In Medium Nucleon Structure Functions, SRC, and the EMC Effect

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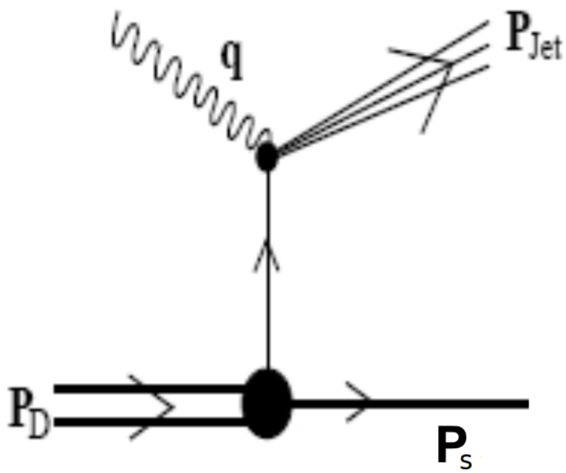
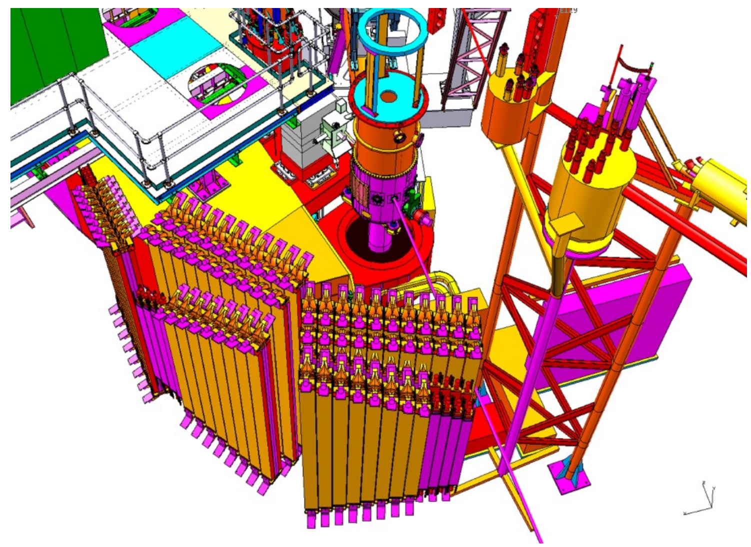
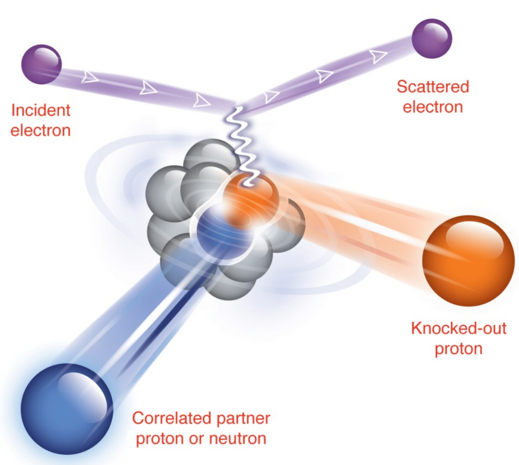
Proposal PR12-11-107, O Hen (contact), L. Weinstein, S. Gilad, S.A. Wood
Scientific Rating: B+, 40 days of beam time

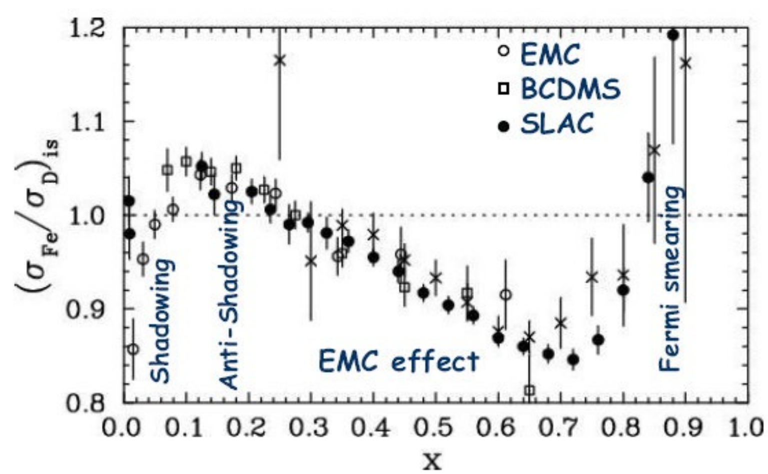




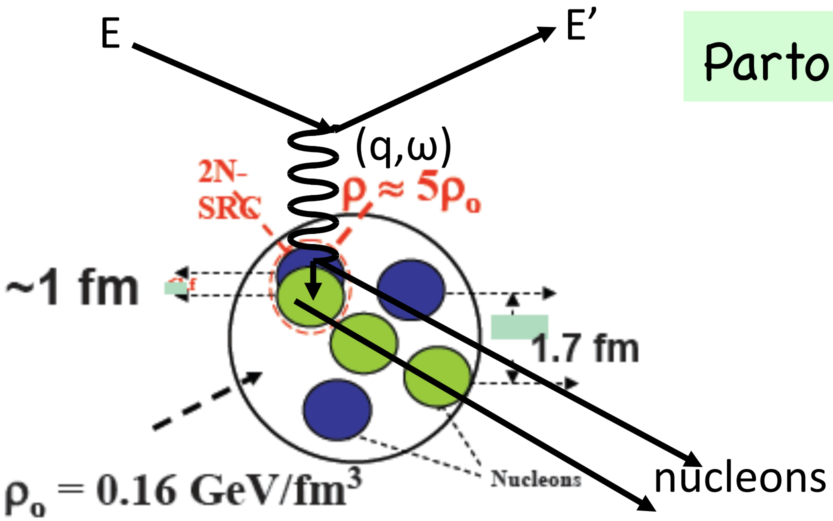
Outline

- ➢ Short Range Correlations
- ➢ The EMC Effect and nucleon modification
- ➢ The EMC – SRC correlation
- ➢ 12 GeV Measurement of nucleon modification





Short-Range Correlations (SRC)



Partonic (nucleonic) structure of nuclei

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

$$\omega = E' - E$$

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

$E, E' \approx$ 3-5 GeV

$Q^2 \geq 1.5$ GeV^2

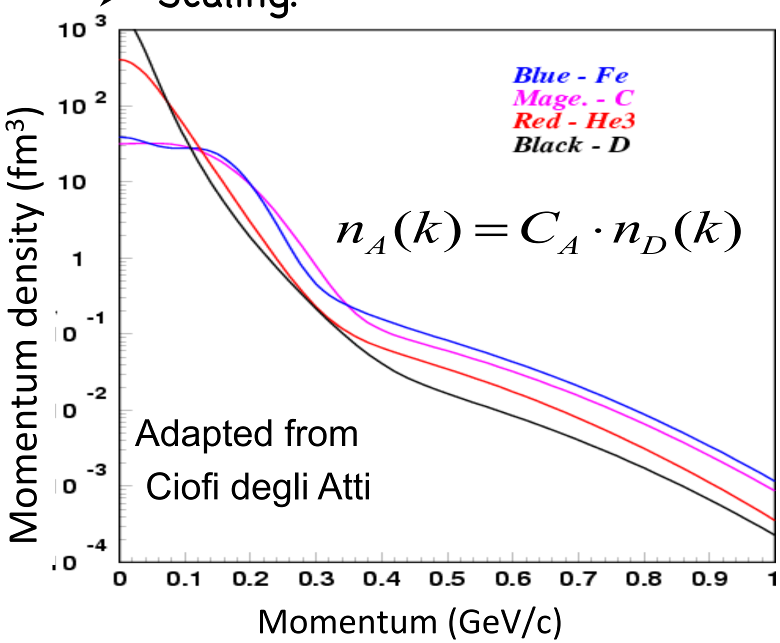
$0 \leq x_B \leq A$

x_B counts the number of nucleons involved : $x_B > n$ ==> at least n+1 nucleons

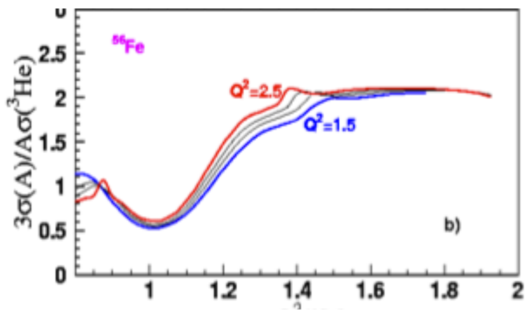
x_B and Q^2 also determine the minimum momentum of struck nucleon in nucleus (the y of y-scaling)

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

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

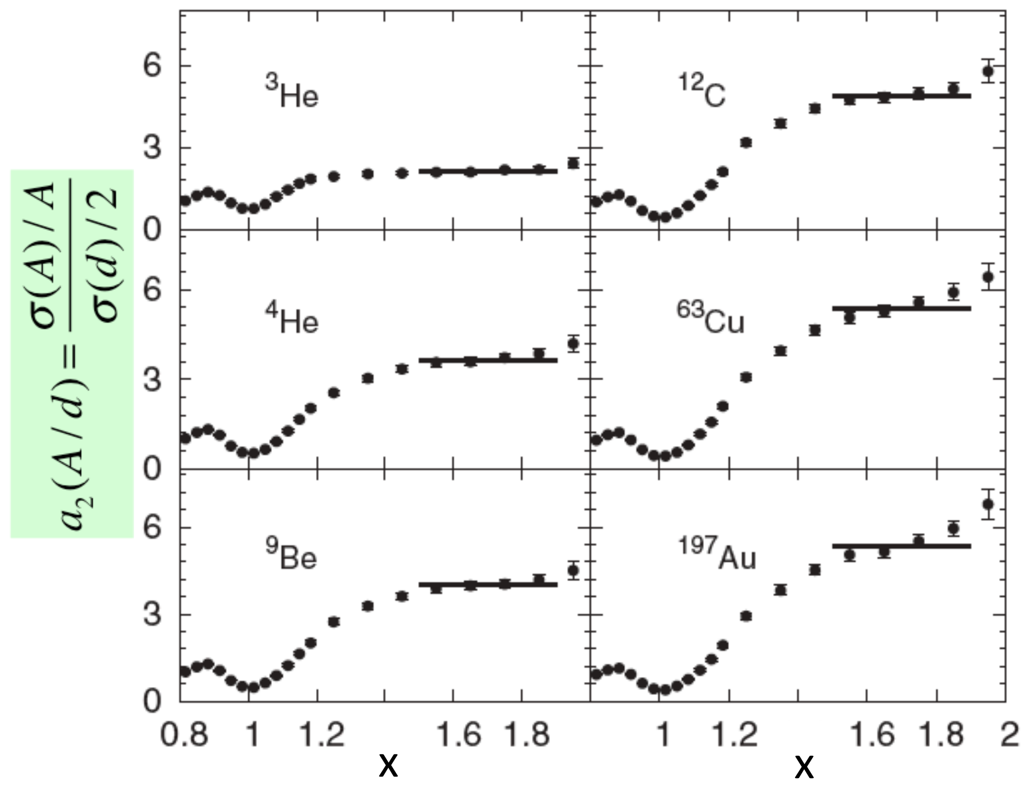


Nucleus	% 2N corr.
d	4.1 ± 0.8
^{3}He	8.0 ± 1.6
^{4}He	15.4 ± 3.2
^{12}C	19.8 ± 4.4
^{56}Fe	23.9 ± 5.3



Ratio predictions by Frankfurt, Strikman, and Sargsian

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



JLAB Hall A Experiment E01-015

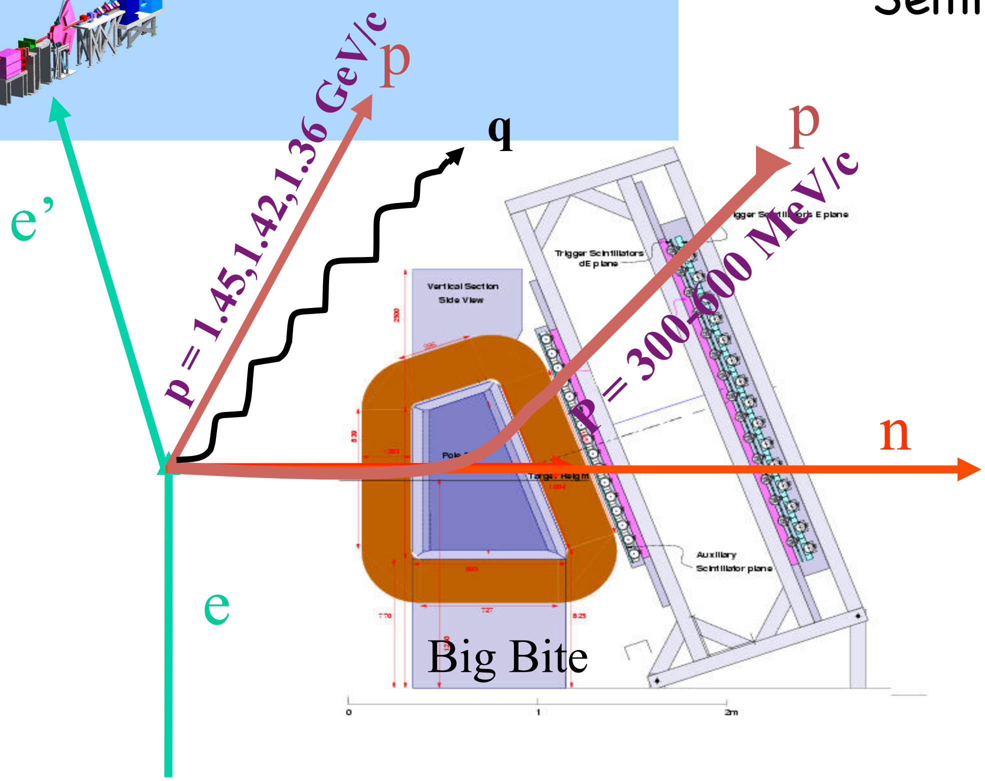
Use $^{12}C(e,e'p)$ as a tag to measure $^{12}C(e,e'pN)/^{12}C(e,e'p)$

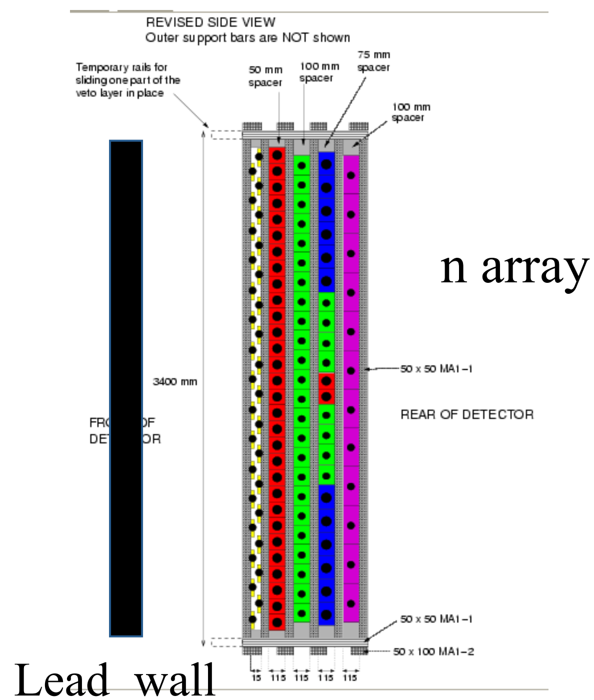
Optimized kinematics:

$Q^2 \approx 2.0$

$x_B \approx 1.2$

"Semi anti-parallel" kinematics





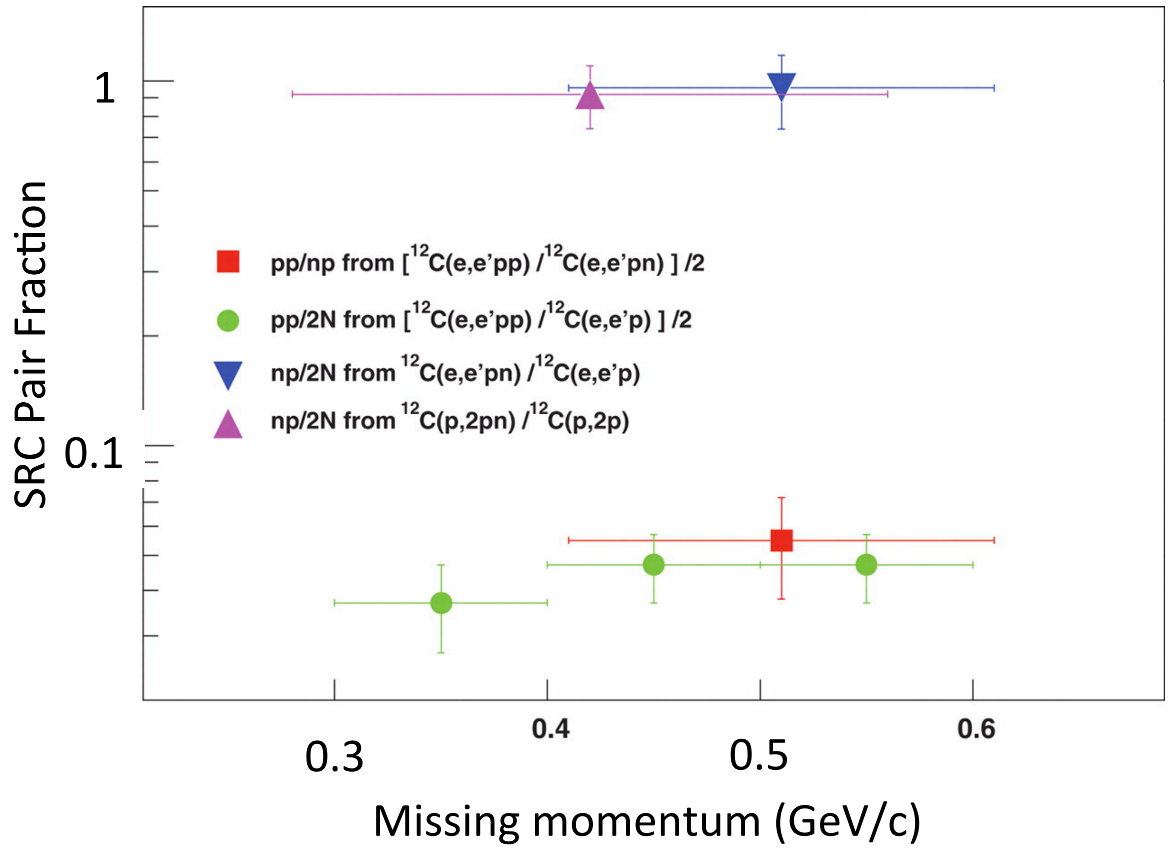
Looking for correlated partners

- 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)



Ratios corrected for acceptance, det. efficiency and SCX

R. Subedi et al., Science **320** (5882), 1476 (2008)

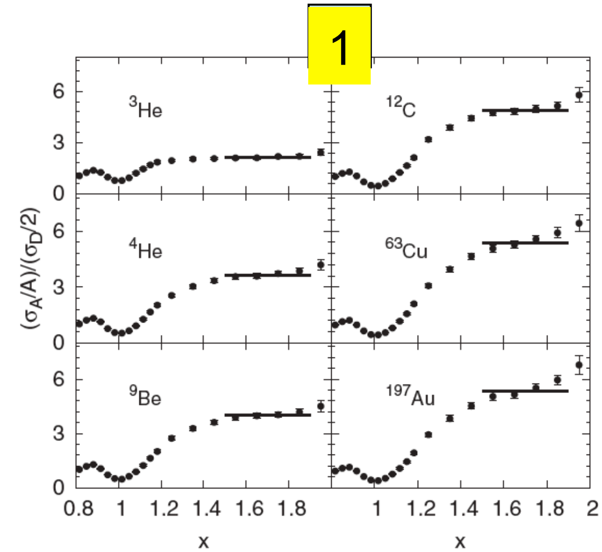
R. Shneor *et al.*, PRL**99, 072501 (2007)**

What do we know about SRC?

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

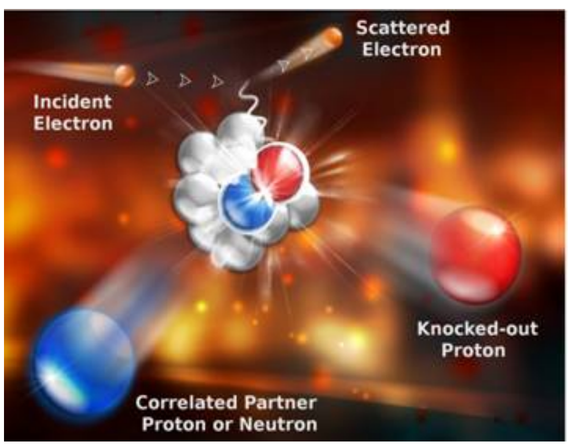
2 **More than ~90% of all nucleons with momentum ≥ 300 MeV / c belong to 2N-SRC.**

1 2 ⇒ **~80% of kinetic energy of nucleon in nuclei is carried by nucleons in 2N-SRC.**

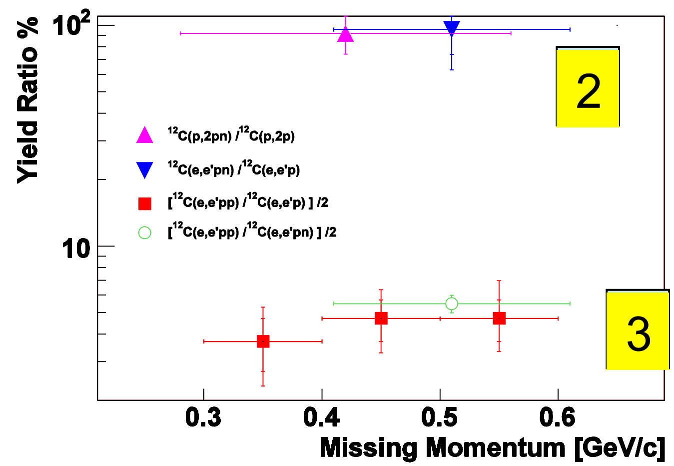


PRL **108** (2012) 092502

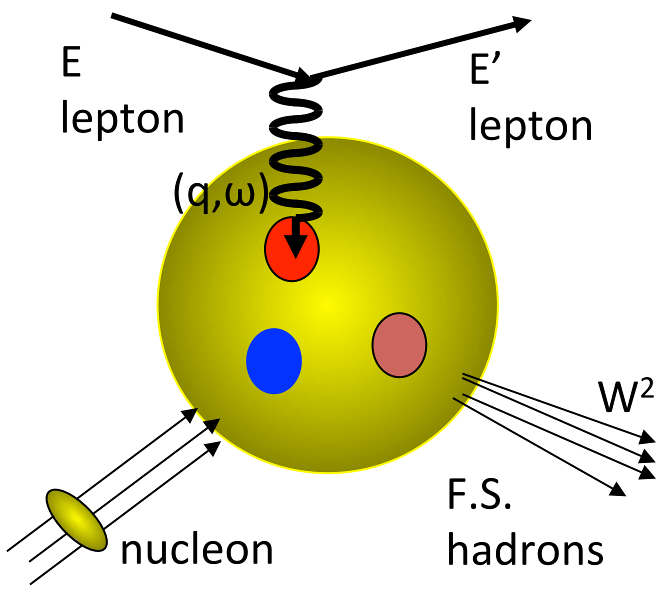
3 **2N-SRC dominated by np pairs**



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



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

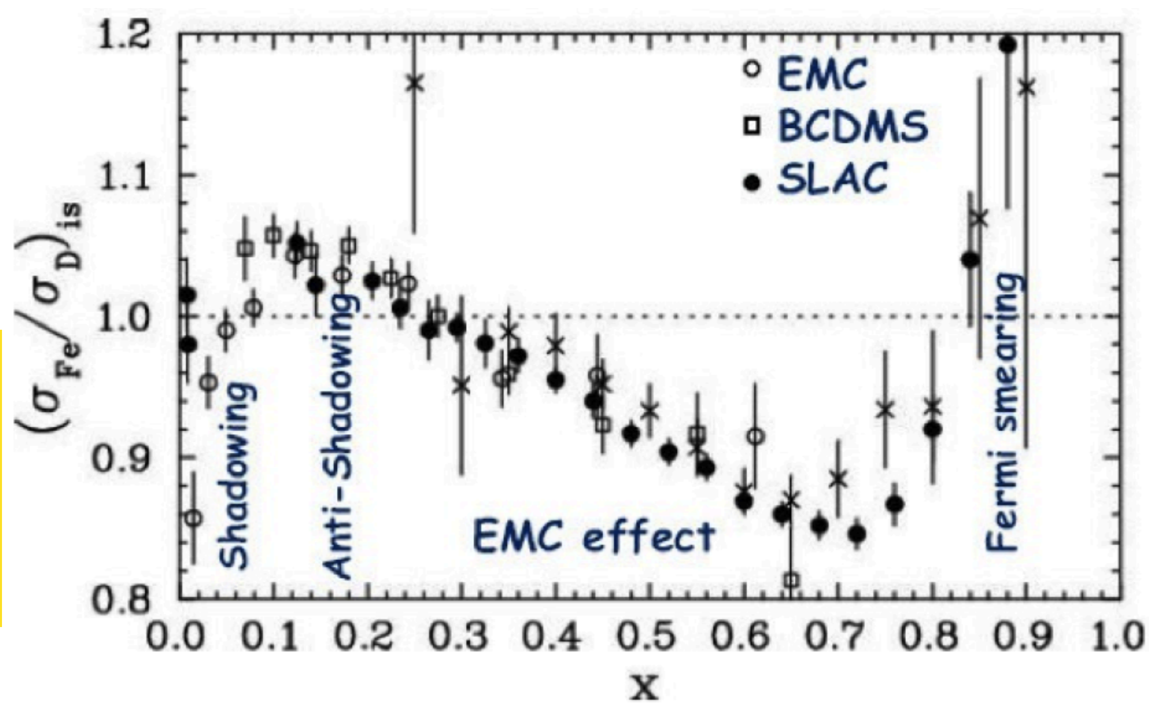
Expectation: DIS of bound nucleons ≅ DIS of a free nucleons

EMC: DIS off bound N ≠ DIS off free N

Origin of EMC effect unknown!!

Nucleon modification needed.

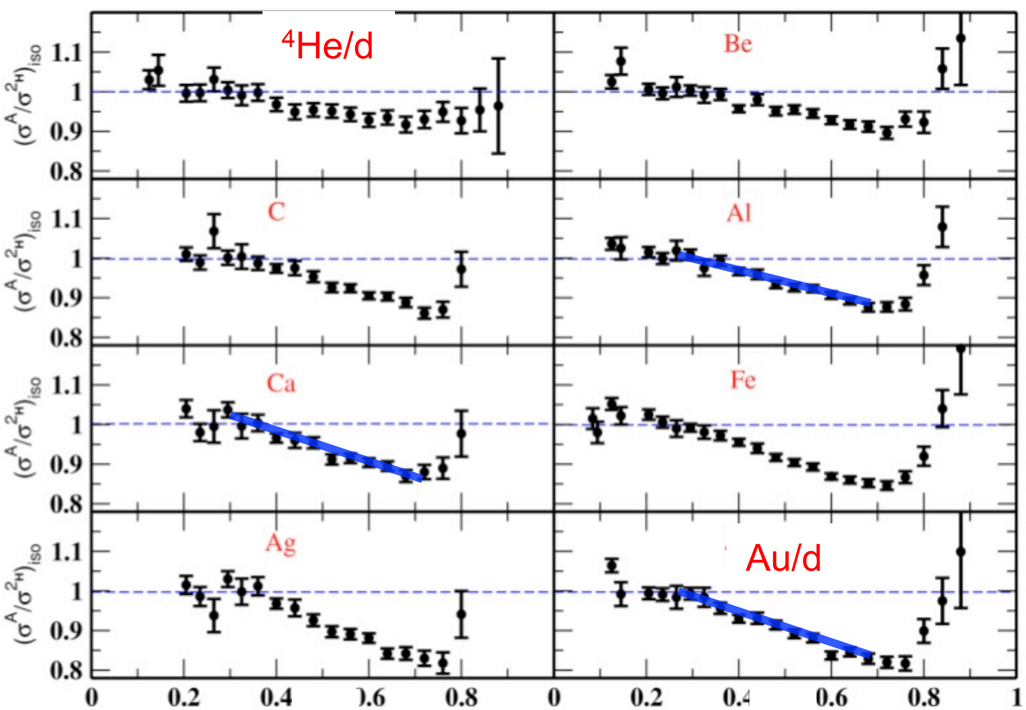
≈10^3 publications



EMC Effect: Universal

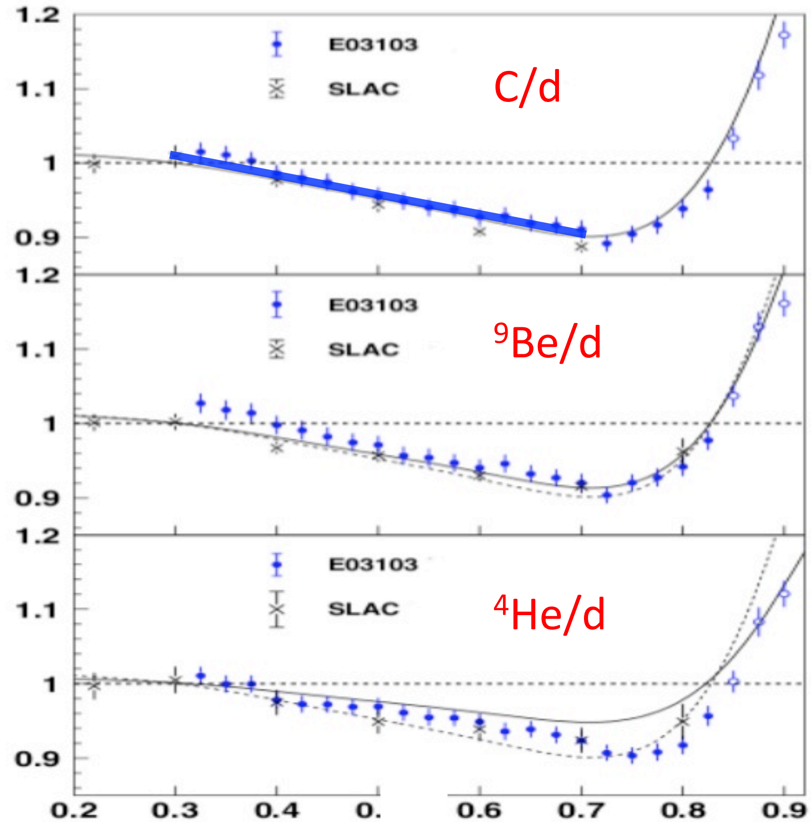
$$\frac{2}{A} \cdot \frac{\sigma^A}{\sigma^d}$$

SLAC



x x

Hall C



x

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

J. Seely, PRL 103, 202301 (2009)

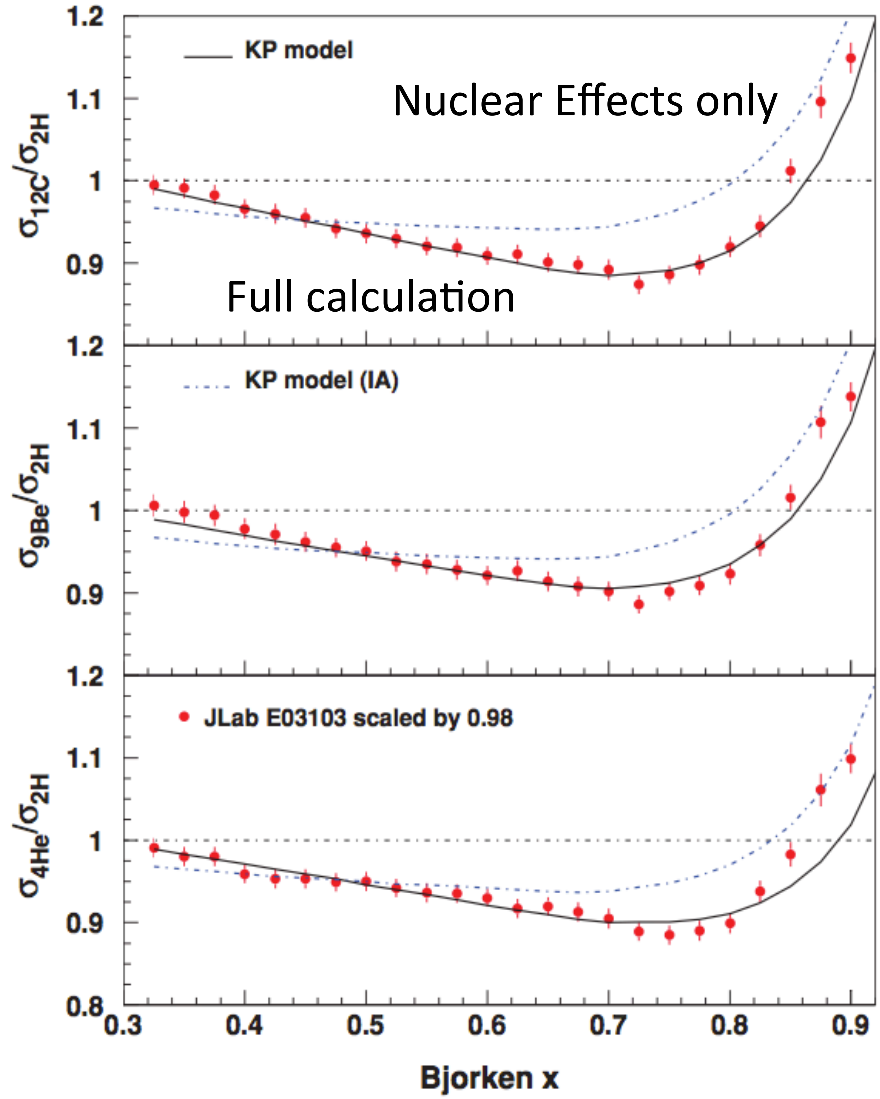
J. Gomez, PRD **49**, 4348 (1994).

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

EMC Effect: Theory

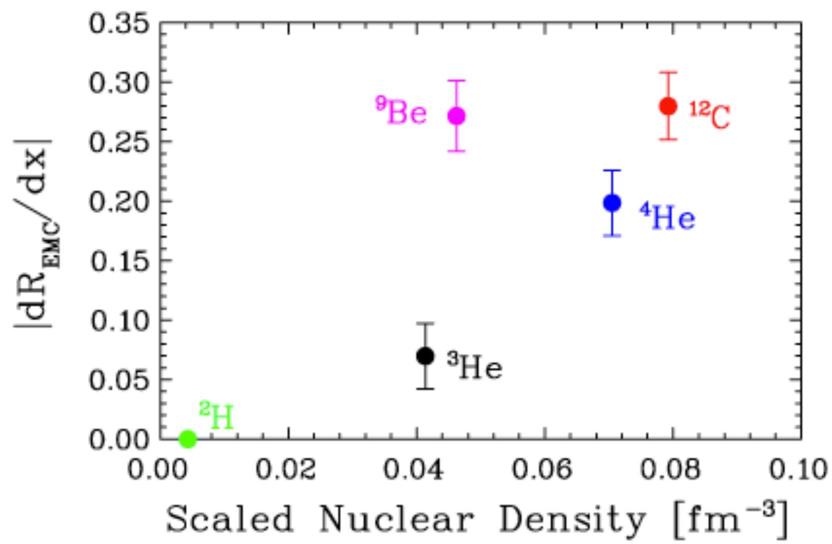
- Nuclear Effects:
  - Fermi motion
  - Binding energy
- Full Calculation
  - Nucleon modification
  - Nuclear pions
  - shadowing

Nucleon modification:
Phenomenological change to bound nucleon structure functions, change proportional to virtuality (p^2)



Kulagin and Petty, PRC 82, 054614 (2010)

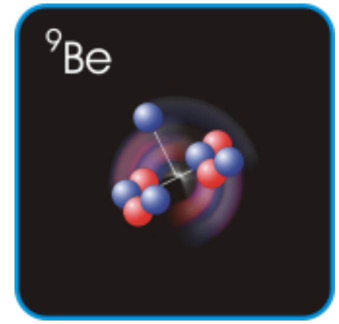
Eureka Moment!



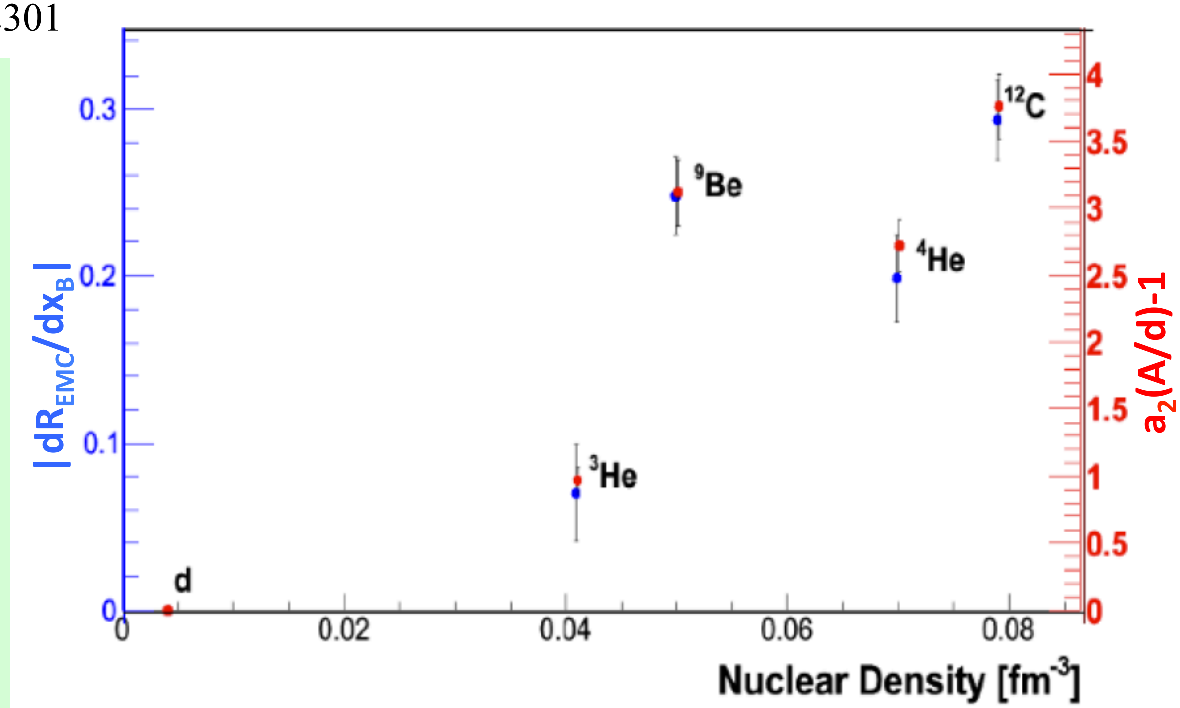
J. Seely et al., PRL **103** (2009) 202301

"…effect scales with the local environment of the nucleons…"

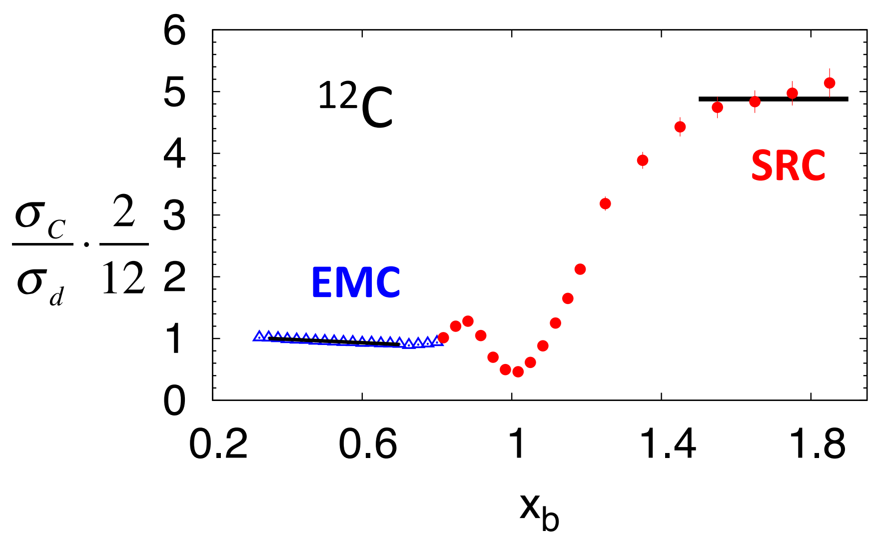
Local density?



- SRC is a local-density effect related to high-momentum nucleons
- Effective number of high-momentum nucleons in SRC is given by a_2
- **Is EMC related to modified SF of high-momentum nucleons?**



Correlations Between EMC and SRC!



JLab data

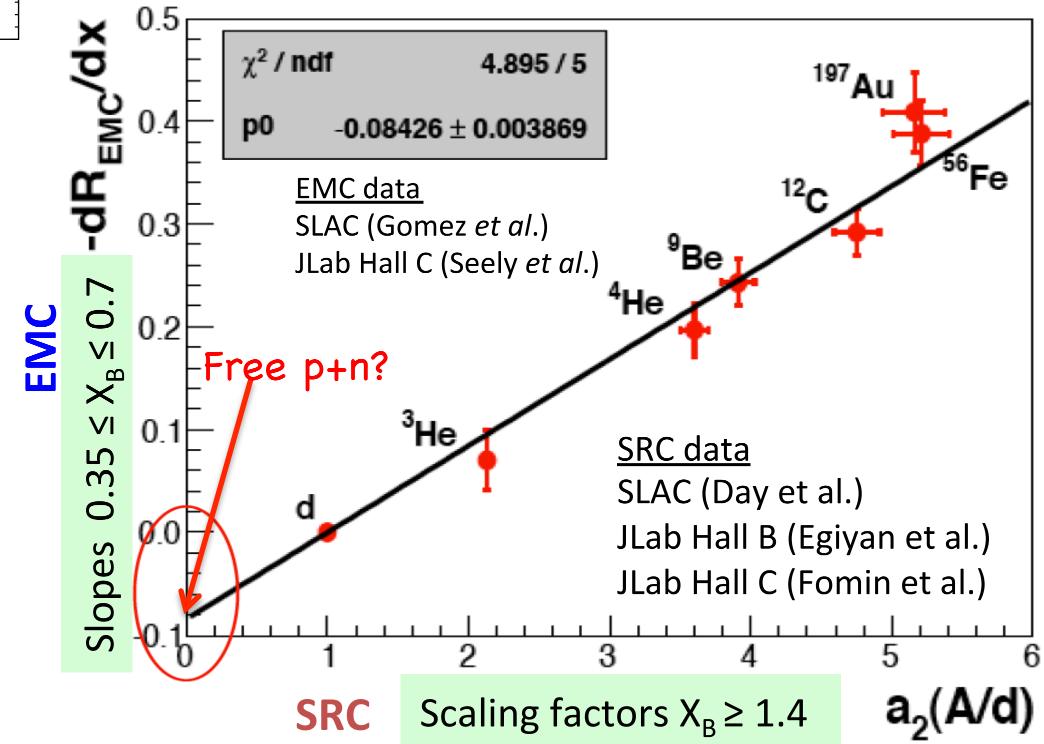
J. Seely *et al.*, PRL **103** (2009) 202301
N. Fomin et al., Phys. Rev. Lett. **108** (2012) 092502

SRC

- High local density
- High nucleons momenta

EMC

- Is EMC related to high-momentum nucleons?



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

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 in nuclei
- High momentum (high virtuality) nucleons in the medium are modified

Hmm..

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

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

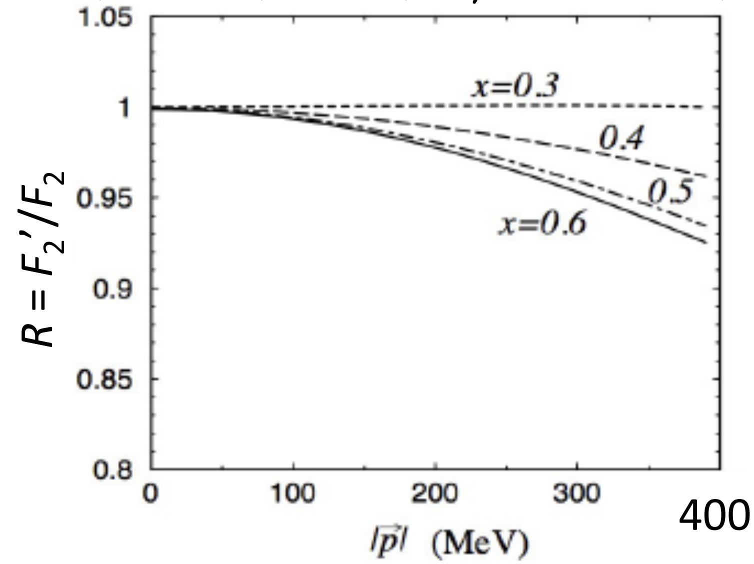
(F_1 and F_2 are related by R, the measured ratio of longitudinal and transverse cross sections. Thus measuring the cross section yields F_2.)

Predicted Dependence of F_2 on Momentum

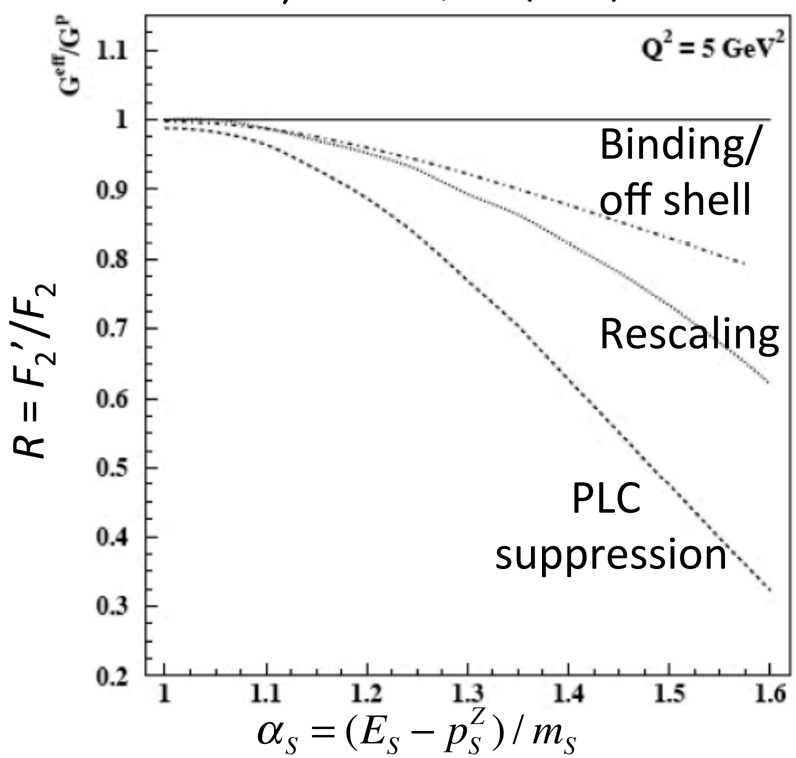
Dependence on:

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

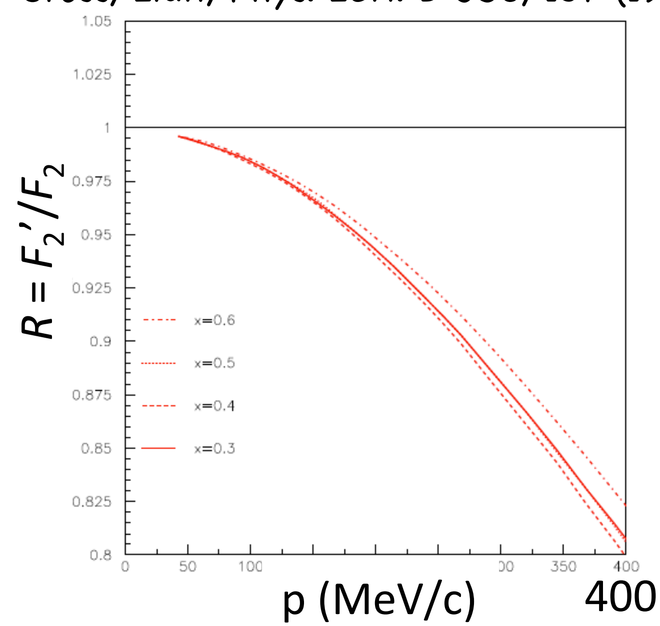
Melnitchouk, Screiber, Thomas, Phys. Lett. B **335**, 11 (1994)



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

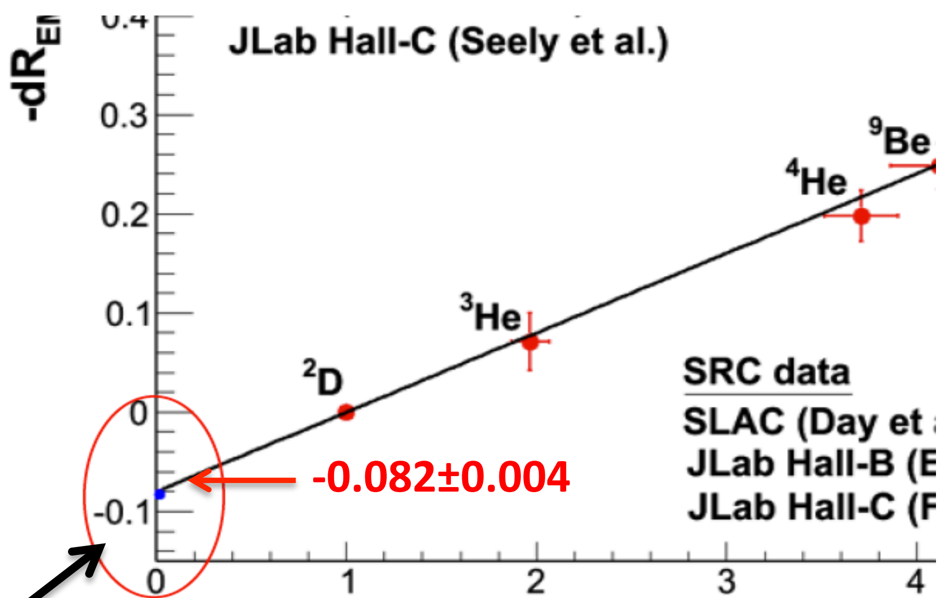


Gross, Liuti, Phys. Lett. B **356**, 157 (1995)



Explore Connection between EMC and SRC

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 there a large "EMC" effect in the high-momentum tail of the deuteron?
- Does the structure function F_2 depend on nucleon momentum (virtuality)?

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

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

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

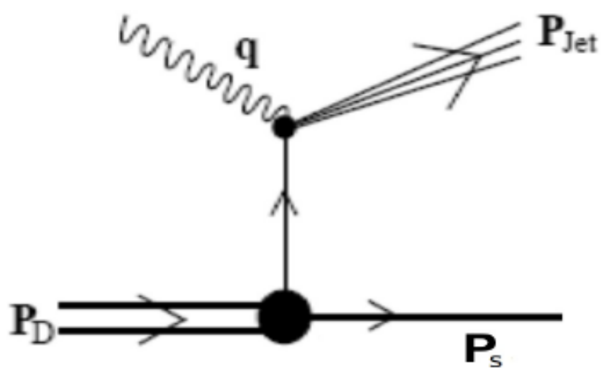
$$\frac{\sigma_p^*}{\sigma_p} \approx \frac{\sigma_n^*}{\sigma_n} \approx \frac{2.4\%}{5\%} \approx 0.5$$

In Medium Nucleon Structure Functions, SRC, and the EMC Effect

E12-11-107 – TAU, ODU, MIT JLAB

Experimental method

- Use deuteron as a target in DIS
- Tag high-momentum nucleons with high-momentum backward-recoiling ("spectator") partner nucleon as in SRC using the reaction $d(e,e'N_S)$



Experimental Method

Use factorization of the d(e,e′N_S) cross section into the cross section (F_2) and the distorted momentum distribution.

Keeping the recoil kinematics fixed and measuring x-section ratios at 2 different x′, the ratio is:

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

For $x_1' \approx 0.45 - 0.6$ and $x_2' \approx 0.3$ we shall measure:

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

Integrating over $\theta_{pq} > 107°$ (small FSI), we'll compare the measured ratio $f(\alpha_S)$ to the BONUS results for free neutron, and to the free proton SF in d(e,e′n_S)

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

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

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

R_{FSI}: FSI correction factor

x′ = x from a moving nucleon

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

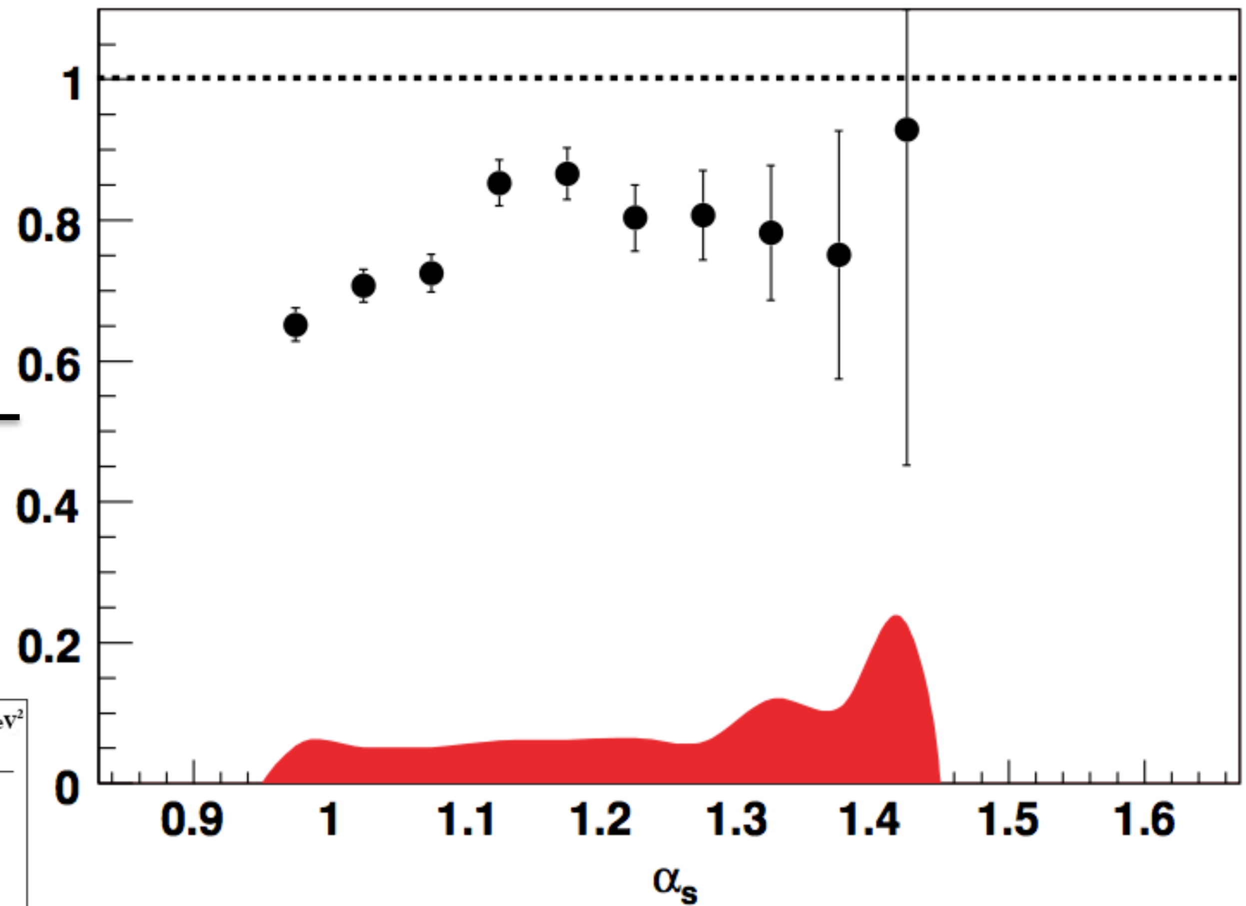
$$0.25 \geq x'_{low} \geq 0.35$$ No EMC is expected

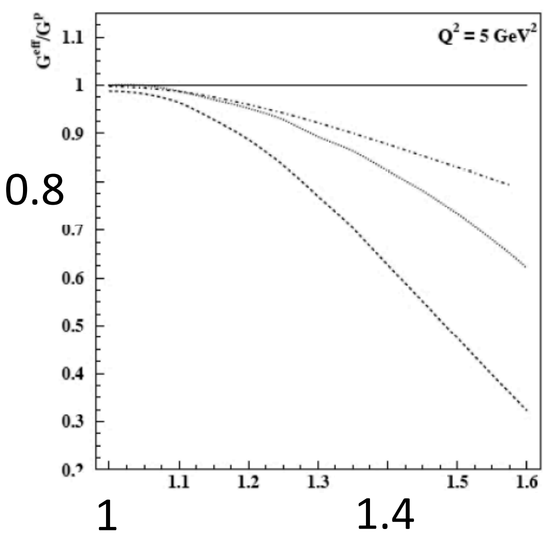
$$x'_B = \frac{Q^2}{2p_\mu q^\mu} \overset{\text{(For d)}}{=} \frac{Q^2}{2[(M_d - E_S)\omega + \vec{p}_S \cdot \vec{q}]}$$

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

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

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



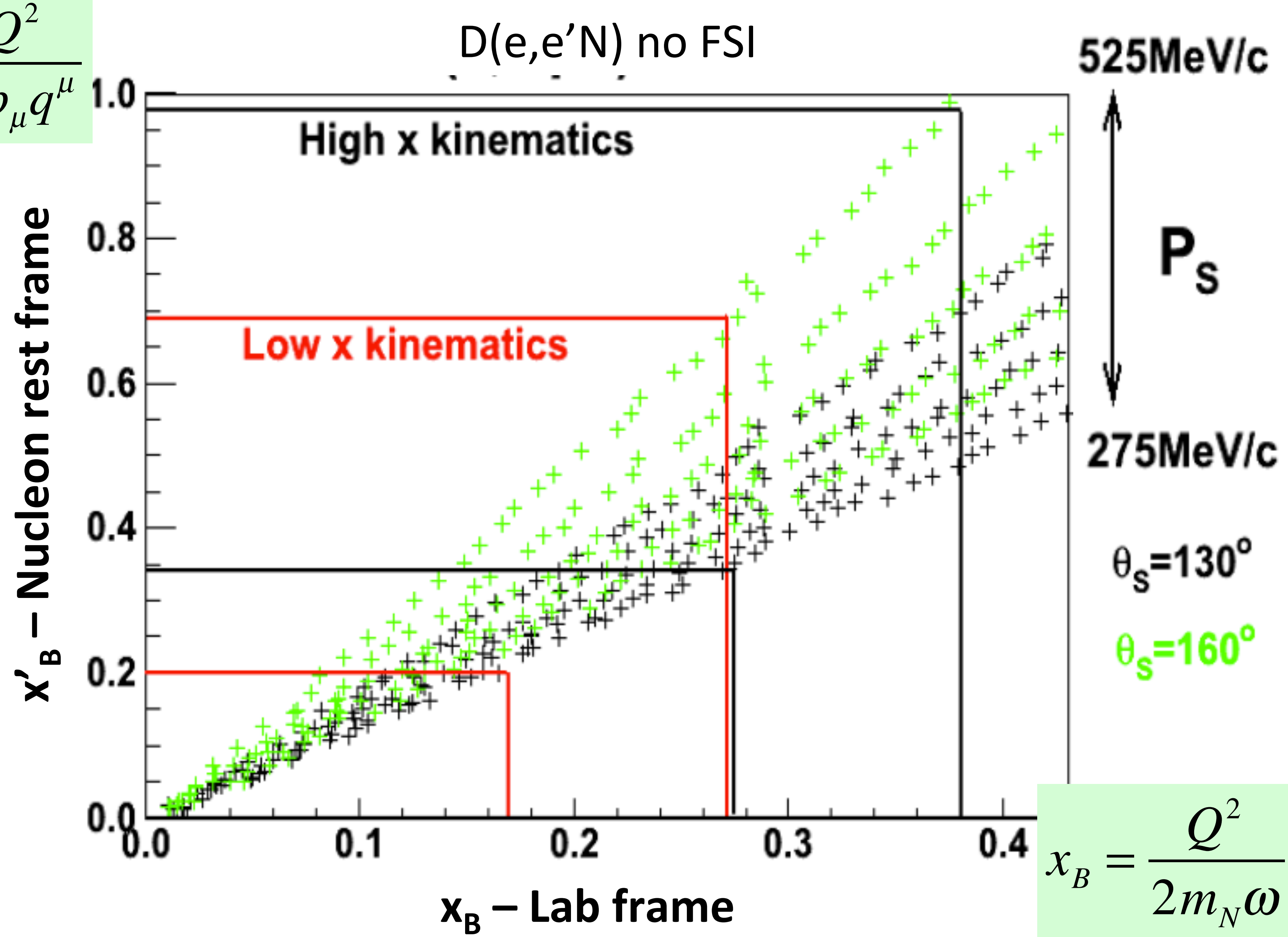


Inconclusive!

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

x_B' vs. x_B (Why x'?)

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



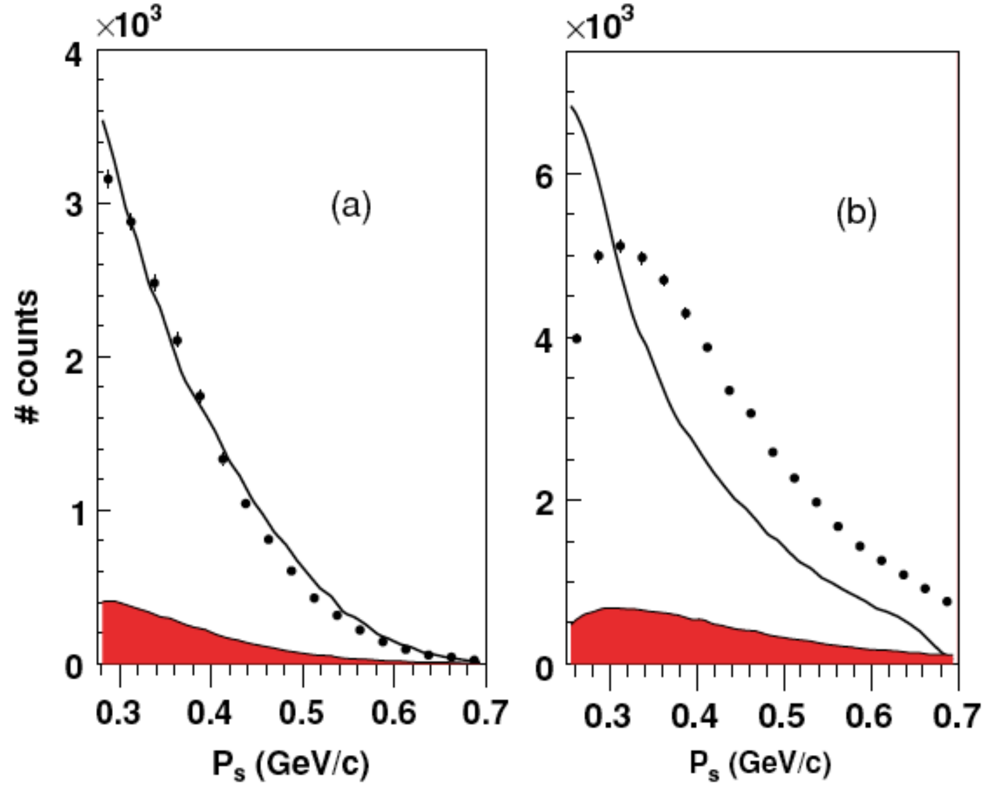
$$x_B = \frac{Q^2}{2m_N\omega}$$

How to Deal with FSI?

We know that 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:

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

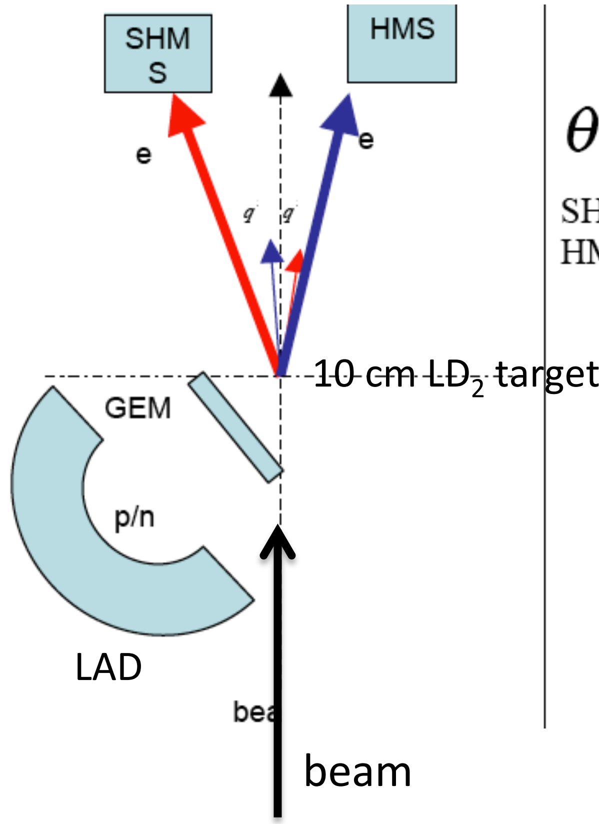
Experimental Setup – Hall C

HMS and SHMS detect electrons

LAD detect recoiling nucleon

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
$\theta_q = -8.8^0$	$\theta_q = 10.8^0$
$x = 0.217$	$x = 0.34$

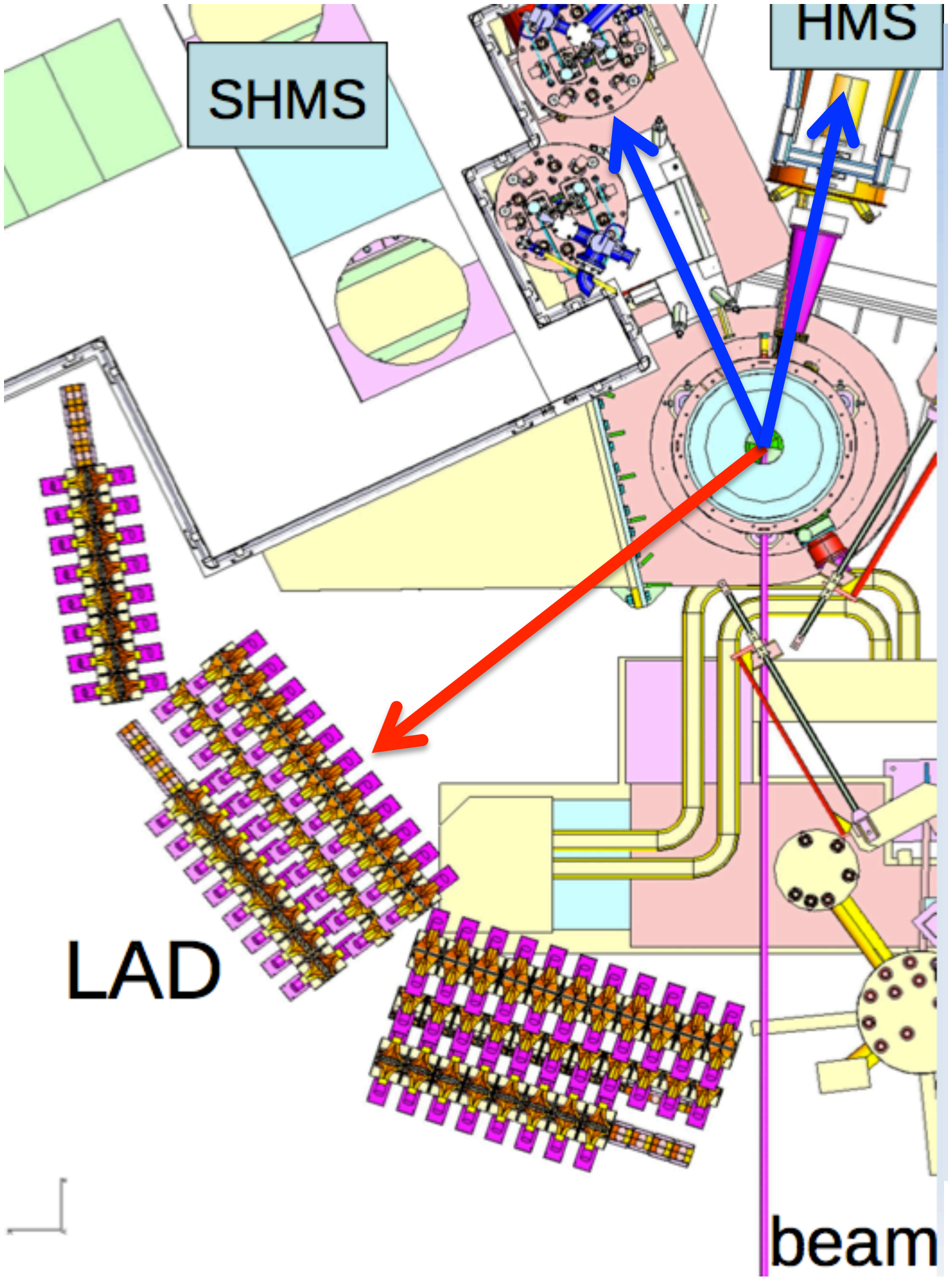


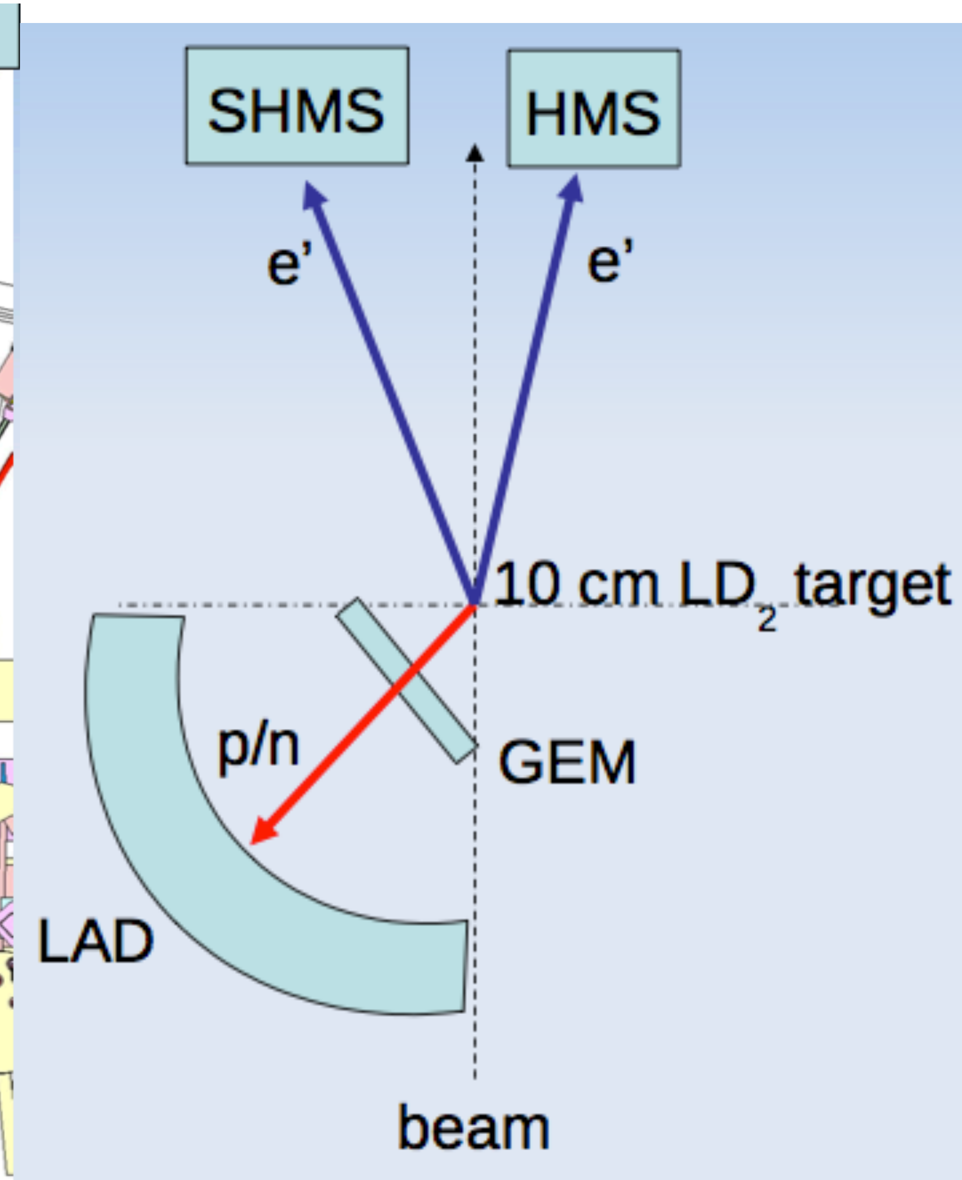
θ_{pq}

SHMS/LAD	95-185^0
HMS/LAD	75-165^0

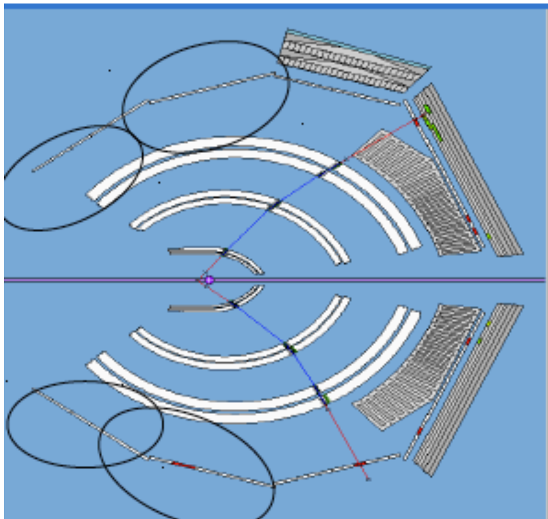
Collect both LAD-HMS and LAD-SHMS coincidences

Experimental Set Up - Hall C





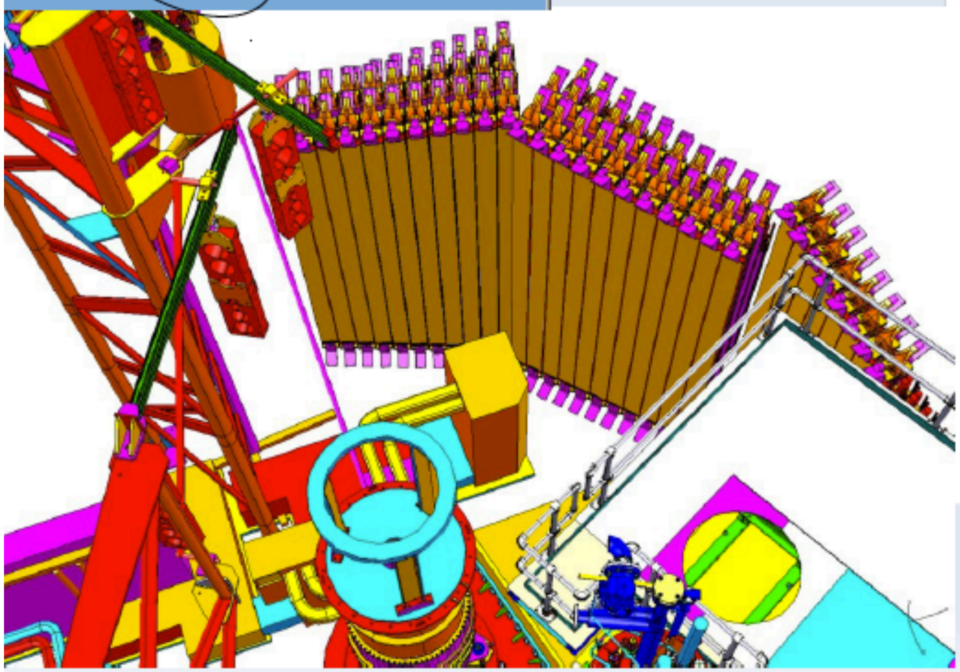
Large Acceptance Detector (LAD)

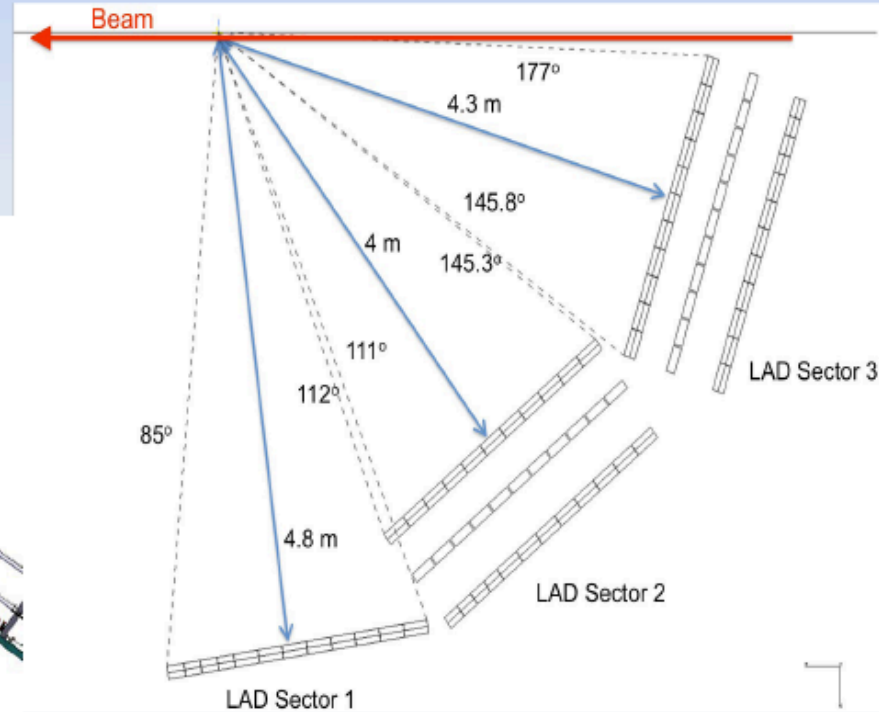


Use retired CLAS-6 TOF counters.

132, 5-cm thick counters in 12 panels.

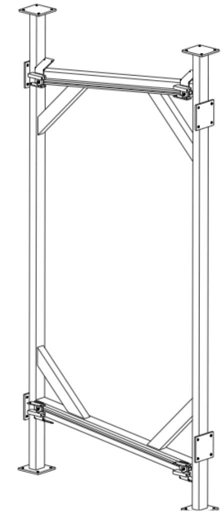
1.5 sr, ~20% neutron detection efficiency



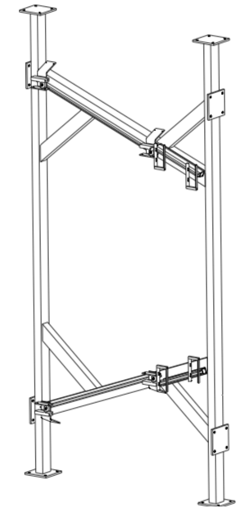


CLAS6 TOF → LAD

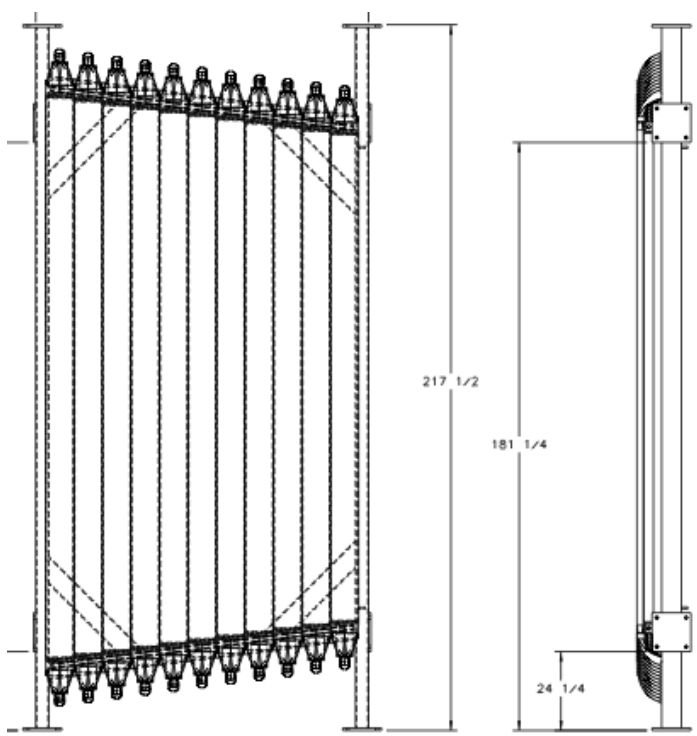
1. Design (Dan Young) and build (Hall C shop)
   1. 12 storage and support frames - Done
   2. 2 storage carts - Done
2. Remove large angle CLAS TOF panels from Hall B
   1. Panel4: July 6-7
   2. Panel3: August-September
3. Move the TOF detectors to the new frames
4. Test and Refurbish the detectors

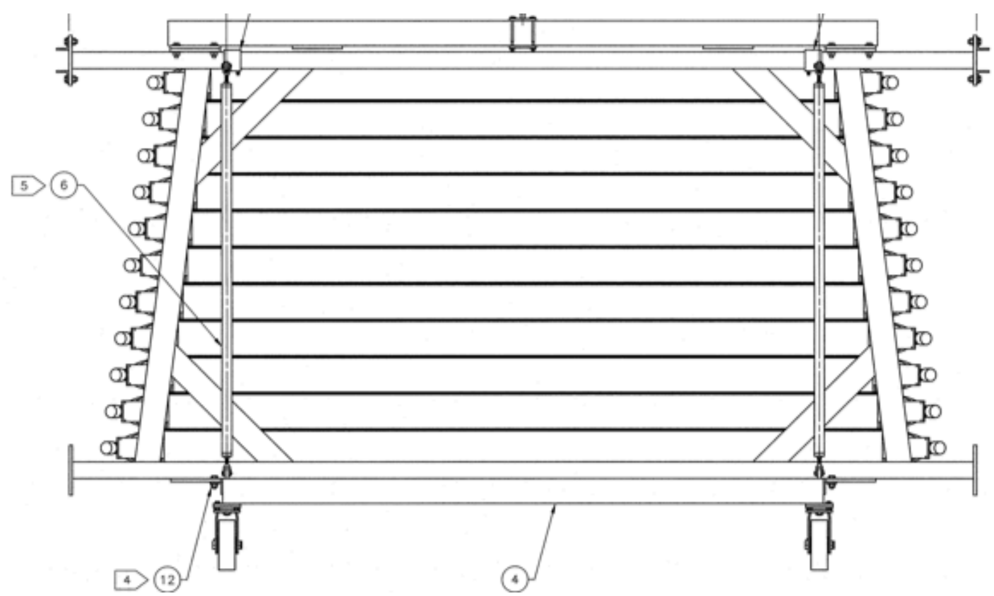


Panel3 Frame



Panel4 Frame





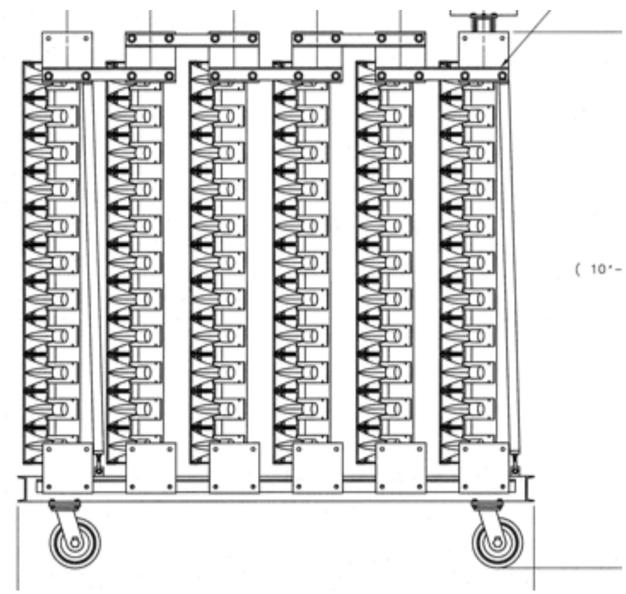
One frame on cart with TOF detectors

CLAS6 TOF → LAD

Frame under construction

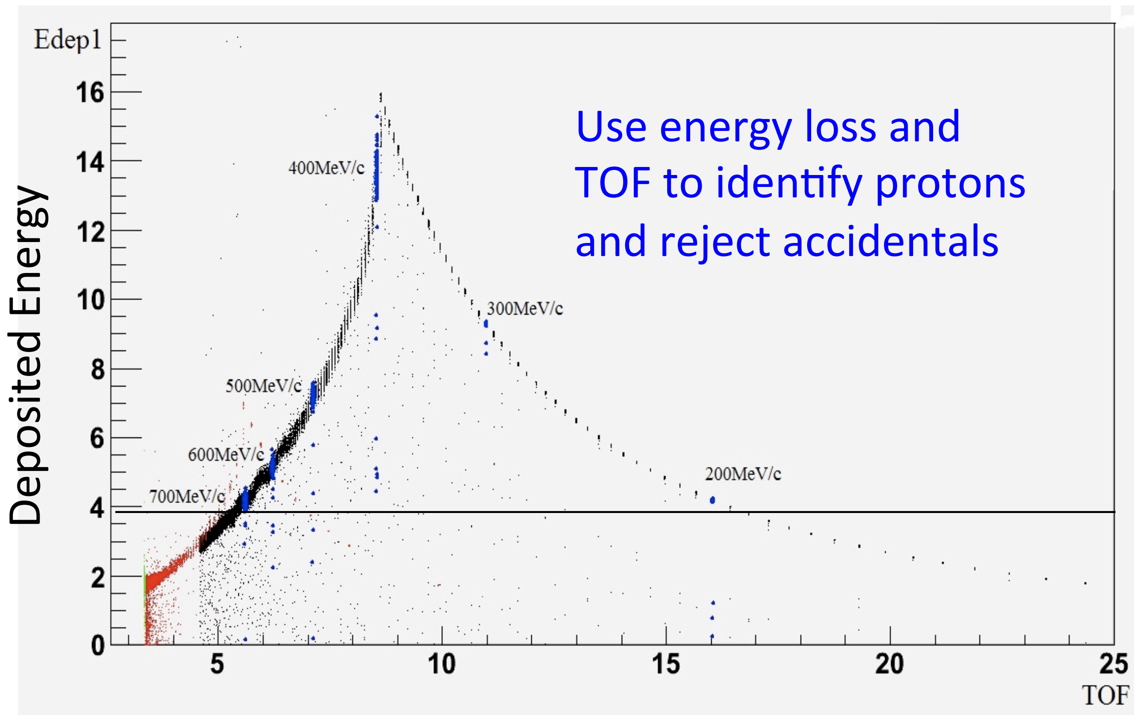
Cart

Frames stacked on cart



Goal: All frames on cart with TOF detectors

LAD Performance



Time of Flight (ns)

- Singles rates measured in Hall A at 90°
- Overestimates larger angle backgrounds
- Detailed signal to background simulations

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

S/BG

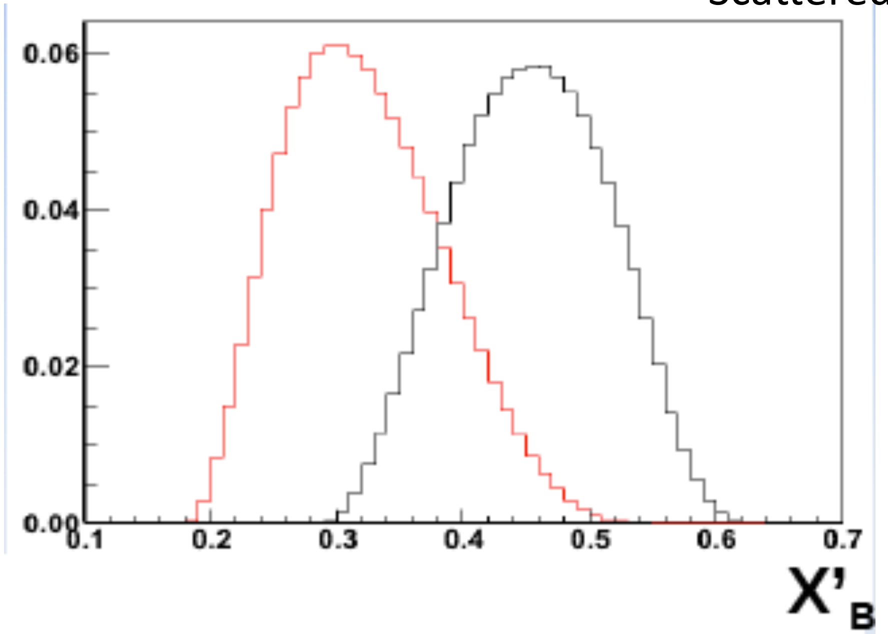
α_s	1.2	1.3	1.4	1.5
$x'_B > 0.45$	1:1	1:2	1:2	1:2
$x'_B \approx 0.3$	3:1	1:1	1:1	1:1

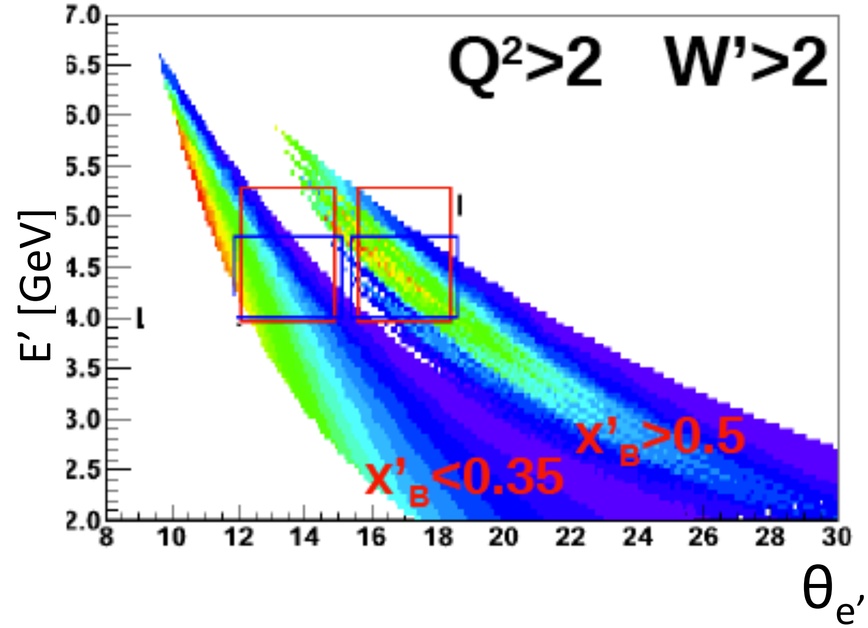
Neutron Detection

- 5 LAD layers
- Veto charged particles using GEM and 1st layer
- 5 MeVee threshold to reduce backgrounds
- Experience from scintillator neutron detection in Halls A and B
- Detailed, bin-by-bin, background simulation
  - 1:200 S/BG ratio at high x' before cuts
    - x', and W' cuts
    - $\theta_{pq} > 110^o$
  - 1:20 S/BG at high x' after cuts
- Subtract random background with mixed events

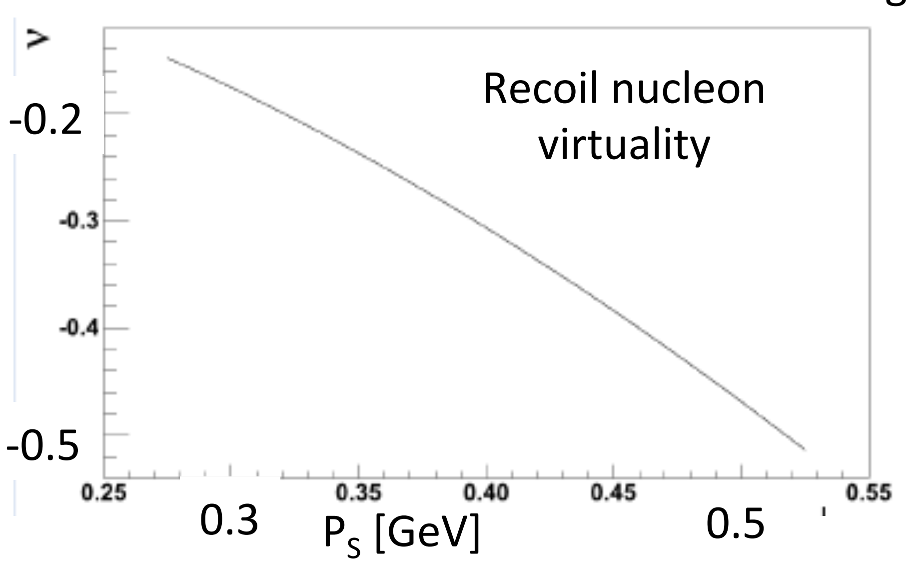
Kinematic Coverage

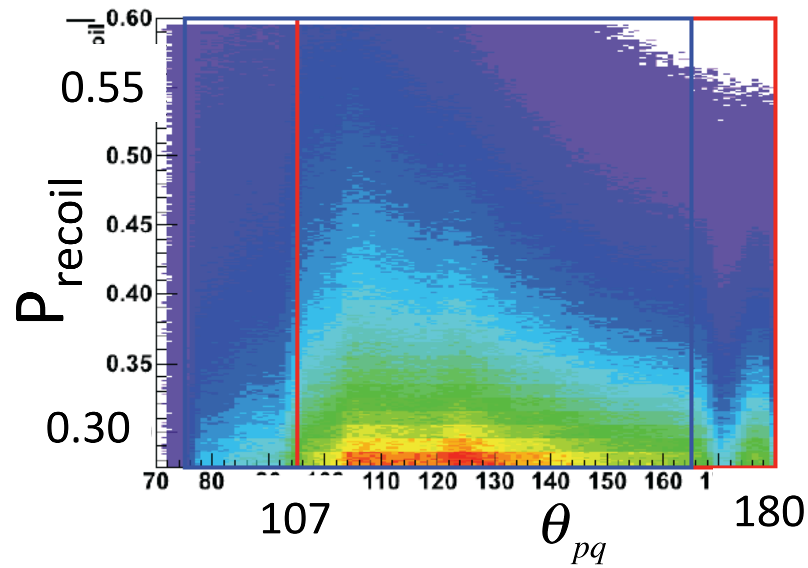
Scattered electrons



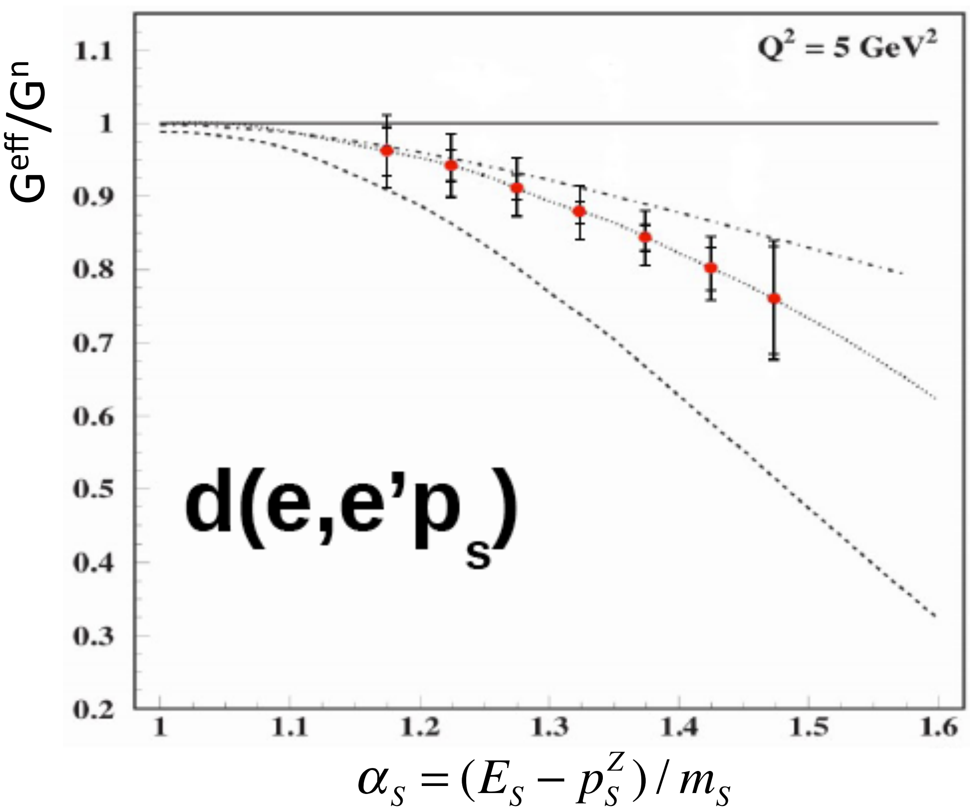


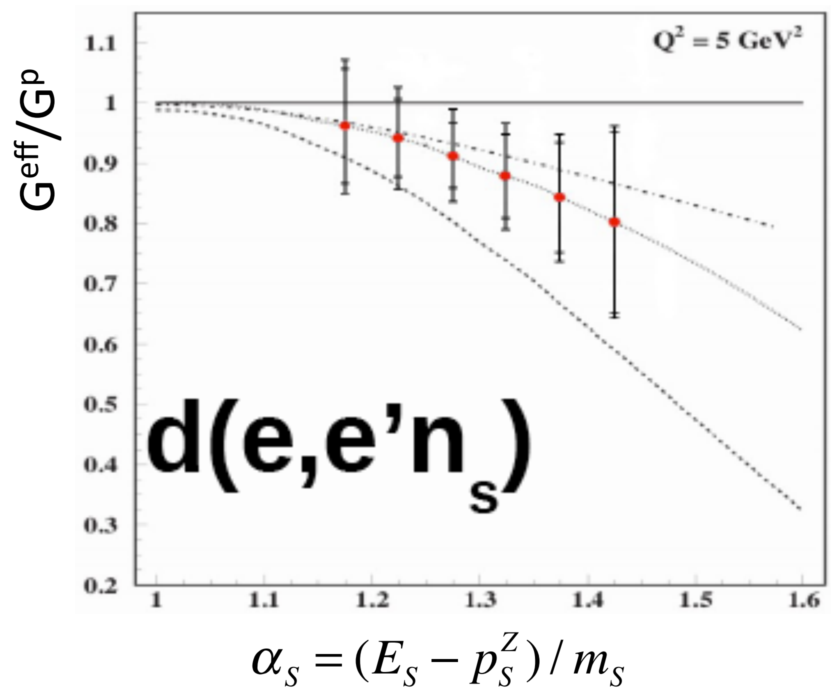
Recoiling nucleons





Expected Results





Systematic uncertainty (4-7% total)

- SHMS and HMS efficiency and acceptances (1-2%)
- LAD efficiency (3% protons, 5% neutrons)
- Al walls subtraction (1%)
- FSI ratio (4%)
- Free nucleons structure functions ratio (1% protons, 4% neutrons)

Summary – Nucleon Medium Modification

Physics:

- SRC and EMC are linearly correlated
- Both phenomena are likely related to high-momentum nucleons
- EMC effect strongly implies that bound nucleons are modified
  - We want to measure highly virtual bound nucleon structure functions

Experiment:

- E12-11-107 will measure F_2 for highly virtual nucleons in the deuteron and compare that to F_2 for free nucleons
  - Use spectator tagging to select highly virtual nucleons in DIS
  - Minimize systematic uncertainties by measuring ratios

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

Backup slides

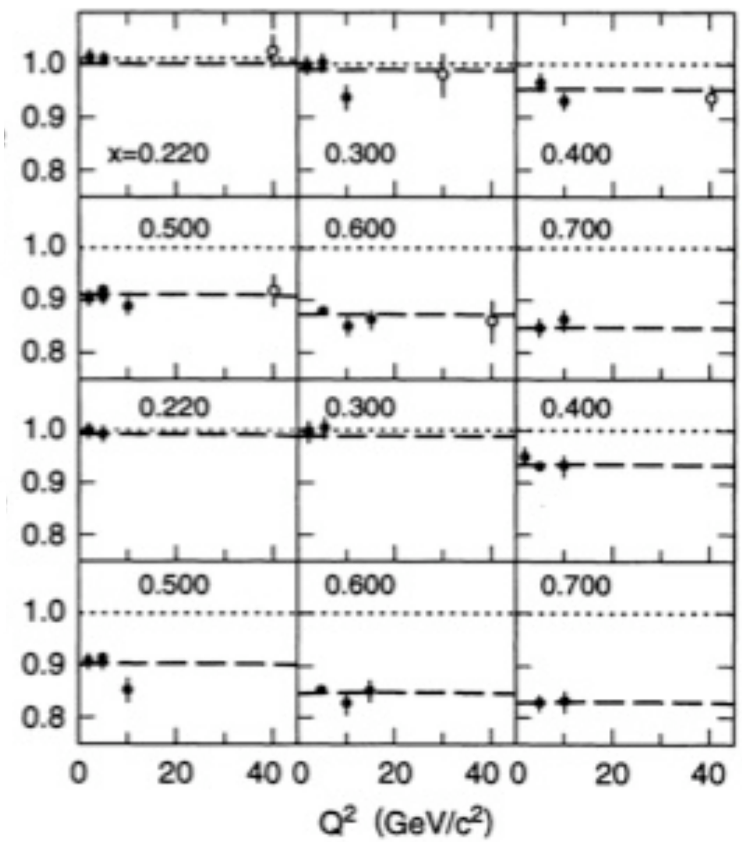
EMC Effect: Q^2 Independence

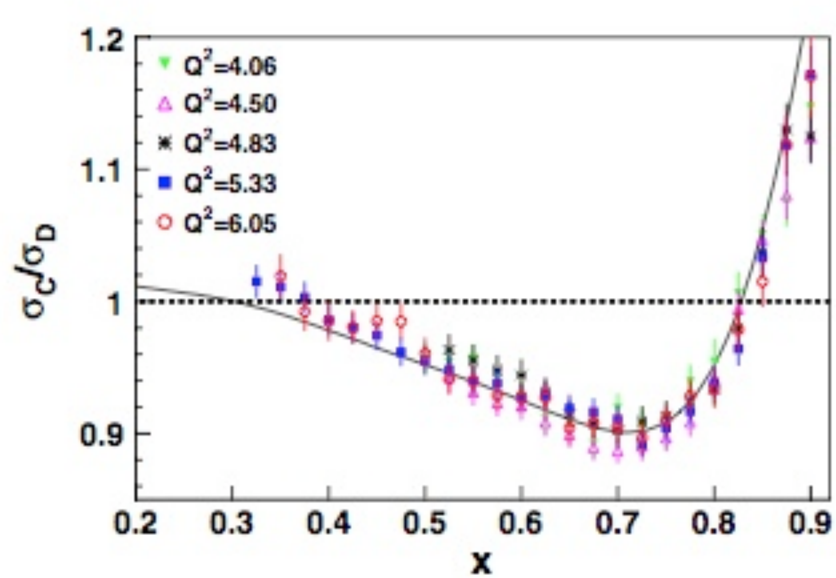
J. Gomez et al., Phys. Rev. D **49**, 4348 (1994).

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

Fe/d

Au/d





No Q^2 dependence for $2 < Q^2 < 40$ GeV^2

Robustness of SRC-EMC Correlations

O. Hen *et al.*, arXiv:1202.3452 [nucl-ex]

Nucleus	Egiyan *et al.* [12]	EMC-SRC Prediction [8]	Fomin *et al.* [18] [Analysis as in Ref. [12]]	Fomin *et al.* [18]	Fomin *et al.* [18] [excluding the CM motion correction]	SLAC [10]**	EMC Slope [8] dR_{EMC}/dx
column #	2	3	4	5	6	7	8
^{3}He	$1.97 \pm 0.10^*$		1.87 ± 0.06	1.93 ± 0.10	2.13 ± 0.04	1.7 ± 0.3	-0.070 ± 0.029
^{4}He	3.80 ± 0.34		3.64 ± 0.07	3.02 ± 0.17	3.60 ± 0.10	3.3 ± 0.5	-0.197 ± 0.026
^{9}Be		4.08 ± 0.60	4.15 ± 0.09	3.37 ± 0.17	3.91 ± 0.12		-0.243 ± 0.023
^{12}C	4.75 ± 0.41		4.81 ± 0.10	4.00 ± 0.24	4.75 ± 0.16	5.0 ± 0.5	-0.292 ± 0.023
^{56}Fe(^{63}Cu)	5.58 ± 0.45		5.29 ± 0.12	4.33 ± 0.28	5.21 ± 0.20	5.2 ± 0.9	-0.388 ± 0.032
^{197}Au		6.19 ± 0.65	5.29 ± 0.16	4.26 ± 0.29	5.16 ± 0.22	4.8 ± 0.7	-0.409 ± 0.039
EMC-SRC slope a	0.079 ± 0.006		0.082 ± 0.004	0.106 ± 0.006	0.084 ± 0.004		
$\frac{\sigma(n+p)}{\sigma_d}\|_{x_B=0.7}$	1.032 ± 0.004		1.033 ± 0.004	1.043 ± 0.005	1.034 ± 0.004		
χ^2/ndf	$0.7688/3$		$4.742/5$	$4.078/5$	$4.895/5$		

Insensitive to:

- Isoscalar corrections
- Radiative corrections
- Coulomb corrections
- Inelastic contributions

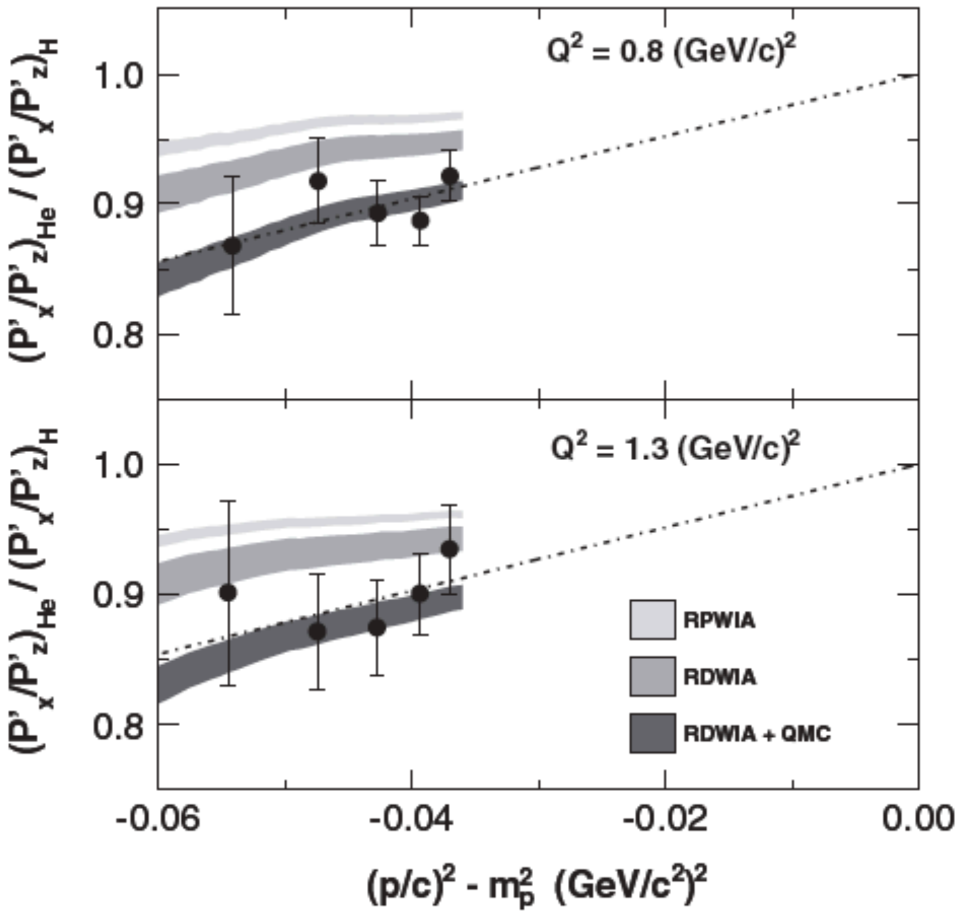
Pair C.M. motion correction for A > 2:

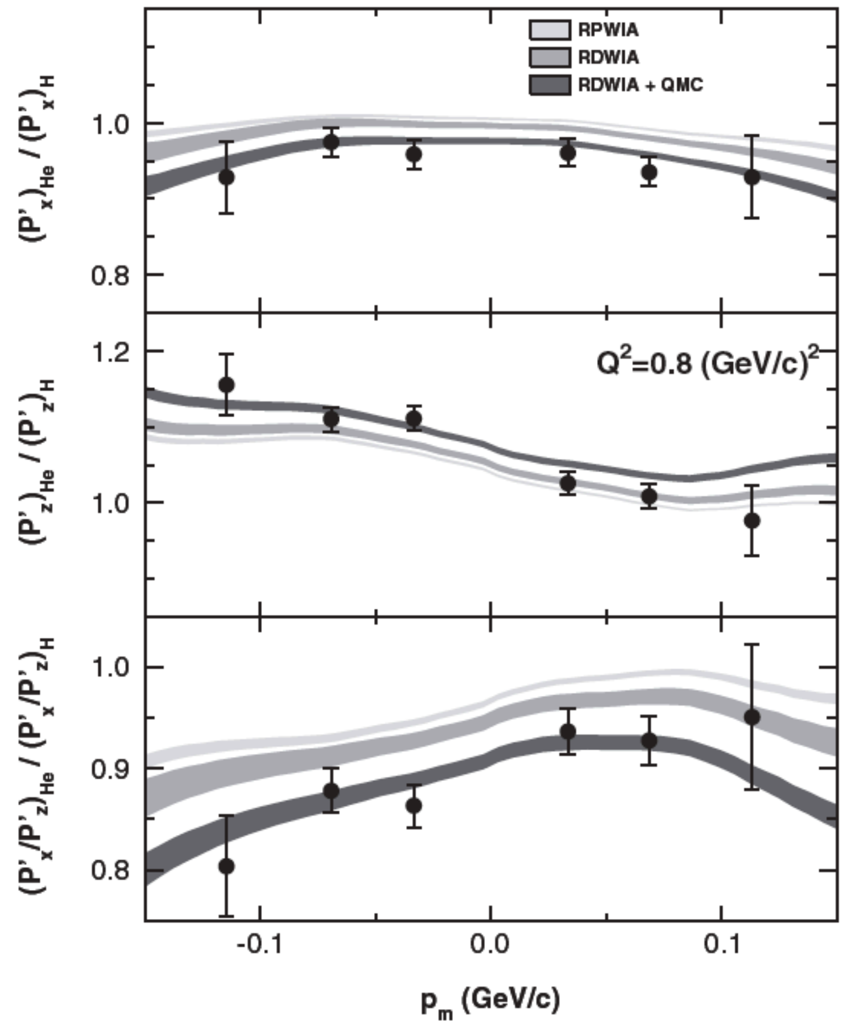
- Reduces x-sections by ~20%
- Reduces intercept by ~20%

Does not make a qualitative change to conclusions

Nucleons Modified at High Momentum

M. Paolone *et al*. PRL **105**,072001 (2010)





This is in quasi-elastic scattering, not DIS!

Our experiment will cover the range of virtuality 0.2 – 0.5