In Medium Proton Structure Functions, SRC, and the EMC Effect
E12-11-003A

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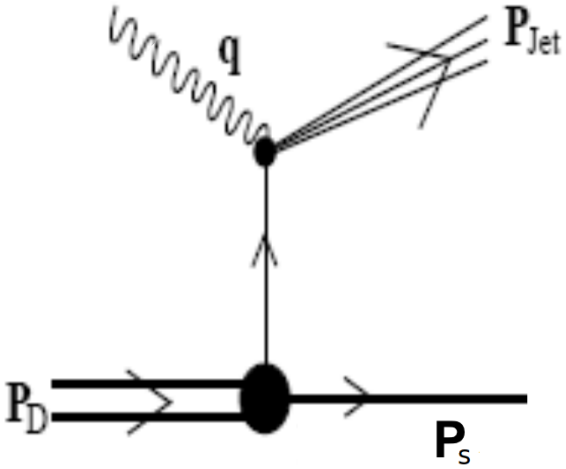
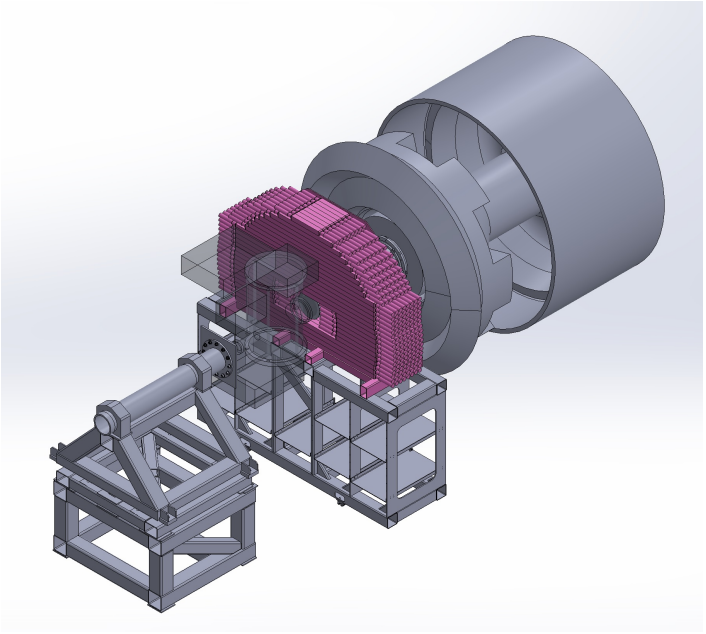
Approved to run with deuterium targets in CLAS12





EX UMBRA IN SOLEM

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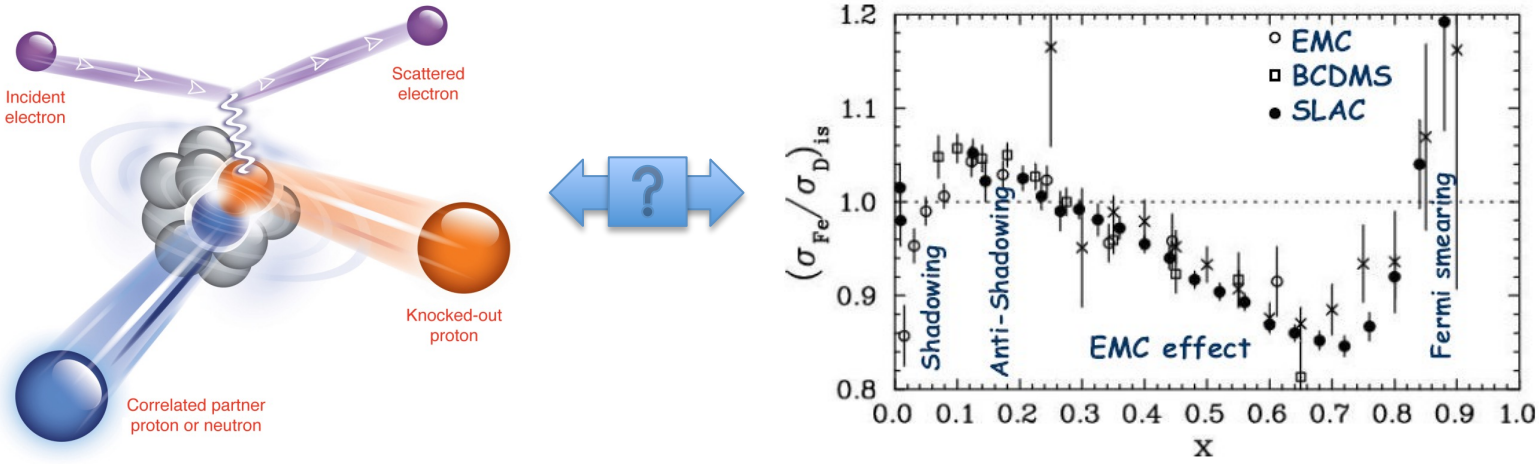
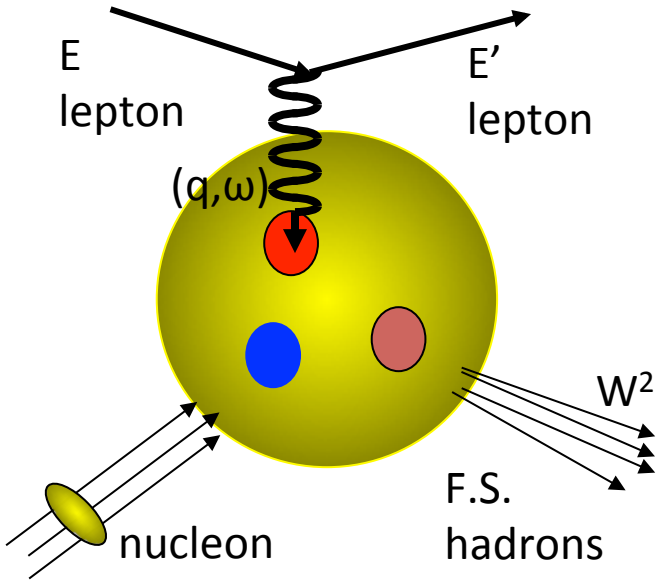
Outline

- The EMC Effect and nucleon modification
- Short Range Correlations
- The EMC – SRC correlation
- Measuring nucleon modification



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

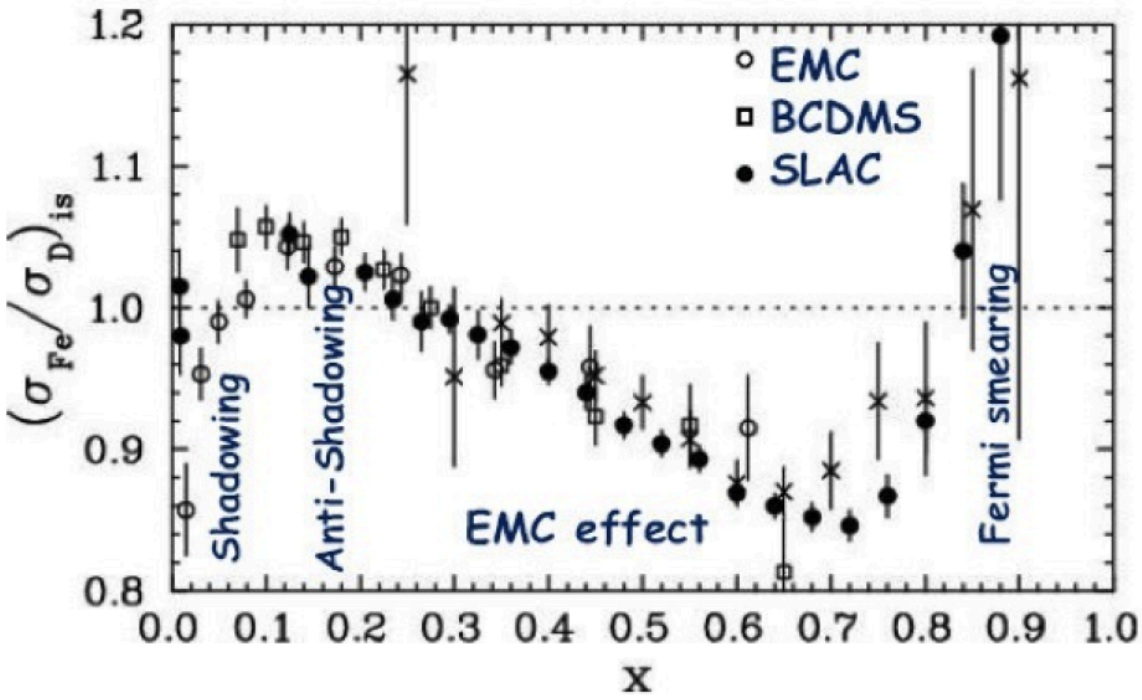
Expectation: DIS of bound nucleons ≅ DIS of a free nucleons

EMC: DIS off bound N ≠ DIS off free N

Origin of EMC effect unknown!!

Nucleon modification needed.

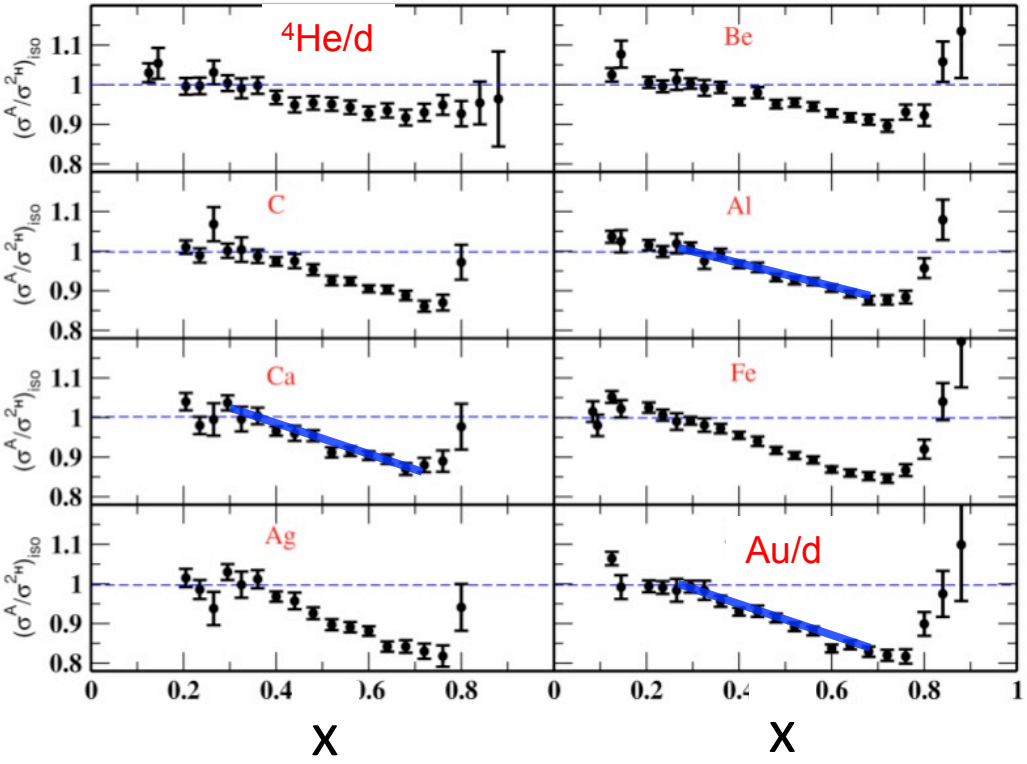
≈10^3 publications



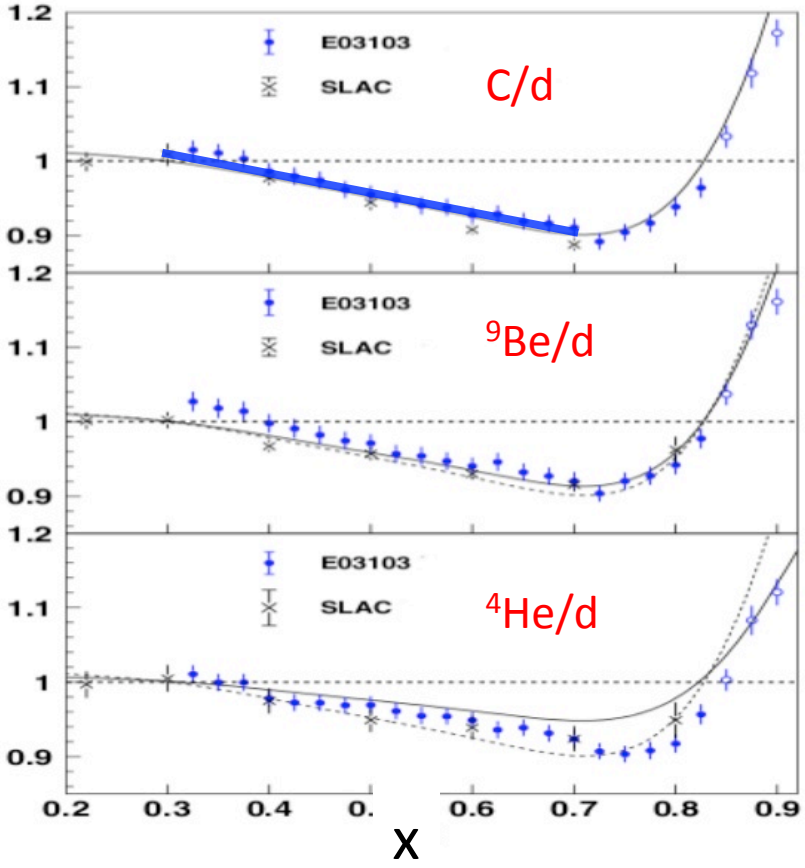
EMC Effect: Universal

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

SLAC



Hall C



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

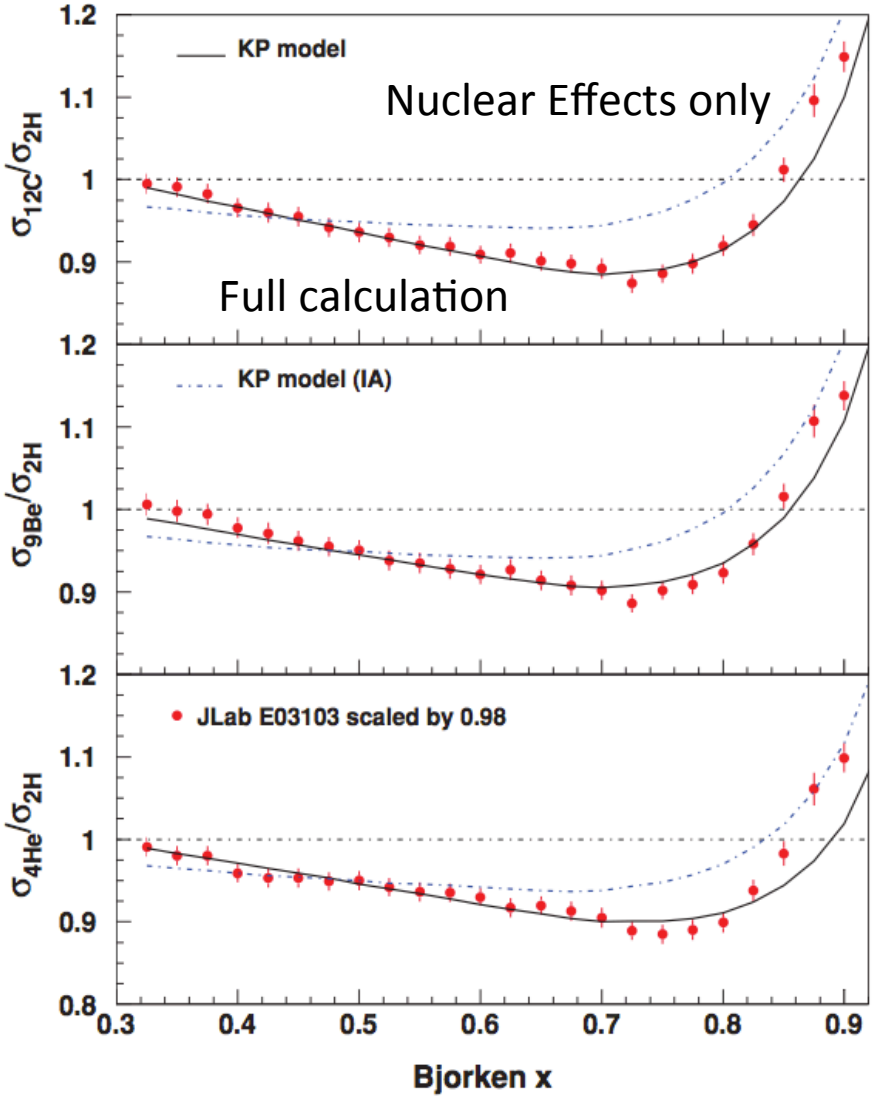
J. Seely, PRL 103, 202301 (2009)

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

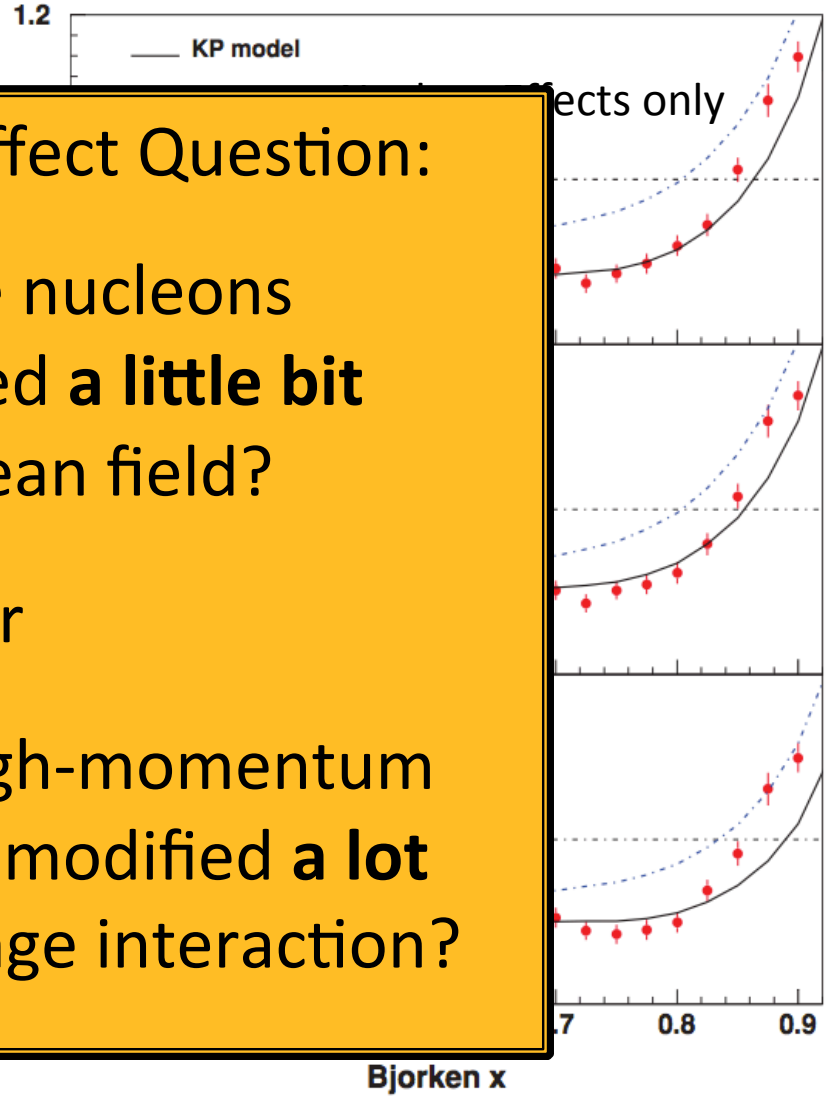


Kulagin and Petty, PRC 82, 054614 (2010)

The EMC Effect

- Nuclear Effect
  - Fermi mo
  - Binding e
- Full Calculatio
  - Nucleon r
  - Nuclear p
  - shadowin

Nucleon modific
Phenomeno
nucleon stru
proportional to virtuality (p^2)



The Big EMC Effect Question:

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

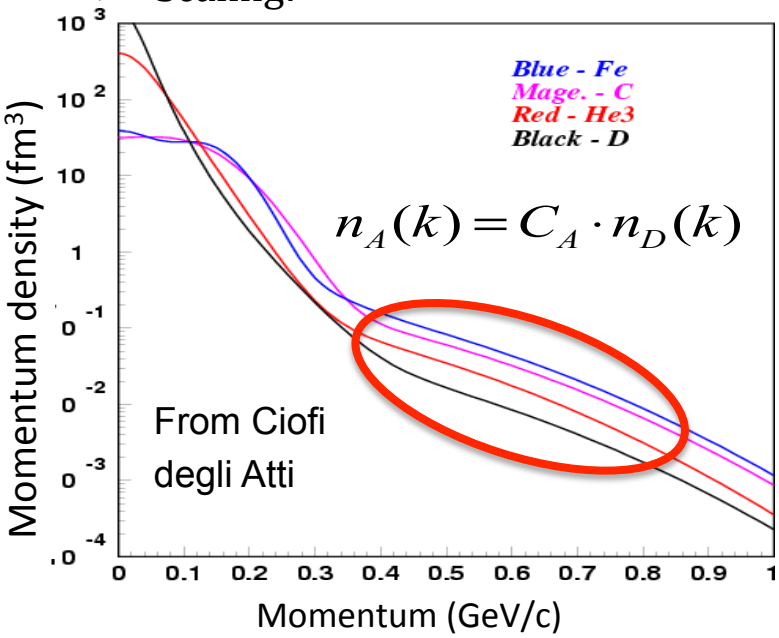
or

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

Kulagin and Petty, PRC 82, 054614 (2010)

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

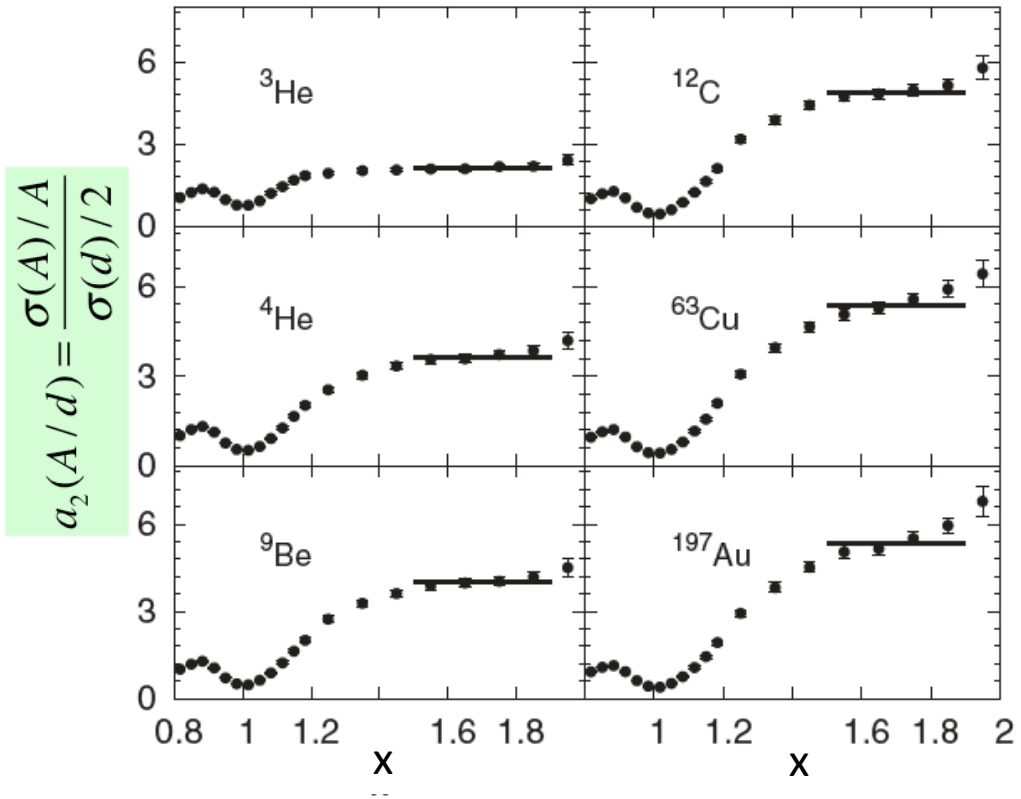
- At high nucleon momenta, strength is different but shapes of distributions are similar
- Scaling!



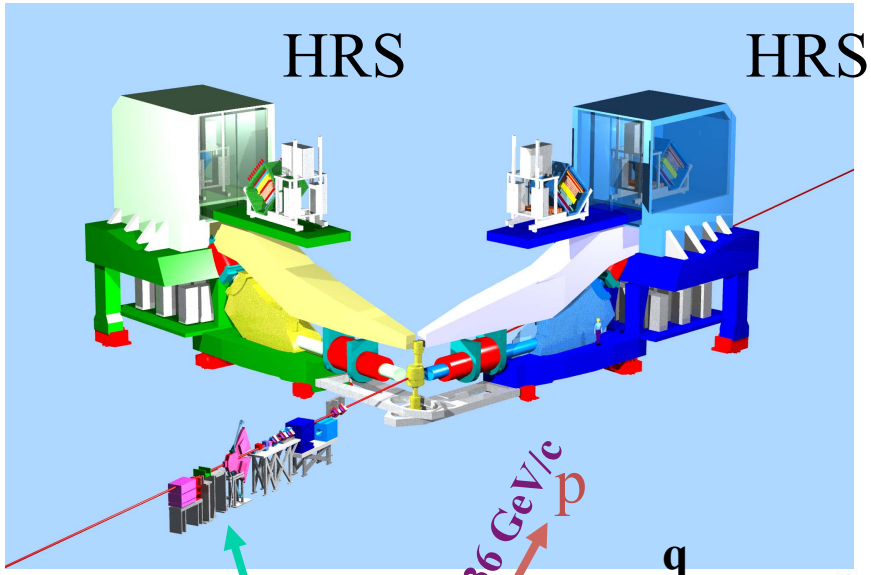
Nucleus	% 2N corr.
d	4.1 ± 0.8
^{3}He	8.0 ± 1.6
^{4}He	15.4 ± 3.2
^{12}C	19.8 ± 4.4
^{56}Fe	23.9 ± 5.3

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

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



JLAB Hall A Experiment E01-015



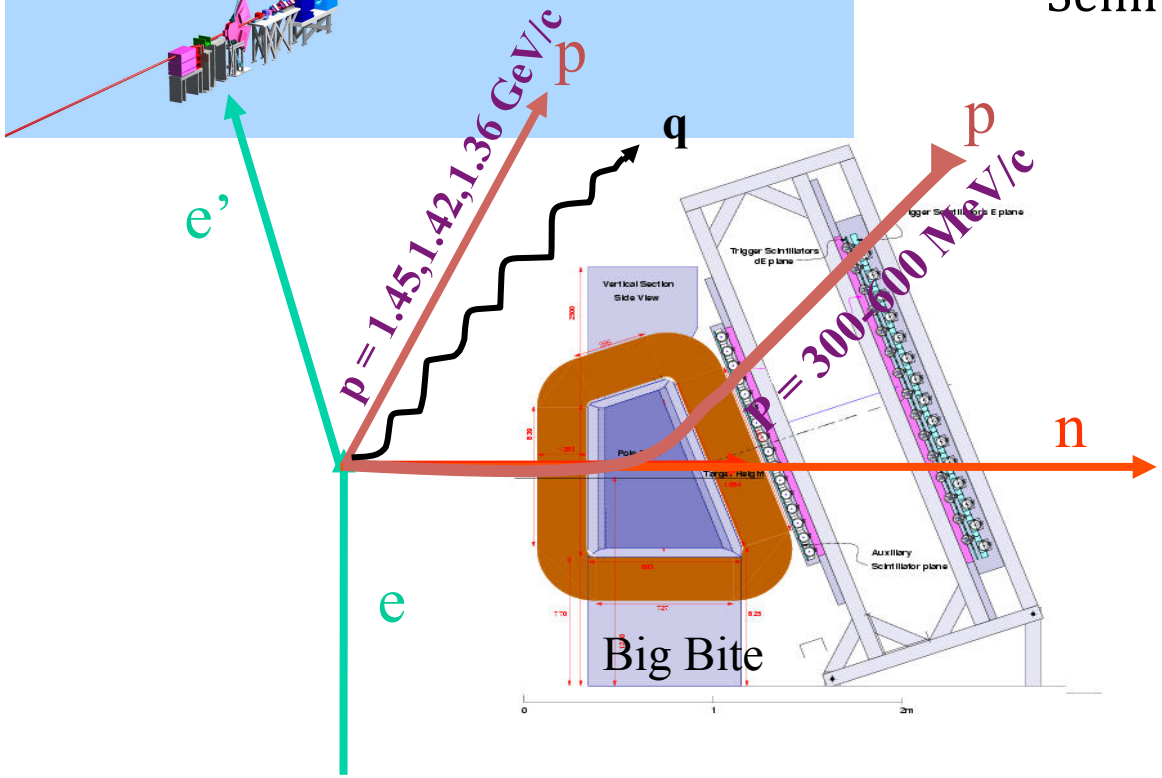
Use $^{12}C(e,e'p)$ as a tag to measure $^{12}C(e,e'pN)/^{12}C(e,e'p)$

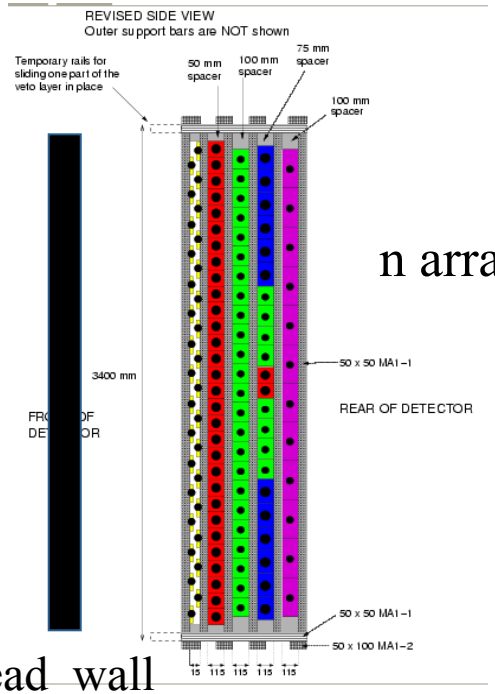
Optimized kinematics:

$Q^2 \approx 2.0$ GeV^2

$x_B \approx 1.2$

"Semi anti-parallel" kinematics





n array

Lead wall

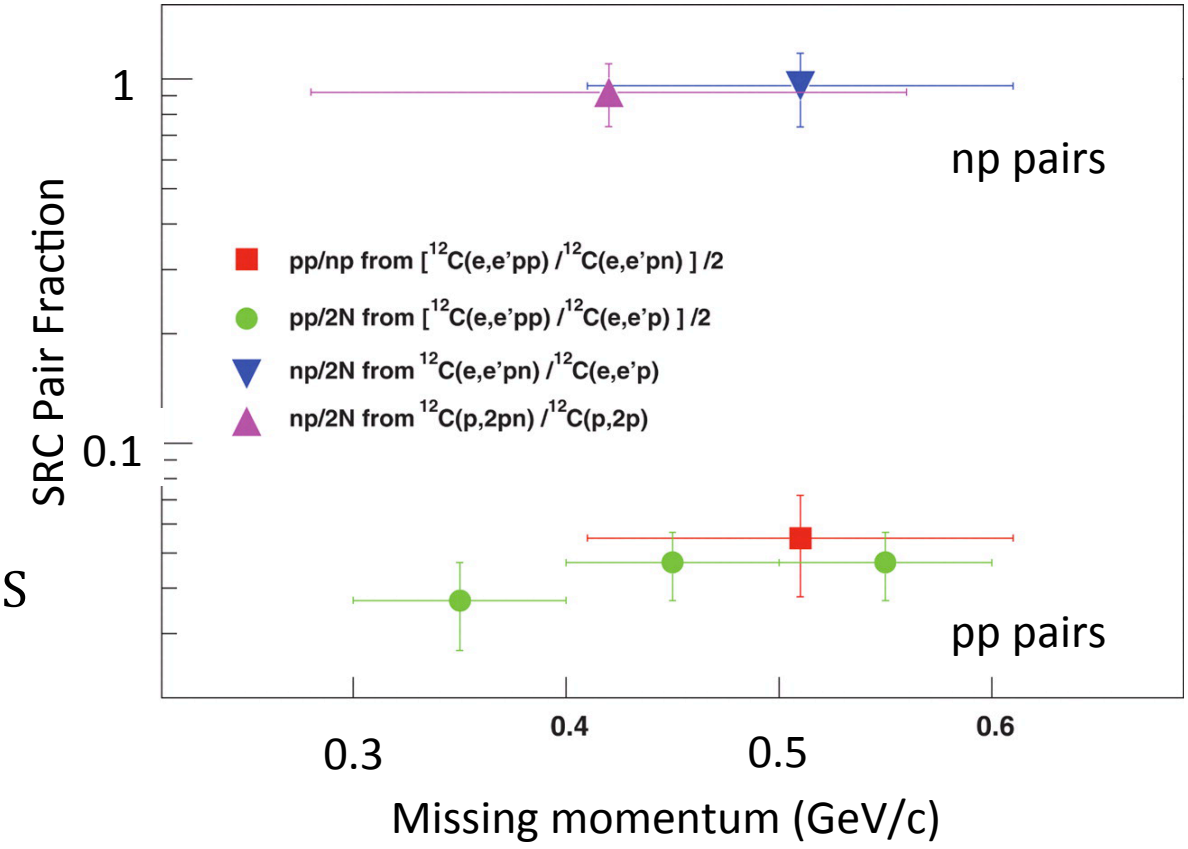
Looking for correlated partners

- Almost **all** protons with p_i > 300 MeV/c in ^{12}C(e,e'p) have a paired proton or neutron with similar momentum in opposite direction

$$\frac{^{12}C(e,e'pn)}{^{12}C(e,e'p)} = 96^{+4}_{-23}\%$$

$$\frac{^{12}C(e,e'pp)}{^{12}C(e,e'p)} = 9.5 \pm 2\%$$

np SRC is ~18 times pp (nn) S



Ratios corrected for acceptance, det. efficiency and SCX

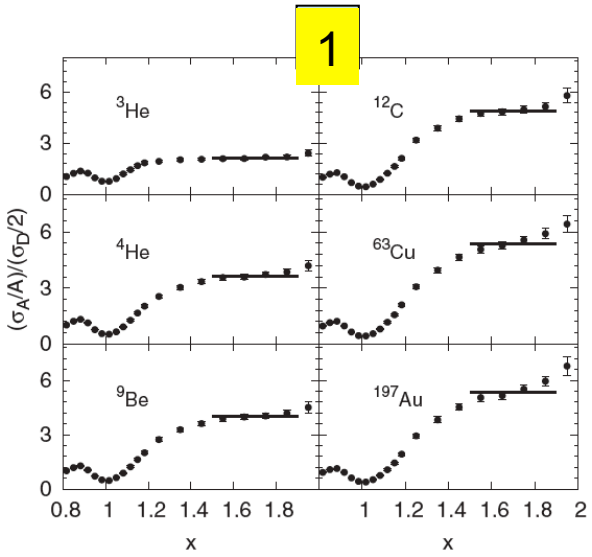
R. Shneor *et al.*, PRL**99, 072501 (2007)** R. Subedi et al., Science **320** (5882), 1476 (2008)

What do we know about SRC?

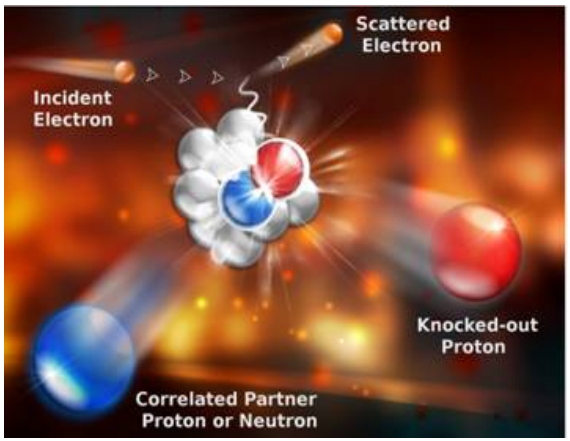
1 The probability for a nucleon to have momentum ≥ 300 MeV/c in medium nuclei is ~25%

2 More than ~90% of all nucleons with momentum ≥ 300 MeV/c belong to 2N-SRC.

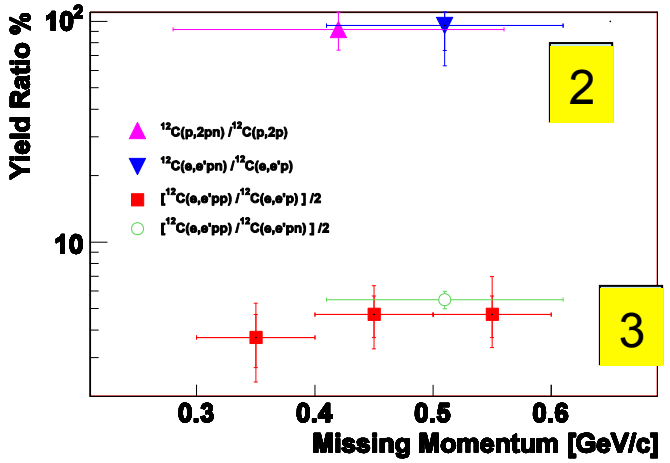
3 2N-SRC dominated by np pairs



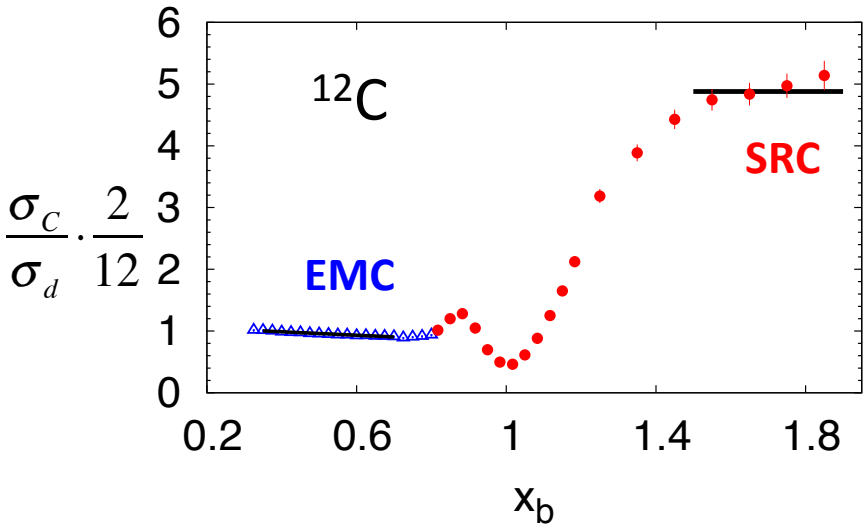
PRL **108** (2012) 092502



PRL 162504(2006); Science 320, 1476 (2008)



Correlations Between EMC and SRC



SRC

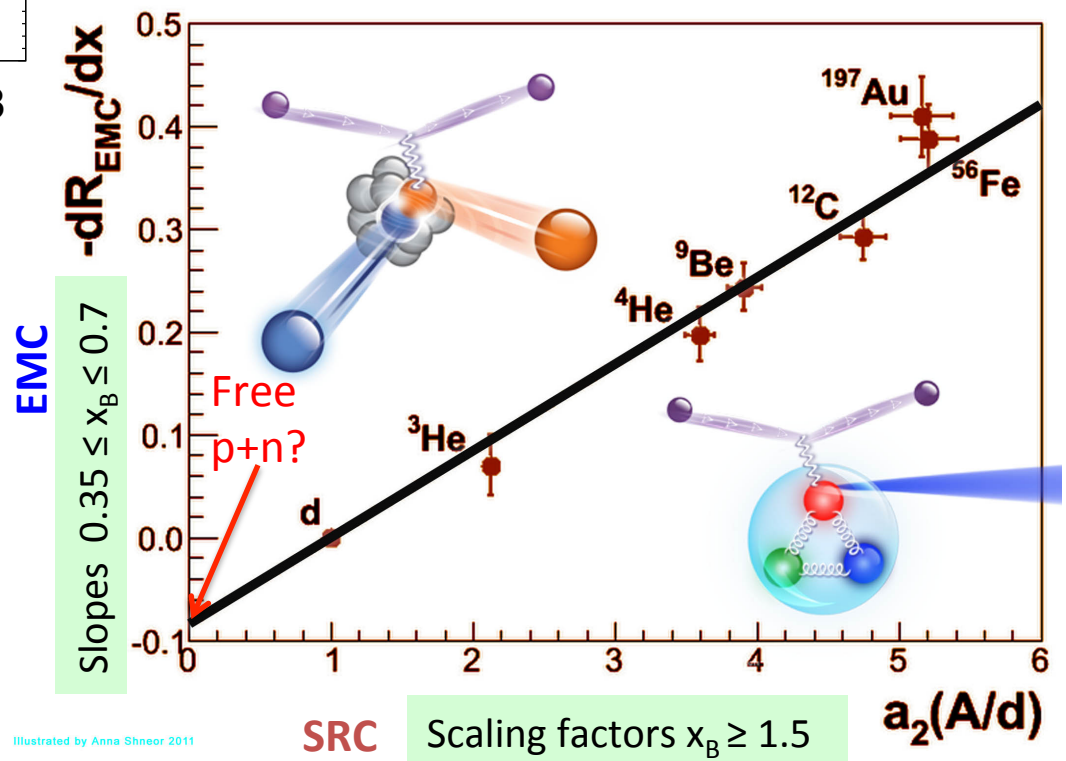
- High nucleon momenta

EMC

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

JLab data

J. Seely *et al.*, PRL **103** (2009) 202301
N. Fomin et al., Phys. Rev. Lett. **108** (2012) 092502



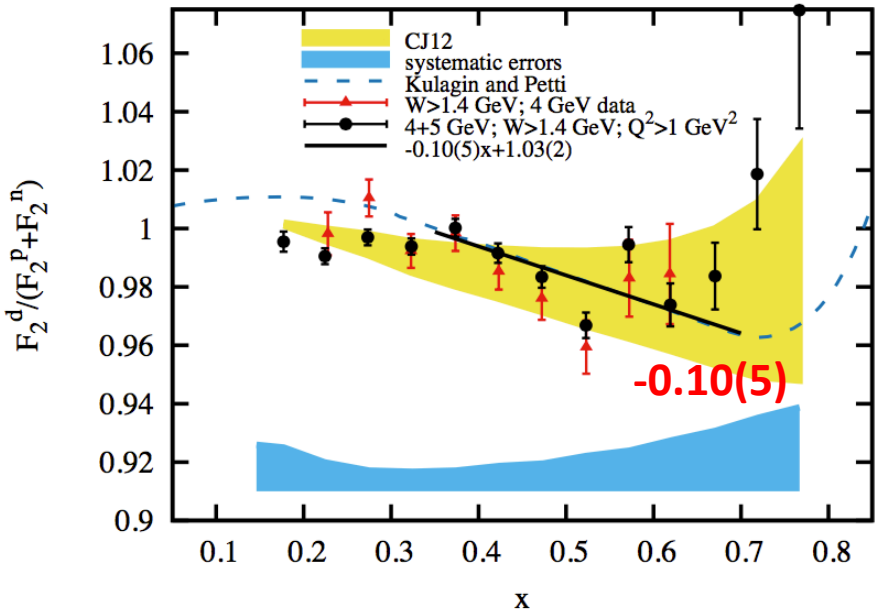
Weinstein *et al.*, PRL **106**, 052301 (2011)
O. Hen *et al.*, PRC **85**, 047301 (2012)

Explore Connection between EMC and SRC

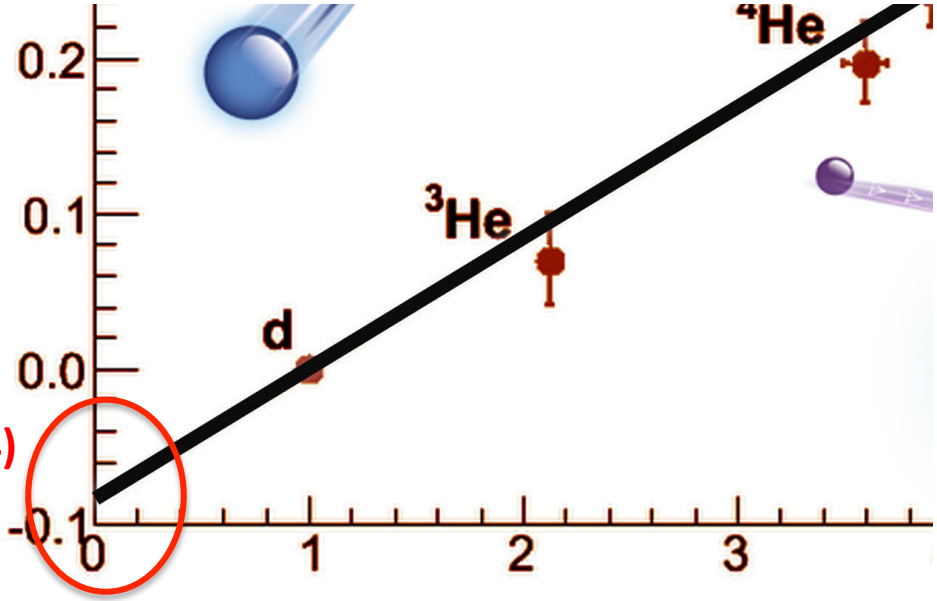
Do high-momentum nucleons have a large EMC effect?

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.)

- No nucleons modified

- All nucleons modified
  - ➔ F_2 independent of momentum
  - ➔ F_2 ≠ free F_2 (small difference)

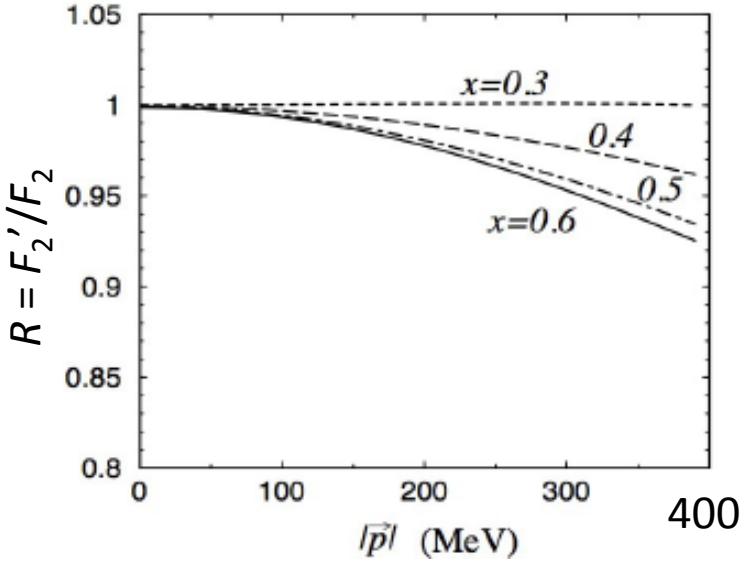
- SRC nucleons modified
  - ➔ F_2 varies with momentum
  - ➔ F_2 ≠ free F_2 (big difference)

Predicted Dependence of F_2 on Momentum

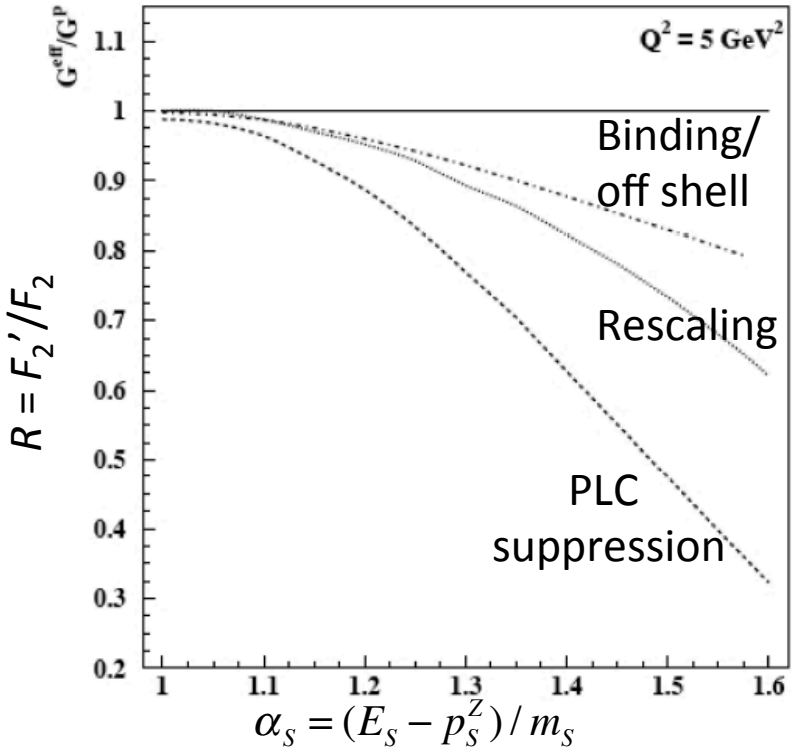
Dependence on:

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

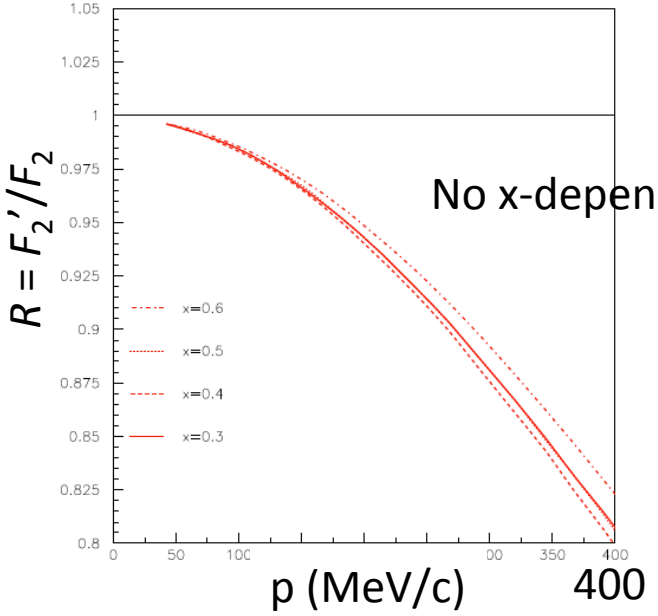
Melnitchouk, Schreiber, Thomas, Phys. Lett. B **335**, 11 (1994)



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



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



400

Predicted Dependence of F_2 on Momentum

Dependence on:

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- Nucleon momentum and x_B
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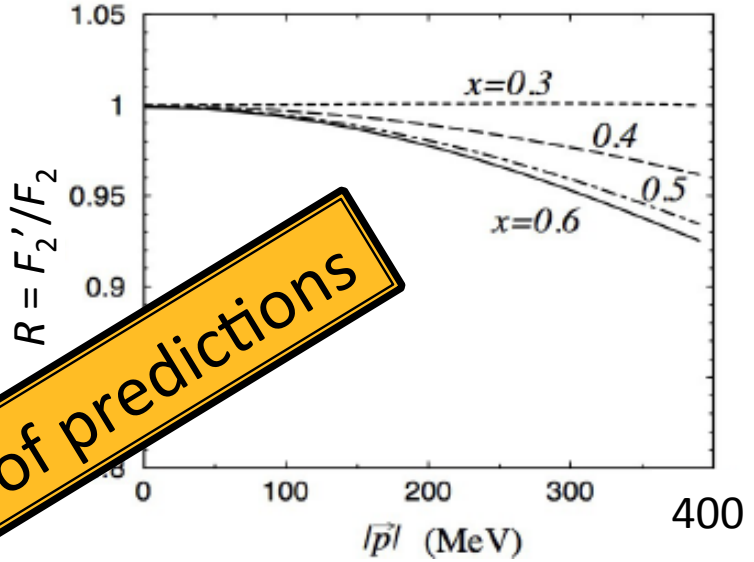
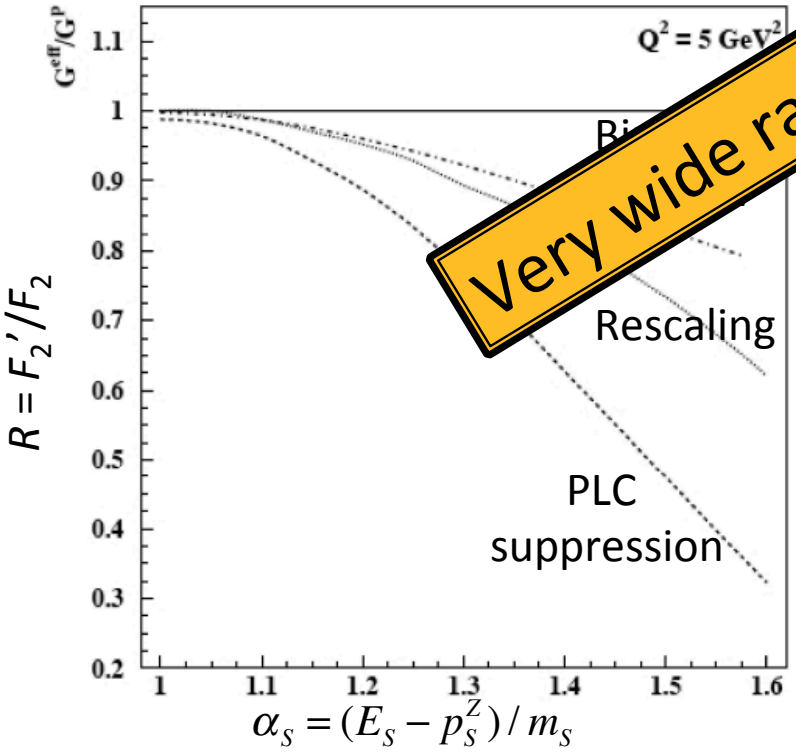
Melnitchouk, Screiber, Thomas, Phys. Lett. B **335**, 11 (1994)

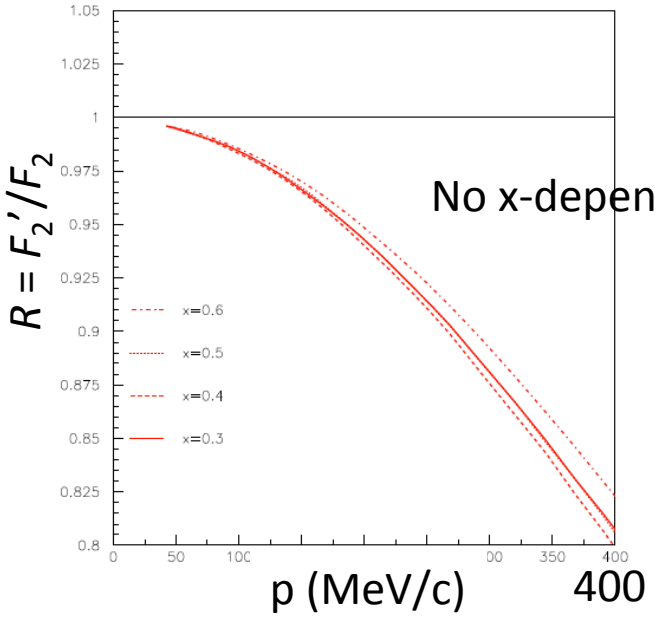


Very wide range of predictions

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



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



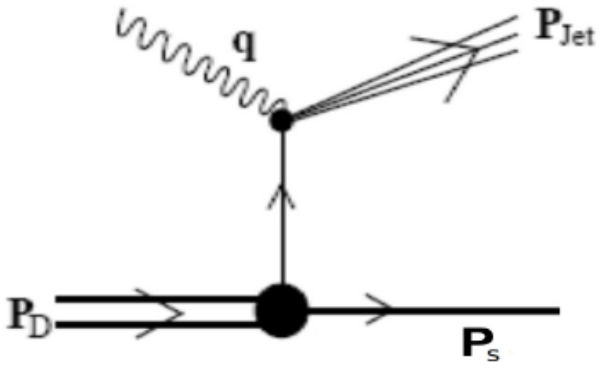
No x-dependence

Spectator Tagging

d(e,e'p_s) – CLAS6 (recoil p)
E12-11-107 – Hall C + LAD (recoil p)
This experiment – CLAS12 + BAND (recoil n)

Experimental method

- (e,e') Deep Inelastic Scattering from deuterium
- Tag high-momentum nucleons with 300-700 MeV/c backward-recoiling ("spectator") partner nucleon using d(e,e'N_S)



Experimental Method

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

Fix the recoil kinematics and measure x-section ratios at 2 different x':

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

For x_1' ≈ 0.5 – 0.6 and x_2' ≈ 0.3 we shall measure:

$$F_2^*(x_1', \alpha_S, p_T, Q_1^2) / F_2^*(x_2', \alpha_S, p_T, Q_2^2) = \left(\frac{d^4\sigma}{dx_1' dQ_1^2 d\vec{p}_S} / K_1 \right) \Big/ \left(\frac{d^4\sigma}{dx_2' dQ_2^2 d\vec{p}_S} / K_2 \right)$$

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

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

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

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

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

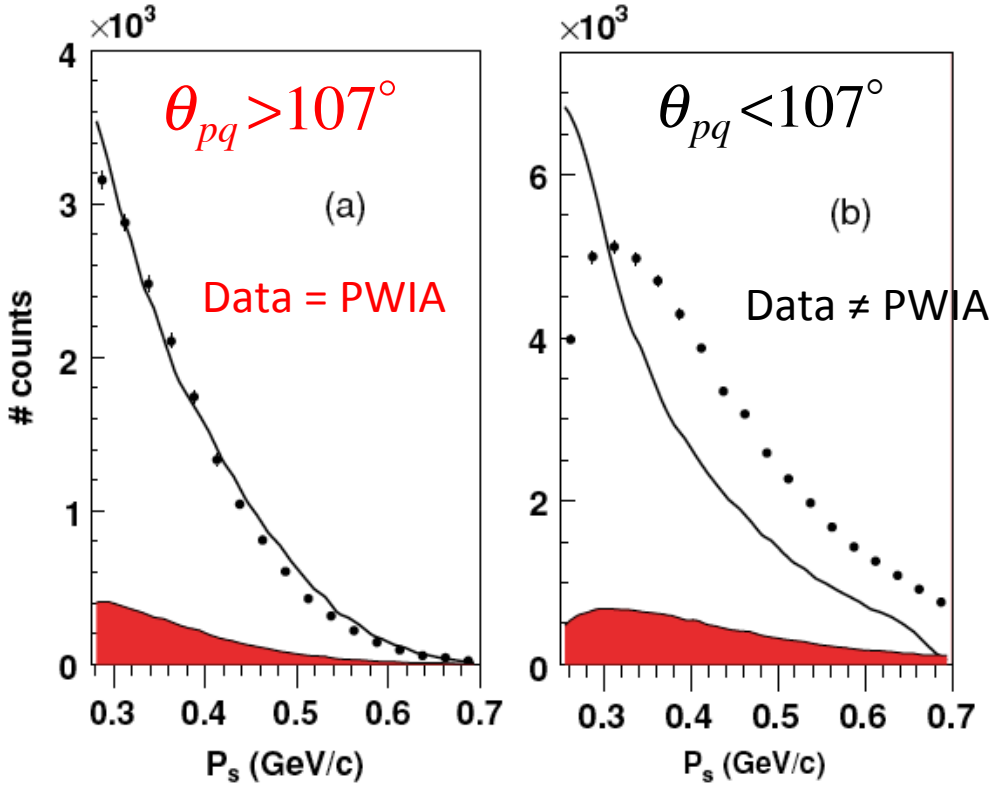
$$x_B=\frac{Q^2}{2m_N\omega}$$

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$_s$)



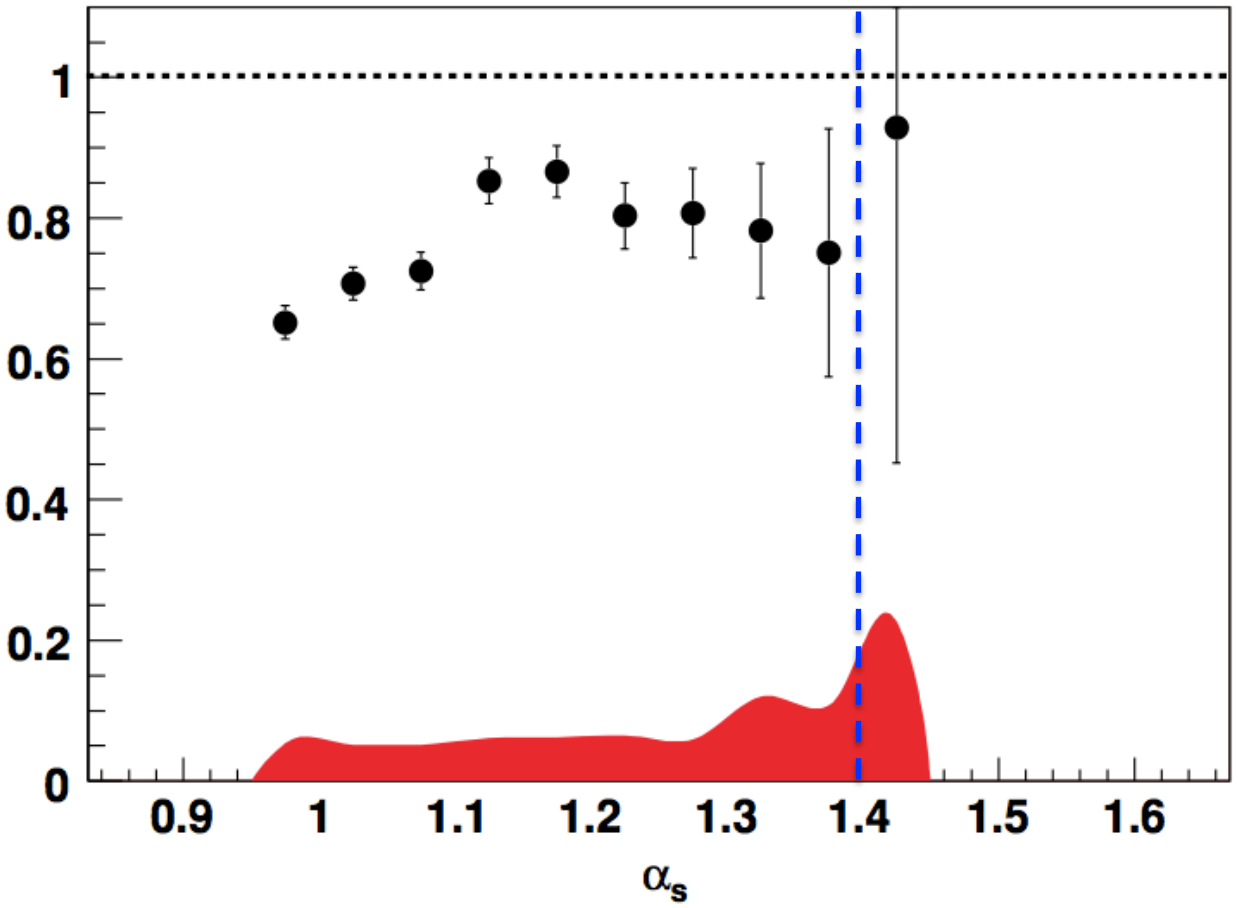
A. V. Klimenko *et al.*, PRC **73**, 035212 (2006)

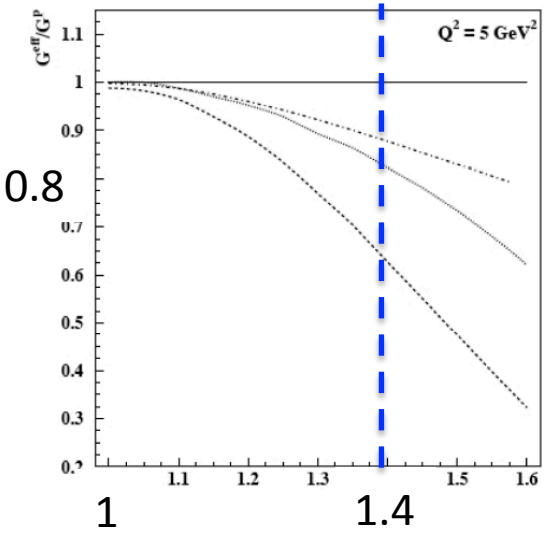
We shall:

- 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)

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





Inconclusive!

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

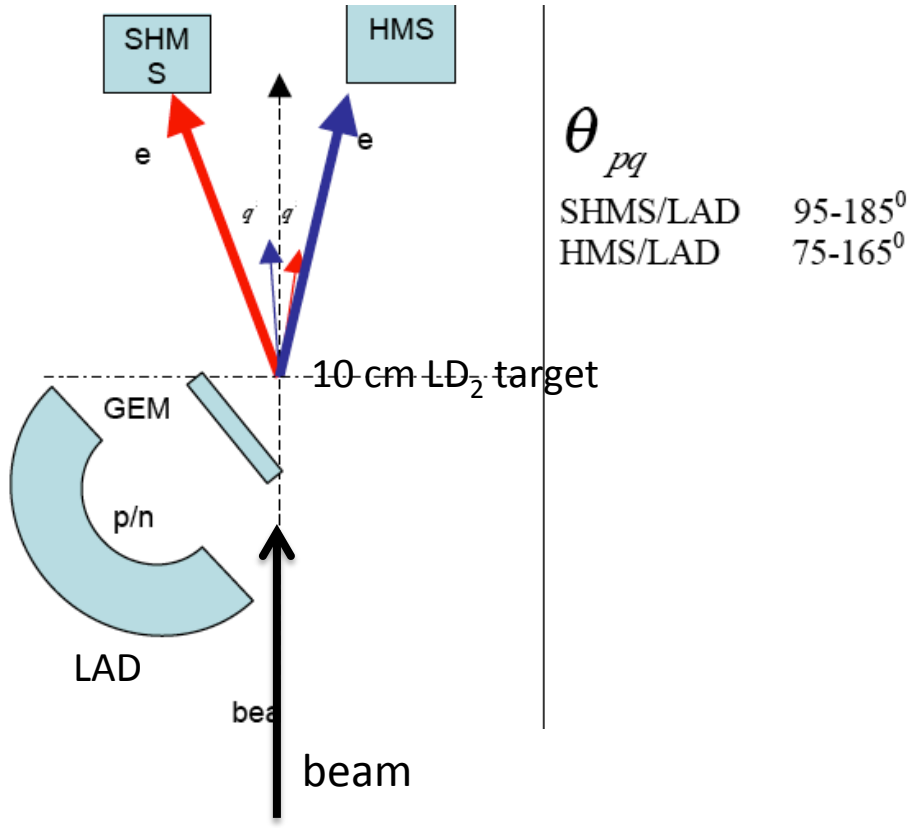
Detecting recoil protons in Hall C

HMS and SHMS detect electrons

LAD detects recoiling proton

LAD: ~1.5 sr of CLAS6 TOF counters

Central values of kinematics

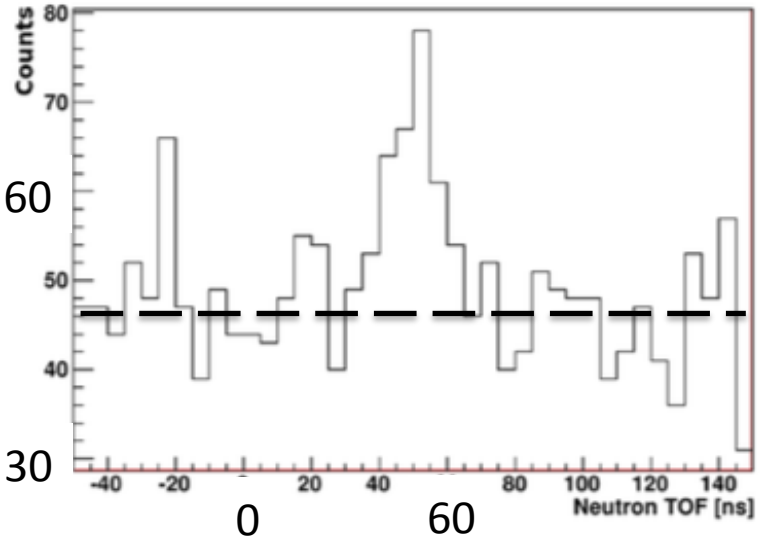


Low x'	High x'
$E_{in} = 10.9$ GeV	$E_{in} = 10.9$ GeV
$E' = 4.4$ GeV	$E' = 4.4$ GeV
$\theta_e = 13.5^o$	$\theta_e = -17^0$
$Q^2 = 2.65$ GeV^2	$Q^2 = 4.19$ GeV^2
$\lvert\vec{q}\rvert = 6.7$ GeV/c	$\lvert\vec{q}\rvert = 6.8$ GeV/c
$\theta_q = -8.8^0$	$\theta_q = 10.8^0$
$x = 0.217$	$x = 0.34$

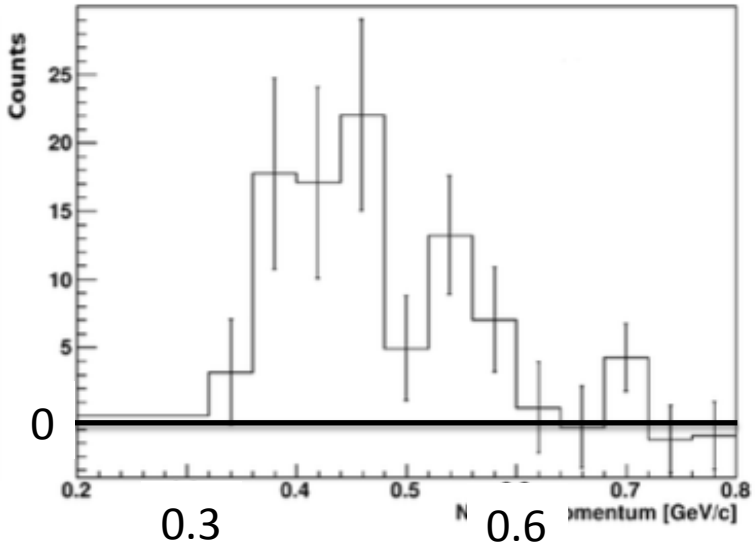
Collect both LAD-HMS and LAD-SHMS coincidences

Measuring neutrons with Time of Flight (TOF)

HAND: Hall A Neutron Detector



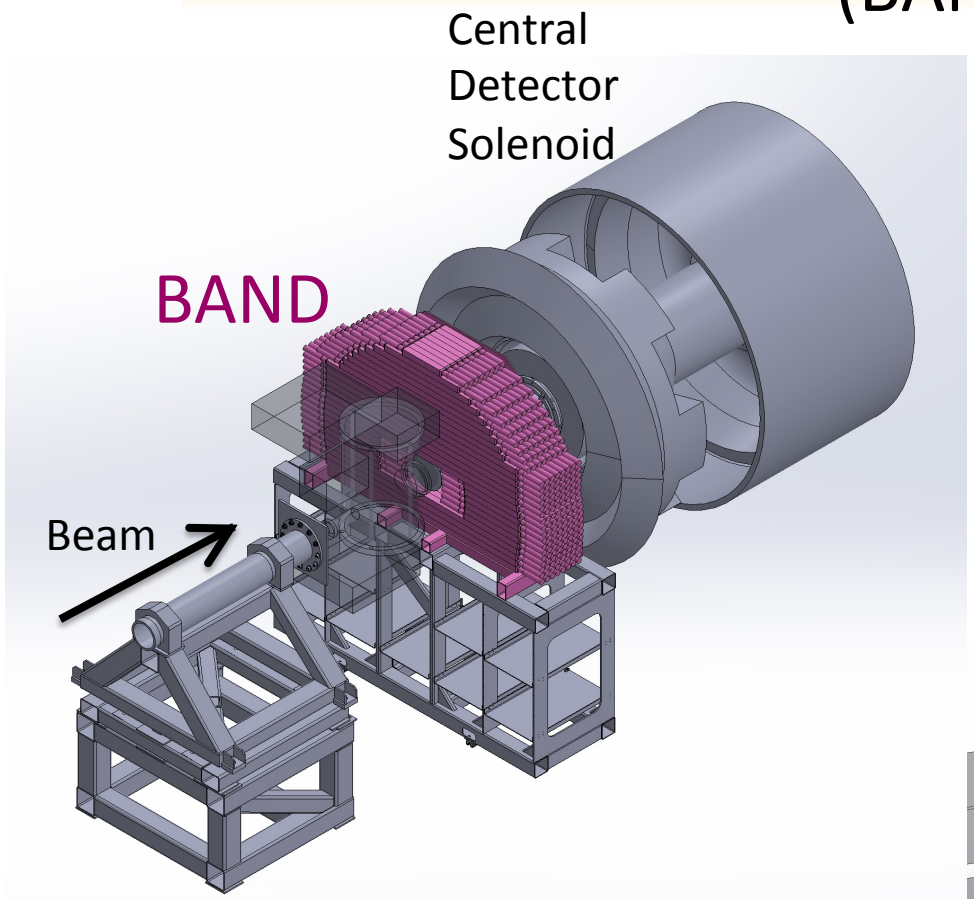
Neutron TOF (ns)



Neutron momentum (GeV/c)

I. Korover, Tel Aviv U, PhD Thesis 2015

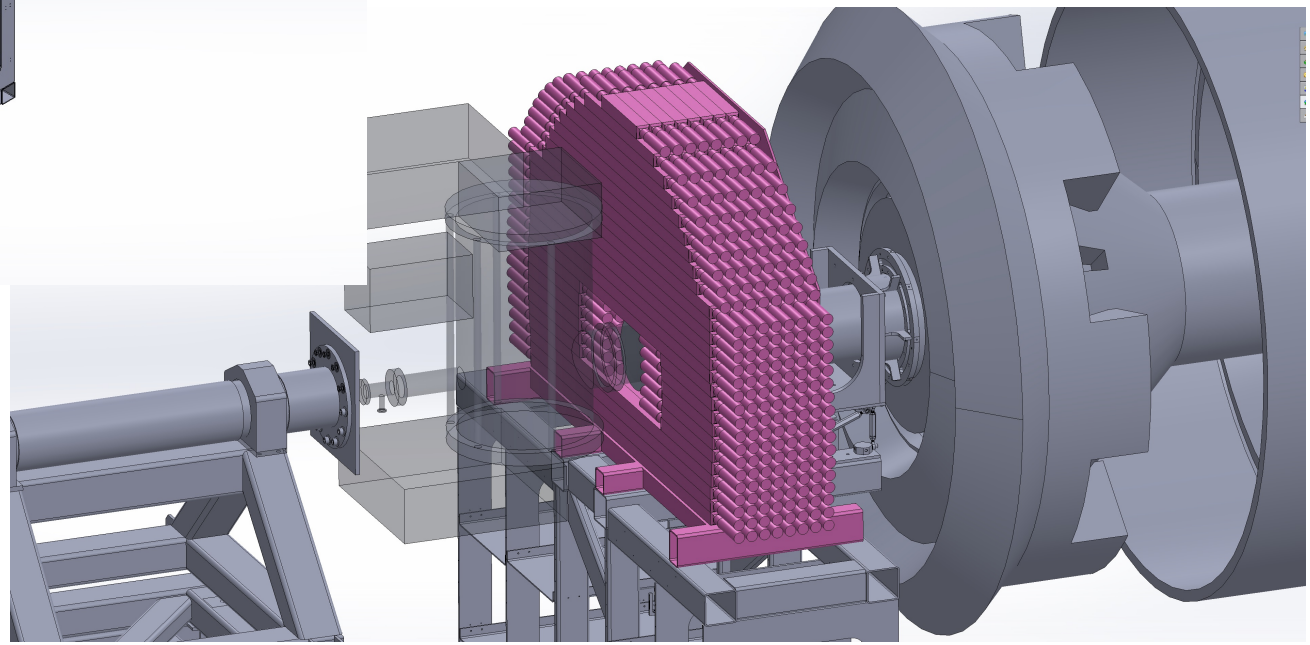
CLAS12 + Backward Angle Neutron Detector (BAND)



BAND:

- $160^{o} < \theta_{n} < 170^{o}$
- 2.5 m from target
- Eight 6-cm layers of scintillant
  - 48 cm thick
- 26 rows, 512 PMTs

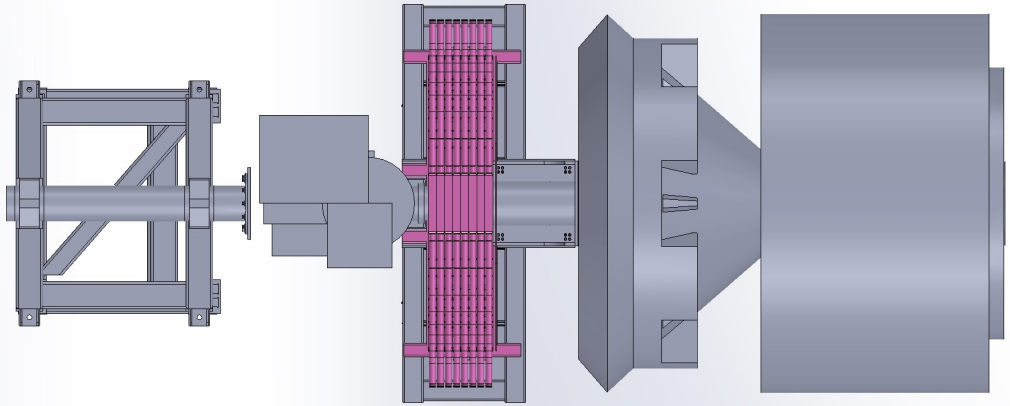
Mounted on SVT electronics cart



Engineering by Inaki Vega,
UTFSM, Valparaiso, Chile

BAND Design

Top View

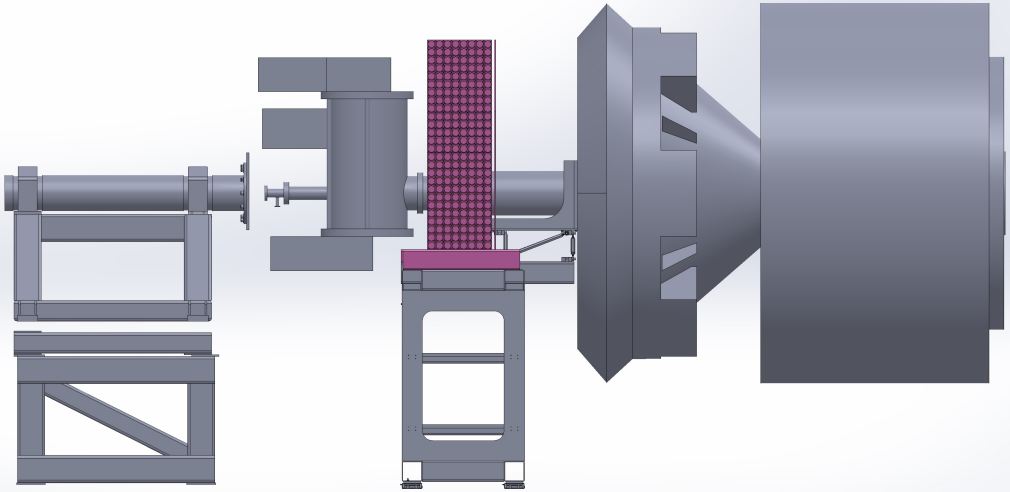


Beam →

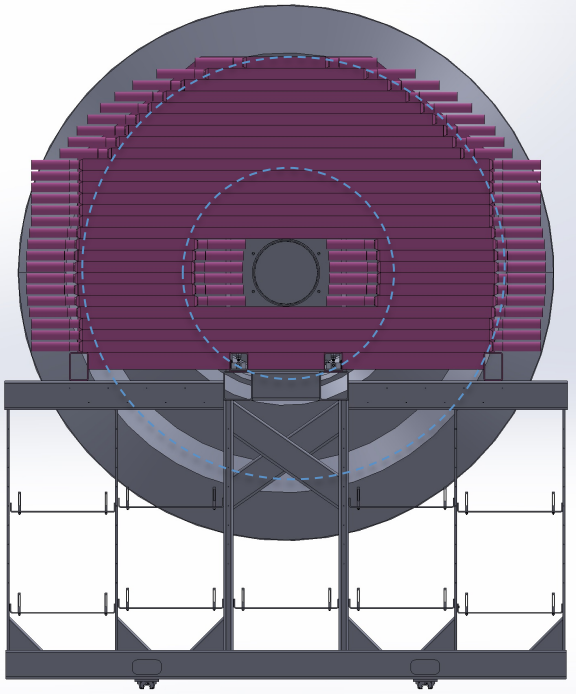
BAND

Solenoid

Side View

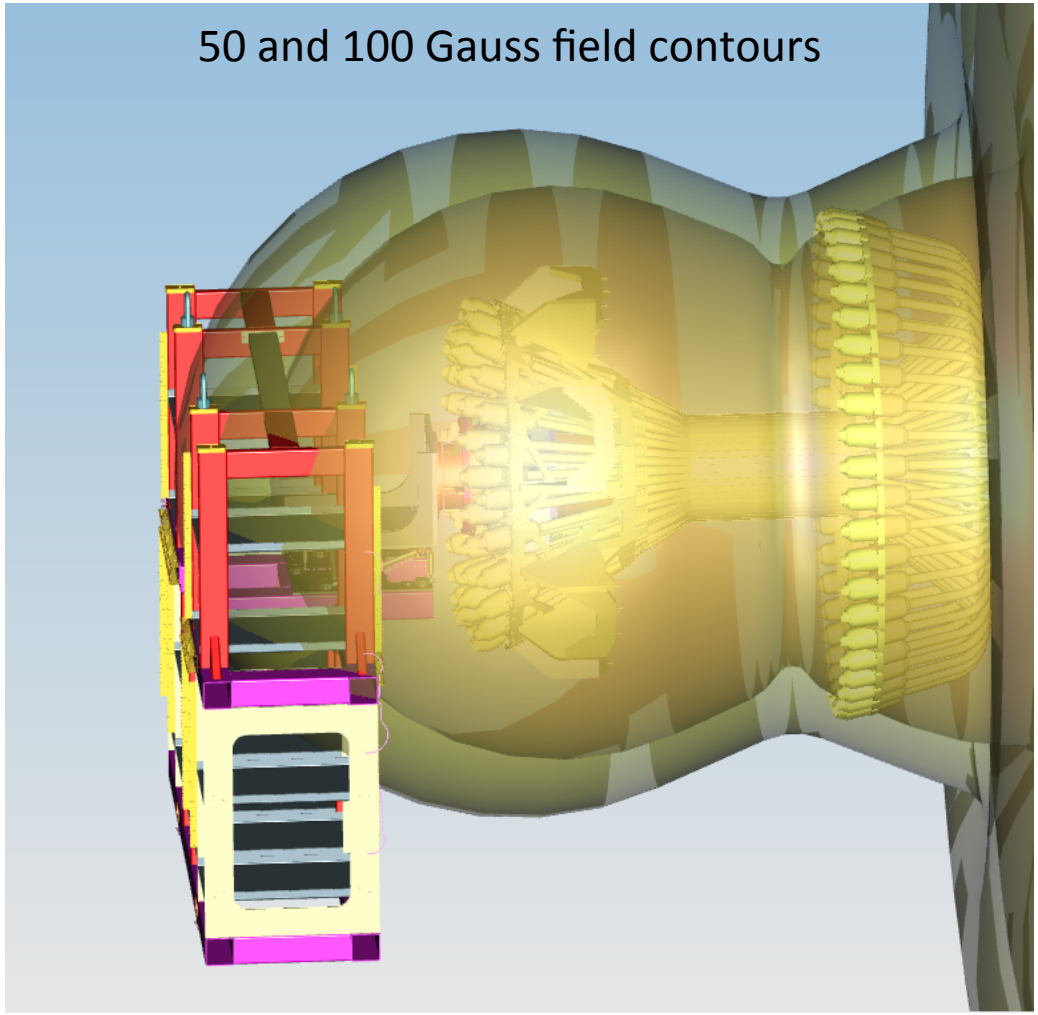


Looking Downstream



Circles show ~160° and ~170°

Magnetic Field Issues



PMT Shielding studies at ODU this summer

BAND Development

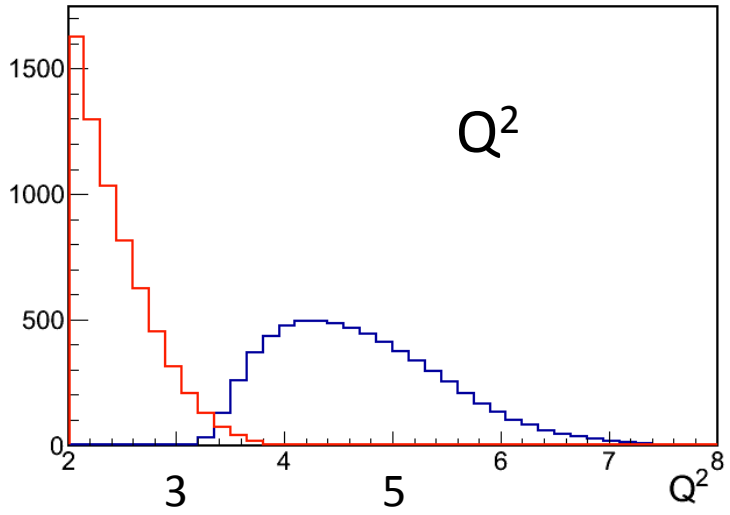
- PMT and scintillant timing tests: Tel Aviv, MIT
- Magnetic field tests: ODU
- Engineering: UTFSM
- Laser Calibration system development: MIT

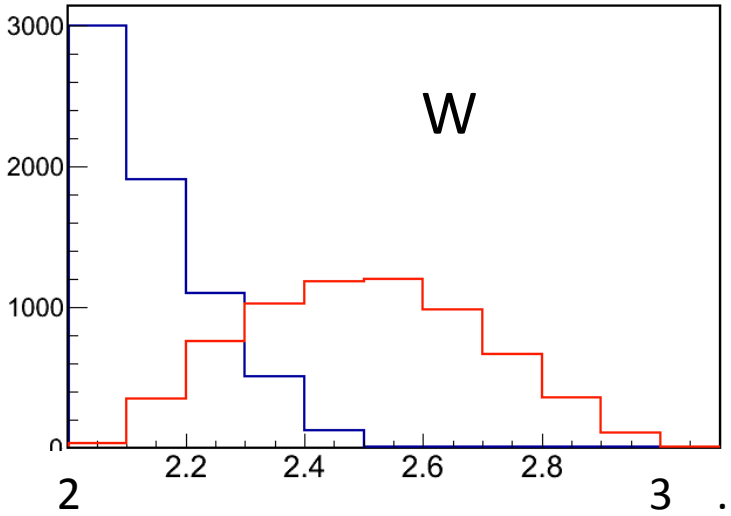
- Approximate cost: $650K
  - Scintillant: $100K
  - 512 PMTs: $300K
  - Light pipes, mu metal, cables: $75K
  - Laser calibration system: $70K
  - Support structure and shielding: $100K
- Funding: NSF-MRI(?), MIT, Tel Aviv
- Submit MRI January 2017
- Construct BAND, 2017/2018
- Install in Hall B, 9/2018

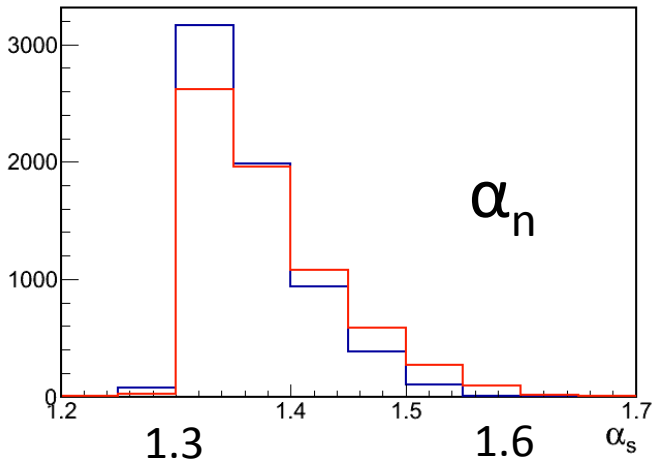
Deuteron (e,e'n_s) Kinematics

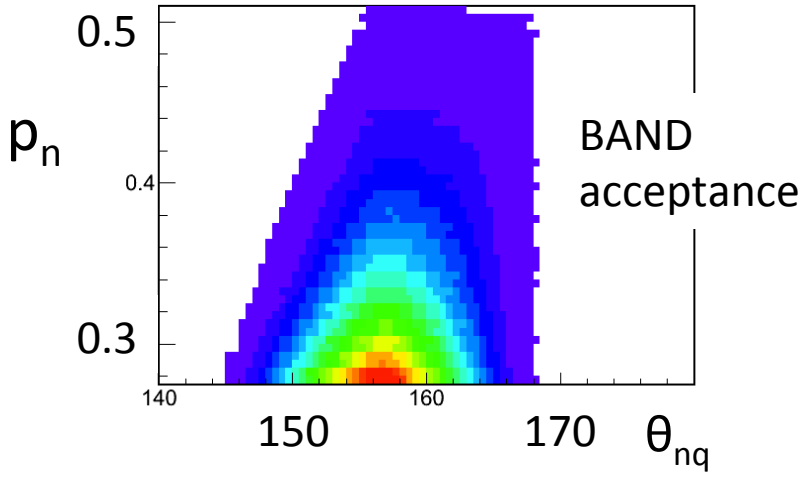
E_0 = 11 GeV
Q^2 > 2 GeV^2
W' > 2 GeV

Measure cross section ratio
- for 0.5 < x' to 0.25 < x' < 0.35
- as a function of p_n or α_n



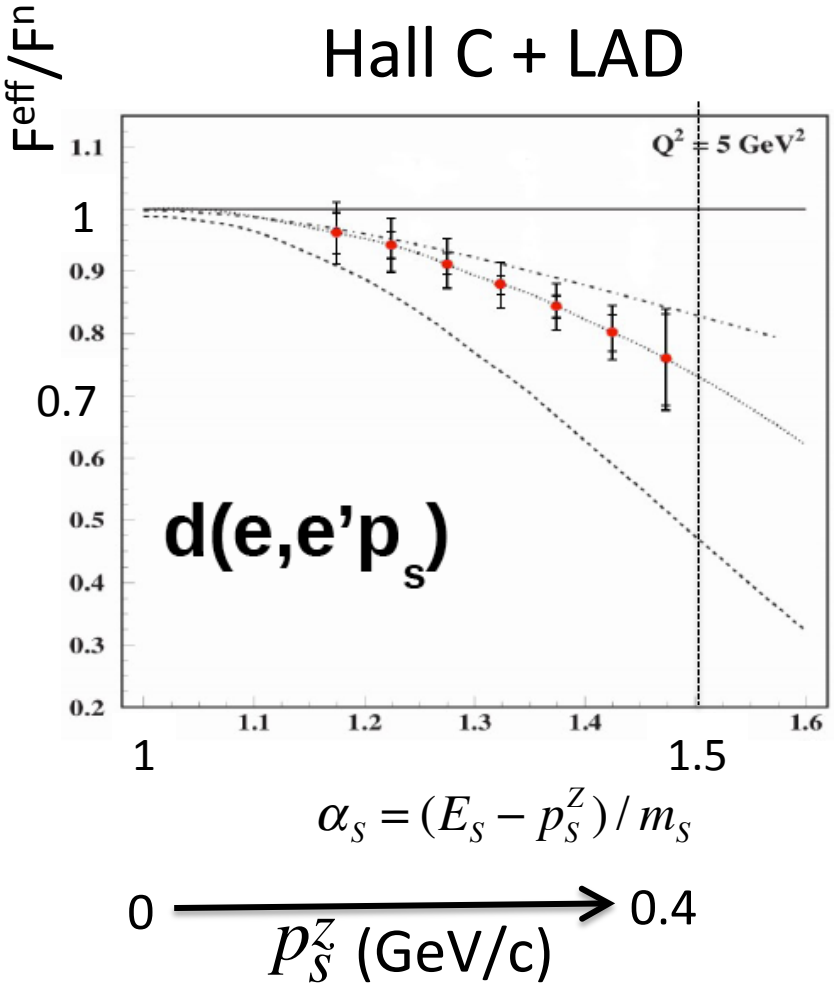




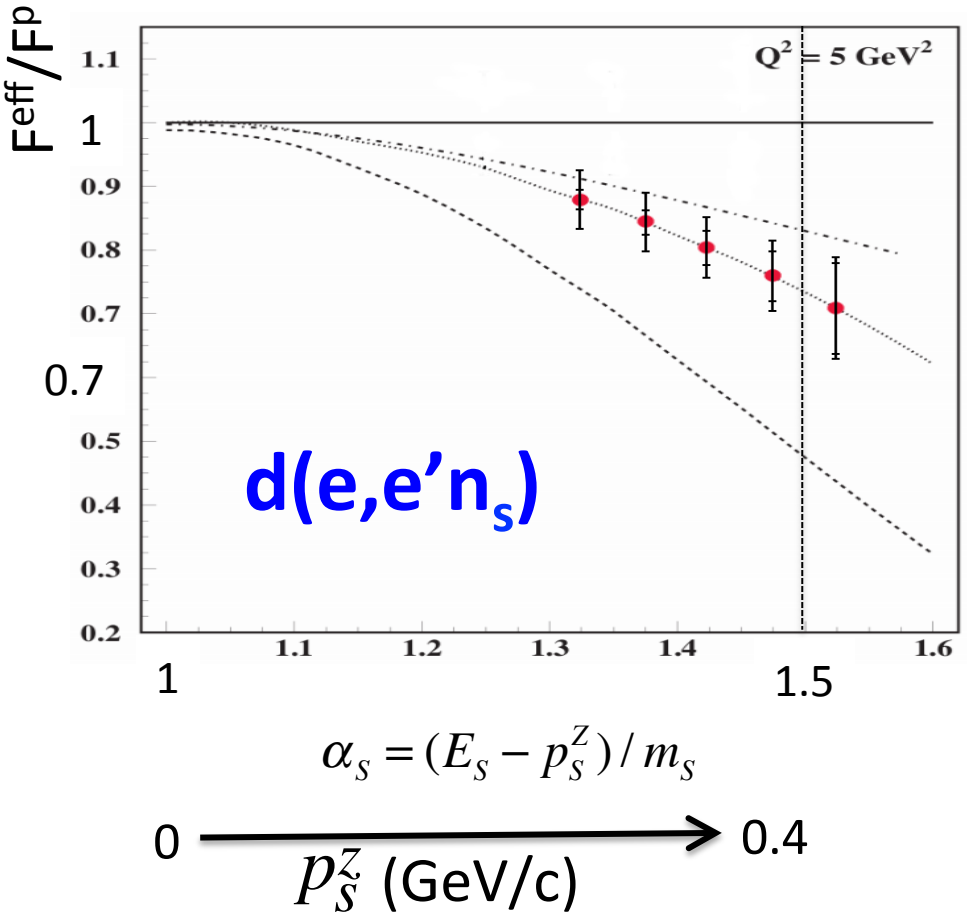


Expected Results

Hall C + LAD



CLAS12 + BAND



(results for 75 days beam time at $L = 10^{35}$)

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'n_s) with CLAS12 + BAND:

- Directly measure the proton structure function in the nuclear medium as a function of momentum (virtuality)
  - Use spectator tagging to select highly virtual protons in DIS
  - Minimize systematic uncertainties by measuring ratios
  - Run with Run Group B (and other deuteron target run groups)
- Complements neutron s.f. measurements using d(e,e'p_s) E12-11-107 (Hall C + LAD)

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