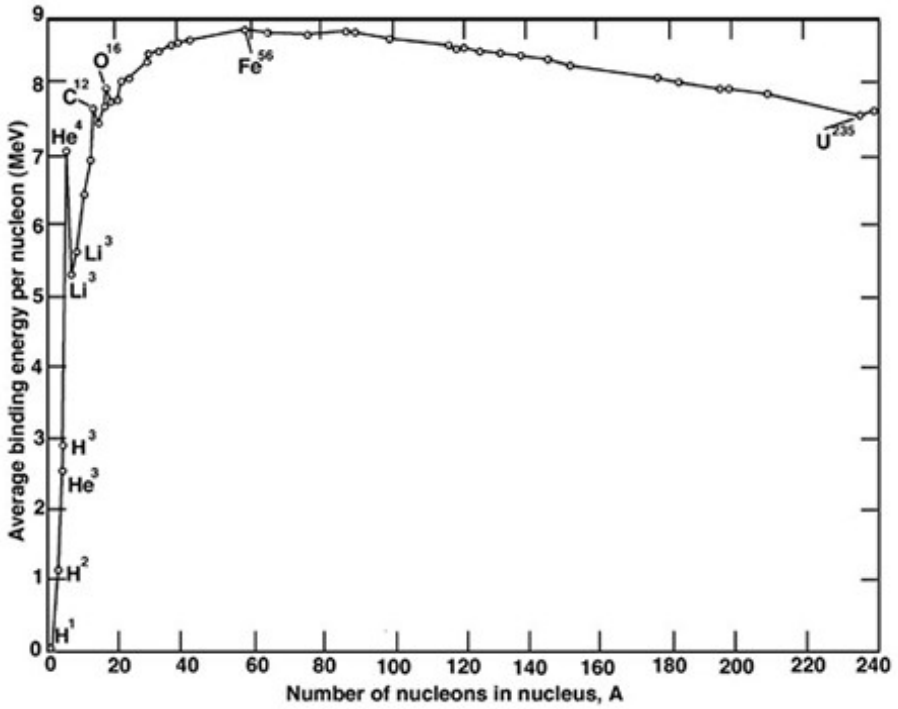
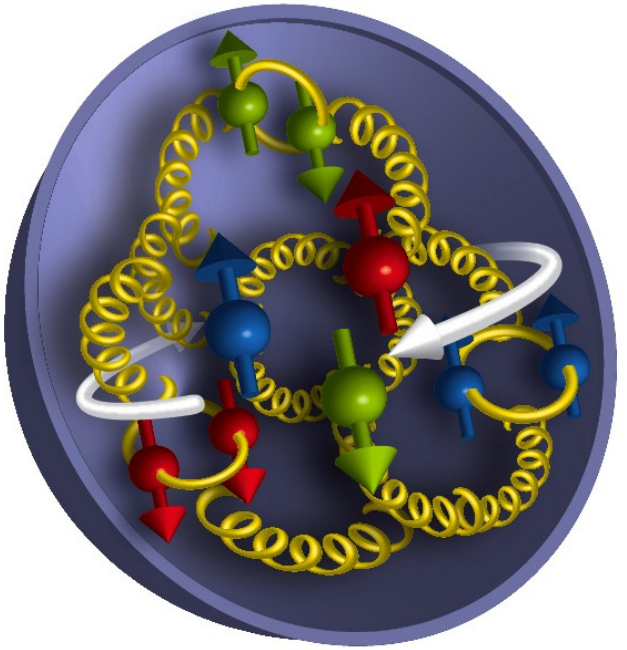
# Modified Structure of Protons and Neutrons in Correlated Pairs

Barak Schmookler

*Nature 566, 354-358 (2019)*

# Scale Separation in the Nucleus

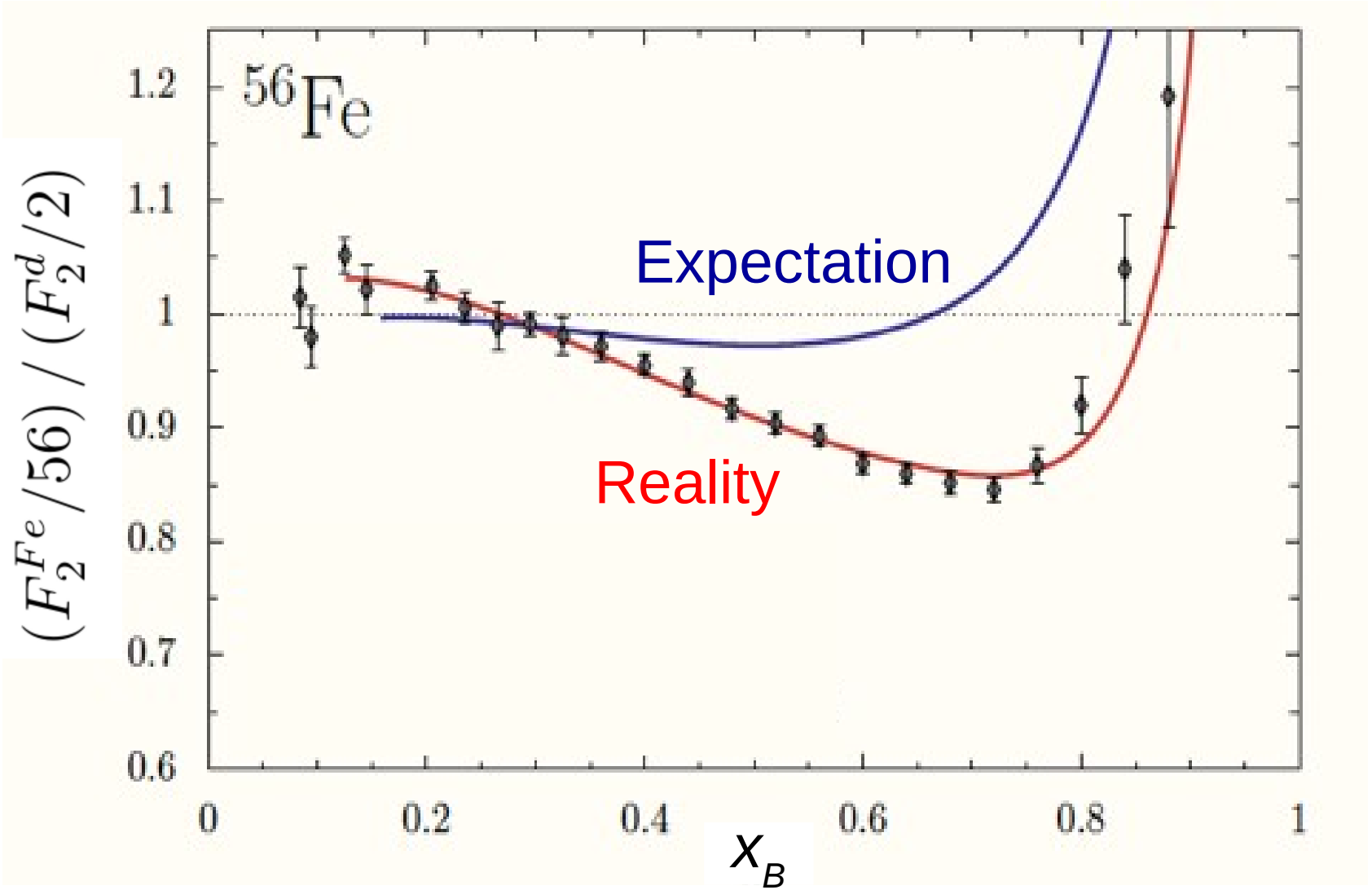


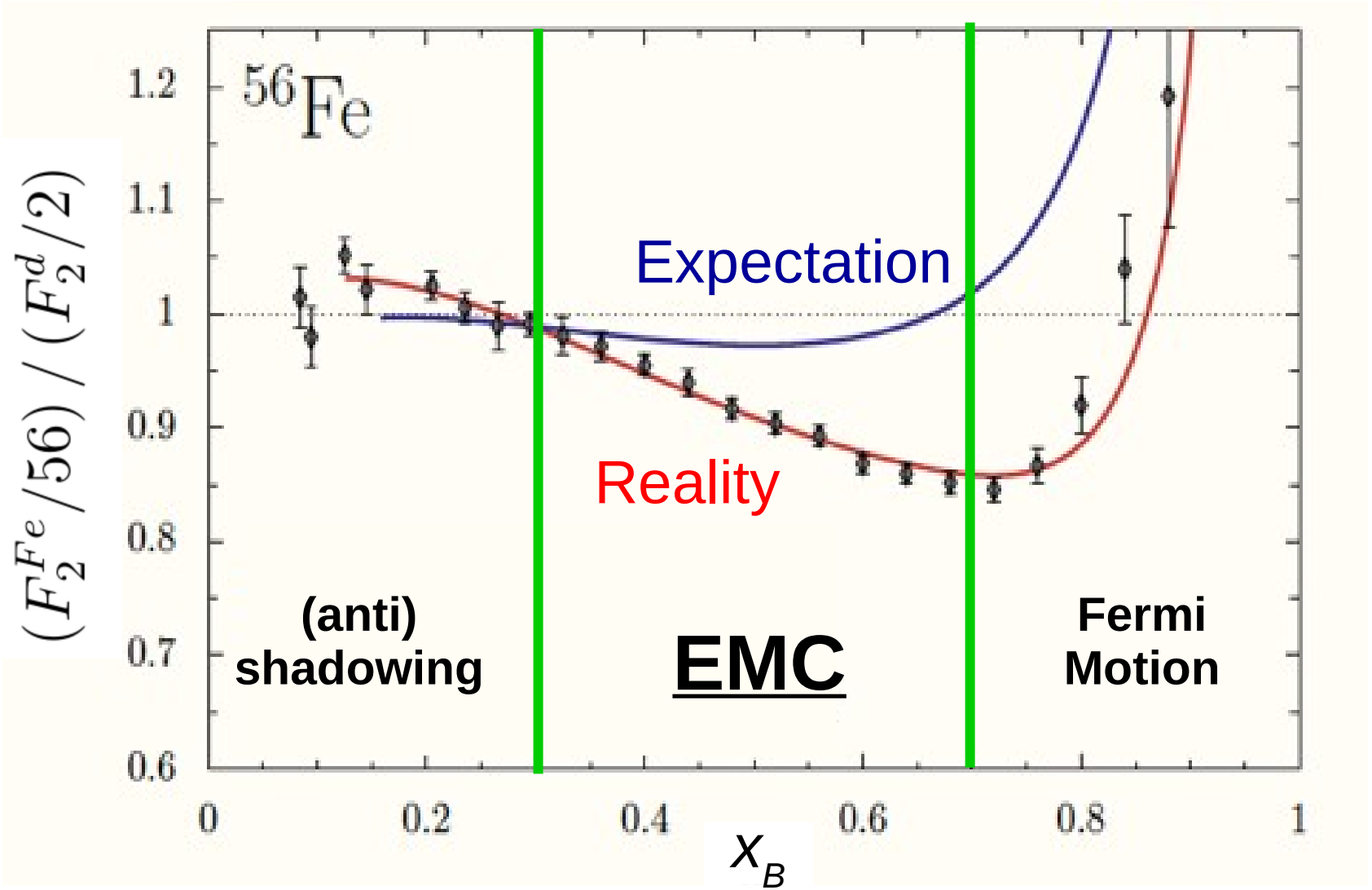
Weak Binding: MeV

Strong Binding: GeV

# The EMC Effect

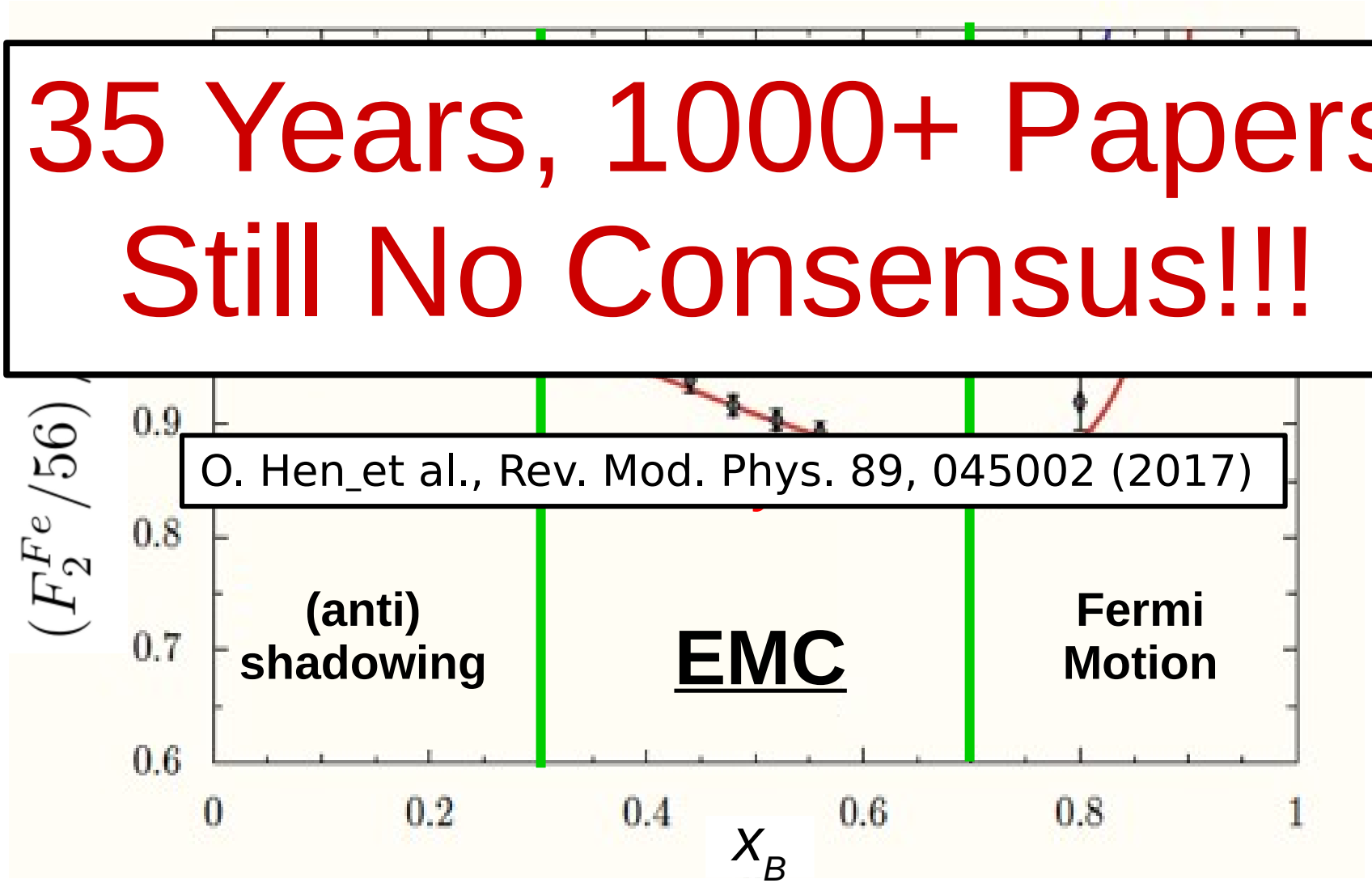


# The EMC Effect – Quarks Move “Slower” in the Nucleus



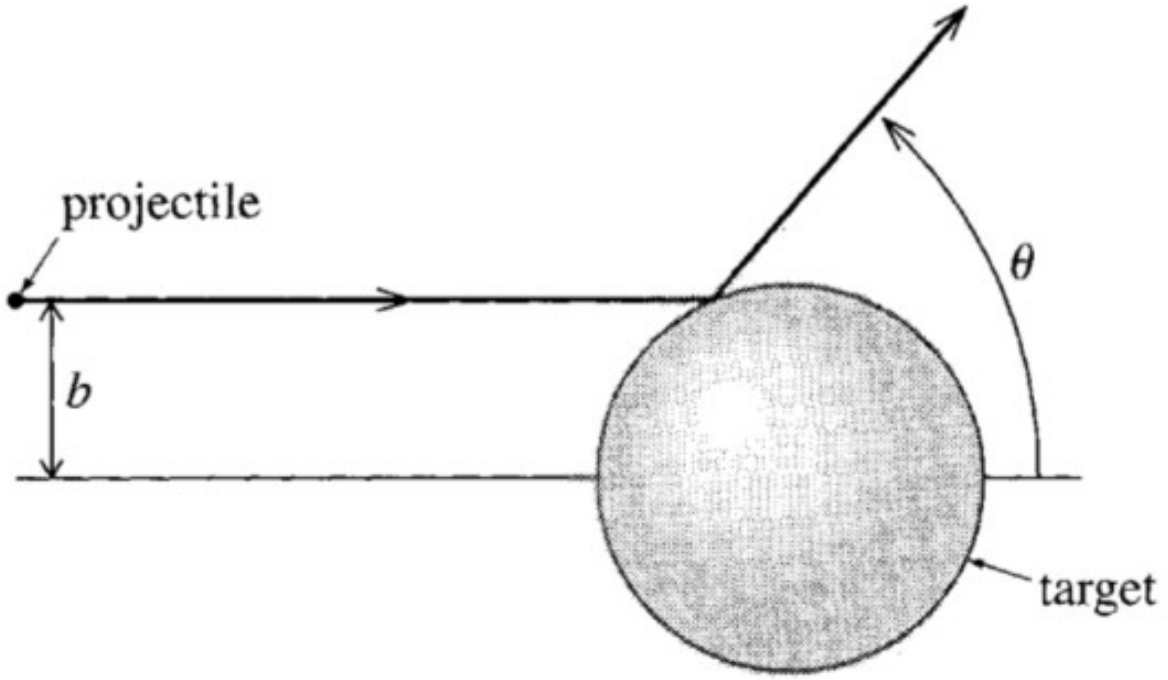
# The EMC Effect – Quarks Move “Slower” in the Nucleus

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

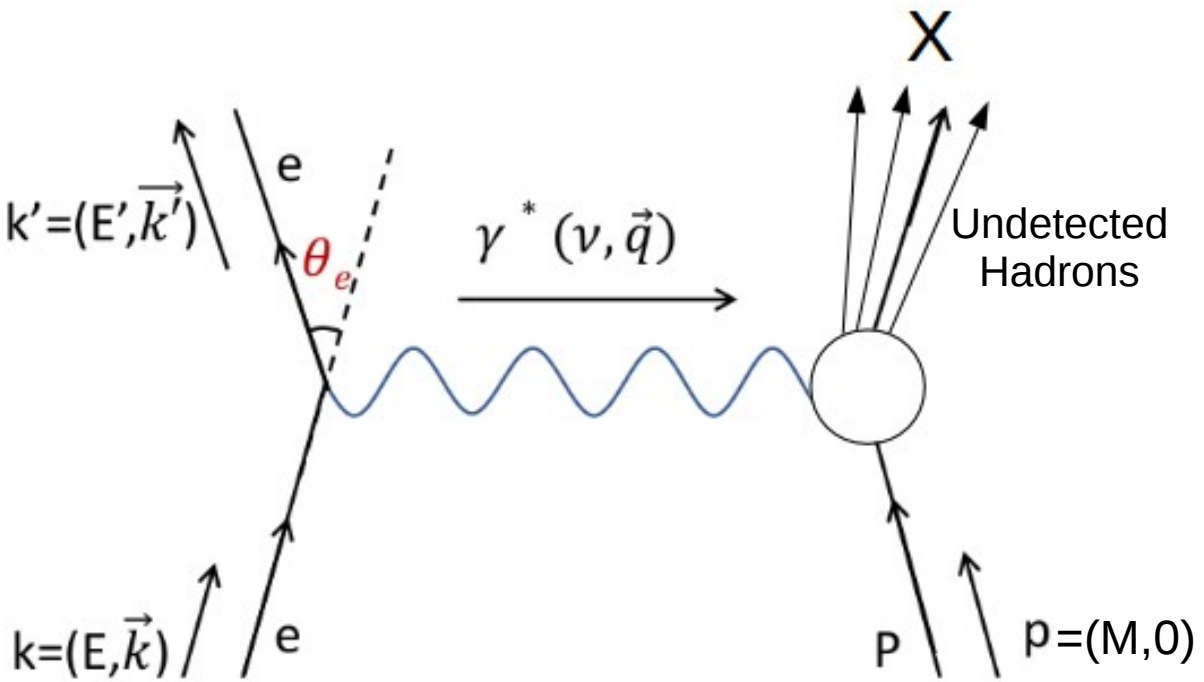



O. Hen_et al., Rev. Mod. Phys. 89, 045002 (2017)

# We Can Study the Structure of Complex Objects with Inclusive Scattering

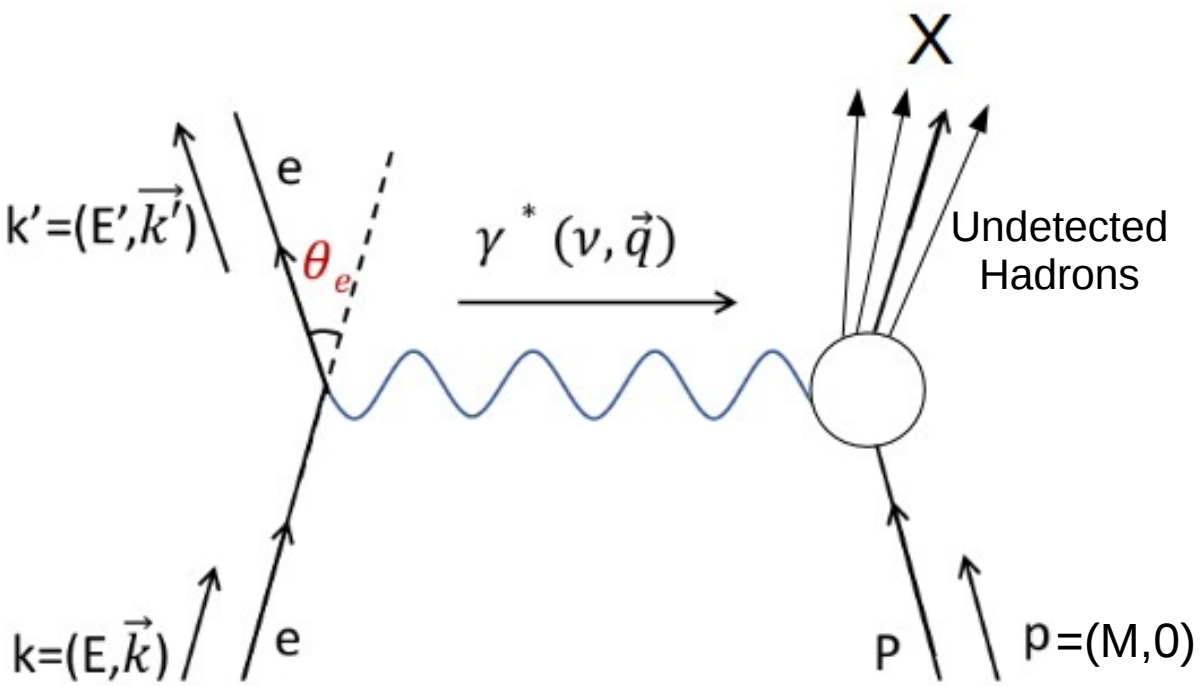


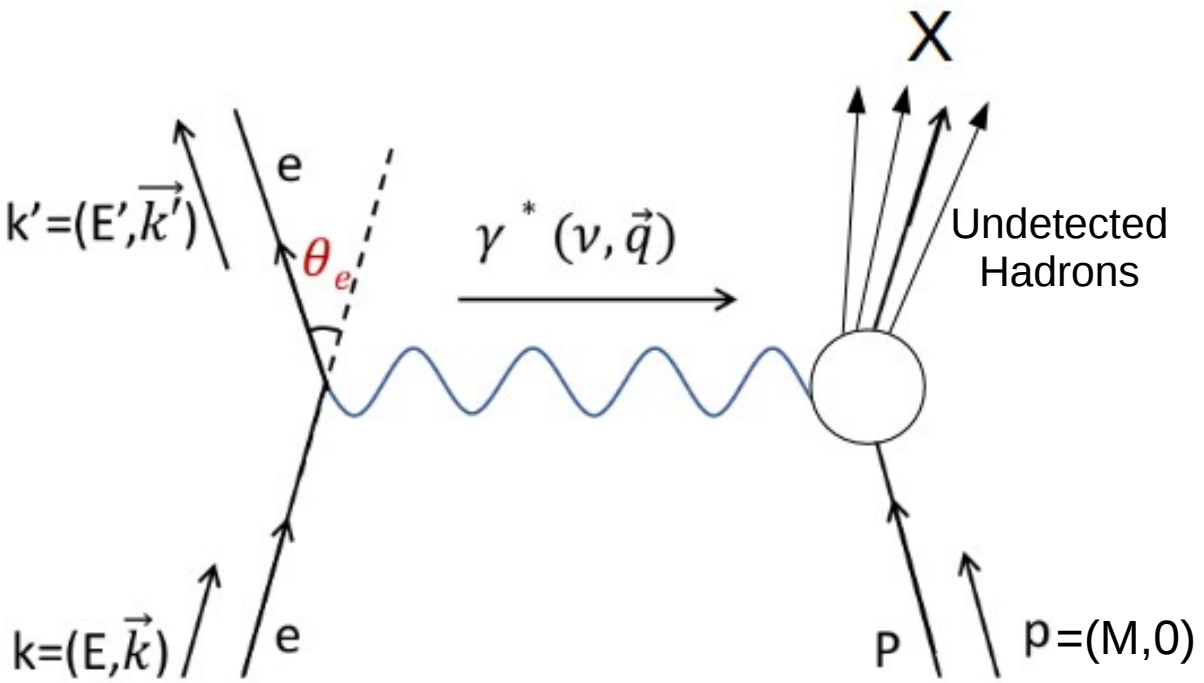

$$\sigma = \pi R^2$$


X
e
k'=(E',$\vec{k'}$)
$\theta_e$
$\gamma^*(\nu,\vec{q})$
Undetected
Hadrons
k=(E,$\vec{k}$)
e
P
p=(M,0)

*Energy Transfer:*

$$\nu = E - E'$$



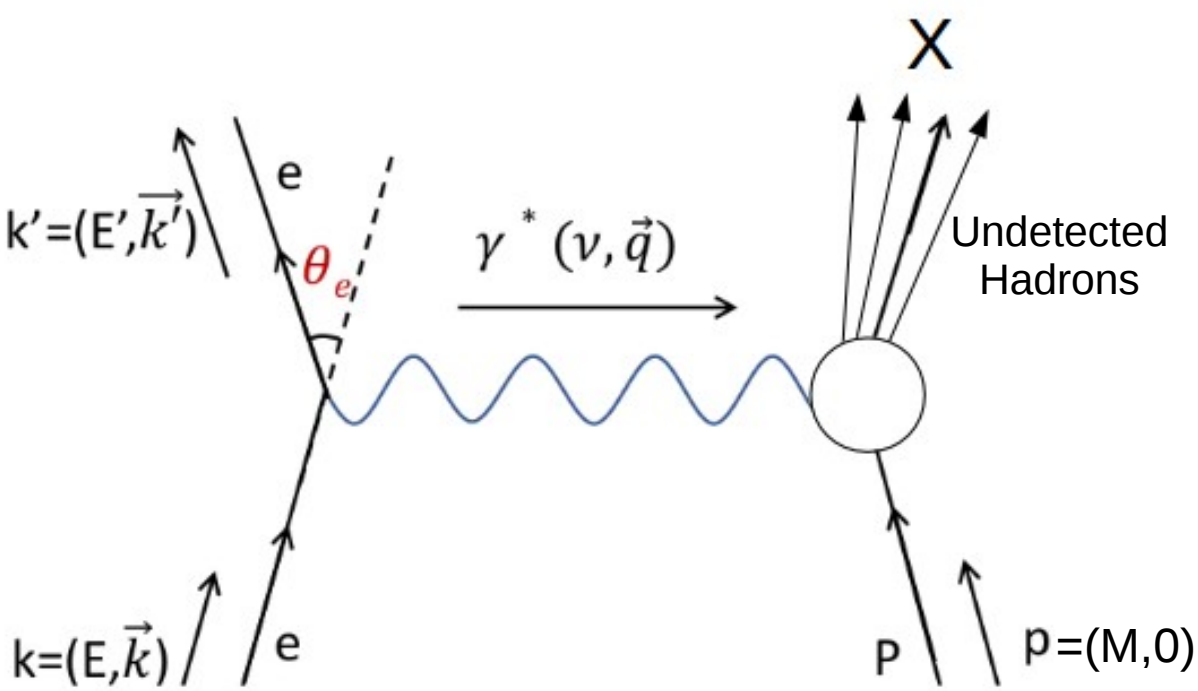



*Energy Transfer:*

$$\nu = E - E'$$

*Four-Momentum Transfer Squared:*

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

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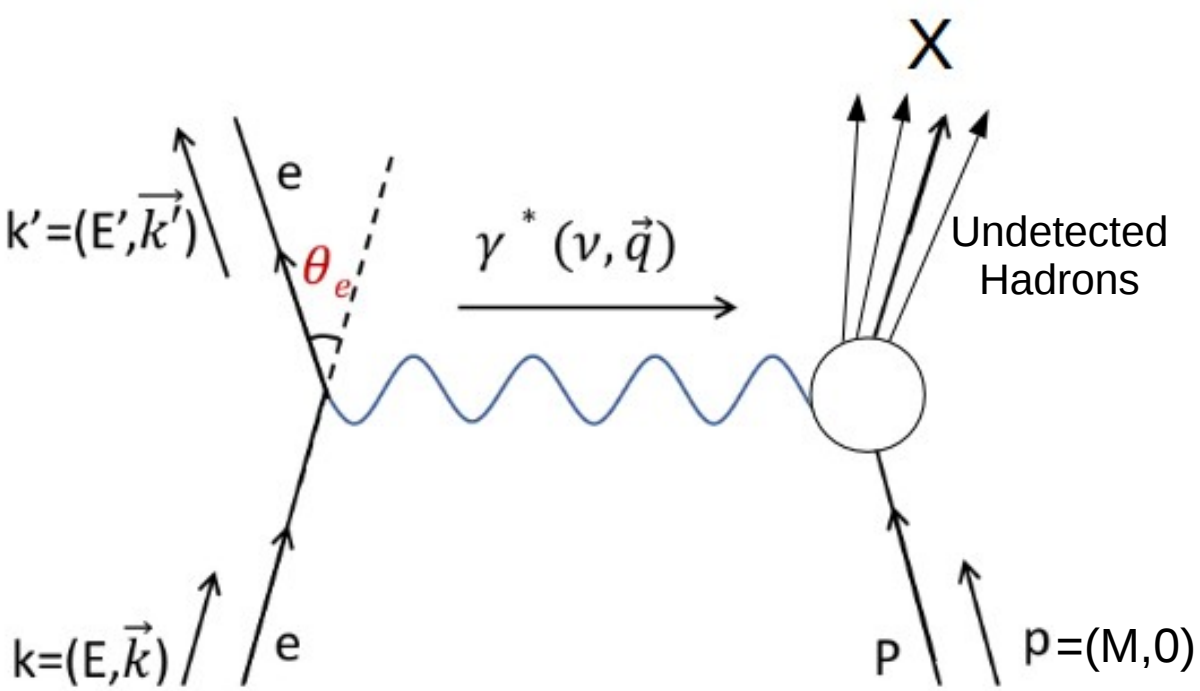
$$W = \sqrt{(P+q)^2} = \sqrt{M^2 + 2M\nu - Q^2}$$

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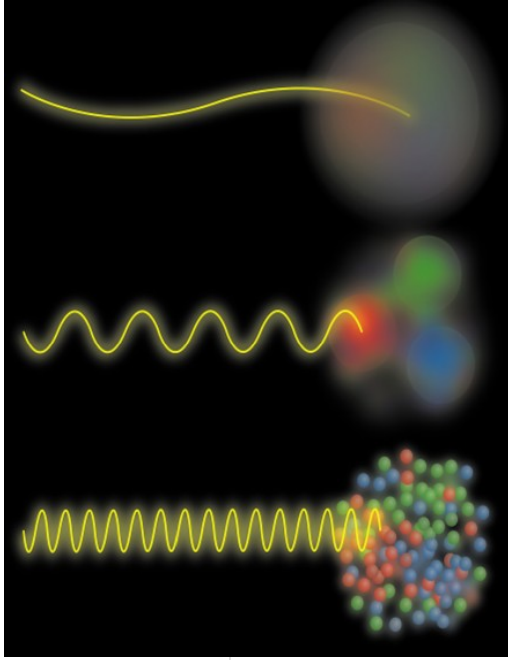
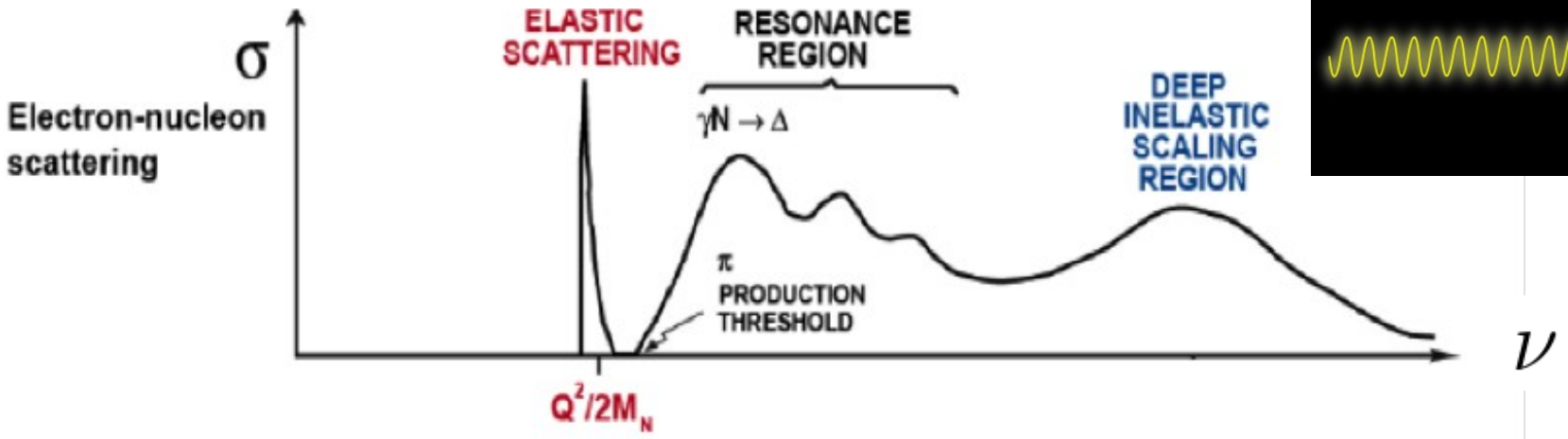
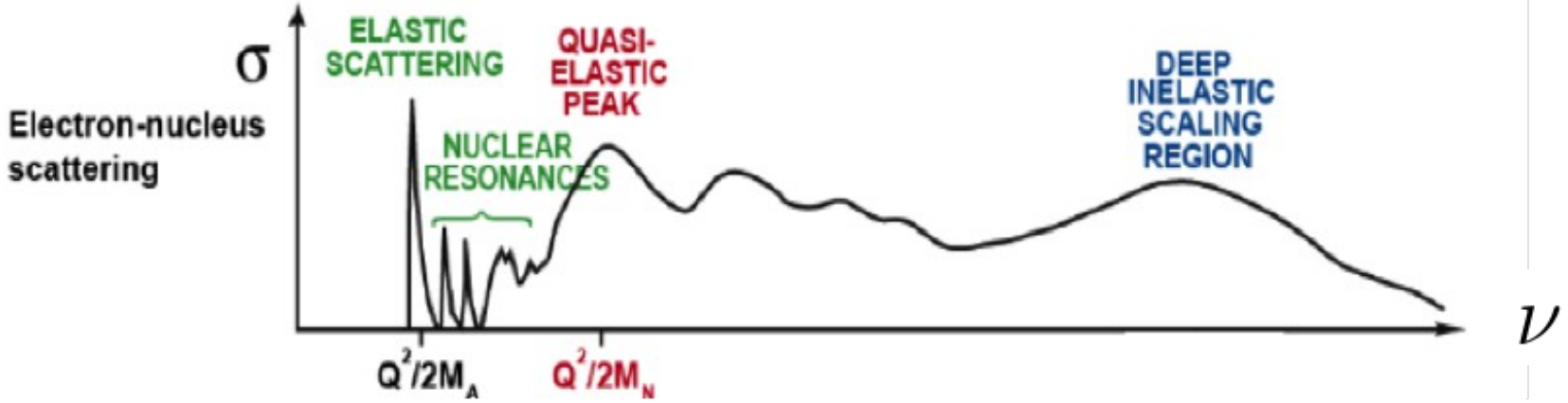
*Bjorken x:*

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

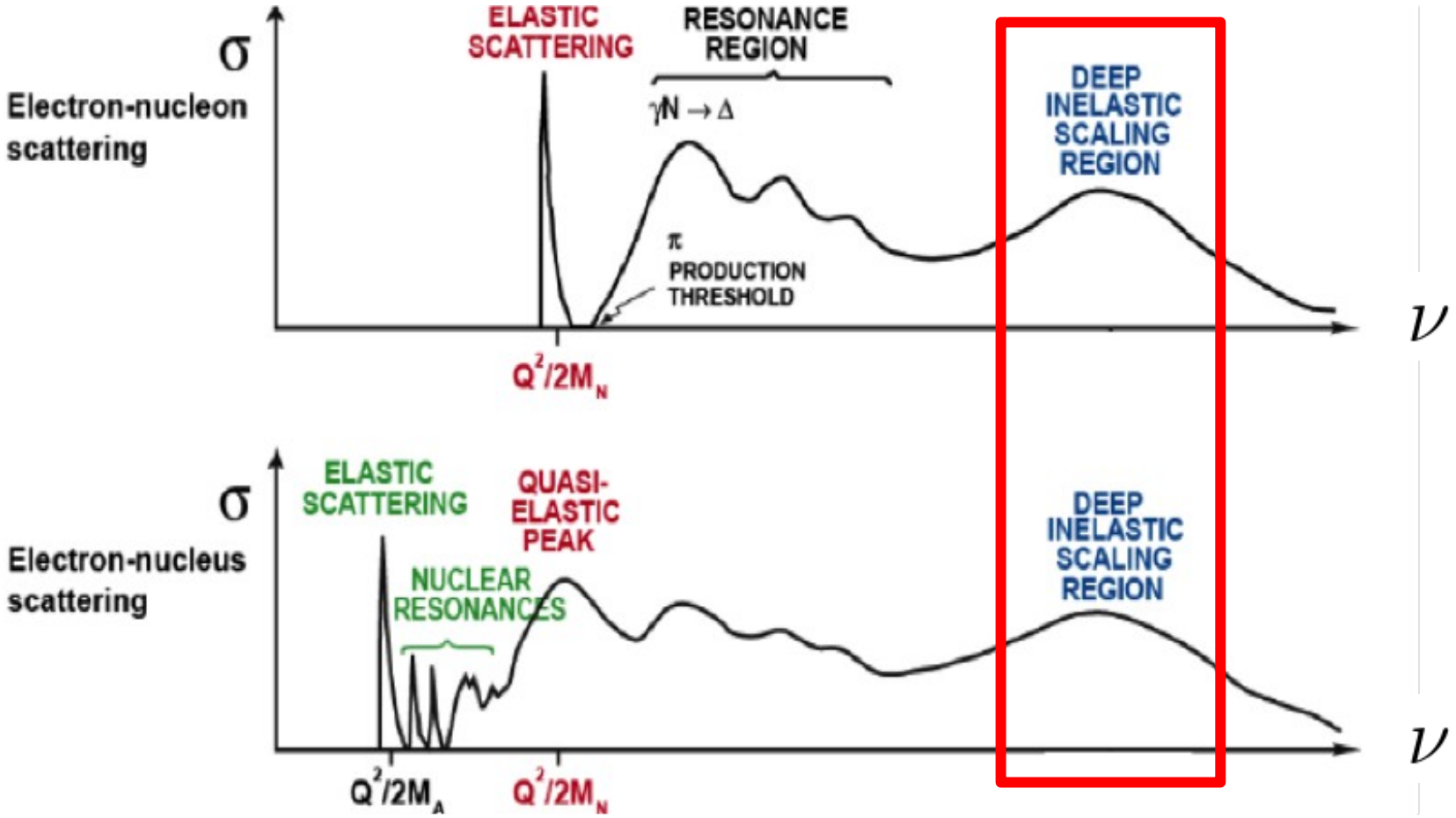



σ
Electron-nucleon scattering
ELASTIC SCATTERING
RESONANCE REGION
γN → Δ
DEEP INELASTIC SCALING REGION
π PRODUCTION THRESHOLD
ν
Q²/2M_N


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



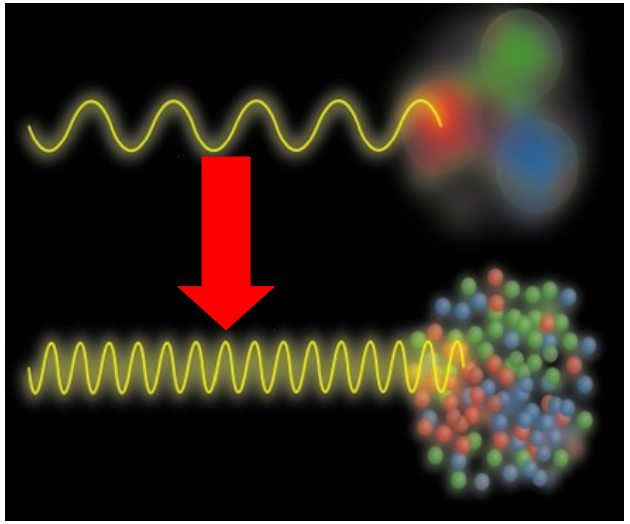
# Inelastic Electron-Proton Inclusive Scattering

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

# Inelastic Electron-Proton Inclusive Scattering

Structure Functions

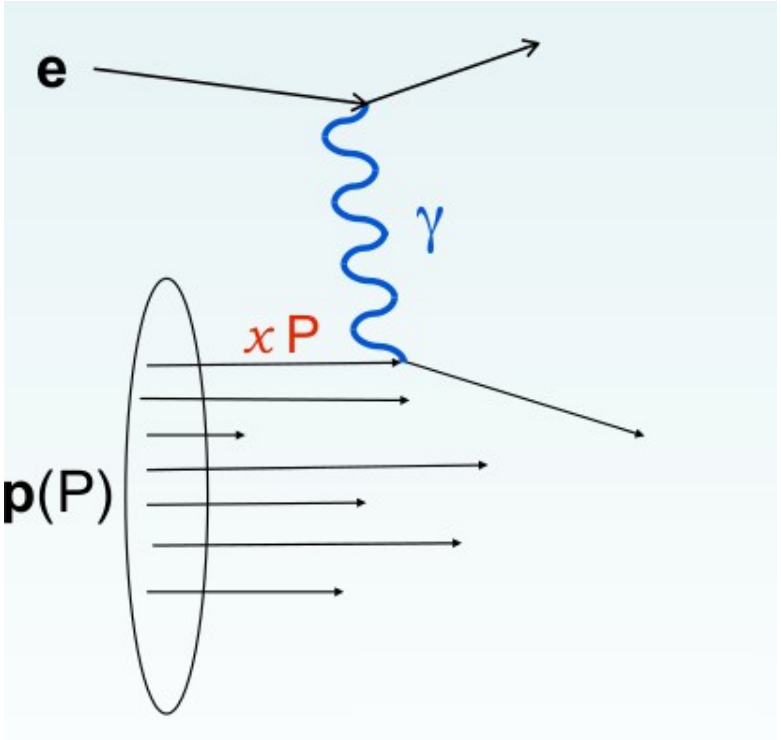
$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{Q^4}\left[2\frac{F_1(x_B,Q^2)}{M}\sin^2\frac{\theta_e}{2} + \frac{F_2(x_B,Q^2)}{\nu}\cos^2\frac{\theta_e}{2}\right]$$



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

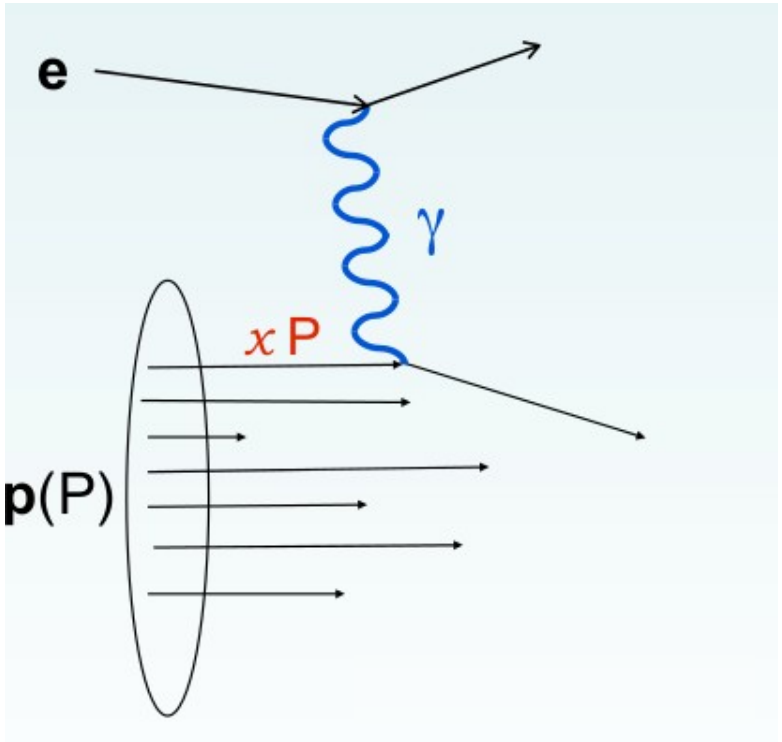
$$F_2(x_B,Q^2) \longrightarrow F_2(x_B)$$

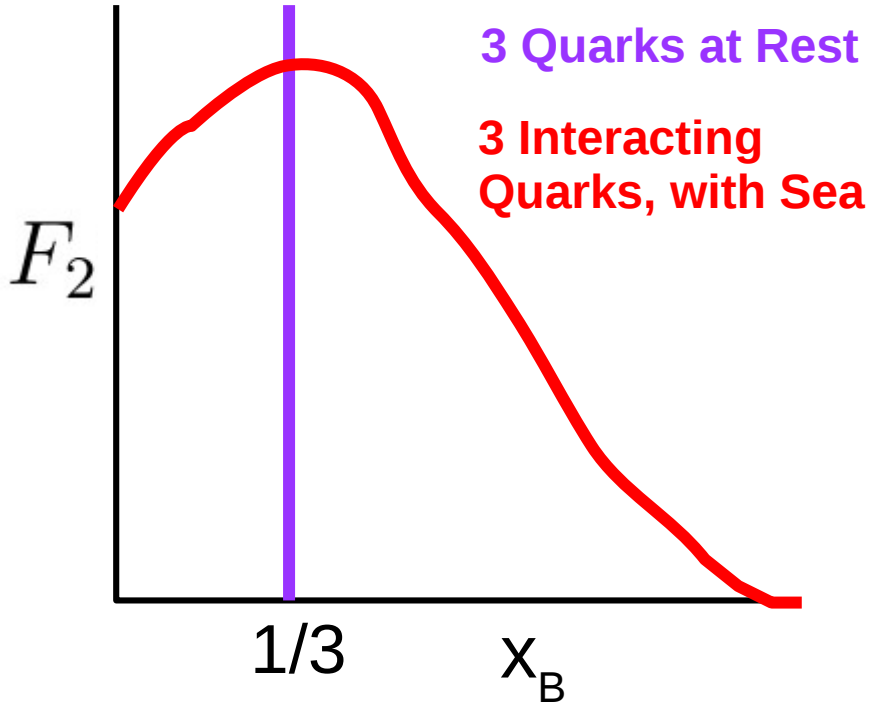
# Structure functions in DIS



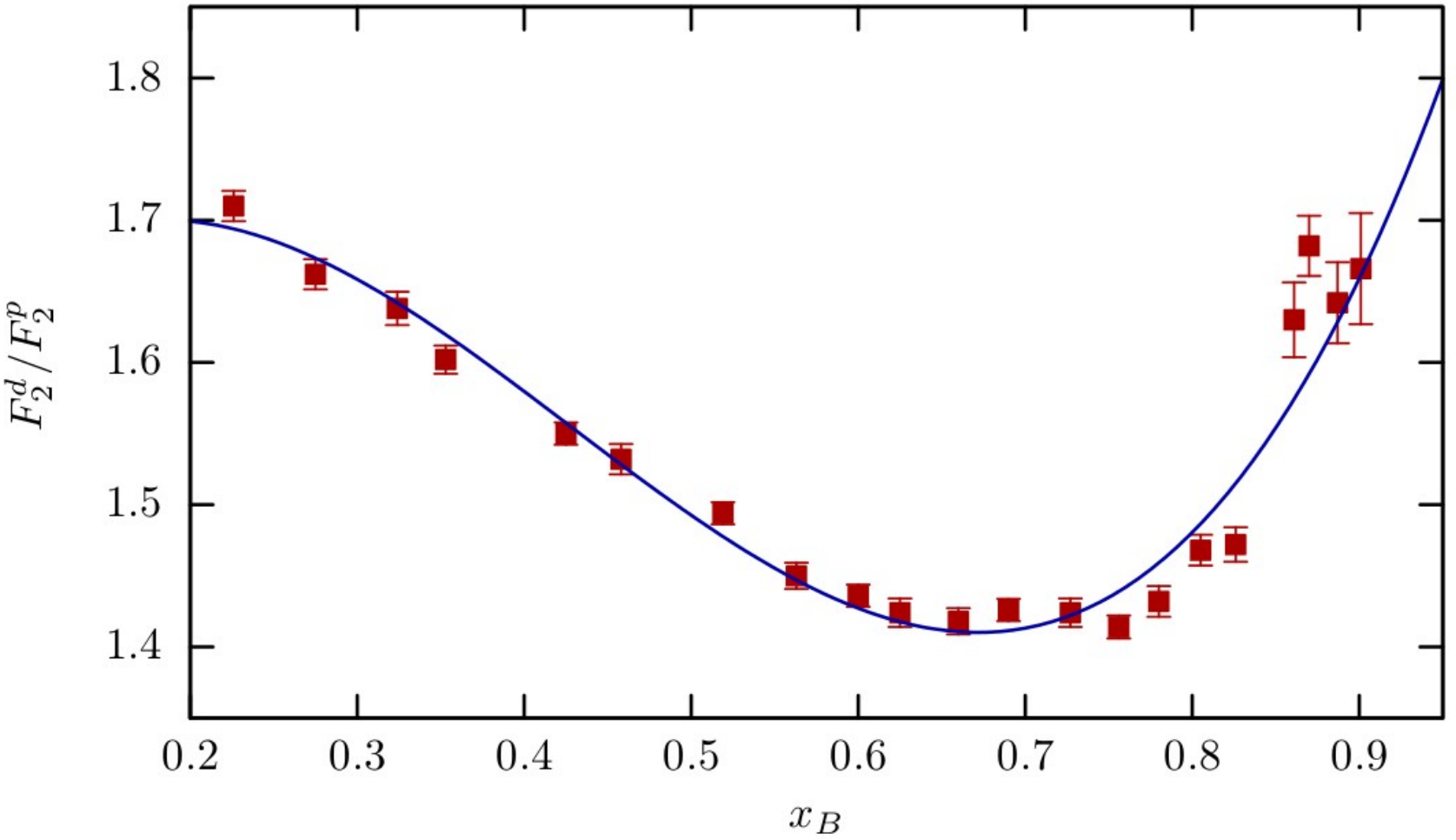
# Structure functions in DIS

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



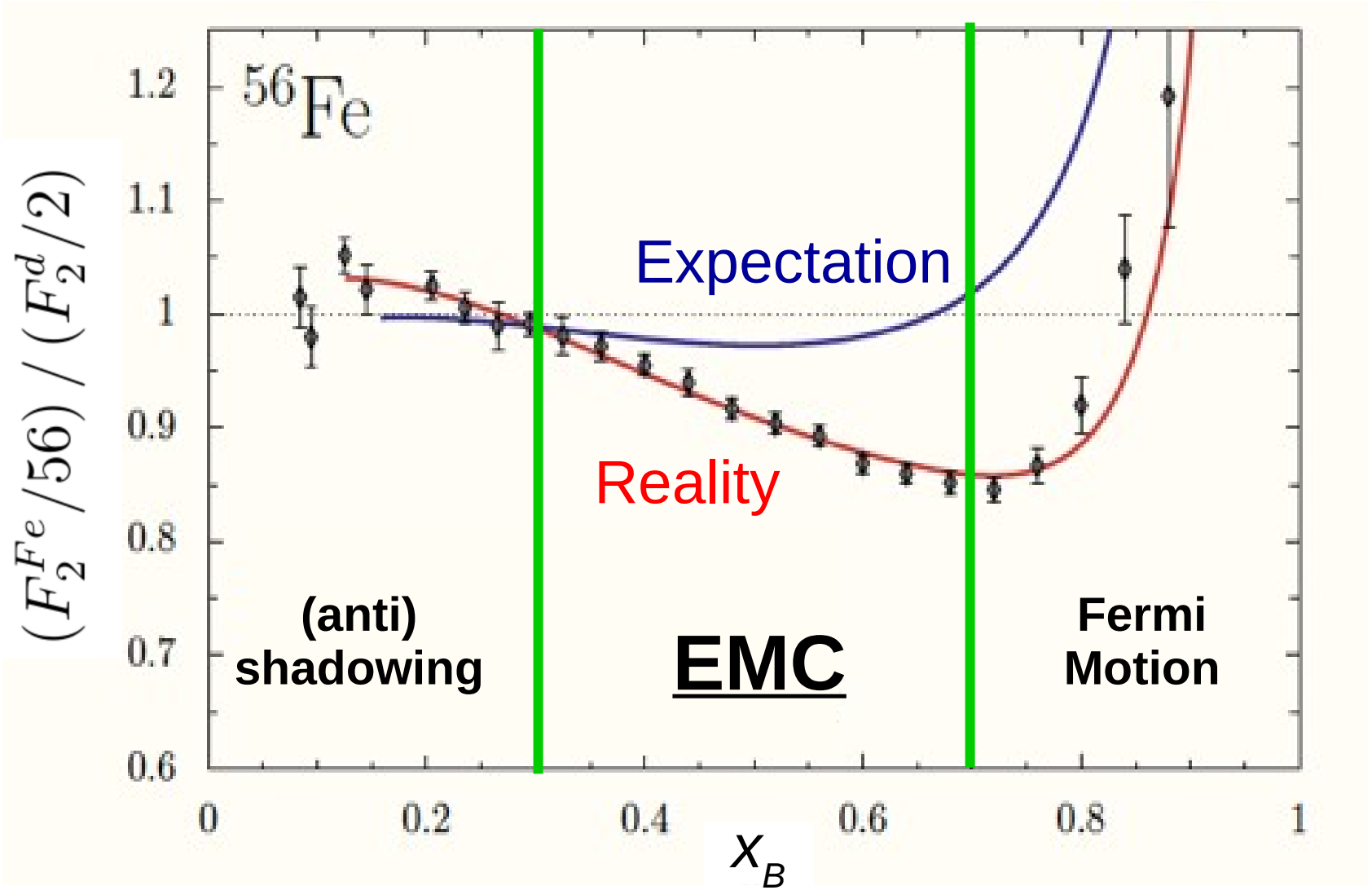



# Compare DIS on Deuterium



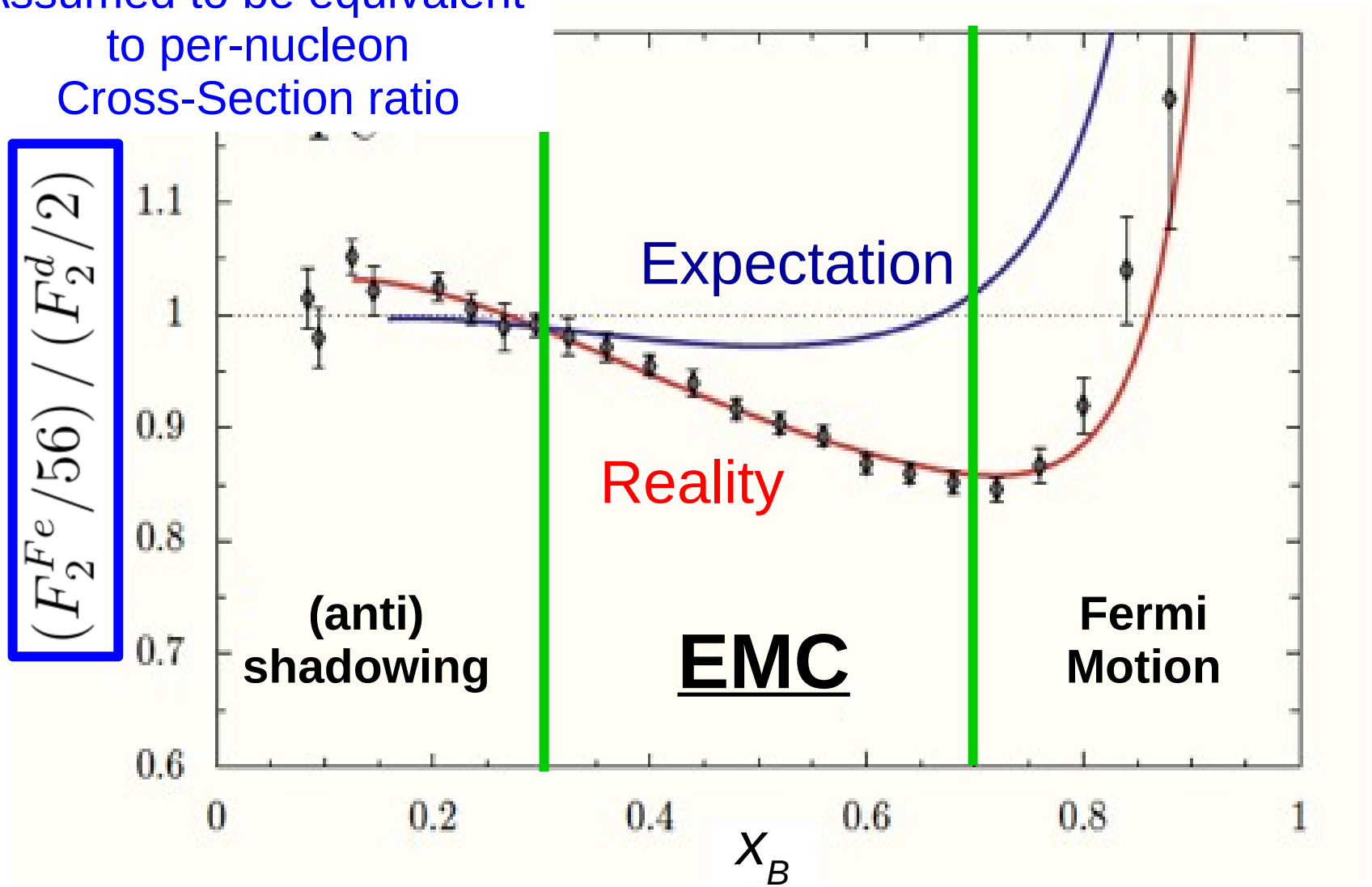

*J. Arrington, et. al. J. phys. G36, 025005 (2009)*

# DIS and the EMC Effect

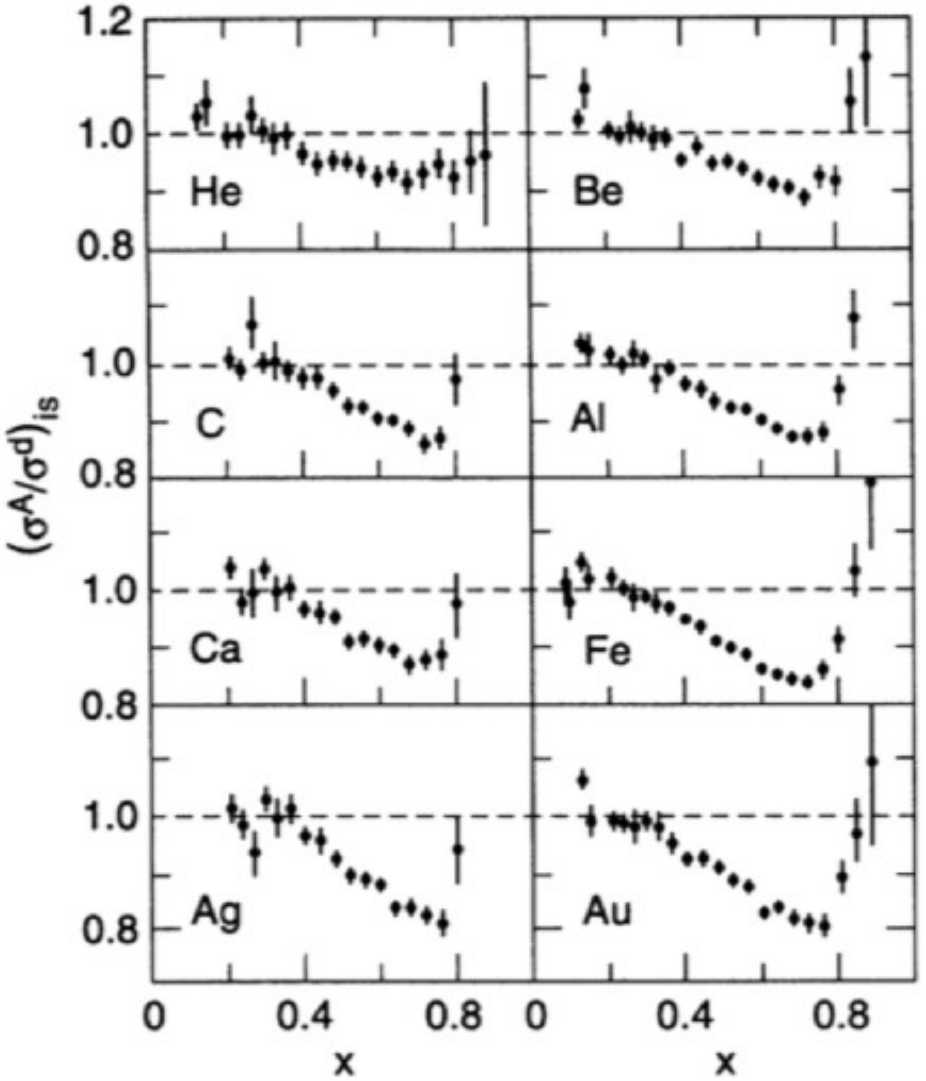


# DIS and the EMC Effect

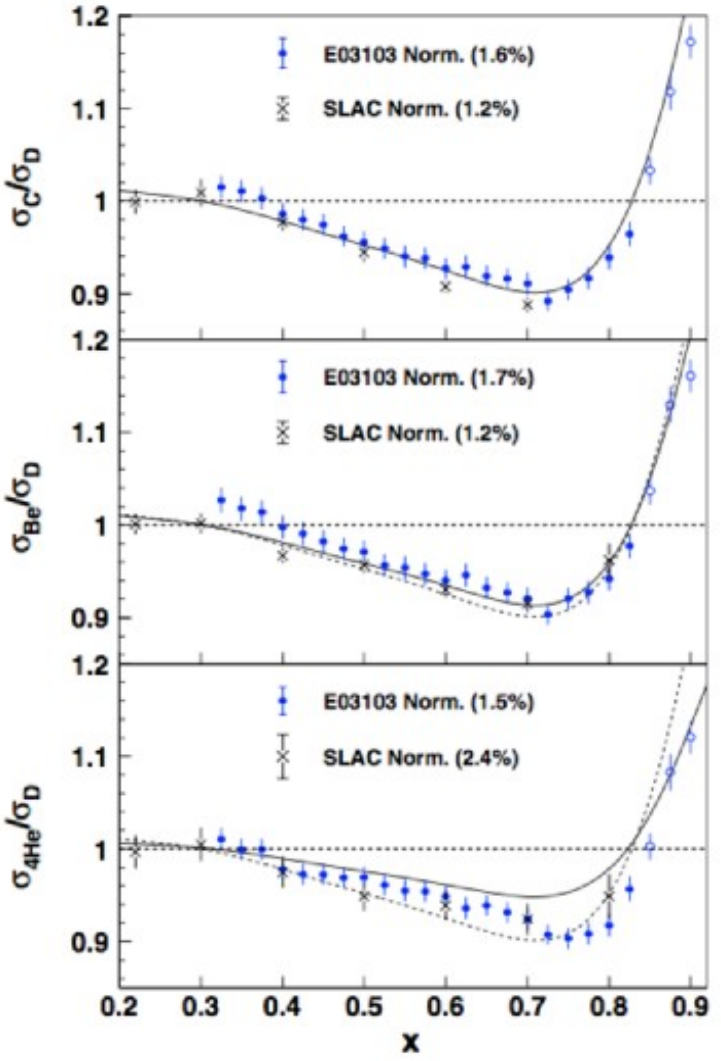
Assumed to be equivalent to per-nucleon Cross-Section ratio



# The EMC Effect: Universal Nuclear Effect




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

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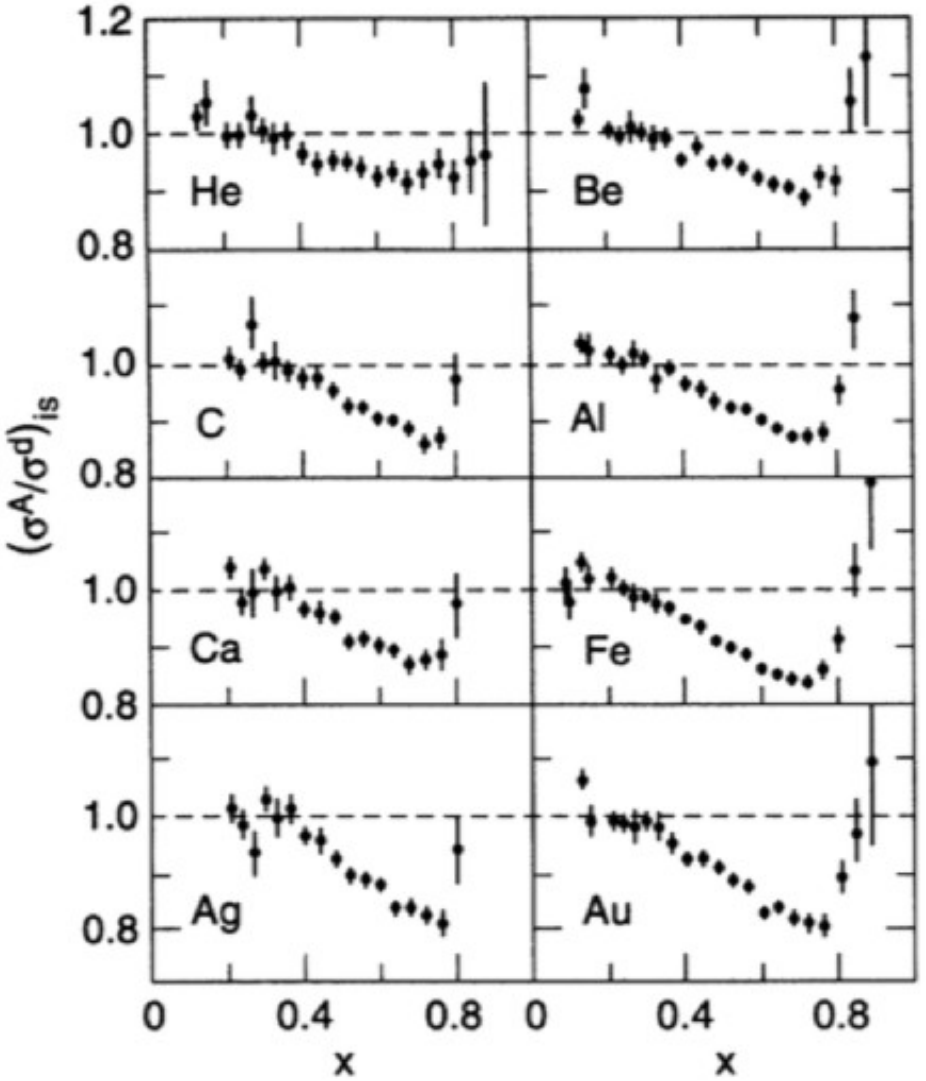


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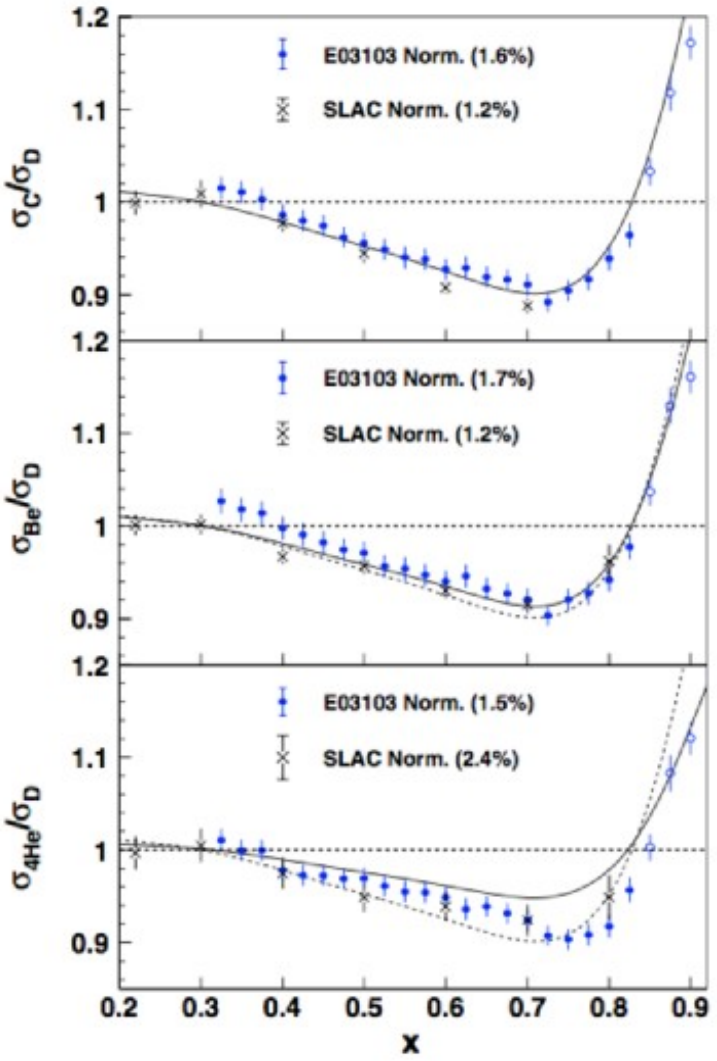


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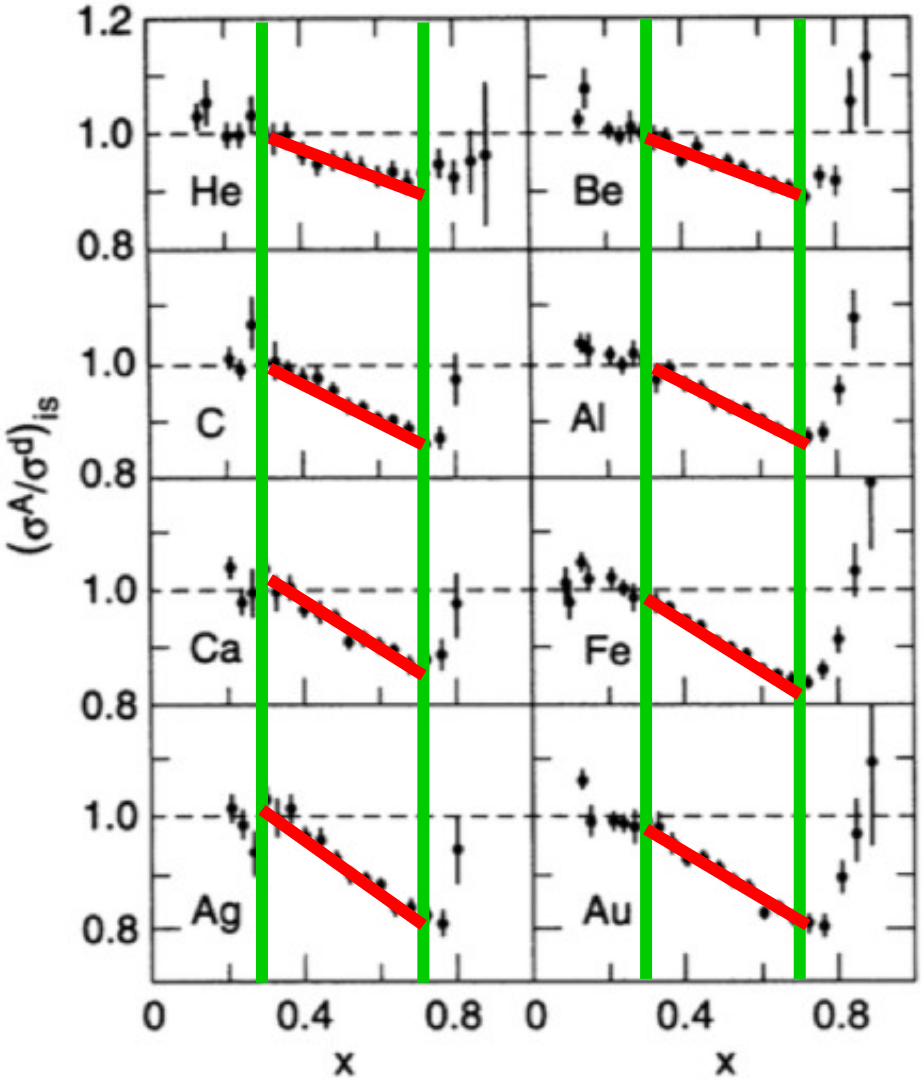


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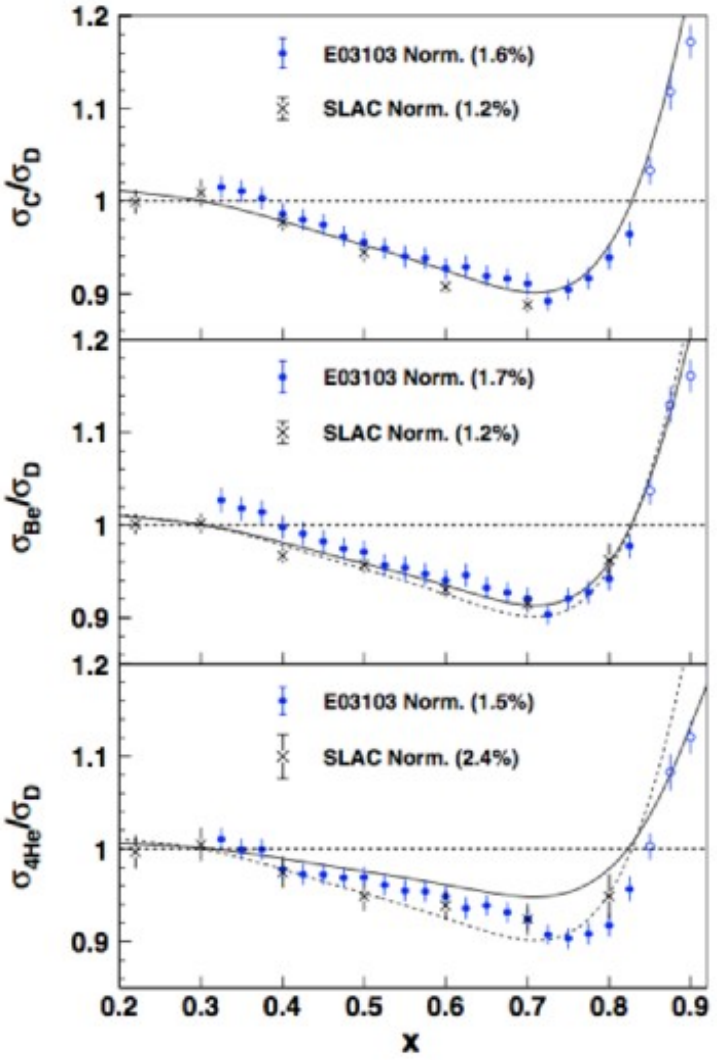


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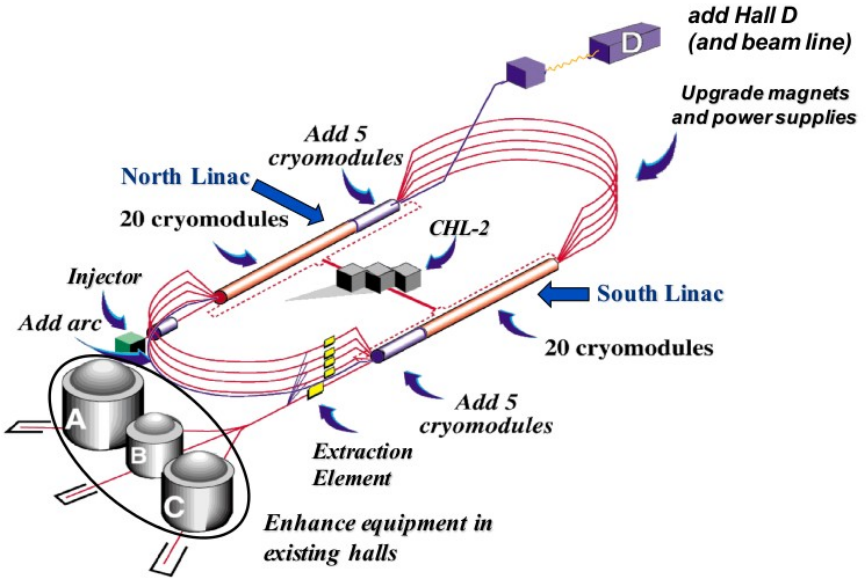
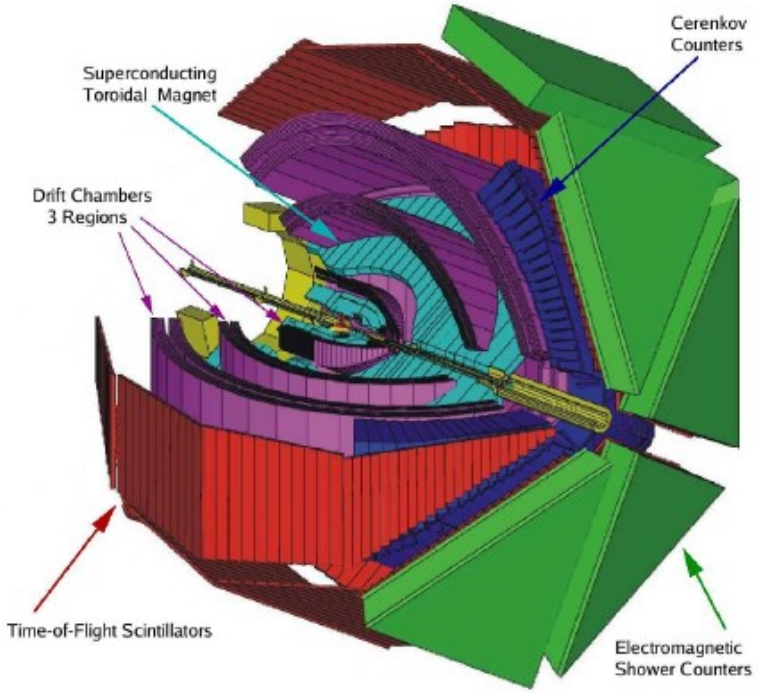
# Thomas Jefferson National Accelerator Facility (JLab)




# The CLAS Detector in Hall B at JLab



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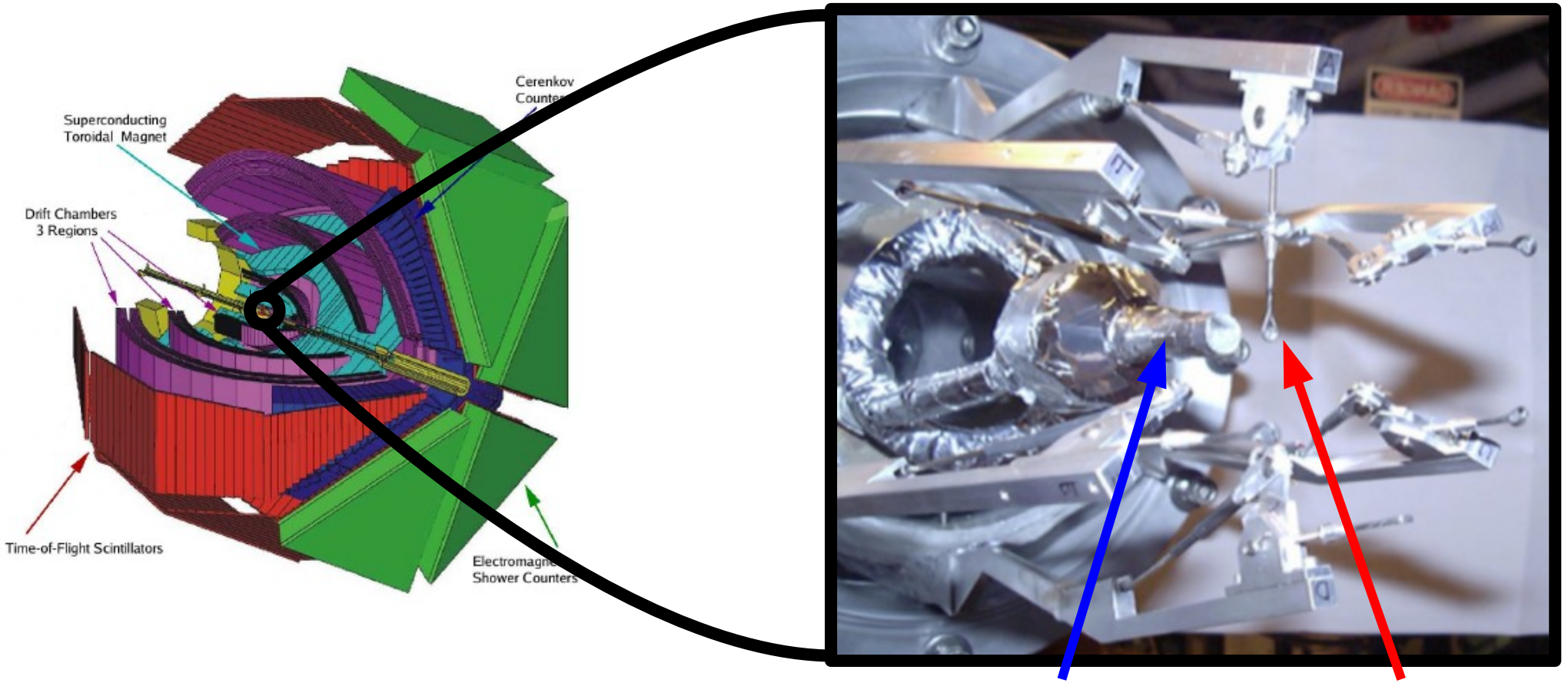
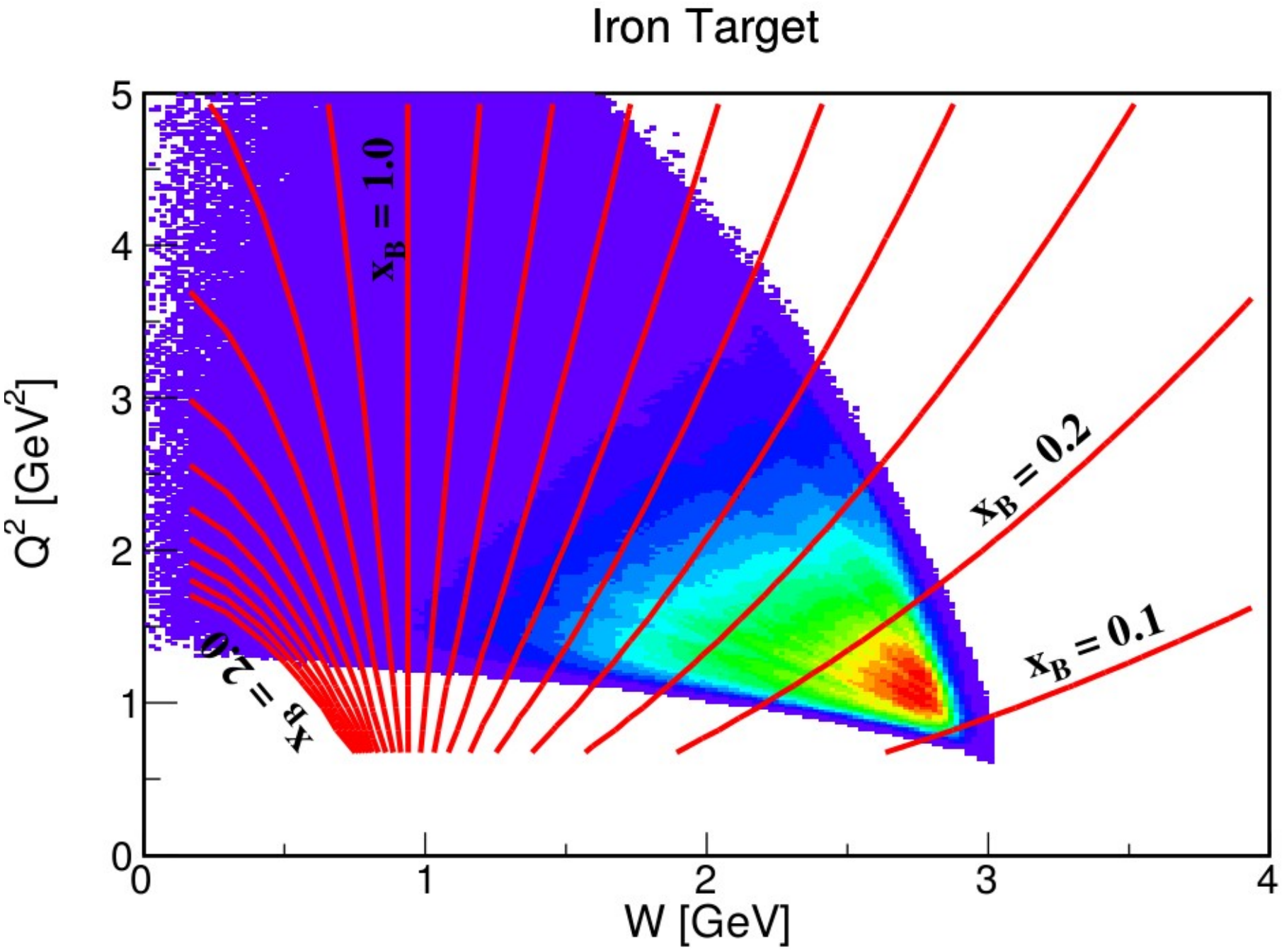
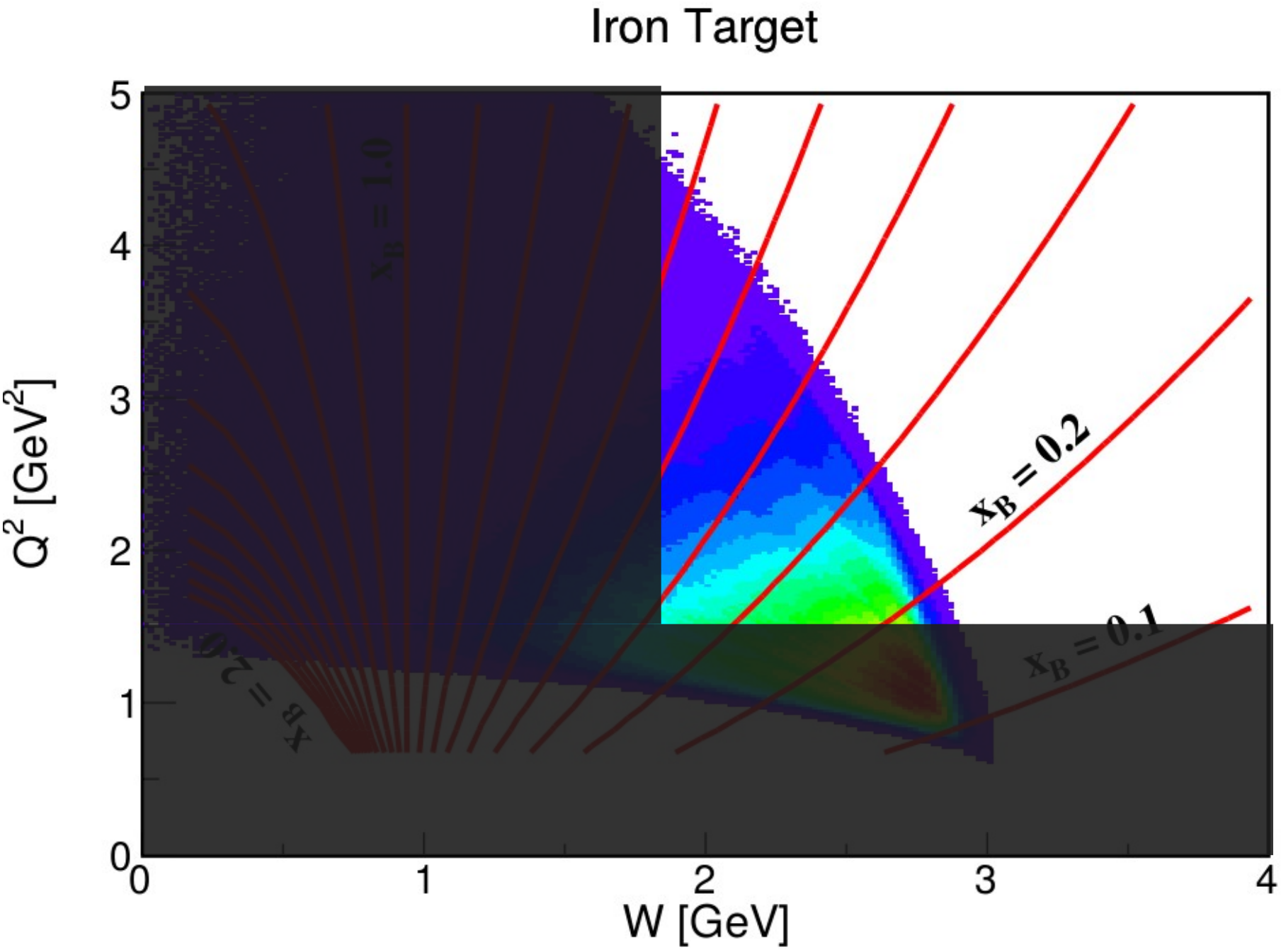



5.01 GeV Incident Electrons


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


Iron Target
$Q^2$ [GeV$^2$]
W [GeV]
$x_B = 1.0$
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# We want to Extract Cross-Section Ratios to Deuterium

- Bin data in $x_B$

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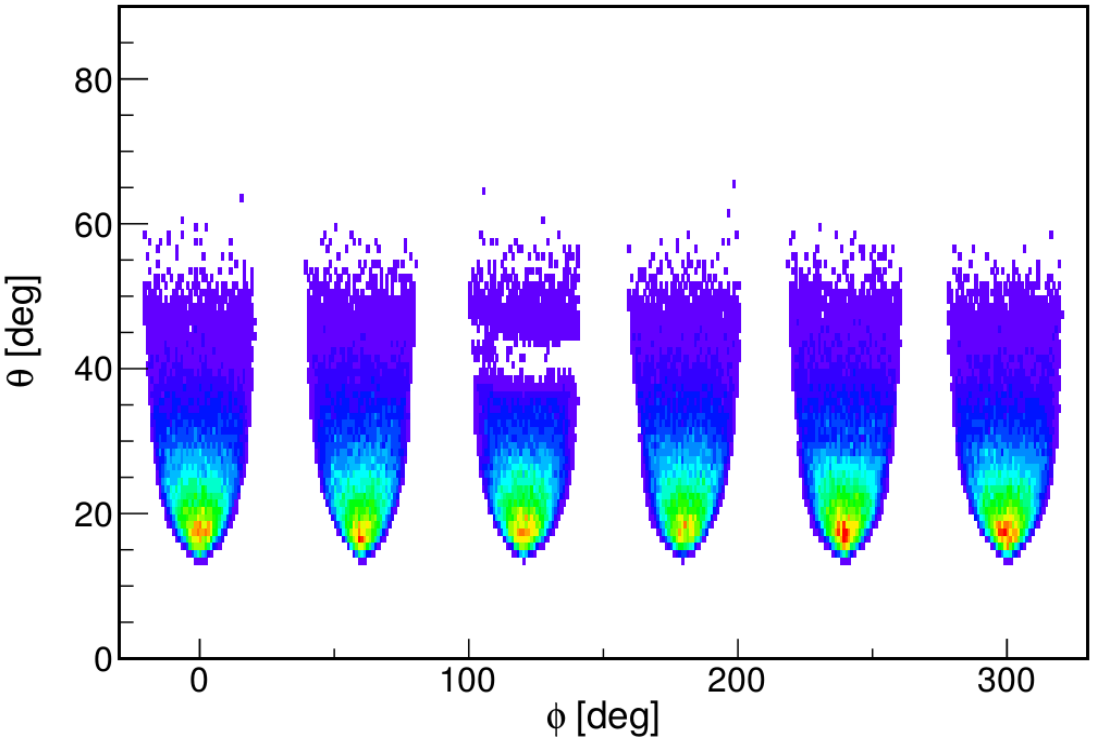
  - ✔ Acceptance Corrections



# We want to Extract Cross-Section Ratios to Deuterium

- Bin data in $x_B$
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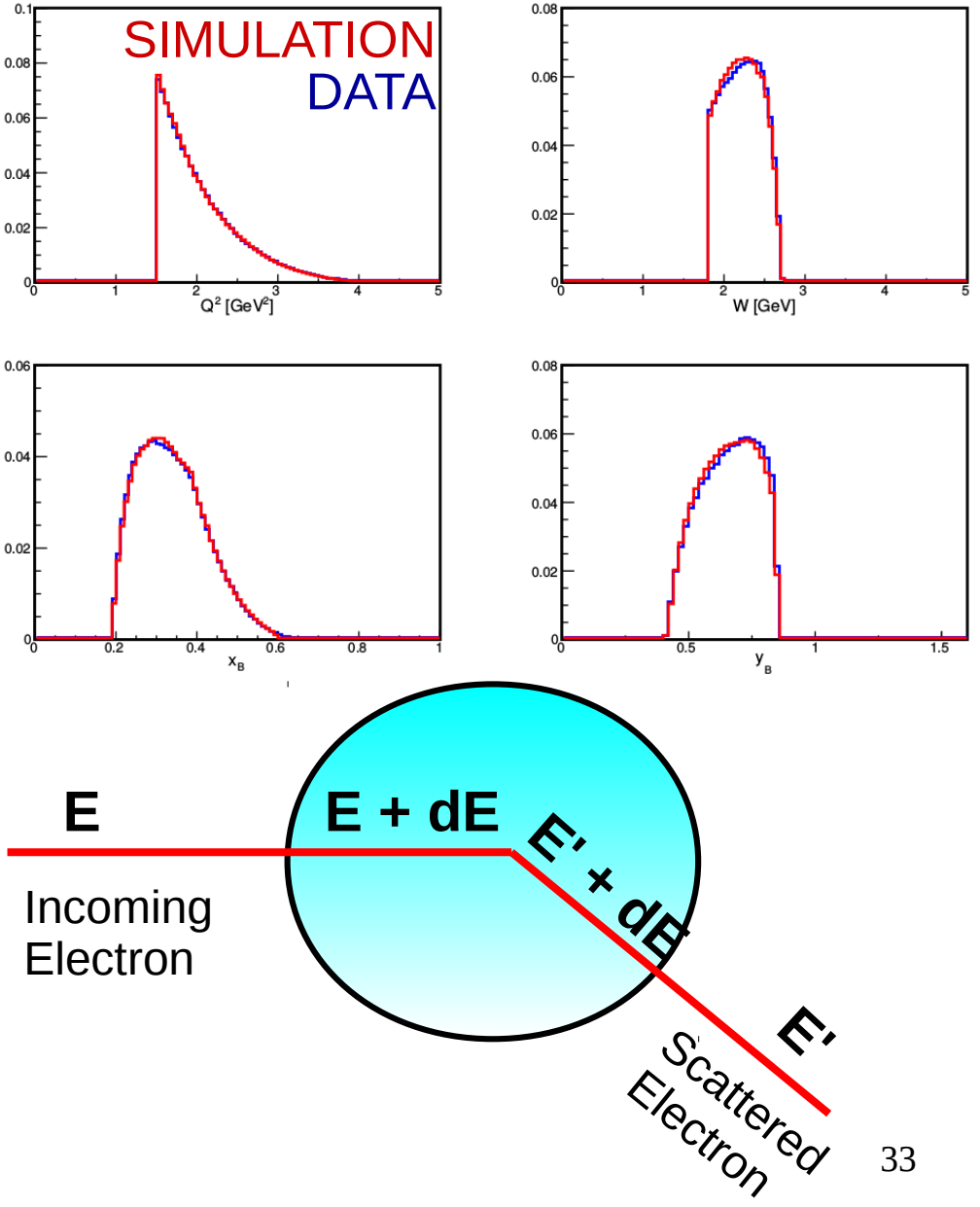
  - ✔ Acceptance Corrections
  - ✔ Radiative and Coulomb Corrections



# We want to Extract Cross-Section Ratios to Deuterium

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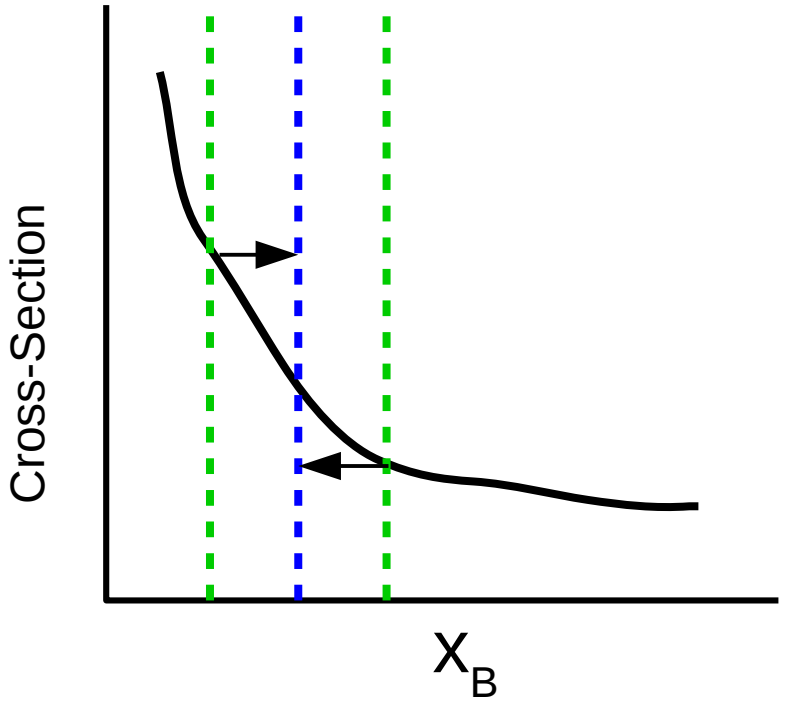
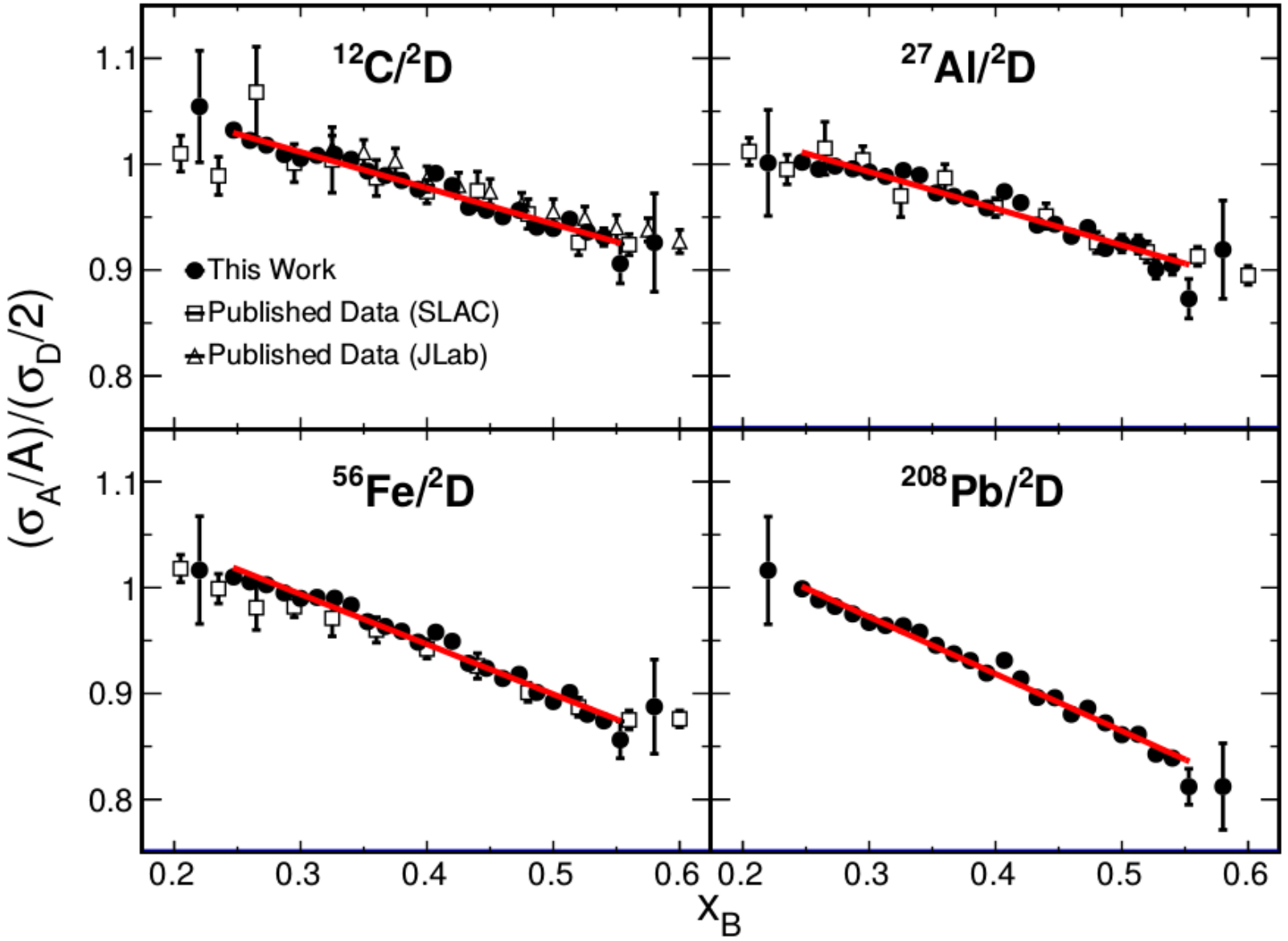
  - Acceptance Corrections
  - Radiative and Coulomb Corrections
  - Bin-Centering Corrections



# Our New EMC Effect Measurements



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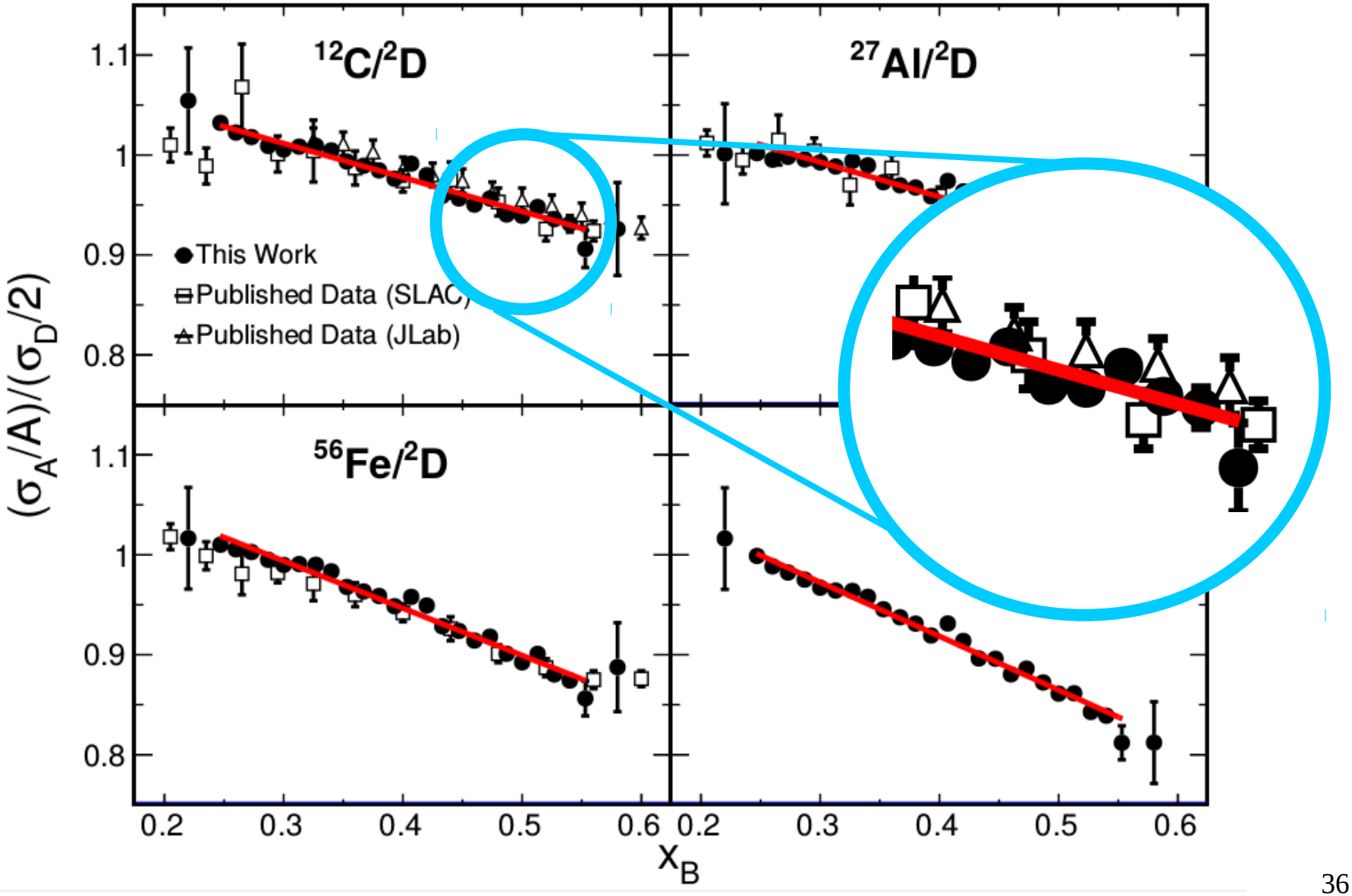

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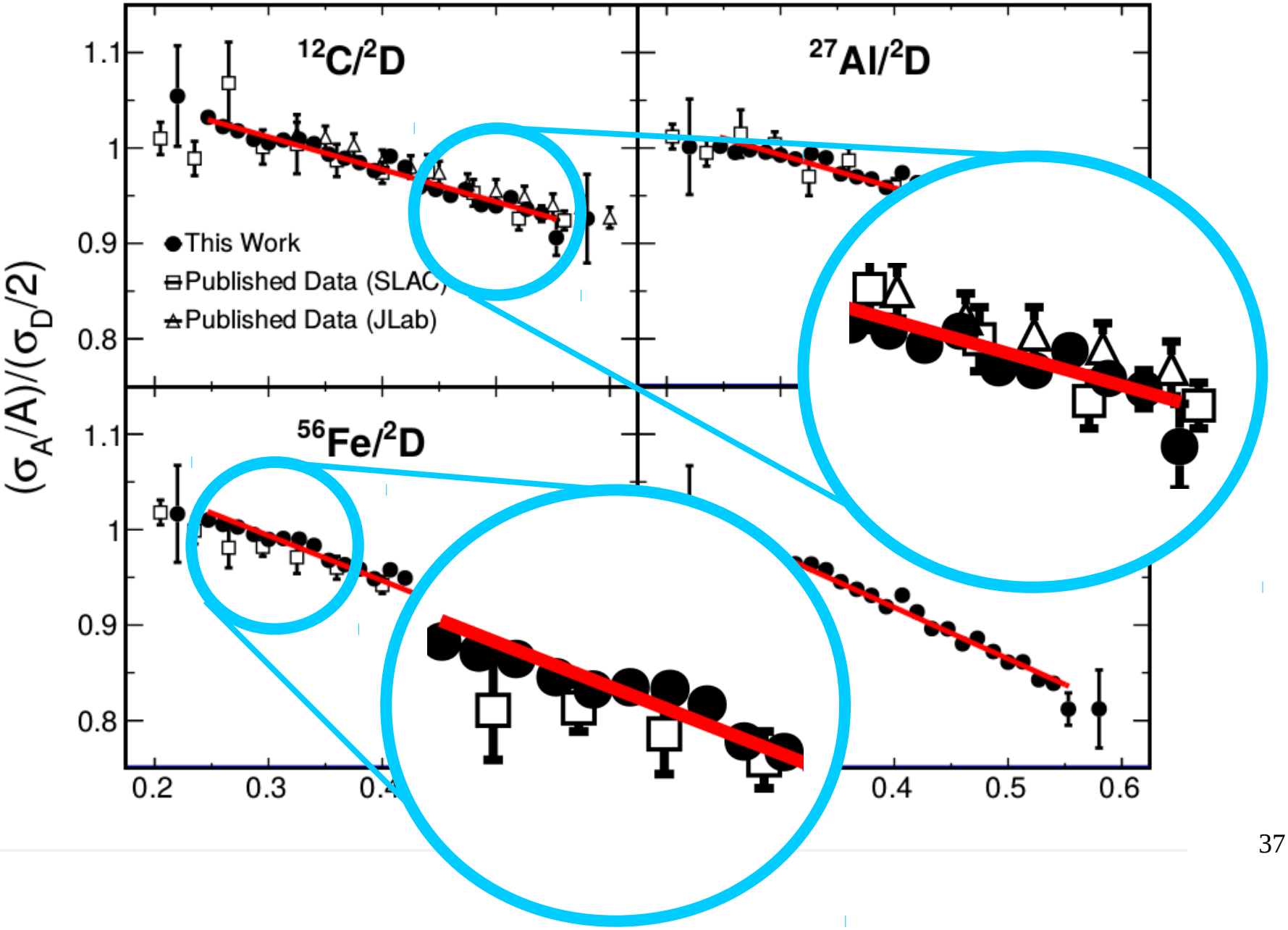
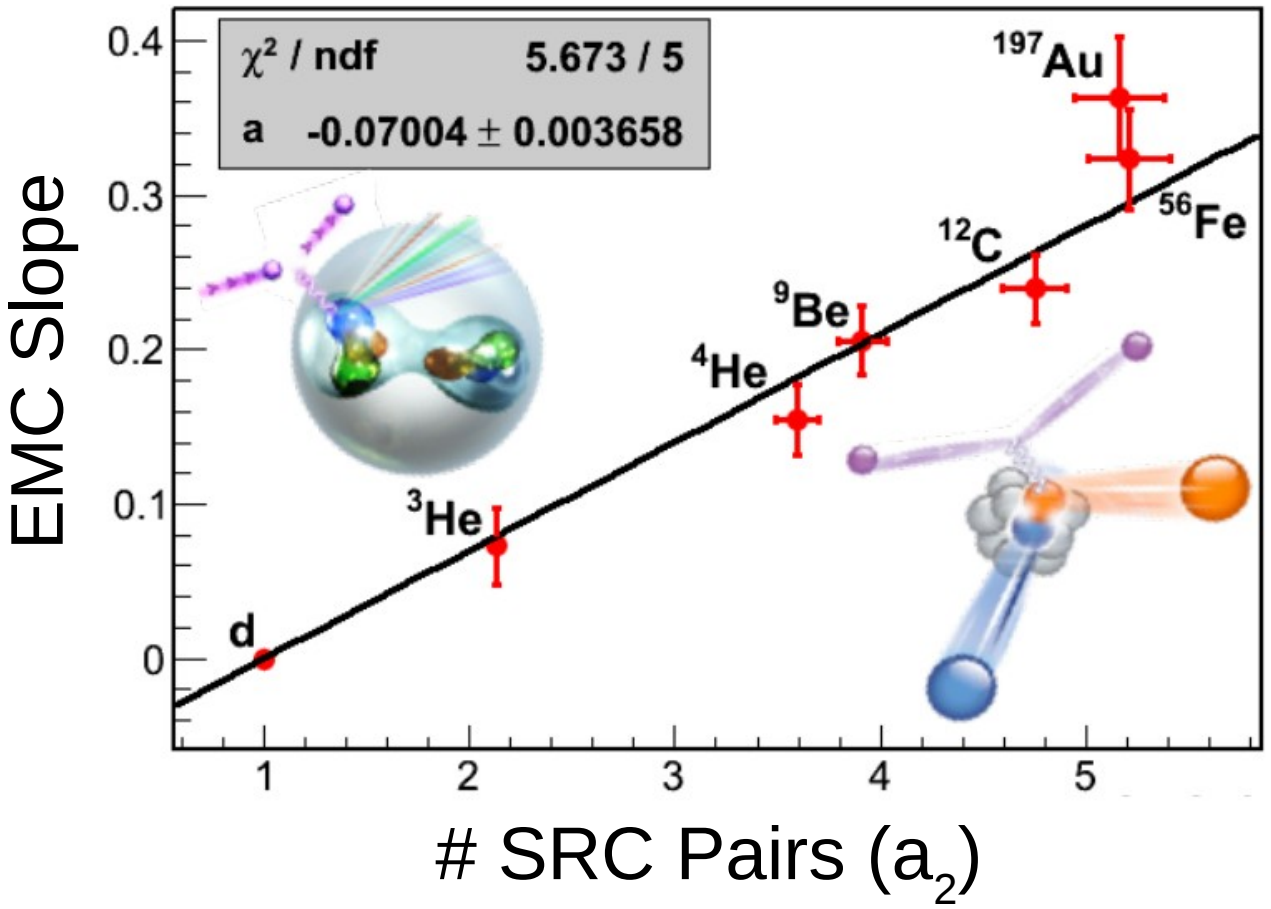
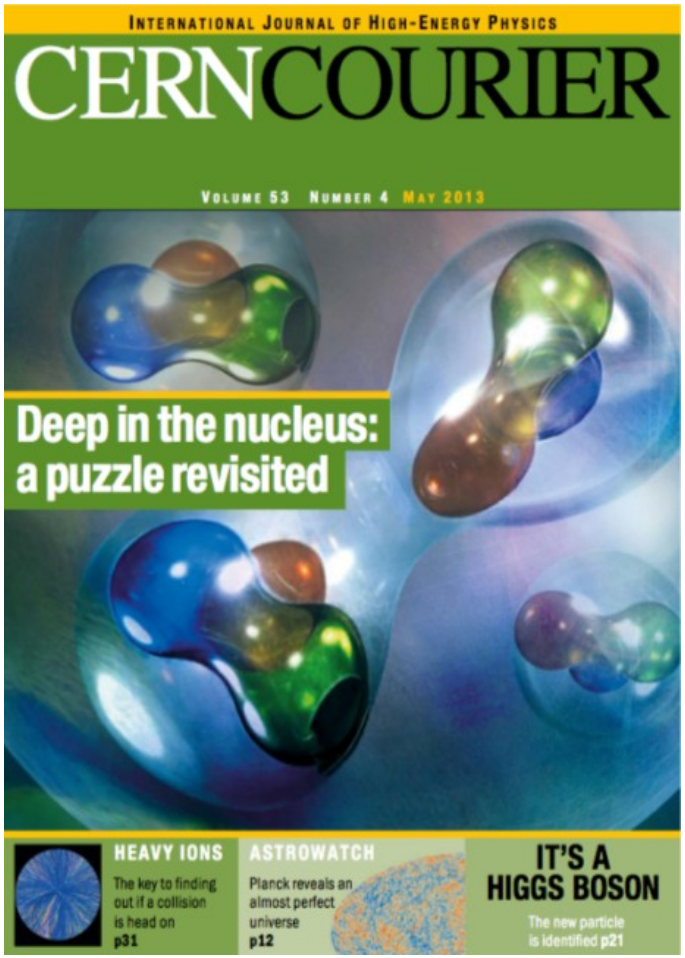


# Current Explanations of the EMC Effect

- 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



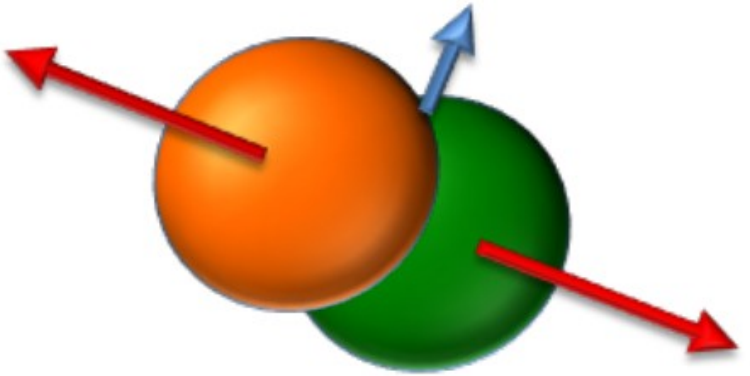




L. Weinstein et. al., Phys. Rev. Lett.06, 052301 (2011).
O. Hen et al. Phys. Rev. C 85 047301 (2012).
O. Hen et al., Rev. Mod. Phys. 89, 045002 (2017).

# Short Range Correlations (SRC)

Nucleon pairs that are close together in the nucleus

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



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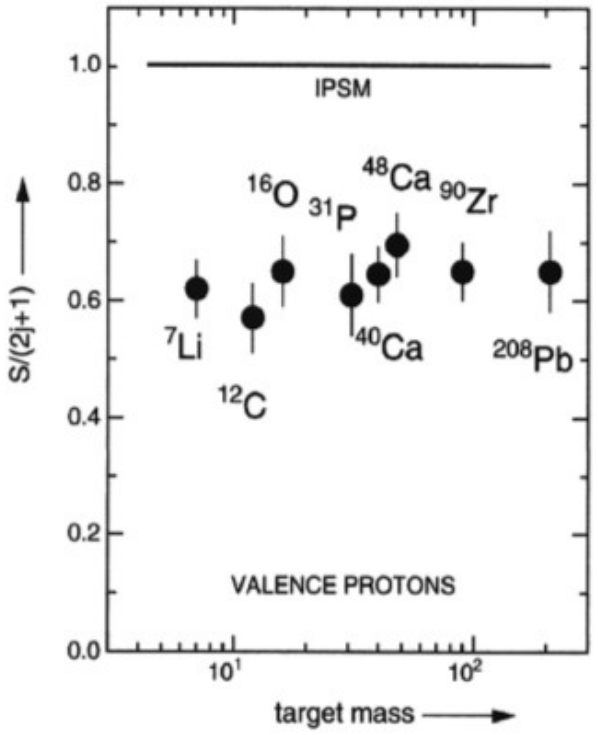


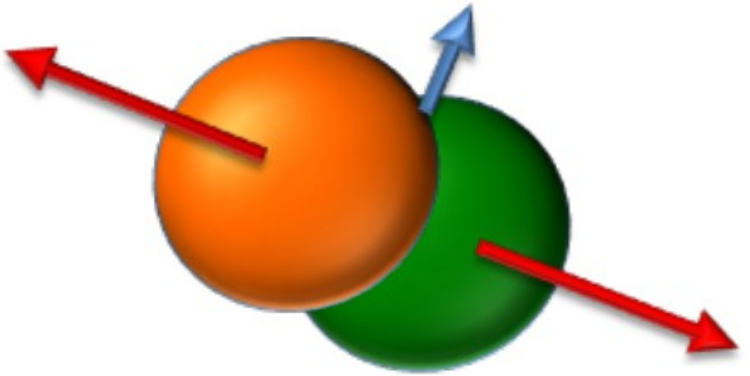

*L. Lapikas, Nucl. Phys. A 553, 297 (1993)*

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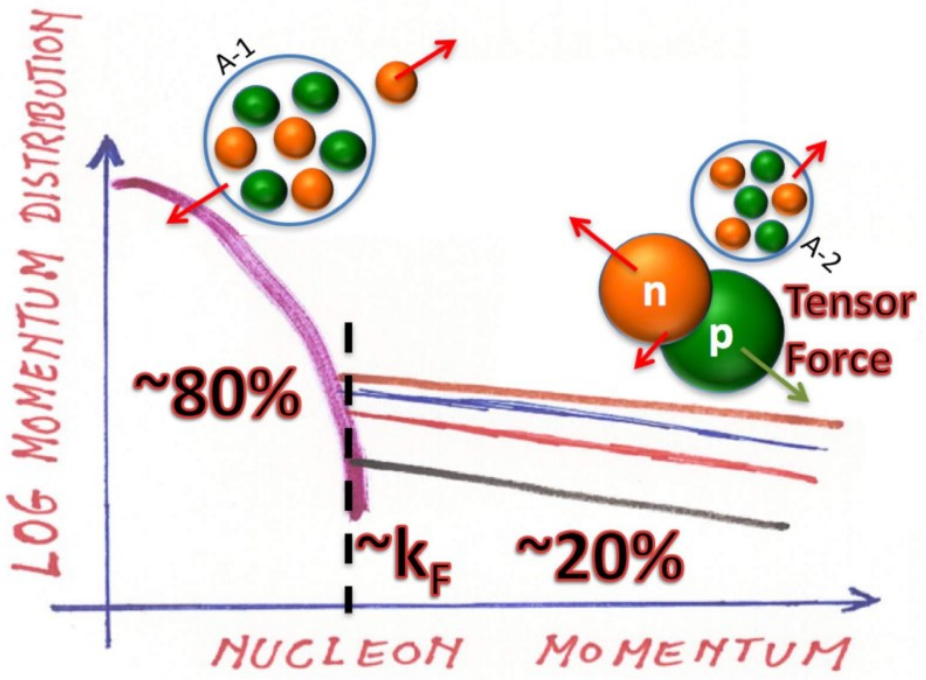
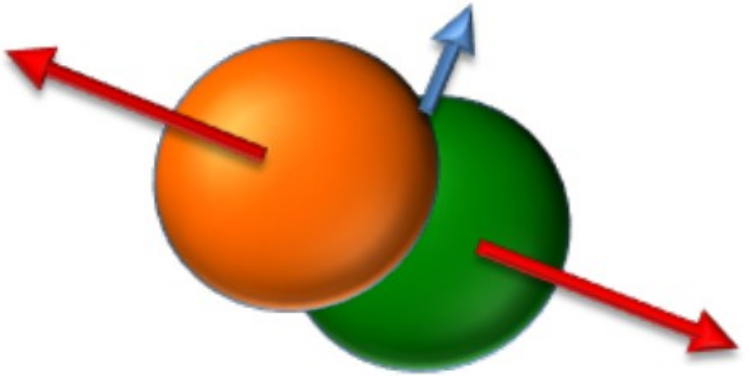
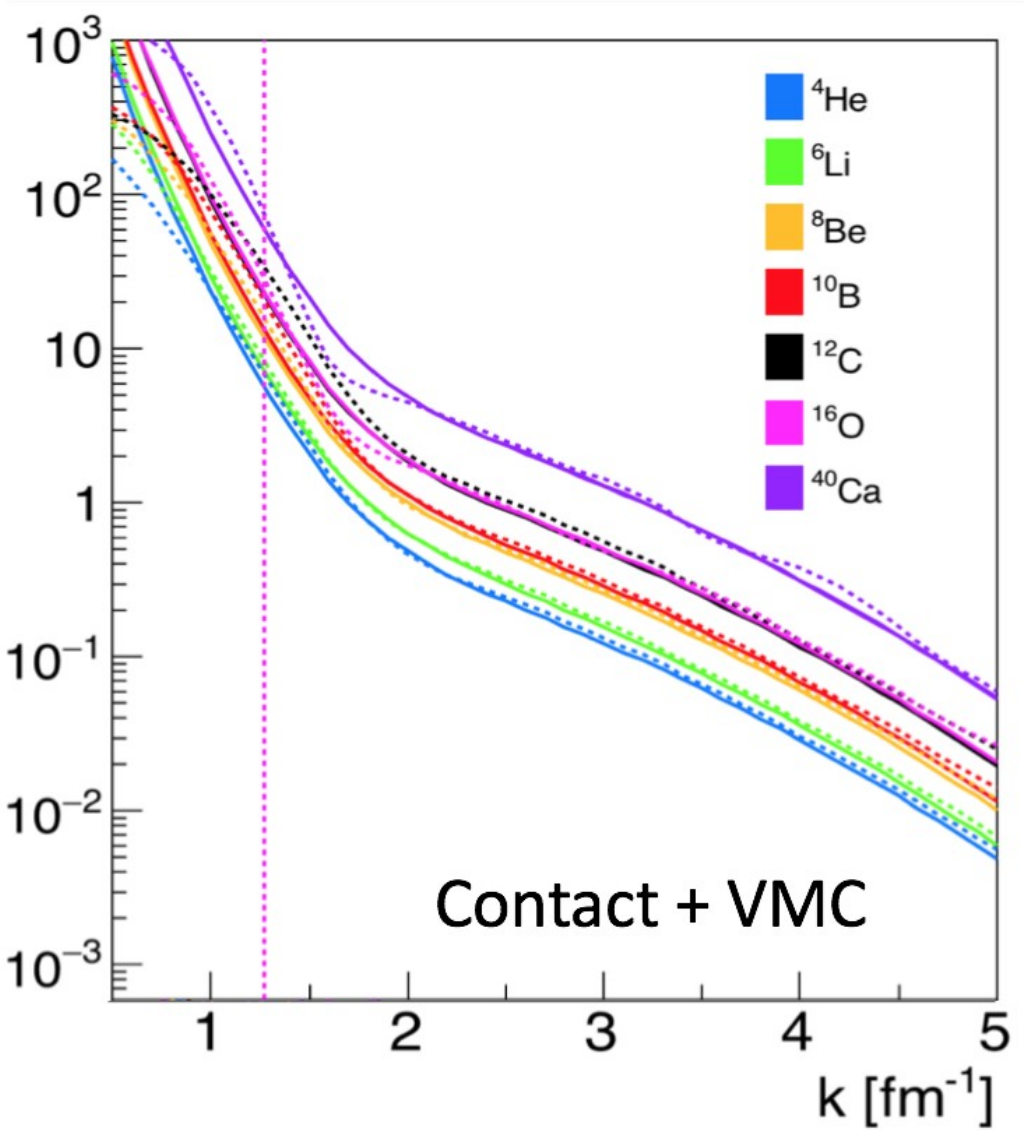


# Short Range Correlations (SRC)

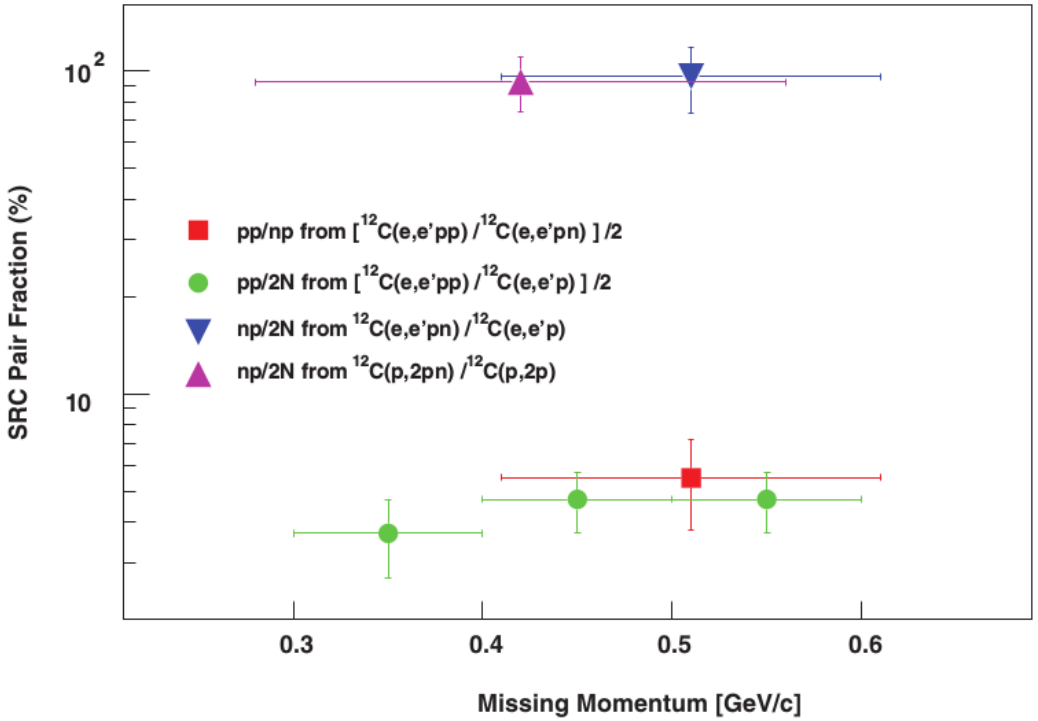



**Scaling: High-momentum component of nuclear wave function is deuteron-like.**

**$a_2$: 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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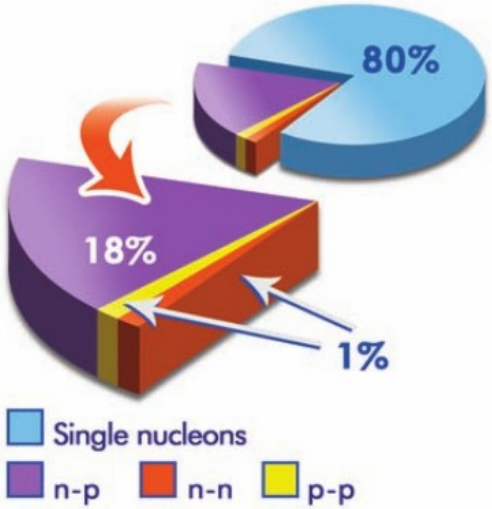
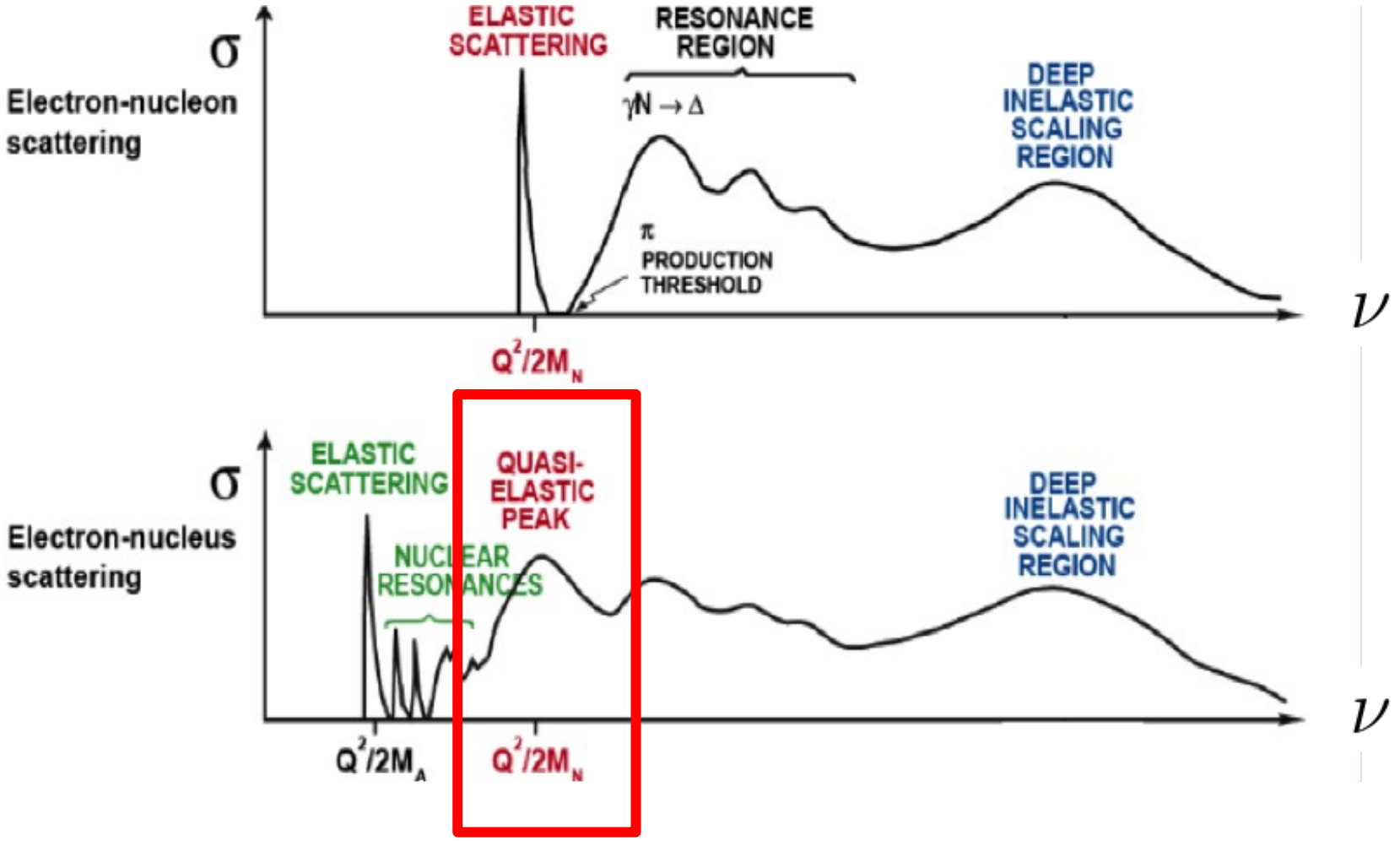
**Isospin Dependence: Dominated by neutron-proton pairs**



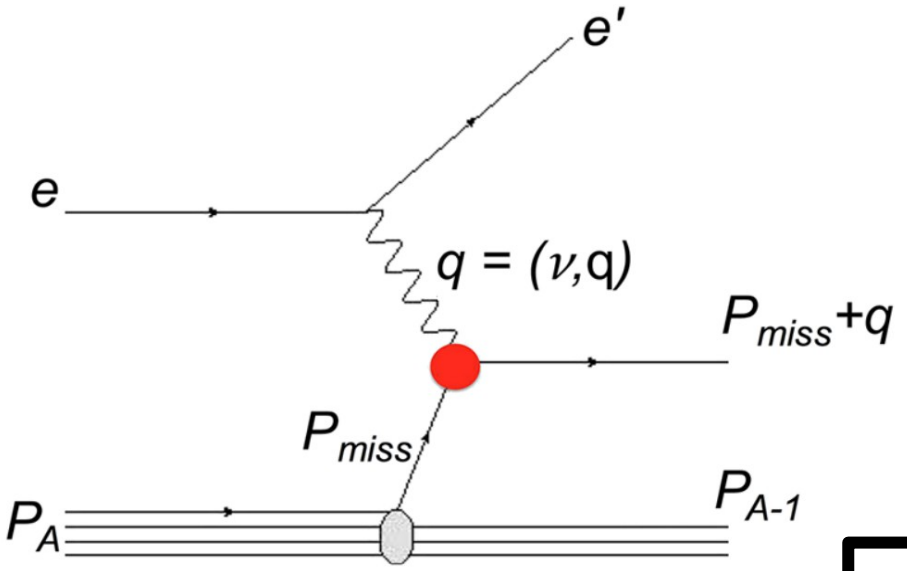

*R. Subedi et al., Science 320, 1476 (2008)*

# Quasi-Elastic (QE) Scattering:

Provides information on how the Nucleons move in the Nucleus



# QE Scattering: Impulse Approximation

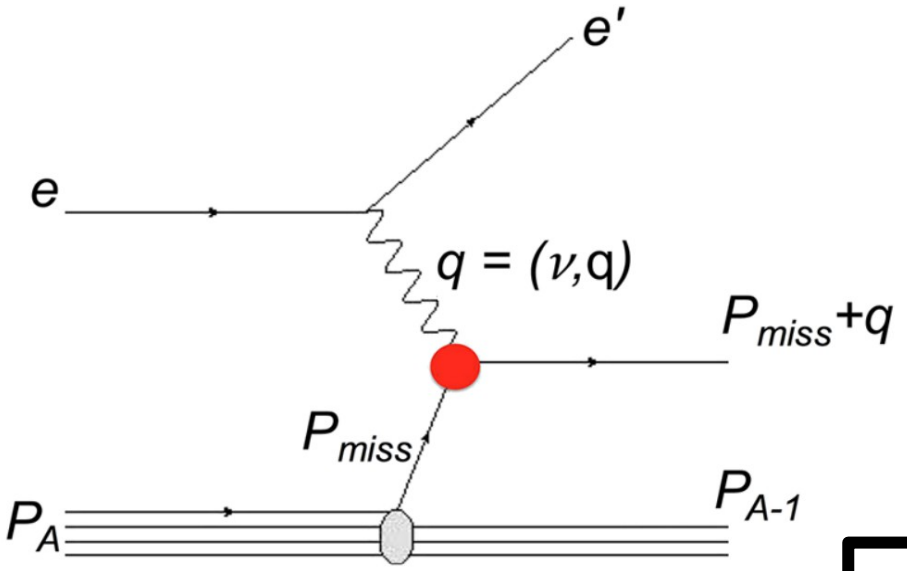



QE A(e,e'N)X scattering:

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

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

# QE Scattering: Impulse Approximation

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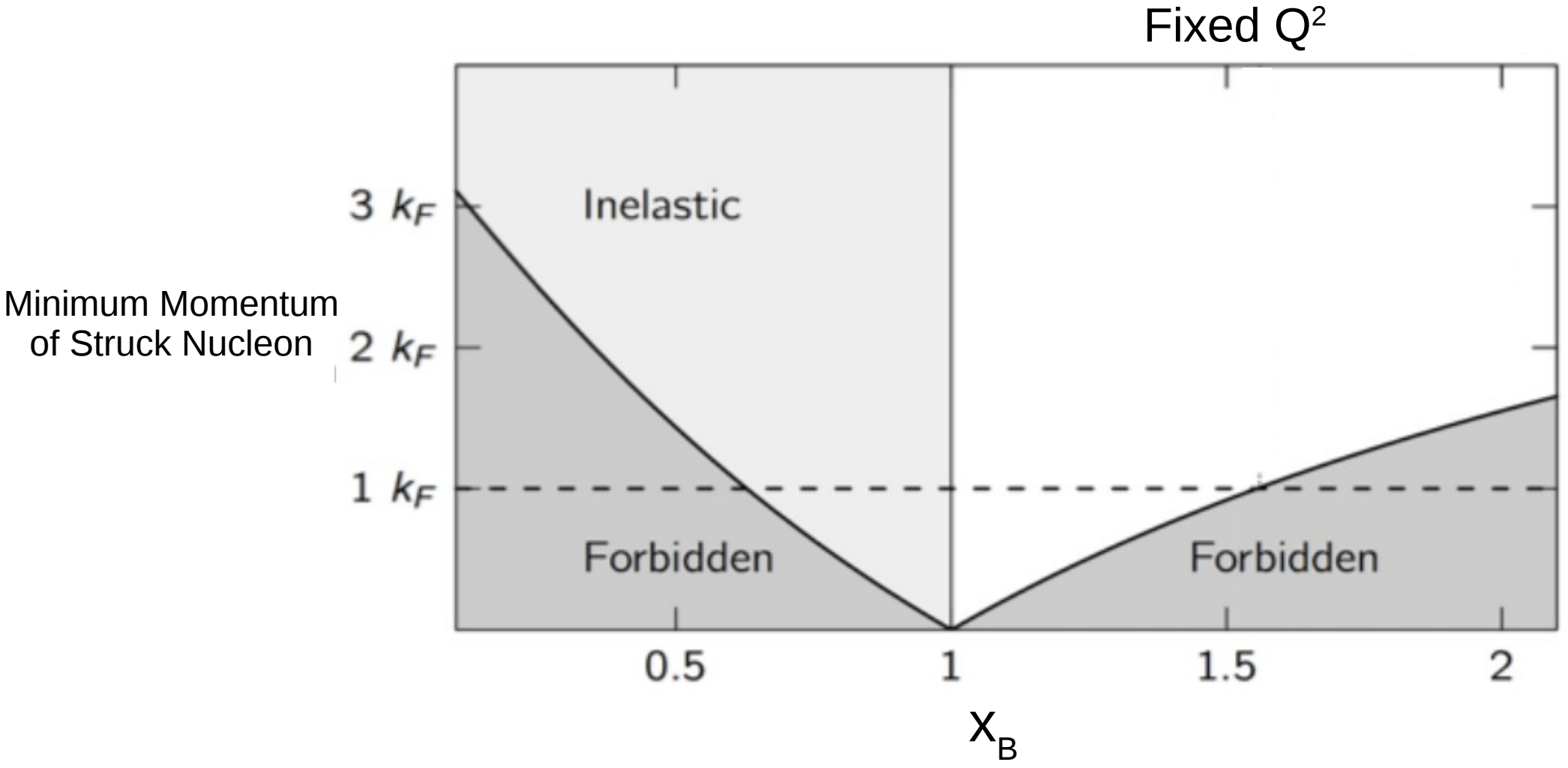
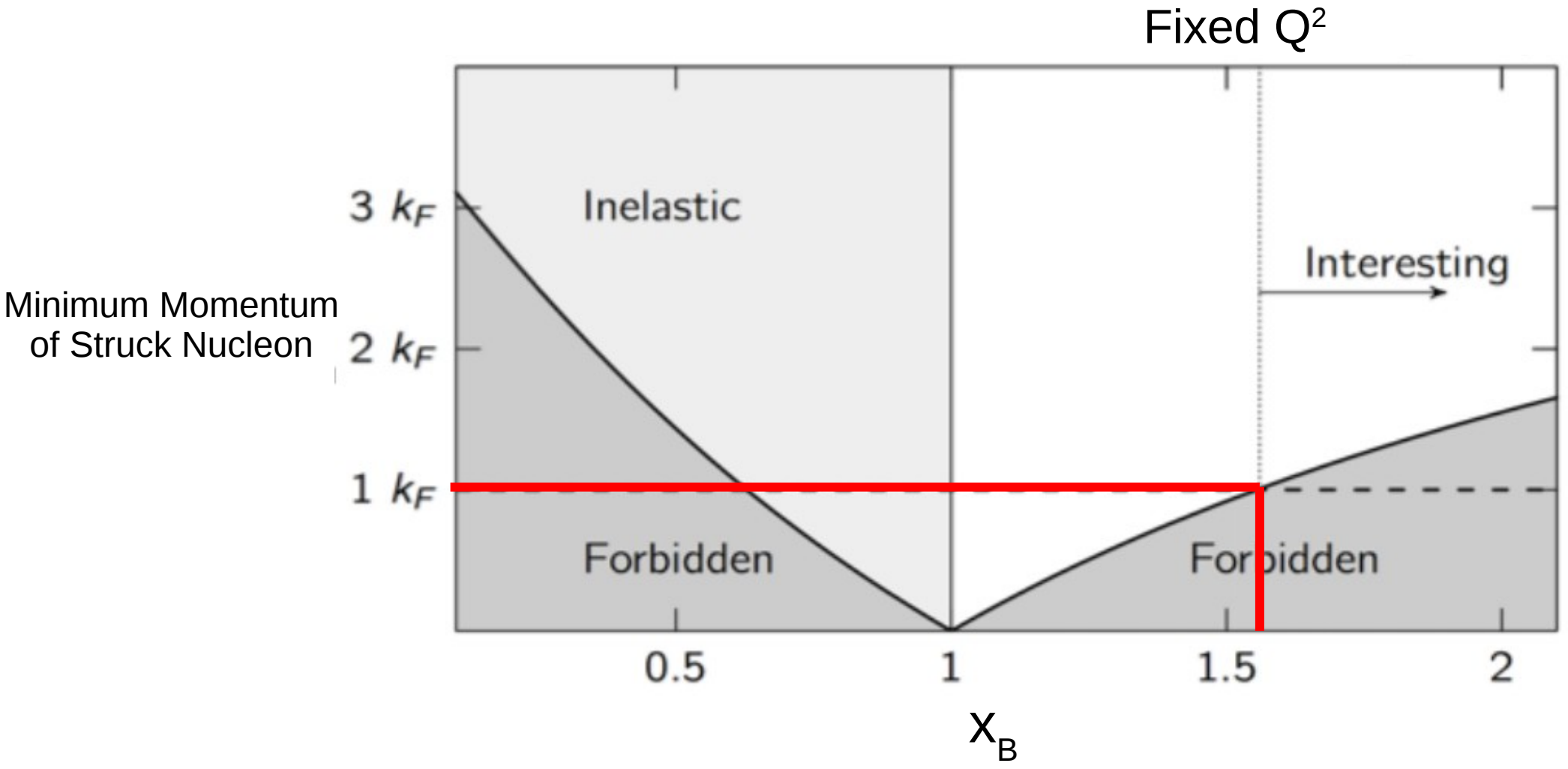
Inclusive QE scattering is an integral over the above cross-section

# What can be done with Inclusive Scattering

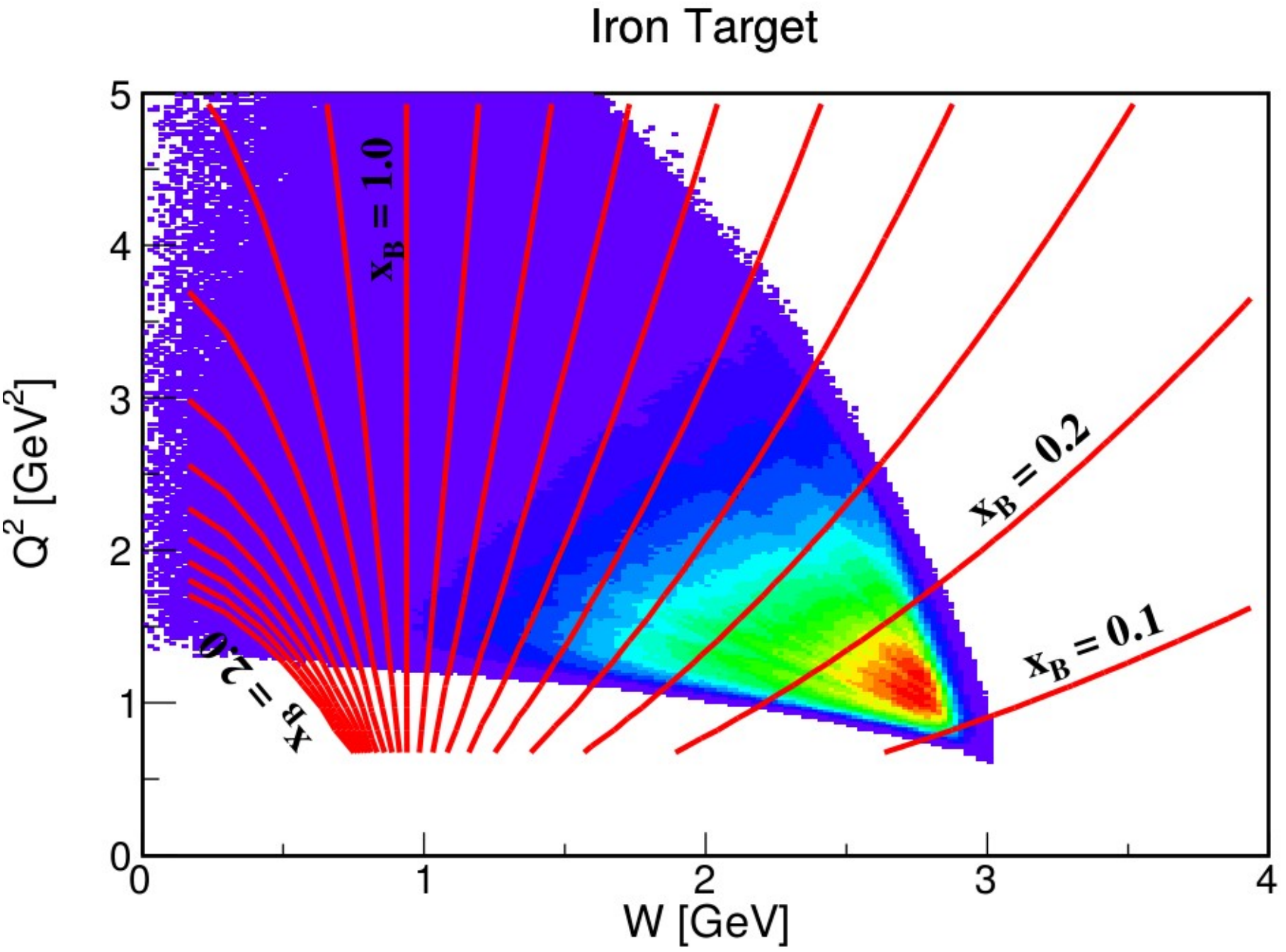


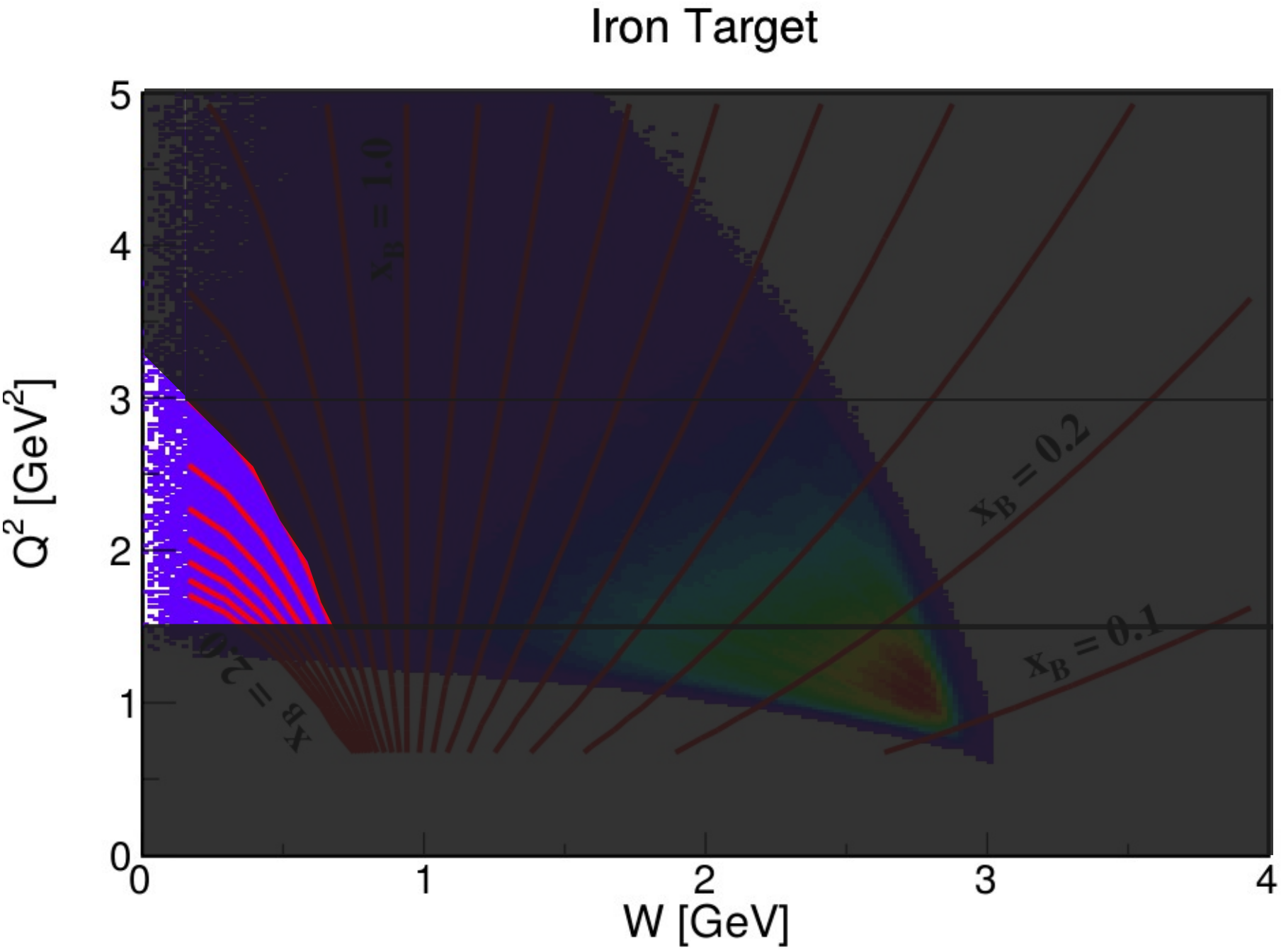

$$(q + p_A - p_{A-1})^2 = p_f^2 = m_N^2$$

# What can be done with Inclusive Scattering




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


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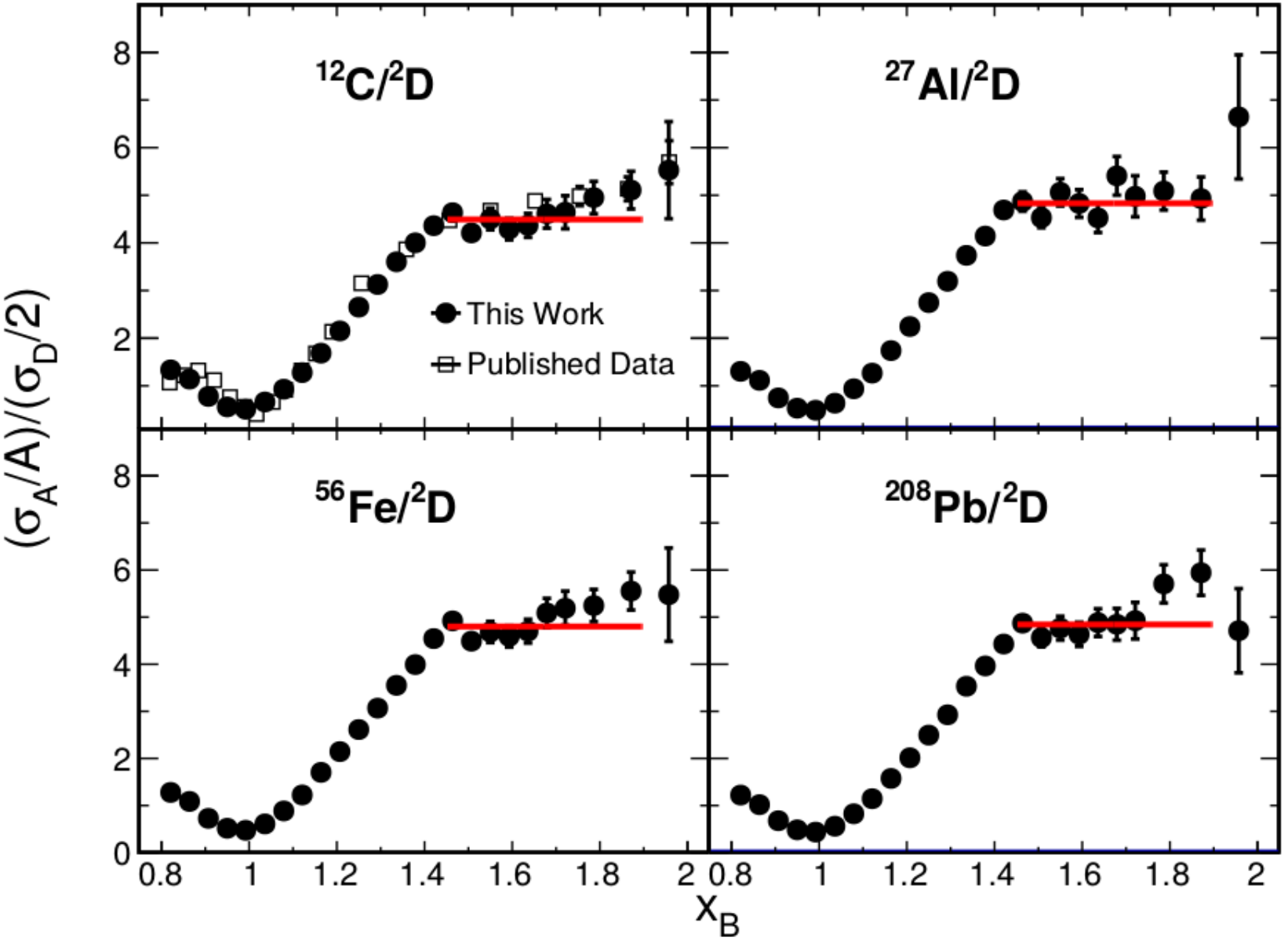
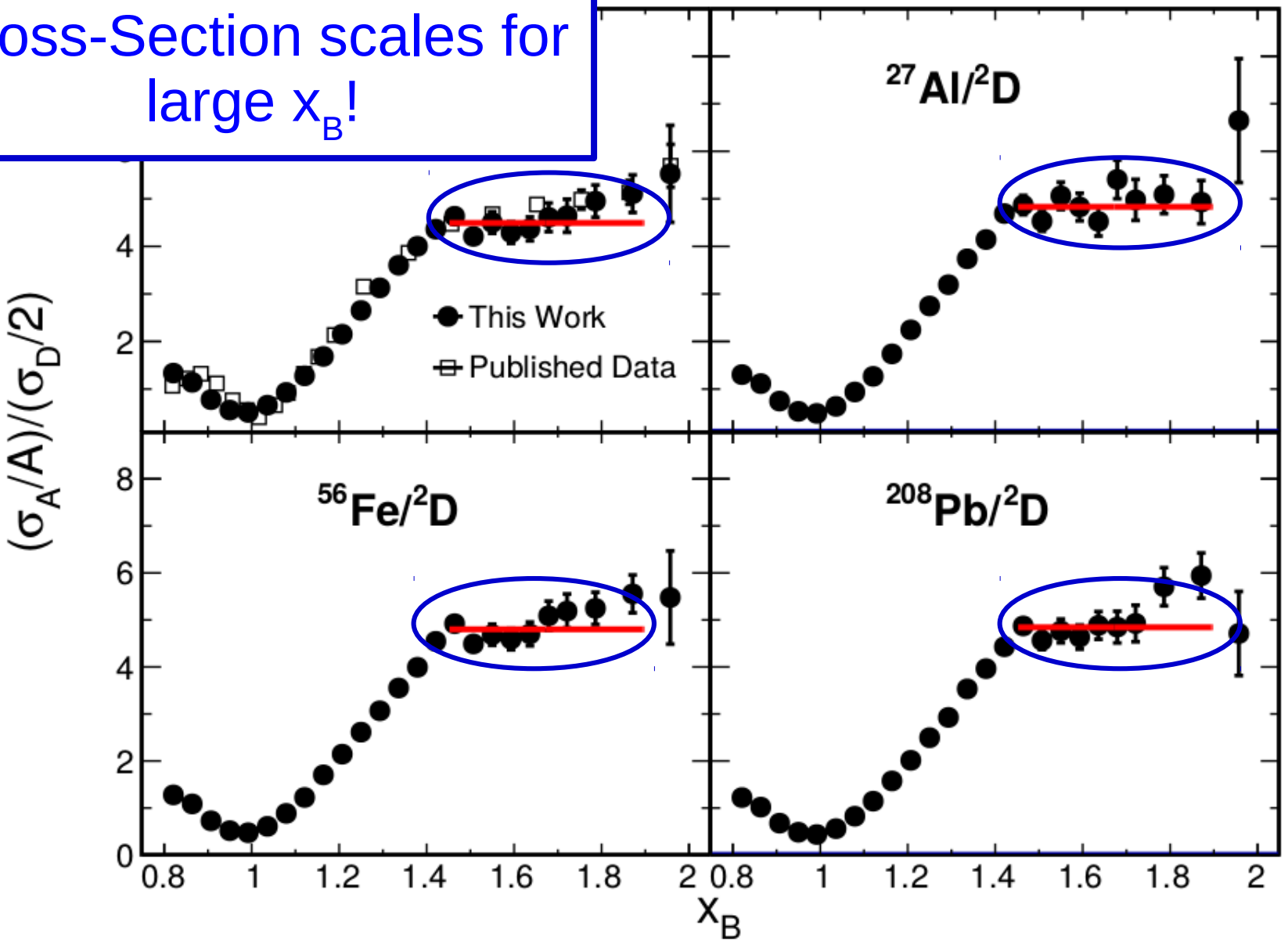
0
1
2
3
4
5

# Our New $a_2$ Measurements



# Our New $a_2$ Measurements

Cross-Section scales for large $x_B$!



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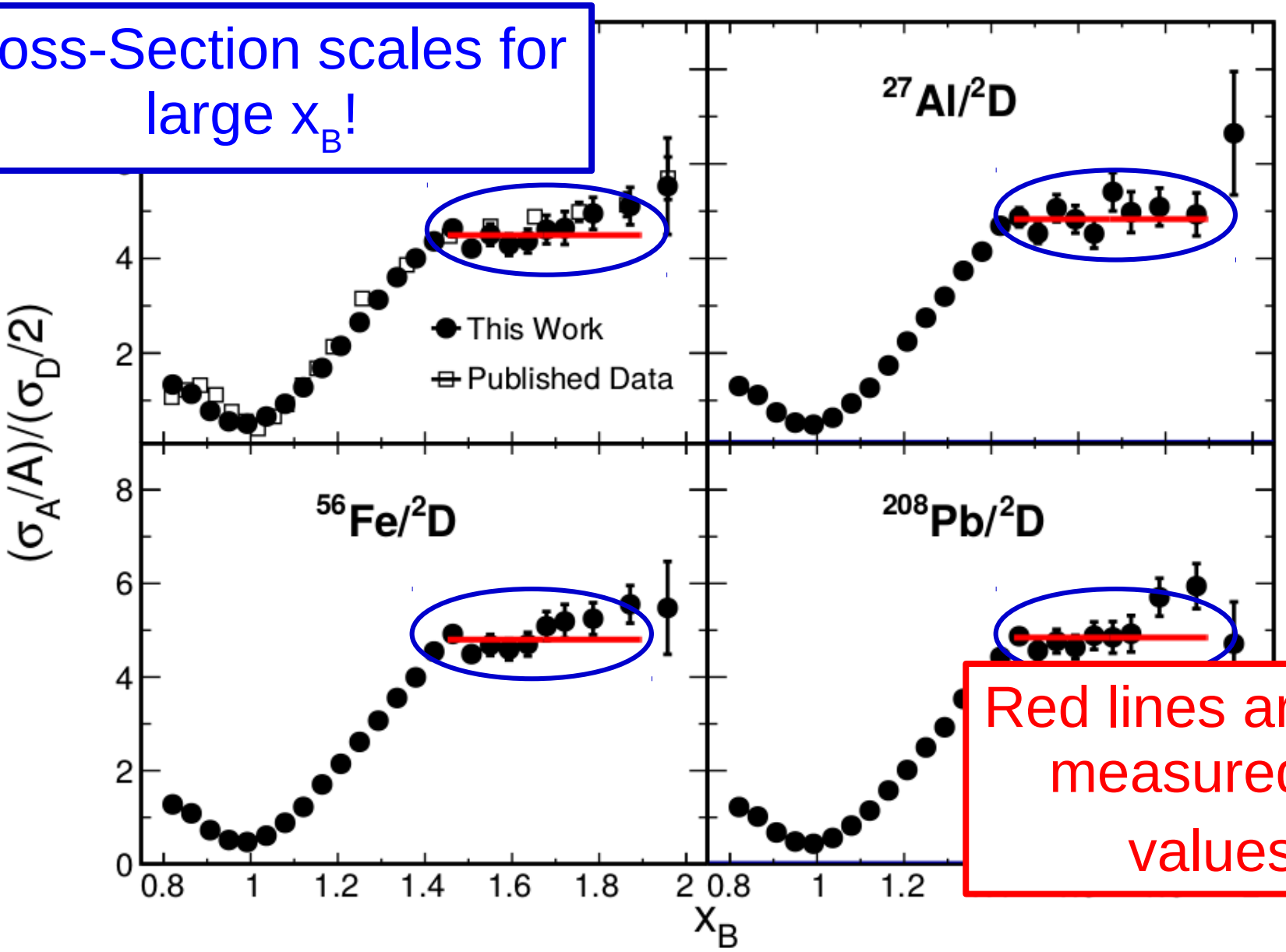
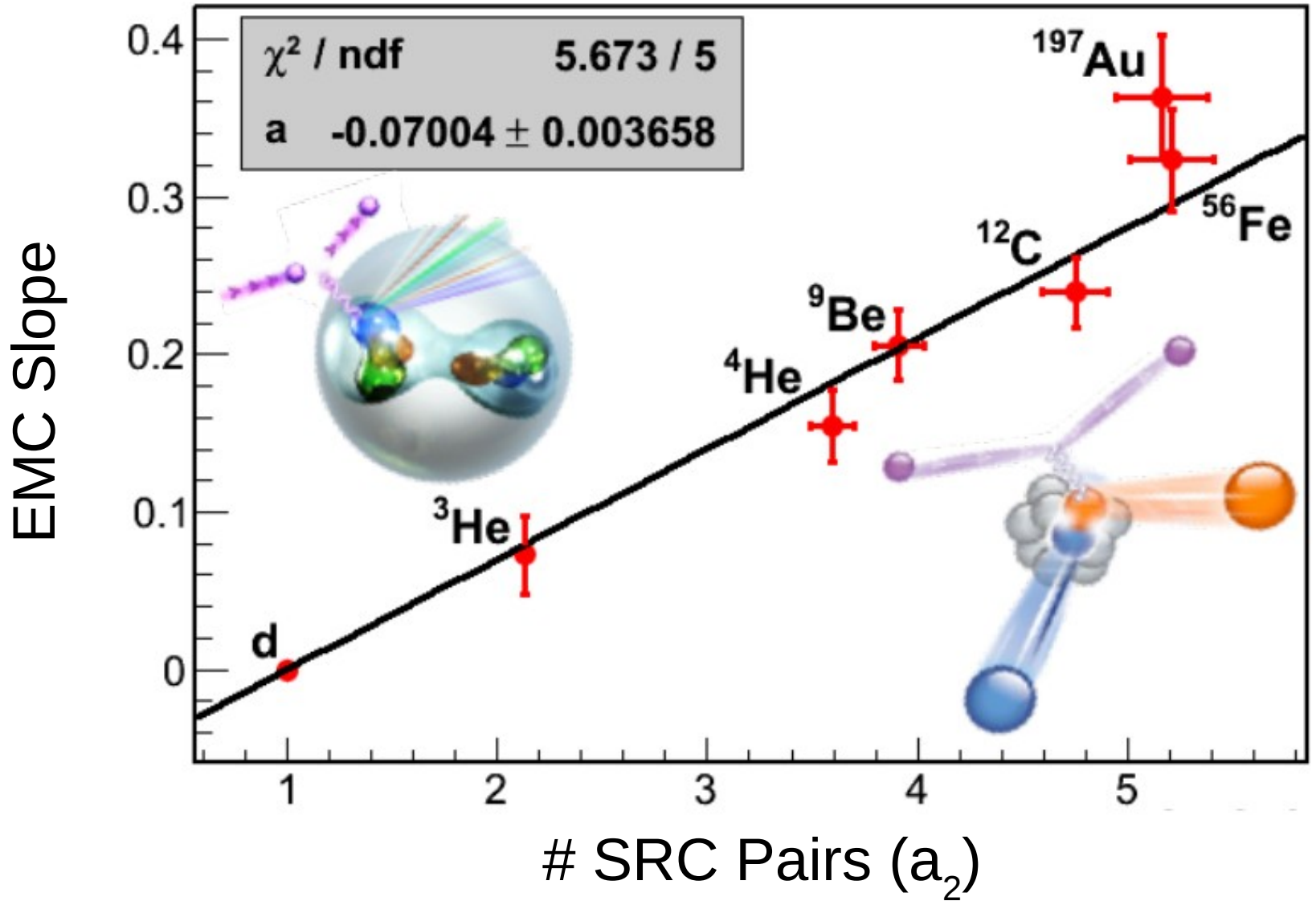


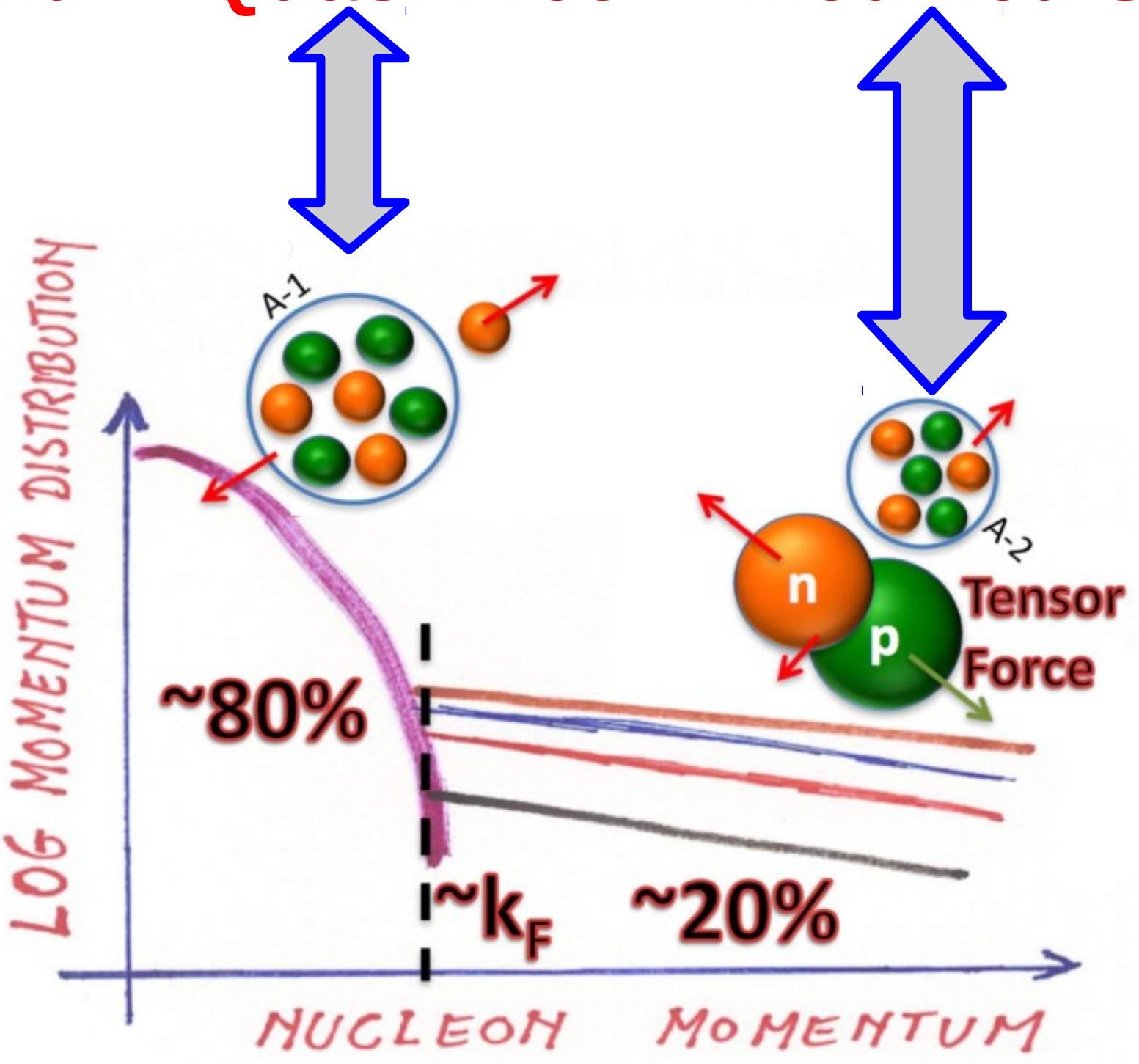

Red lines are the measured $a_2$ values

# Back to the EMC-SRC Correlation



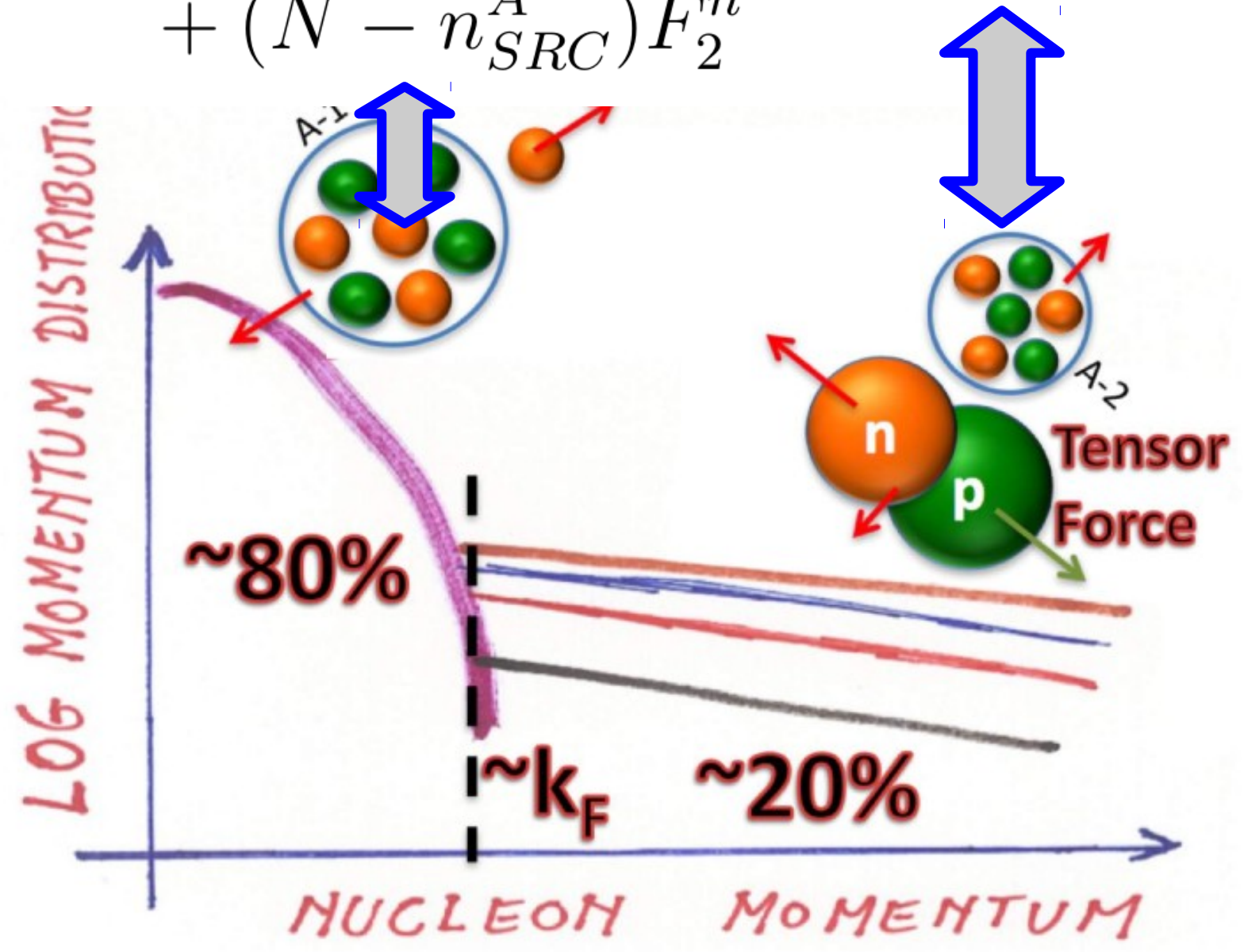

L. Weinstein et. al., Phys. Rev. Lett.06, 052301 (2011).
O. Hen et al. Phys. Rev. C 85 047301 (2012).
O. Hen et al., Rev. Mod. Phys. 89, 045002 (2017).

# Bound = 'Quasi Free' + Modified SRCs



# Bound = 'Quasi Free' + Modified SRCs

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



# Bound = 'Quasi Free' + Modified SRCs

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

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

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

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

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

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

# Our Model's Prediction for the EMC Effect

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

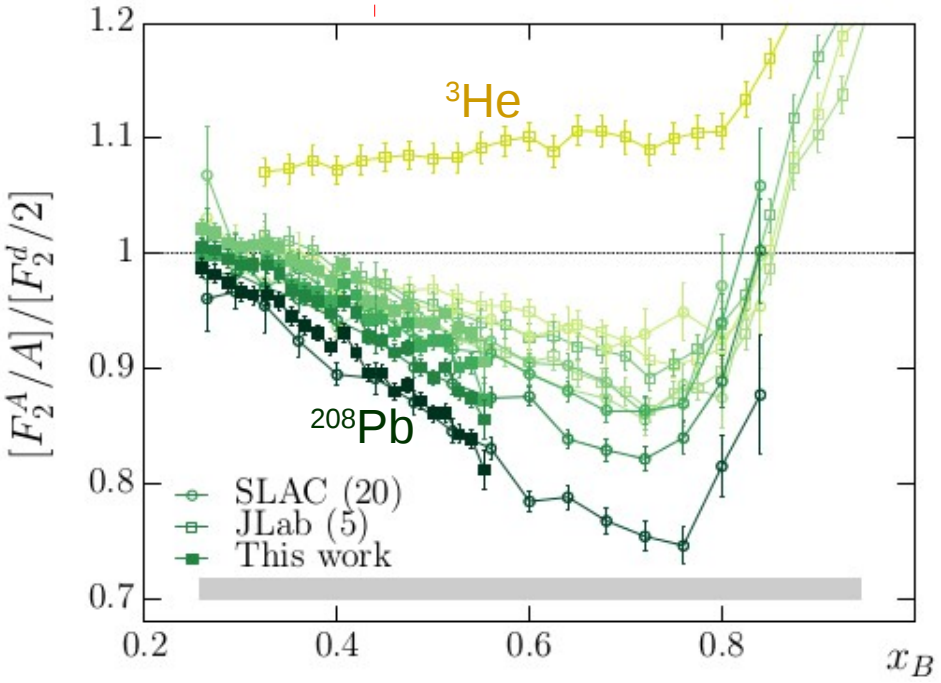
$$\boxed{a_2 = \frac{n_{SRC}^A/A}{n_{SRC}^d/2}}$$

# Our Model's Prediction for the EMC Effect

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

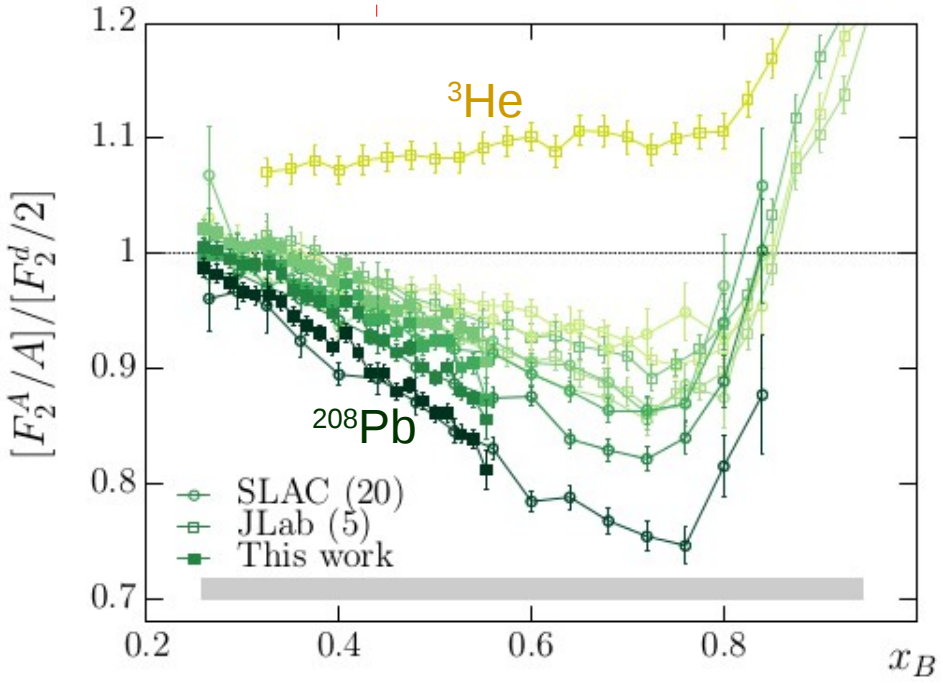
**Universal?**

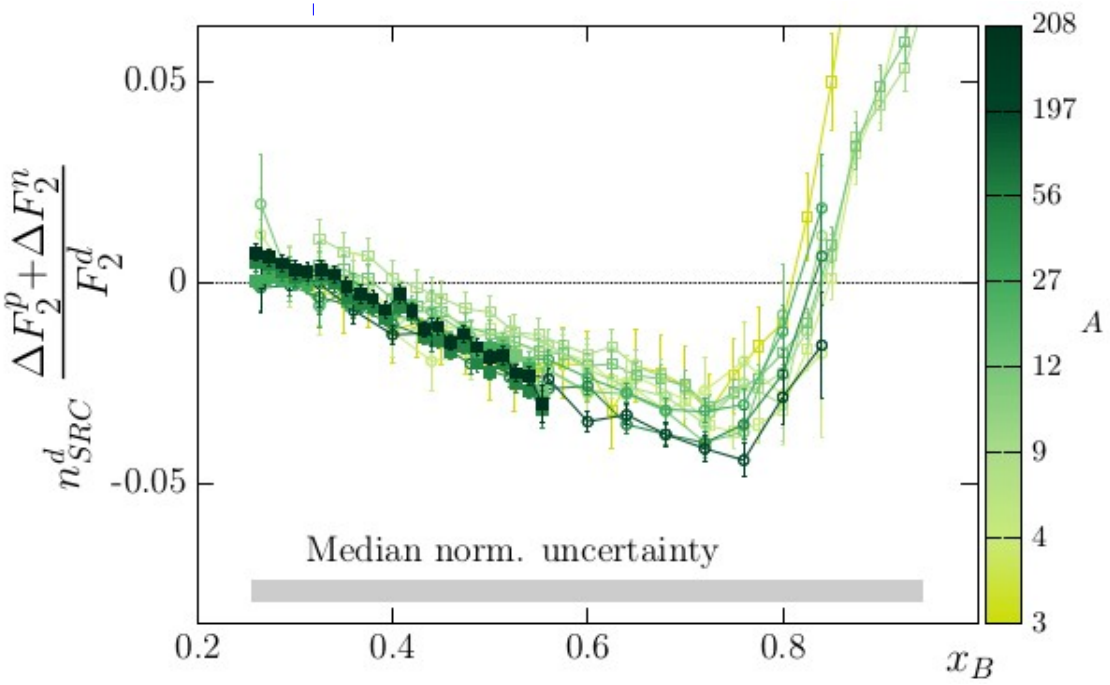
$$\frac{F_2^A/A}{F_2^d/2} = (a_2 - 2\frac{N}{A})(n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}) + 2 \cdot \frac{Z-N}{Z+N} \cdot \frac{F_2^p}{F_2^d} + 2\frac{N}{A}$$



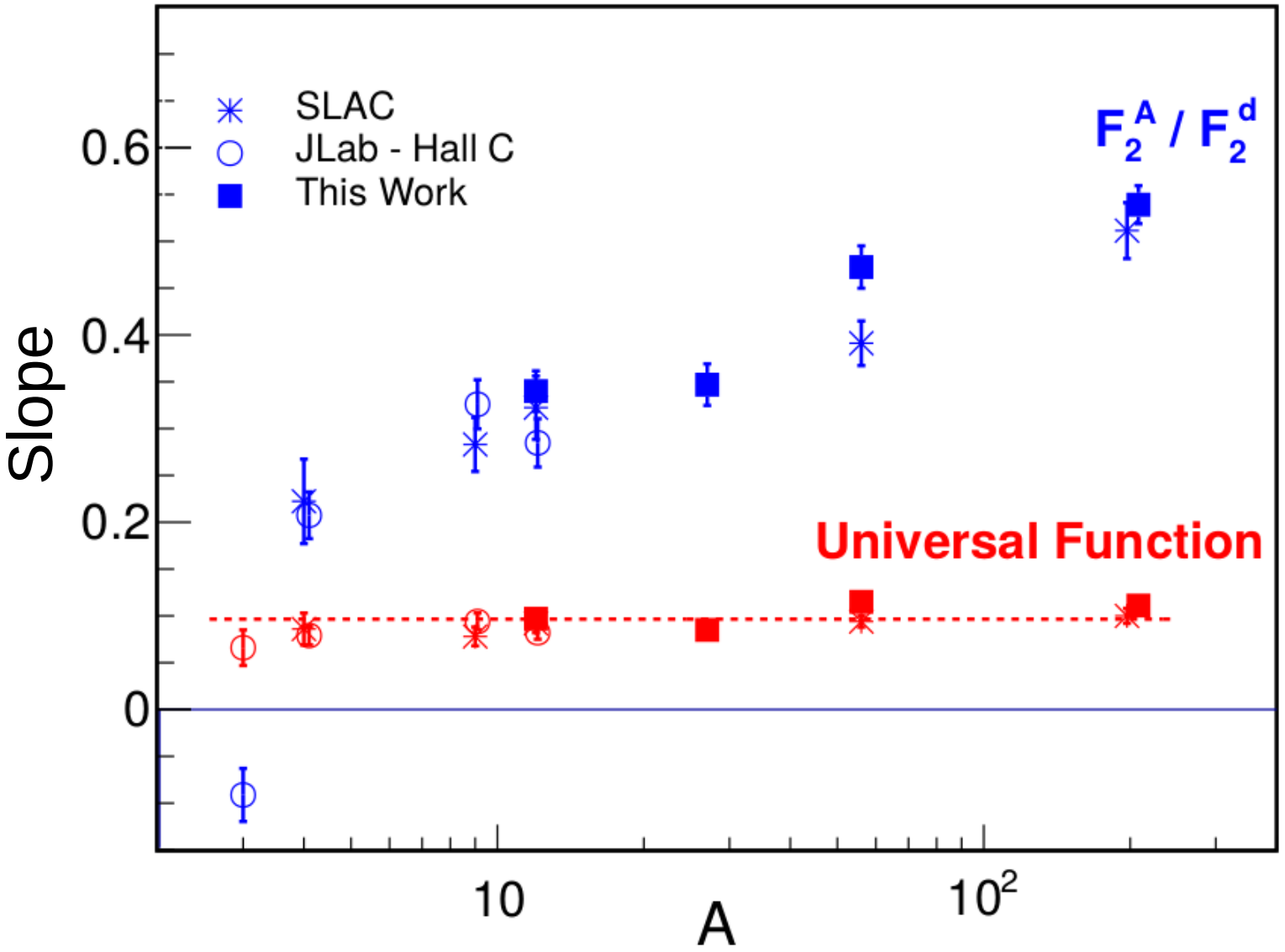
$$\frac{F_2^A/A}{F_2^d/2} = (a_2 - 2\frac{N}{A}) + (n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}) + 2 \cdot \frac{Z-N}{Z+N} \cdot \frac{F_2^p}{F_2^d} + 2\frac{N}{A}$$

**Universal!!**

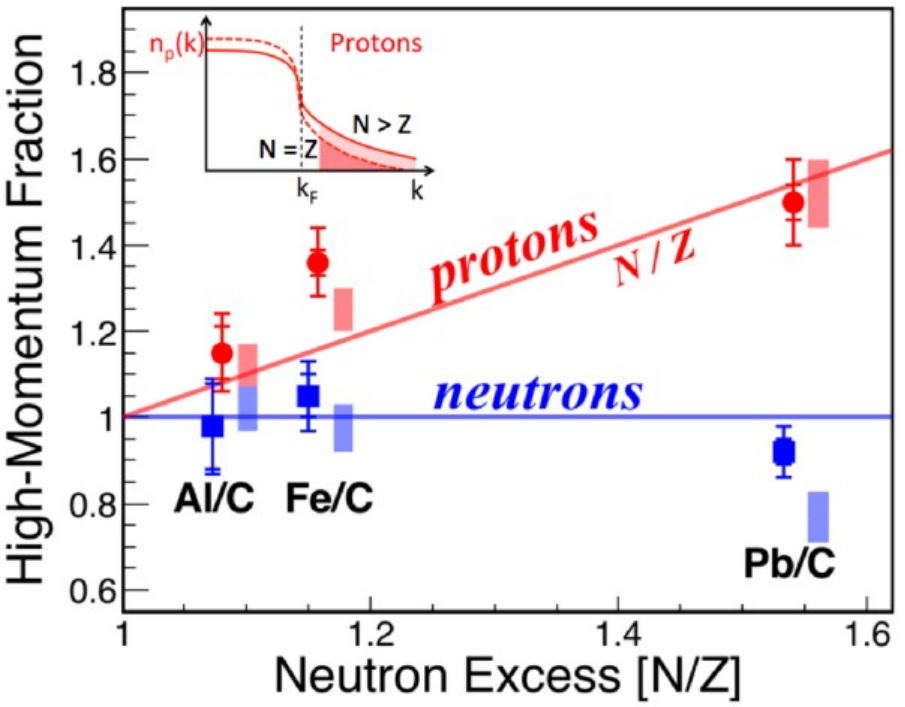


# EMC Universal Modification Function



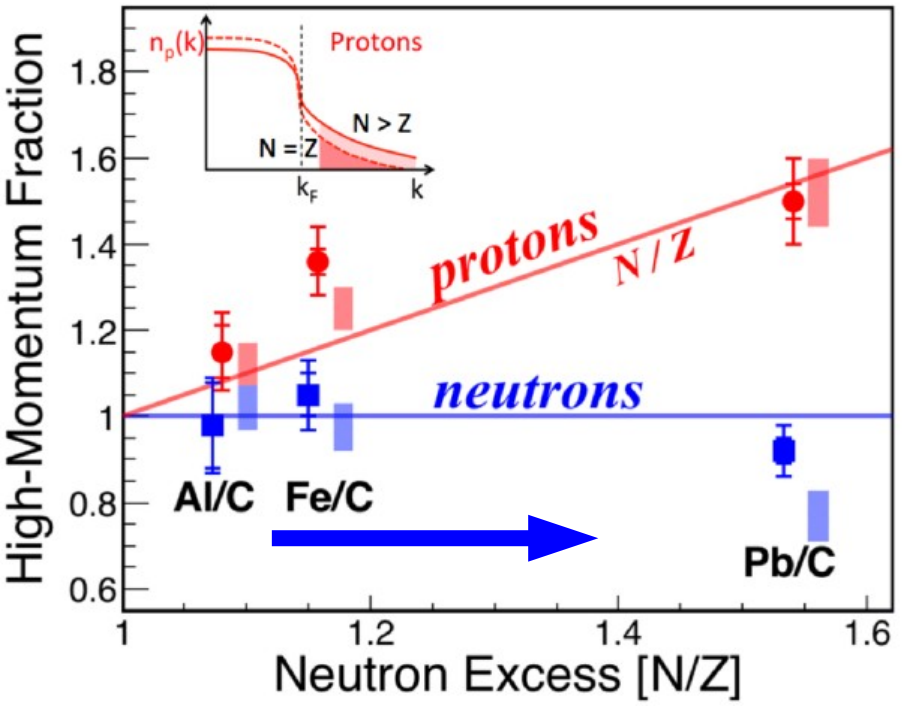
# Focus on Neutron-Rich Nuclei




*M.Duer, CLAS Collaboration, Nature 560, 617 (2018)*

# Focus on Neutron-Rich Nuclei

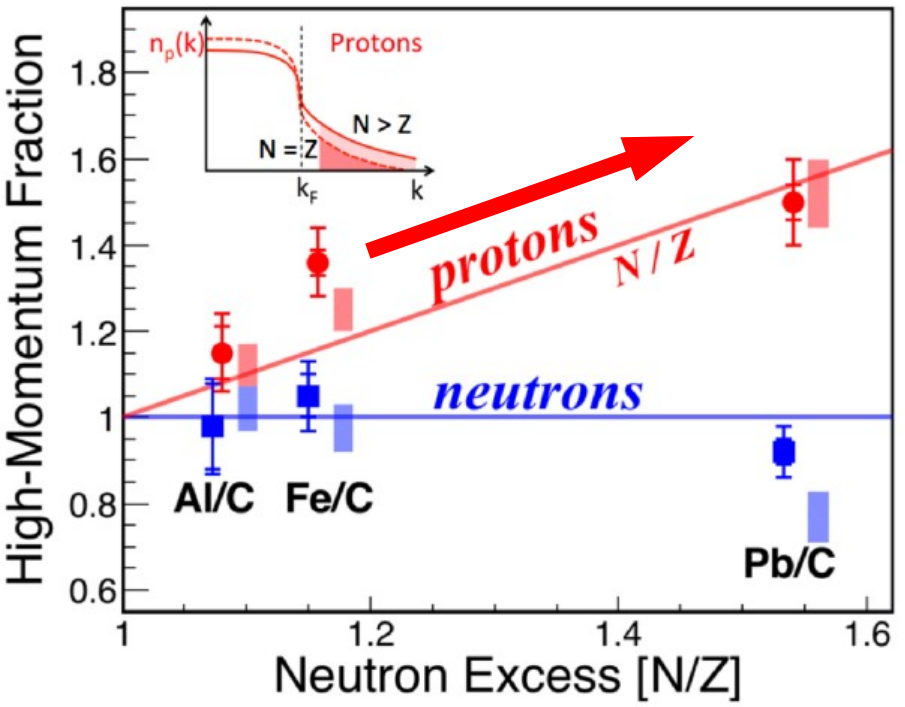
**Prediction**: EMC effect will show no growth for neutrons ...




*M.Duer, CLAS Collaboration, Nature 560, 617 (2018)*

# Focus on Neutron-Rich Nuclei

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




*M.Duer, CLAS Collaboration, Nature 560, 617 (2018)*

# Calculate Per-Neutron (Per-Proton) Ratios

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

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

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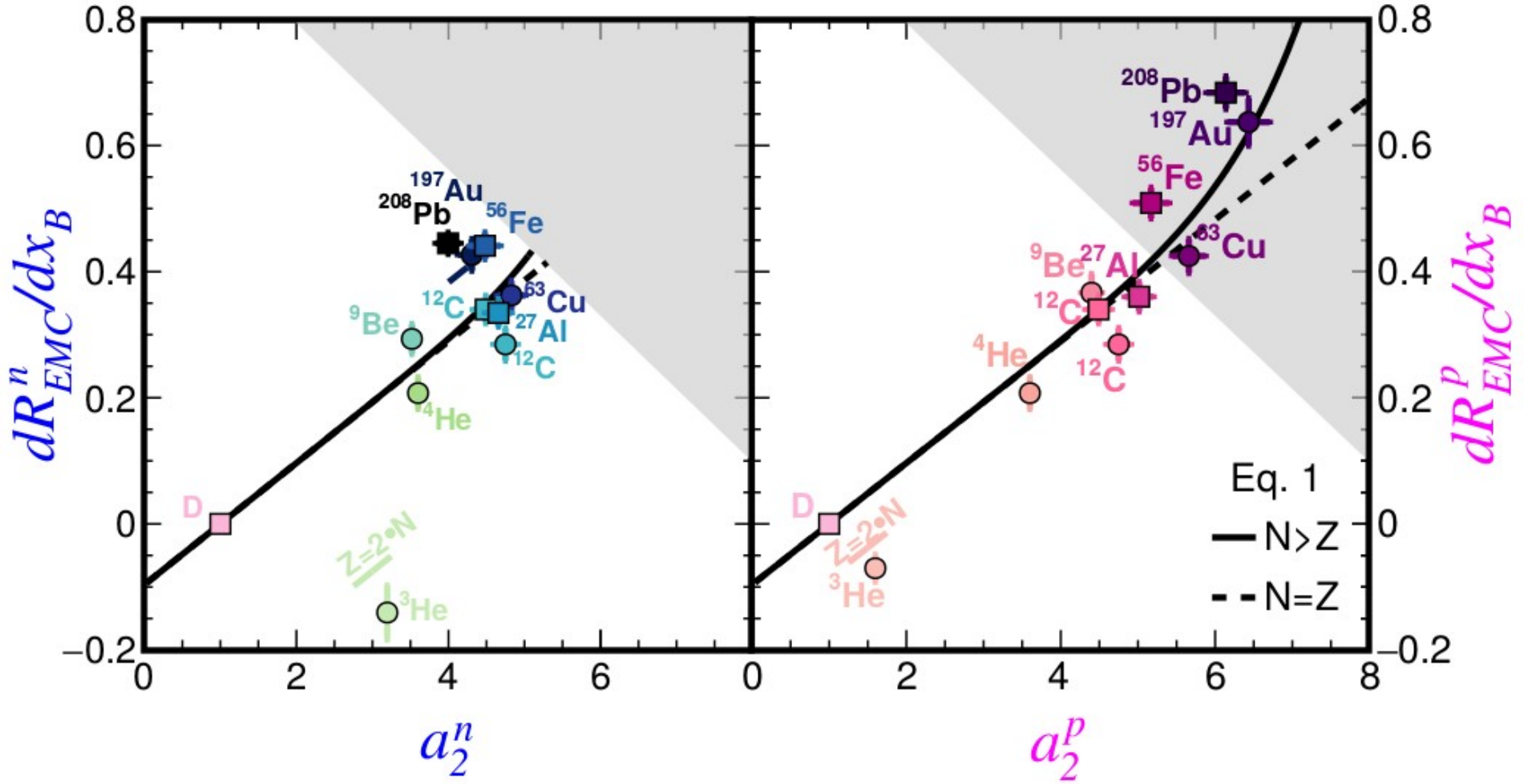
Per-Neutron: $\dfrac{\sigma_A/N}{\sigma_D/1}$

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

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

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

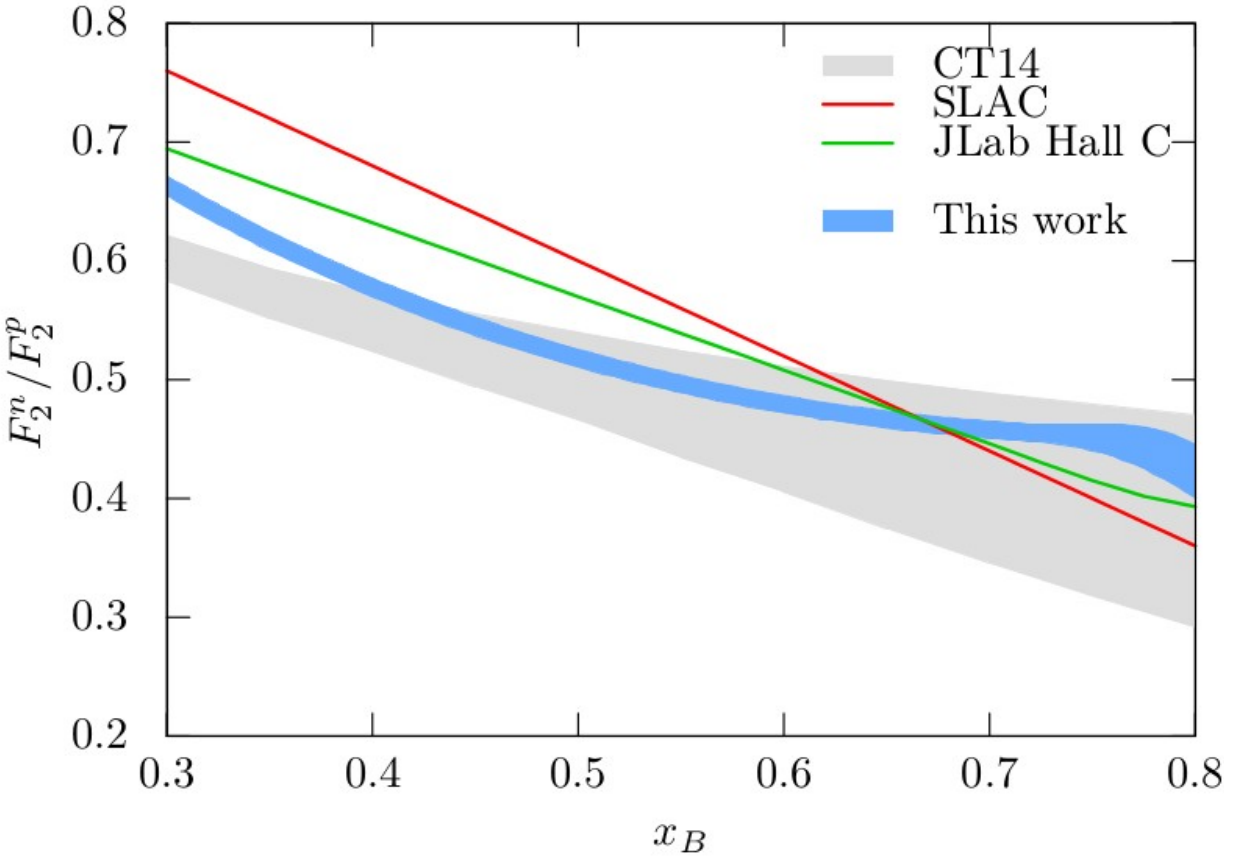
# New EMC-SRC Correlation



# Isoscalar Corrections for DIS Ratios

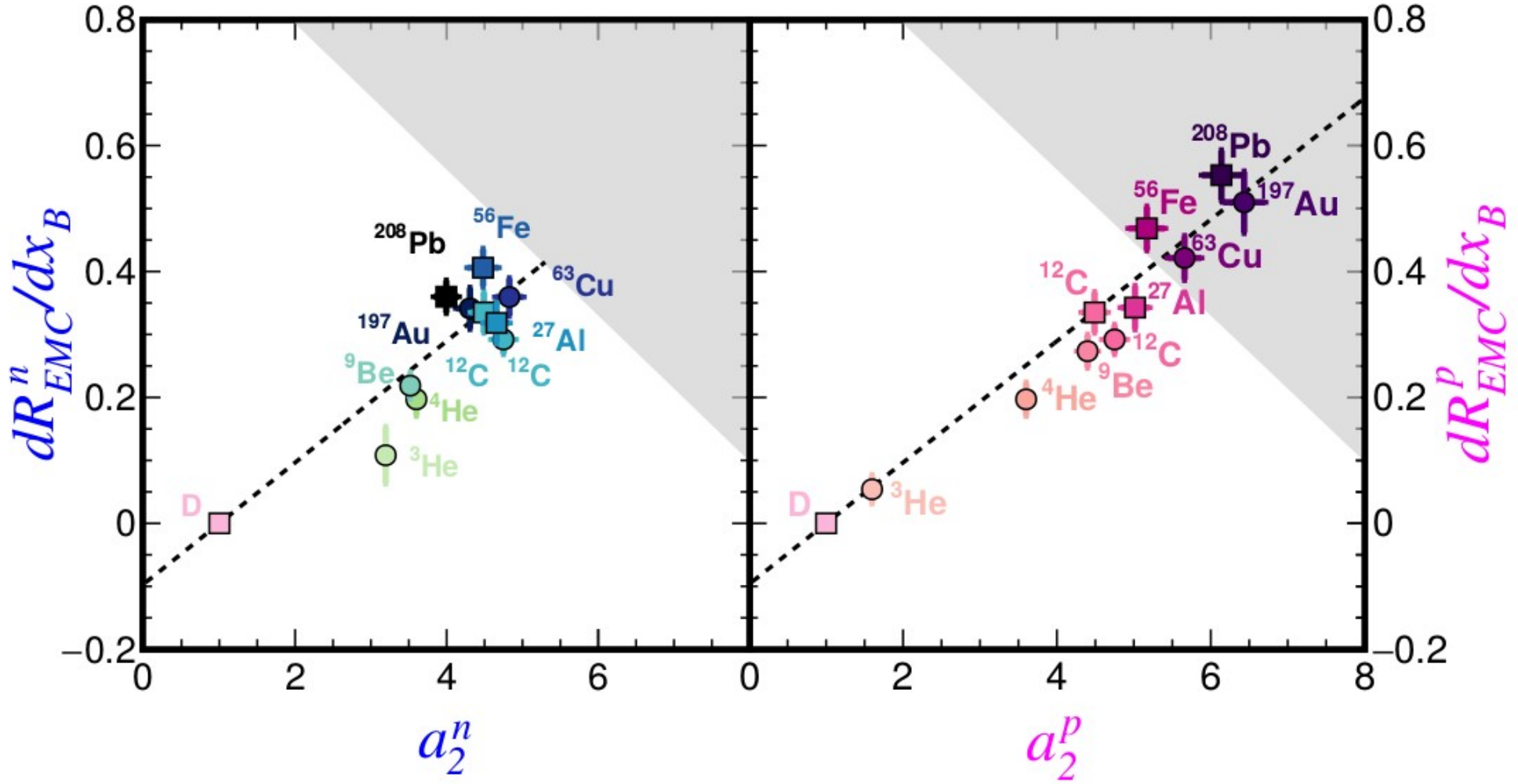
Correction Factor:

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




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

# New EMC-SRC Correlation: Version II



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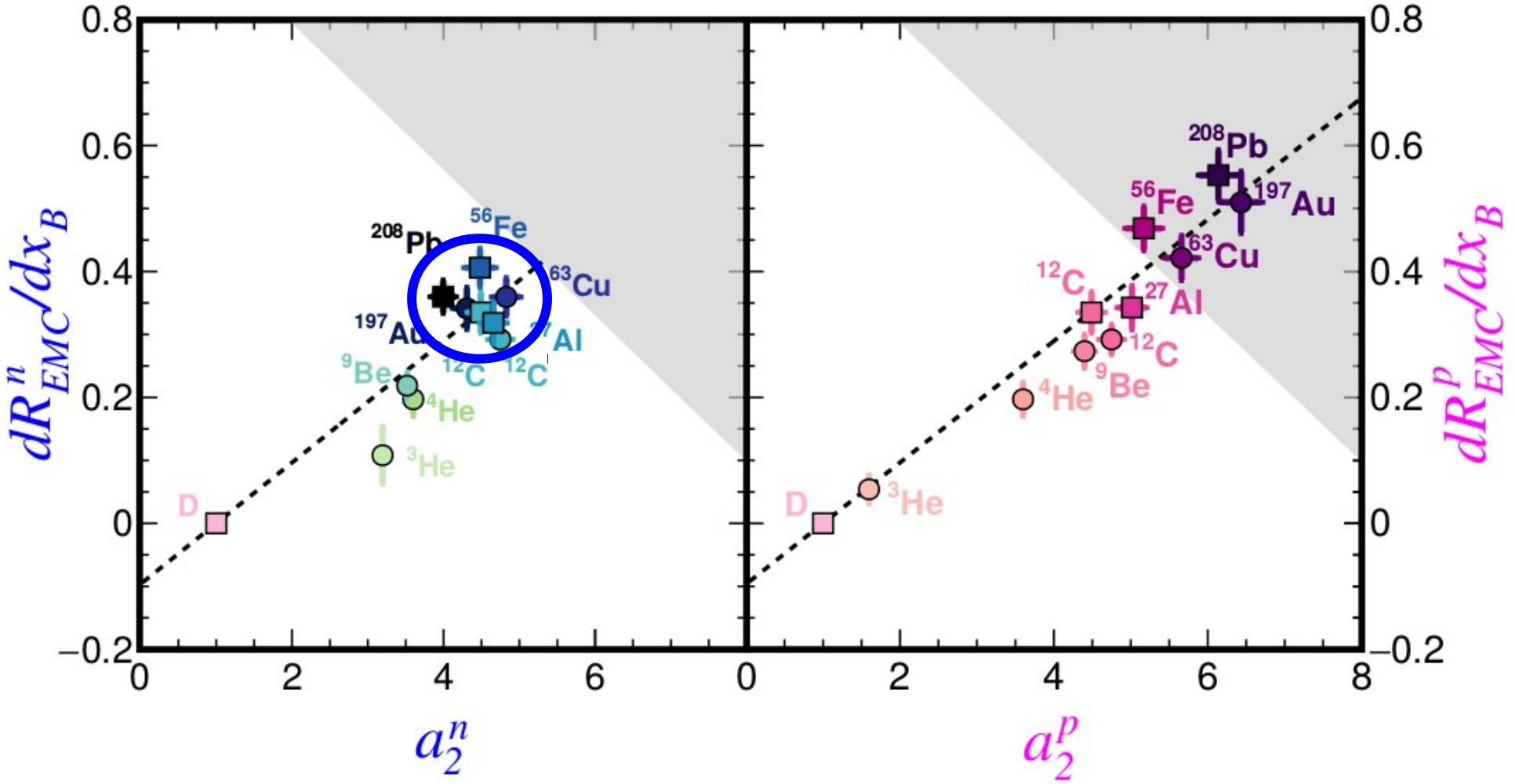
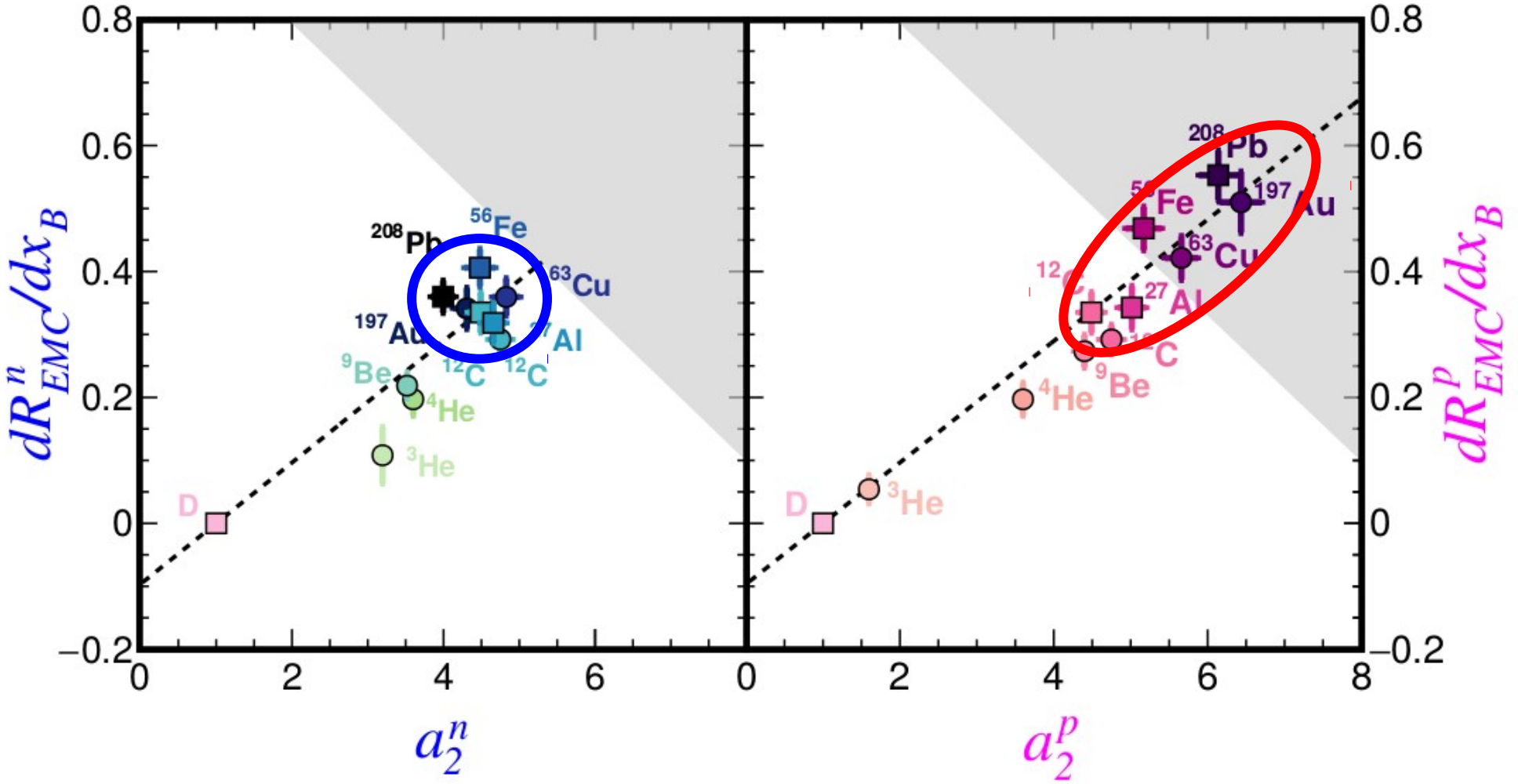
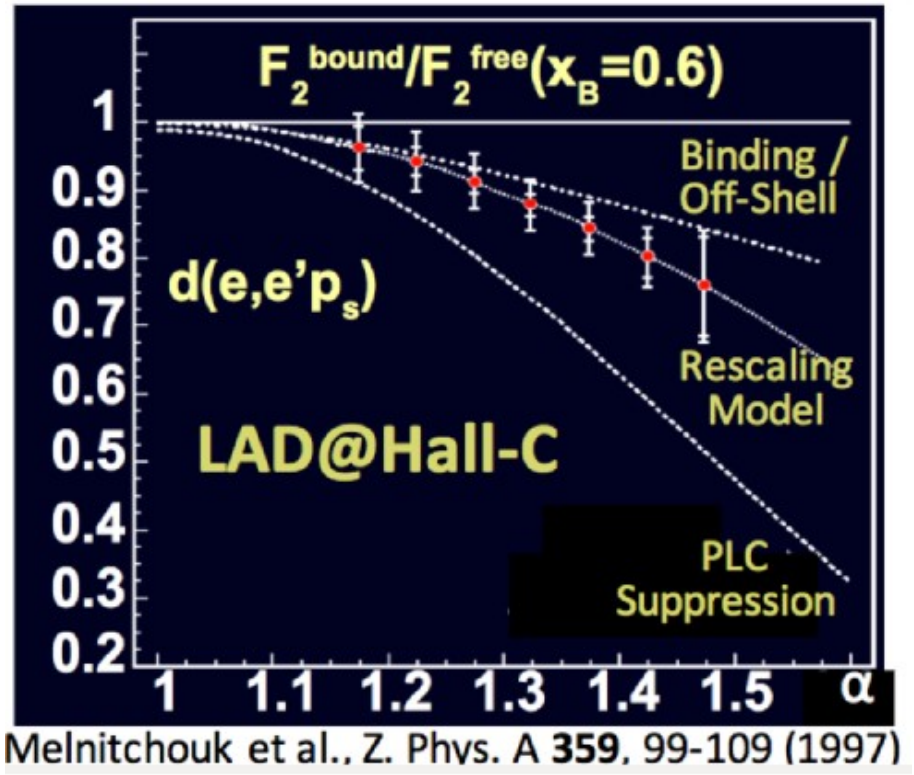


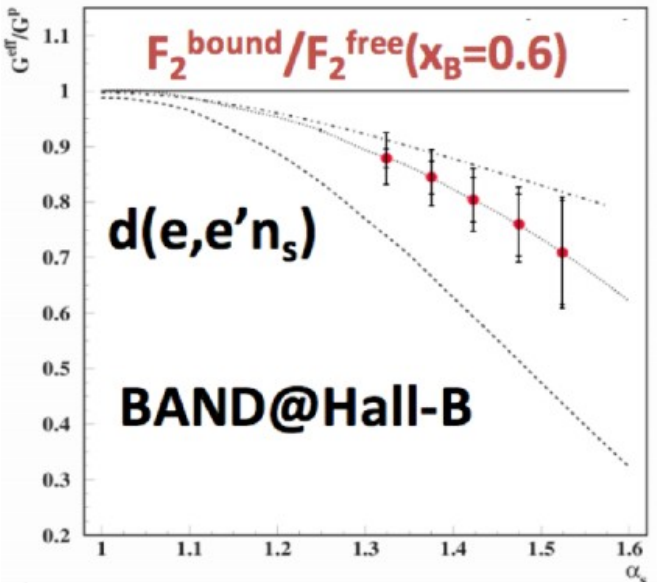
# New EMC-SRC Correlation: Version II

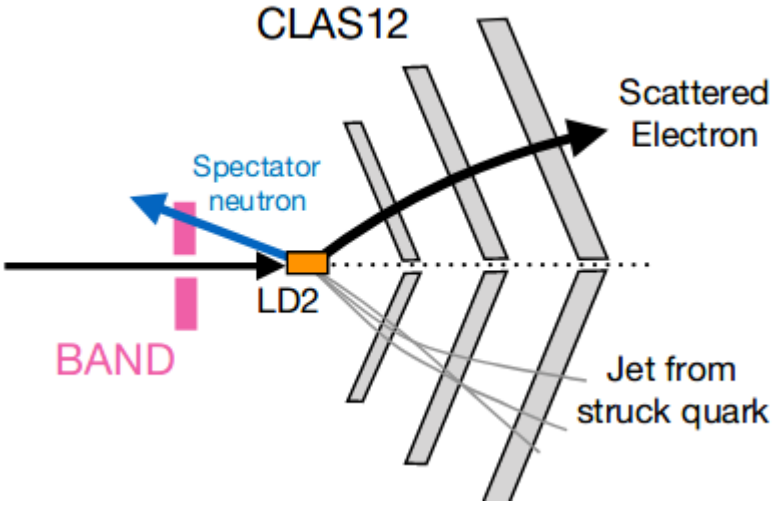


# DIS Recoil Tagging D(e,e'$N_s$)X




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



# np-SRC Fluctuations in Nuclei