INSTITUTE for NUCLEAR THEORY

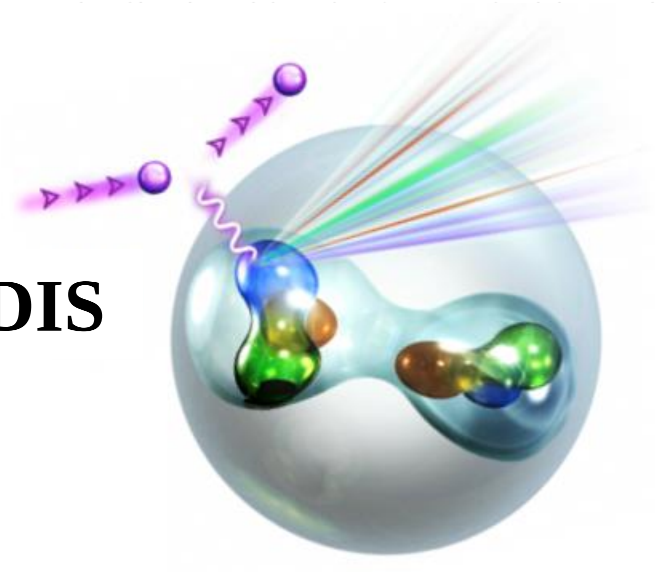
TEL AVIV UNIVERSITY

INT PROGRAM INT-23-1A

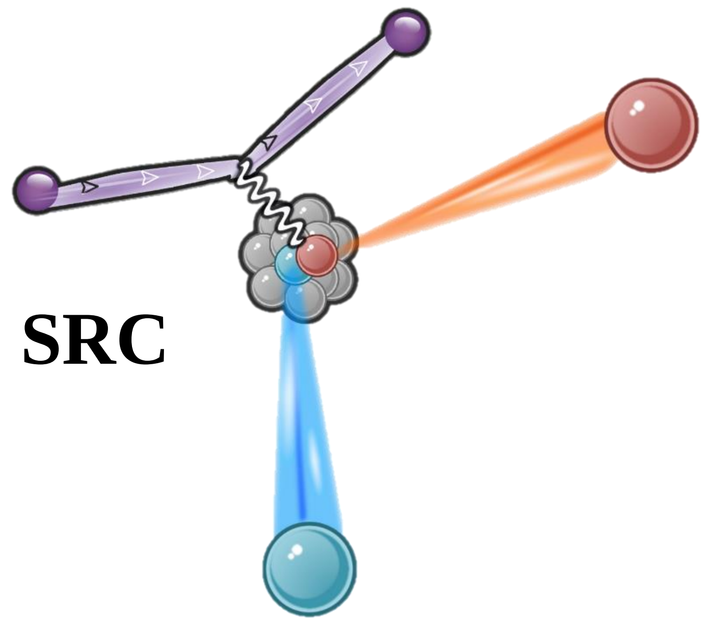
Intersection of nuclear structure and high-energy nuclear collisions

January 23, 2023 - February 24, 2023

DIS



SRC



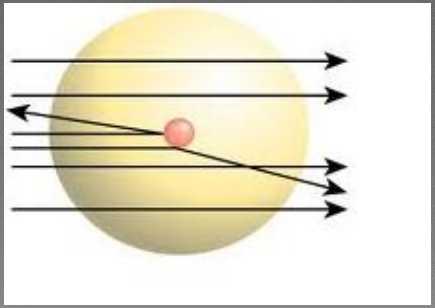
High resolution study of nucleons and nuclei

Eli Piasetzky

Tel Aviv University

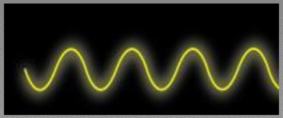
Physicists view nuclei with different resolution

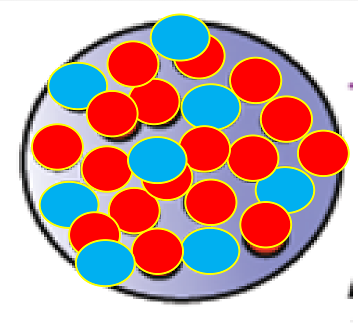
TEL AVIV UNIVERSITY



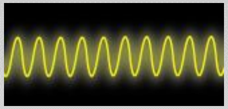
Rutherford scattering

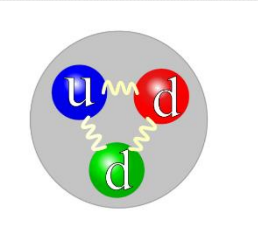
Nucleons in the Nucleus

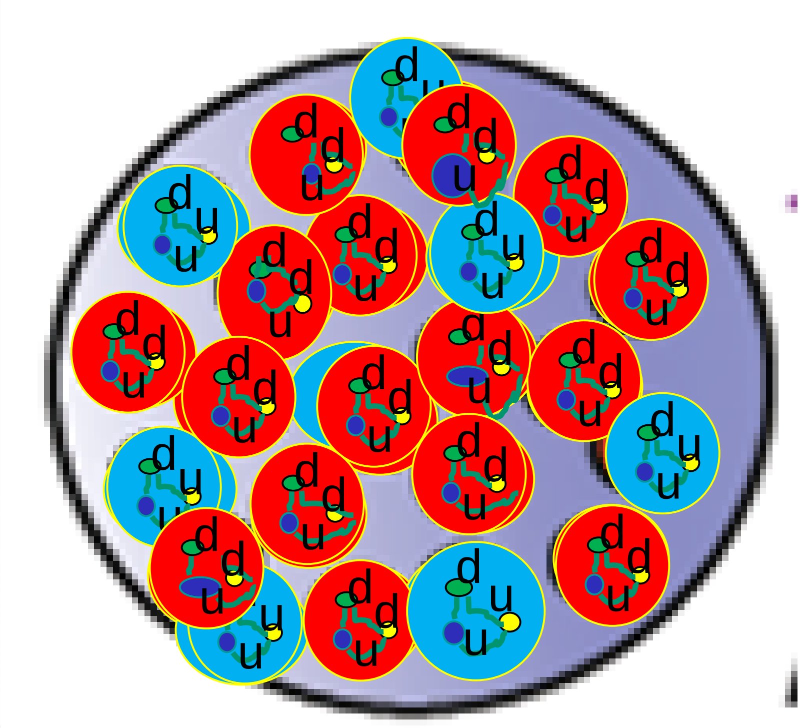




Quarks in Nucleons in the Nucleus







Monday, February 20, 2023

Start Time	Presentation Title	Presenter
9:00 AM	Equation of motion approach to nuclear structure	Elena Litvinova
10:20 AM	Break	
10:40 AM	Proton-deuteron correlation functions in pionless effective field theory	Sebastian Koenig

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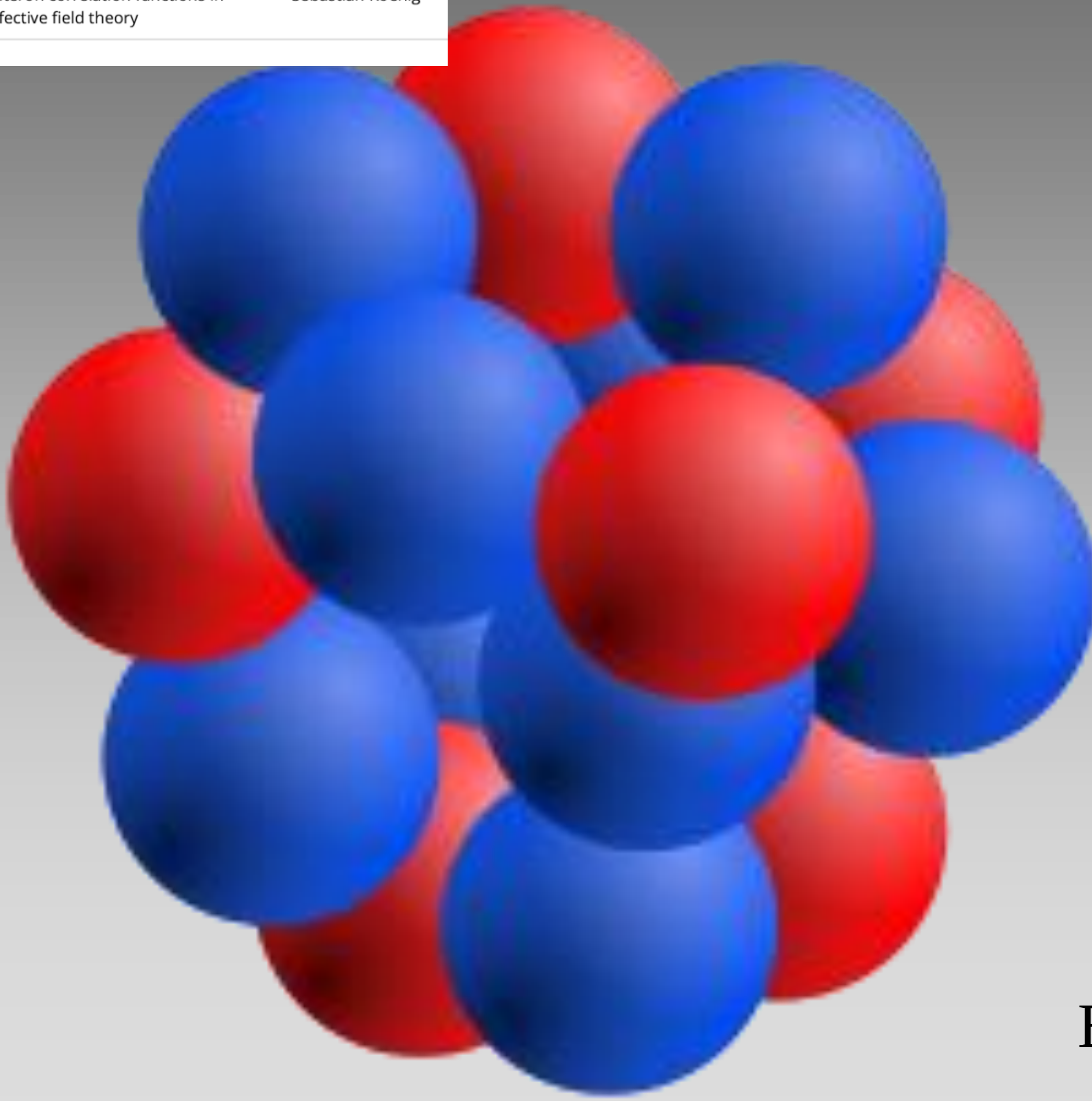

B.E ~10 Mev

Tuesday, February 21, 2023

Start Time	Presentation Title	Presenter
9:00 AM	EIC science	Abhay Deshpande
10:20 AM	Break	
10:40 AM	Small-x physics at the EIC	Anna Stasto

Thursday, February 23, 2023

Start Time	Presentation Title	Presenter
9:00 AM	Diquark-based SRC & hidden color with EIC	Jennifer Rittenhouse-West
10:20 AM	Break	
10:40 AM	Tagged DIS for bound nucleon structure	Tyler Kutz
2:00 PM	Discussions or Short talks	

Friday, February 24, 2023

Start Time	Presentation Title	Presenter
9:00 AM	Parton structure and fluctuations via exclusive probes	Zhoudunming Tu

Confinement ~1 Gev/c

INT PROGRAM INT-23-1A

Intersection of nuclear structure and high-energy nuclear collisions

January 23, 2023 - February 24, 2023

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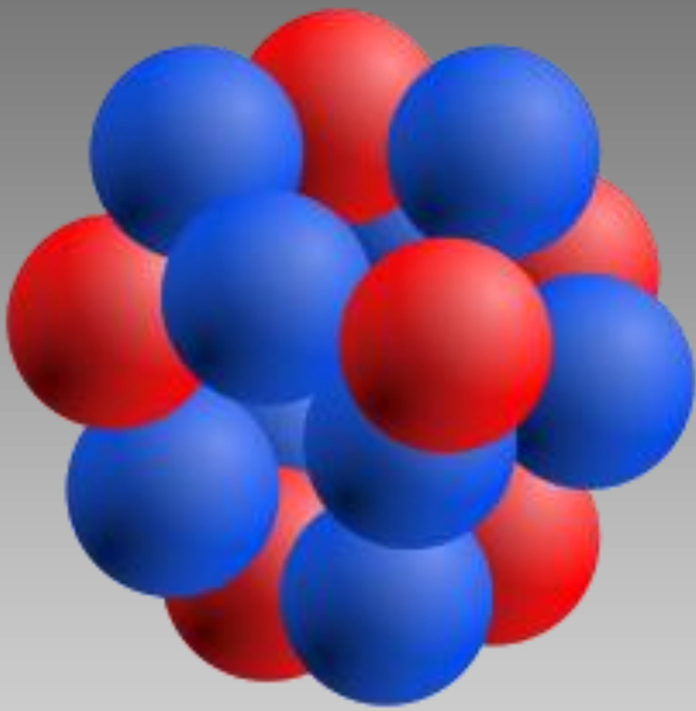
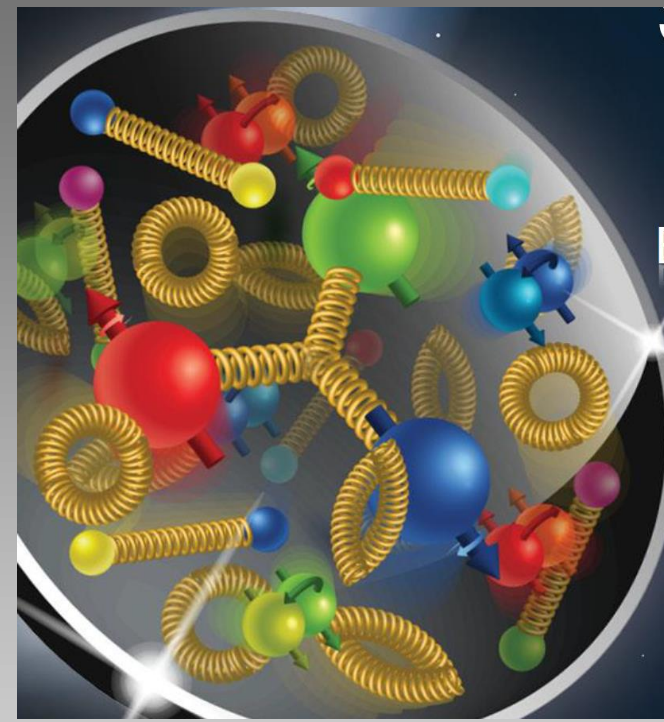




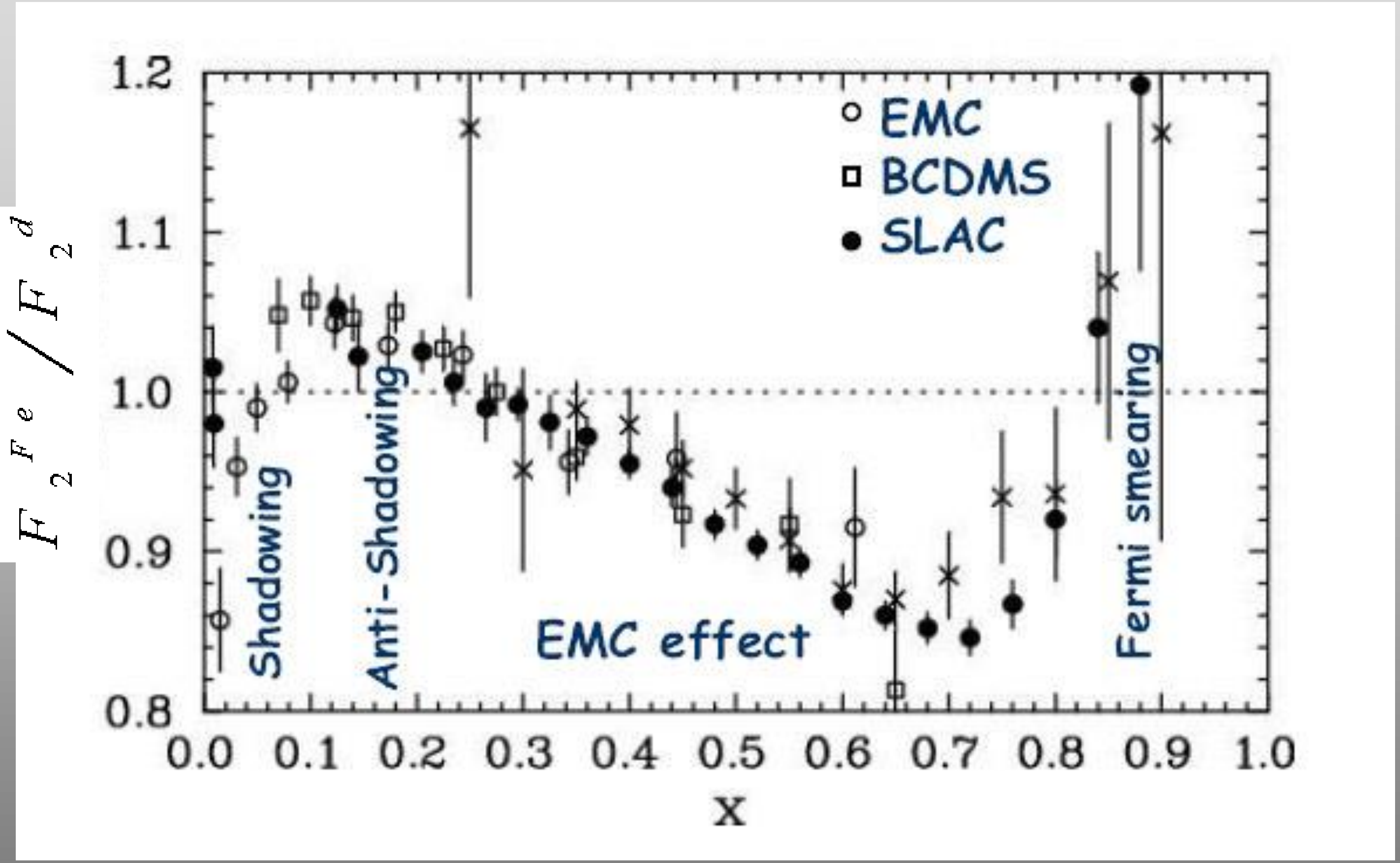
Confinement ~1 Gev/c

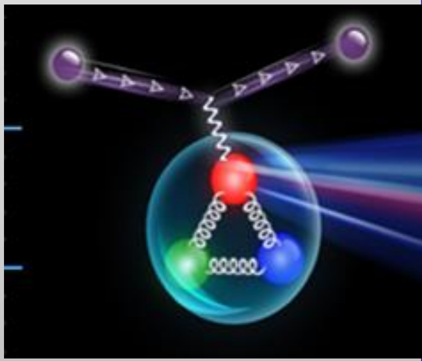
B.E ~1% M_N

Low energy nuclear physics

high energy particle physics

The European Muon Collaboration (EMC) effect

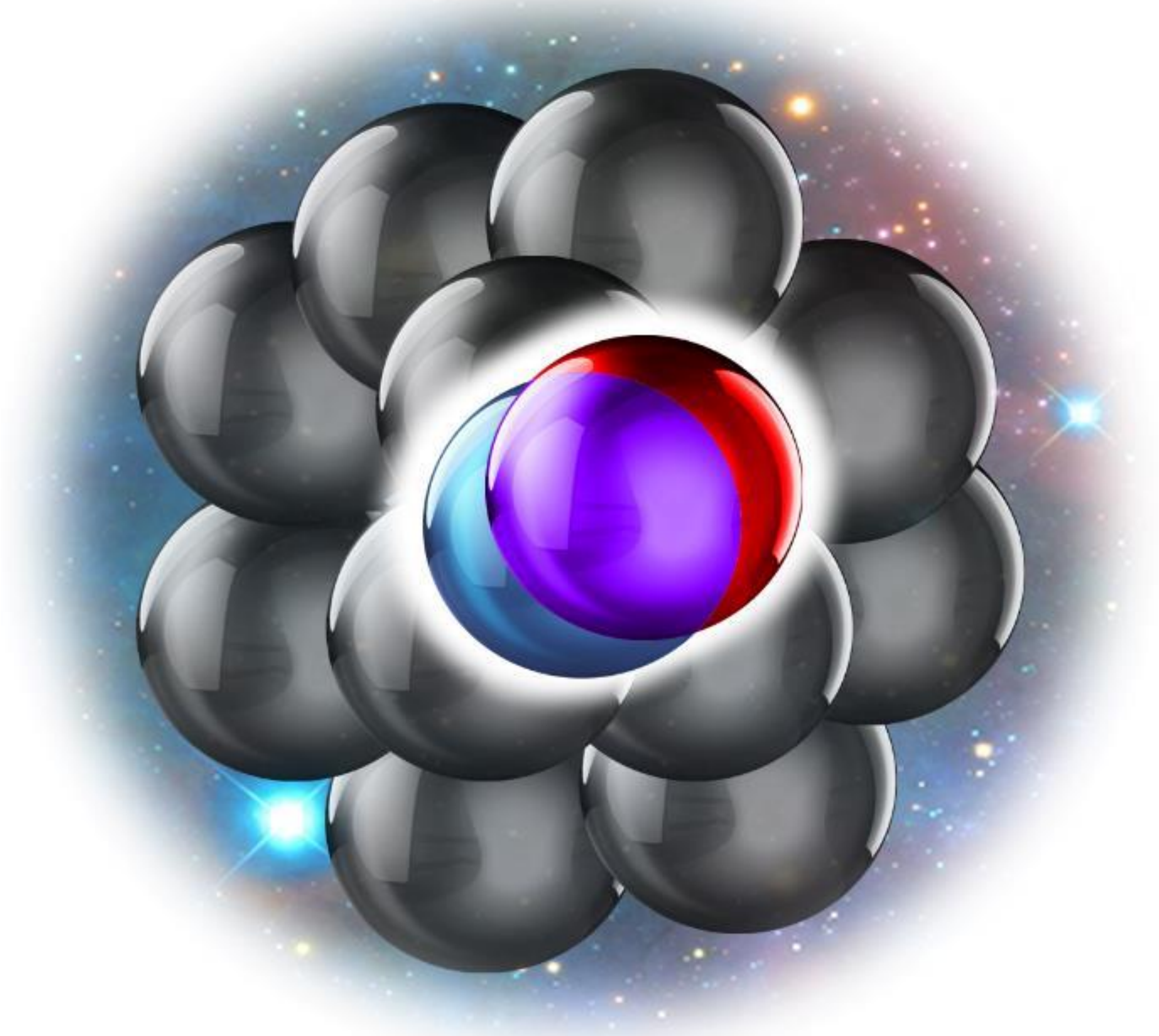




Aubert et al., PLB (1983); Ashman et al., PLB (1988); Arneodo et al., PLB (1988); Allasia et al., PLB (1990); Gomez et al., PRD (1994); Seely et al., PRL (2009); Schmookler et al., Submitted (2018)

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

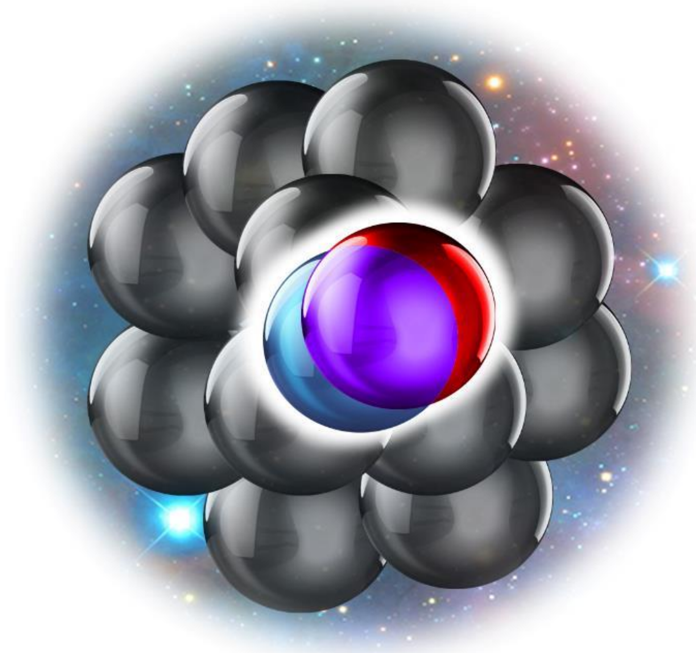
2N – SRC (two nucleons Short range Correlation)



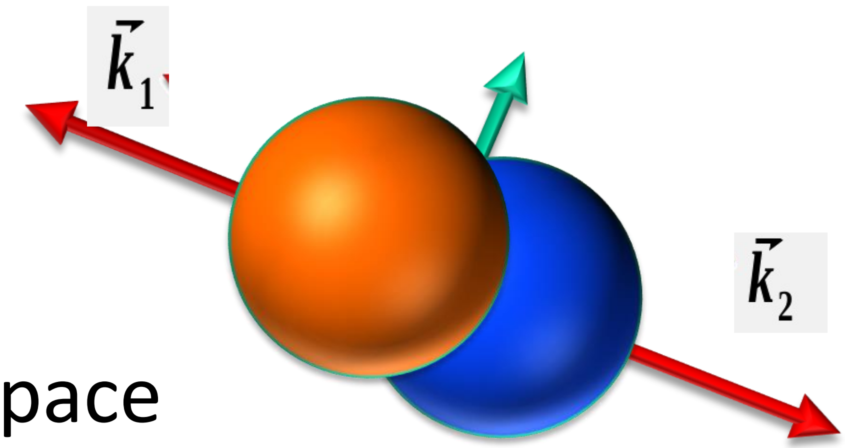
Short-Range Nucleon Correlations (SRC)

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)



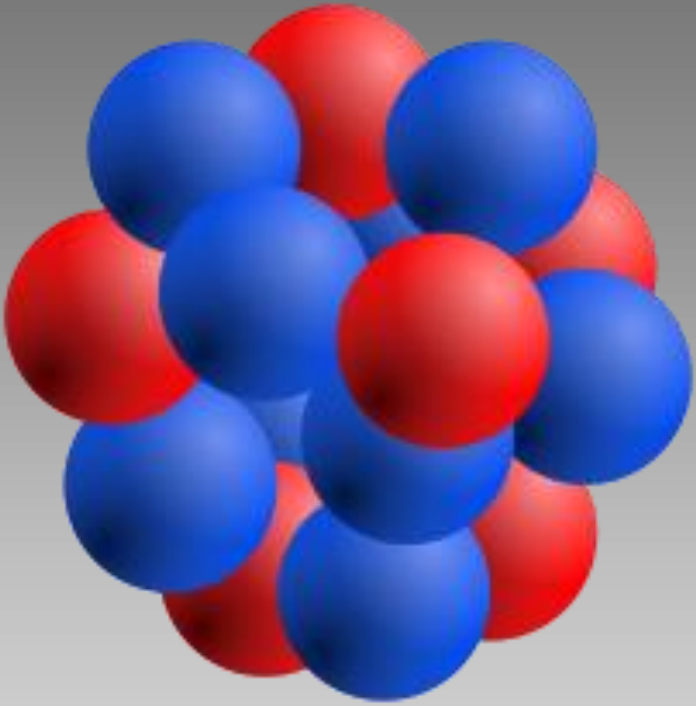
r-space

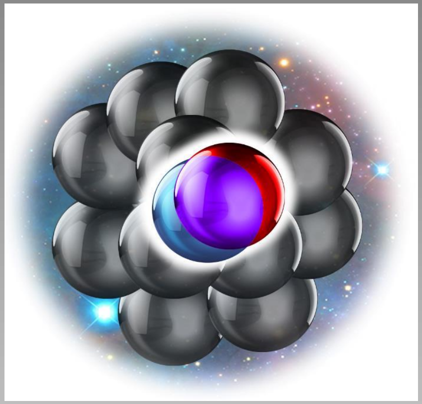


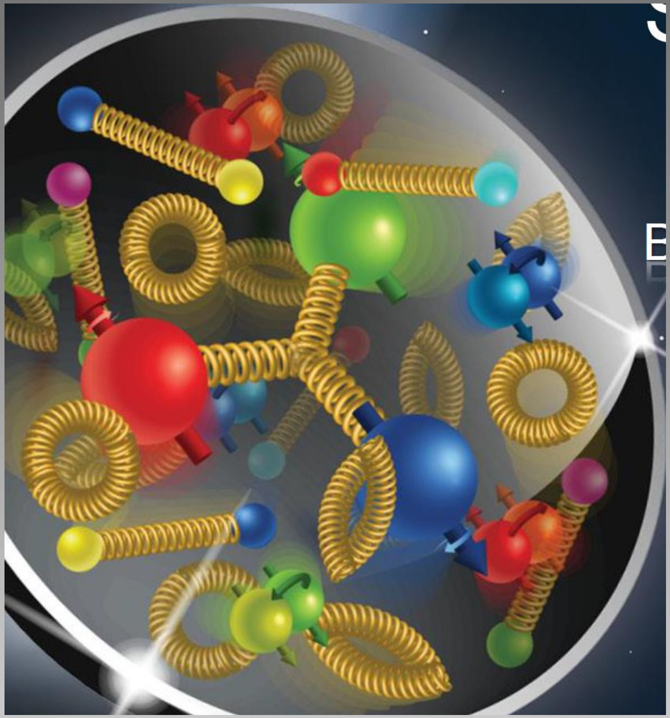
k-space

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

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







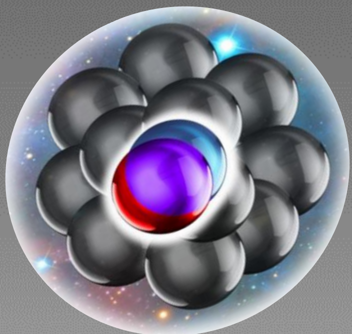
Confinement ~1 Gev/c

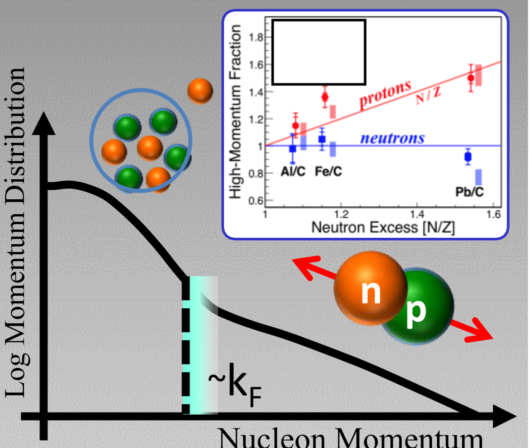
B.E ~10 Mev

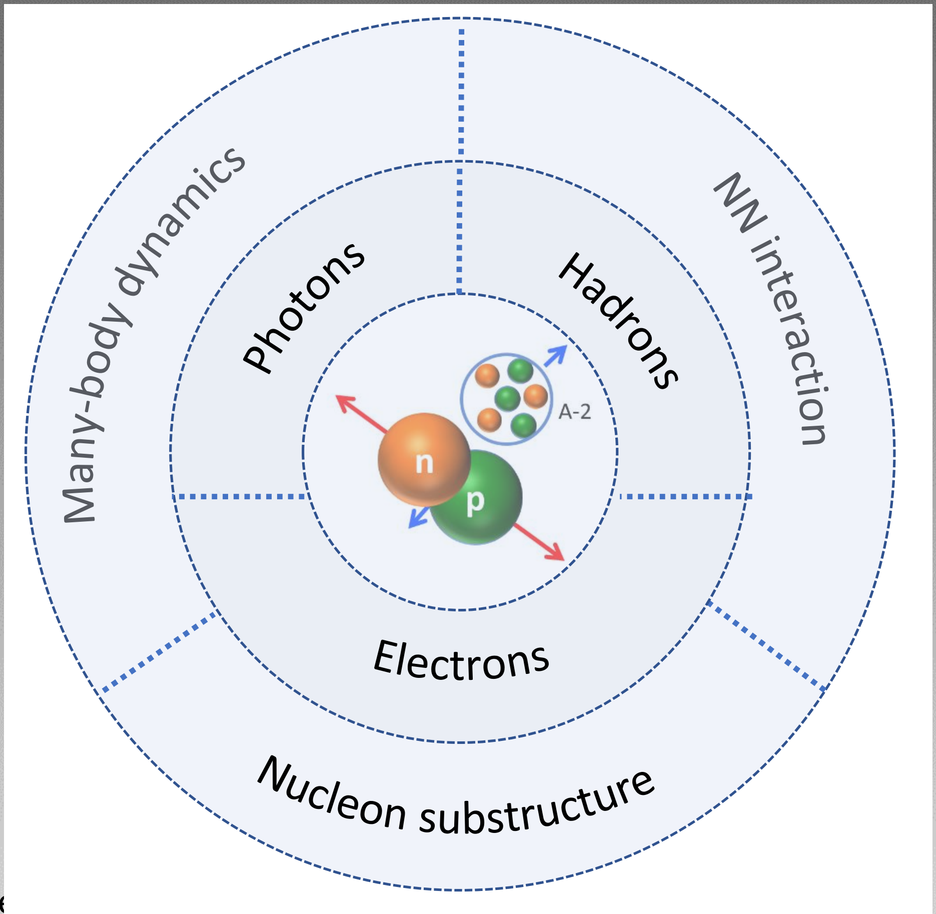
Low energy nuclear physics

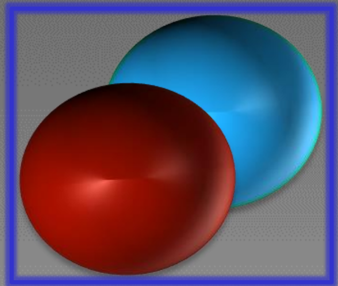
high energy particle physics

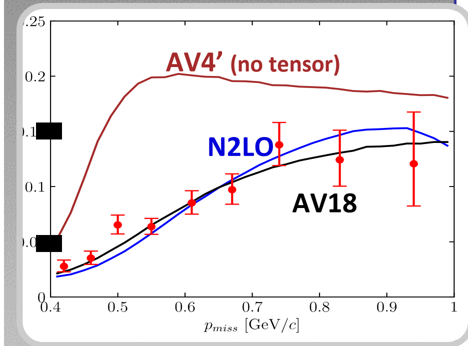
SRC Universe with multimessenger studies











Nature '20
Phys. Rev. Lett. '20
Phys. Lett. B '20
Phys. Lett. B '21

Nature '18
Phys. Rev. Lett. '18
Phys. Lett. B '18a
Phys. Lett. B '18b

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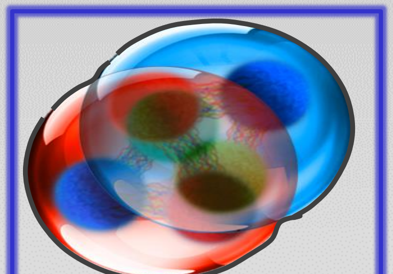
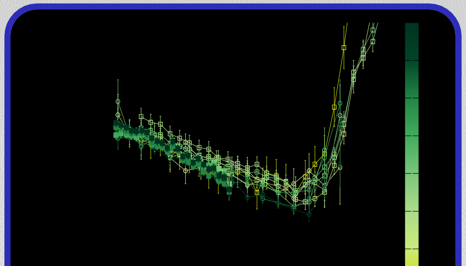
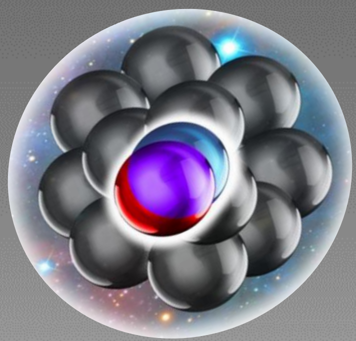
Phys. Lett. B '19
Nature Phys. '21a
Nature Phys. '21b

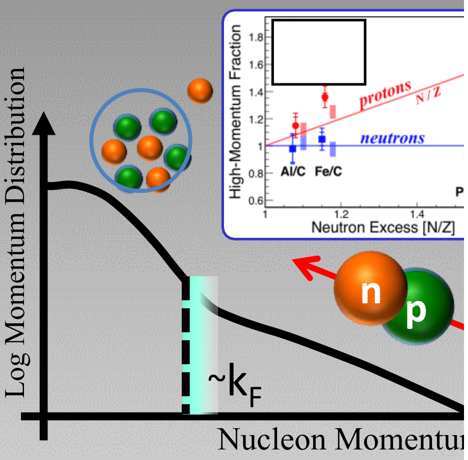


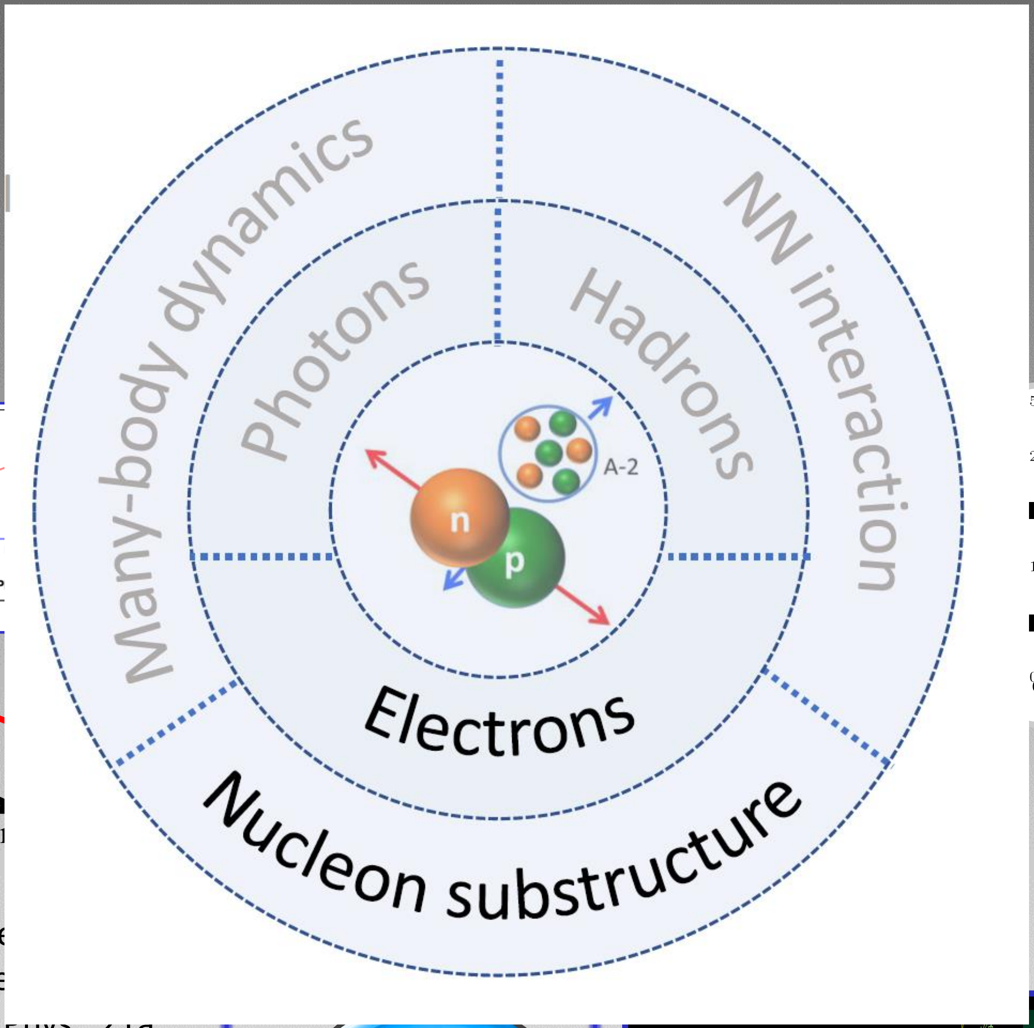


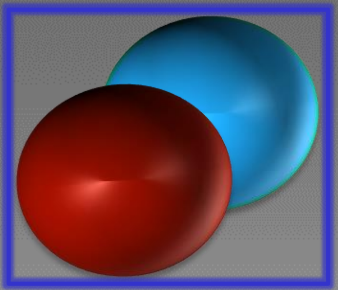
Nature '19
Phys. Rev. Lett. '20
Phys. Rev. Research '21

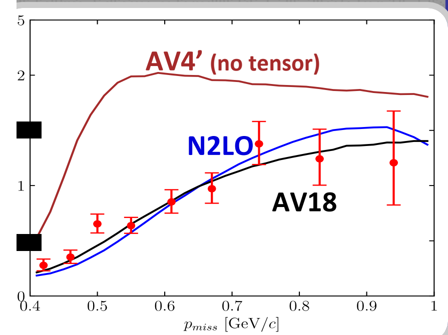
SRC Universe with multimessenger studies











Nature '20
Phys. Rev. Lett. '20
Phys. Lett. B '20
Phys. Lett. B '21

Nature '18
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Phys. Lett. B '18a
Phys. Lett. B '18b

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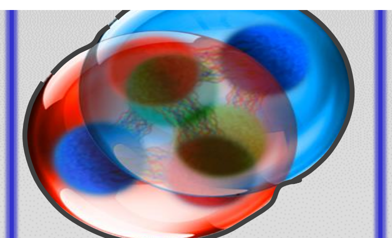
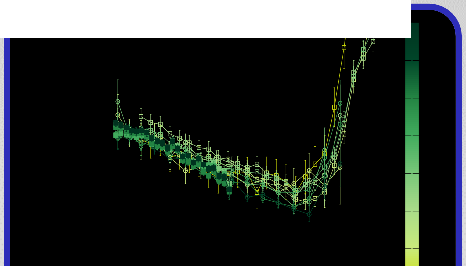
Nature Phys. '21a
Nature Phys. '21b





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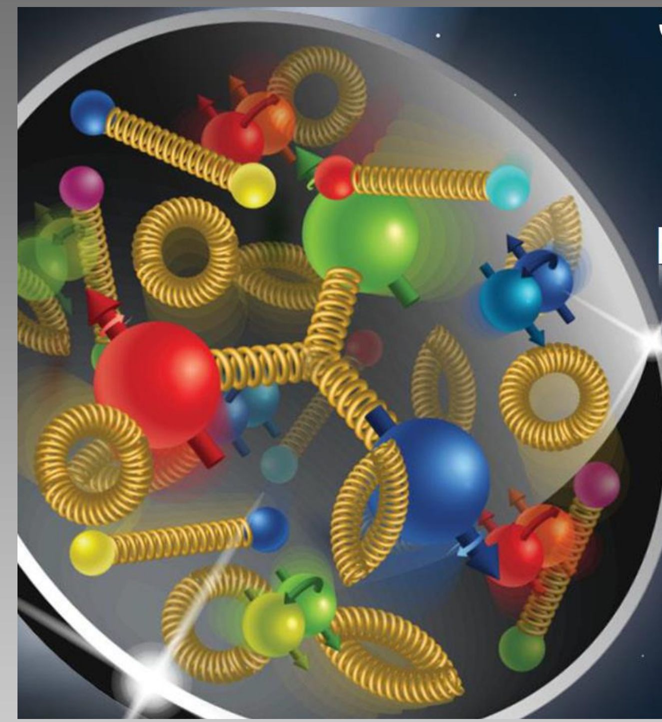
The EMC effect

2N SRC

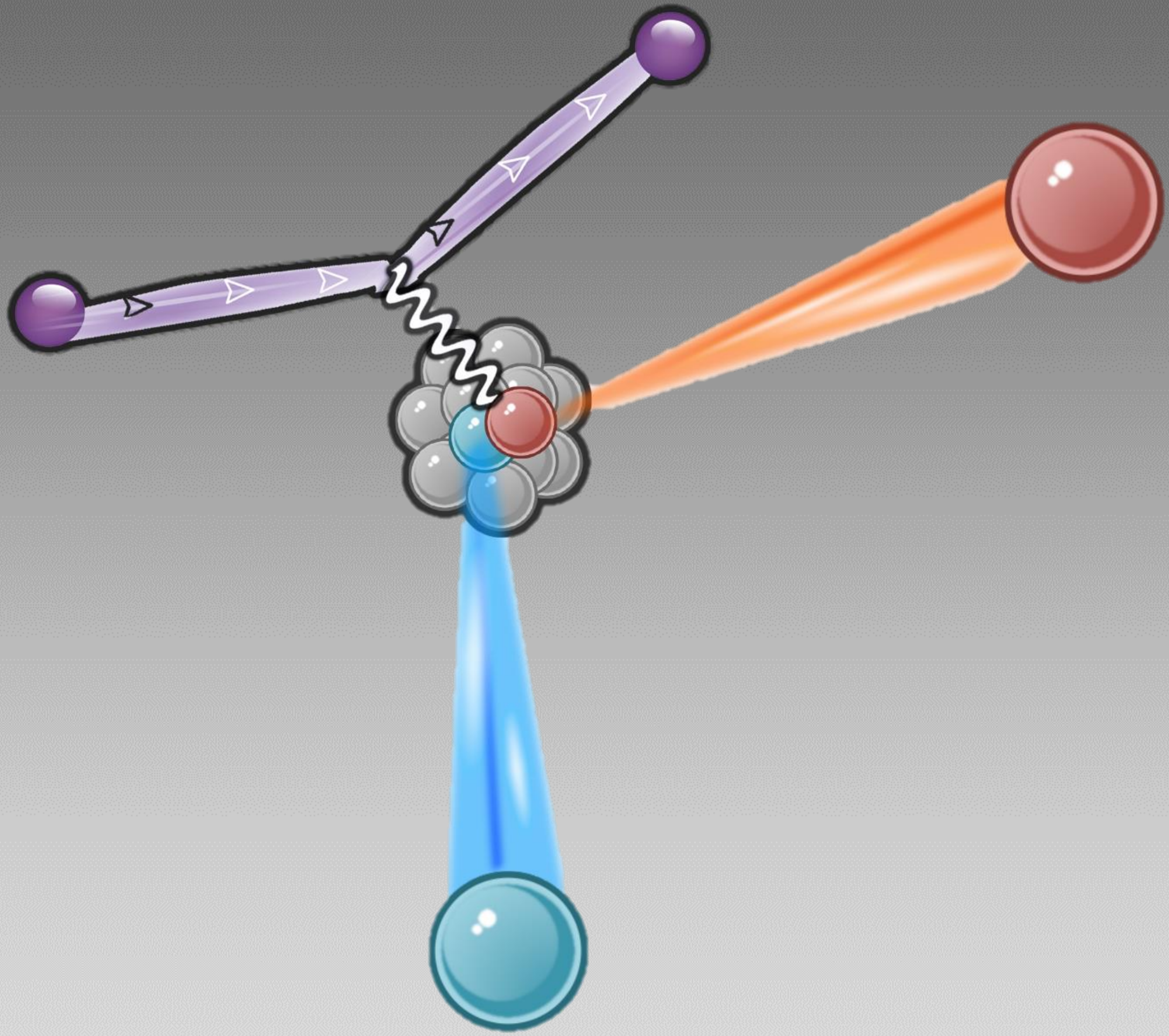


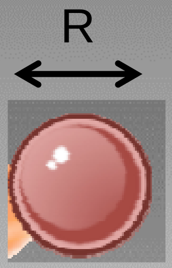
Confinement ~1 Gev/c

nuclear physics

high energy particle physics

Exclusive hard scattering

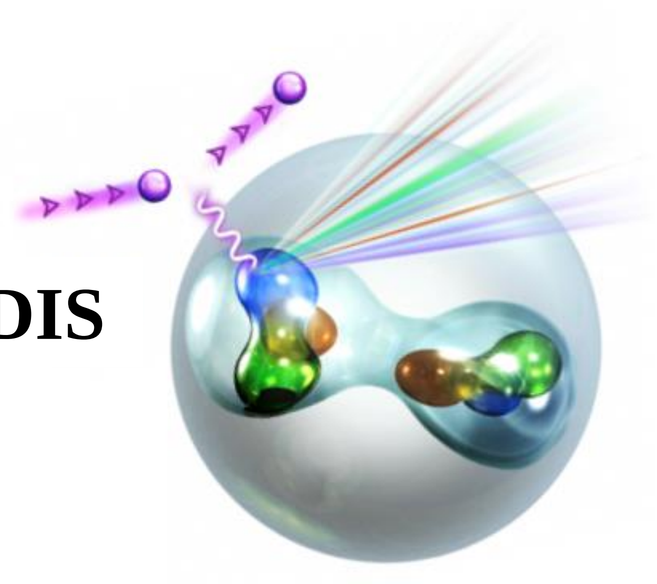




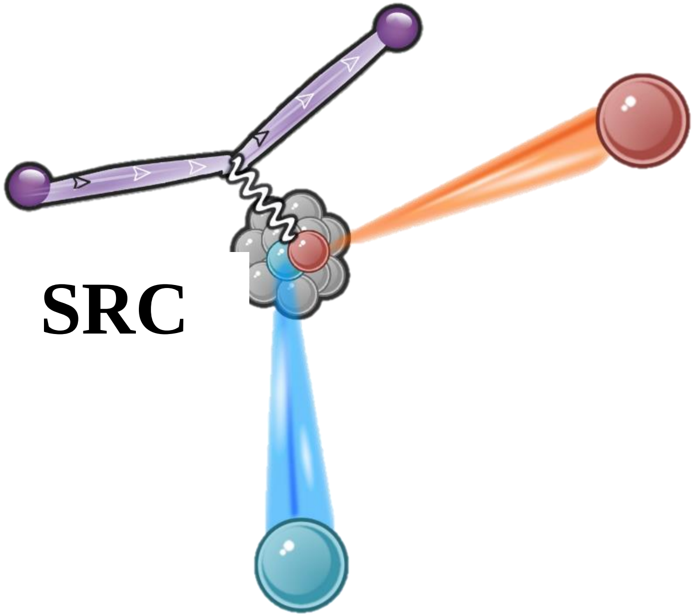
$$\lambda < R$$

$$q \cdot R < 1$$

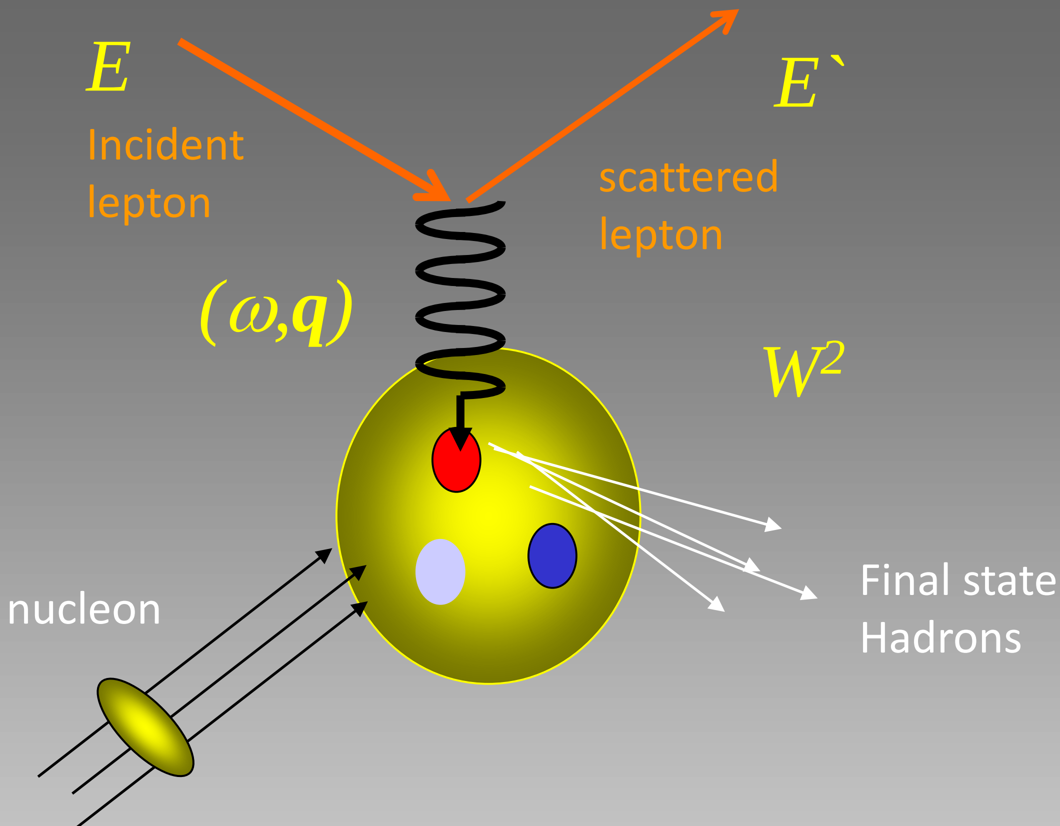
DIS



SRC



Deep Inelastic Scattering (DIS)



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

$$\omega = E' - E$$

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

$$0 \le x_B \le 1$$

Electrons, muons, neutrinos

SLAC, CERN, HERA, FNAL, JLAB

E, E' 5-500 GeV

Q^2 5-50 GeV^2

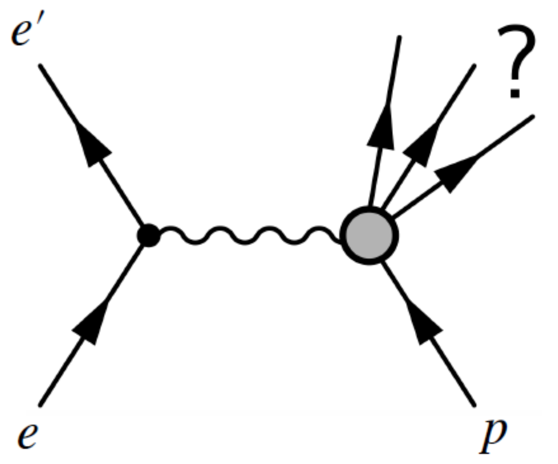
w^2 >4 GeV^2

$0 \le X_B \le 1$

X_B gives the fraction of nucleon momentum carried by the struck parton

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

Deep Inelastic Scattering (DIS)



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

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

$$\omega = E' - E$$

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

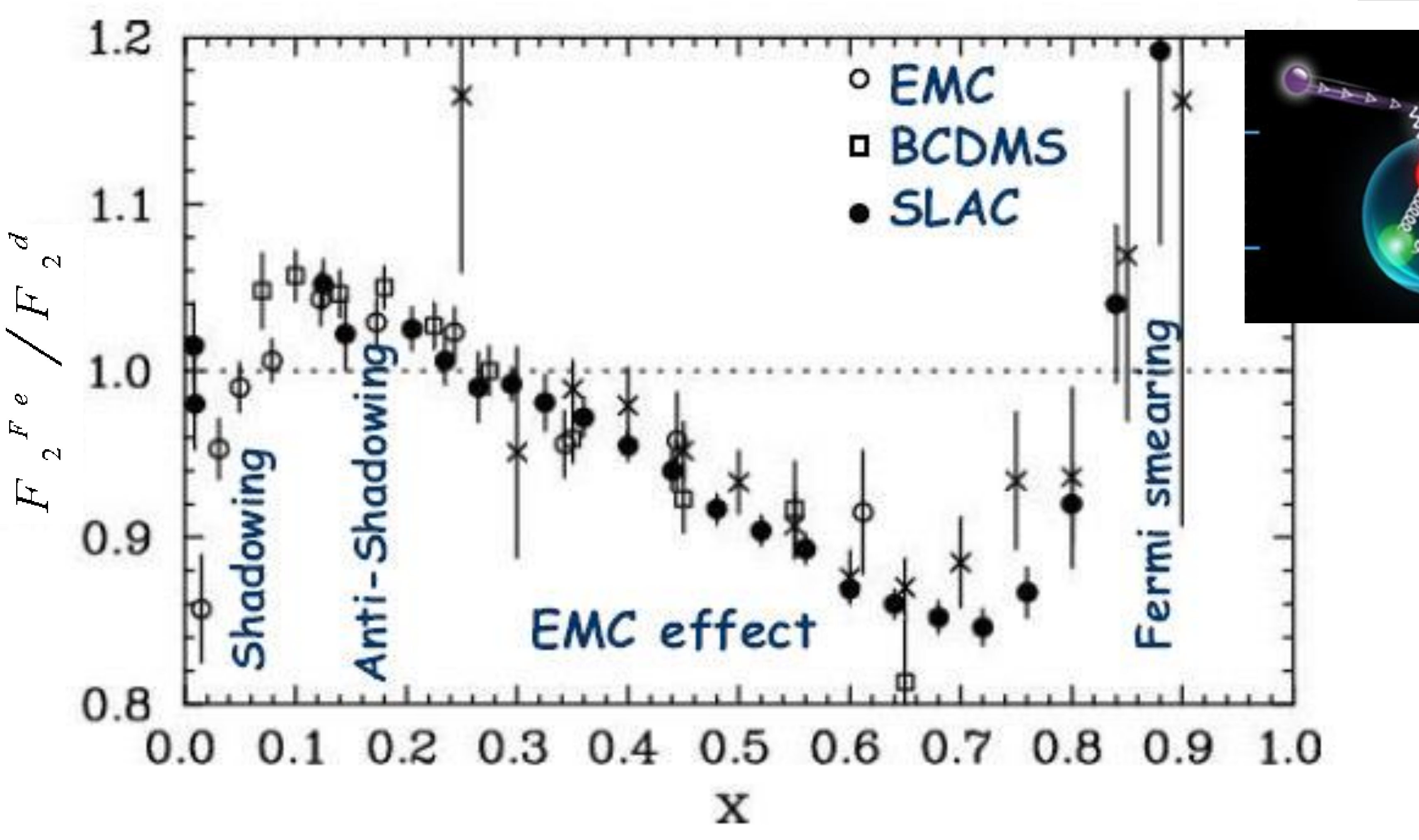
$$0 \le x_B \le 1$$

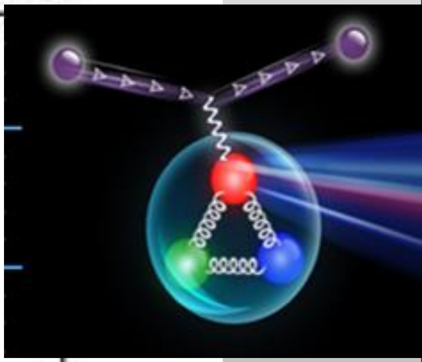
The fraction of nucleon momentum carried by the struck parton.

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

$$\frac{d\sigma}{dx dQ^2} \Big\} \; F_2^p(x,Q^2) \qquad \frac{d\sigma^A}{dx dQ^2} \Big\} \; F_2^A(x,Q^2)$$

The European Muon Collaboration (EMC) effect





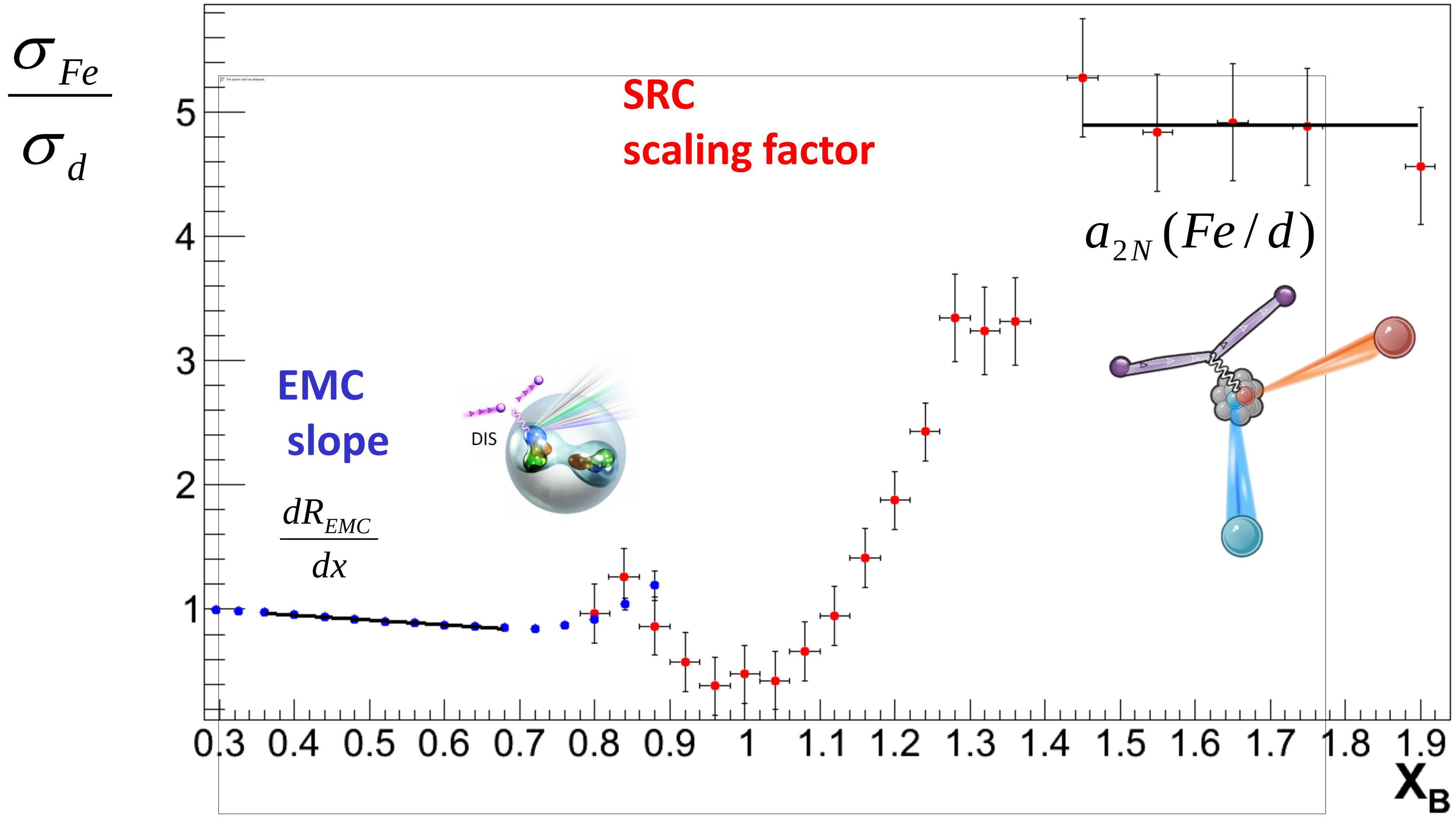
Aubert et al., PLB (1983 … neodo et al., PLB (1988); Allasia et al., PLB (1990); Gomez et a … (2009); Schmookler et al., Submitted (2018)

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

After 40 years no consensus on cause … ct

Close nucleons

Comparing magnitude of EMC effect and SRC scaling factors



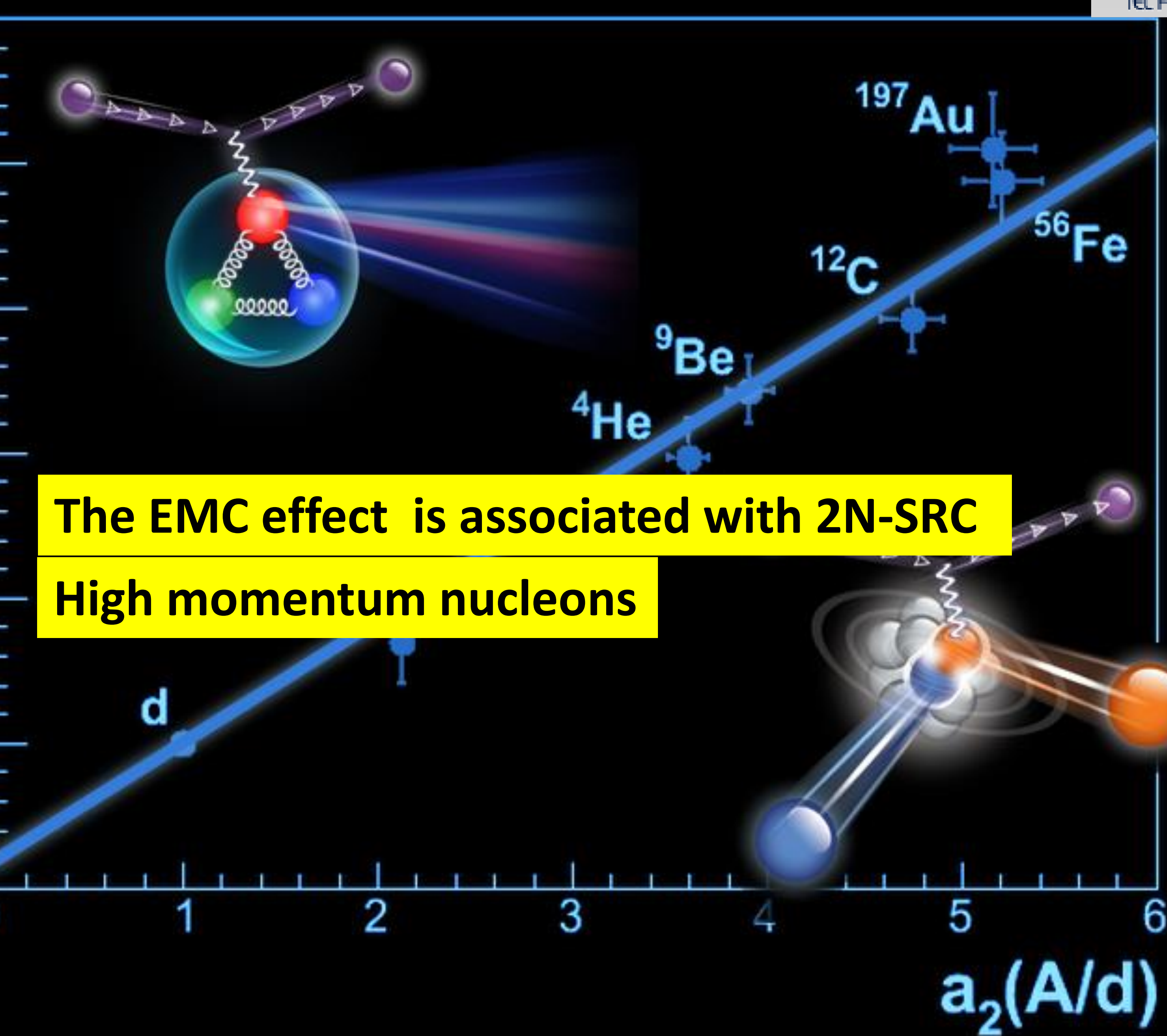
SLAC data:

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

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

Q^2=2, 5, 10, 15 GeV/c^2 (averaged)

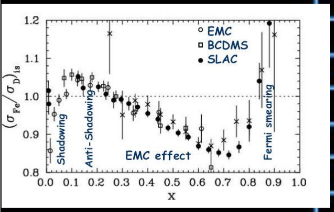
Q^2=2.3 GeV/c^2

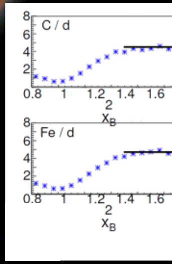


The EMC effect is associated with 2N-SRC

High momentum nucleons

EMC





SRC

Illustrated by Anna Shneor 2011

PRL 106, 052301 (2011), PRC 85 047301 (2012), RMP 89, 04500 (2017)

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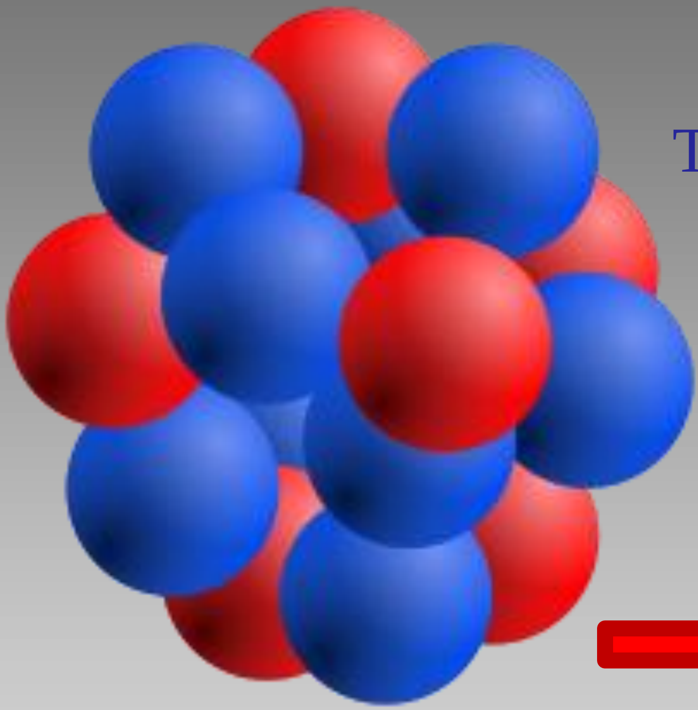
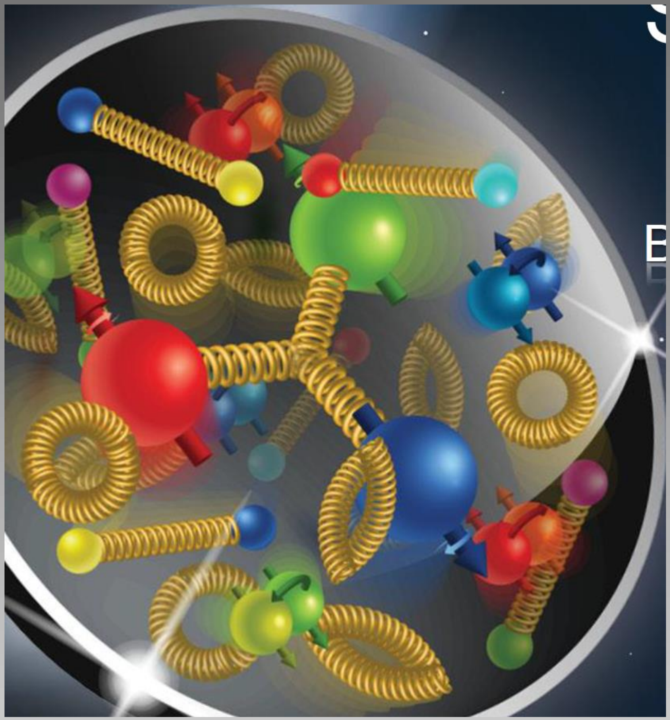


The EMC effect

2N SRC



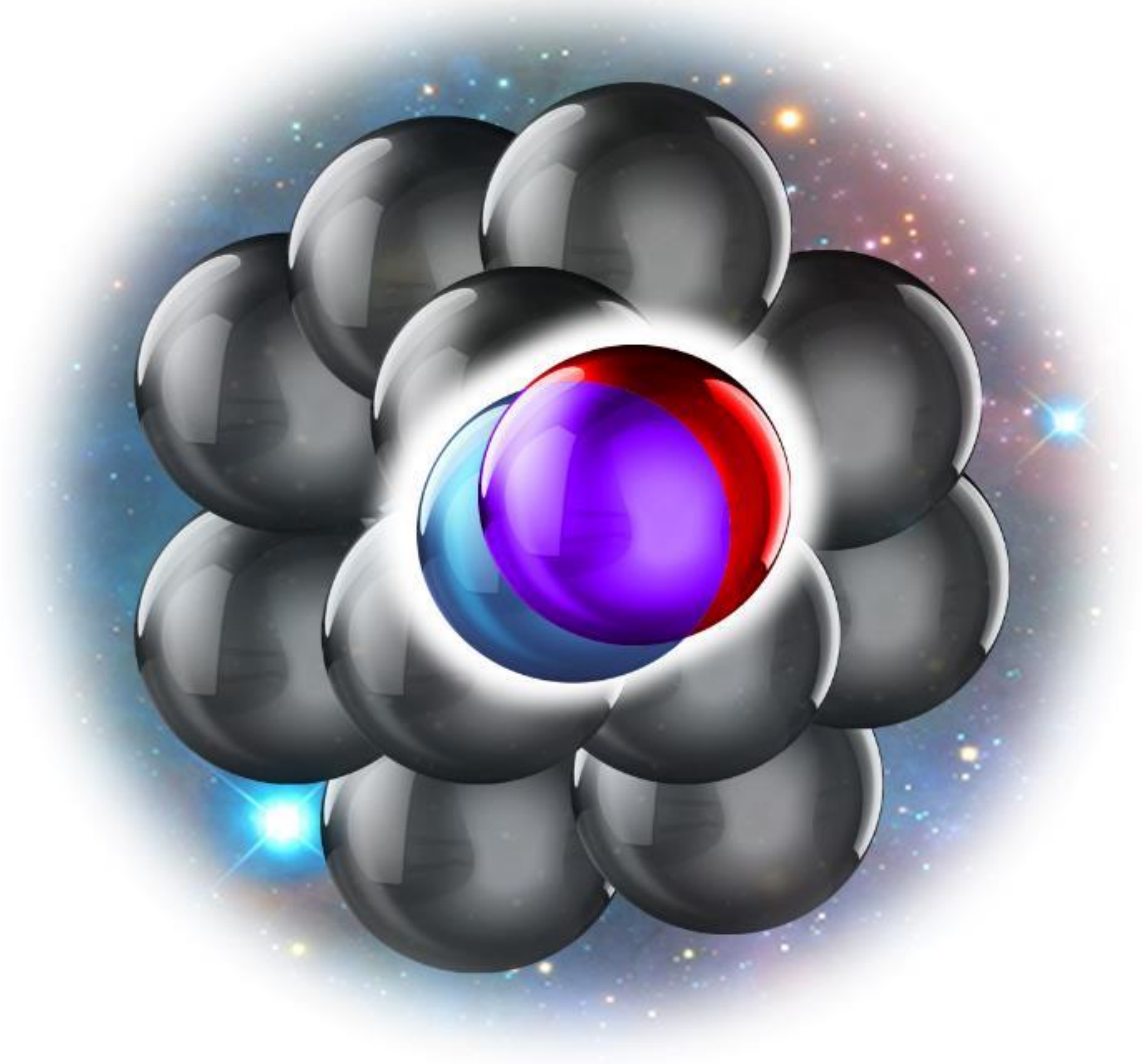
B.E ~10 Mev

Confinement ~1 Gev/c

Low energy nuclear physics

high energy particle physics

Short-Range Correlations (SRC)

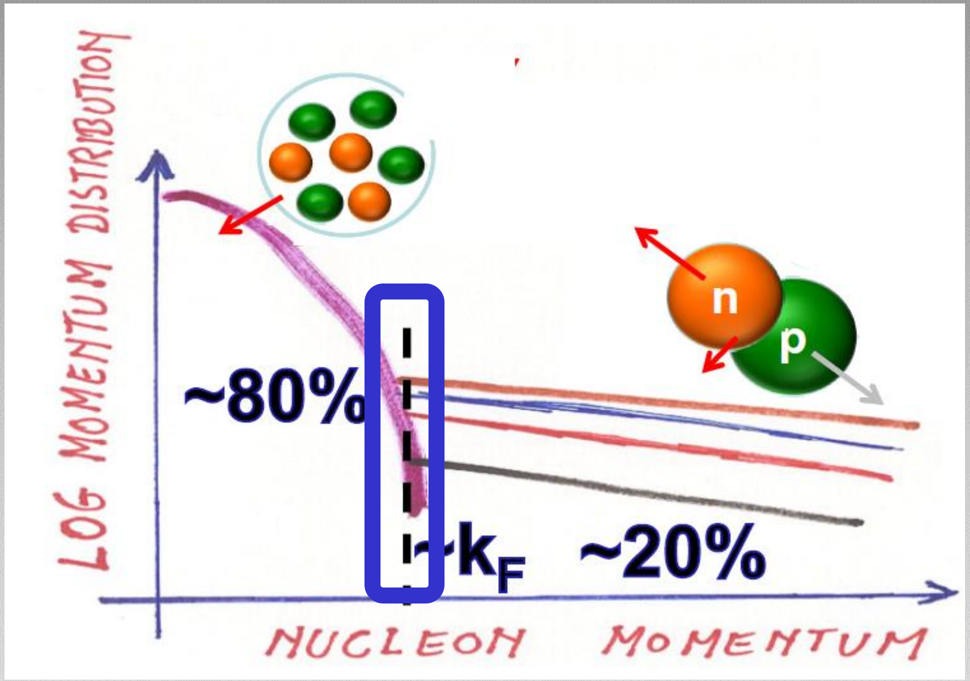


Summary of SRC results

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

$k<\sim0.8k_F$	$k>1.5\ k_F$
Mean field region	Correlated / high momentum region
Single nucleons	SRC pairs

SRC domain



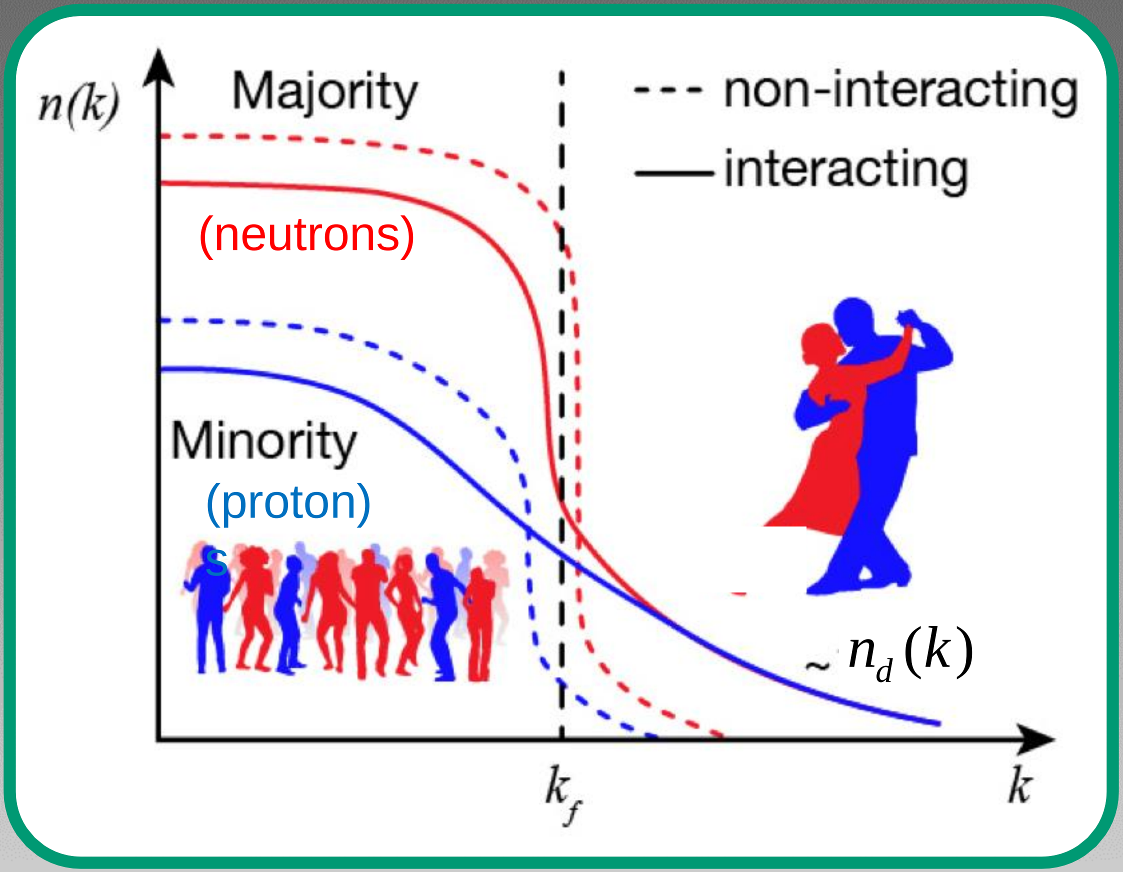
np-SRC dominance (tensor force)

Universality

E. Piasetzky et al., PRL. 97 (2006) 162504.
R. Subedi et al., Science 320, 1476 (2008).
A. Schmidt et al., Nature (in print)

np-dominance in asymmetric nuclei

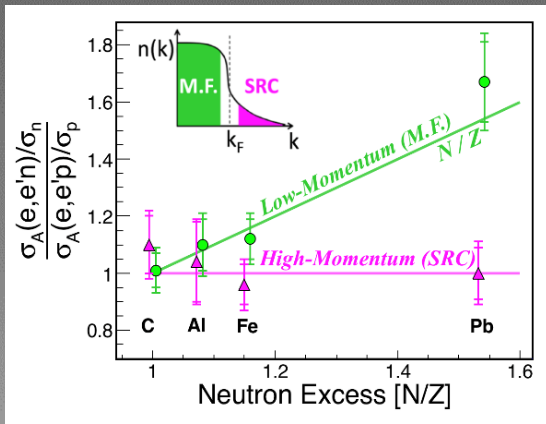
N>Z

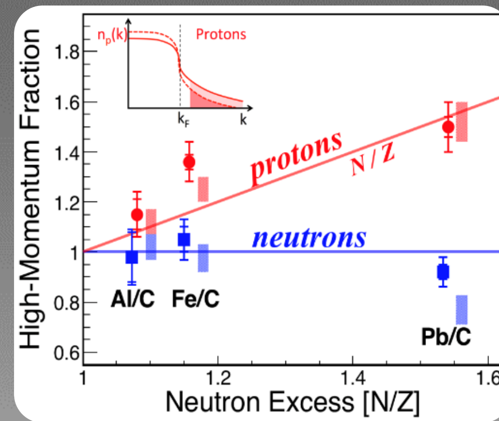


Boys have a greater probability than Girls to be above the Fermi sea.

The fraction of correlated girls/boys is grow/constant , as a function of the girls excess.

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.

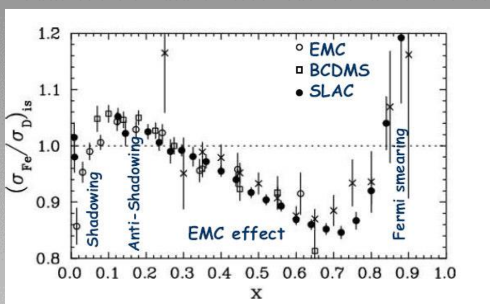
Protons have a greater probability than neutrons to be above the Fermi sea.

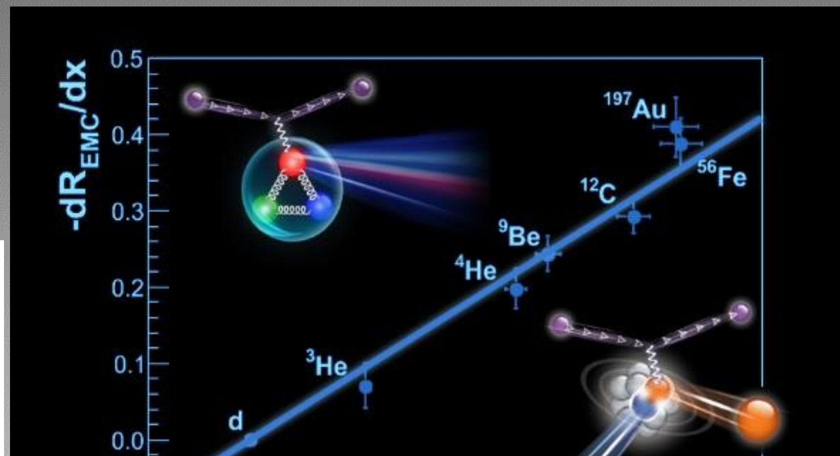
The fraction of correlated protons /neutrons is grow/constant , as a function of neutron excess.

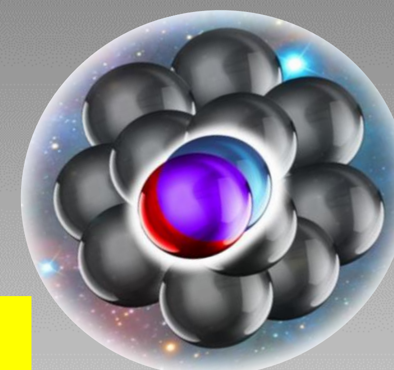
Generalized Nuclear Contact Formalism Phys. Lett. B780 (2018) 211.

2N SRC

EMC





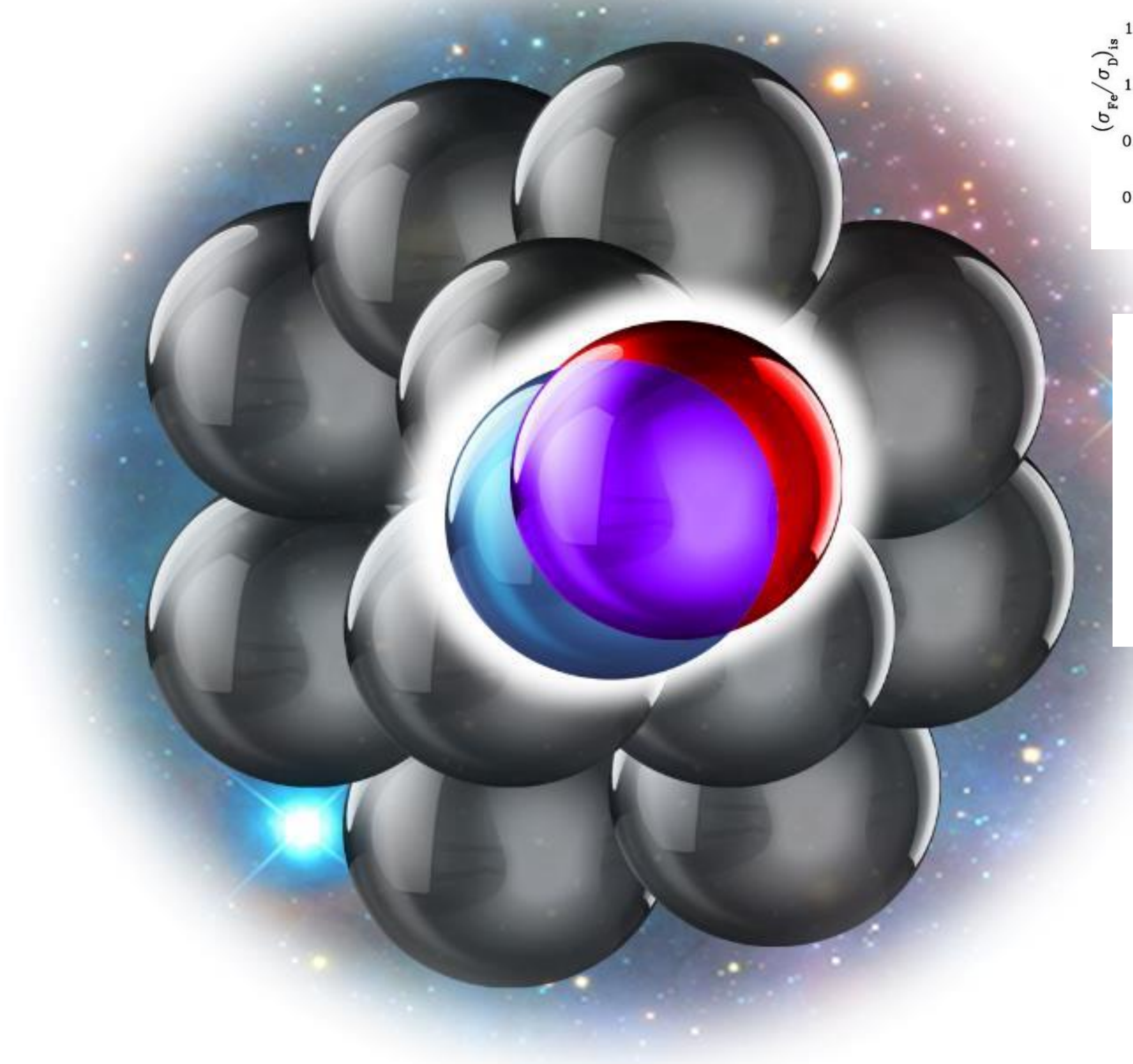


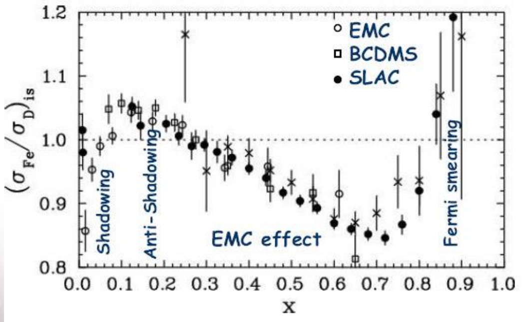
If both EMC and 2N-SRC are associated
high-momentum nucleons

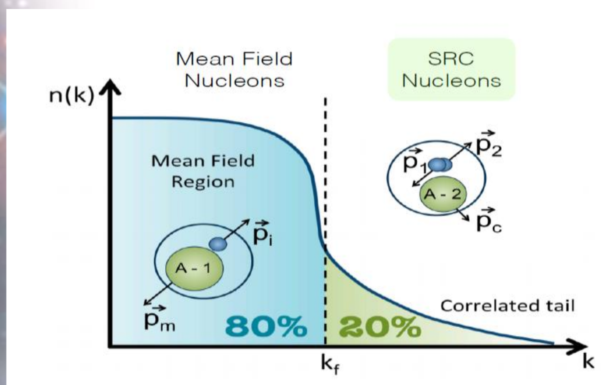
nucleon structure

SRC

Prediction for the EMC effect







EMC: small number of strongly modified nucleons.

Prediction for the 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

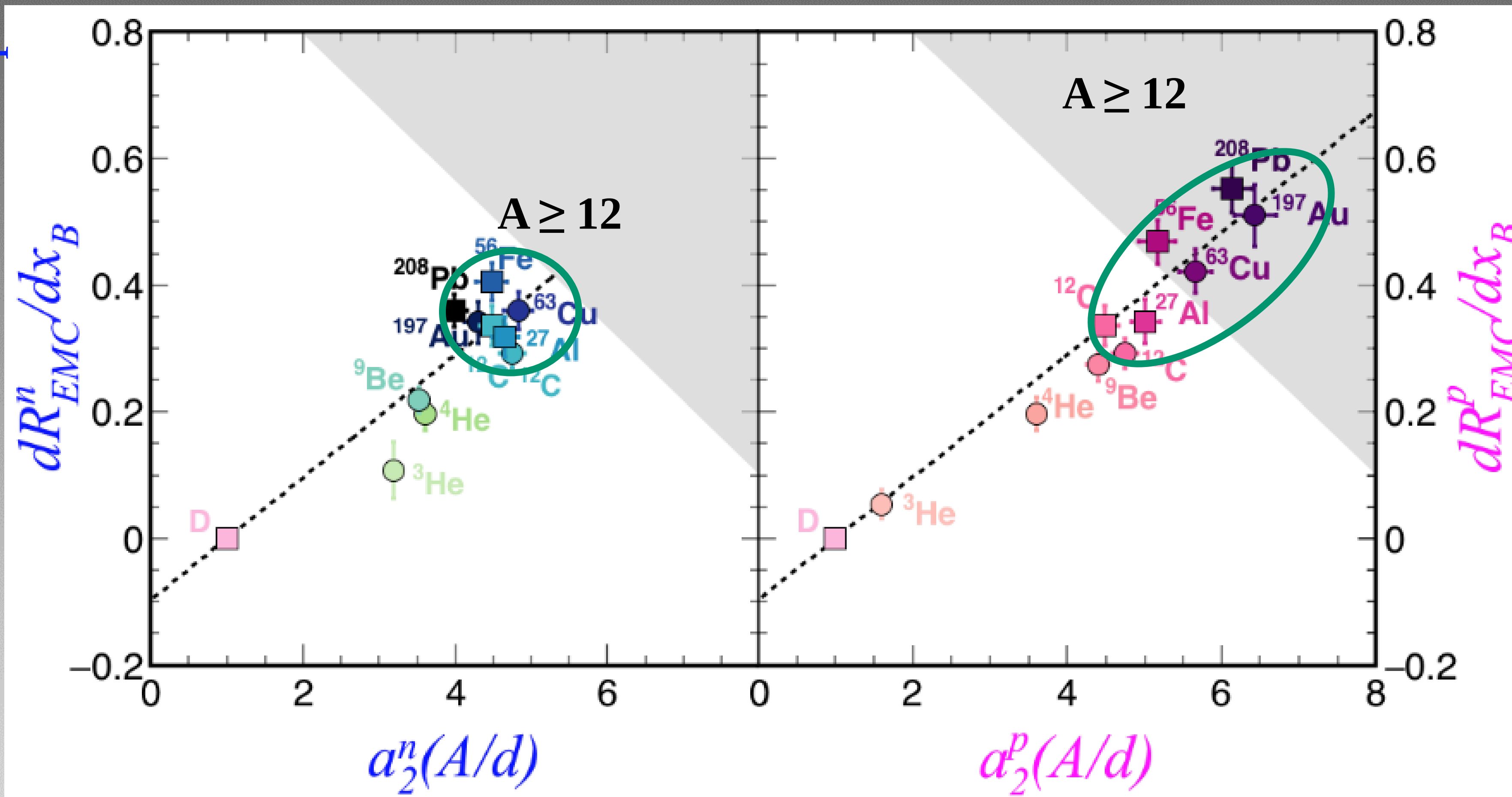
More protons larger EMC effect.

More Neutrons Saturation.

Neutrons Saturate, Protons Grow

DIS slop/N

DIS slop/Z



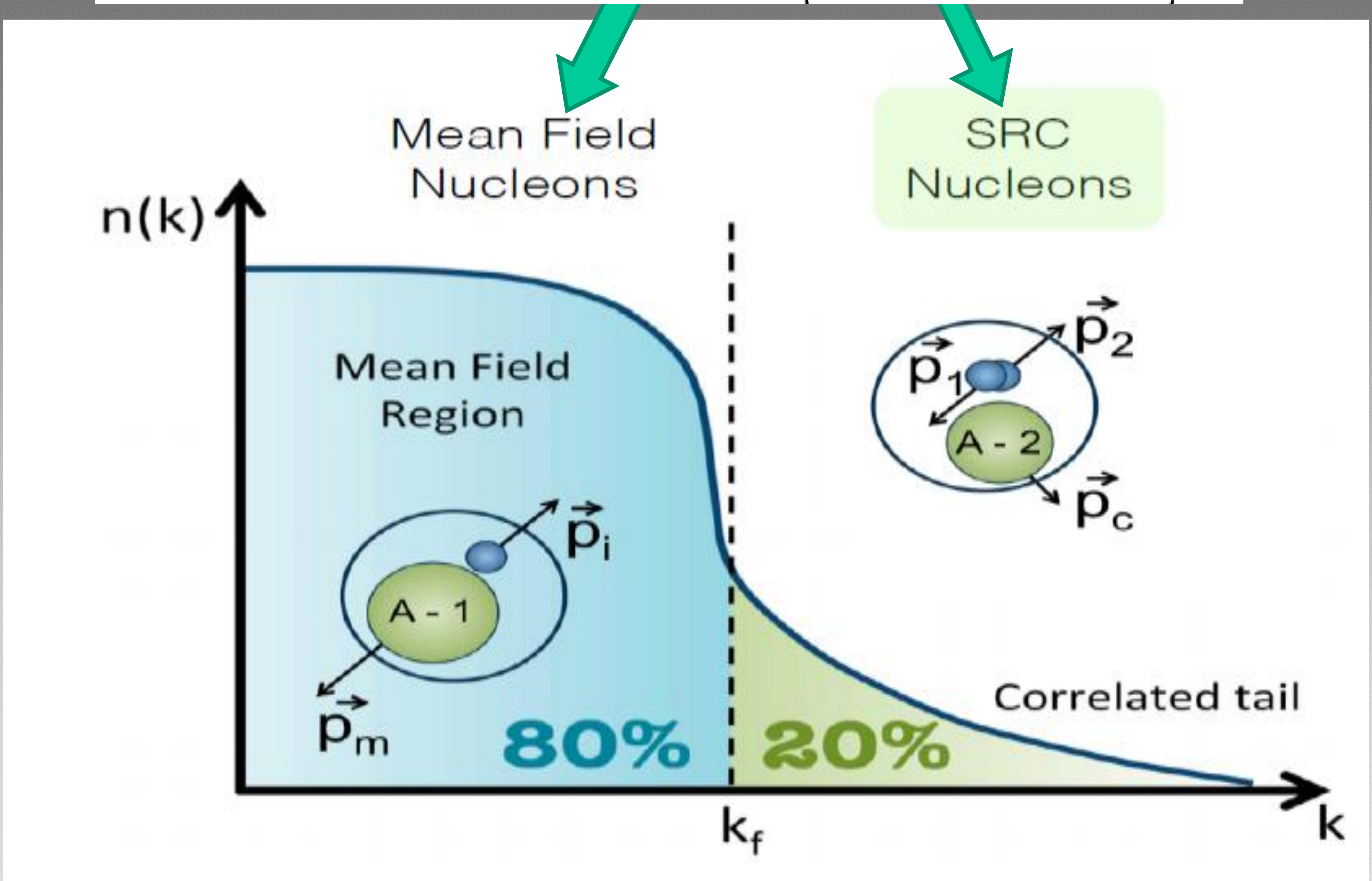
$$a_2^n = {}^{(\sigma_A / N)}\!\big/_{\sigma_d}$$

$$a_2^p = {}^{(\sigma_A / Z)}\!\big/_{\sigma_d}$$

Schmookler, Duer, and Schmidt et al., Nature 566 (2018) 354-358

Nucleus -independent

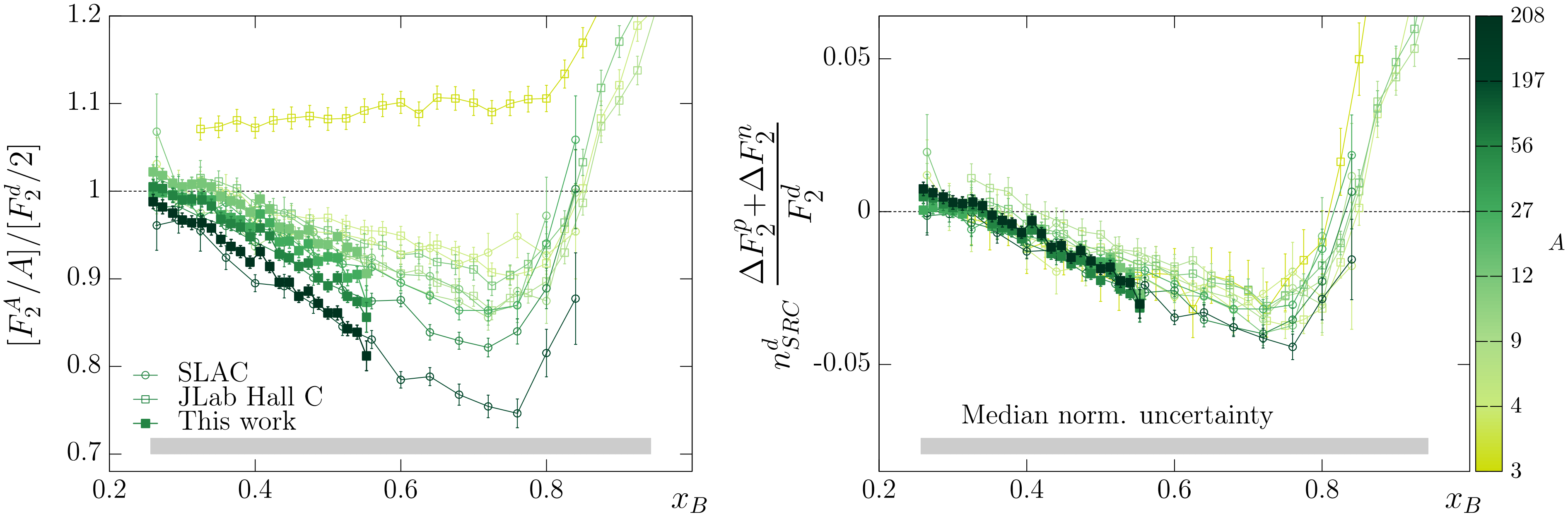
$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A \left(\Delta F_2^p + \Delta F_2^n \right)$$



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

A Dependent **Universal!** **A Dependent**

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



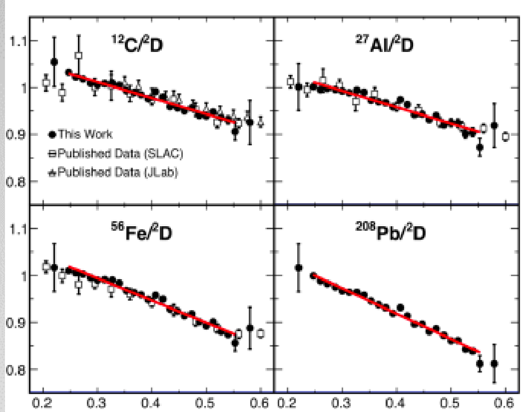
Schmookler, Duer, and Schmidt et al., Nature 566 (2018) 354-358

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

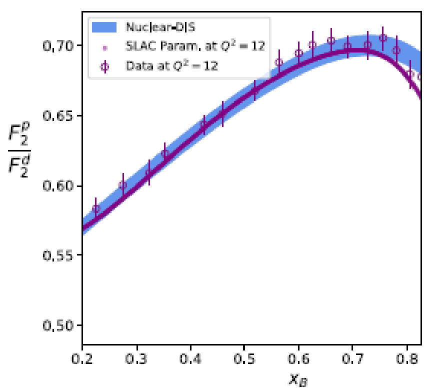
$$\frac{F_2^A}{F_2^d} = (Z-N)\frac{F_2^p}{F_2^d} + N + \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right)\frac{n_{SRC}^d}{F_2^d}\left(\Delta F_2^p + \Delta F_2^n\right)$$

Universal modification function

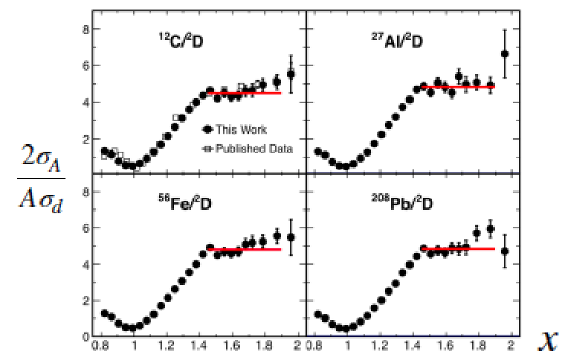
EMC-DIS Data



F_2^p/F_2^d Data



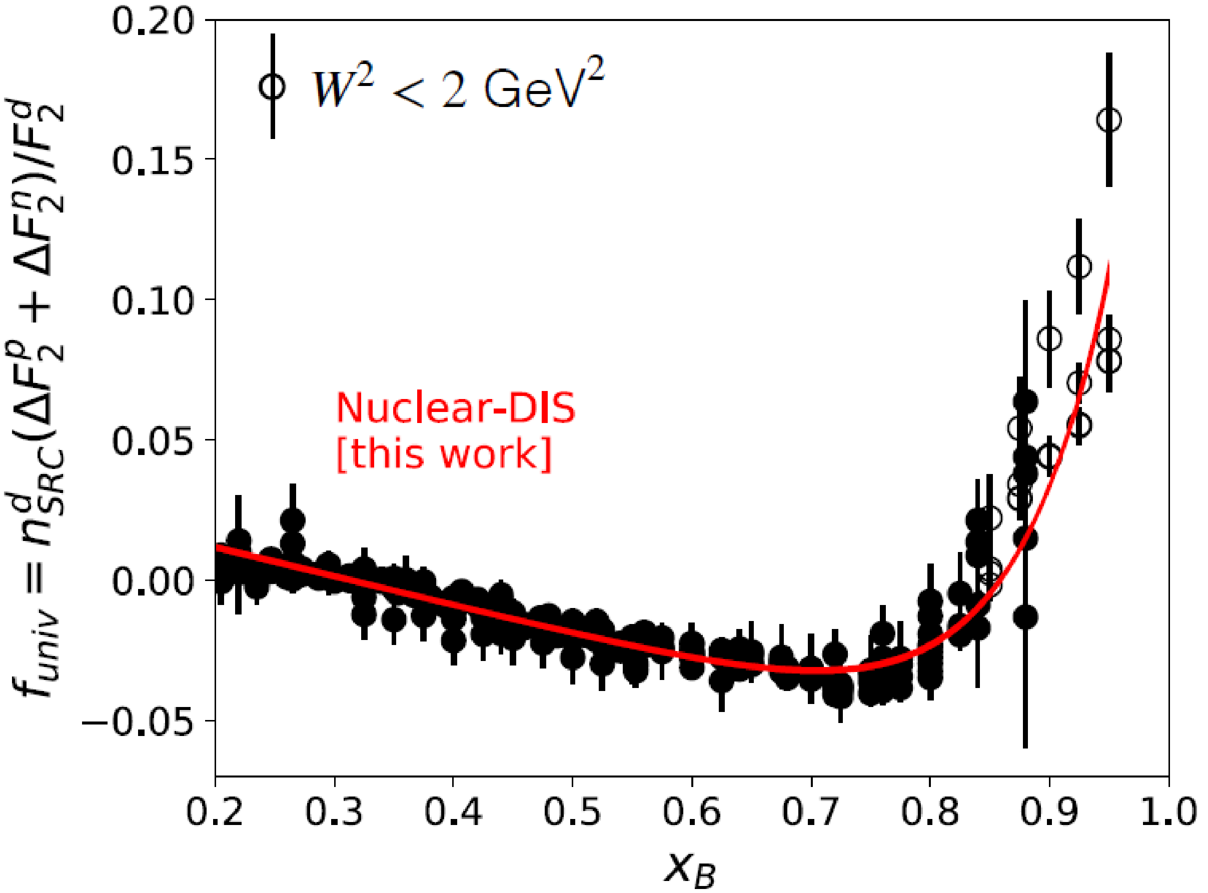
a_2 Pair Abundances



Nature 566 (2018) 354-358

Nature 566 (2018) 354-358

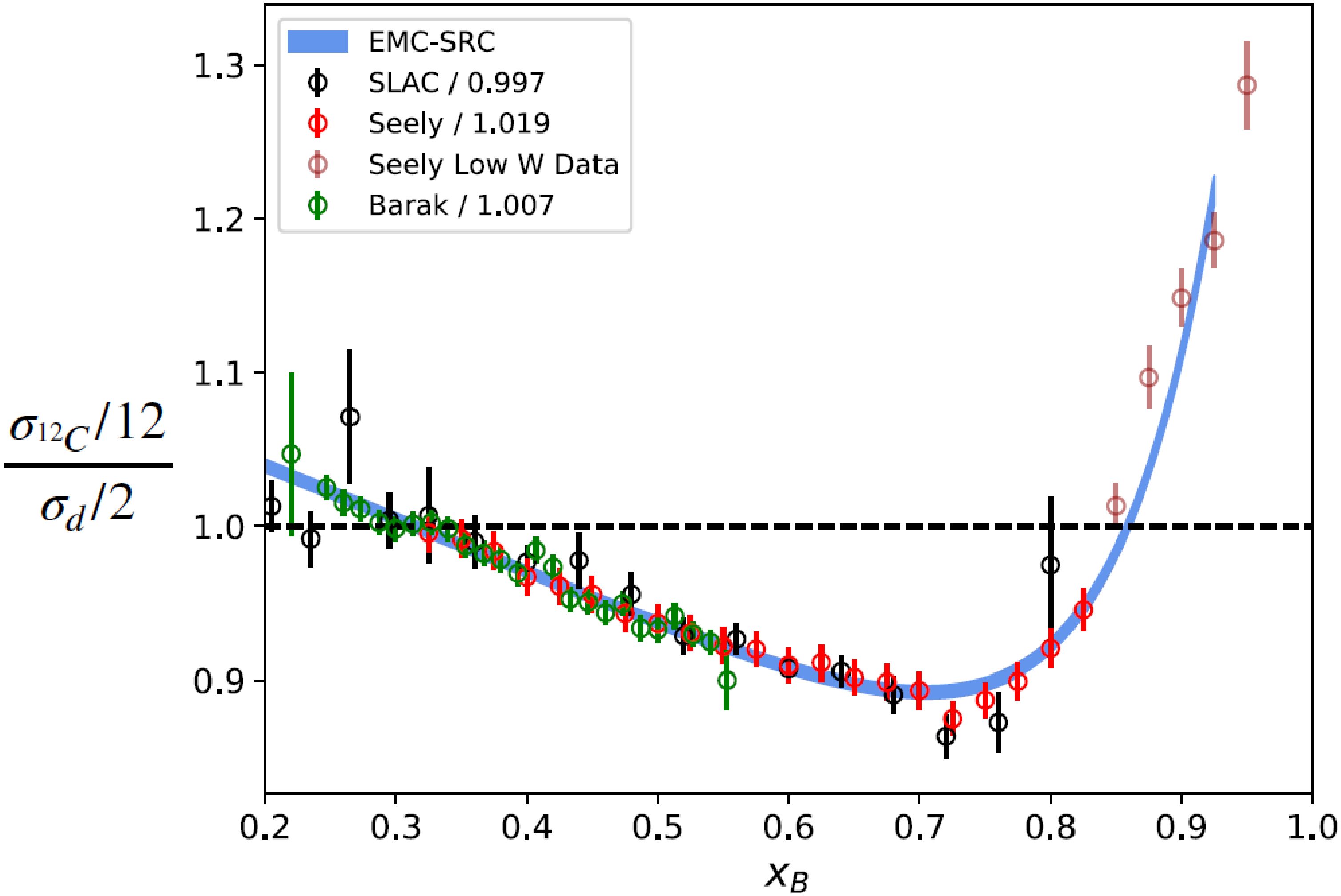
Universal modification function of nuclei



(All 31 model parameters simultaneously extracted from joint posterior)

Segarra et al., Phys. Rev. Lett. (2020);
Segarra and Pybus et al., Phys. Rev. Research (2021)

Reproduce the data remarkably well



Segarra et al., Phys. Rev. Lett. (2020);
Segarra and Pybus et al., Phys. Rev. Research (2021)

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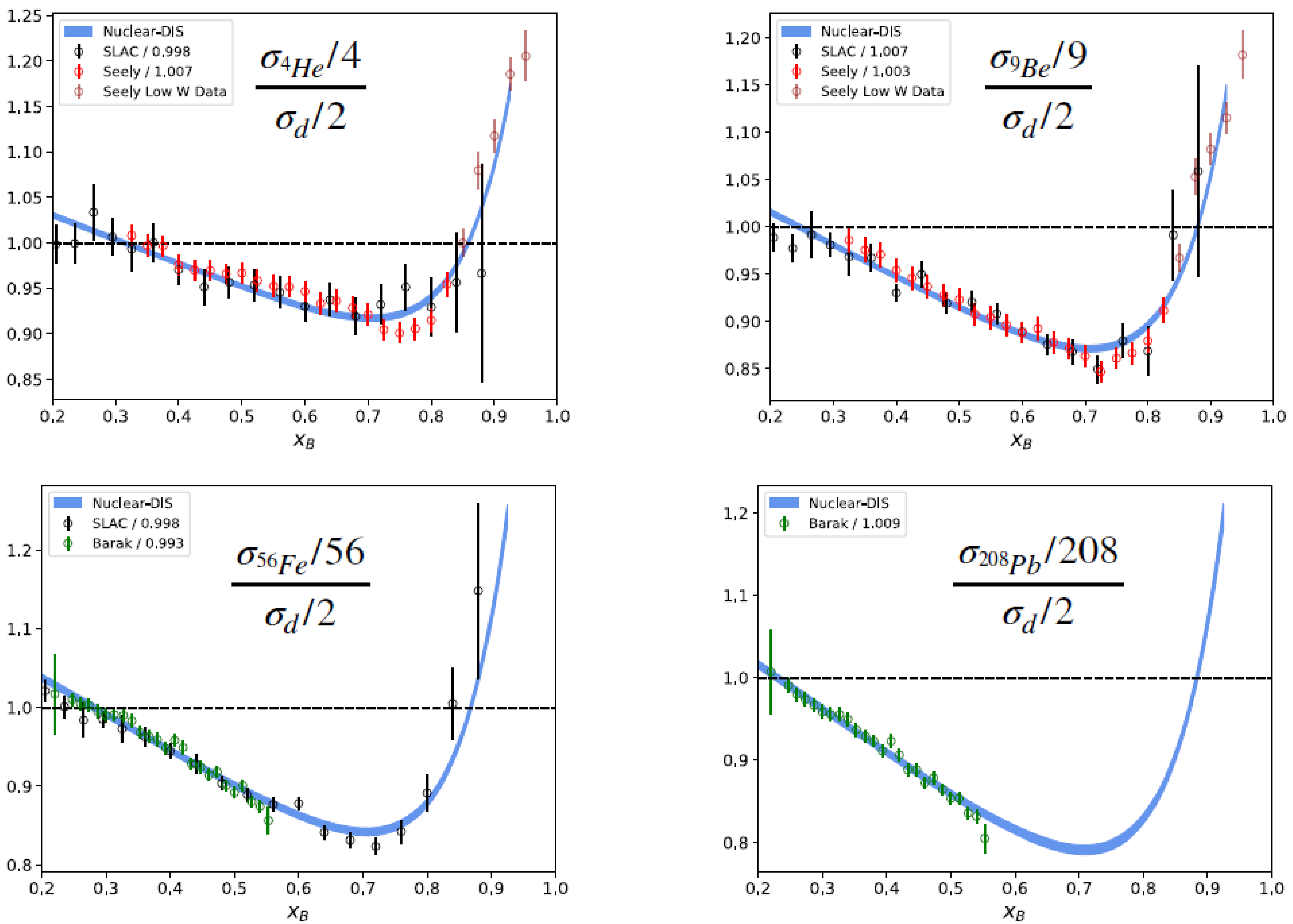
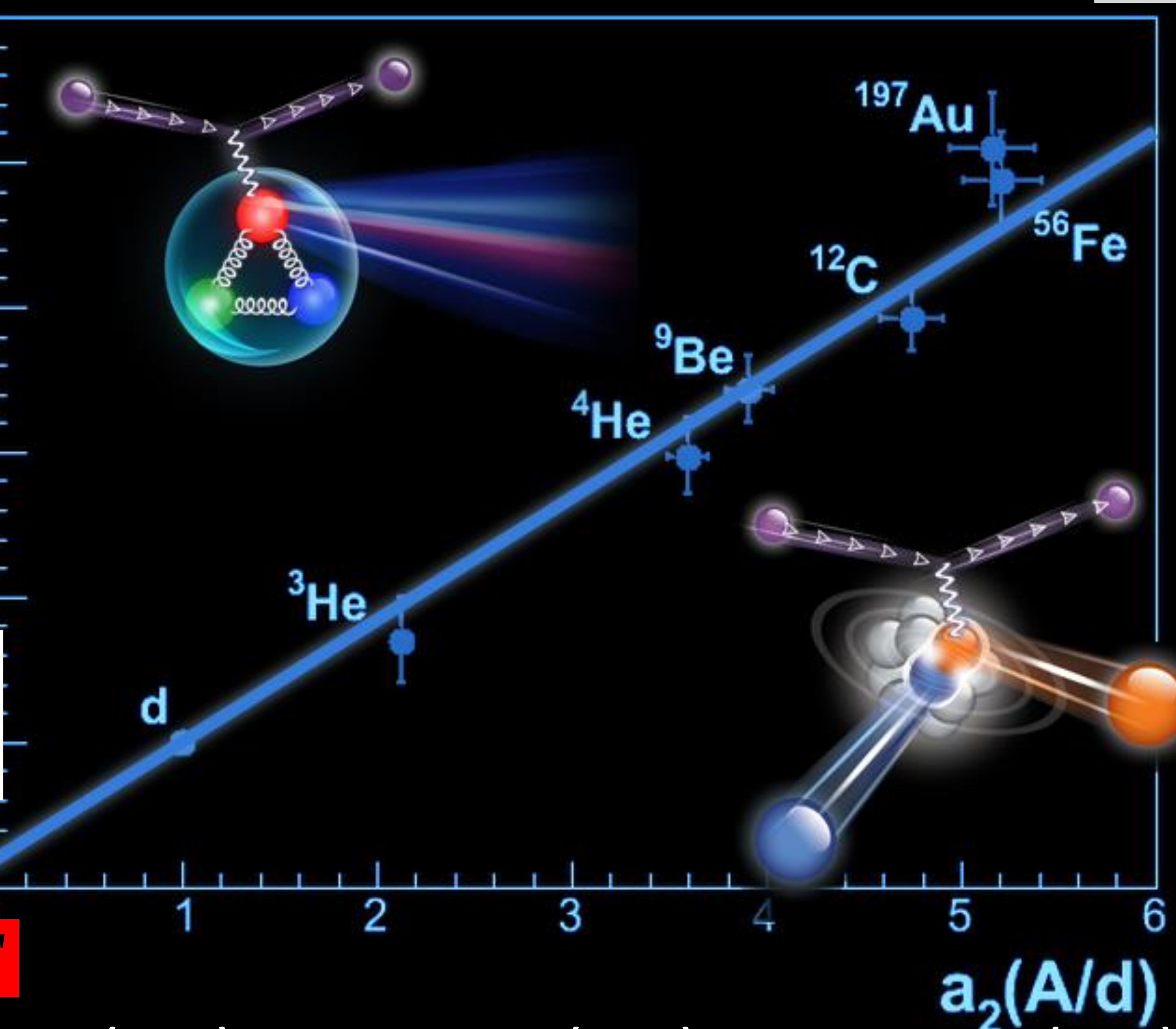
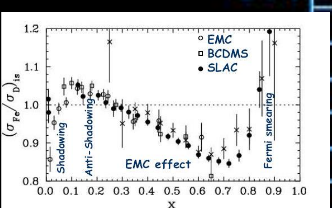
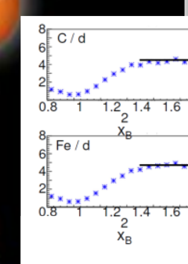


Segarra et al., Phys. Rev. Lett. (2020);
Segarra and Pybus et al., Phys. Rev. Research (2021)



EMC





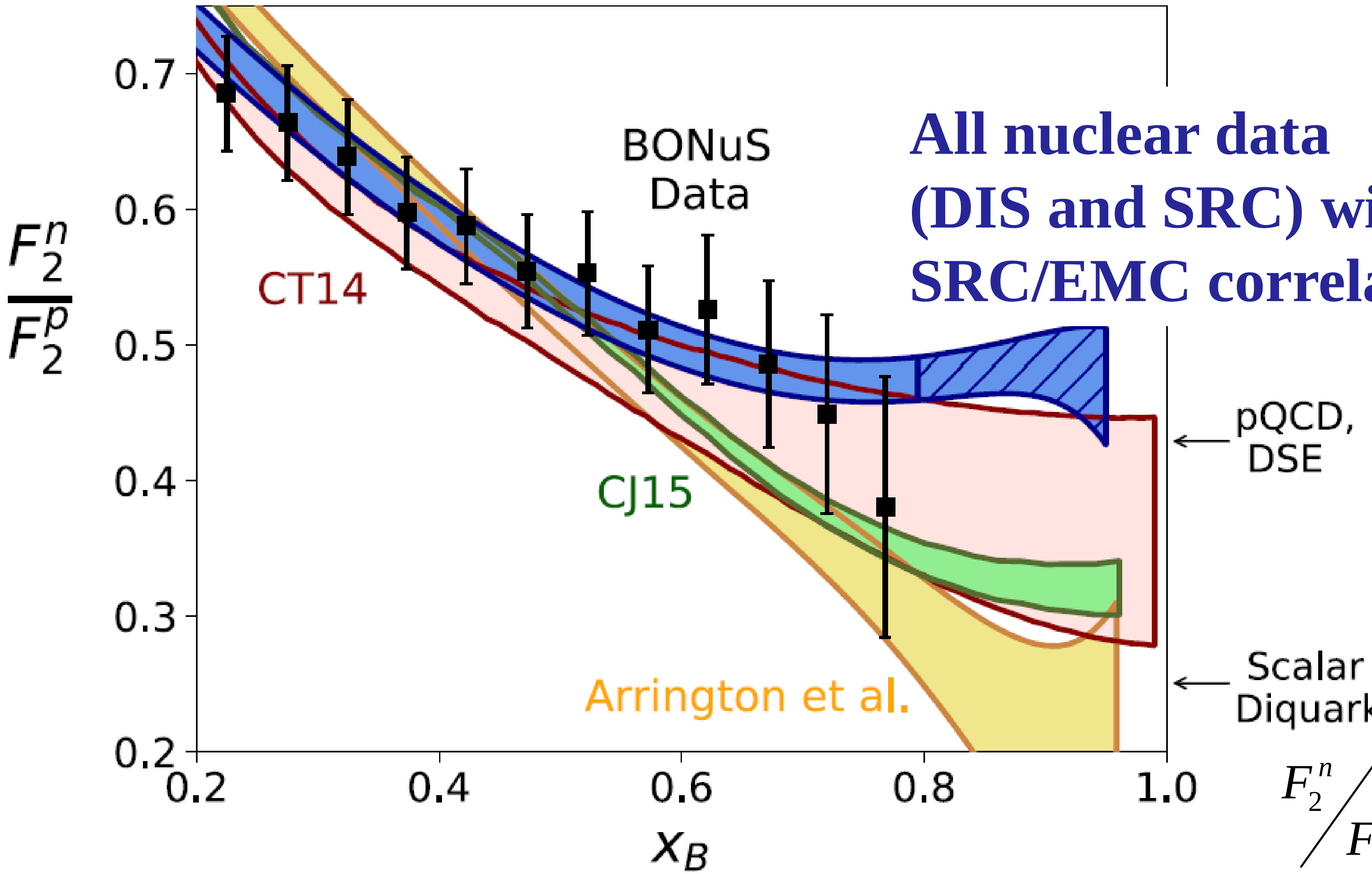
$$"d \neq n + p"$$

SRC

PRL 106, 052301 (2011), PRC 85 047301 (2012), RMP 89, 04500 (2017)

ARATON
diction

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

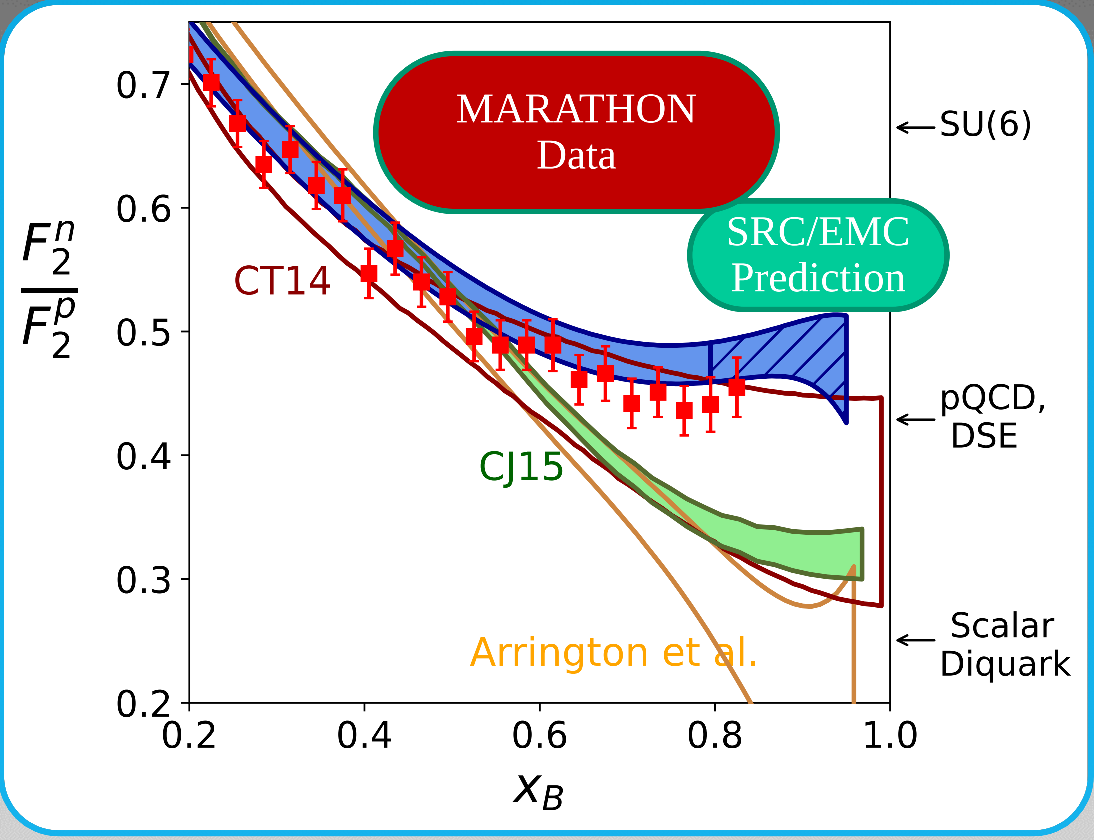


All nuclear data (DIS and SRC) with SRC/EMC correlations

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

Segarra et al., Phys. Rev. Lett. (2020)

Verified Predictions!



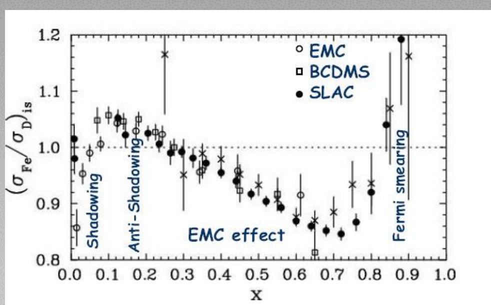
MARATHON Data: Abrams et al., Phys. Rev. Lett. (2022)

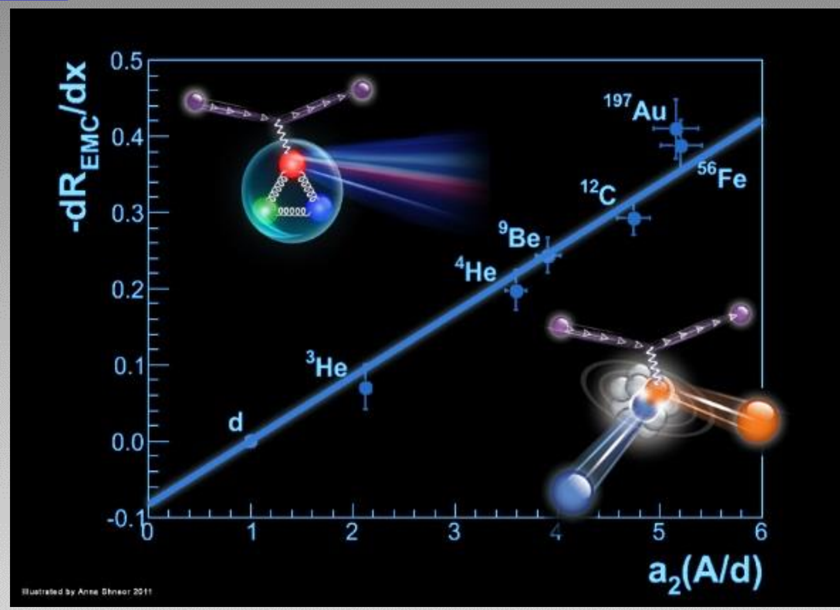
SRC/EMC Prediction: Segarra et al., Phys. Rev. Lett. (2020)

nucleon structure (nPDF)

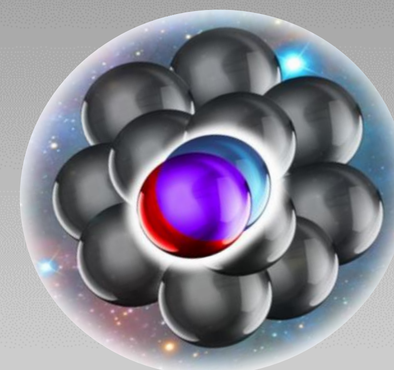
SRC

EMC





2N SRC



Extracting nPDFs

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

Data

DIS

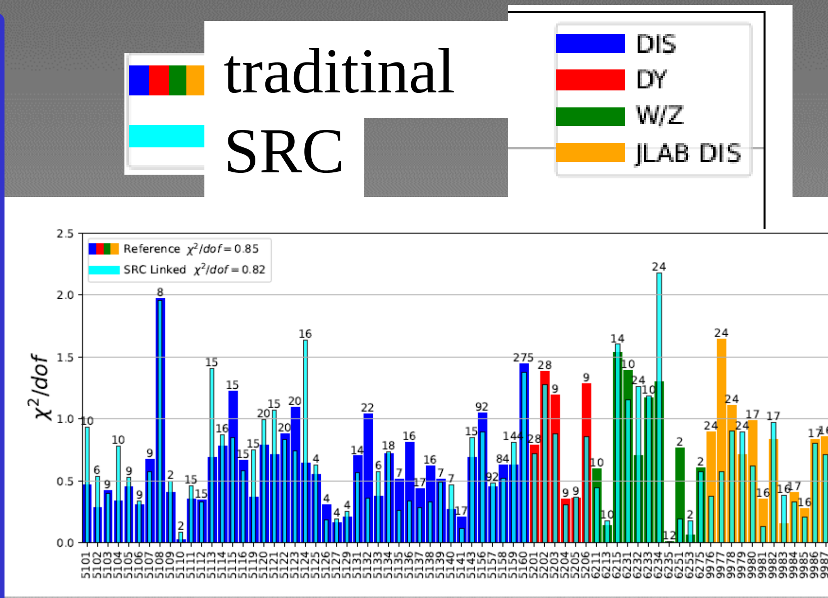
DY

W Z production

Traditional nCTEQ

All nucleons modified

nucleus (A) dependent parameters



Equal quality global fits

SRC inspire nCTEQ

Only pairs are universally modified

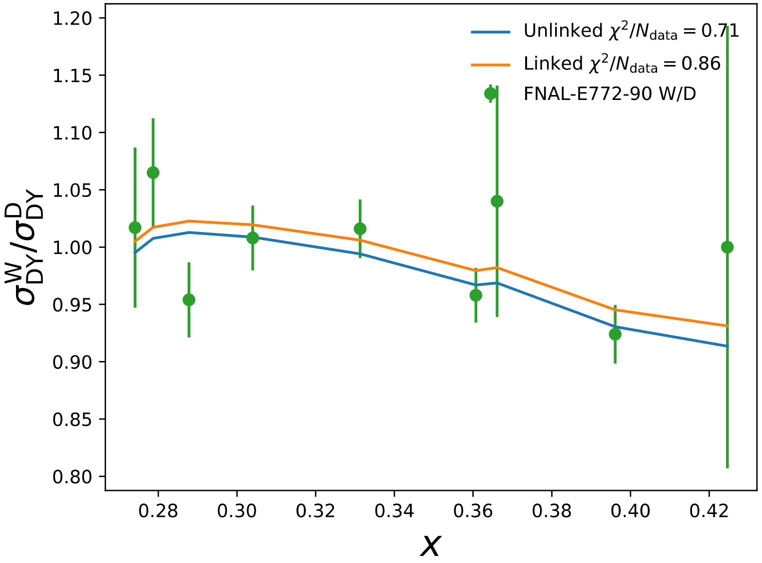
Fit well non DIS data

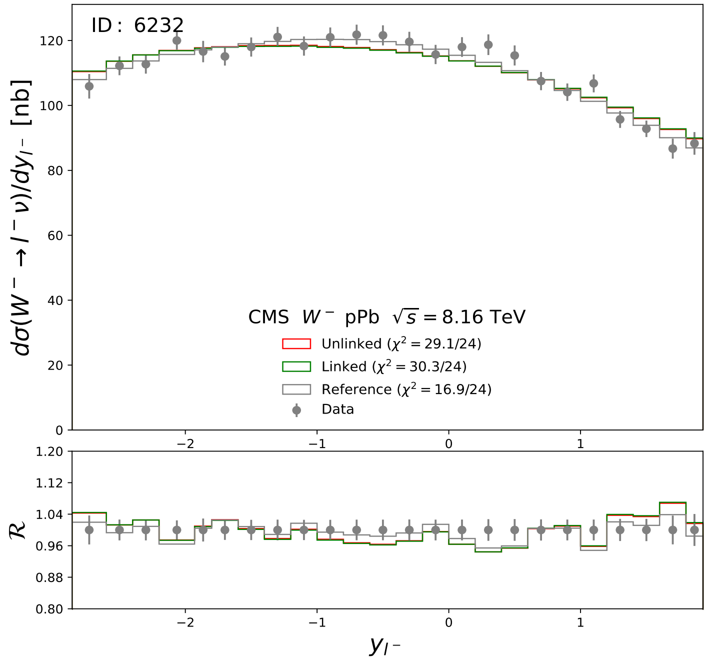
Fit well large and low XB beyond the EMC range

A. Kusina talk, DIS202

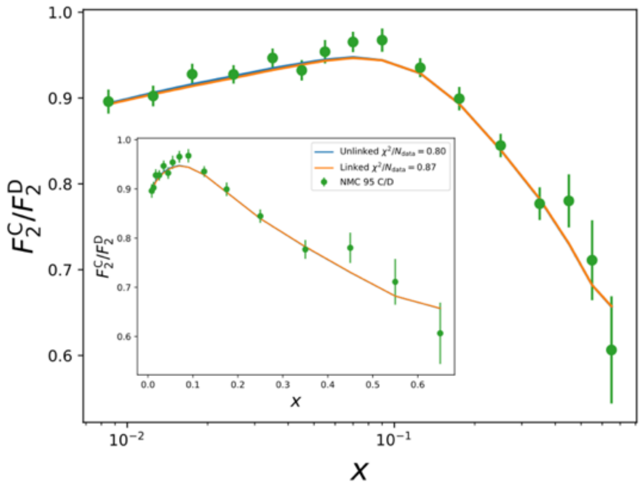
Can go beyond EMC data?

Nuclear Drell-Yan Data





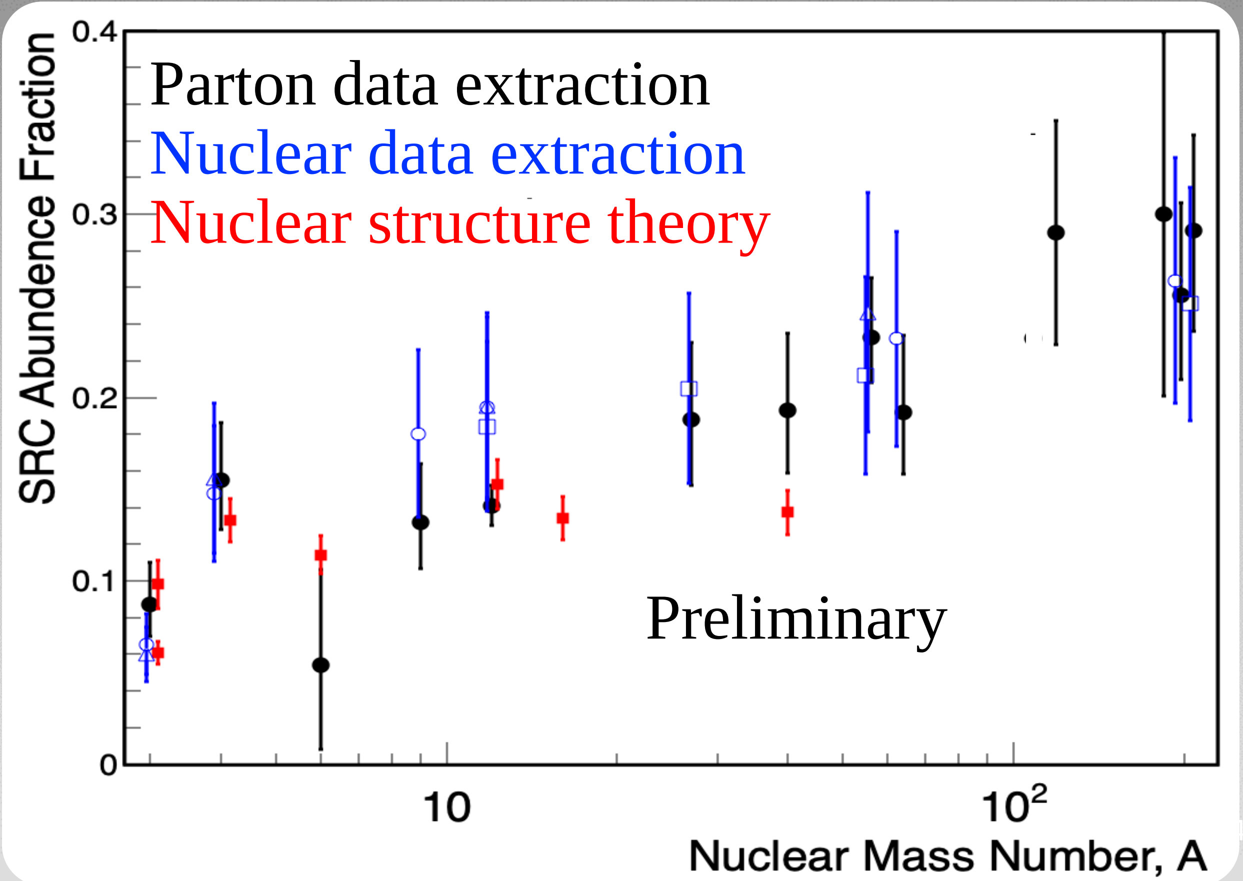
LHC p+Pb W production



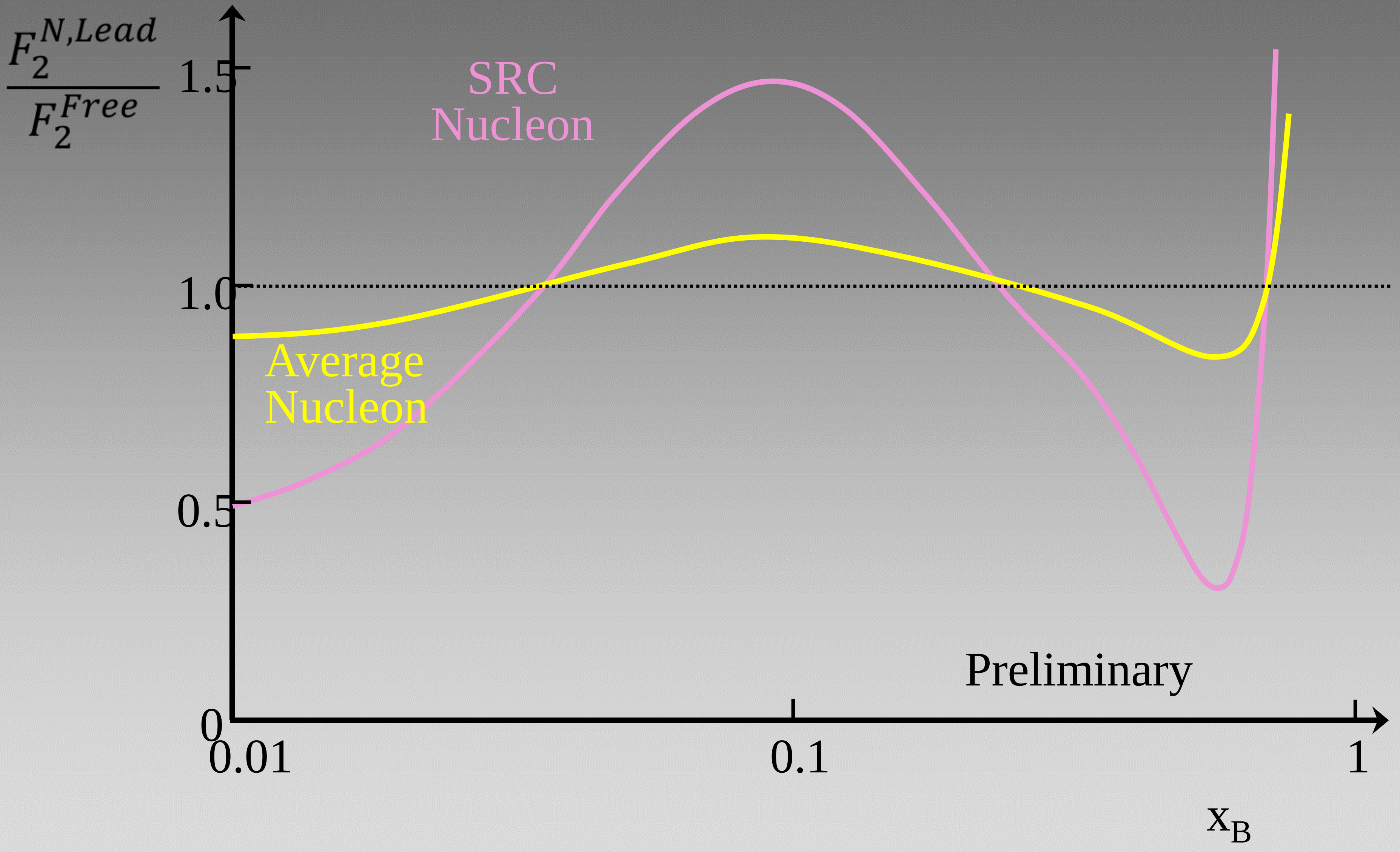
Nuclear DIS
(EMC + Shadowing)

Predict: np dominance and SRC Abundances

 # modified p = # modified n

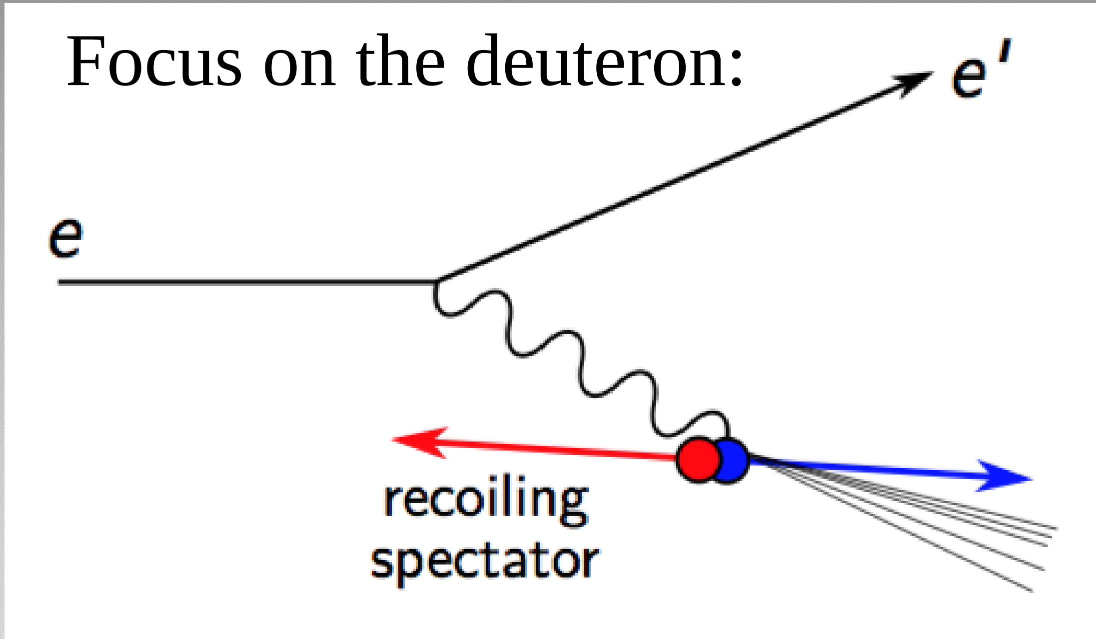


Predict large modification in SRC pairs



Is the EMC effect associated with large momentum nucleons ?

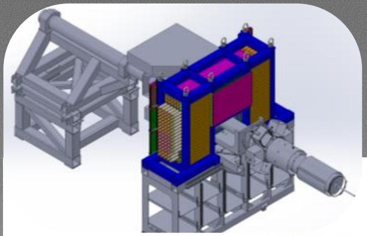
Hypothesis can be verified by measuring DIS off Deuteron tagged with high momentum recoil nucleon

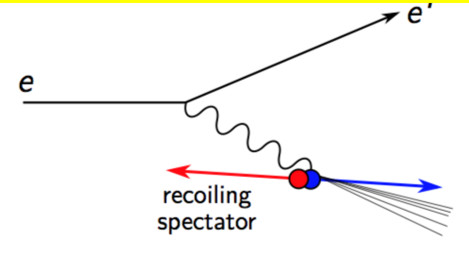


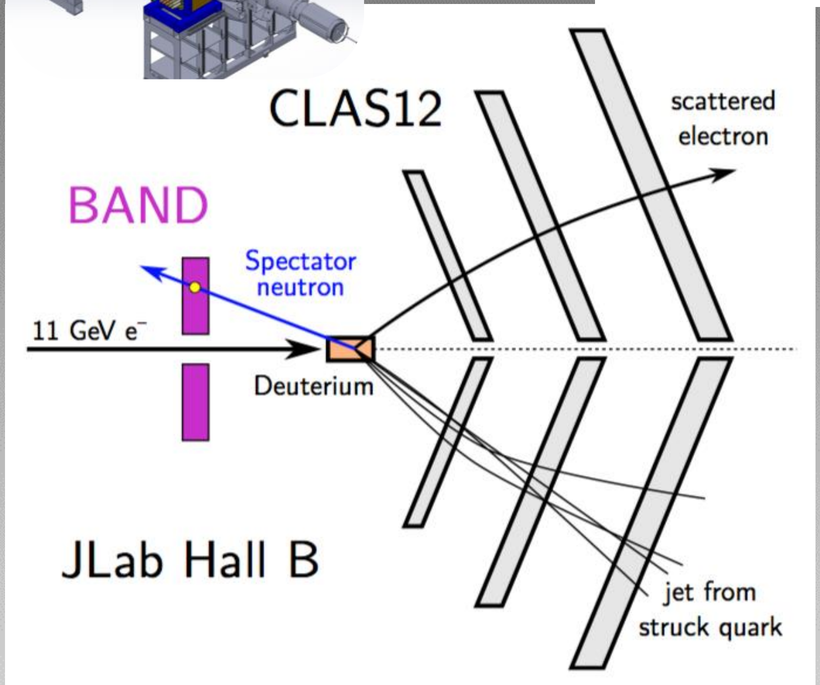
Thursday, February 23, 2023

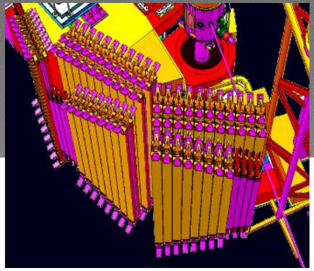
10:40 AM	Tagged DIS for bound nucleon structure	Tyler Kutz

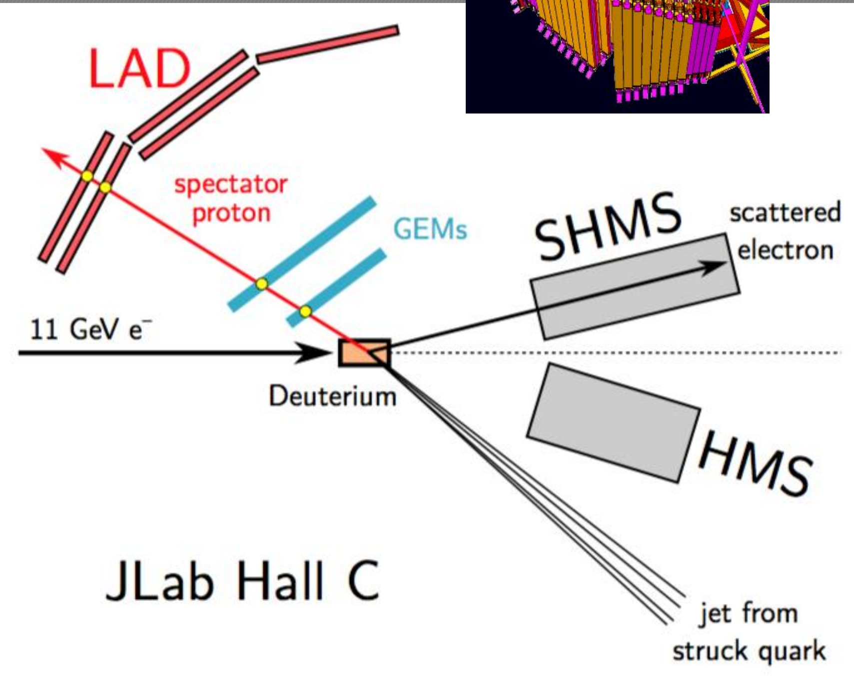
Is the EMC effect associated with large momentum nucleons ?



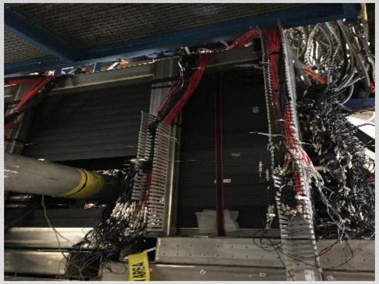








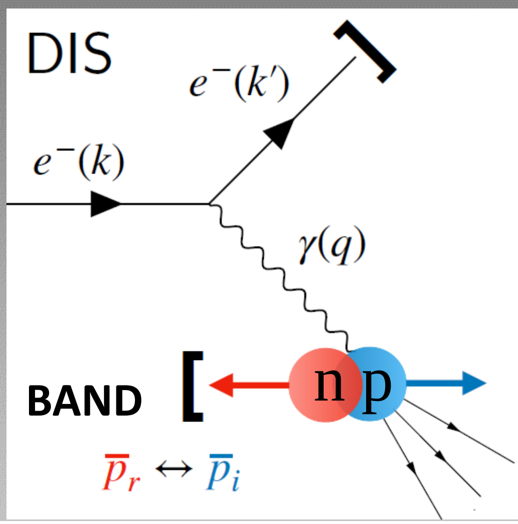
12 GeV JLab/ Hall B took data in 2019 **E 12-11-107**



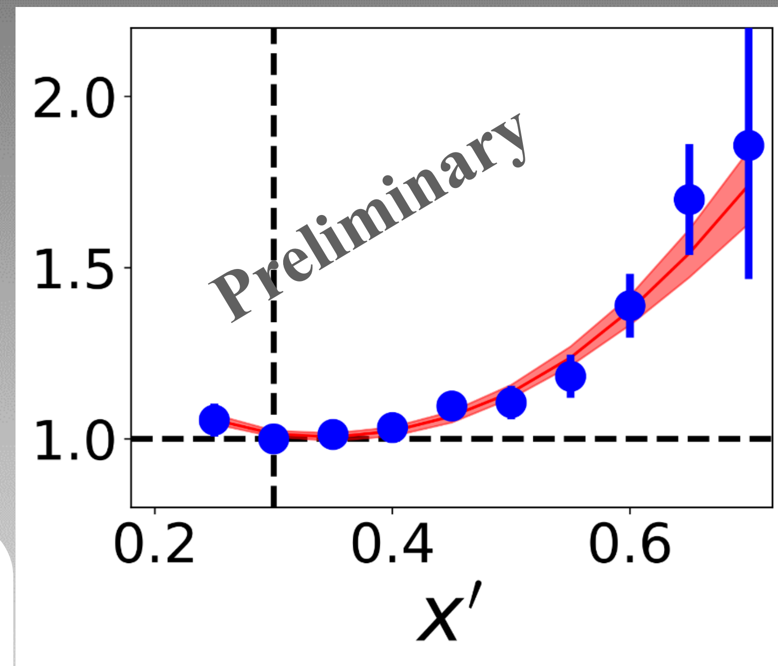
12 GeV JLab/ Hall C approved experiment **E12-11-003a**

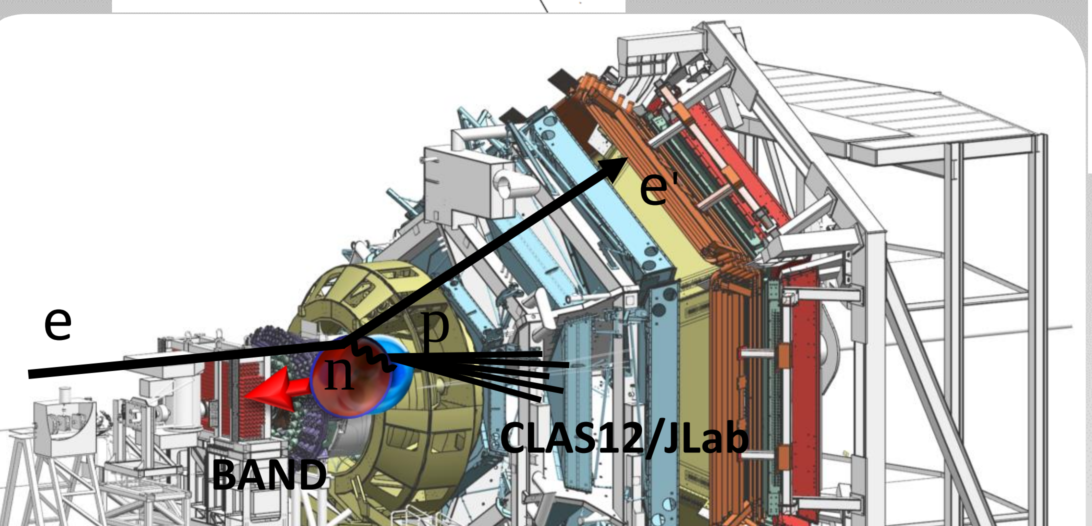
Neutron tagged DIS on ^{2}H

BAND experiment at CLAS12/JLab:



$1.3 < \alpha_s < 1.4$
(~ large missing momentum)





large modification of deeply bound proton

Thursday, February 23, 2023

10:40 AM Tagged DIS for bound nucleon structure Tyler Kutz

Summary

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

$k<k_F$

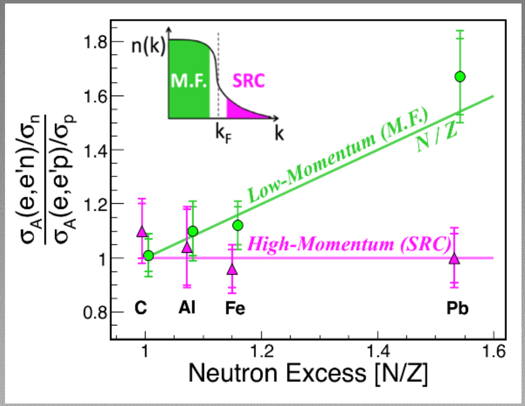
Mean field region

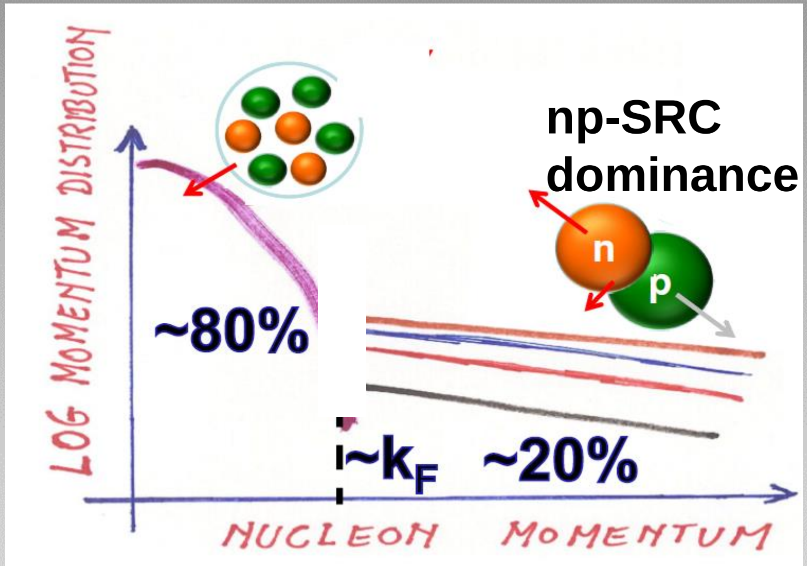
Single nucleons

$k>k_F$

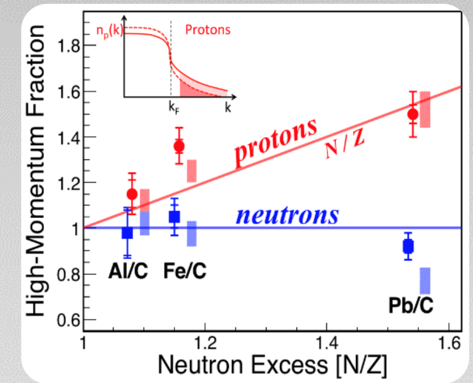
Correlated / high momentum region

SRC pairs





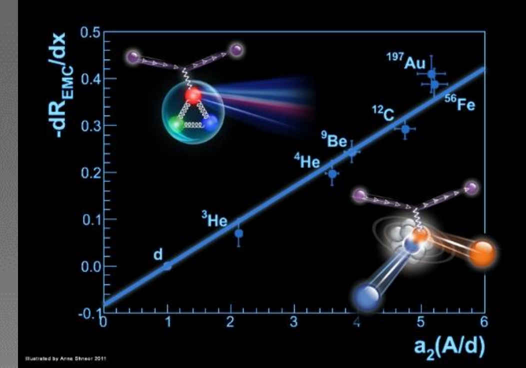
#protons = #neutrons, irrespectively of the neutron excess.



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

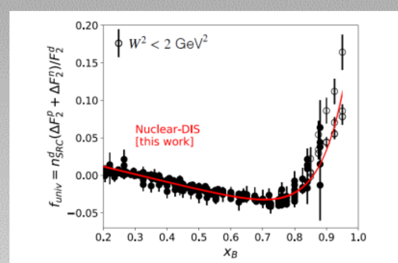
Generalized Nuclear Contact Formalism

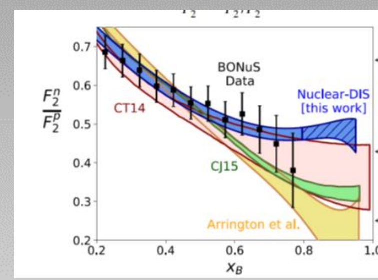
Summary

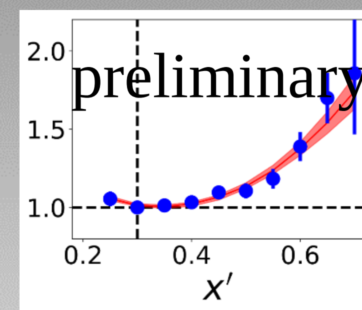


EMC is associate with 2N SRC:

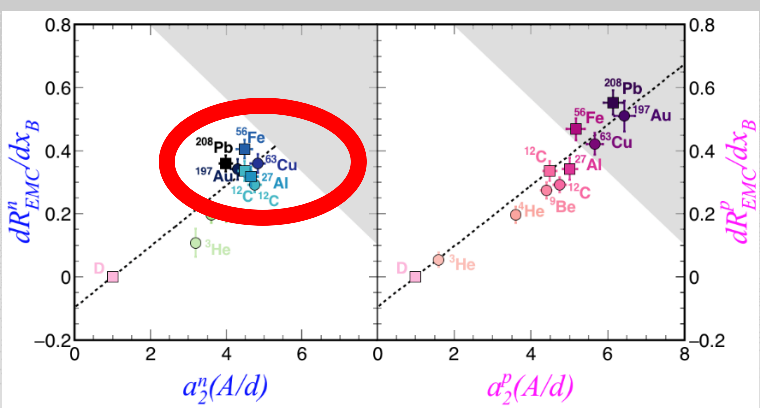
*** Nucleon is normally normal except when close to another nucleon.**
*** Small number of universal strongly modified nucleons.**
***Protons are more medium modified than neutron**



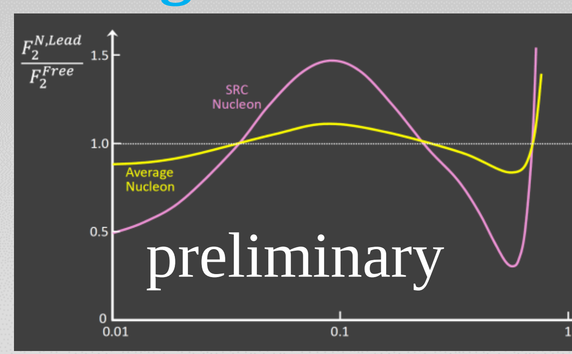




Universality



Strong modification



EMC effect is isospin dependent

Organizers

INT PROGRAM INT-23-1A

Intersection of nuclear structure and high-energy nuclear collisions

January 23, 2023 - February 24, 2023

Acknowledgment

TEL AVIV UNIVERSITY

Collaborators

Larry Weinstien

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Axel Schmidt

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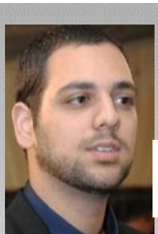
Barak Schmookler

Efrain Segarra

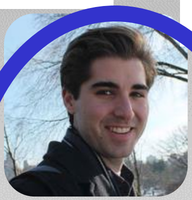
F. Hauenstein



Or Hen

Wim Cosyn

Jan Ryckebush



Tyler Kutz

Justin Estee

Nir Barnea

Ronen Weiss

Jerry Miller

Mark Strikman

Leonid Frankfurt

Misak Sargsian

Data-Mining collaboration

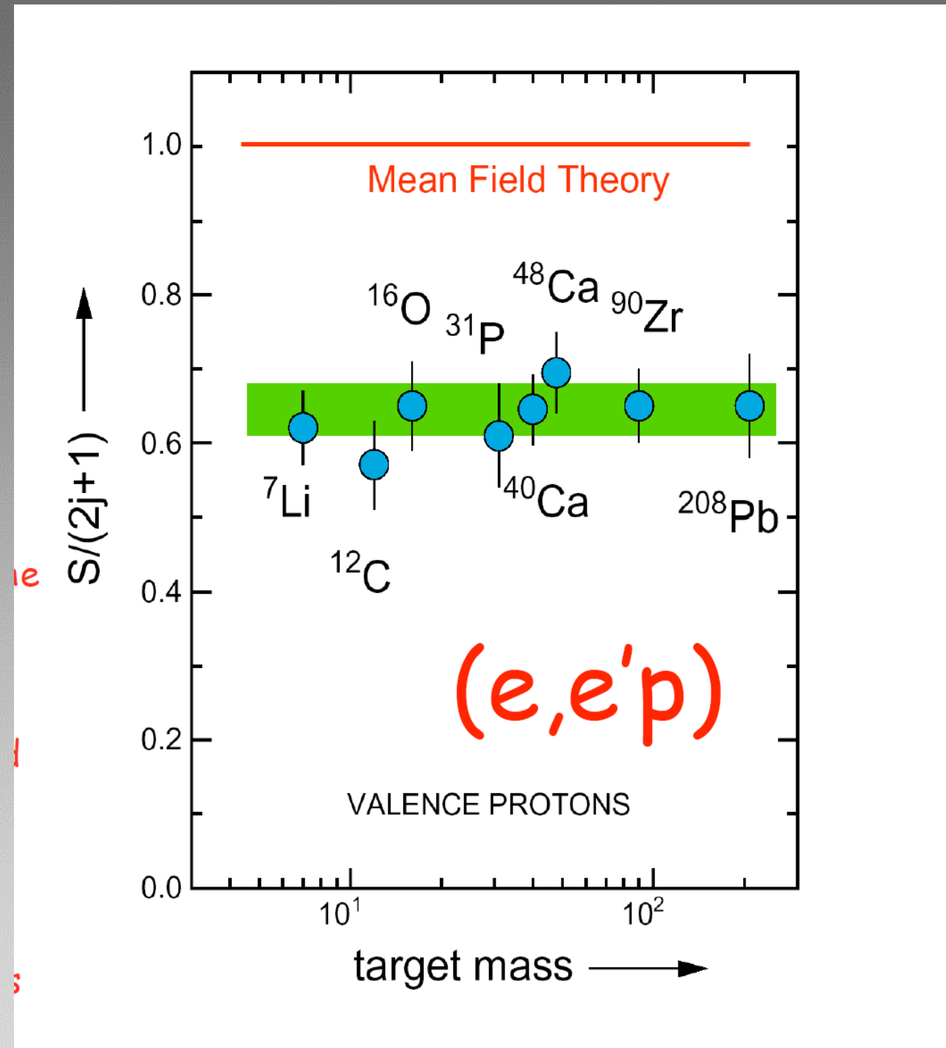
CLAS collaboration

Jefferson Lab

Removal probability for valence protons from NIKHEF data

L. Lapikás, Nucl. Phys. A553,297c (1993)

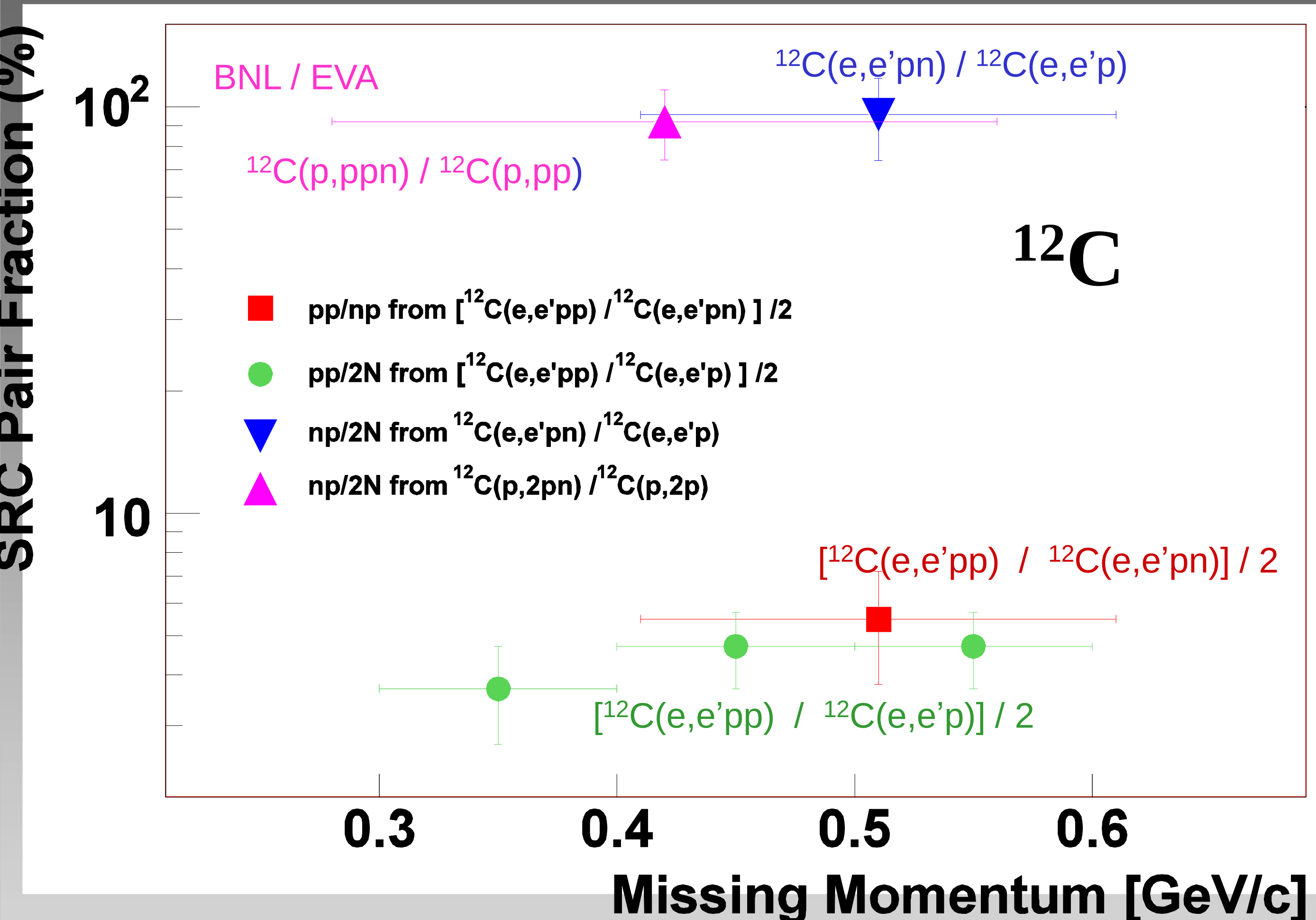
$S \approx 0.65$ for valence protons
Reduction $\Rightarrow$ both SRC and LRC

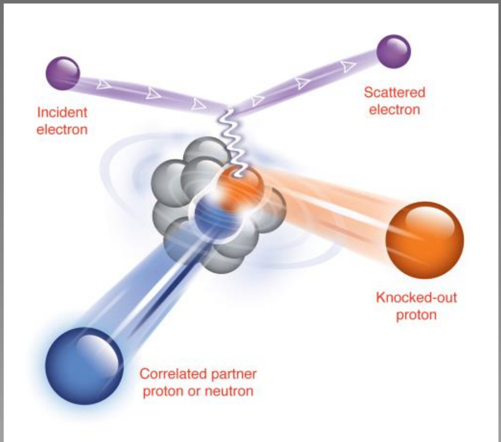


Piasetzky et al., PRL. 97 (2006) 162504.

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

TEL AVIV UNIVERSITY

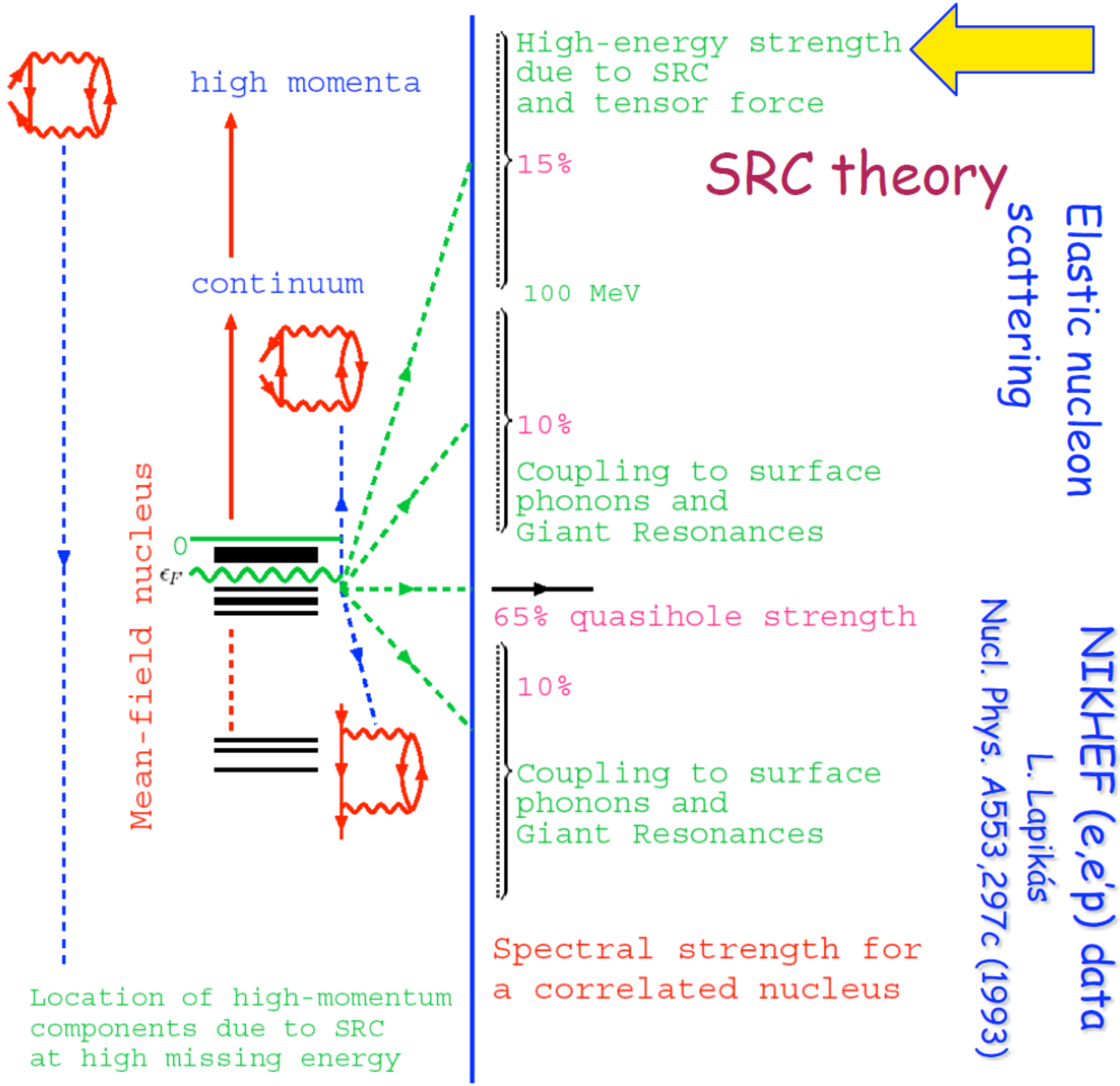




The high momentum tail in nuclei is dominated by SRC pairs

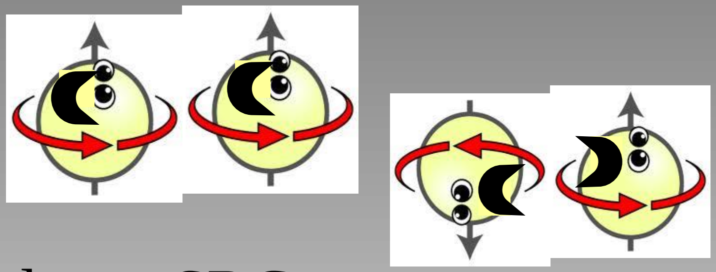
Most of the SRC pairs (90%) are np only 5% pp and 5% nn

Reviewed in Prog. Part. Nucl. Phys. 52 (2004) 377-496



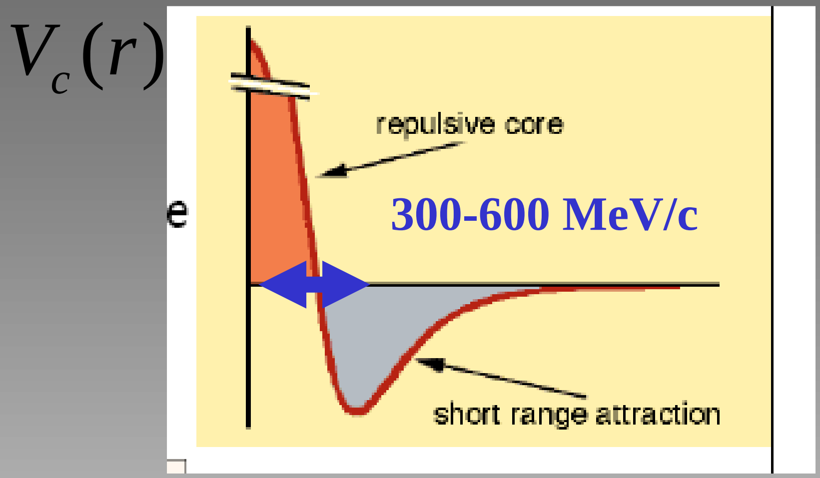
Nucleons has Isophobia (np – dominance)

The reason: tensor force



only np-SRC

pp- nn- np- SRC



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

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

The consequences:

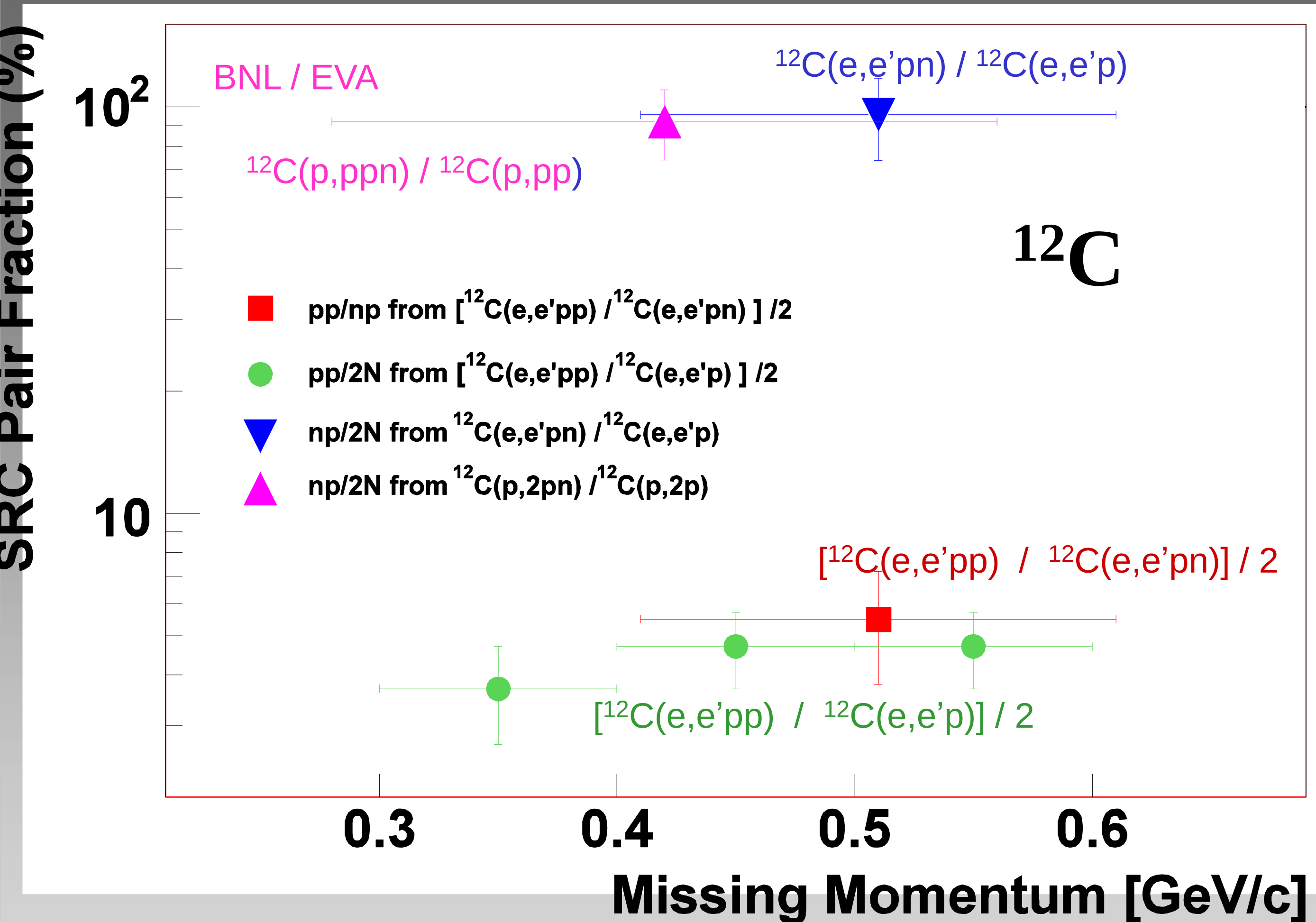
Protons have a greater probability than neutrons to be above the Fermi sea.

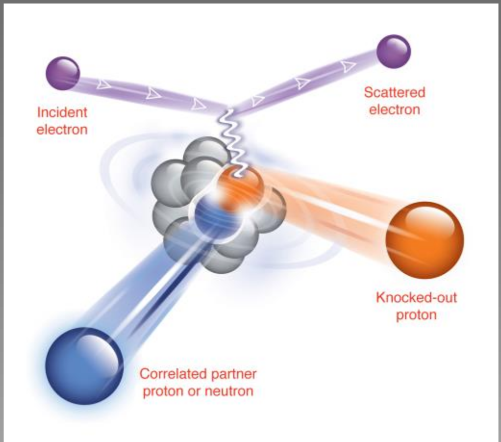
For nuclei with N>Z

More Neutrons => More Correlated Protons

Piasetzky et al., PRL. 97 (2006) 162504.

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

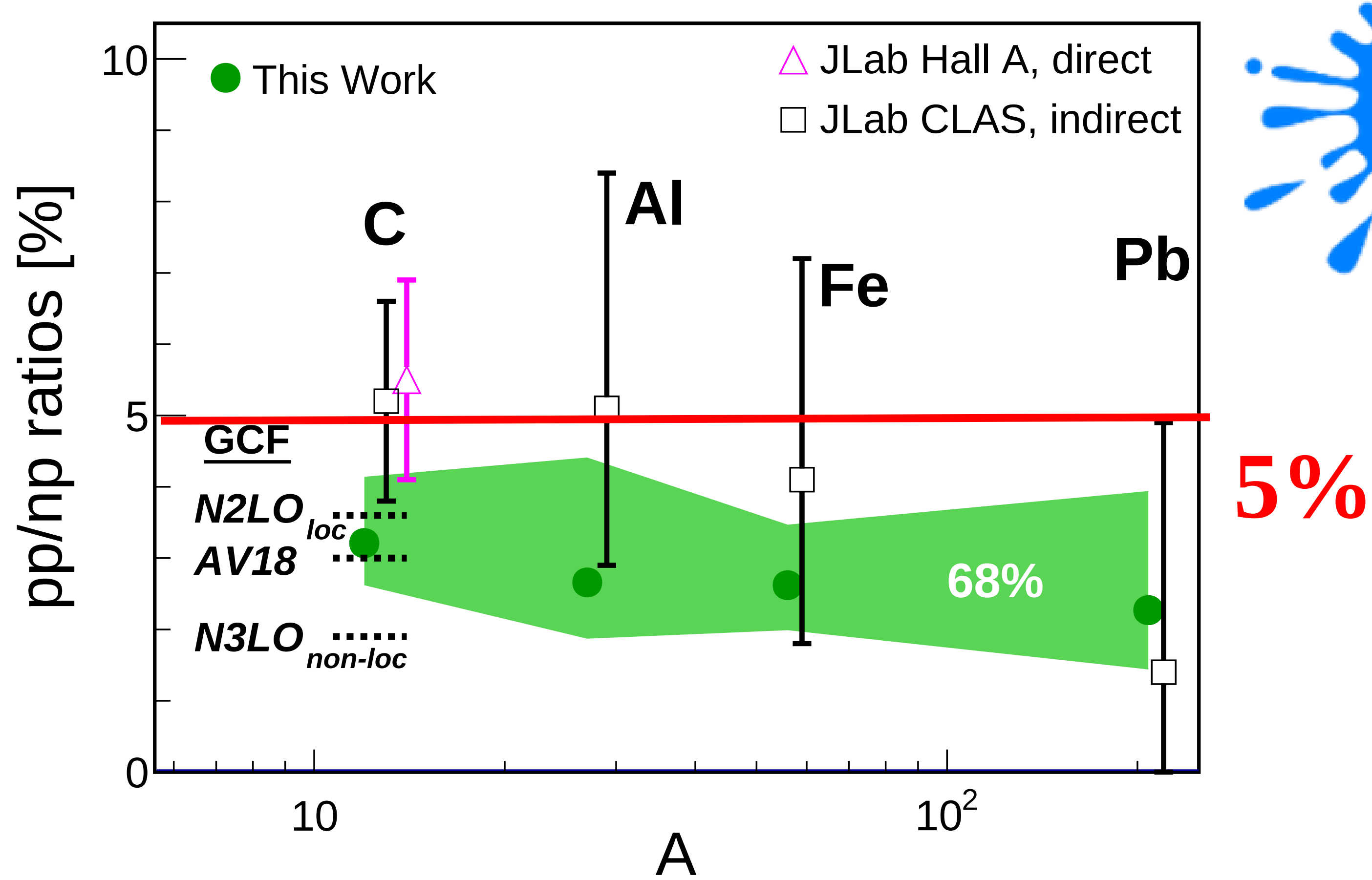




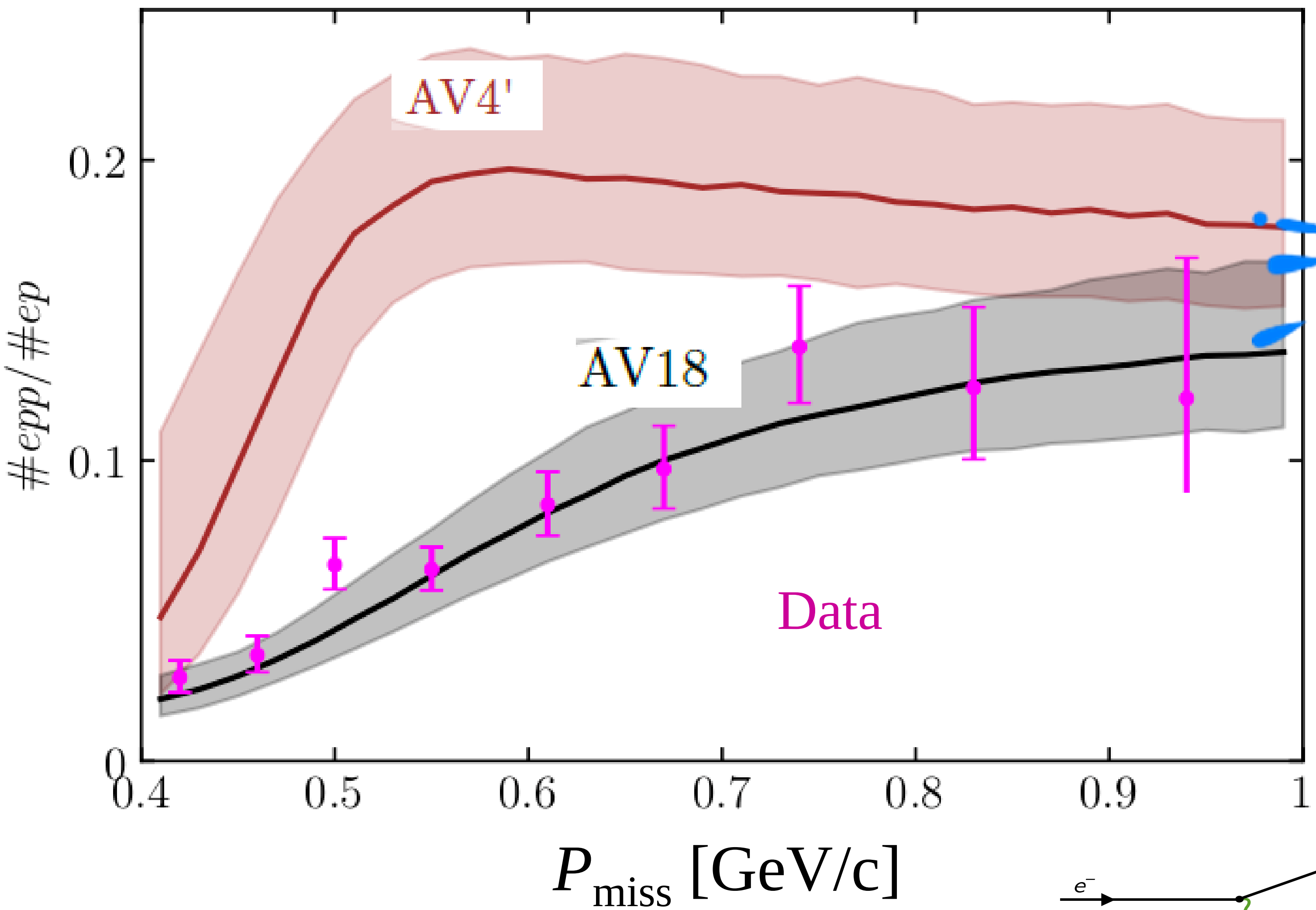
The high momentum tail in nuclei is dominated by SRC pairs

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

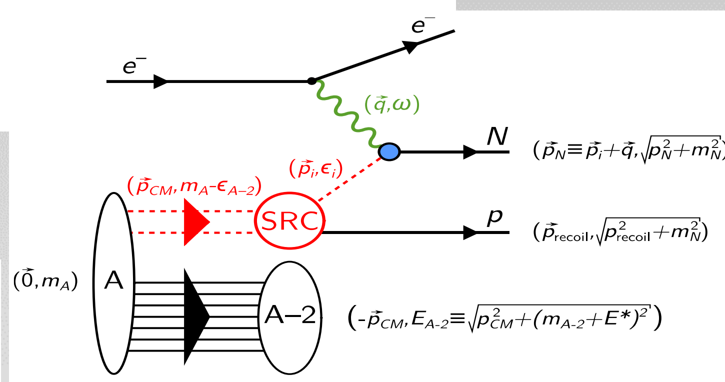
SRCs Dominated by np pairs



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



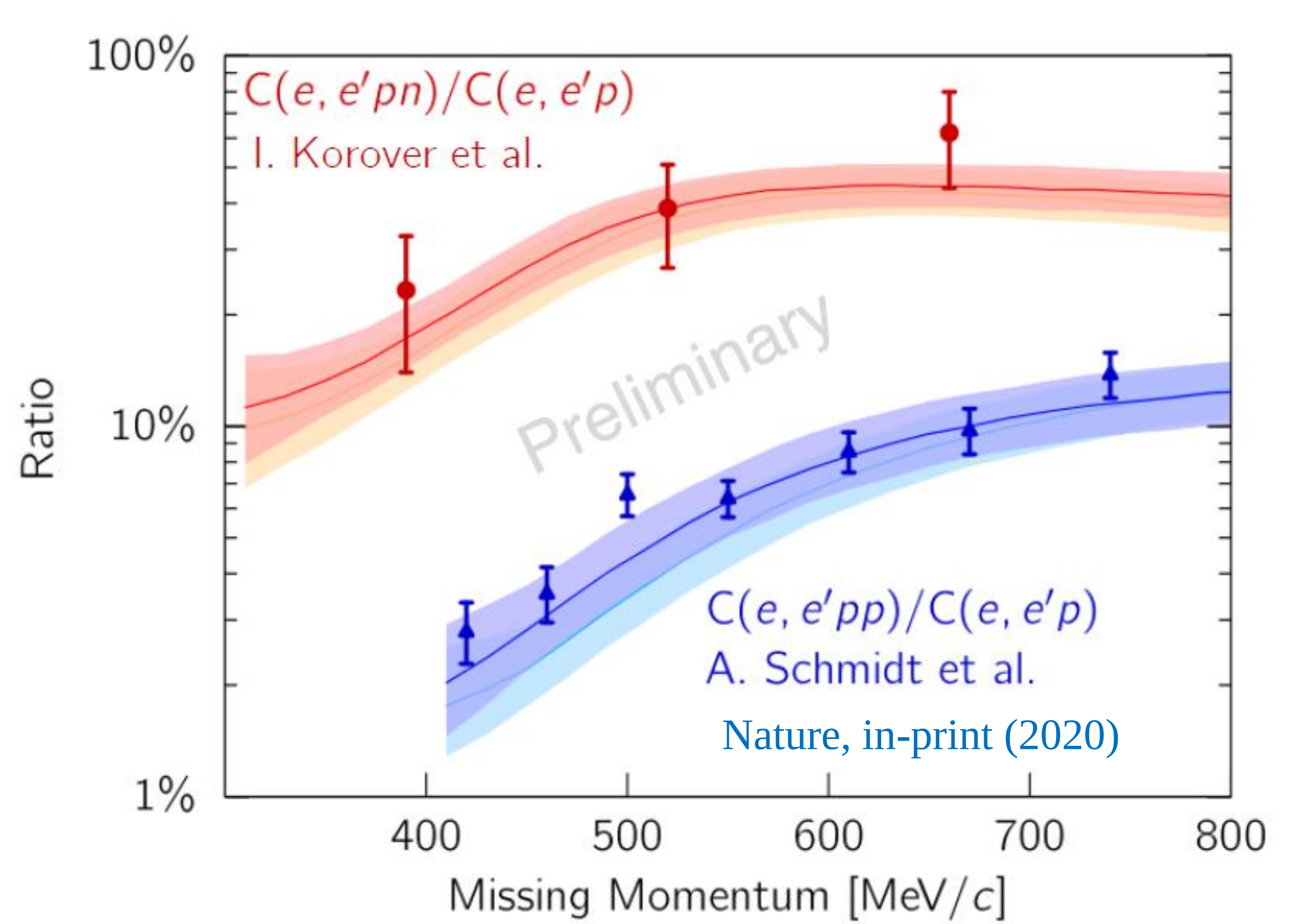
NEW! 2018-2019



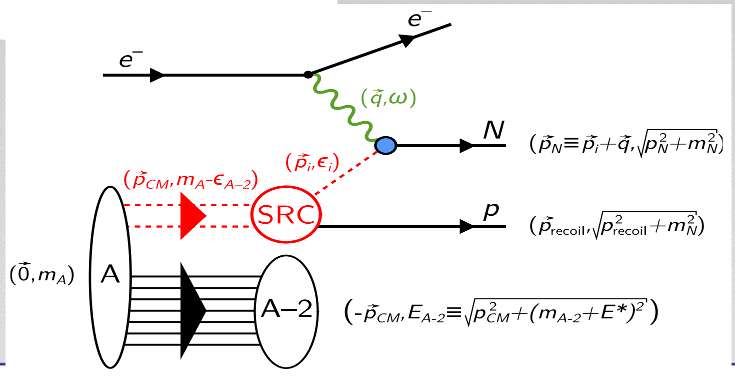
Probing the core of the strong nuclear interaction

A. Schmidt et al. (CLAS Collaboration) Nature (in print)

TEL AVIV UNIVERSITY



NEW!
2020

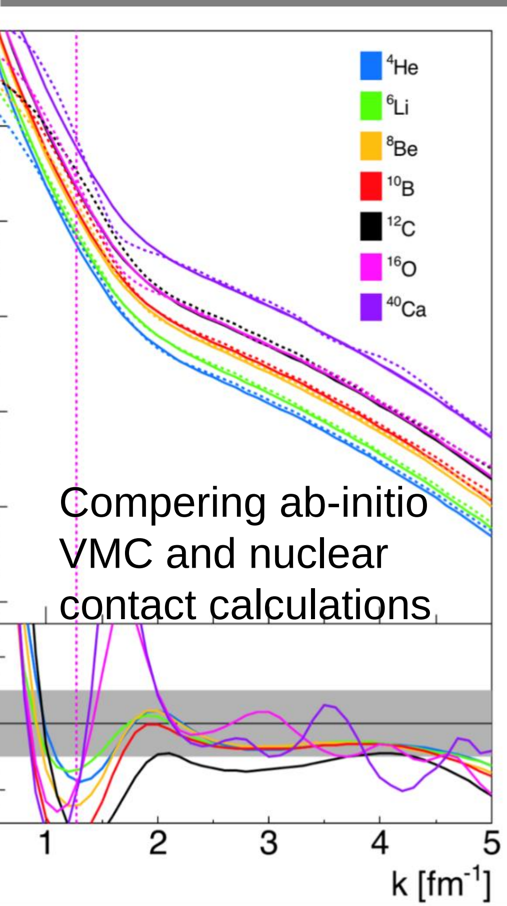


Probing the core of the strong nuclear interaction

A. Schmidt et al. (CLAS Collaboration) Nature (in print)

Universality (factorization)

Momentum Distribution



Compering ab-initio VMC and nuclear contact calculations

a factorized ansatz

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

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

GCF: Generalized Contact Formalism

Phys. Lett. B780 (2018) 211.

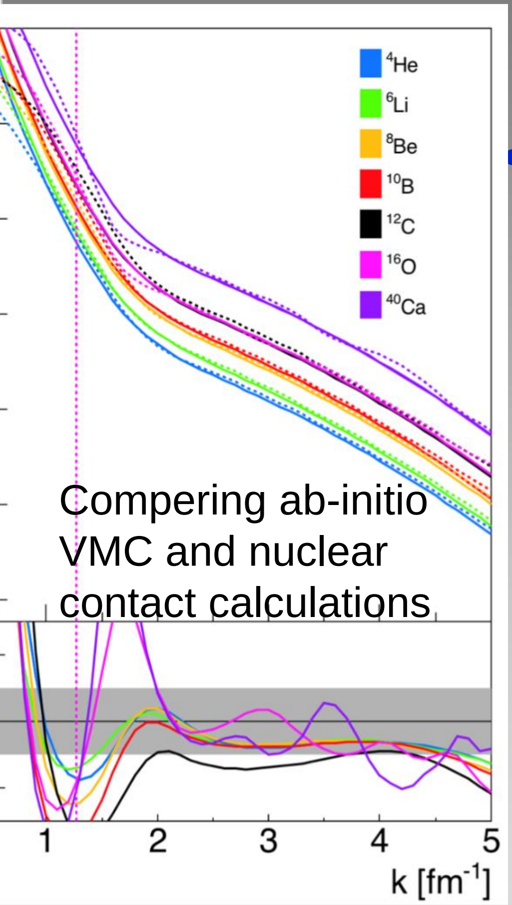
GCF: Generalized Contact Formalism

a factorized ansatz

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

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

Momentum Distribution



Residual

Compering ab-initio VMC and nuclear contact calculations

The nuclear contacts and short range correlations in nuclei

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

Phys. Lett. B780 (2018) 211.

A universal description of SRC:

$$n_p(k) \xrightarrow[k\to\infty]{} C_{pn}^{d}\left|\varphi_{pn}^{d}(k)\right|^2 + C_{pn}^{0}\left|\varphi_{pn}^{0}(k)\right|^2 + 2C_{pp}^{0}\left|\varphi_{pp}^{0}(k)\right|^2$$

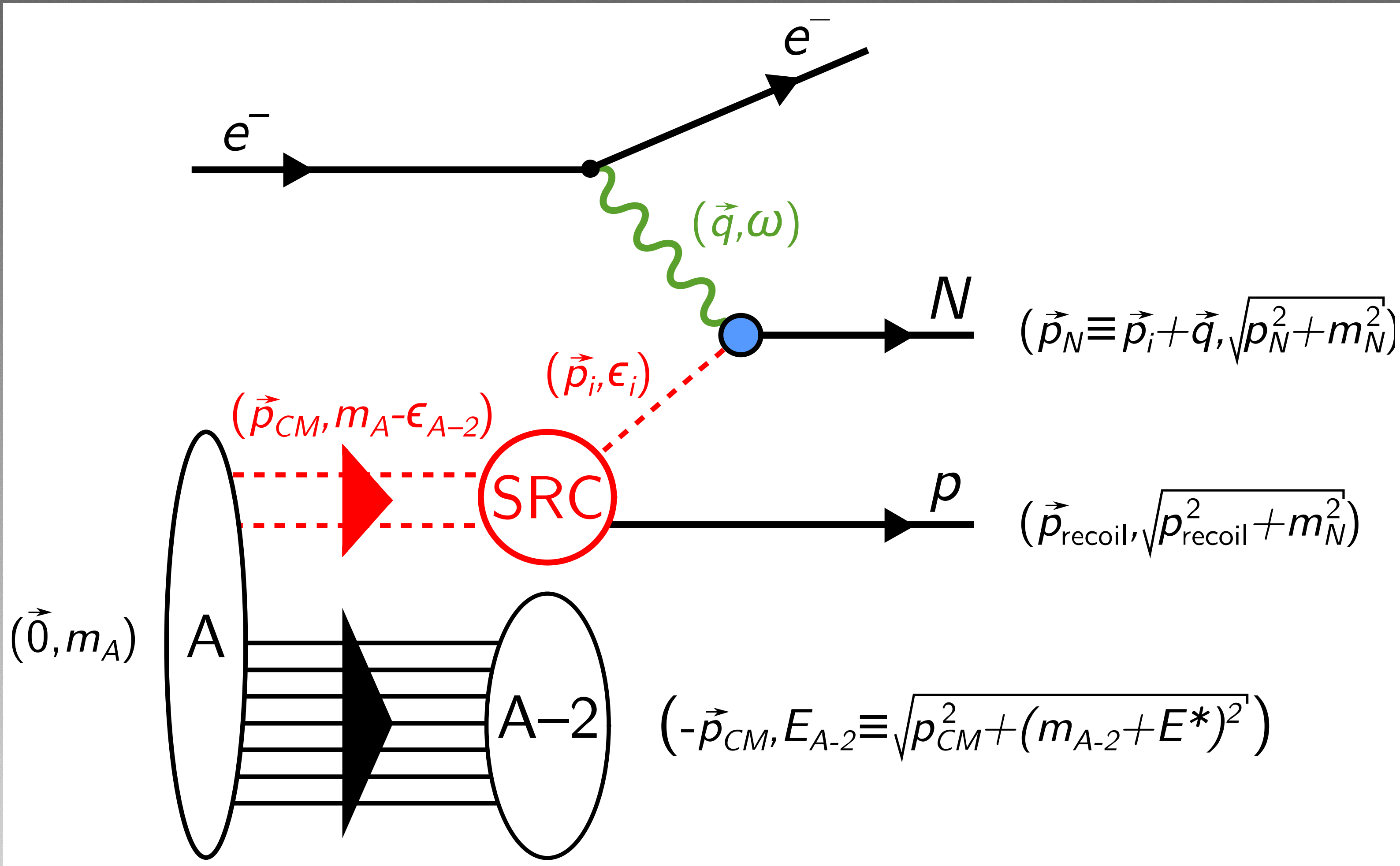
$l = 0, 2\ s = 1\ j = 1$

np pairs

$l = s = j = 0$

pp, nn, np pairs

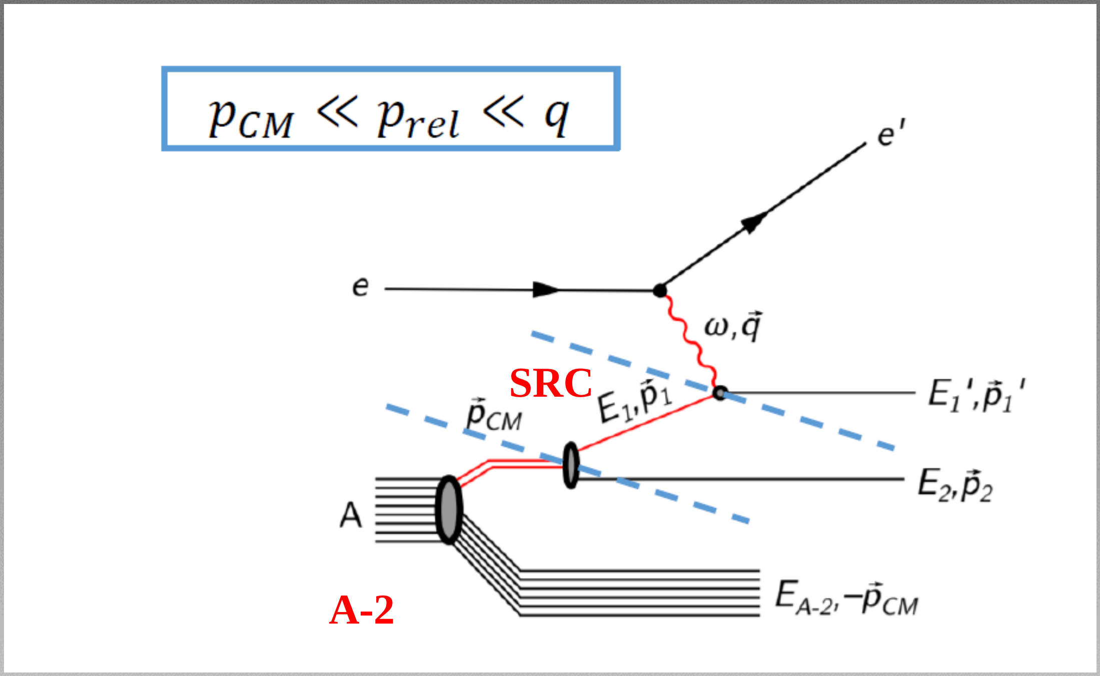
Exclusive Hard scattering in selected kinematics



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

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

selected kinematics
→ scale separation, factorization



Sensitivity to NN interaction

Universality

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

GCF

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

A. Schmidtet al. (CLAS Collaboration), Nature, in print (2020)

Adapted from Rolf

Valance quarks

sea quarks

anti quarks

gluons

Structure functions

PDF

GPDF

TMD

All these particles you cannot see. That’s what drove me to drink. But now I can see them.