LAD ERR

In Medium Nucleon Structure Functions, SRC, and the EMC Effect
E12-11-107

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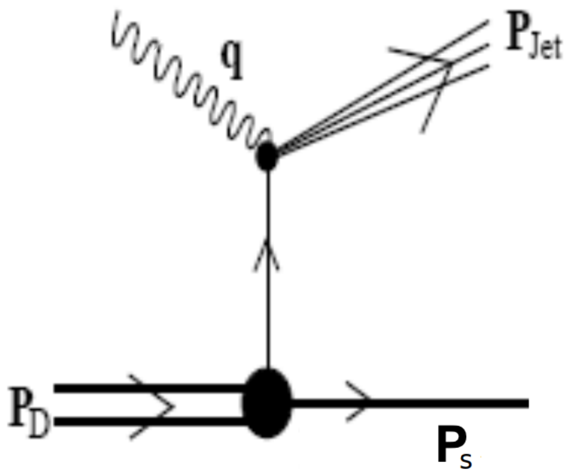
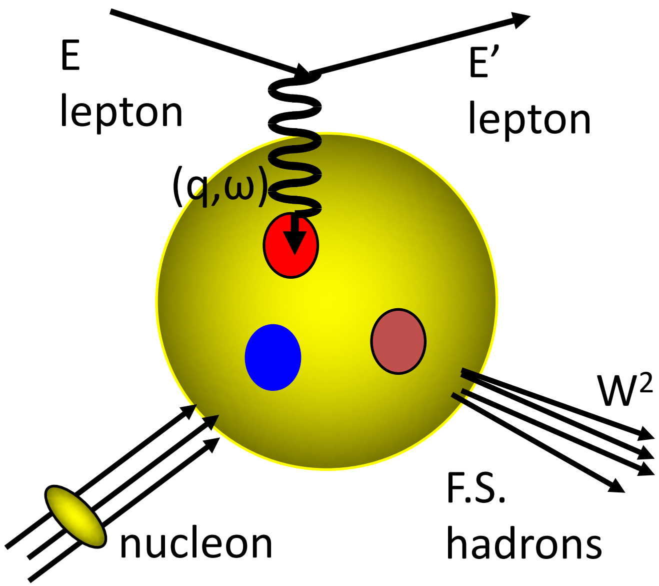


This talk addresses part of Charge 1: What are the running conditions for the experiment?

Jefferson Lab Old Dominion University Tel Aviv University

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

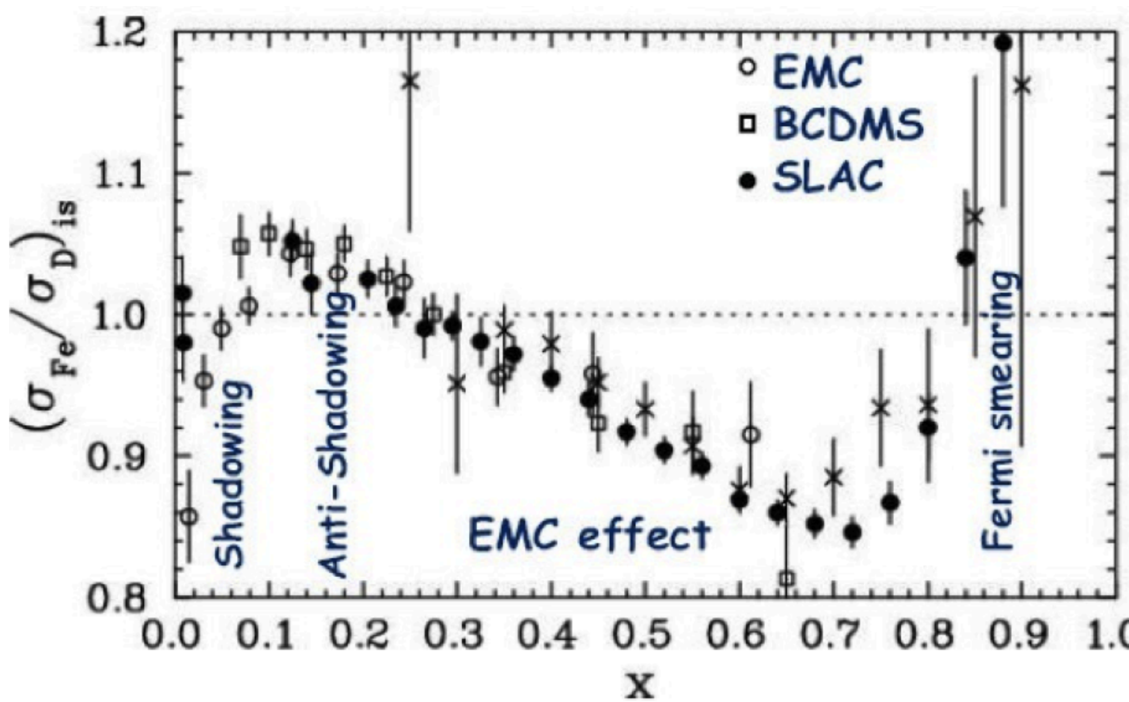
Expectation: DIS of bound nucleons ≅ DIS of a free nucleons

EMC: DIS off bound N ≠ DIS off free N

Origin of EMC effect unknown!!

Nucleon modification needed.

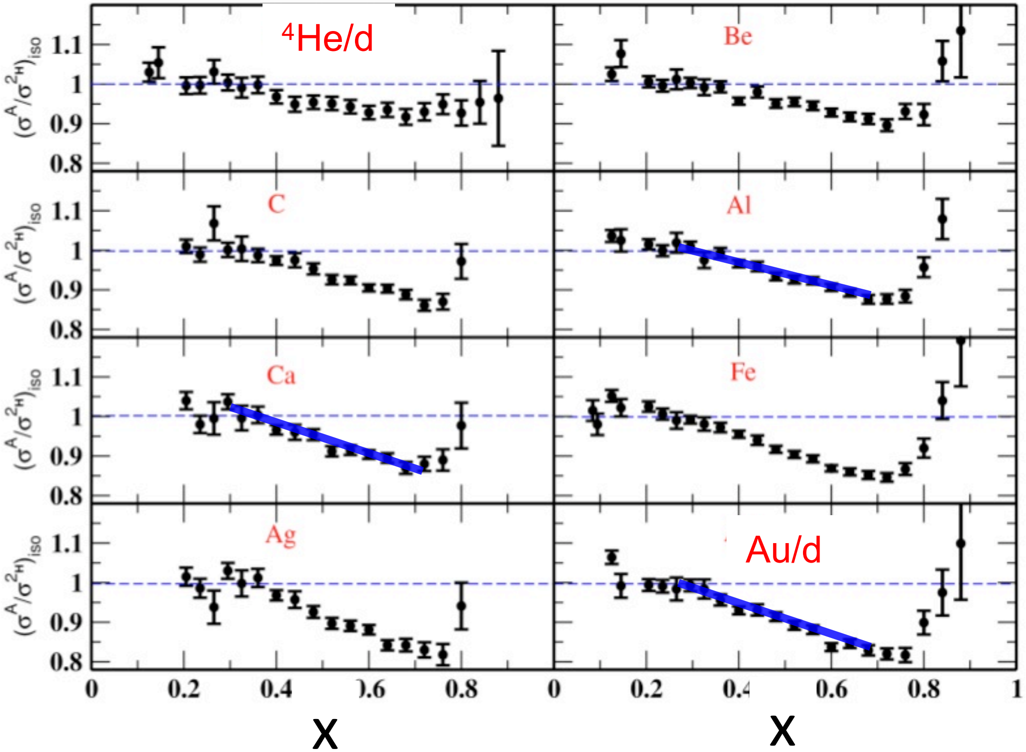
≈10^3 publications



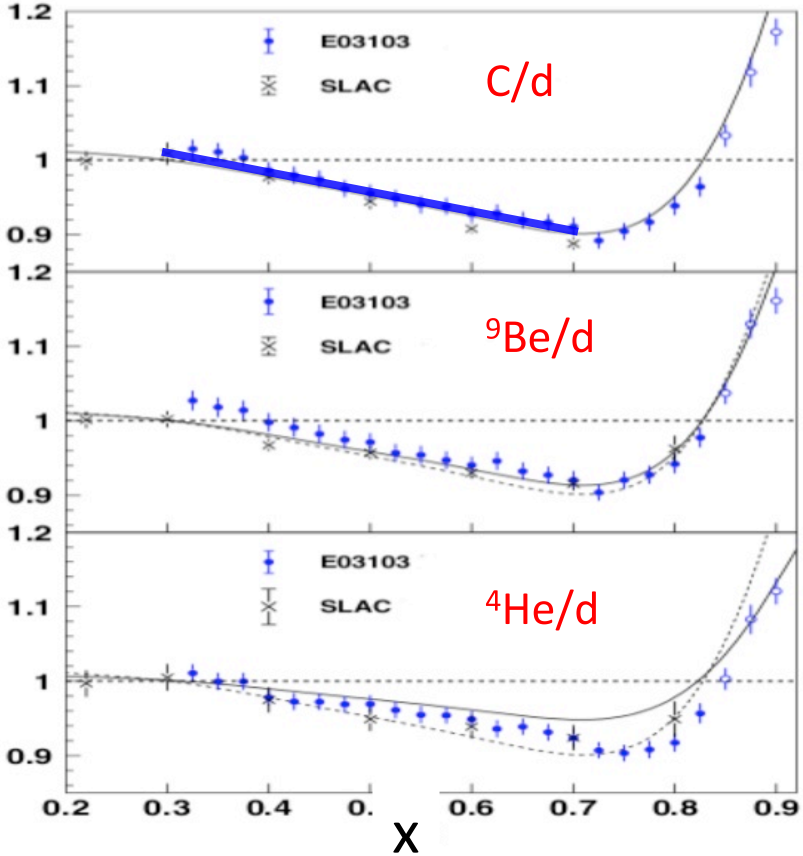
EMC Effect: Universal

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

SLAC



Hall C



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

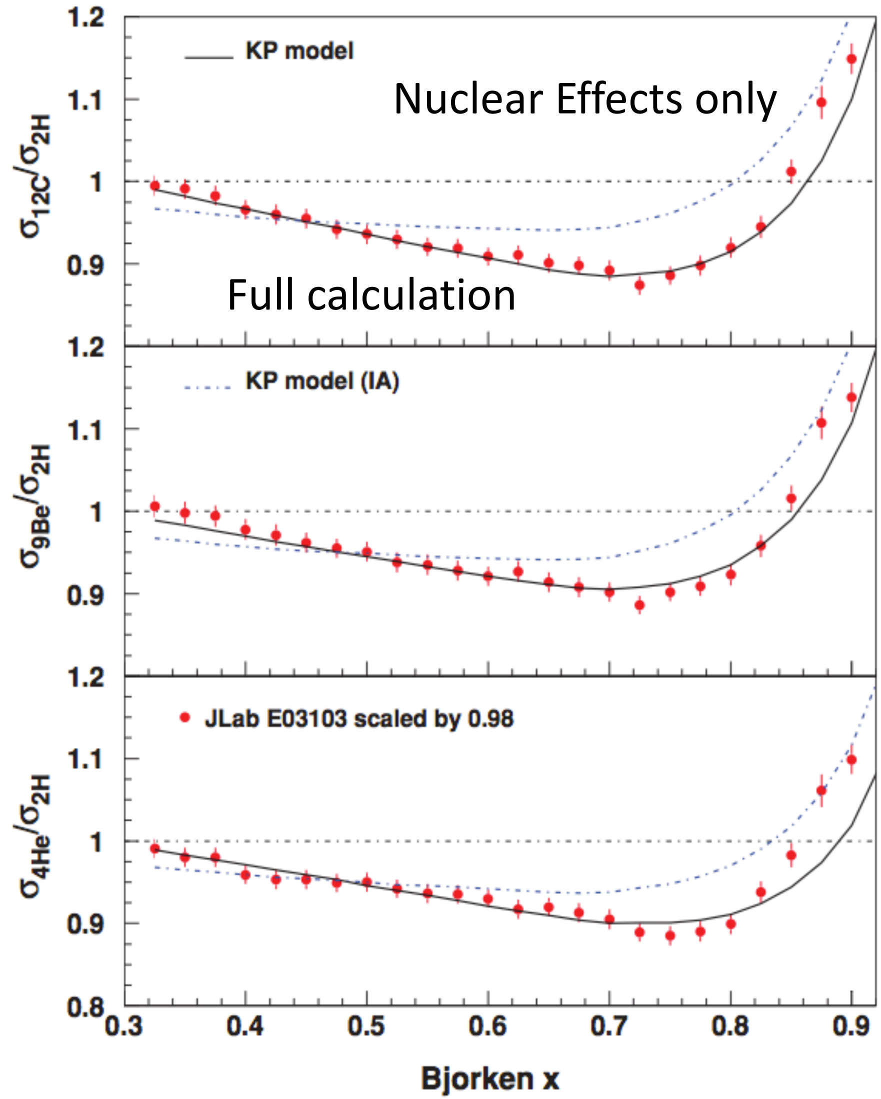
J. Seely, PRL 103, 202301 (2009)

J. Gomez, PRD **49**, 4348 (1994).

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

EMC Effect: Theory

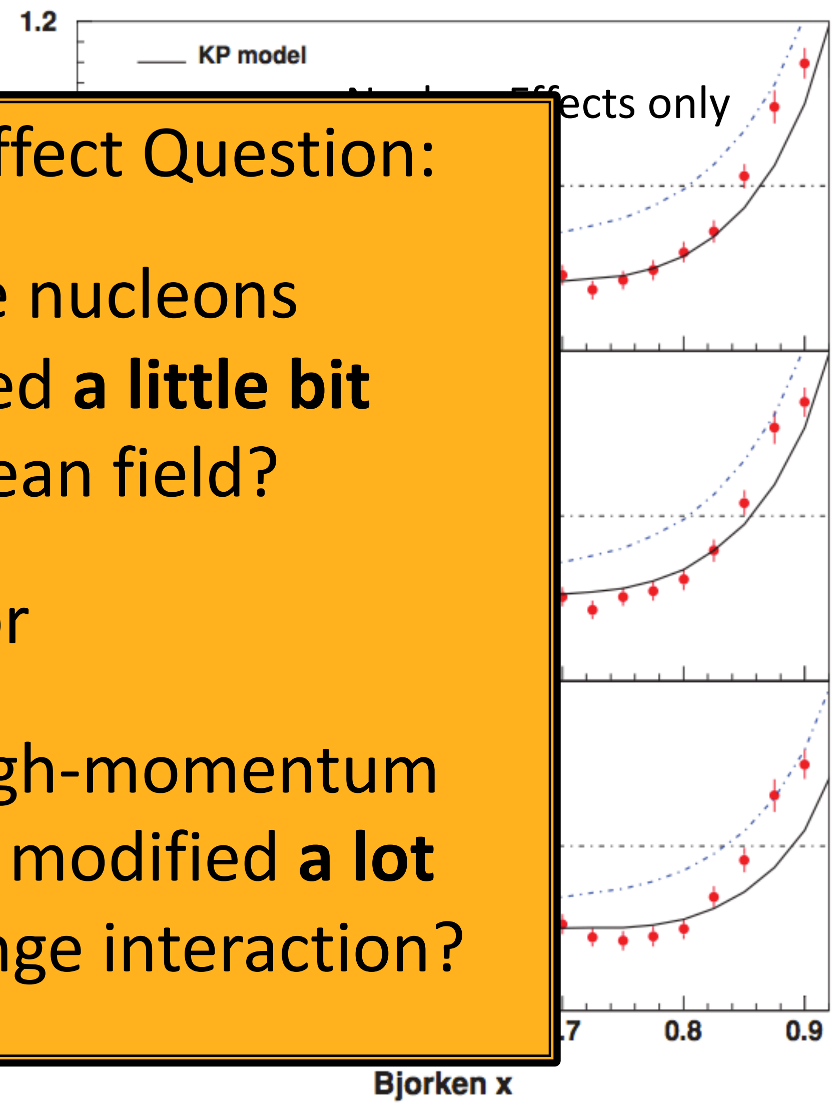
- Nuclear Effects:
  - Fermi motion
  - Binding energy
- Full Calculation
  - Nucleon modification
    - Phenomenological change to bound nucleon structure functions, proportional to virtuality (p^2)
  - Nuclear pions
  - Shadowing



Nucleon modification needed to describe the data

Kulagin and Petty, PRC 82, 054614 (2010)

EMC Effect: Theory



The Big EMC Effect Question:

Are **all** the nucleons
each modified **a little bit**
by the mean field?

or

Are the **few** high-momentum
nucleons each modified **a lot**
by the short range interaction?

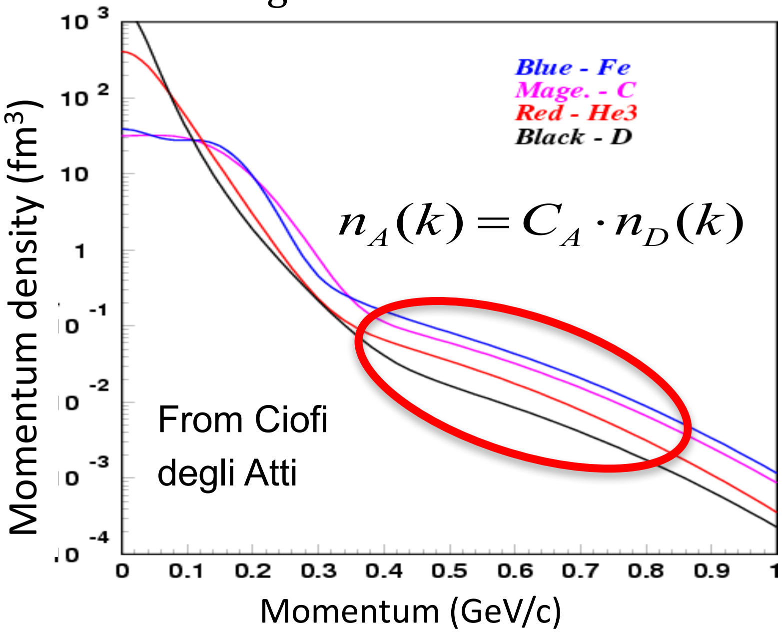
- Nuclear Effect
  - Fermi mo
  - Binding e
- Full Calculatio
  - Nucleon r
    - Phen
      boun
      funct
      virtu
  - Nuclear p
  - Shadowin

Nucleon modification needed
to describe the data

Kulagin and Petty, PRC 82, 054614 (2010)

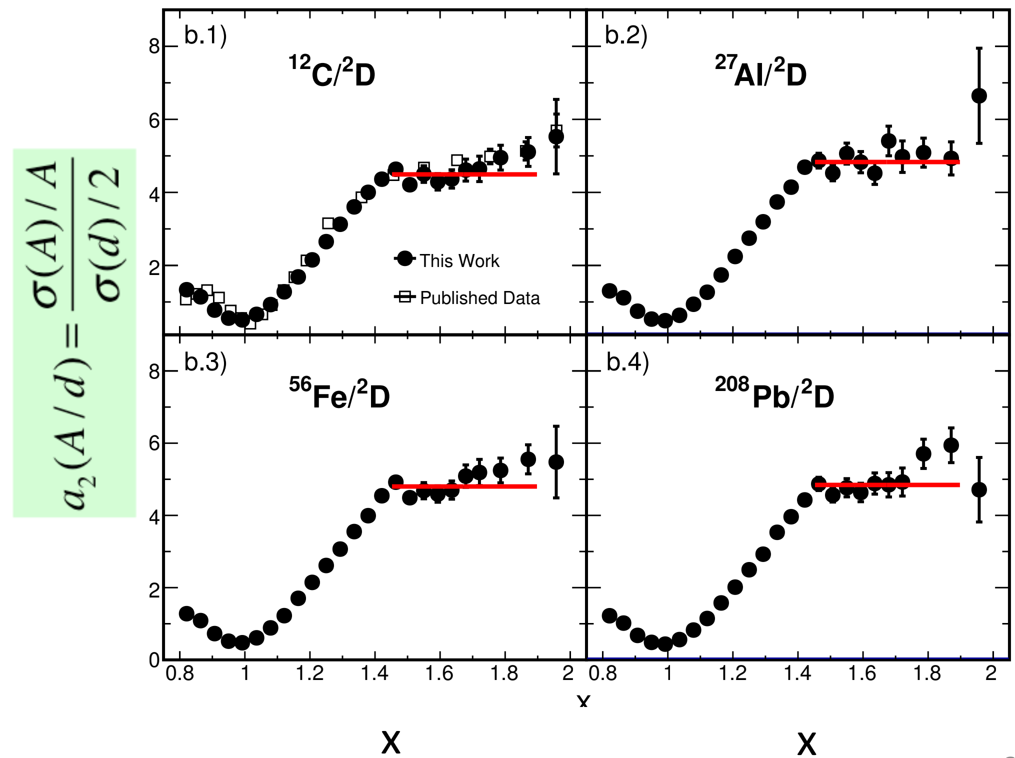
A(e,e') ratios: Universality of SRC (Scaling)

- At high nucleon momenta, strength is different but shapes of distributions are similar
- Scaling!

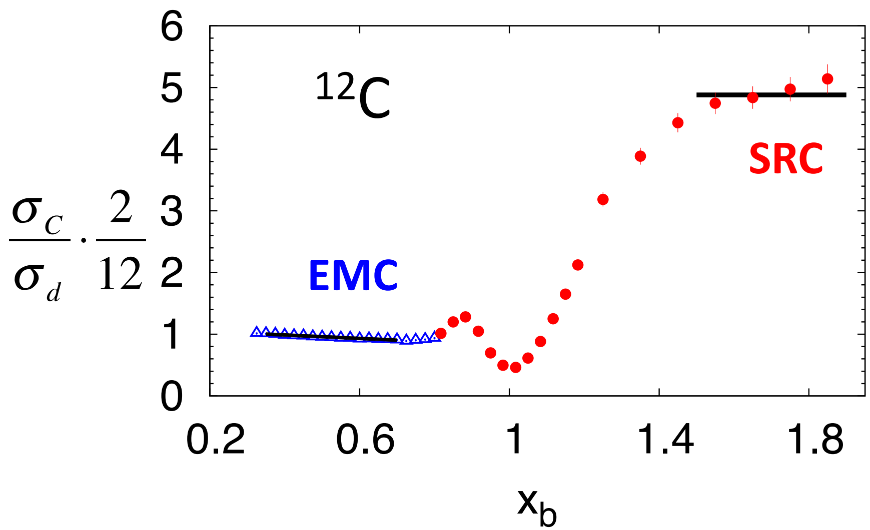


$x = Q^2/2m\nu$ related to the minimum struck nucleon momentum

B. Schmookler et al, Nature **566**, 354 (2019)



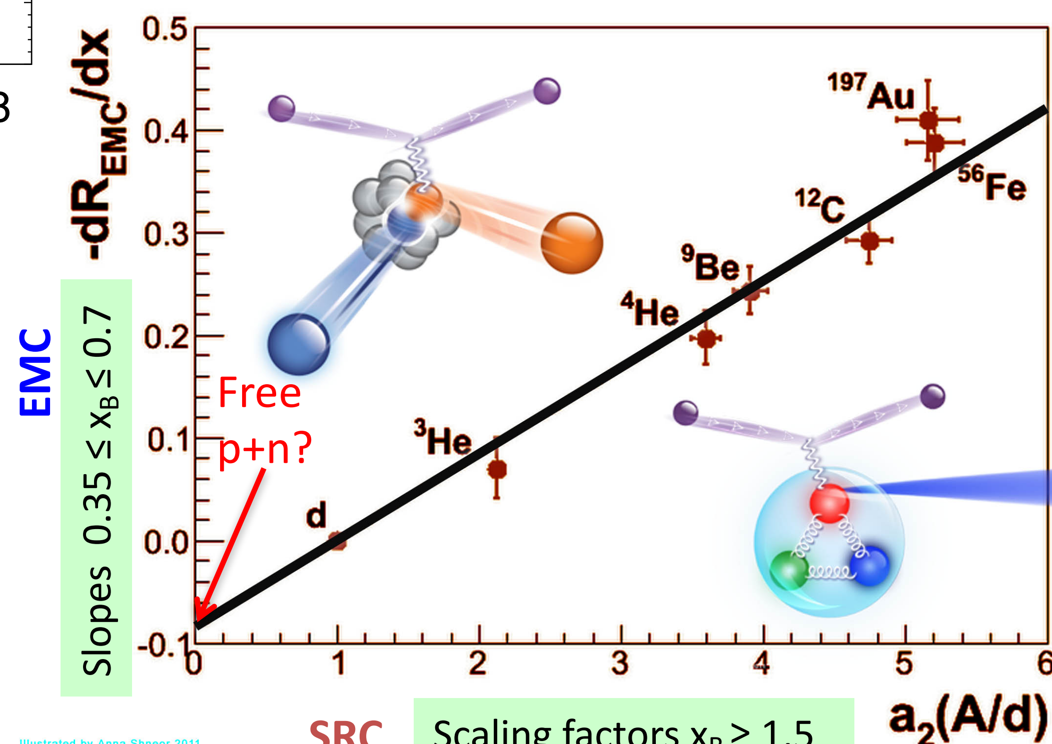
Correlations Between EMC and SRC



JLab data

J. Seely *et al.*, PRL **103** (2009) 202301

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



SRC

- ➢ High nucleon momenta

EMC

- ➢ Is EMC related to high-momentum nucleons?
- ➢ Are high-momentum nucleons modified?

Weinstein *et al.*, PRL **106**, 052301 (2011)

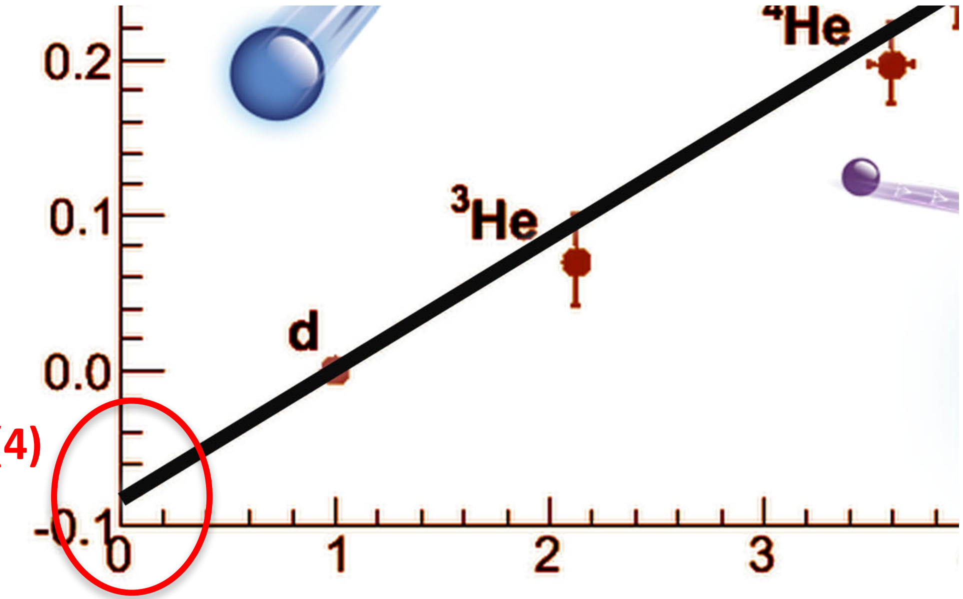
O. Hen *et al.*, PRC **85**, 047301 (2012)

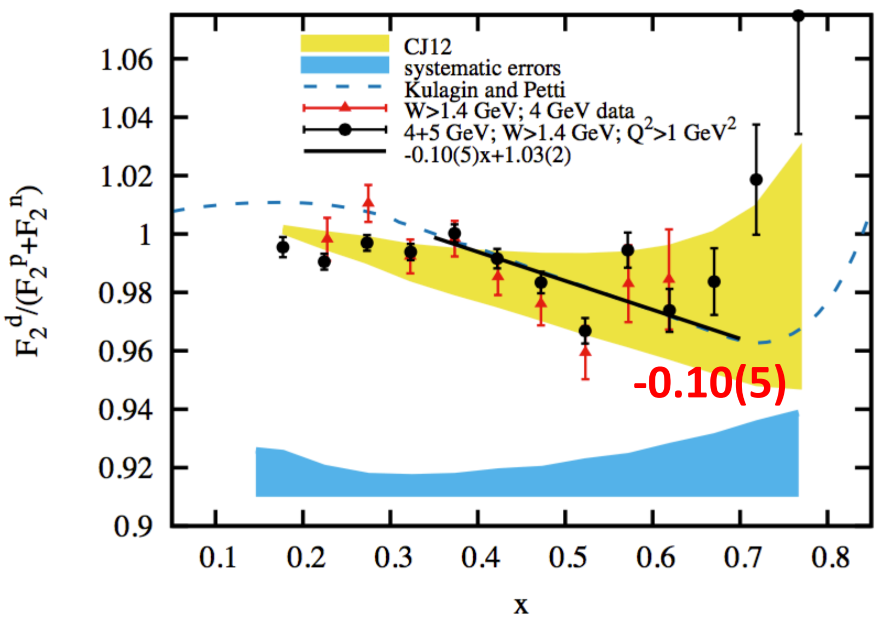
Explore Connection between EMC and SRC

Do high-momentum nucleons have a large EMC effect?

Deuteron

- Is there an "EMC" effect in the deuteron?
- Is the "EMC" effect larger at high-momentum?





[BoNuS: Griffioen et al, PRC **92,** 015211 (2015)]

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

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

~2.4% modification, ~5% high momentum:

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

Testing the BIG Question:

Measure the in-medium modified(?) structure function F_2 in DIS as a function of nucleon momentum

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

(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.)

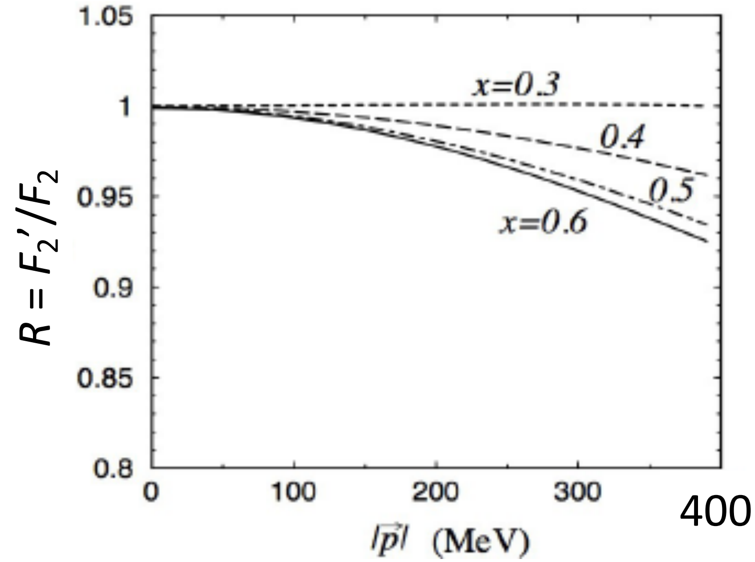
- All nucleons modified
  - ➔ F_2 independent of momentum
  - ➔ $F_2 \neq$ free F_2 (small difference for all nucleons)
- SRC nucleons modified
  - ➔ F_2 varies with momentum
  - ➔ $F_2 \neq$ free F_2 (big difference for high-p nucleons)

Predicted Dependence of F_2 on Momentum

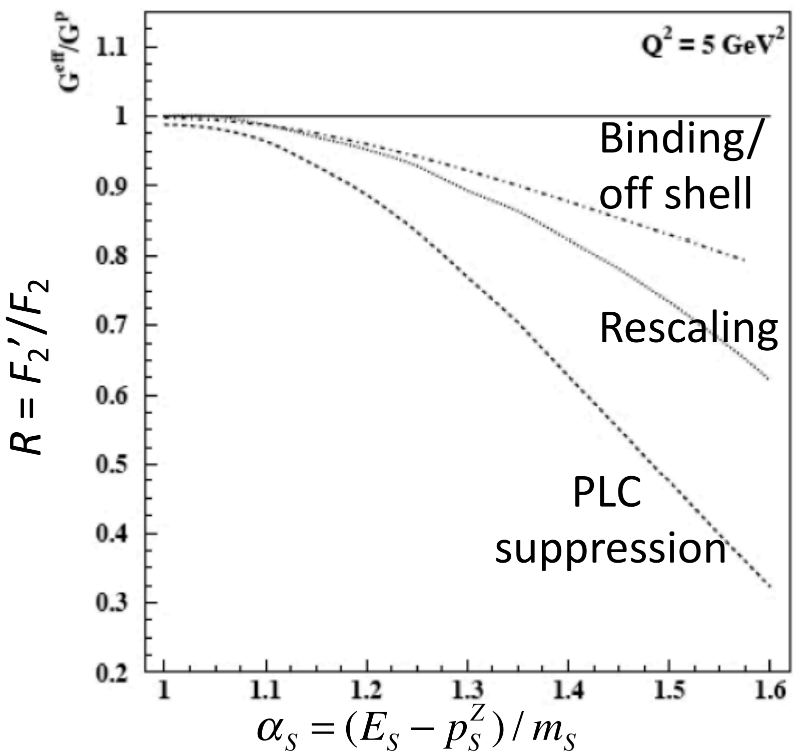
Dependence on:

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

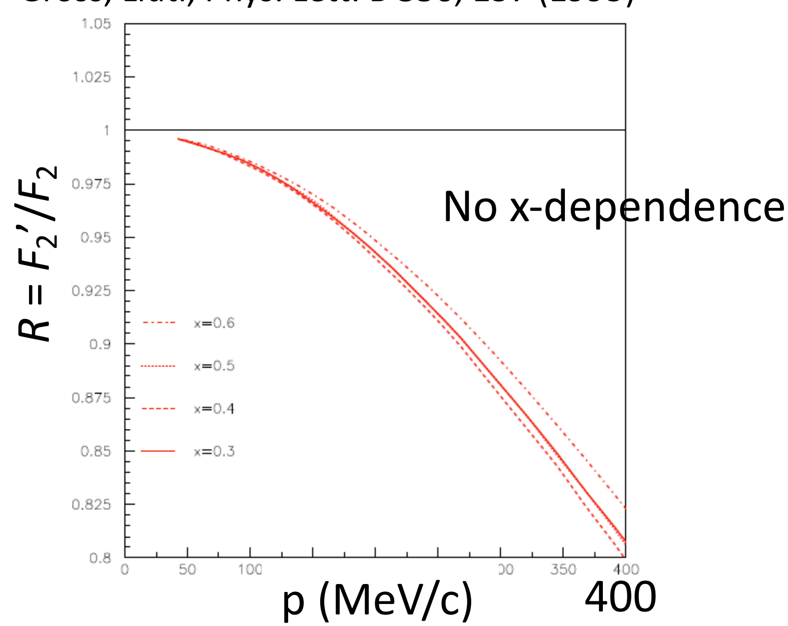
Melnitchouk, Schreiber, Thomas, Phys. Lett. B **335**, 11 (1994)



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



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



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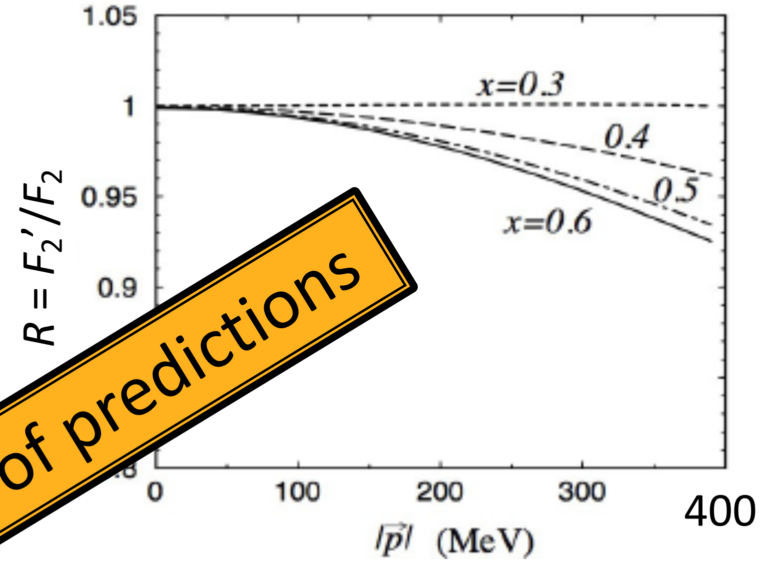

Melnitchouk, Sargsian, Strikman,
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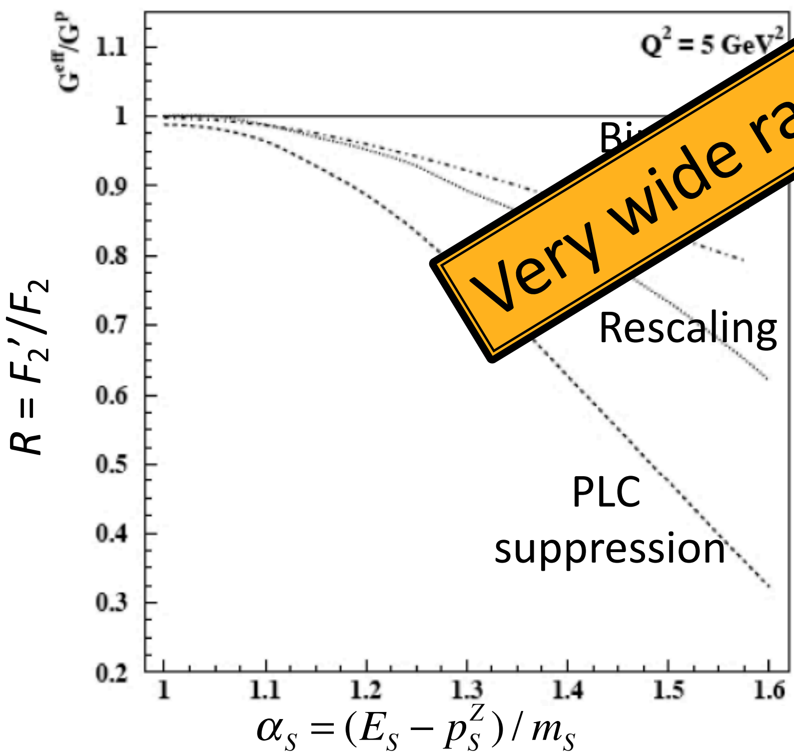
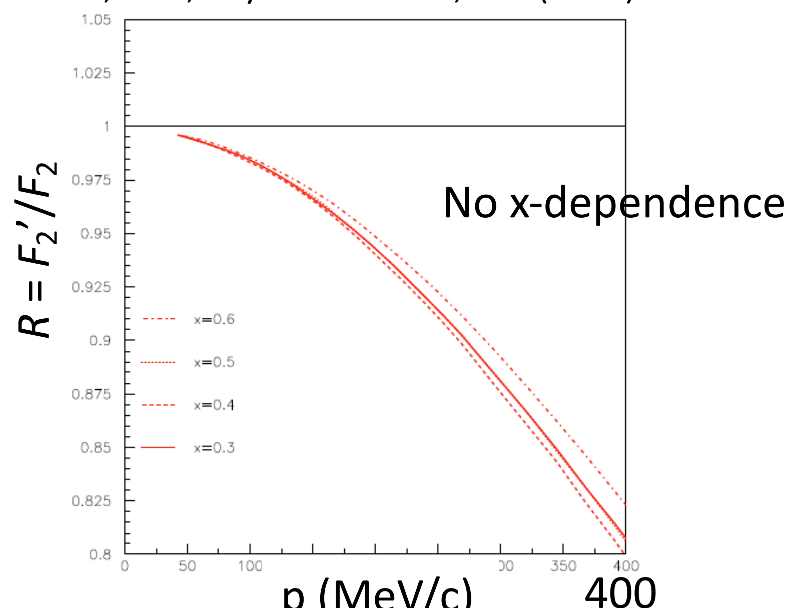


Very wide range of predictions

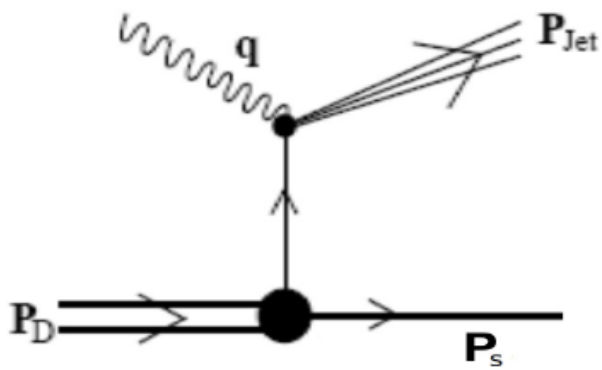
Gross, Liuti, Phys. Lett. B **356**, 157 (1995)



Spectator Tagging

Experimental method

- ➢ (e,e') Deep Inelastic Scattering from deuterium
- ➢ Tag high-momentum neutrons with 300-700 MeV/c backward-recoiling ("spectator") partner protons using d(e,e'p_S)



Experimental Method

d(e,e'p$_S$) cross section factorizes into the cross section (F_2) and the distorted momentum distribution.

Fix the recoil kinematics: $\vec{p}_s$ or (α_s, p_T)
measure x-section ratios at 2 different x':

$$\frac{d^4\sigma}{dx_1' dQ_1^2 d\vec{p}_S} \Big/ \frac{d^4\sigma}{dx_2' dQ_2^2 d\vec{p}_S} = \left(K_1/K_2\right)\left[F_2^*(x_1', \alpha_S, p_T, Q_1^2)\big/F_2^*(x_2', \alpha_S, p_T, Q_1^2)\right]$$

For $x_{hi}' \approx 0.5 - 0.6$ and $x_{lo}' \approx 0.3$ we shall measure:

$$\frac{F_2^*(x_{hi}', \alpha_S, p_T, Q_1^2)}{F_2^*(x_{lo}', \alpha_S, p_T, Q_2^2)} = \left(\frac{d^4\sigma}{dx_{hi}' dQ_1^2 d\vec{p}_S} / K_1\right) \Big/ \left(\frac{d^4\sigma}{dx_{lo}' dQ_2^2 d\vec{p}_S} / K_2\right)$$

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

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 and double ratios

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

$$\frac{F_2^{bound}(x'_{high},Q_1^2,\vec{p}_s)}{F_2^{free}(x_{high},Q_1^2)} = \frac{\sigma_{tag}(x'_{hi},Q_1^2,\vec{p}_s)/\sigma_d(x_{hi},Q_1^2)}{\sigma_{tag}(x'_{lo},Q_2^2,\vec{p}_s)/\sigma_d(x_{lo},Q_2^2)} \cdot \frac{\sigma_d/\sigma_n^{free}(x_{hi},Q_1^2)}{\sigma_d/\sigma_n^{free}(x_{lo},Q_2^2)} \cdot R_{FSI}$$

$$x'_{high} \geq 0.5$$

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

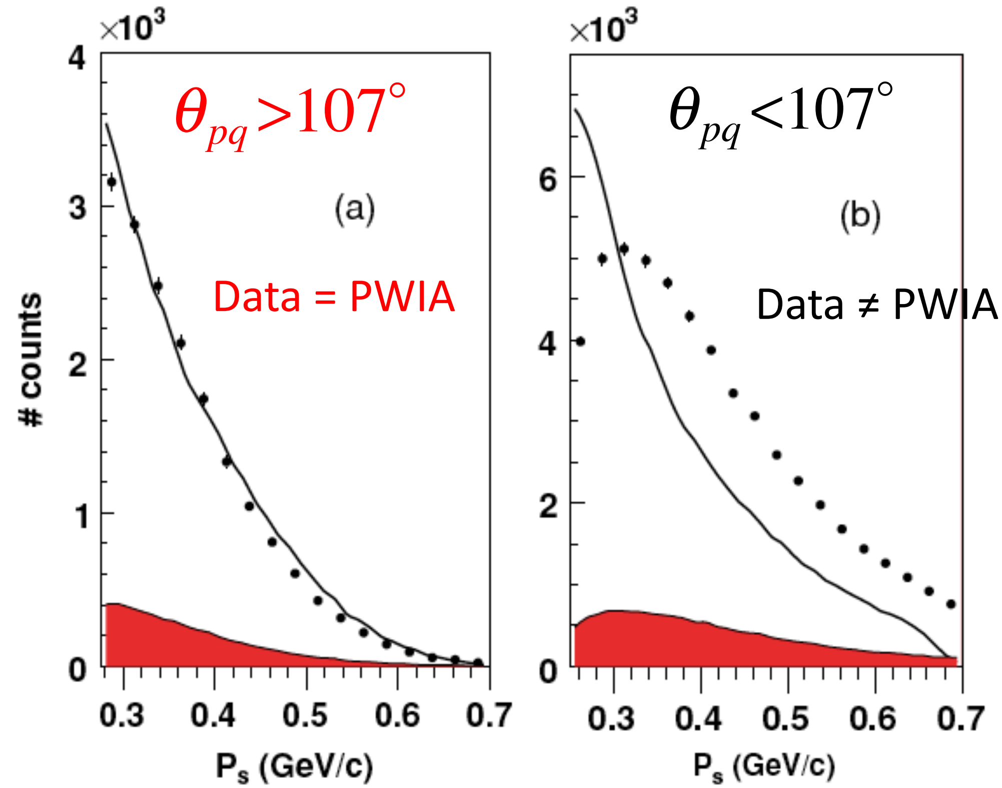
$$0.25 \geq x'_{low} \geq 0.35$$ No EMC Effect expected

Minimizing Final State Interactions (FSI)

FSI:

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

D(e,e'p_S)



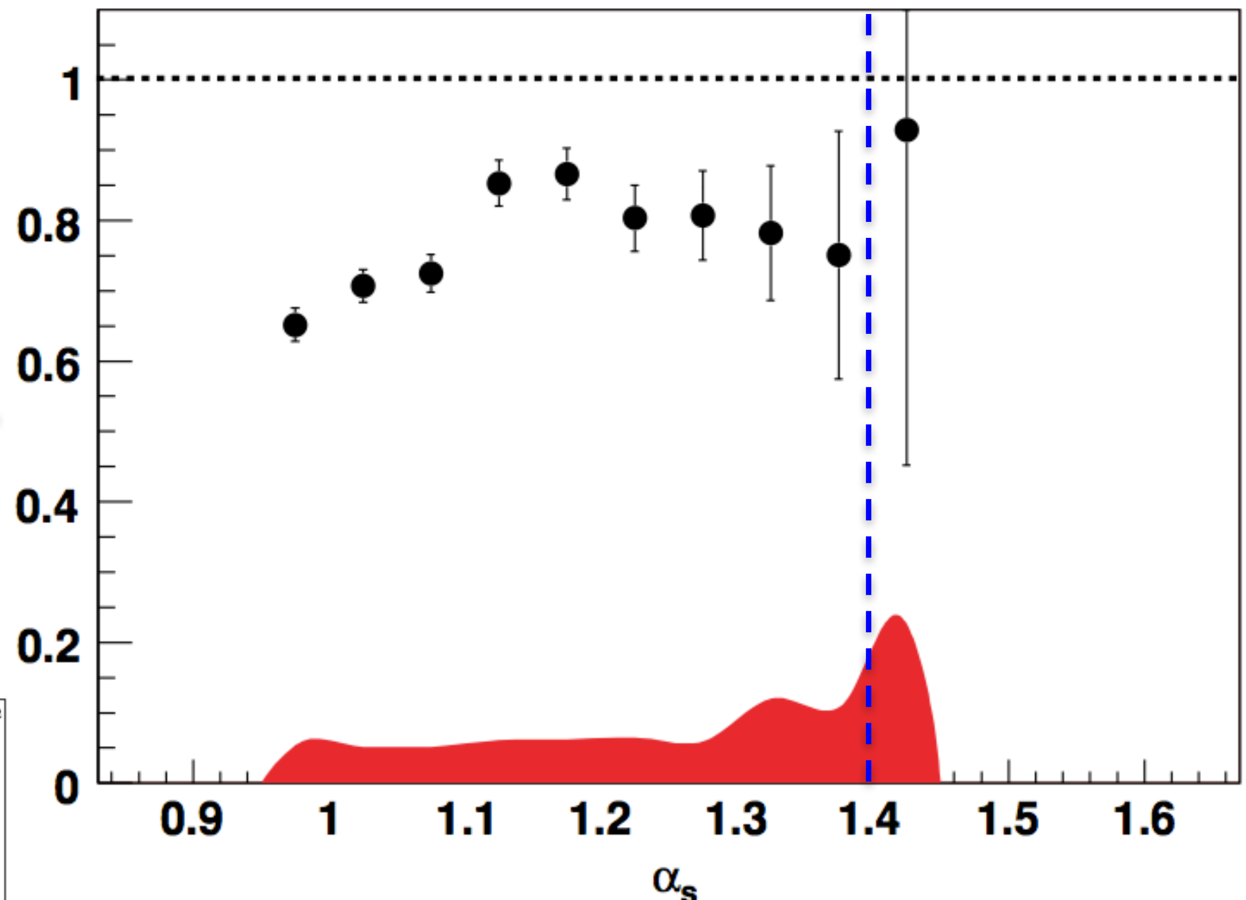
A. V. Klimenko *et al*., PRC **73**, 035212 (2006)

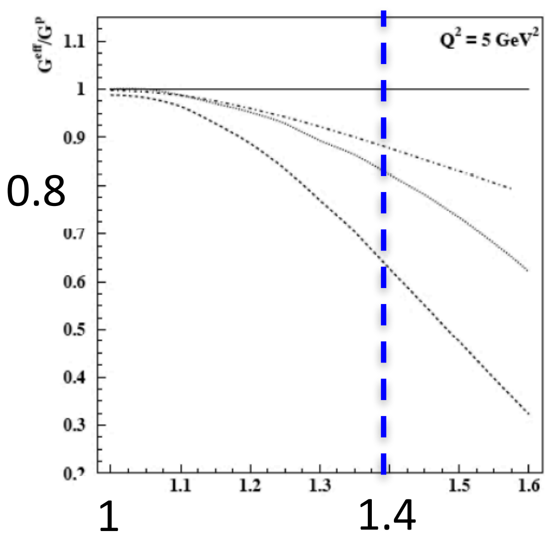
We shall:

- Take ratios at large recoil angles
- Involve theoretical colleagues
- Take more data at $\theta_{pq} \sim 90°$ (to characterize FSI)
- Take data at two x'
- Use low x' data to study FSI dependence on Q^2, W'^2, θ_{pq}

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

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





Inconclusive!

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

Experimental Details

1 μA, 10.9 GeV beam,

$$L = 10^{37}\ cm^{-2}s^{-1}$$

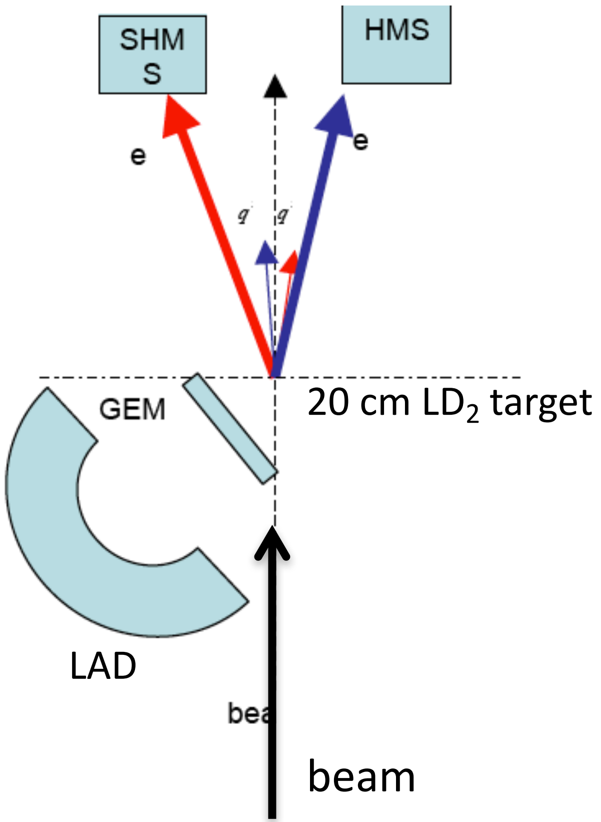
HMS and SHMS detect electrons

PRAD GEMs measure proton vertex

LAD detects recoiling proton

0.9 sr of CLAS6 TOF counters

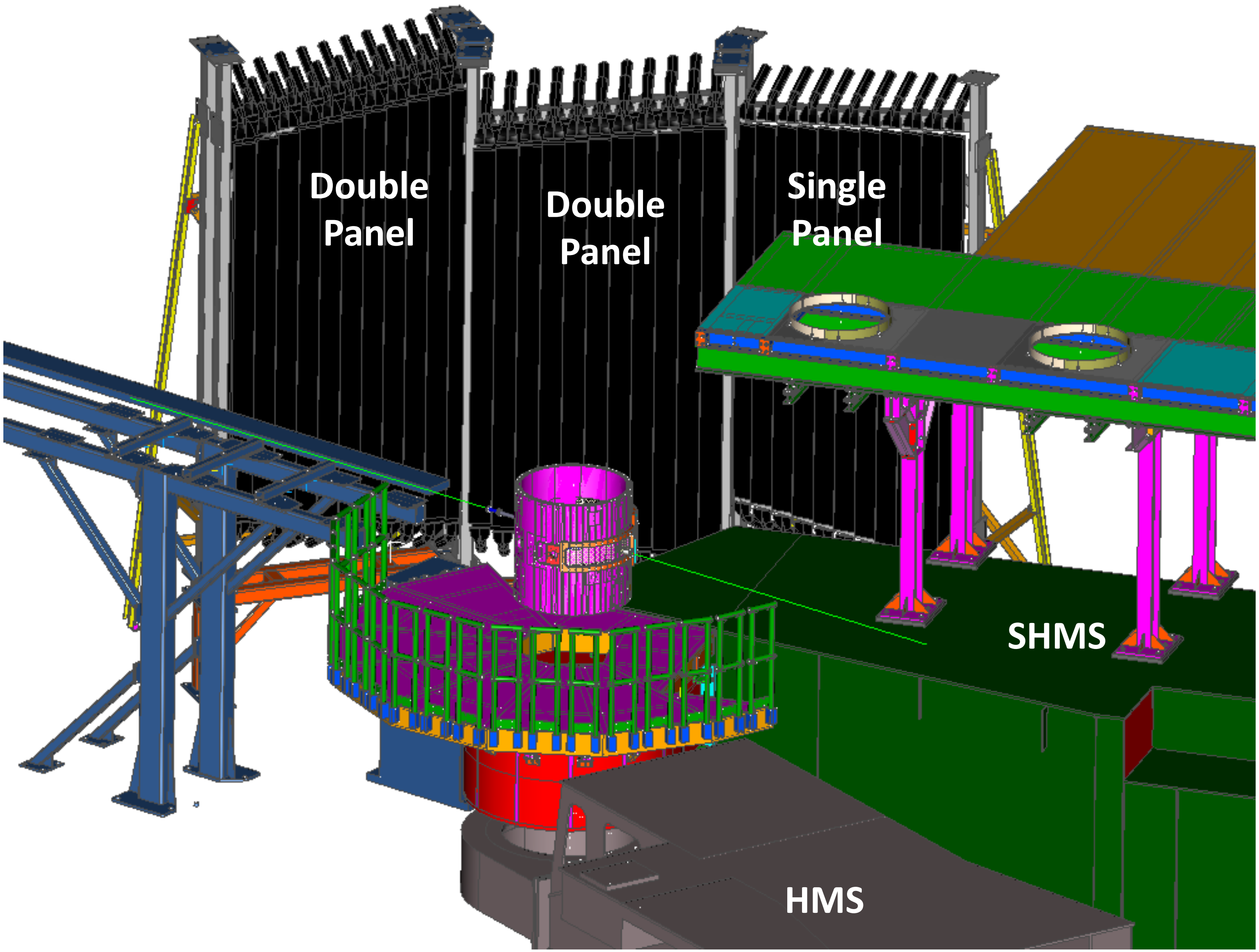
$95^\circ < \theta_p < 157^\circ$



Central kinematics

	Low x'	Hi x'
E' (GeV)	4.4	4.4
θ_e	13.5°	-17°
Q^2 (GeV^2)	2.7	4.2
$\|\vec{q}\|$ (GeV/c)	6.7	6.8
θ_q	-8.8°	10.8°
x	0.22	0.34

Collect both LAD-HMS and LAD-SHMS coincidences

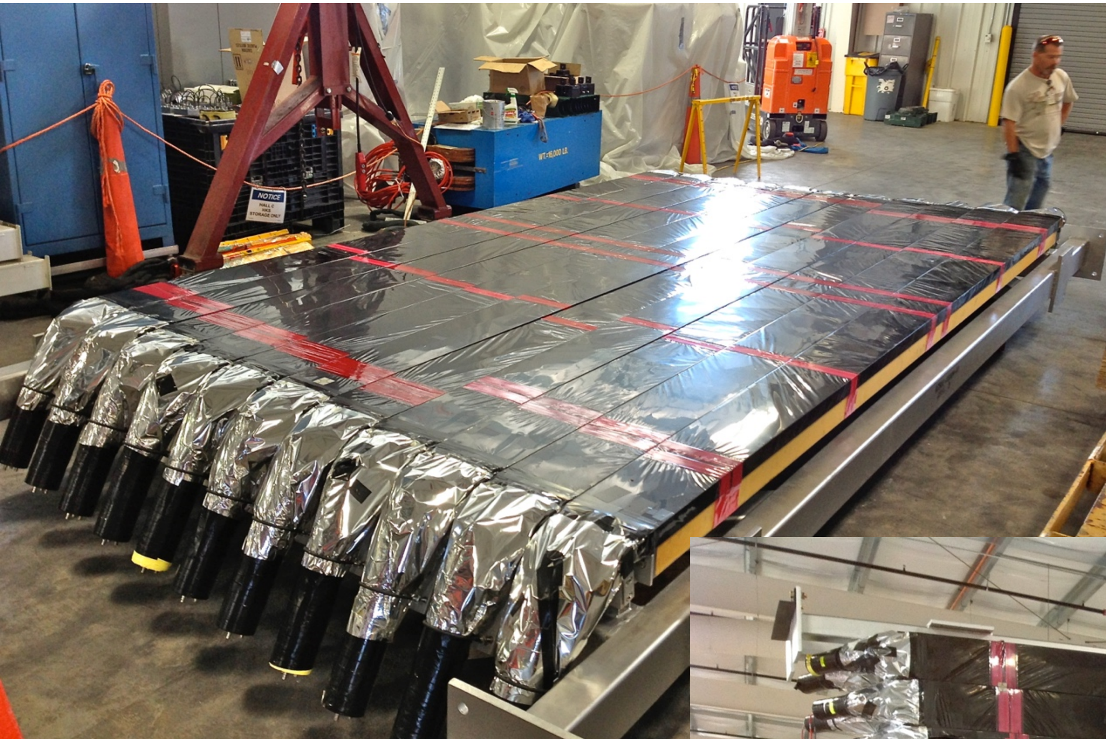


EMC-SRC Detectors

Detectors at the different planes from Target

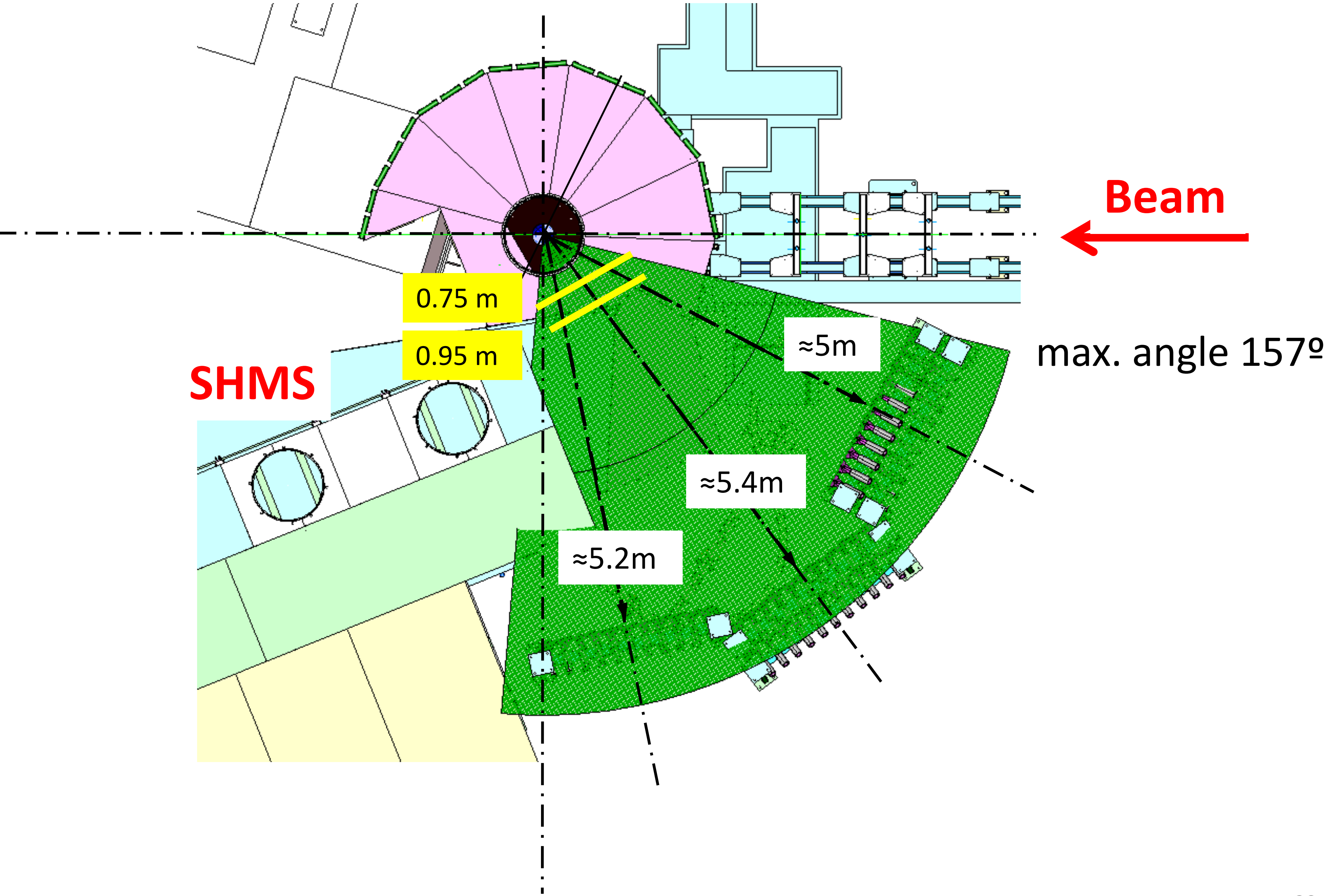
Panels overlap reducing or eliminating gap

CLAS6 TOF ➔ LAD



CLAS6 TOF scintillators
12 planes
138 scintillator bars
- Using 5 larger planes
Refurbished and tested at ODU

Tel Aviv, Kent State, MIT, JLab, ODU



Beam
0.75 m
0.95 m
SHMS
≈5m
max. angle 157º
≈5.4m
≈5.2m

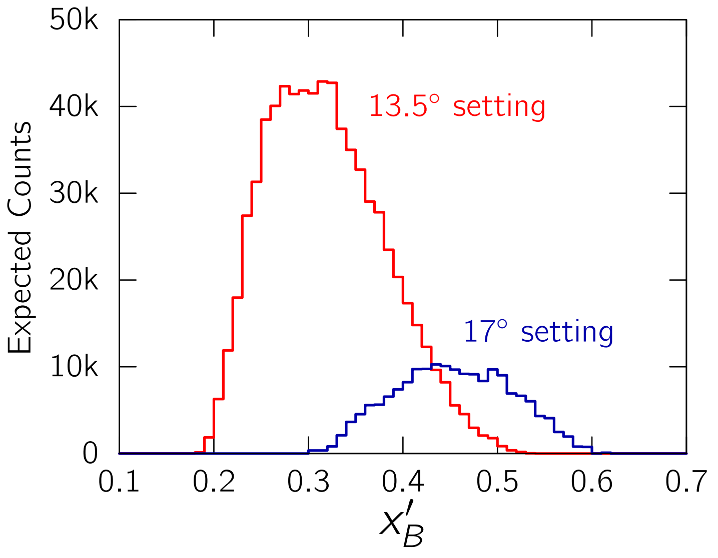
Measuring protons with LAD

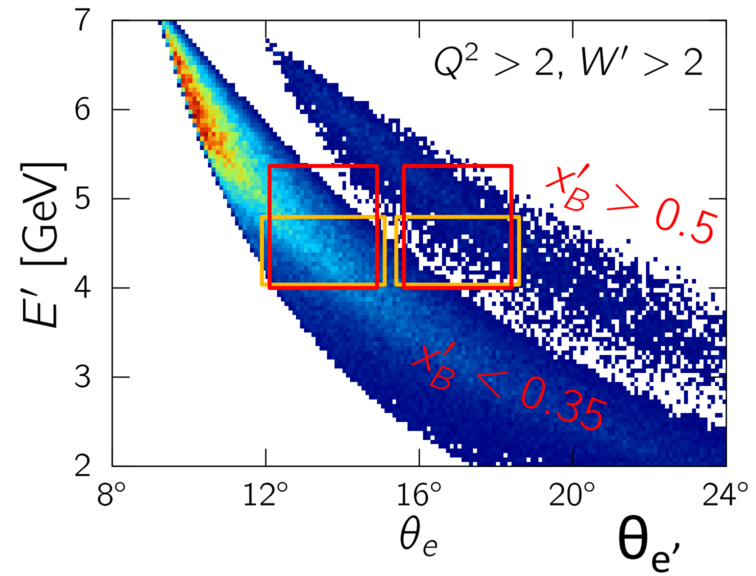
- Five panels of refurbished CLAS6 scintillators
  - 55 scintillators, each 3.9 to 4.4 m by 22 cm by 5-cm thick
  - $95^\circ < \theta_p < 157^\circ, |\phi| \leq 17^\circ$
  - 5 to 5.4 m from target
    - One panel at smaller angles, two panels each at larger angles (to identify punch-thru protons)
    - Identify protons by dE/dx vs TOF
    - Measure proton momentum using TOF
  - Laser calibration system for timing and energy calibration
    - Used successfully for BAND
- GEMS to measure proton vertex to reject accidentals
  - PRAD GEMs: 55 x 120 cm^2,
  - 75 and 95 cm from target
- Trigger on electron in either HMS or SHMS (~1 kHz total rate)

E. Smith, et al, NIM A432 (1999) 265.

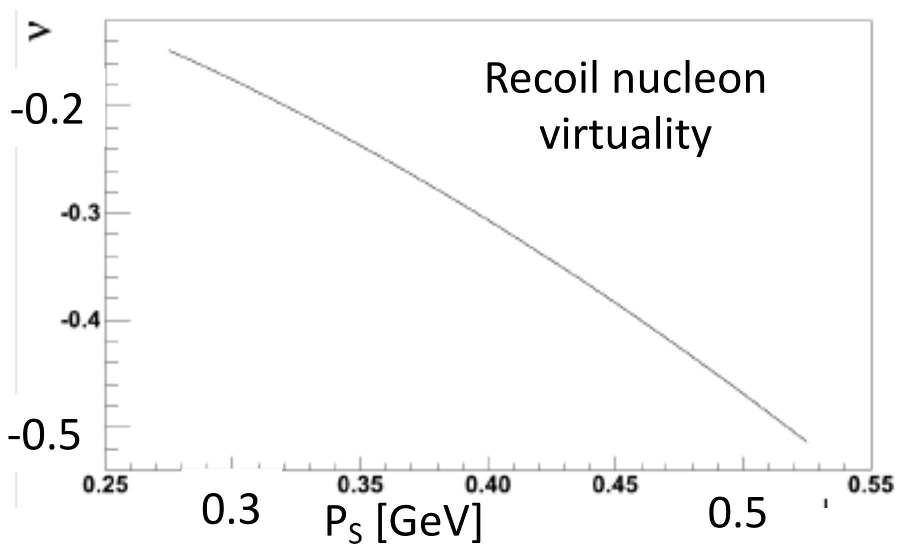
Kinematic Coverage

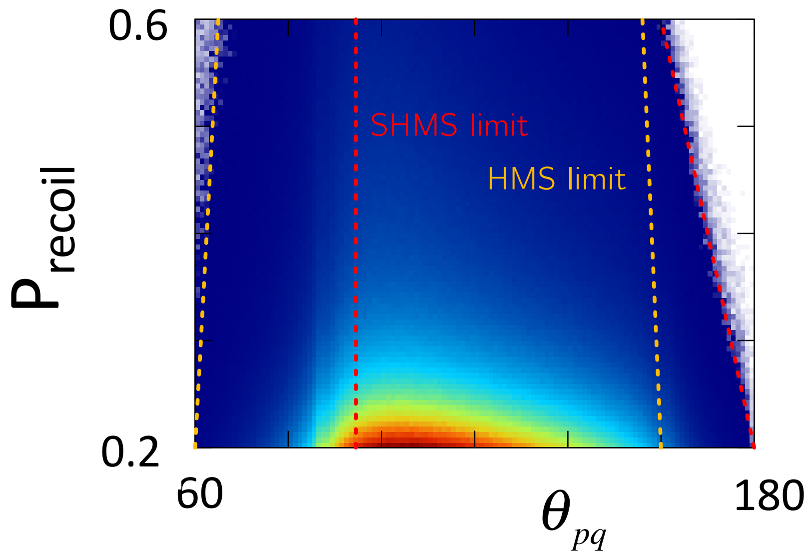
Scattered electrons



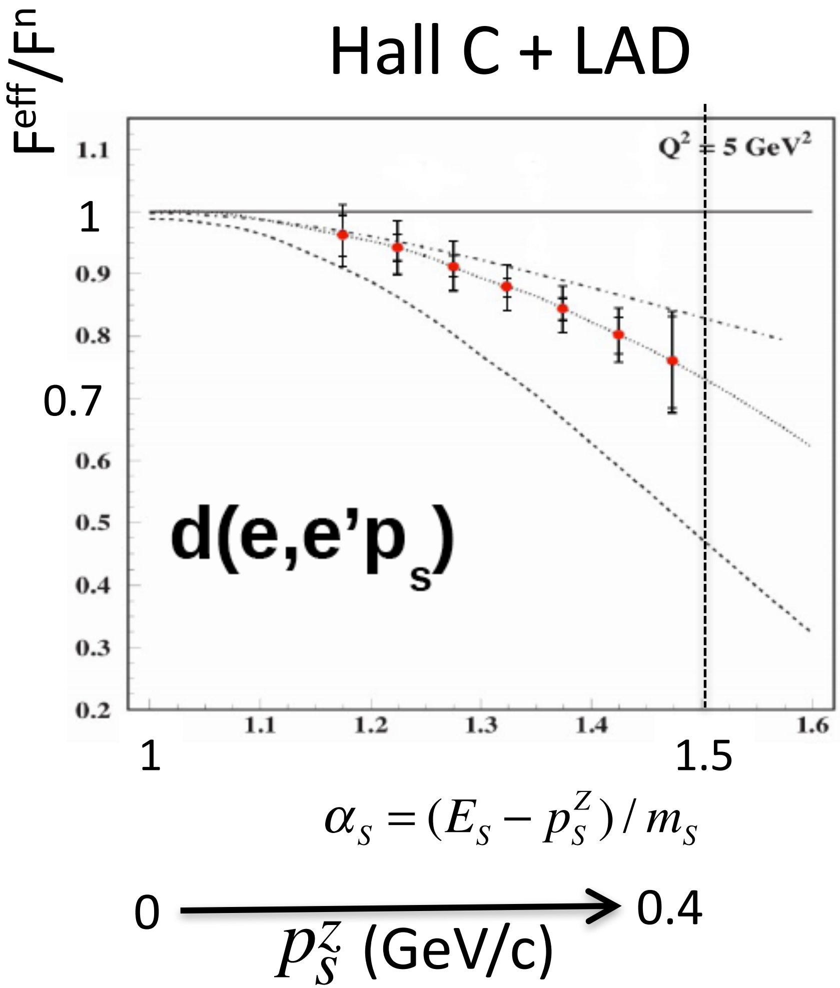


Recoiling nucleons





Expected Results



Summary:
Measuring Nucleon Medium Modification

Physics:

- EMC effect strongly implies that bound nucleons are modified
- SRC and EMC are linearly correlated
- Both phenomena are likely related to high-momentum nucleons

Experiment d(e,e'p_s) with HMS/SHMS and LAD:

- Directly measure the neutron structure function in the nuclear medium as a function of momentum (virtuality)
    - Use spectator tagging to select highly virtual neutrons in DIS
    - Minimize systematic uncertainties by measuring ratios
- Complements proton s.f. measurements using d(e,e'n_s) E12-11-003B (CLAS12 and BAND) and low-momentum neutron (BoNuS)

- Are nucleons modified in the nucleus? If so, which ones?
- Can this explain the EMC effect?
- How is this related to short range correlations?