TEL AVIV UNIVERSITY

INSTITUTE FOR NUCLEAR THEORY

Review of EMC/SRC Correlation Studies
[Theory – Phenomenology - Experiment]

Or Hen

Tel-Aviv University

Based on a new review paper in preparation with:

D. W. Higinbotham (JLab)

G. A. Miller (UW)

L. B. Weinstein (ODU)

E. Piasetzky (TAU)

February 11 -22, 2013

Nuclear Structure and Dynamics at Short Distances

EMC Effect is 30 years old

[and still unresolved....]

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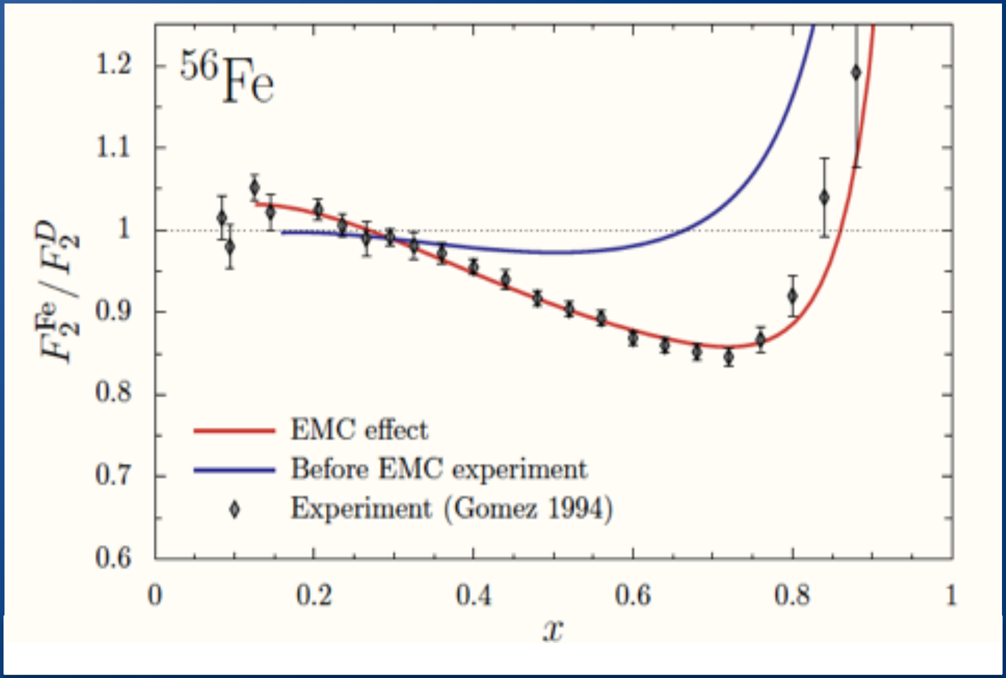
[and still unresolved….]

Great Challenge!

Great Frustration?

EMC Effect

- Reduction in the per-nucleon DIS cross section ratio of nuclei relative to deuterium
- Universal shape for 0.3<x<0.7 and 3<A<197
- ~Independent of Q^2
- Overall increasing as a function of A
- No fully accepted theoretical explanation



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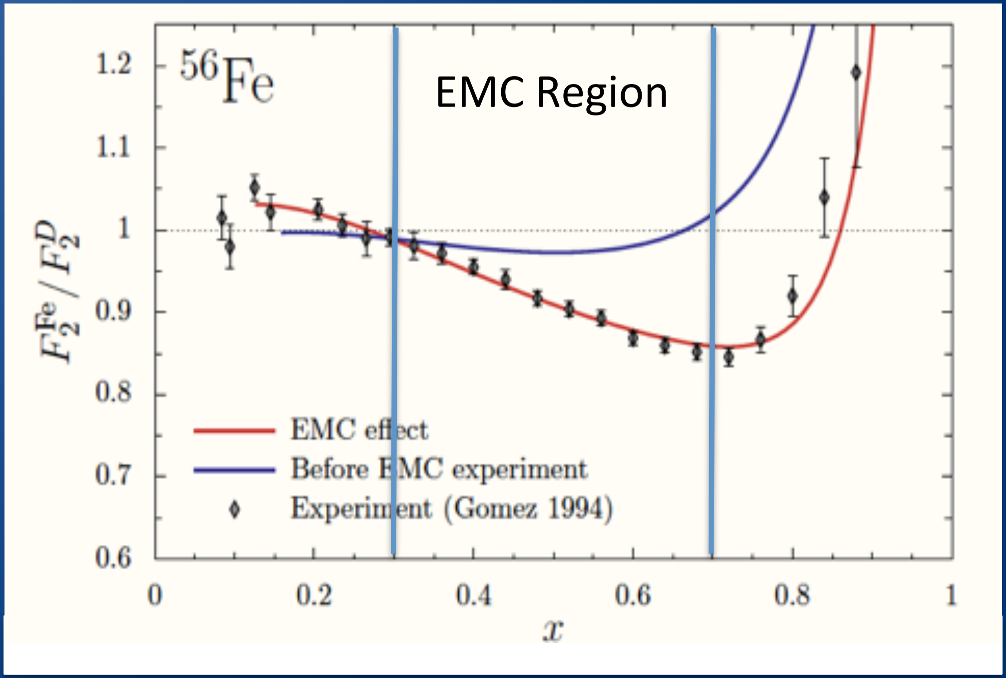

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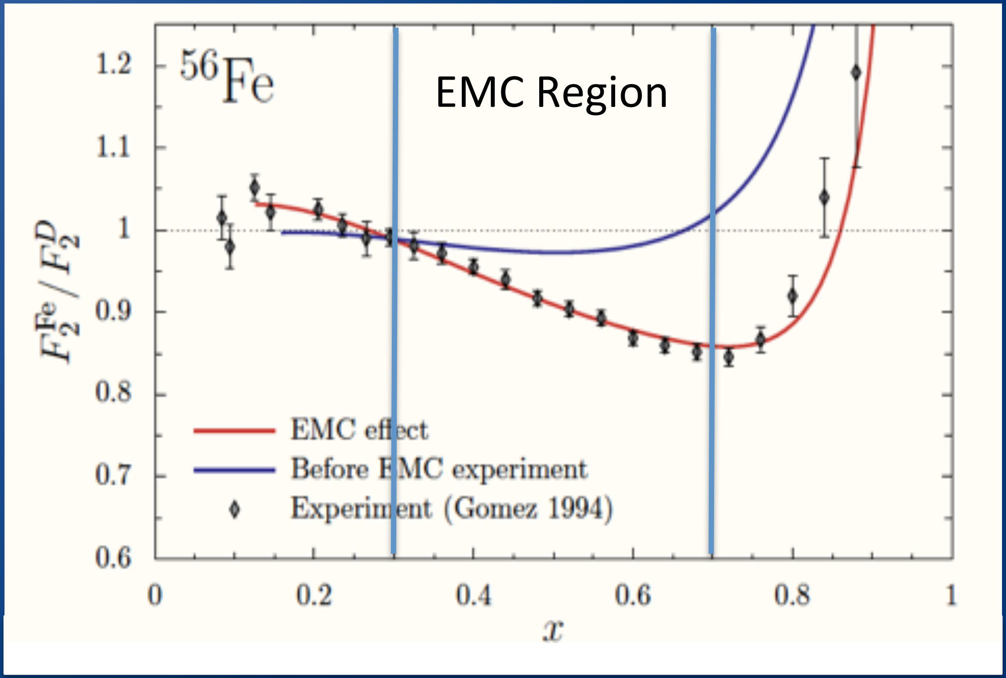

Need Phenomenological guidance *and* new independent observables

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EMC Theory

See talk by G. Miller

- Standard nuclear effects that contribute:
  - Binding and Fermi motion
  - Coulomb Field
- Explain most of the effect up to $x \approx 0.5$
- Fail to explain the effect at larger values of x
- Various theoretical models – Most incorporate modification of the structure of bound nucleons

- EMC – Everyone's Model is Cool (G. A. Miller)

EMC Measurements

- EMC experiments measure the DIS cross section ratio for nuclei, A, relative to deuterium
- Cross section ratios are taken at equal Q^2 and x_B kinematics (Mott cross section cancels)
- Assuming $R=\sigma_L/\sigma_T$ is independent of A:

Cross section ratio = Structure function ratio

+ added ISO correction for asymmetric nuclei

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Outline

- Reference frame corrected EMC data-base
- 2N-SRC overview
- EMC-SRC correlation
  - Possible Implications
  - Universal modification assumption
  - Future Experiments
- np-SRC dominance and ISO corrections for EMC effect in asymmetric nuclei

Most of the talk is based on a new EMC/SRC review paper by O. Hen, D. W. Higinbotham, G. Miller, E. Piasetzky, L. B. Weinstein (In Preparation).

Moving to the nucleon reference frame

- FS 2012: The EMC effect should be measured as a function of x_A and not x_p (=x_B)

$$x_A = \frac{Q^2}{2q \cdot P_A/A} = \frac{AQ^2}{2\omega m_A} = x_p \cdot \frac{Am_p}{m_A},$$

- EMC measurements were done at equal x_p kinematics in which $x_A \neq x_d$

L. Frankfurt and M. Strikman, Int.J.Mod.Phys. E 21 (2012) 1230002

Moving to the nucleon reference frame

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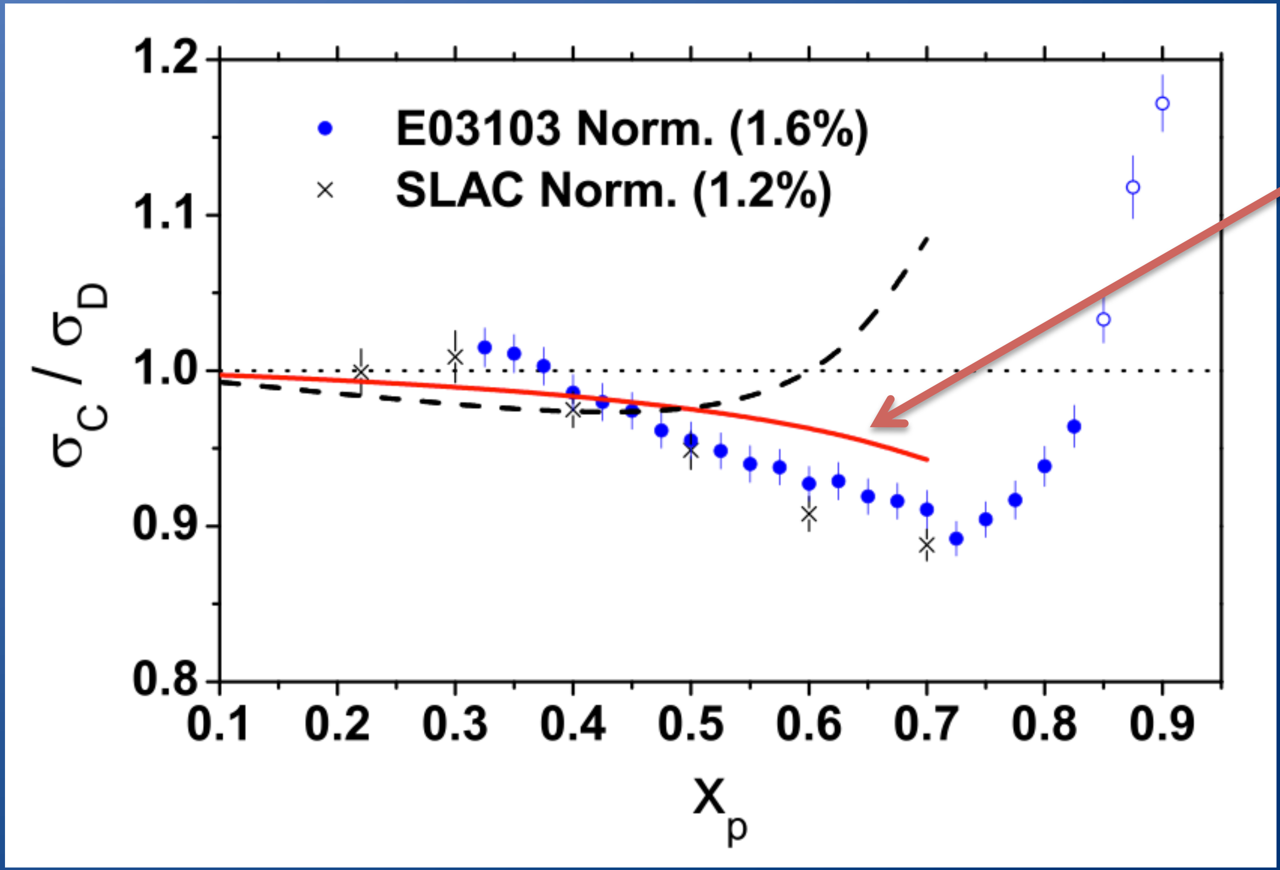
The EMC data compares the nucleus and deuterium structure functions at *<u>different values</u>*

L. Frankfurt and M. Strikman, Int.J.Mod.Phys. E 21 (2012) 1230002

Moving to the nucleon reference frame

- FS Taylor series expansion of $F_2(x_A)$:



$F_2^A(x_p)/F_2^d(x_p)$
Assuming
$F_2^A(x_A)=F_2^d(x_A)$

L. Frankfurt and M. Strikman, Int.J.Mod.Phys. E 21 (2012) 1230002

Moving to the nucleon reference frame

- For symmetric nuclei (n=z)

$$\frac{\sigma^A_{DIS}(x_p,Q^2)}{\sigma^d_{DIS}(x_p,Q^2)} = \frac{F_2^A(x_A,Q^2)}{F_2^d(x_d,Q^2)} = \frac{F_2^A(x_A,Q^2)}{F_2^d(x_A,Q^2)} \cdot \frac{F_2^d(x_A,Q^2)}{F_2^d(x_d,Q^2)},$$

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$x_A \neq x_d$

What we want to extract

Correction Factor

O. Hen, D. W. Higinbotham, G. Miller, E. Piasetzky, L. B. Weinstein, In Preparation.

Moving to the nucleon reference frame

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- And therefore

$$\frac{F_2^A(x_A, Q^2)}{F_2^d(x_A, Q^2)} = \frac{\sigma^A_{DIS}(x_p, Q^2)}{\sigma^d_{DIS}(x_p, Q^2)} \cdot \frac{F_2^d(x_d, Q^2)}{F_2^d(x_A, Q^2)},$$

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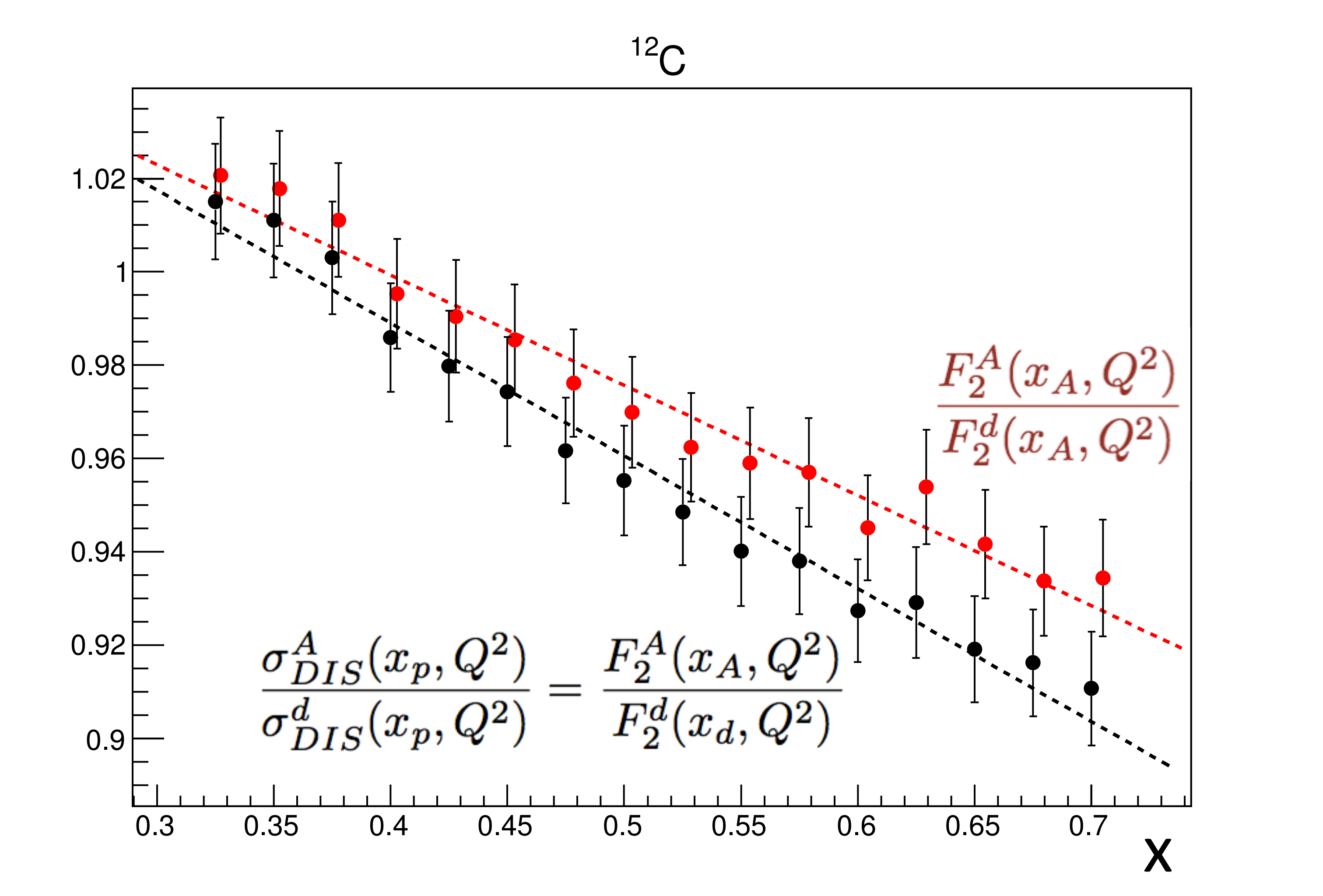
Measured World Data

O. Hen, D. W. Higinbotham, G. Miller, E. Piasetzky, L. B. Weinstein, In Preparation.

Moving to the nucleon reference frame



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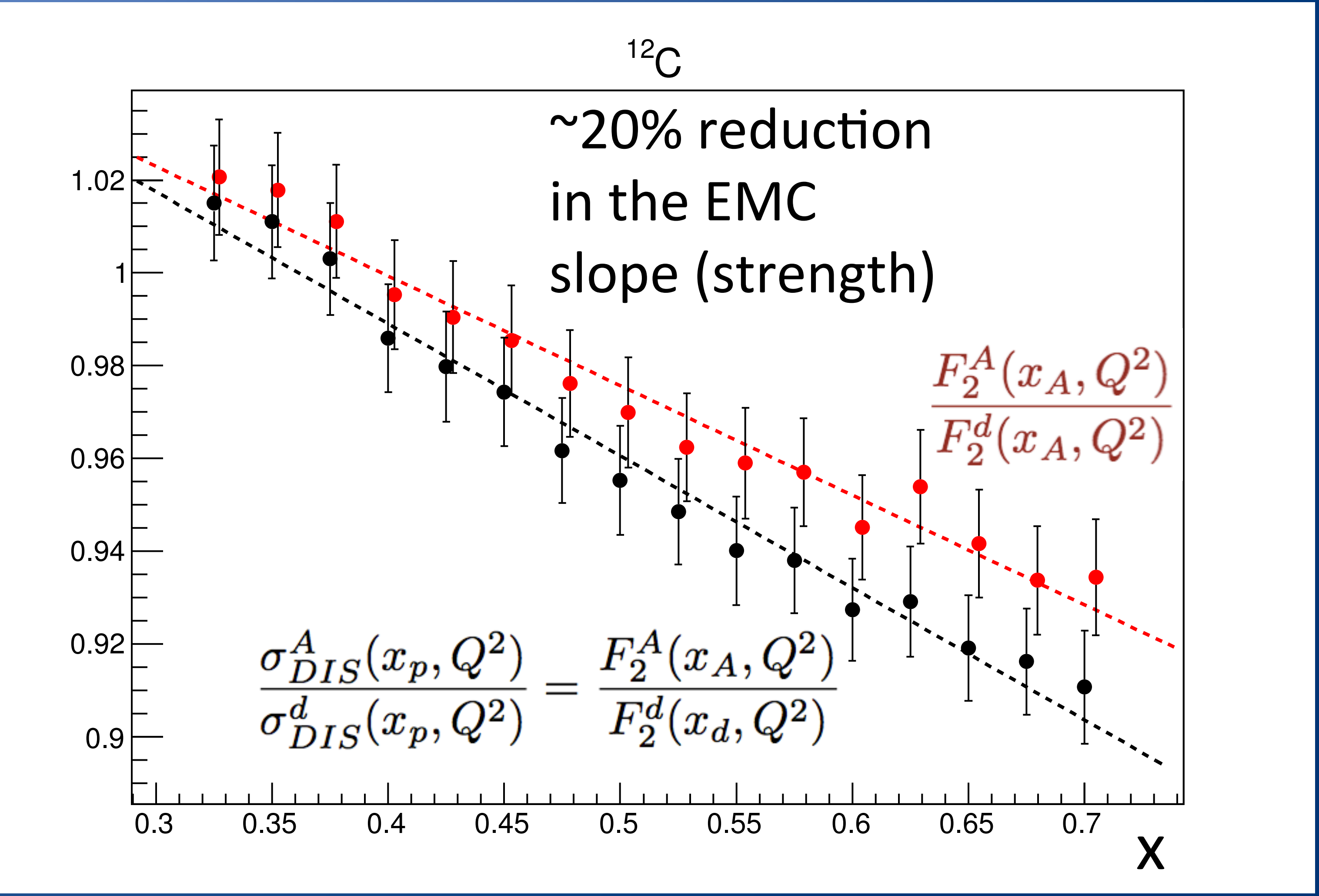

O. Hen, D. W. Higinbotham, G. Miller, E. Piasetzky, L. B. Weinstein, In Preparation.

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New EMC Data-Base

- Using the formalism described above we correct the JLab and SLAC EMC measurements to be taken at equal x_A
  - $F_2^d(x,Q^2)$ taken from Bosted & Christy
  - ISO corrections applied using the $F_2^n/F_2^p(x,Q^2)$ parameterization of Arrington et al.

P. E. Bosted and M. E. Christy, Phys.Rev. C77 (2008) 065206
J. Arrington et al., J. Phys. G: Nucl. Part. Phys. 36 (2009) 025005
O. Hen, D. W. Higinbotham, G. Miller, E. Piasetzky, L. B. Weinstein, In Preparation.

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- Main implications:
  - **Reduction of ~20% in the strength (slope) of the EMC effect**
  - **EMC transition point, where the F_2 ratio equals 1, is now x_A=0.34±0.02 (was 0.31±0.04 before)**

O. Hen, D. W. Higinbotham, G. Miller, E. Piasetzky, L. B. Weinstein, In Preparation.

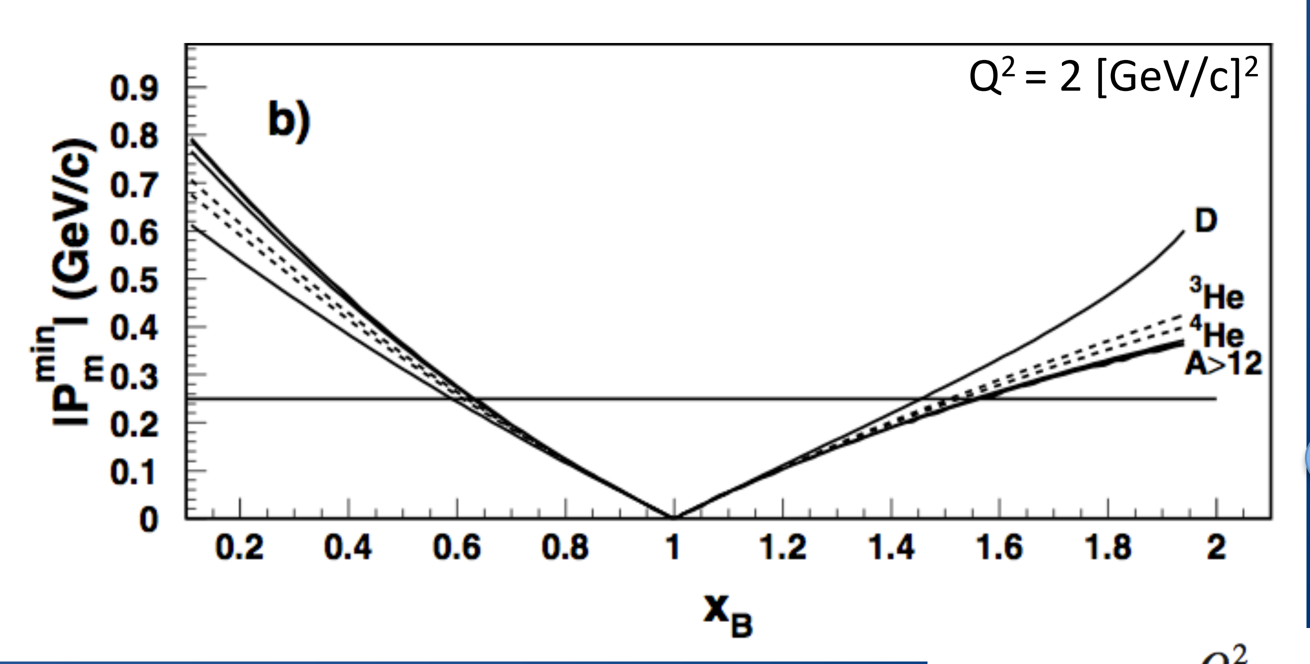
2N-SRC 101

2N-SRC are pairs of nucleons that:

- Are close together (overlap) in the nucleus
- Have high relative momentum and low c.m. momentum, where high and low is compared to the Fermi momentum (k_F) of the nucleus

2N-SRC 101

- Inclusive (e,e') QE electron scattering is sensitive to the high momentum tail of the nuclear wave function



See talk by P. Solvignon

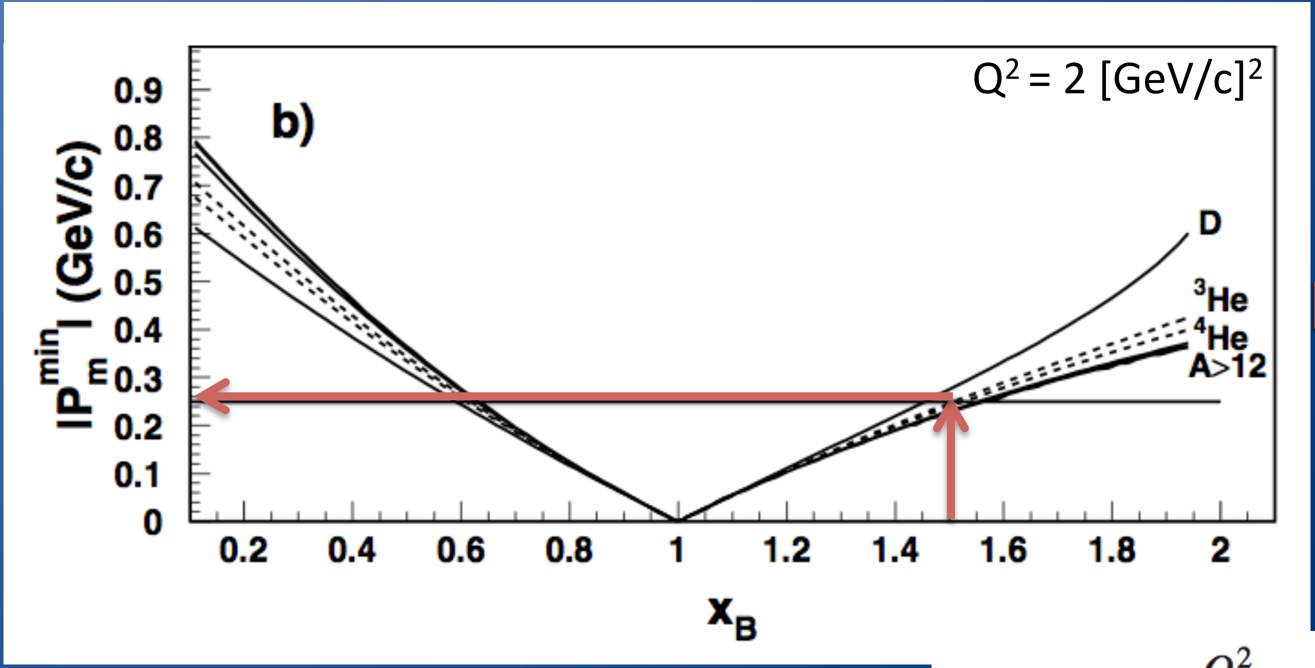
$$(q+p_A-p_{A-1})^2=p_f^2=m_N^2,$$

$$\Delta M^2-Q^2+\frac{Q^2}{m_N x_B}\left(M_A-\sqrt{M_{A-1}^2+\vec{p}_m^{\,2}}\right)-2\vec{q}\cdot\vec{p}_m$$
$$-2M_A\sqrt{M_{A-1}^2+\vec{p}_m^{\,2}}=0,$$

K. Egiyan et al., Phys.Rev. C 68 (2003) 014313

2N-SRC 101

- Inclusive (e,e') QE electron scattering is sensitive to the high momentum tail of the nuclear wave function



High x_B ←→ High Initial Momentum

$$(q+p_A-p_{A-1})^2=p_f^2=m_N^2,$$

$$\Delta M^2-Q^2+\frac{Q^2}{m_N x_B}\left(M_A-\sqrt{M_{A-1}^2+\vec{p}_m^{\,2}}\right)-2\vec{q}\cdot\vec{p}_m$$
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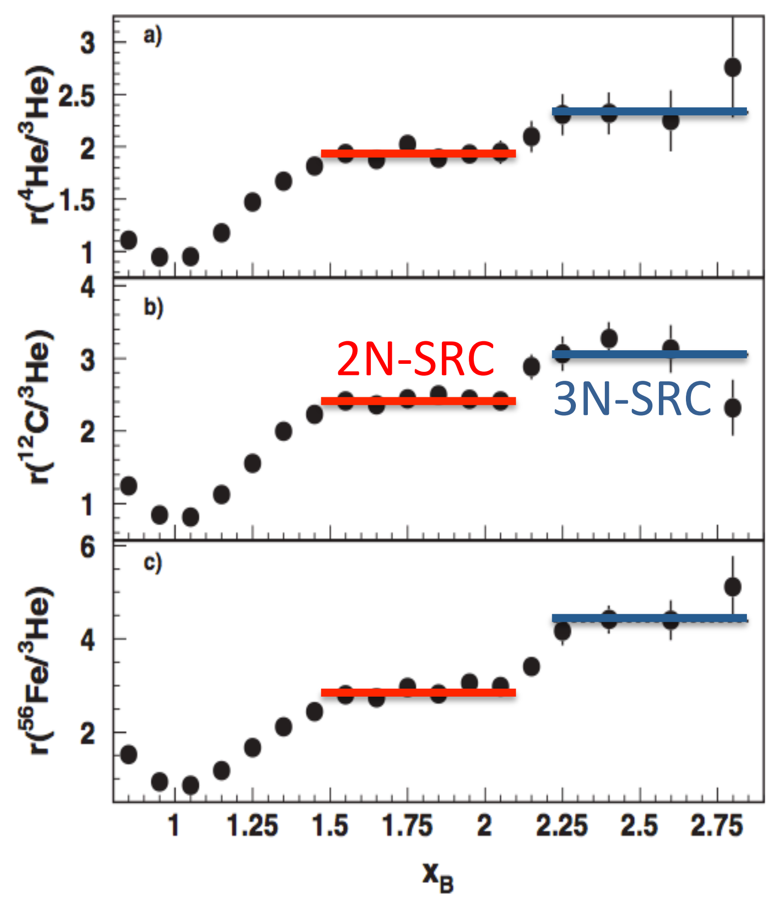
K. Egiyan et al., Phys.Rev. C 68 (2003) 014313

2N-SRC 101

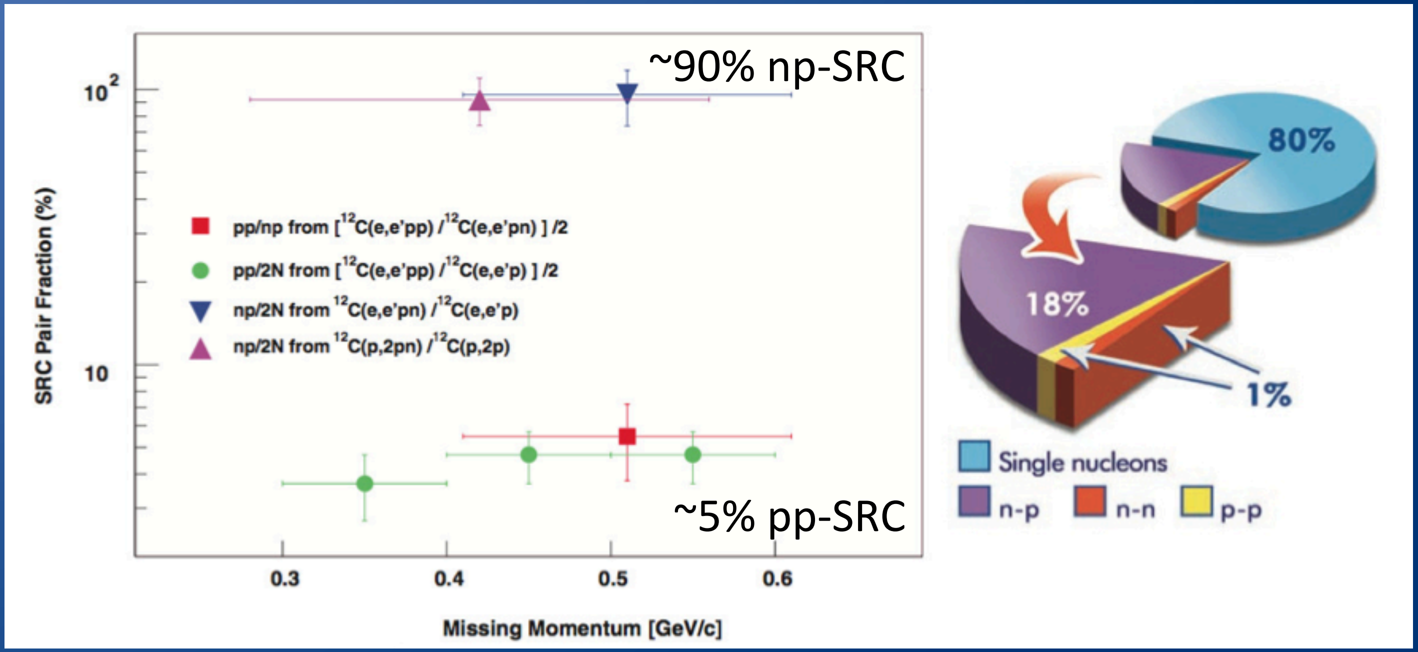
- Inclusive (e,e’) QE electron scattering is sensitive to the high momentum tail of the nuclear wave function
- QE (e,e’) per-nucleon cross section ratios scale
  - The scale factors are noted as a_2 and a_3
  - Evidence for universality of the high momentum tail of the nuclear wave function



L. Frankfurt et al. , Phys.Rev. C48 (1993) 2451
K. Egiyan et al., Phys.Rev. C 68 (2003) 014313
K. Egiyan et al., Phys.Rev.Lett 96 (2006) 082501
N. Fomin et al., Phys.Rev.Lett 108 (2012) 092502

2N-SRC 101

- Exclusive $^{12}C(p,2pn)$ and $^{12}C(e,e'pN)$ measurements probe the structure of the high momentum tail of the nuclear wave function
- Results show that for $300 < P_{miss} < 600$ MeV/c all nucleons are part of 2N-SRC pairs



A. Tang et al., Phys.Rev.Lett. 90 (2003) 042301
E. Piasetzky et al., Phys.Rev.Lett. 97 (2006) 162504
R. Shneor et al., Phys.Rev.Lett. 99 (2007) 072501
R. Subedi et al., Science 320 (2008) 1476

2N-SRC 101

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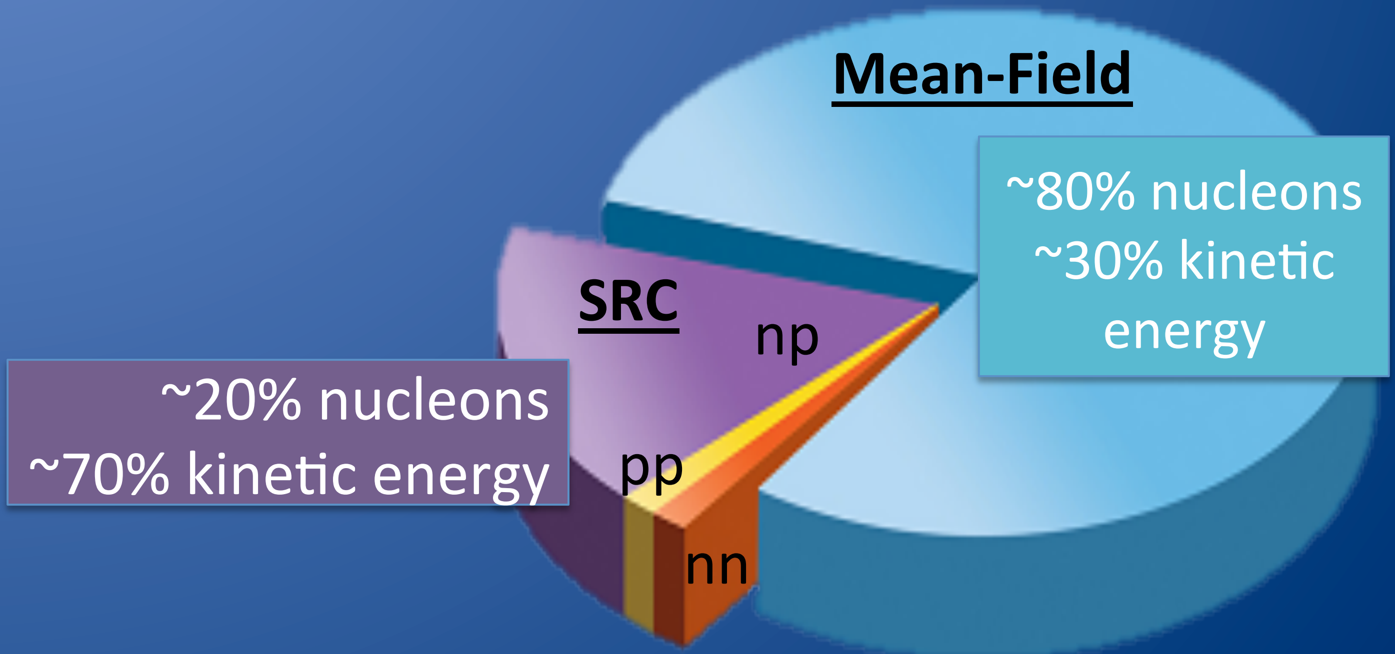
- Results show that for $300<P_{miss}<600$ MeV/c all nucleons are part of 2N-SRC pairs
- Preliminary results from exclusive (e,e'pN) measurements in various nuclei (^{3}He, ^{4}He, ^{12}C, ^{27}Al, ^{56}Fe, and ^{208}Pb) show that 2N-SRC are a

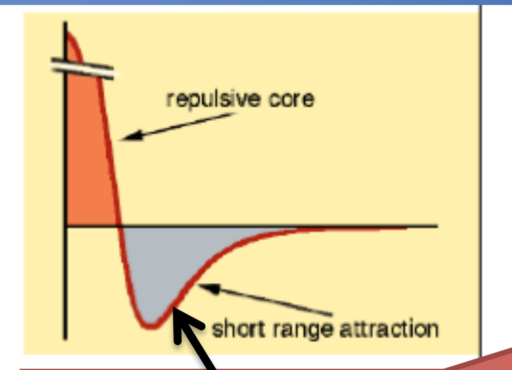
universal phenomena

See talks by J. Ryckebusch, C. Ciofi degli Atti, I. Korovar and O. Hen

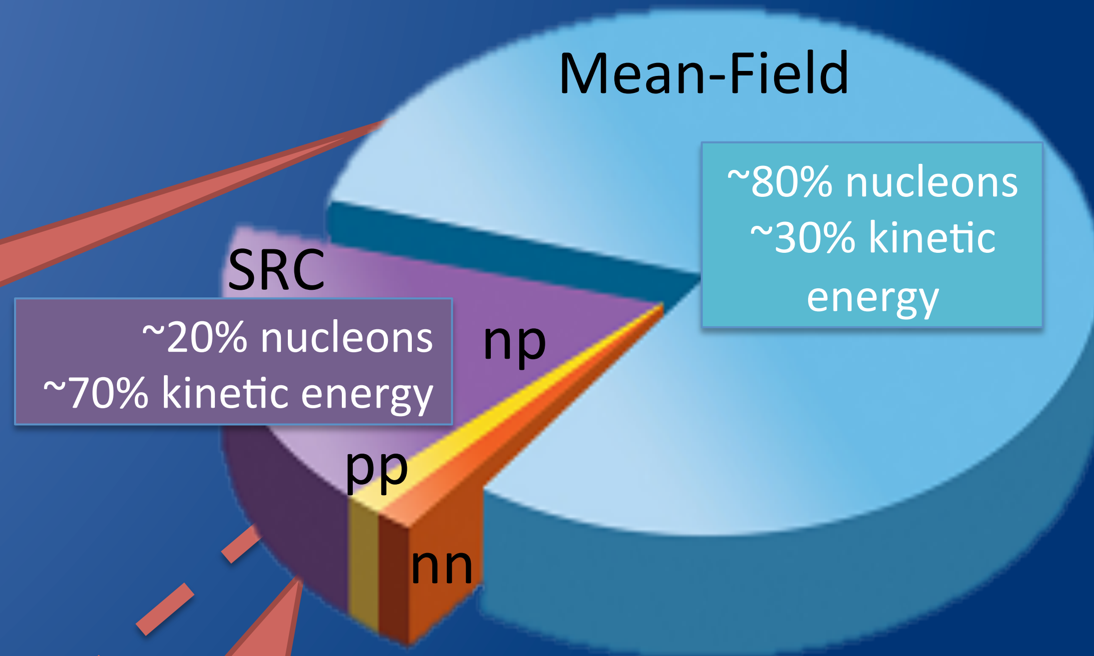
^{12}C Nucleus:


Mean-Field
~80% nucleons
~30% kinetic energy
SRC
np
pp
nn
~20% nucleons
~70% kinetic energy

Where is the EMC Effect?



Largest attractive force

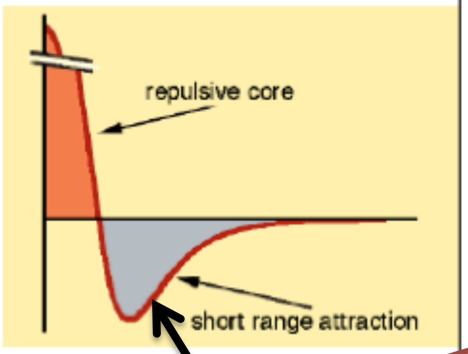


Mean-Field

SRC

High local nuclear matter density, large momentum, large off shell, large virtuality

Where is the EMC Effect?



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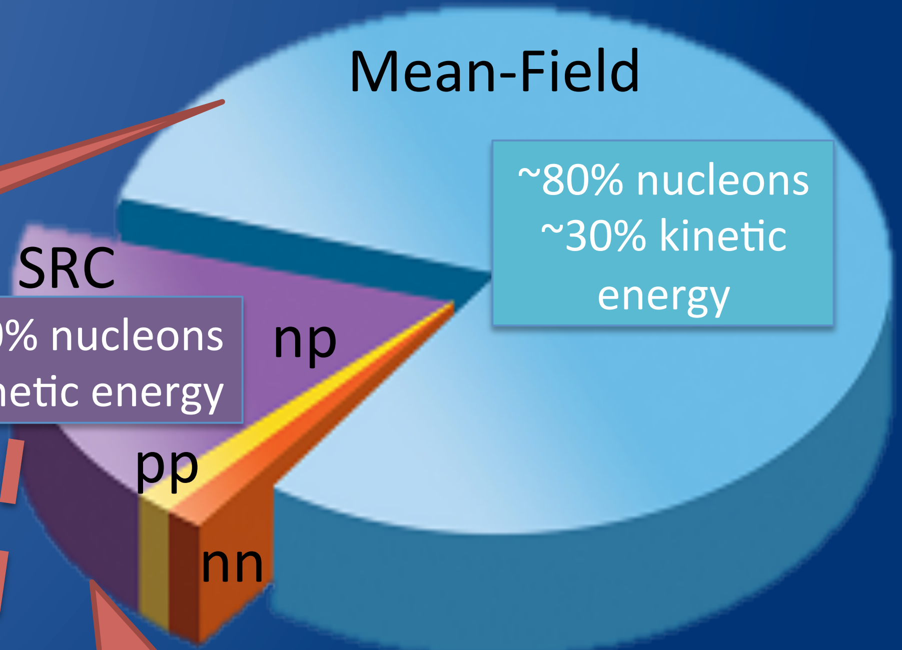
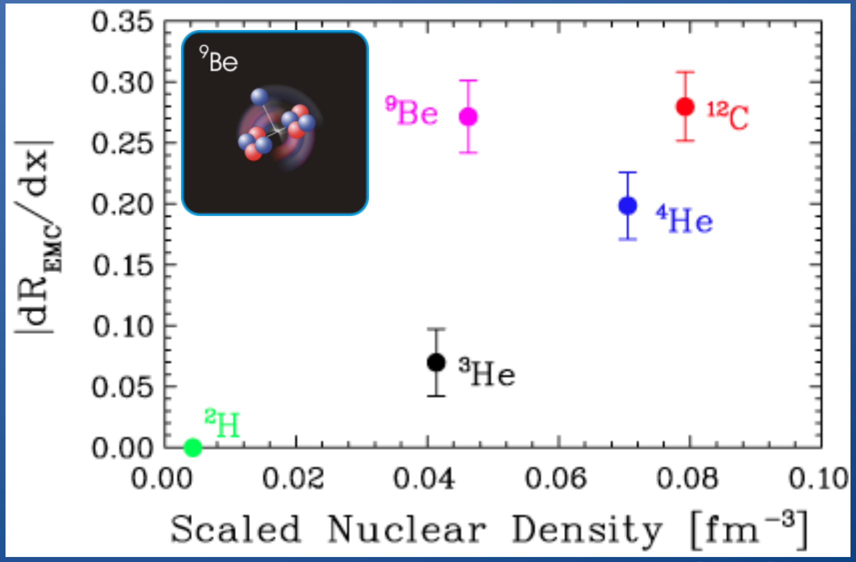


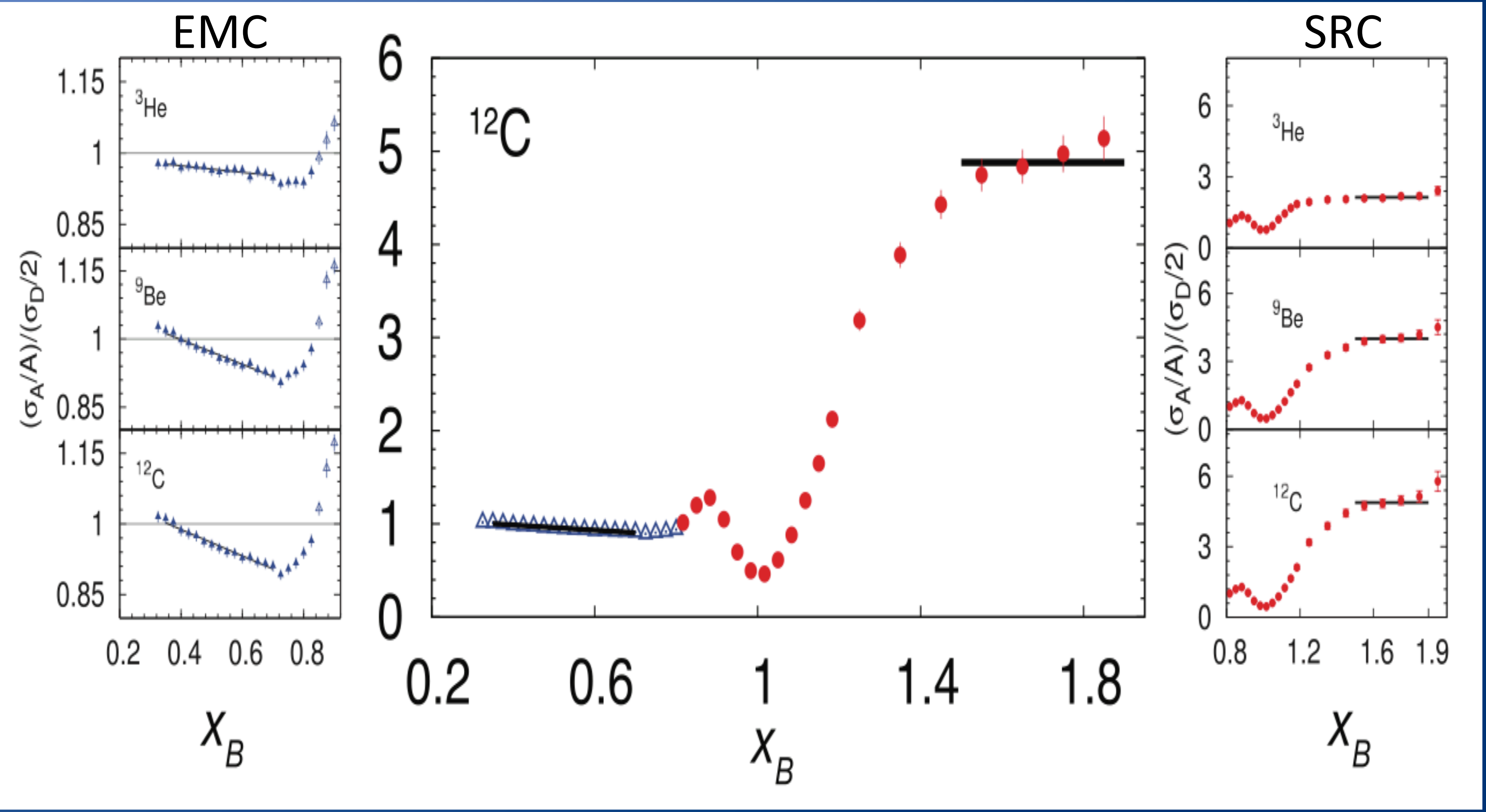


High local nuclear matter density, large momentum, large off shell, large virtuality

J. Seely et al., Phys.Rev. Lett. 103 (2009) 202301

See talk by D. Gaskel

EMC-SRC Correlation



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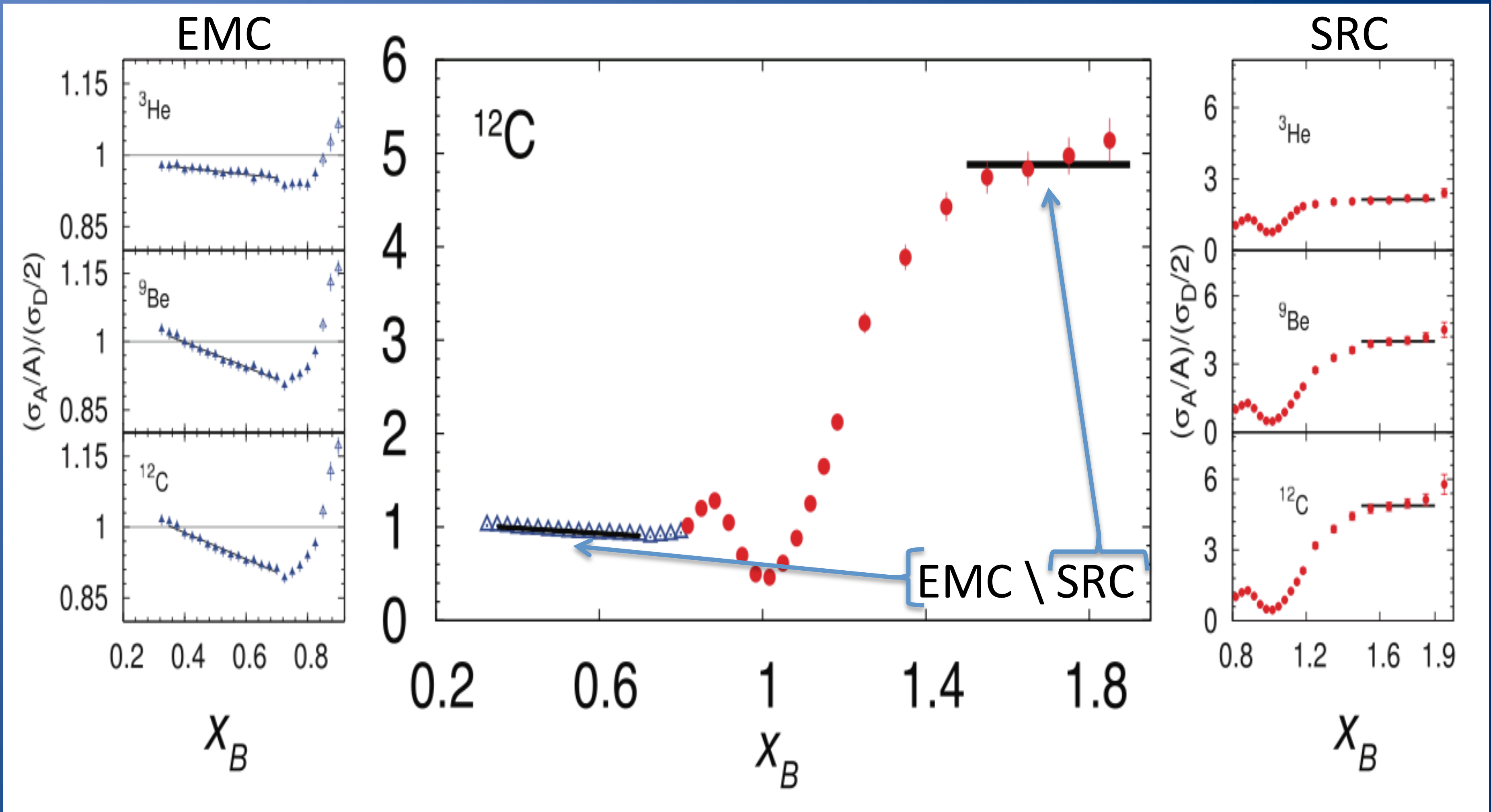

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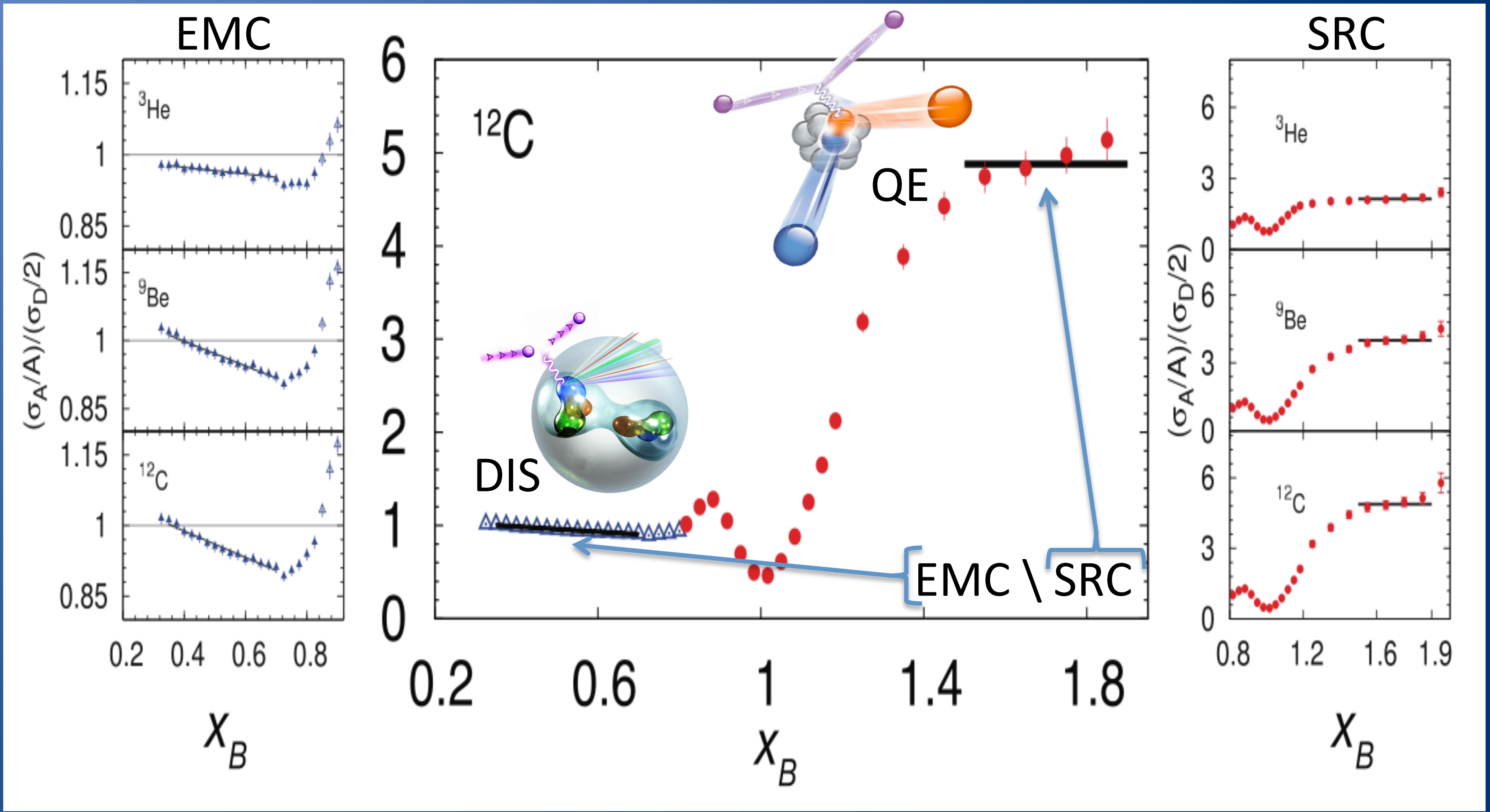

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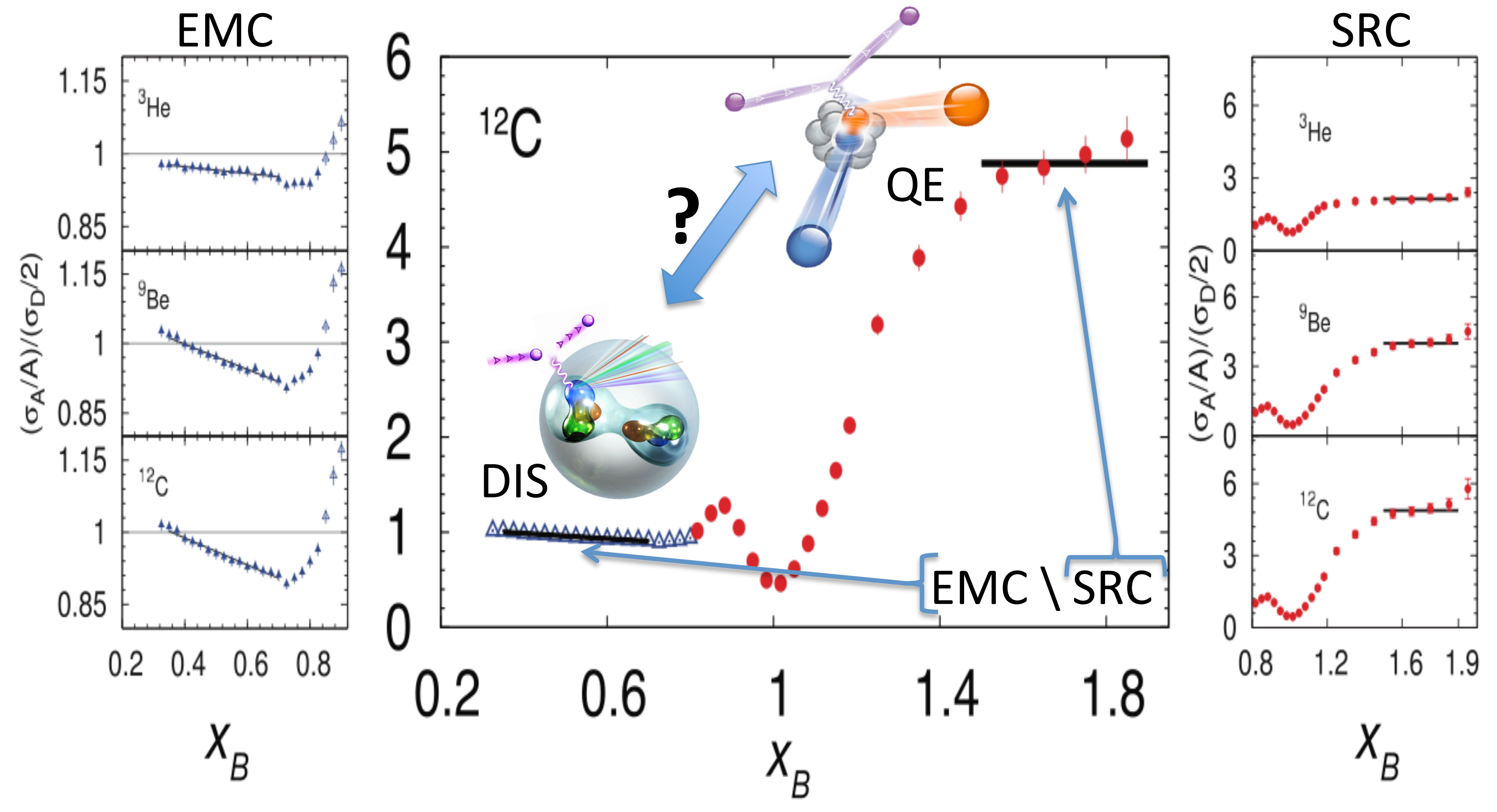

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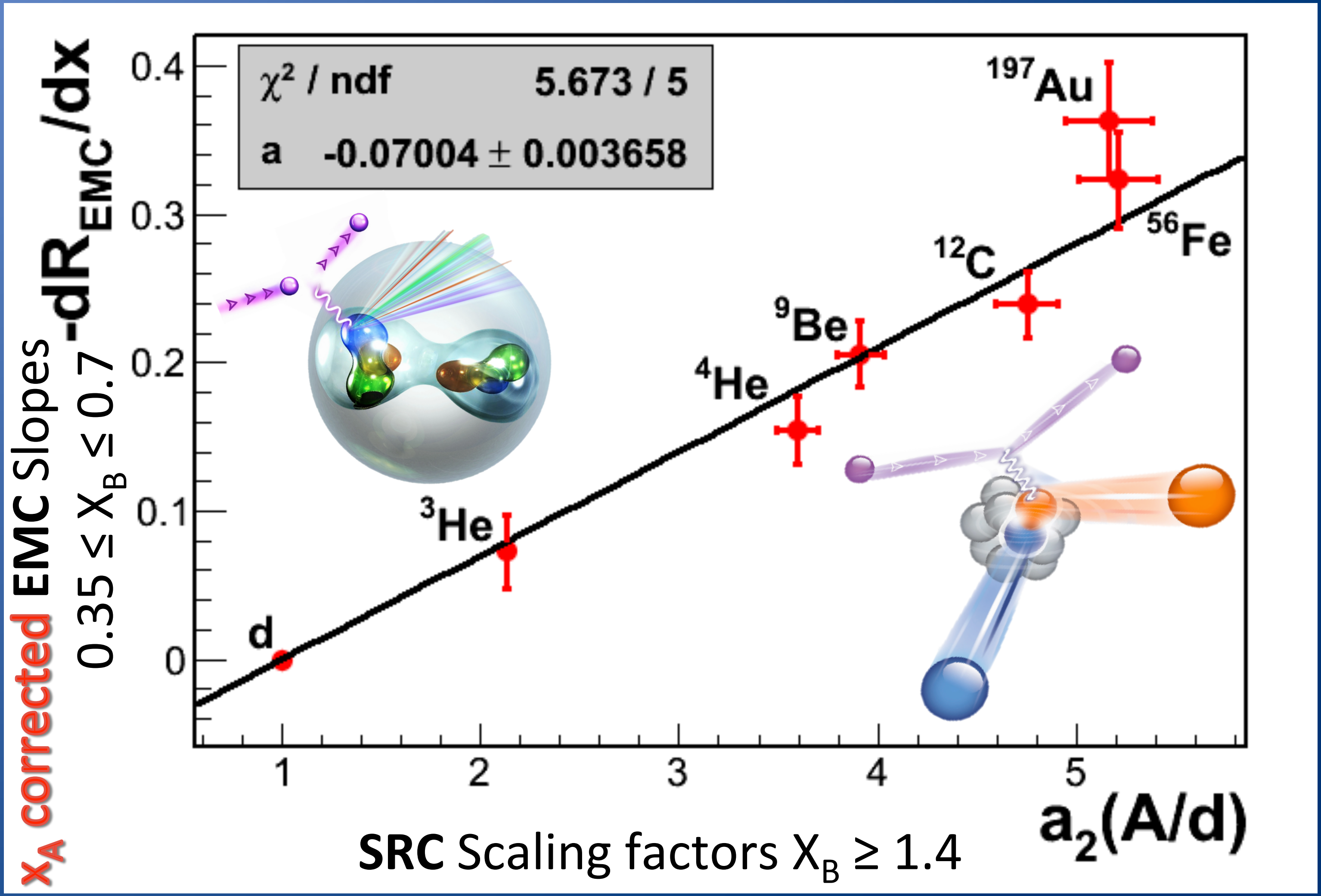


L.B.Weinstein et al., Phys. Rev. Lett. 106 (2011) 052301
O. Hen et al., Phys. Rev. C 85 (2012) 047301
O. Hen, D. W. Higinbotham, G. Miller, E. Piasetzky, L. B. Weinstein, In Preparation.

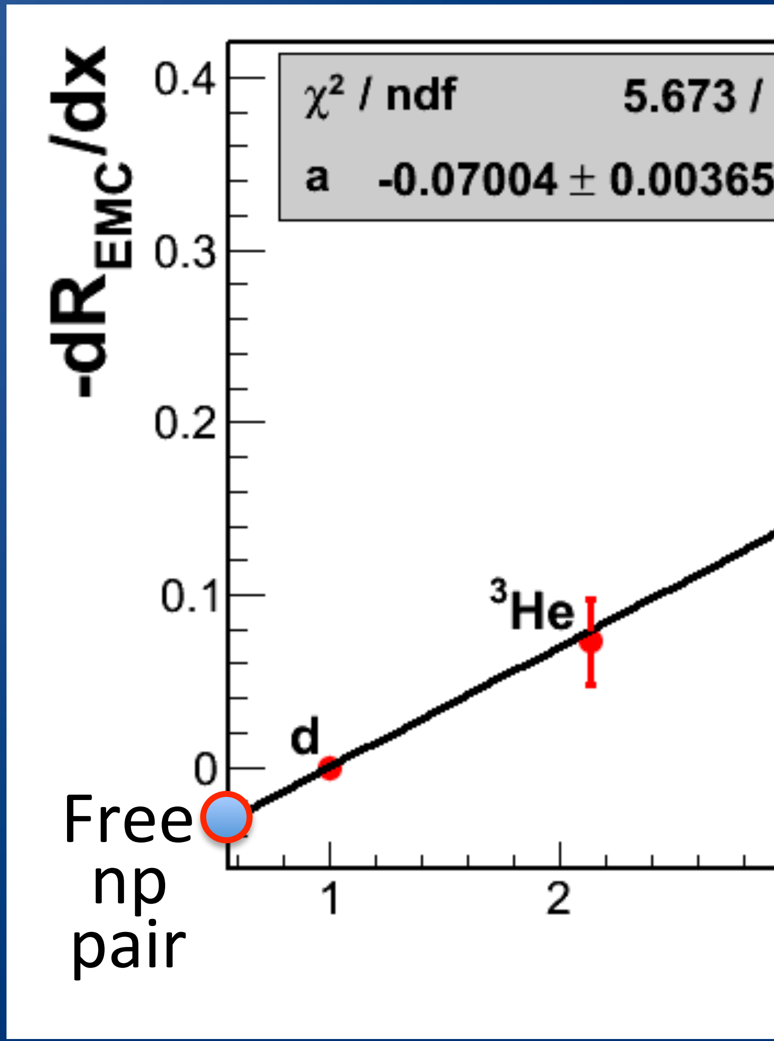
Implications of the EMC-SRC Correlation

- The limit of $a_2 \rightarrow 0$ is the limit of a free proton-neutron pair with no interaction
- Extrapolating the linear fit to the EMC-SRC correlation to $a_2 \rightarrow 0$ gives EMC (IMC) effect for the deuteron:

$$\frac{\sigma_d}{\sigma_p + \sigma_n} = 1 - a(x_p - b) \quad \text{for } 0.3 \leq x_p \leq 0.7,$$

a = 0.070 ± 0.003

b = 0.340 ± 0.020



L.B.Weinstein et al., Phys. Rev. Lett. 106 (2011) 052301
O. Hen et al., Phys. Rev. C 85 (2012) 047301
O.Hen et al., Phys.Rev.D 84 (2011) 117501

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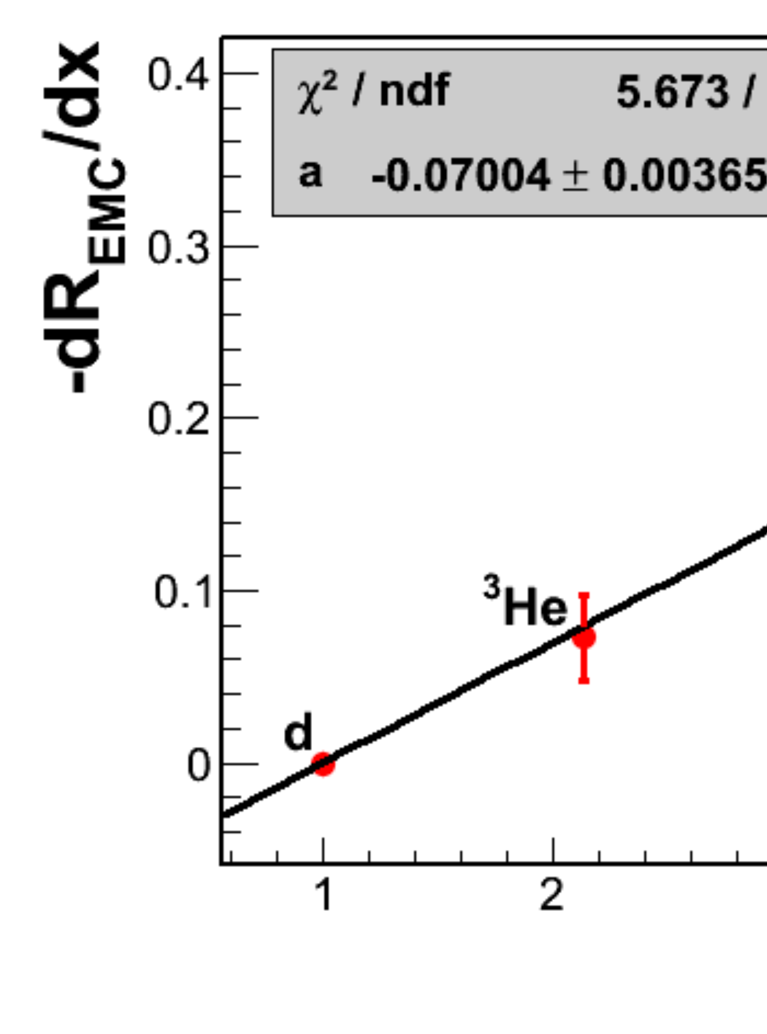
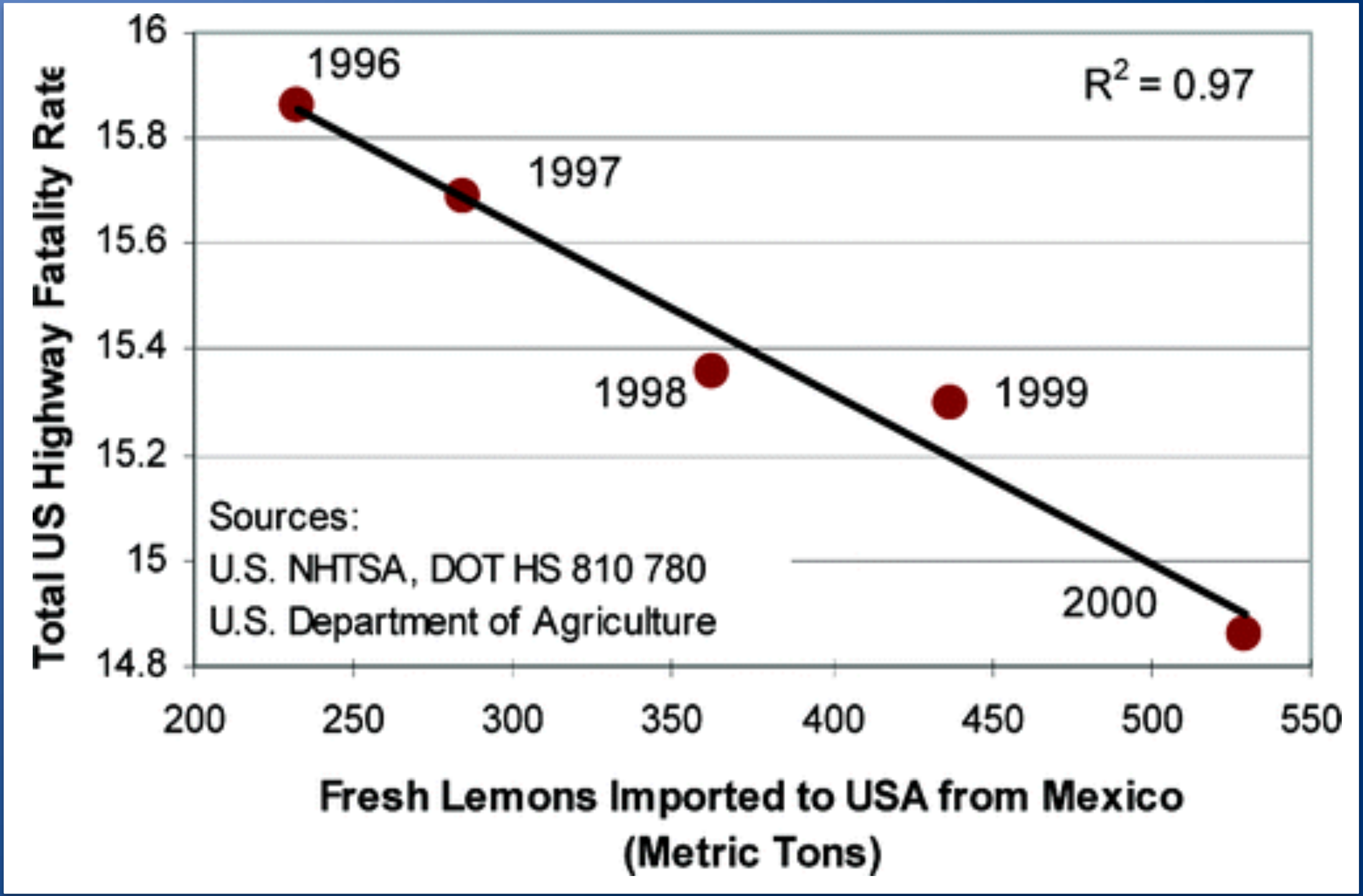
$$\frac{\sigma_d}{\sigma_p + \sigma_n} = 1 - a(x_p - b) \quad \text{for } 0.3 \le x_p \le 0.7,$$

Allows the extract σ_n – DIS cross section for a free neutron



L.B.Weinstein et al., Phys. Rev. Lett. 106 (2011) 052301
O. Hen et al., Phys. Rev. C 85 (2012) 047301
O.Hen et al., Phys.Rev.D 84 (2011) 117501

Other Correlations…



Mexican Lemonade Saves Lives!

Is there Physics Behind the EMC-SRC Correlation ?

- The EMC-SRC Correlation is robust.
  - Independent of different experimental and theoretical corrections applied to the SRC scaling data
- Models suggested that the EMC effect depends on the average kinetic energy, <T>, carried by nucleons in the nucleus
  - <T> is dominated by 2N-SRC
- **The correlation with the EMC effect survives the challenge of scaling with high precision EMC data on both light, medium and heavy nuclei**

O. Hen et al., Phys. Rev. C 85 (2012) 047301 J. Arrington et al., Phys.Rev. C 86 (2012) 065204

Can we test things? (Yes! Partly..)

- 2N-SRC pairs are universal
- Their interaction is largely independent of the (spectator) A-2 system
  - Depends mainly on the basic nucleon-nucleon interaction
- If SRC nucleons are modified – it should be a universal modification, independent of A

Can we incorporate a universal SRC modification with a simple EMC convolution model to explain the data?

O. Hen, D. W. Higinbotham, G. Miller, E. Piasetzky, L. B. Weinstein, In Preparation.

FS Convolution Model

- FS derive a convolution formula:

$$\frac{1}{A}F_2^A(x_A, Q^2) = \int_0^A \alpha\rho_A(\alpha)F_2^N(x_A/\alpha, Q^2)d\alpha,$$

- This formalism accounts primarily for binding and Fermi motion effects
- $\rho(\alpha)$ is the light-cone momentum distribution of the nucleus which is peaked around unity

L. Frankfurt and M. Strikman, Phys.Lett. B183 (1987) 254

FS Convolution Model

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$$\frac{1}{A}F_2^A(x_A,Q^2)=\int_0^A \alpha\rho_A(\alpha)F_2^N(x_A/\alpha,Q^2)d\alpha,$$

- Expending F_2^N around α=1 gives:

$$\frac{1}{A}F_2^A(x_A)\approx F_2^N(x_A)I_1(A)+x_AF_2^{\prime N}I_2(A)+[x_AF_2^{\prime N}+\frac{1}{2}x_A^2F_2^{\prime\prime N}]I_3(A),$$

with

$$I_n(A)\equiv\int\rho_A(\alpha)\alpha(1-\alpha)^{n-1}d\alpha,\; n=1,2,3$$

L. Frankfurt and M. Strikman, Phys.Lett. B183 (1987) 254

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FS Convolution Model

- Keeping orders of ϵ_A/m, k^2/m^2 and using the Koltum sum rule we get

$$n_A(k) \equiv \langle A|a_k^\dagger a_k|A\rangle,\ I_1(A) = \int d^3k n_A(k).$$

$$I_2(A) = \int d^3k n_A(k)(2\epsilon_A/m + \frac{A-4}{A-1}k^2/6m^2) \equiv \frac{2\epsilon_A}{m} + \frac{A-4}{A-1}\langle\frac{k^2}{6m^2}\rangle,$$

$$I_3(A) = \int d^3k n_A(k)k^2/3m^2 = \langle\frac{k^2}{3m^2}\rangle.$$

Where $n_A(k)$ is the nucleon momentum distribution and $I_1=1$ is a normalization condition

$$\frac{1}{A}F_2^A(x_A) \approx F_2^N(x_A)I_1(A) + x_A F_2'^N I_2(A) + [x_A F_2'^N + \frac{1}{2}x_A^2 F_2''^N]I_3(A),$$

(Modified) Convolution Model

- Isolating the Mean-Field and SRC contribution using realistic n(k) from Ciofi and Simula.

$$n_A(k) = n_A^{(0)}(k) + n_A^{(1)}(k),$$

Mean-Field Part

Correlated Part

C. Ciofi degli Atti and S. Simula, Phys. Rev. C 53, (1996) 1689
O. Hen, D. W. Higinbotham, G. Miller, E. Piasetzky, L. B. Weinstein, In Preparation.

(Modified) Convolution Model

- Isolating the Mean-Field and SRC contribution using realistic n(k) from Ciofi and Simula.

$$n_A(k) = n_A^{(0)}(k) + n_A^{(1)}(k),$$

Free Nucleon Structure Function

$$F_2^N(x_A)$$

SRC Nucleons Structure Function

$$\widetilde{F}_2^N(x_A)$$

$$\Delta F_2^N(x_A) = \widetilde{F}_2^N(x_A) - F_2^N(x_A).$$

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(Modified) Convolution Model

Combining it all we get:

$$I_1(A)F_2 \to I_1^{(0+1)}(A)F_2^N + I_1^{(1)}(A)\Delta F_{2N}, \text{ etc},$$

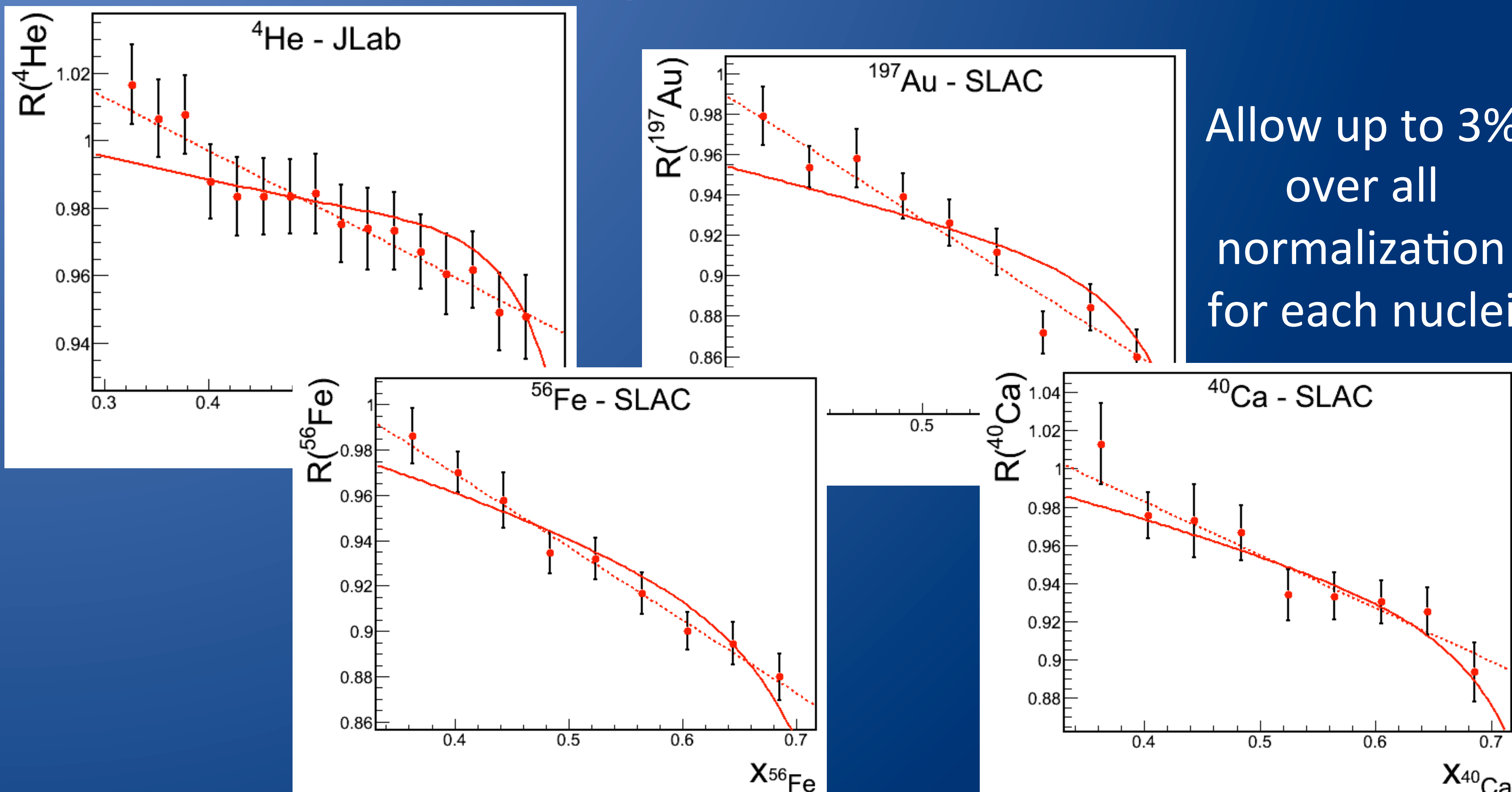
Standard nuclear term

Correlation modification term

$$\frac{1}{A}F_2^A(x_A) \approx F_2^N(x_A)I_1(A) + x_A F_2'^N I_2(A) + [x_A F_2'^N + \frac{1}{2}x_A^2 F_2''^N]I_3(A),$$

Fitting ΔF to the EMC data

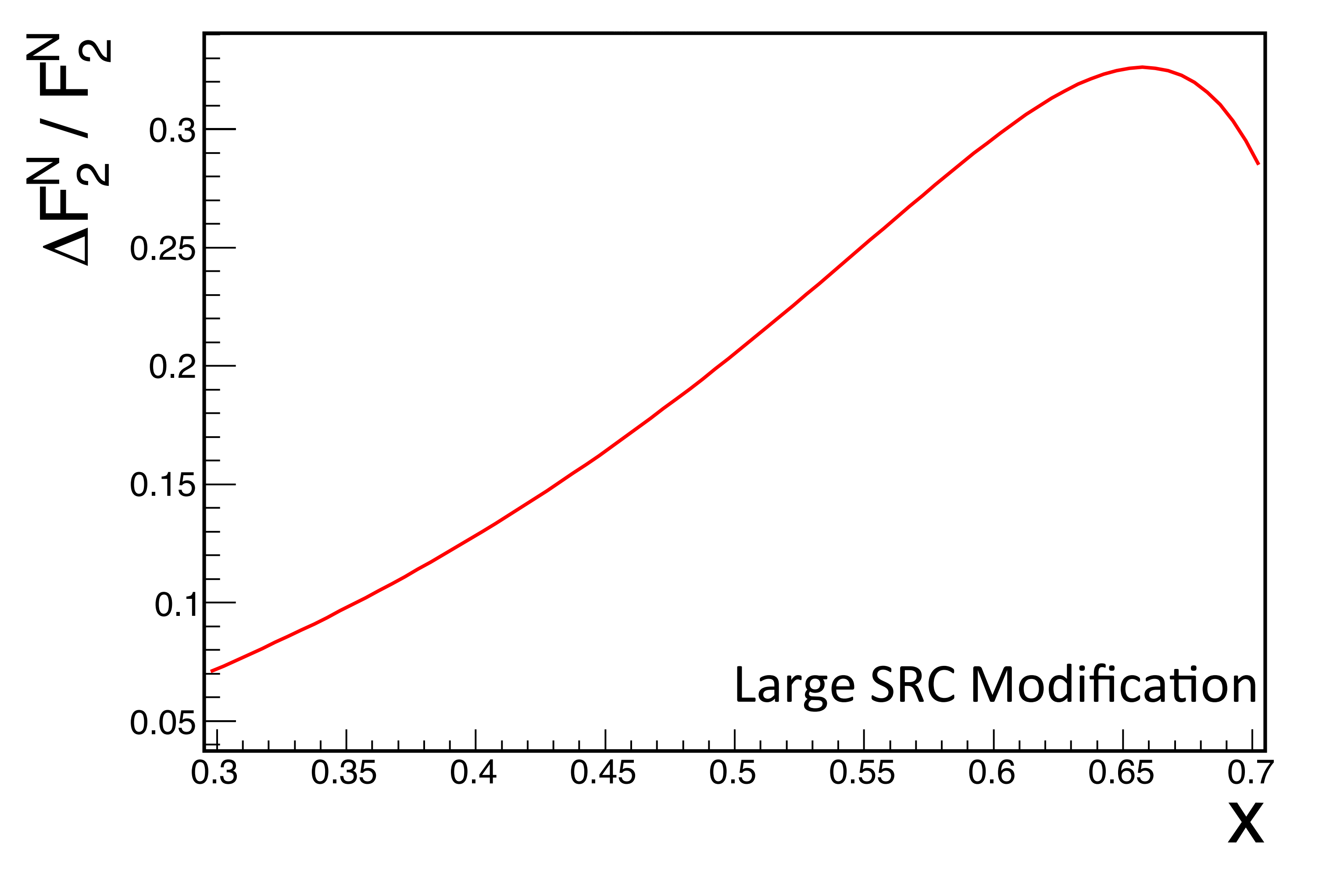
Assuming ΔF is a second order polynomial in x and fitting it to the EMC data



Allow up to 3% over all normalization for each nuclei

O. Hen, D. W. Higinbotham, G. Miller, E. Piasetzky, L. B. Weinstein, In Preparation.

Amount of modifications: ΔF/F



O. Hen, D. W. Higinbotham, G. Miller, E. Piasetzky, L. B. Weinstein, In Preparation.

Does it rule out the Mean-Field hypothesis? (No!)

Assuming global modification of Mean-Field nucleons and using the same model we get good fits to the data with a smaller ΔF term

$$n_A(k) = n_A^{(0)}(k) + n_A^{(1)}(k),$$

M.F. Nucleon Structure Function $\widetilde{F}_2^N(x_A)$

Free Nucleon Structure Function $F_2^N(x_A)$

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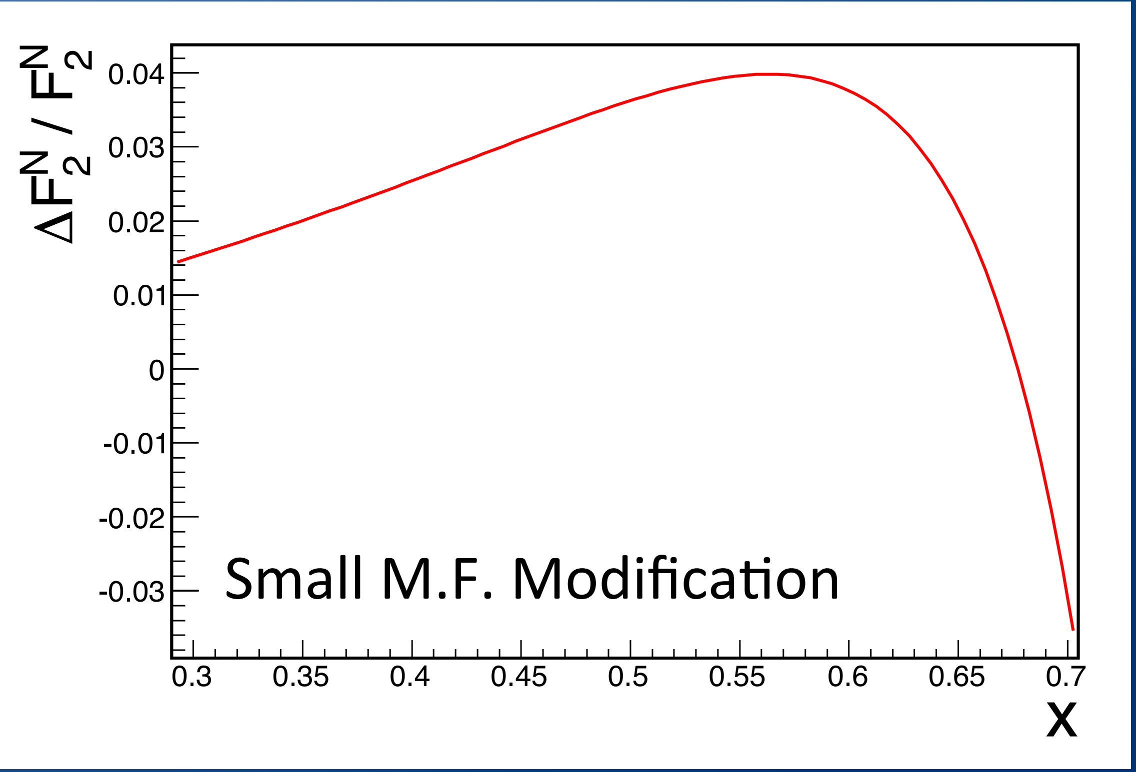

O. Hen, D. W. Higinbotham, G. Miller, E. Piasetzky, L. B. Weinstein, In Preparation.

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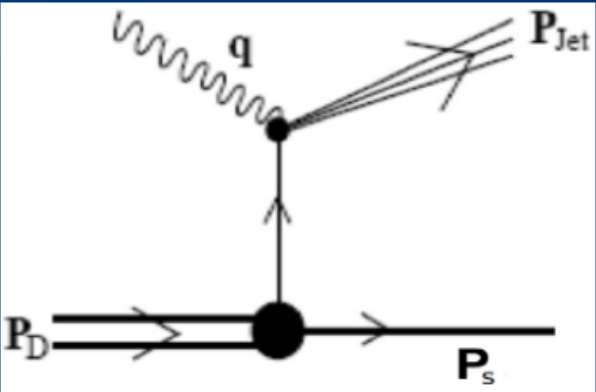
Experimental Tests ?

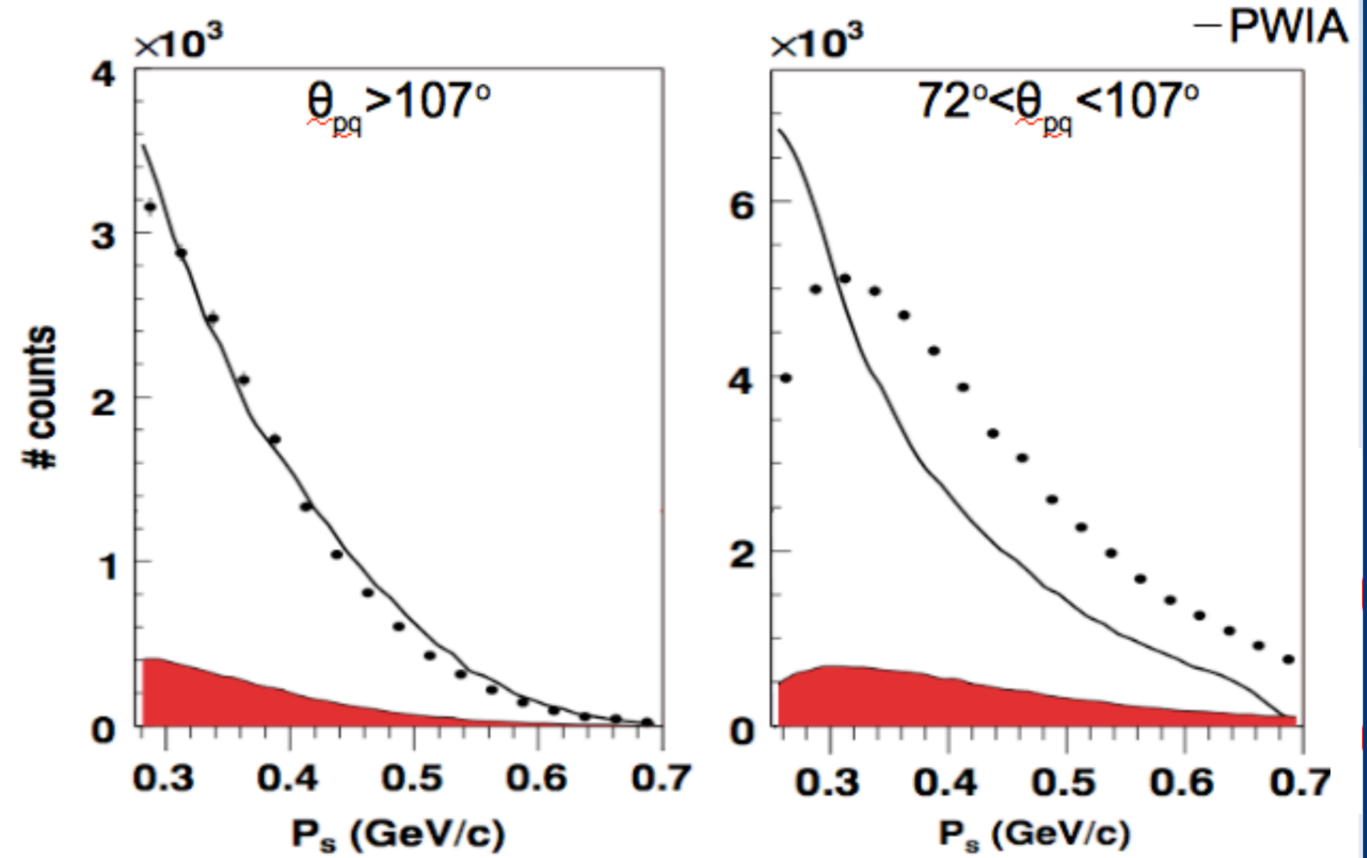
- Goal: measure the virtuality (nuclear density) dependence of the structure function
- (our) Method: tagged DIS using d(e,e'N_{recoil}) reactions

Deuterium is the only system in which the momentum of the struck nucleon equals that of the recoil (Assuming no FSI)

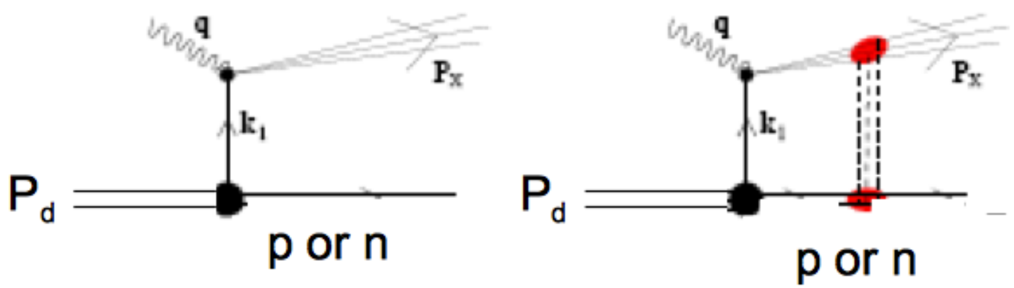
See talks by D. Higinbotham and S. Wood



First attempt: DEEPS (JLab-CLAS)

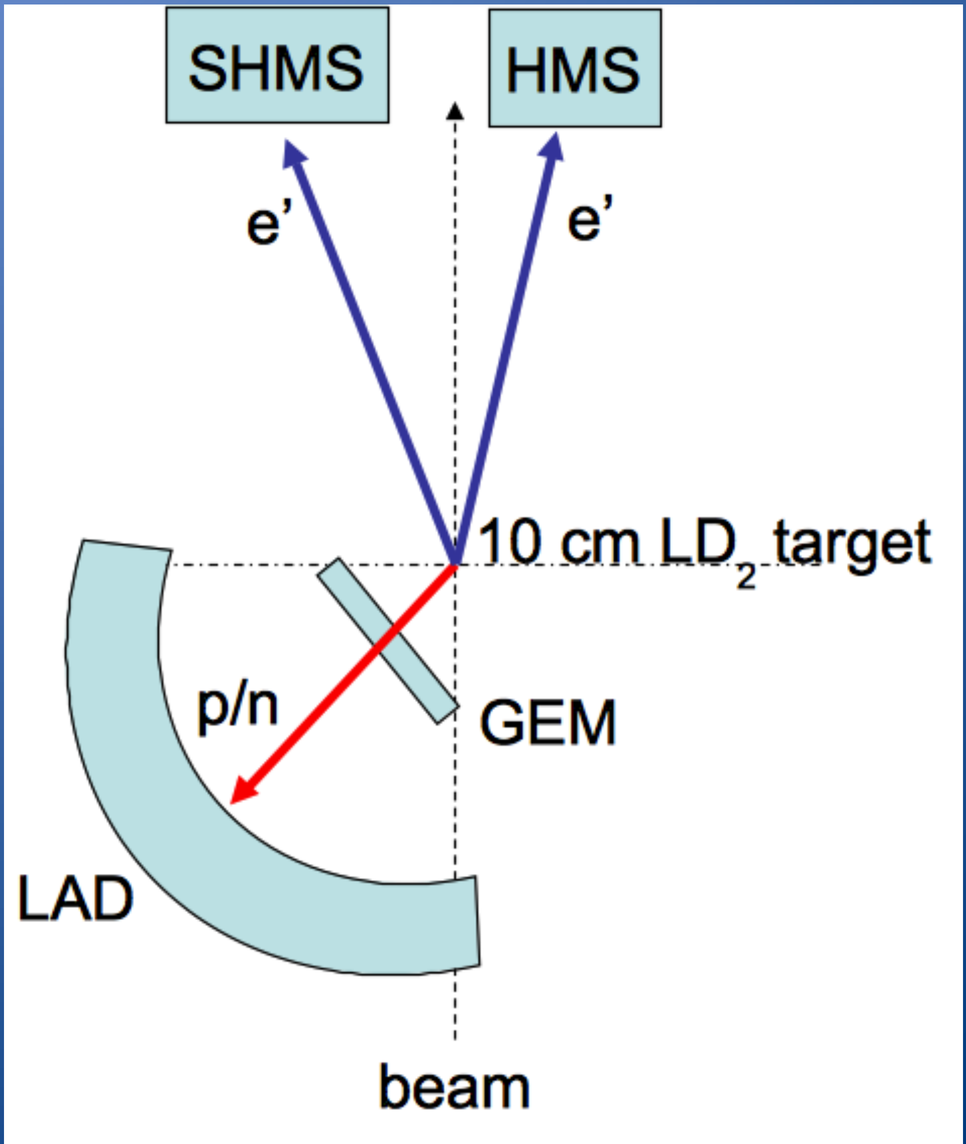


A. V. Klimenko et al., PRC 73, 035212 (2006)



FSI are reduced at large backward angles

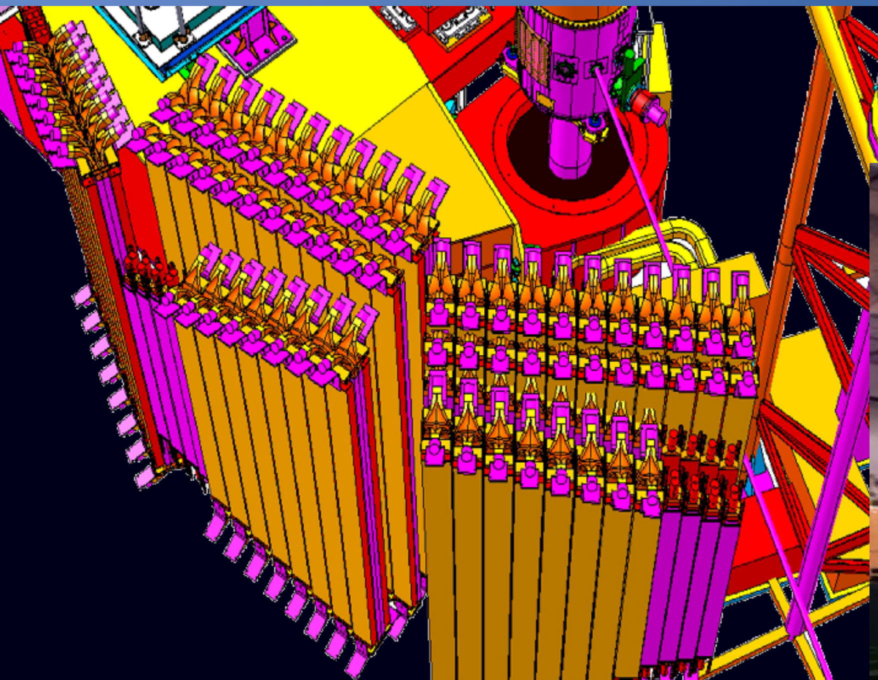
Our Concept…



- High resolution spectrometers for (e,e') measurement in DIS kinematics
- Large acceptance recoil proton \ neutron detector
- Long target + GEM detector – reduce random coincidence

d(e,e'N$_{recoil}$)

…It's realization (JLab E11-107)



Large Acceptance Detector (LAD)

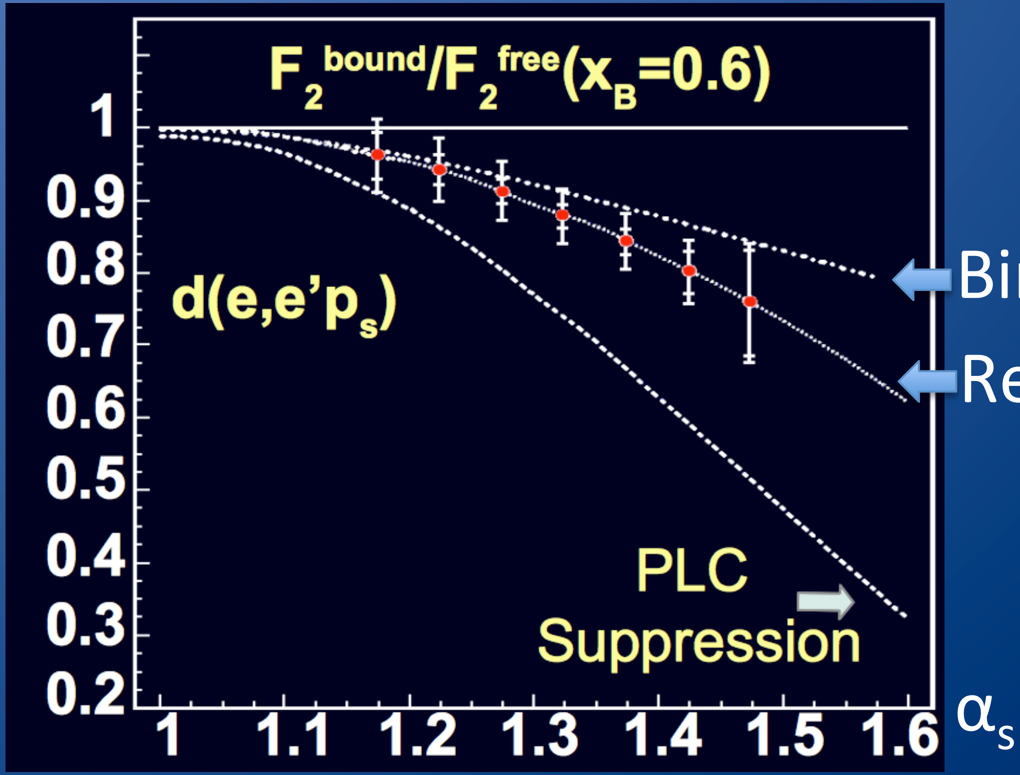
133 scintillators

22cm X 5cm X 2-4m

80º-180º@4m from target

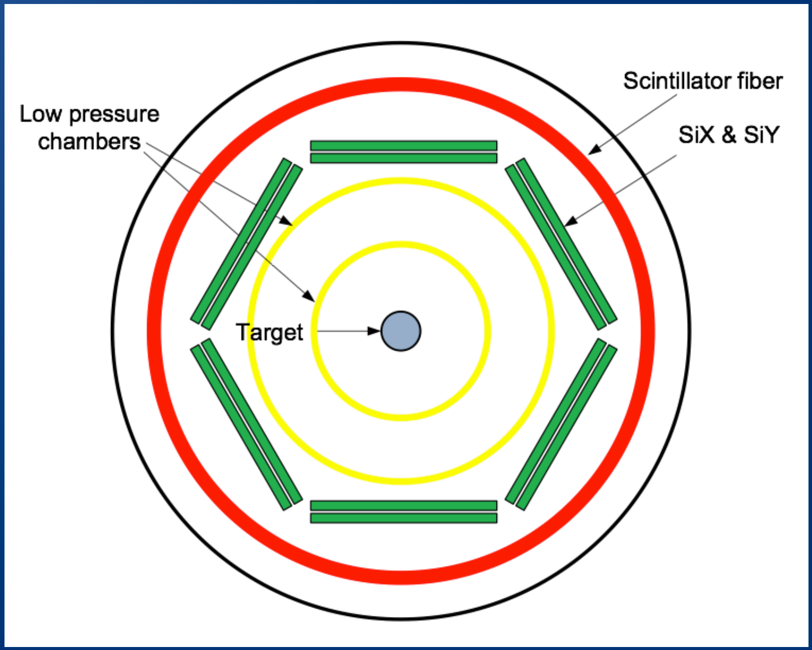
Kinematics and Uncertainties

- Tagging allows to extract the structure function in the nucleon reference frame: $x' = \frac{Q^2}{2(\bar{q} \cdot \bar{p})}$
- Expected coverage: x'~0.3 & 0.45<x'<0.55 @ $W^2 > 4\ [\mathrm{GeV/c}]^2$



Intent to measure Mean-Field structure functions

- Use the forward CLAS-12 detector to measure A(e,e') scattering in DIS kinematics
- Detect low momentum recoil nucleon (p,d, 3He,3H) using a new central detector
- Various Mean-Field tagging reactions:
  - d(e,e'p)X
  - ^{3}He(e,e'd)X
  - ^{4}He(e,e'^{3}He)X
  - ^{4}He(e,e'^{3}H)X
  - ^{4}He(e,e'dp)X



K. Hafidi et al., JLab Letter Of Intent (2012)

SRC & the Nuclear W.F.

- Symmetric nuclei are made up of ~80% mean-field (M.F.) nucleons and 20% np-SRC pairs
- We define the transition point as k_0 ($\approx k_F \sim 300$ MeV/c)
- Allows to construct a simple wave function:

See talks by M. Sargsian and E. Piasetzky

$$n_A(k) = \begin{cases} \eta \cdot n_A^{M.F.}(k) & k \le k_0 \\ a_2(A/d) \cdot n_d(k) & k \ge k_0 \end{cases}$$

η determined from:

$$\int_0^\infty n(k) k^2 \, dk \equiv 1$$

M. Sargsian, arXiv: 1210.3280 (2012)

SRC in asymmetric nuclei

$$n(k) = \frac{1}{A}\left[z \cdot n^{p}(k) + n \cdot n^{n}(k)\right]$$

- Assuming SRC are dominated by np pairs, there's an EQUAL ABSOLUTE NUMBER of high momentum protons and neutrons (i.e. different relative number)
  - The high momentum tail of the $n^{p(n)}(k)$ should be renormalized according to 1/z (1/n) to have an equal number of protons and neutrons.

M. Sargsian, arXiv: 1210.3280 (2012)

SRC in asymmetric nuclei

- Assuming SRC are dominated by np pairs, there's an <u>EQUAL ABSOLUTE NUMBER</u> (i.e. different relative number) of high momentum protons and neutrons:

$$n_A^p(k) = \begin{cases} \eta \cdot n_A^{M.F.}(k) & k \le k_F \\ \frac{A}{2z} \cdot a_2(A/d) \cdot n_d(k) & k \ge k_F \end{cases}$$

$\frac{A}{2z}$ >1

$$n_A^n(k) = \begin{cases} \eta \cdot n_A^{M.F.}(k) & k \le k_F \\ \frac{A}{2n} \cdot a_2(A/d) \cdot n_d(k) & k \ge k_F \end{cases}$$

$\frac{A}{2n}$ <1

M. Sargsian, arXiv: 1210.3280 (2012)

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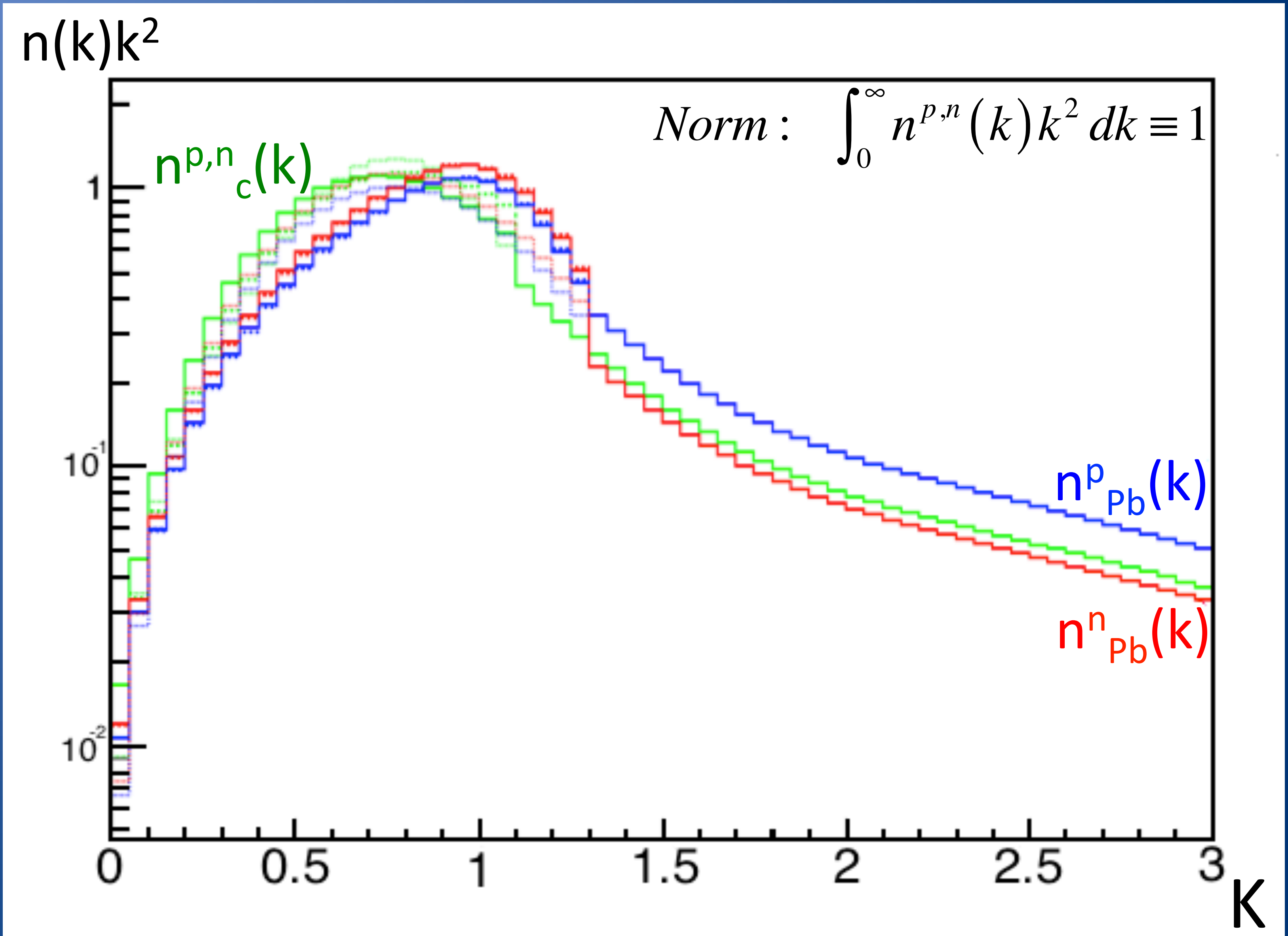

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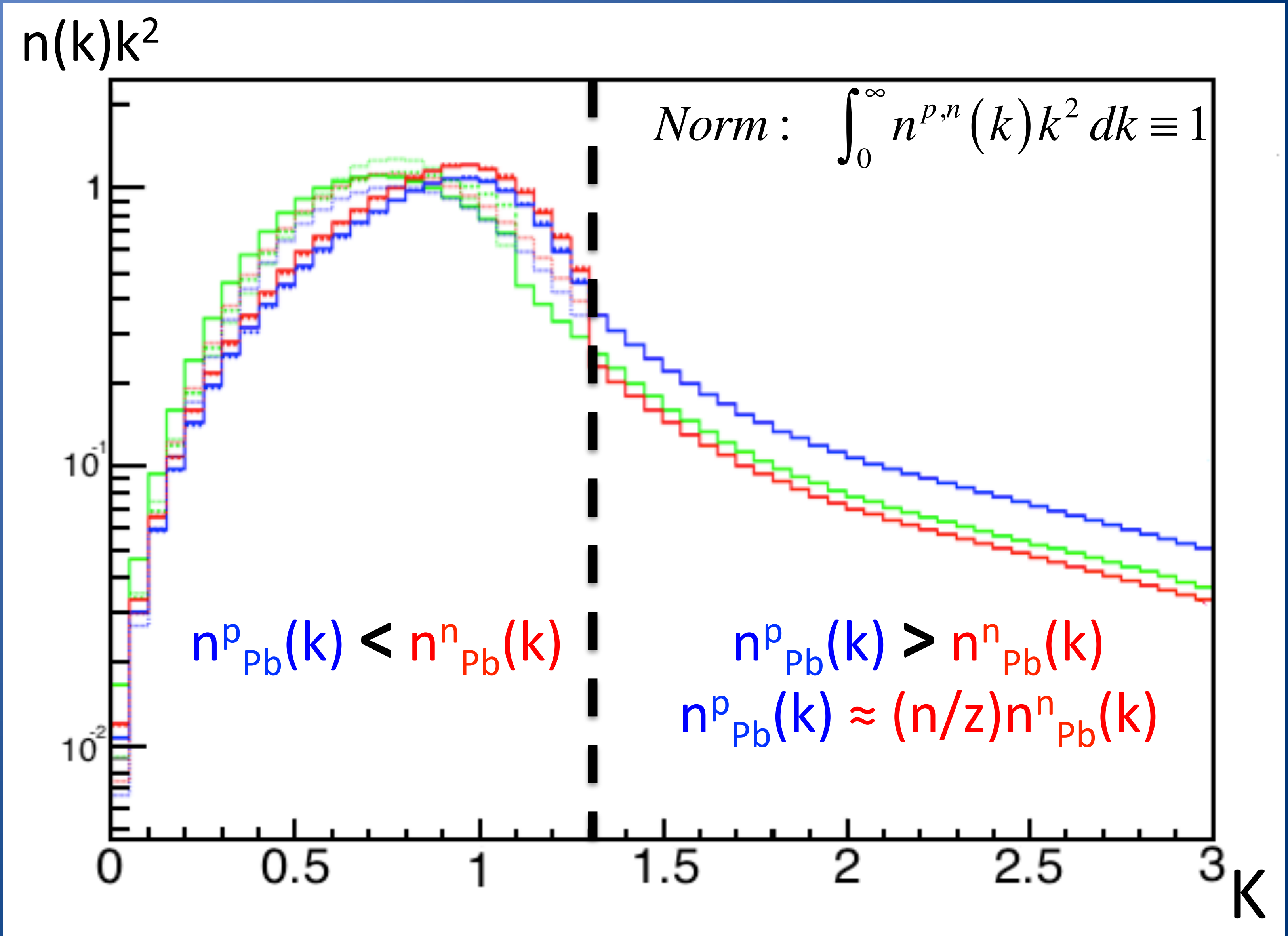
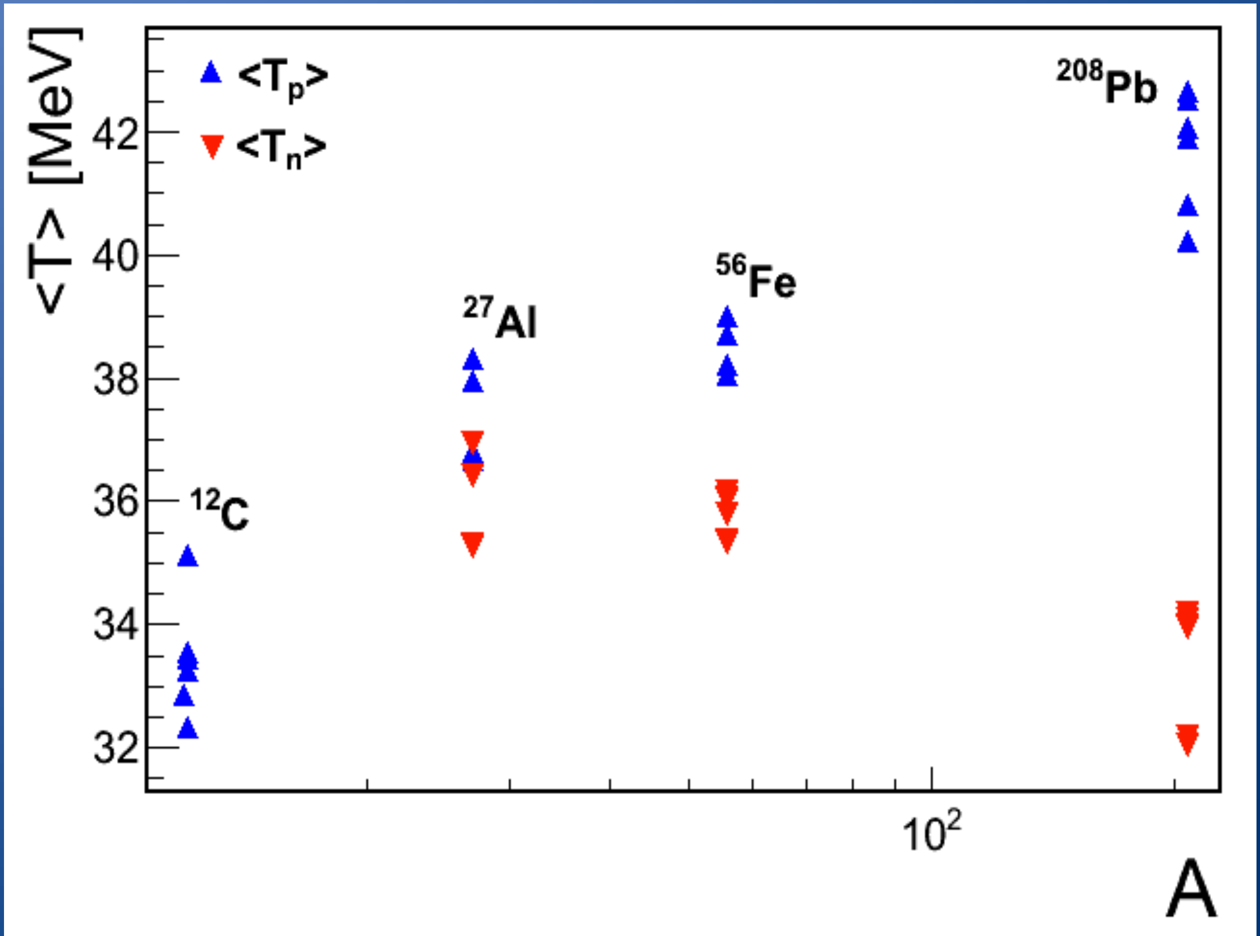


SRC in asymmetric nuclei

Allows to calculate $\langle T_p \rangle$ and $\langle T_n \rangle$ for protons and neutrons in various nuclei



<u>Consider 3 models for $n^{M.F.}(k)$:</u>

- Ciofi and Simula
- Wood-Saxon
- Serot-Walecka

<u>Consider 2 values for k_0:</u>

- k_F
- 300 MeV/c

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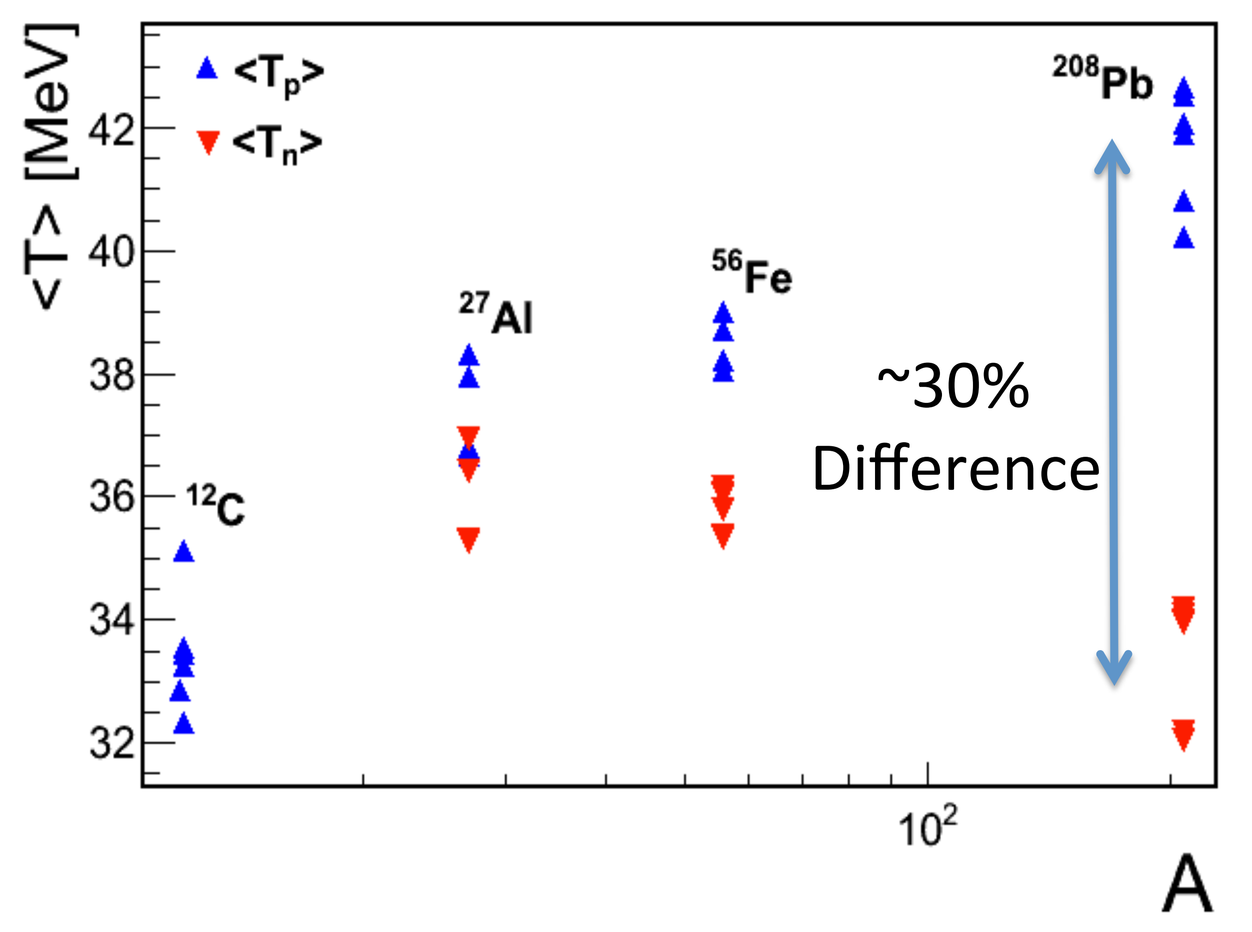

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EMC↔SRC in asymmetric nuclei

- The contribution of standard nuclear effects (e.g. binding and Fermi motion) to the EMC effect is proportional to <T>
- Several EMC models relate medium modification effects to <T>

These <T>s are different for protons and neutrons in asymmetric nuclei

e.g. FS PLC suppression: $\delta(k) = 1 - 2k^2/m_N \Delta E.$

EMC↔SRC in asymmetric nuclei

Protons "Feel" a Larger EMC Effect then neutrons

Notice that applying ISO Corrections to the EMC data 'washout' this effect

M. Sargsian, arXiv: 1209.2477 (2012)

Conclusions - I

- EMC effect should be extracted in the nucleus reference frame (i.e. equal x_A)
- EMC strength and the amount on 2N-SRC pairs in nuclei are correlated
- Correlation indicated that both steam from the same cause -> high momentum nucleons
- Universal modification of SRC (M.F.) nucleons can explain the EMC effect

Conclusions - II

- SRC are dominated by np-SRC pairs
  - In asymmetric, neutron reach, nuclei protons have *larger* average kinetic energy then neutrons
- Protons play a larger role then neutrons in the EMC effect of asymmetric nuclei

- Review paper in preparation (Hen, Higinbotham, Miller, Piasetzky, and Weinstein) to be published in *International Journal of Modern Physics E*

Thank You !