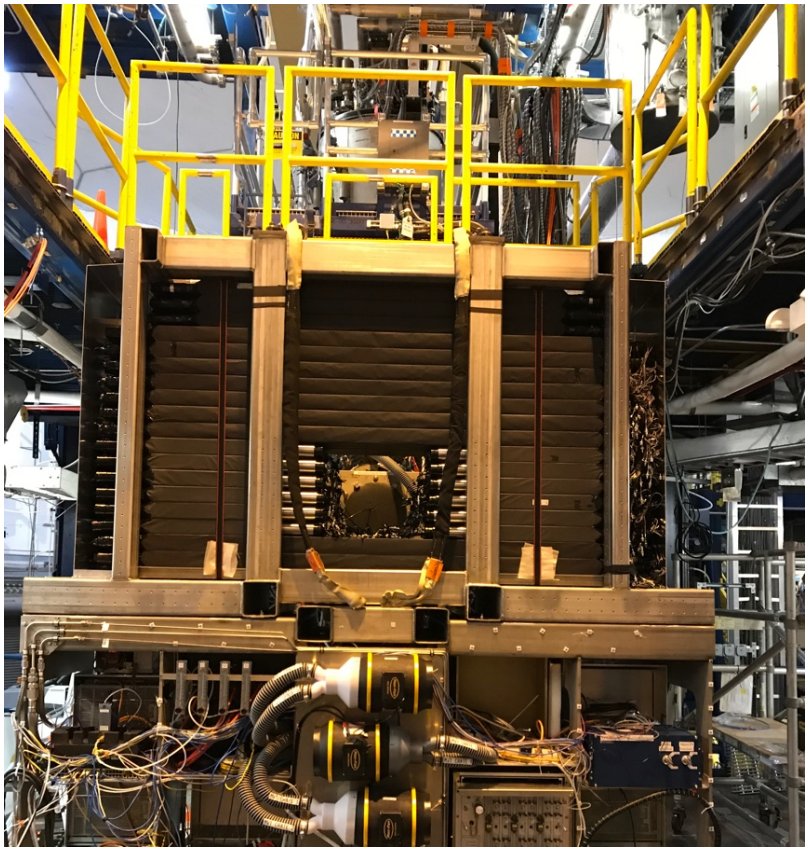
CLAS12 detects electrons
Back Angle Neutron Detector (BAND):

- 116 double ended scintillator bars plus a veto layer.
- $160^o \leq \theta_n \leq 170^o$
- Efficiency ~ 40%





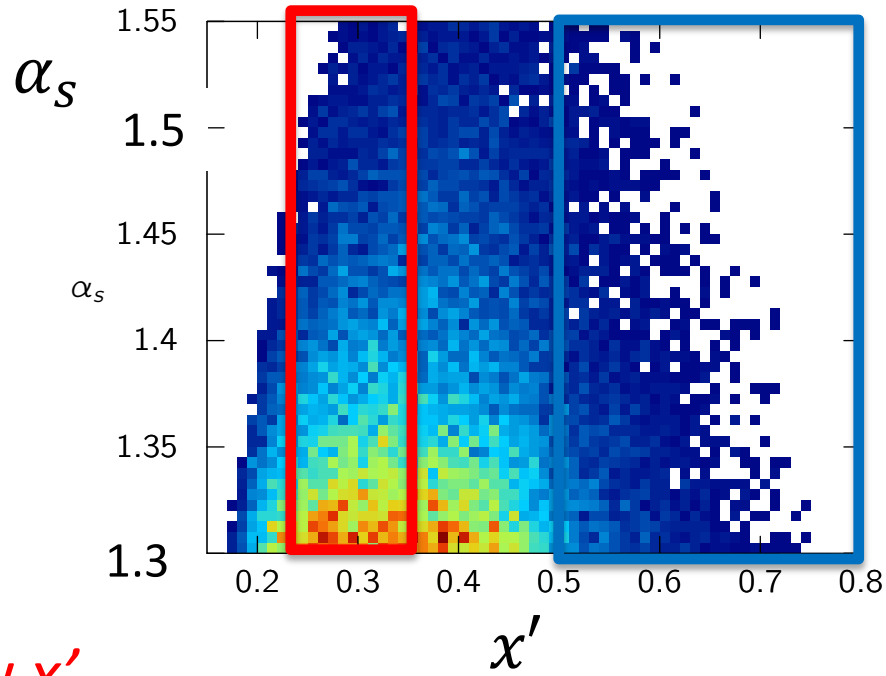


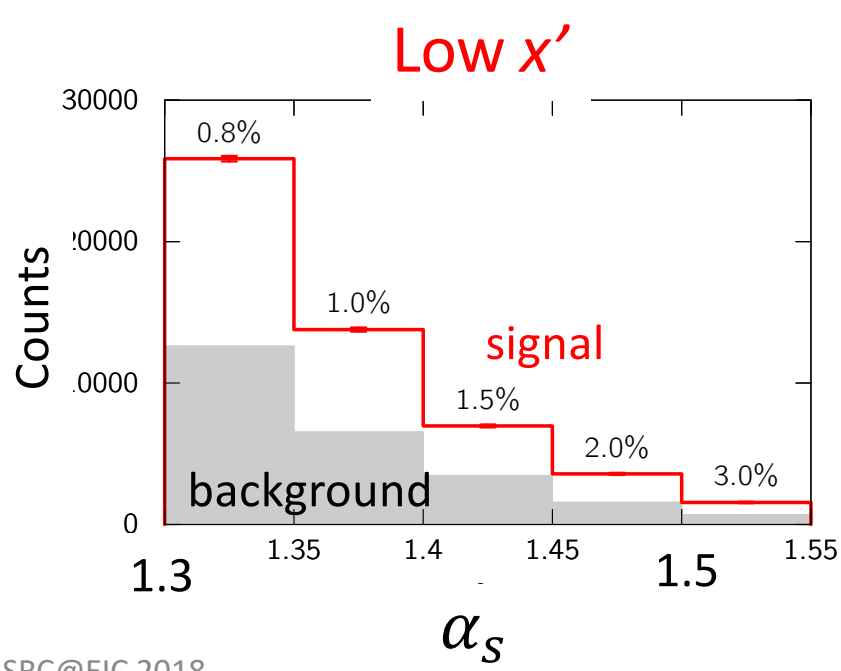


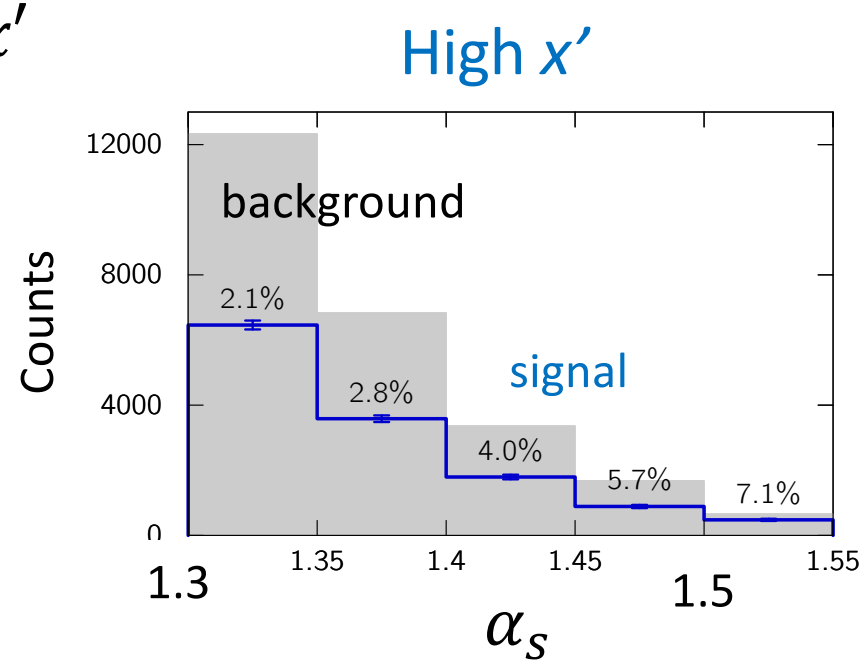
Commissioning BAND now
Deuteron data run starting winter 2019

ODU, MIT, UTFSM, Tel Aviv, FSU, GWU

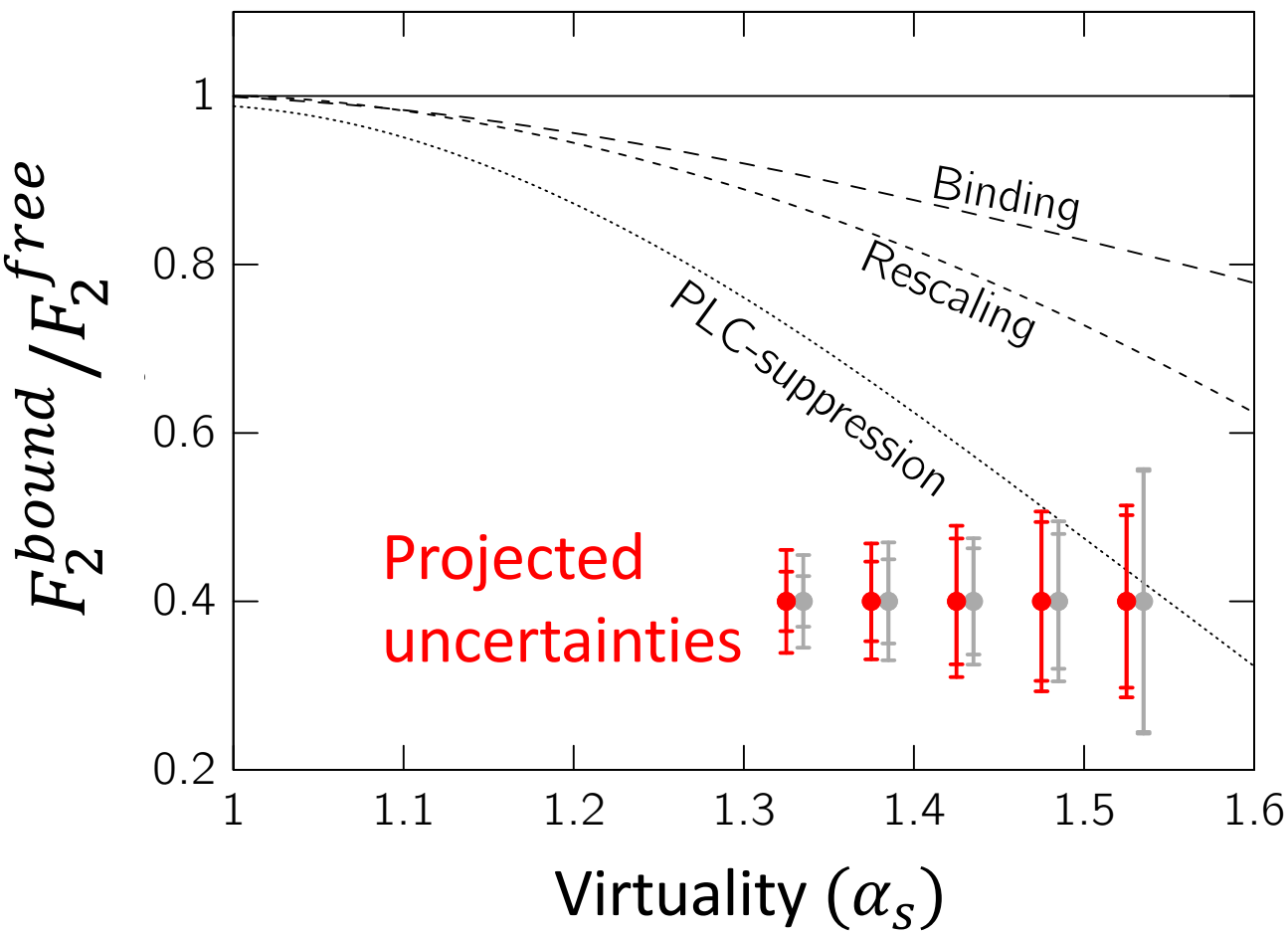
Expected Results







BAND reach

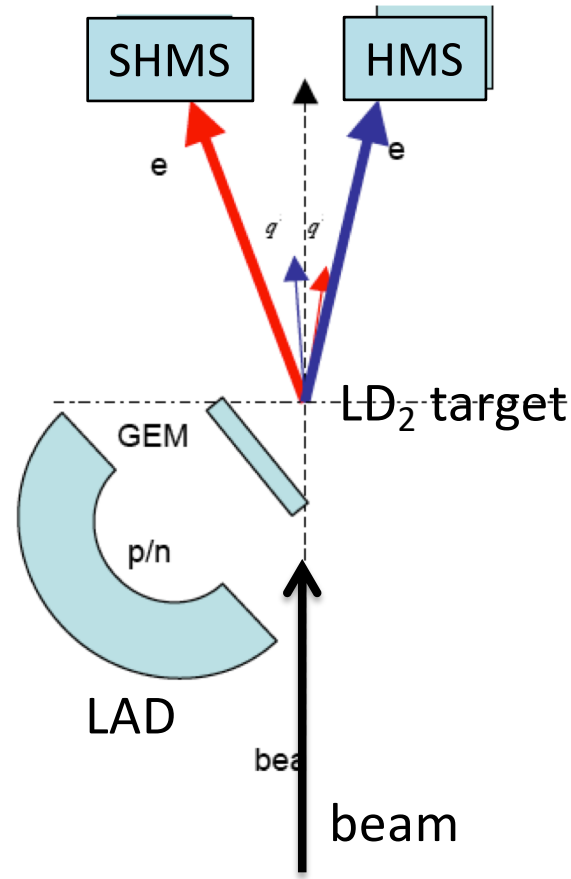

F_2^{bound}/F_2^{free}
1
0.8
0.6
0.4
0.2
1
1.1
1.2
1.3
1.4
1.5
1.6
Virtuality (α_s)
Binding
Rescaling
PLC-suppression
Projected uncertainties

12 GeV – Hall C + LAD

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

HMS and SHMS detect electrons

Large Angle Detector (LAD) (132 reused CLAS6 TOF detectors, 1.5 sr) detects recoiling proton

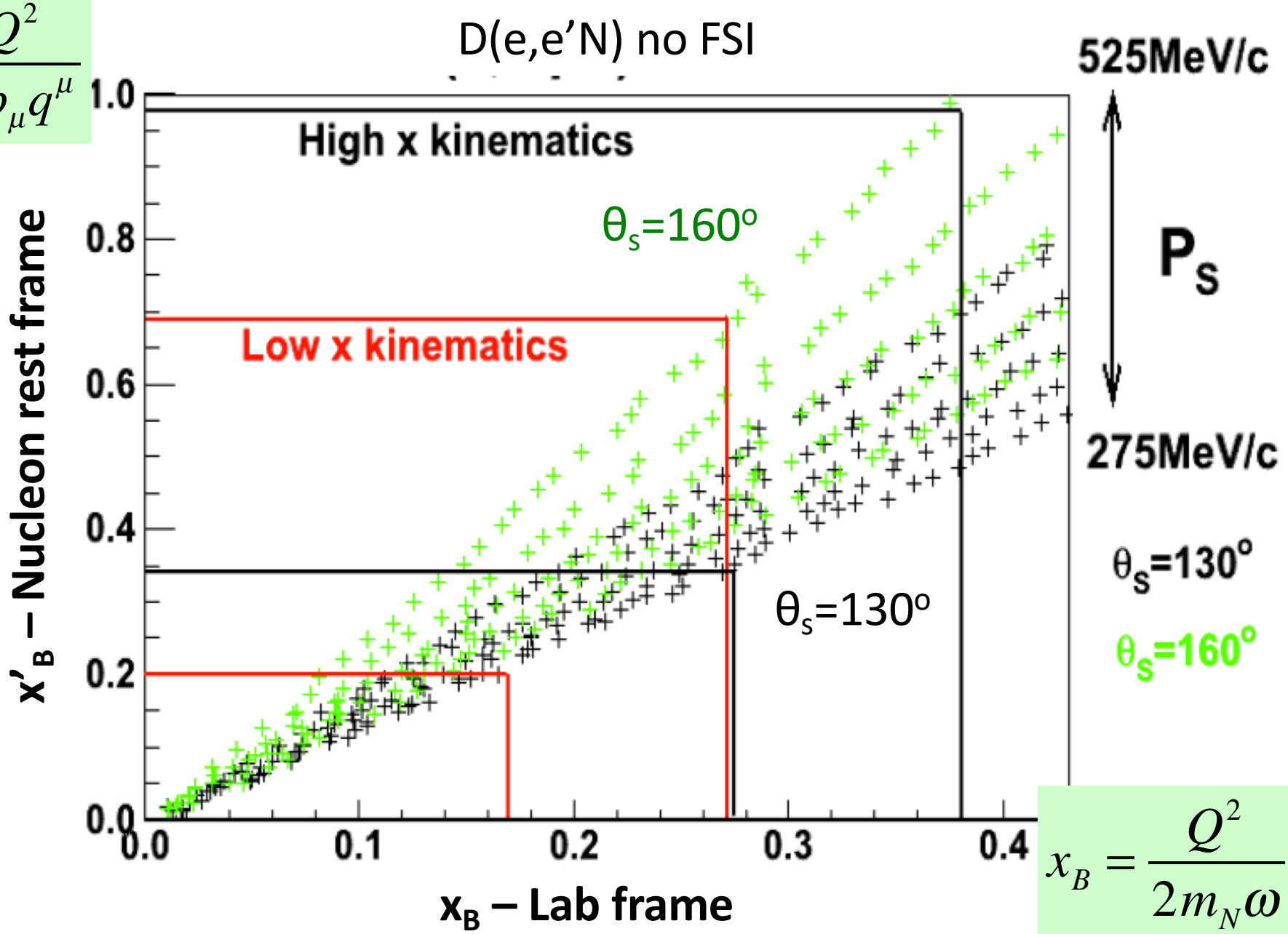


Low x'	High x'
$E_{in} = 10.9$ GeV	$E_{in} = 10.9$ GeV
$E' = 4.4$ GeV	$E' = 4.4$ GeV
$\theta_e = 13.5^o$	$\theta_e = -17^0$
$Q^2 = 2.65$ GeV^2	$Q^2 = 4.19$ GeV^2
$\lvert\vec{q}\rvert = 6.7$ GeV/c	$\lvert\vec{q}\rvert = 6.8$ GeV/c
$\theta_q = -8.8^0$	$\theta_q = 10.8^0$
$x = 0.217$	$x = 0.34$

Collect both LAD-HMS and LAD-SHMS coincidences

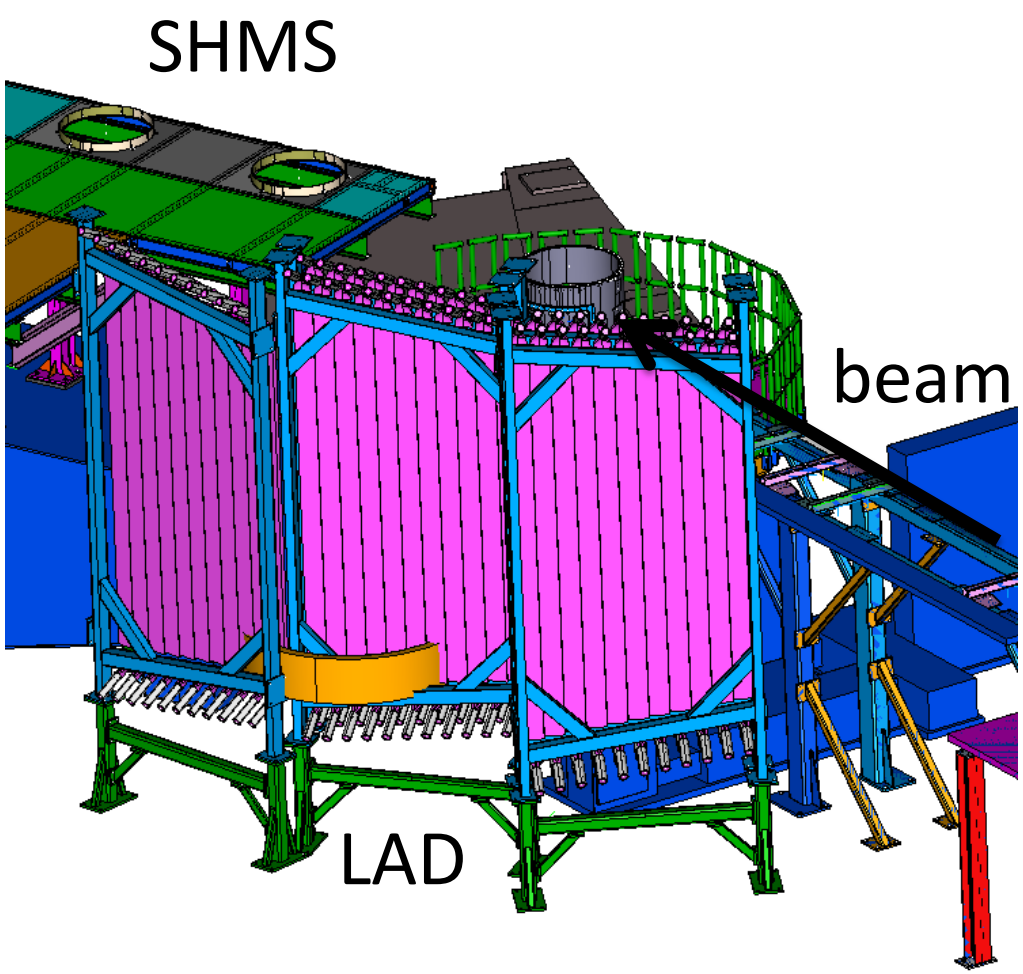
x_B' vs. x_B (Why x'?)

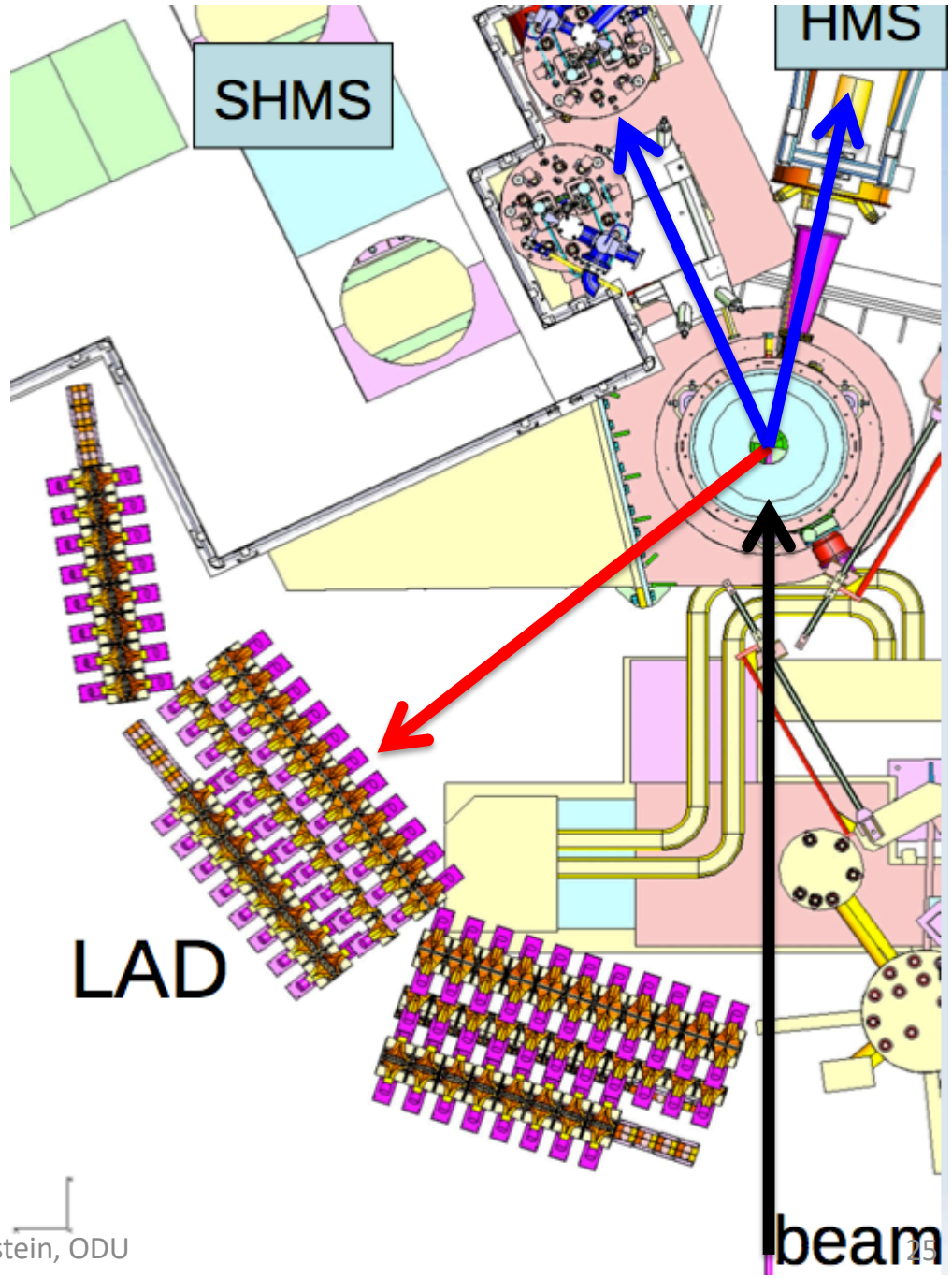
$$x_B' = \frac{Q^2}{2p_\mu q^\mu}$$



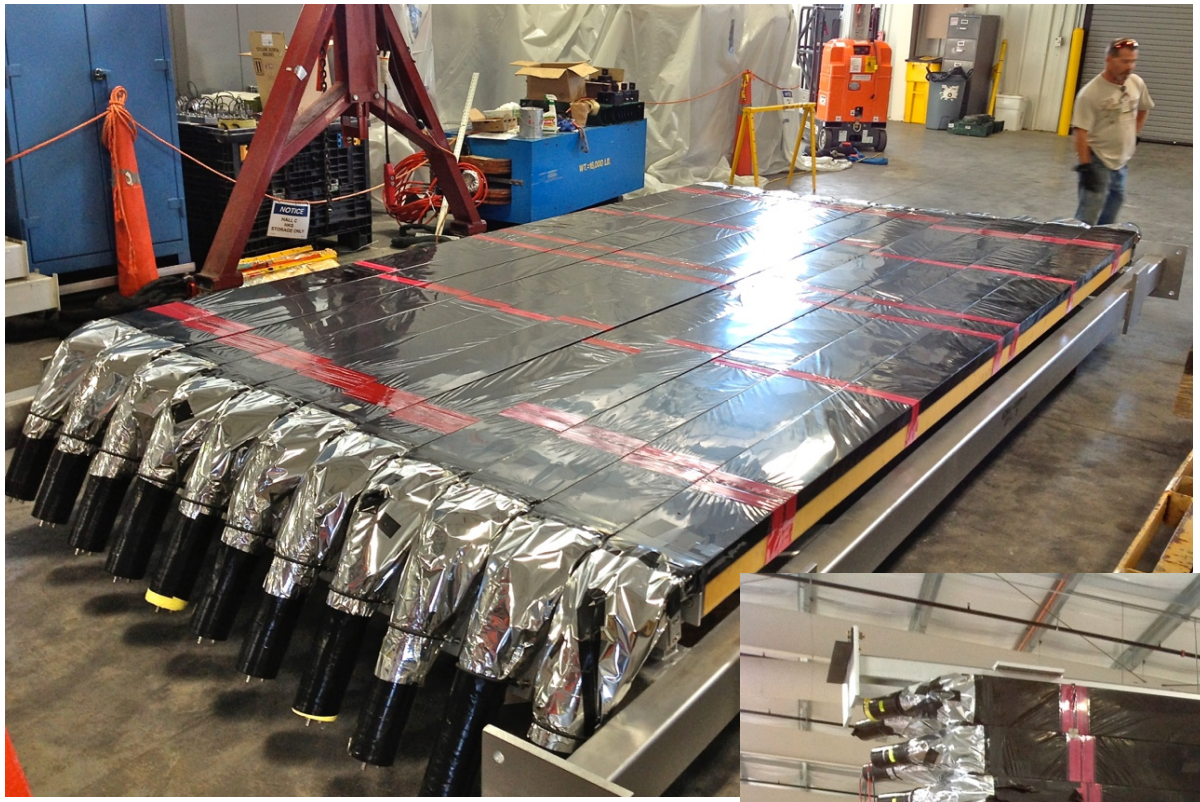
$$x_B = \frac{Q^2}{2m_N\omega}$$

Experimental Set Up – Hall C





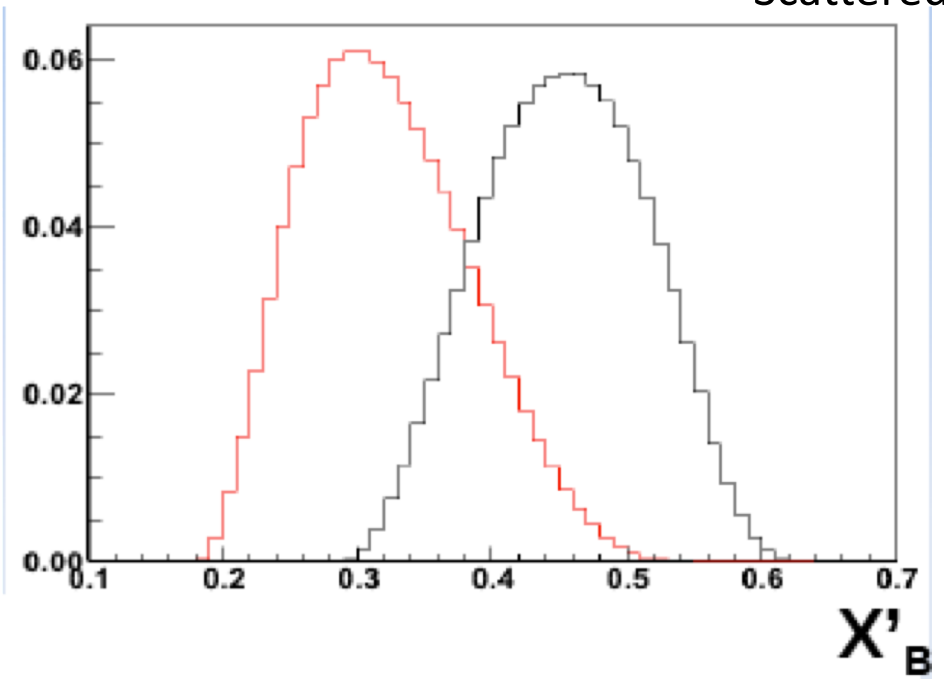
CLAS6 TOF ➔ LAD

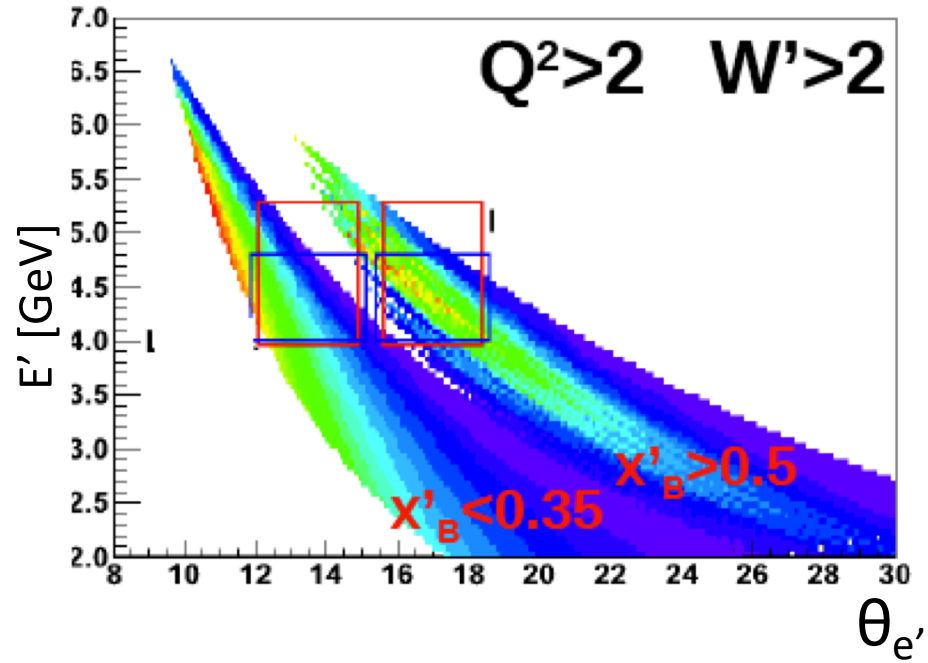


Tel Aviv, Kent State, MIT, JLab, ODU

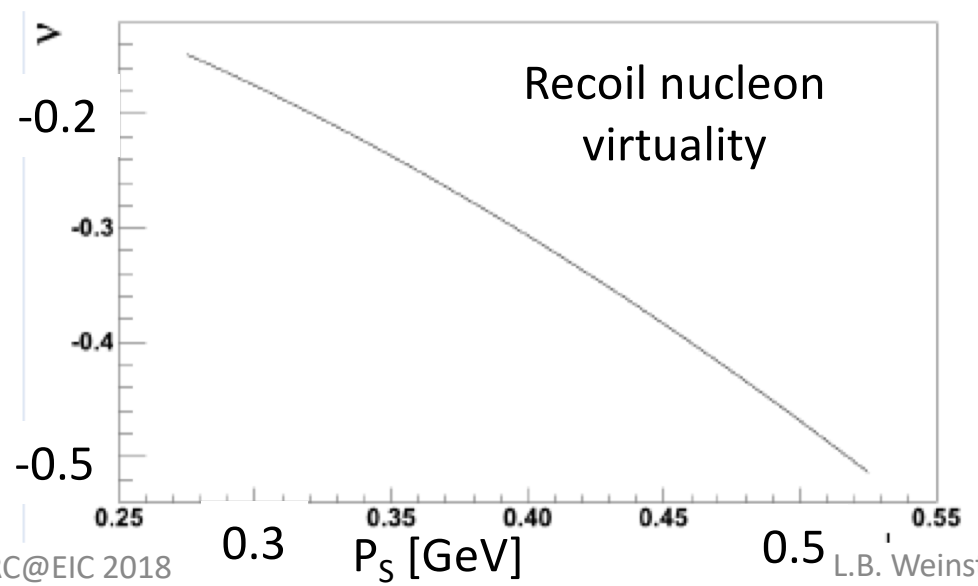
Kinematic Coverage

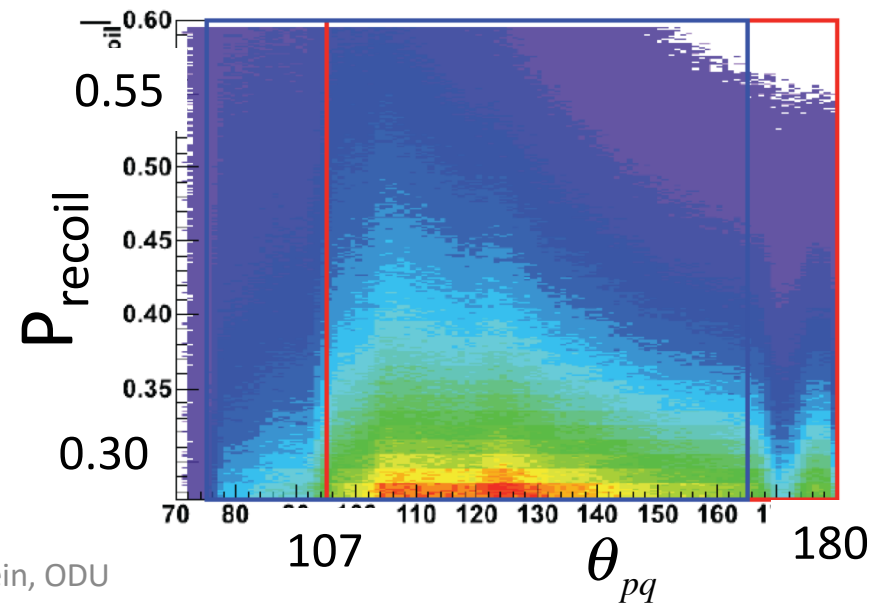
Scattered electrons



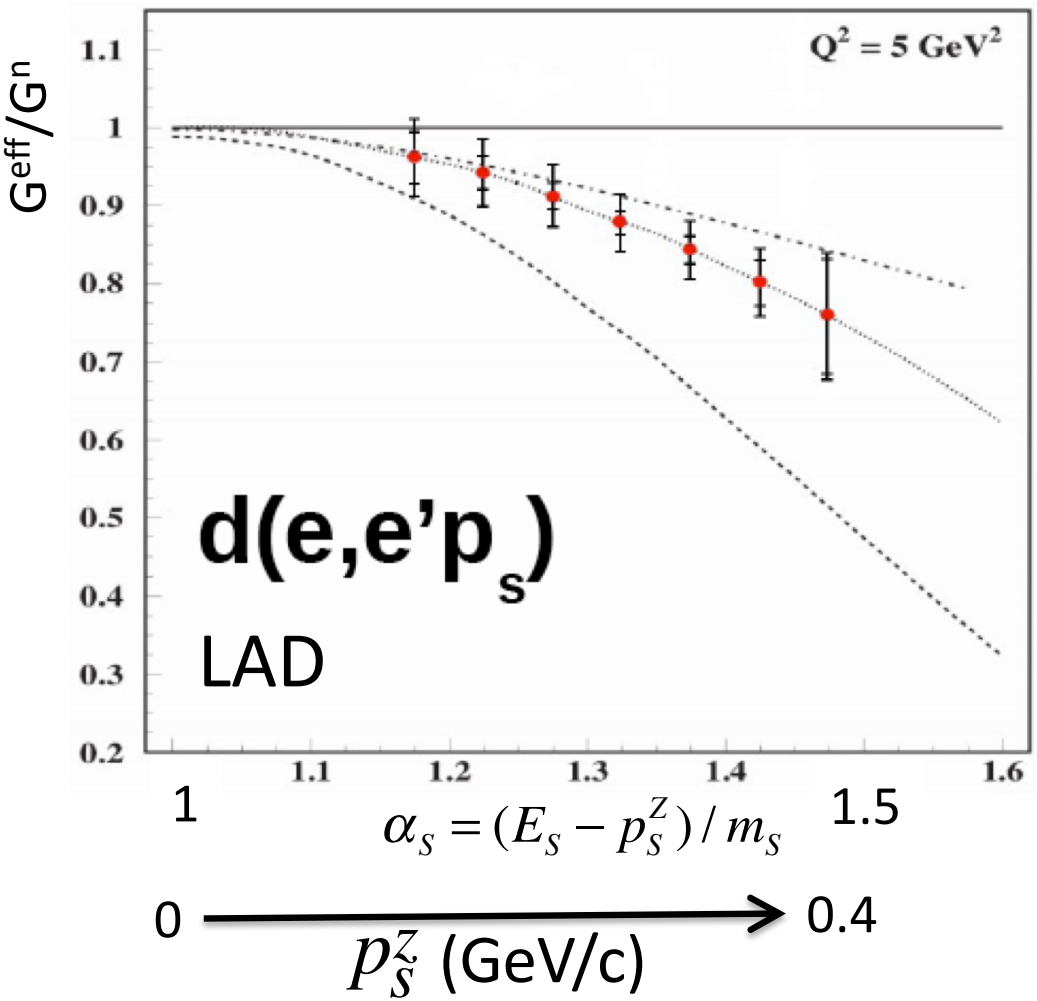


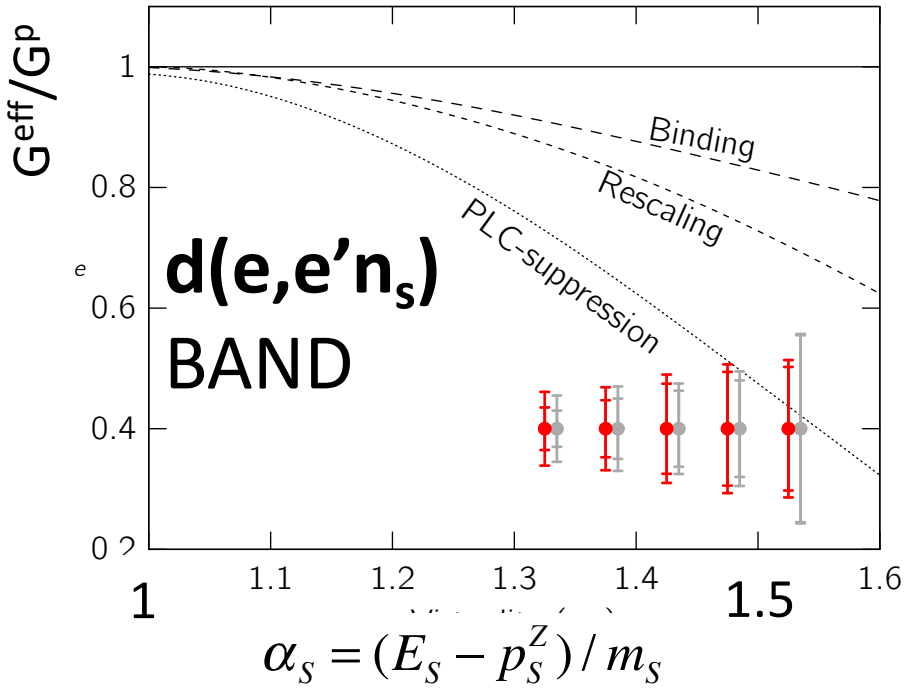
Recoiling nucleons





JLab12: Expected Results





Collider Tagging Kinematics

100 GeV d (γ = 50)

Spectator Momentum (GeV/c)

Center of Mass | Lab

P_z (CM)	$P_{\perp}$ (CM)	P_z (Lab)	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

Small changes in spectator P_CM → big changes in P_lab

Need to detect and measure very small angles

Need similar luminosity to CLAS12 (10^{35} cm^{-2} s^{-1})

See Christian's talk tomorrow

Tagged Quasielastic Ratios

- $\sigma_A(e,e')/\sigma_d(e,e')$ has a plateau starting at x = 1.5 where $p_i > 275$ MeV/c
- If we tag large p_i events, will we see a plateau at smaller x?
- Expected cross section ratio: *en* and *ep* cross sections

$$\frac{2}{A}\cdot\frac{\sigma_A}{\sigma_d}(e,e'p_{recoil}) = \frac{2}{A}\cdot\frac{\#np_A\cdot\sigma_n + 2\#pp_A\cdot\sigma_p}{\#np_d\cdot\sigma_n}\cdot Trans_p$$

Number of pairs

Proton transparency

B. Schmookler, preliminary

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≈ 2.5

$$\frac{2}{A}\cdot\frac{\sigma_A}{\sigma_d}(e,e'p_{recoil}) = a_2\left(1 + 2\cdot\frac{\#pp_A}{\#np_A}\cdot\frac{\sigma_p}{\sigma_n}\right)\cdot Trans_p$$

≈ 0.1 $\quad$ $0.3 - 0.7$

B. Schmookler, preliminary

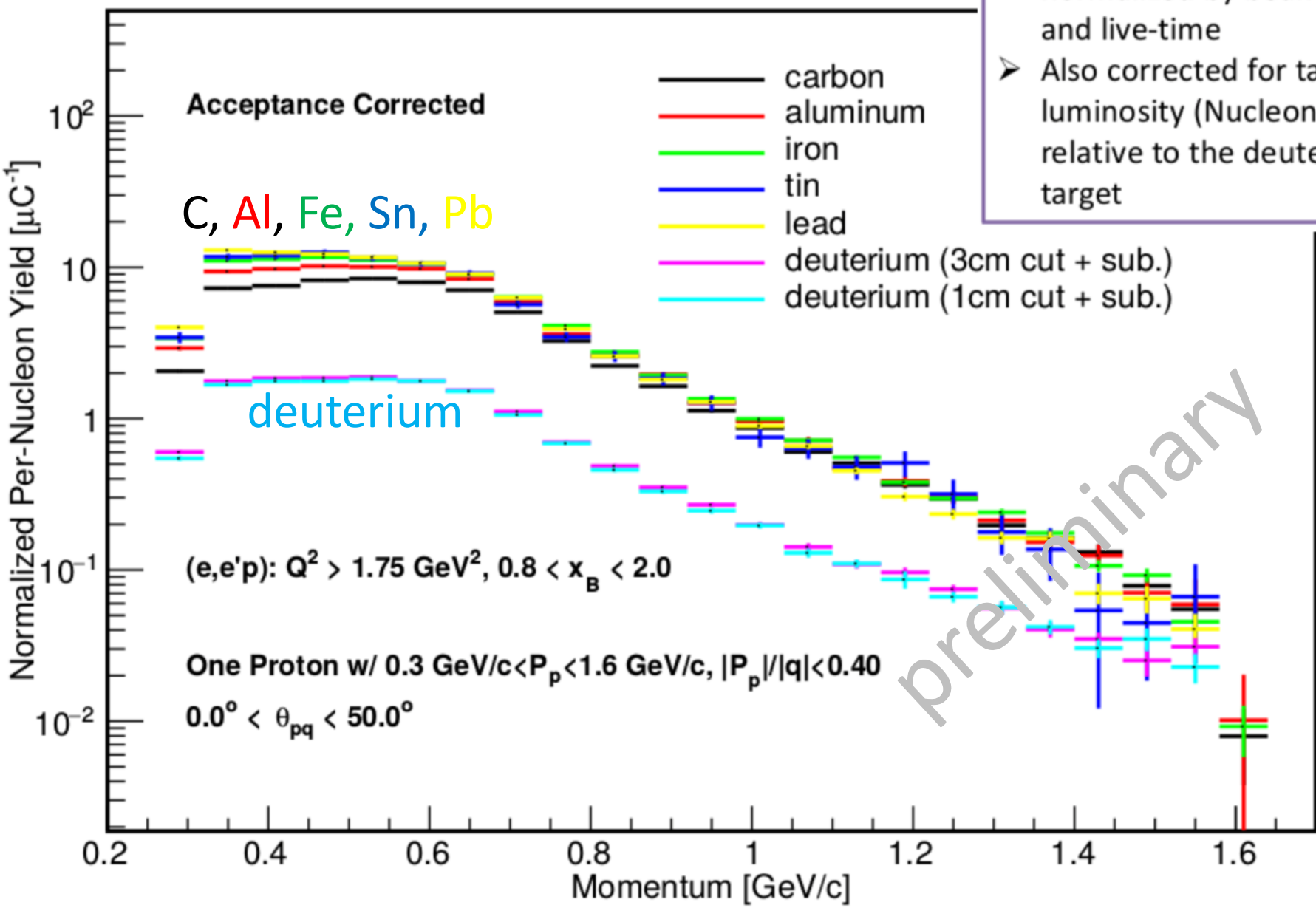
Selecting (e,e'p_{recoil}) events

- $Q^2 > 1.75\ \mathrm{GeV}^2$
- $0.8 < x < 2$
- Spectator (?) proton
  - Slow protons far from rescattering peak at 70°
  - $0.3 < p_\mathrm{p} < 1.6\ \mathrm{GeV/c}$
  - $\frac{p_p}{q} < 0.4$
  - $\theta_{pq} < 50^o$

B. Schmookler, preliminary

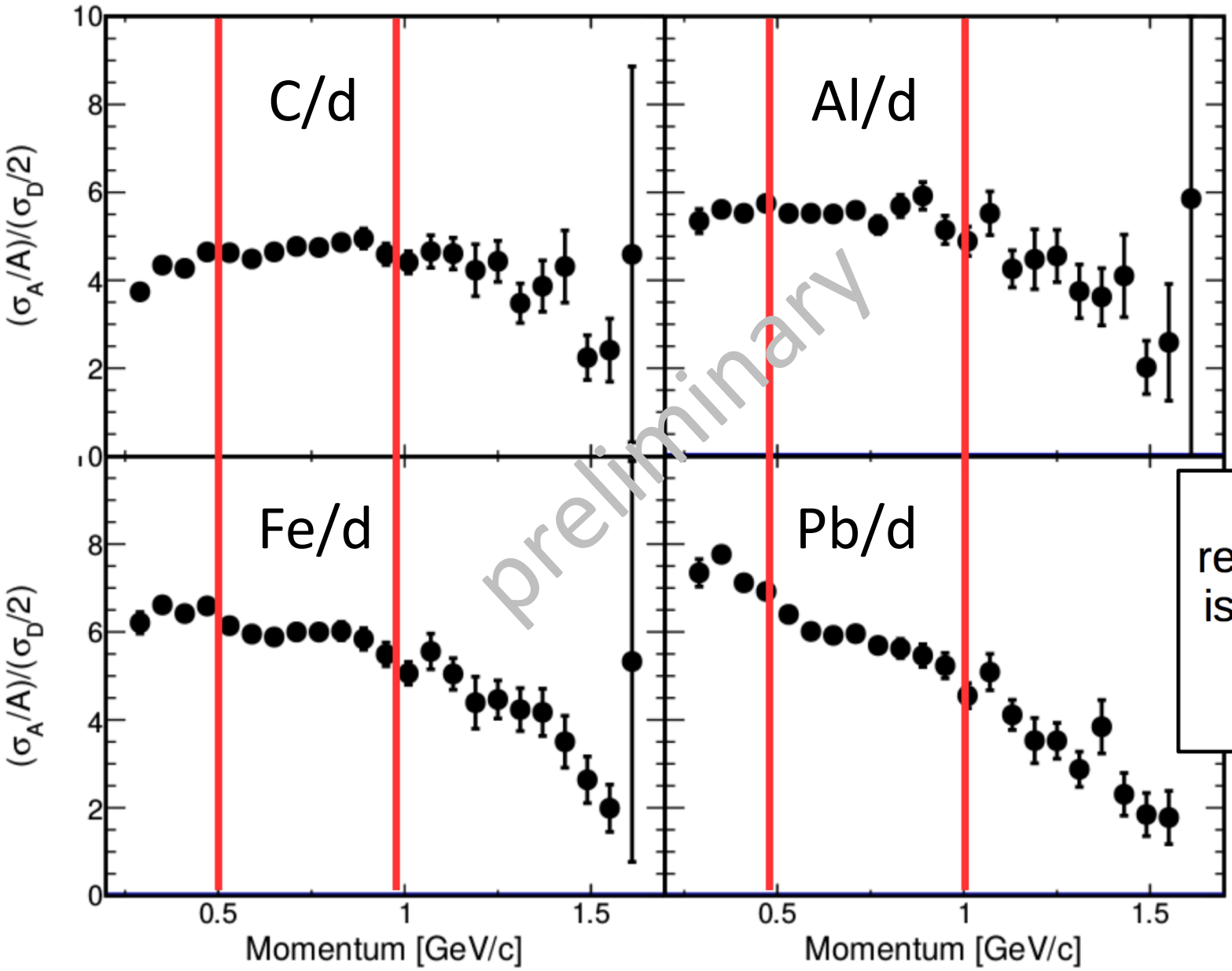
Proton Momentum

- Yields shown here are normalized by beam-charge and live-time
- Also corrected for target luminosity (Nucleons/cm^2), relative to the deuterium target



B. Schmookler, preliminary

Ratios vs proton momentum



We select region where ratio is mostly flat and then look at x_B ratios.

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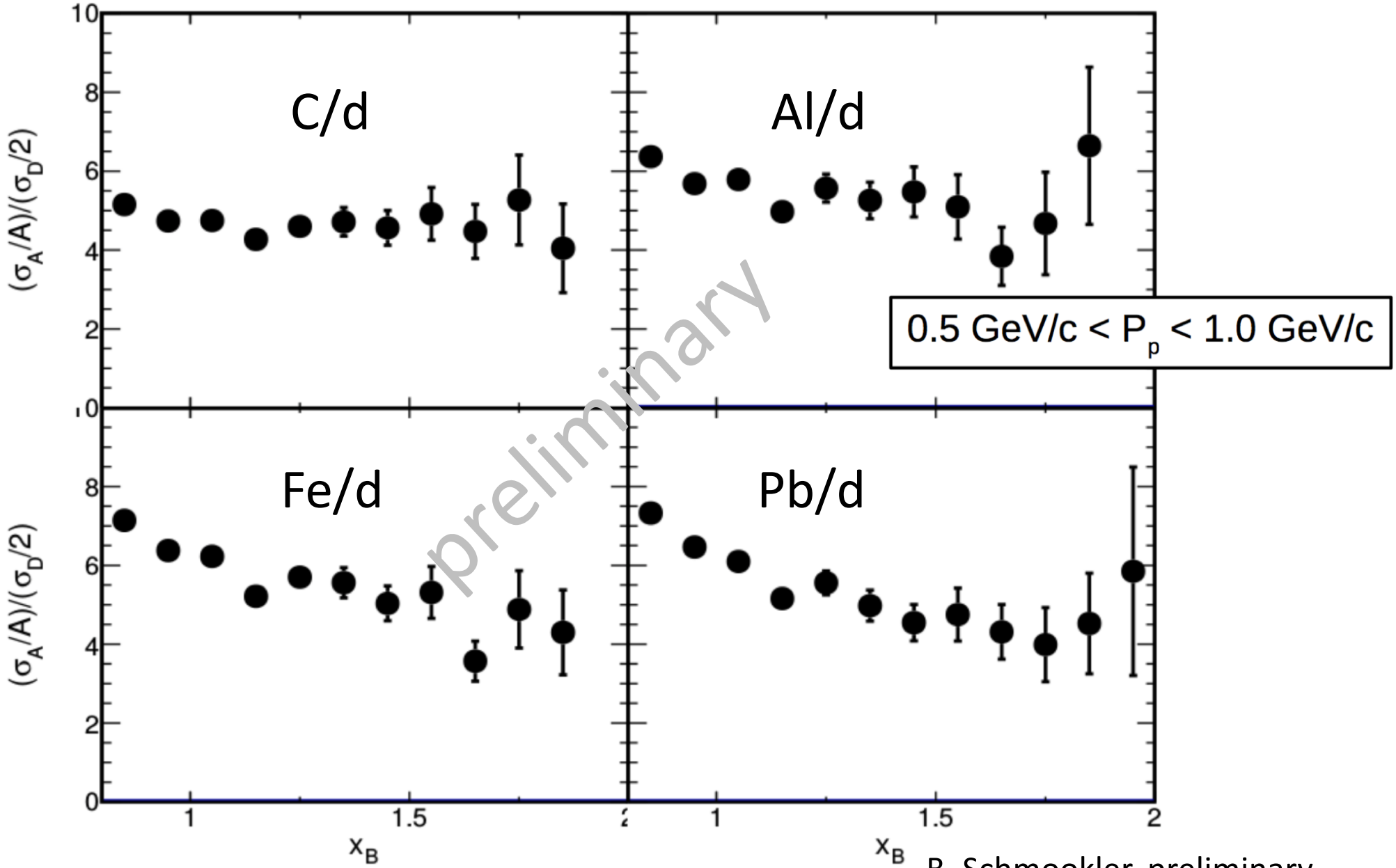
Cross section ratios vs x



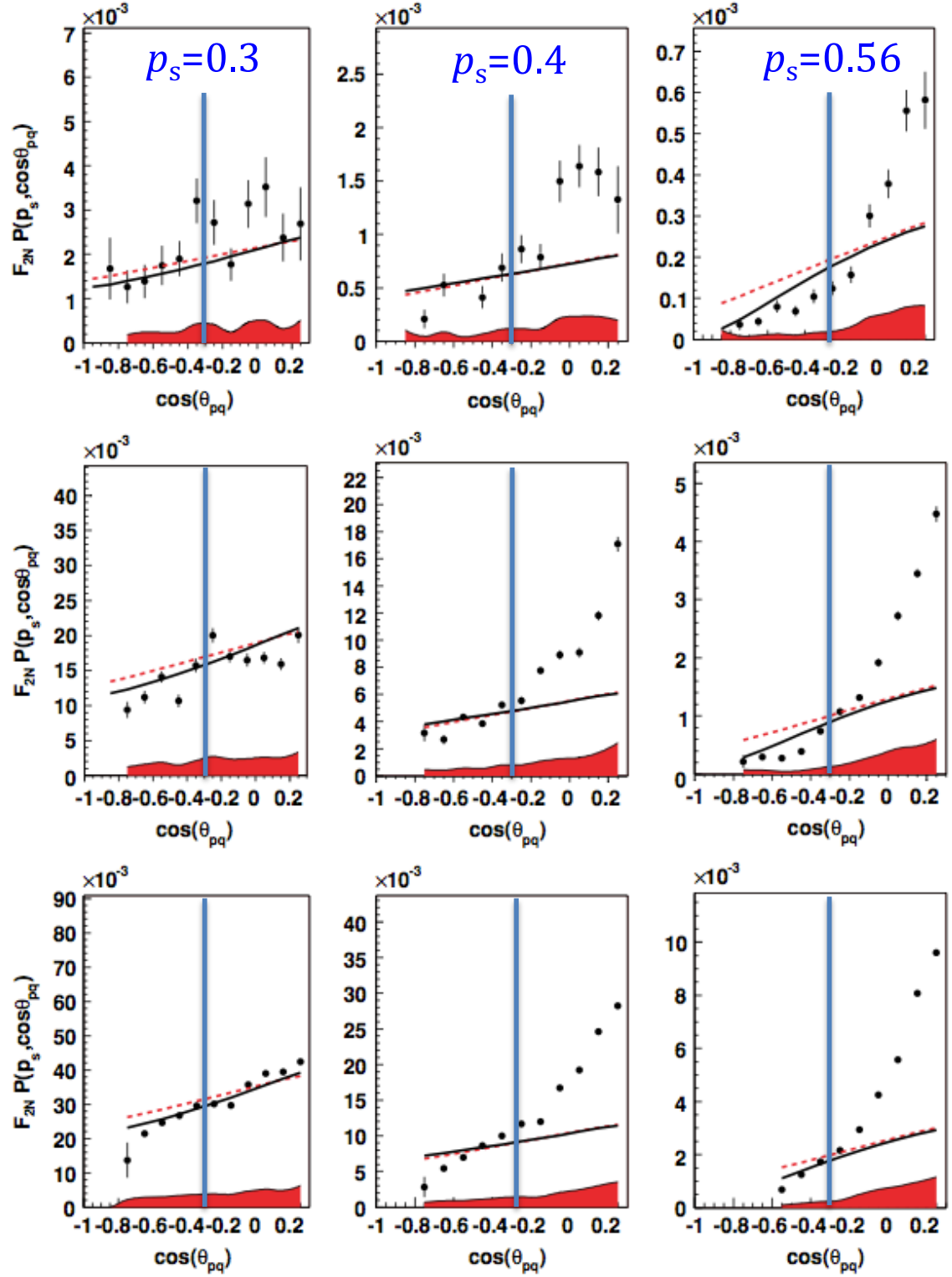
B. Schmookler, preliminary

Summary

- We can tag both QE and DIS reactions to select high-momentum nucleons
  - Selectivity?
- Bound nucleon structure is almost certainly modified, even in the deuteron
  - Modification should increase with momentum
- Test this with $d(e,e'N_s)$ spectator tagging
  - Ratio of cross sections
  - Upcoming measurements at JLab
  - Exciting possibilities at the EIC

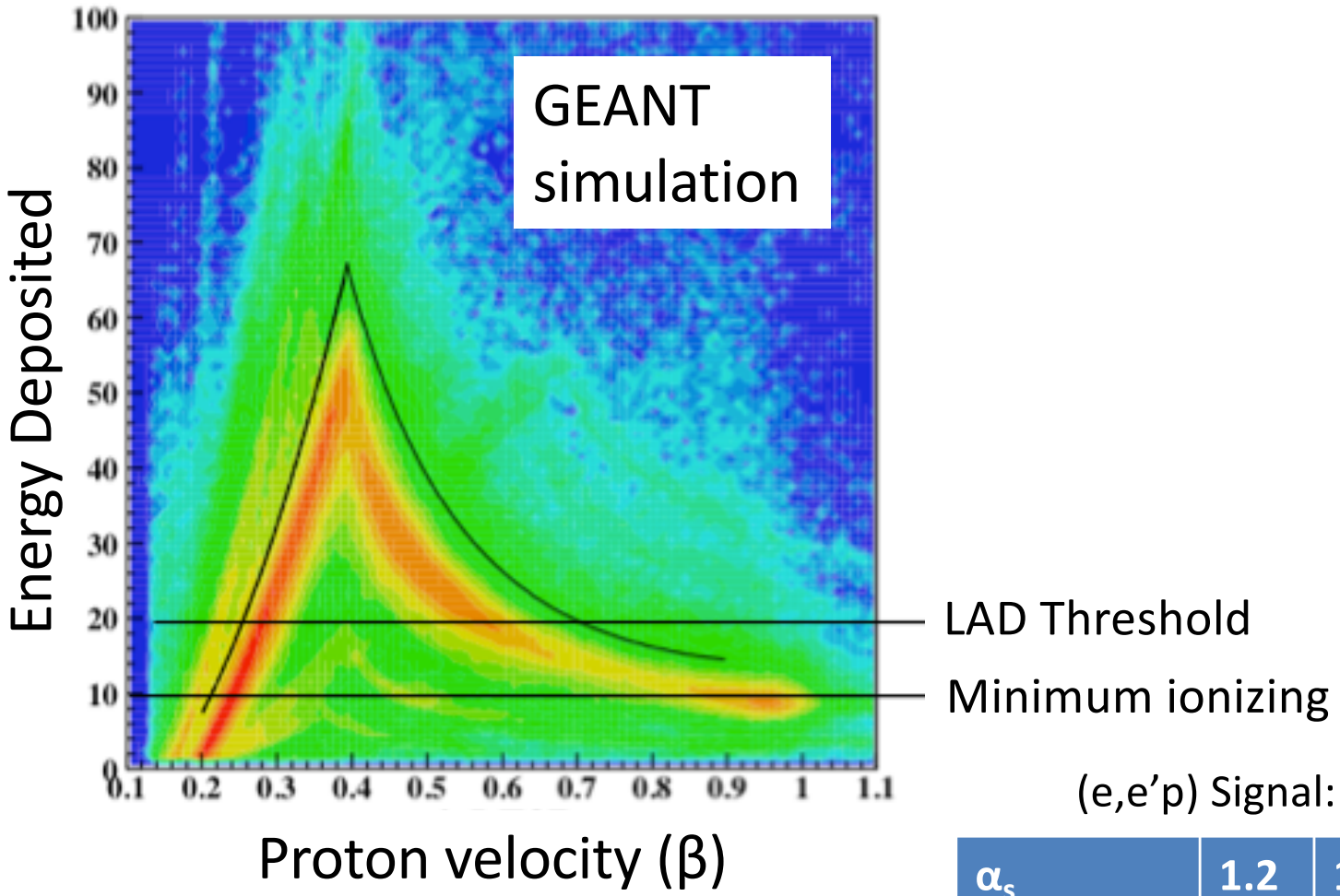
backup

Minimize nucleon rescattering (FSI)



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

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