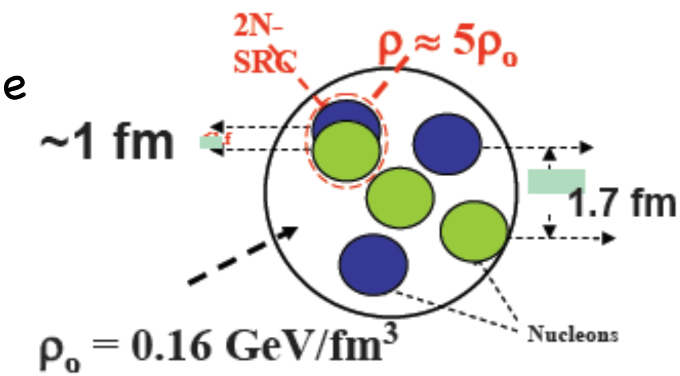
JLab Nucleon-Nucleon Short-Range Correlations Program

- What is N-N short-range correlations (SRC)
  - 2 nucleons with high relative momentum $k_{rel} > k_F$ and small total (cm) momentum $k_{cm} < k_F$
  - Associated with the high-momentum tail of the nucleon's momentum distribution
  - Very high cold local nuclear density
- Why is it interesting/important
- Favorable kinematics for studying SRC
- What have we done and what have we learned
- Implications to other fields
- Future program

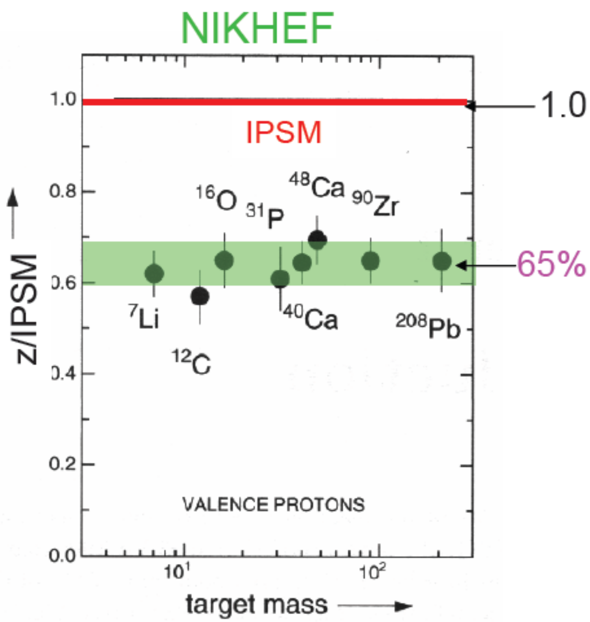


Shalev Gilad, MIT

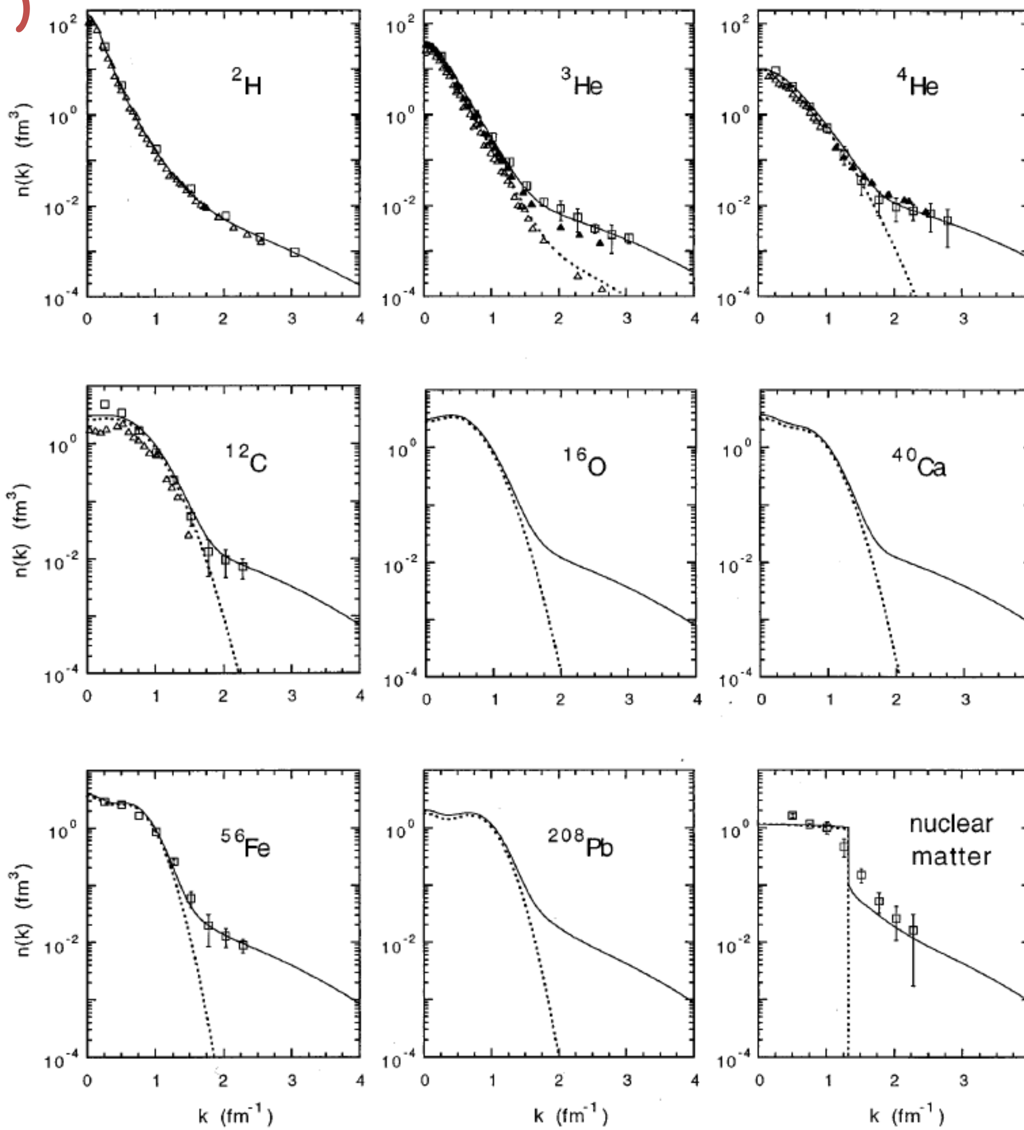
Momentum Structure of Nuclei

Momentum distributions from A(e,e')

- up to k_F distribution described well by fermions in a mean field
- Strength depleted from mean-field region to high momentum tail



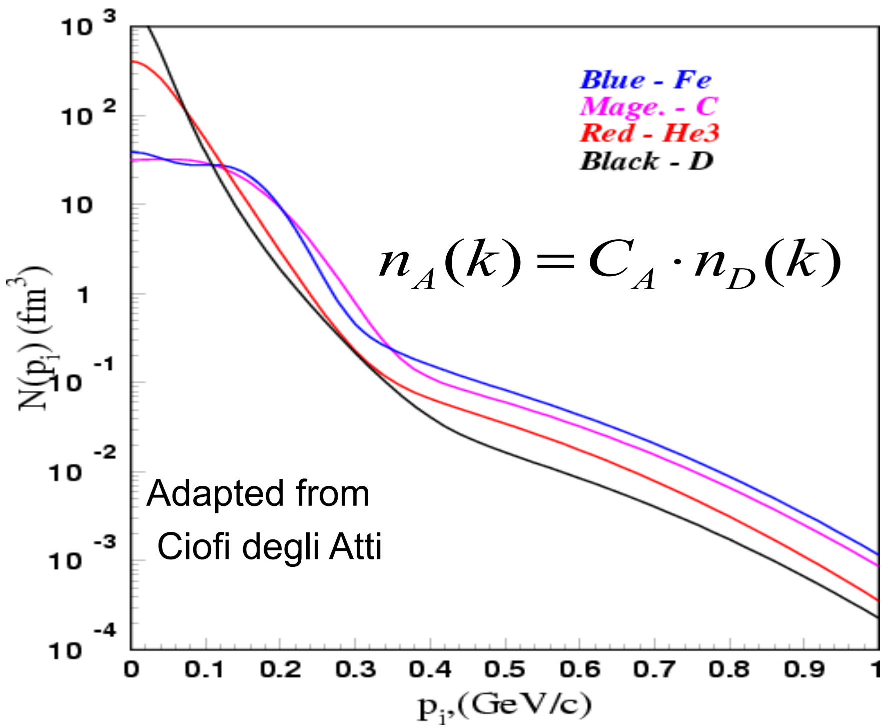
- High-momentum tail is orders of magnitude larger than mean-field predictions
- Universal to all nuclei



C. Ciofi degli Atti and S. Simula, Phys. Rev. C53 (1996) 1689

The Nature of the High-Momentum Tail

- At high nucleon momenta, strength of tail is different for various nuclei but shapes of distributions are similar to that of deuteron – 2 nucleons with high relative and low CM momentum
- Short-Range correlations!



Percentage of nucleons in 2-nucleons SRC

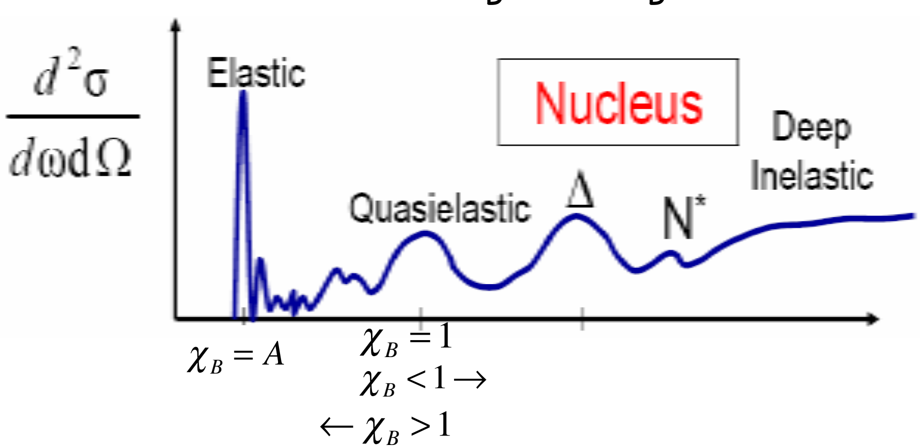
Nucleus	% 2N corr.
d	4.1 ± 0.8
^{3}He	8.0 ± 1.6
^{4}He	15.4 ± 3.2
^{12}C	19.8 ± 4.4
^{56}Fe	23.9 ± 5.3

Short-range correlated nucleons carry ~70% of nucleons' kinetic energy

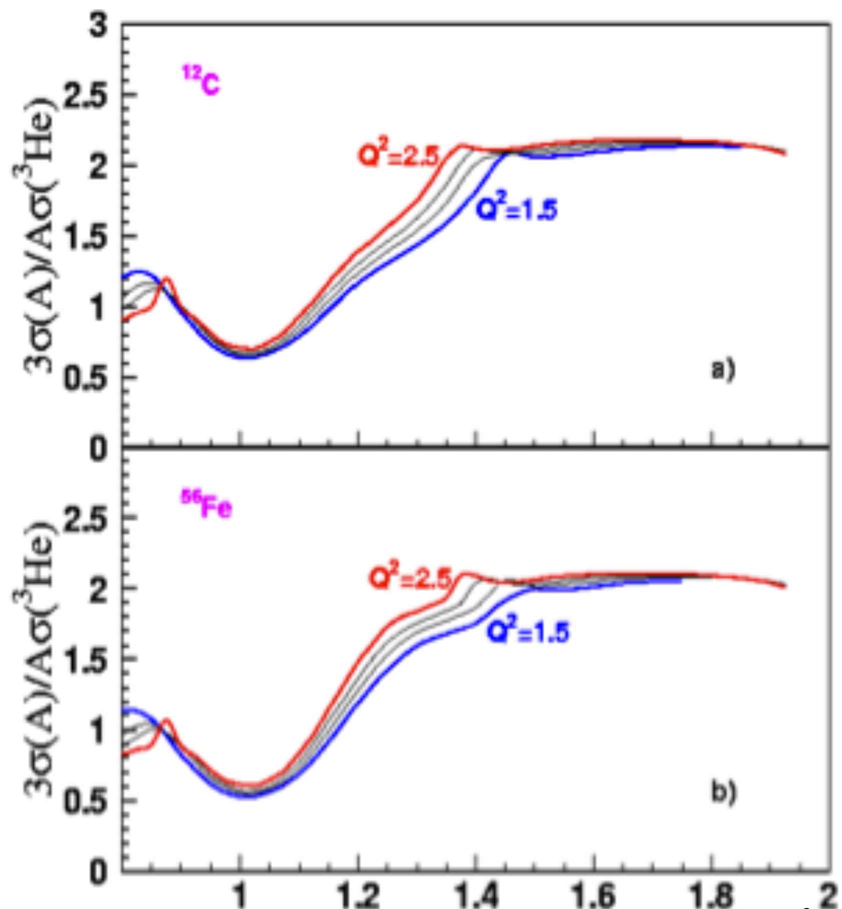
Experimental Handle on SRC?

Predictions by Frankfurt, Strikman, and Sargsian:

- In the high-momentum tail region, the **per-nucleon** inclusive cross-section ratio for nuclei to that of deuterium will scale (be flat) with the value of the ratio of the integrated n(p) strength
- Can be studied by measuring the inclusive A(e,e′) x-section ratio as a function of x_B for $x_B > 1$



A(e,e′)



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

What is the Story with $x_B > 1$?

DIS

- x_B is the fraction of momentum carried by struck quark

$$0 \le x_B \le 1$$

Nuclear Reactions

- x_B determines the number of nucleons involved in the reaction

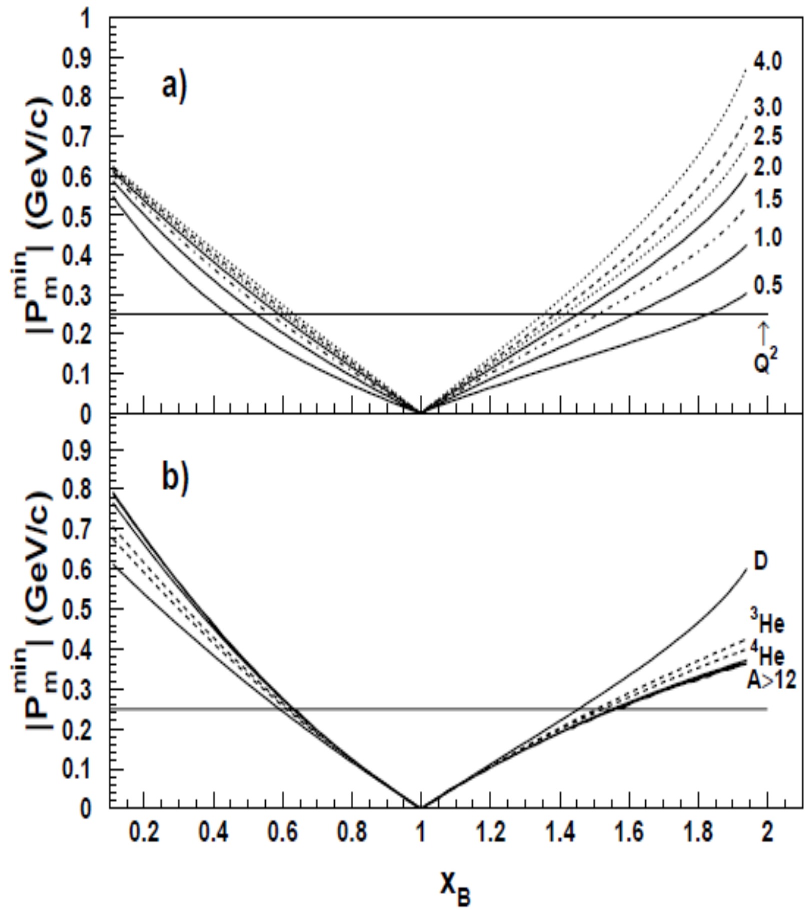
$$0 \le x_B \le A$$

- In A(e,e'), x_B determines the minimum momentum of the struck nucleon
- Small contributions from MEC, Δ

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

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

$$\omega = E' - E$$



Preferred Kinematics for Studying SRC

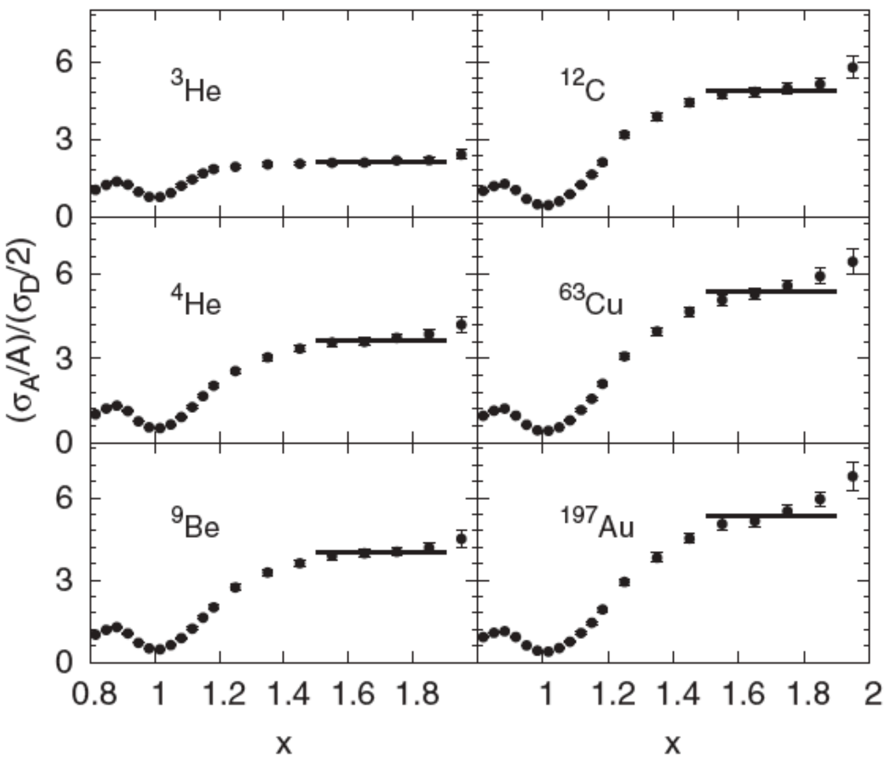
We can select kinematics that minimize competing dynamical processes that mimic SRC

- $Q^2 > 1$ (GeV/c)^2
  - Minimize competing 2-body effects i.e. MEC
  - Minimize and provide handle on FSI
- Low ω side of quasi-elastic peak
  - Minimize contribution from nucleon excitation i.e. pion production, Δ and other resonances
- $x_B > 1$
  - Select minimum momentum of nucleon – can select nucleons in the high-momentum tail

Universality of SRC (Scaling)

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

$$a_2(A/d) = \frac{\sigma(A)/A}{\sigma(d)/2}$$



A	$\theta_e = 18°$	$\theta_e = 22°$	$\theta_e = 26°$	Inel. sub.
^{3}He	2.14 ± 0.04	2.28 ± 0.06	2.33 ± 0.10	2.13 ± 0.04
^{4}He	3.66 ± 0.07	3.94 ± 0.09	3.89 ± 0.13	3.60 ± 0.10
Be	4.00 ± 0.08	4.21 ± 0.09	4.28 ± 0.14	3.91 ± 0.12
C	4.88 ± 0.10	5.28 ± 0.12	5.14 ± 0.17	4.75 ± 0.16
Cu	5.37 ± 0.11	5.79 ± 0.13	5.71 ± 0.19	5.21 ± 0.20
Au	5.34 ± 0.11	5.70 ± 0.14	5.76 ± 0.20	5.16 ± 0.22
$\langle Q^2 \rangle$	2.7 GeV^2	3.8 GeV^2	4.8 GeV^2	
x_{min}	1.5	1.45	1.4	

Additional data on A/d and A/^{3}He from SLAC, Hall B

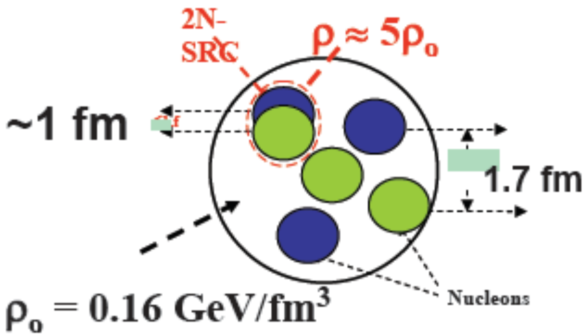
- **Note:** Can study 3-nucleons SRC in kinematics with $x_B > 2$
- Data available, to be published

Limitations of A(e,e')

- Cannot study relative momenta of nucleons in pair
- Cannot study CM motion of pair
- Cannot study isospin structure of pair
- Cannot study NN interactions at small distances

Triple-Coincidence SRC Experiments

Coordinate-space view of nucleus



- High local density

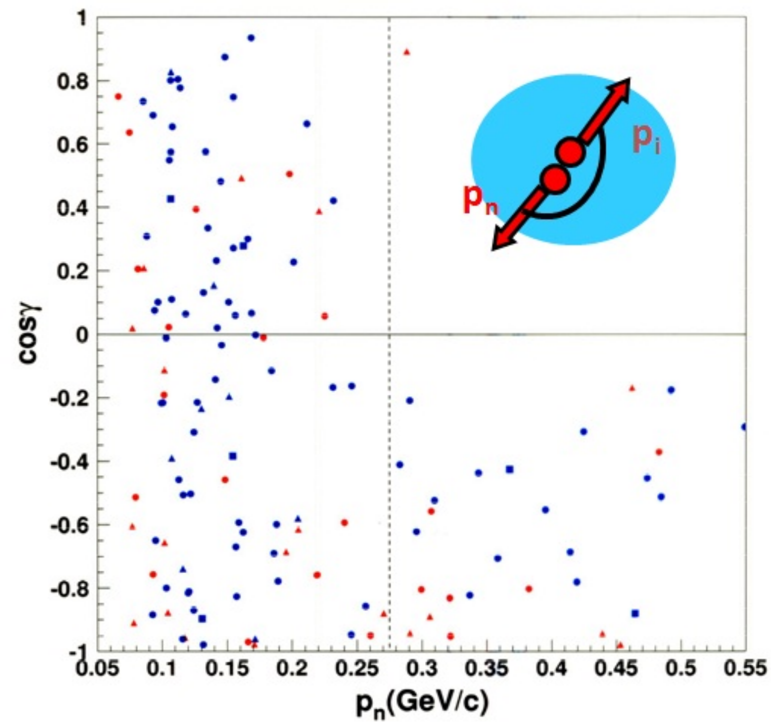
Momentum-space view of 2N SRC

- "Deuteron-like" pair of nucleons with high relative momenta in opposite directions – "High" is above Fermi momentum, k_F
- Pair has low CM momentum relative to K_F
- When one of the pair's nucleons is kicked out in hard scattering, the second recoils out in the direction opposite to p_i
- A-2 remains relatively undisturbed

First experiment in BNL

Tang *et al.* **PRL** 042301 (2003)

$^{12}C(p,ppn)$



pn pair detected in opposite directions

92^{+8}_{-18} of high p_i protons have a paired neutron

First $^{12}C(e,e'pN)$ Experiment - JLab

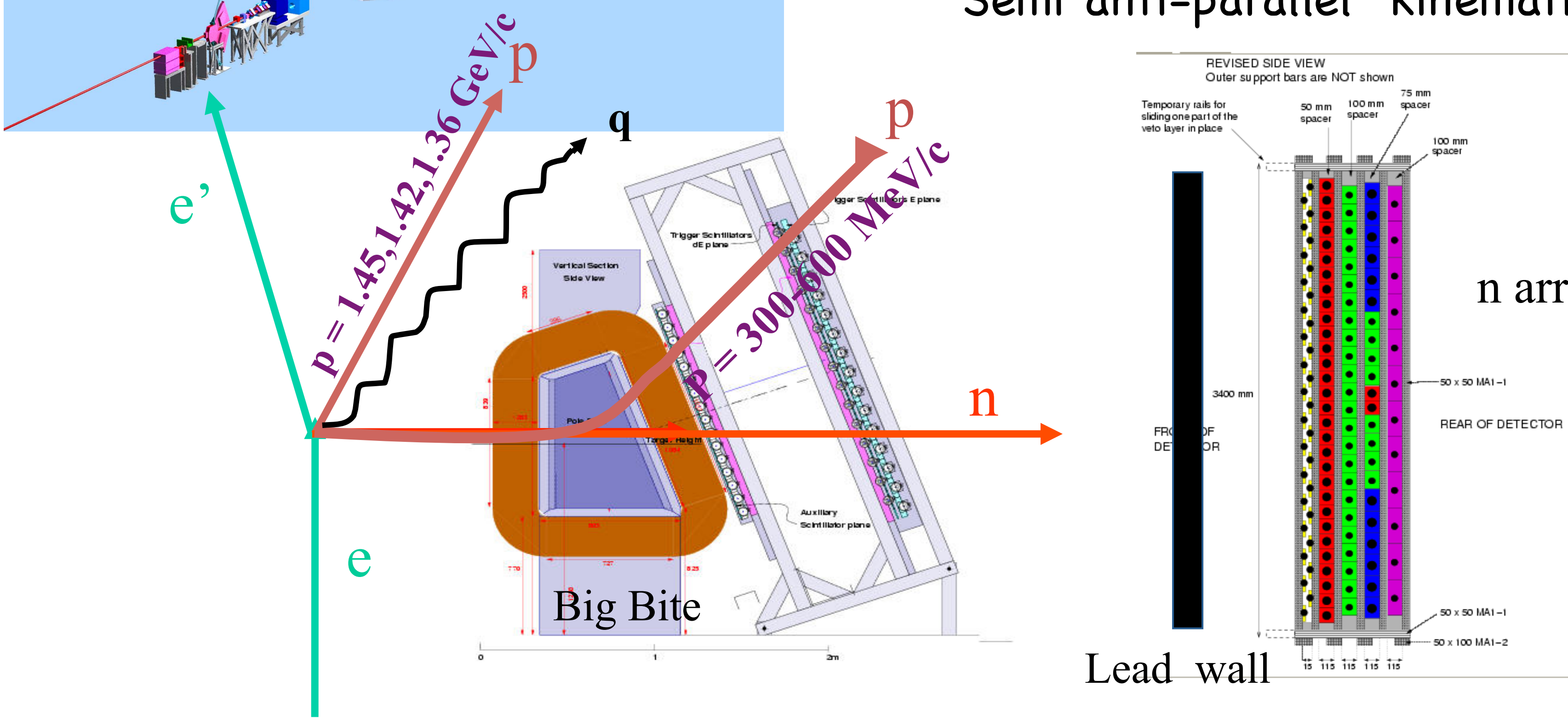
Use $^{12}C(e,e'p)$ as a tag to measure $^{12}C(e,e'pN)/^{12}C(e,e'p)$

Optimized kinematics:

$Q^2 \approx 2.0$

$x_B \approx 1.2$

"Semi anti-parallel" kinematics



What Did We Measure?

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

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

Corrected for acceptance

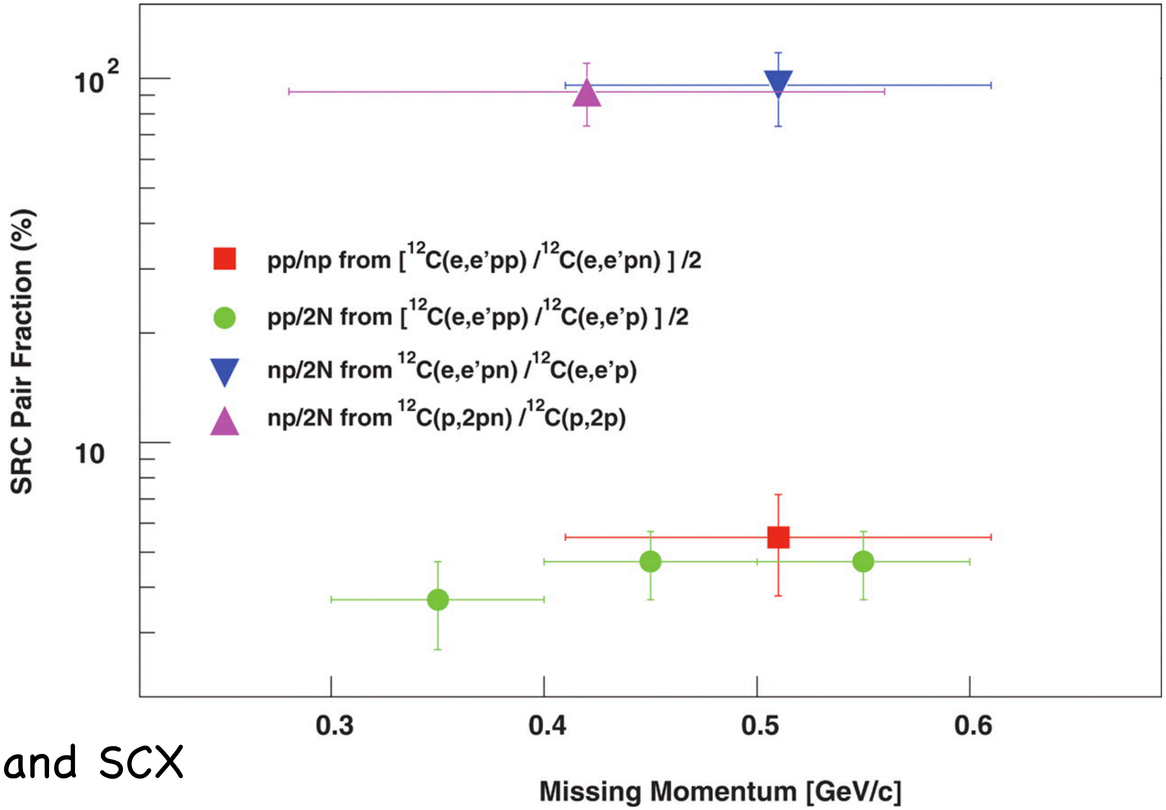
$$\frac{^{12}C(e,e'pn)}{^{12}C(e,e'p)} = 96^{+4}_{-23}\%$$

$$\frac{^{12}C(e,e'pn)}{^{12}C(e,e'pp)} = 9.0 \pm 2.5$$

Corrected for det. Efficiency and SCX

- CM momentum of pair σ_{CM}=136±20 MeV/c {(σ_{CM}(BNL)=143±17; σ_{CM}(Ciofi degli Atti & Simula)=139 MeV/c}

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

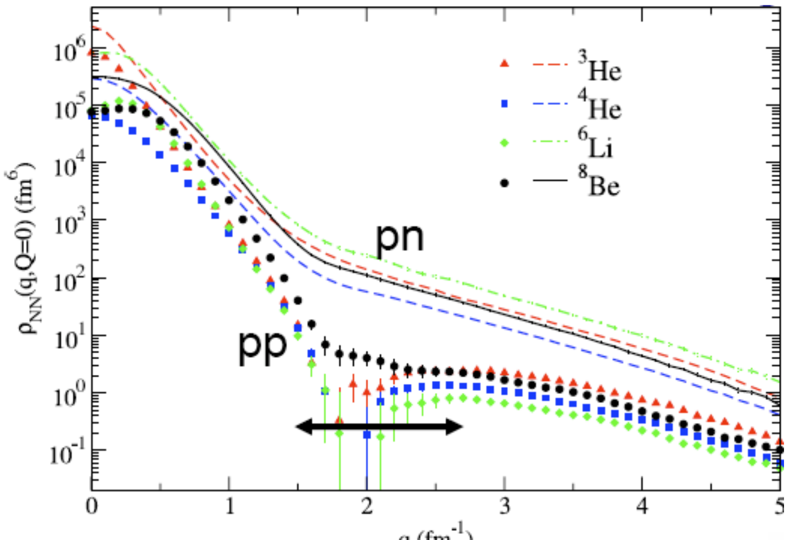


R. Subedi et al., Science **320** (5882), 1476 (2008)

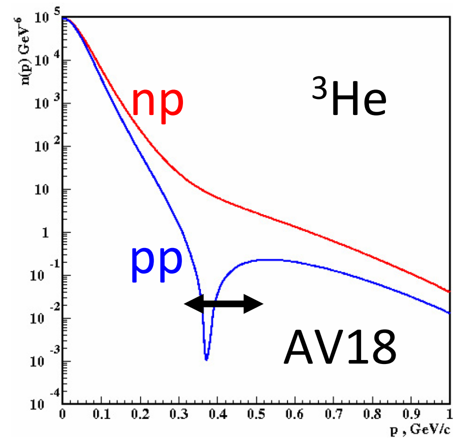
np SRC is ~18 times pp (nn) SRC!!!

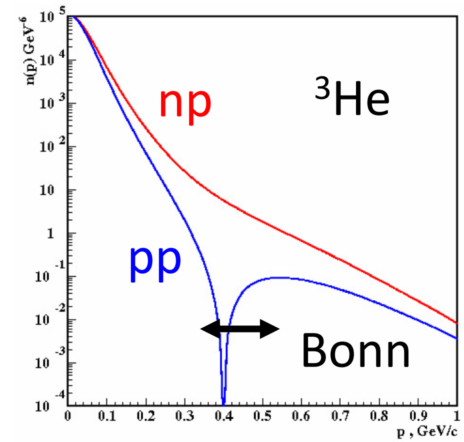
pp vs. pn Short-Range Correlated Pairs

Why are there ~18 times more np than pp correlated pairs?



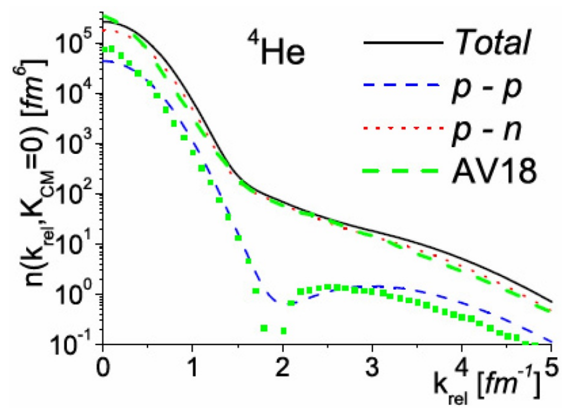
Schiavilla, Wiringa, Pieper, Carlson, PRL **98**, 132501 (2007)



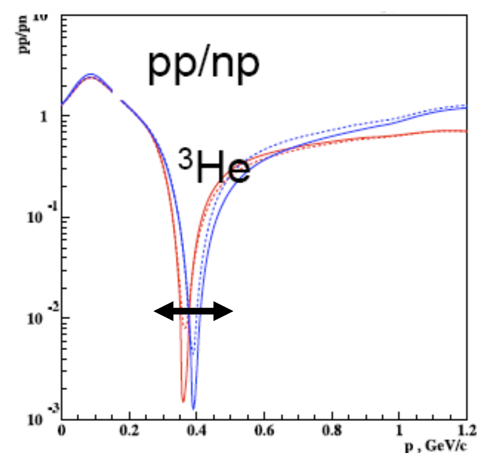


Excess strength in the np momentum distribution at 300-500 MeV/c due to short-range tensor NN potential

All calculations at $Q=p_{CM}=0$
pn/pp ratio is smaller for larger p_{CM}

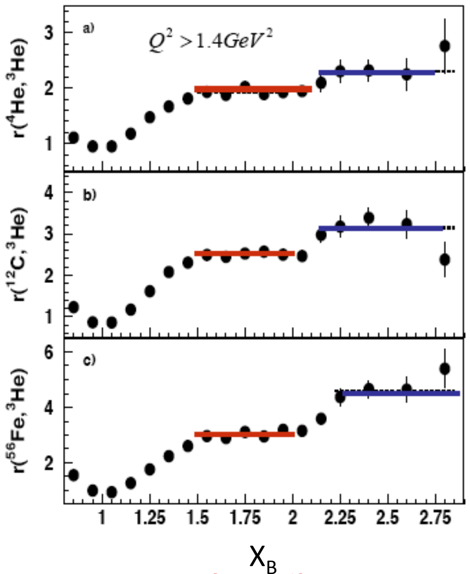


Ciofi degli Atti and Alvioli, PRL **100**, 162503 (2008)



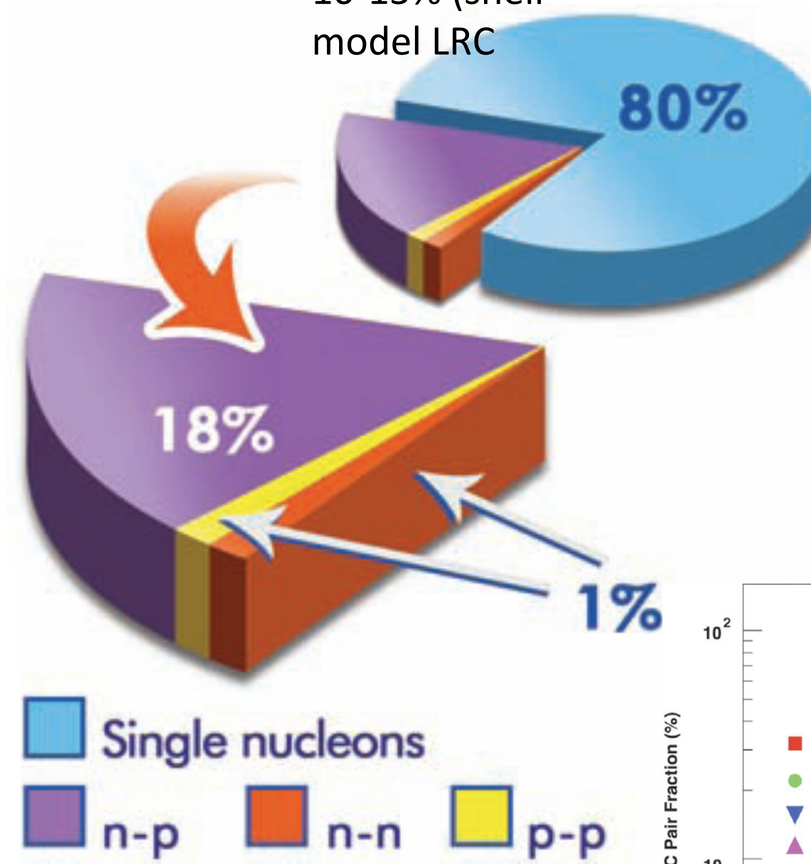
Sargsian, Abrahamyan, Strikman, Frankfurt **PRC 71** 044615 (2005)

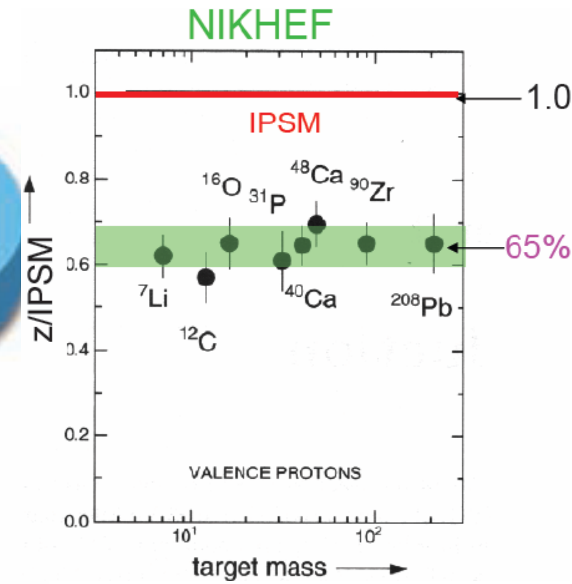
Structure of ^{12}C



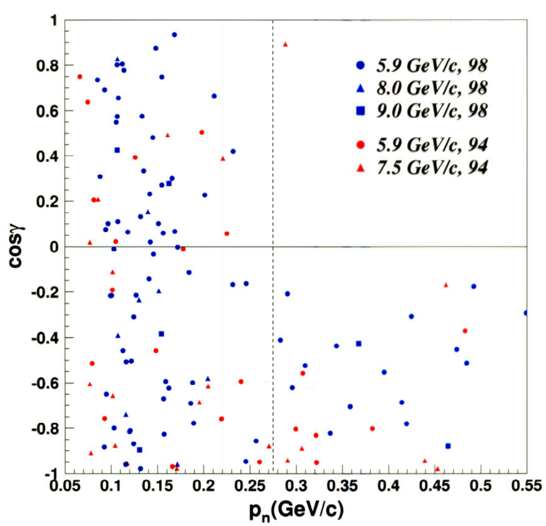
A(e,e‘)

Including 10-15% (shell-model LRC

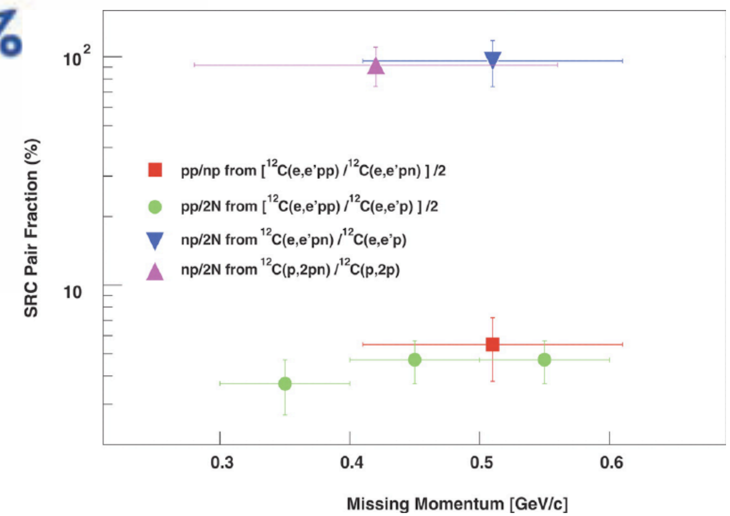




A(e,e‘p)



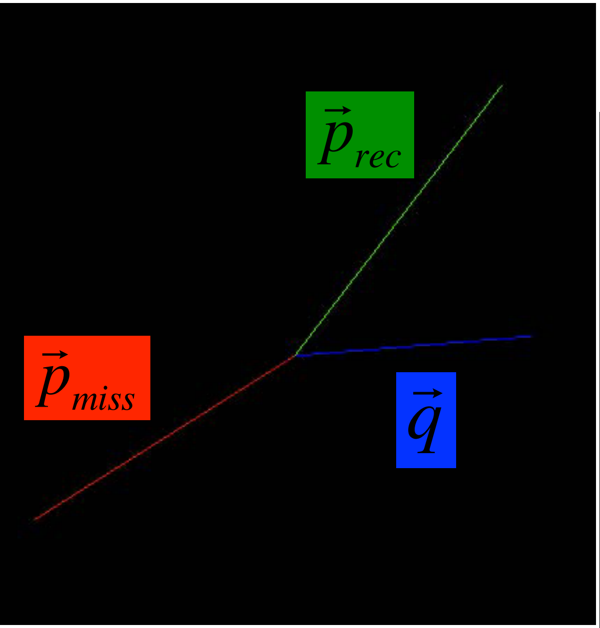
$^{12}C(p,2pn)$



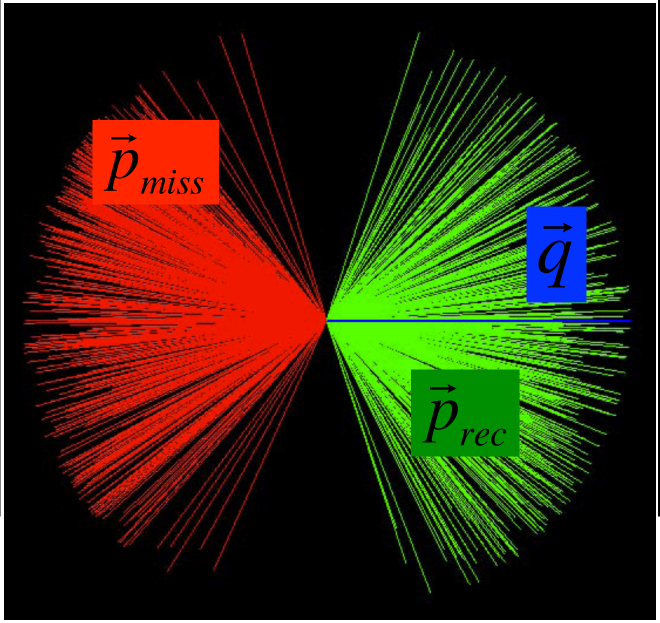
$^{12}C(e,e'pN)$

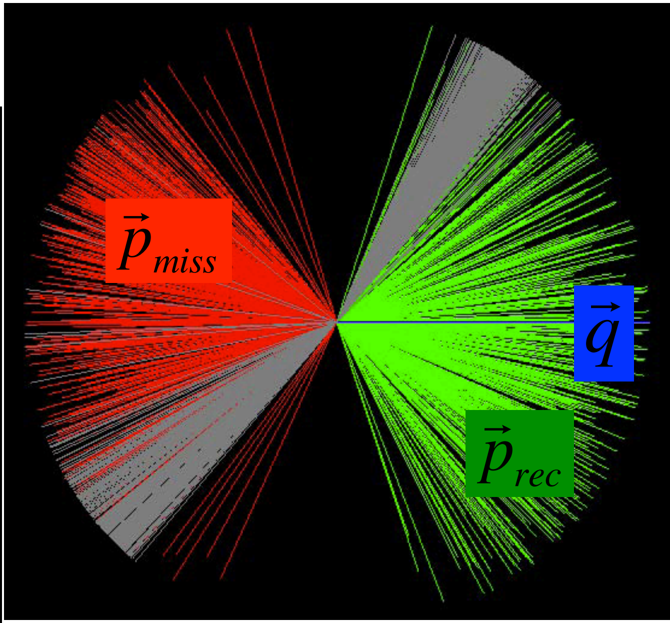
SRC in Data Mining from CLAS E2

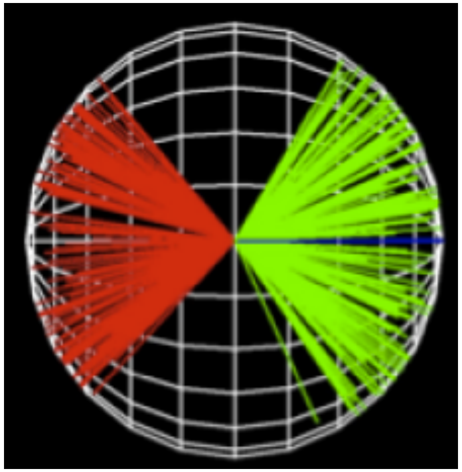
$^{12}C(e,e'pp)$



$\vec{p}_{miss}$ from $^{12}C(e,e'p)$



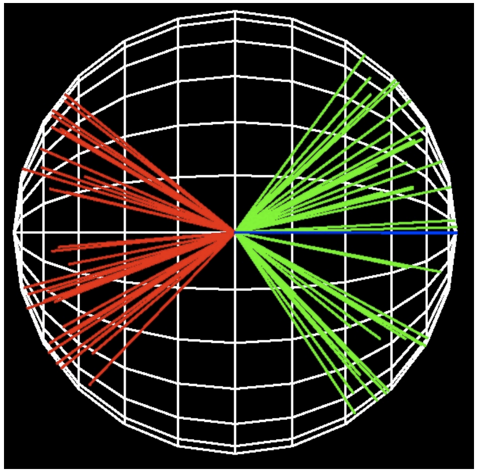




Similar data from

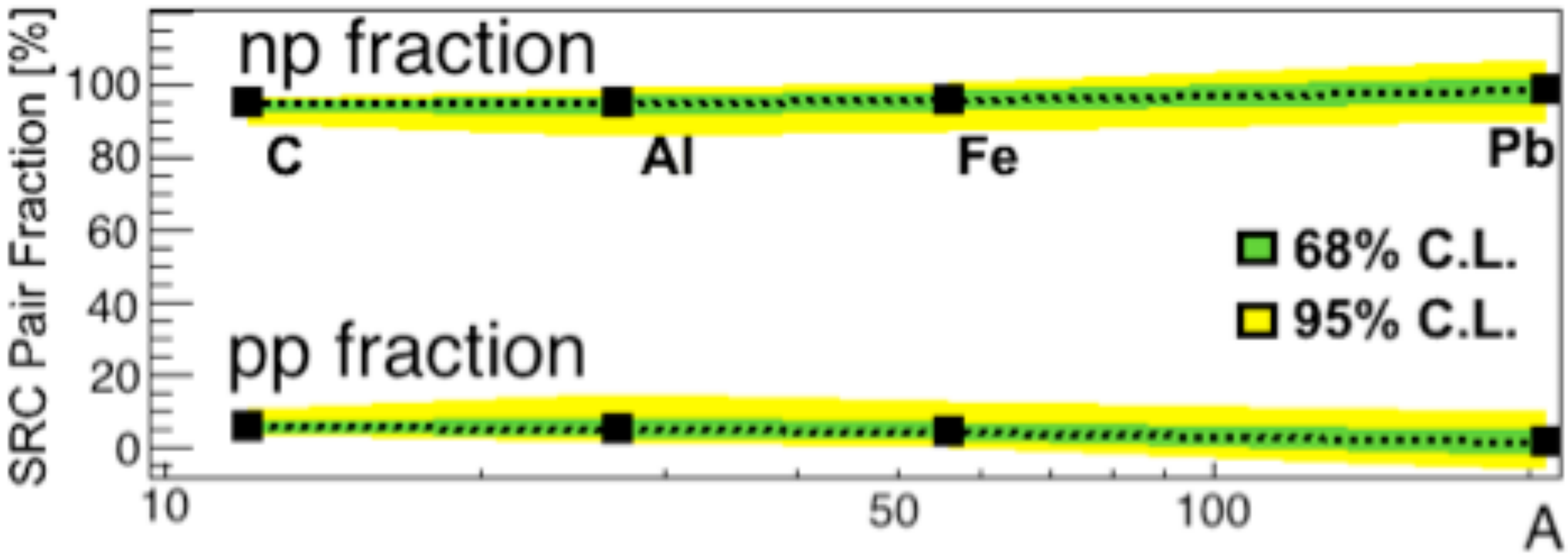
$^{56}Fe(e,e'pp)$

$^{208}Pb(e,e'p)$



Data from O. Hen, TAU

Universal Behavior of SRC



At relative nucleon momenta $300 \leq p_{rel} \leq 500$ MeV/c, where tensor force dominates, np pairs are about 90% all SRC pairs for symmetric and asymmetric nuclei

O. Hen *et al.*, submitted to Science

JLAB Experiment E07-006

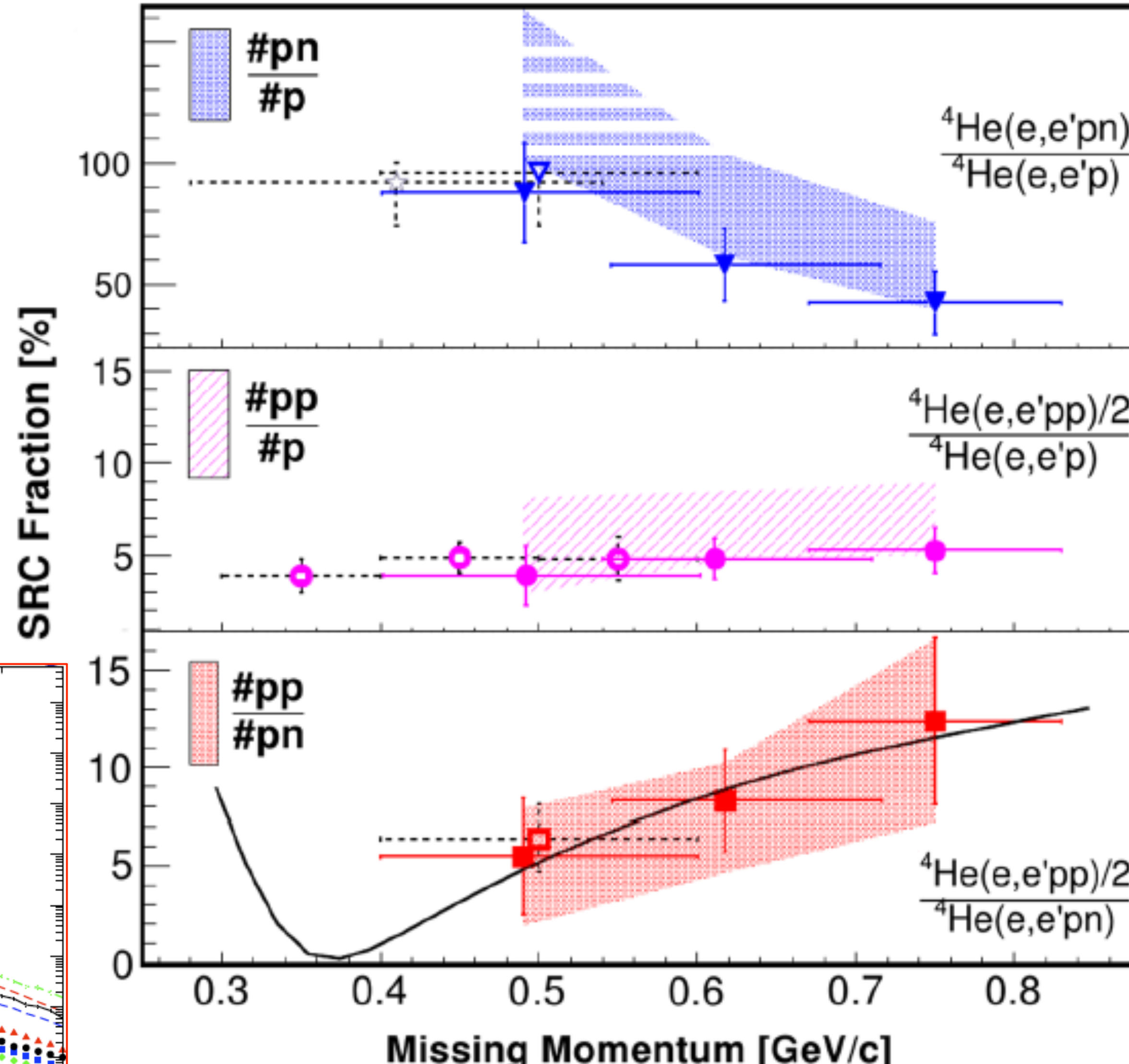
- Similar experimental set-up to $^{12}C(e,e'pN)$ measurement
- ^{4}He target
- Measure $^{4}He(e,e'pn)/^{4}He(e,e'p)$, $^{4}He(e,e'pp)/^{4}He(e,e'p)$, $^{4}He(e,e'pp)/^{4}He(e,e'pn)$ ratios
- Explore higher-momenta nucleons (smaller distances)

Questions:

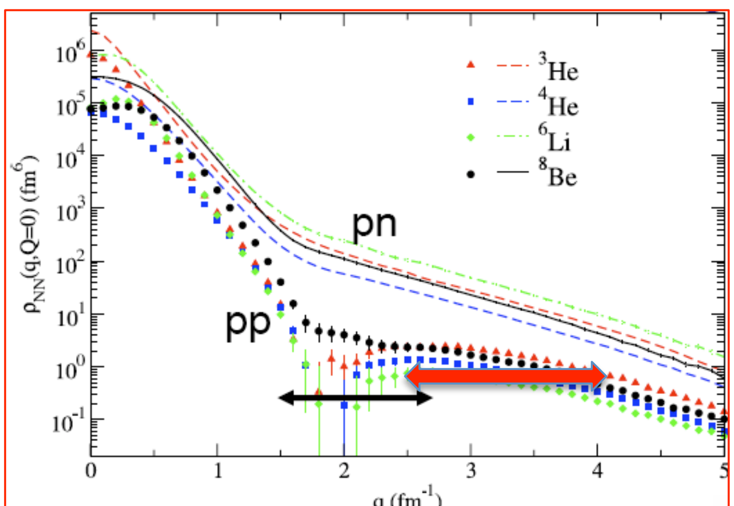
- Does pp/pn ratio change with relative momenta?
- Are there signs of repulsive core?
- Can we use $A(e,e'N_{recoil})$ to study SRC
- Can the reactions be calculated?

^{4}He(e,e'pN) Just Published!

- (e,e'pn)/(e,e'p) decreases with p_{miss}
- (e,e'pp)/(e,e'p) is flat
- (e,e'pp)/(e,e'pn) increases with p_{miss}
- Getting away from tensor force!
- p_{CM} = 100±20 MeV/c
- (e,e'p_{recoil}) in analysis – extract x-sections!



I. Korover *et al.*, PRL **113** 022501 (2014)



Advantages and Limitations of A(e,e′pN)

- Very good control of kinematics
- Can measure pair relative momentum distribution – different components of NN potential
- Can measure pair CM momentum distribution
- Good handle on isospin structure of pair
- Provides more complete data for theory to construct, constrain and test theoretical models

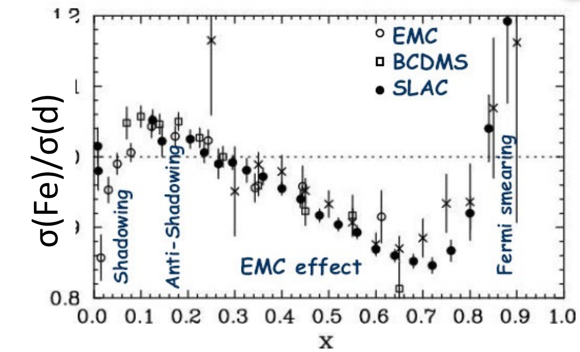
BUT

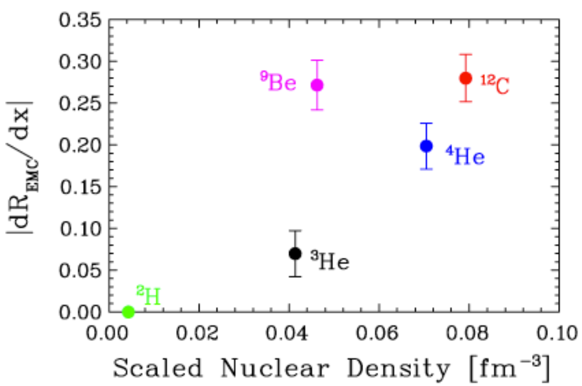
- Very low count rates – large statistical uncertainties
- Relatively small acceptance of recoiling nucleon (because of pair CM motion) – large extrapolations
- If using large acceptance spectrometers (i.e. CLAS), then need to integrate over wide kinematics
- Low neutron detection efficiencies - large extrapolations
- Very difficult to measure and calculate x-sections
- We are currently analyzing data to check whether it is sufficient to use the reactions A(e,e′p_{recoil}) and A(e,e′n_{recoil}), including x-sections

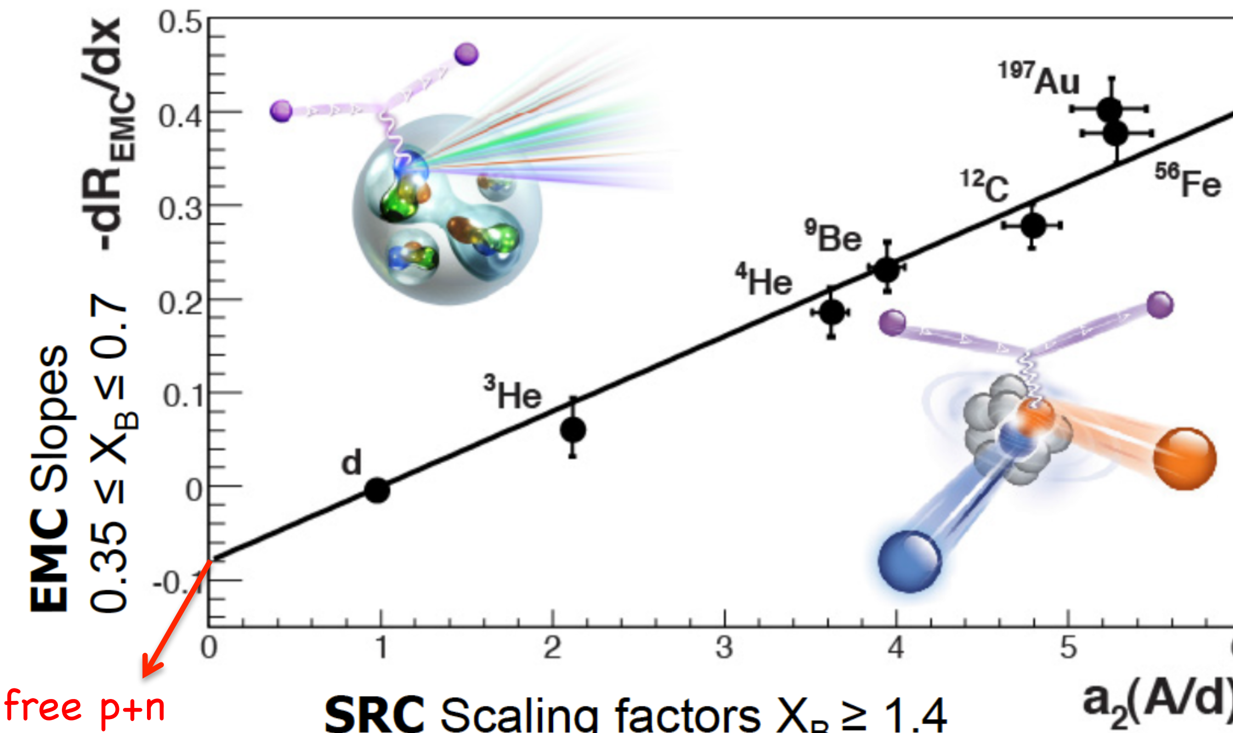
Long Reach of Short-Range Correlations

SRC have a very long reach with possible/probable implications to other aspects of nuclear, particle, and astrophysics

Short-Range Correlations and EMC Effect



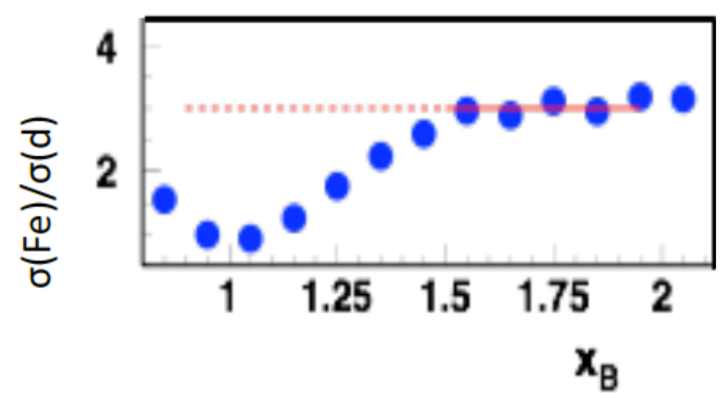




free p+n
b=-0.084±0.004
Constrains F_{2n}/F_{2p}
for free n

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

- Both EMC effect and SRC related to high- momentum nucleons in nuclei
- Large modification of high-momentum nucleons – modification is a function of nucleons virtuality PR12-11-107



Constraining the Free F_{2n}/F_{2p} and u/d PDFs

Constraining the Free F_{2n}/F_{2p}

Using $\frac{\sigma_d}{\sigma_p+\sigma_n} = 1 - a(x_p - b)$ for $0.3 \le x_p \le 0.7$

Where $a = |dR_{EMC}| = 0.07 \pm 0.004$;
$b = 0.34 \pm 0.02$

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

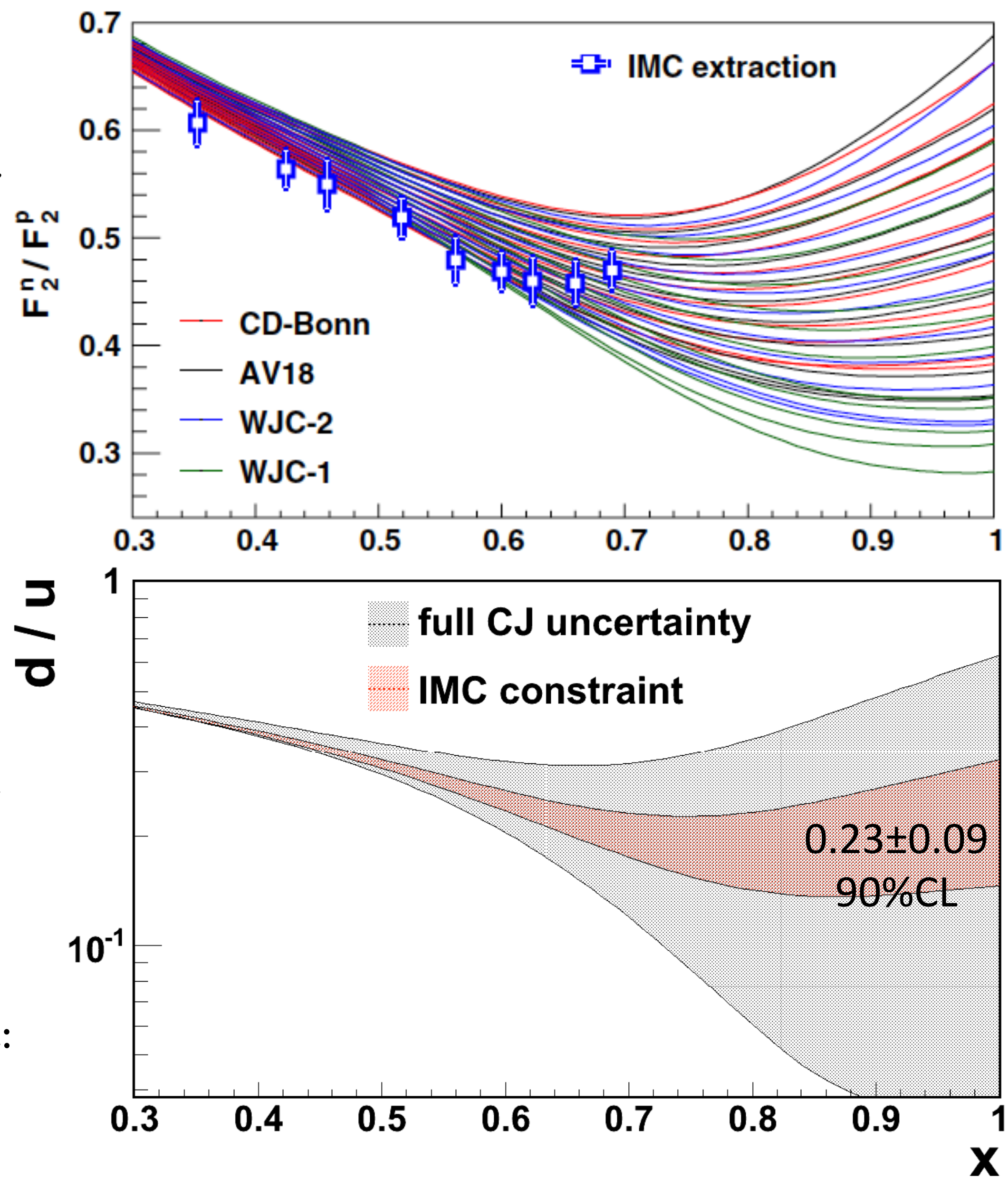
O. Hen *et al.*, PRD **84** 117501 (2011)

Constraining u/d PDF to x_B=1

CTEQ-JLab (CJ): A. Accardi *et al.*, Phys. Rev. D **84**, 014008 (2011)

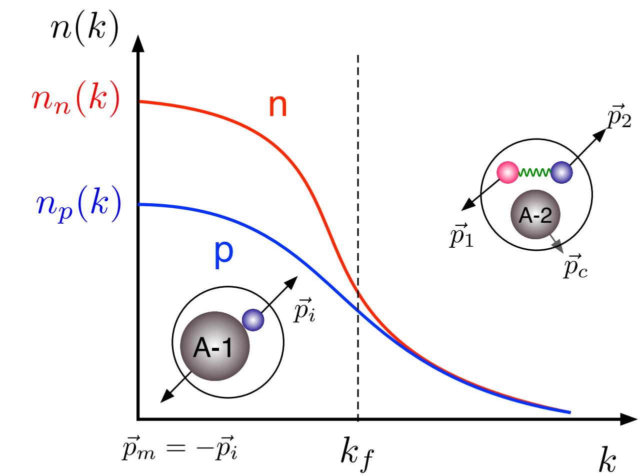
In-Medium Corrections: O. Hen *et al.*, Phys. Rev. D **84** 117501 (2011)

Discussion of additional corrections see: E. Piasetzky, O. Hen and L. Weinstein, arXiv:1209.0636 (2012)



SRC in Asymmetric Nuclei

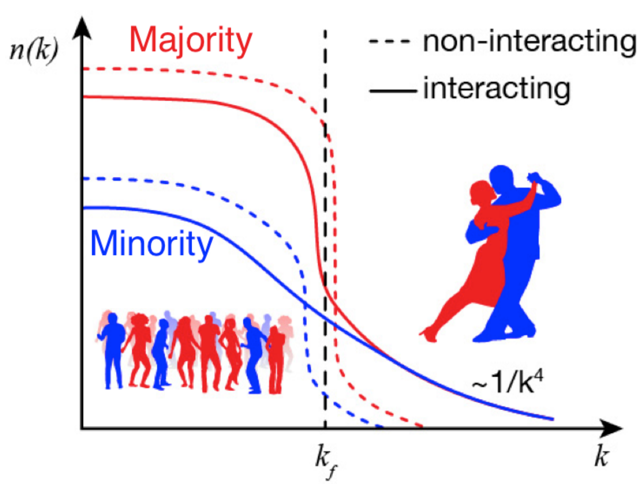
$p < k_f$
Dominated by independent (mean-field) nucleons



$p > k_f$
Dominated by nucleons belonging to SRC np pairs

- On average, the minority type of nucleons will have a larger internal momentum (kinetic energy) than the majority type nucleons.
- Can be tested experimentally!! PR12-13-012

Think of a dance party..



Nucleus	Asymmetry $(N-Z)/A$	$\langle T_p \rangle$	$\langle T_n \rangle$	$\langle T_p \rangle / \langle T_n \rangle$
^{8}He	0.50	30.13	18.60	1.62
^{6}He	0.33	27.66	19.60	1.41
^{9}Li	0.33	31.39	24.91	1.26
^{3}He	-0.33	14.71	19.35	**0.76**
^{3}H	0.33	19.61	14.96	**1.31**
^{8}Li	0.25	28.95	23.98	1.21

Additional Implications

Possible Explanation of the NuTev Anomaly

- 3σ difference between standard model prediction of $\sin^2(\theta)_W$ and measurement in ν–Fe scattering is due to faster average u than d due to SRC

I. C. Cloet, W. Benz, A. W. Thomas, PRL 102, 252301 (2009)

Astrophysical Implications

- Constraining the kinetic symmetry energy, the per-nucleon average energy as a function of the fraction of protons, at saturation

C. Xu, A. Li, B.A. Li, J. of Phys: Conference Series **420**, 012190 (2013)

I. Vidana, A. Polls, C. Providencia, Phys. Rev. C **84**, 062801(R) (2011)

A. Carbone, A. Polls, A. Rios, Euro. Phys. Lett. **97**, 22001 (2012)

- Equation-of-state of neutron stars

J. M. Lattimer and Y. Lim, Astro. Phys. J **771**, 51 (2013)

- Cooling rate of neutron stars

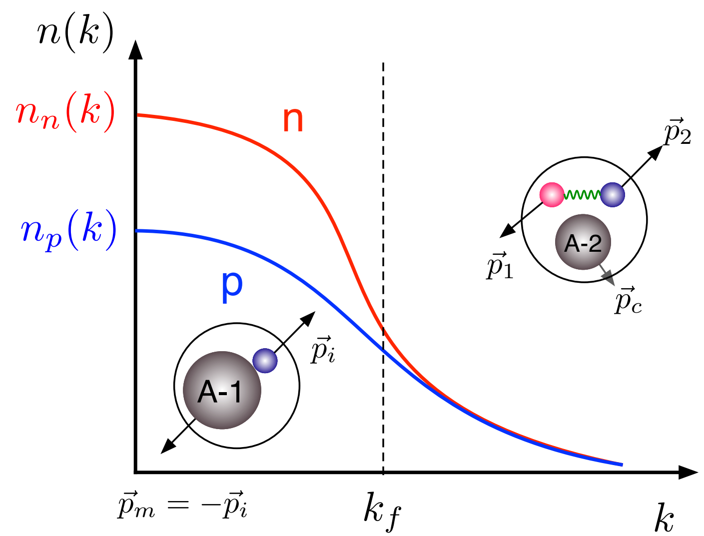
L. Frankfurt, M. Strikman, M. Sargsian

Future Experiments

- PR12-06-105: Inclusive Scattering from Nuclei at x > 1 in the quasi-elastic and deeply inelastic regimes – systematic studies of A(e,e′) on symmetric and asymmetric light, medium, and heavy nuclei to study SRC and EMC

- PR12-11-112: Precision studies of the isospin structure of 2N and 3N correlations using ^{3}He(e,e′) and ^{3}H(e,e′)

- PR12-13-012: Extracting the protons and neutrons momentum distributions in A=3 systems by measuring ^{3}H(e,e′p)/^{3}He(e,e′p) for mean-field and SRC protons



Future Experiments (cont.)

- PR12-11-107: Study of in-medium protons and neutrons F_2 as a function of their virtuality with the reactions $^2H(e,e'p_{recoil})$ and $^2H(e,e'n_{recoil})$ for a range of recoil momenta (smaller and larger than k_F) using HMS, SHMS and LAD

- LOI: Using the above setup, measure the "tagged" EMC effect for SRC recoiling nucleons in $^4He(e,e'p_{recoil})$ and $^4He(e,e'n_{recoil})$

Notes: Expect a flat "tagged" EMC ratio

Expect a steep "tagged" to "untagged" ratio

Preliminary "mined" data analysis (B. Schmookler, MIT) support these expectations

Summary

- Extensive program using various reactions and targets
- Many possible far-reaching implications
- Exciting program ahead

Summary and Outlook

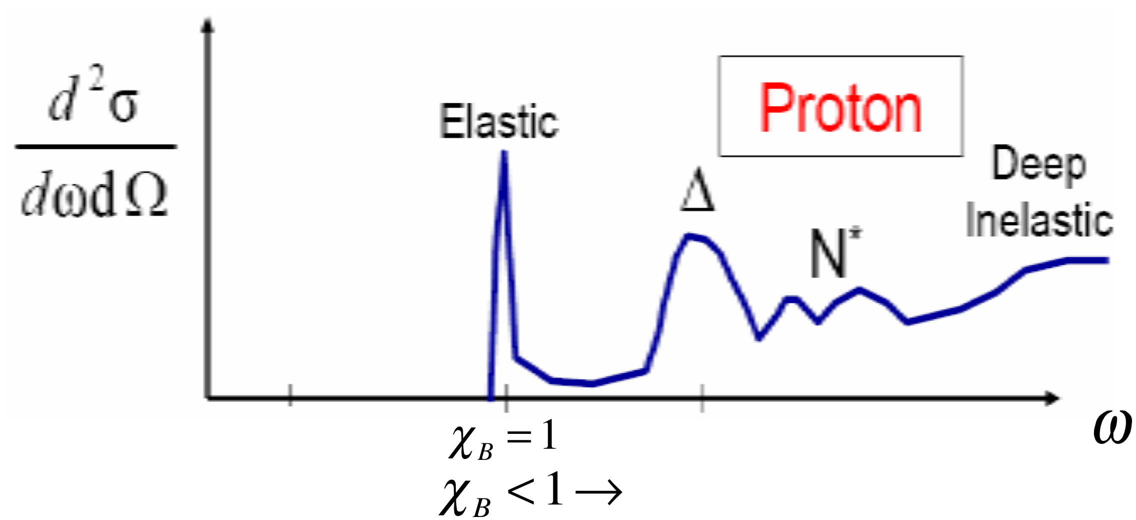
- Huge advances in the experimental studies of SRC in the last ~15 years
- Huge increase in theoretical interest and activities
- Electron inclusive, semi-inclusive, and triple-coincidence measurements are complementary
- SRC studies may have significant implications to our understanding of topics in nuclear physics, particle physics, and astrophysics
- Future studies possible using hadron beams, 12 GeV electron beam at JLAB, and electron-ion colliders
- Among future topics:
  - Systematic studies of symmetric and asymmetric nuclei using A(e,e′)
  - Possible studies of momentum distributions in ^{3}H and ^{3}He using A(e,e′p) – proposal
  - Delta-Delta correlations – L. Weinstein, M. Strikman
  - Three nucleon correlations using A(e,e′) and A(e,e′pNN)
  - Nucleon modifications in high-momentum pairs – approved proposal – S. Wood
  - EMC effect with tagged high-momentum recoiling nucleons – B. Schmookler
  - ....

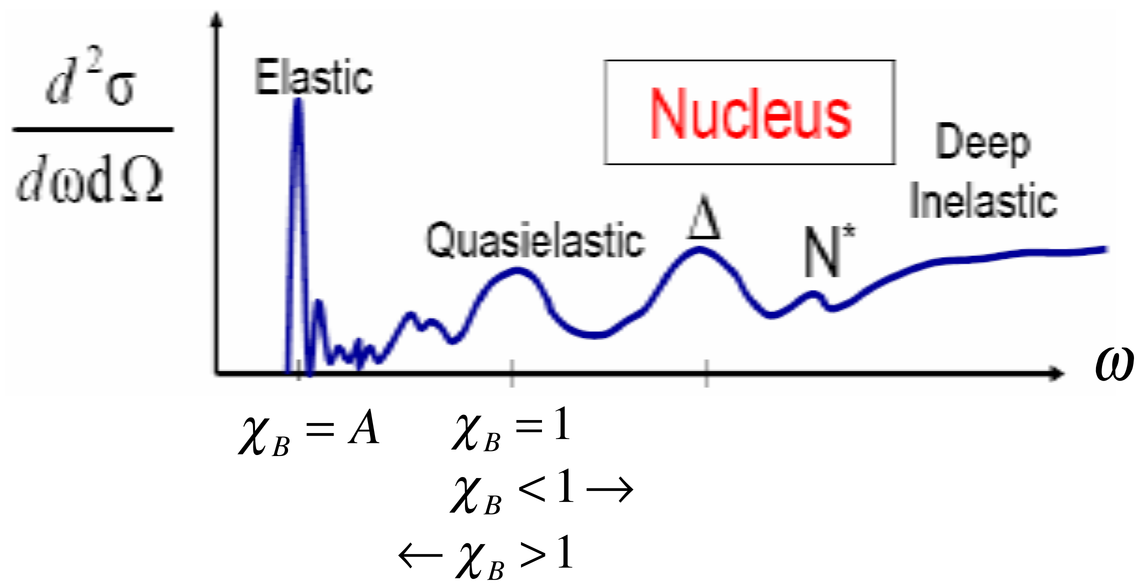
Inclusive Electron scattering

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

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

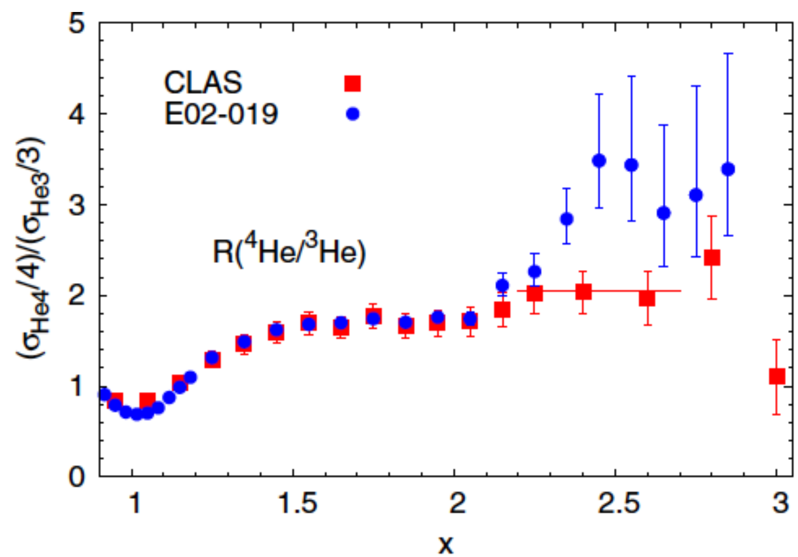
$$\omega = E' - E$$





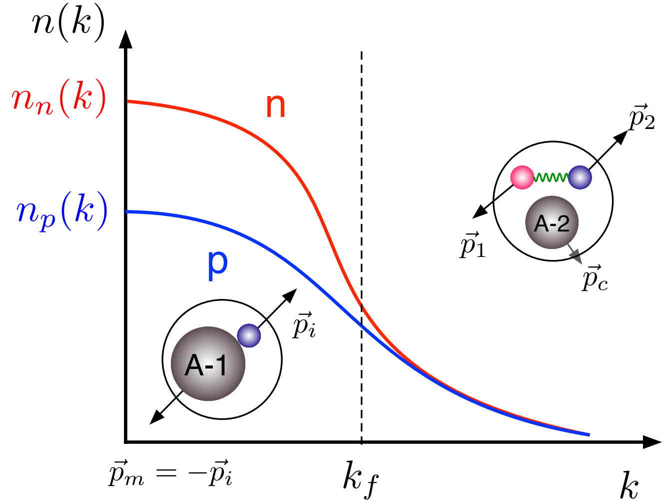
Limitation of Inclusive Scattering in Studying SRC

- No way to study relative momentum of nucleons in pair
- No handle on pair CM momentum
- No handle on isospin structure of pair
- can't use to study N-N interactions at small distances
- And, not all is well..



SRC in Asymmetric Nuclei

$p < k_f$
Dominated by independent (mean-field) nucleons

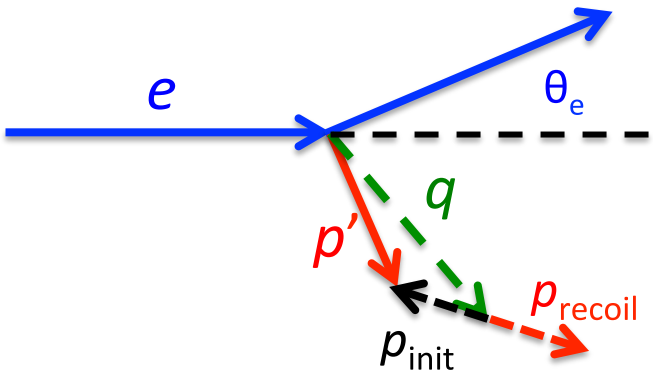


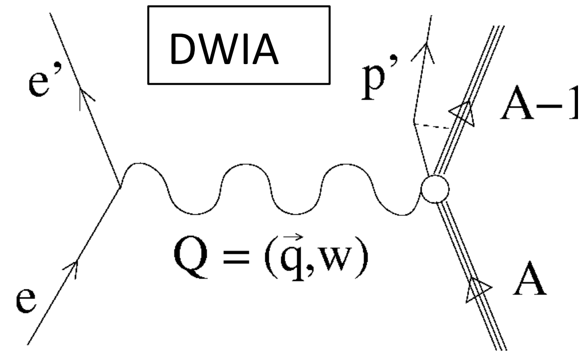
$p > k_f$
Dominated by nucleons belonging to SRC np pairs

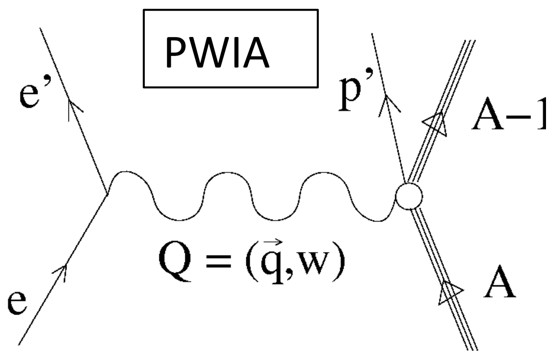
- If there are fewer protons (neutrons) than neutrons (protons) then the protons (neutrons) should have higher average momentum and kinetic energy
- Can be tested experimentally – largest effect in $^3H/^3He$

- Possible explanation to NuTeV anomaly if u quark moves faster than d quark
- if $p_p > k^p_{Fermi}$ then possible affect on cooling rate of neutron stars

Semi-inclusive scattering A(e,e′p)







$$E_m = \omega - T_p - T_{A-1}$$

$$= \omega - T_p - \frac{p_m^2}{4m_p}$$

$$\vec{p}_m = \vec{q} - \vec{p}' = -\vec{p}_{init}$$

A(e,e′p) formalism

$S(E_m, p_m)$: probability of finding a nucleon with momentum p_m & separation energy E_m

$\rho(p_m) = \int S(E_m, p_m)\, dE_m$ Nuclear momentum dist.

In PWIA: $$\frac{d^6\sigma}{d\omega\, d\Omega_e\, dE_m\, d\Omega_p} = \kappa \sigma_{ep} S(E_m, p_m)$$

K is a known kinematic factor

σ_{ep} is the half-off-shell electron-proton elementary cross section

In DWIA: $$S_{red}(E_m, p_m, p') = \left[\frac{d^6\sigma}{d\omega\, d\Omega_e\, dE_m\, d\Omega_p}\right] / [\kappa \sigma_{ep}]$$

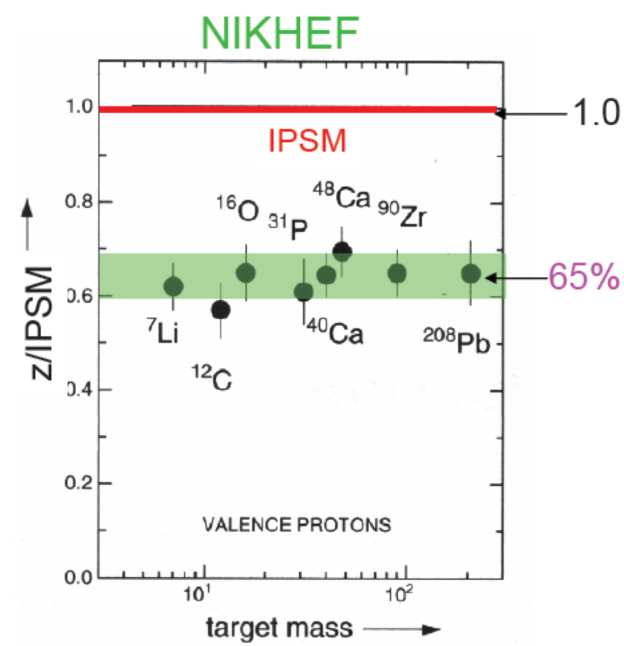
Attractiveness of A(e,e'p)

- Can be used to measure spectral function of nuclei for specific shells
- Shape of spectral functions for $k < k_F$ agrees well with shell-model predictions
- Occupation number is low by ~35%

$$Z_{IPSM} = 2j + 1$$

$$Z_\alpha = 4\pi \int^{k_F} dE\, dk\, k^2\, S(E, k)$$

single particle state α



- Strength is transferred from mean-field region to high-momentum region
- Correlations!
  - ~15% long-range correlations
  - ~20% short-range correlations

2bbu, 3bbu "Distorted" Spectral Functions

$$\frac{d^6\sigma}{dE_e dE_p d\Omega_e d\Omega_p} = K \cdot \sigma_{ep} \cdot S^D(E_m, p_m)$$

$$\eta(p_m) = \int \left(\frac{d^6\sigma}{dE_e dE_p d\Omega_e d\Omega_p} / K \cdot \sigma_{ep}\right) dE_m$$

Compare $S^D(E_m,p_m)$, $n(p_m)$ to model

Performed with High Q^2

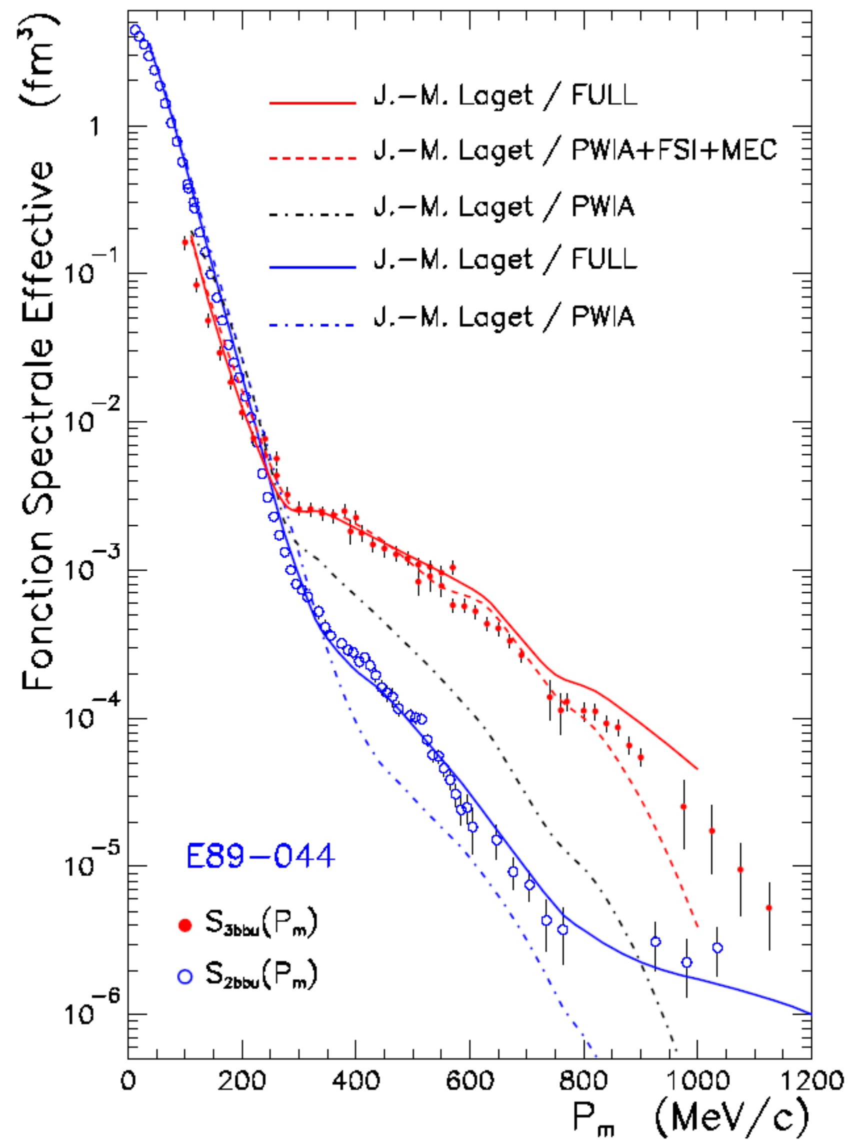
Reduced MEC, Δ contributions

At $p_m > p_F$ distorted spectral function is much larger for 3bbu than for 2bbu due to correlations (SRC)

Calculations reproduce both 2bbu and 3bbu – confidence

No information about whether paired particle is proton or neutron

$x_B \approx 1$



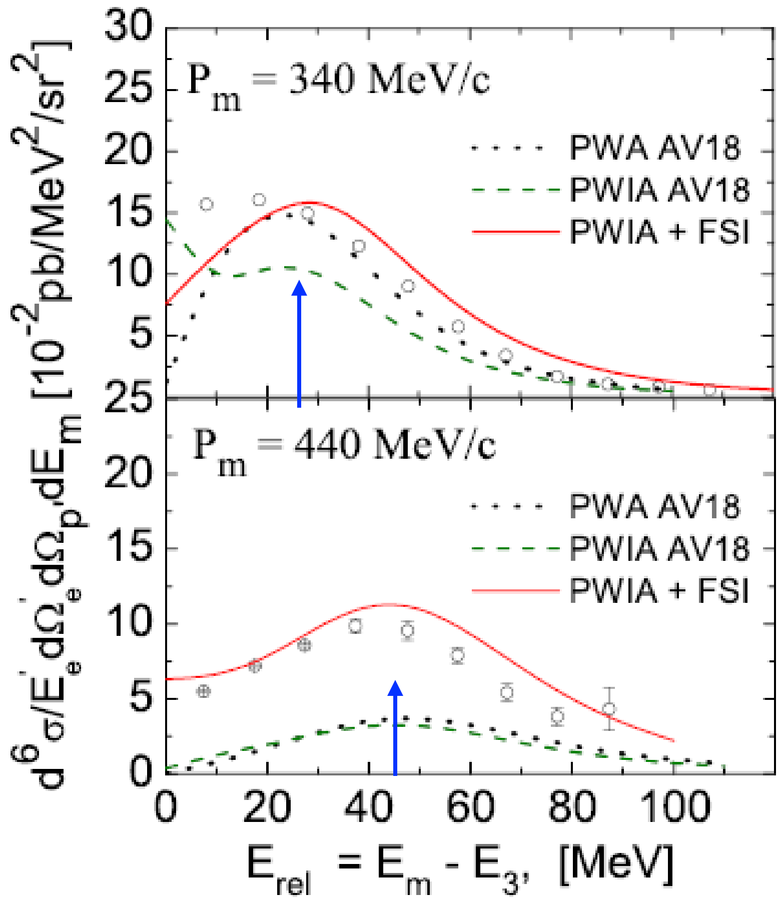
M. Rvachev, F. Benmokhtar

^{3}He(e,e'p)pn – 3bbu (High E_m) and High p_m

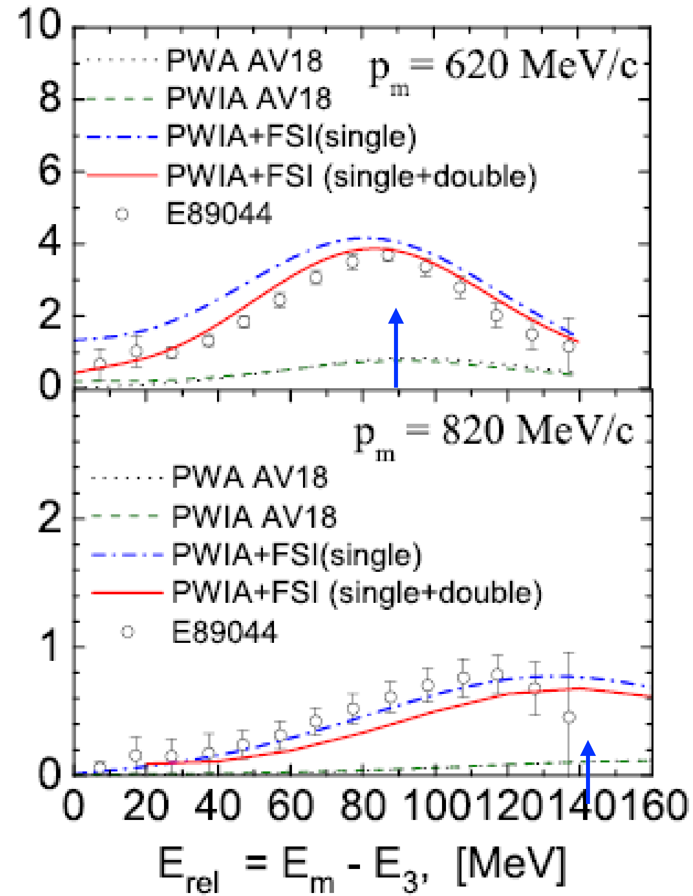
Pair SRC: large p_{rel}; small p_{CM}

→ $$E_m - E_{th} \approx \frac{p_m}{2M_N}$$

Low p_m (still > k_f): correlations



High p_m dominated by FSI



Data: F. Benmokhtar *et al.*, PRL **94**, 082305 (2005)
Calculations: C. Ciofi degli Atti *et al.*

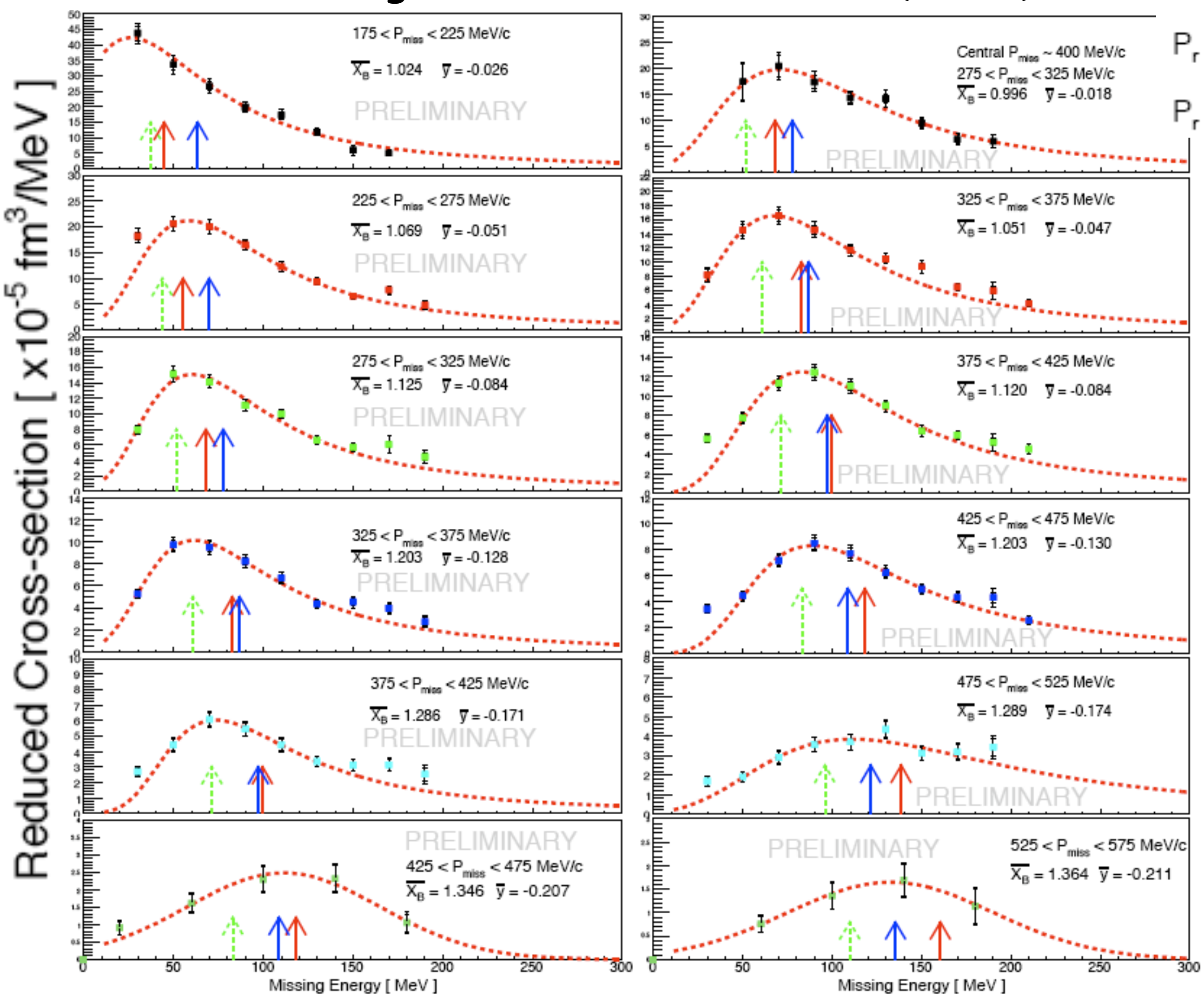
Can We Really Extract Spectral Functions?

P. Monaghan, Ph.D. Thesis, MIT (2008)

$$E_m = \sqrt{\left(M_{A-2} + \sqrt{M_N^2 + p_r^2}\right)^2 - p_r^2} + M_p - M_A$$

$P_r = 0.8\, p_m$

$P_r = 0.8\, p_m$ and A-2=(A-2)+25 MeV



Kin 1 Kin 2

Data at $x_B > 1$

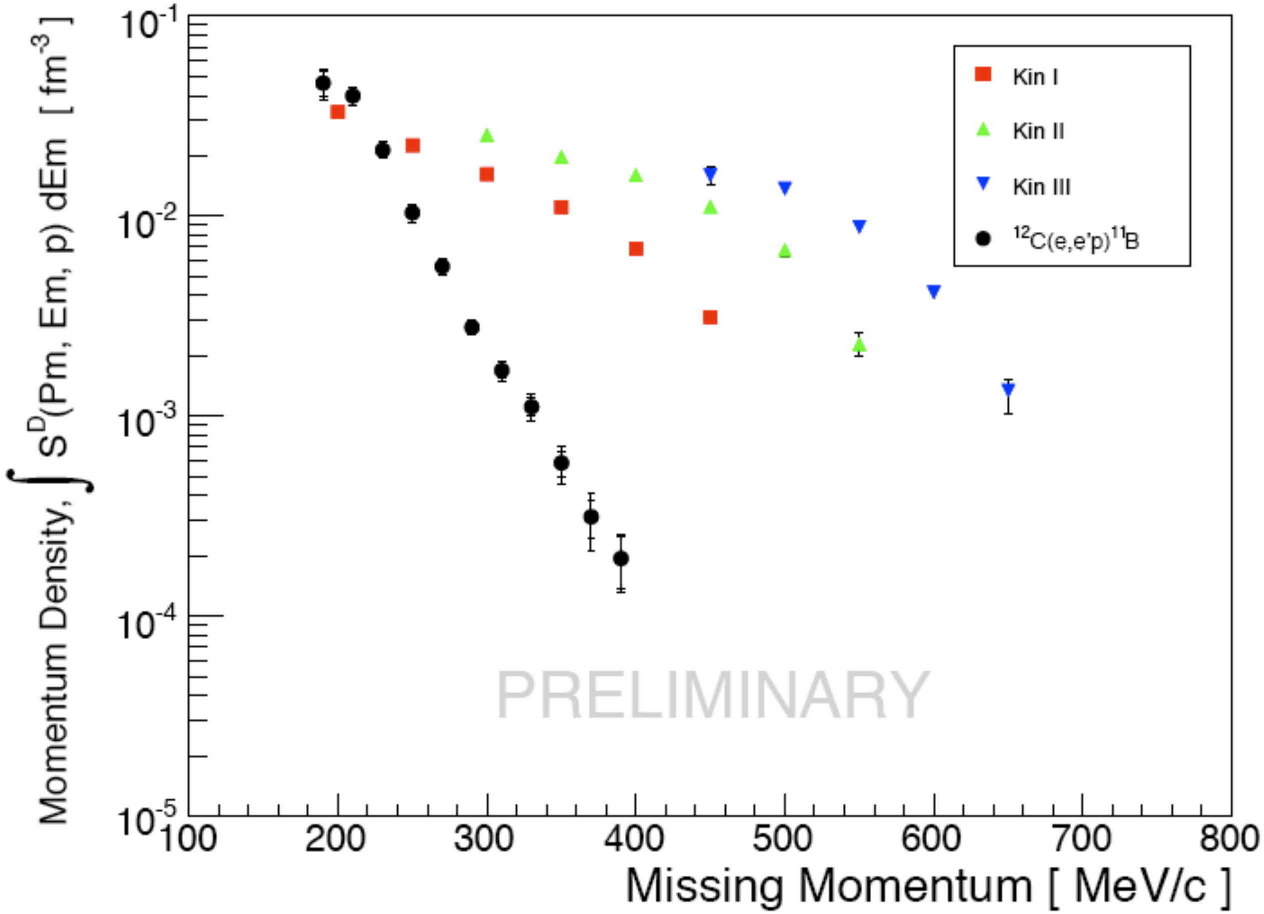
Kin 3 with higher p_m range also available

Extract "effective spectral function" $S^D(E_m,p_m)$

Different $S^D(E_m,p_m)$ for same E_m, p_m but from different kinematics!!!

Cross section does not factorize!!!

Distorted Momentum Density



Not meaningful!! - different for different kinematics

Must compare to model calculations at different kinematics
Or do non-factorized calculations – difficult!

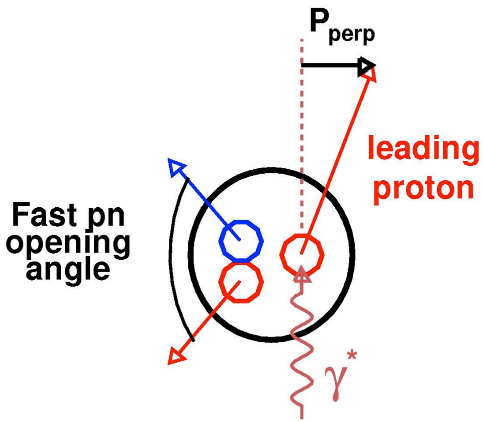
Advantages and Limitations of A(e,e'p)

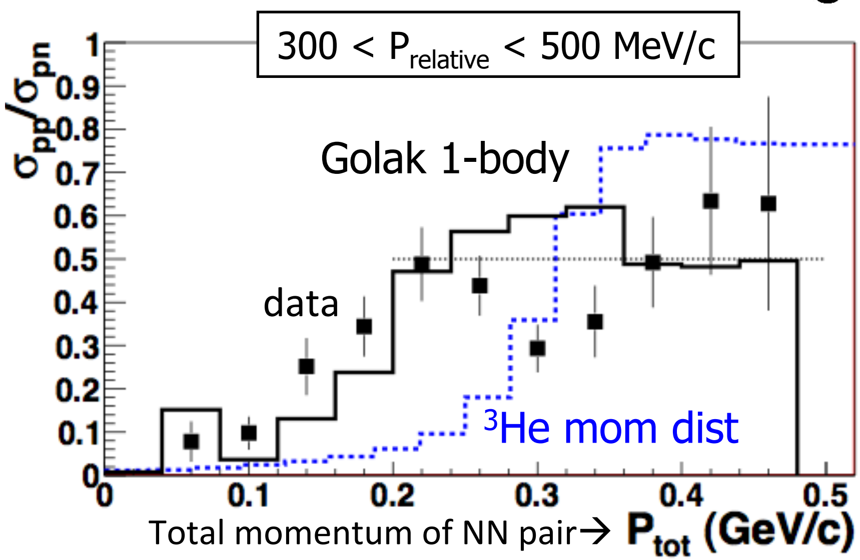
- Relatively easy to perform
- Can control kinematics well
- Reasonable count rate
- Can extract model-dependent spectral functions

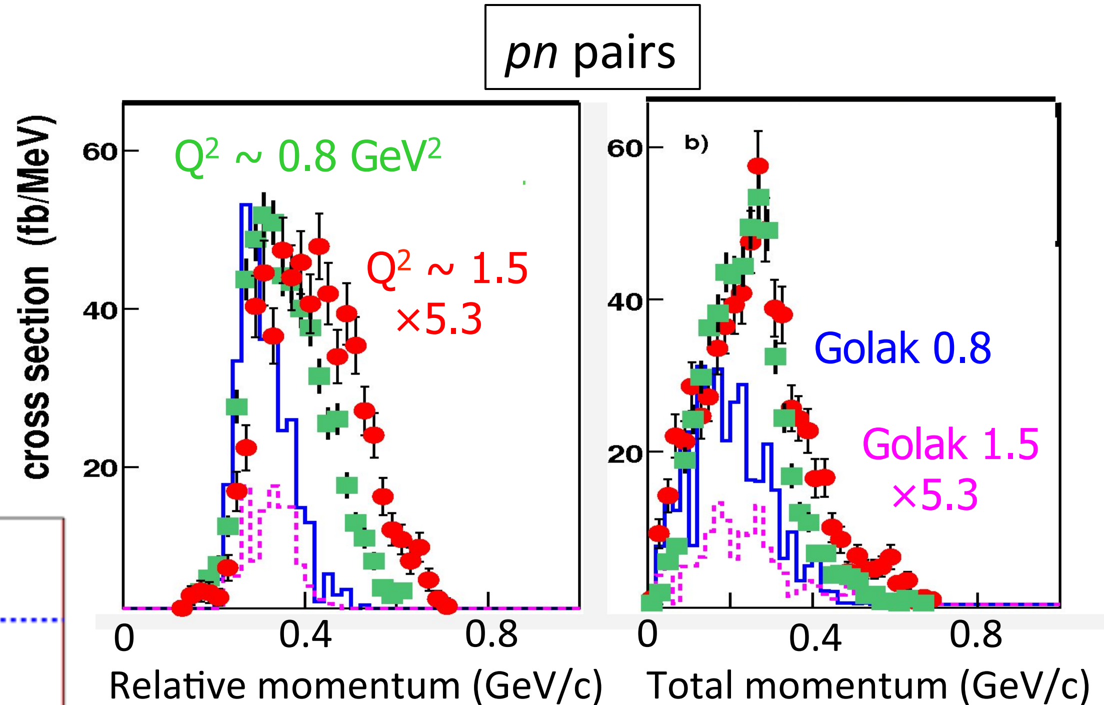
But

- FSI have a significant impact
- Must compare to model calculations
- Must perform non-factorized calculations - difficult
- No information on correlated partner
- No information on pair CM motion

3He(e,e'pp)n Short Range Correlations







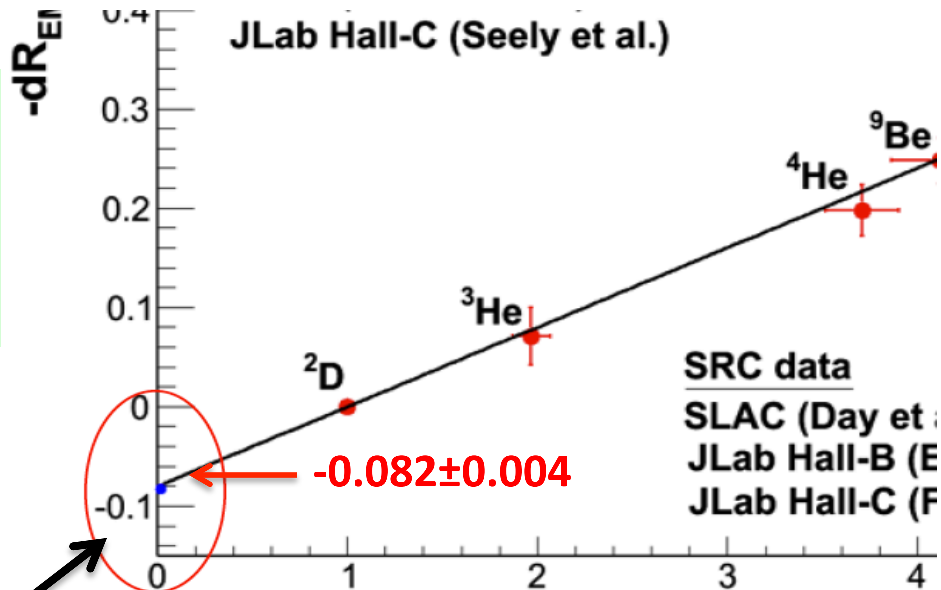
pn pairs dominate at small P_{tot} only
At small P_{tot}: *pp* pair in s-wave (no tensor)
→tensor correlations dominate here

- Measured correlated pair momentum distributions
- Confirmed tensor dominance of SRC at small pair total momentum

Baghdasaryan, Weinstein, et al, PRL **105** (2010) 222501

Explore Connection between EMC and

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)?
- Consequences for F_{2n}

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

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

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

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

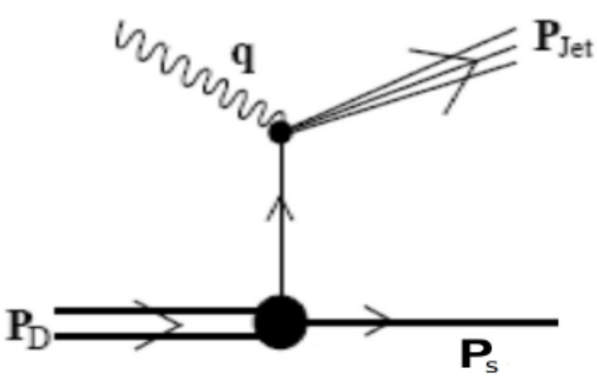
Experimental Program at JLAB

Compare F_2 in DIS off high-momentum nucleons to F_2 of free nucleons

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

Utilize factorization of the d(e,e'N_S) cross section to SF and distorted momentum distribution.

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

$$\frac{d^4\sigma}{d\chi_1 dQ^2 d\vec{p}_S} \Big/ \frac{d^4\sigma}{d\chi_2 dQ^2 d\vec{p}_S} = (K_1/K_2)\left[F_2^*(\chi_1{}', \alpha_S, p_T, Q_1^2)/F_2^*(\chi_2{}', \alpha_S, p_T, Q_1^2)\right]$$

For χ_1'≈0.45 – 0.6 and χ_2'≈0.3 we shall measure:

$$F_2^*(\chi_1{}', \alpha_S, p_T, Q_1^2)/F_2^*(\chi_2{}', \alpha_S, p_T, Q_1^2) = \left(\frac{d^4\sigma}{d\chi_1 dQ^2 d\vec{p}_S}/K_1\right) \Big/ \left(\frac{d^4\sigma}{d\chi_2 dQ^2 d\vec{p}_S}/K_2\right)$$

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

Experimental Method (cont.)

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

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

R_{FSI}: FSI correction factor

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

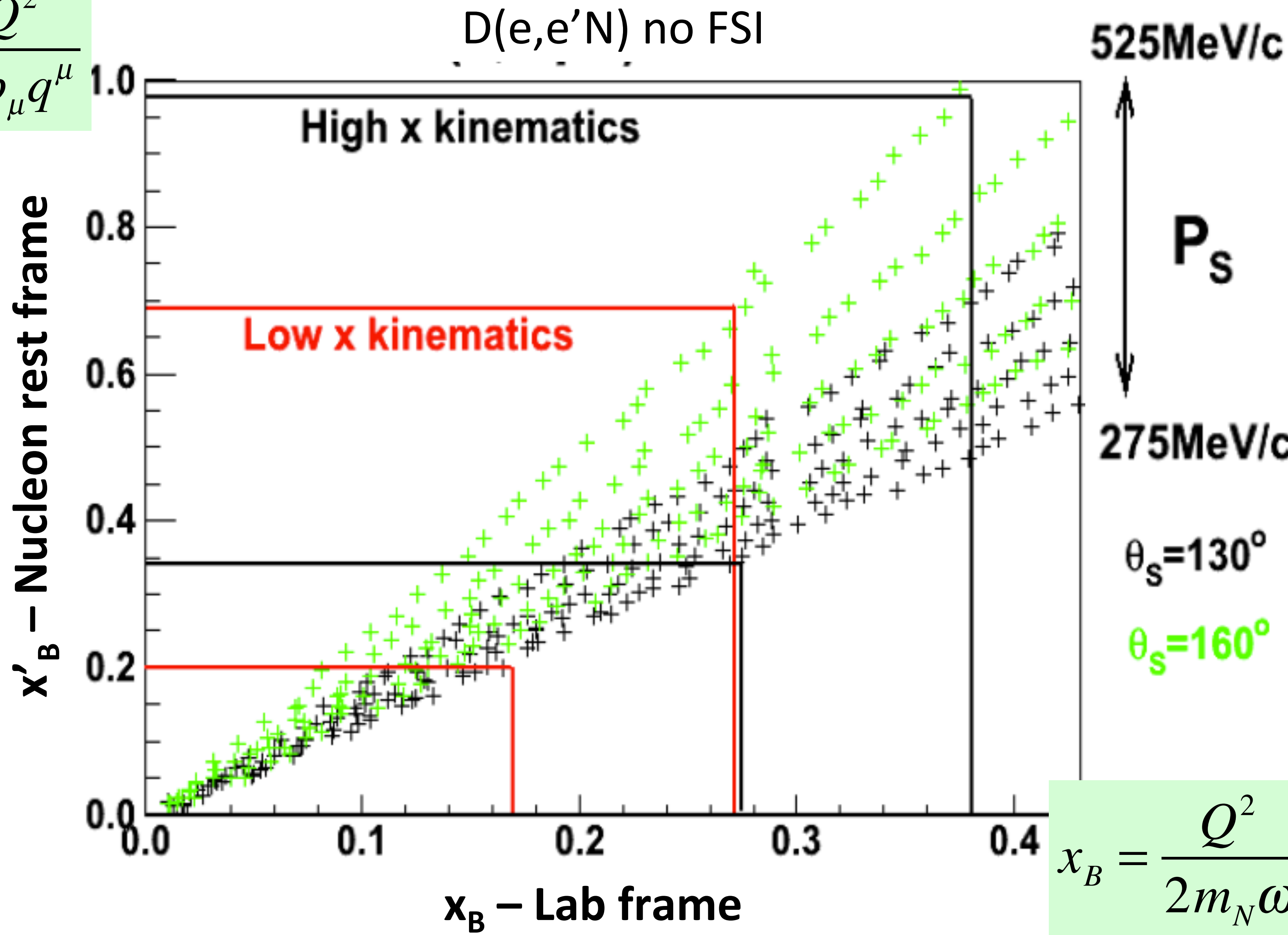
$$0.25 \geq x'_{low} \geq 0.35$$ No EMC is expected

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

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

x_B' vs. x_B (Why x'?)

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

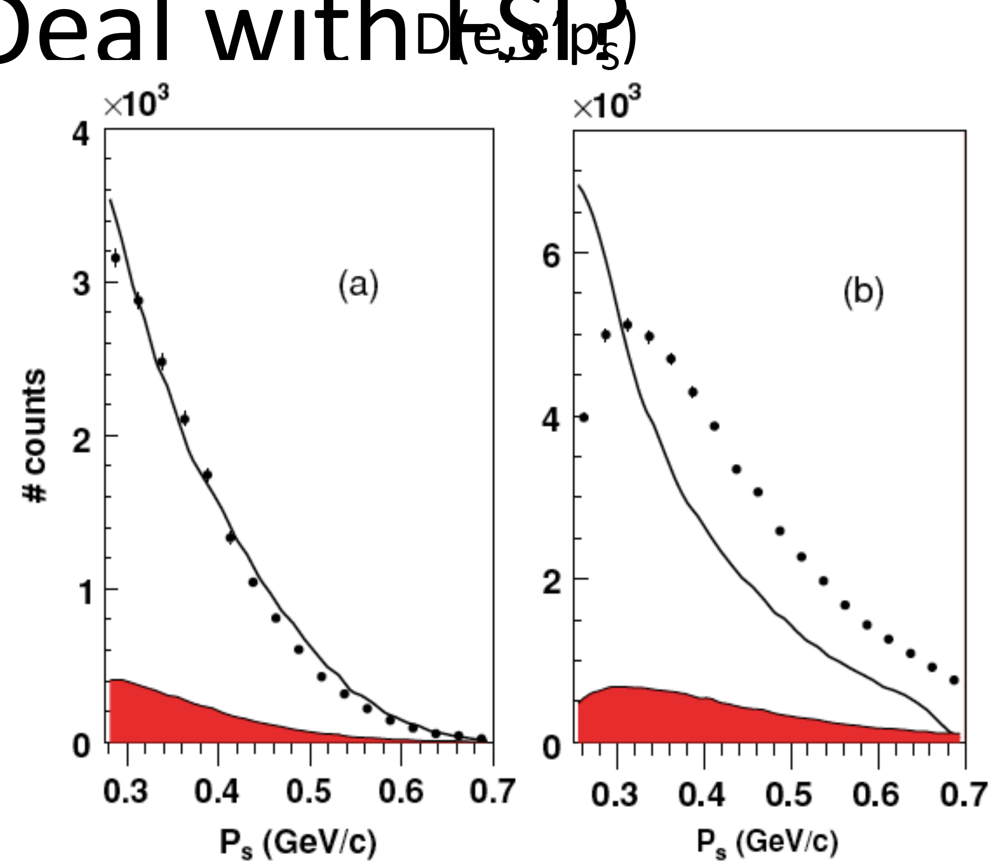


$$x_B = \frac{Q^2}{2 m_N \omega}$$

How to Deal with FSI?

We know that FSI:

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



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

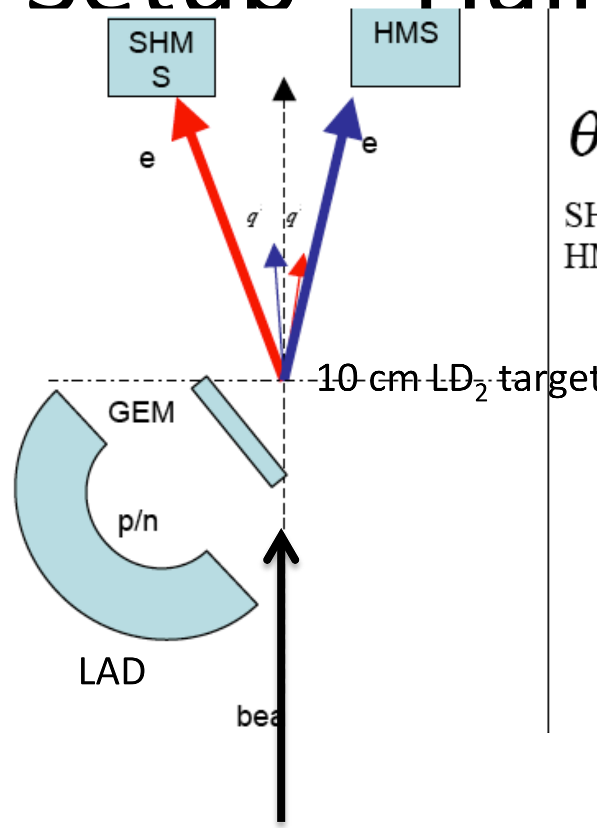
We shall:

- Involve theoretical colleagues
- Take data at large recoil angles
- Take data at 90°
- 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



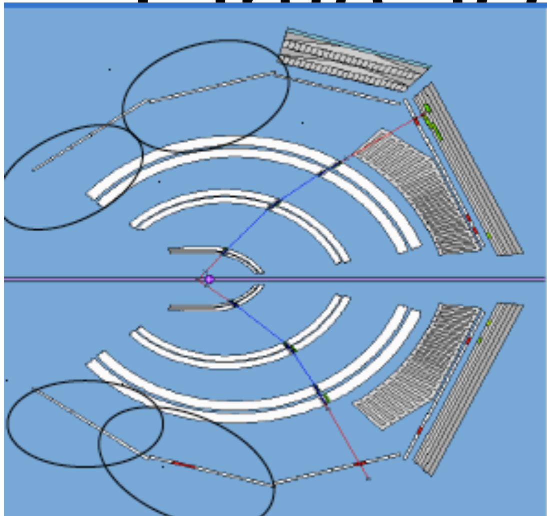
θ_{pq}

SHMS/LAD	$95\text{-}185^0$
HMS/LAD	$75\text{-}165^0$

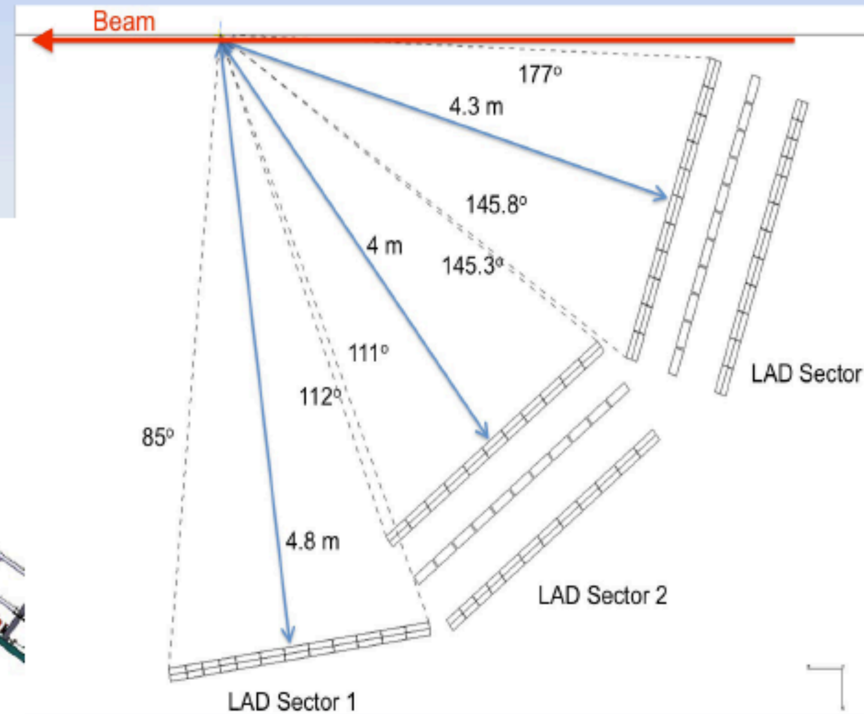
Central values of kinematics

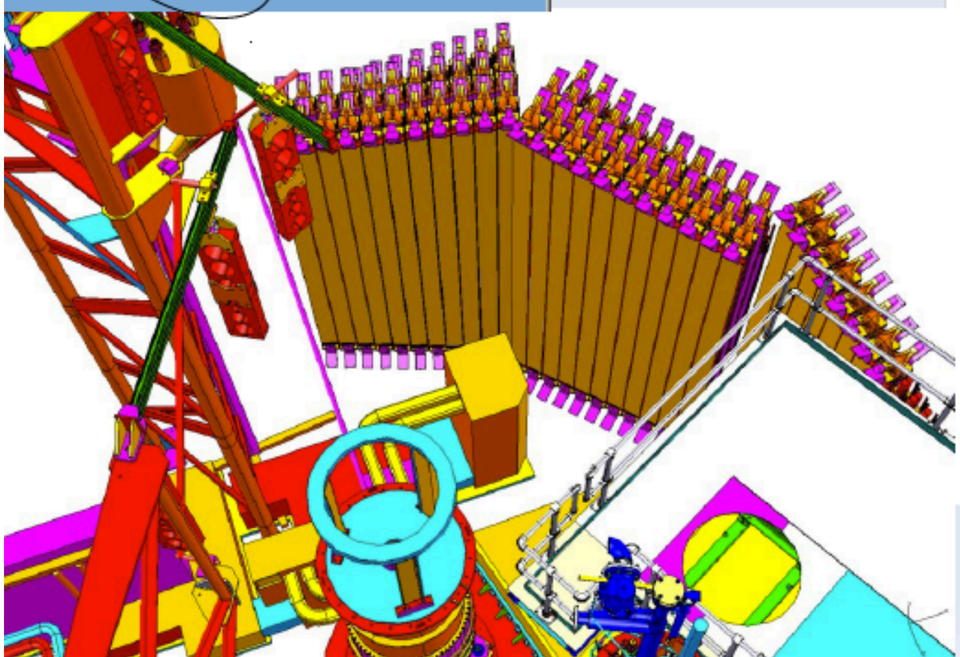
Low x'	High x'
$E_{in} = 10.9$ GeV	$E_{in} = 10.9$ GeV
$E' = 4.4$ GeV	$E' = 4.4$ GeV
$\theta_e = 13.5^o$	$\theta_e = -17^0$
$Q^2 = 2.65\ \text{GeV}^2$	$Q^2 = 4.19\ \text{GeV}^2$
$\lvert\vec{q}\rvert = 6.7\ \text{GeV}/c$	$\lvert\vec{q}\rvert = 6.8\ \text{GeV}/c$
$\theta_q = -8.8^0$	$\theta_q = 10.8^0$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

Large acceptance Detector (LAD)



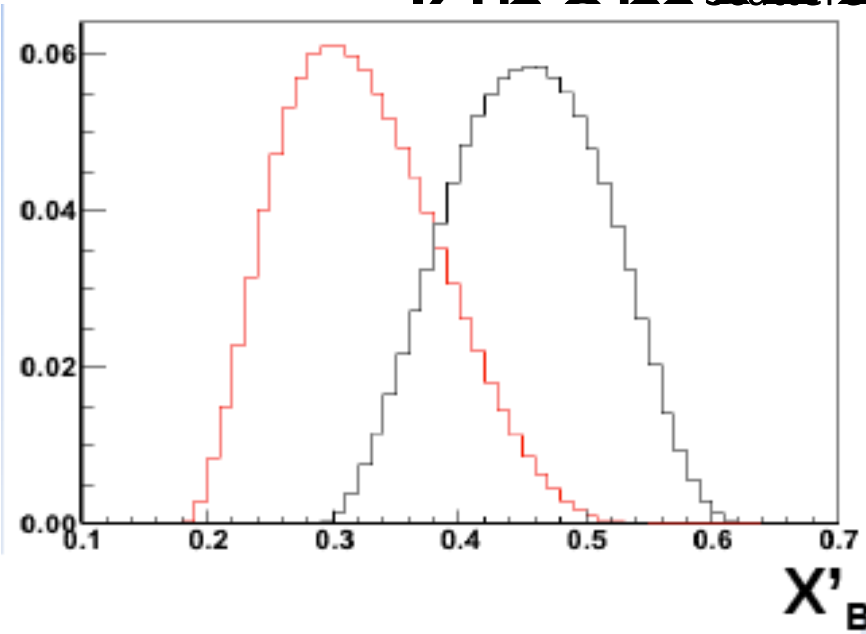
Use retired CLAS-6 TOF counters.
132, 5-cm thick counters in 12 panels.
1.5 sr, ~20% neutron detection efficiency

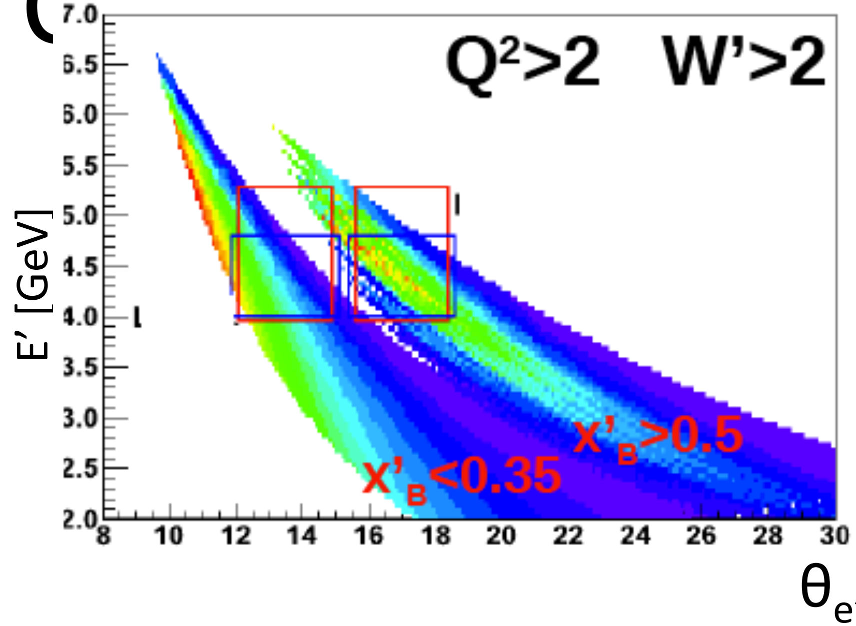




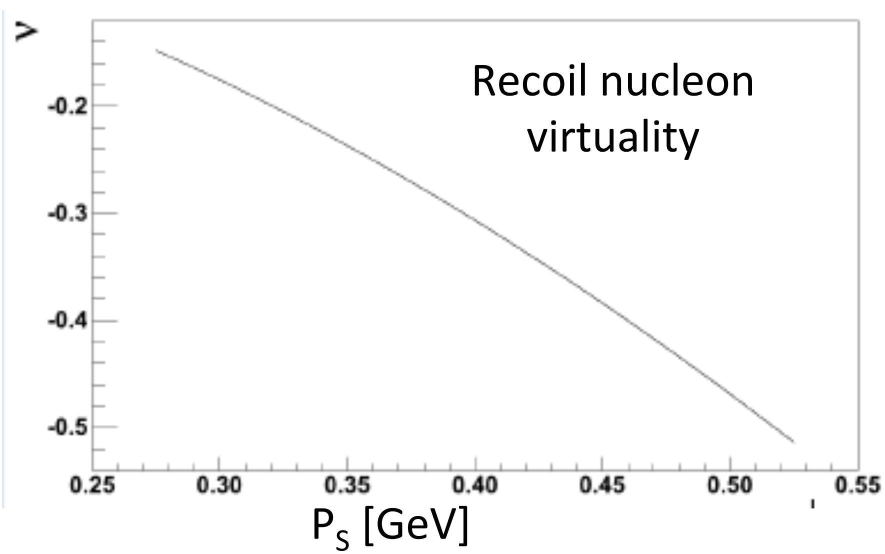
Kinematic Coverage

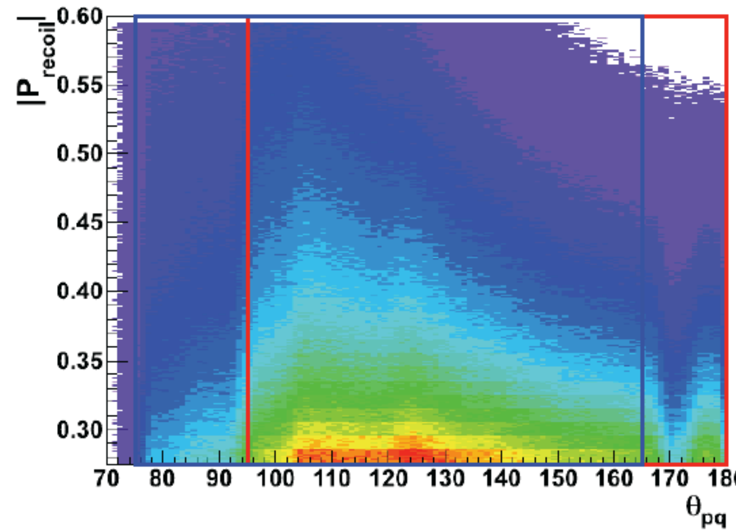
Scattered electrons



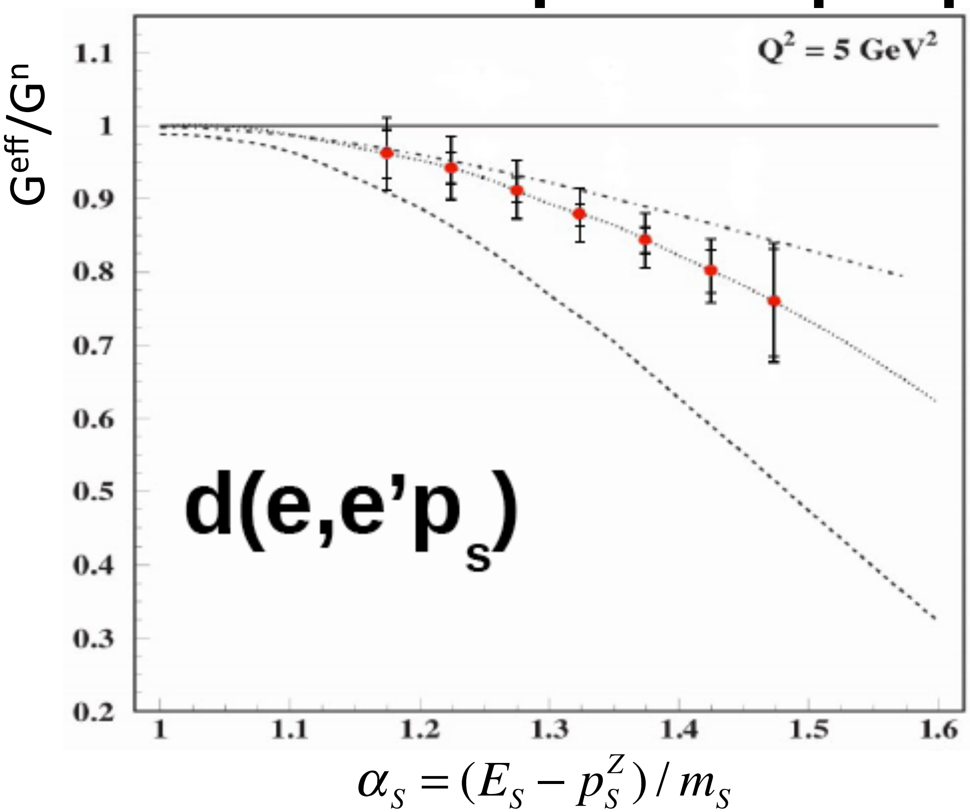


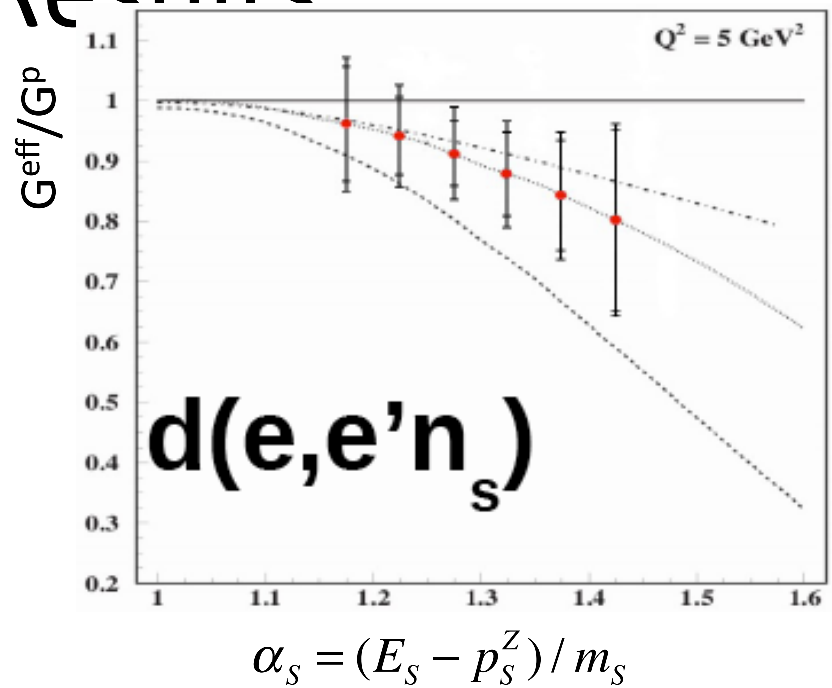
Recoiling nucleons





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 – Nucleons Medium Modification

- SRC and EMC are linearly correlated
- We suggest that this correlation is because both phenomena are related to high-momentum nucleons
- We assume that highly virtual nucleons are modified
- E12-11-107 is approved to measure at JLAB the ratio of F_2 for highly virtual nucleons to F_2 of free nucleons in the deuteron
- Use spectator tagging to select highly virtual nucleons in DIS
- Minimize systematic uncertainties by measuring ratios
- This is not (yet) an EMC measurement

Second Stage of Program - EMC

Measuring EMC with Tagged High-Momentum Recoil Nucleons

LOI-11-104 - TAU, ODU, MIT, JLAB

Basic idea of measurement

- Perform DIS ($Q^2 > 2$; $W > 2$) on high-momentum (vituality) nucleons by tagging the high-momentum recoiling nucleons
- Remember, almost all high-momentum nucleons have a SRC partner!!
- Measure per-nucleon x-sections ($p_S > 275$ MeV/c; $\theta_{pq} > 110°$) ratio of ^{4}He to deuteron, $\sigma[^4He(e,e'p_S)]/\sigma[d(e,e'p_S)]$, $f(0.3 < X_B < 0.6)$

Signal

- If EMC depend on virtuality, $\sigma[^4He(e,e'p_S)]/\sigma[d(e,e'p_S)]$ should not depend on x_B
- Magnitude of ratio should be $a_{2N}(^4He/d) \approx 4$

Basic Idea of Measurement (cont.)

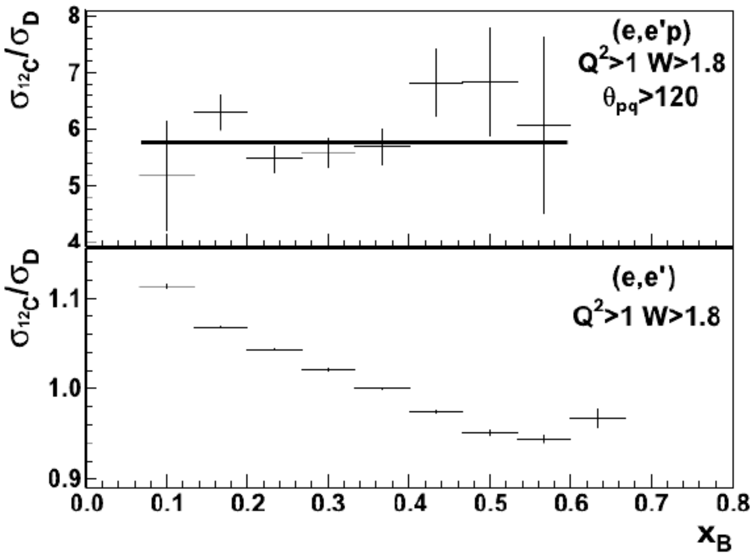
Second Measurement

- Ratio of per-nucleon cross section, $\sigma[^4He(e,e'p_S)]/\sigma[d(e,e')]$, at the same kinematic range
- Only $\sigma[^4He(e,e'p_S)]$ is tagged by p_S > 275 MeV/c while $\sigma[d(e,e')]$ is not!

Signal

- Ratio depends on x_B
- Shape similar to universal EMC shape BUT **signal is larger**

Experimental setup of both measurements will be similar to that of E12-11-107



CLAS data, very preliminary!
Or Hen, TAU

Remember $a_{2N}(^{12}C/d) = 4.8 \pm 0.4$

Summary - EMC

- LOI-11-104 plans to measure the doubly-tagged per-nucleon cross-sections ratio $\sigma[^4He(e,e'p_S)]/\sigma[d(e,e'p_S)]$ for $p_S > 275$ MeV/c, $\theta_{pq} > 110°$, and as $f(0.3 < X_B < 0.6)$
- LOI-11-104 also plans to measure the singly-tagged per-nucleon cross-sections ratio $\sigma[^4He(e,e'p_S)]/\sigma[d(e,e')]$ in the same conditions
- If the EMC effect is related to highly virtual nucleons, then both measurements will have a very unique signatures
- A full proposal will be submitted to the next JLAB PAC
- This **IS** an EMC measurement

Experimental setup for both measurements