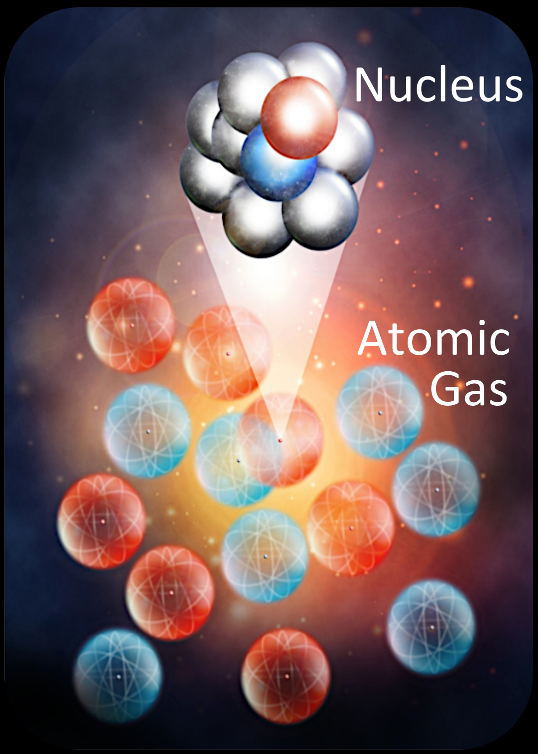
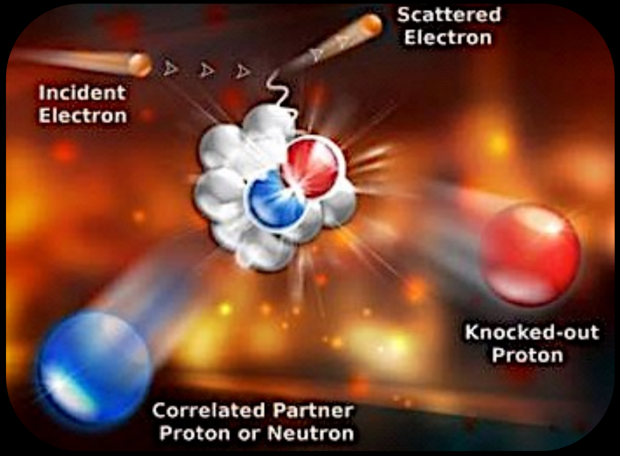
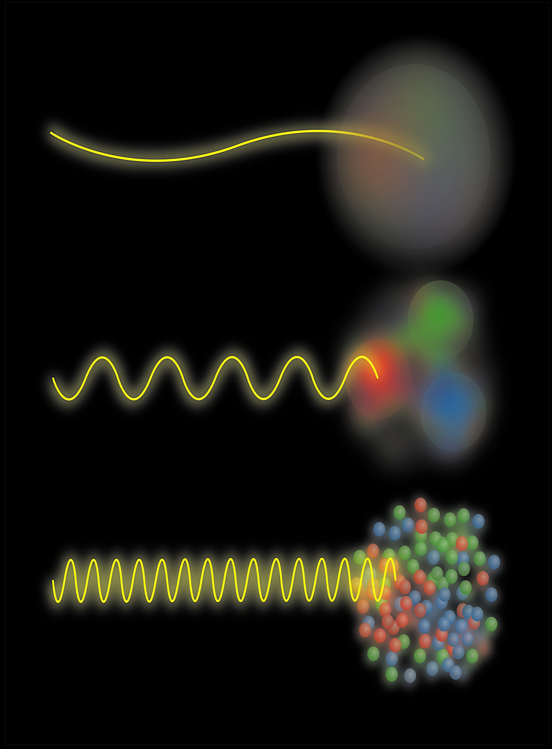
SRC and the EMC Effect



Or Hen

Tel-Aviv (-> MIT)

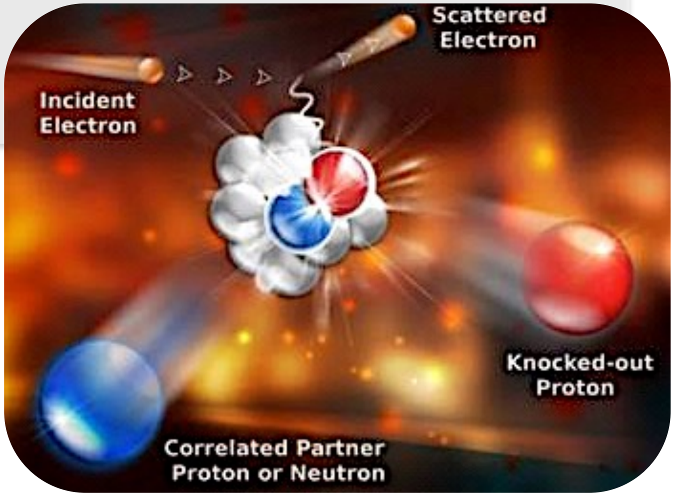


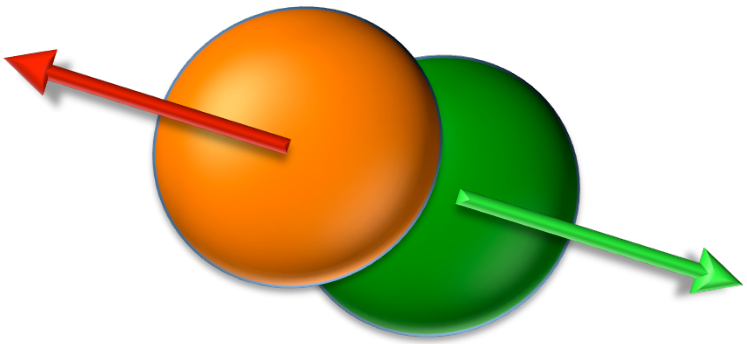


EMMI Workshop, GSI, Germany (October 14th 2015)

Short-Range Correlation (SRC)

- Are close together (wave function overlap)
- <u>Have *high relative momentum* and *low c.m. momentum* compared to the Fermi momentum (k_F)</u>

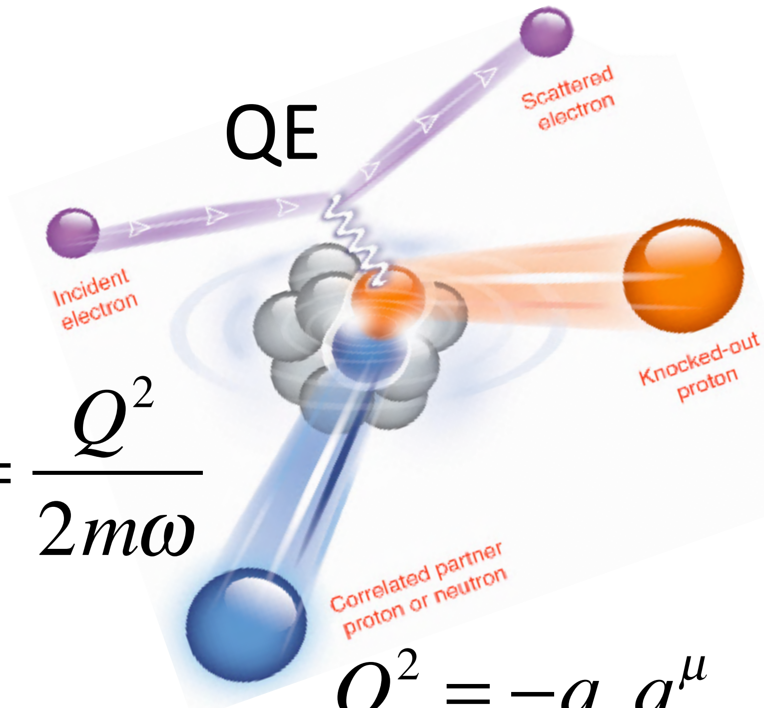




Quasi-Elastic Scattering

QE: Study of the <u>nucleonic</u> structure of the <u>nucleus</u>

QE scale: <u>several GeV</u>



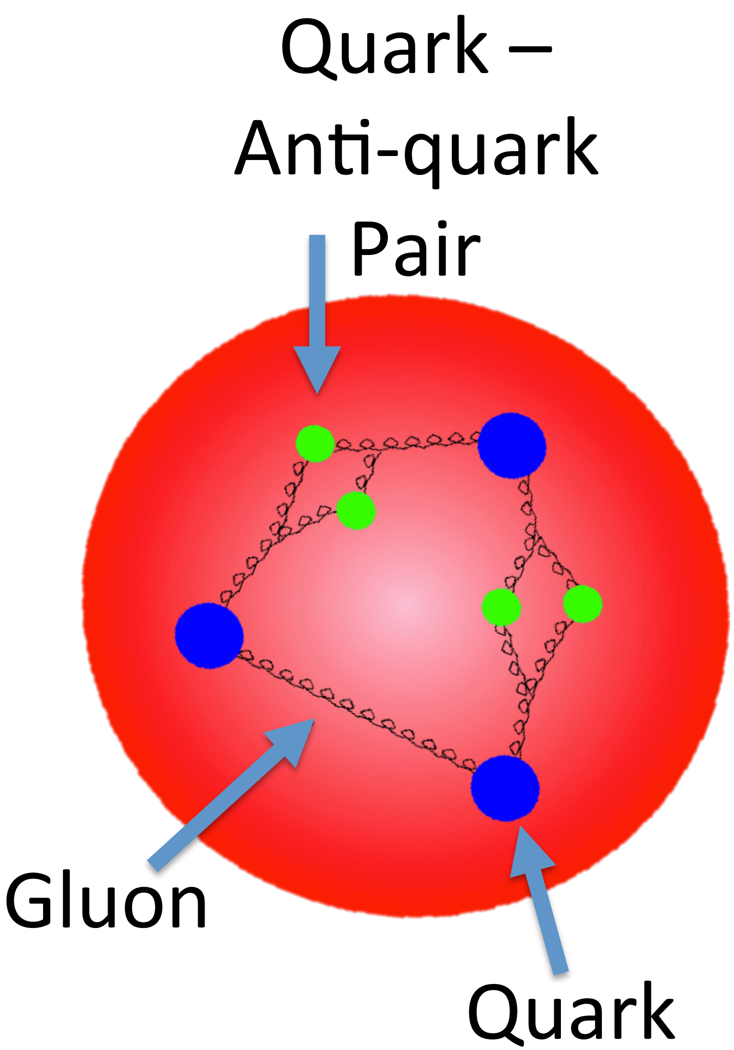
$$x_B = \frac{Q^2}{2m\omega}$$

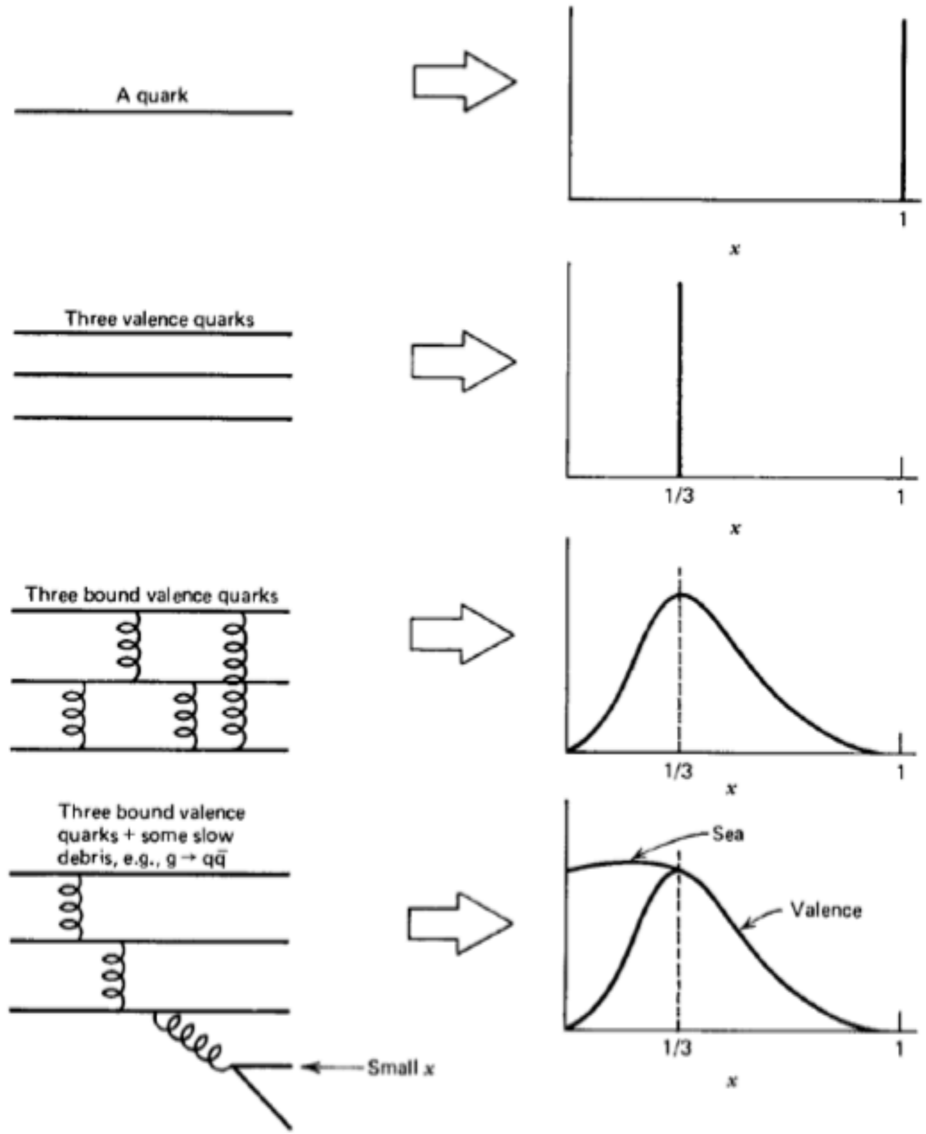
$$Q^2 = -q_\mu q^\mu$$

<u>$0<x_B<A$:</u>

- Counts the *number of nucleons involved* in the reaction.
- Determines the *minimal initial momentum* of the scattered nucleon.

Deep-Inelastic Structure Functions

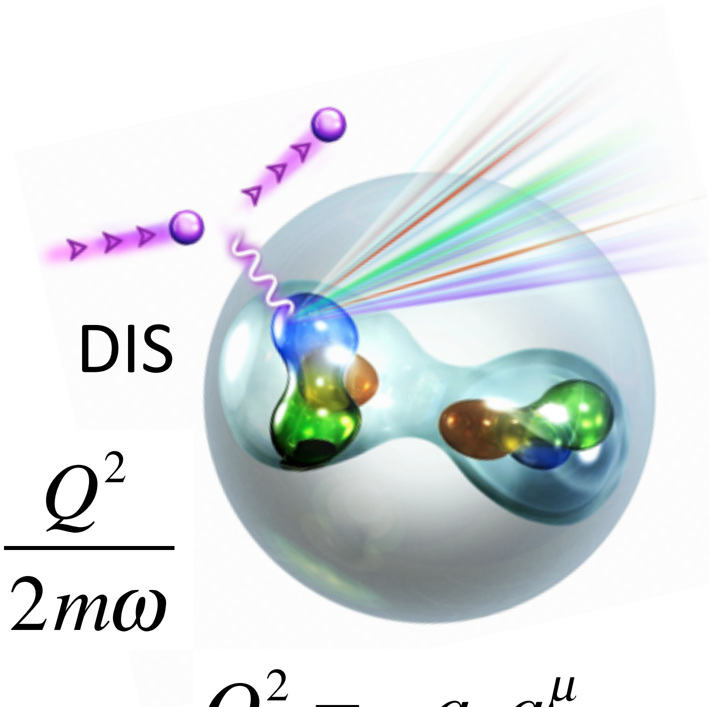




Deep Inelastic Scattering

DIS: Study of the partonic structure of the nucleon

DIS scale: several tens of GeV



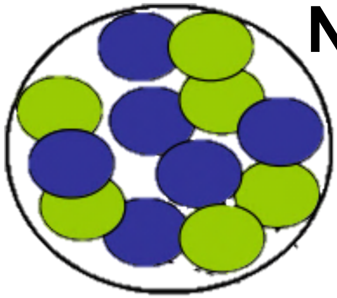
$$x_B = \frac{Q^2}{2m\omega}$$

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

$0<x_B<1$:
equals the fraction of nucleon momentum carried by the struck parton (in the infinite momentum frame).

Deep Inelastic Scattering *Off-Nuclei*

DIS scale: several tens of GeV



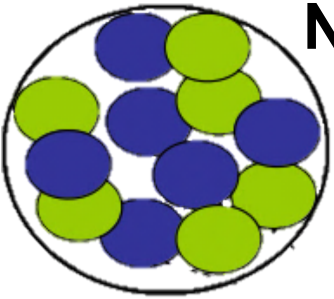
Nucleon in nuclei are bound by a few MeV

Naive expectation :

DIS off a bound nucleon = DIS off a free nucleon

(Except some small Fermi momentum correction)

DIS scale: several tens of GeV



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Deuteron: binding energy ~2 MeV

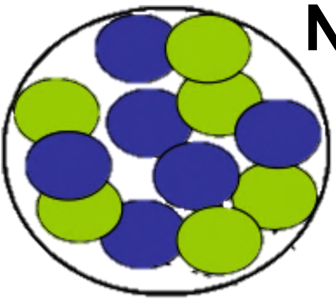
Average nucleons separation ~2 fm

Naive expectation :

DIS off a deuteron = DIS off a free proton neutron pair

Deep Inelastic Scattering *Off-Nuclei*

DIS scale: several tens of GeV



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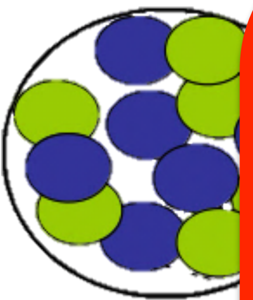
General Naive Expectation :

DIS off nucleons in *nuclei*

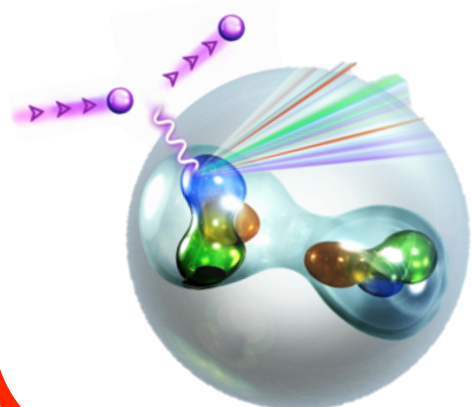
= DIS off nucleons in *deuterium*

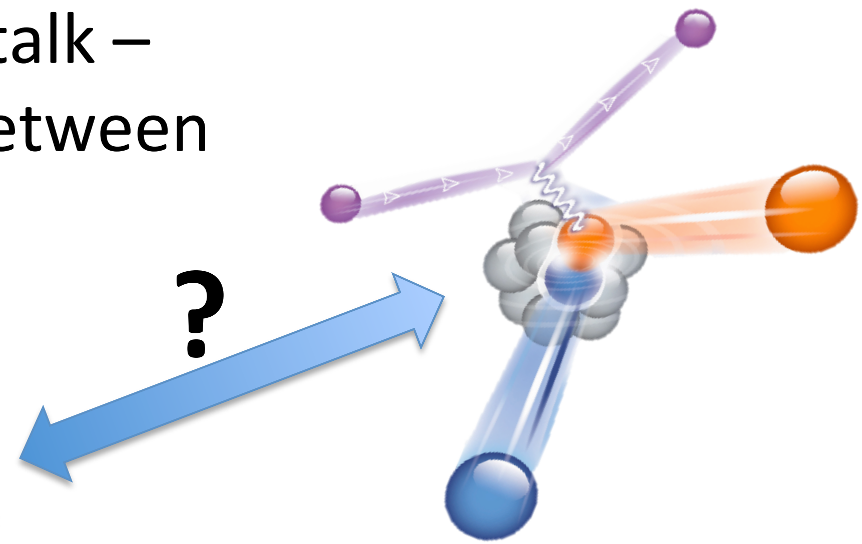
Deep Inelastic Scattering *Off-Nuclei*

DIS sc



Focus of this talk – connection between DIS and QE





eon

Deu

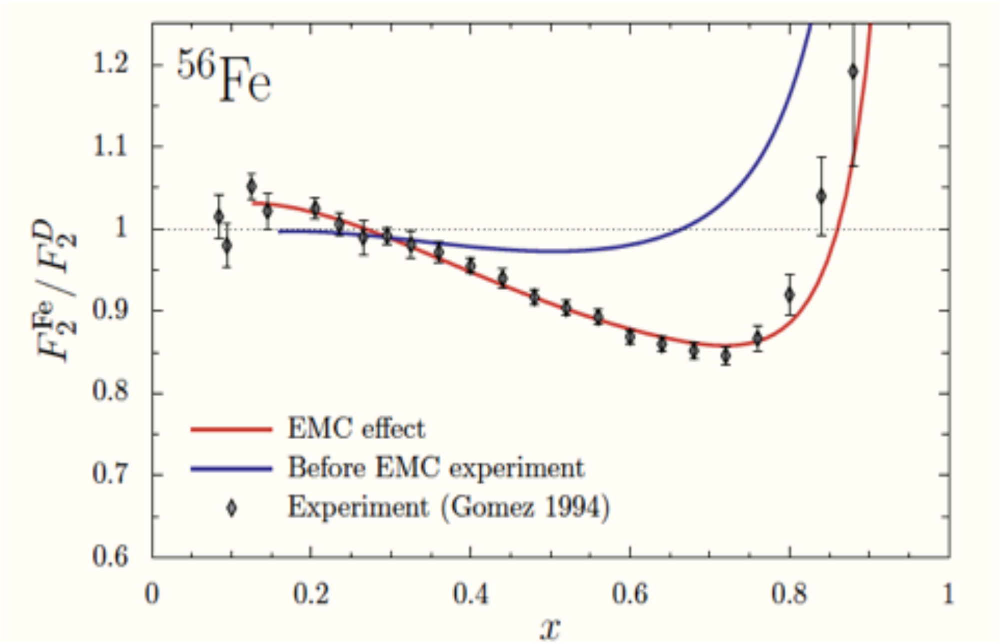
eutron pair

General Naive Expectation :

DIS off nucleons in *nuclei*
= DIS off nucleons in *deuterium*

EMC Effect

- Deviation of the per-nucleon DIS cross section ratio of nuclei relative to deuterium from unity.
- 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.



$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_A = \frac{4\alpha^2 E'^2}{Q^4}\left[2\frac{F_1}{M}\sin^2\left(\frac{\theta}{2}\right) + \frac{F_2}{\nu}\cos^2\left(\frac{\theta}{2}\right)\right] \qquad F_2\left(x,Q^2\right) = \sum_i e_i^2 \cdot x \cdot f_i(x)$$

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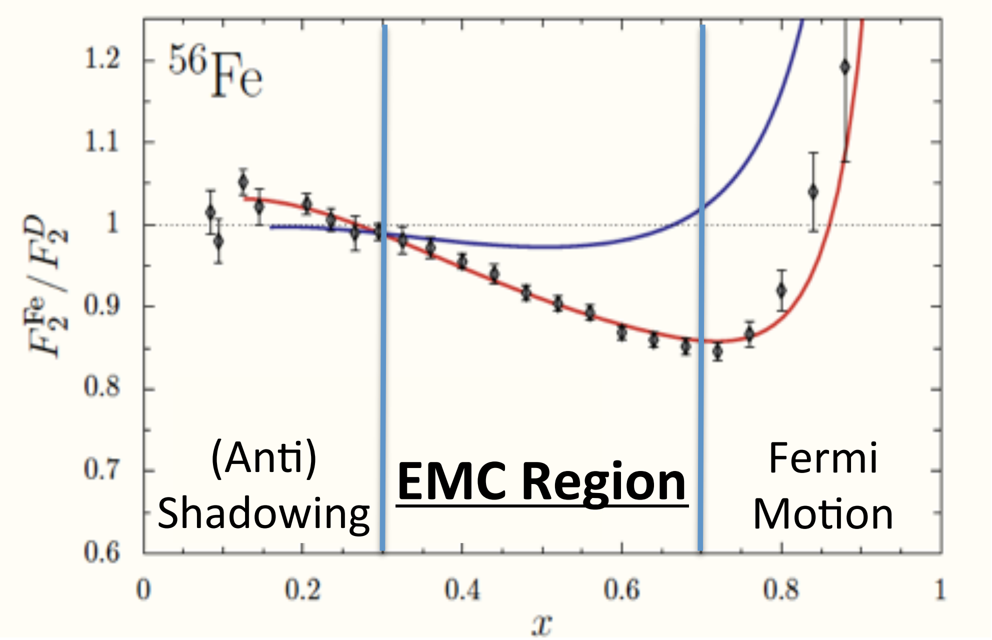

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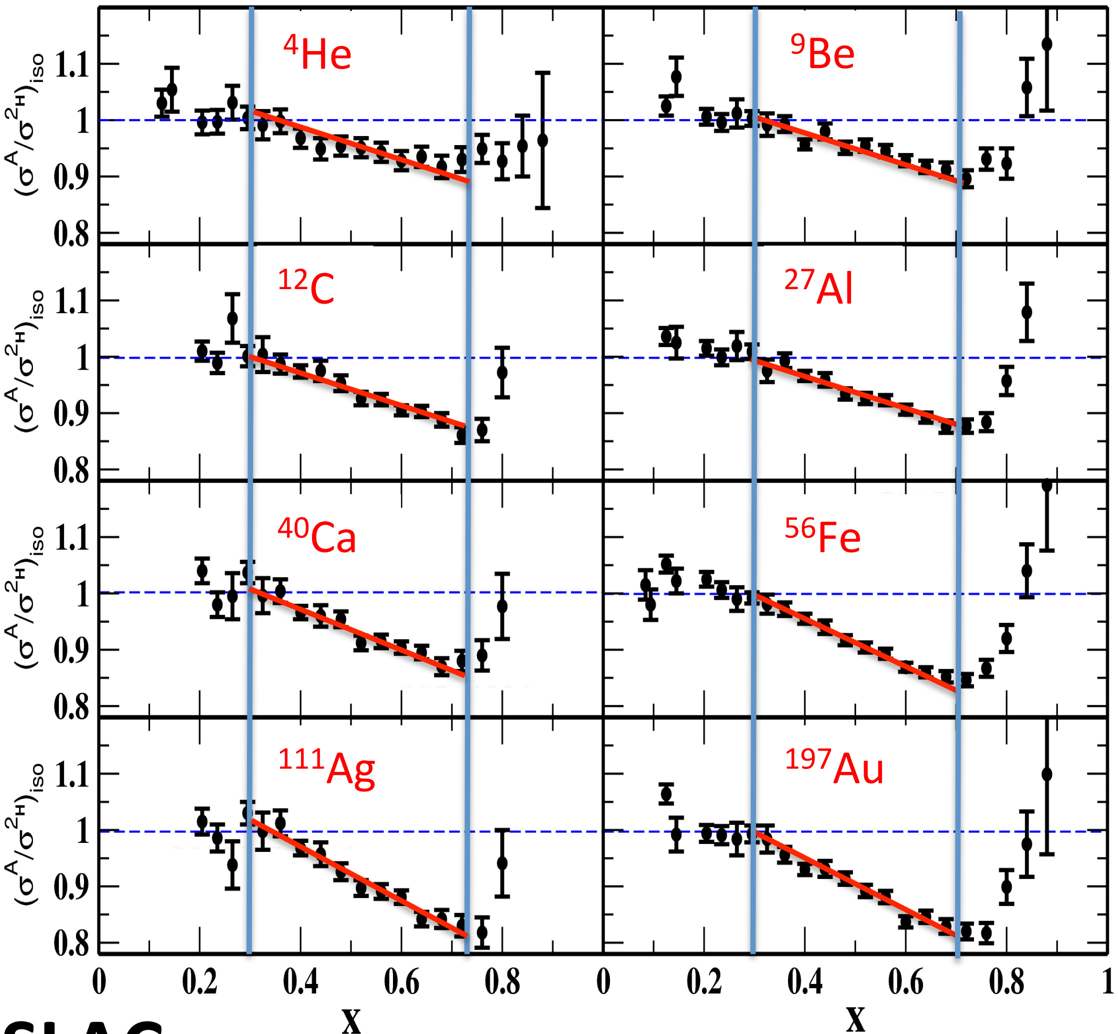
EMC Theory

- Standard nuclear effects:
  - Binding and Fermi motion
  - Coulomb Field
- Explain most of the effect up to $x \approx 0.5$.

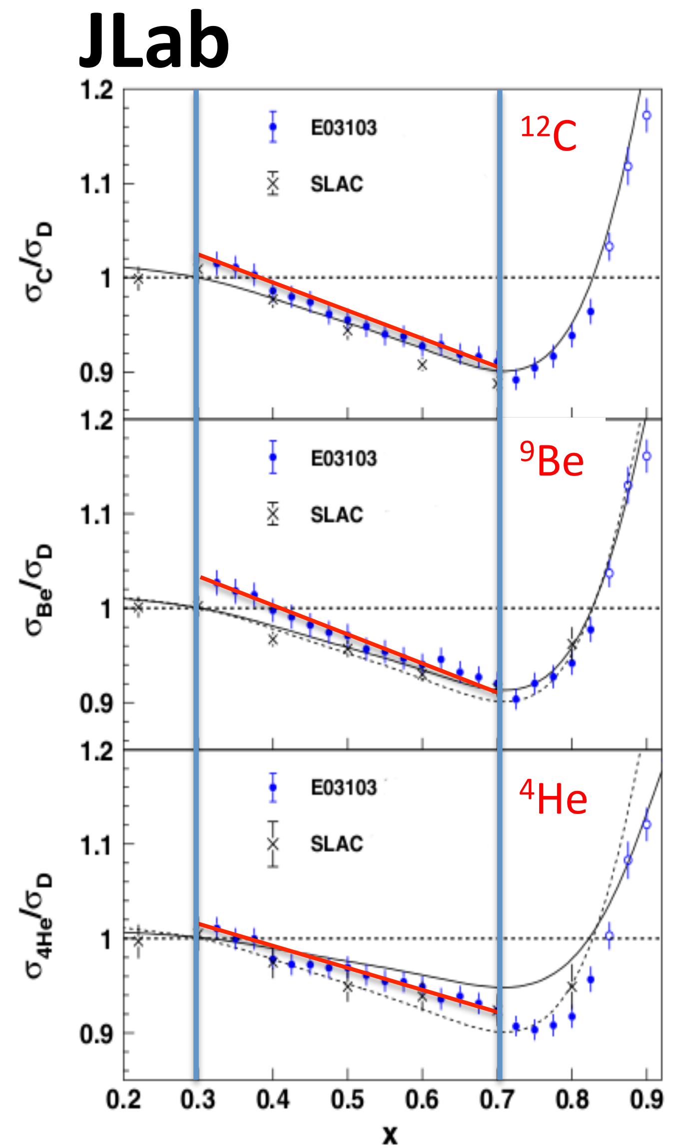
  Fail to explain the effect at larger values of x.
- Various theoretical models – Most incorporate modification of the structure of bound nucleons
- EMC – Everyone's Model is Cool (G. A. Miller)

Universality of the EMC Effect



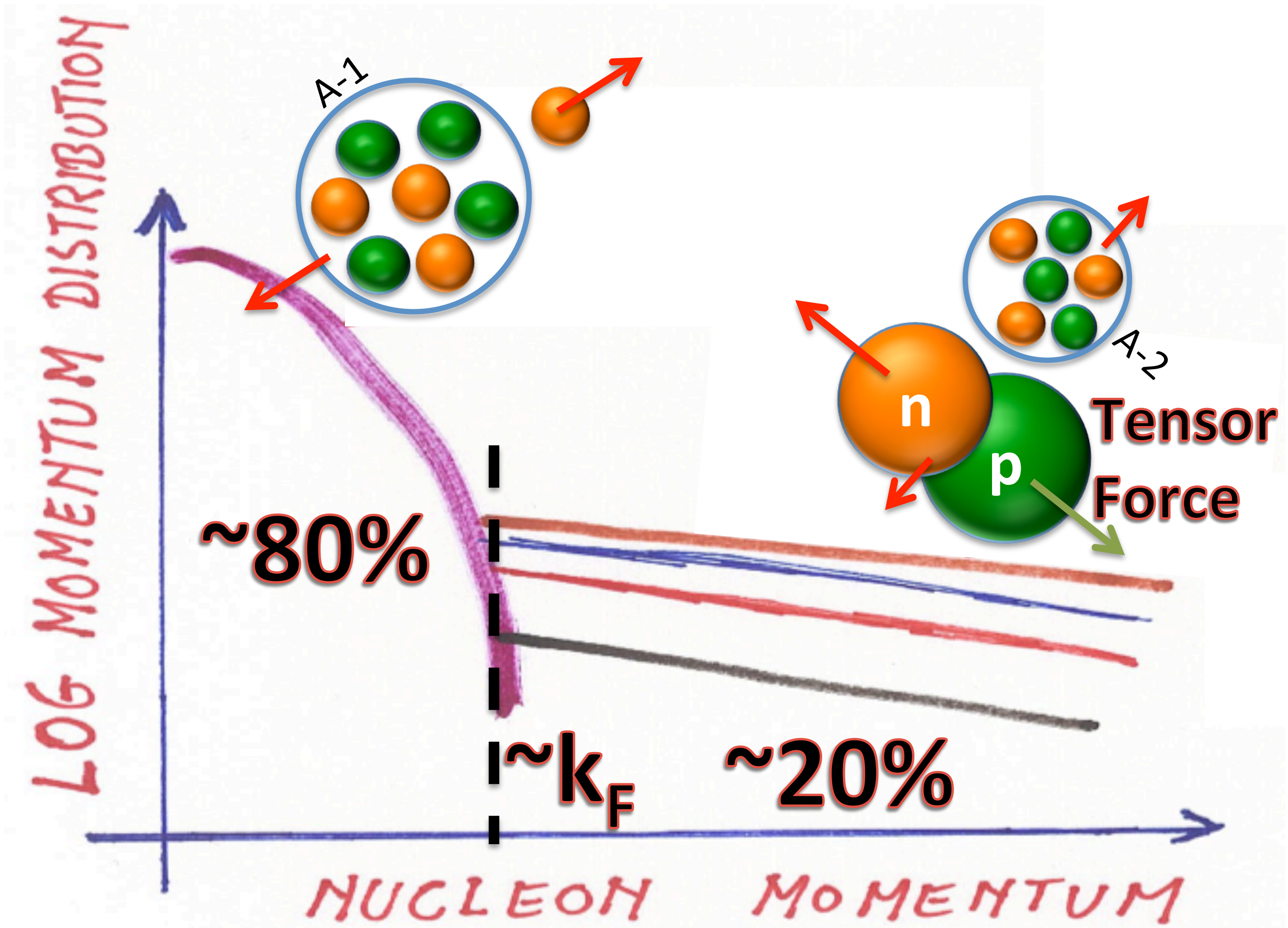
SLAC

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

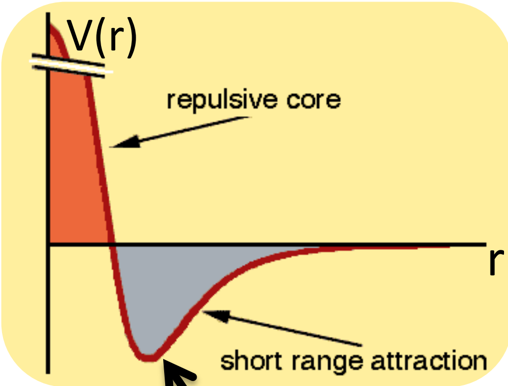


J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009).

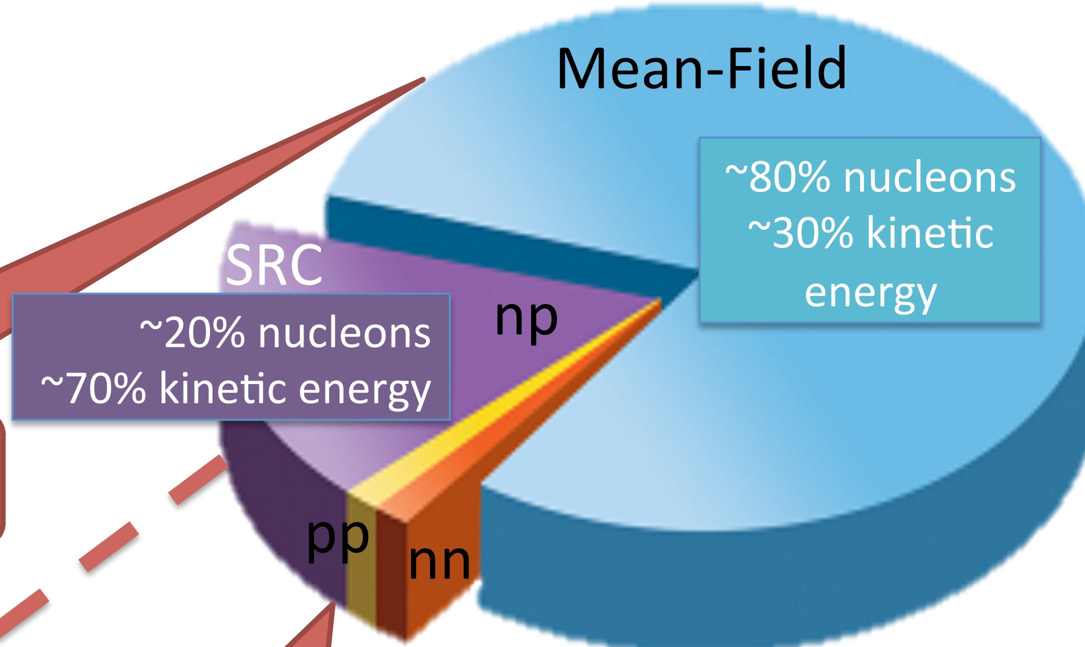
Nuclear Structure



Where is the EMC Effect?

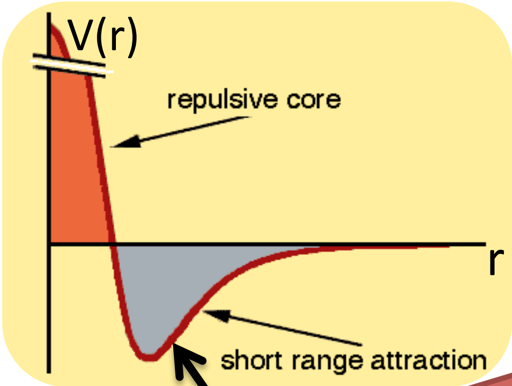


Largest attractive force



High local nuclear matter density, large momentum, large off shell, large virtuality ($v = p^{\mu 2} - m^2$)

Where is the EMC Effect?



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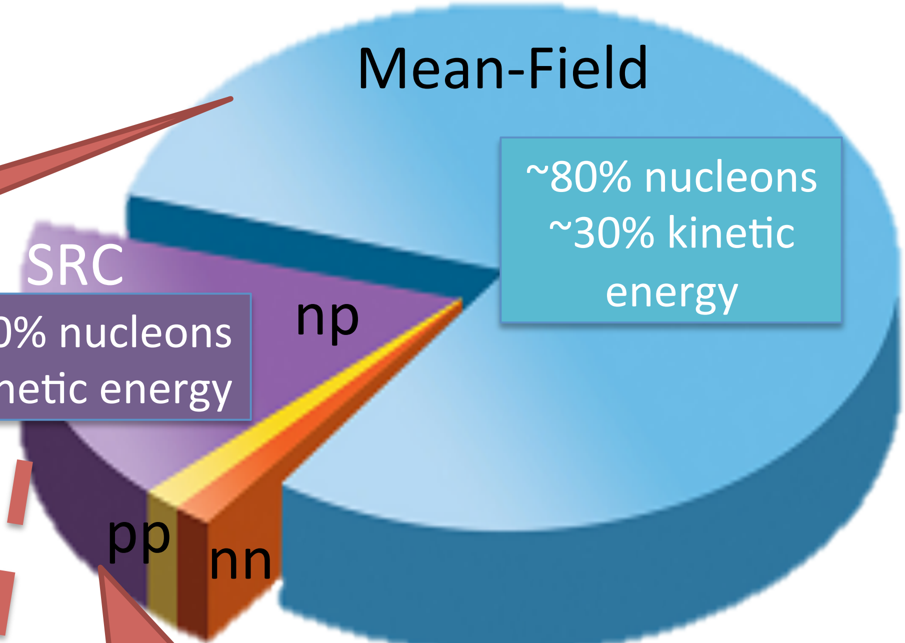

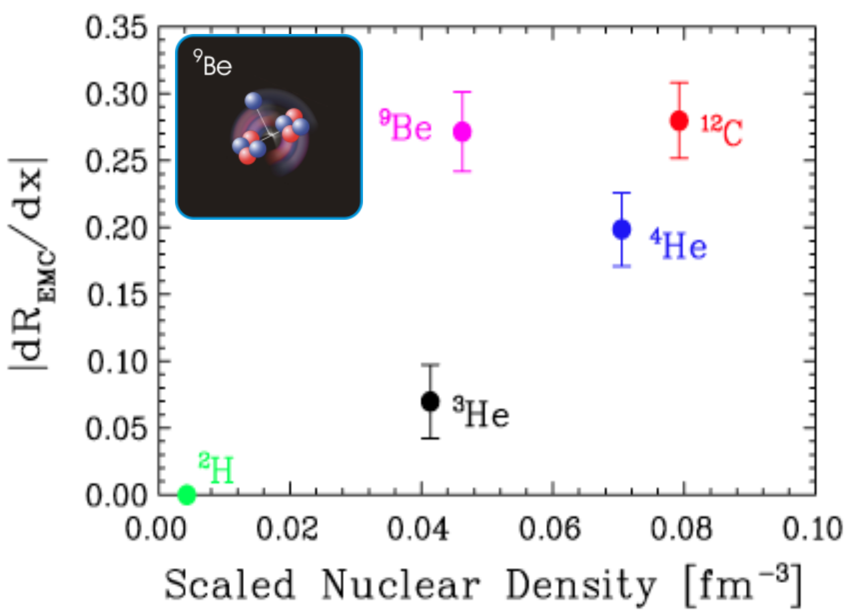

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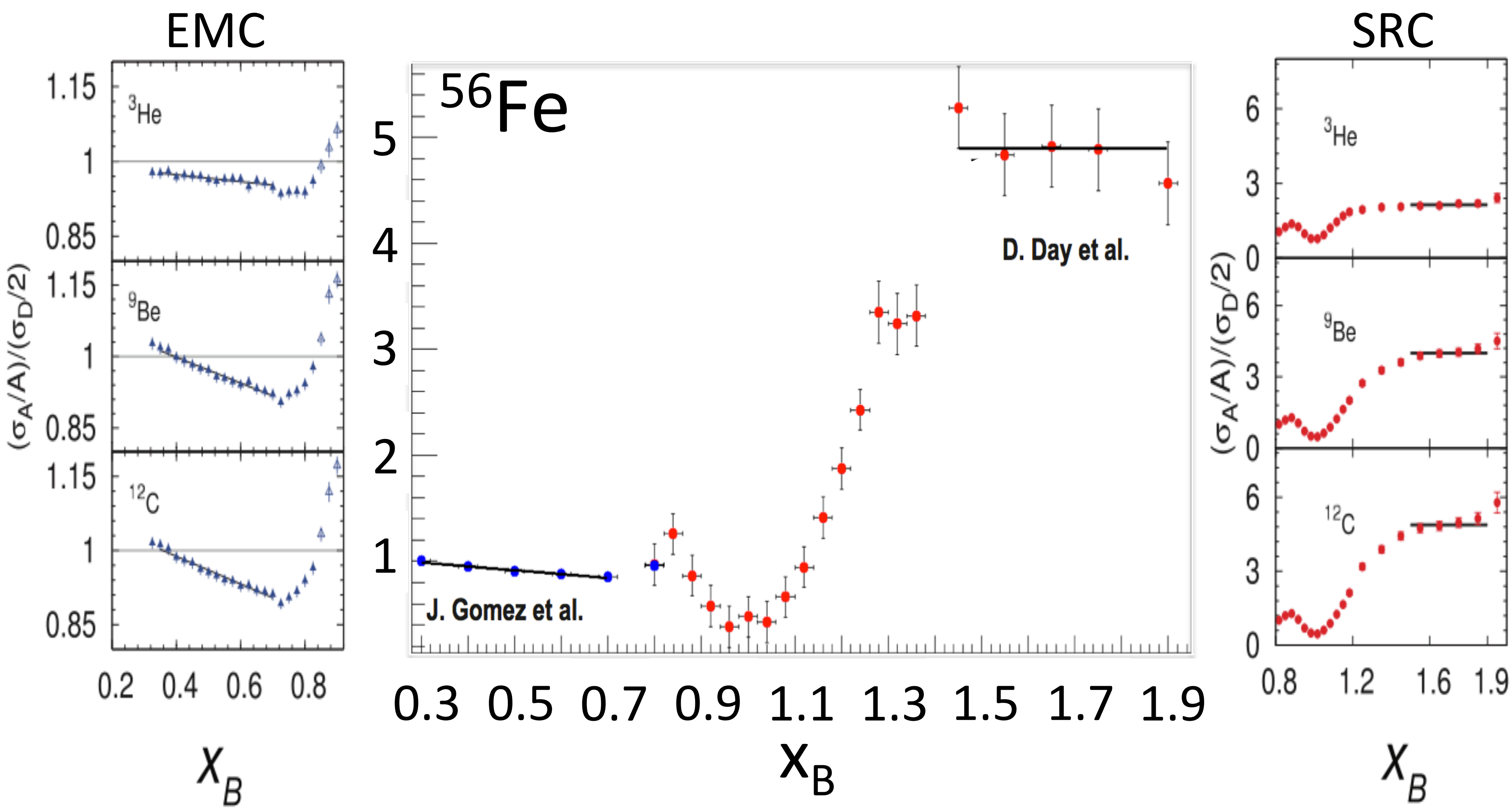
EMC-SRC Correlation



SRC Data:
L. Frankfurt et al. , Phys.Rev. C48 (1993) 2451
N. Fomin et al., Phys.Rev.Lett 108 (2012) 092502

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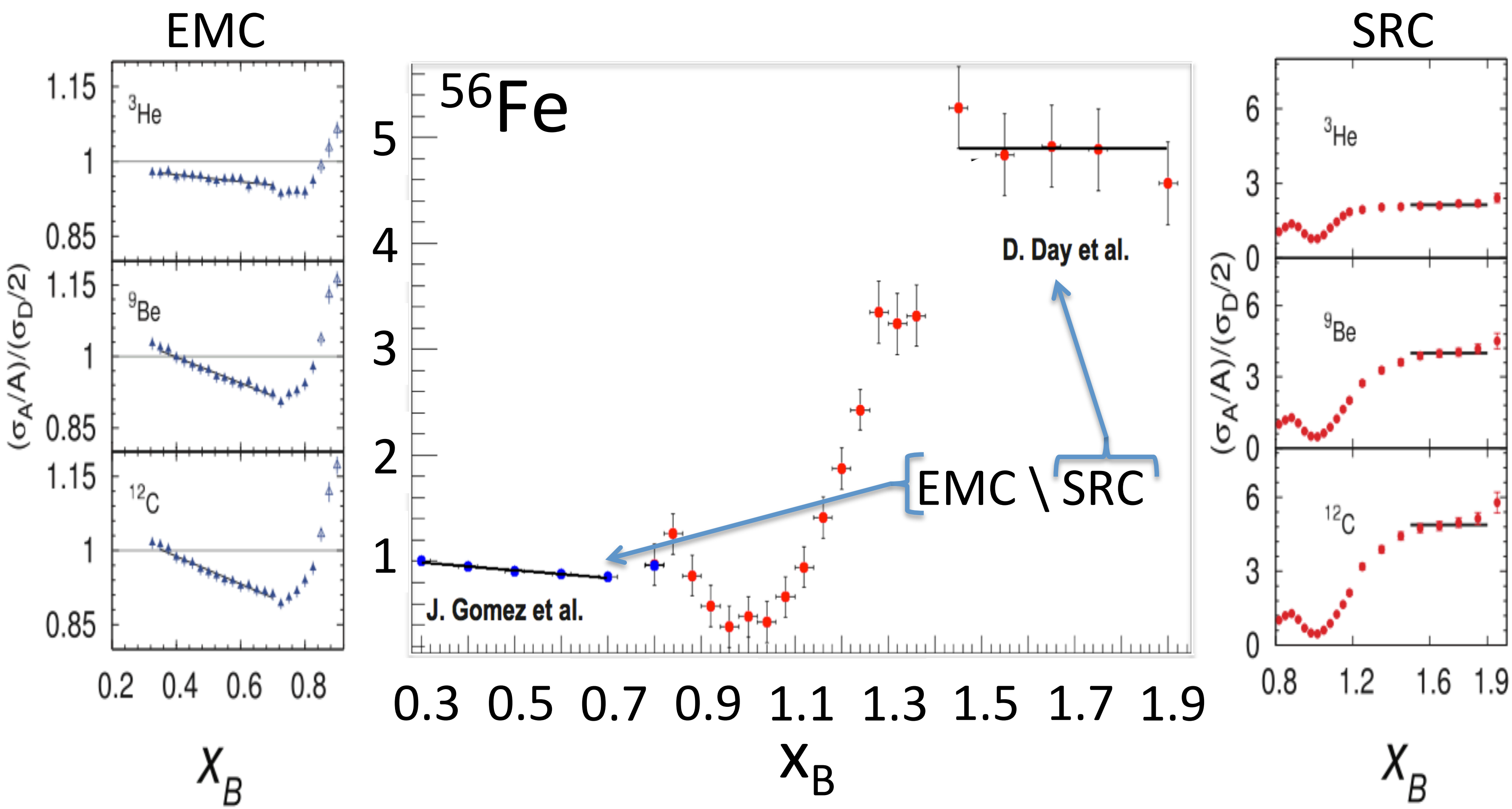

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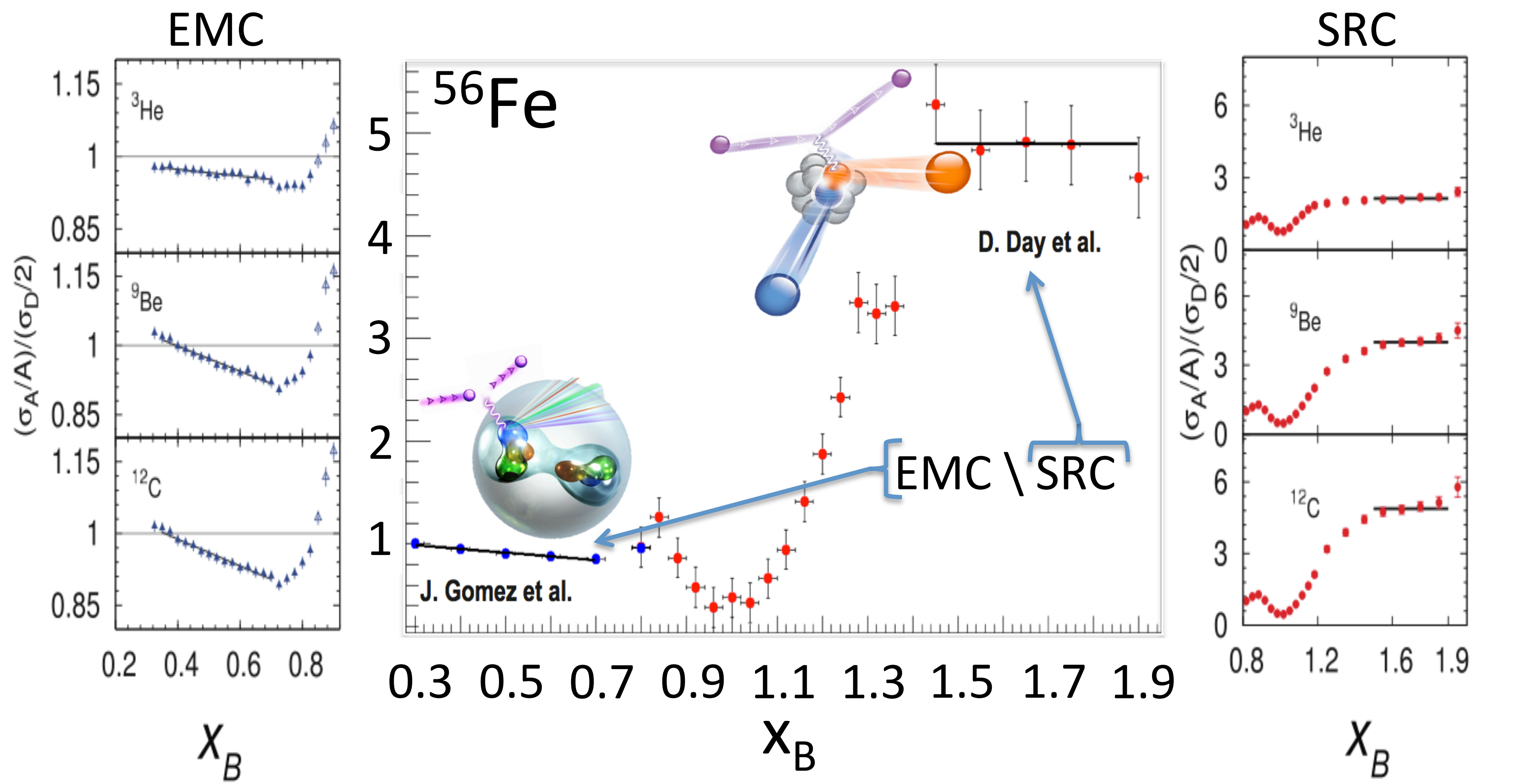

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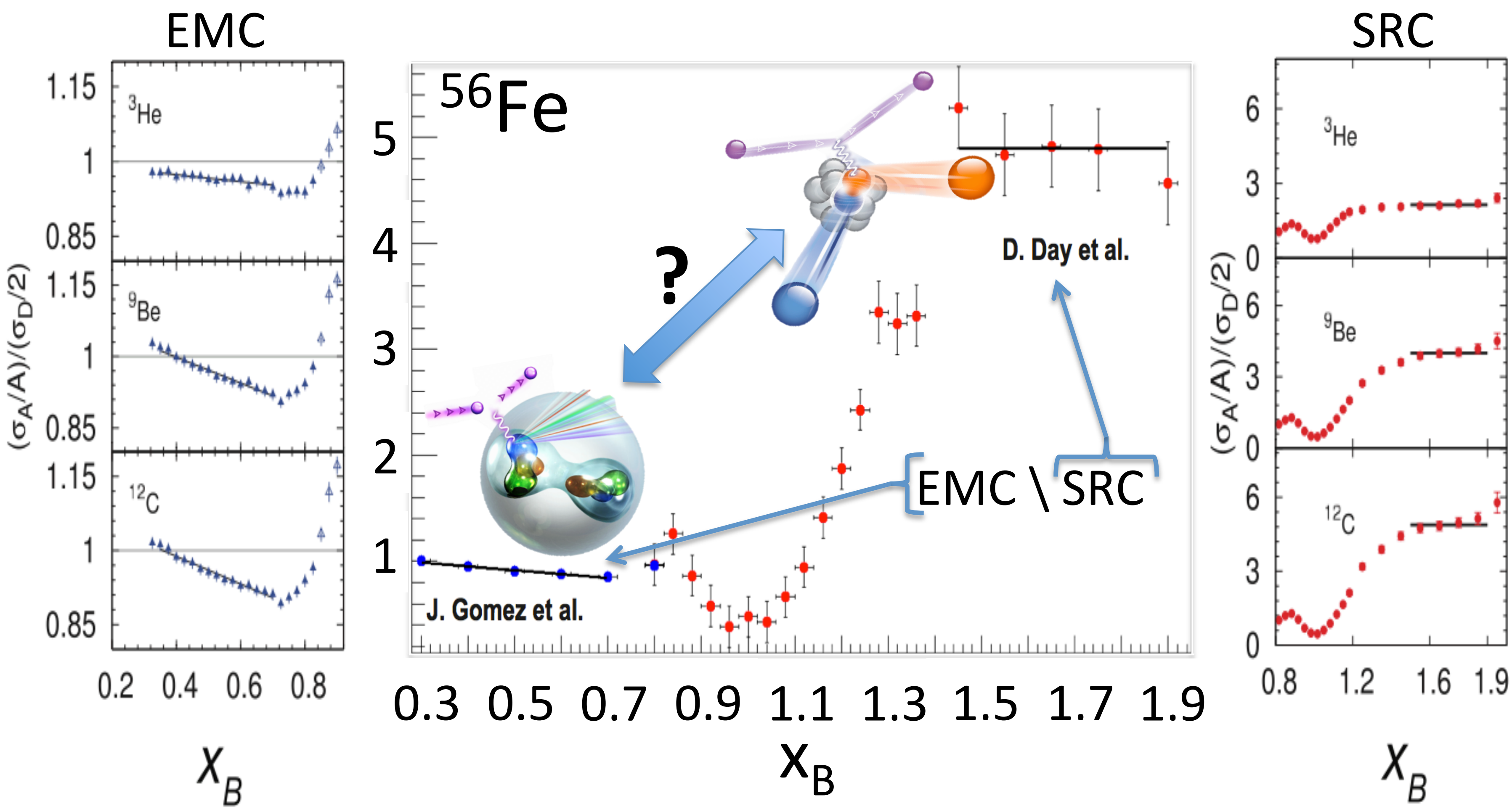

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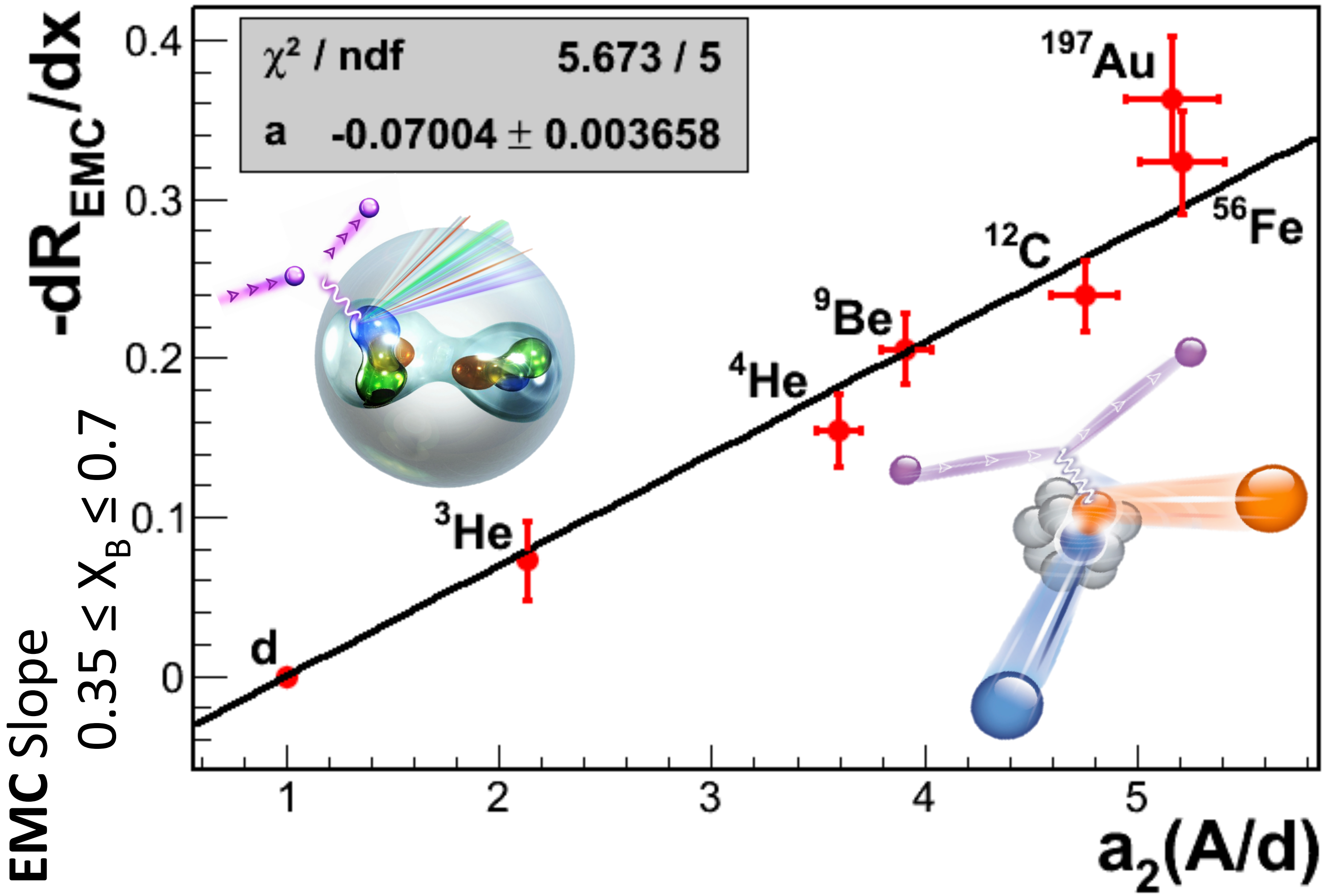

O. Hen et al., Int. J. Mod. Phys. E. **22**, 1330017 (2013).

O. Hen et al., Phys. Rev. C **85** (2012) 047301.

L. B. Weinstein, E. Piasetzky, D. W. Higinbotham, J. Gomez, O. Hen, R. Shneor, Phys. Rev. Lett. **106** (2011) 052301.

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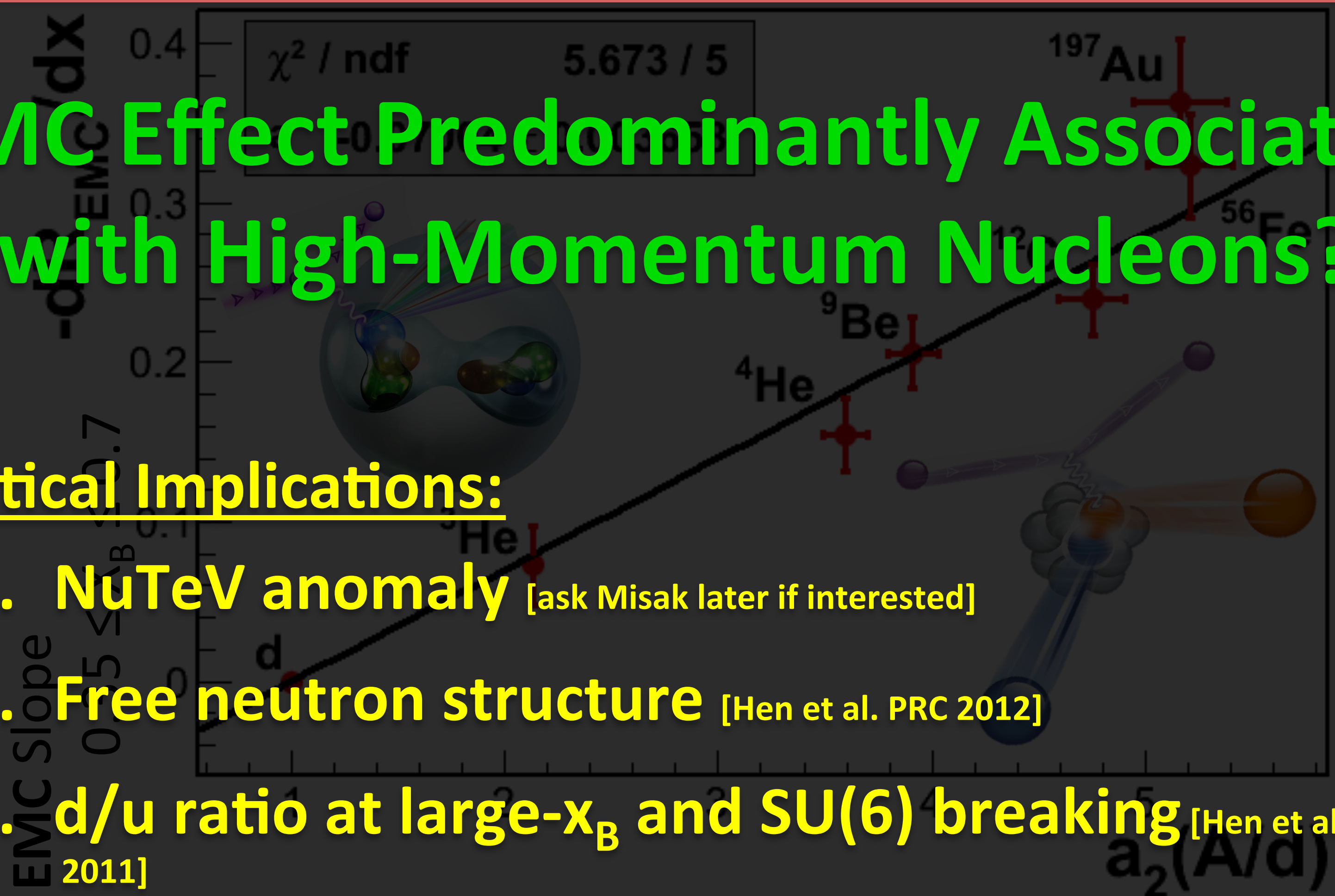


EMC Effect Predominantly Associated with High-Momentum Nucleons?

Practical Implications:

1. NuTeV anomaly [ask Misak later if interested]
2. Free neutron structure [Hen et al. PRC 2012]
3. d/u ratio at large-x_B and SU(6) breaking [Hen et al. PRD 2011]

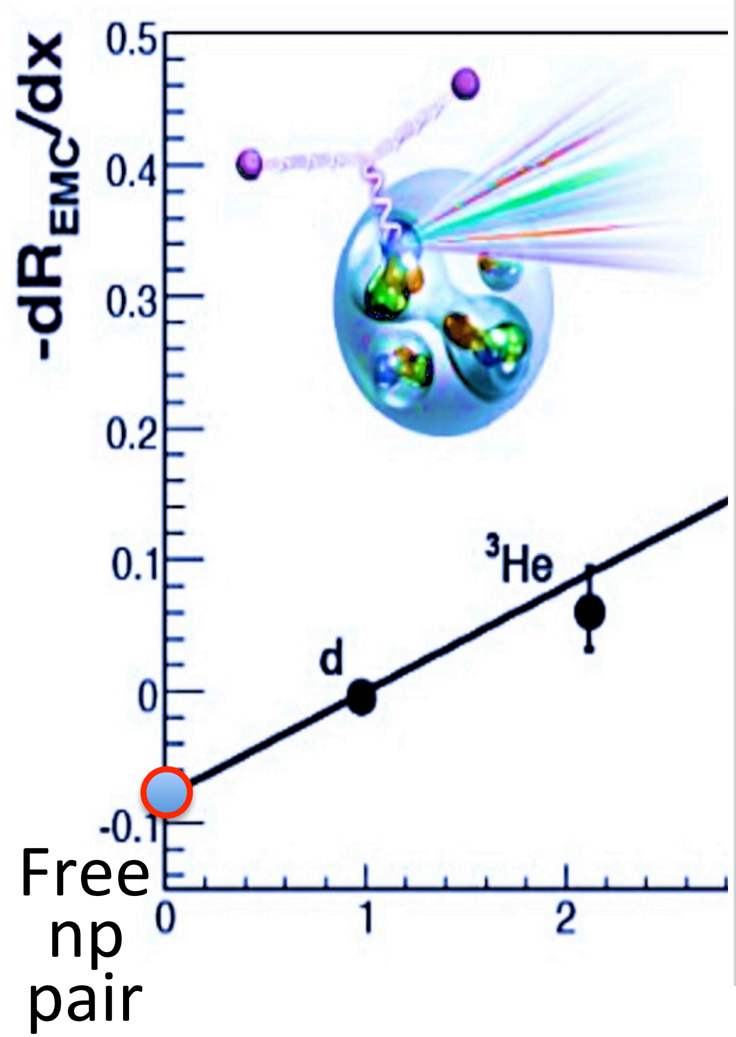
O. Hen et al., Int. J. Mod. Phys. E. **22**, 1330017 (2013).
O. Hen et al., Phys. Rev. C **85** (2012) 047301.
L. B. Weinstein, E. Piasetzky, D. W. Higinbotham, J. Gomez, O. Hen, R. Shneor, Phys. Rev. Lett. **106** (2011) 052301.

Probing the Free Neutron

- $a_2 \rightarrow 0$ is the limit of a free proton-neutron pair with no interaction
- Extrapolating the EMC-SRC correlation to a_2=0 gives EMC (IMC) effect for the free p+n:

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

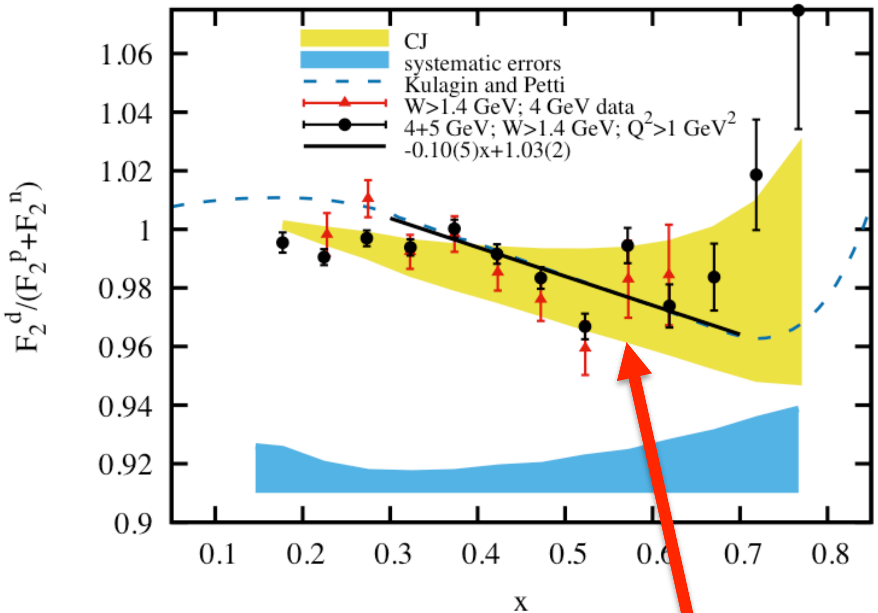
➔ the free neutron cross-section

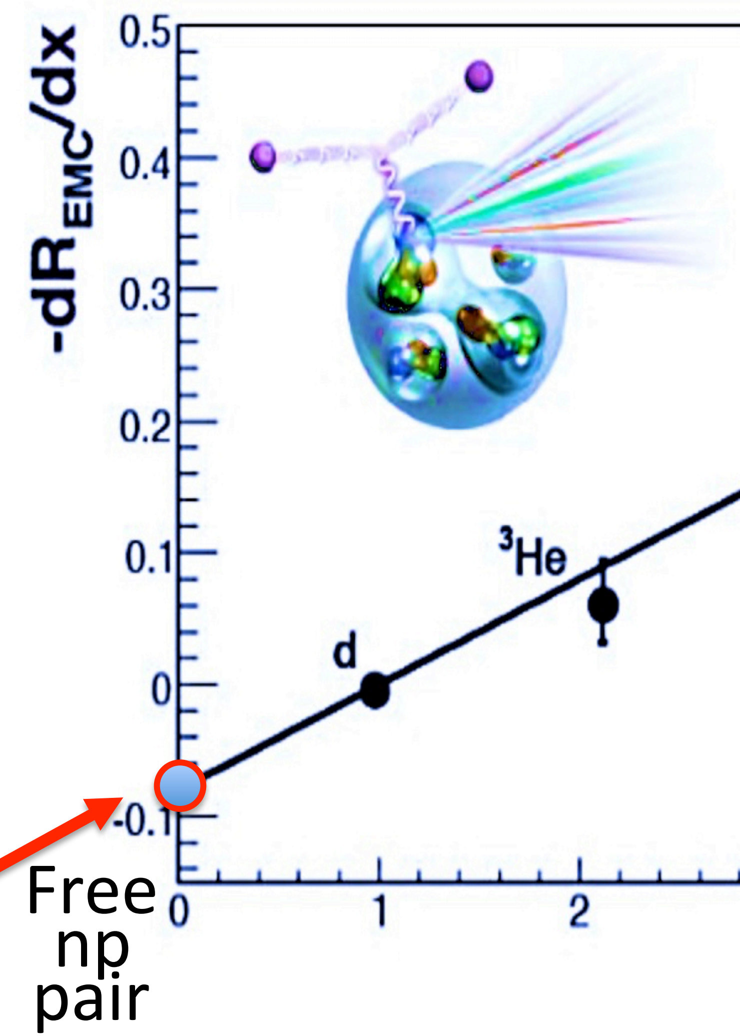


L.B.Weinstein et al., Phys. Rev. Lett. 106 (2011) 052301
O. Hen et al., Phys. Rev. C 85 (2012) 047301; O. Hen et al., Phys. Rev. D 84 (2011) 117501

Comparing with the BONUS Experiment

BONUS IMC measurement (d/p+n)





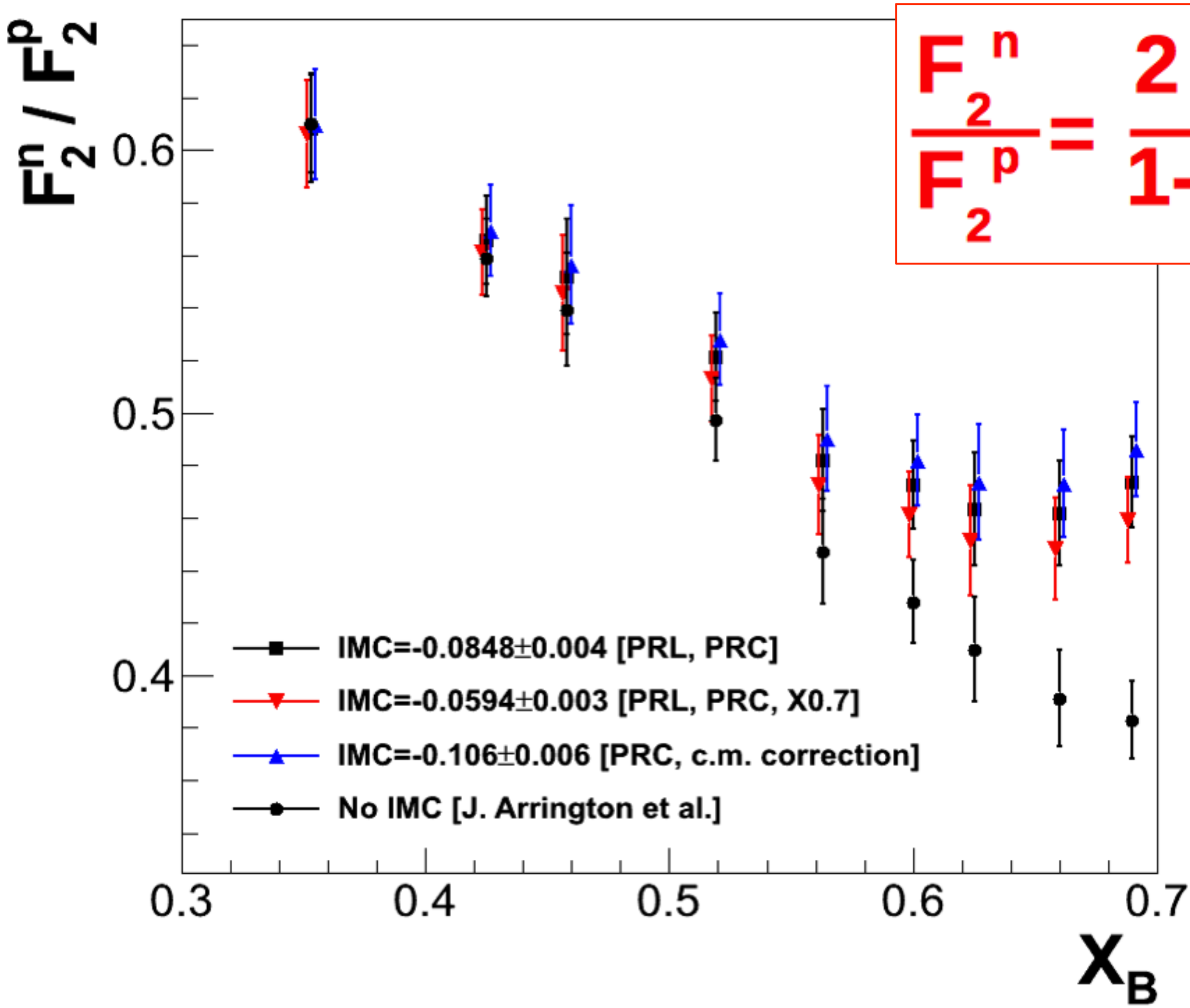
IMC Effect Slope

BONUS (2015): -0.10(5)

EMC/SRC (2011): -0.09(1)

O. Hen et al., Phys. Rev. C 85, 047301 (2012); K. Griffioen et al., arXiv: 1506.00871 (2015).

Extracting F_2^n/F_2^p



$$\frac{F_2^n}{F_2^p} = \frac{2\,F_2^d/F_2^p}{1-a(x_B-b)} - 1$$

Large x_B Approximation: $$\frac{d_v}{u_v} \approx \frac{4F_2^n/F_2^p - 1}{4 - F_2^n/F_2^p}$$

Proton Wave-Function in QCD ($x_B \rightarrow 1$)

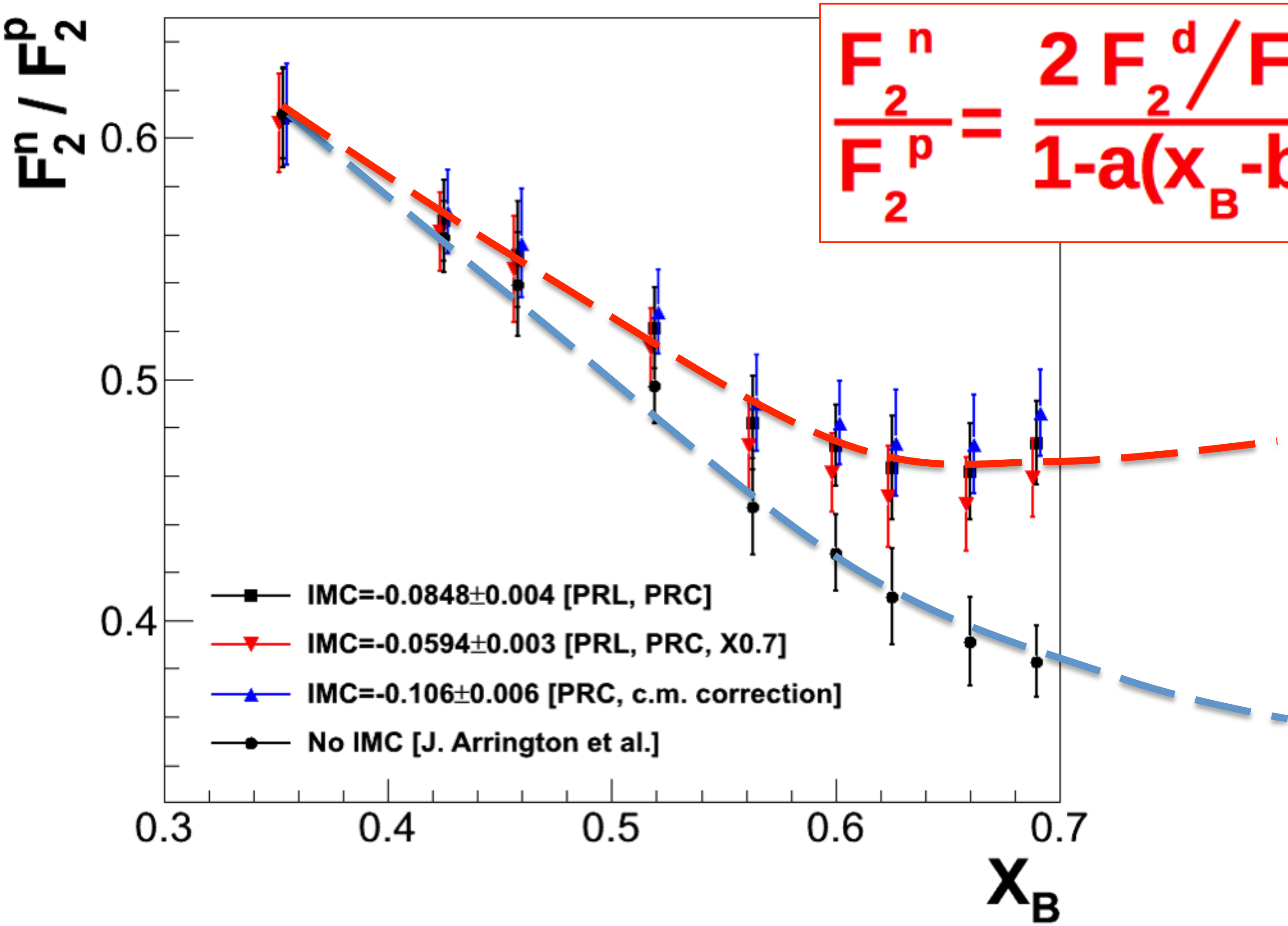
$$|p\uparrow\rangle = \frac{1}{\sqrt{2}}|u\uparrow(ud)_{S=0}\rangle + \frac{1}{\sqrt{18}}|u\uparrow(ud)_{S=1}\rangle - \frac{1}{3}|u\downarrow(ud)_{S=1}\rangle - \frac{1}{3}|d\uparrow(uu)_{S=1}\rangle + \frac{\sqrt{2}}{3}|d\downarrow(uu)_{S=1}\rangle$$

- SU(6) predict
  - ✧ N - Δ mass difference implies SU(6) is broken
- Diquark dominance with S_z=0 predict d/u = 0.2
- Scalar (S=0) diquark dominance predict d/u = 0

Nucleon Model	F2n / F2p	d / u
SU(6)	2 / 3	0.5
pQCD (S_z=0)	3 / 7	0.2
Scalar Diquark	1 / 4	0

Brodsky et al., Nucl. Phys. B441, 197 (1995); Melnitchouk and Thomas, Phys. Lett. B377, 11 (1996)

Extracting F_2^n/F_2^p



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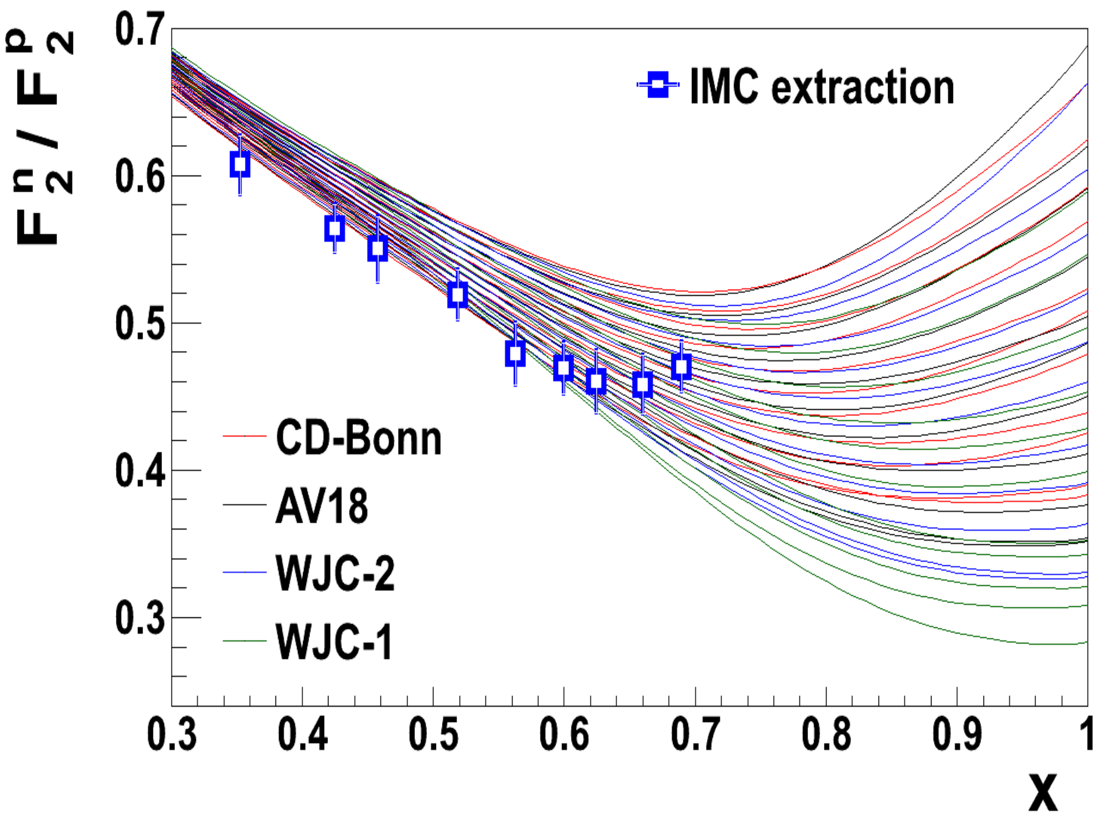
Comparing with CTEQ-JLab Analysis



$$\lambda = \frac{\partial \Lambda^2}{\partial \log p^2}\Big|_{p^2=M^2} = -2\frac{\delta R_N}{R_N}\frac{\delta p^2}{M^2},$$

Swelling Level

Average Nucleon Virtuality

Smearing Function

Free Nucleon S.F.

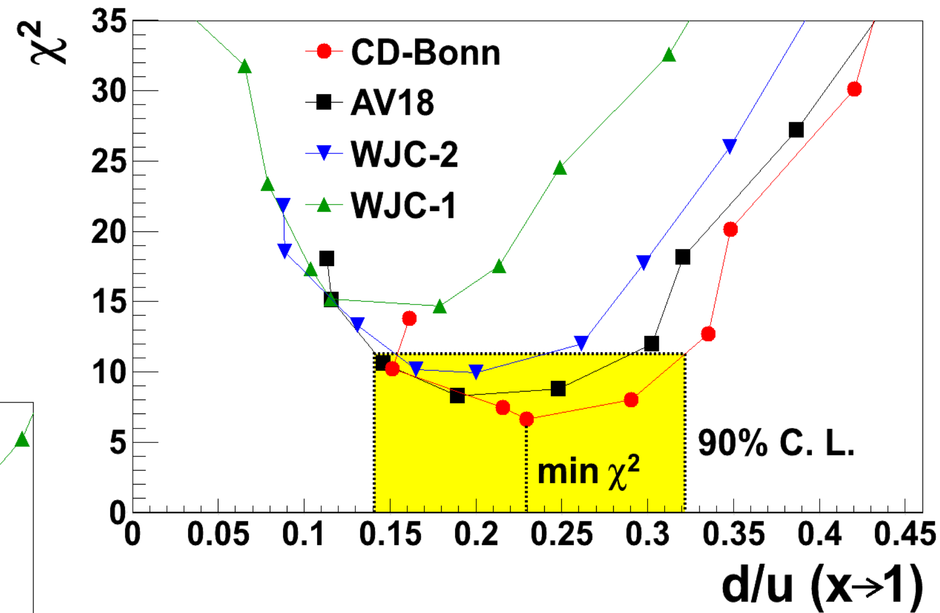
Off-Shell Correction

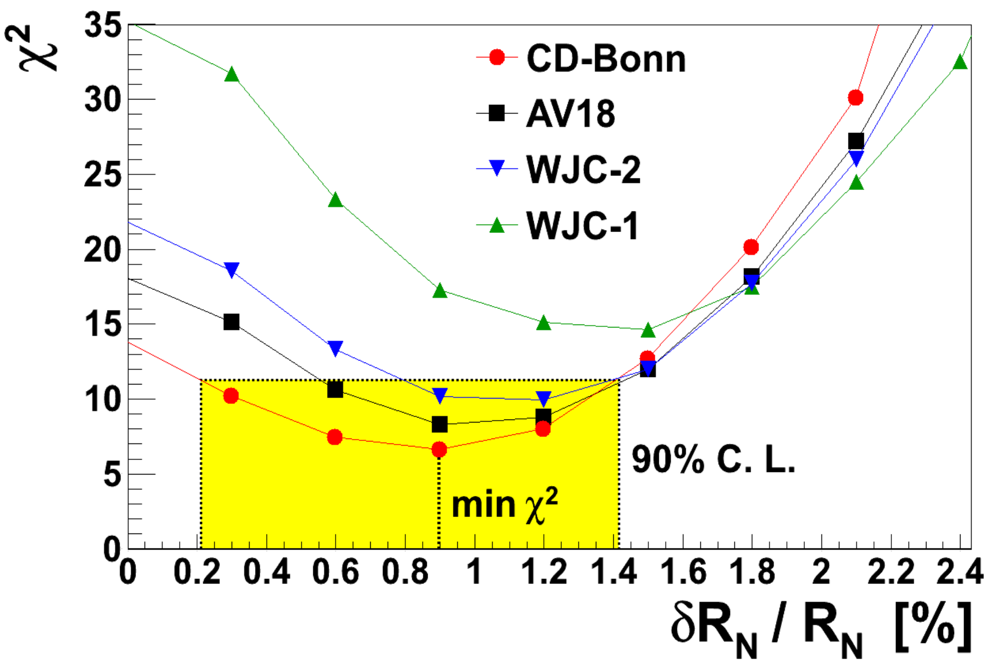
$$F_{2d}(x_B) = \int_{x_B}^{A} dy S_A(y, \gamma, x_B) F_2^{TMC+HT}(x_B/y, Q^2)\left(1 + \frac{\delta^{\text{off}} F_2(x)}{F_2(x)}\right)$$

O. Hen, A. Accardi, W. Melnitchouk, and E. Piasetzky, Phys. Rev. D 84, 117501 (2011).

Comparing with CTEQ-JLab Analysis

Constraining nuclear off-shell parameters and the d/u ratio at x ➔ 1





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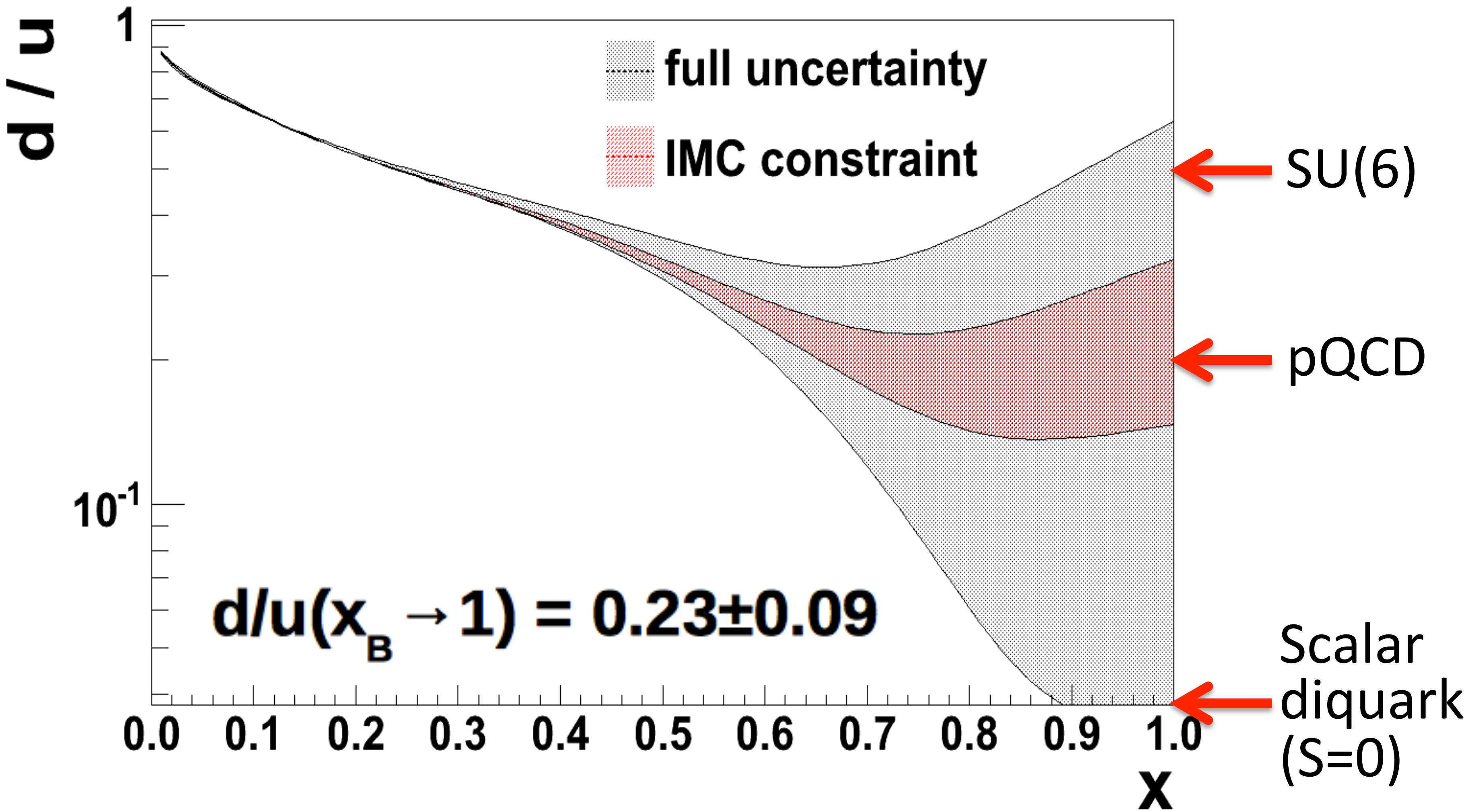

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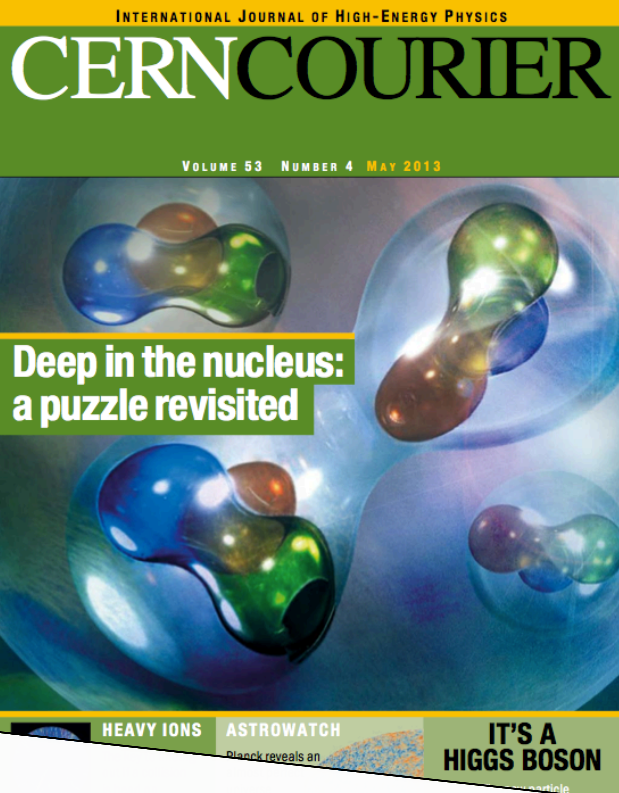


52301 (2011) PHYSICAL REVIEW LETTERS week 4 FEBRU

Short Range Correlations and the EMC Effect

L. B. Weinstein,[1,*] E. Piasetzky,[2] D. W. Higinbotham,[3] J. Gomez,[3] O. Hen,[2] and R. Shneor[2]

PHYSICAL REVIEW C **85**, 047301 (2012)

he connection between short range correlations and the EMC effect

O. Hen,[1] E. Piasetzky,[1] and L. B. Weinstein[2]

Short range correlations and the EMC effect

E. Piasetzky[a], L.B. Weinstein[b], D.W. Higinbotham[c], J. Gomez[c], O. Hen[a], R. Shneor[a]

NUCLEAR PHYSICS A

PHYSICAL REVIEW D **84**, 117501 (2011)

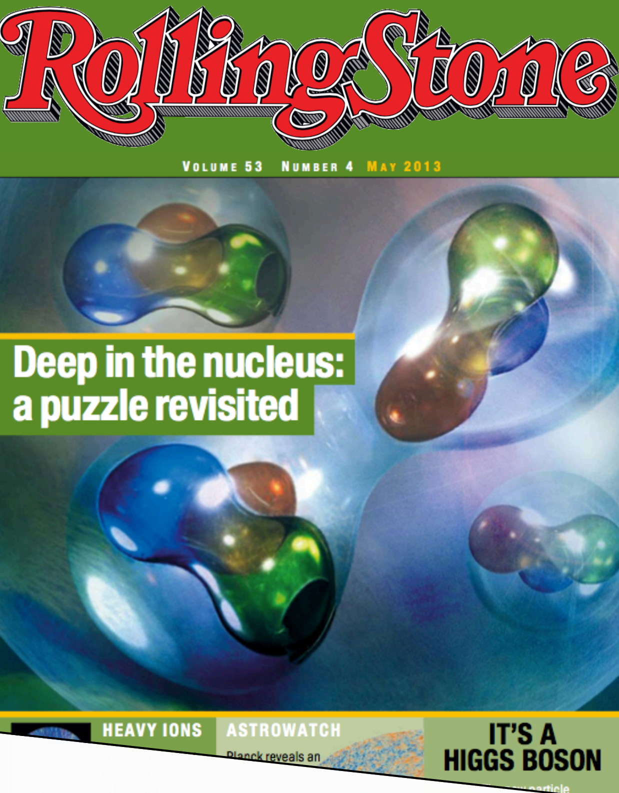
Constraints on the large-x d/u ratio from electron-nucleus scattering at $x > 1$

O. Hen,[1] A. Accardi,[2,3] W. Melnitchouk,[3] and E. Piasetzky[1]

International Journal of Modern Physics E
Vol. 22, No. 7 (2013) 1330017 (30 pages)

THE EMC EFFECT AND HIGH MOMENTUM NUCLEONS IN NUCLEI

World Scientific
www.worldscientific.com



52301 (2011) PHYSICAL REVIEW LETTERS week
4 FEBRU

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E. Piasetzky[a], L.B. Weinstein[b], D.W. Higinbotham[c], J. Gomez[c], O. Hen[a], R. Shneor[a]

NUCLEAR PHYSICS A

PHYSICAL REVIEW D **84**, 117501 (2011)

Constraints on the large-x d/u ratio from electron-nucleus scattering at $x > 1$

O. Hen,[1] A. Accardi,[2,3] W. Melnitchouk,[3] and E. Piasetzky[1]

International Journal of Modern Physics E
Vol. 22, No. 7 (2013) 1330017 (30 pages)

THE EMC EFFECT AND HIGH MOMENTUM NUCLEONS IN NUCLEI

World Scientific
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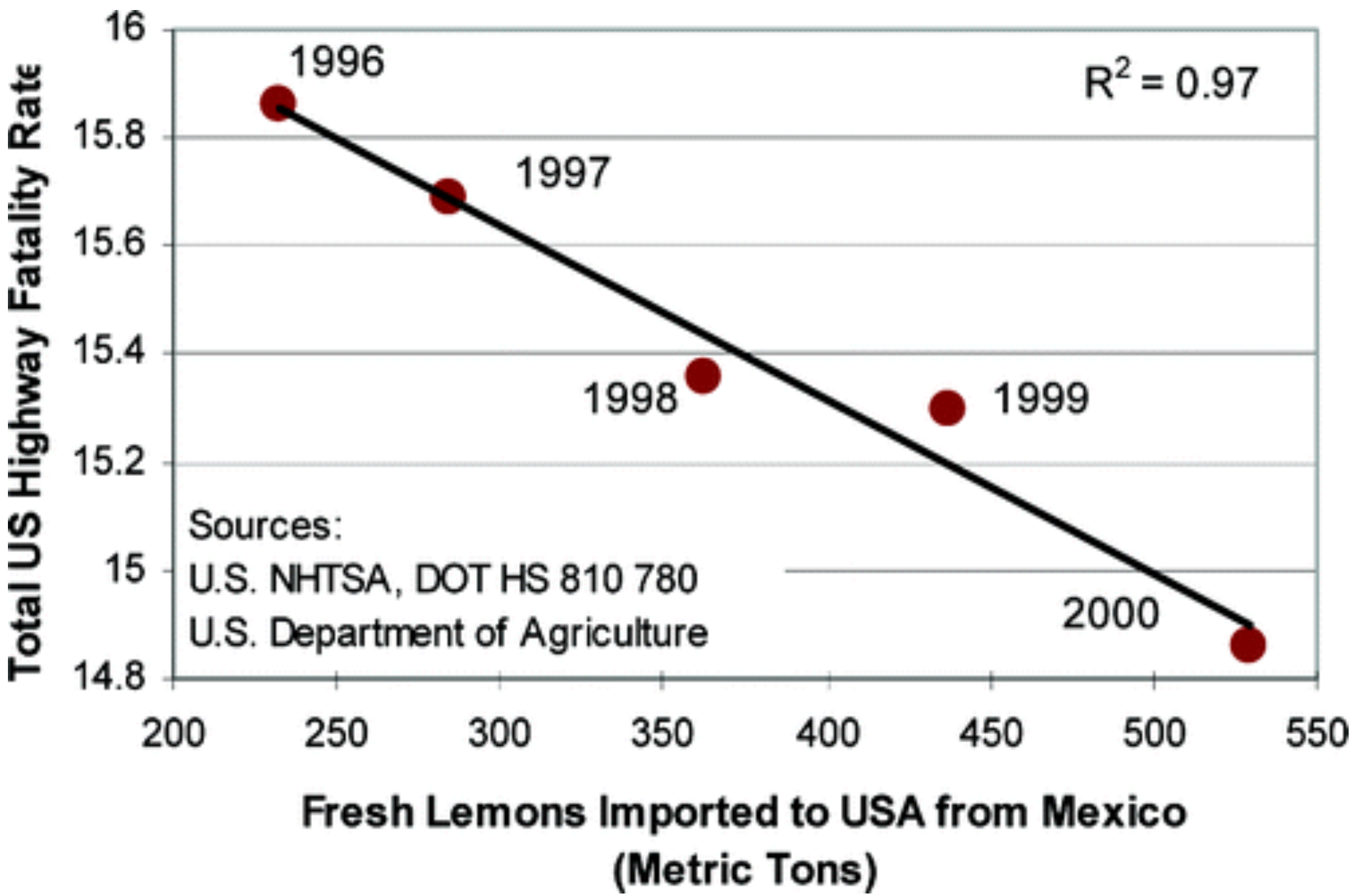
Other Correlations…



Mexican Lemonade Saves Lives!

Physics Behind the 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

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

Can We Test It? (Yes! Partially…)

- 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:

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

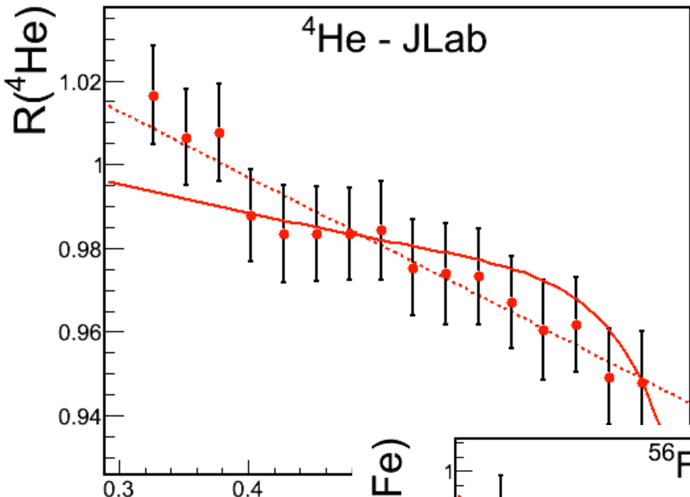
- This formalism accounts primarily for binding and Fermi motion effects
- ρ(α) is the light-cone momentum distribution of the nucleus which is peaked around unity

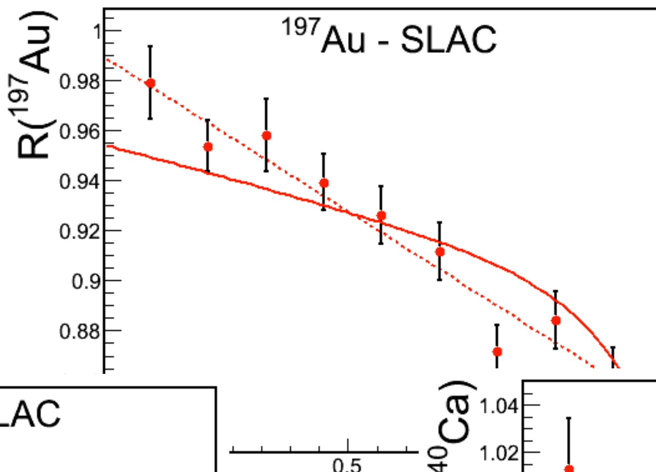
*For SRC Nucleons: $\Delta F_2^N(x_A) = \widetilde{F}_2^N(x_A) - F_2^N(x_A).$

L. Frankfurt and M. Strikman, Phys.Lett. B183 (1987) 254
O. Hen et al., Int. J. Mod. Phys. E. 22, 1330017 (2013).

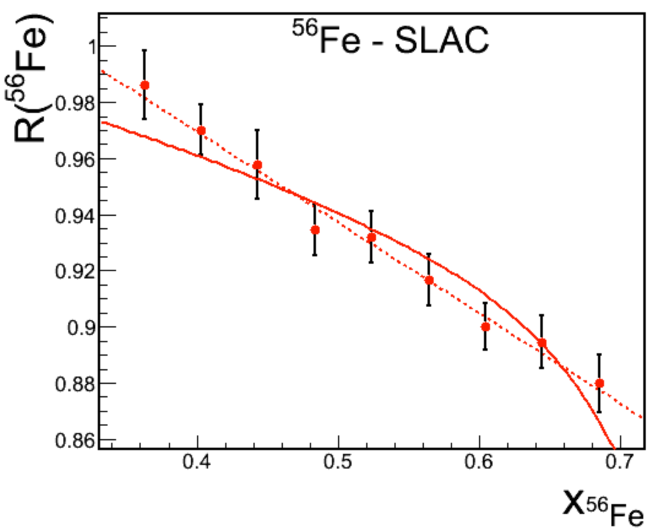
Fitting ΔF to the EMC data

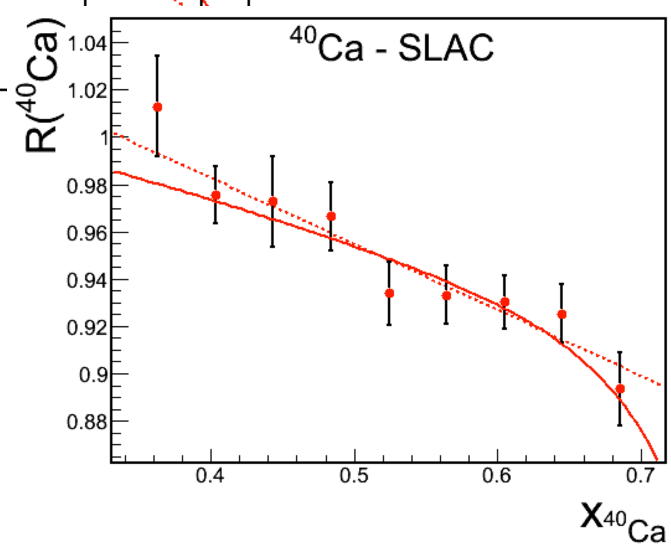
Assuming ΔF is a second order polynomial in x and fitting it to the (x_A binned) EMC data





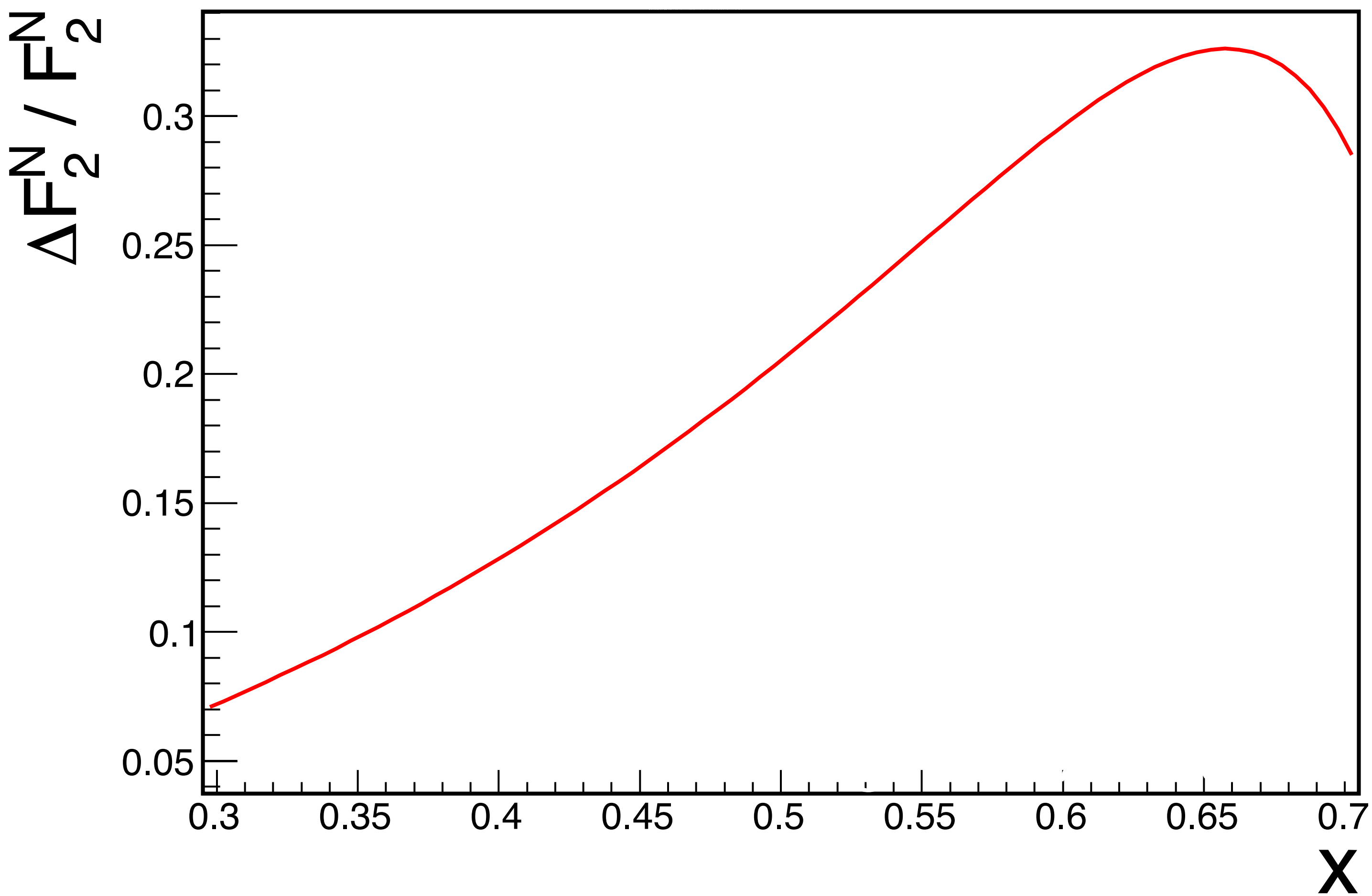
Allow up to 3% over all normalization for each nuclei





O. Hen et al., Int. J. Mod. Phys. E. 22, 1330017 (2013).

Amount of modifications: ΔF/F

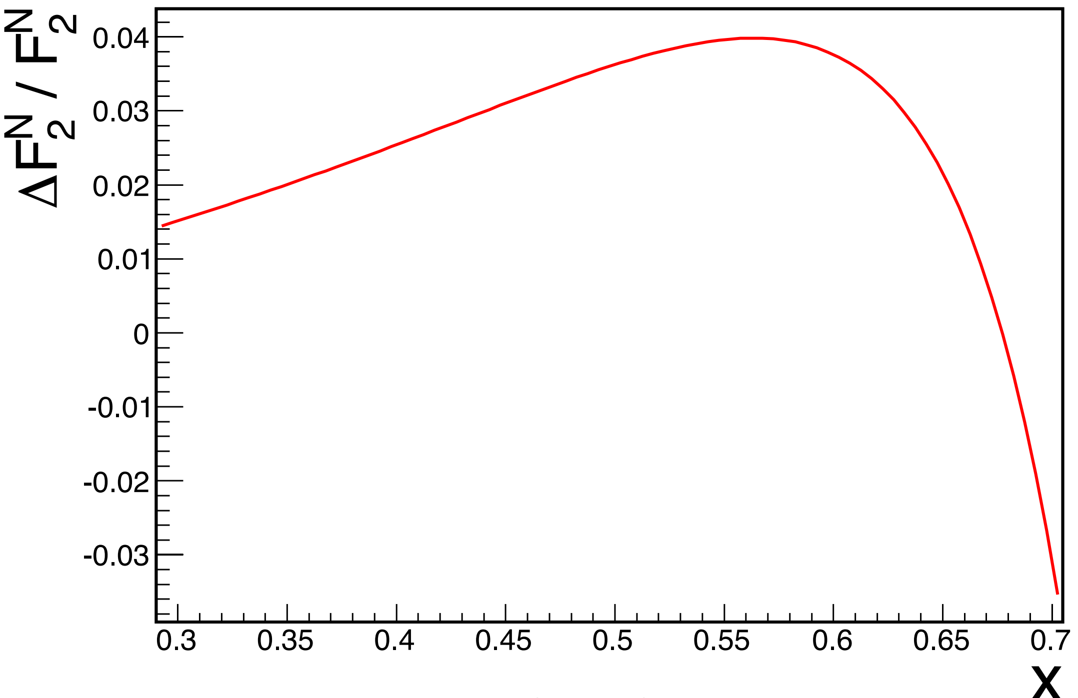


O. Hen et al., Int. J. Mod. Phys. E. 22, 1330017 (2013).

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



O. Hen et al., Int. J. Mod. Phys. E. 22, 1330017 (2013).

Experimental Tests ?

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

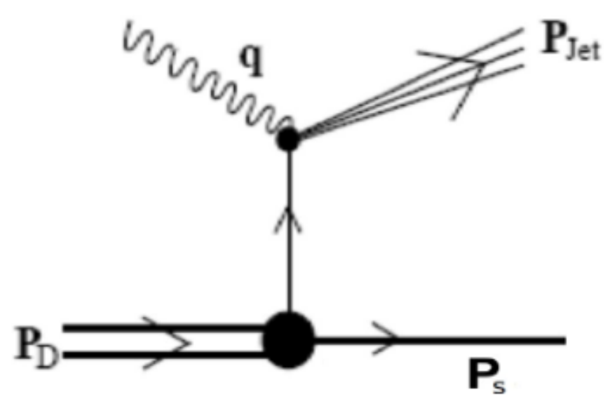
Deuterium is the only system in which the momentum of the struck nucleon equals that of the recoil (Assuming no FSI)

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

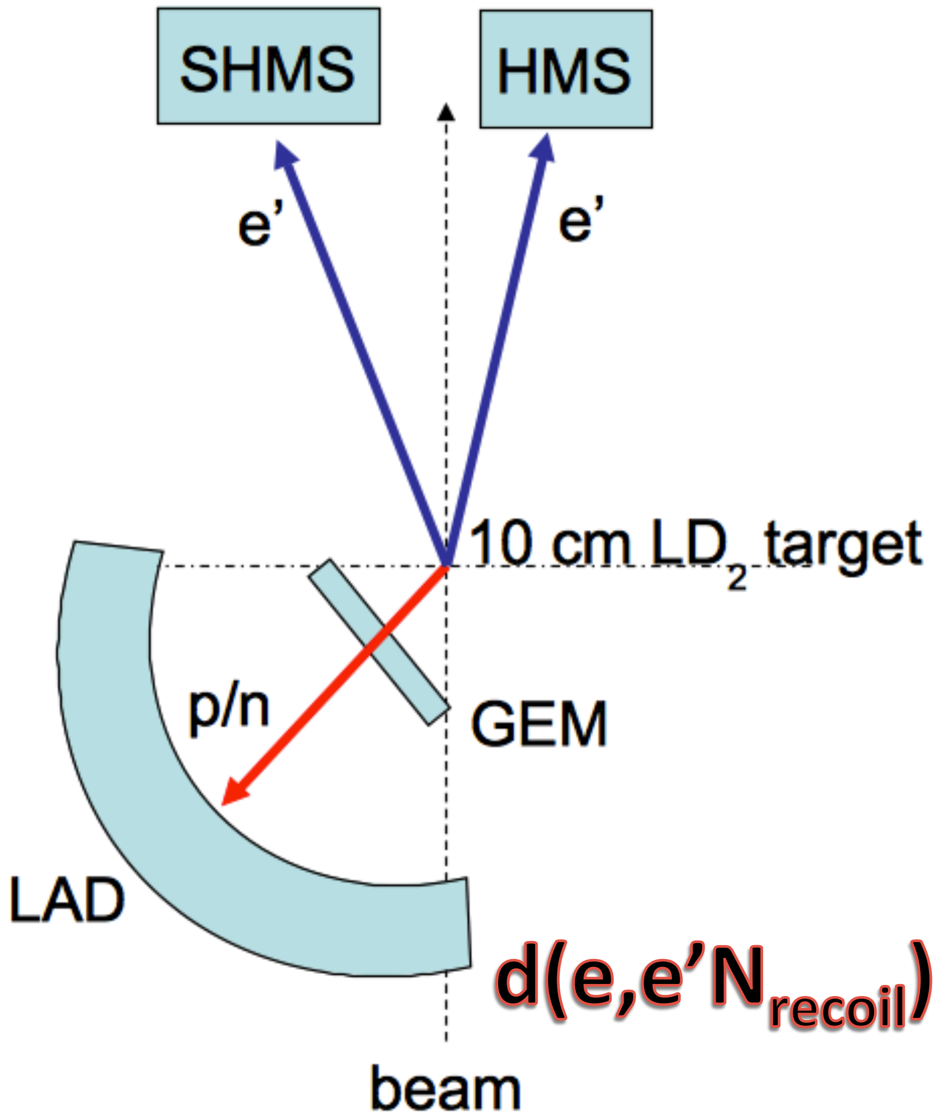
Study the role played by high-momentum nucleons in nuclei

A proposal to Jefferson Lab PAC 38, Aug. 2011

O. Hen (contact person), E. Piasetzky, I. Korover, J. Lichtenstadt, I. Pomerantz, I. Yaron, and R. Shneor
Tel Aviv University, Tel Aviv, Israel

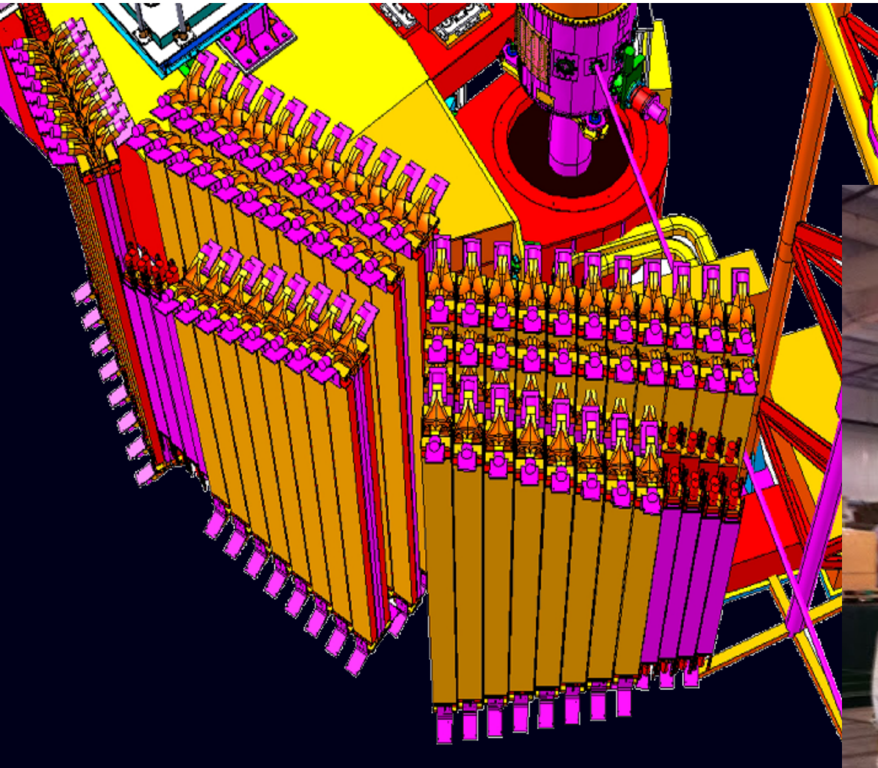


Our Concept…

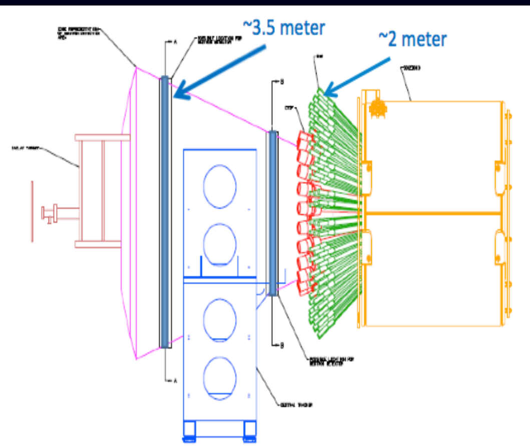


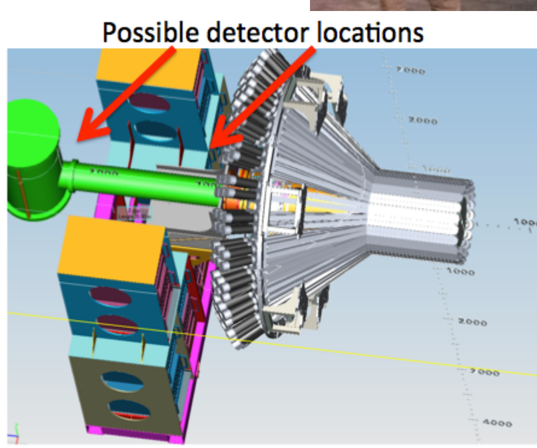
- High resolution spectrometers for (e,e’) measurement in DIS kinematics
- Large acceptance recoil proton \ neutron detector
- Long target + GEM detector – reduce random coincidence

...Its realization (LAD / BAND)



Large Acceptance Detector (LAD@Hall-C)

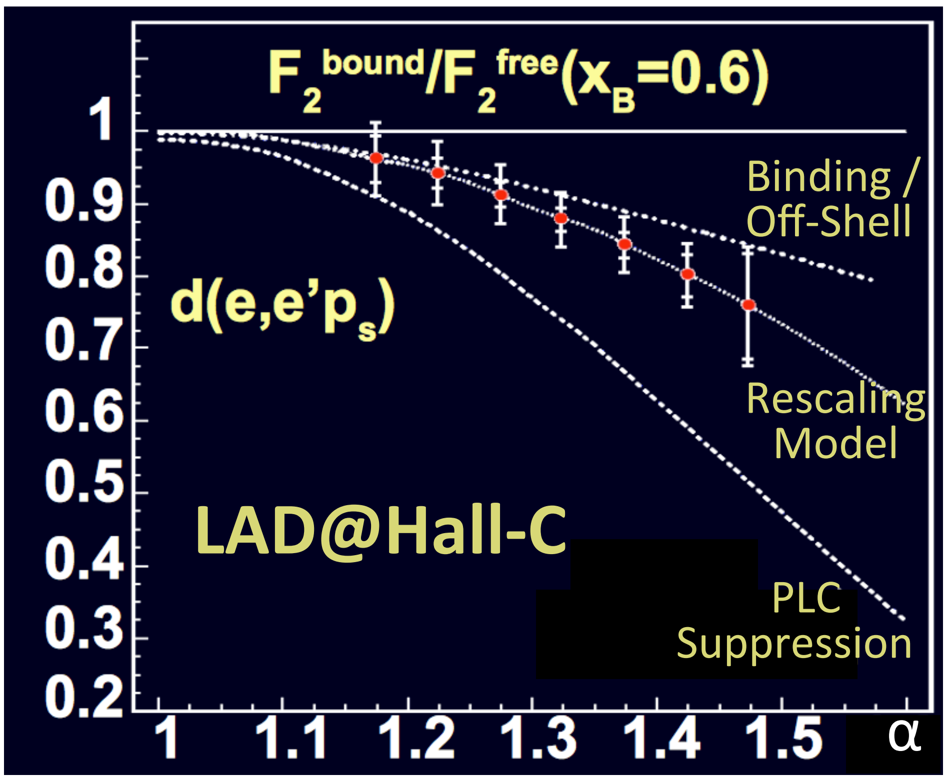




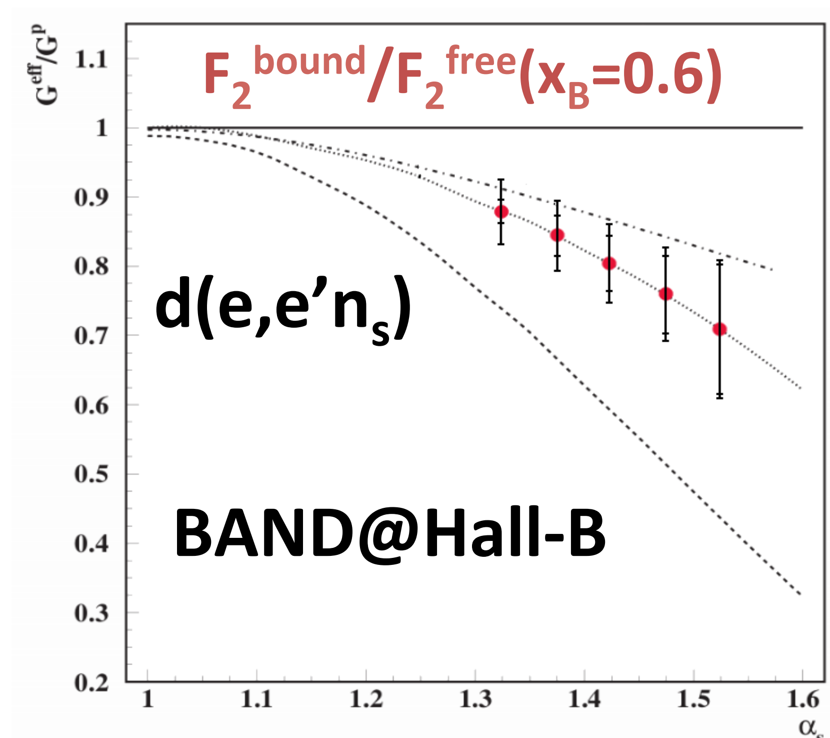
Backward Angle Neutron Detector (BAND@Hall-B)

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(0.5) < x’ < 0.55(0.7) @ $W^2 > 4$ [GeV/c]^2



Melnitchouk et al., Z. Phys. A **359**, 99-109 (1997)

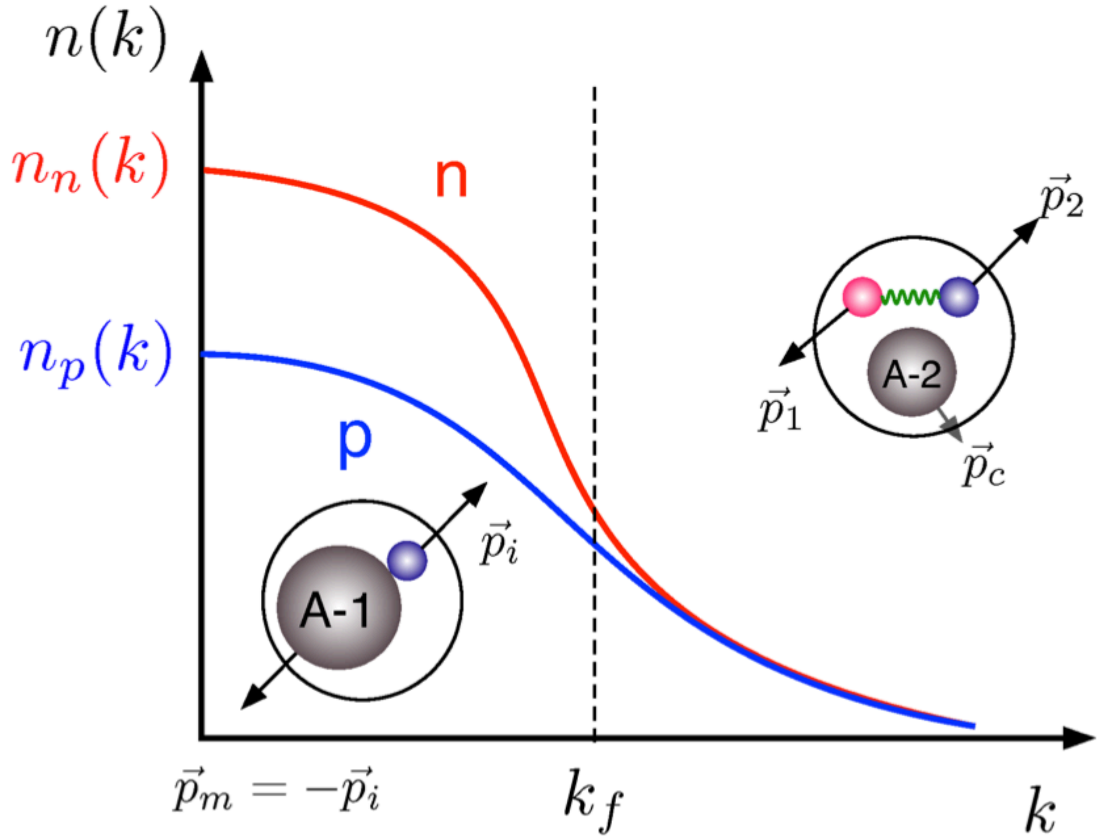


SRC & the Nuclear W.F.

High momentum tail dominated by np-SRC pairs

- Equal amount of high momentum ($k>k_F$) protons and neutrons in asymmetric nuclei

- protons have larger average kinetic energy in neutron rich nuclei,



O. Hen et al., Science **346**, 614 (2014)
M. Sargsian, Phys. Rev. C **89**, 034305 (2014)

SRC & the Nuclear W.F.

- Symmetric nuclei: ~80% mean-field (M.F.)
  ~20% np-SRC pairs
- M.F.-SRC transition point: ≈ k_F ~ 300 MeV/c
- Construct a simple wave function:

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

η determined from:

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

O. Hen et al., Science **346**, 614 (2014)
M. Sargsian, Phys. Rev. C **89**, 034305 (2014)

SRC in Asymmetric Nuclei

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

- SRC dominated by np pairs -> EQUAL (ABSOLUTE) NUMBER of high momentum protons and neutrons (i.e. different fractional 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.

O. Hen et al., Science **346**, 614 (2014)
M. Sargsian, Phys. Rev. C **89**, 034305 (2014)

SRC in Asymmetric Nuclei

- SRC dominated by np pairs -> EQUAL (ABSOLUTE) NUMBER of high momentum protons and neutrons:

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

>1 ← $\frac{A}{2z}$

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

<1 ← $\frac{A}{2n}$

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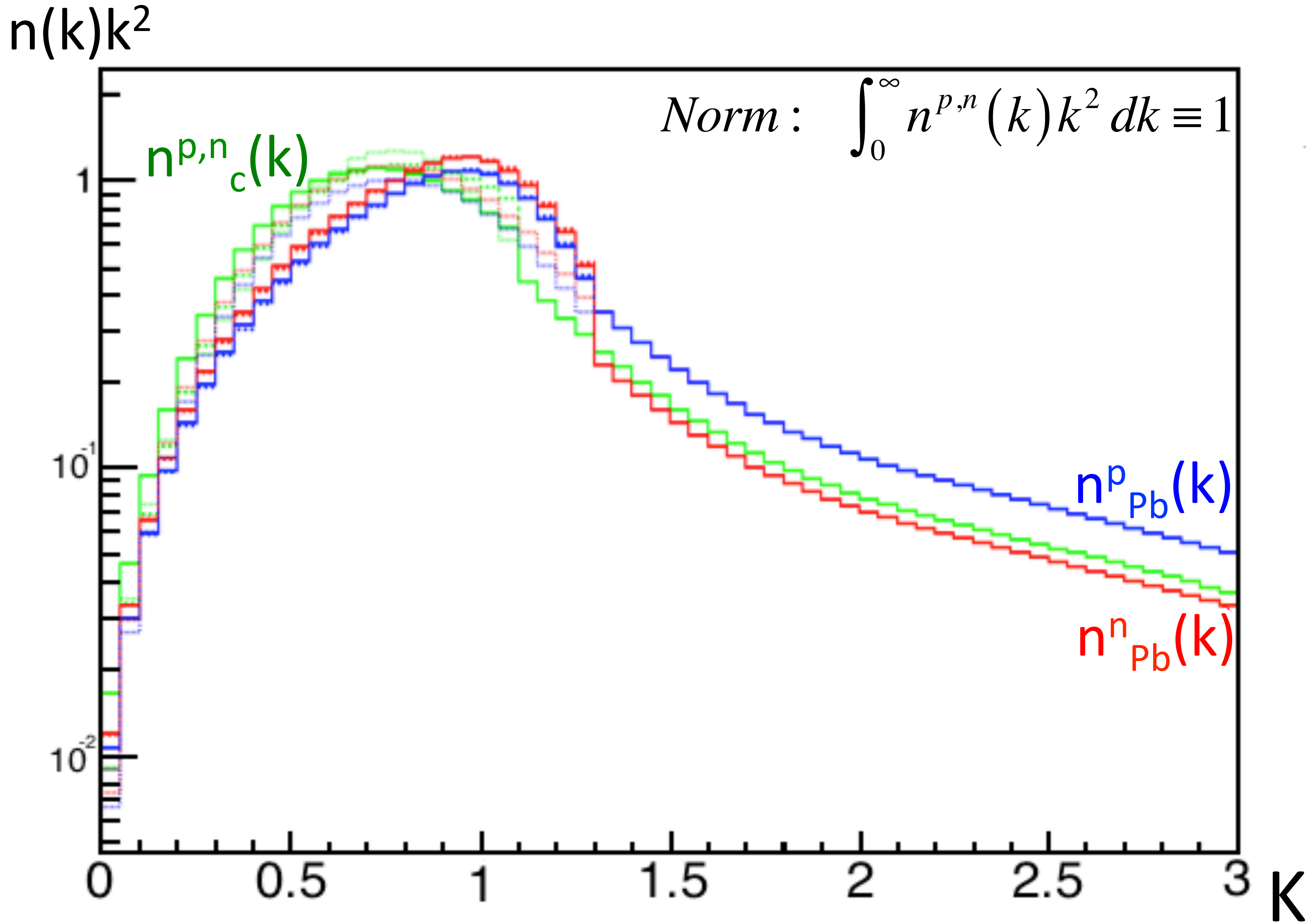

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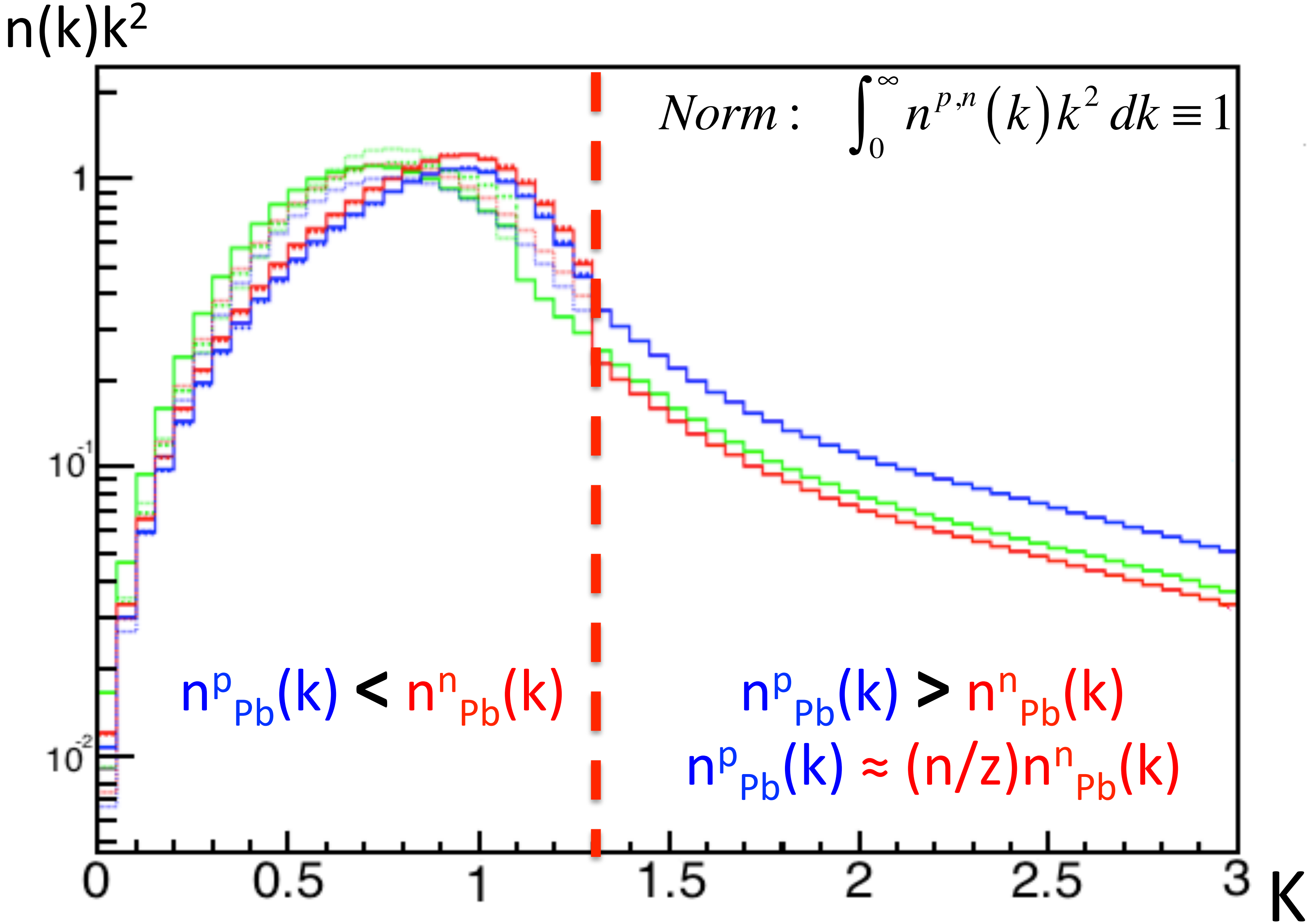
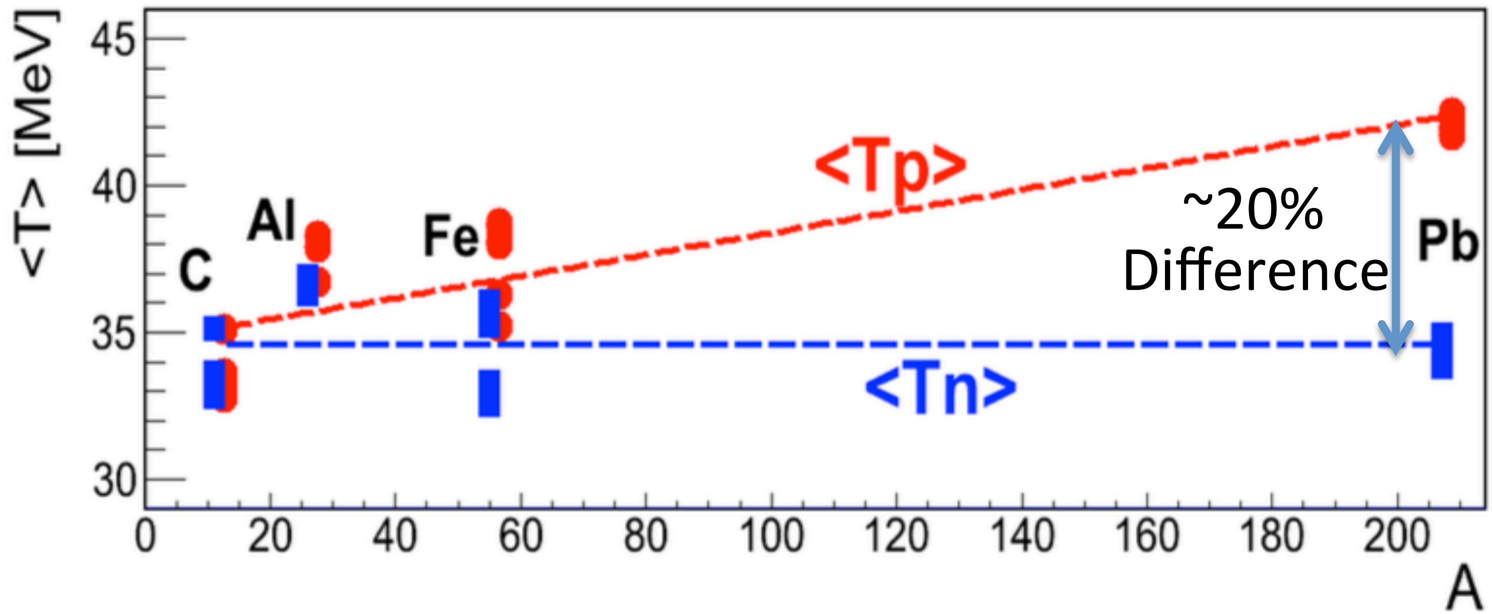


SRC in Asymmetric Nuclei

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



3 models for $n^{M.F.}(k)$:

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

2 values for k_0:

- k_F
- 300 MeV/c

O. Hen et al., Science **346**, 614 (2014)

EMC in Asymmetric Nuclei

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

- Contribution of standard n…

Do protons "Feel" a Larger EMC Effect then neutrons ?

(Can it explain the NuTeV anomaly?)

$\ldots(k) = 1 - 2k^2/m_N \Delta E.$

Conclusions - I

- 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.
- EMC-SRC correlation can be used to extract F_2^n/F_2^p and constrain the d/u ratio at large x_B.
- Universal modification of SRC (M.F.) nucleons can explain the EMC effect.
- Future experiment @ JLab 12GeV will study the virtuality (momentum) dependence of the bound nucleon structure function.

Conclusions - II

- SRC are dominated by np-SRC pairs
  - In asymmetric, neutron reach, nuclei <u>protons have *larger* average kinetic energy then neutrons</u>

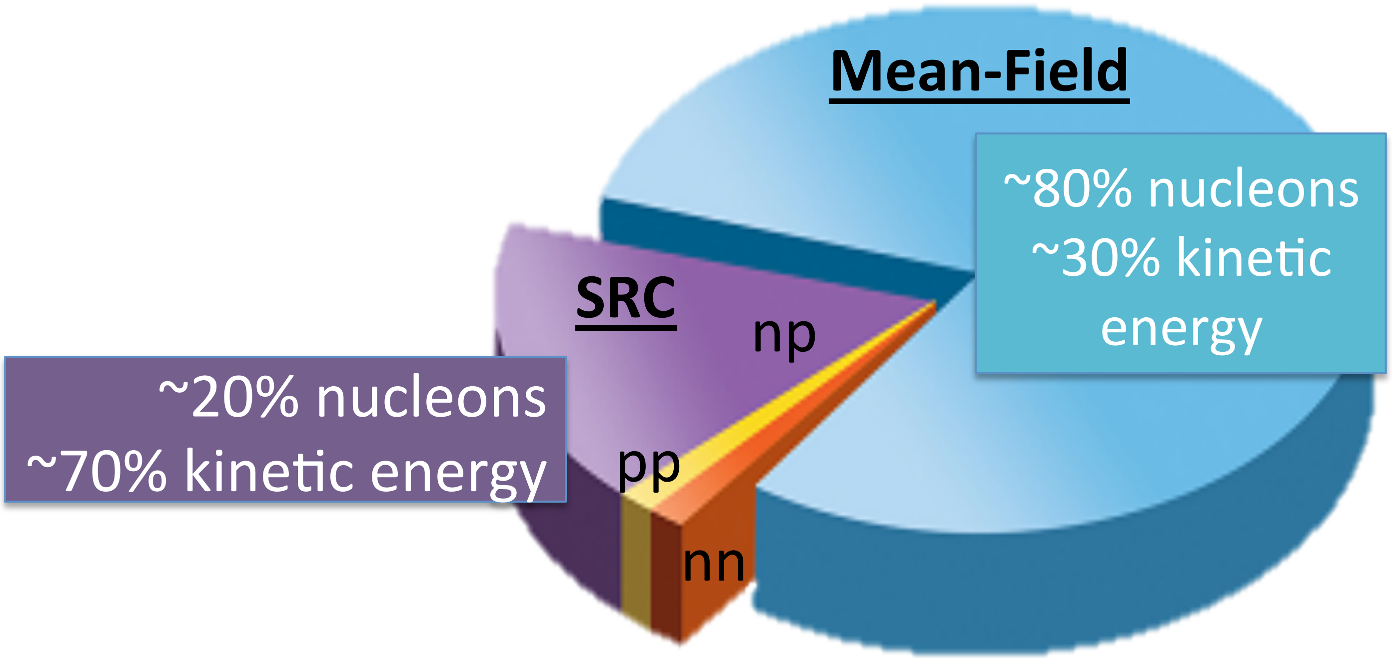
Protons play a larger role then neutrons in the EMC effect of asymmetric nuclei!

Thank You!

Questions?

EMMI

Atomic Nucleus:



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

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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:

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

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

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.

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

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

$\widetilde{F}_2^N(x_A)$ SRC Nucleons Structure Function

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

C. Ciofi degli Atti and S. Simula, Phys. Rev. C 53, 1689 (1996).
O. Hen et al., Int. J. Mod. Phys. E. 22, 1330017 (2013).

(Modified) Convolution Model

Combining it all we get:

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

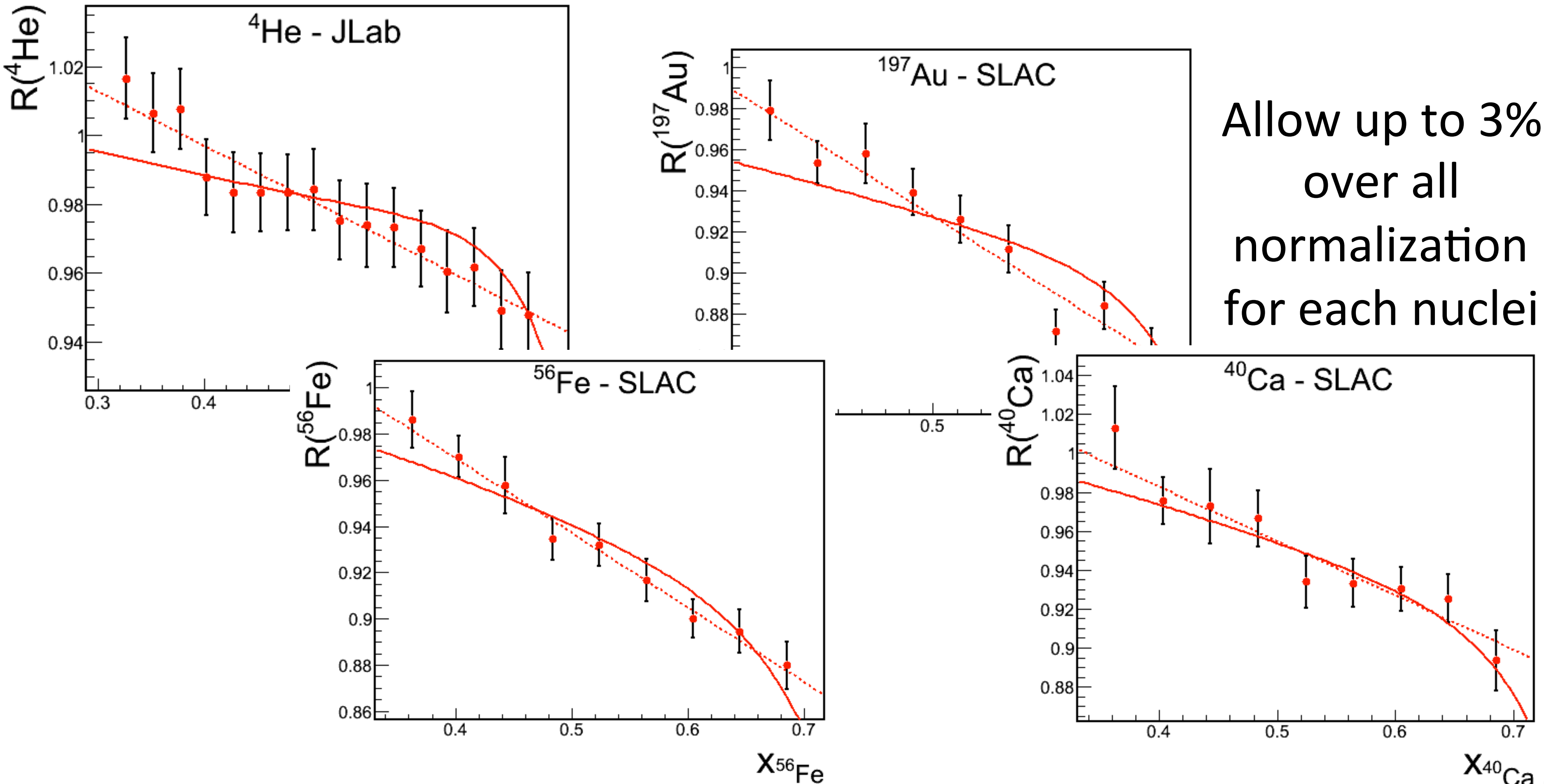
Standard nuclear term

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

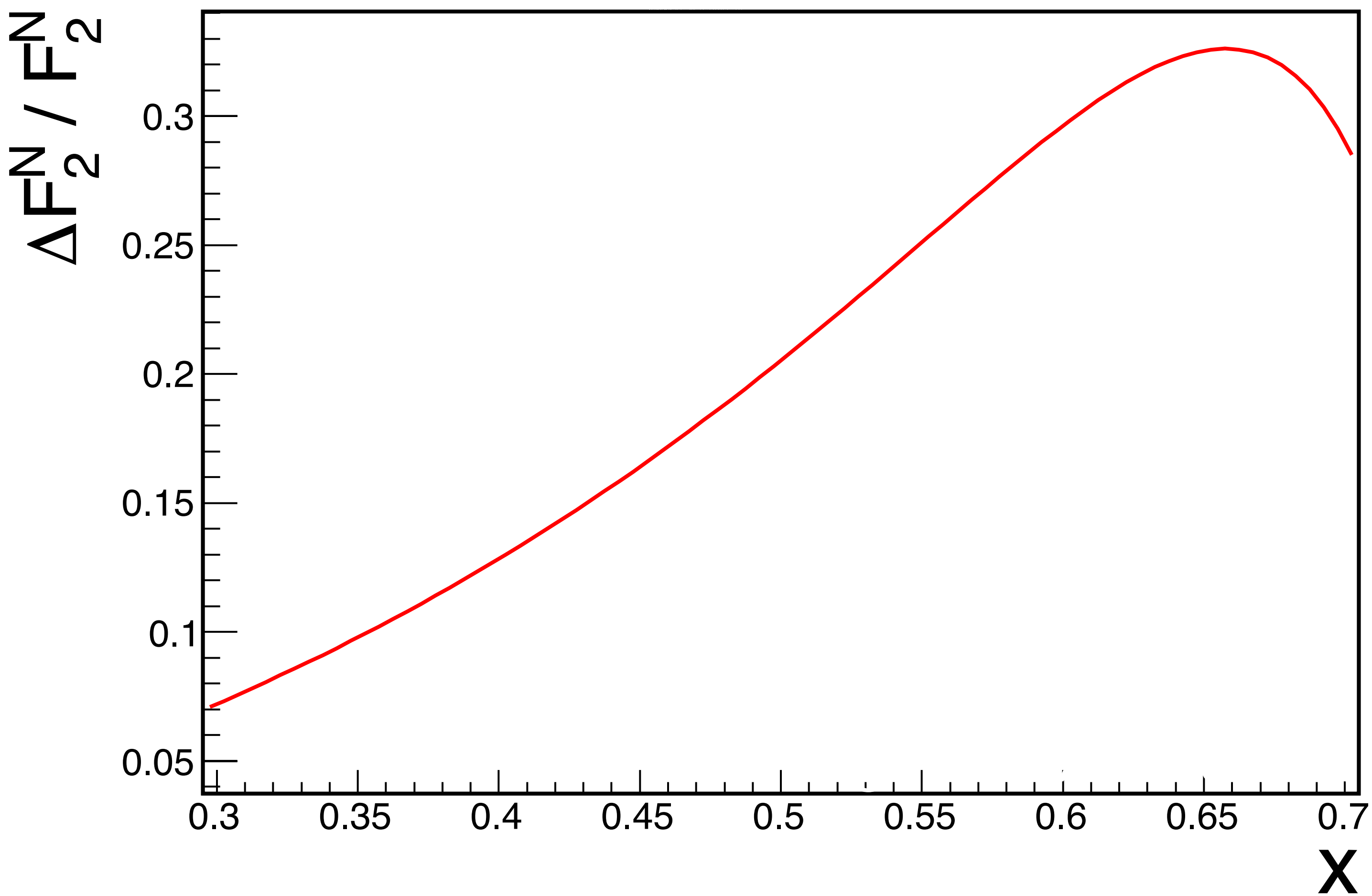
Assuming ΔF is a second order polynomial in x and fitting it to the EMC data



Allow up to 3% over all normalization for each nuclei

O. Hen et al., Int. J. Mod. Phys. E. 22, 1330017 (2013).

Amount of modifications: ΔF/F



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(*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

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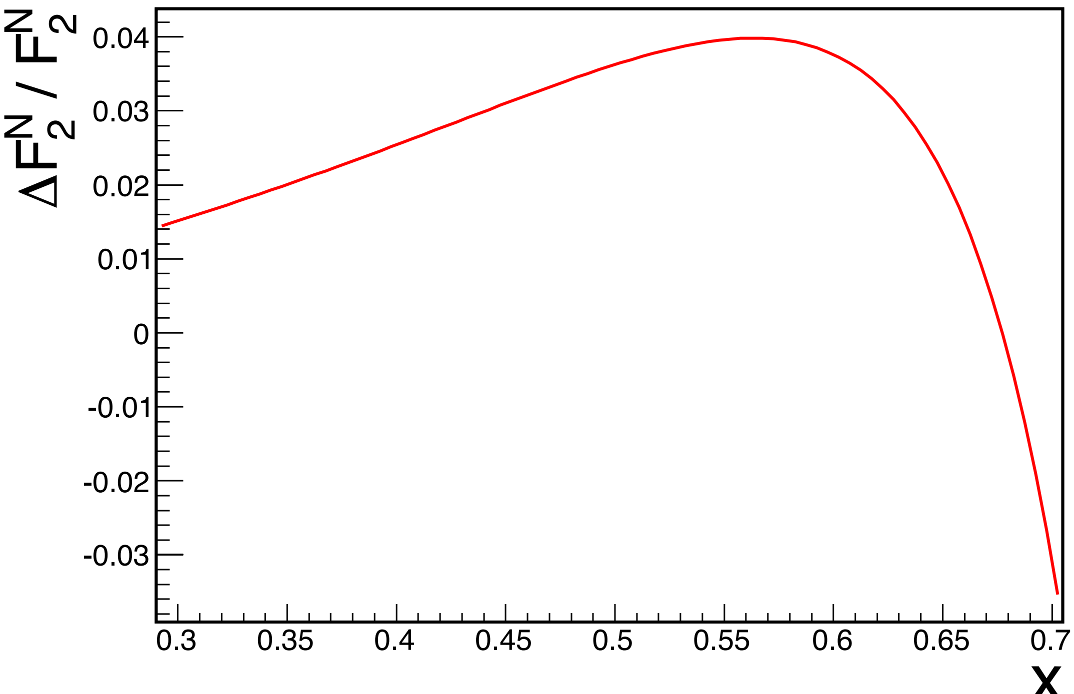

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