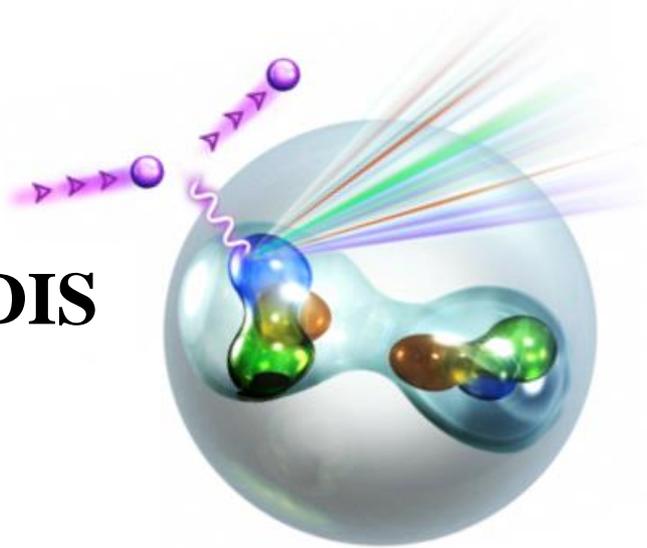


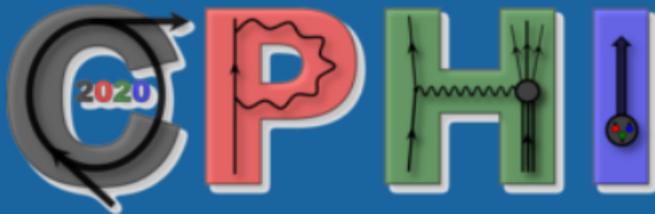
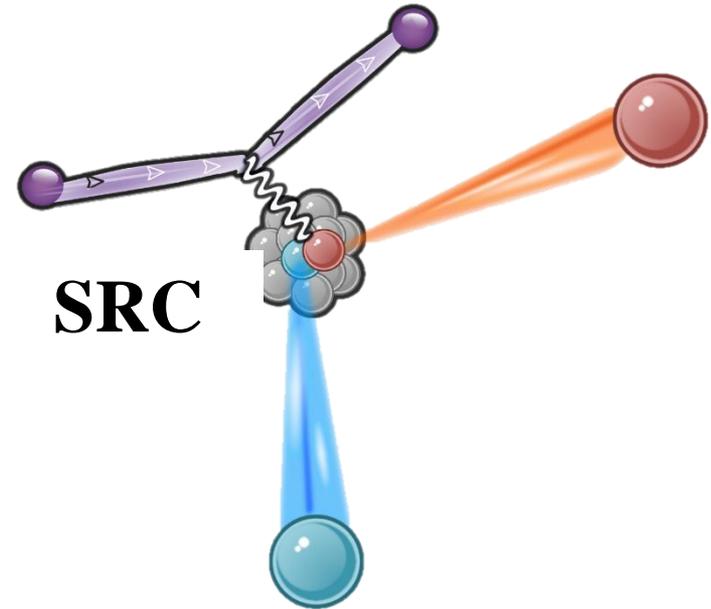


Bound and Free Nucleon Structure

DIS



SRC



Correlations in Partonic and Hadronic Interactions - 2020 (CPHI-2020)

3-7 February 2020
CERN

Eli Piassetzky

Tel Aviv University

Is the distribution of partons in bound nucleons same as in free nucleons ?

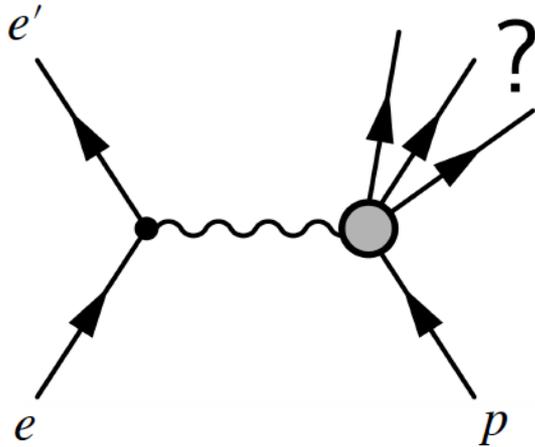
What is the connection between the quark / gluon structure of bound nucleons and nuclear structure ?

How to extract the distribution of partons in a free neutron ?

**Close
nucleons**



Deep Inelastic Scattering (DIS)



$$\frac{d\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{Q^4} \left[\left(1 - y - \frac{m_p^2 y^2}{Q^2} \right) \frac{F_2(x, Q^2)}{x} + y^2 F_1(x, Q^2) \right]$$

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

$$\omega = E' - E$$

$$x_B = \frac{Q^2}{2m\omega} \quad \left(= \frac{Q^2}{2(q \cdot p_T)} \right)$$

$$0 \leq x_B \leq 1$$

The fraction of nucleon momentum carried by the struck parton.

Information about the nucleon is contained in $F_1(x, Q^2)$ and $F_2(x, Q^2)$, the unpolarized structure functions.

$$\left. \frac{d\sigma}{dx dQ^2} \right\} F_2^P(x, Q^2)$$

$$\left. \frac{d\sigma^A}{dx dQ^2} \right\} F_2^A(x, Q^2)$$

Is the distribution of partons in bound nucleons same as in free nucleons ?

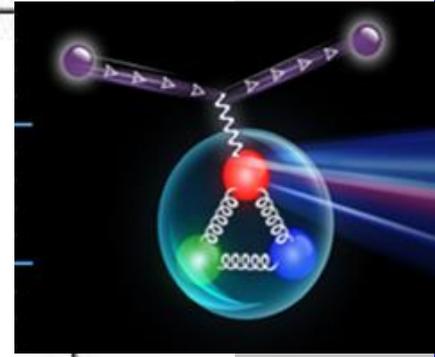
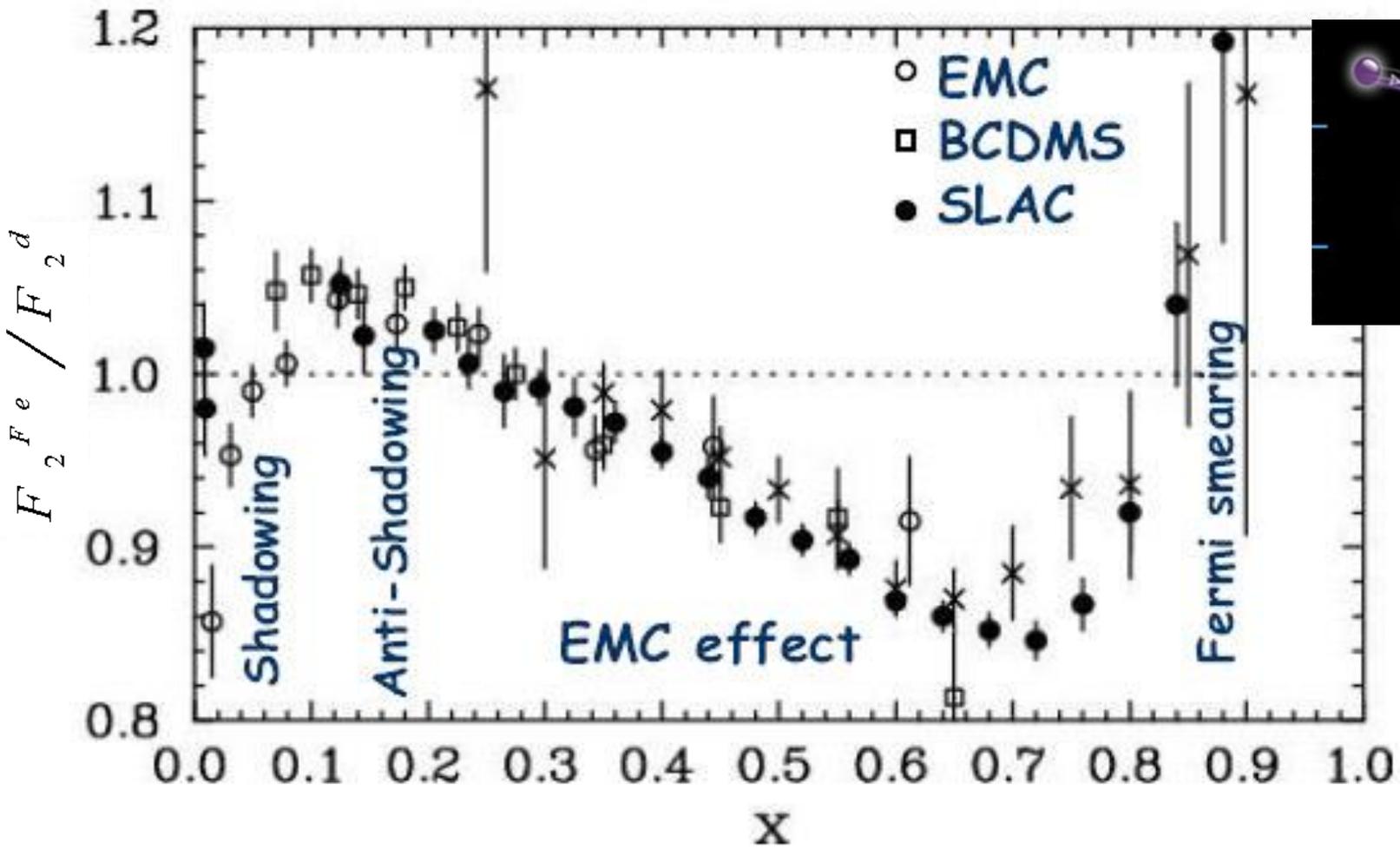
$$F_2^A(x, Q^2) = Z \cdot F_2^p(x, Q^2) + N \cdot F_2^n(x, Q^2)$$



$$F_2^d(x, Q^2) = F_2^p(x, Q^2) + F_2^n(x, Q^2)$$

free neutron?

The European Muon Collaboration (EMC) effect



Aubert et al., PLB (1983)
 PLB (1990); Gomez et al. (2018)

$$F_2^A \neq Z \cdot F_2^p + N \cdot F_2^n$$

neodo et al., PLB (1988); Allasia et al., (2009); Schmookler et al., Submitted

After 30 years no consensus on cause

Close
nucleons

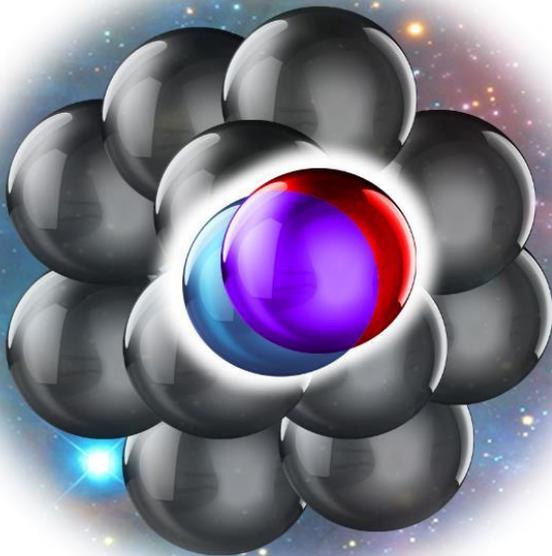


st

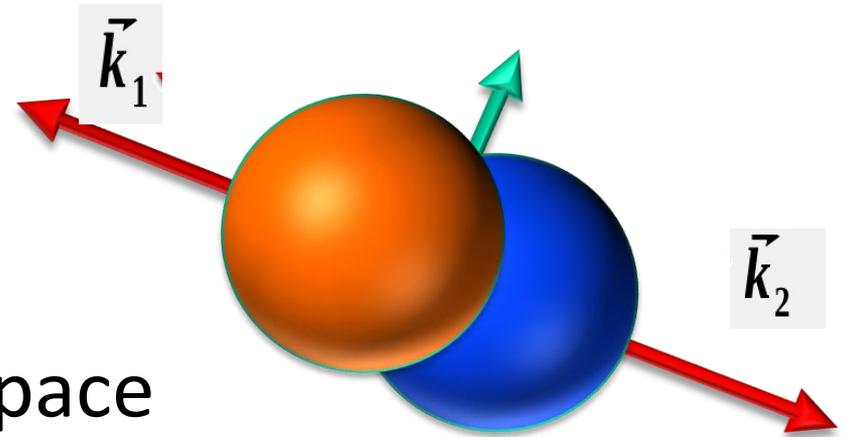
Short-Range Nucleon Correlations (SRC)

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)



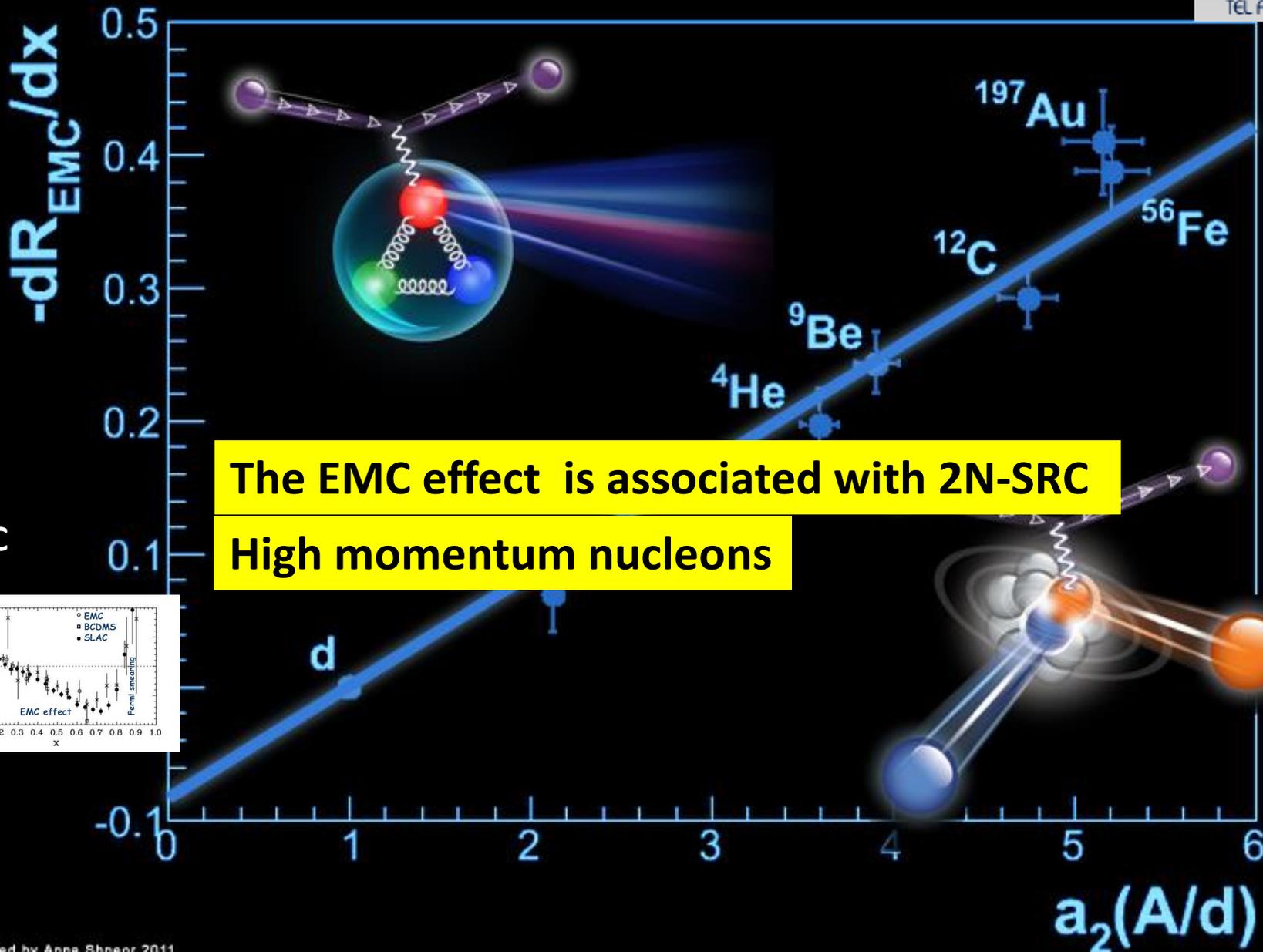
r-space



k-space

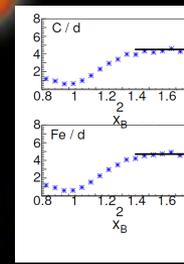
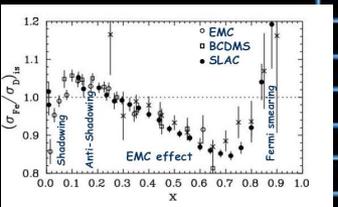
$$k_1 > k_F \quad k_2 > k_F \quad k_1 \simeq k_2$$

$$k_F \approx 250 \text{ MeV}/c$$



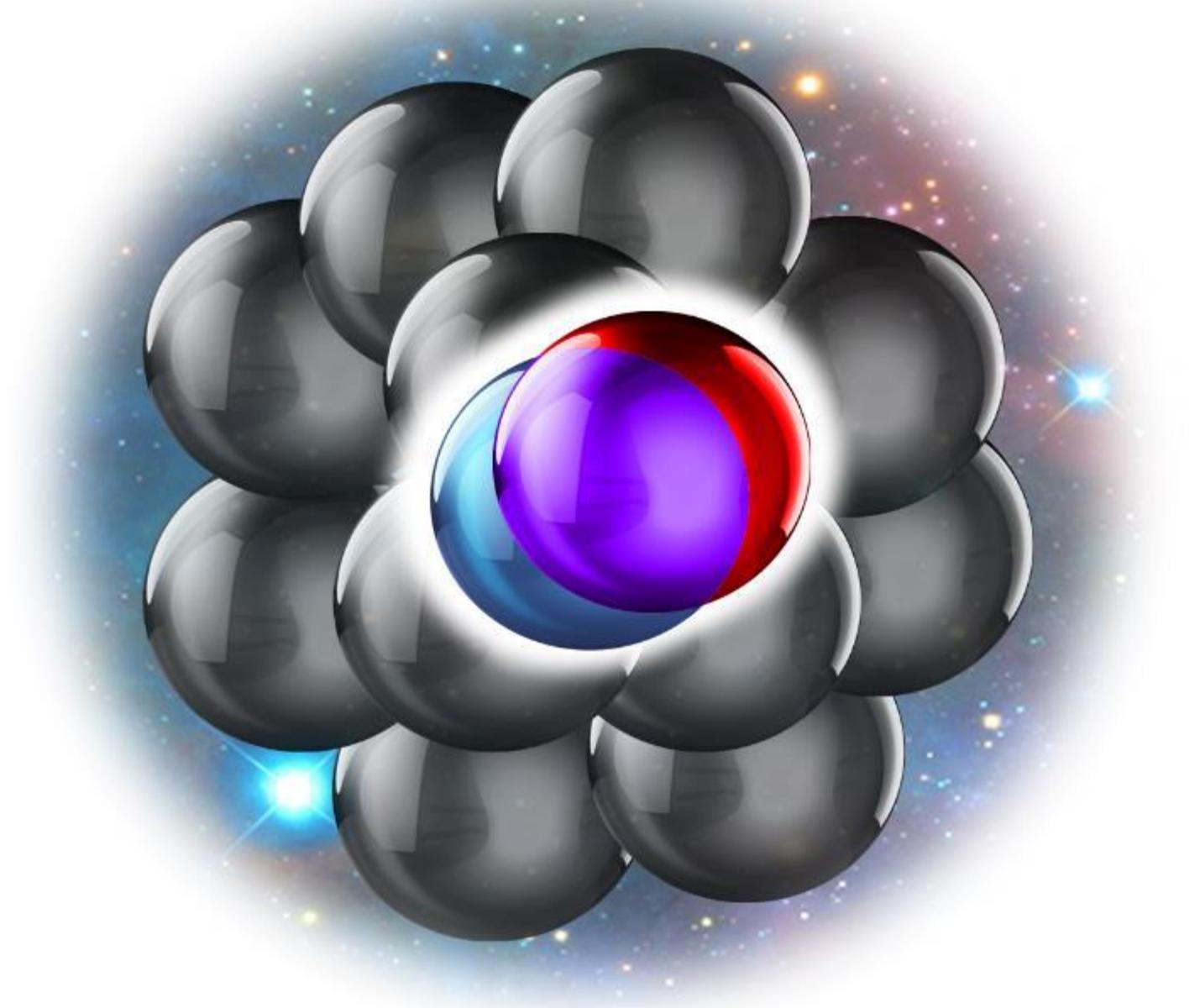
The EMC effect is associated with 2N-SRC
High momentum nucleons

EMC

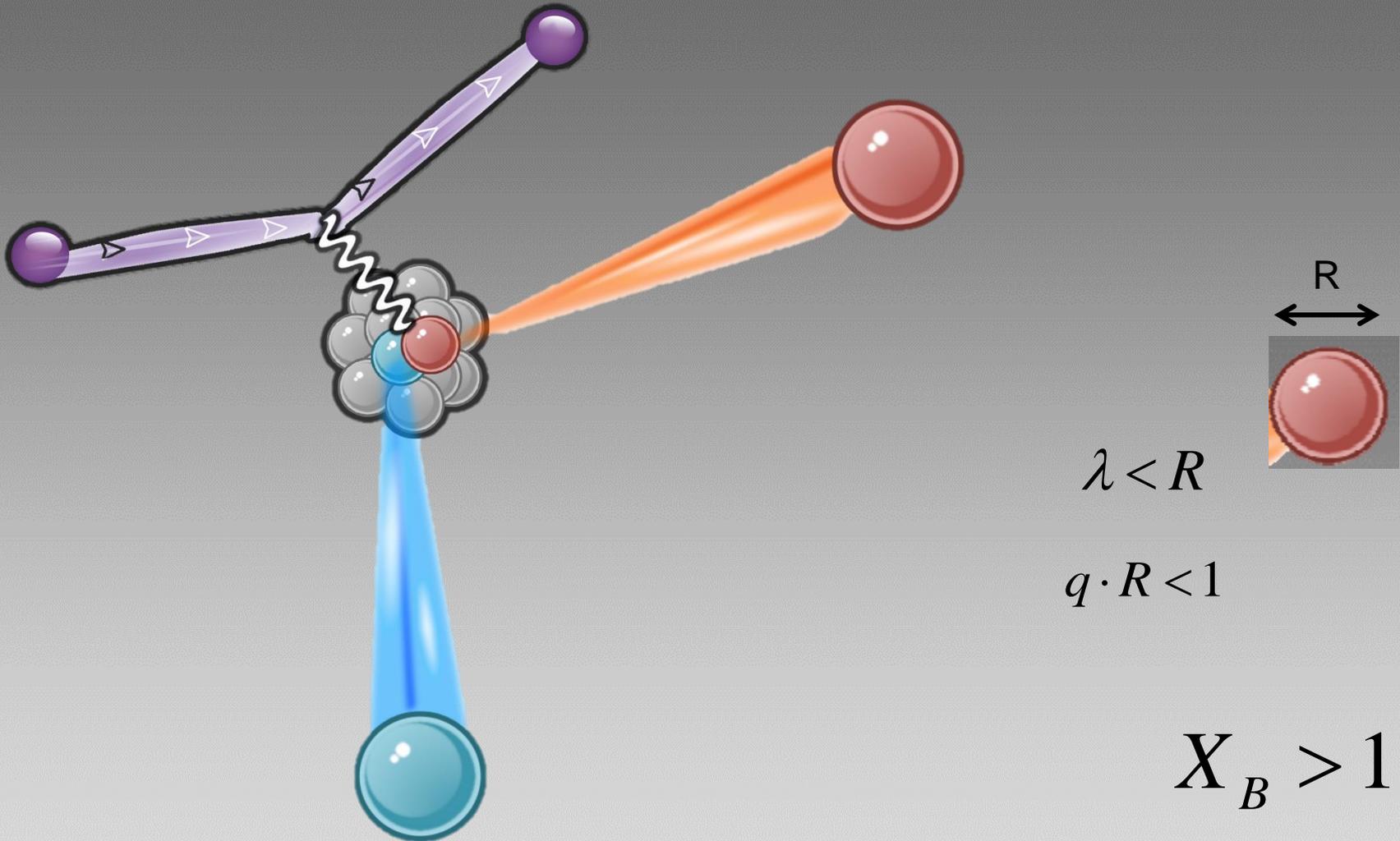


$a_2(A/d)$ SRC

Short-Range Correlations (SRC)



How do we study SRC?



**Exclusive hard scattering in selected kinematics
(almost entirely electron scattering)**

Nature 560 617 (2018). [asymmetric nuclei]

Nature In-Print (2020). [NN Int]

Nature 566 354 (2019). [EMC]

Phys. Rev. Lett 122 172502 (2019). [np]

Phys. Rev. Lett. 121 092501 (2018). [cm]

Phys. Lett. B 797 134890 (2019). [A=3]

Phys. Lett. B 797 134792 (2019). [Transparency]

Phys. Lett. B 791 242 (2019). [GCF Spectral func]

Phys. Lett. B 785 304 (2018). [correlation fuction]

Phys. Lett. B 780 211 (2018). [contact formalism]

arXiv: 1907.03658 [scale scheme]

arXiv: 1908.02223 [F2n]

arXiv 2001.07230 [A=3]

+ new results not yet published



SRC and NN interaction

SRC and nucleon structure



Summary of SRC results

In nuclei the momentum distribution of nucleons can be divided into two distinct regions

$$k < k_F$$

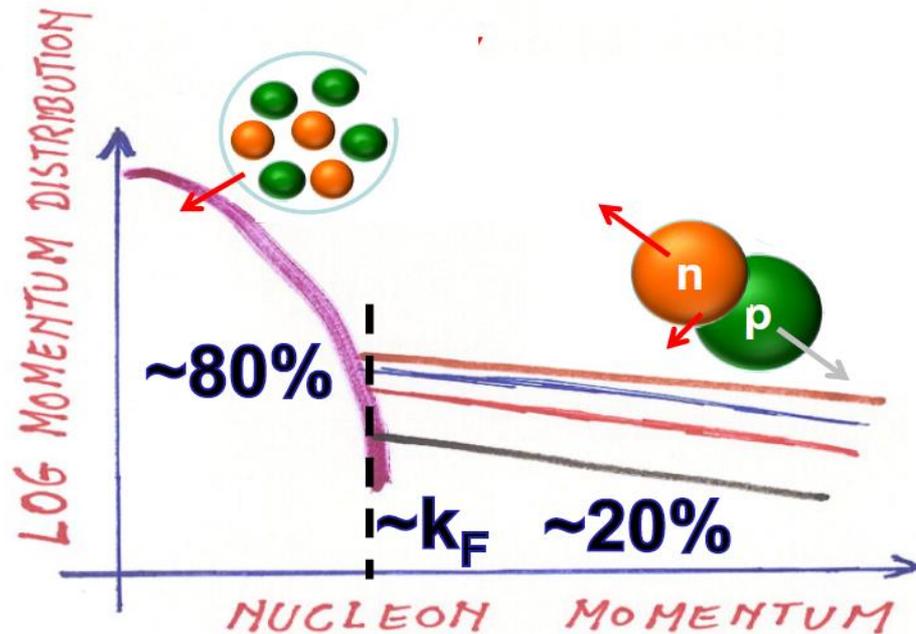
Mean field region

Single nucleons

$$k > k_F$$

Correlated / high momentum region

SRC pairs



Universality

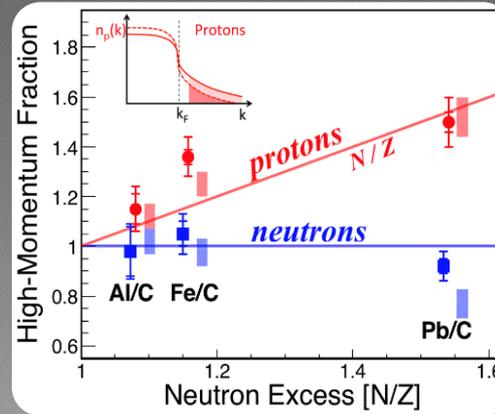
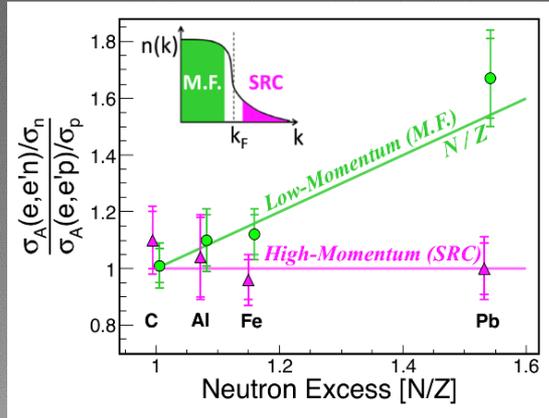
np-SRC dominance (tensor force)

E. Piasezky et al., PRL. 97 (2006) 162504.

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

A. Schmidt et al., Nature (in print)

Summary of SRC results



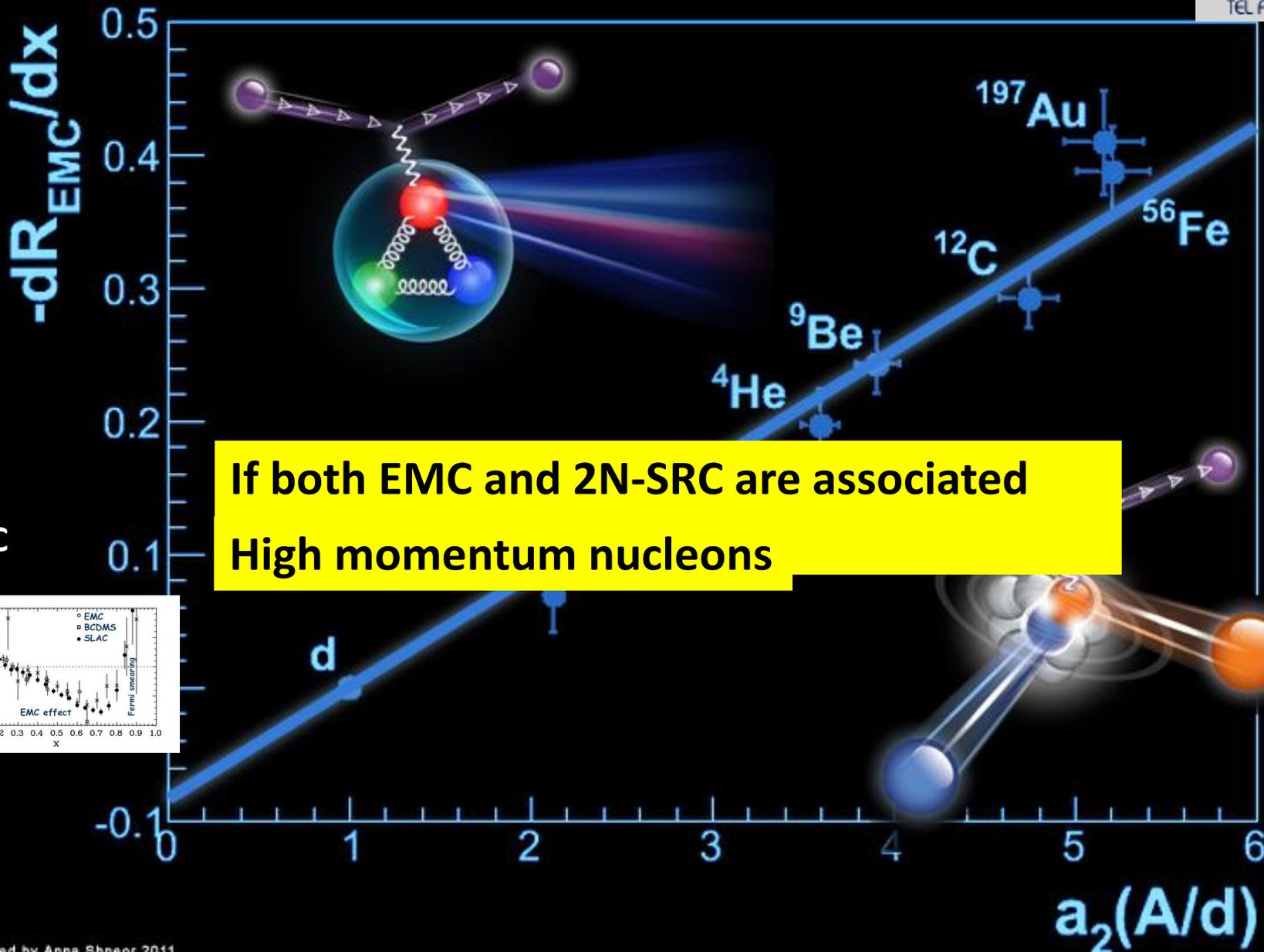
Nature, 560 (2018) 617-621.

For nuclei with $N > Z$

In the high momentum tail, **#protons** = **#neutrons**, irrespectively of the neutron excess.

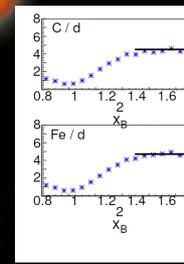
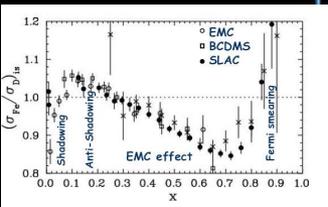
Protons have a greater probability than **neutrons** to be above the Fermi sea.

The fraction of correlated **protons** / **neutrons** is **grow/constant**, as a function of neutron excess.



**If both EMC and 2N-SRC are associated
High momentum nucleons**

EMC



Prediction for the SF and EMC effect

SRC universality →

Universal modification of the bound nucleon structure function (same for all nuclei).

Universal function (data from all nuclei) can be used to extract F_2^n

SRC np-dominance →

For nuclei with $N > Z$

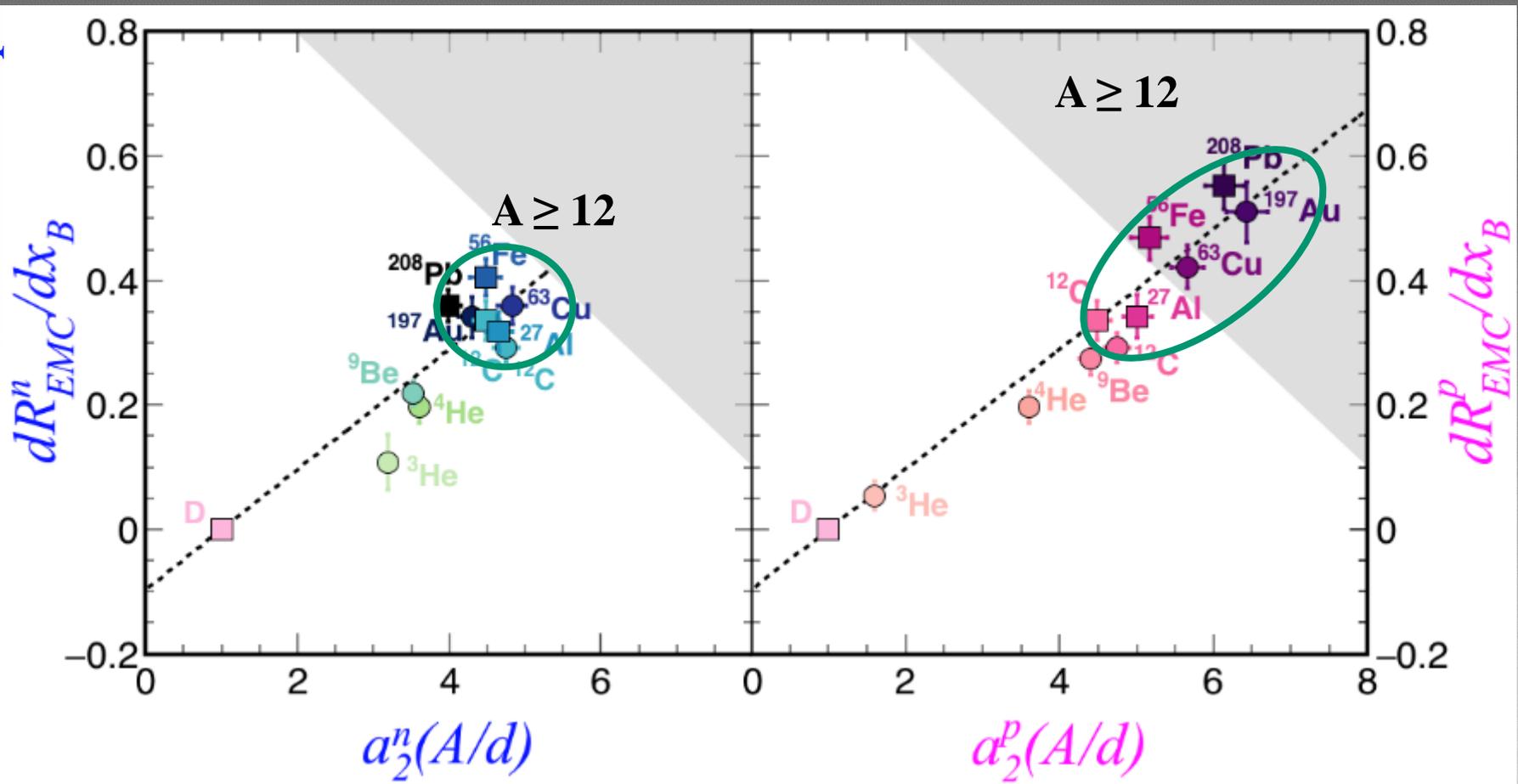
More protons larger EMC effect.

More Neutrons Saturation.

Neutrons Saturate, Protons Grow



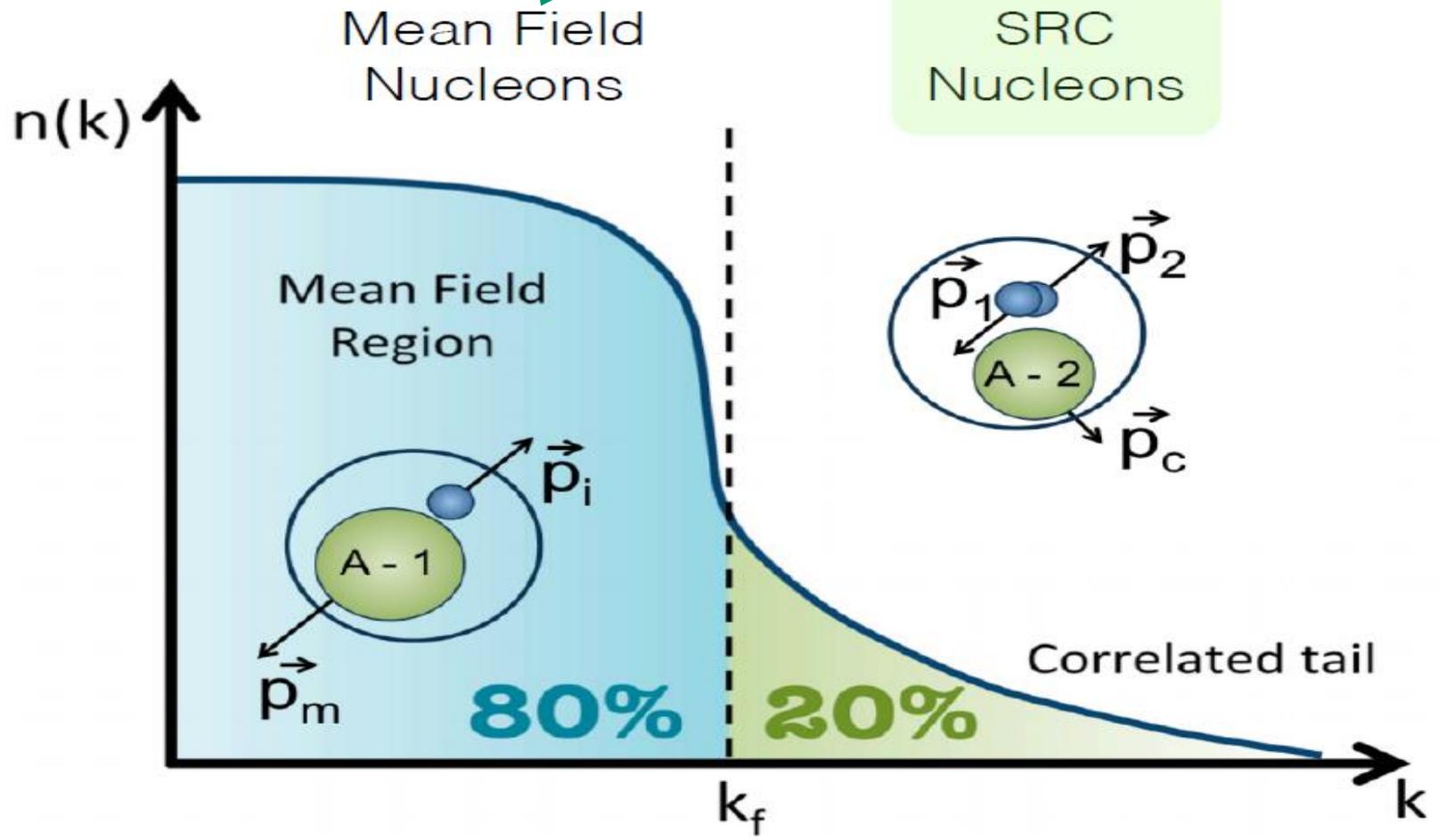
TEL AVIV UNIVERSITY



$$a_2^n = \frac{(\sigma_A / N)}{\sigma_d}$$

$$a_2^p = \frac{(\sigma_A / Z)}{\sigma_d}$$

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



EMC-SRC hypothesis universal modification

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

Nucleus-independent

$$\frac{F_2^A}{F_2^d} = \underbrace{\left(n_{SRC}^A - N n_{SRC}^d\right)}_{\text{A Dependent}} \underbrace{\frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}}_{\text{Universal!}} + \underbrace{(Z - N) \frac{F_2^p}{F_2^d} + N}_{\text{A Dependent}}$$

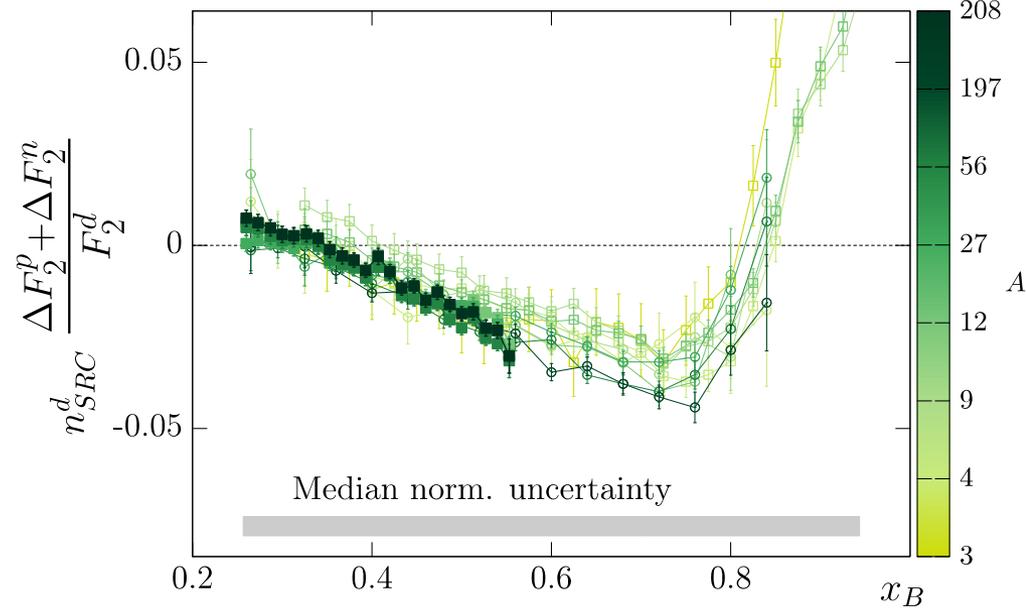
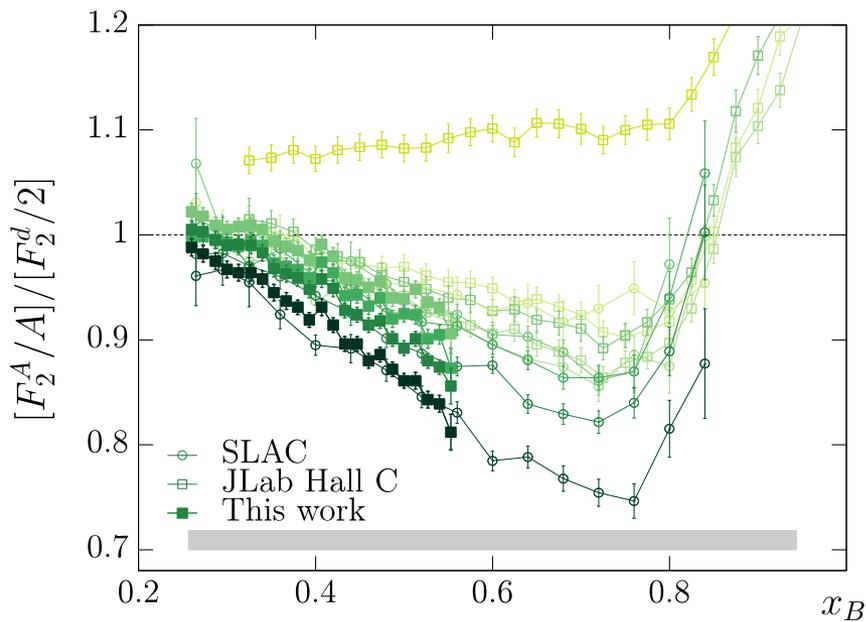
A Dependent

Universal!

A Dependent



$$\Delta F_2^N = F_2^{N*} - F_2^N$$

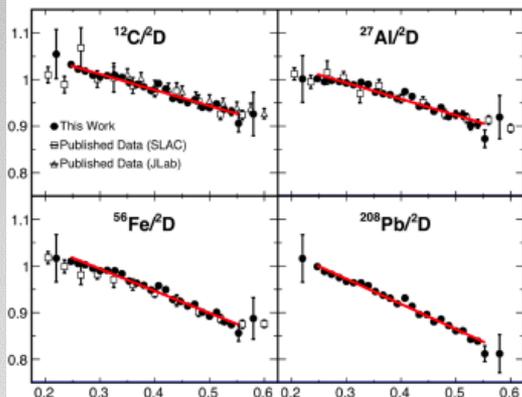


Extract universal modification using Bayesian inference via Hamiltonian Markov Chain Monte Carlo

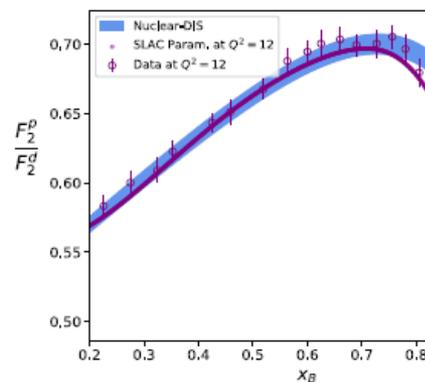
$$\frac{F_2^A}{F_2^d} = (Z - N) \frac{F_2^p}{F_2^d} + N + \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N \right) \frac{n_{SRC}^d}{F_2^d} \left(\Delta F_2^p + \Delta F_2^n \right)$$

Universal modification function

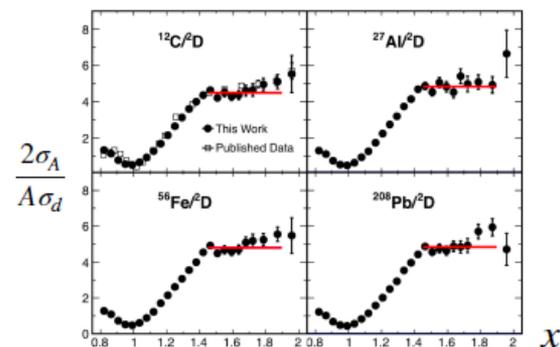
EMC-DIS Data



F_2^p/F_2^d Data

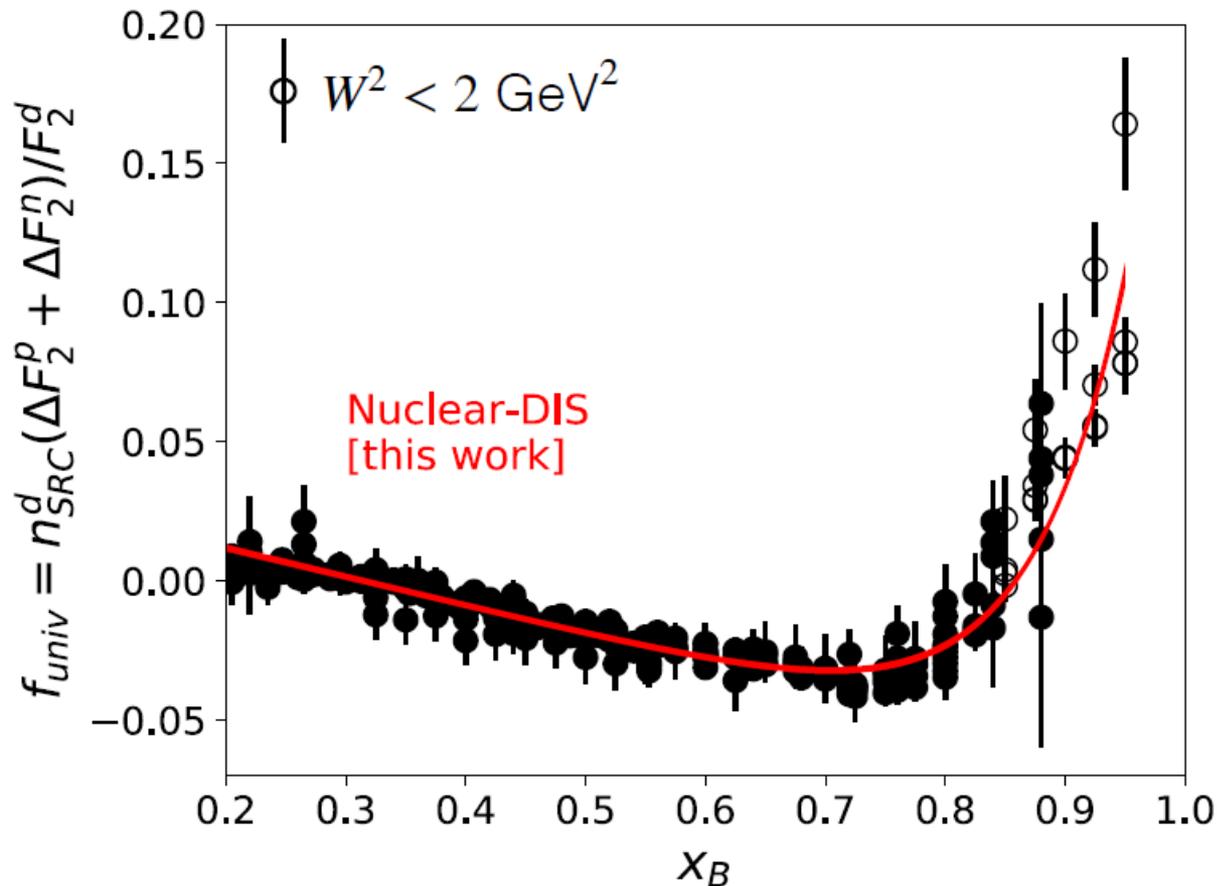


a_2 Pair Abundances



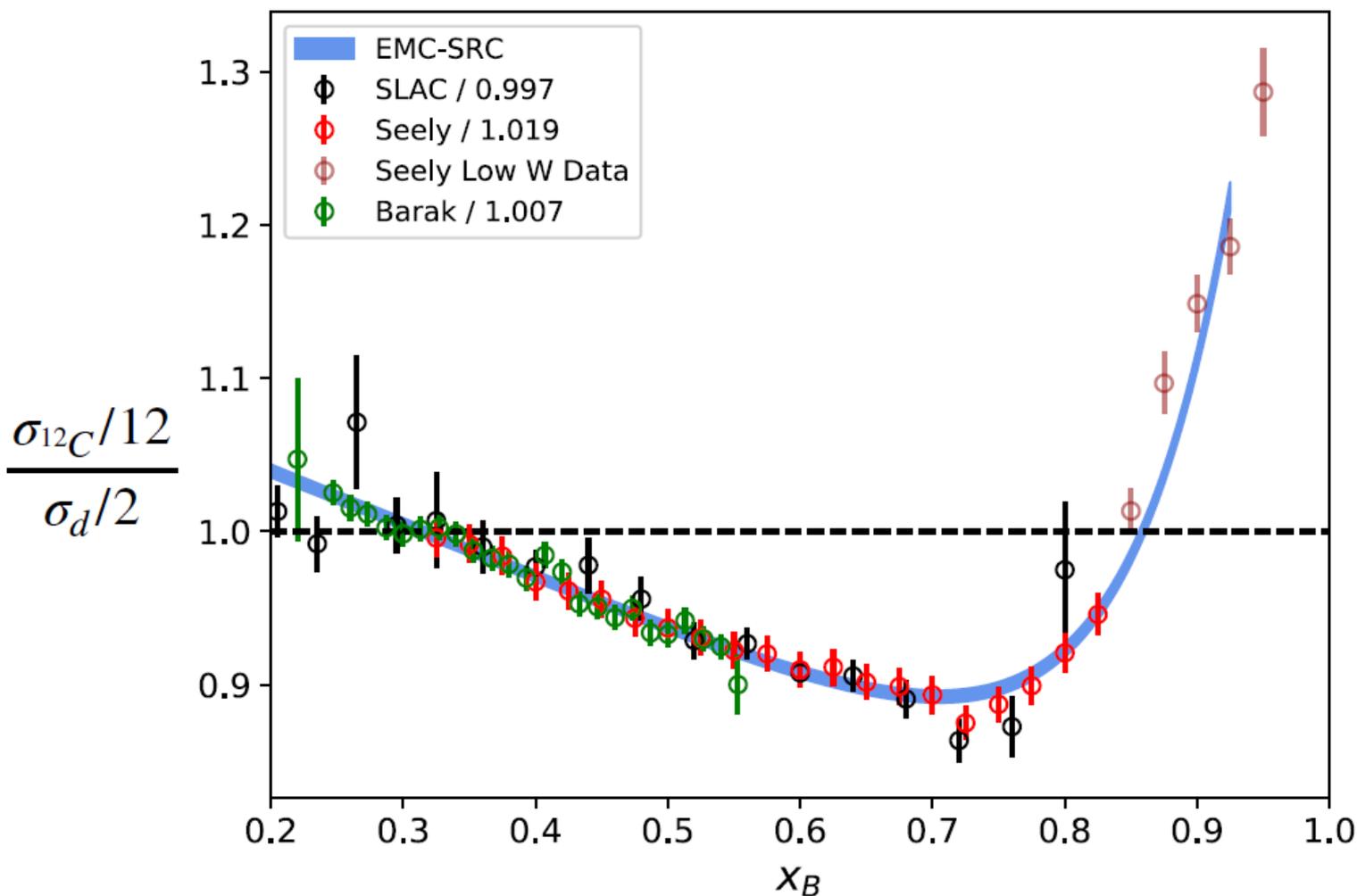


Universal modification function of nuclei

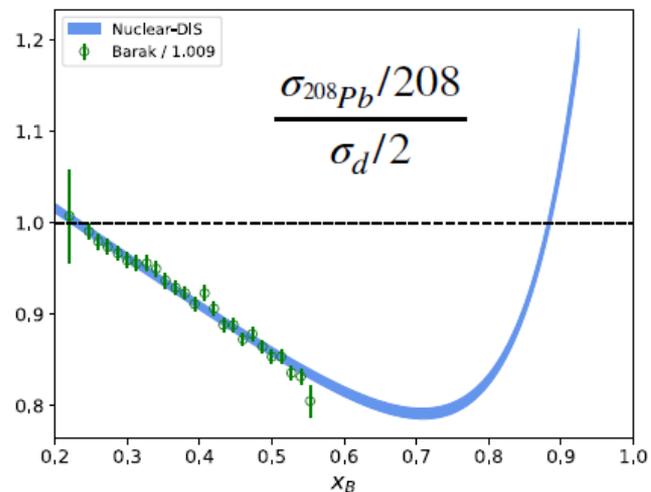
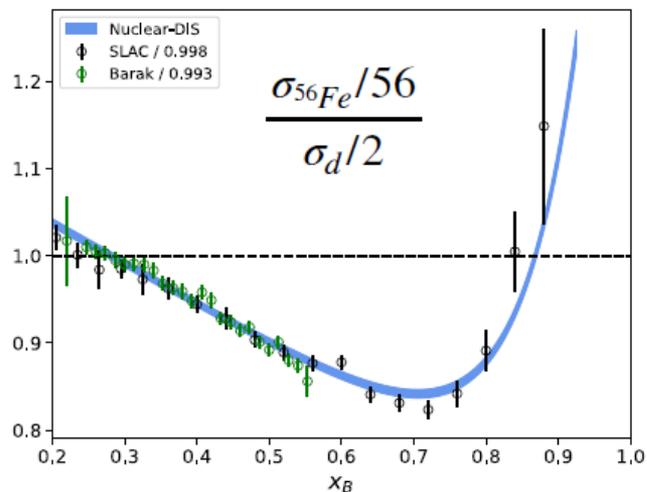
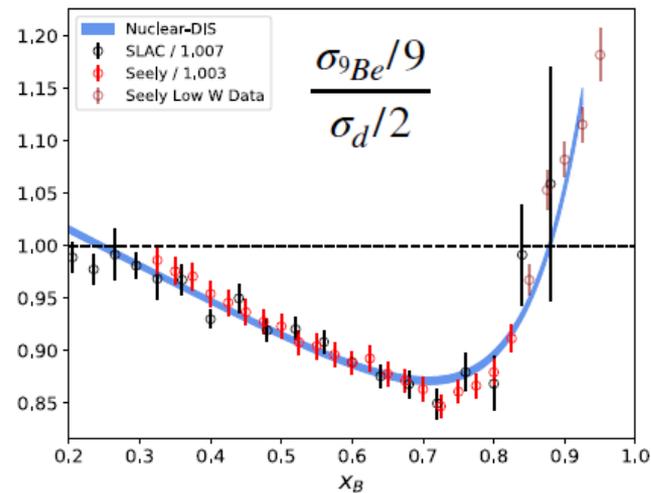
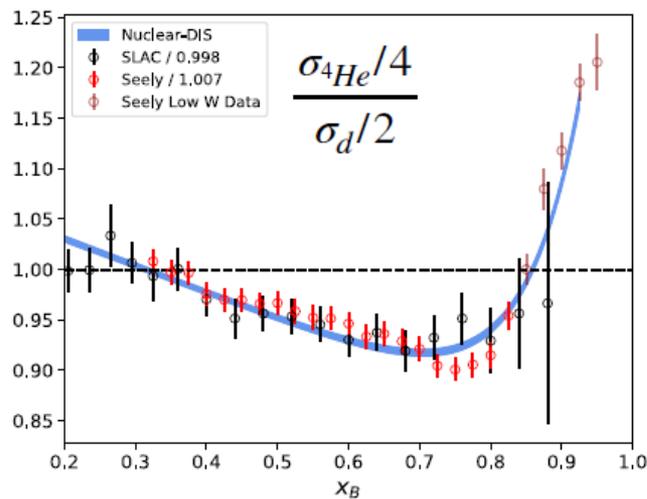


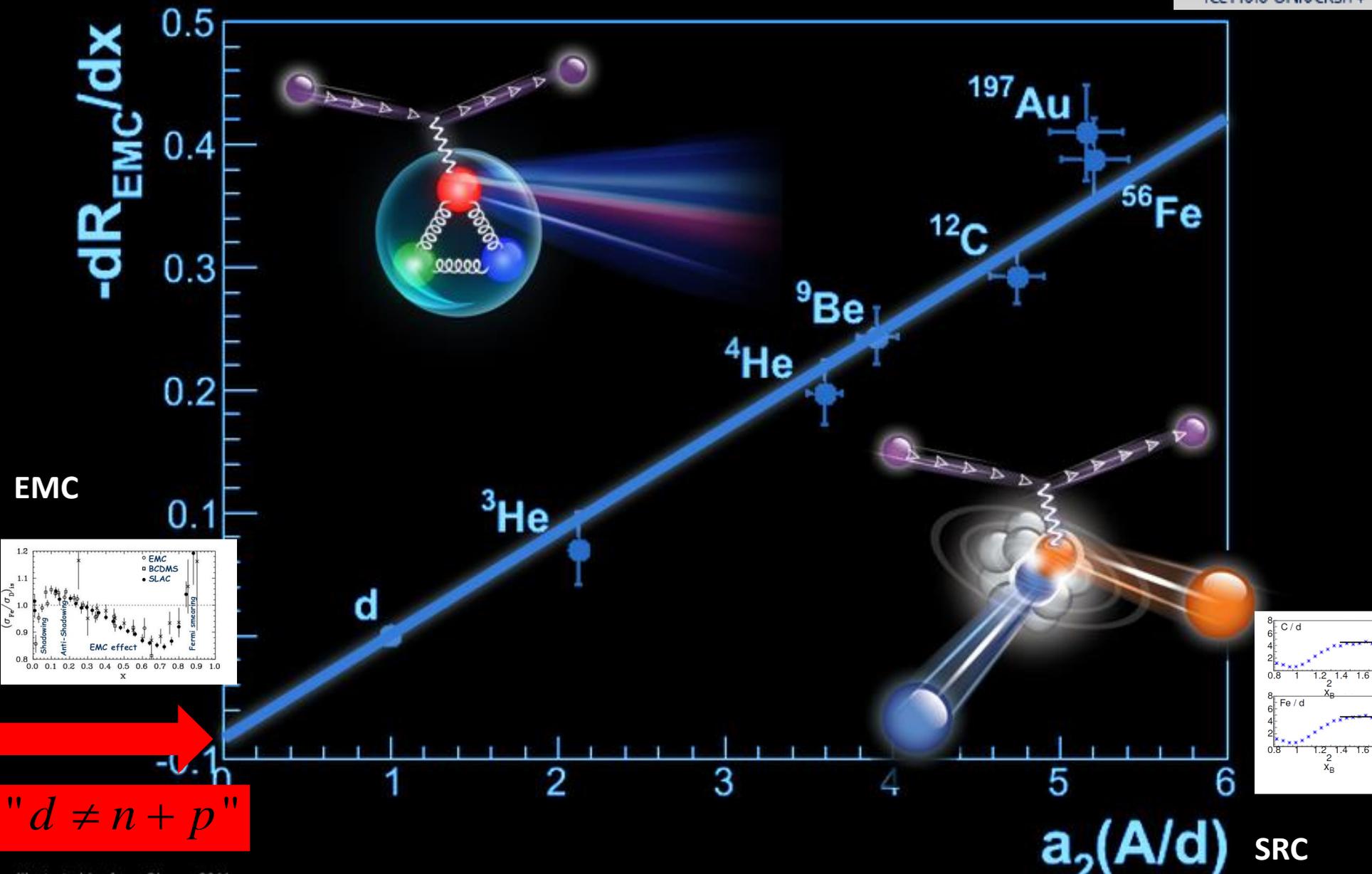
(All 31 model parameters simultaneously extracted from joint posterior)

Reproduce the data remarkably well



Reproduce the data remarkably well





EMC-SRC hypothesis proposes universal modification

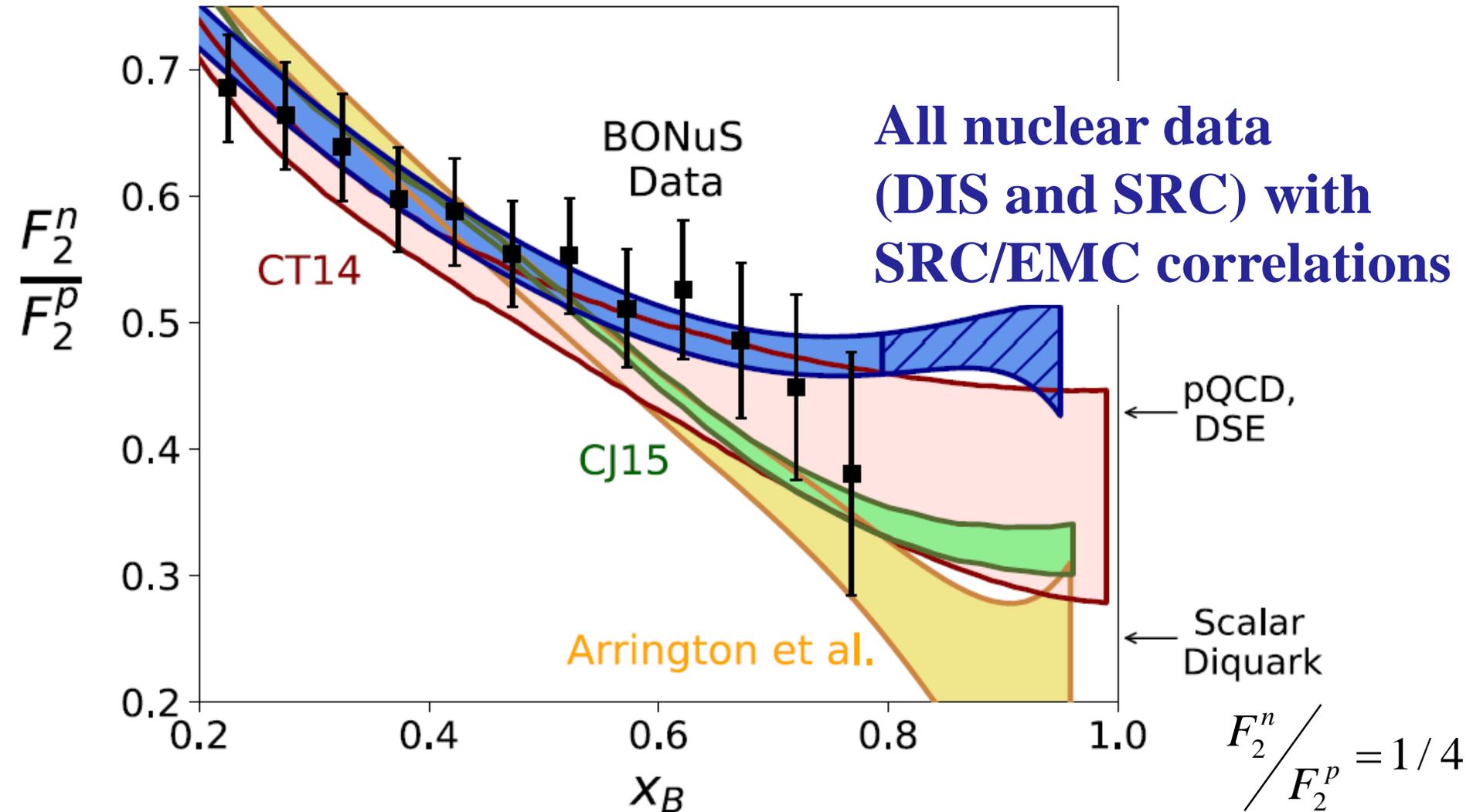
$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A \left(\Delta F_2^p + \Delta F_2^n \right)$$

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

$$F_2^A = (Z - N) F_2^p + NF_2^d + (n_{SRC}^A - Nn_{SRC}^d) \left(\Delta F_2^p + \Delta F_2^n \right)$$

Treat **all** bound nucleon structure **consistently** with **all** nuclear DIS and QE data

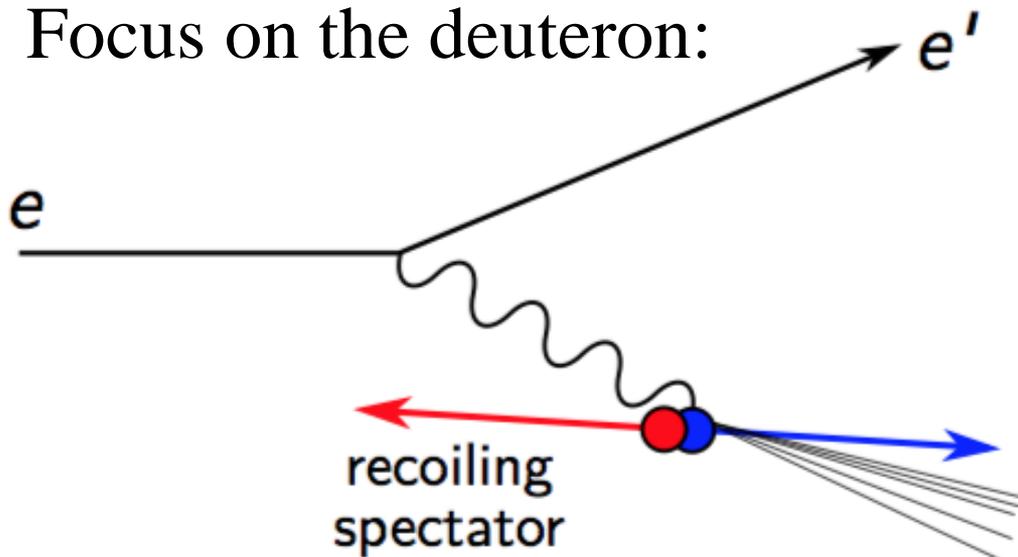
$$\frac{F_2^n}{F_2^p} = \frac{1 - f_{univ}}{F_2^p / F_2^d} - 1$$



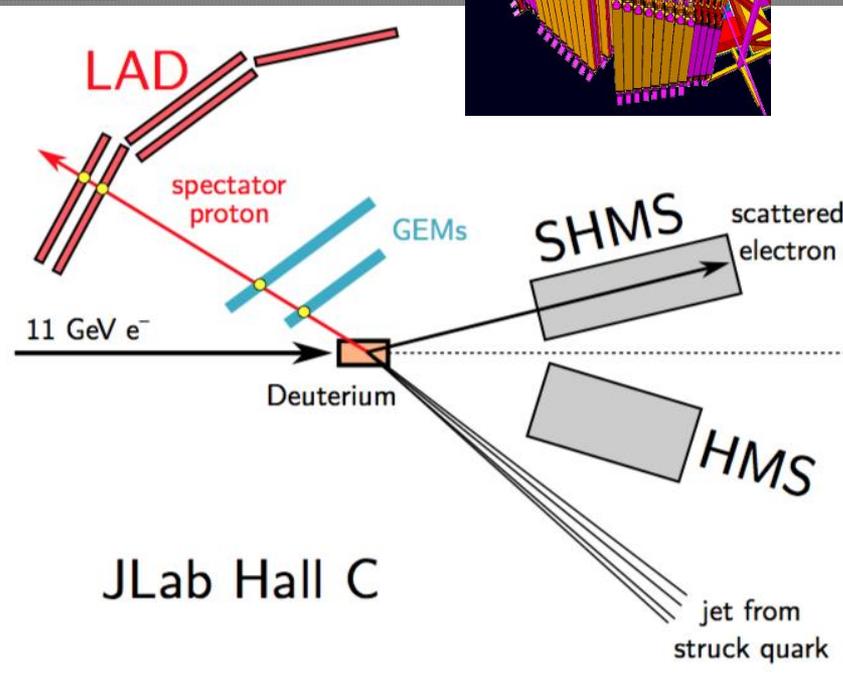
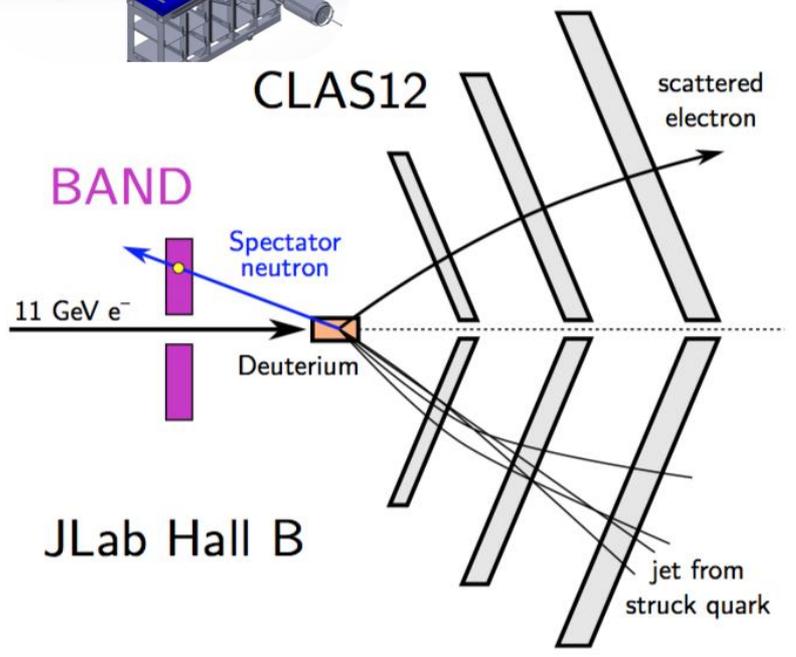
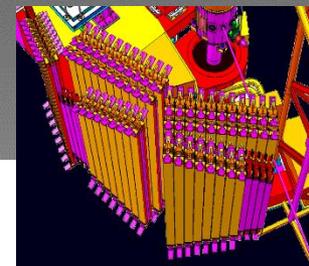
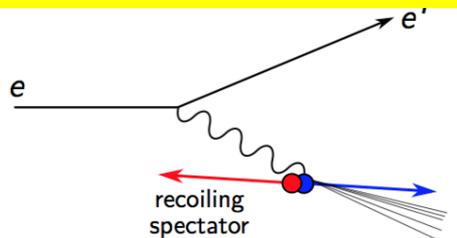
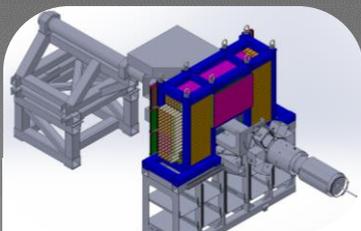
Is the EMC effect associated with large momentum nucleons ?

Hypothesis can be verified by measuring DIS off Deuteron tagged with high momentum recoil nucleon

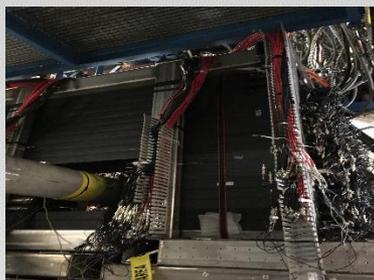
Focus on the deuteron:



Is the EMC effect associated with large momentum nucleons ?



12 GeV JLab/ Hall B took data in 2019 E 12-11-107



12 GeV JLab/ Hall C approved experiment E12-11-003a



Summary

In nuclei the momentum distribution of nucleons can be divided into two distinct regions

$$k < k_F$$

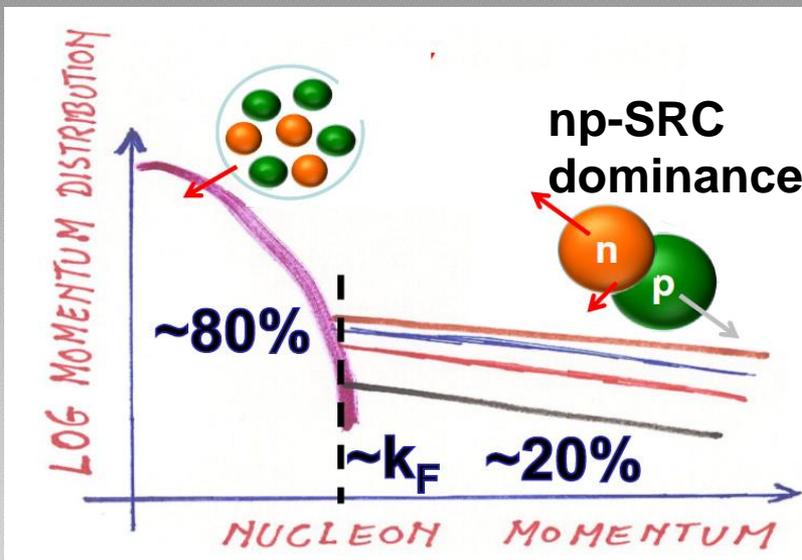
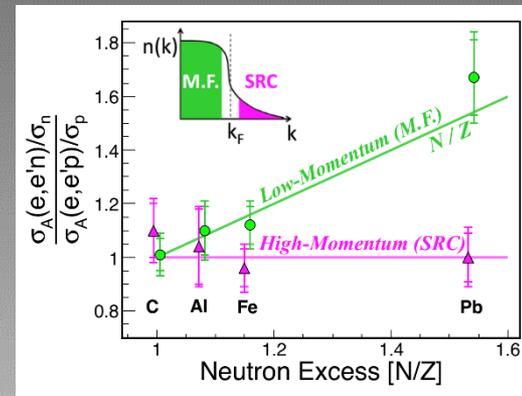
Mean field region

Single nucleons

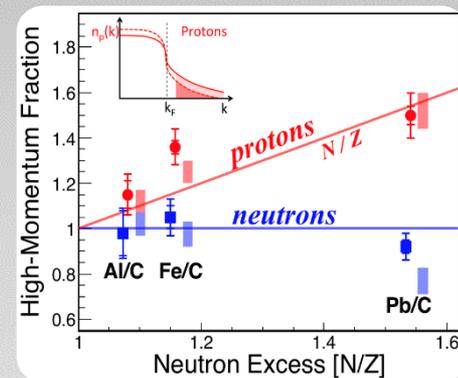
$$k > k_F$$

Correlated / high momentum region

SRC pairs



#protons = #neutrons, irrespectively of the neutron excess.



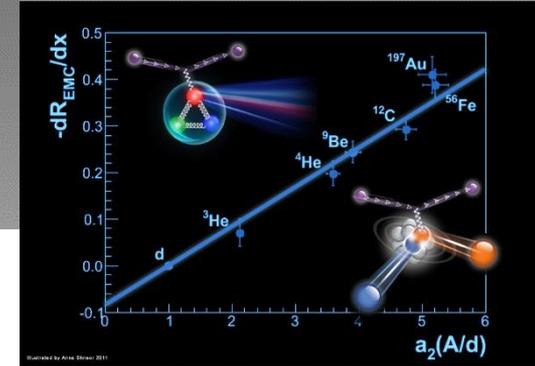
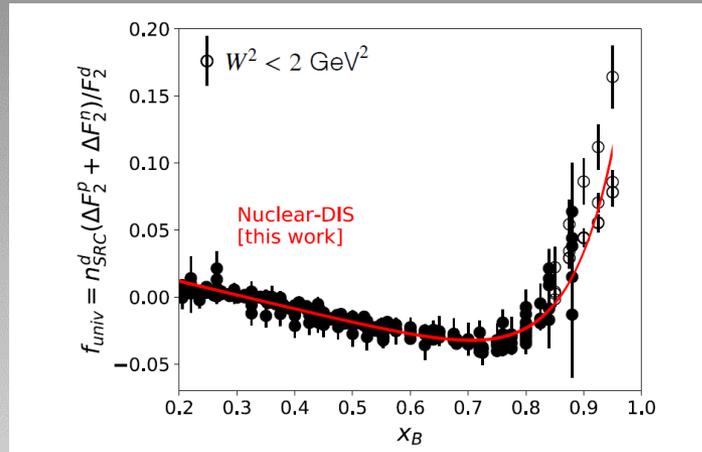
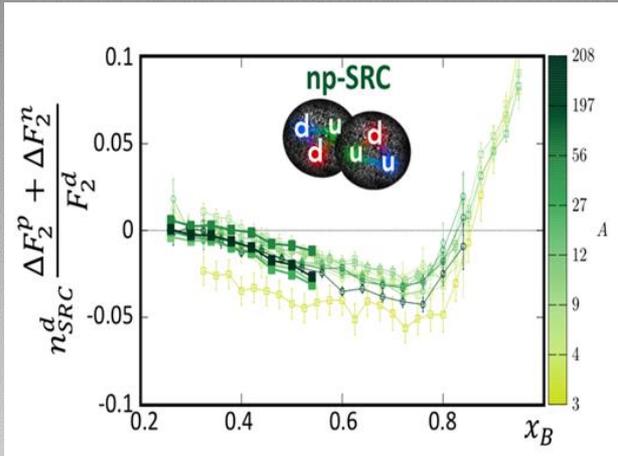
The fraction of correlated **protons** / **neutrons** is **grow** / **constant**, as a function of neutron excess.

Generalized Nuclear Contact Formalism

Summary

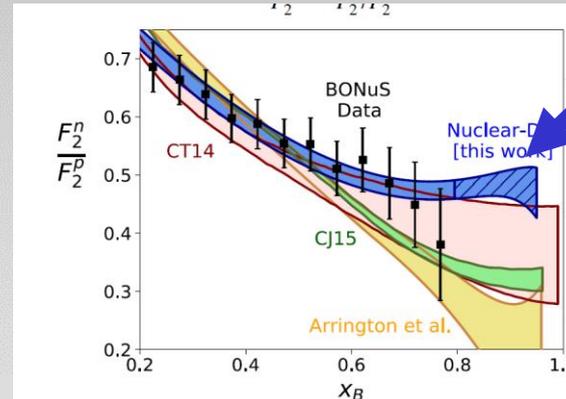
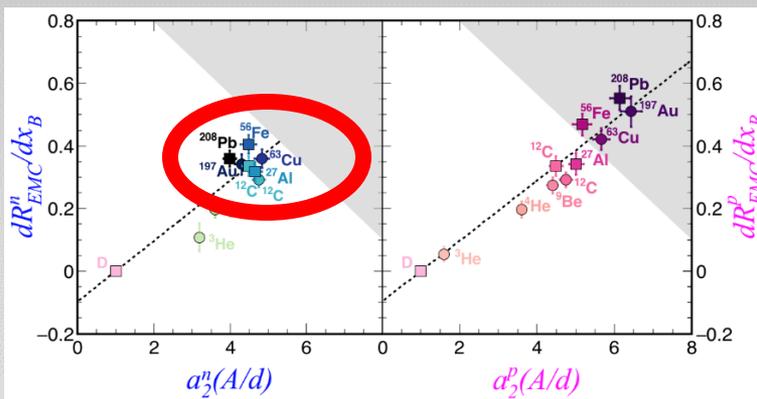
EMC is associate with 2N SRC

EMC: Nucleons are normally normal except when close to others.



Predictions:

MARATHON
results



EMC effect is isospin dependent



Correlations in Partonic and Hadronic Interactions - 2020 (CPHI-2020)

3-7 February 2020
CERN

Acknowledgment



The organizers

Collaborators



Larry Weinstein



Shalev Gilad



Axel Schmidt



Meytal Duer



Barak Schmookler



Or Hen



Wim Cosyn



Jan Ryckebush



Efrain Segarra



Ronen Weiss



Nir Barnea



Jerry Miller



Mark Strikman



Leonid Frankfurt



Misak Sargsian

Data-Mining collaboration
CLAS collaboration

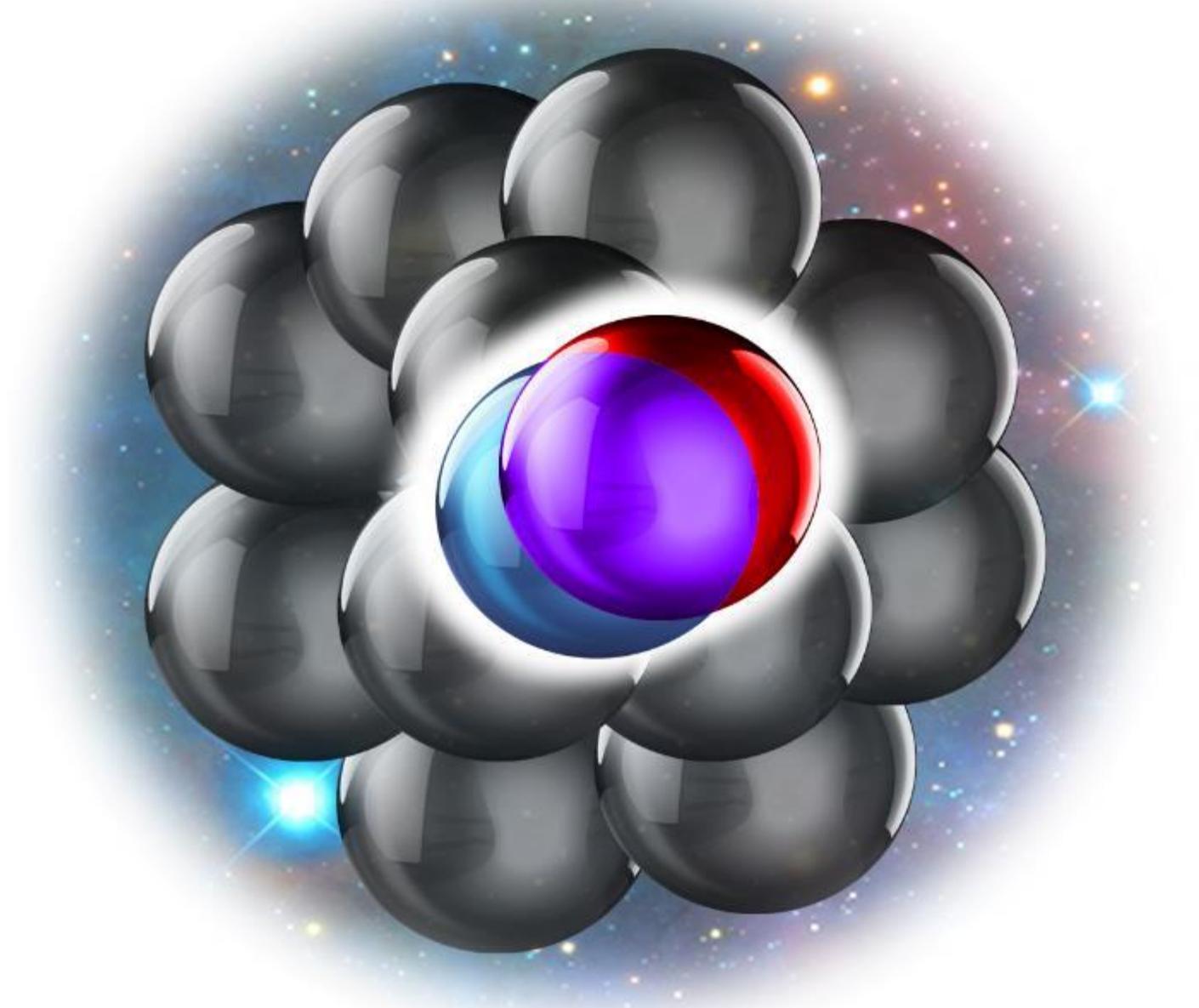




To the two field pillars:

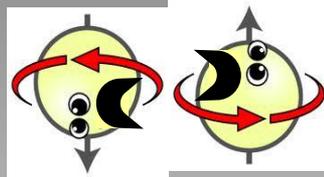
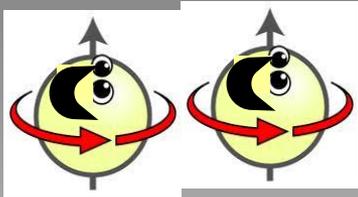
Many more years and achievements –we need you to complete the picture

Short-Range Correlations (SRC)



Nucleons has Isophobia (np – dominance)

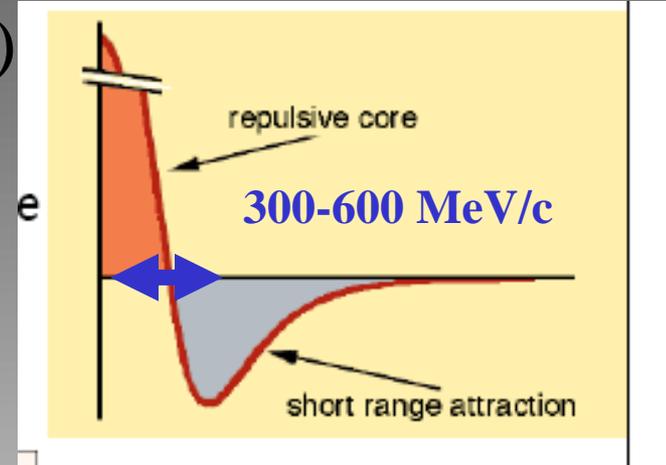
The reason: tensor force



only np-SRC

pp- nn- np- SRC

$$V_c(r)$$



$$V_{NN}(r) = V_c(r) + V_T(r)S_{12}$$

$$S_{12} = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1 \sigma_2$$

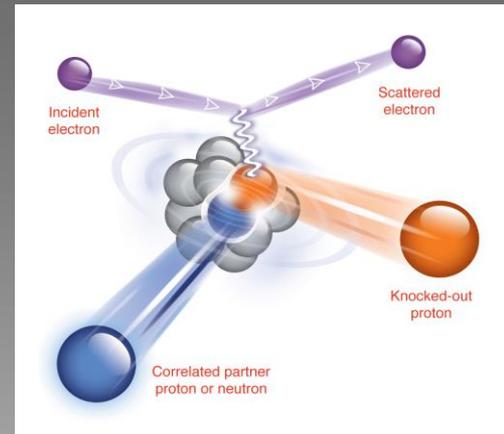
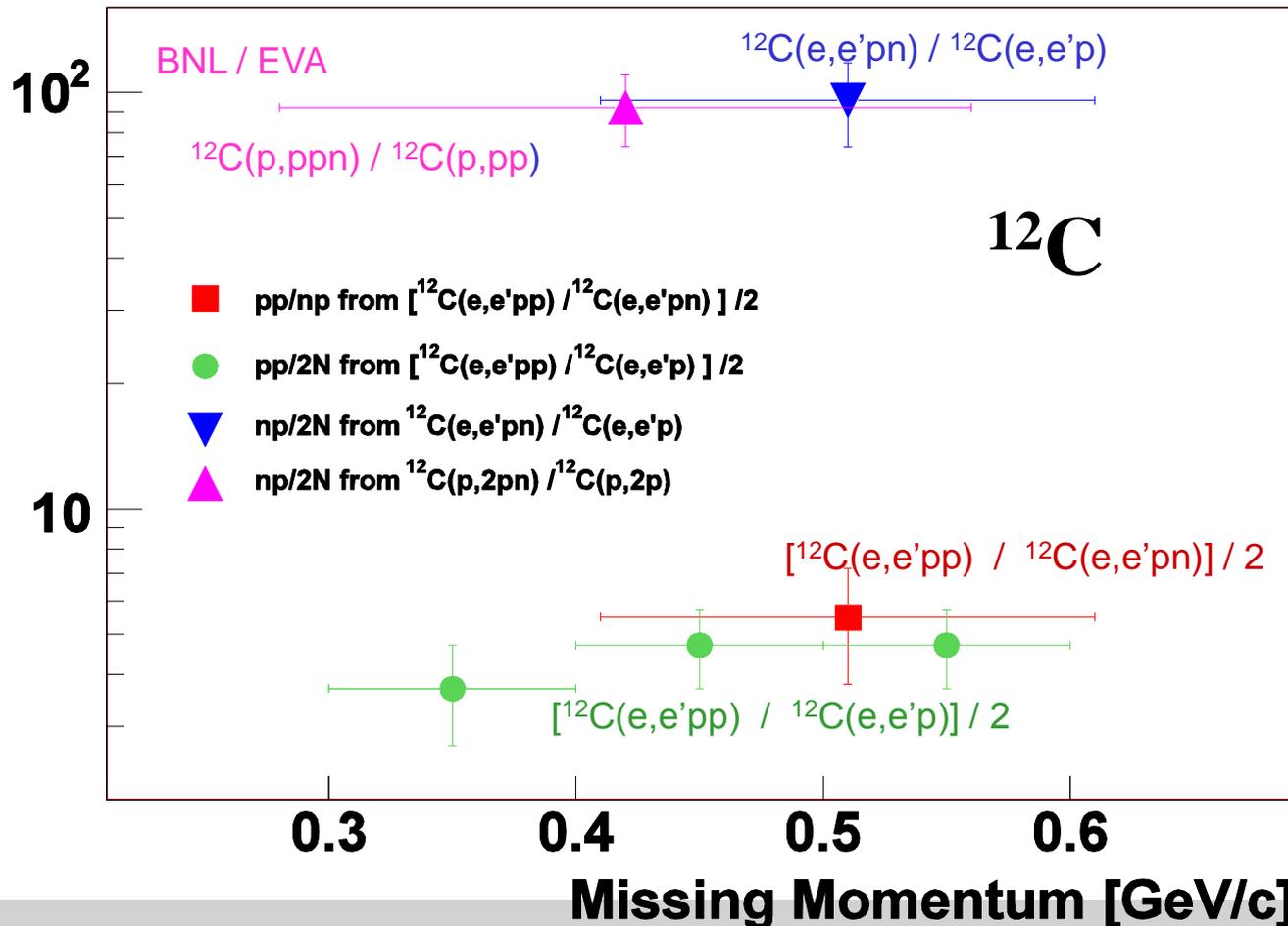
The consequences:

Protons have a greater probability than neutrons to be above the Fermi sea.

For nuclei with $N > Z$

More Neutrons => More Correlated Protons

SRC Pair Fraction (%)

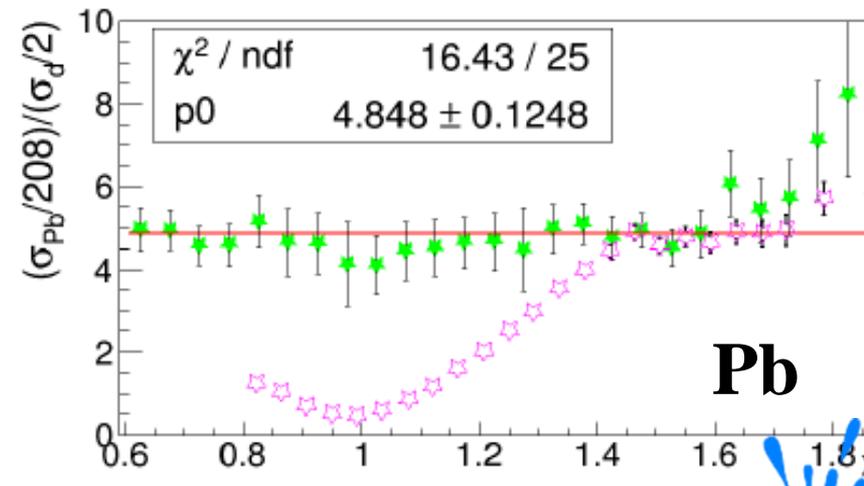
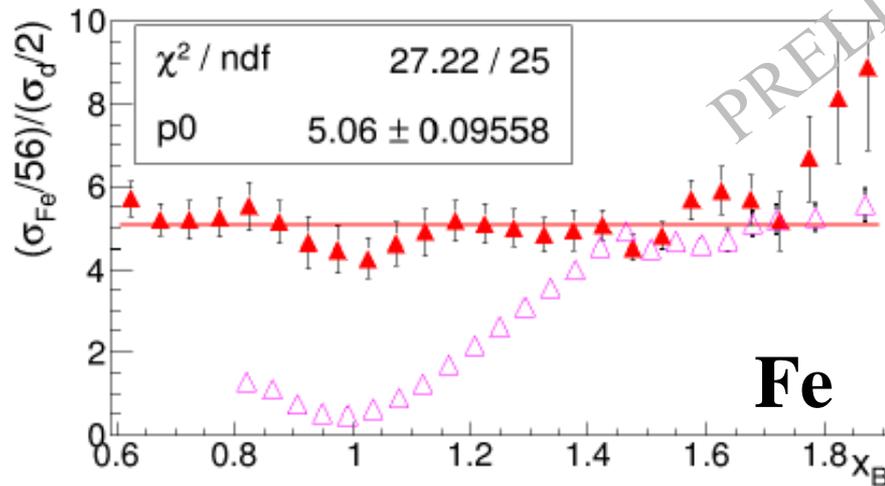
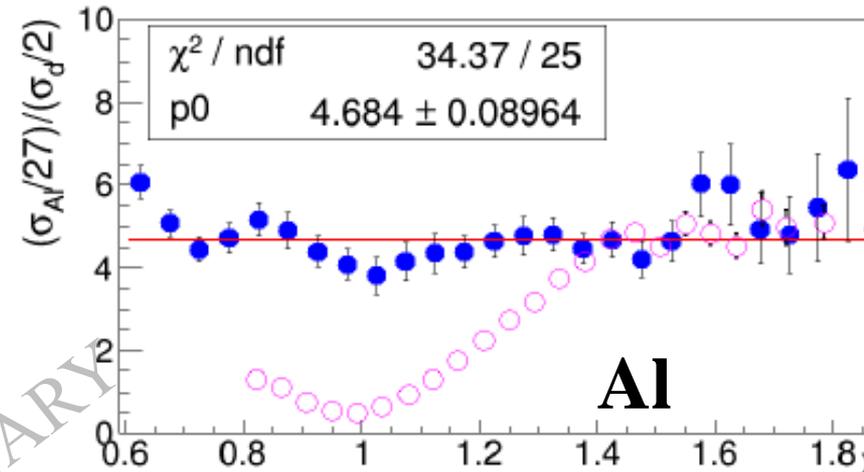
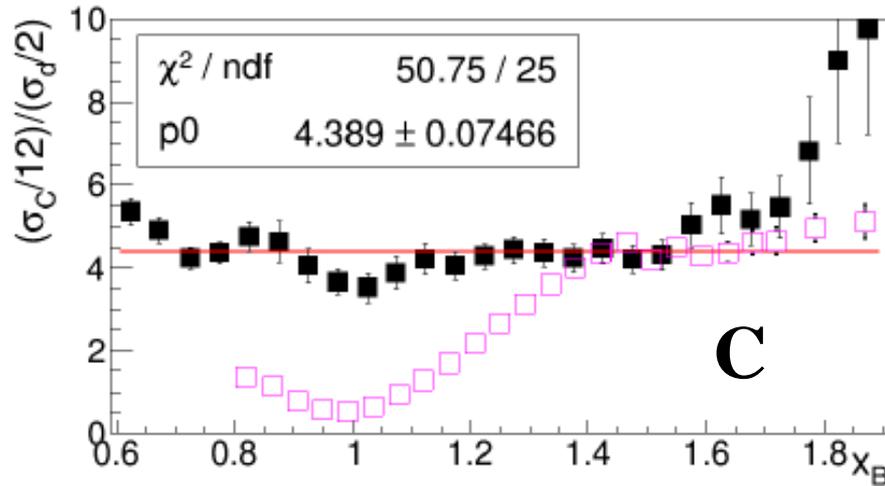


The high momentum tail in nuclei is dominated by SRC pairs

Most of the SRC pairs (90%) are np only 5% pp and 5% nn

$A(e, e' p)$

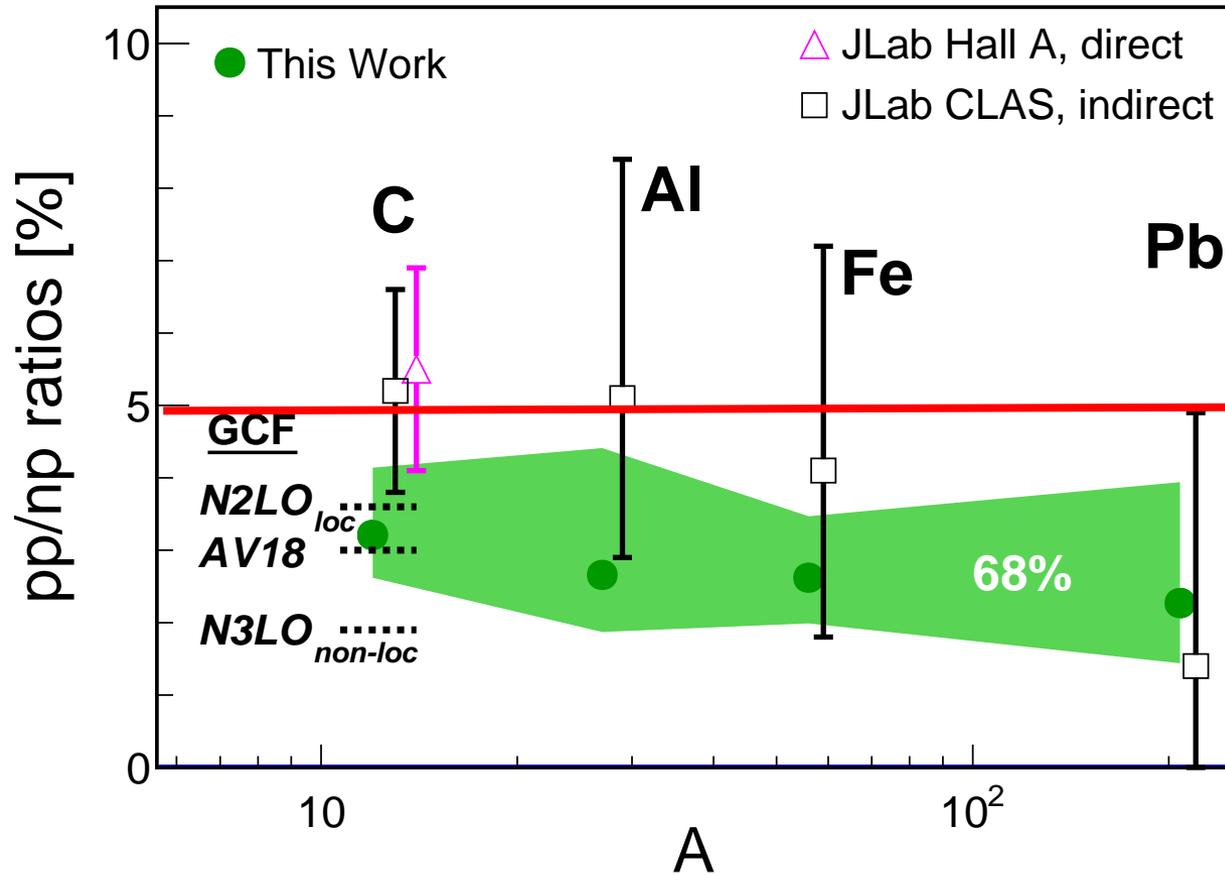
$P_{\text{miss}} > k_F$ and MM cuts replace the $X_B > 1$ cut



PRELIMINARY



SRCs Dominated by np pairs

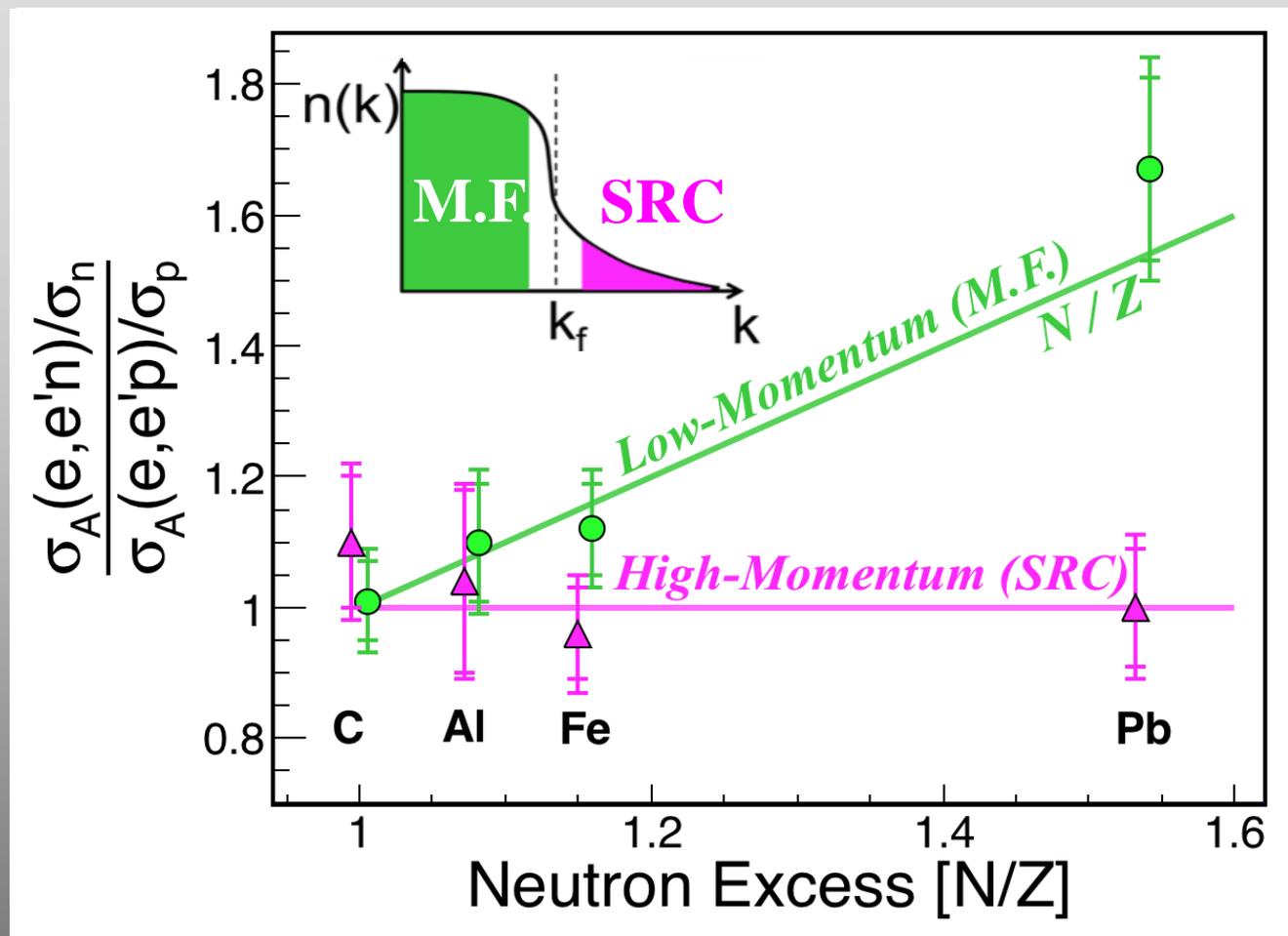


5%

Duer, PRL (2019); Duer, Nature (2018); Hen, Science (2014); Korover, PRL (2014); Subedi, Science (2008); Shneor, PRL (2007); Piassetzky, PRL (2006); Tang, PRL (2003); Review: Hen RMP (2017);

Asymmetric nuclei

$$A(e, e' p) \quad A(e, e' n)$$

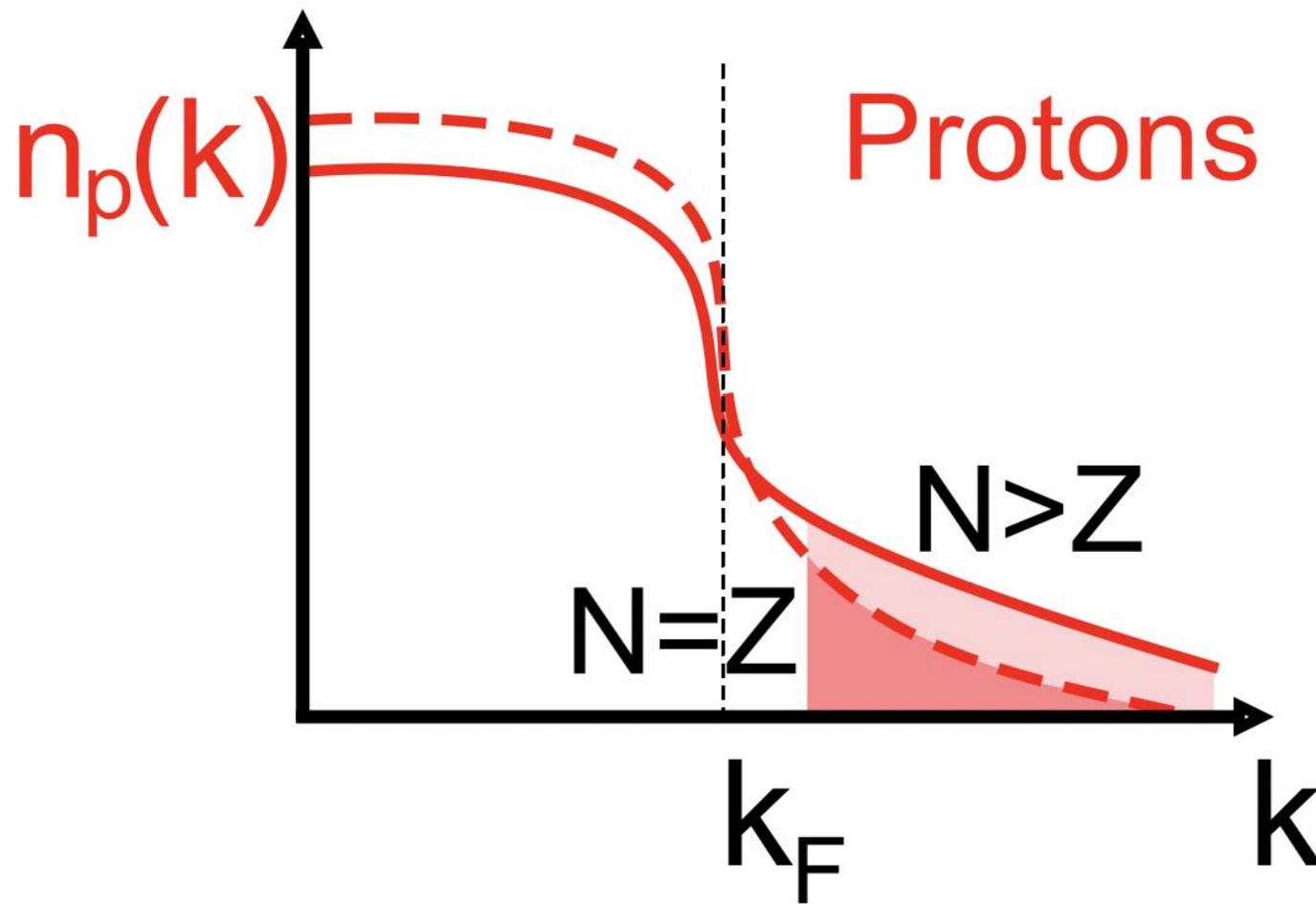


→ Same # of high-momentum protons and neutrons

M. Duer et al. (CLAS Collaboration), Nature, 560 (2018) 617-621



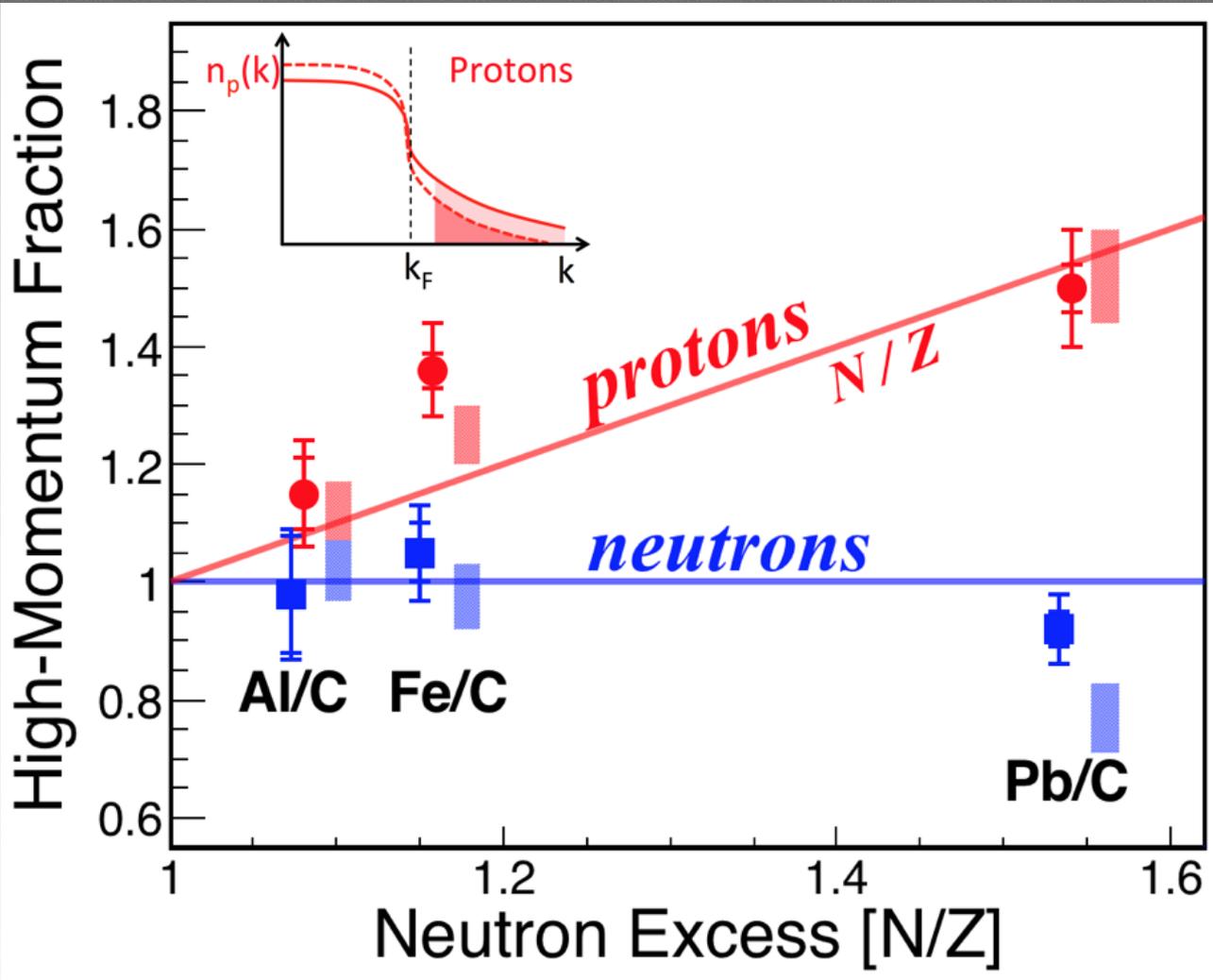
Fraction of Neutrons and Protons in the high momentum tail



$$\frac{A(e, e' N)_{high} / A(e, e' N)_{low}}{^{12}C(e, e' N)_{high} / ^{12}C(e, e' N)_{low}}$$



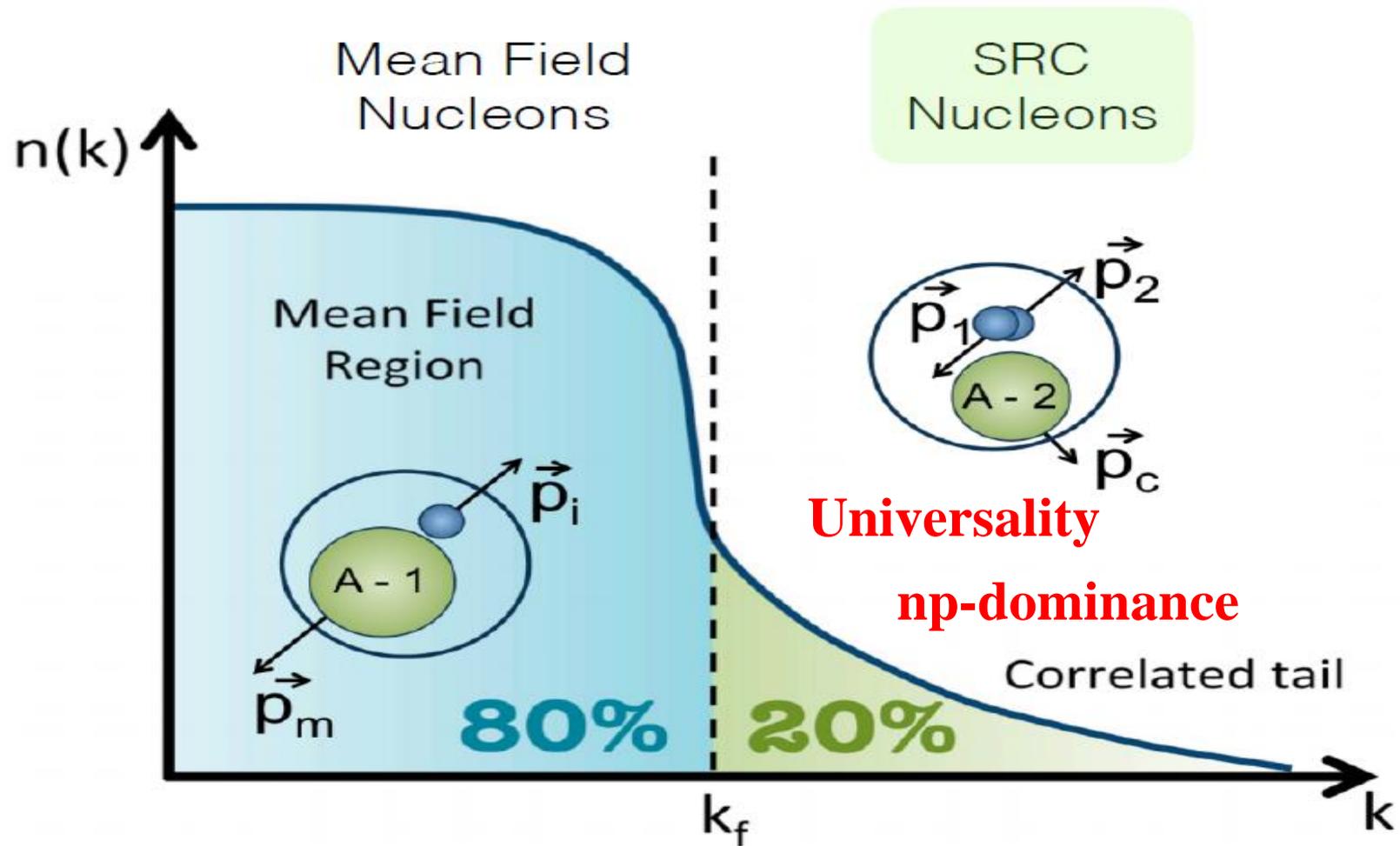
More Neutrons => More Correlated Protons

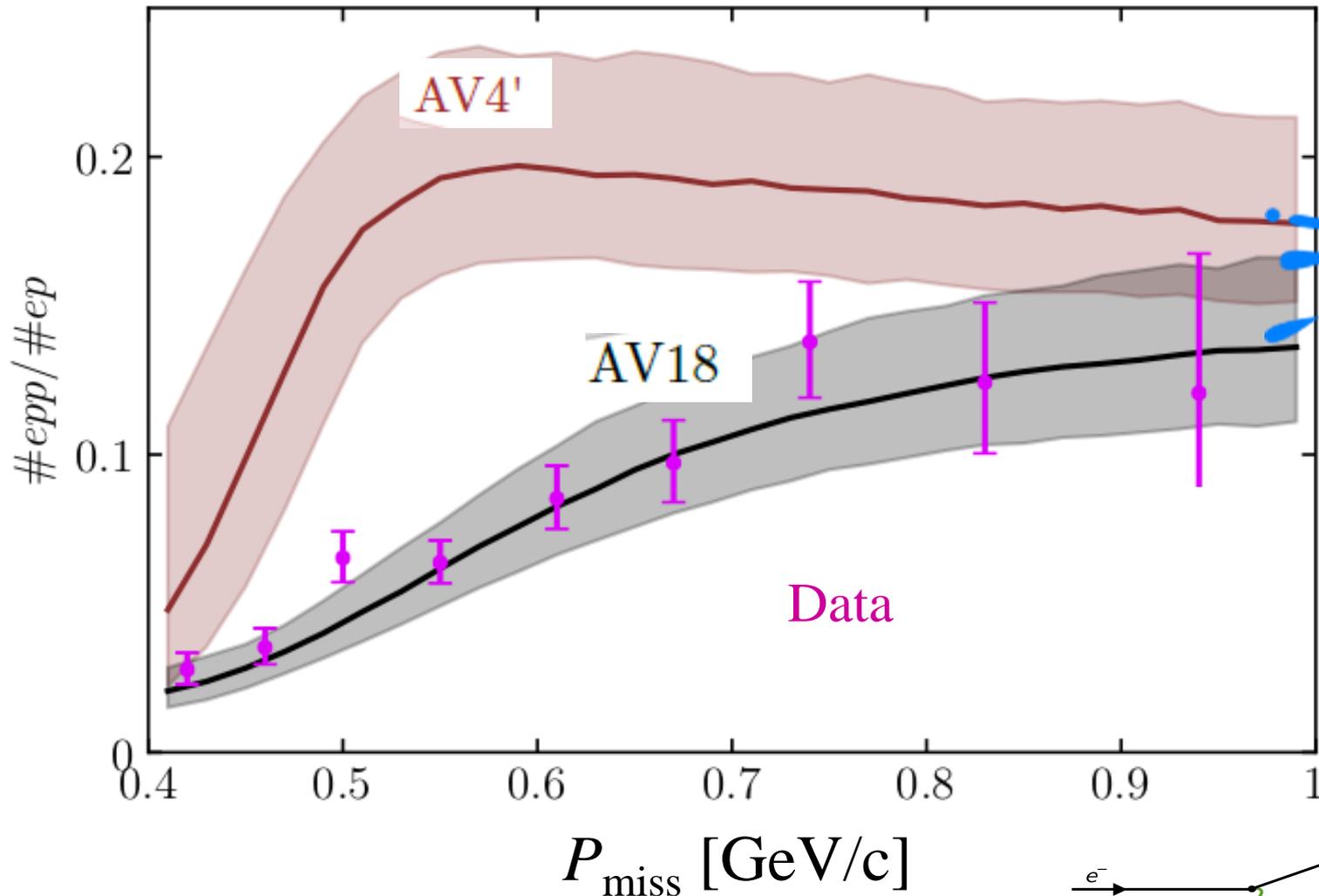


$$\frac{A(e, e' N)_{high} / A(e, e' N)_{low}}{^{12}\text{C}(e, e' N)_{high} / ^{12}\text{C}(e, e' N)_{low}}$$

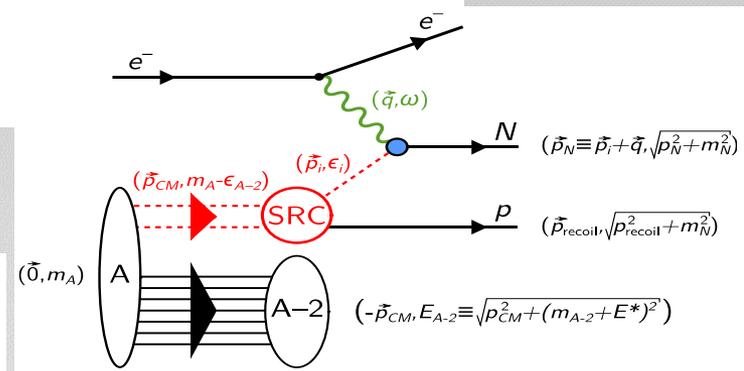


Short-Range Nucleon Correlations (SRC)





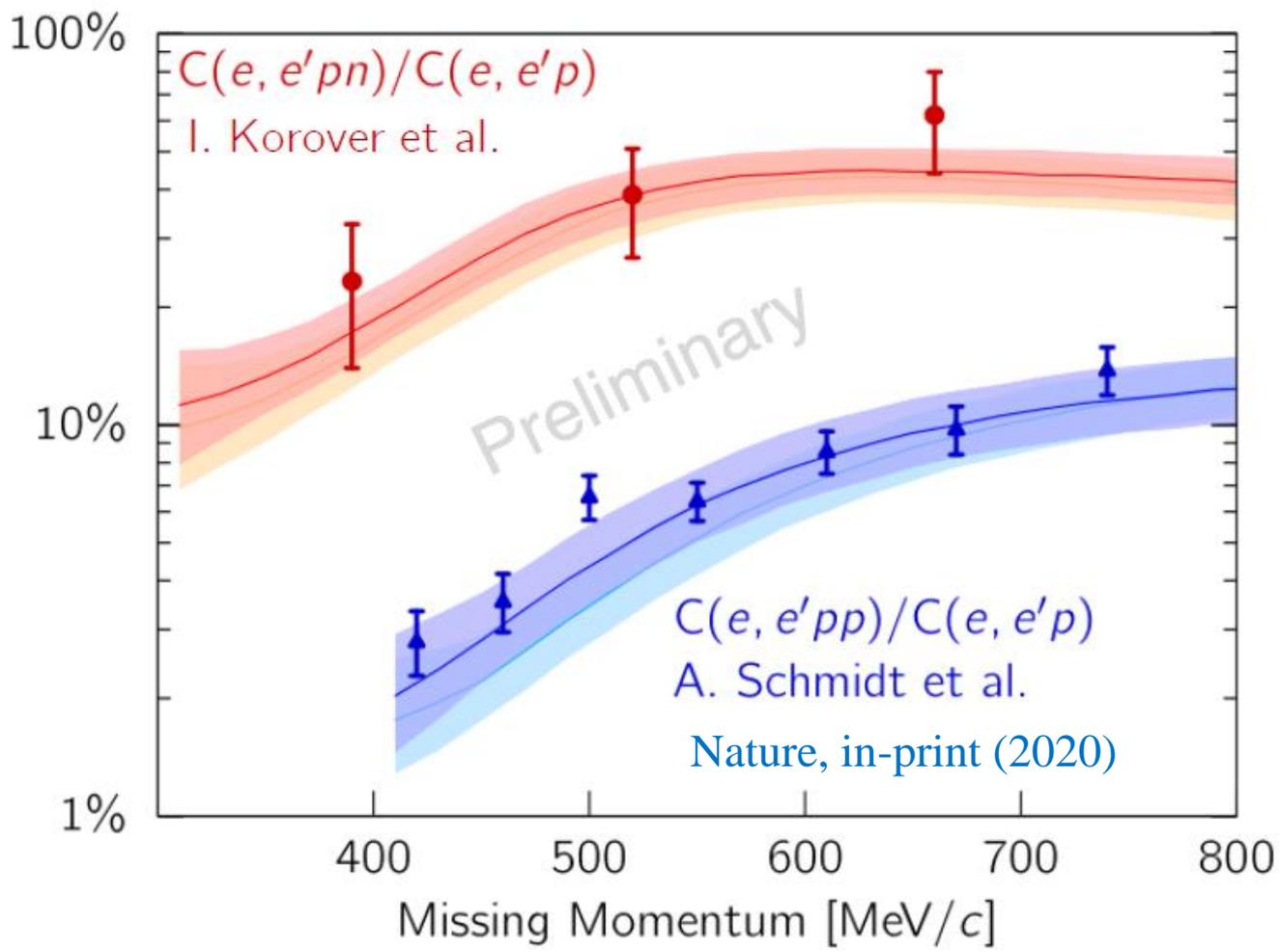
NEW!
2018-2019



Probing the core of the strong nuclear interaction

A. Schmidt et al. (CLAS Collaboration)

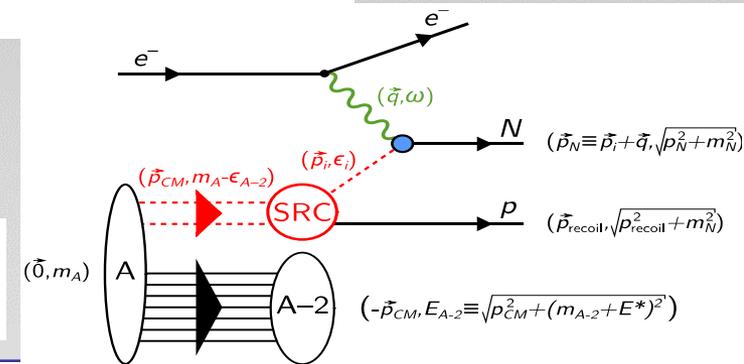
Nature (in print)



Probing the core of the strong nuclear interaction

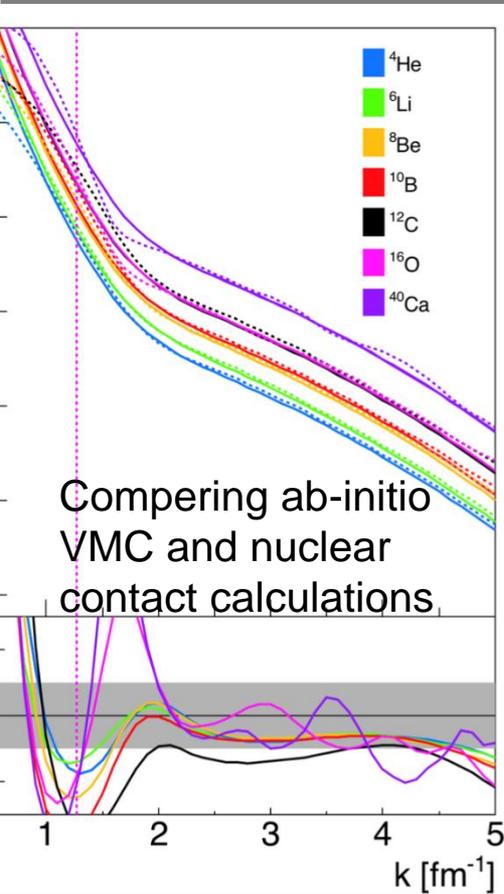
A. Schmidt et al. (CLAS Collaboration)

Nature (in print)



Universality (factorization)

Momentum Distribution



a factorized ansatz

$$\Psi \xrightarrow{r_{ij} \rightarrow 0} \sum_{\alpha} \varphi_{\alpha}(\mathbf{r}_{ij}) A_{ij}^{\alpha}(\mathbf{R}_{ij}, \{\mathbf{r}\}_{k \neq ij})$$

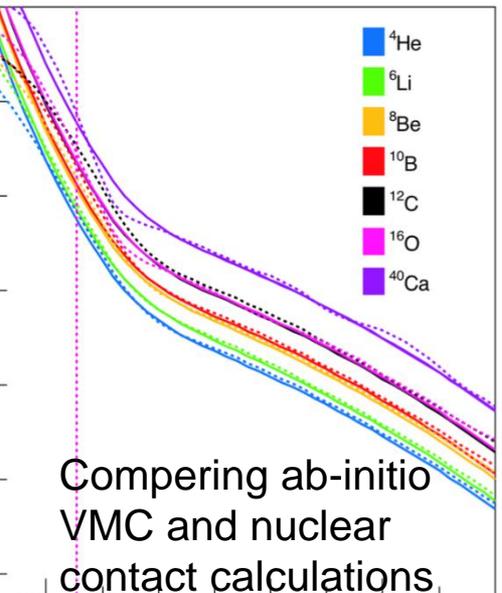
- Universal function: the zero energy solution to the 2 body problem

GCF: Generalized Contact Formalism

a factorized ansatz

$$\Psi \xrightarrow{r_{ij} \rightarrow 0} \sum_{\alpha} \varphi_{\alpha}(\mathbf{r}_{ij}) A_{ij}^{\alpha}(\mathbf{R}_{ij}, \{\mathbf{r}\}_{k \neq ij})$$

Momentum Distribution



- Universal function: the zero energy solution to the 2 body problem
- Nucleus (A-2) specific function

The nuclear contacts and short range correlations in nuclei

R. Weiss,¹ R. Cruz-Torres,² N. Barnea,¹ E. Piasetzky,³ and O. Hen²

Phys. Lett. B780 (2018) 211.

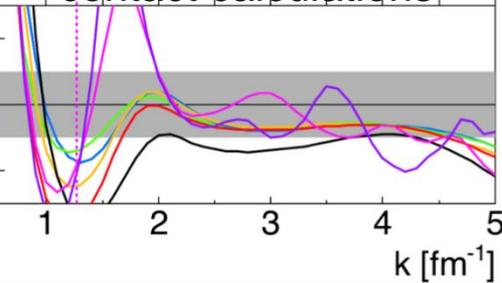
A universal description of SRC:

$$n_p(k) \xrightarrow{k \rightarrow \infty} C_{pn}^d |\varphi_{pn}^d(k)|^2 + C_{pn}^0 |\varphi_{pn}^0(k)|^2 + 2C_{pp}^0 |\varphi_{pp}^0(k)|^2$$

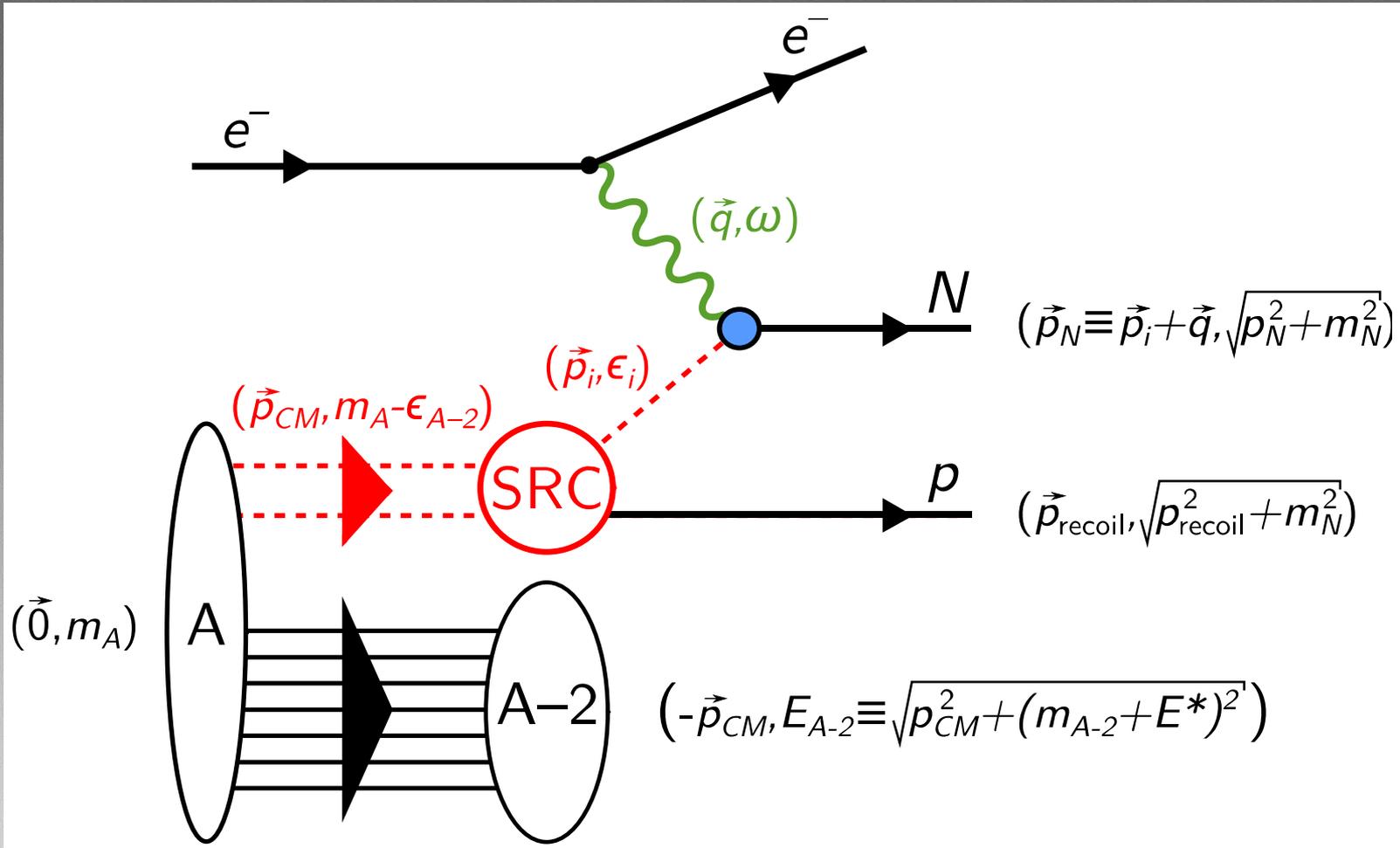
$l = 0, 2 \quad s = 1 \quad j = 1$
np pairs

$l = s = j = 0$
pp, nn, np pairs

Residual



Exclusive Hard scattering in selected kinematics



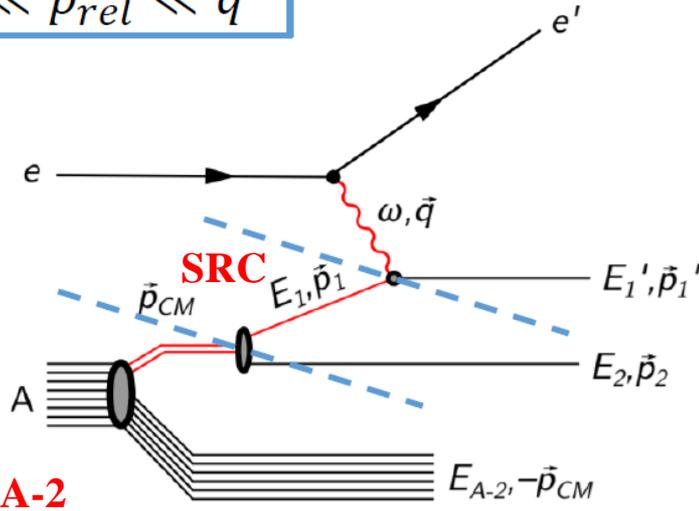
$$\sigma = K \cdot \sigma_{eN} \cdot \underbrace{D(p_i, p_{recoil}, E_{recoil})}_{\text{GCF}} \cdot T_{FSI}$$

$$\text{GCF} \rightarrow n(\vec{p}_{CM}) \cdot \sum C_\alpha \cdot \varphi_{2N}(\vec{p}_{relative})$$

selected kinematics

→ scale separation, factorization

$$p_{CM} \ll p_{rel} \ll q$$



Sensitivity to NN interaction

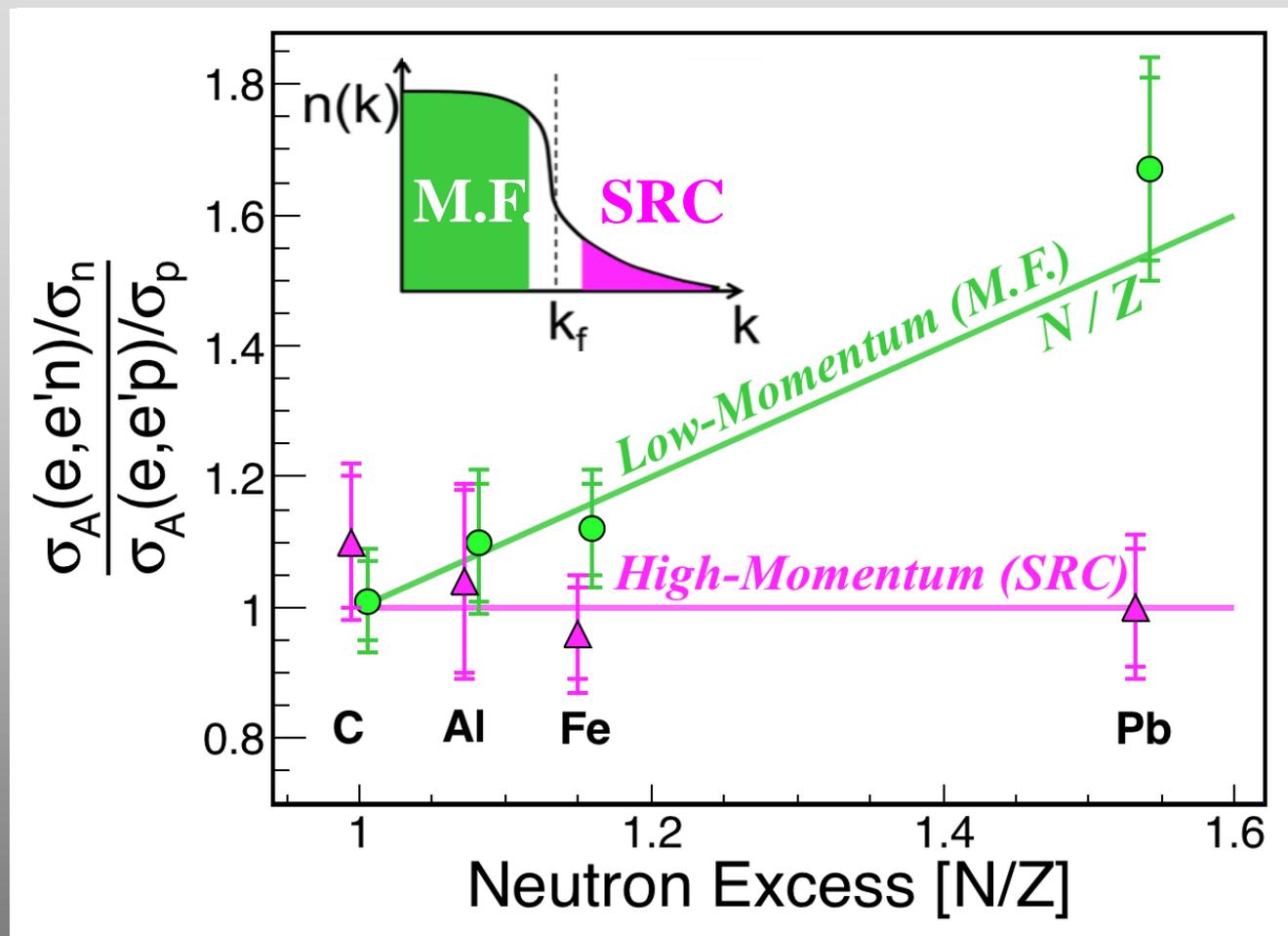
Universality

$$\sigma = K \cdot \sigma_{eN} \cdot \underbrace{D(p_i, p_{recoil}, E_{recoil})}_{\text{GCF}} \cdot T_{FSI}$$

$$\hookrightarrow n(\vec{p}_{CM}) \cdot \sum_{\alpha} C_{\alpha} \varphi_{2N}(\vec{p}_{relative})$$

Asymmetric nuclei

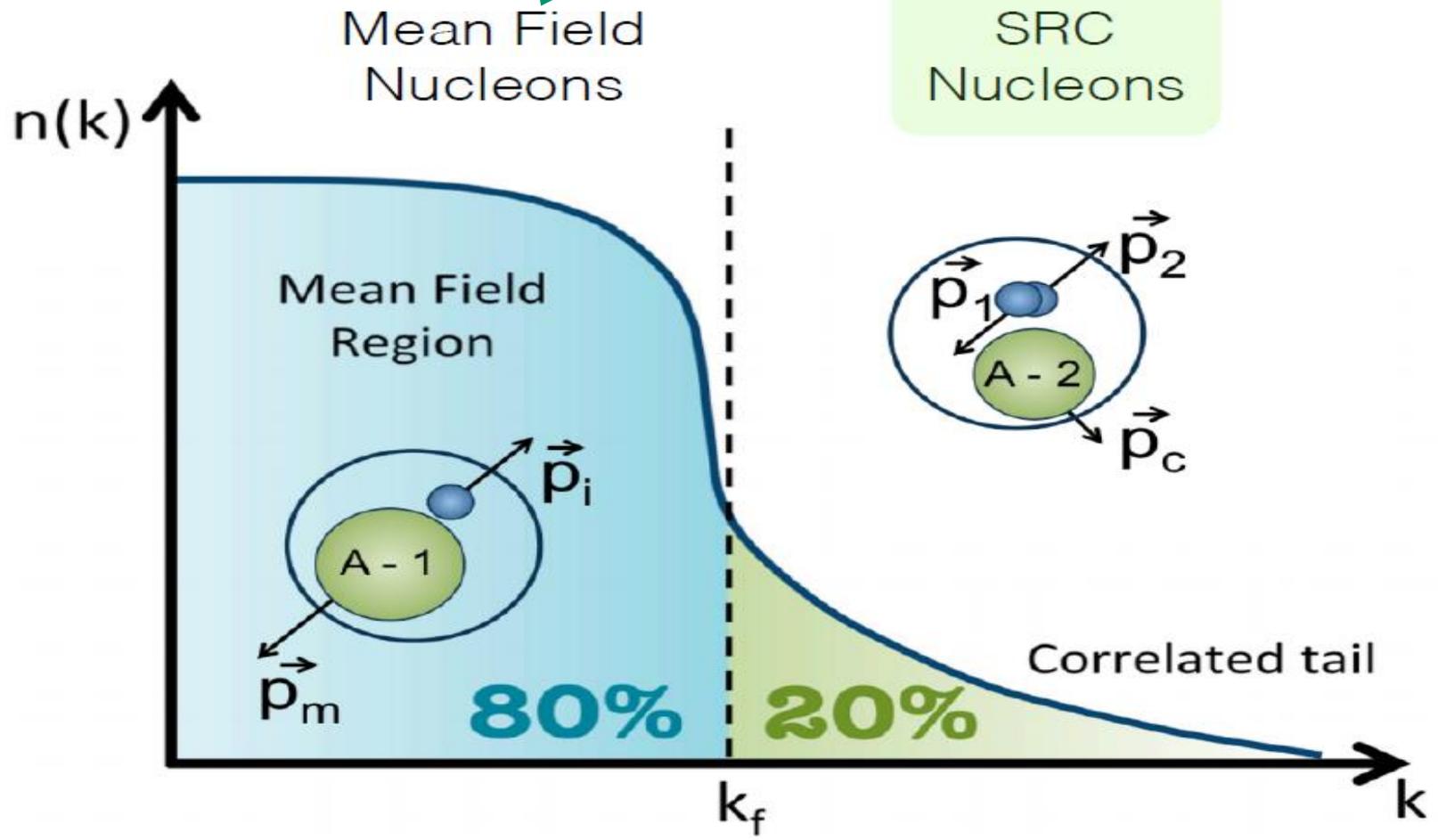
$$A(e, e' p) \quad A(e, e' n)$$



→ Same # of high-momentum protons and neutrons

M. Duer et al. (CLAS Collaboration), Nature, 560 (2018) 617-621

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





3-7 February 2020
CERN

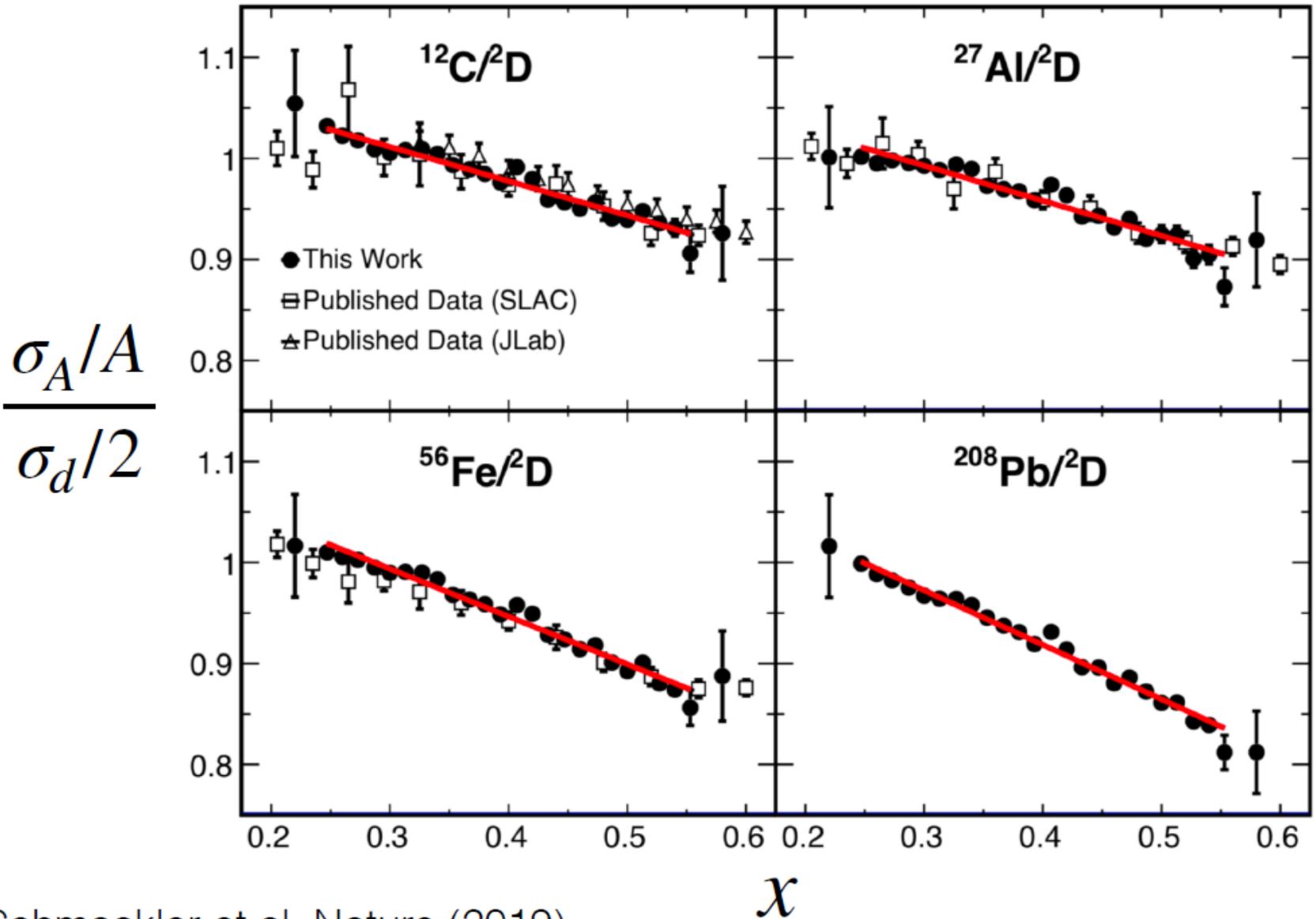
Is there any connection between correlation in partonic and in hadronic interactions ?

Dominance of scalar –diquark @ $\Lambda_B=1$

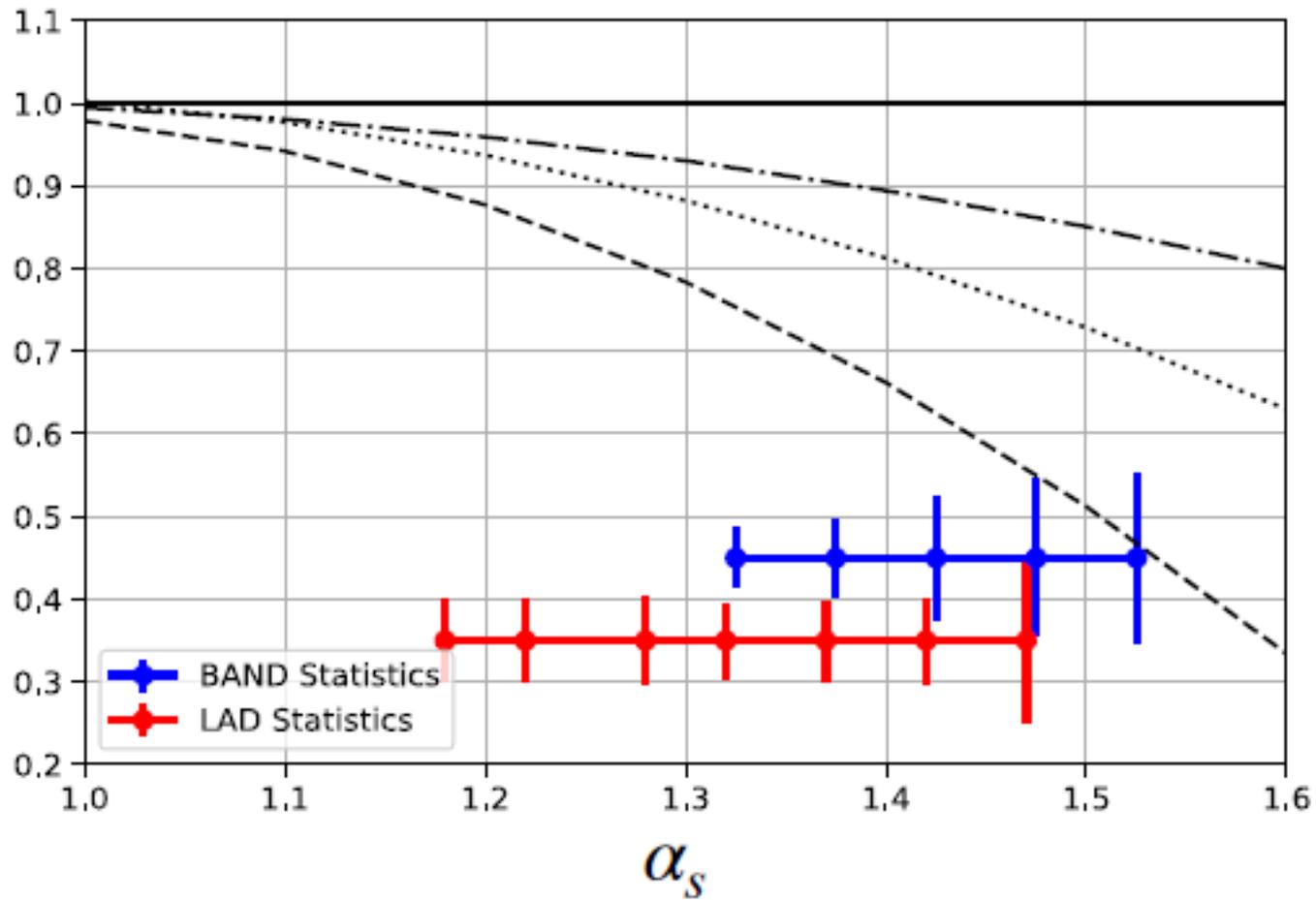
$$\rightarrow F_2^n / F_2^p = 1 / 4$$

Recent high precision (e,e') data

DIS



Bound / Free



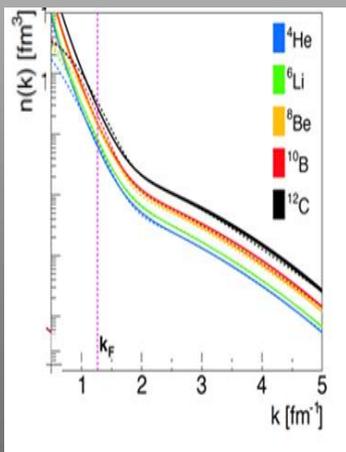
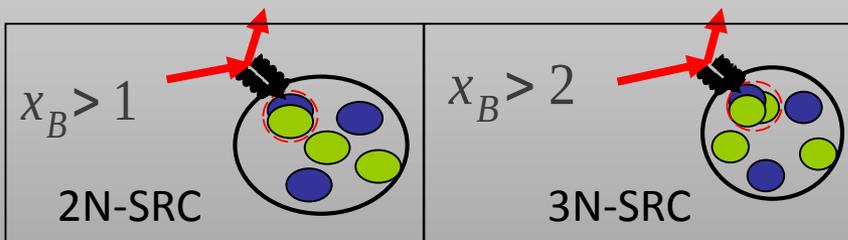
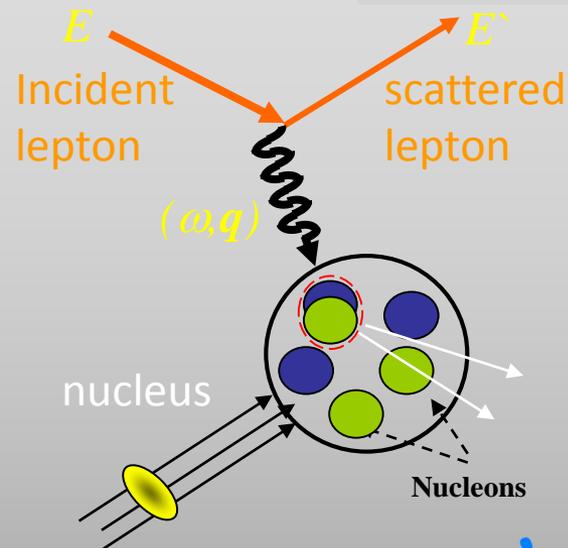
Inclusive electron scattering $A(e,e')$

$$0 \leq x_B \leq A$$

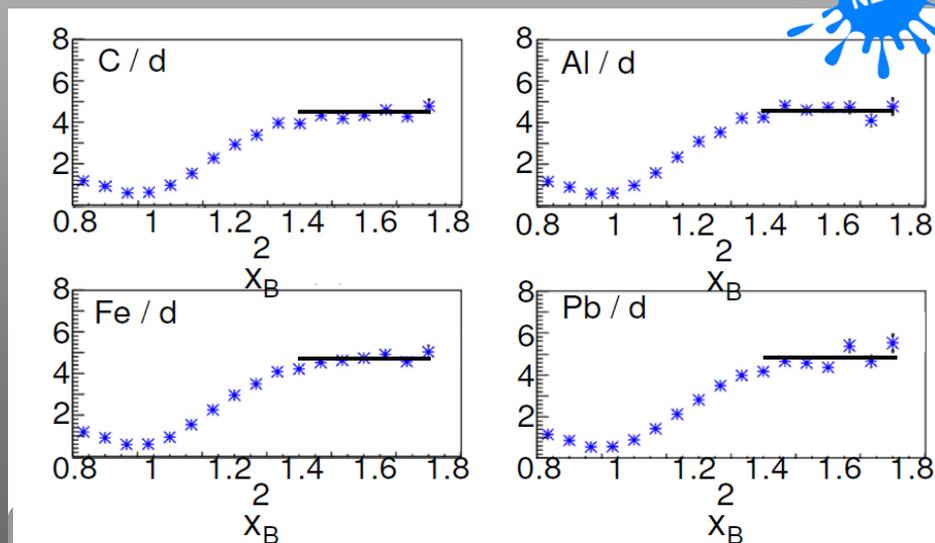
$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

$$\omega = E' - E$$

$$x_B = \frac{Q^2}{2m\omega} \quad (x_B' = \frac{Q^2}{2(q \cdot p_T)})$$



Momentum scaling \rightarrow



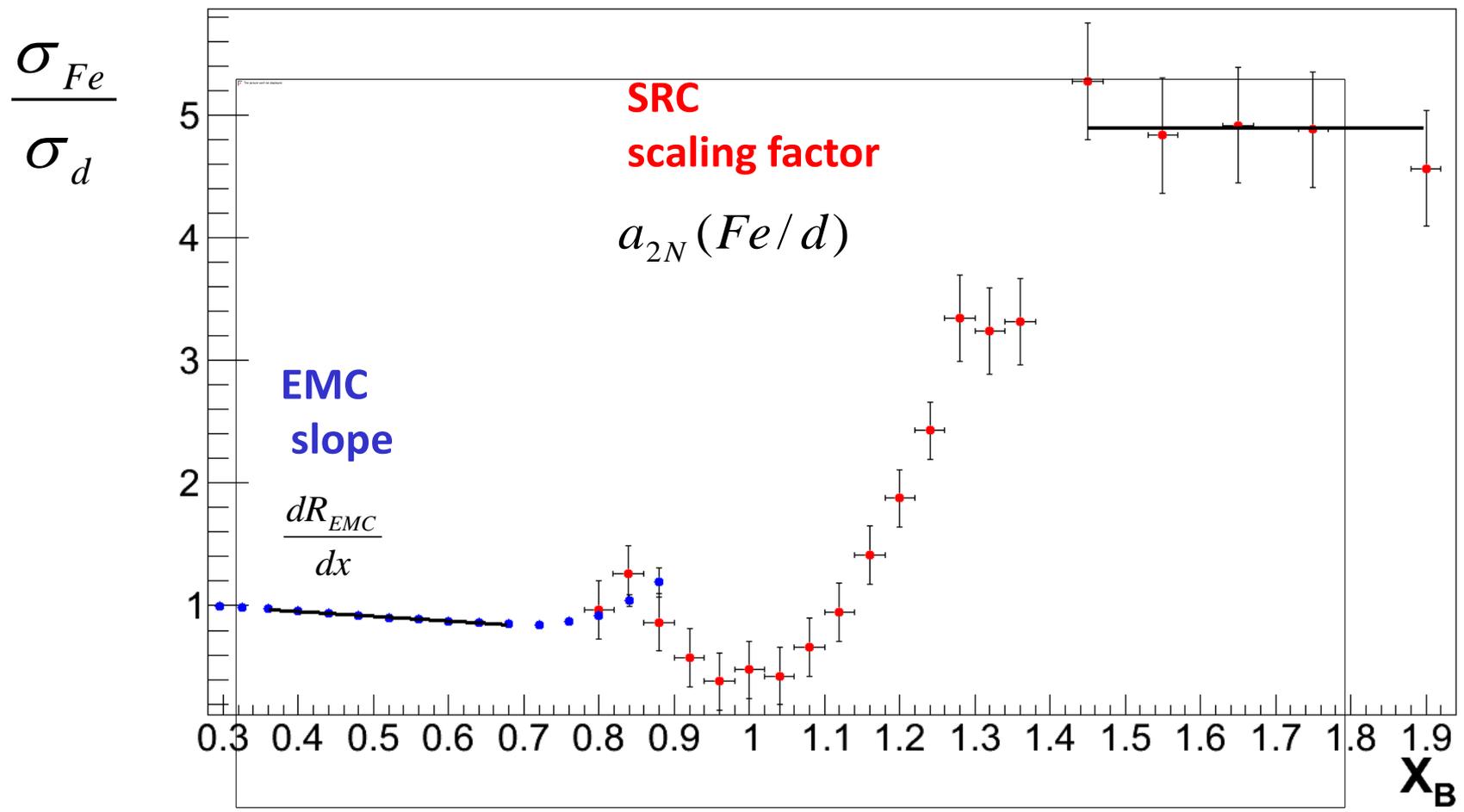
--> Counts the number of SRC clusters in nuclei $a_{2N}(A/d)$

Schmookler Duer et al., Nature 566 (2019) 354-358

Data mining (EG2c)



Comparing magnitude of EMC effect and SRC scaling factors



SLAC data:

Gomez et al., Phys. Rev. D49, 4348 (1983).

Frankfurt, Strikman, Day, Sargsyan, Phys. Rev. C48 (1993) 2451.

$Q^2=2, 5, 10, 15 \text{ GeV}/c^2$ (averaged)

$Q^2=2.3 \text{ GeV}/c^2$