Massachusetts Institute of Technology

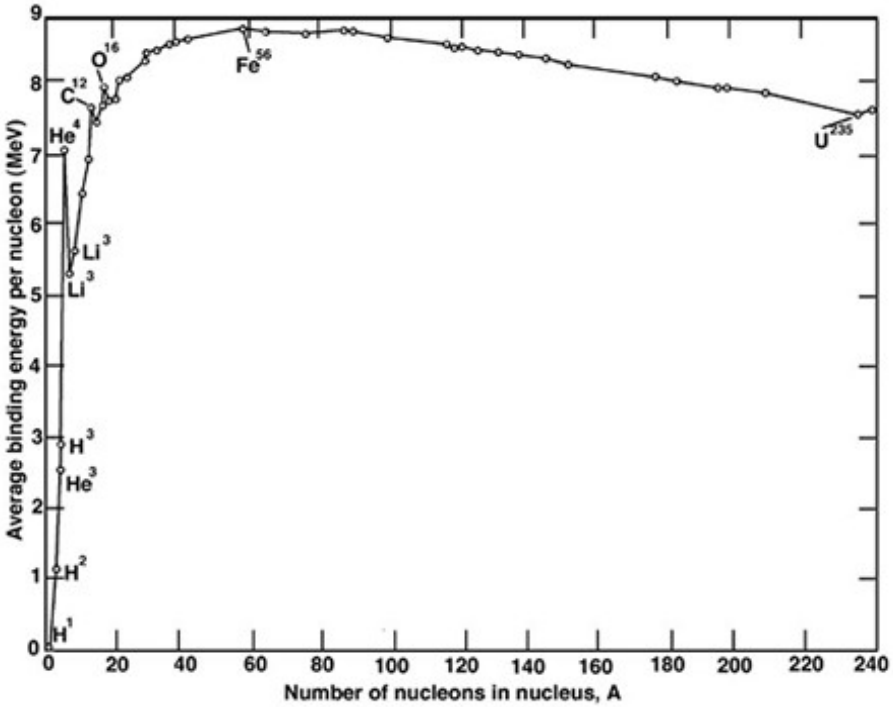
Hen Lab

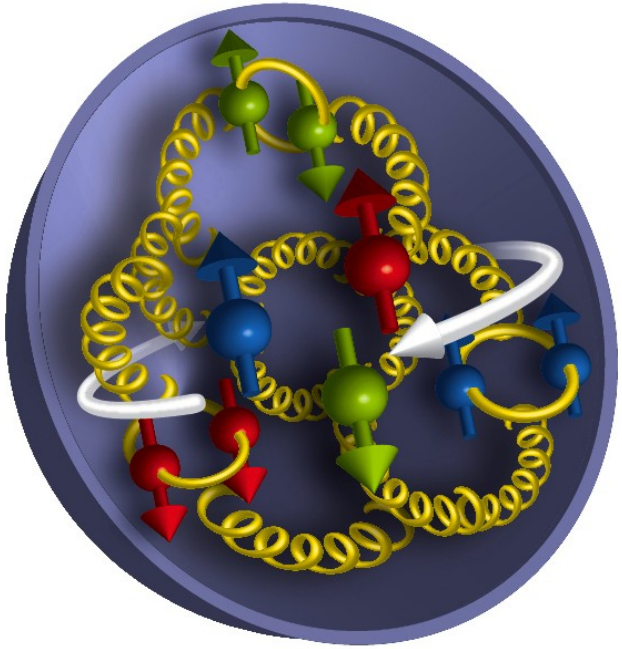
Laboratory for Nuclear Science @ MIT

Isospin Dependence of the EMC Effect and Short Range Correlations

Barak Schmookler

Scale Separation in the Nucleus

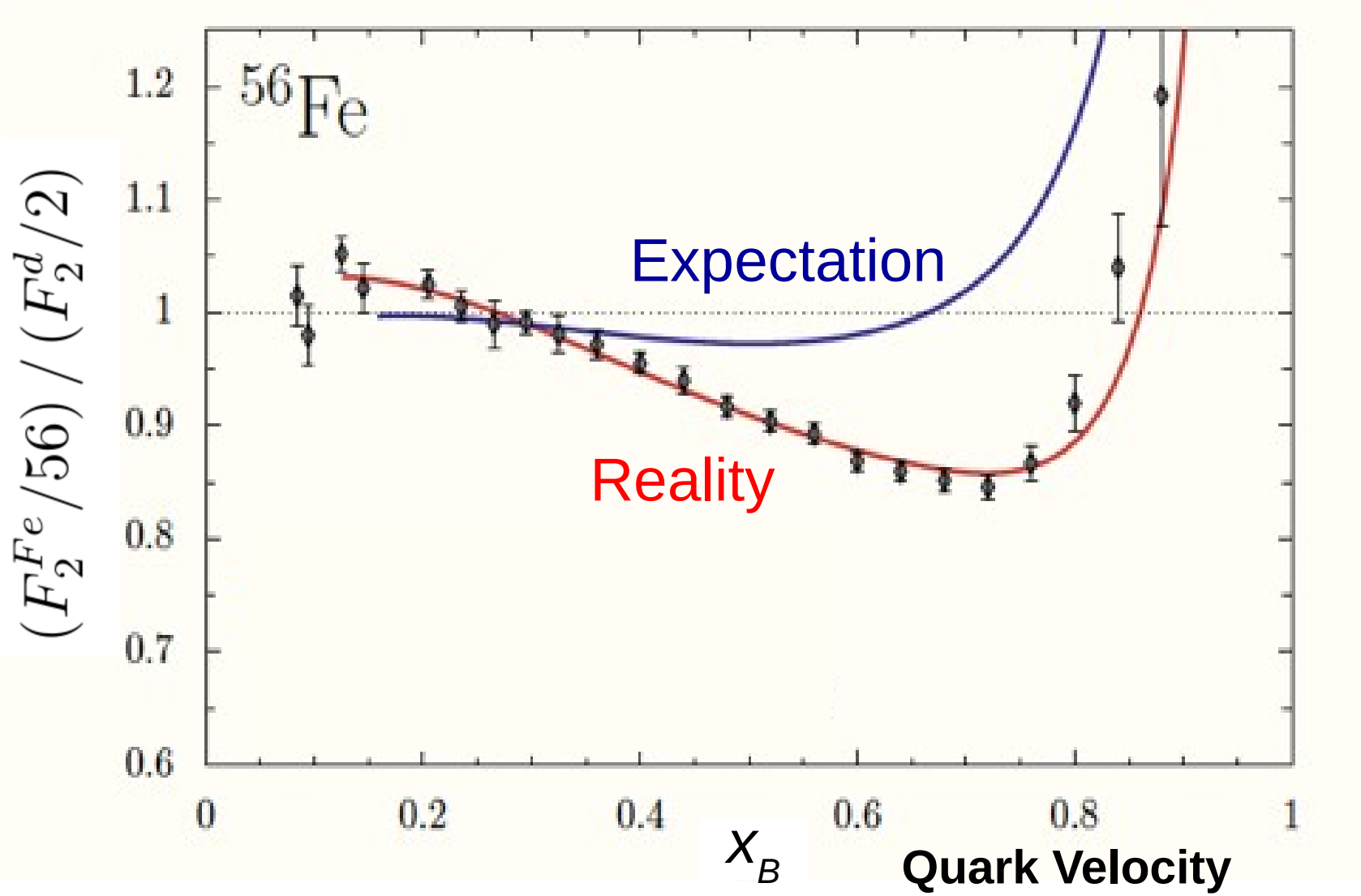




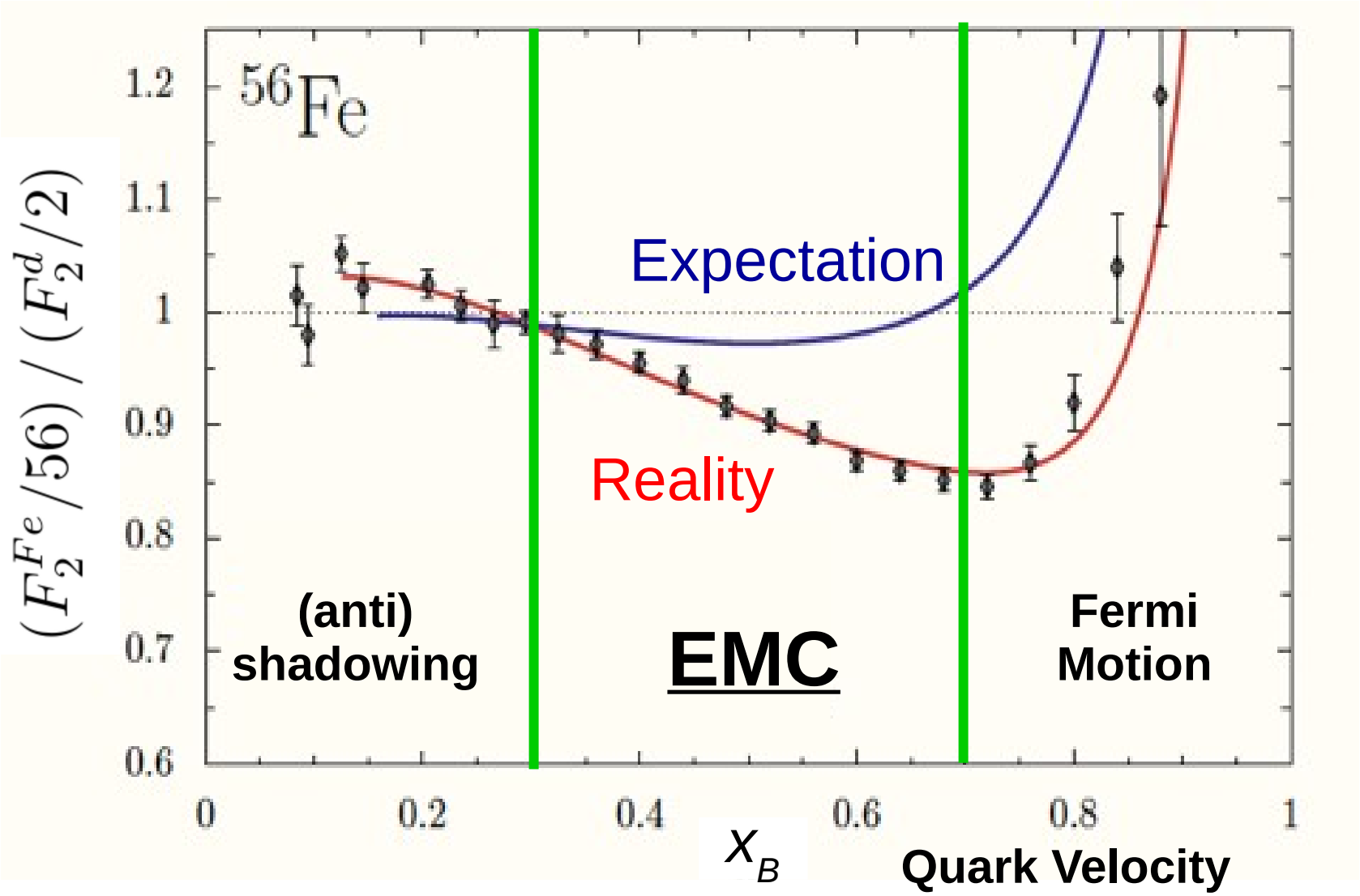
Weak Binding: MeV

Strong Binding: GeV

The EMC Effect

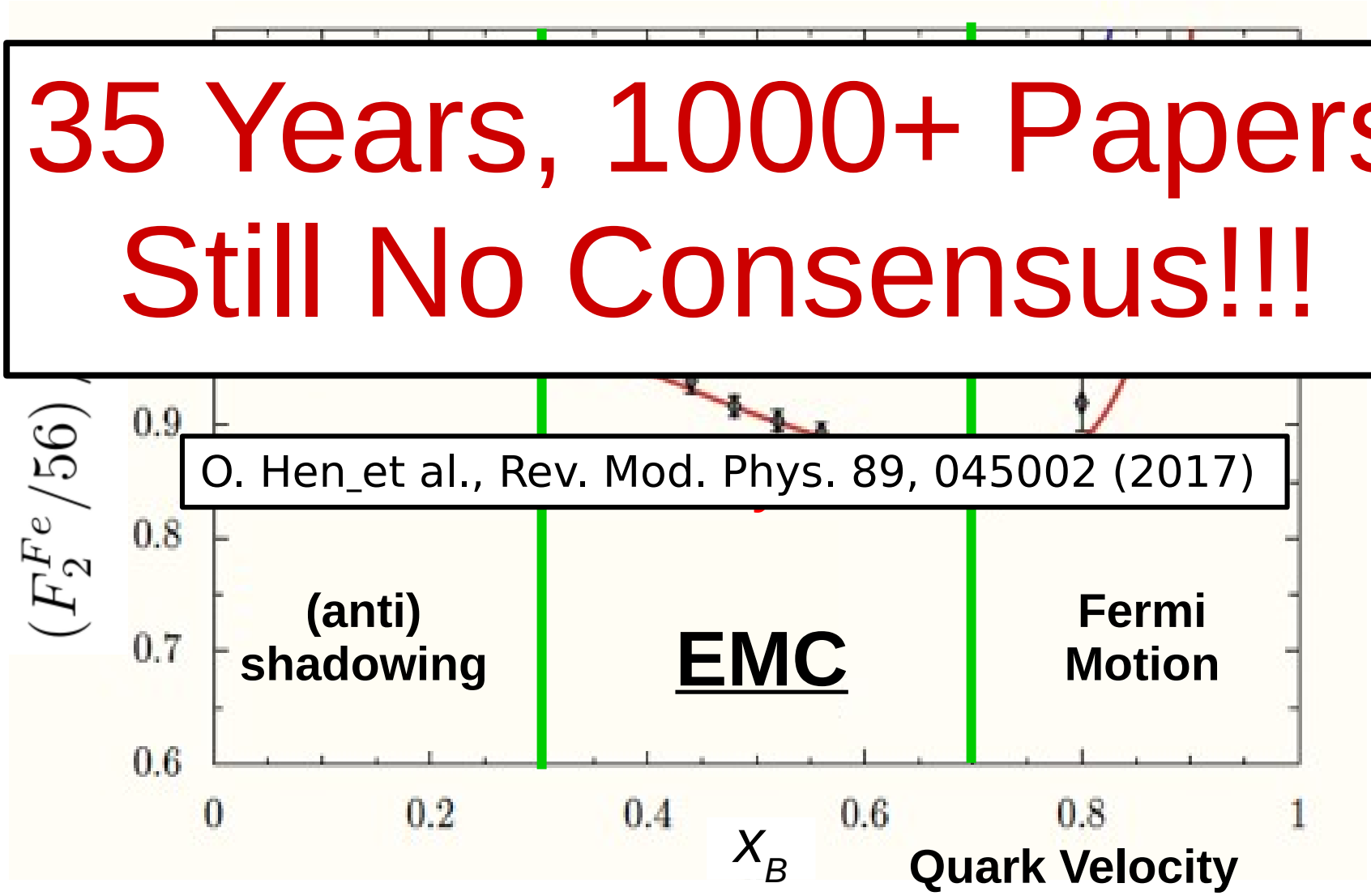


The EMC Effect – Quarks Move “Slower” in the Nucleus



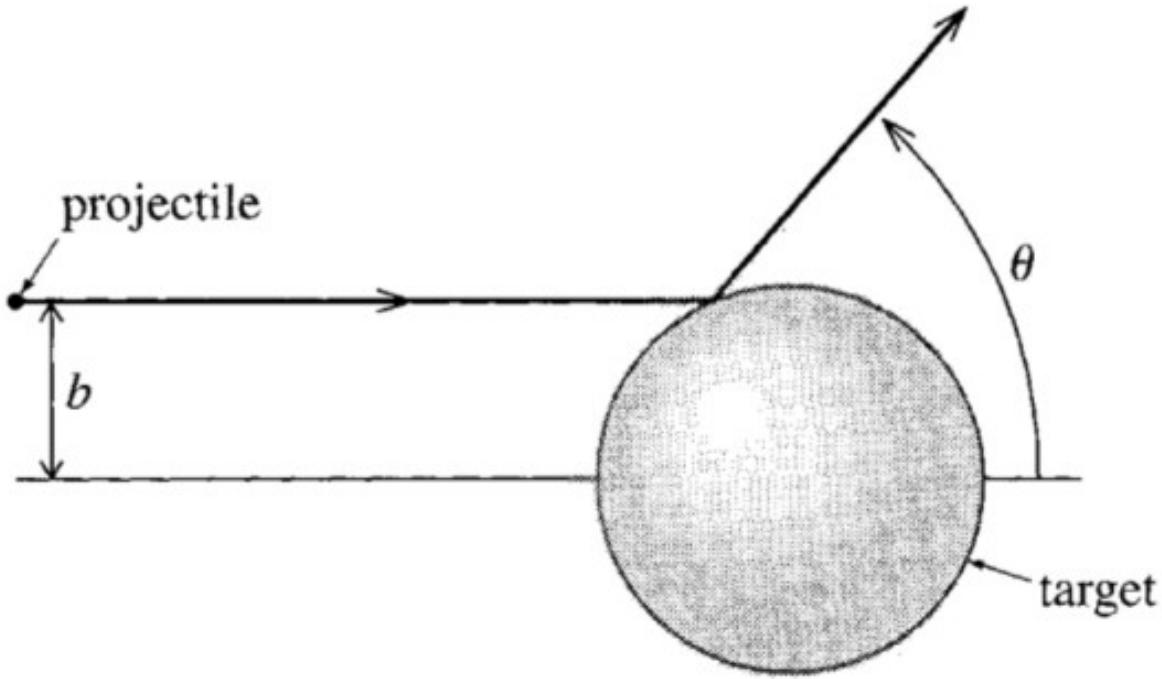
The EMC Effect – Quarks Move “Slower” in the Nucleus

35 Years, 1000+ Papers
Still No Consensus!!!

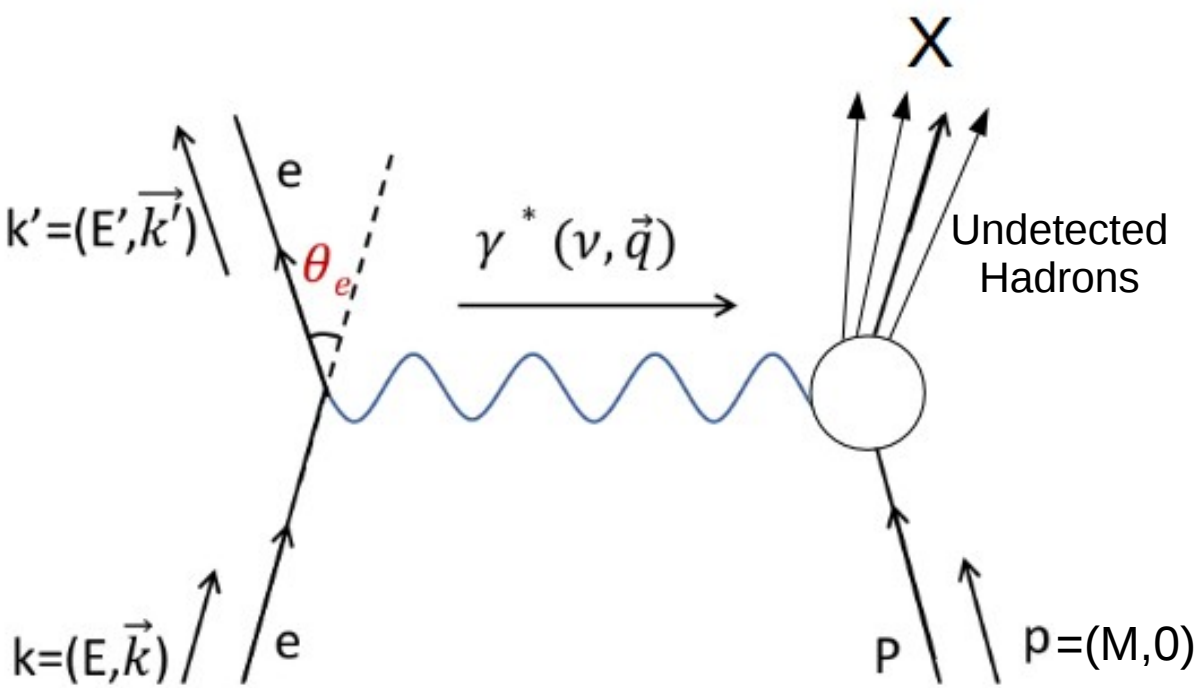


O. Hen_et al., Rev. Mod. Phys. 89, 045002 (2017)

We Can Study the Structure of Complex Objects with Inclusive Scattering



$$\sigma = \pi R^2$$



Energy Transfer:

$$\nu = E - E'$$

Four-Momentum Transfer Squared:

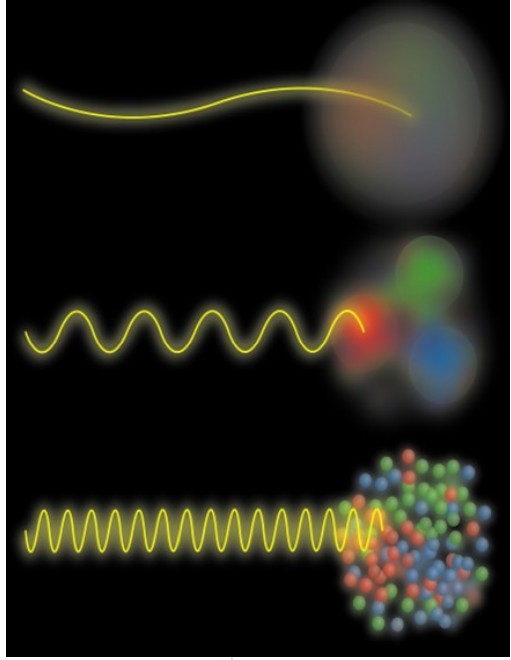
$$Q^2 = -q^2 = 4EE'\sin^2\left(\frac{\theta_e}{2}\right)$$

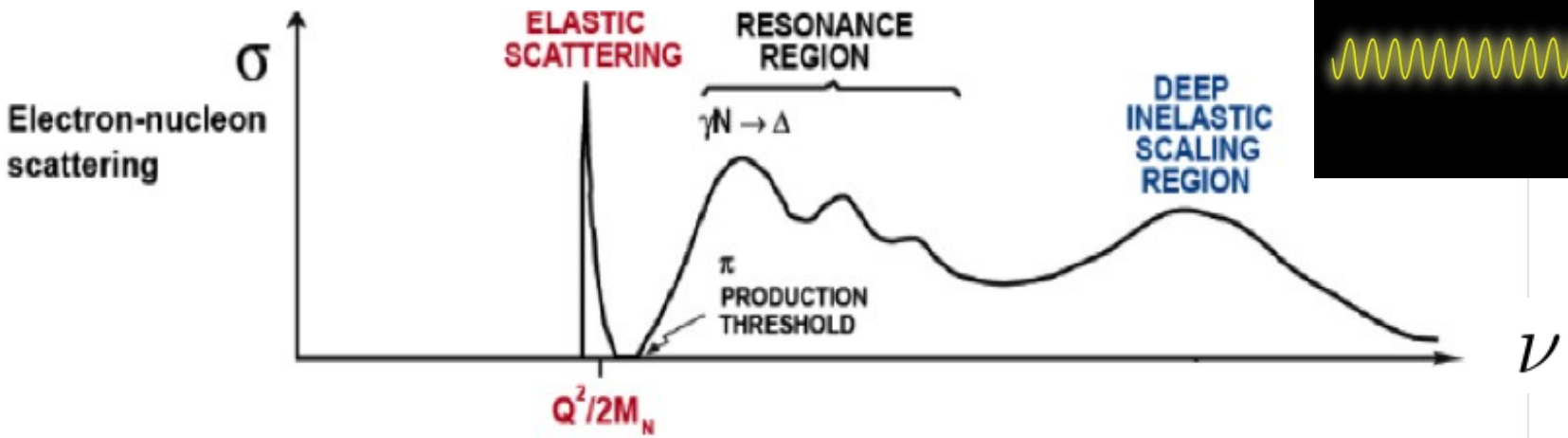
Mass of X:

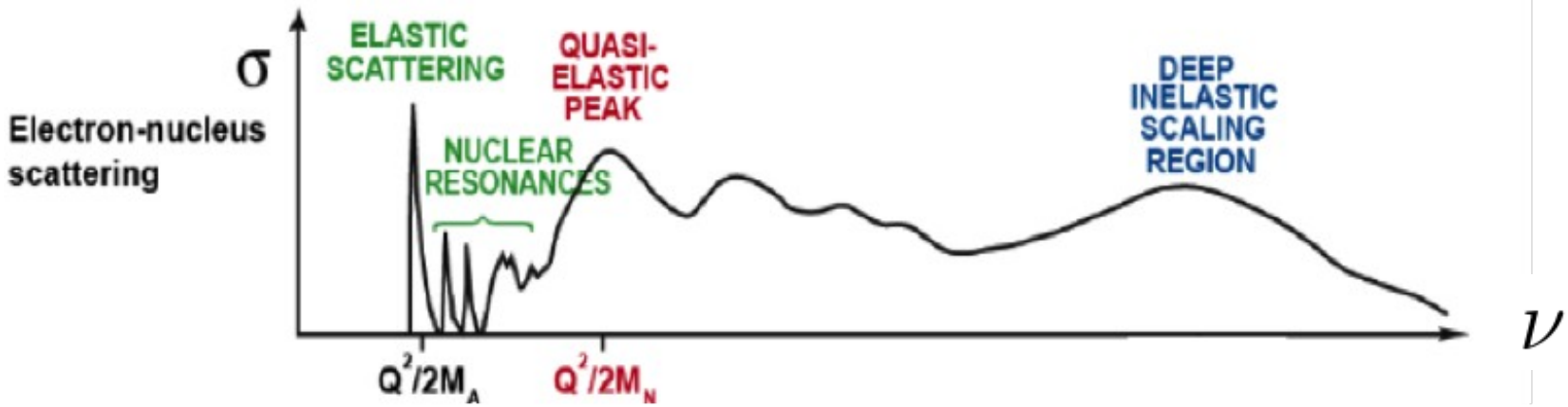
$$W = \sqrt{(P+q)^2} = \sqrt{M^2 + 2M\nu - Q^2}$$

Bjorken x:

$$x_B = \frac{Q^2}{2M\nu}$$

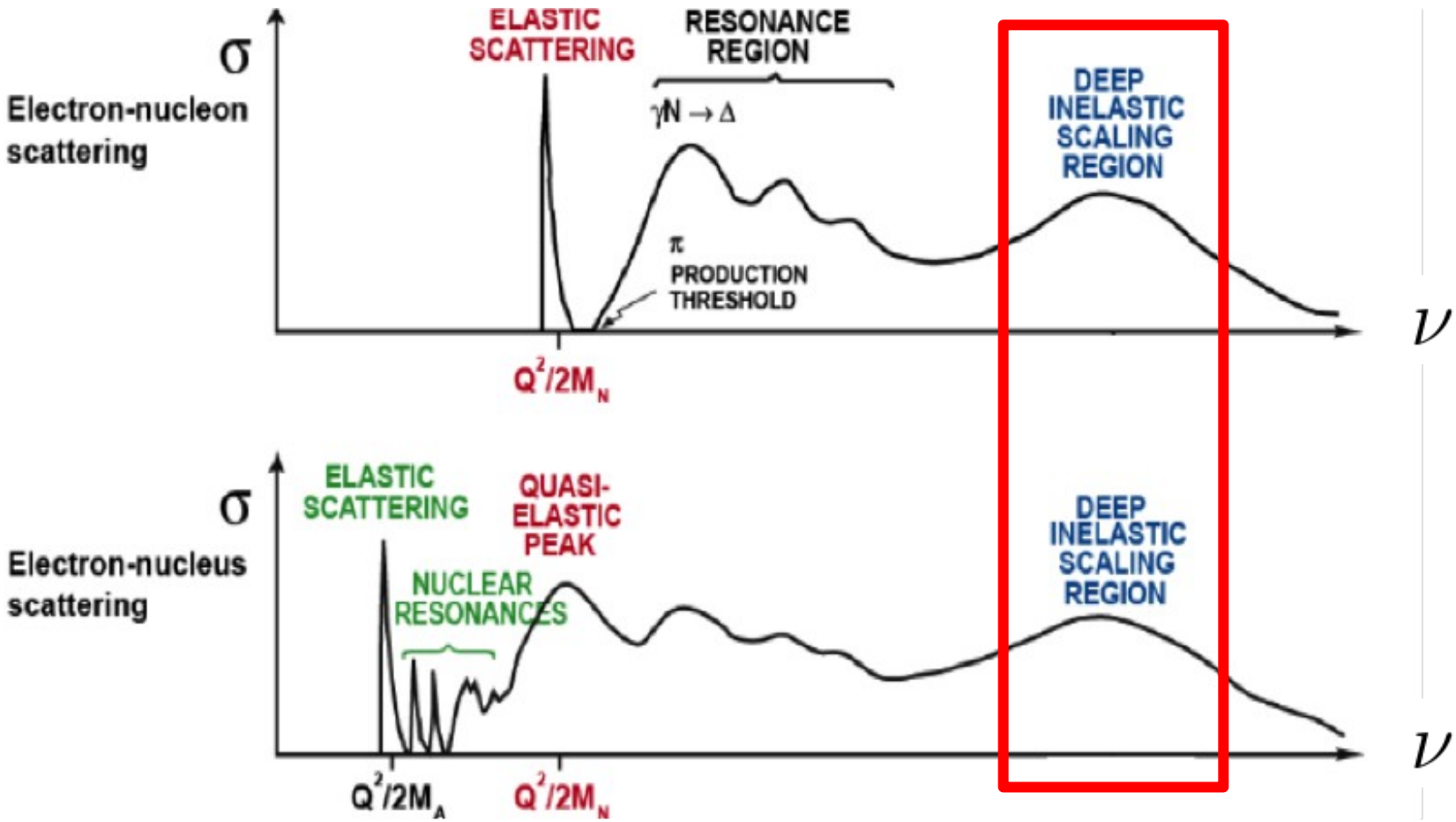



σ
Electron-nucleon scattering
ELASTIC SCATTERING
RESONANCE REGION
γN → Δ
DEEP INELASTIC SCALING REGION
π PRODUCTION THRESHOLD
ν
Q²/2M_N


σ
Electron-nucleus scattering
ELASTIC SCATTERING
QUASI-ELASTIC PEAK
NUCLEAR RESONANCES
DEEP INELASTIC SCALING REGION
ν
Q²/2M_A
Q²/2M_N

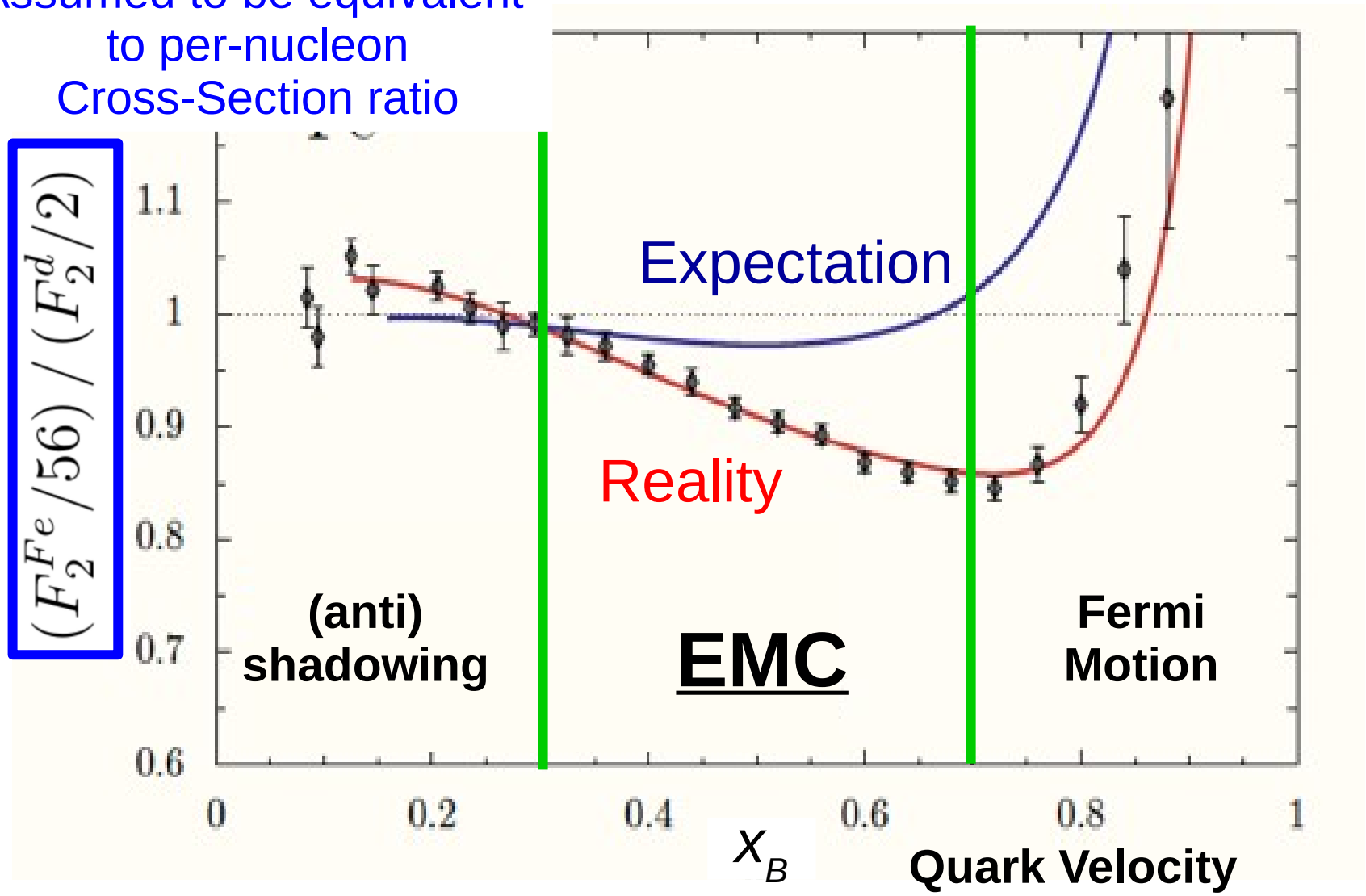
Deep Inelastic Scattering (DIS):

Provides information on the underlying Partonic structure of the Nucleons

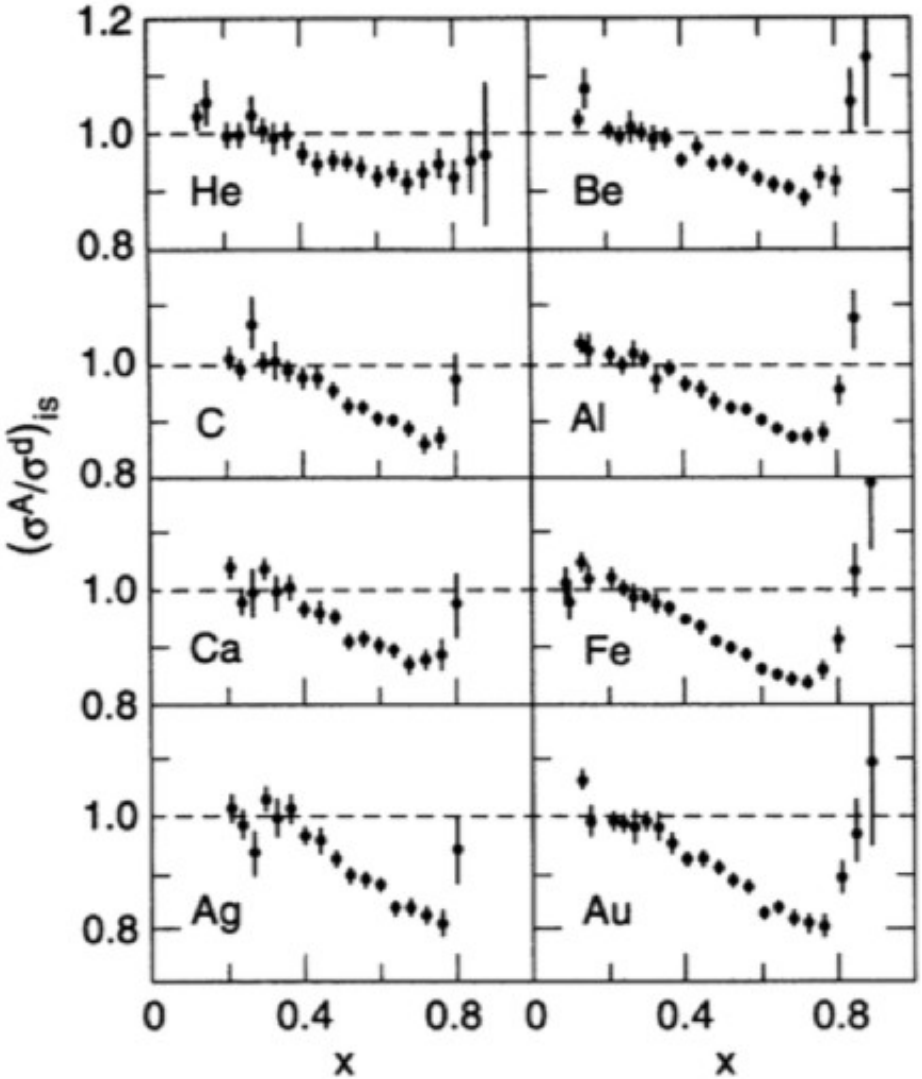


DIS and the EMC Effect

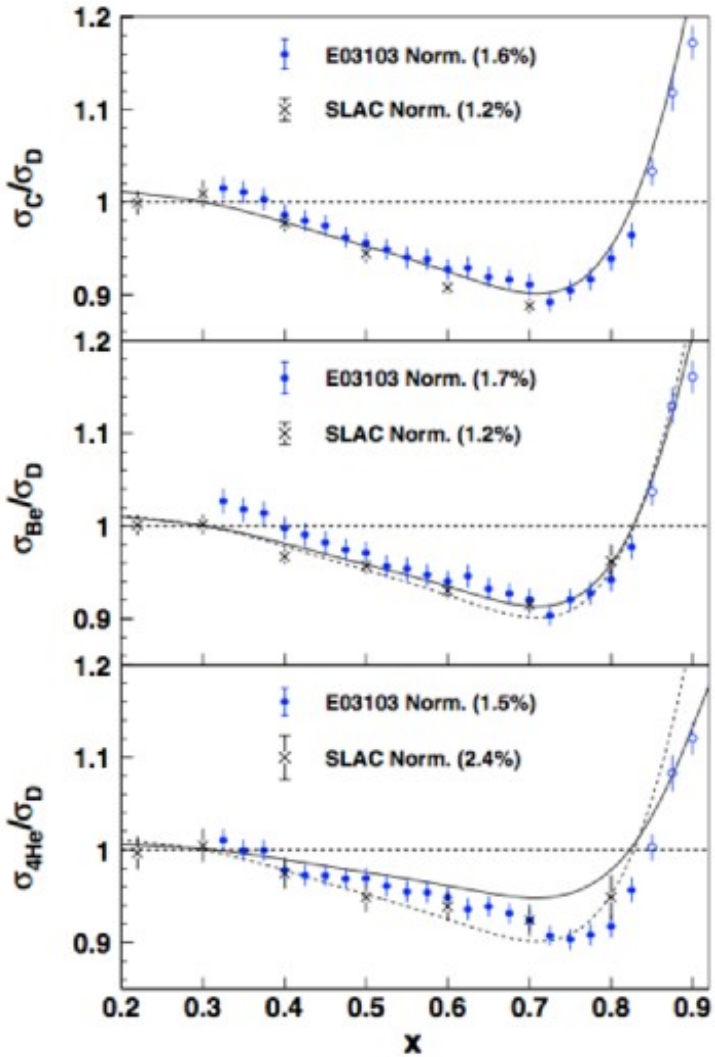
Assumed to be equivalent to per-nucleon Cross-Section ratio



The EMC Effect: Universal Nuclear Effect



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



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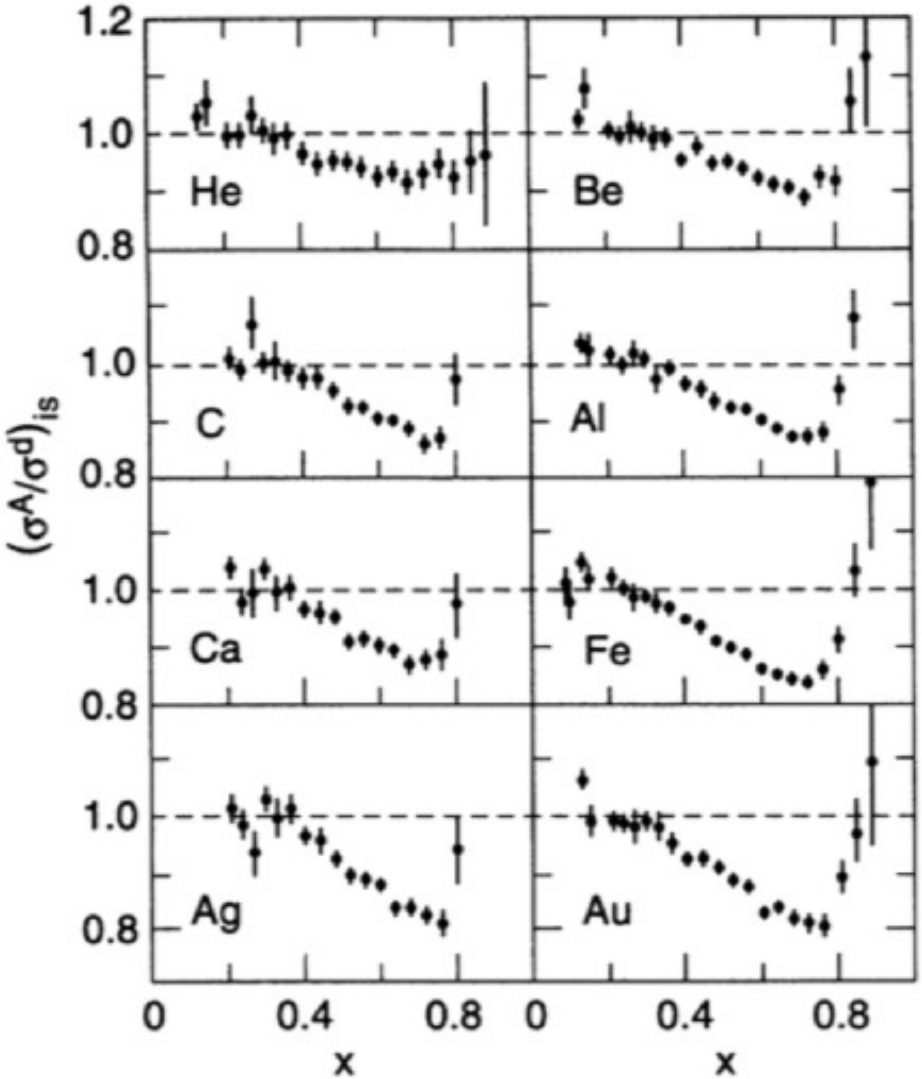
The EMC Effect: **Universal** Nuclear Effect



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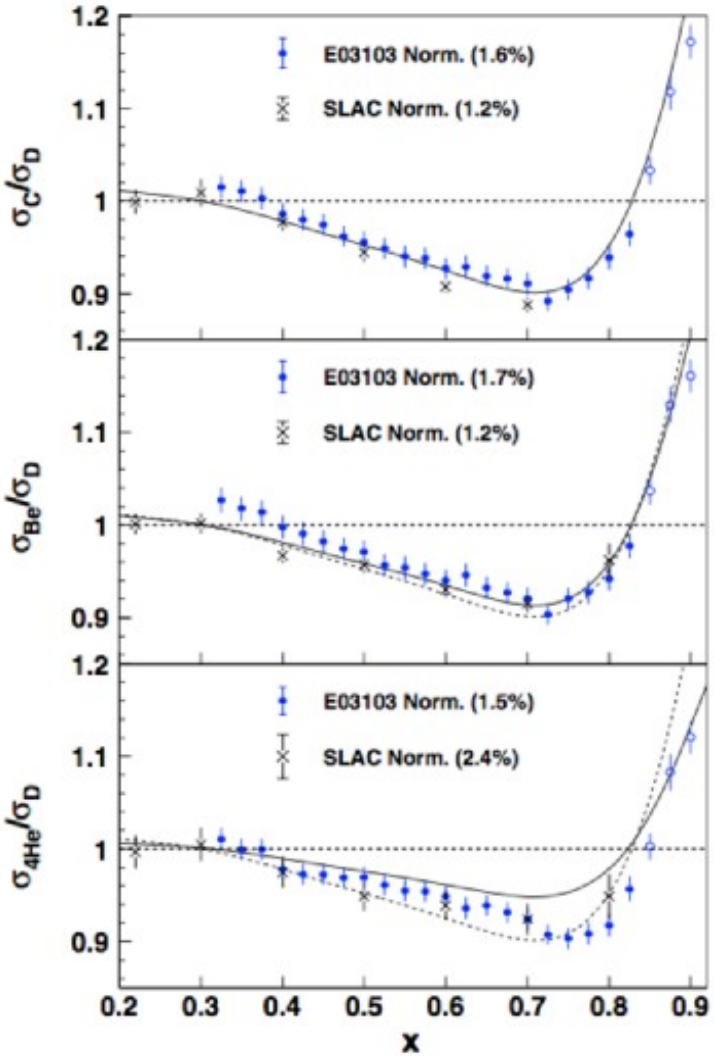

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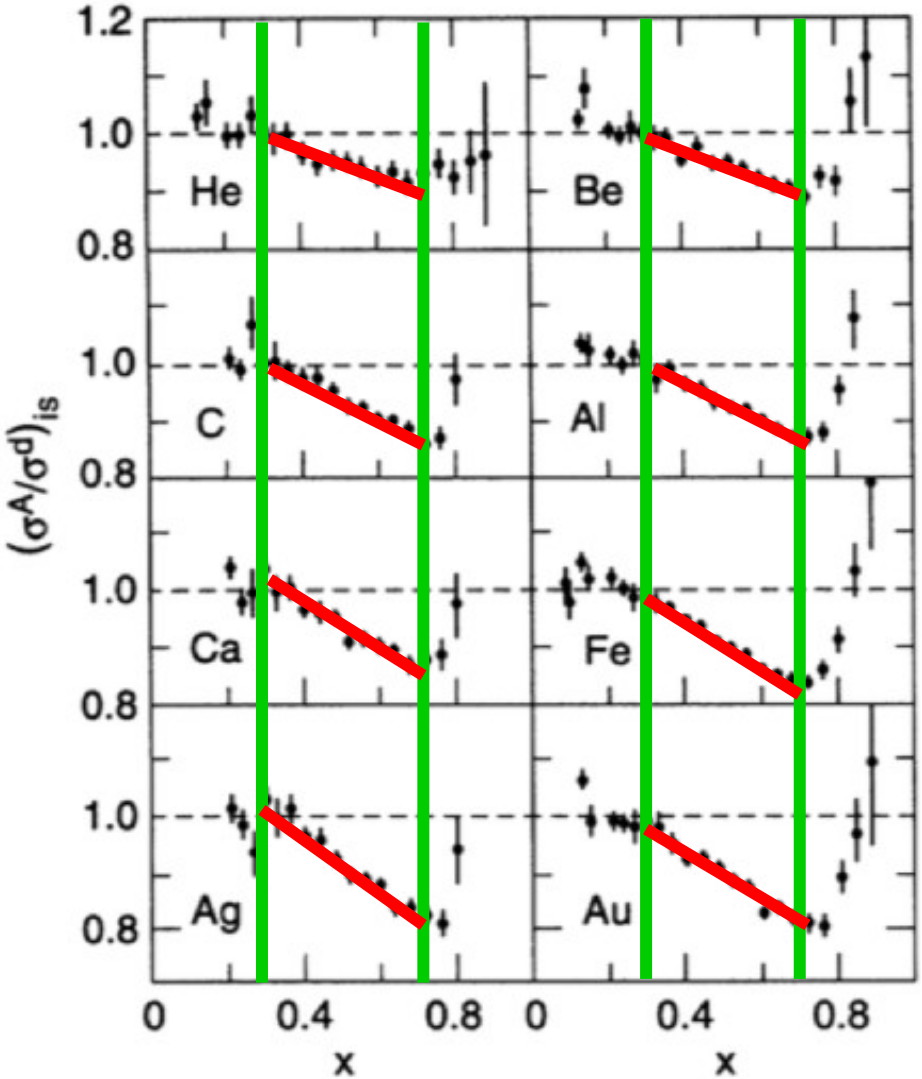
The EMC Effect: Universal **Nuclear** Effect



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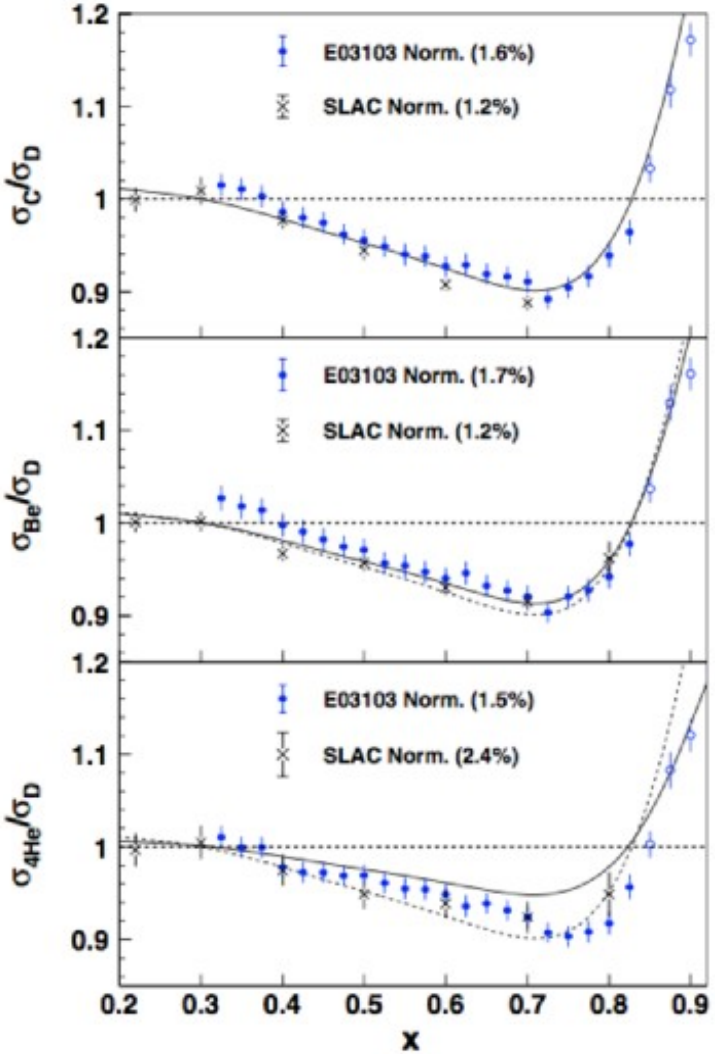

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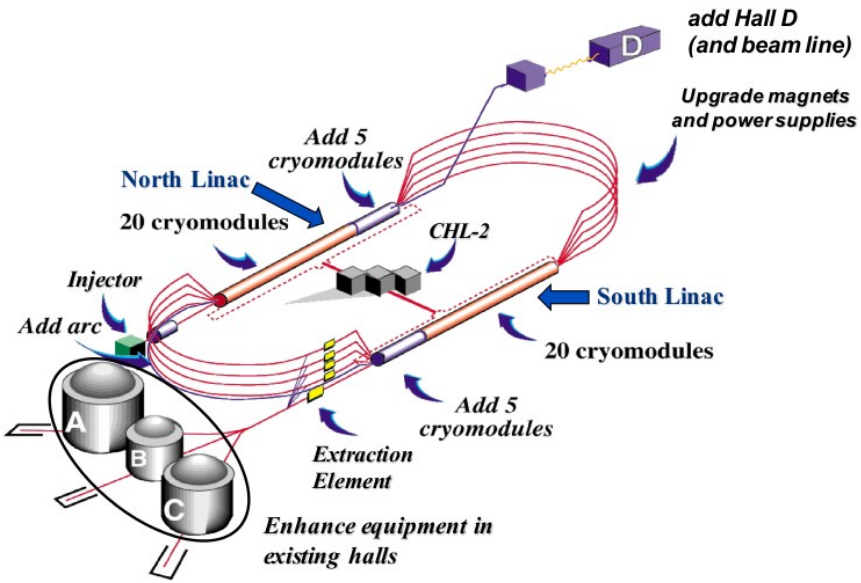
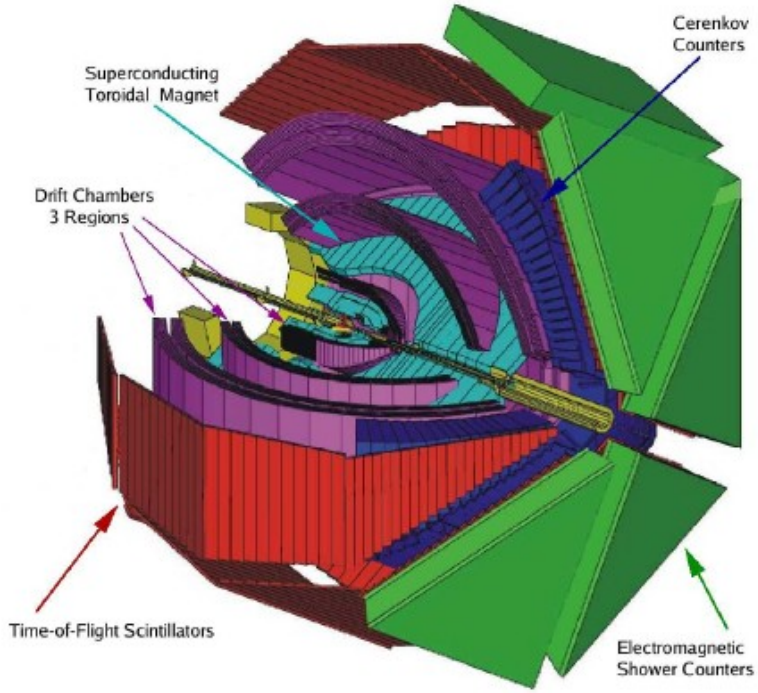
Thomas Jefferson National Accelerator Facility (JLab)



The CLAS Detector in Hall B at JLab



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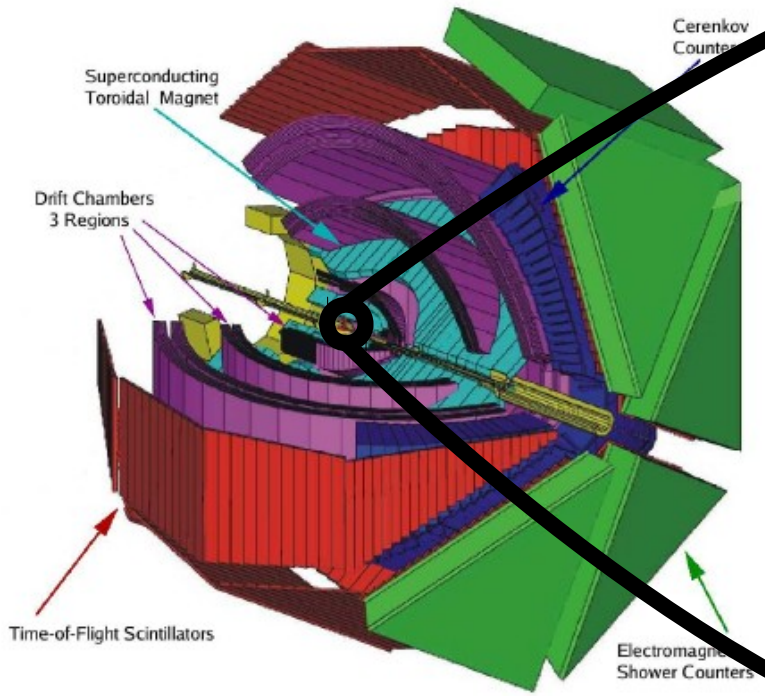
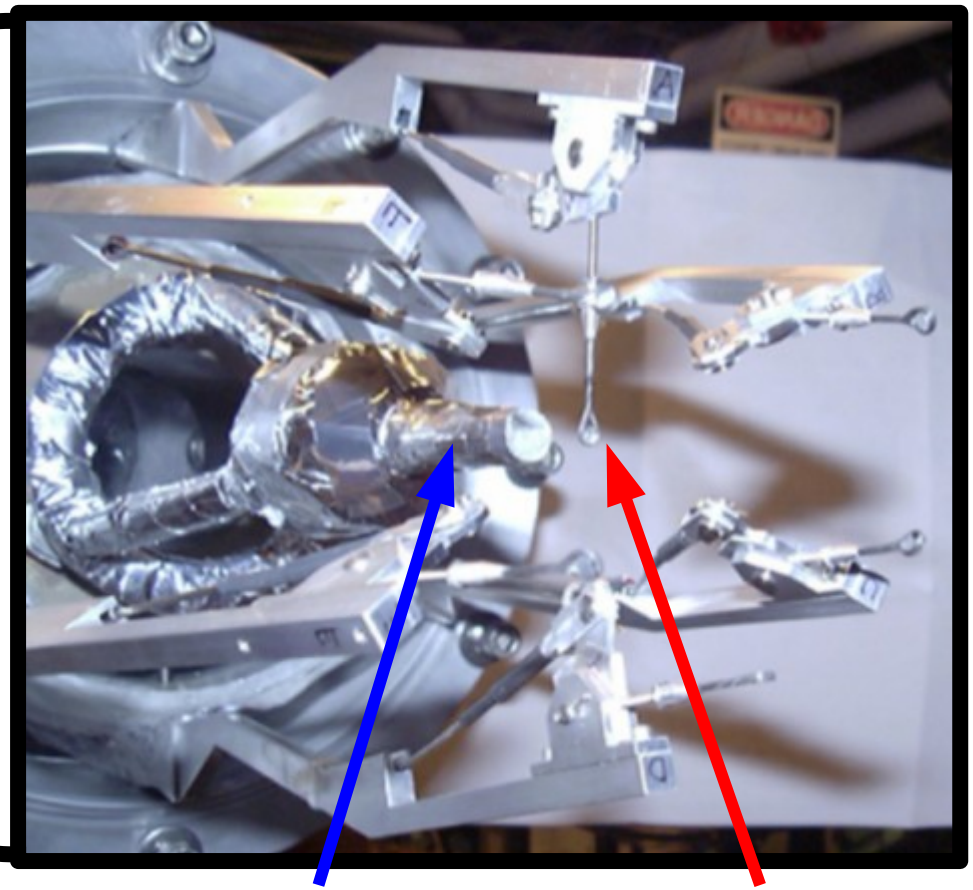
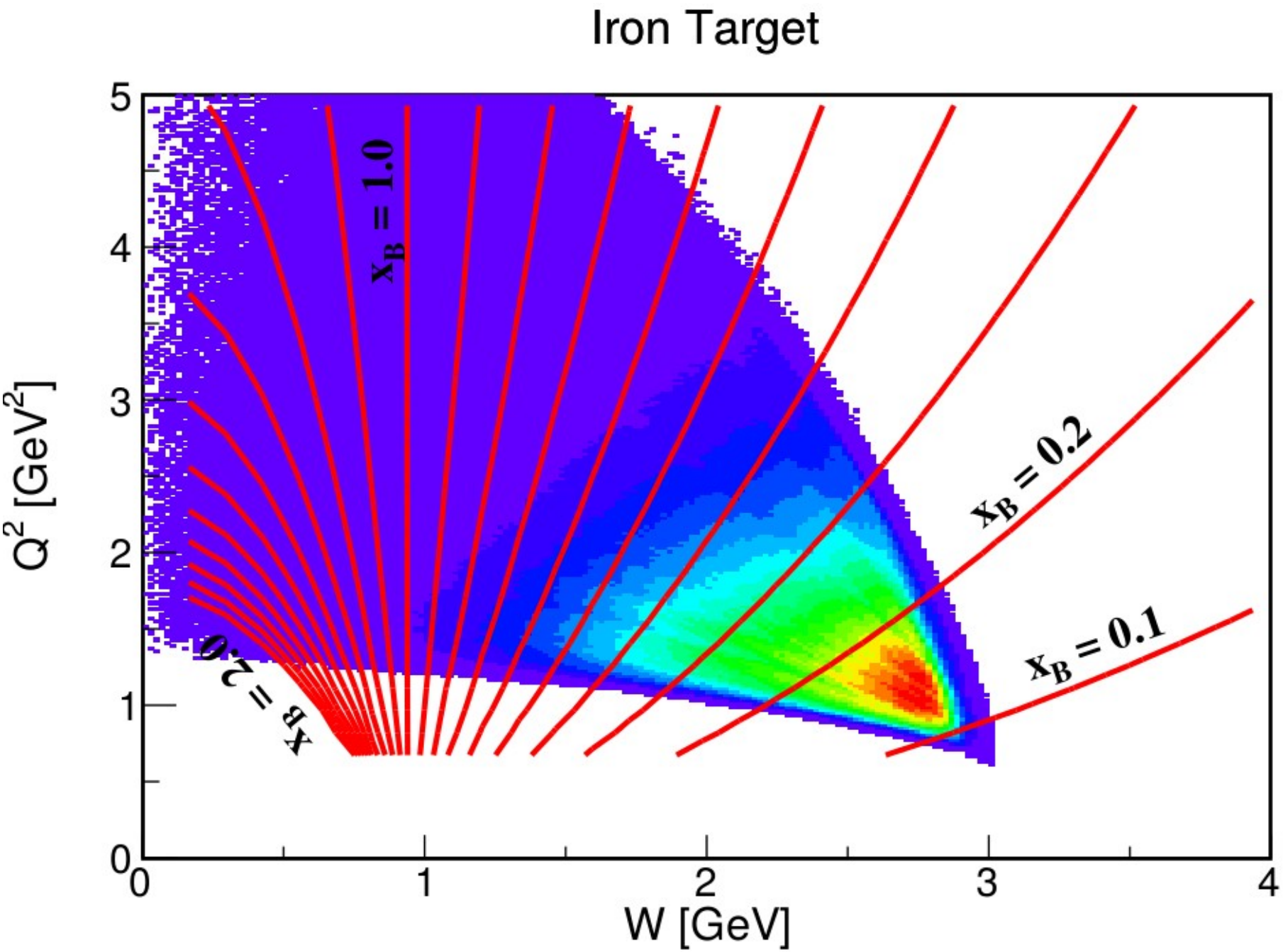


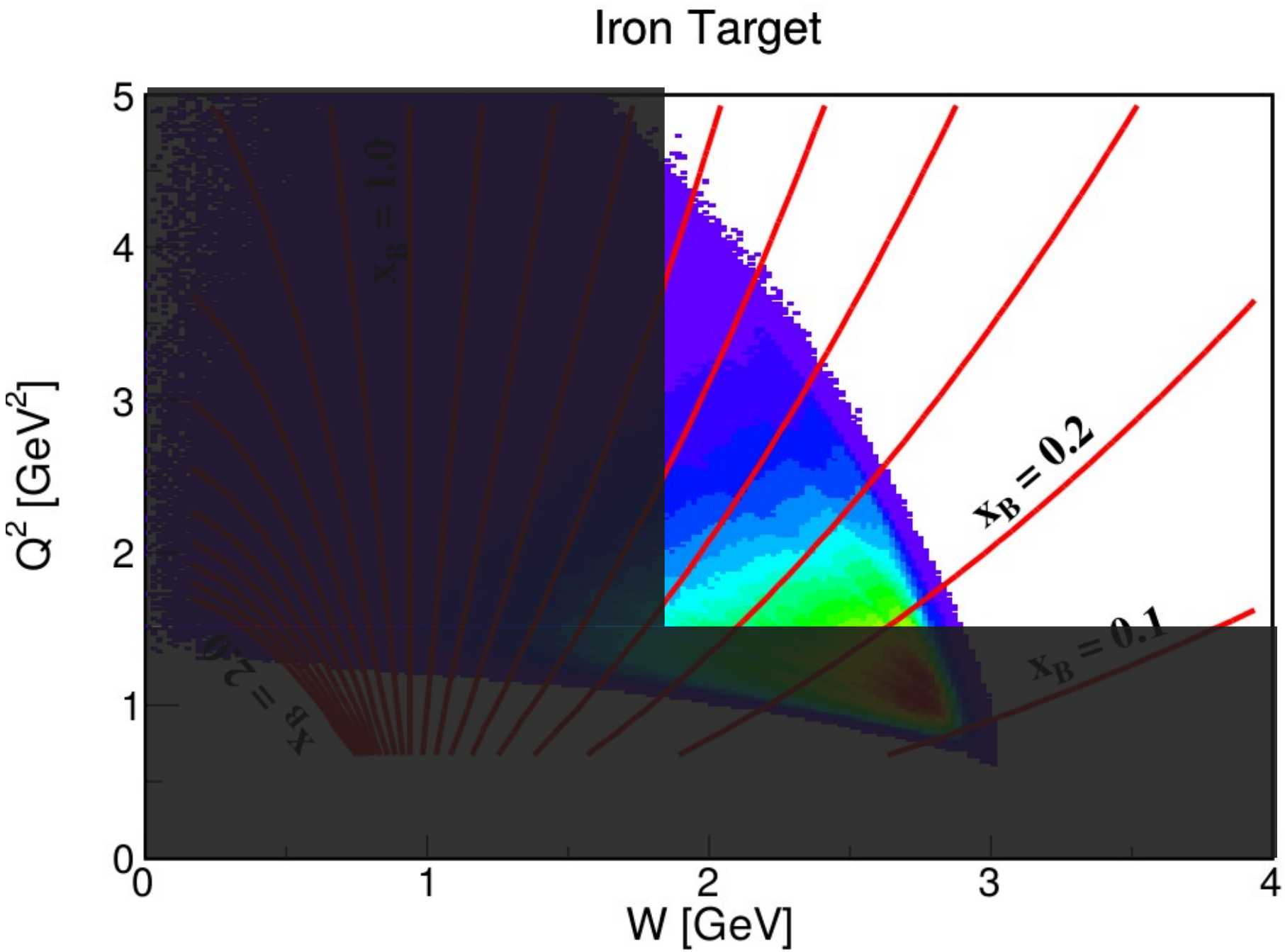


Liquid Hydrogen or Deuterium

C, Al, Fe, or Pb

5.01 GeV Incident Electrons


Iron Target
$x_B = 1.0$
$x_B = 0.2$
$x_B = 0.1$
$x_B = 2.0$
Q^2 [GeV^2]
W [GeV]
0
1
2
3
4
5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Q^2 [GeV^2]
W [GeV]
0
1
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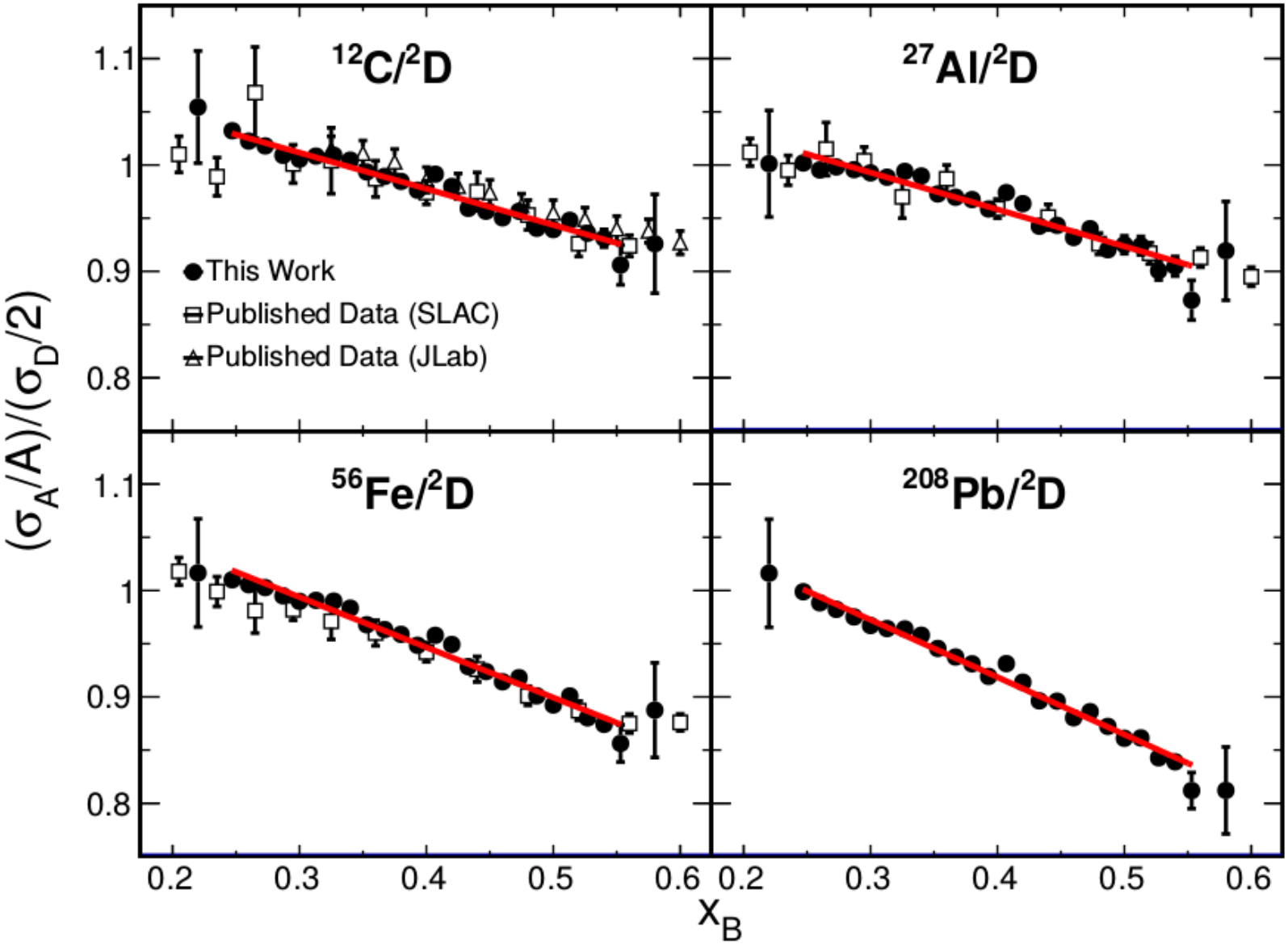
Our New EMC Effect Measurements



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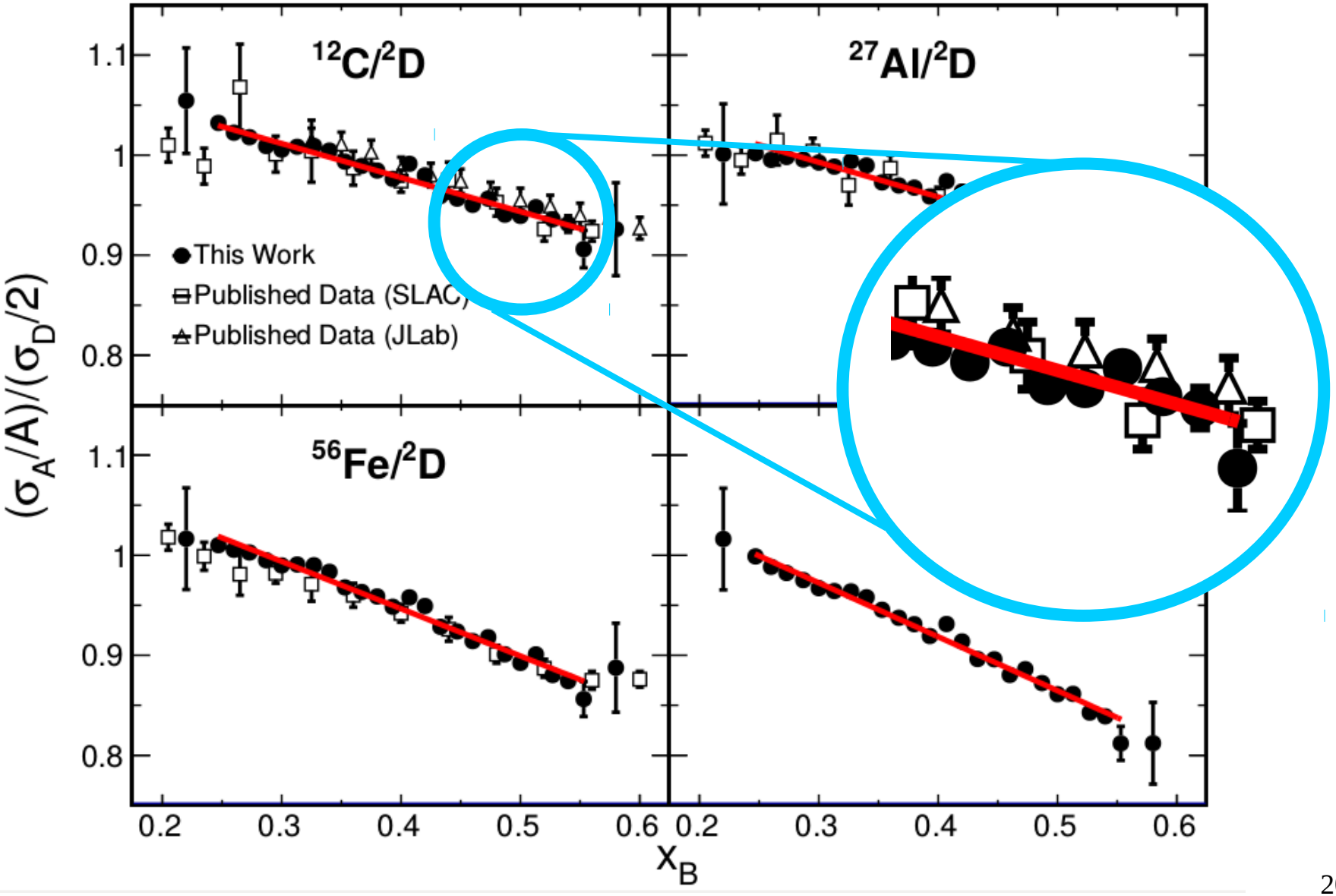

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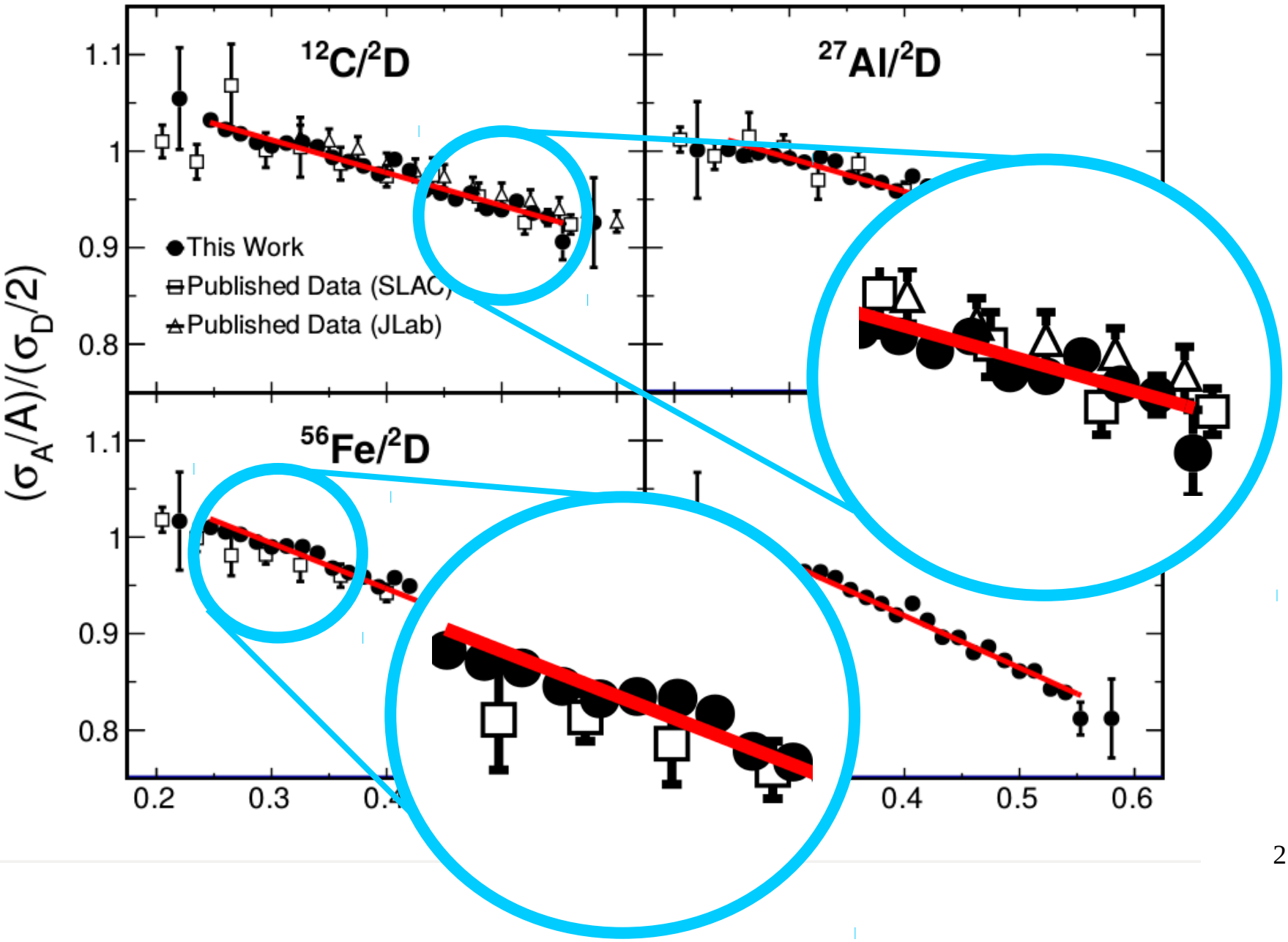
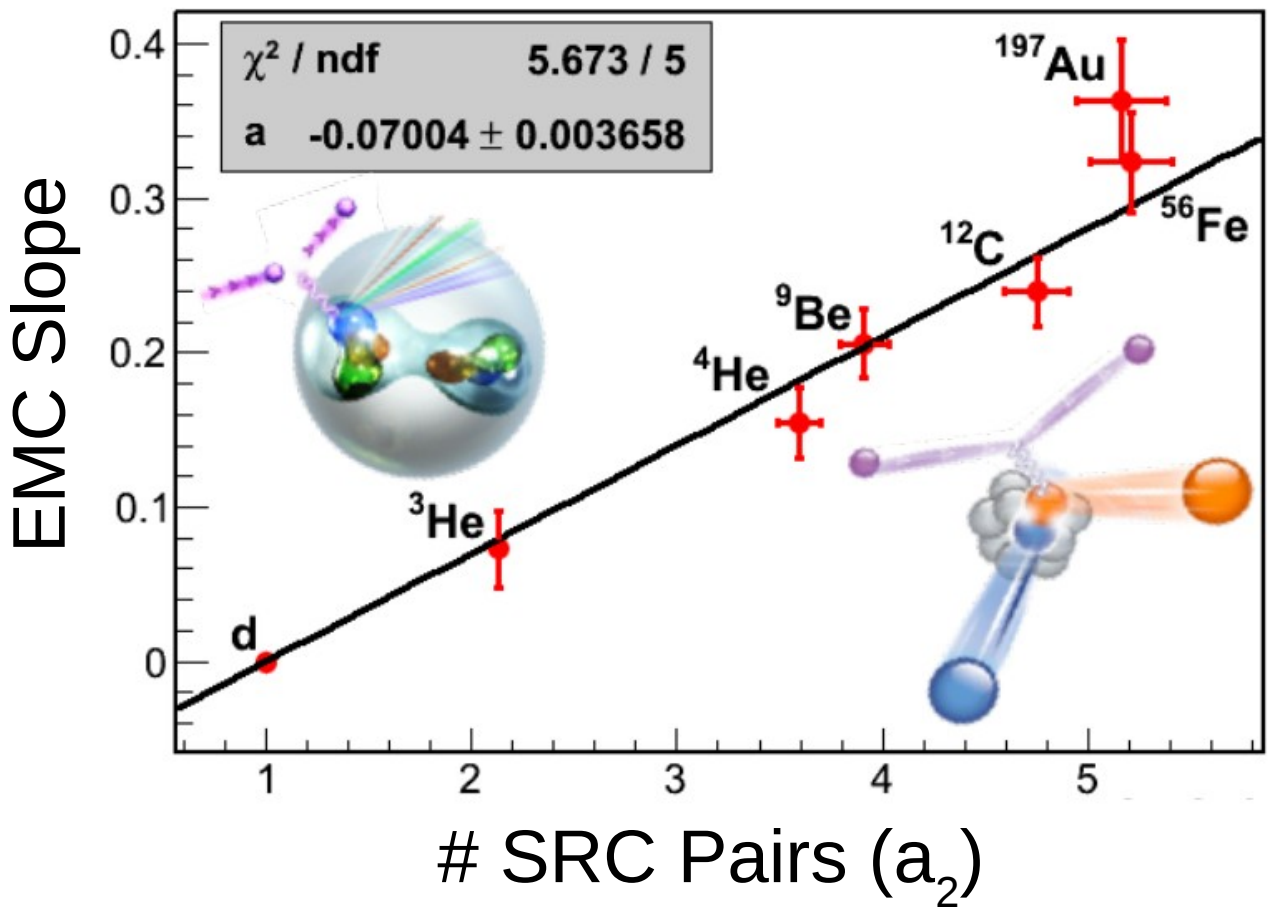
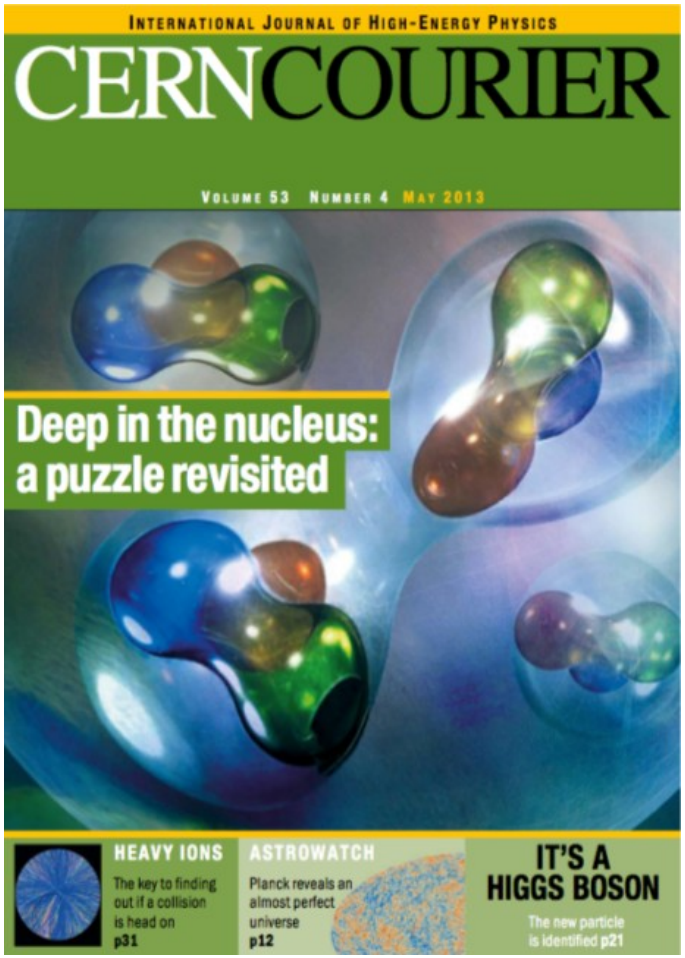


Current Explanations of the EMC Effect

- Two leading approaches for describing the EMC effect:
  - All nucleons are slightly modified when bound in nuclei
  - Nucleons are unmodified most of the time, but are modified significantly when they fluctuate into Short Range Correlation (SRC) pairs

Observed EMC-SRC Correlation



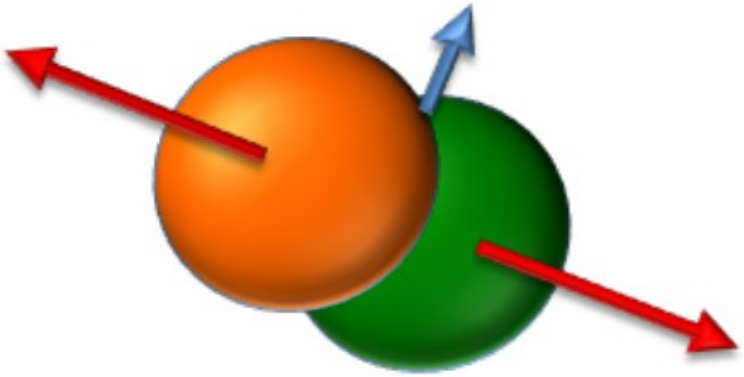


L. Weinstein et. al., Phys. Rev. Lett.06, 052301 (2011).
O. Hen et al. Phys. Rev. C 85 047301 (2012).
O. Hen et al., Rev. Mod. Phys. 89, 045002 (2017).

Short Range Correlations (SRC)

Nucleon pairs that are close together in the nucleus

<u>Momentum space:</u> *high relative* and *low c.m. momentum,* compared to the Fermi momentum (k_F)



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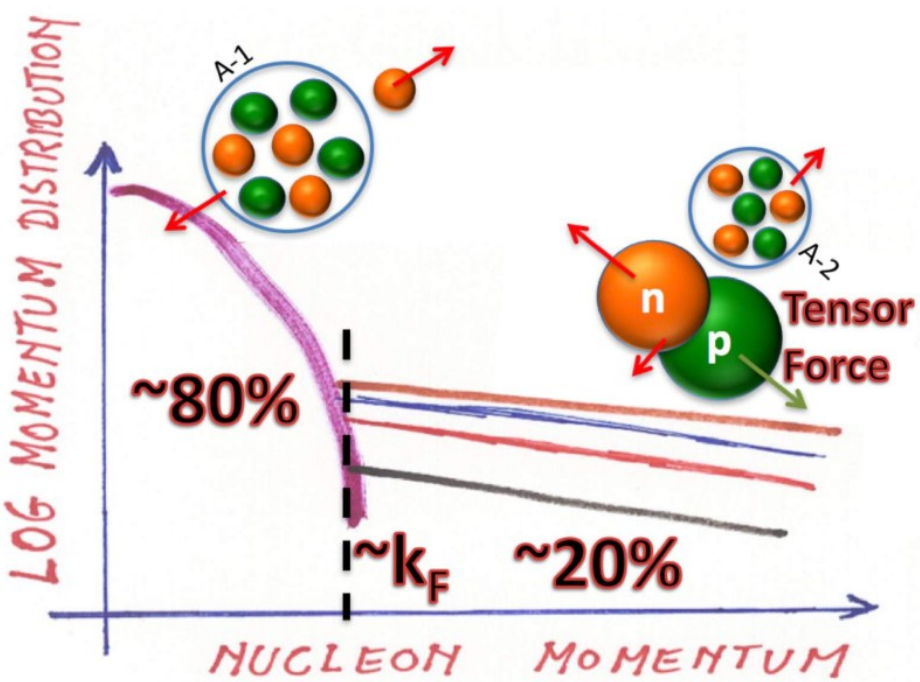

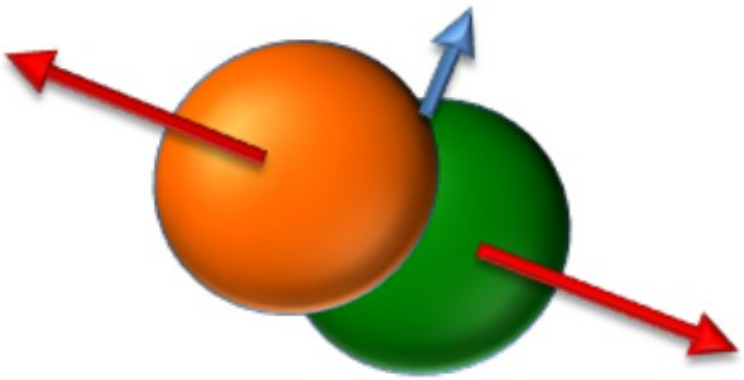

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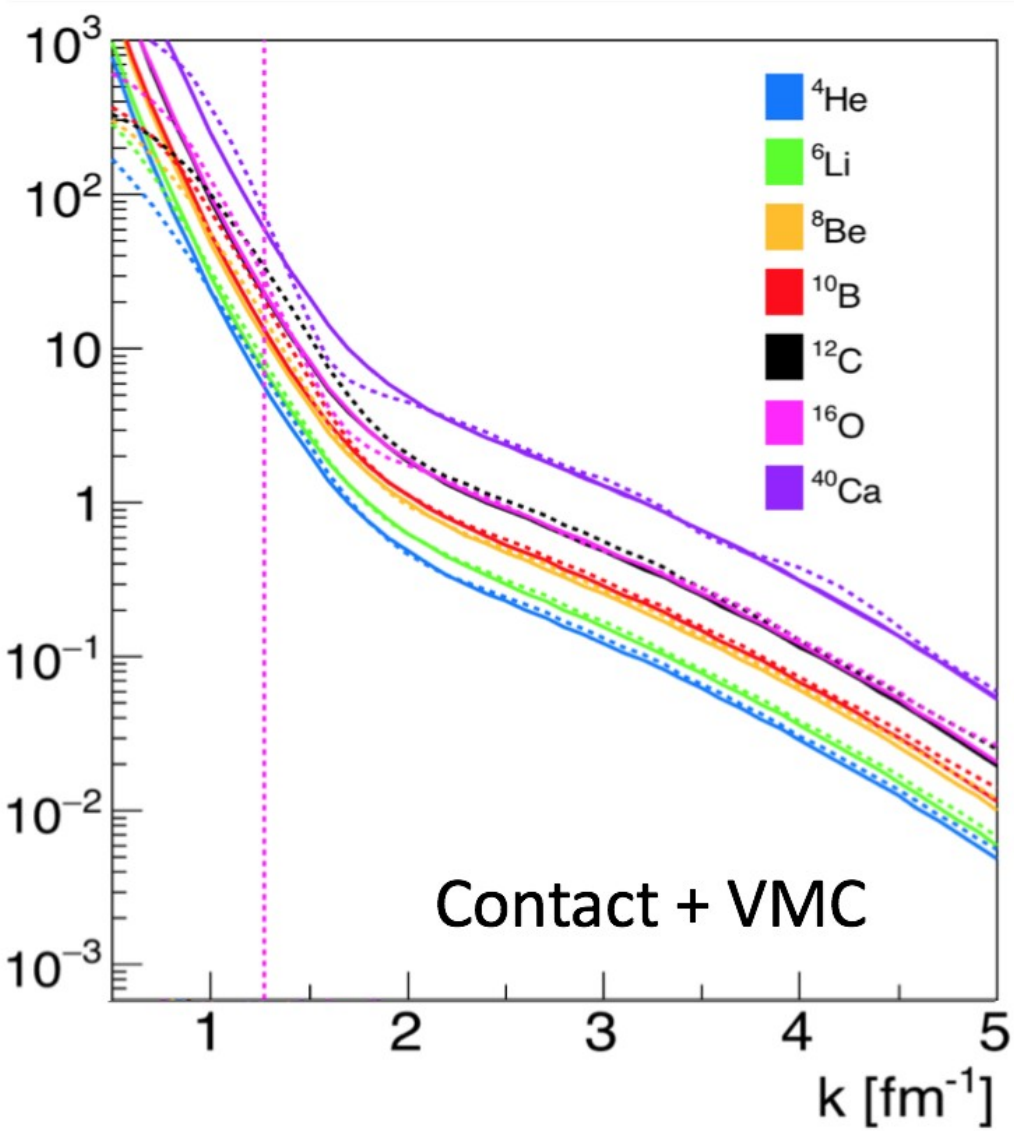
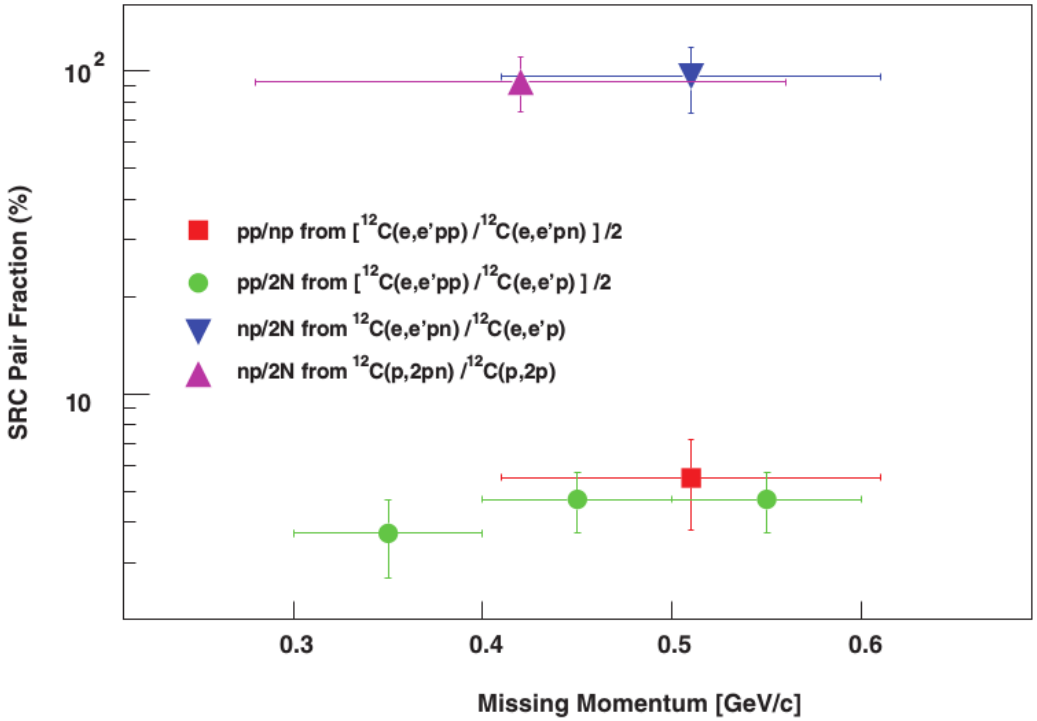


Scaling: High-momentum component of nuclear wave function is deuteron-like.

a_2: Probability of finding a high momentum nucleon in nucleus A relative to deuterium

Weiss, Cruz-Torres, Barnea, Piasetzky and Hen, Phys. Lett. B 780, 211 (2018)

Short Range Correlations (SRC)



Scaling: High-momentum component of nuclear wave function is deuteron-like.

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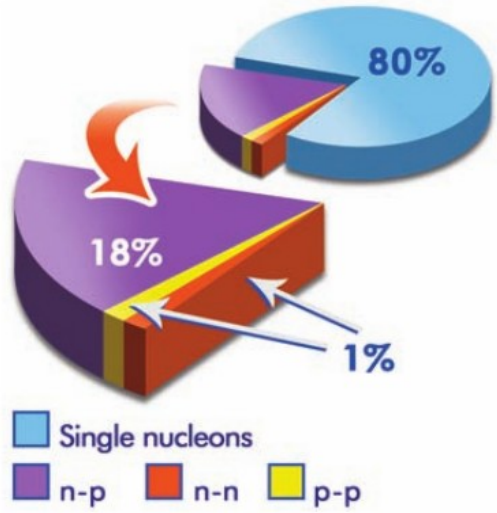
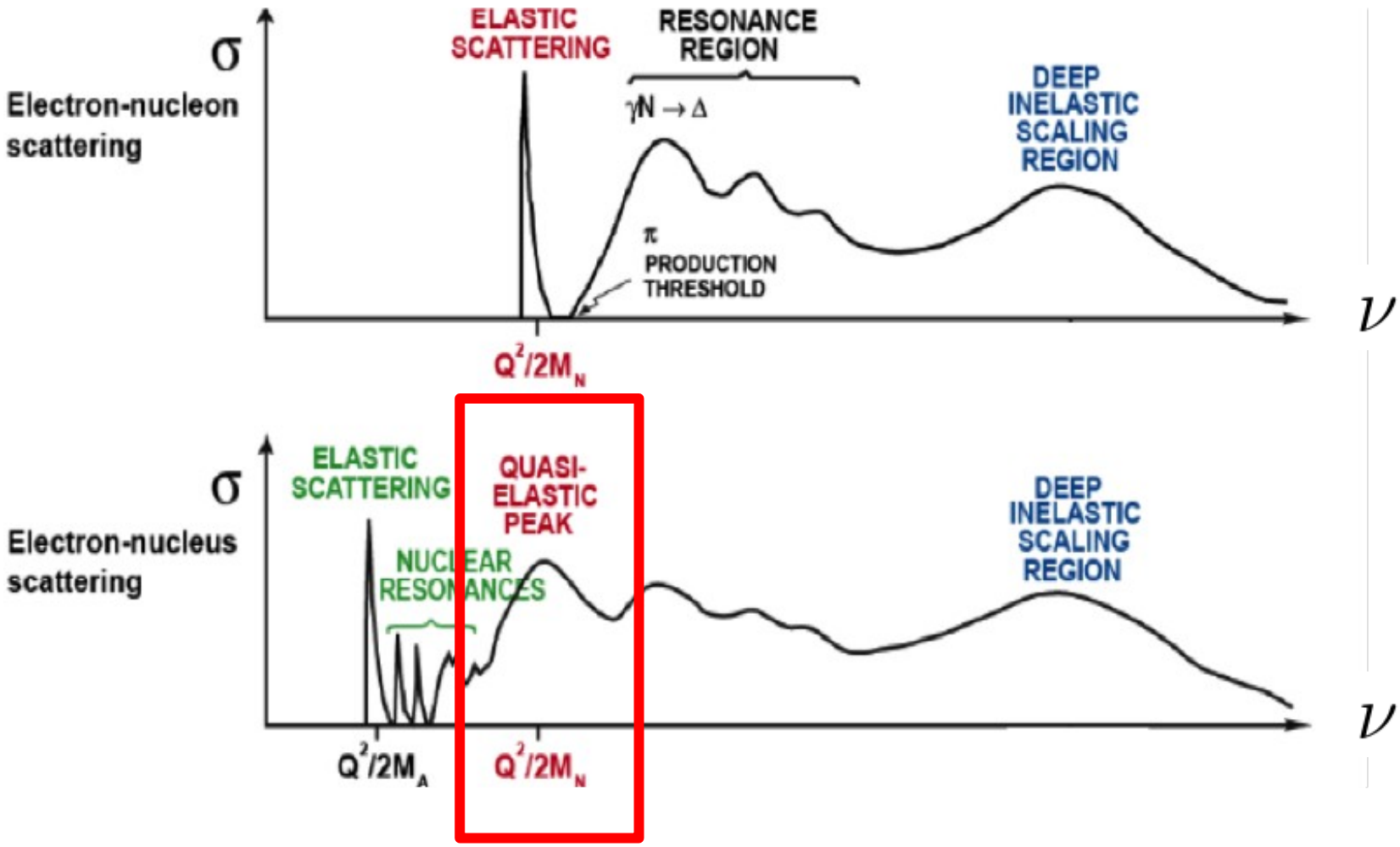
Isospin Dependence: Dominated by neutron-proton pairs



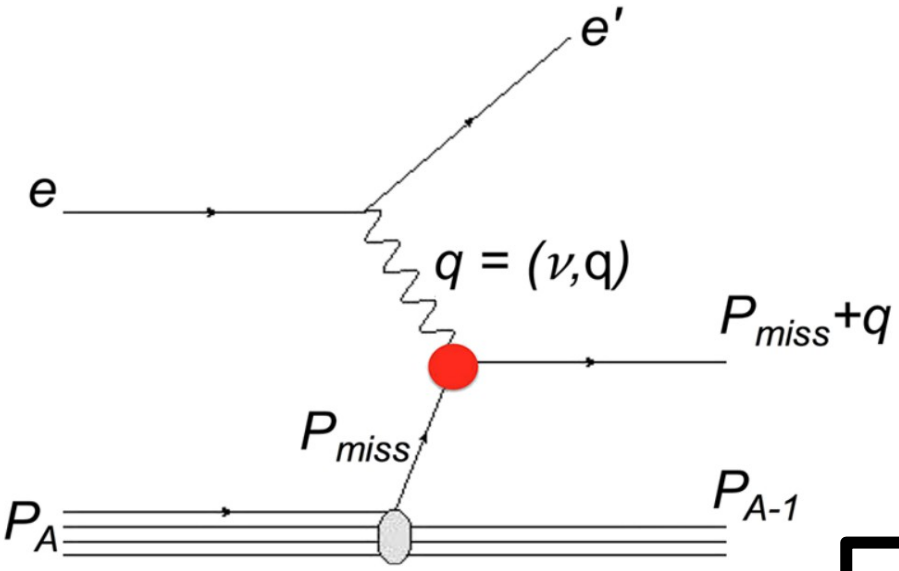
R. Subedi et al., Science 320, 1476 (2008)

Quasi-Elastic (QE) Scattering:

Provides information on how the Nucleons move in the Nucleus



QE Scattering: Impulse Approximation



QE A(e,e'N)X scattering:

$$\frac{d^6\sigma}{d\nu d\Omega_e dE_p d\Omega_p} \propto \sigma_{eN} \times S(P_m, E_m)$$

$S(P_m,E_m)$ is the spectral function – the probability of finding a nucleon with a given momentum and removal energy

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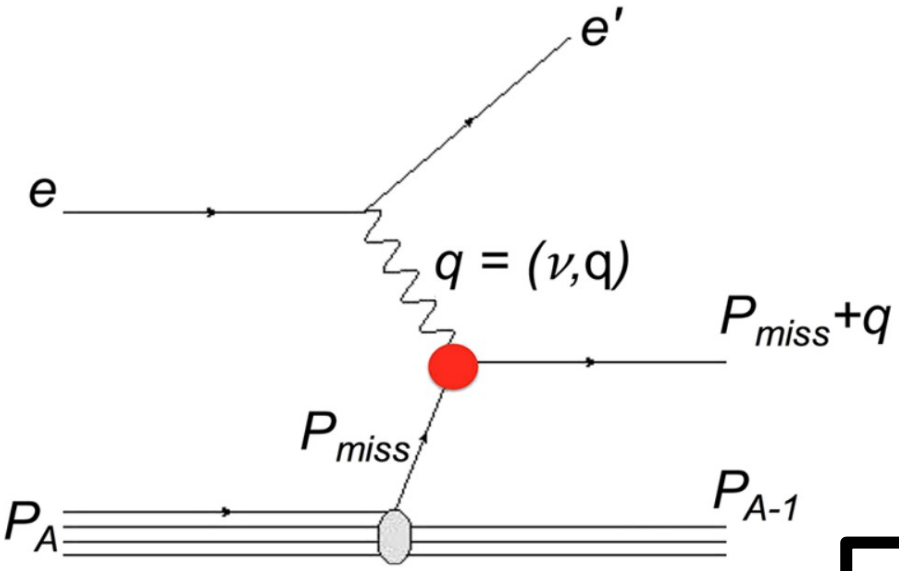

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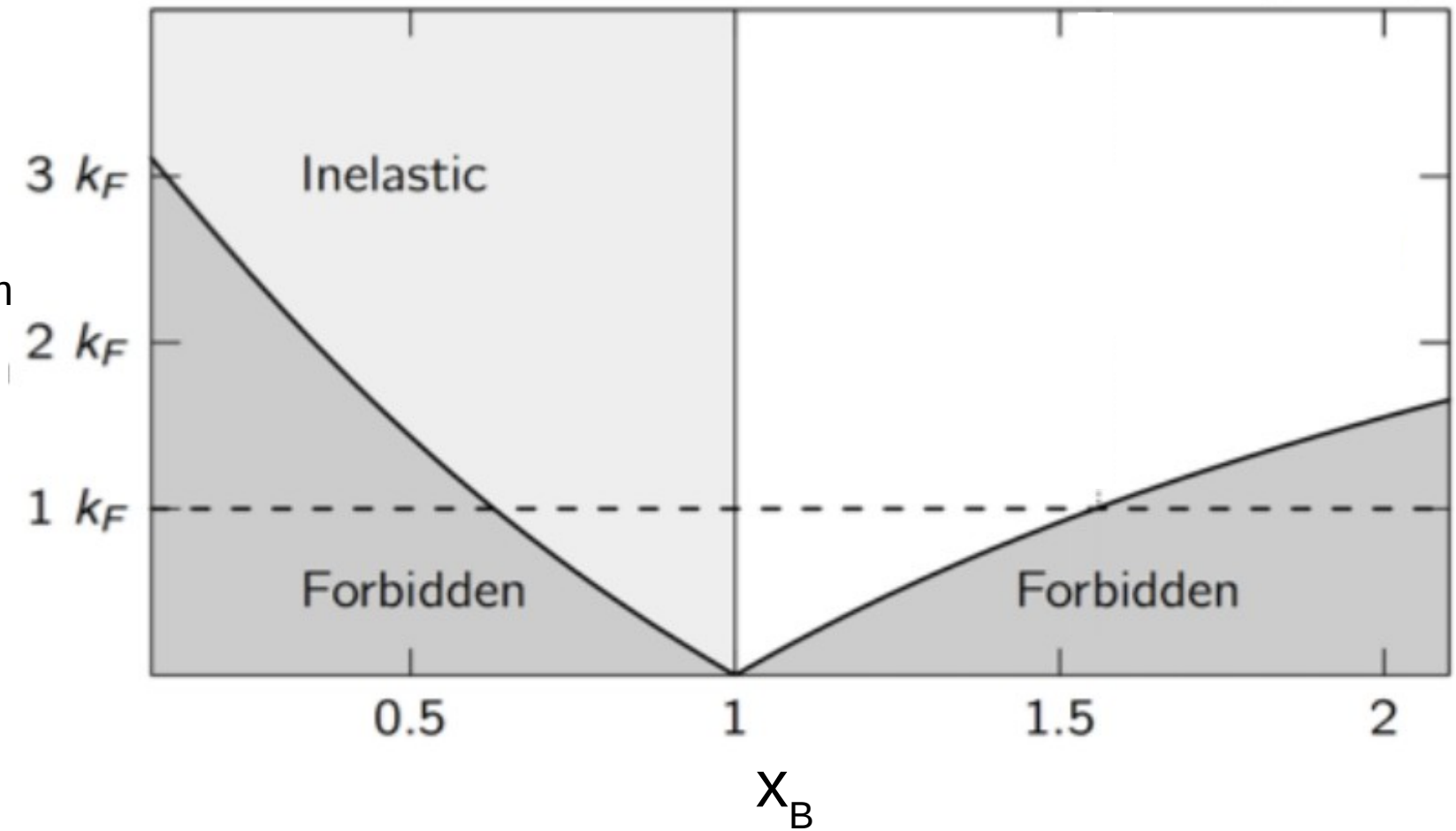
$S(P_m,E_m)$ is the spectral function – the probability of finding a nucleon with a given momentum and removal energy

Inclusive QE scattering is an integral over the above cross-section

What can be done with Inclusive Scattering

Fixed Q^2

Minimum Momentum of Struck Nucleon

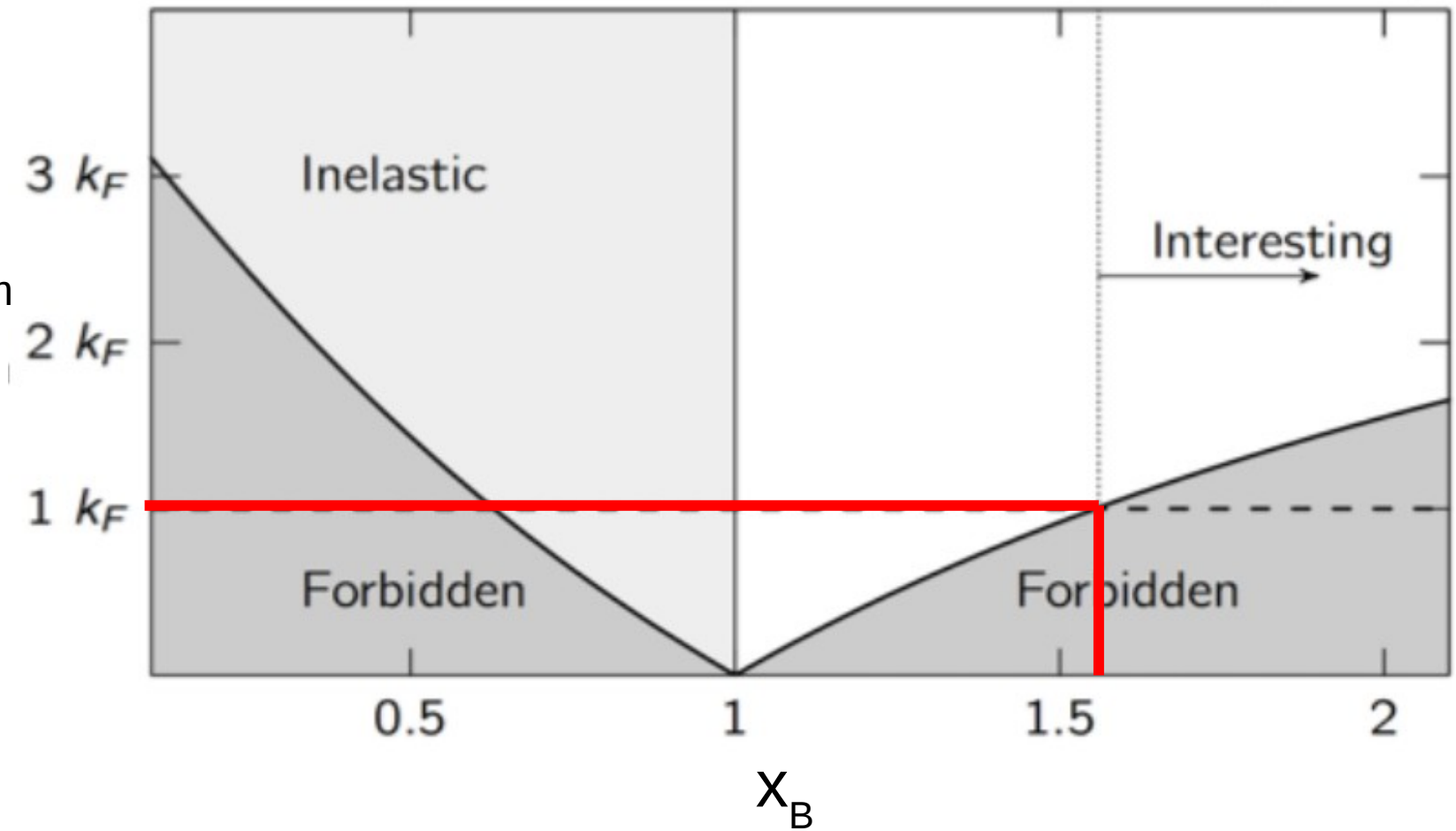


$$(q + p_A - p_{A-1})^2 = p_f^2 = m_N^2$$

What can be done with Inclusive Scattering

Fixed Q^2

Minimum Momentum of Struck Nucleon



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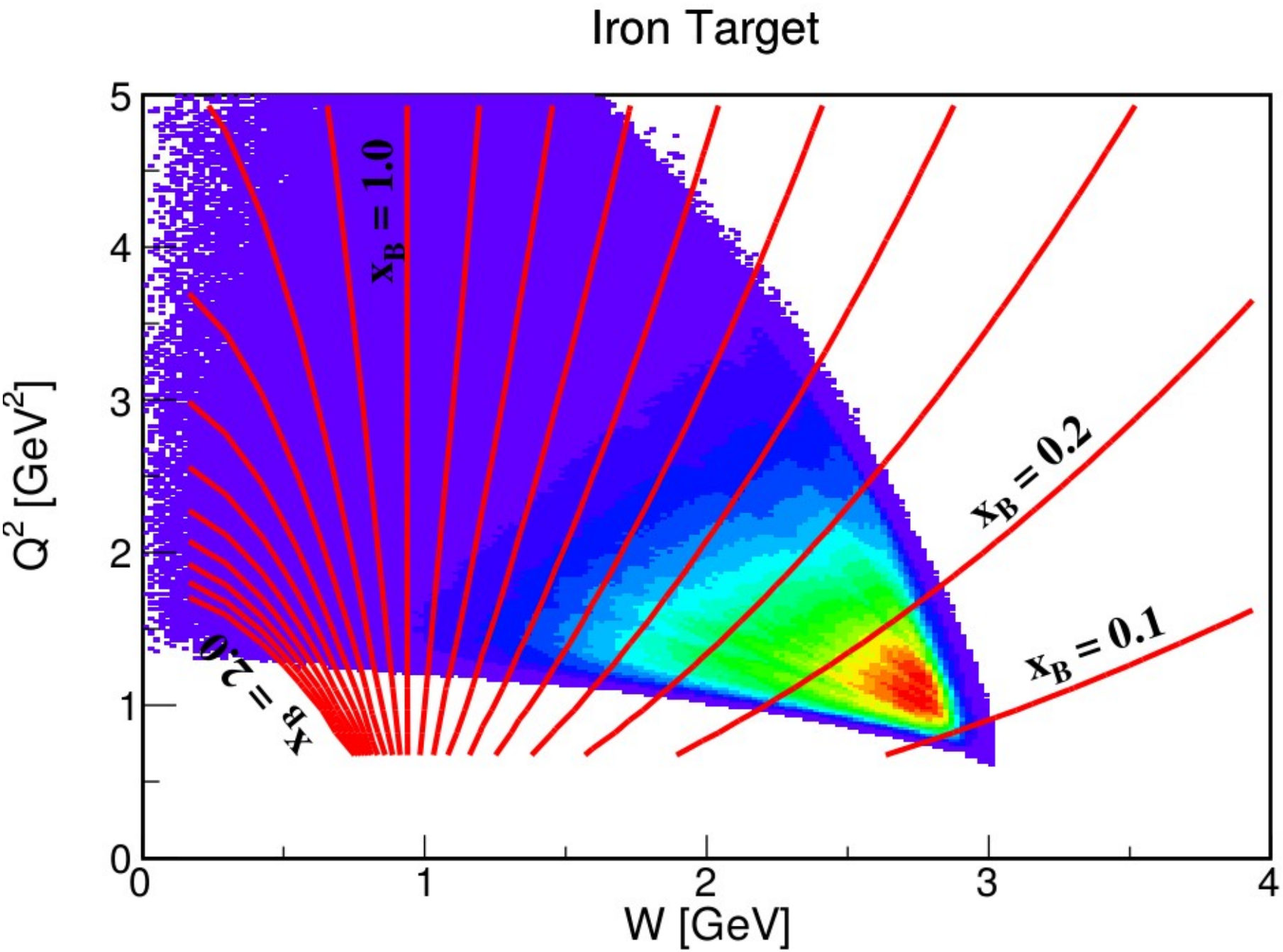
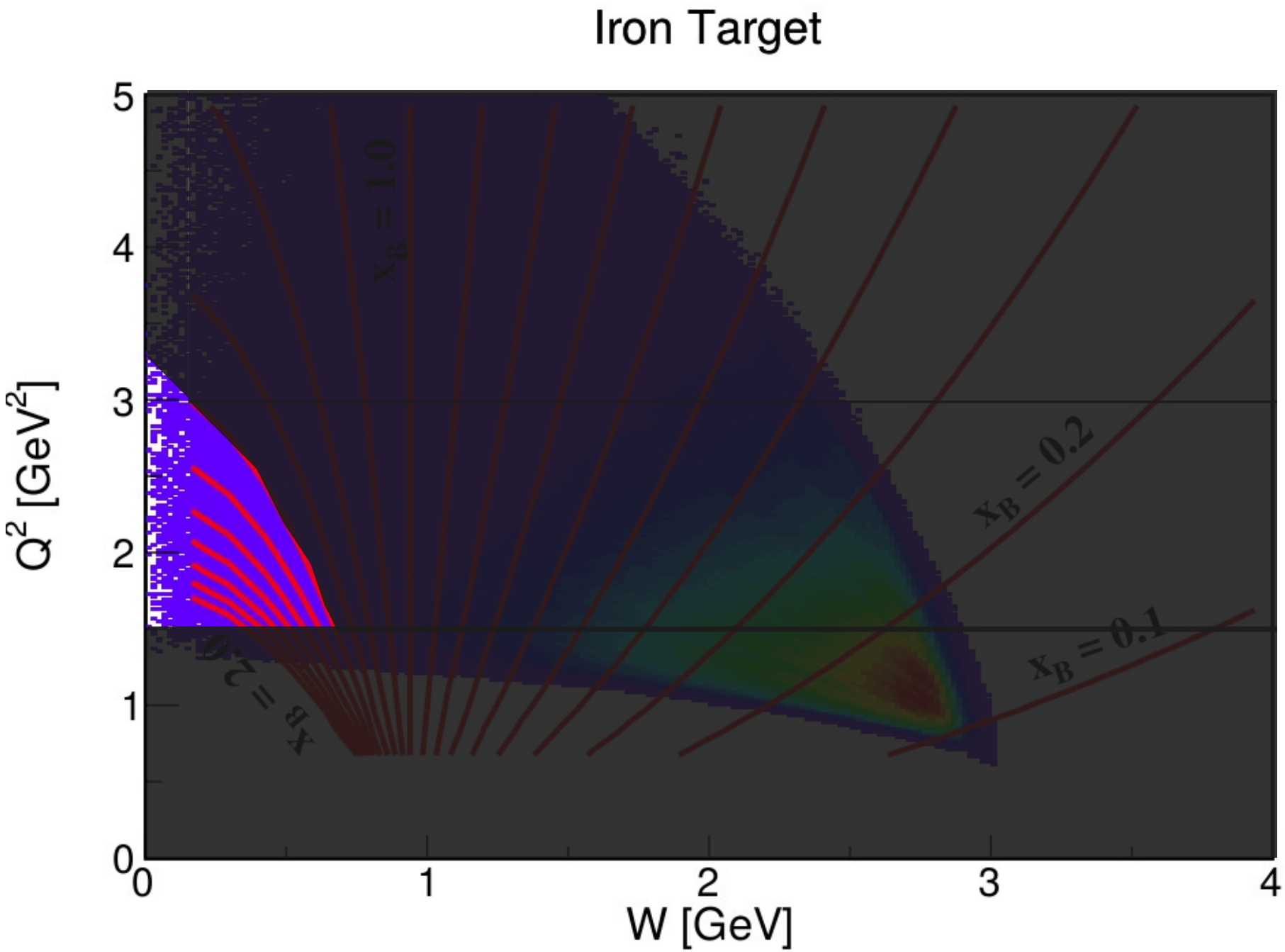

Iron Target
$x_B = 1.0$
$x_B = 0.2$
$x_B = 0.1$
$x_B = 2.0$
Q^2 [GeV^2]
W [GeV]
0
1
2
3
4
5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1
2
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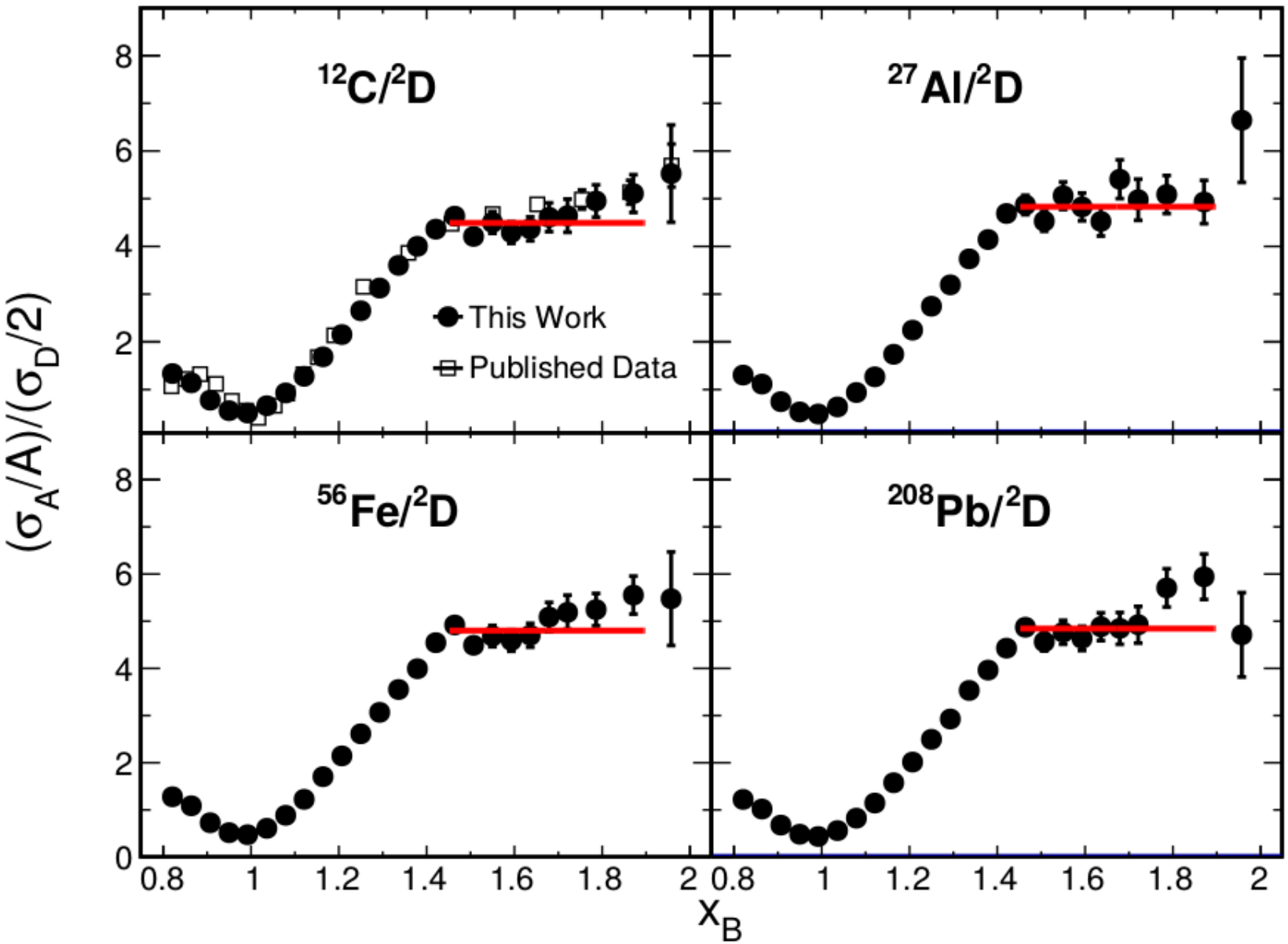
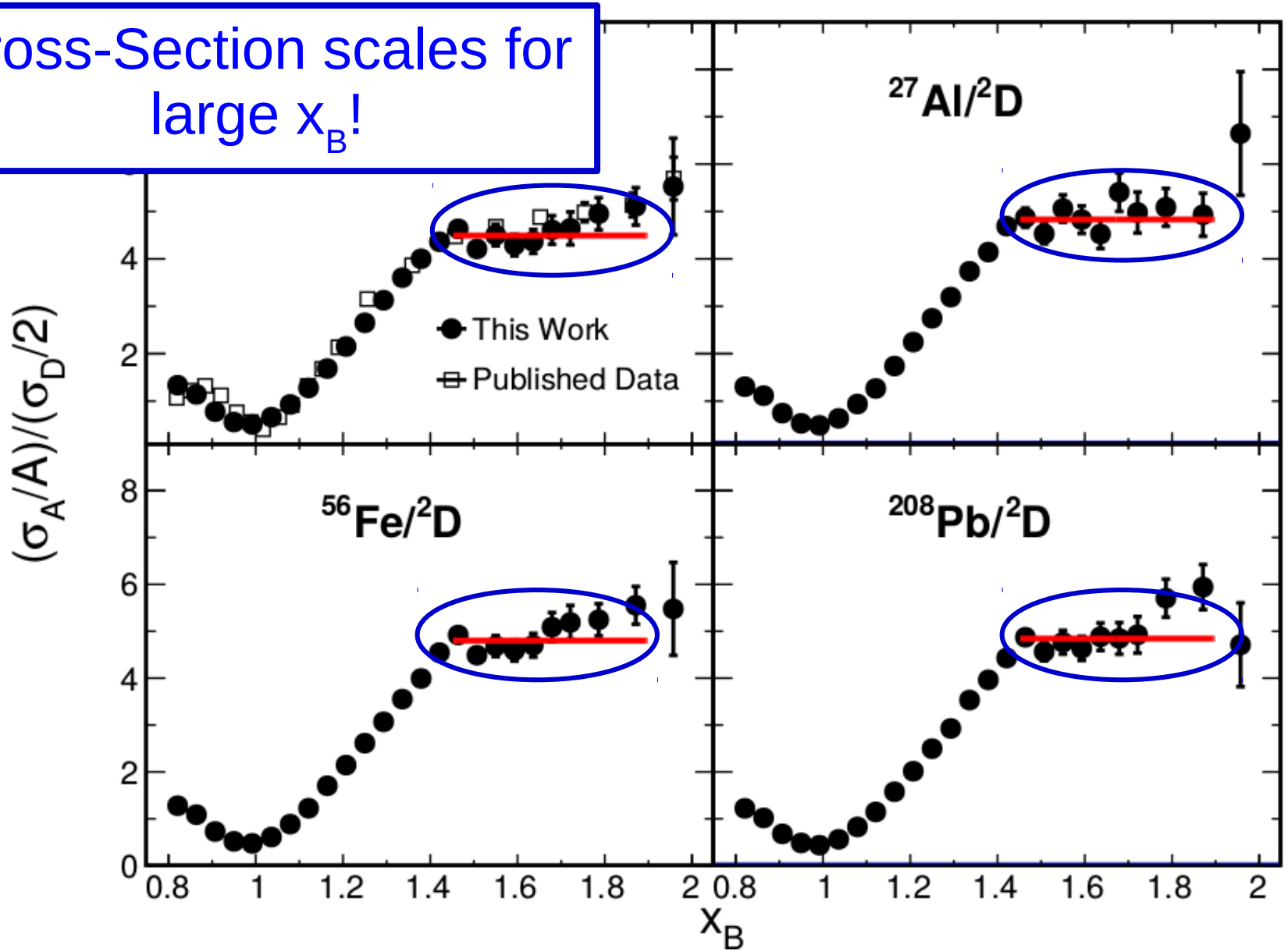
Our New a_2 Measurements



Our New a_2 Measurements

Cross-Section scales for large x_B!



Our New a_2 Measurements

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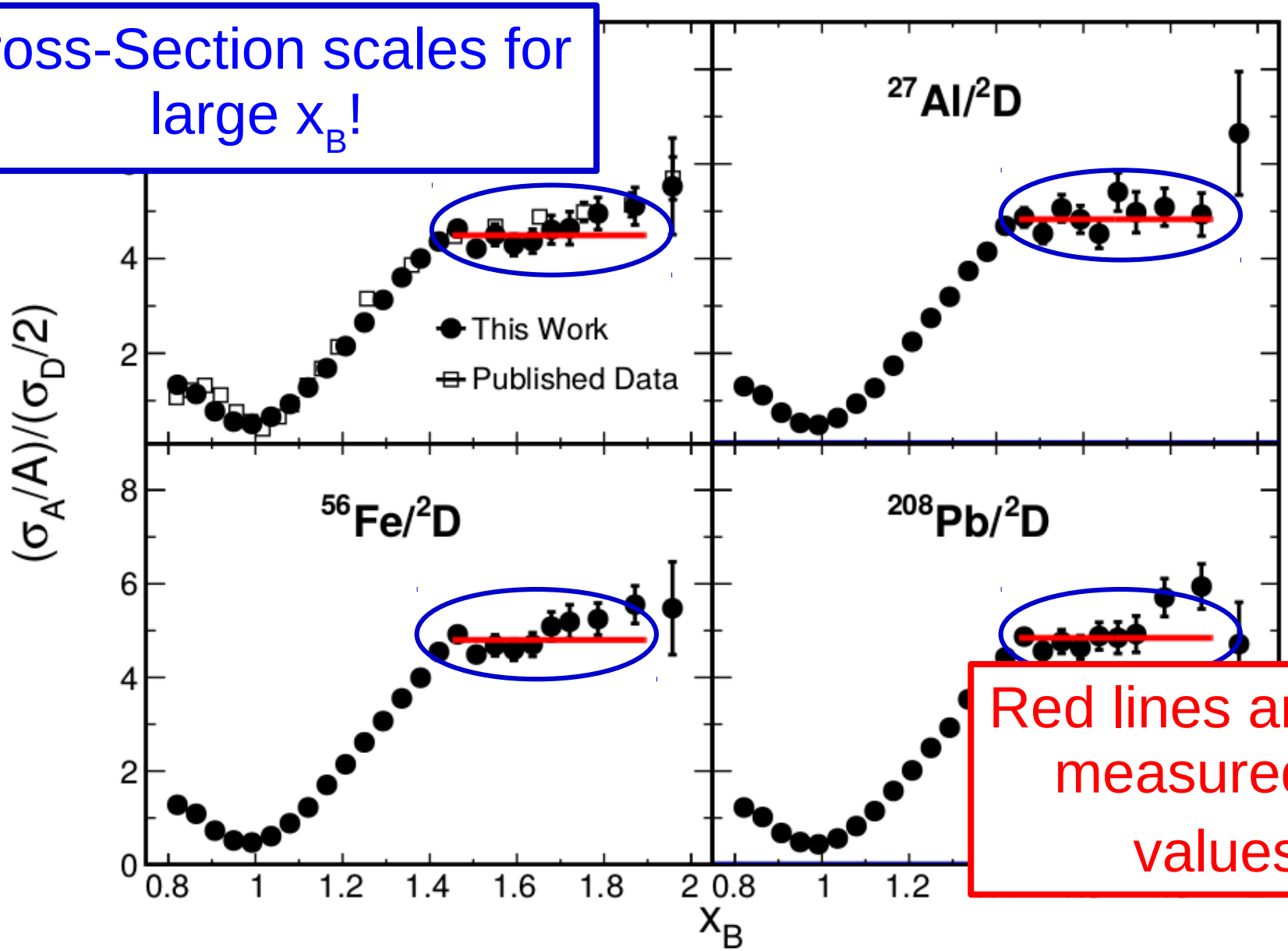
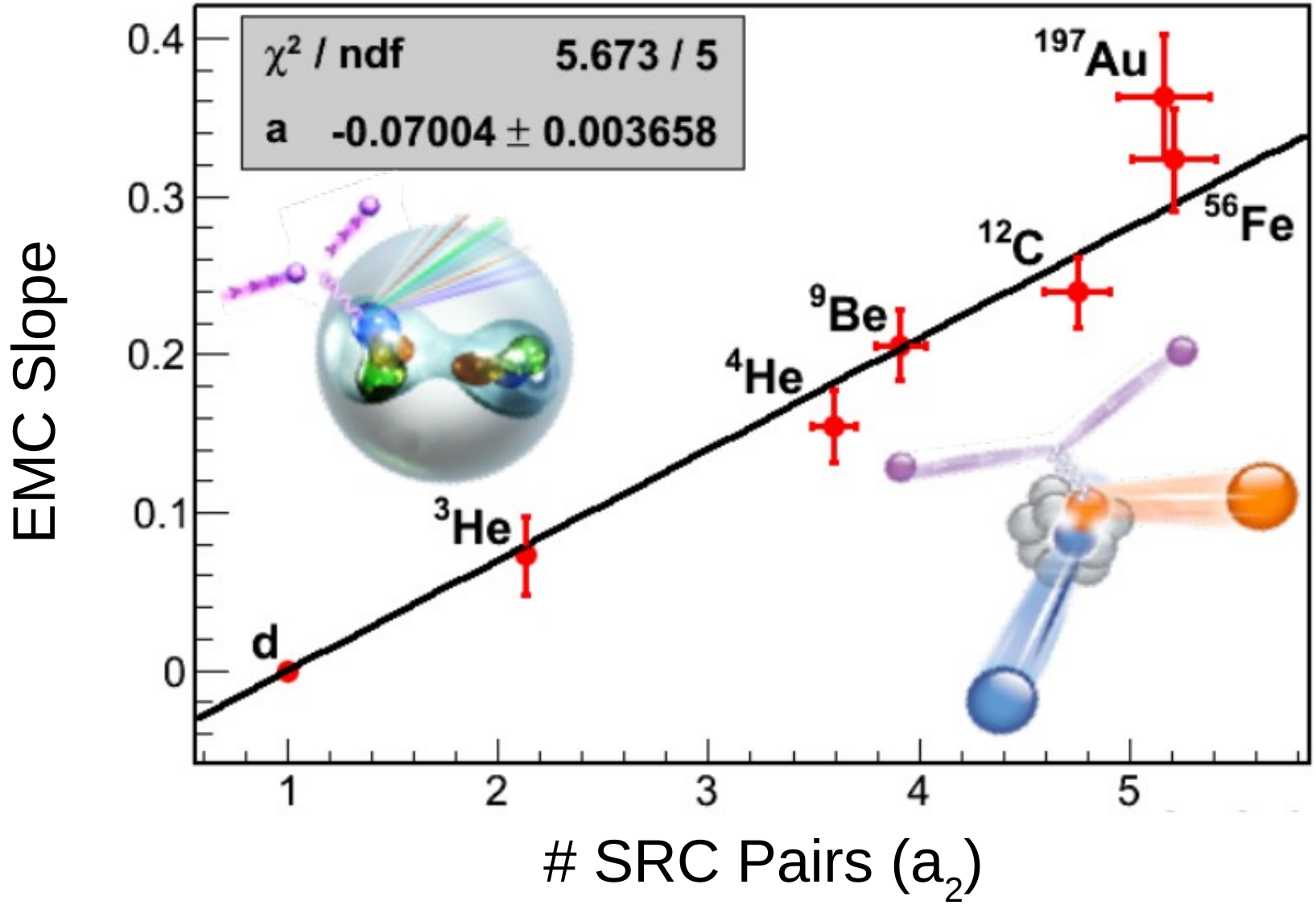


Red lines are the measured a_2 values

Back to the EMC-SRC Correlation



L. Weinstein et. al., Phys. Rev. Lett.06, 052301 (2011).
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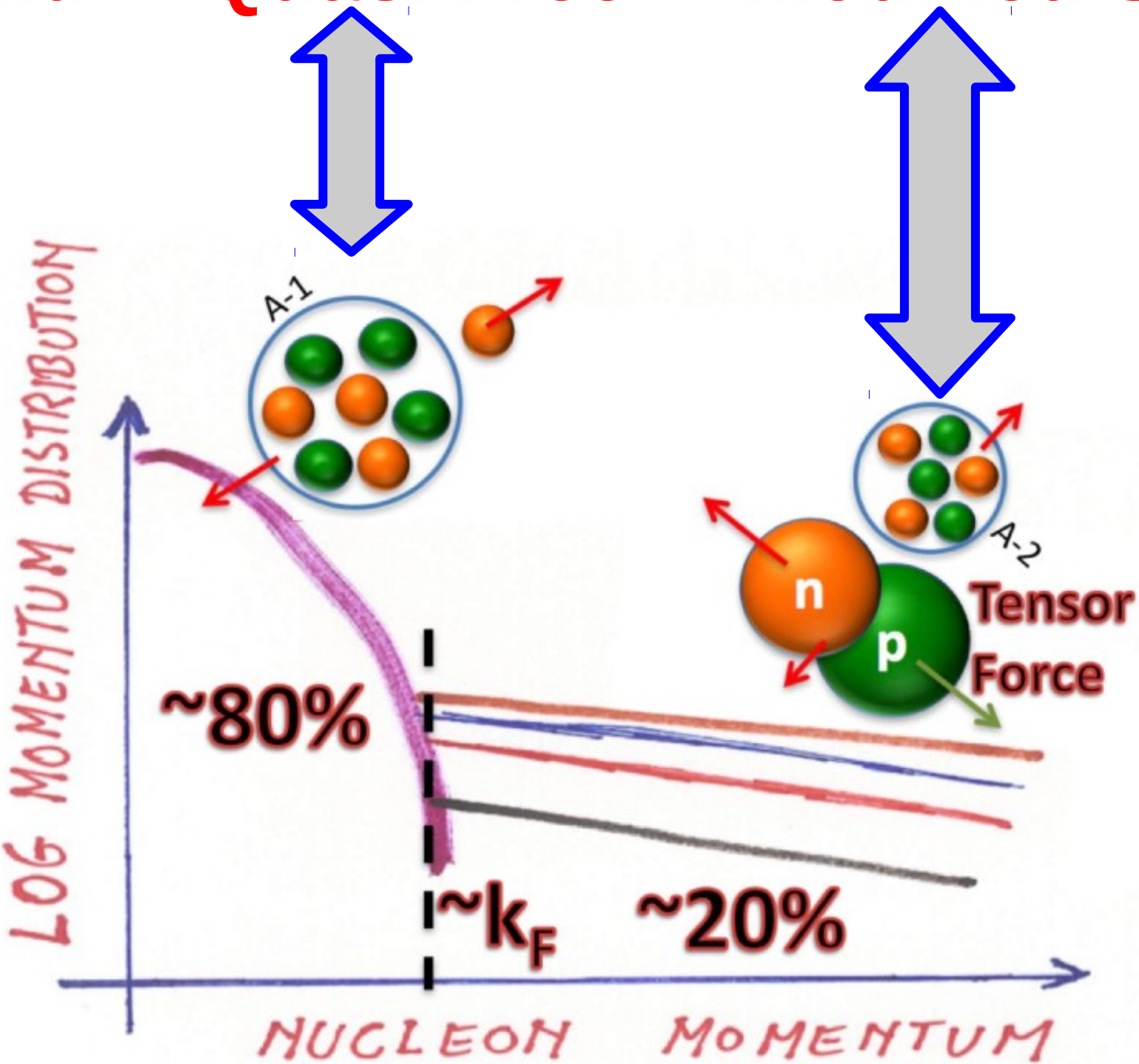
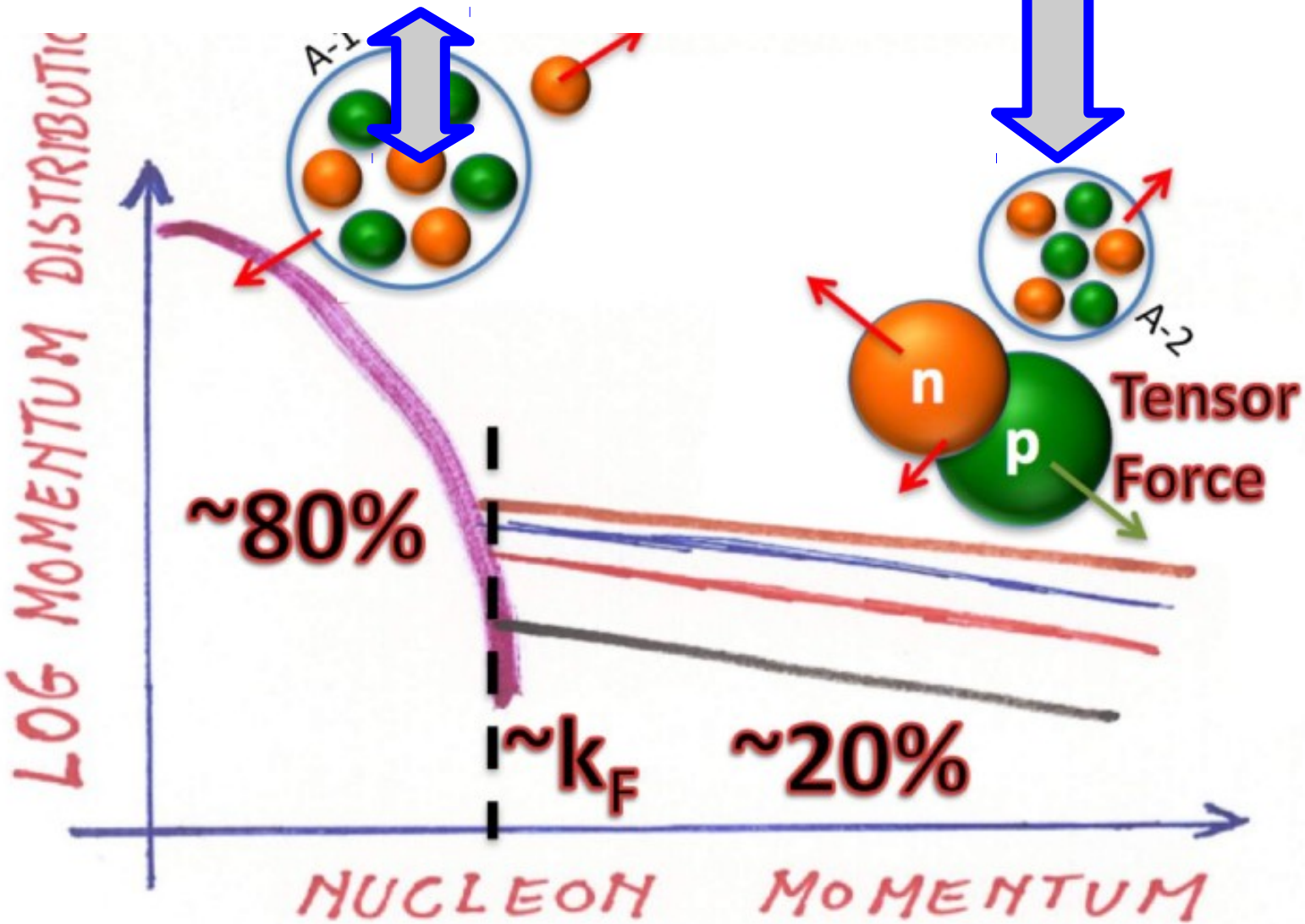
Bound = 'Quasi Free' + Modified SRCs



Bound = 'Quasi Free' + Modified SRCs

$$F_2^A = (Z - n_{SRC}^A)F_2^p + n_{SRC}^A(F_2^{p*} + F_2^{n*}) + (N - n_{SRC}^A)F_2^n$$



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$$= ZF_2^p + NF_2^n + n_{SRC}^A(\Delta F_2^p + \Delta F_2^n)$$

$$\boxed{\Delta F_2^{p(n)} = F_2^{p*(n*)} - F_2^{p(n)}}$$

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$$\boxed{\Delta F_2^{p(n)} = F_2^{p*(n*)} - F_2^{p(n)}}$$

$$F_2^d = F_2^p + F_2^n + n_{SRC}^d(\Delta F_2^p + \Delta F_2^n)$$

Our Model's Prediction for the EMC Effect

$$\frac{F_2^A/A}{F_2^d/2} = (a_2 - 2\frac{N}{A})(n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}) + 2 \cdot \frac{Z-N}{Z+N} \cdot \frac{F_2^p}{F_2^d} + 2\frac{N}{A}$$

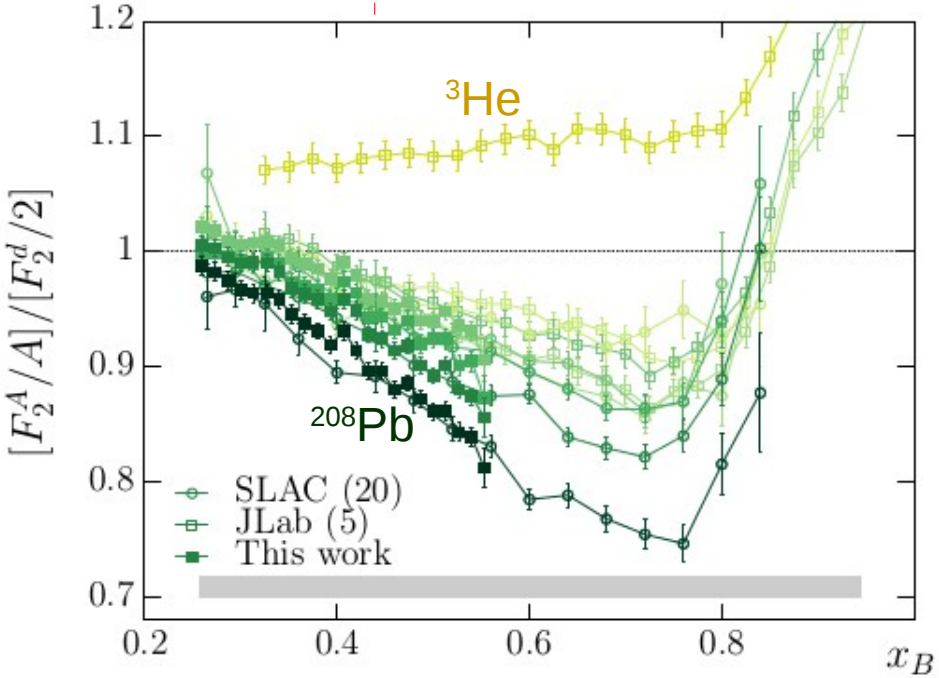
$$\boxed{a_2 \;=\; \frac{n_{SRC}^A/A}{n_{SRC}^d/2}}$$

Our Model's Prediction for the EMC Effect

$$\frac{F_2^A/A}{F_2^d/2} = (a_2 - 2\frac{N}{A})\boxed{(n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d})} + 2 \cdot \frac{Z-N}{Z+N} \cdot \frac{F_2^p}{F_2^d} + 2\frac{N}{A}$$

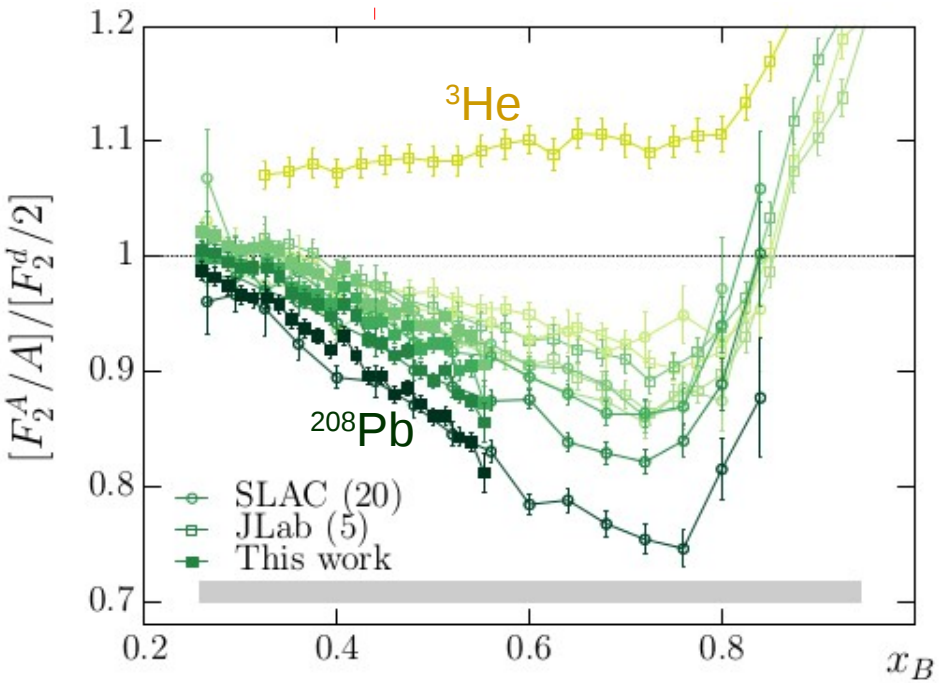
Universal?

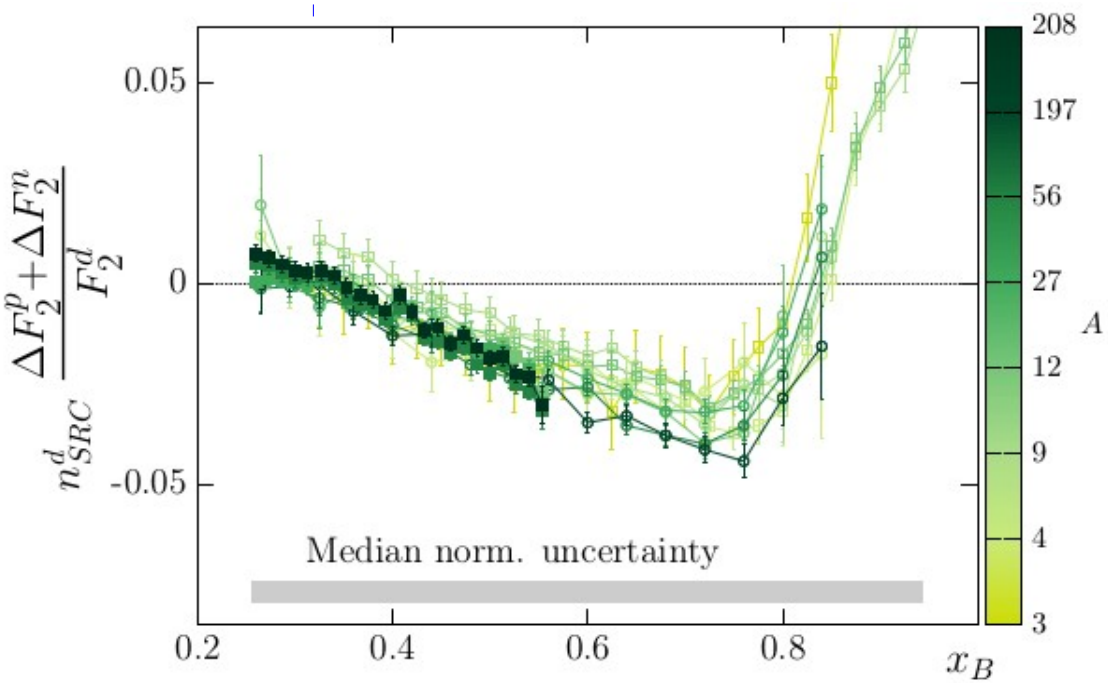
$$\frac{F_2^A/A}{F_2^d/2} = (a_2 - 2\frac{N}{A})(n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}) + 2 \cdot \frac{Z-N}{Z+N} \cdot \frac{F_2^p}{F_2^d} + 2\frac{N}{A}$$



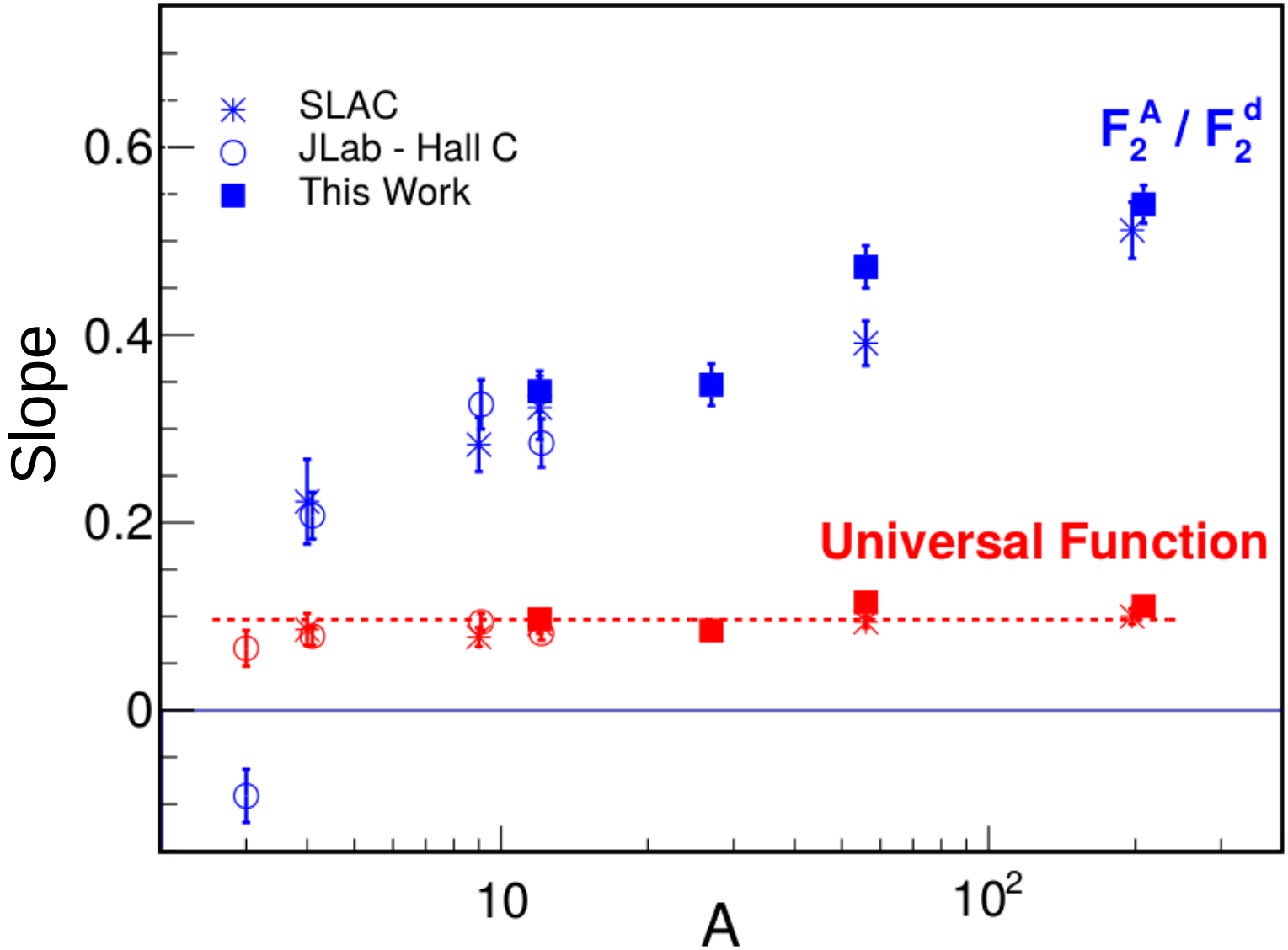
$$\frac{F_2^A/A}{F_2^d/2} = (a_2 - 2\frac{N}{A}) \boxed{(n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d})} + 2 \cdot \frac{Z-N}{Z+N} \cdot \frac{F_2^p}{F_2^d} + 2\frac{N}{A}$$

Universal!!

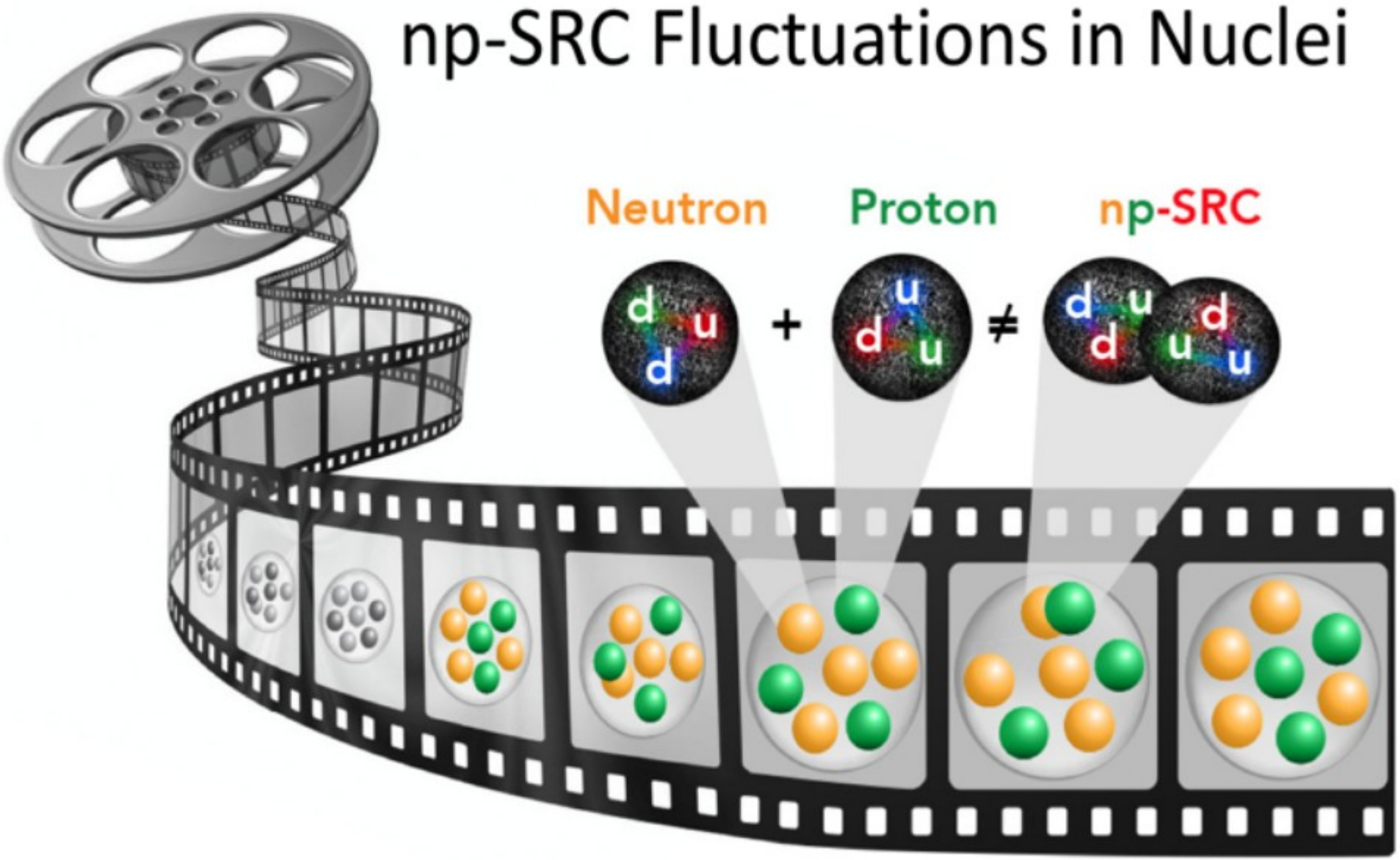




EMC Universal Modification Function



np-SRC Fluctuations in Nuclei



Additional Slides

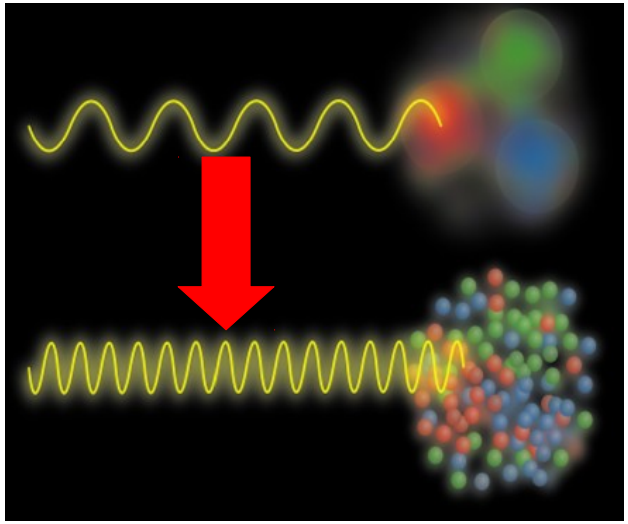
Inelastic Electron-Proton Inclusive Scattering

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{Q^4}\left[2\frac{F_1(x_B, Q^2)}{M}\sin^2\frac{\theta_e}{2} + \frac{F_2(x_B, Q^2)}{\nu}\cos^2\frac{\theta_e}{2}\right]$$

Inelastic Electron-Proton Inclusive Scattering

Structure Functions

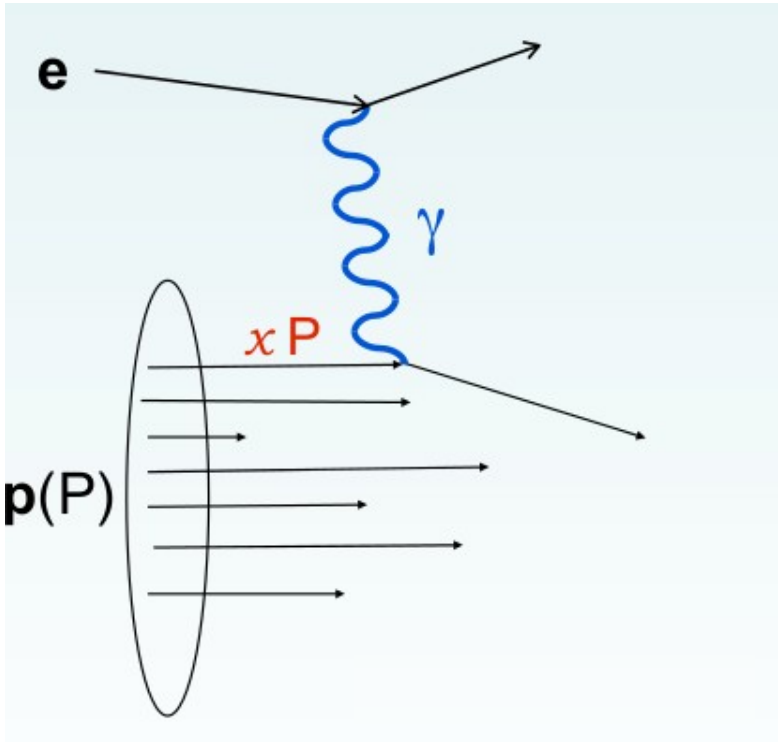
$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{Q^4}\left[2\frac{\boxed{F_1(x_B, Q^2)}}{M}\sin^2\frac{\theta_e}{2} + \frac{\boxed{F_2(x_B, Q^2)}}{\nu}\cos^2\frac{\theta_e}{2}\right]$$



$$F_1(x_B, Q^2) \longrightarrow F_1(x_B)$$

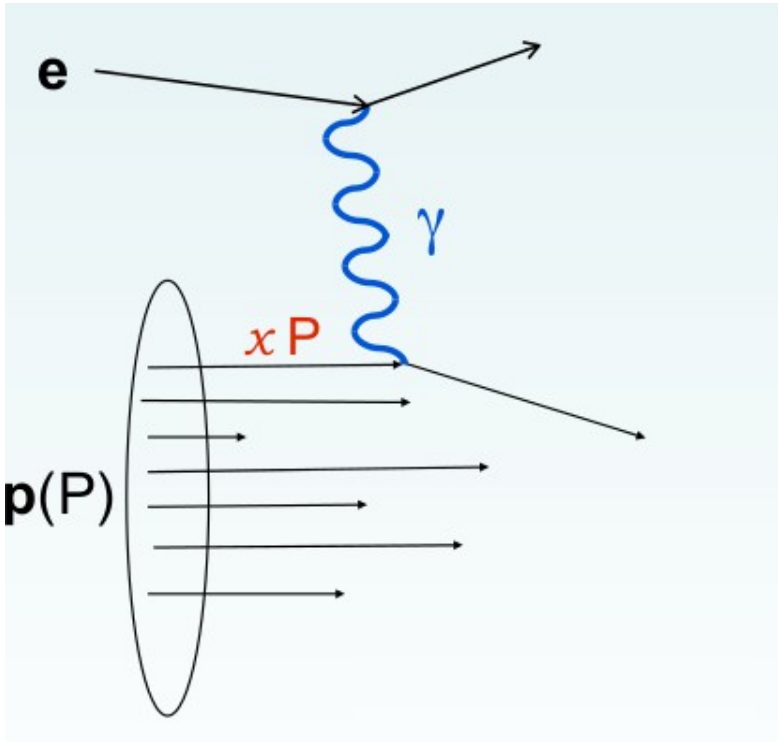
$$F_2(x_B, Q^2) \longrightarrow F_2(x_B)$$

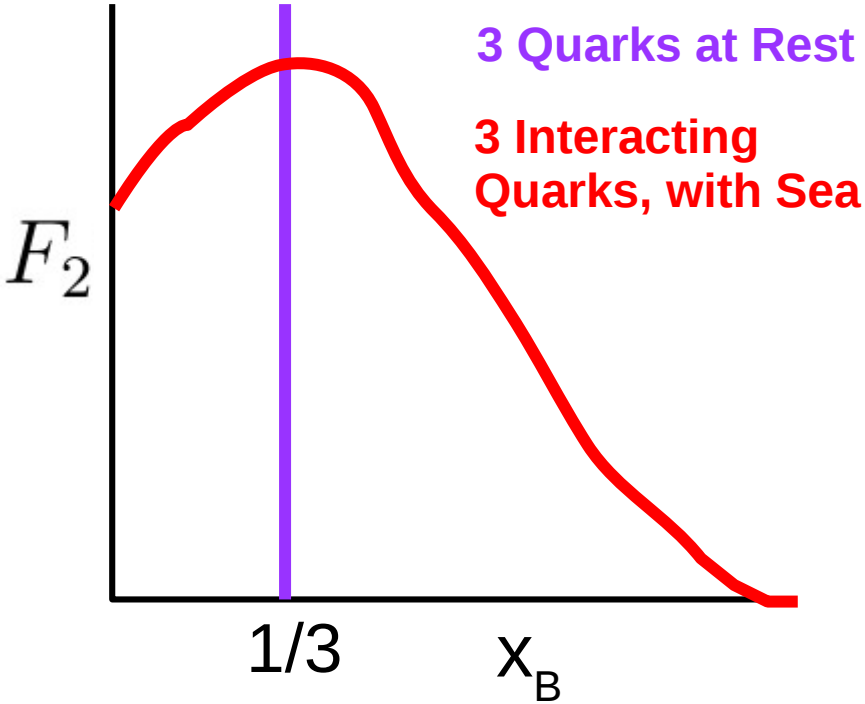
Structure functions in DIS



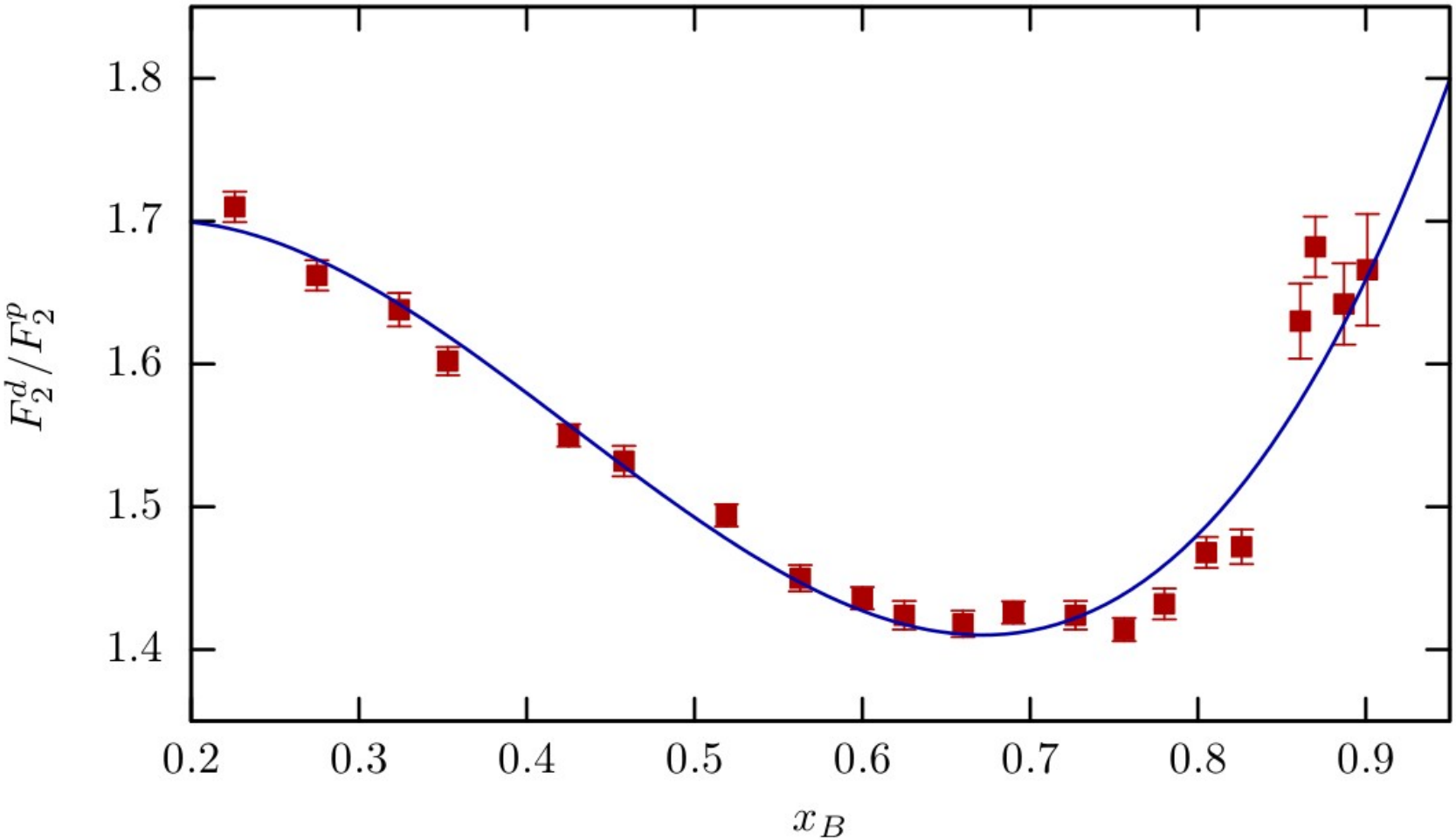
Structure functions in DIS

$$F_2(x_B) = 2x_B F_1(x_B) = \sum_i e_i^2 \, x_B \, [q_i(x_B) + \bar{q}_i(x_B)]$$





Compare DIS on Deuterium



J. Arrington, et. al. J. phys. G36, 025005 (2009)

We want to Extract Cross-Section Ratios to Deuterium

- Bin data in x_B

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- Apply the following corrections:

We want to Extract Cross-Section Ratios to Deuterium

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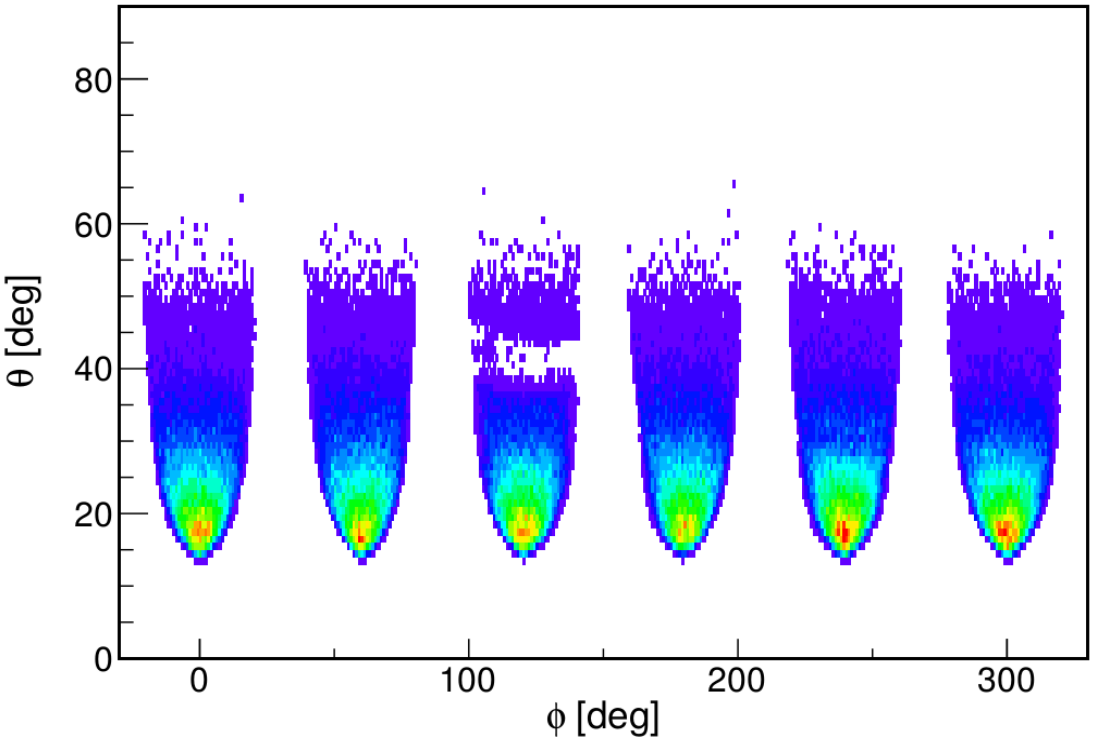
  - ✓ Luminosity Corrections

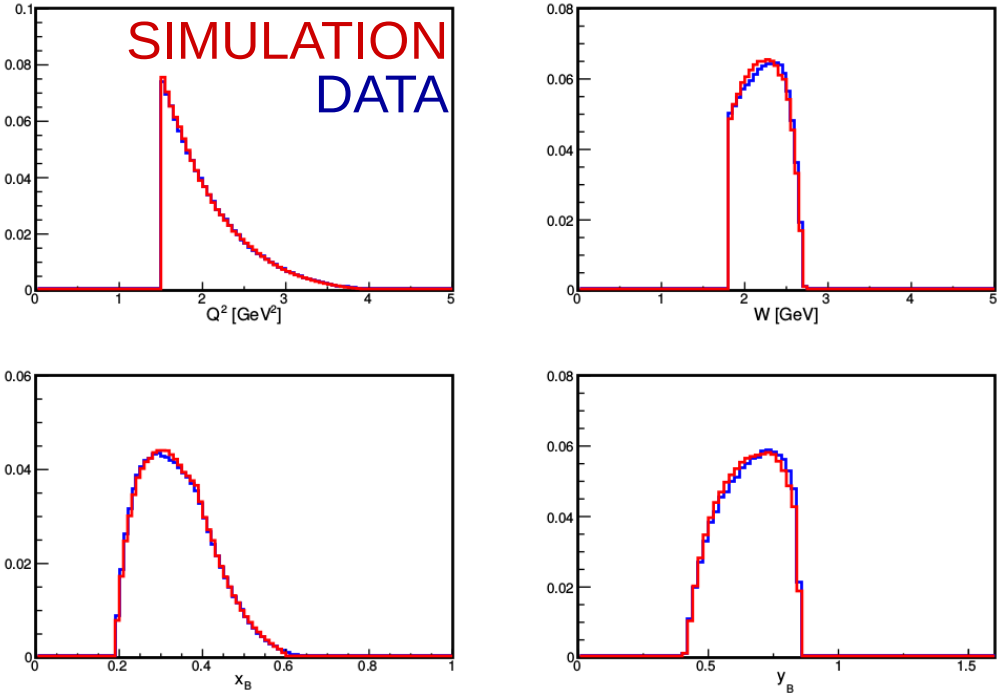
We want to Extract Cross-Section Ratios to Deuterium

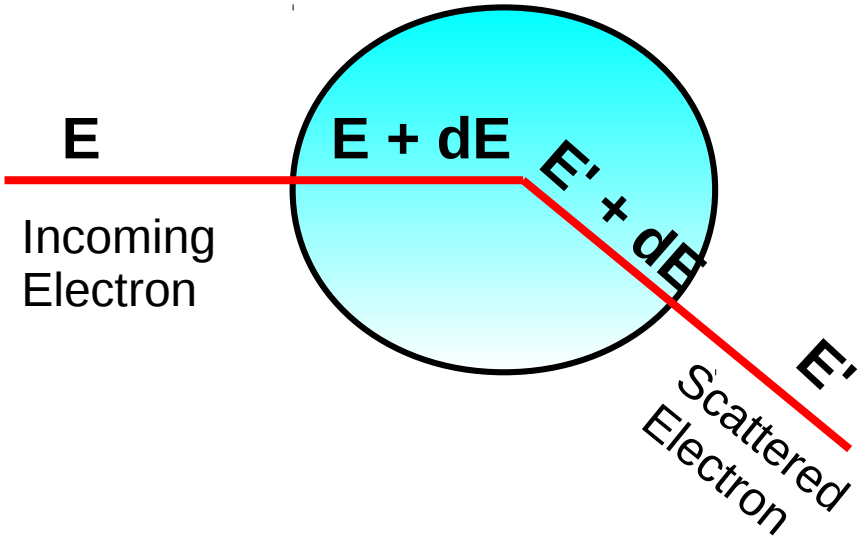
- Bin data in x_B
- Apply the following corrections:
  - ✓ Luminosity Corrections
  - ✓ Acceptance Corrections



We want to Extract Cross-Section Ratios to Deuterium

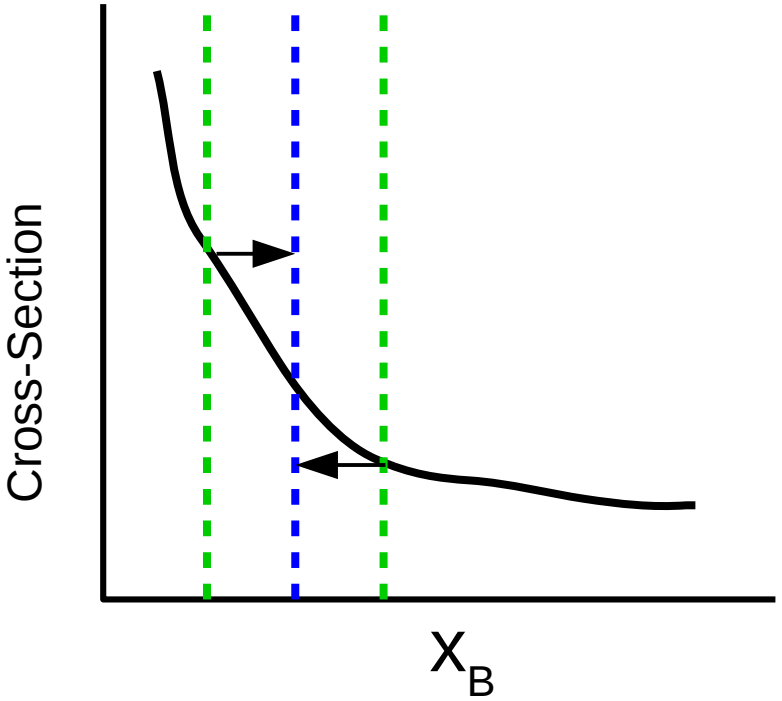
- Bin data in x_B
- Apply the following corrections:
  - ✔ Luminosity Corrections
  - ✔ Acceptance Corrections
  - ✔ Radiative and Coulomb Corrections



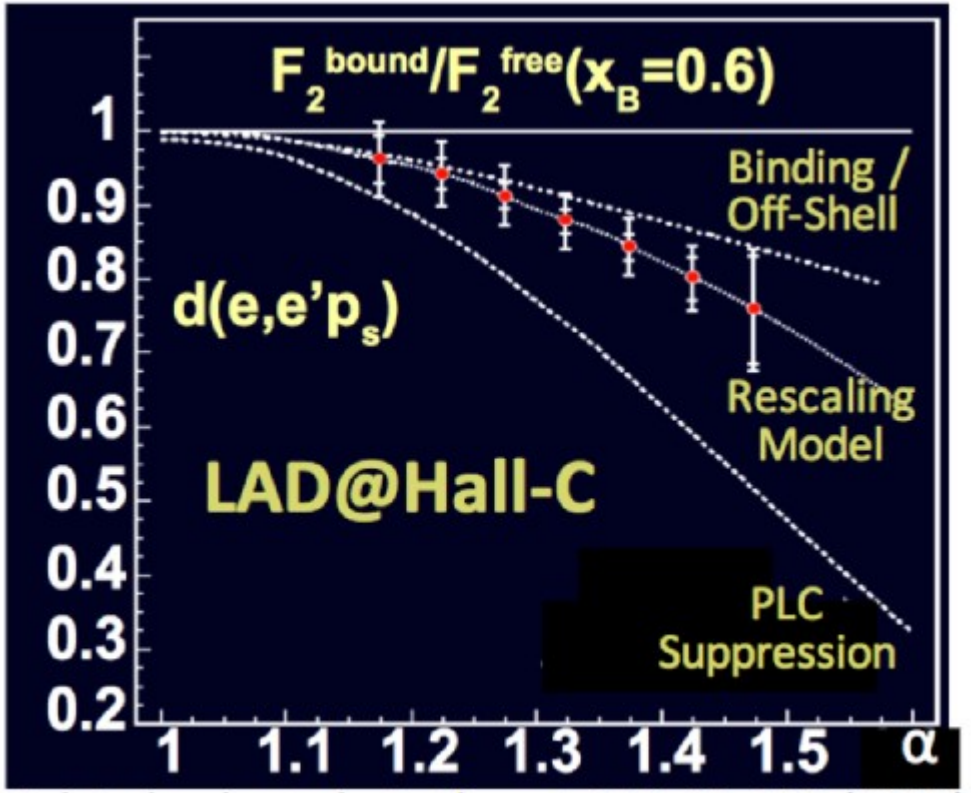


We want to Extract Cross-Section Ratios to Deuterium

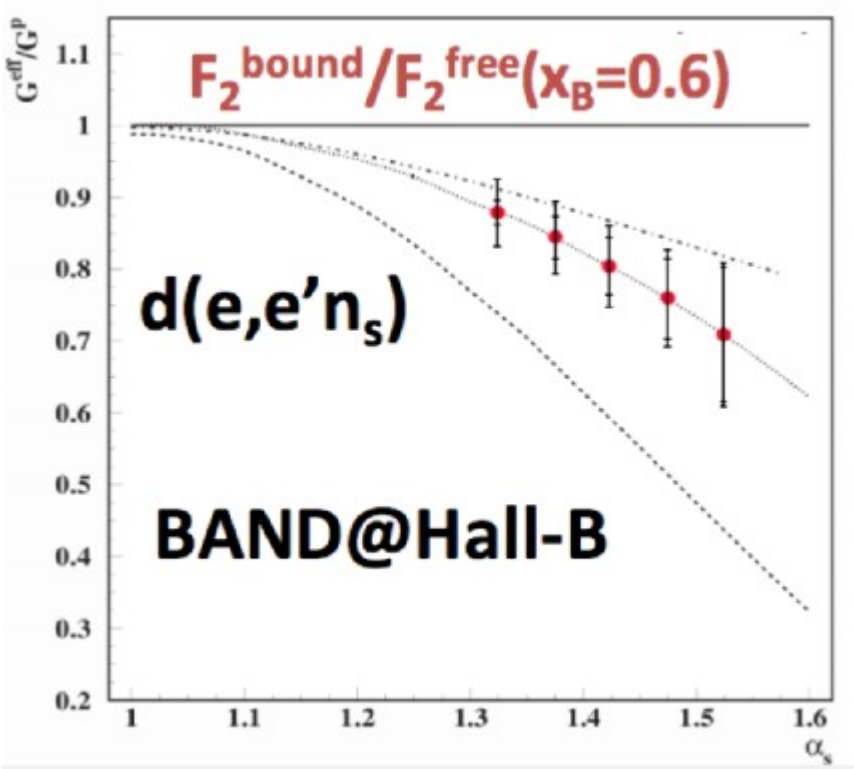
- Bin data in x_B
- Apply the following corrections:
  - ✓ Luminosity Corrections
  - ✓ Acceptance Corrections
  - ✓ Radiative and Coulomb Corrections
  - ✓ Bin-Centering Corrections



EMC Effect: Spectator Tagging



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

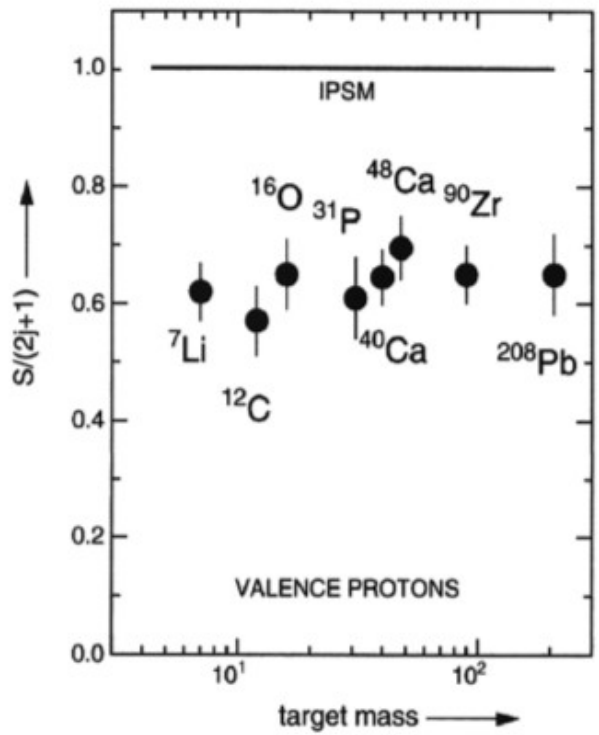


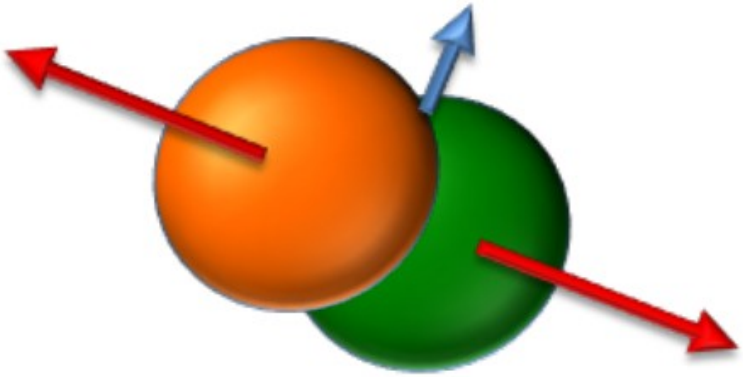
- Tagged measurements beyond the Deuteron?
- Signature of Correlations at a collider?

Short Range Correlations (SRC)

Nucleon pairs that are close together in the nucleus

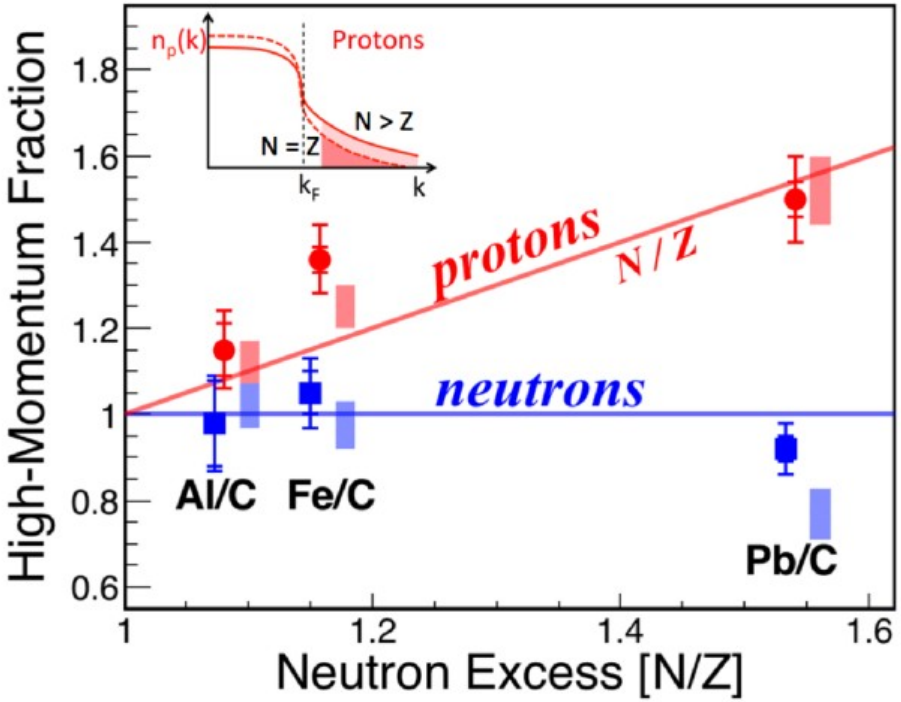
<u>Momentum space:</u> *high relative* and *low c.m. momentum,* compared to the Fermi momentum (k_F)





L. Lapikas, Nucl. Phys. A 553, 297 (1993)

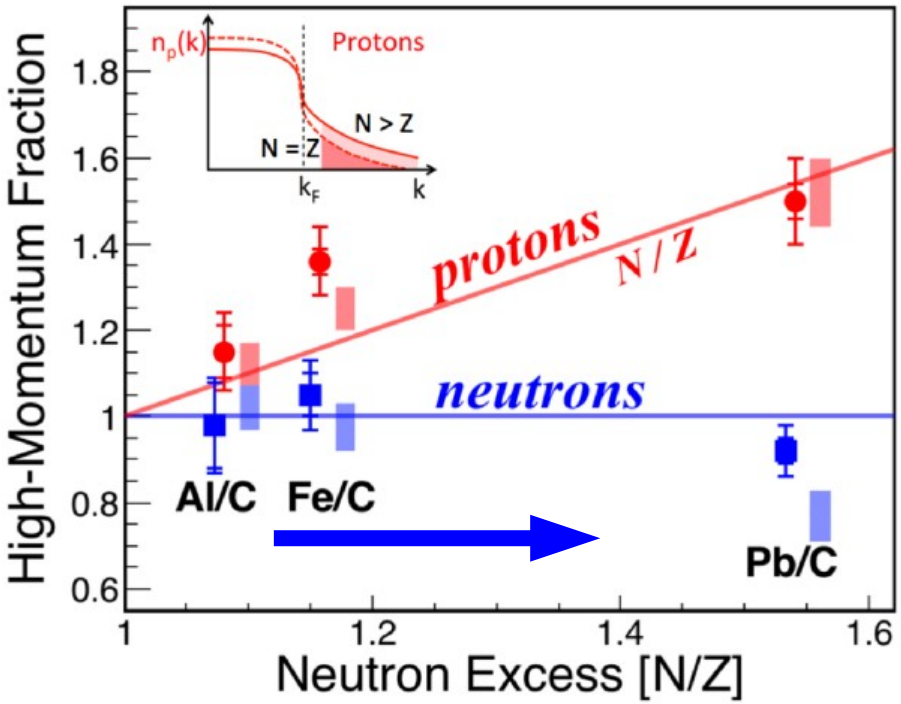
Focus on Neutron-Rich Nuclei



M. Duer et al. (CLAS Collaboration), Nature, In-Print (2018)

Focus on Neutron-Rich Nuclei

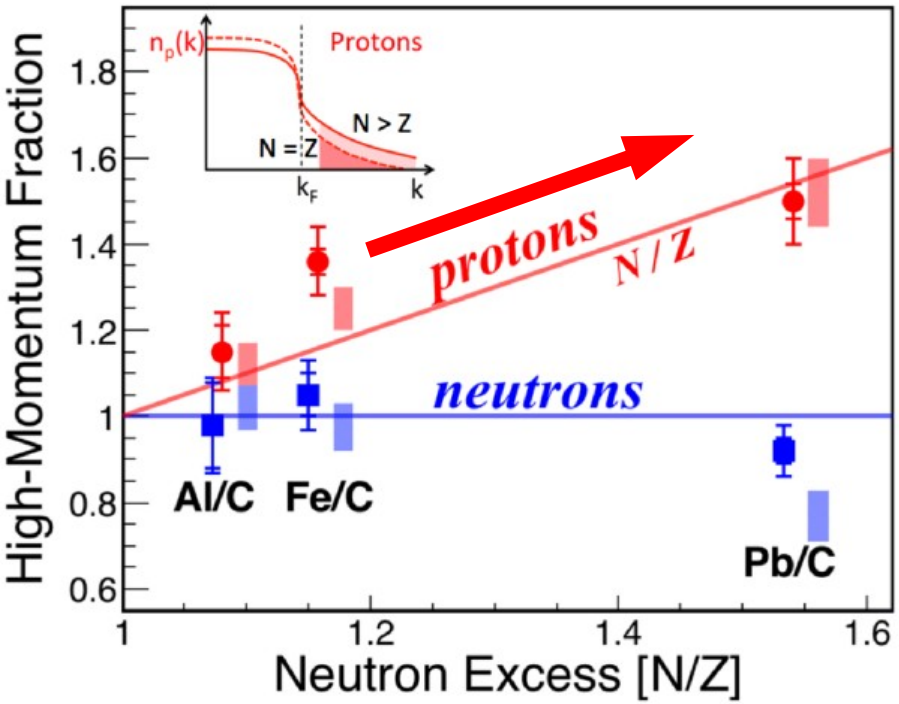
Prediction: EMC effect will show no growth for neutrons ...



M. Duer et al. (CLAS Collaboration), Nature, In-Print (2018)

Focus on Neutron-Rich Nuclei

Prediction: EMC effect will show no growth for neutrons and grow for protons



M. Duer et al. (CLAS Collaboration), Nature, In-Print (2018)

Calculate Per-Neutron (Per-Proton) Ratios

Per-Neutron: $$\frac{\sigma_A/N}{\sigma_D/1}$$

Per-Proton: $$\frac{\sigma_A/Z}{\sigma_D/1}$$

Calculate Per-Neutron (Per-Proton) Ratios

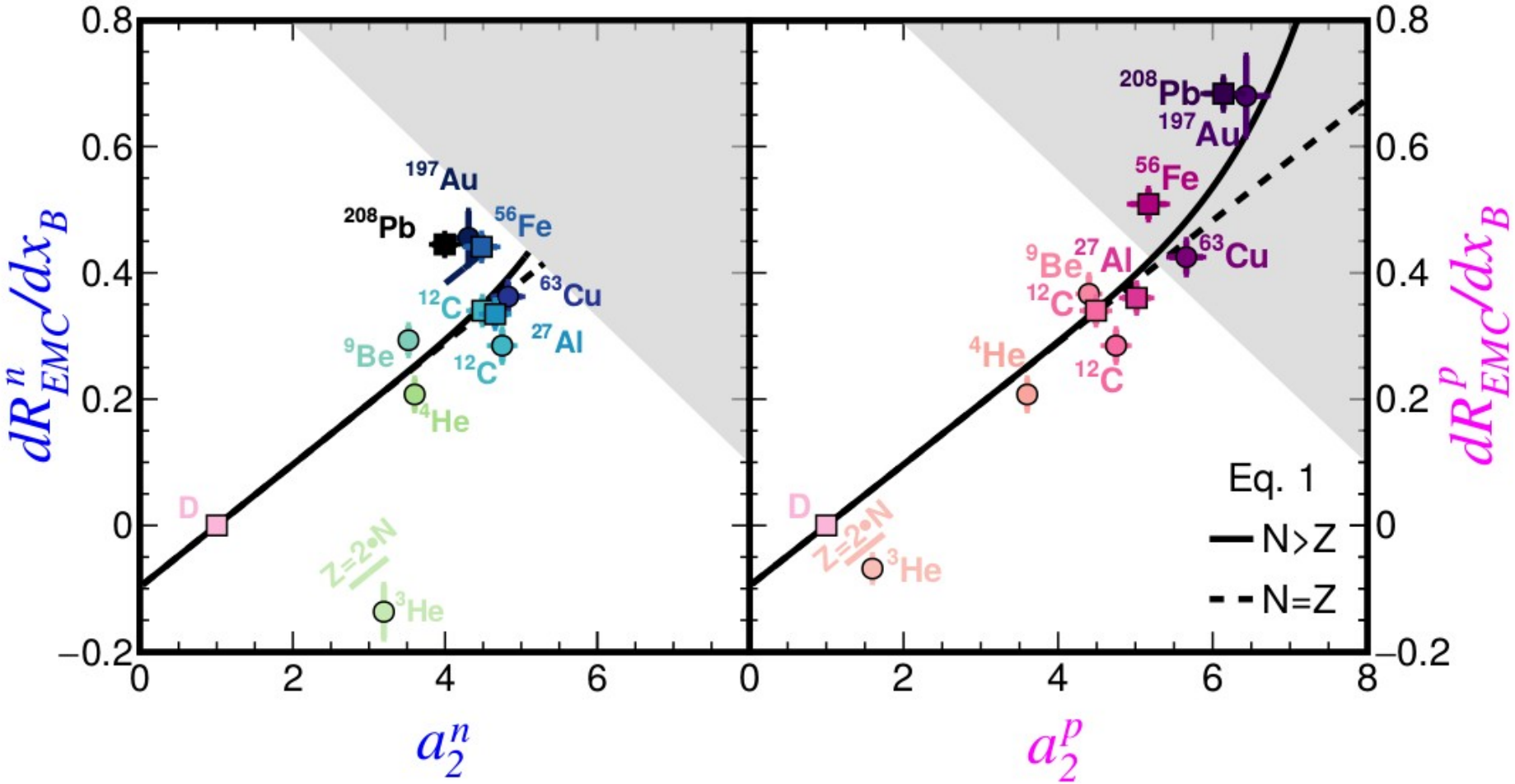
Per-Neutron: $\frac{\sigma_A/N}{\sigma_D/1}$

$$\frac{F_2^A/N}{F_2^d/1} = (a_2^n - 1)(n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}) + (\frac{Z}{N} - 1) \cdot \frac{F_2^p}{F_2^d} + 1$$

Per-Proton: $\frac{\sigma_A/Z}{\sigma_D/1}$

$$\frac{F_2^A/Z}{F_2^d/1} = (a_2^p - \frac{N}{Z})(n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}) + (\frac{Z}{N} - 1) \cdot \frac{F_2^p}{F_2^d} + \frac{N}{Z}$$

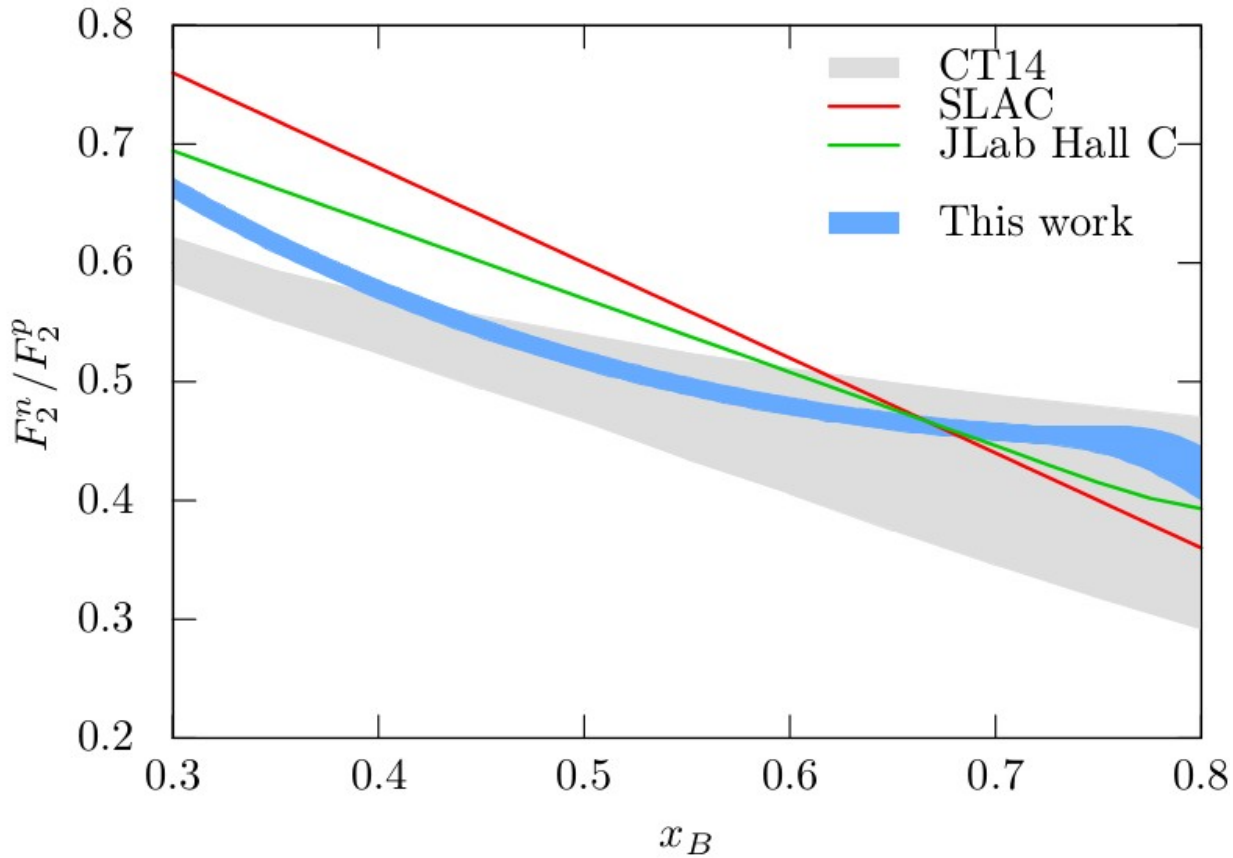
New EMC-SRC Correlation



Isoscalar Corrections for DIS Ratios

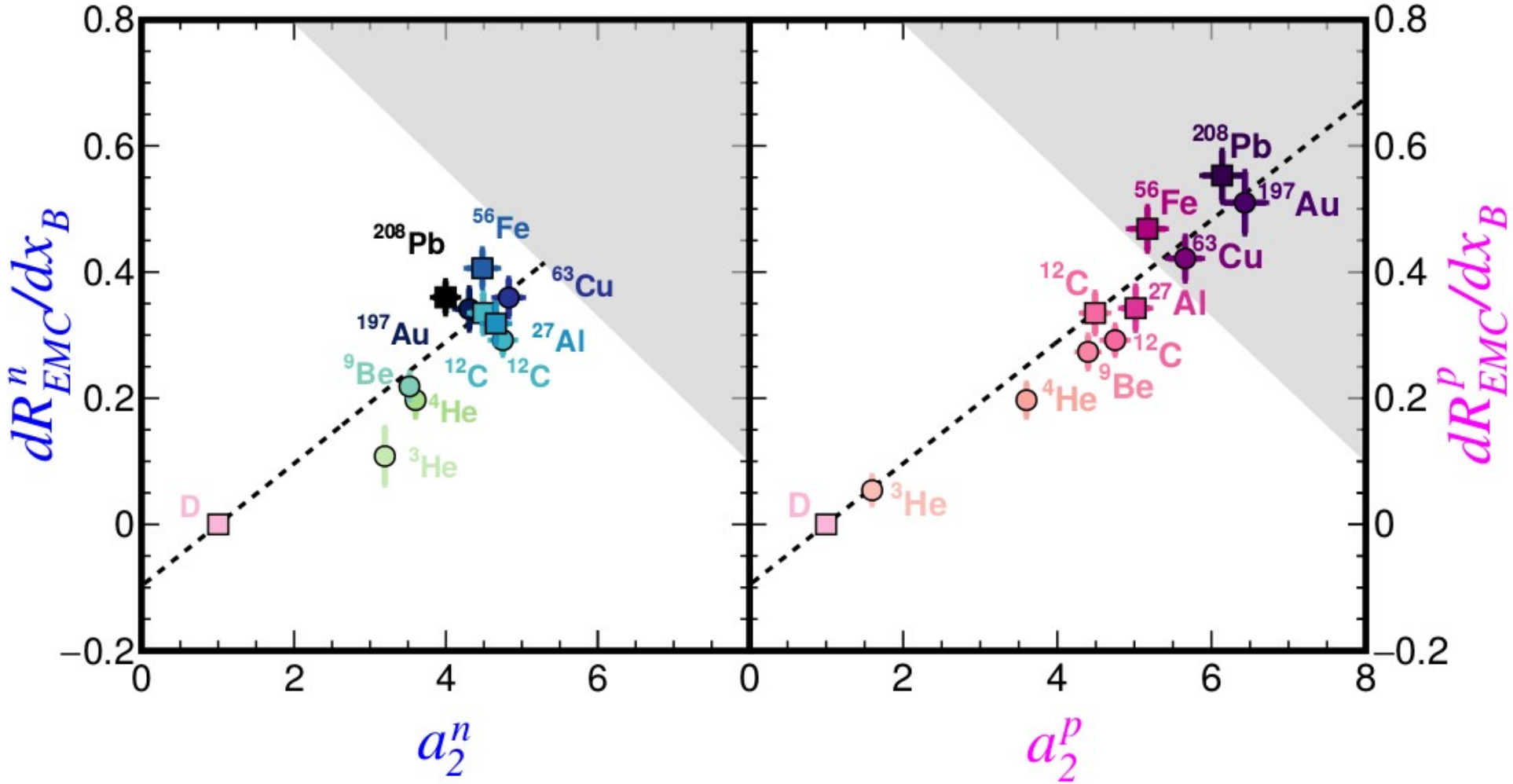
Correction Factor:

$$\frac{\frac{A}{2}\cdot\left(1+\frac{F_2^n}{F_2^p}\right)}{Z+N\cdot\frac{F_2^n}{F_2^p}}$$

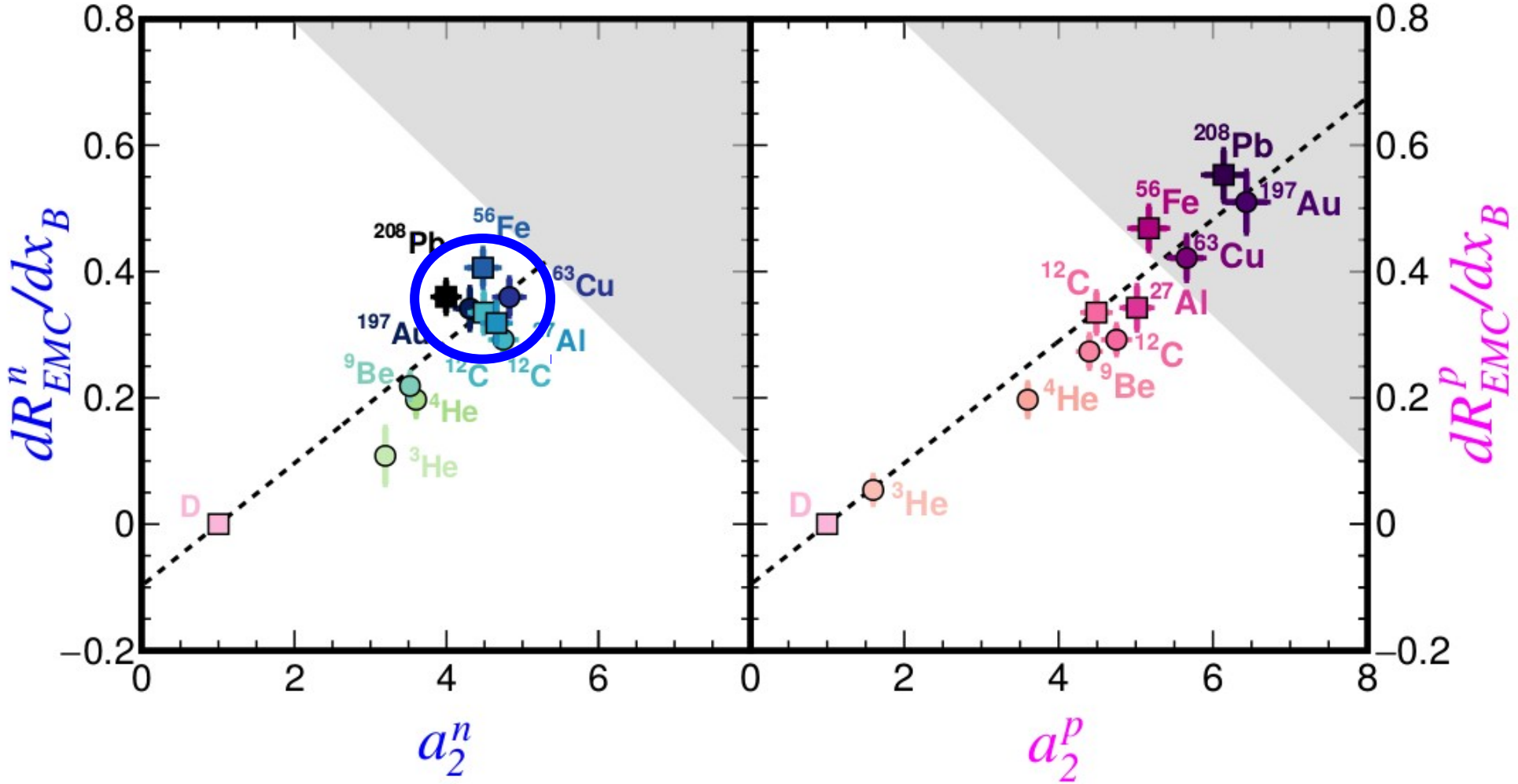


$$F_2^d = F_2^p + F_2^n + n_{SRC}^d(\Delta F_2^p + \Delta F_2^n)$$

New EMC-SRC Correlation: Version II



New EMC-SRC Correlation: Version II



New EMC-SRC Correlation: Version II