

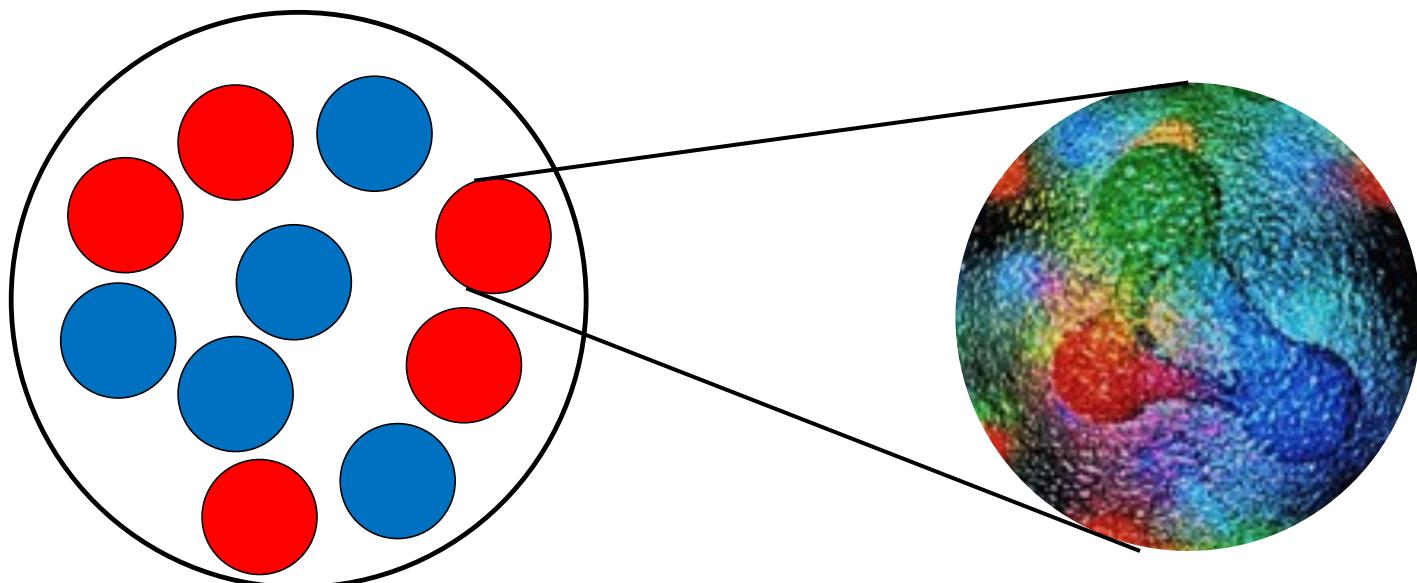
Modification of Quark-Gluon Distributions in Nuclei by Correlated Nucleons Pairs

Andrew Denniston (MIT)

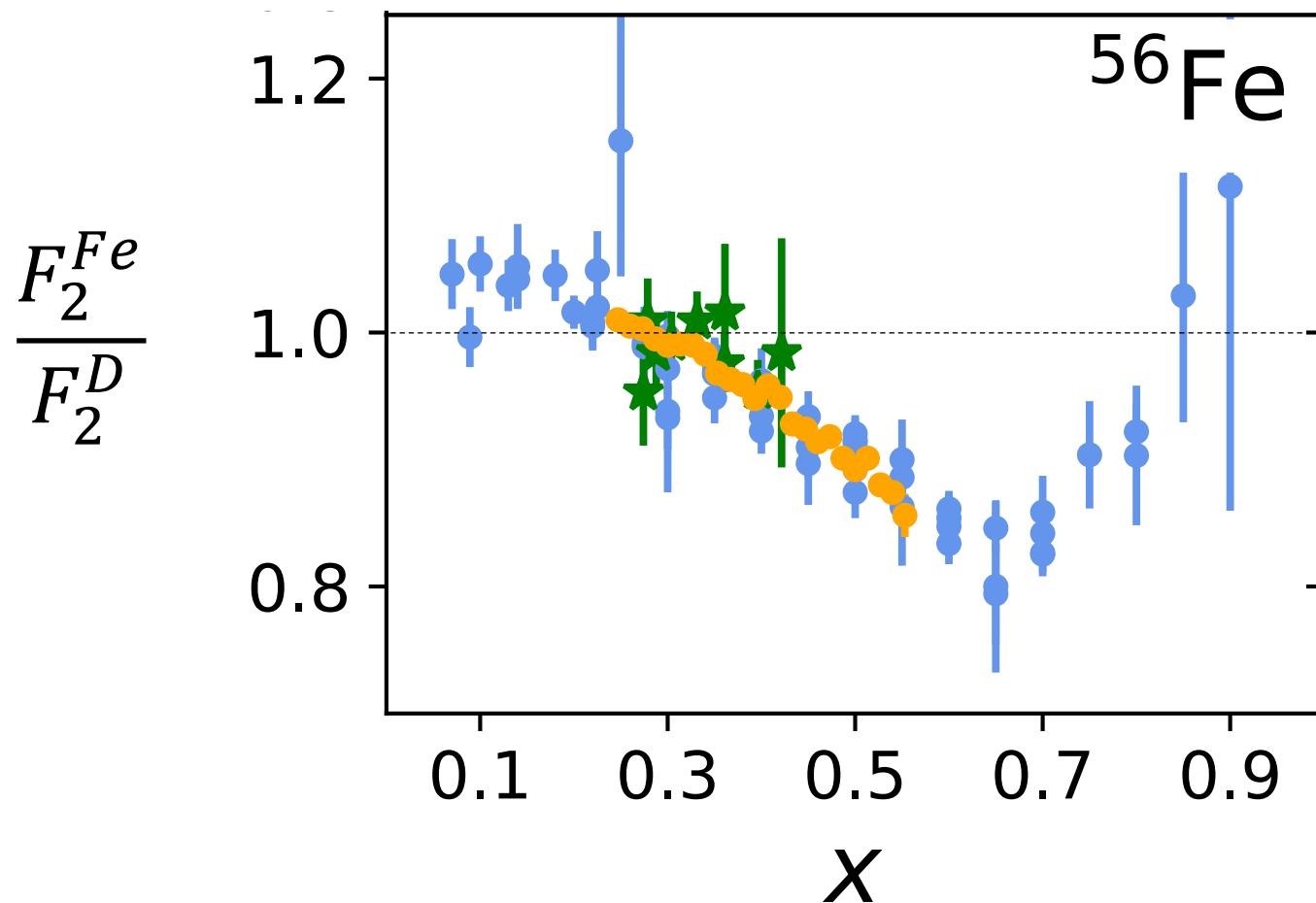
In Collaboration with: Tomas Jezo,
Aleksander Kusina, Fred Olness, Or Hen

March 28th , 2023

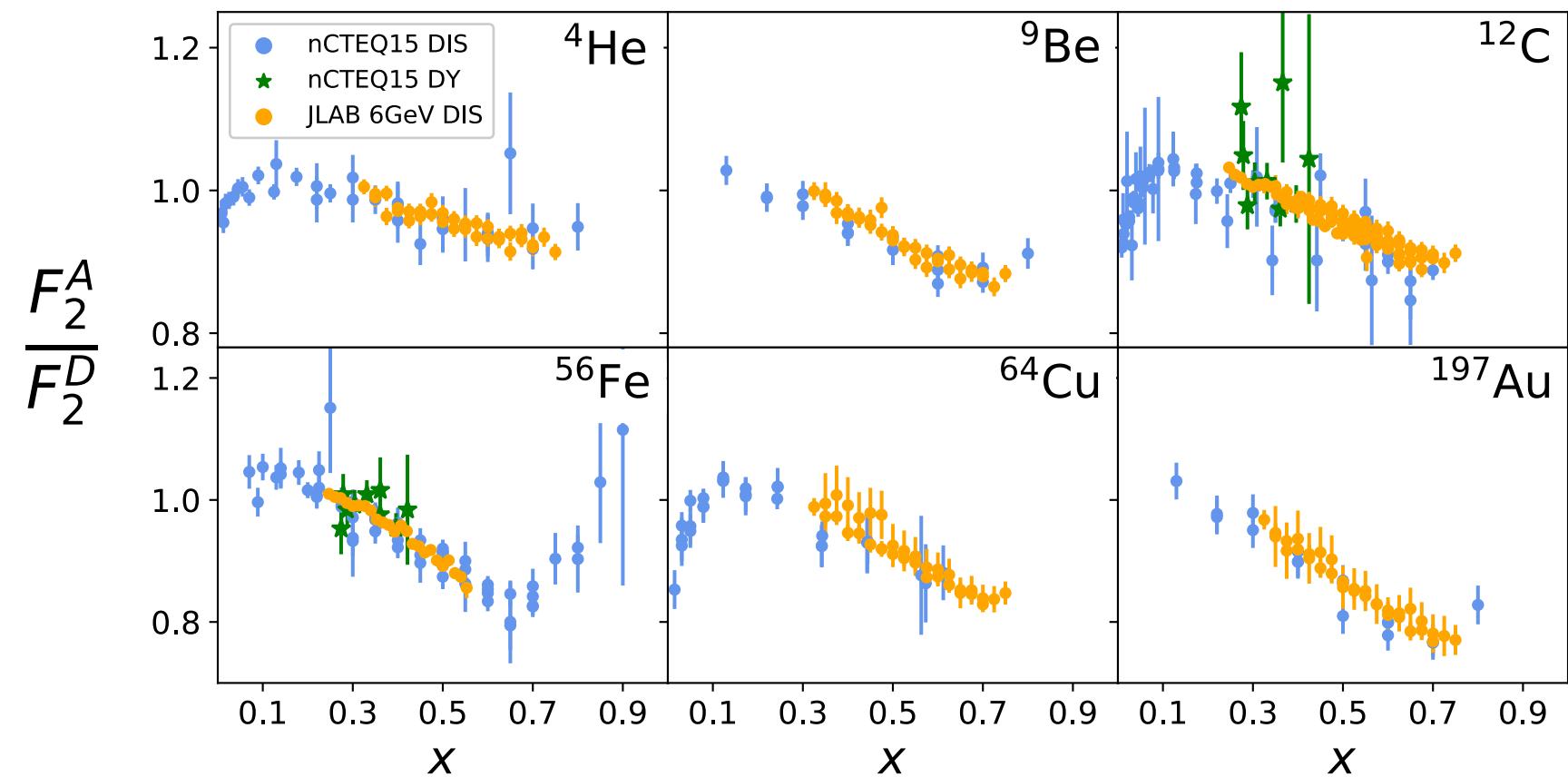
Quarks and Nuclei



The EMC Effect



Nuclear Dependance



Cause of the EMC Effect?



Traditional Nuclear
Effects



Medium
Modification

Cause of the EMC Effect?

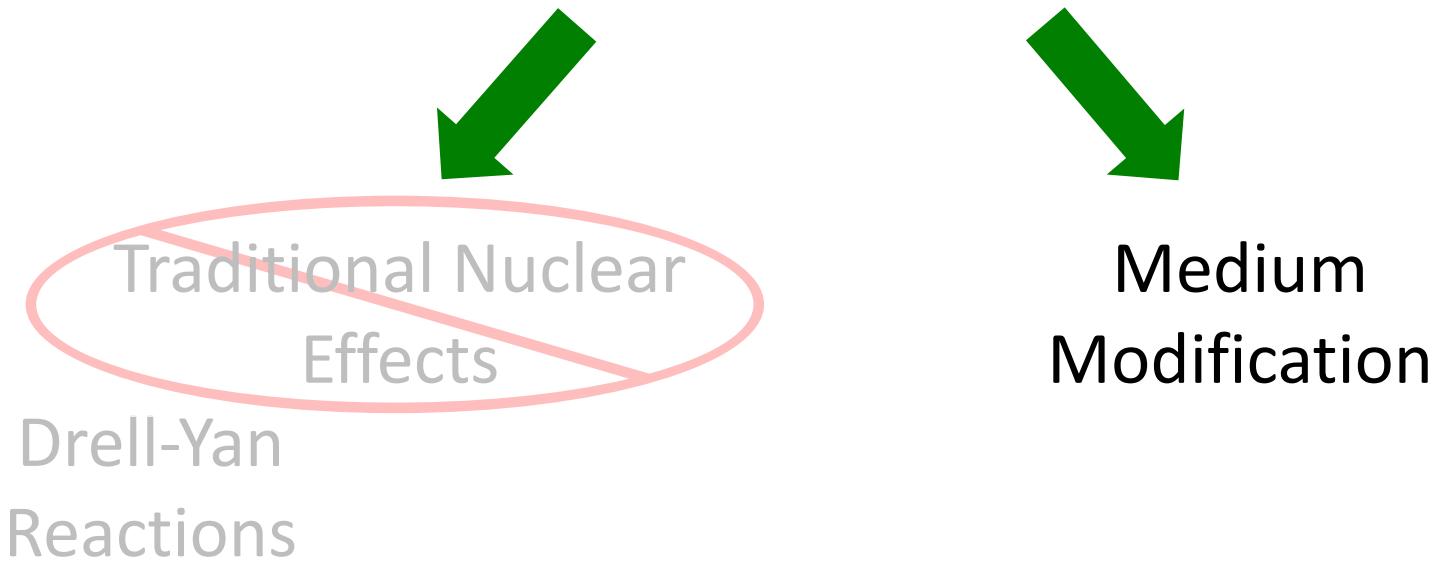
~~Traditional Nuclear Effects~~

Drell-Yan
Reactions

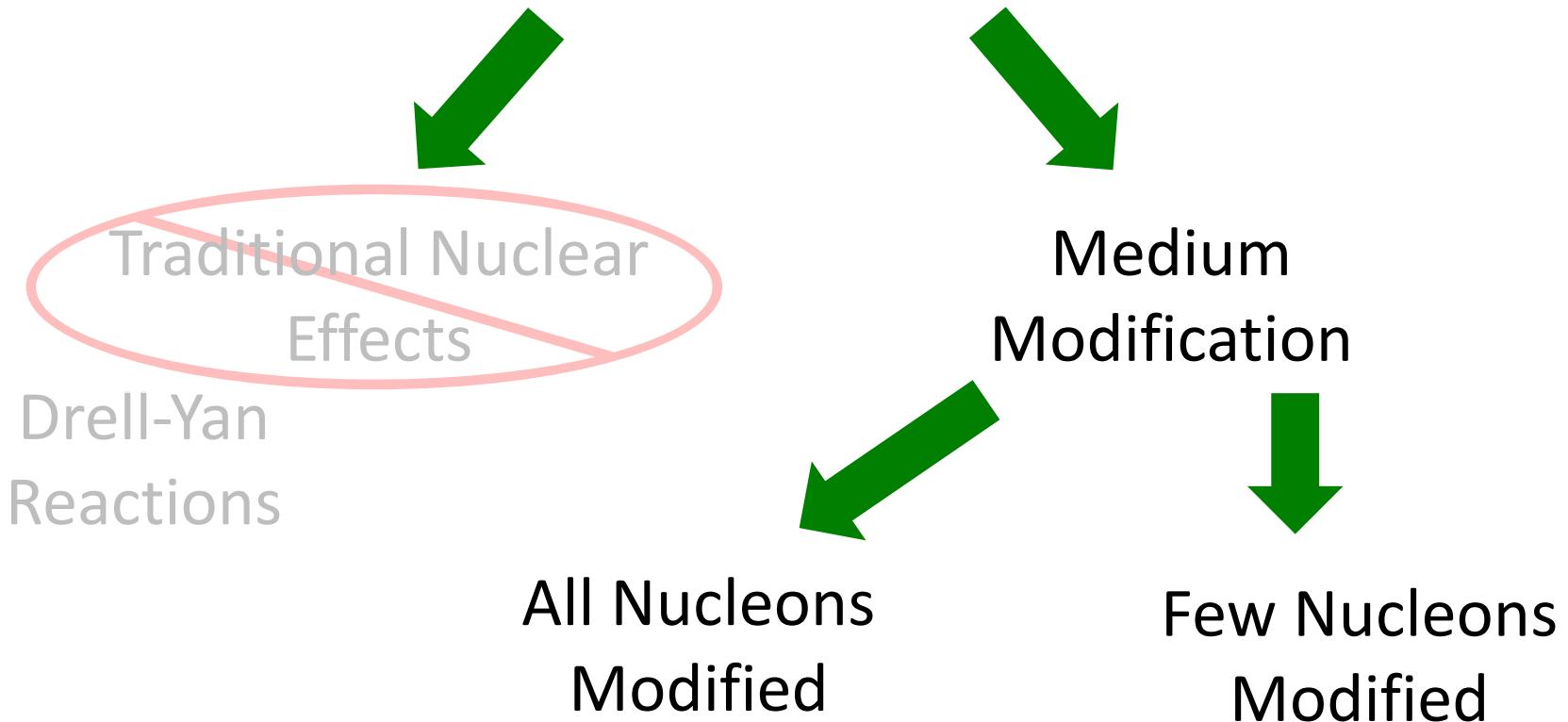


Medium
Modification

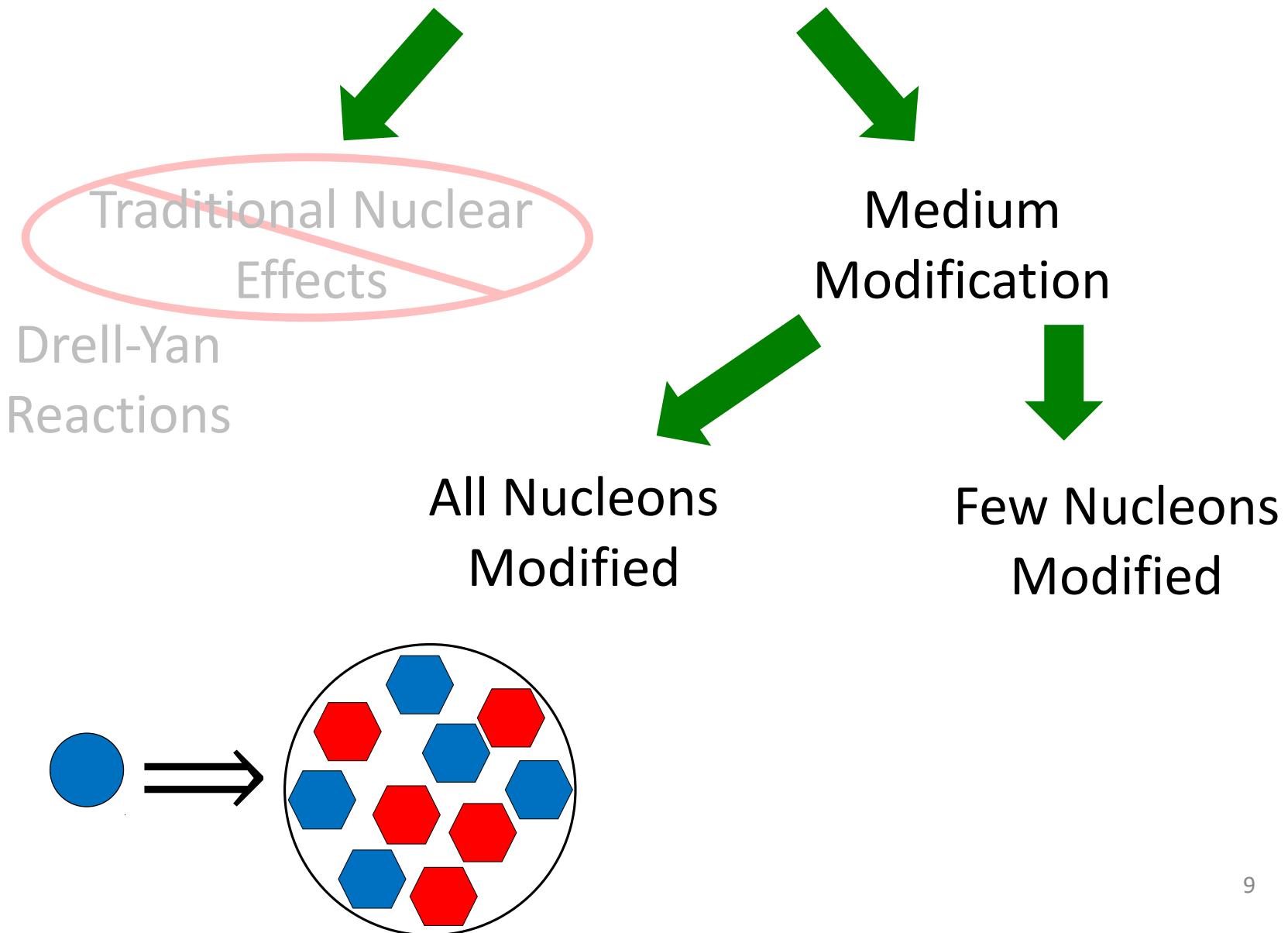
Cause of the EMC Effect?



Cause of the EMC Effect?

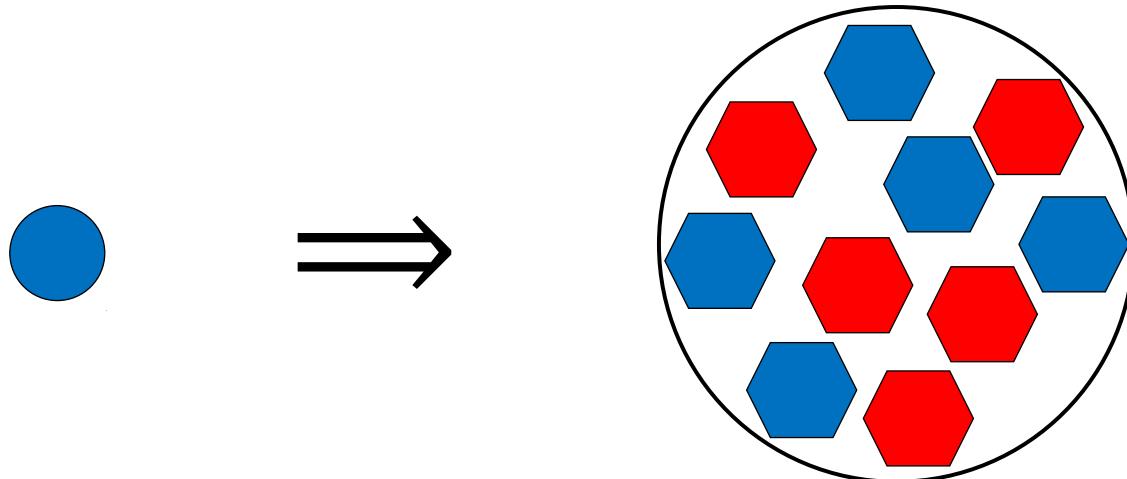


Cause of the EMC Effect?



Mean-Field Approach

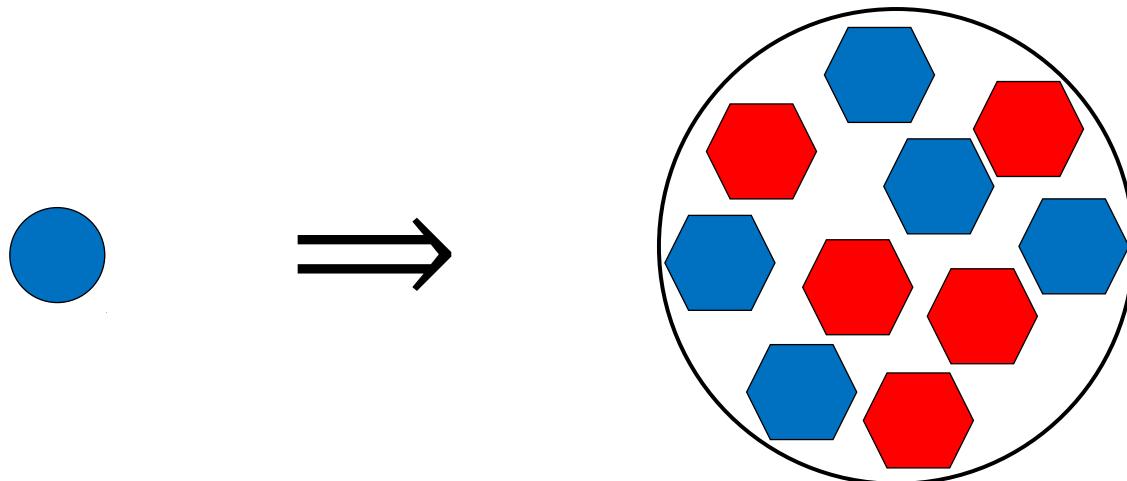
$$f_i^A(x) = \frac{Z}{A} f_i^{p(A)}(x) + \frac{A - Z}{A} f_i^{n(A)}(x)$$



Mean-Field Approach

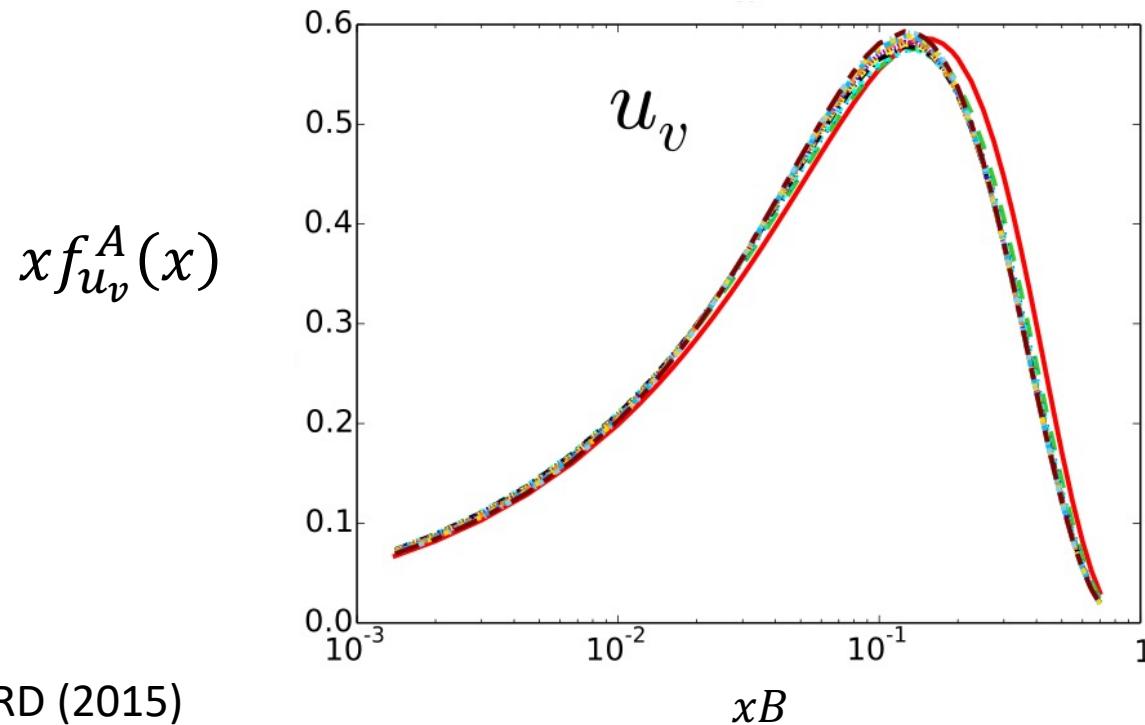
Depend on A

$$f_i^A(x) = \frac{Z}{A} f_i^{p(A)}(x) + \frac{A - Z}{A} f_i^{n(A)}(x)$$



Mean-Field Parametrization

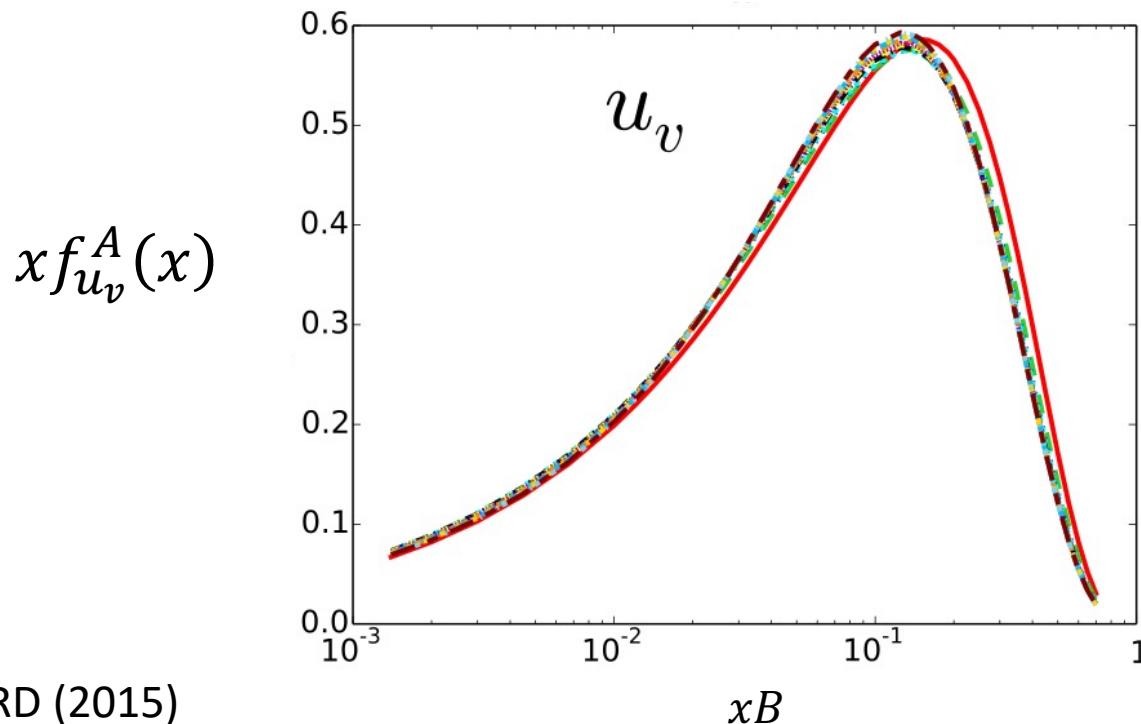
$$x f_i^{p(A)}(x) = c_0 x^{c_1} (1 - x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5}$$



Mean-Field Parametrization

$$x f_i^{p(A)}(x) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1+e^{c_4 x})^{c_5}$$

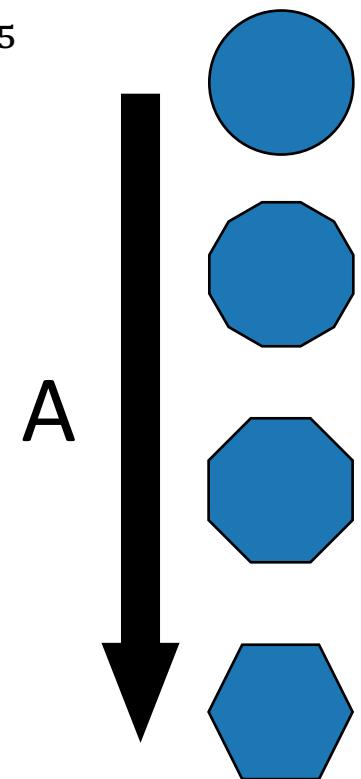
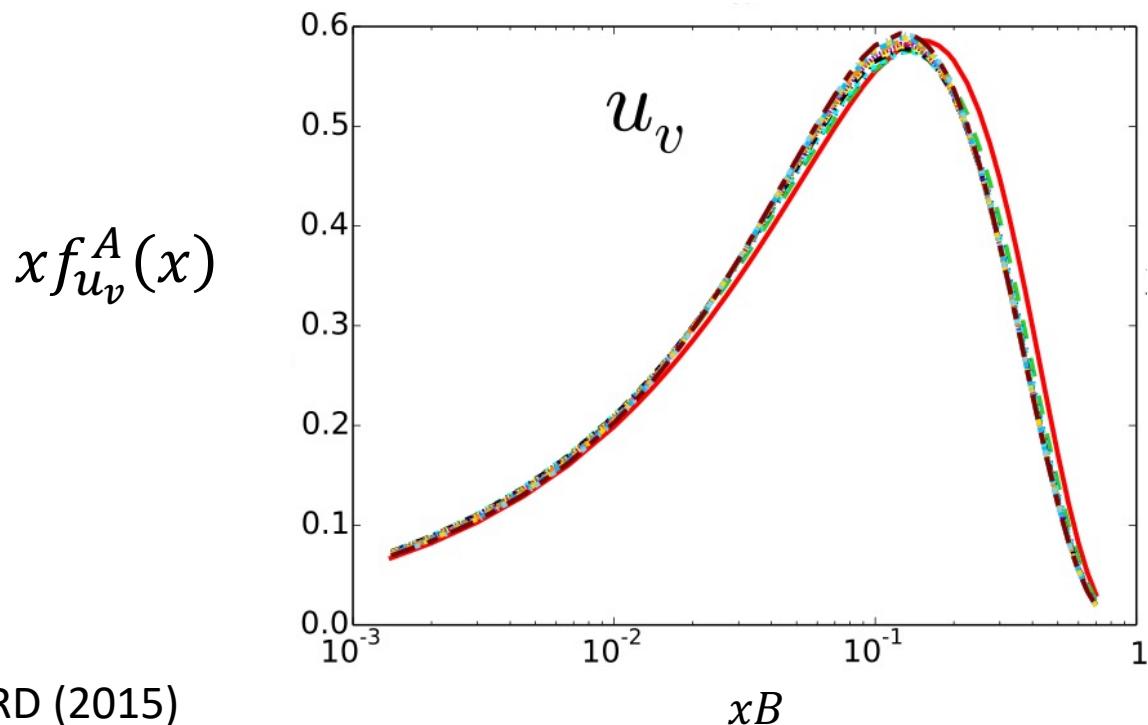
$$c_k(A) = c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$$



Mean-Field Parametrization

$$x f_i^{p(A)}(x) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1+e^{c_4 x})^{c_5}$$

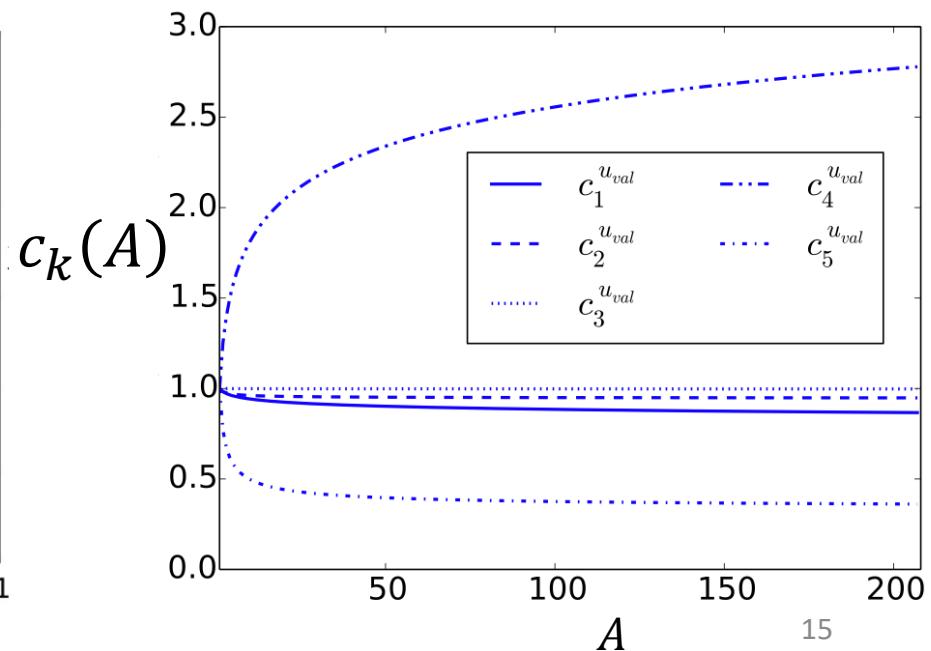
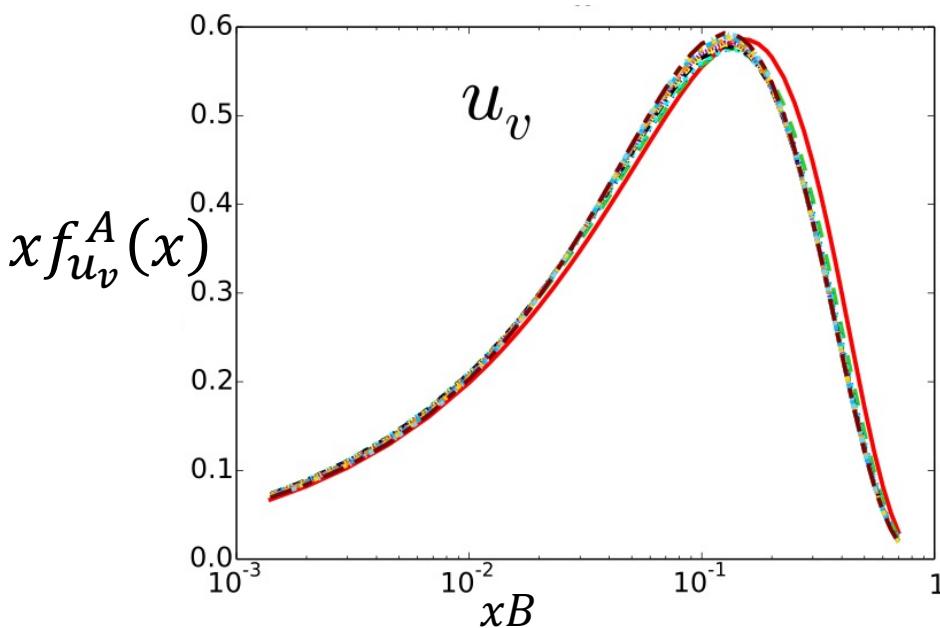
$$c_k(A) = c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$$



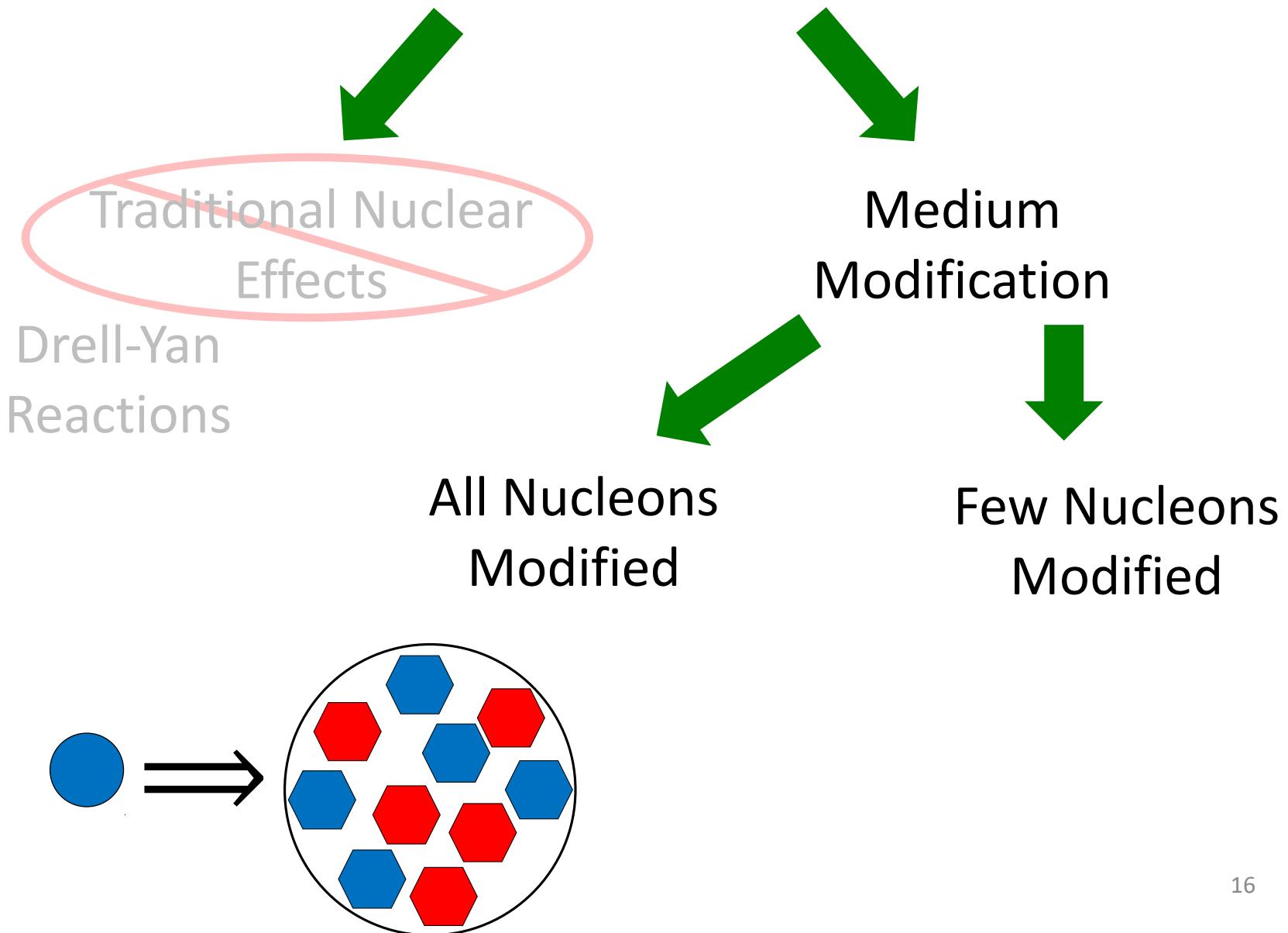
Mean-Field Parametrization

$$x f_i^{p(A)}(x) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1+e^{c_4 x})^{c_5}$$

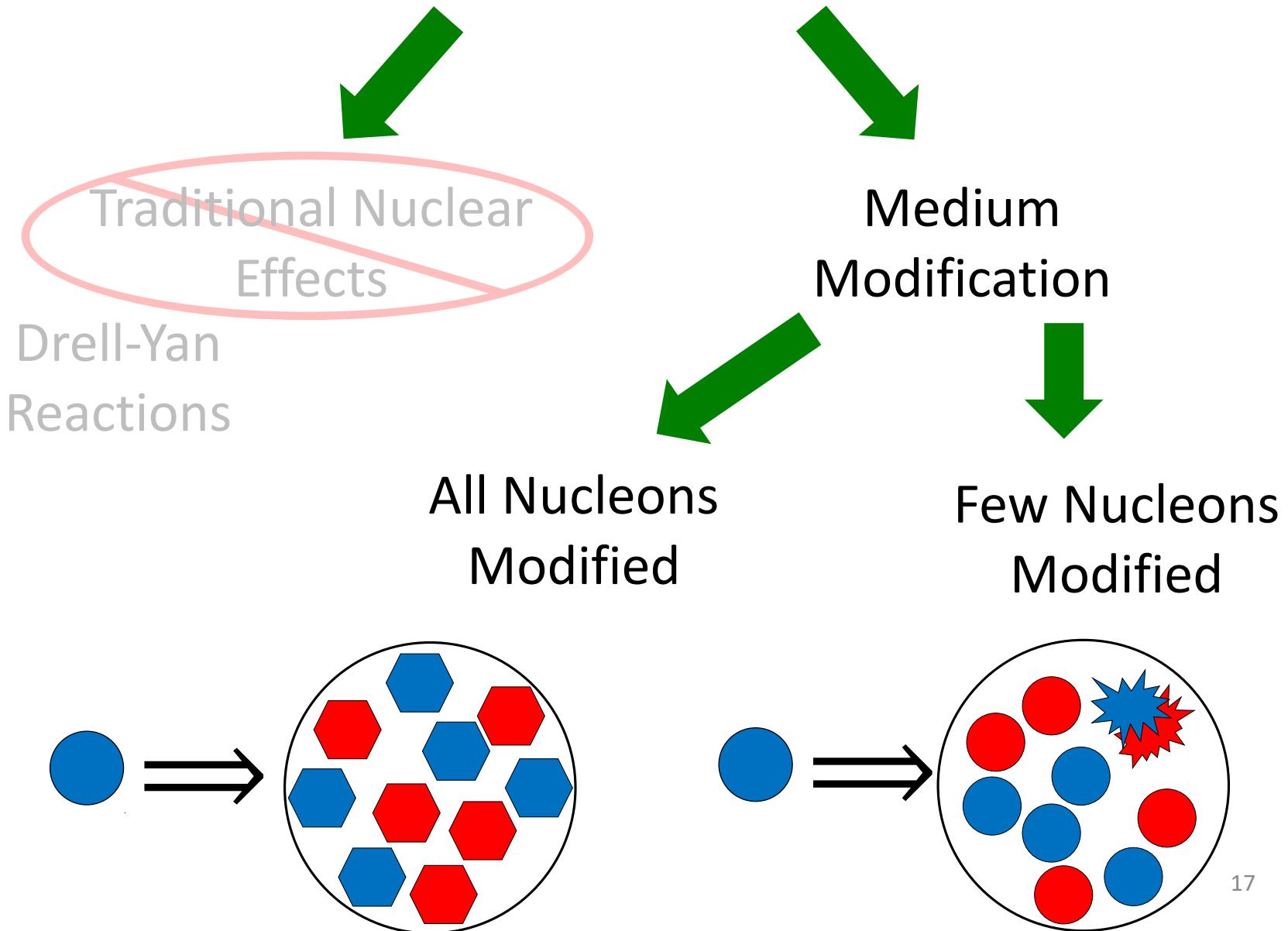
$$c_k(A) = c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$$



Cause of the EMC Effect?



Cause of the EMC Effect?



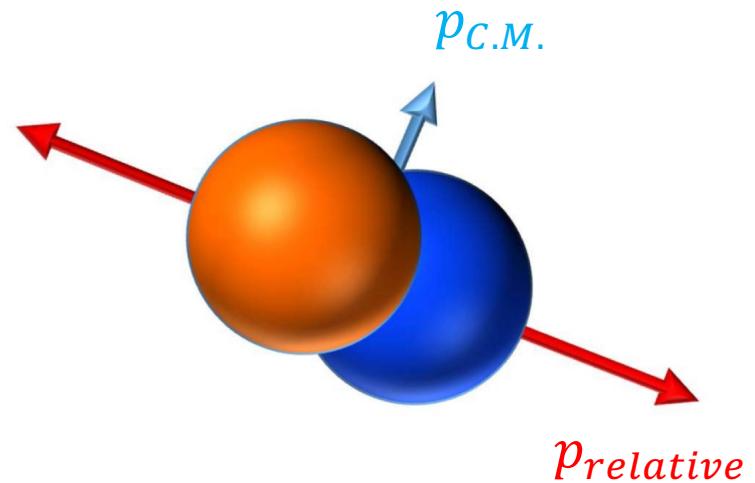
Nuclear Short-Range Correlations

- Pairs with small separation



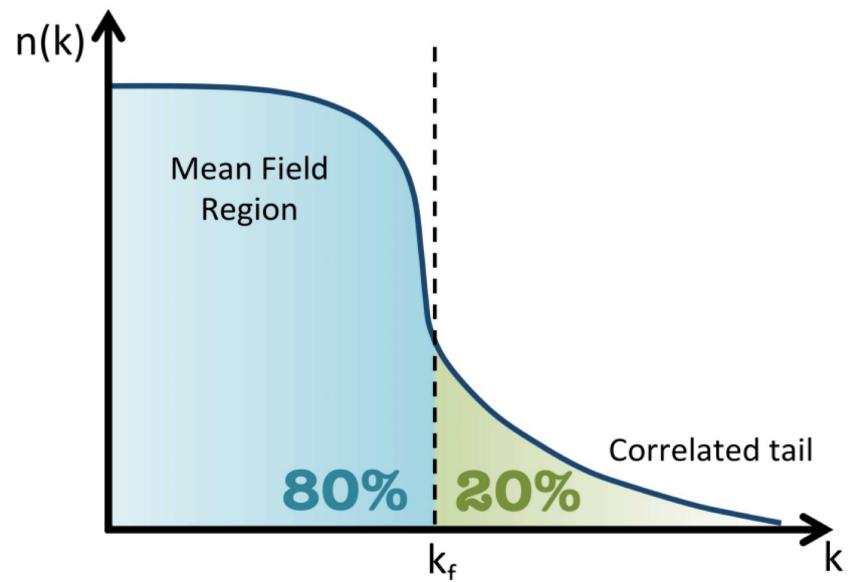
Nuclear Short-Range Correlations

- Pairs with small separation
- High relative momentum compared to k_F



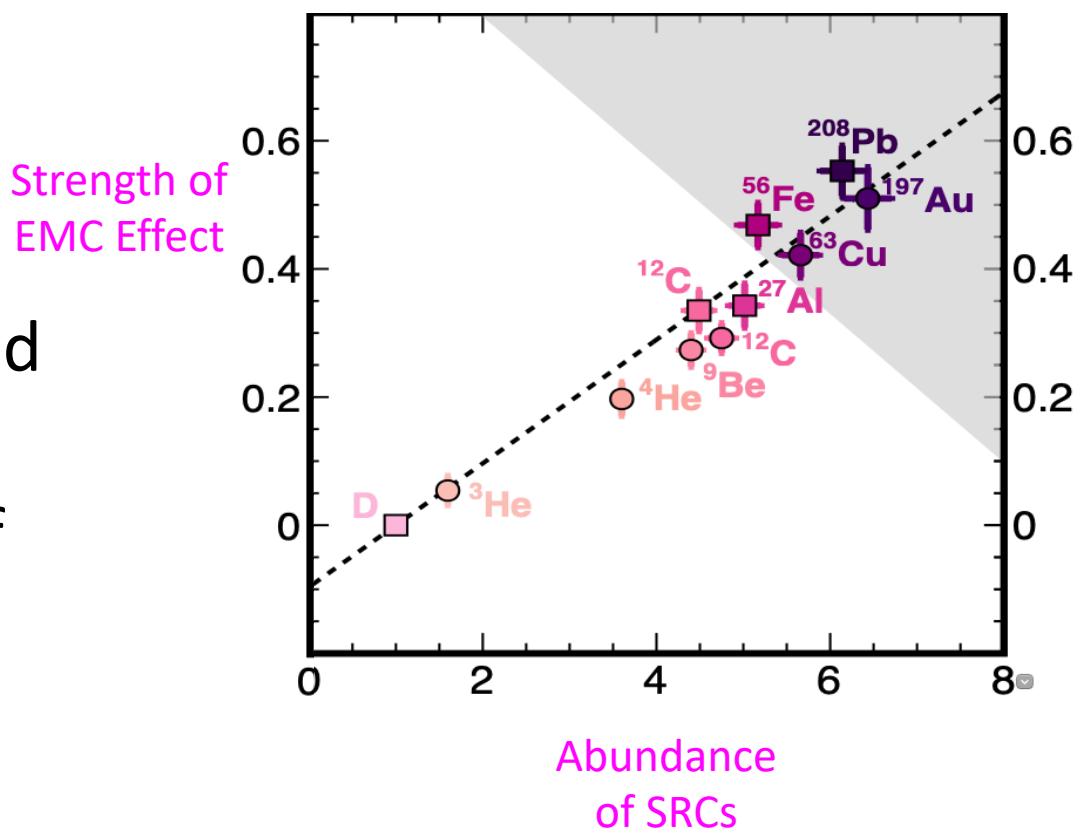
Nuclear Short-Range Correlations

- Pairs with small separation
- High relative momentum compared to k_F
- Significant fraction of the nuclear spectral function

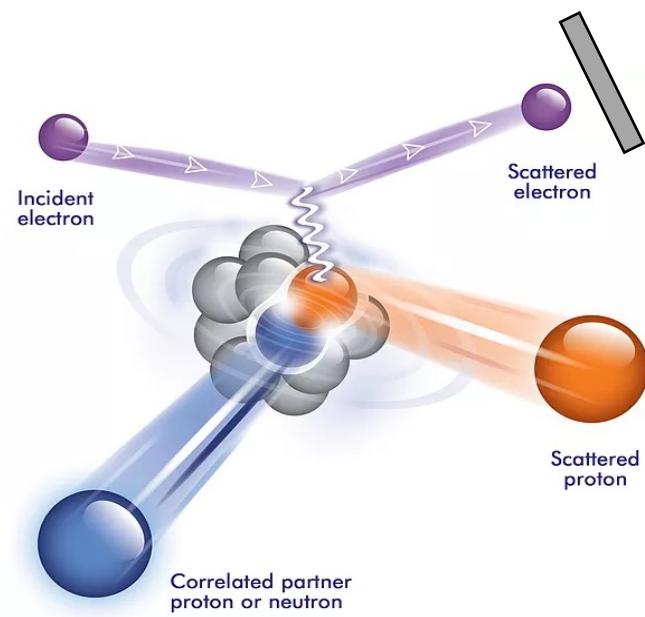


Nuclear Short-Range Correlations

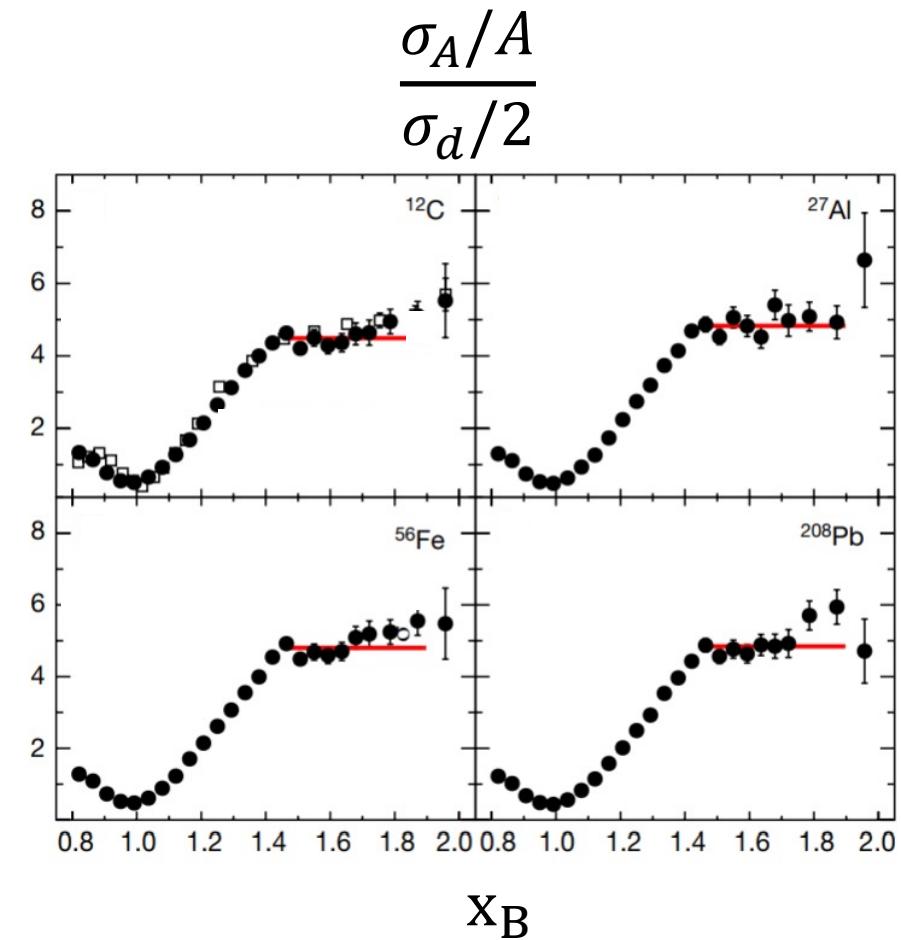
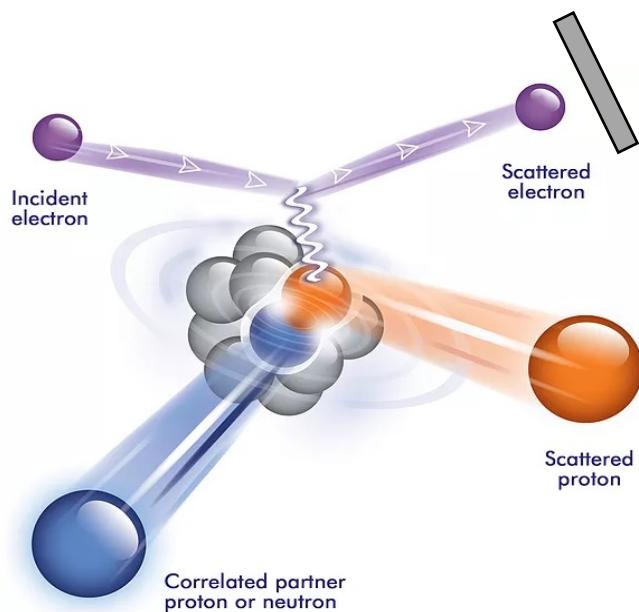
- Pairs with small separation
- High relative momentum compared to k_F
- Significant fraction of the nuclear spectral function
- Correlated with the EMC Effect



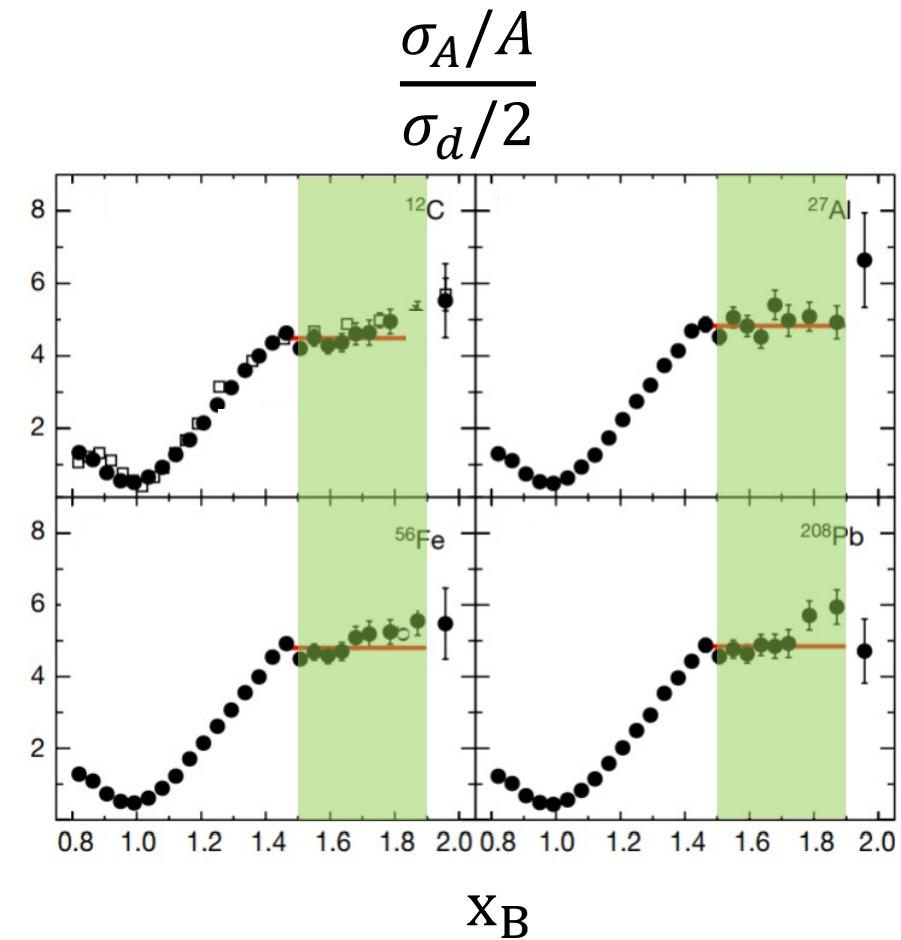
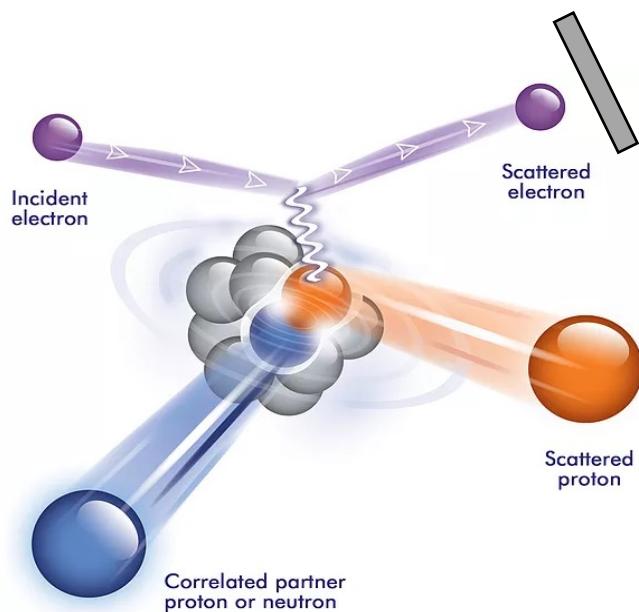
SRC Measurements



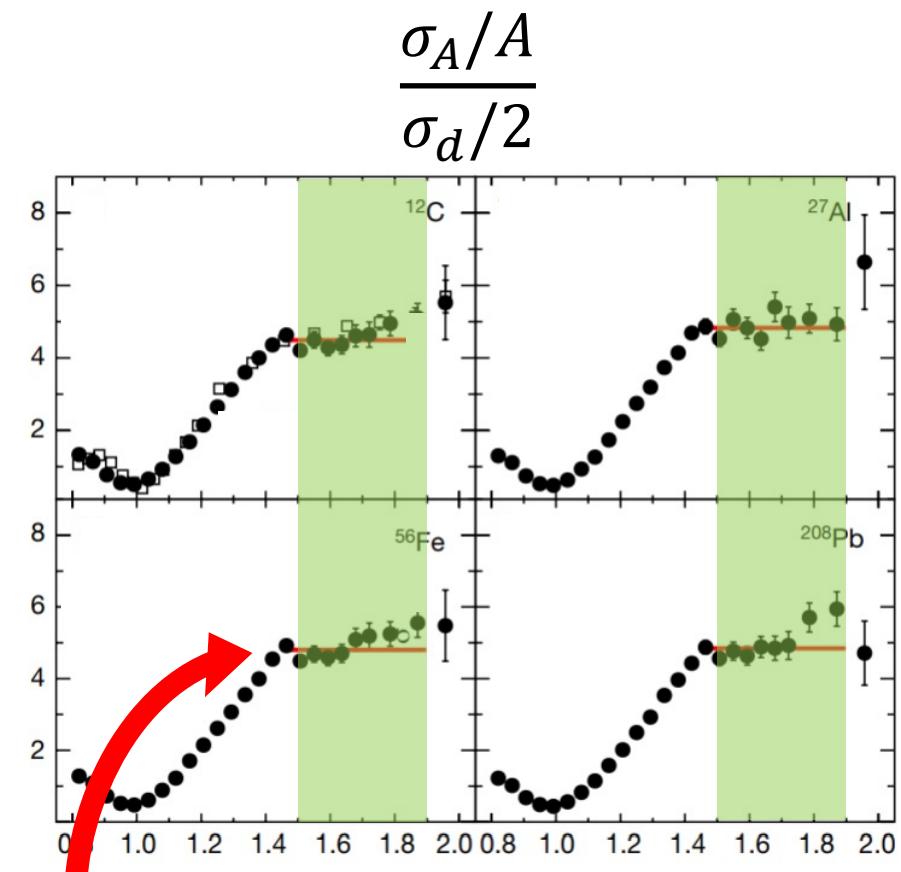
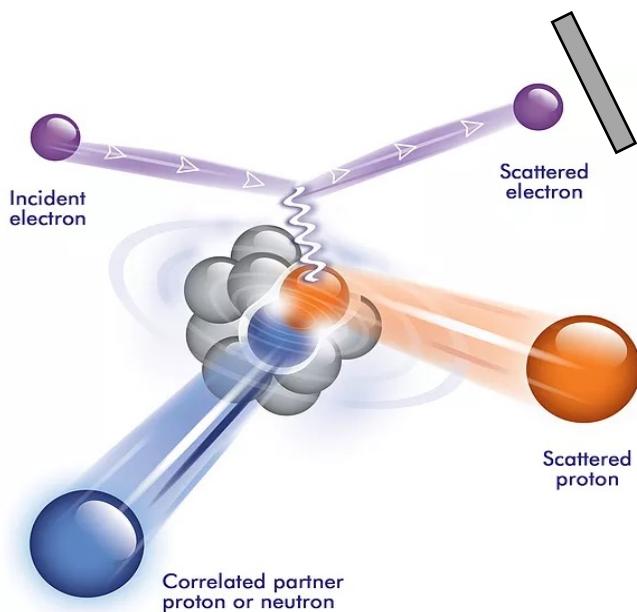
SRC Measurements



SRC Measurements



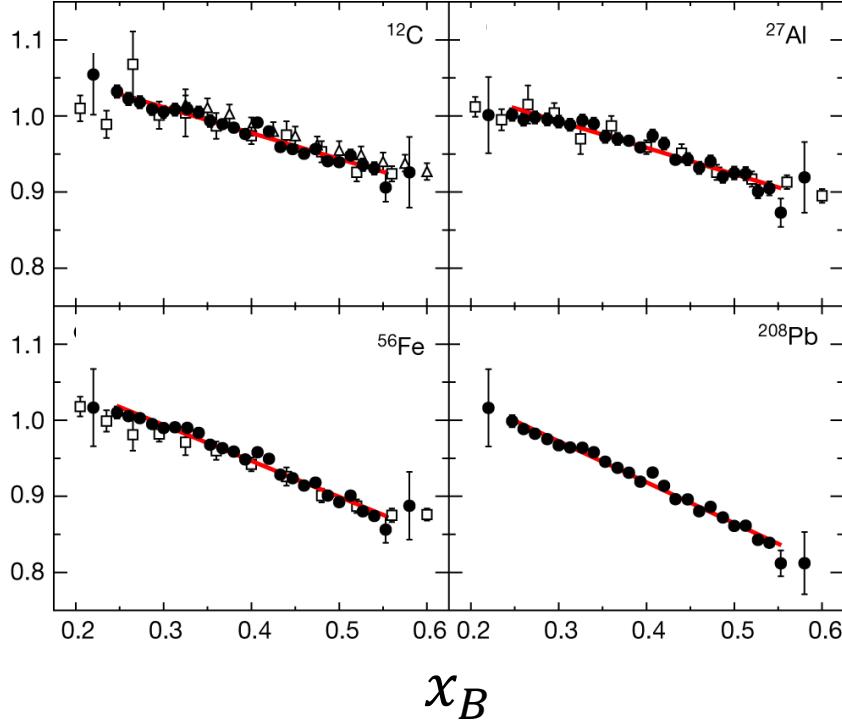
SRC Measurements



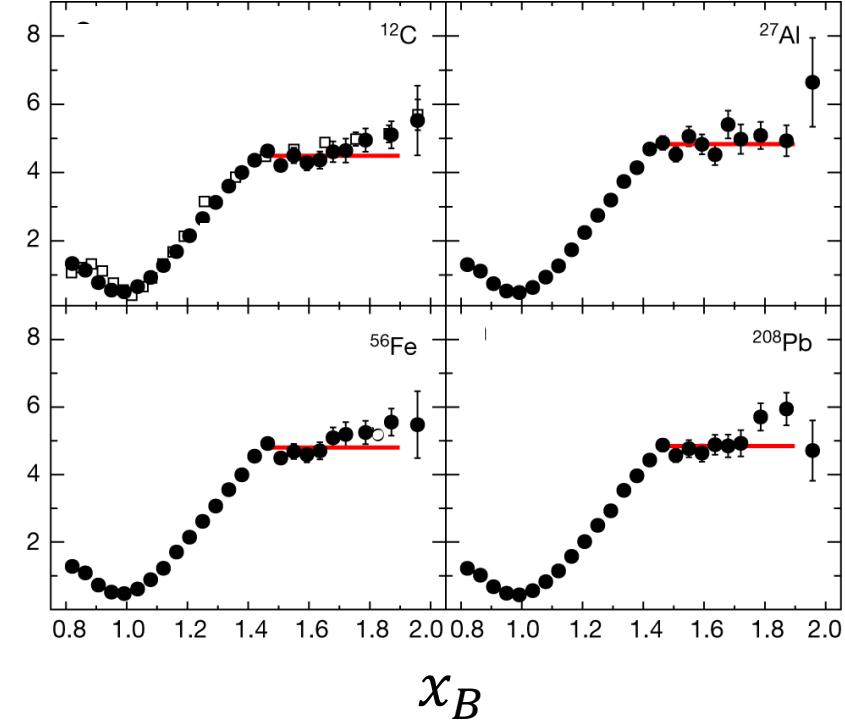
$$a_2 = \frac{\#SRCs \text{ in } A}{\#SRCs \text{ in } d}$$

Comparing SRCs with the EMC Effect

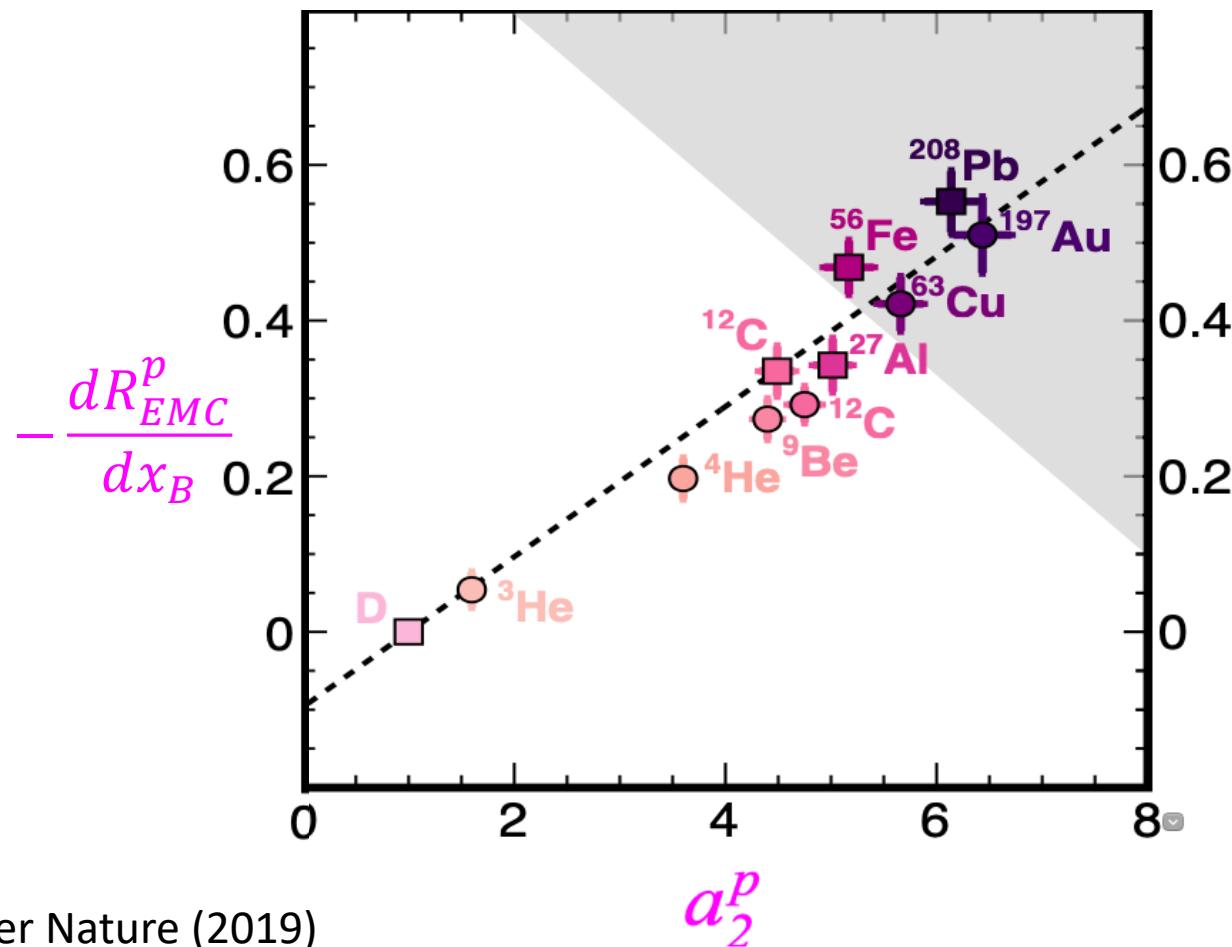
$$\frac{\sigma_A/A}{\sigma_d/2}$$



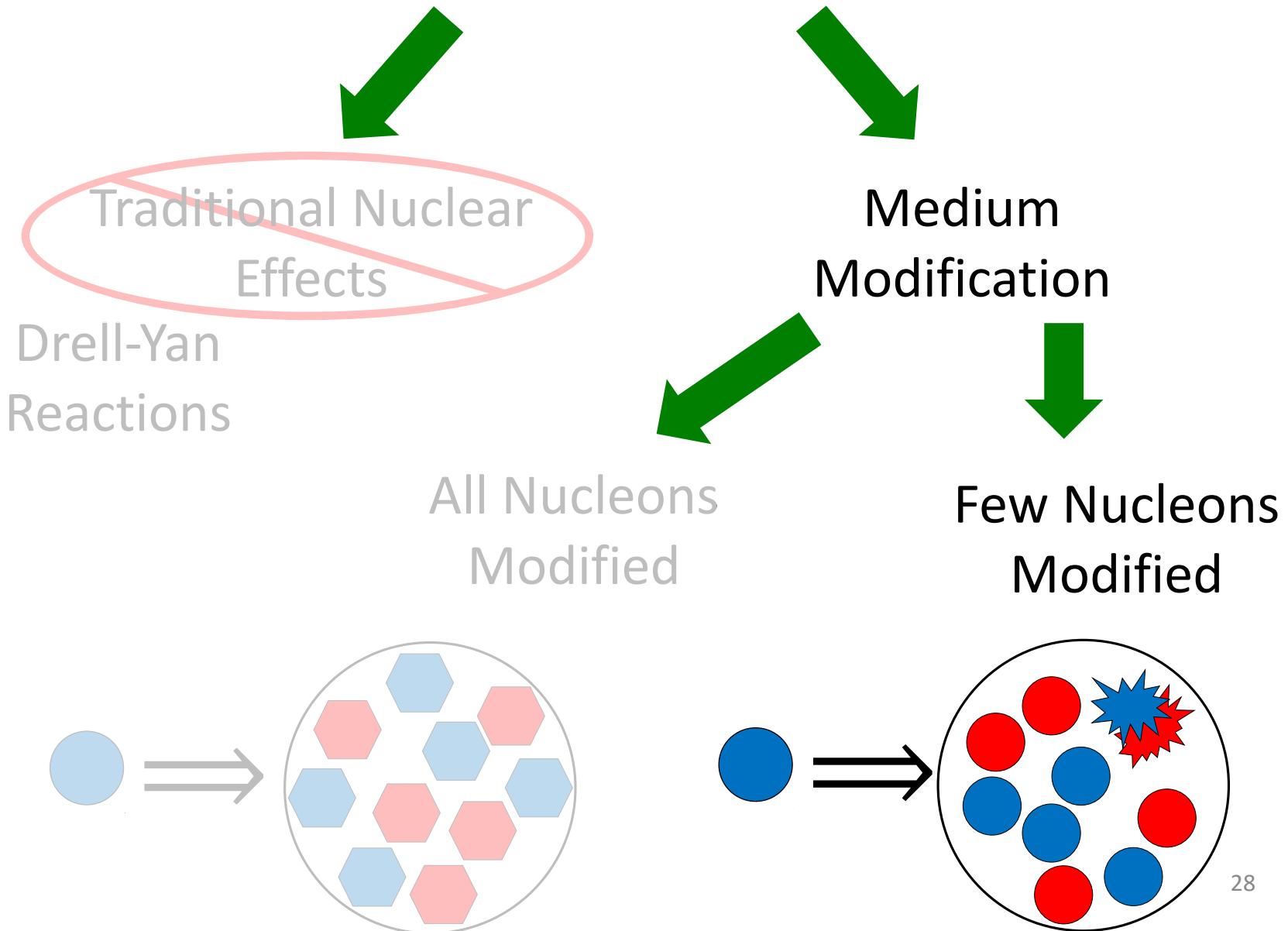
$$\frac{\sigma_A/A}{\sigma_d/2}$$



Comparing SRCs with the EMC Effect

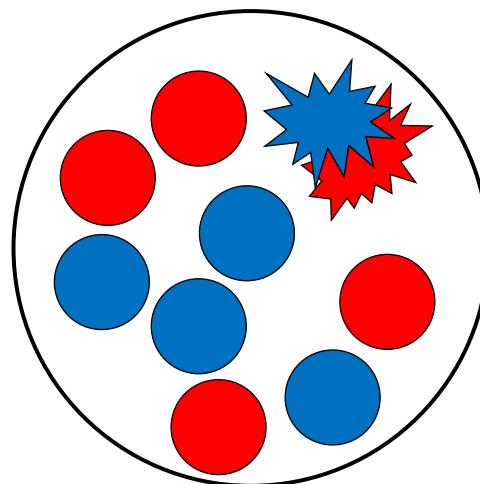


Cause of the EMC Effect?



Incorporating SRCs

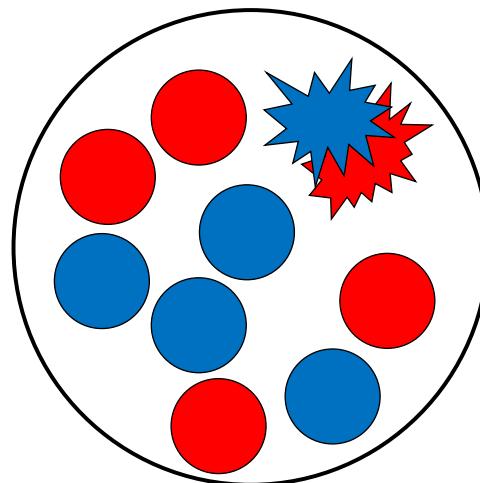
$$f_i^A(x) = \frac{Z}{A} [(1 - C_p^A) f_i^p(x) + C_p^A f_i^{SRC\ p}(x)] + \frac{A - Z}{A} [(1 - C_n^A) f_i^n(x) + C_n^A f_i^{SRC\ n}(x)]$$



Incorporating SRCs

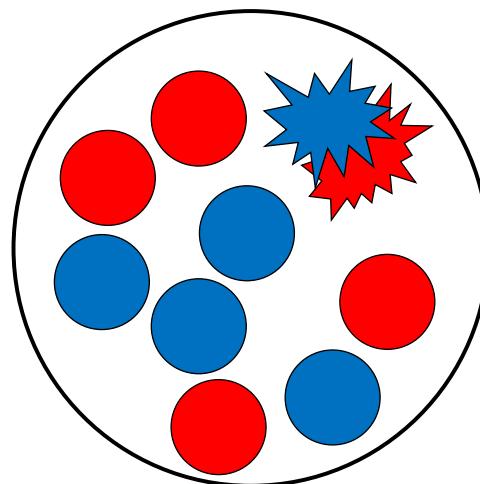
$$f_i^A(x) = \frac{Z}{A} [(1 - C_p^A)f_i^p(x) + C_p^A f_i^{SRC\ p}(x)] +$$

$$\frac{A - Z}{A} [(1 - C_n^A)f_i^n(x) + C_n^A f_i^{SRC\ n}(x)]$$



Incorporating SRCs

$$f_i^A(x) = \frac{Z}{A} \left[(1 - C_p^A) f_i^p(x) + C_p^A f_i^{SRC\ p}(x) \right] + \frac{A - Z}{A} \left[(1 - C_n^A) f_i^n(x) + C_n^A f_i^{SRC\ n}(x) \right]$$

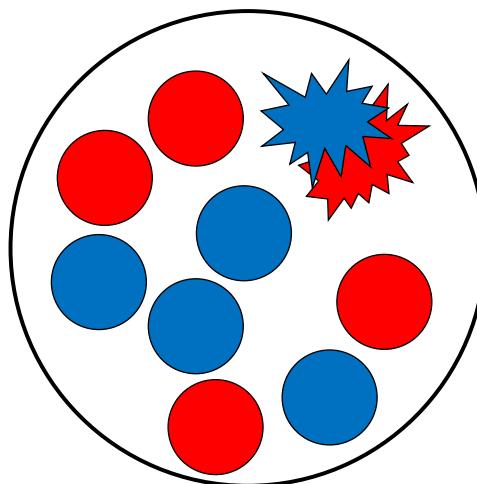


Incorporating SRCs

$$f_i^A(x) = \frac{Z}{A} [(1 - C_p^A) f_i^p(x) + C_p^A f_i^{SRC\ p}(x)] + \frac{A - Z}{A} [(1 - C_n^A) f_i^n(x) + C_n^A f_i^{SRC\ n}(x)]$$

Independent of A

$$f_i^p(x) \quad f_i^{SRC\ p}(x)$$
$$f_i^n(x) \quad f_i^{SRC\ n}(x)$$



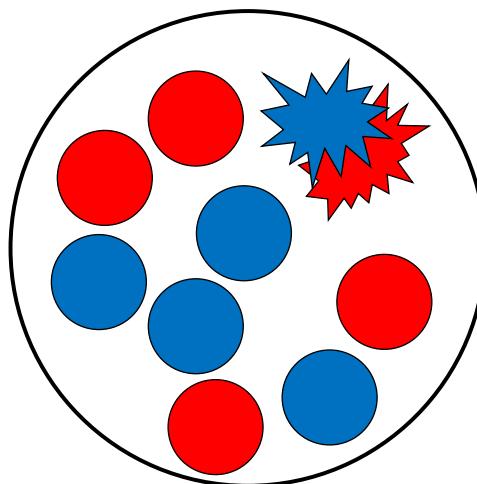
Incorporating SRCs

Free Nucleons SRC Nucleons

$$f_i^A(x) = \frac{Z}{A} [(1 - C_p^A) f_i^p(x) + C_p^A f_i^{SRC\ p}(x)] +$$
$$\frac{A - Z}{A} [(1 - C_n^A) f_i^n(x) + C_n^A f_i^{SRC\ n}(x)]$$

Independent of A

$$f_i^p(x)$$
$$f_i^{SRC\ p}(x)$$
$$f_i^n(x)$$
$$f_i^{SRC\ n}(x)$$

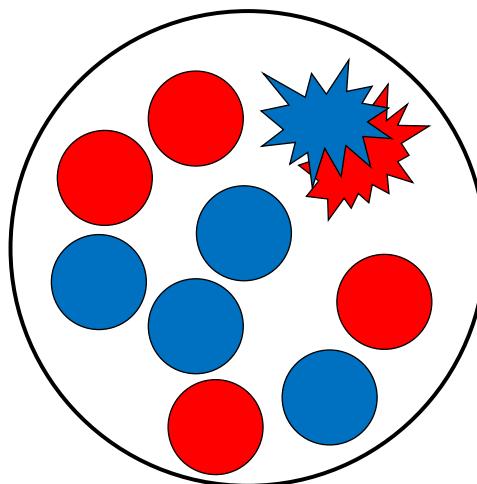


Incorporating SRCs

$$f_i^A(x) = \frac{Z}{A} [(1 - C_p^A) f_i^p(x) + C_p^A f_i^{SRC\ p}(x)] + \frac{A - Z}{A} [(1 - C_n^A) f_i^n(x) + C_n^A f_i^{SRC\ n}(x)]$$

Independent of A

$$f_i^p(x), f_i^{SRC\ p}(x)$$
$$f_i^n(x), f_i^{SRC\ n}(x)$$



Depend on A

SRC Abundancies
 C_p^A, C_n^A

Incorporating SRCs

$$f_i^A(x) = \frac{Z}{A} \left[(1 - C_p^A) f_i^p(x) + C_p^A f_i^{SRC\ p}(x) \right] + \frac{A - Z}{A} \left[(1 - C_n^A) f_i^n(x) + C_n^A f_i^{SRC\ n}(x) \right]$$

Free Nucleons SRC Nucleons

Incorporating SRCs

$$f_i^A(x) = \frac{Z}{A} [(1 - C_p^A) f_i^p(x) + C_p^A f_i^{SRC\ p}(x)] + \frac{A - Z}{A} [(1 - C_n^A) f_i^n(x) + C_n^A f_i^{SRC\ n}(x)]$$

New Fit:

- $f_i^p(x)$ comes from nCTEQ15 free proton
- $f_i^{SRC\ p}(x)$ is fit without A dependence:

$$x f_i^{SRC\ p}(x) = c_0 x^{c_1} (1 - x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5}$$

- SRC Abundancies (C_p^A, C_n^A) are fit for each nucleus
- $f_i^n(x)$ and $f_i^{SRC\ n}(x)$ are the isospin symmetric partners to the proton PDFs

Details of Fit:

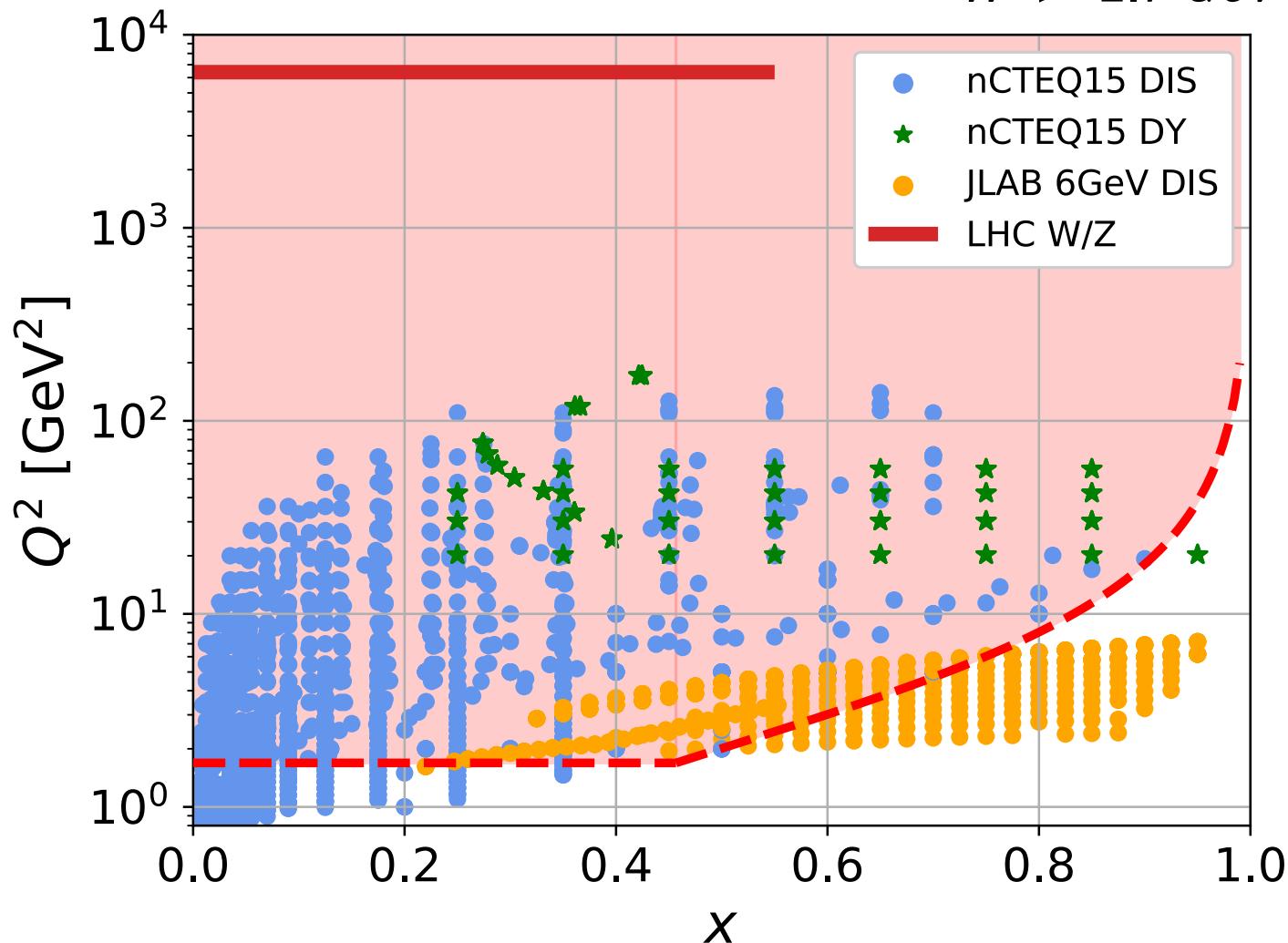
1. Minimize χ^2
2. Cut out non-DIS kinematics
3. Satisfy Sum Rules
4. Full Theoretical Calculations
5. DGLAP Evolve PDFs
6. All PDFs are defined for $x \in (0,1)$

$$\int_0^1 dx x f_i^A(x, Q) = 1 \quad \int_0^1 dx f_{u_\nu}^A(x, Q) = \frac{A + Z}{A} \quad \int_0^1 dx f_{d_\nu}^A(x, Q) = \frac{A + N}{A}$$

$$F_2^{A,Z}(x, Q) = \sum_i C_i(x, Q) \otimes f_i^{A,Z}(x, Q)$$

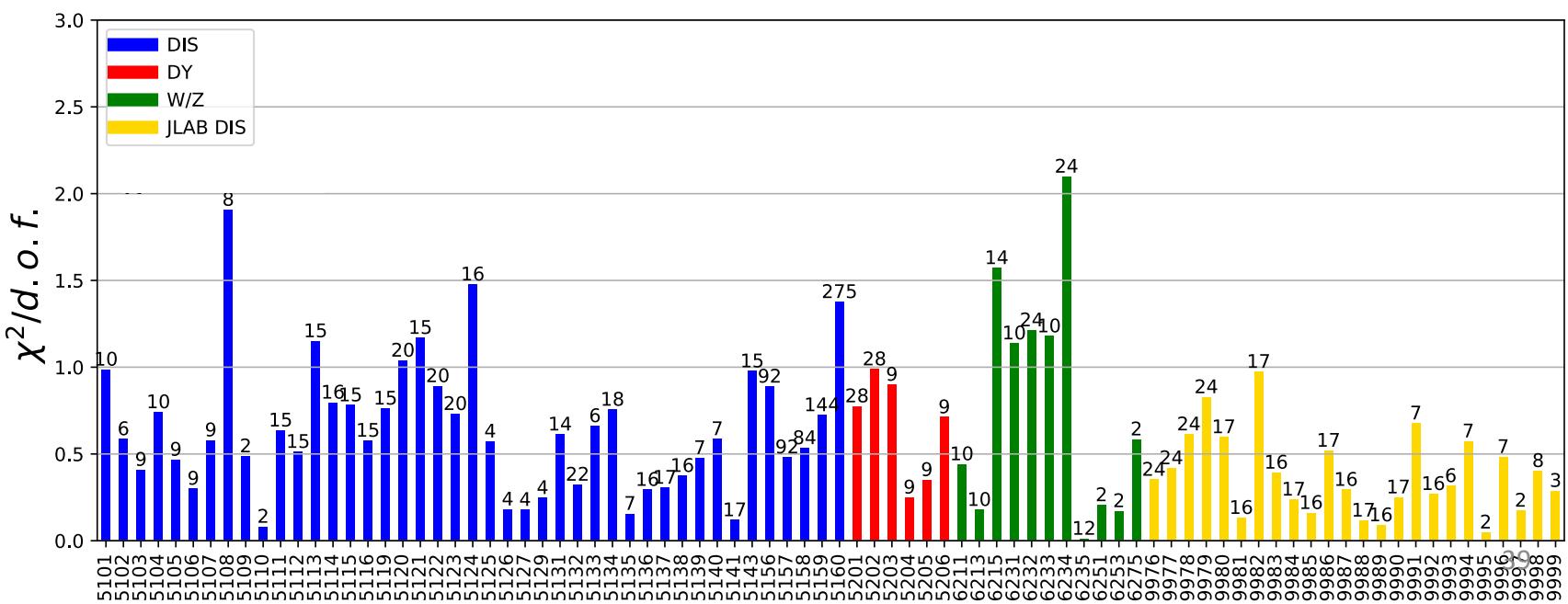
Data to Fit:

$Q > 1.3 \text{ GeV}$
 $W > 1.7 \text{ GeV}$

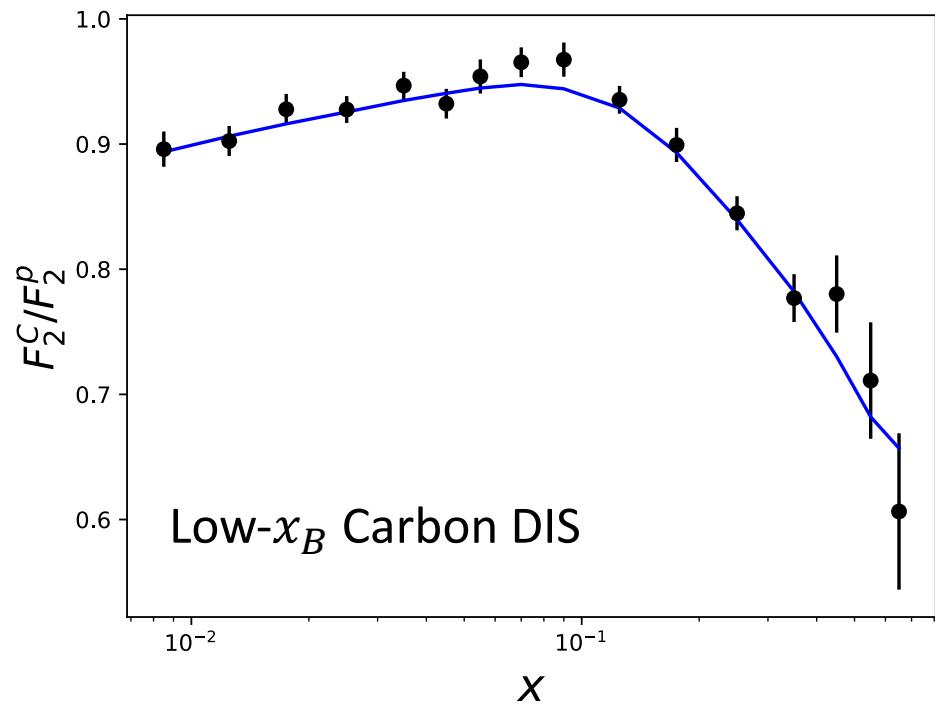
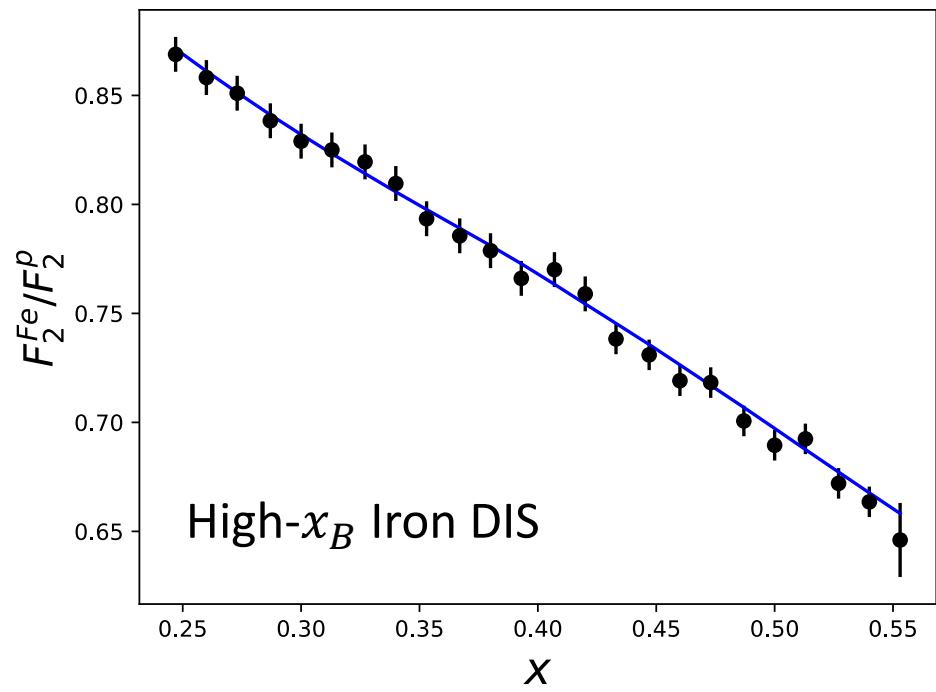


Fit Result:

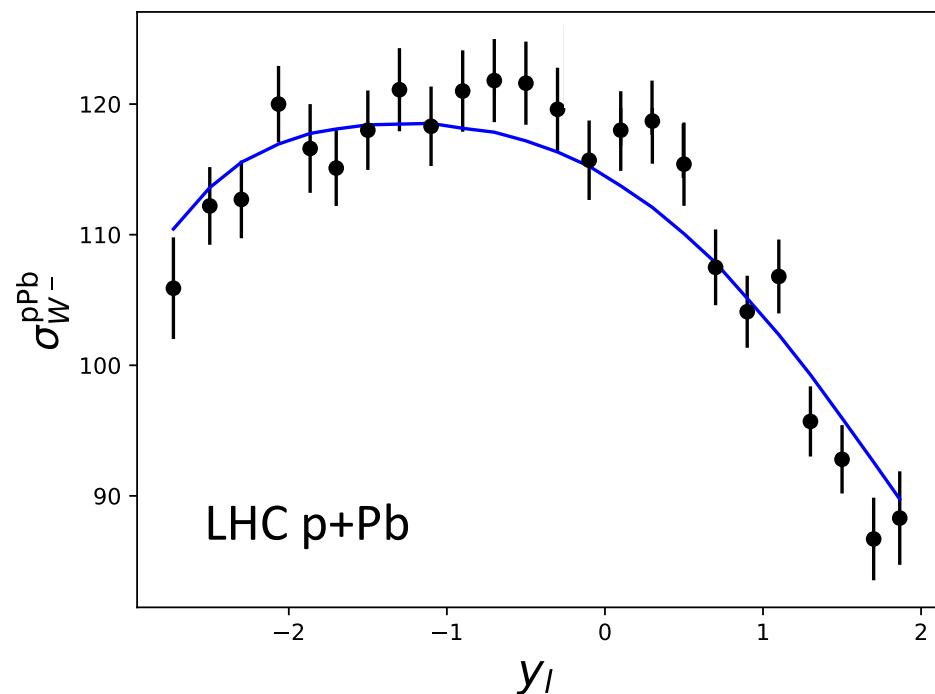
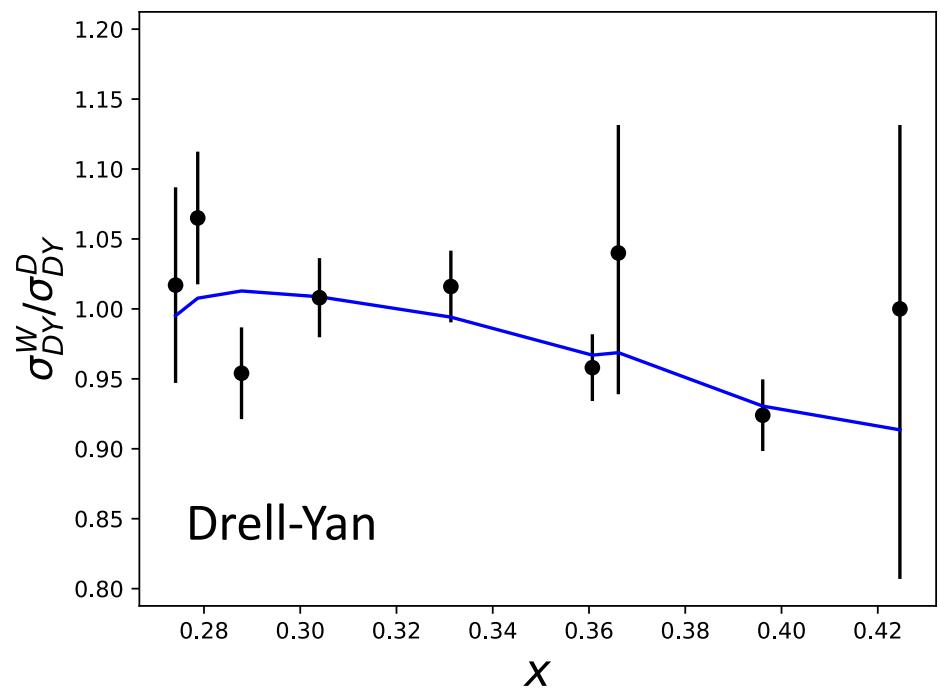
χ^2/N_{data}	DIS	DY	W/Z	JLab	χ^2_{tot}	$\frac{\chi^2_{\text{tot}}}{N_{\text{DOF}}}$
Mean-Field	0.85	0.97	0.88	0.72	1408	0.85
SRC	0.84	0.75	1.11	0.41	1300	0.80



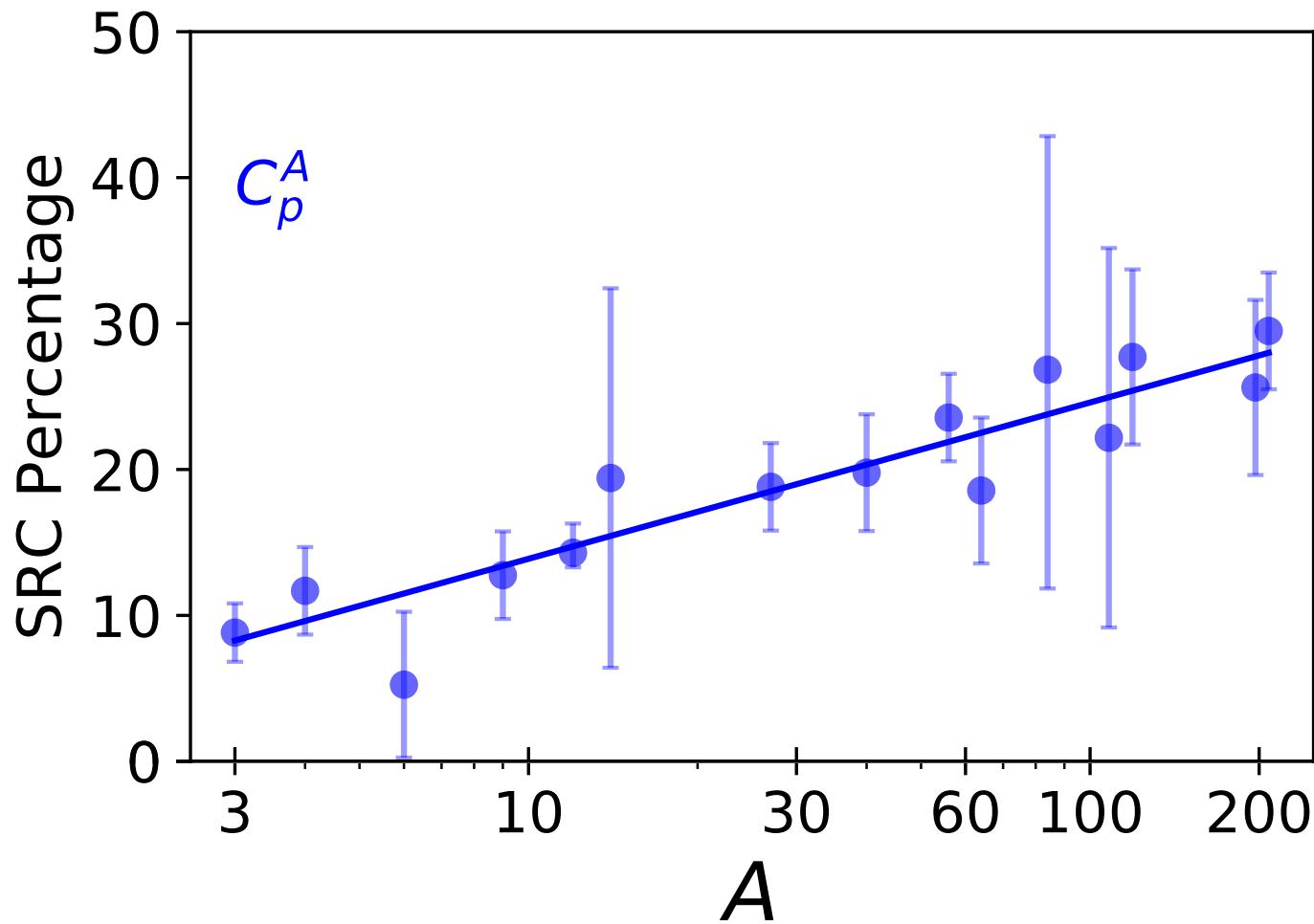
Fit Over Wide x_B Range



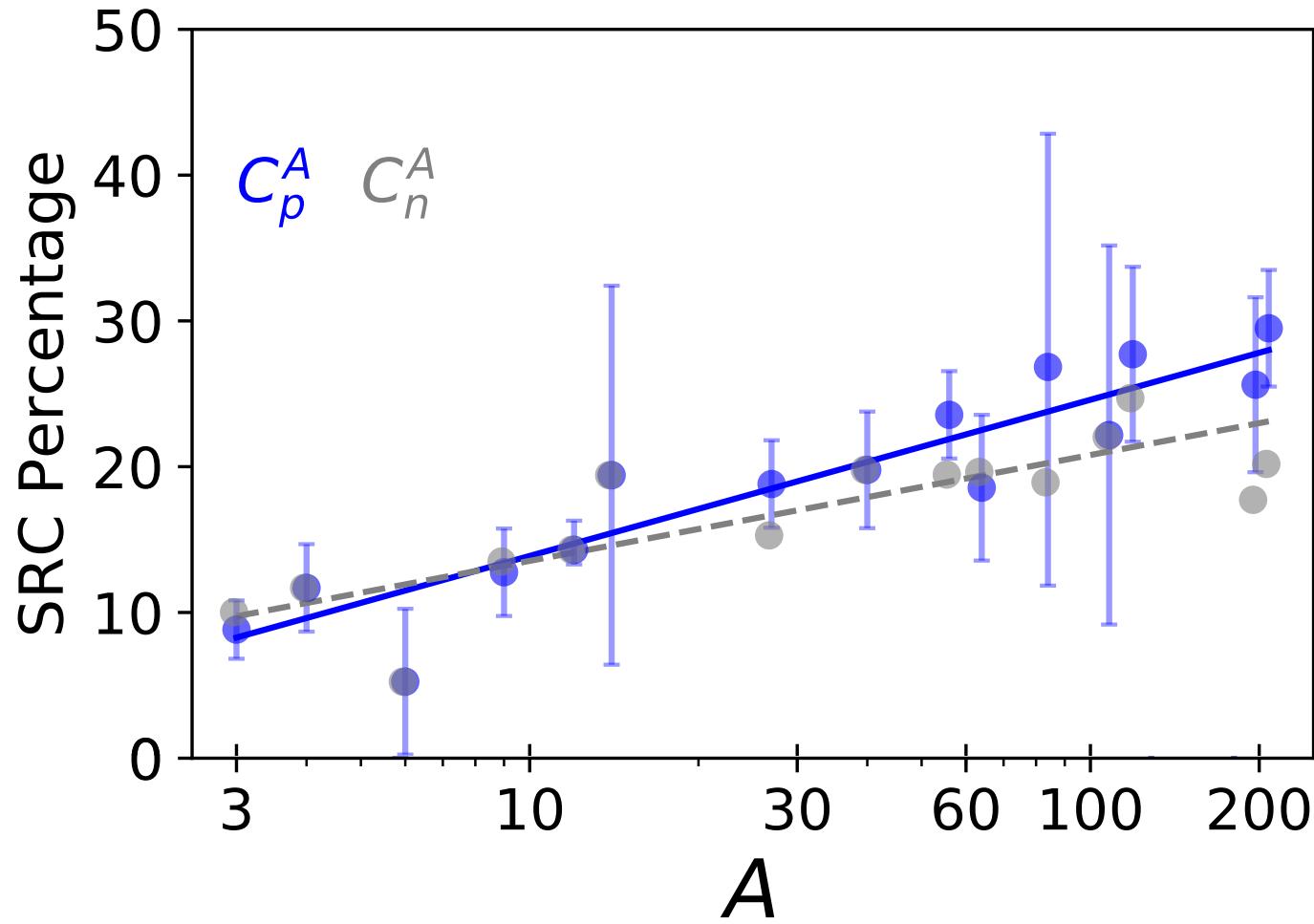
Drell-Yan and W Production are Well Described



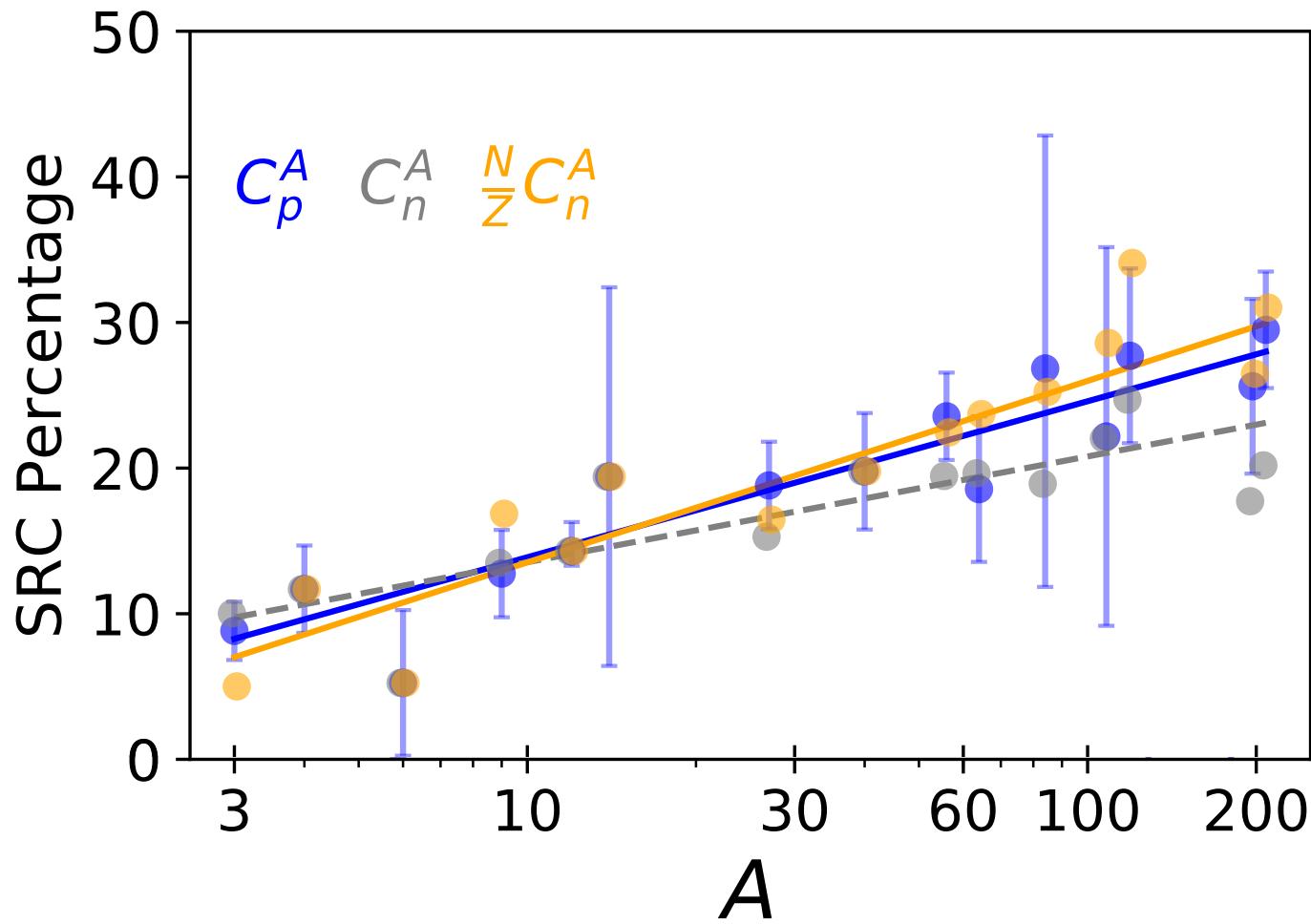
SRC Abundancy



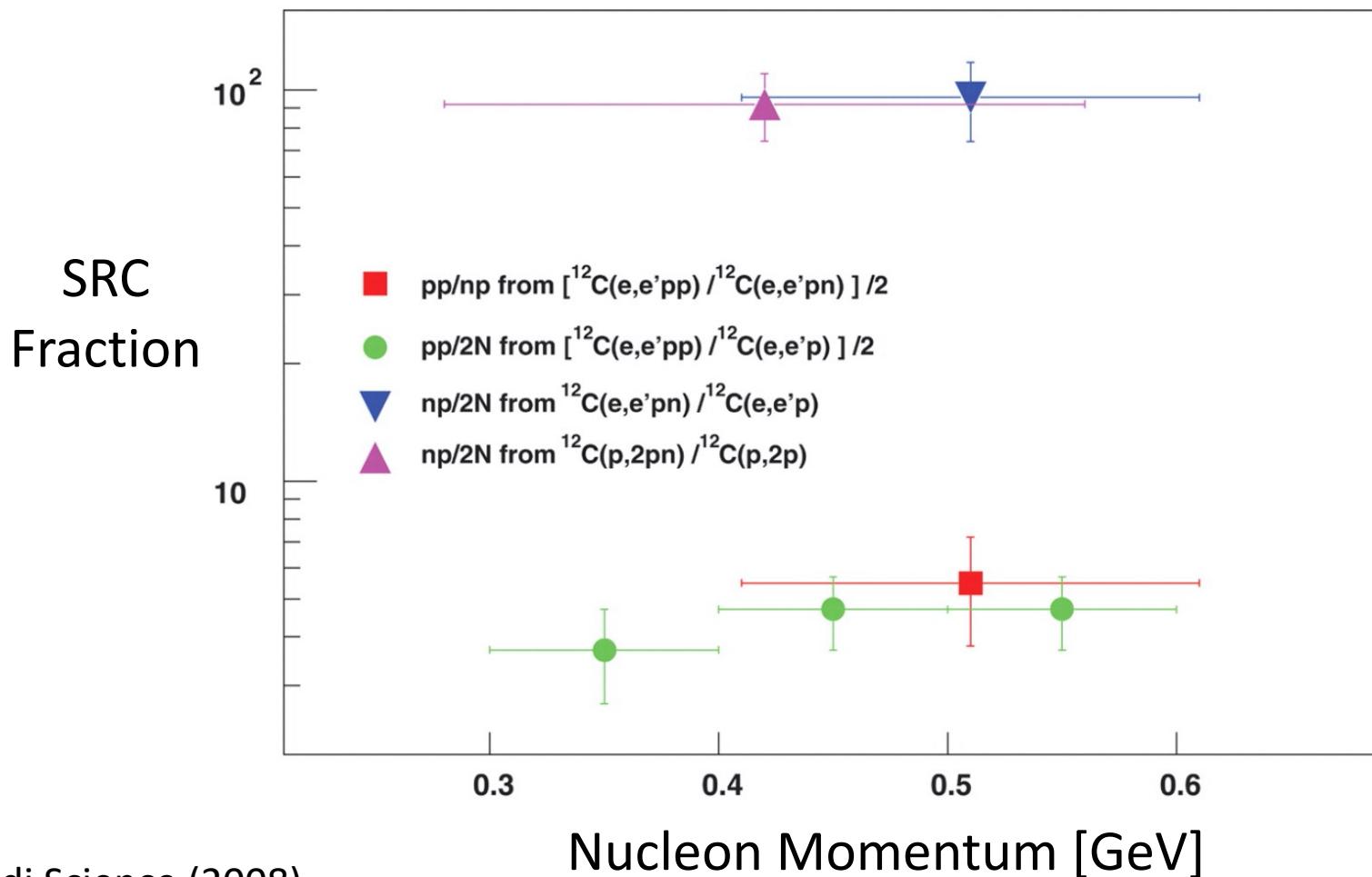
SRC Abundancy



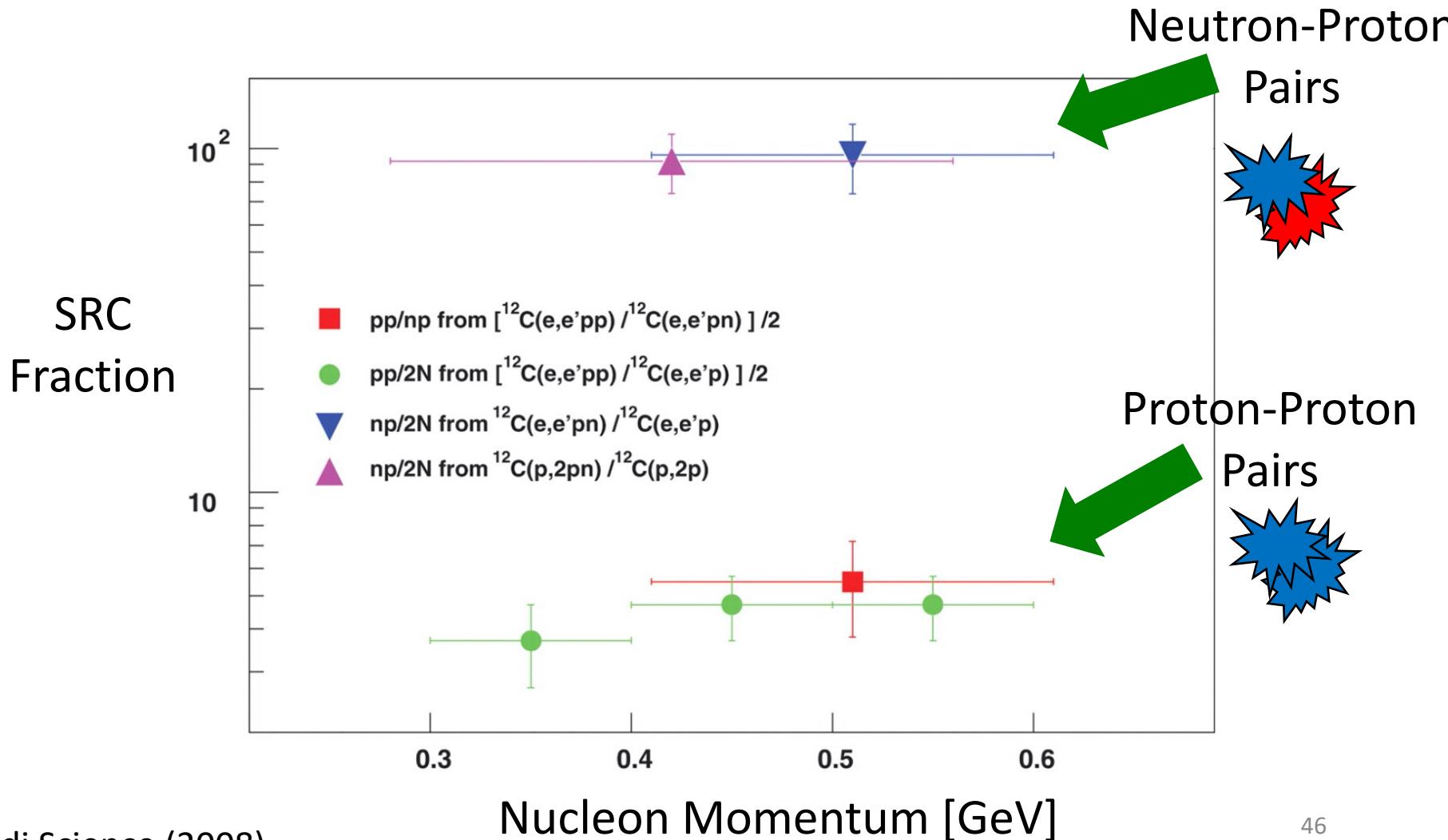
SRC Abundancy



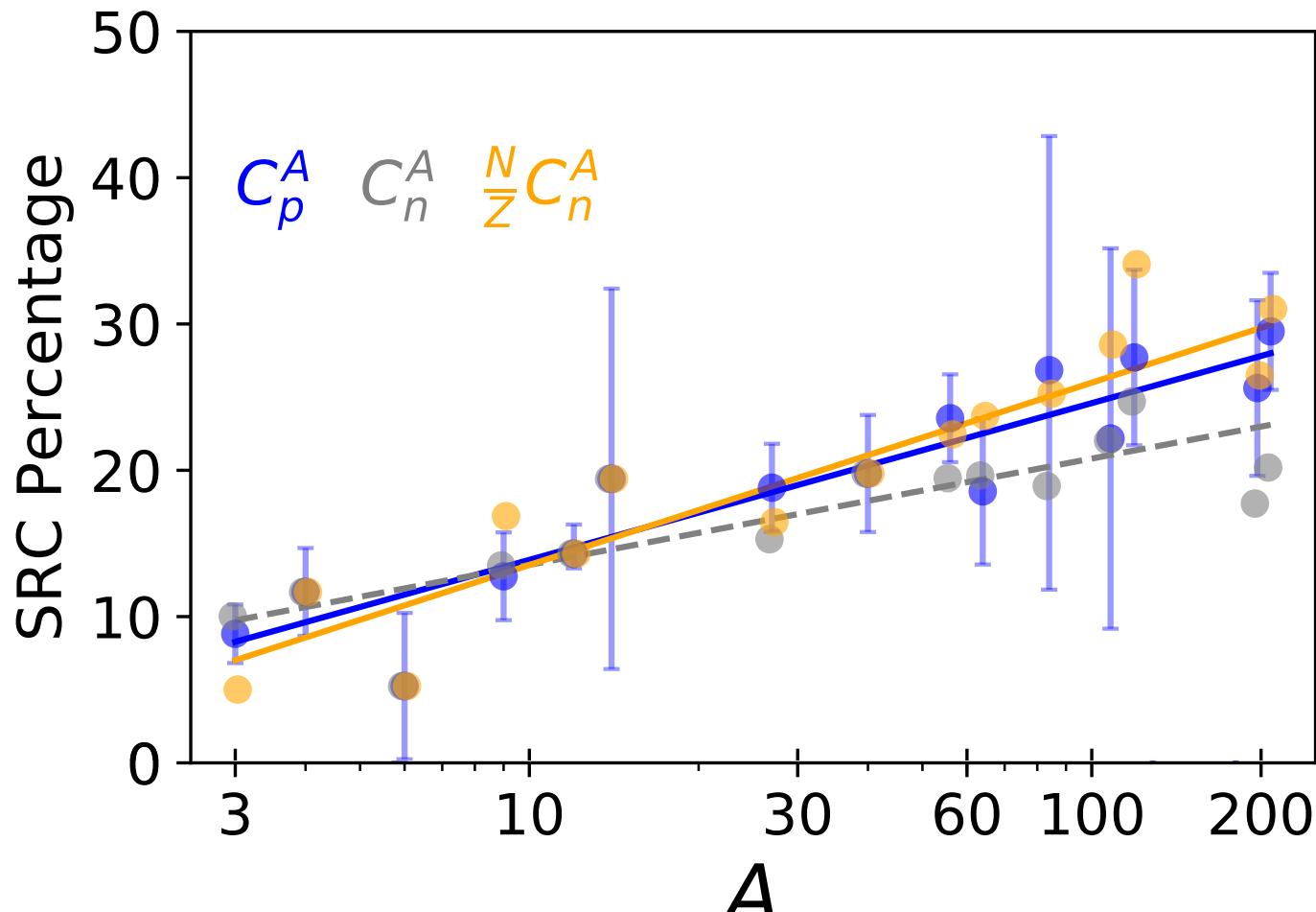
Neutron-Proton Pairs Dominate



Neutron-Proton Pairs Dominate

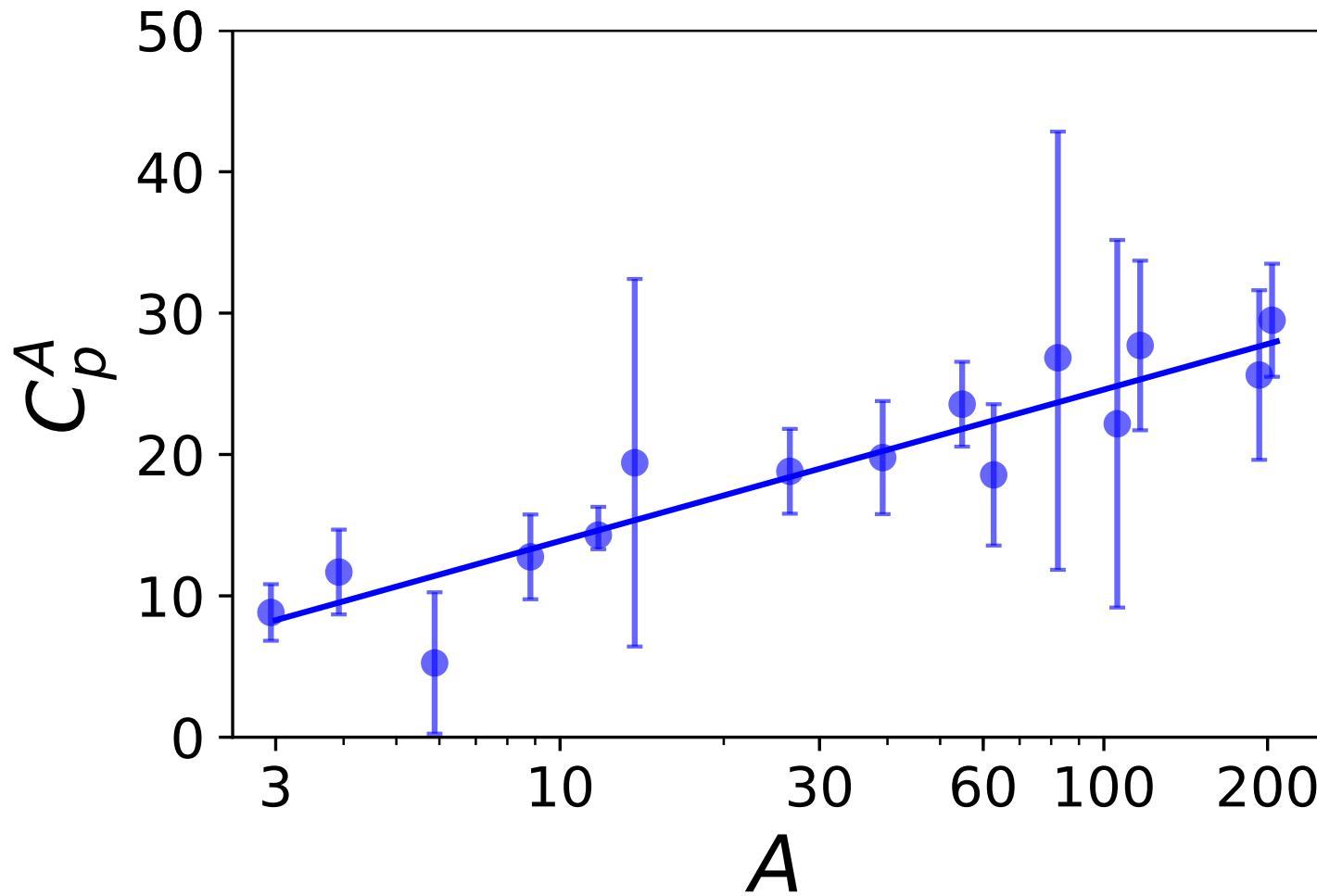


Fit Results in pn-dominance

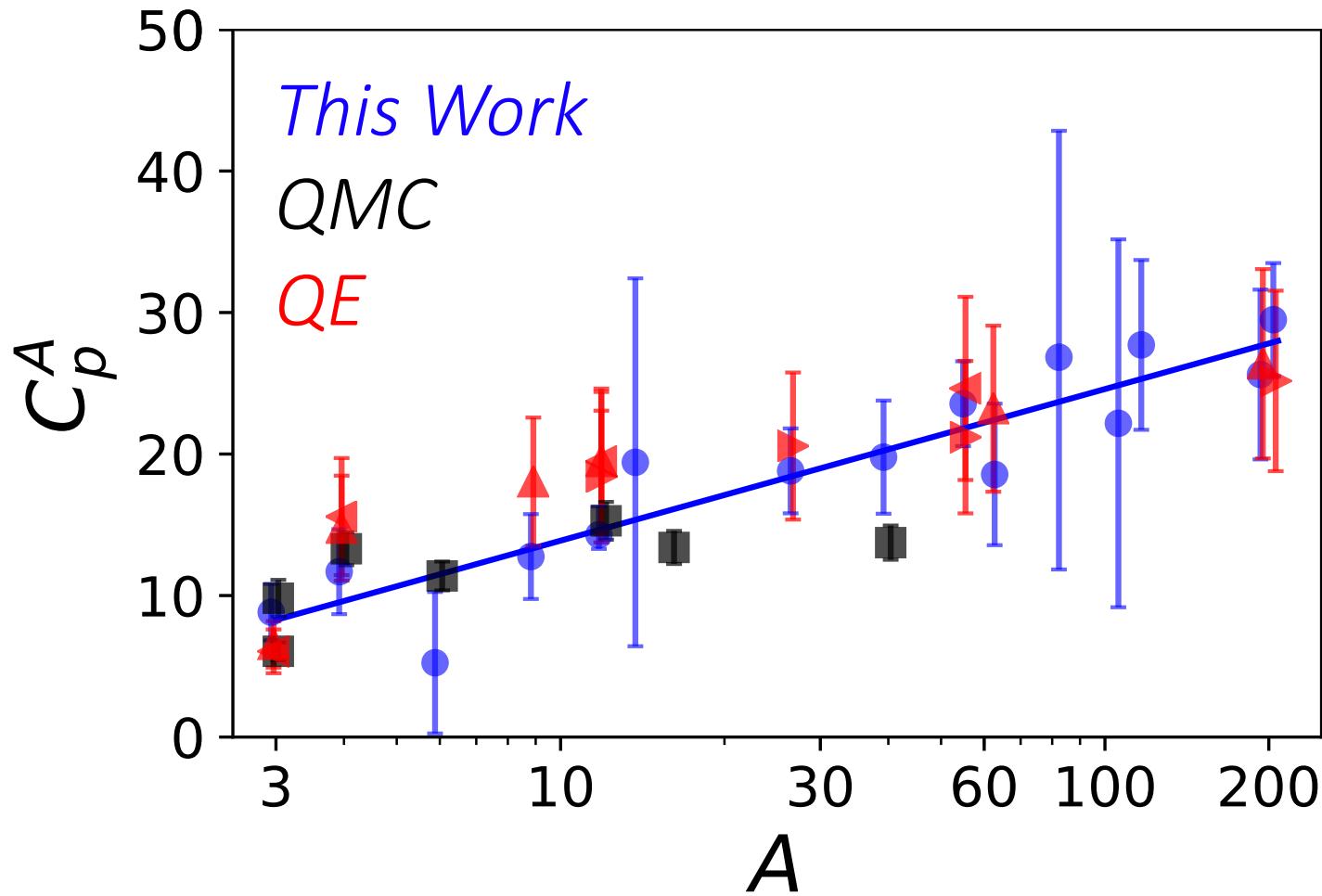


#SRC Protons = #SRC Neutrons

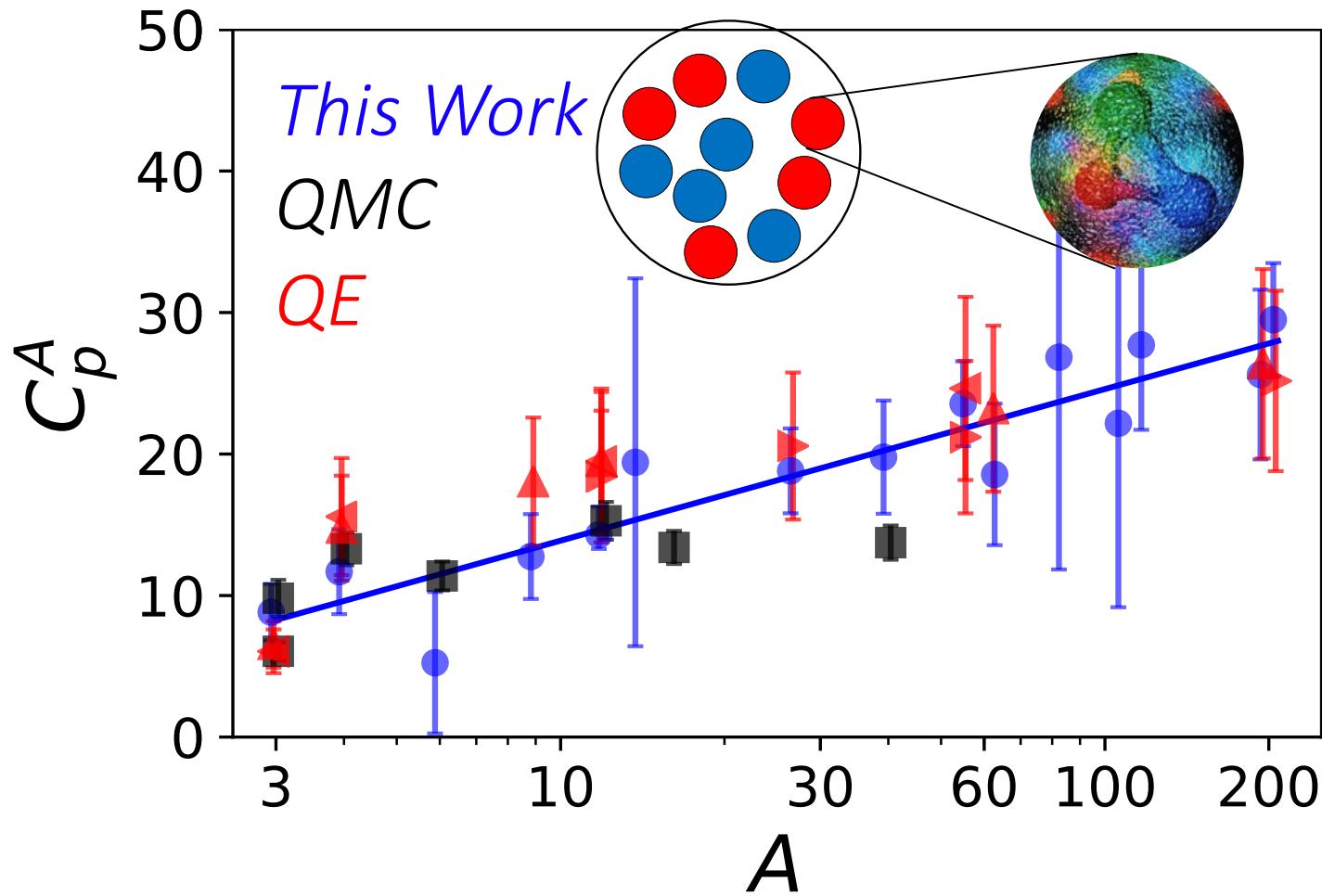
How Many SRCs do we expect?



Nuclear Physics Extracted from Parton Measurements

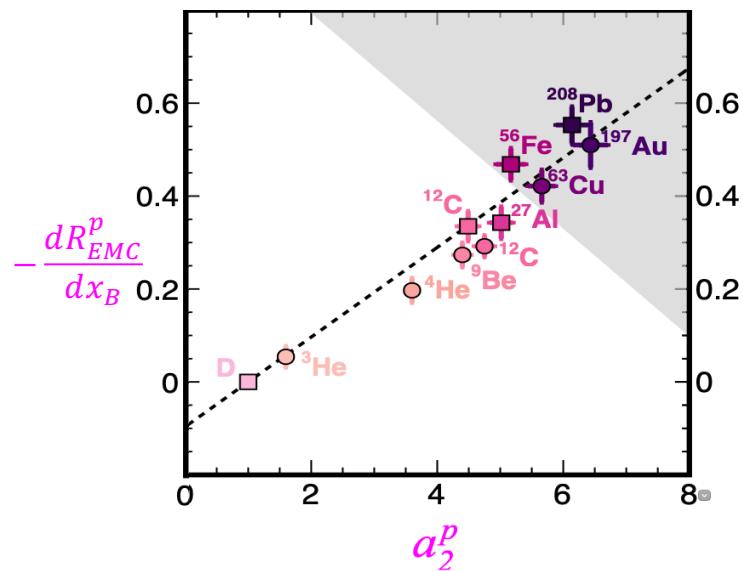


Nuclear Physics Extracted from Parton Measurements



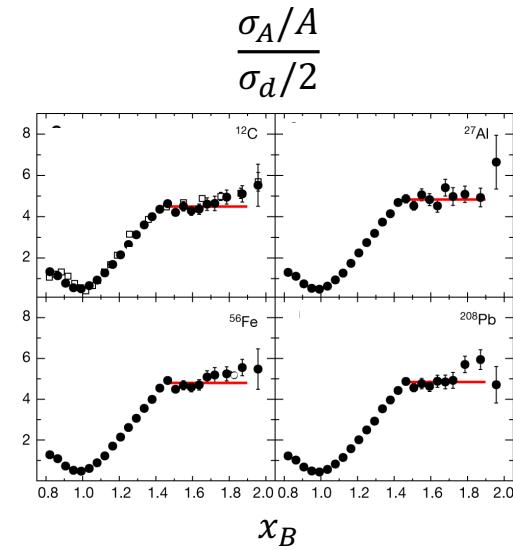
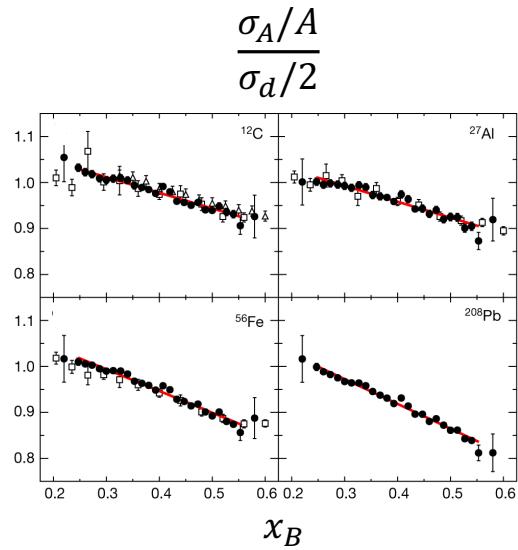
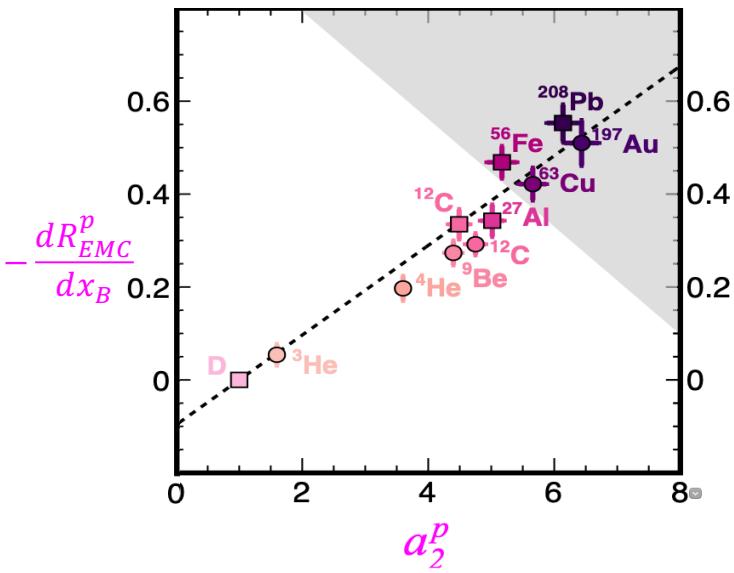
Beyond the SRC-EMC Relation

SRC \Leftrightarrow EMC



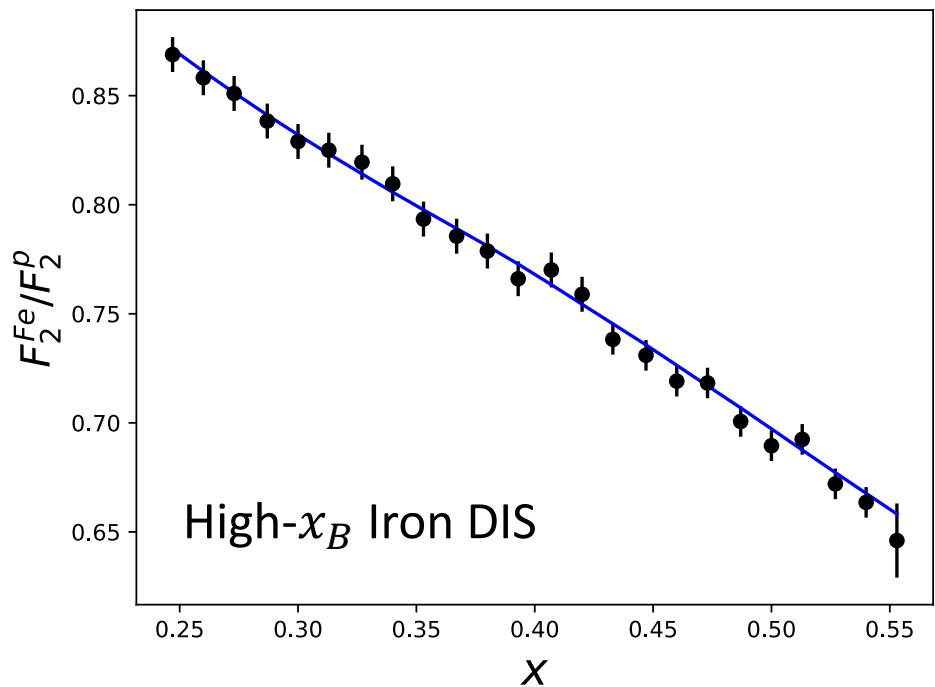
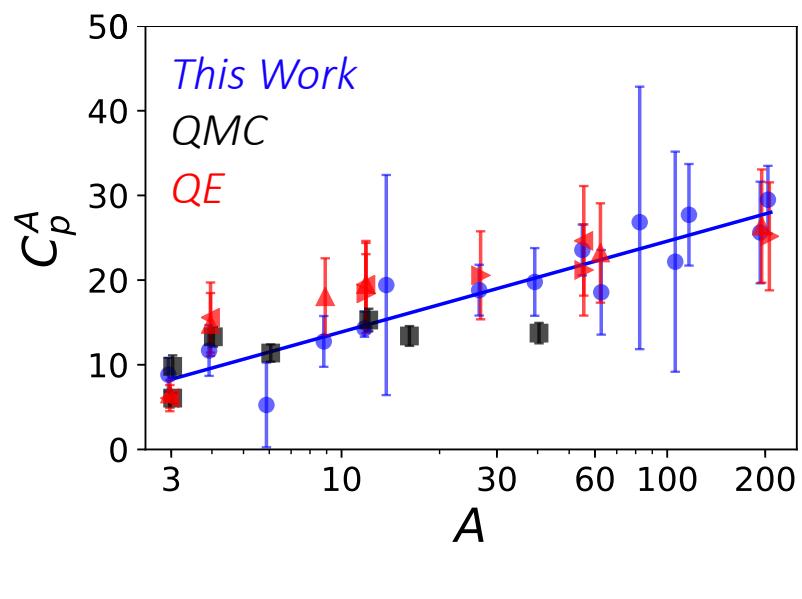
Beyond the SRC-EMC Relation

$\text{SRC} \Leftrightarrow \text{EMC}$



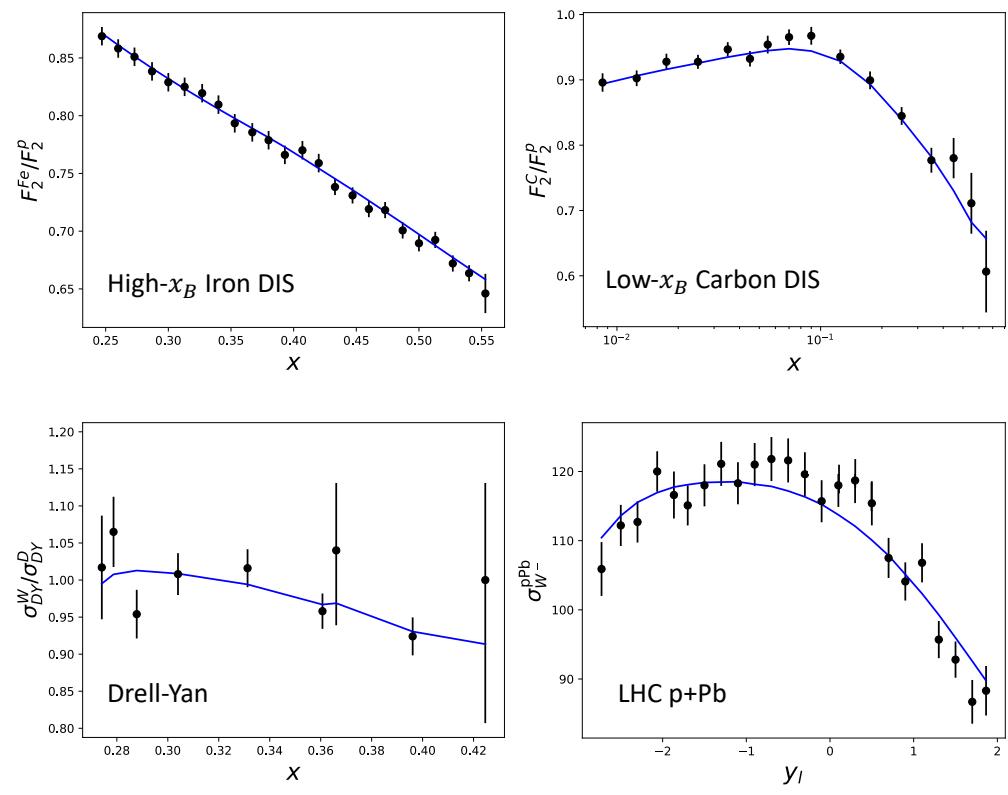
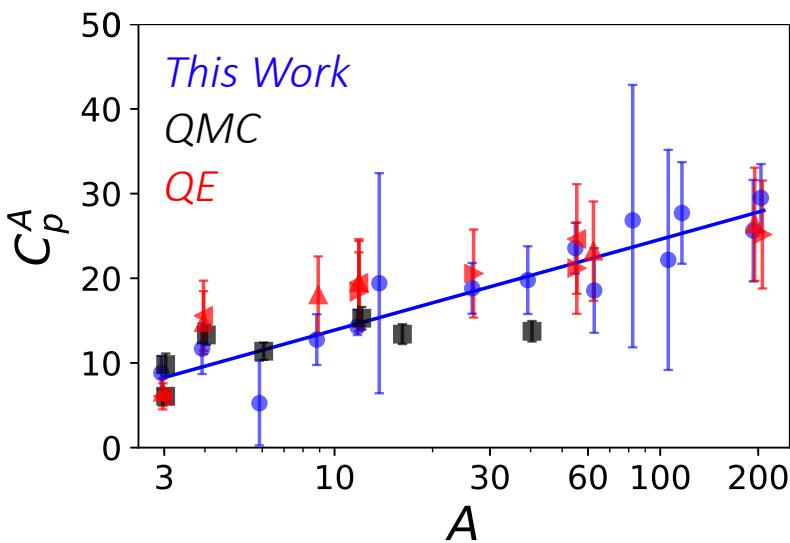
Beyond the SRC-EMC Relation

SRC \Leftrightarrow EMC



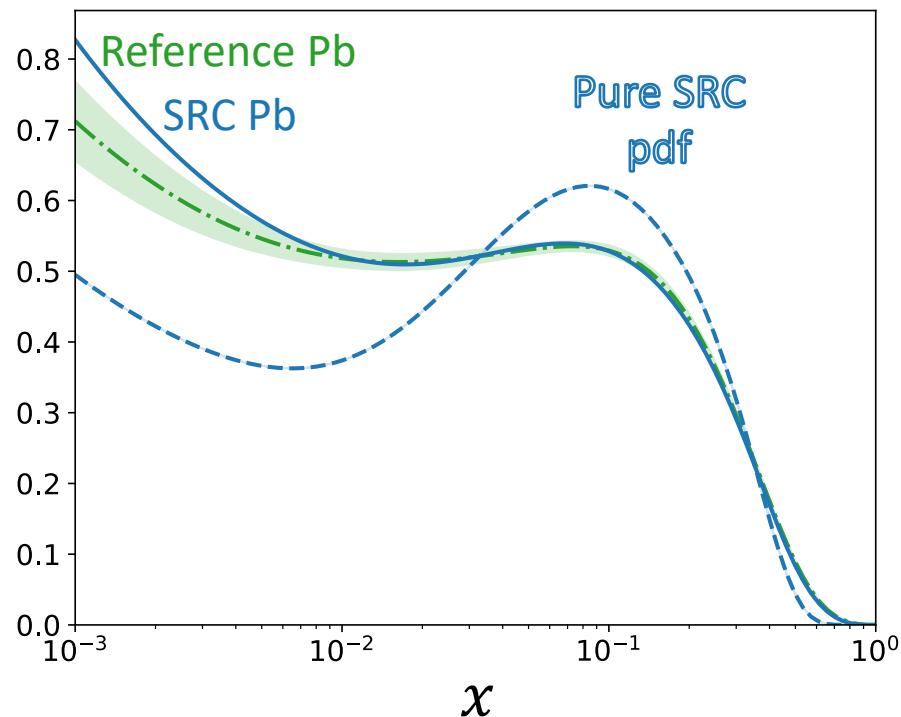
Beyond the SRC-EMC Relation

EMC
 Shadowing
 SRC \leftrightarrow Anti-shadowing
 Drell-Yan
 W/Z

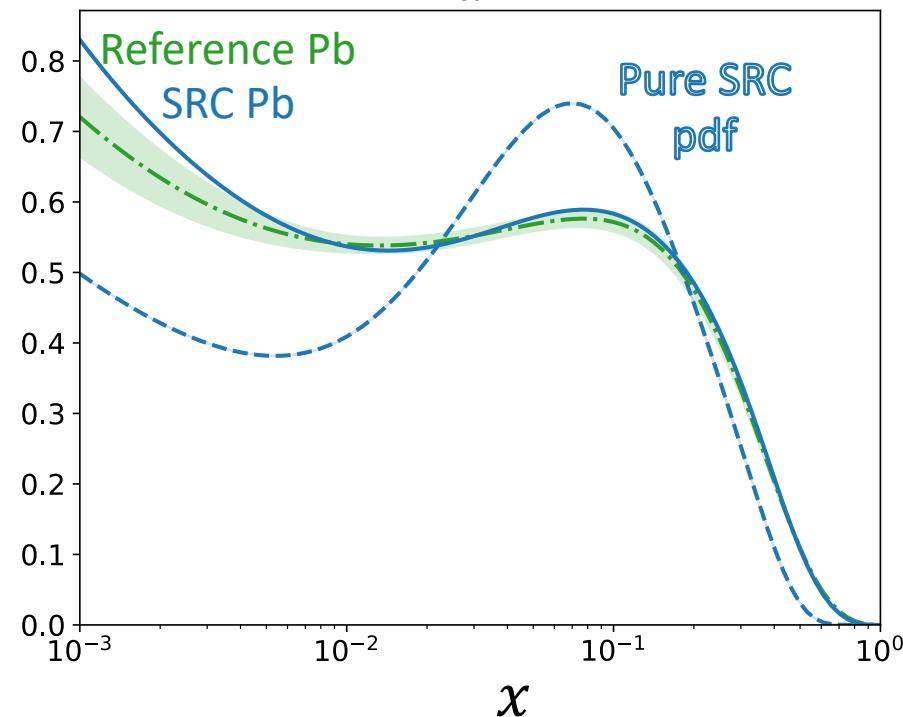


Nuclear PDF and SRC PDF

$xf_u^p(x)$

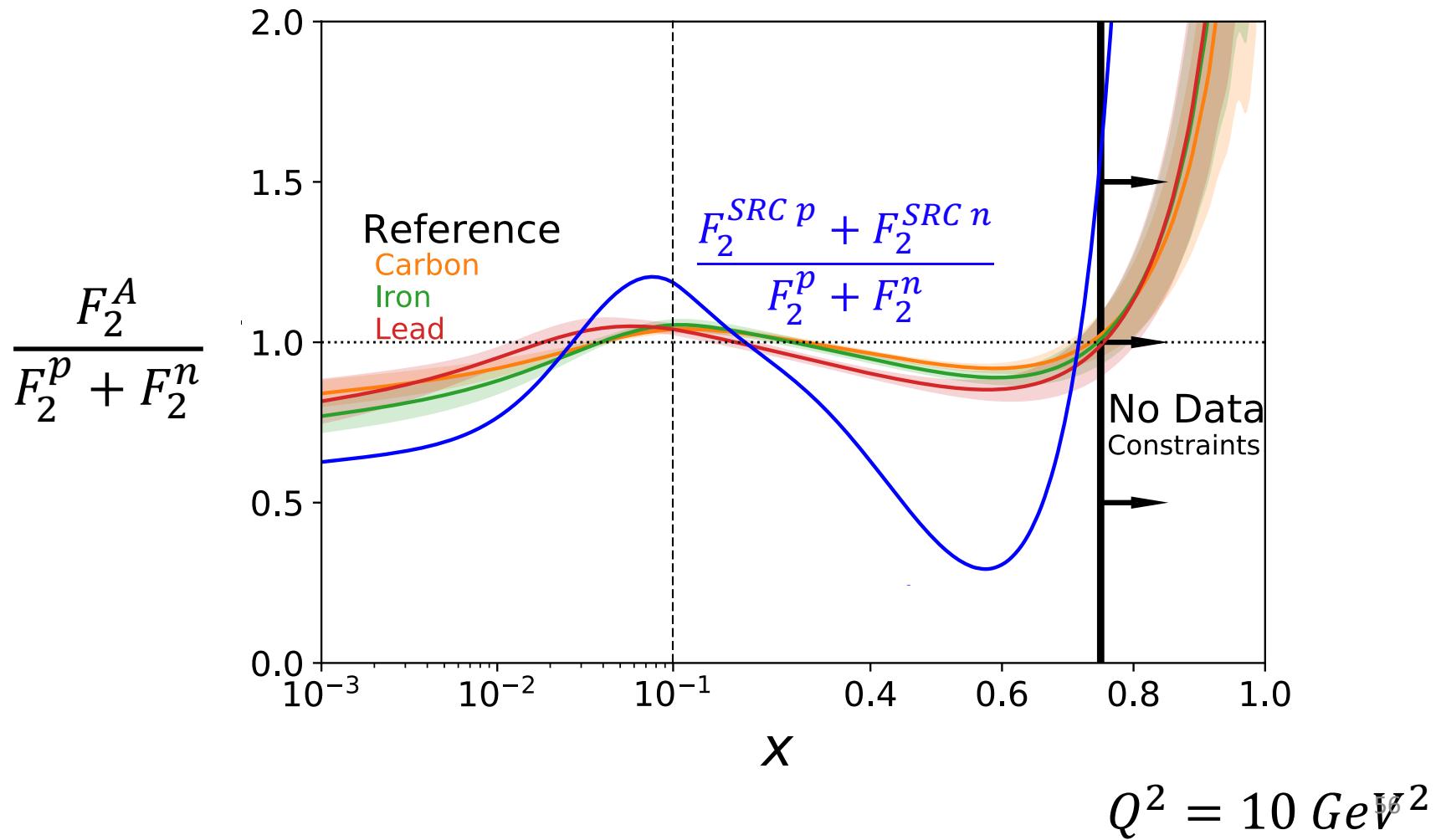


$xf_d^p(x)$



$$Q^2 = 10 \text{ GeV}^2$$

Structure of SRC Nucleons



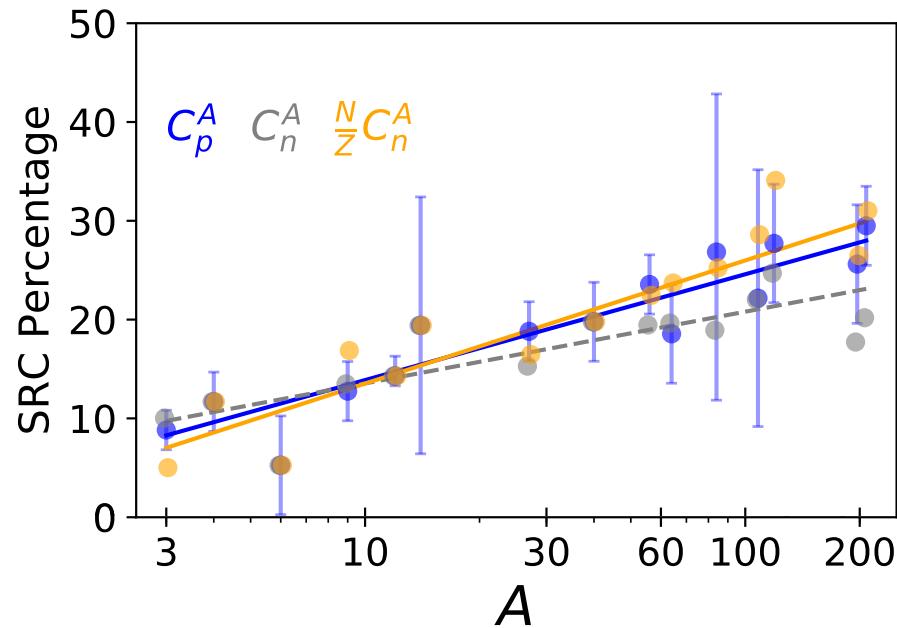
Summary

- SRC Parameterization produces a good fit.

χ^2/N_{data}	$\frac{\chi^2_{\text{tot}}}{N_{\text{DOF}}}$
Mean-Field	0.85
SRC	0.80

Summary

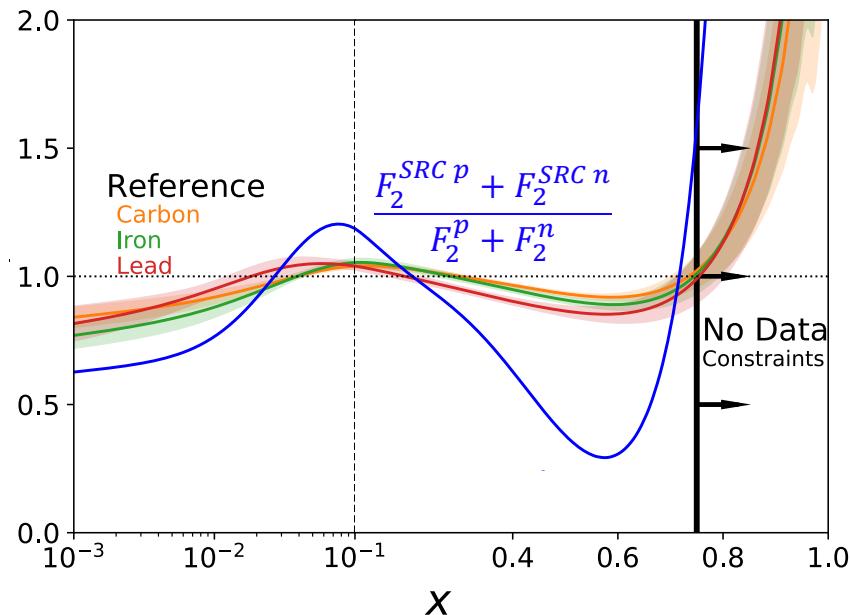
- SRC Parameterization produces a good fit.
- pn-dominance naturals emerges from the fit.



Summary

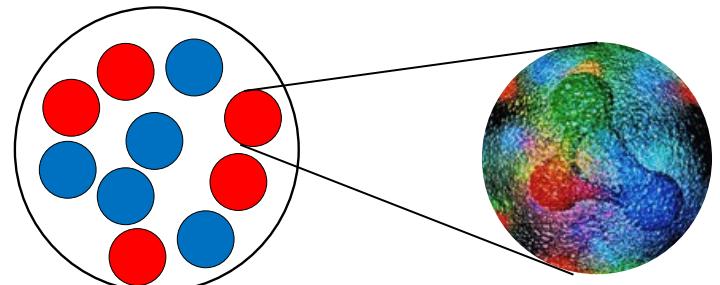
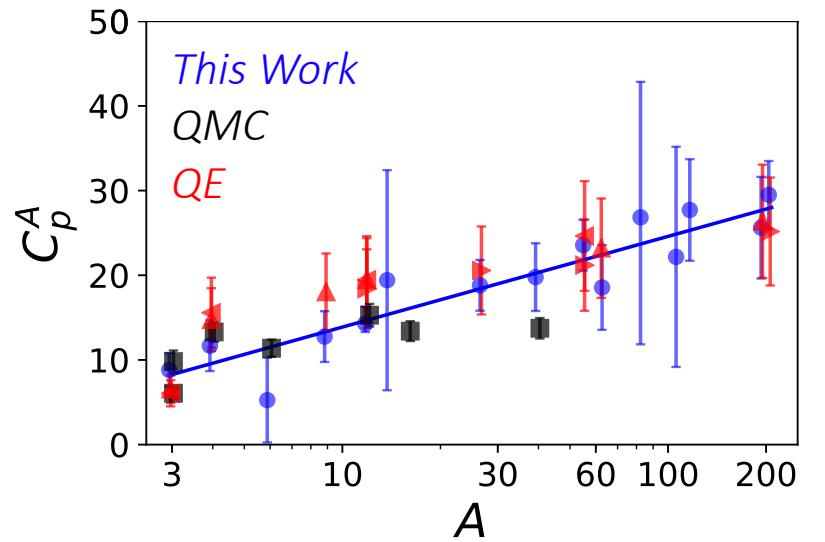
- SRC Parameterization produces a good fit.
- pn-dominance naturals emerges from the fit.
- The SRC Structure is heavily modified.

$$\frac{F_2^A}{F_2^p + F_2^n}$$



Summary

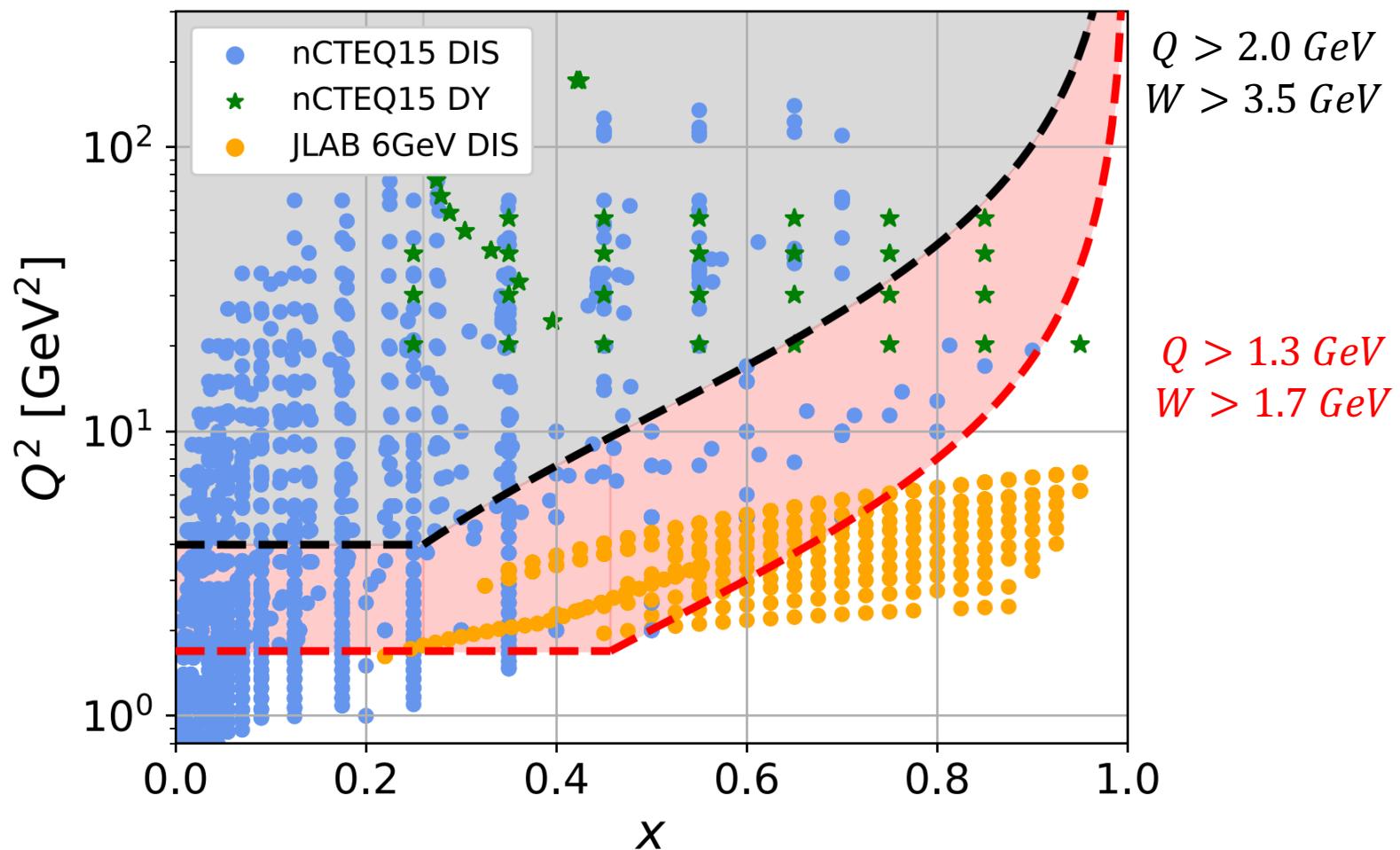
- SRC Parameterization produces a good fit.
- pn-dominance naturals emerges from the fit.
- The SRC Structure is heavily modified.
- Nuclear physics extracted from parton measurements.



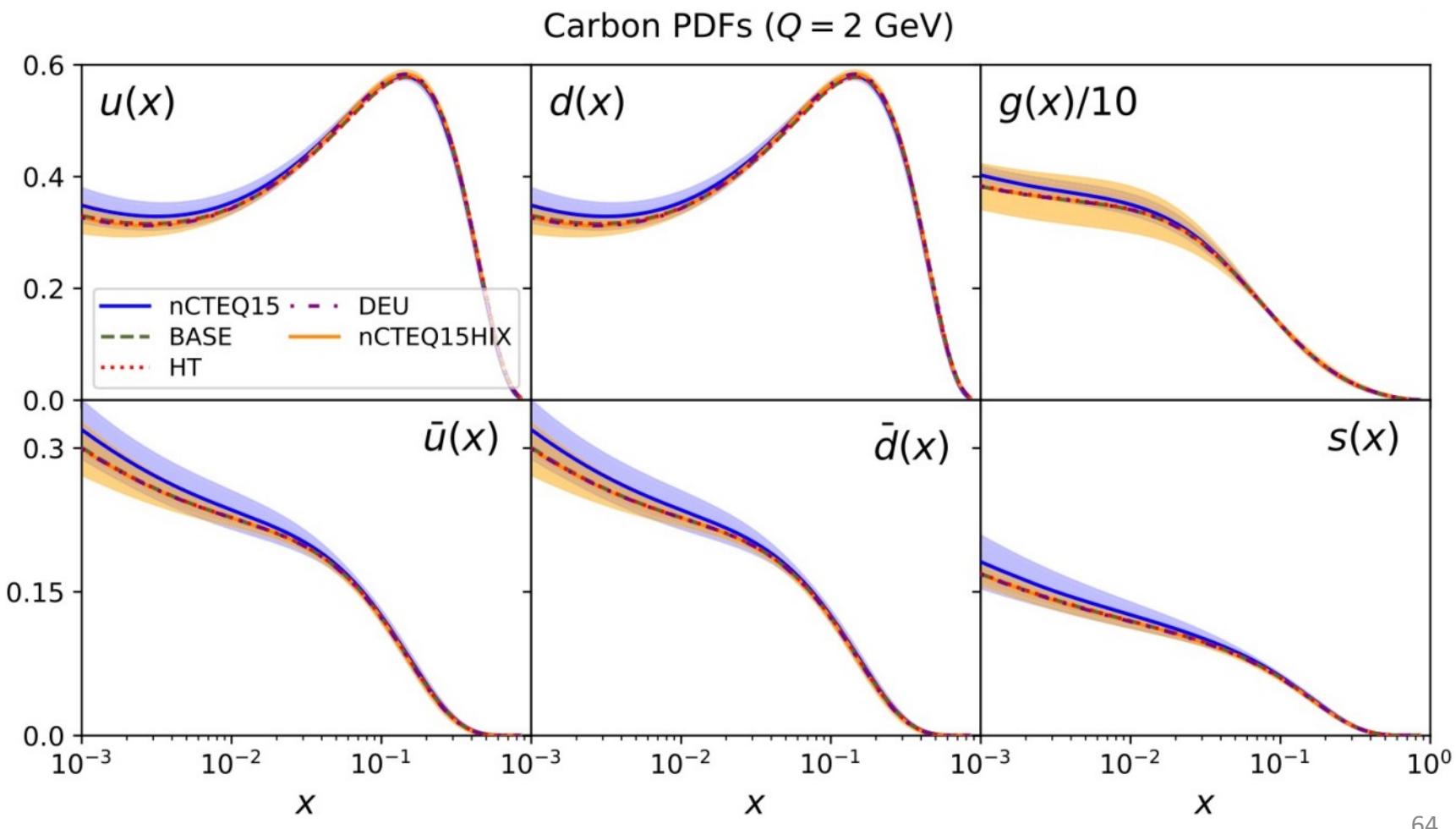
End

Extra

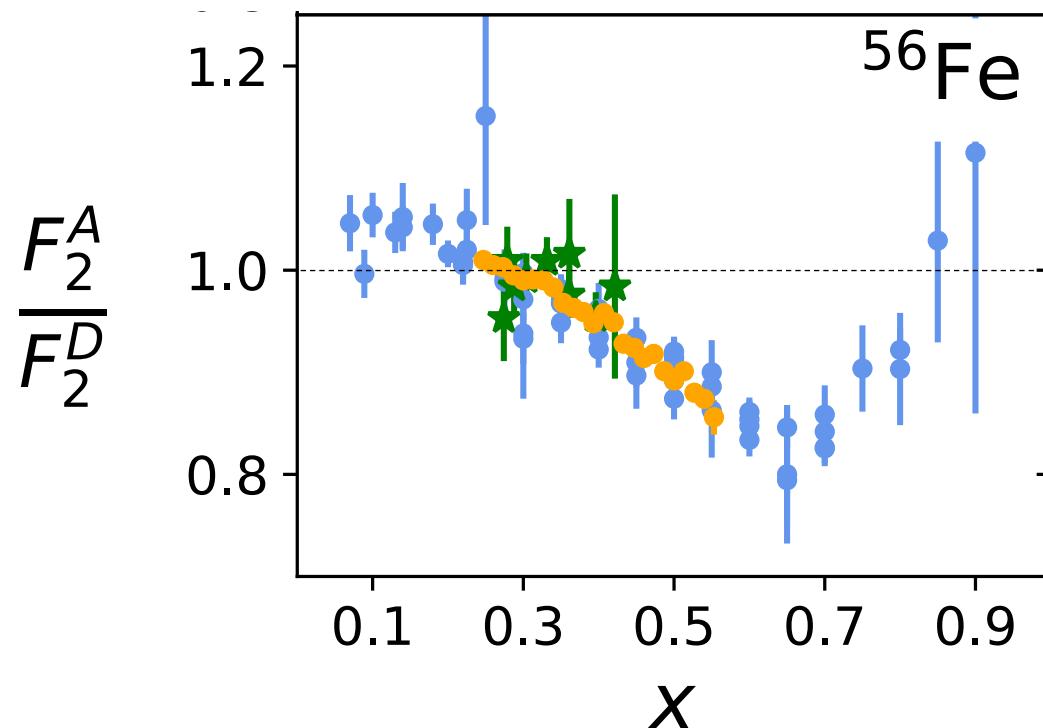
Cut out data with non-DIS Kinematics



Previous PDF fits

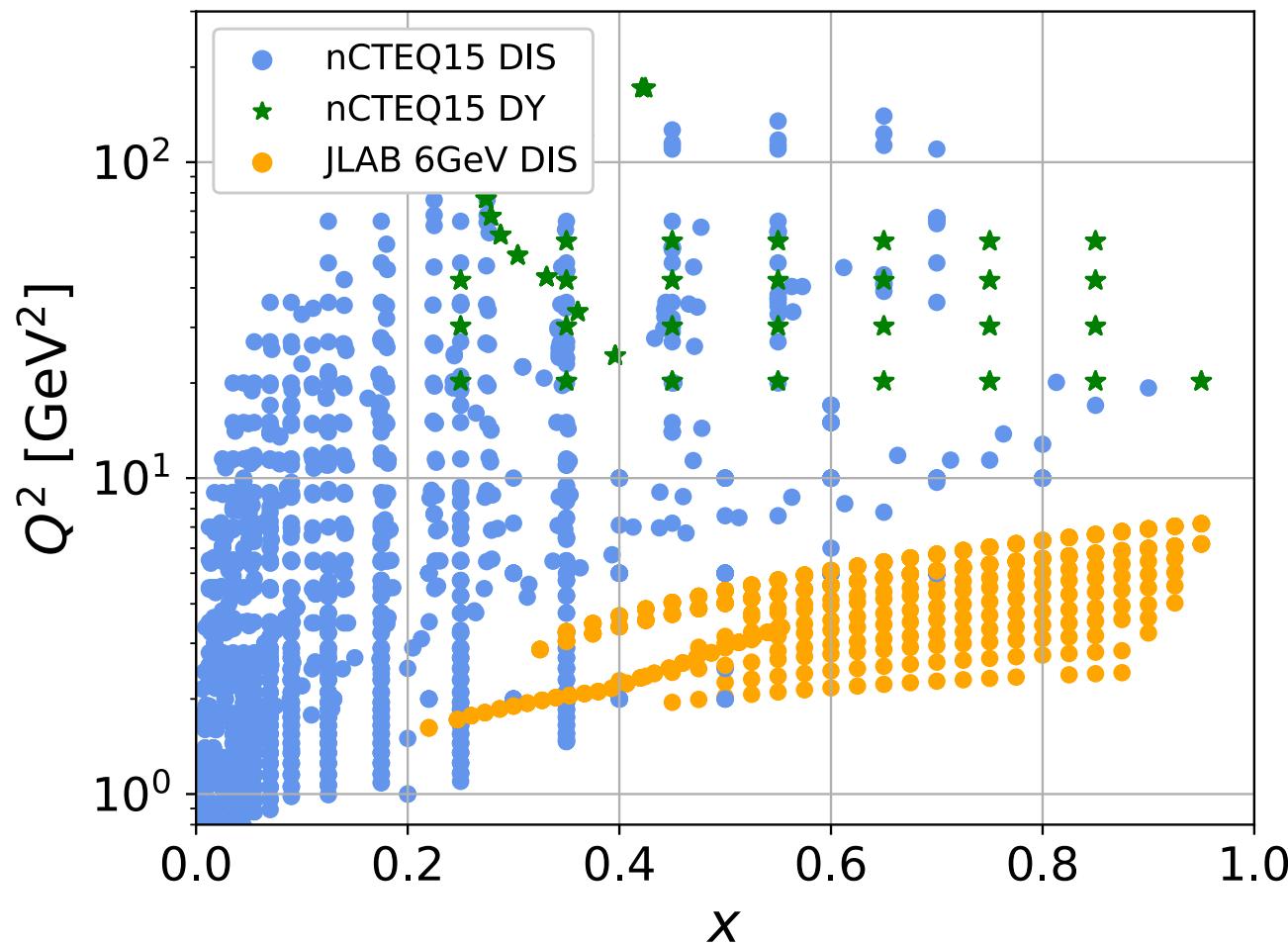


Medium Modification and nPDFs



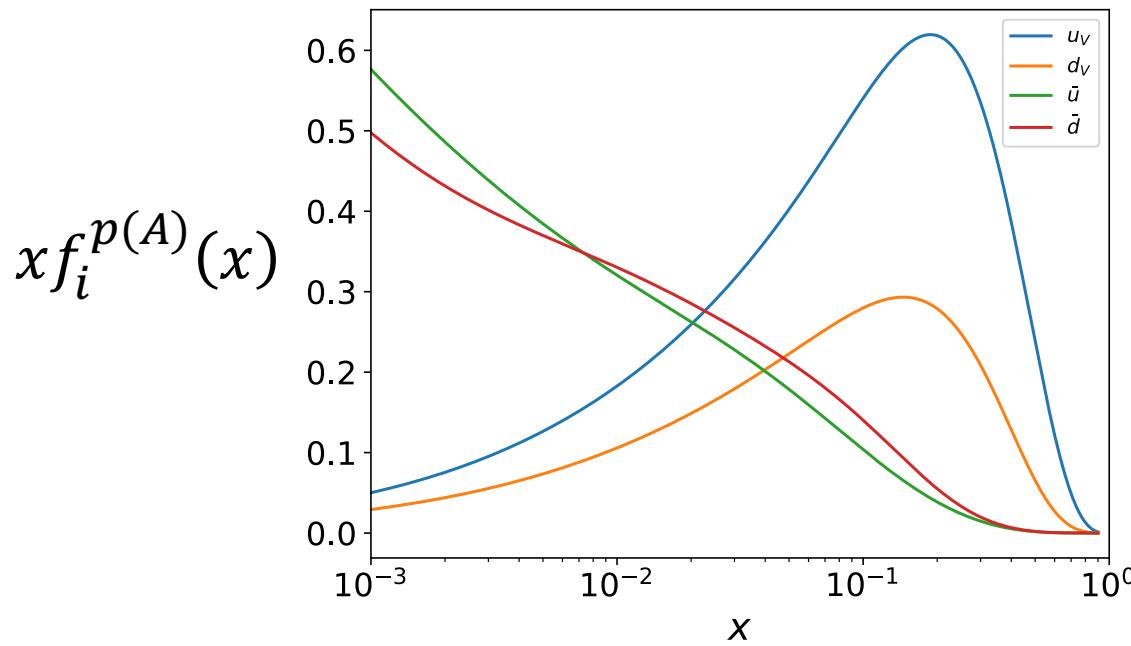
$$F_2^{A,Z}(x, Q) \sim x \sum_i C_i^2 f_i^{A,Z}(x)$$

World Data of Medium Modification

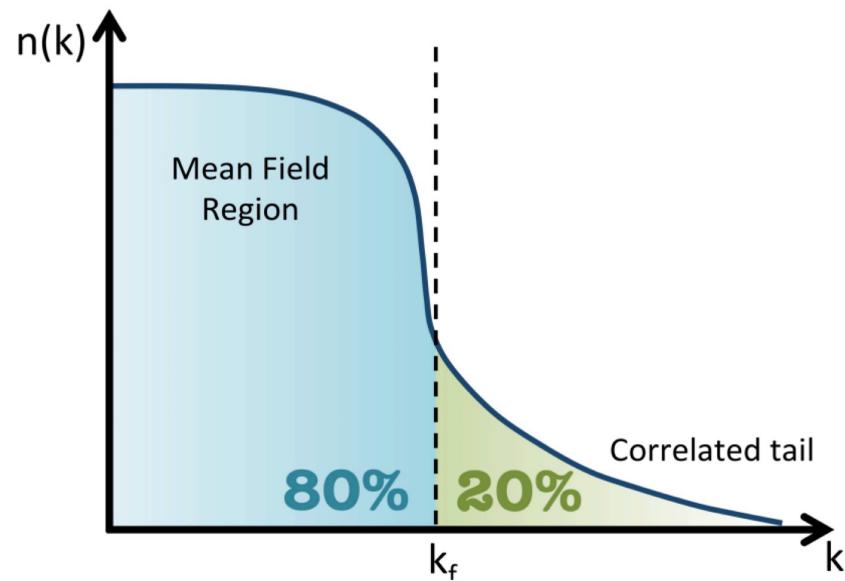


Proton PDF parametrization

$$x f_i^{p(A)}(x) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5}$$



Spectral Function

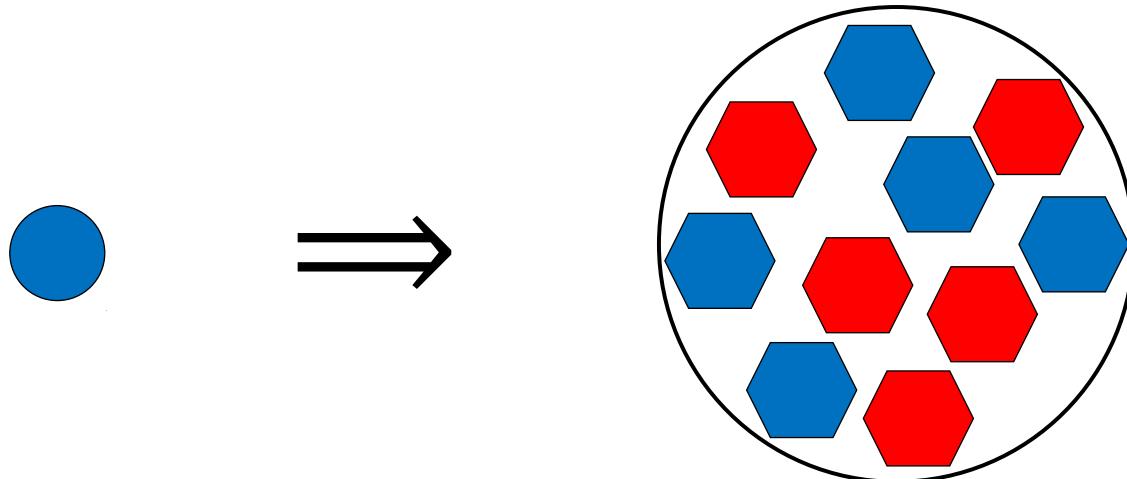


$$S_A(k, E) = S_A^{MF}(k, E) + S_A^{SRC}(k, E)$$

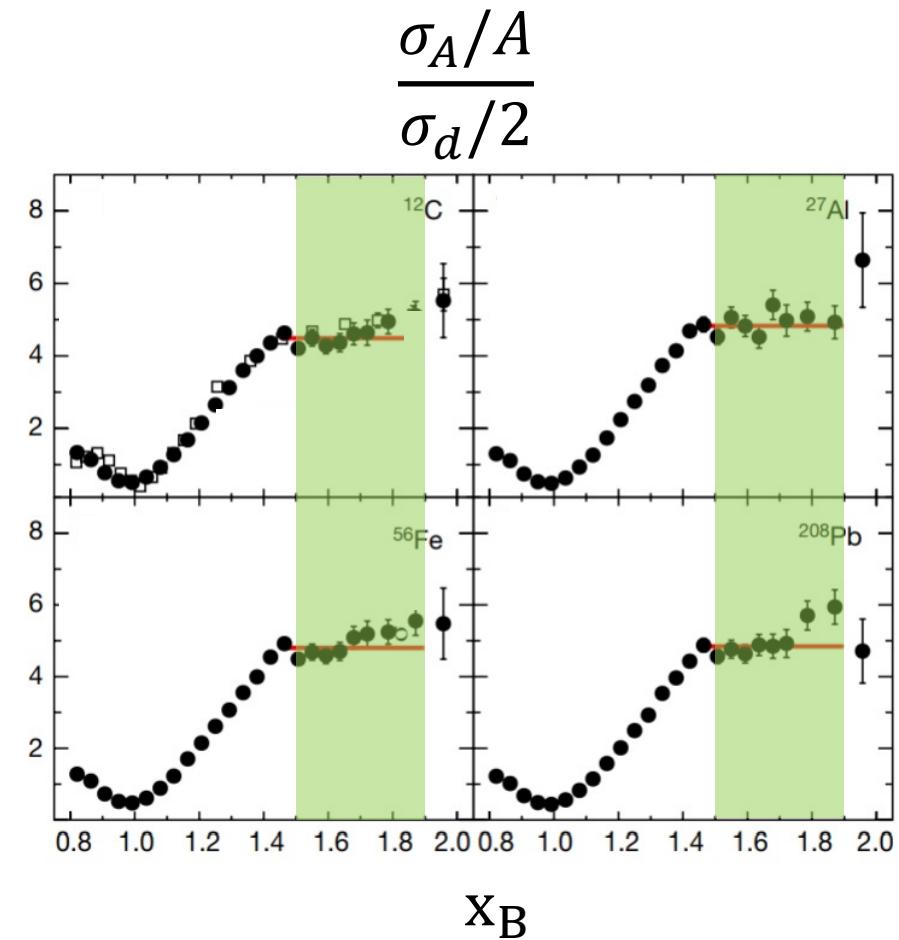
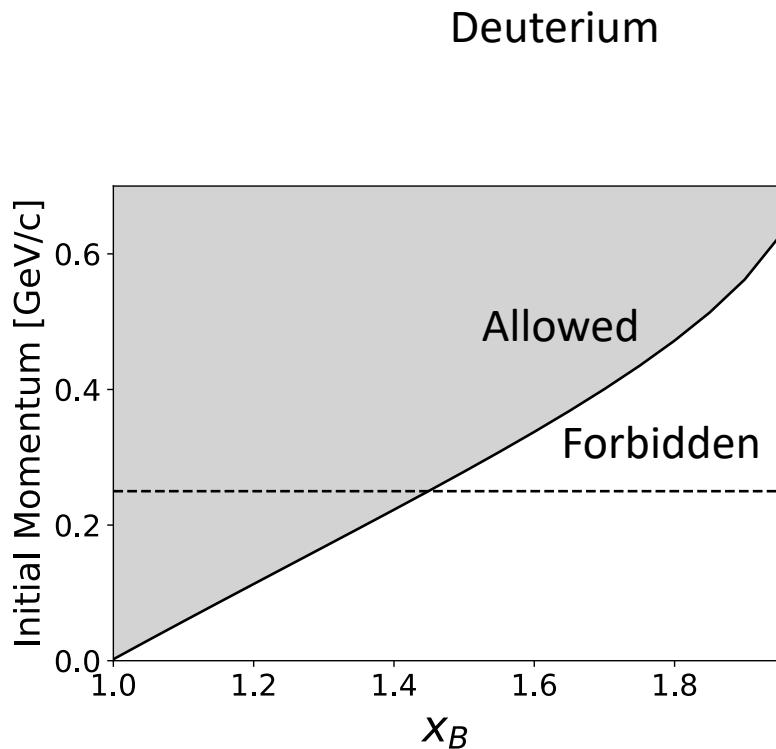
Original Parametrization

Depend on A

$$f_i^A(x) = \frac{Z}{A} f_i^{p(A)}(x) + \frac{A - Z}{A} f_i^{n(A)}(x)$$

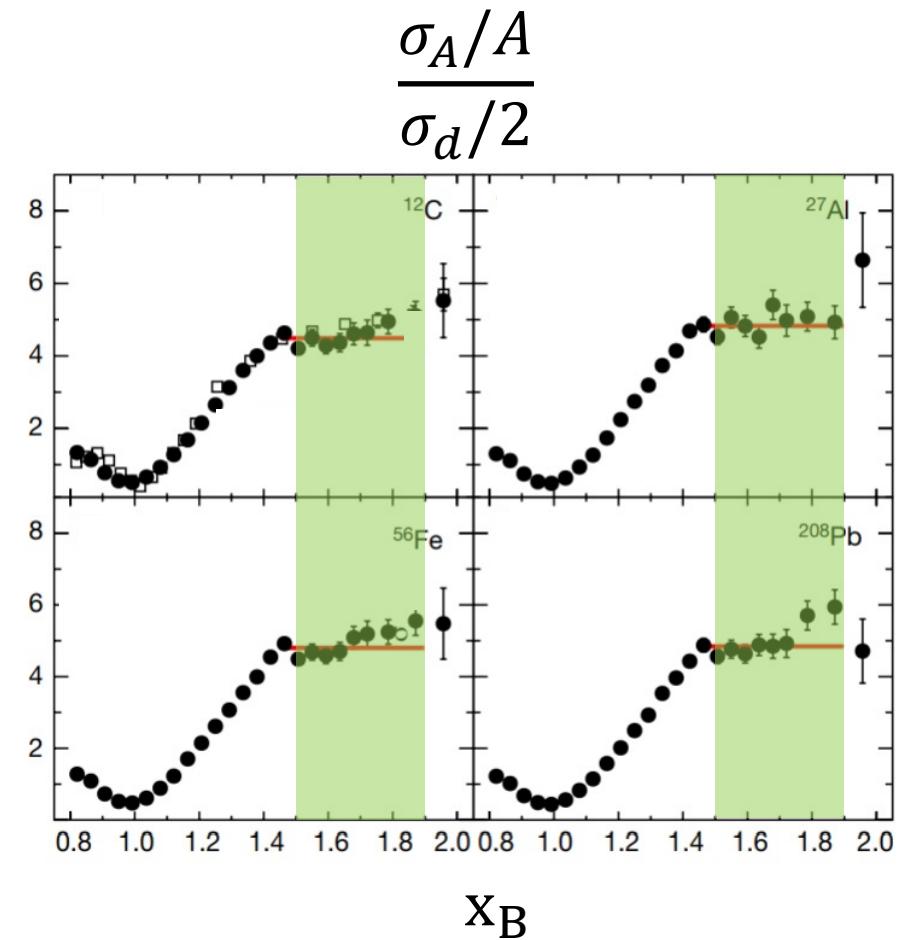
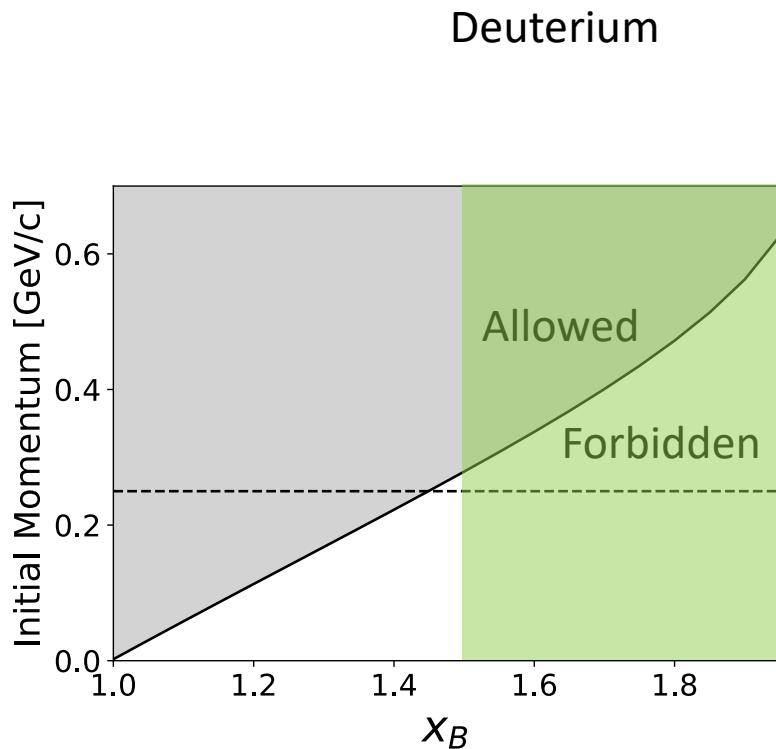


SRC Measurements

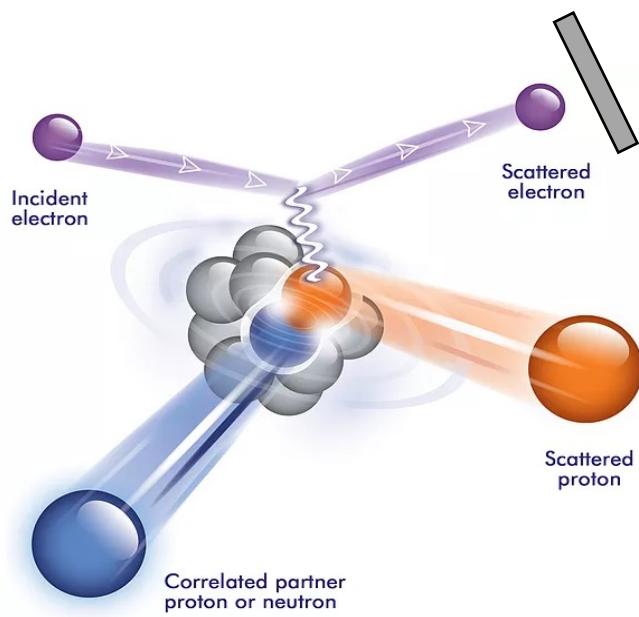


- Schmookler Nature (2019)

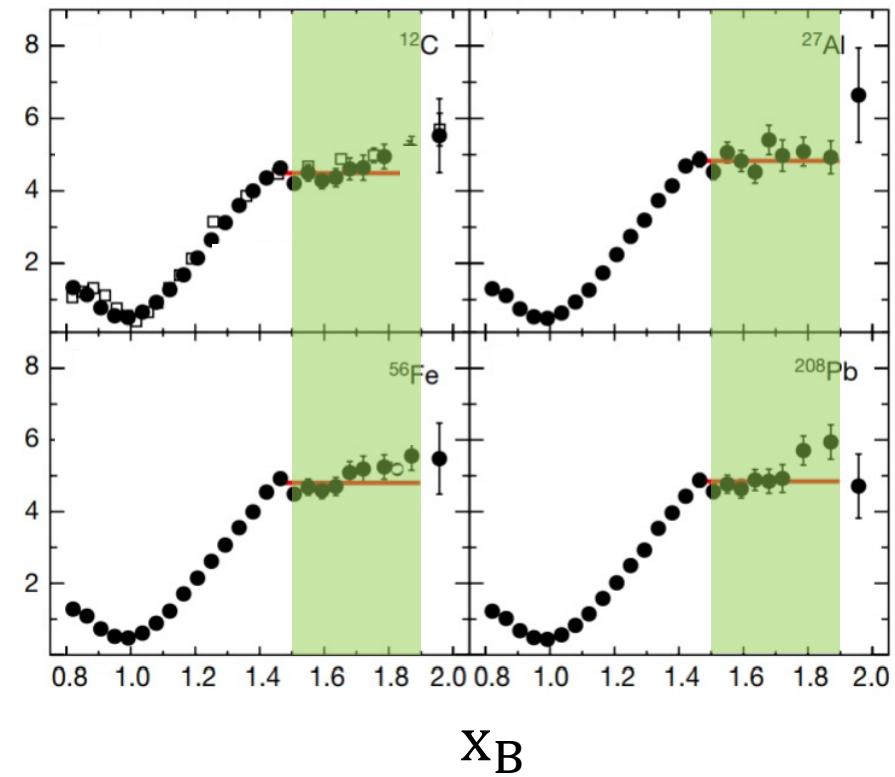
SRC Measurements



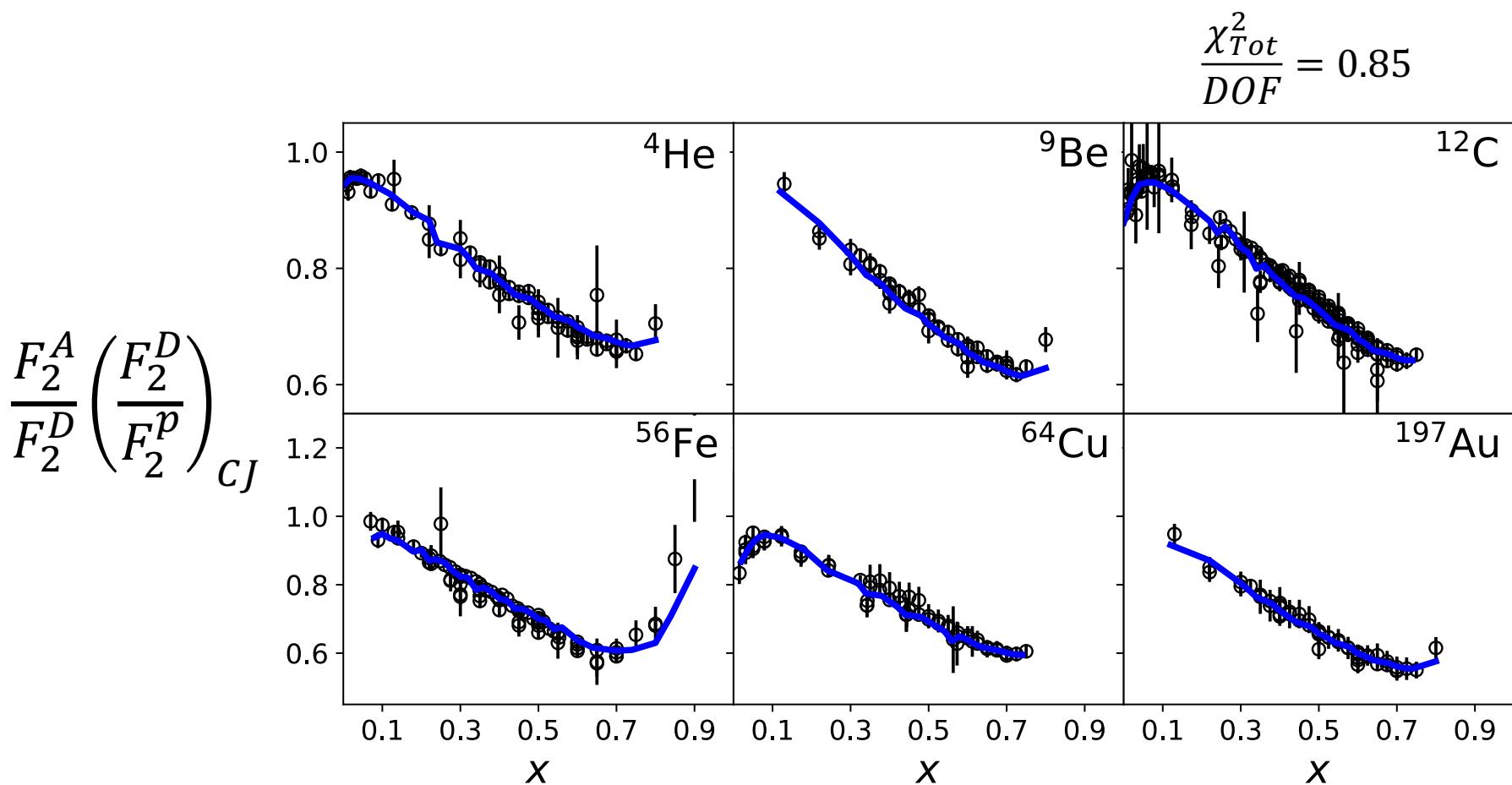
SRC Measurements



$$\frac{\sigma_A/A}{\sigma_d/2}$$



Fitting to World Data



Fit using pn-dominance

$$f_i^A(x) = \frac{Z}{A} [(1 - C_p^A) f_i^p(x) + C_p^A f_i^{SRC\ p}(x)] +$$

$$\frac{A - Z}{A} [(1 - C_n^A) f_i^n(x) + C_n^A f_i^{SRC\ n}(x)]$$

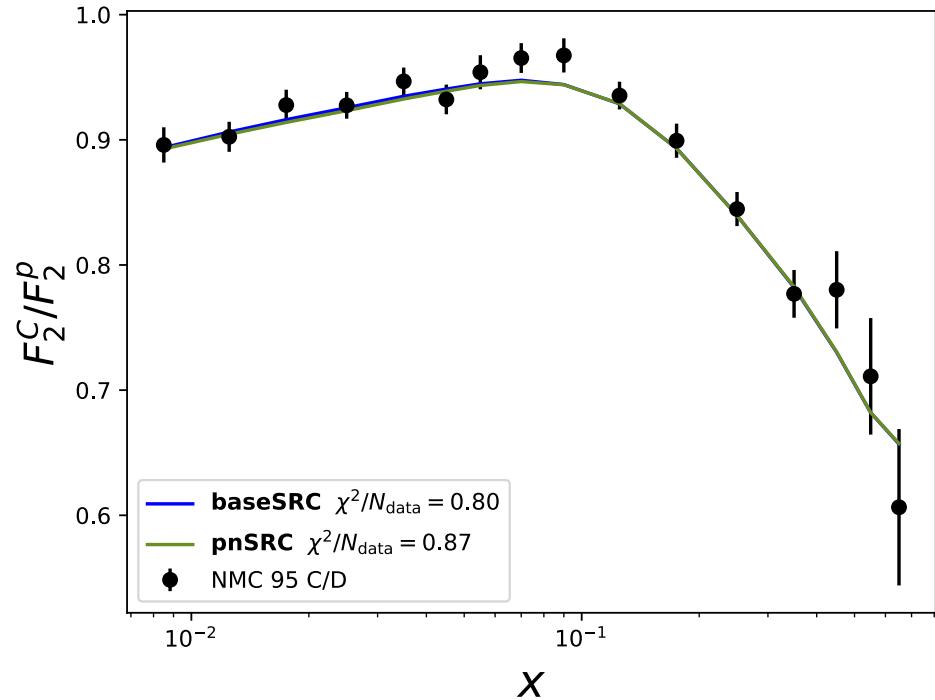
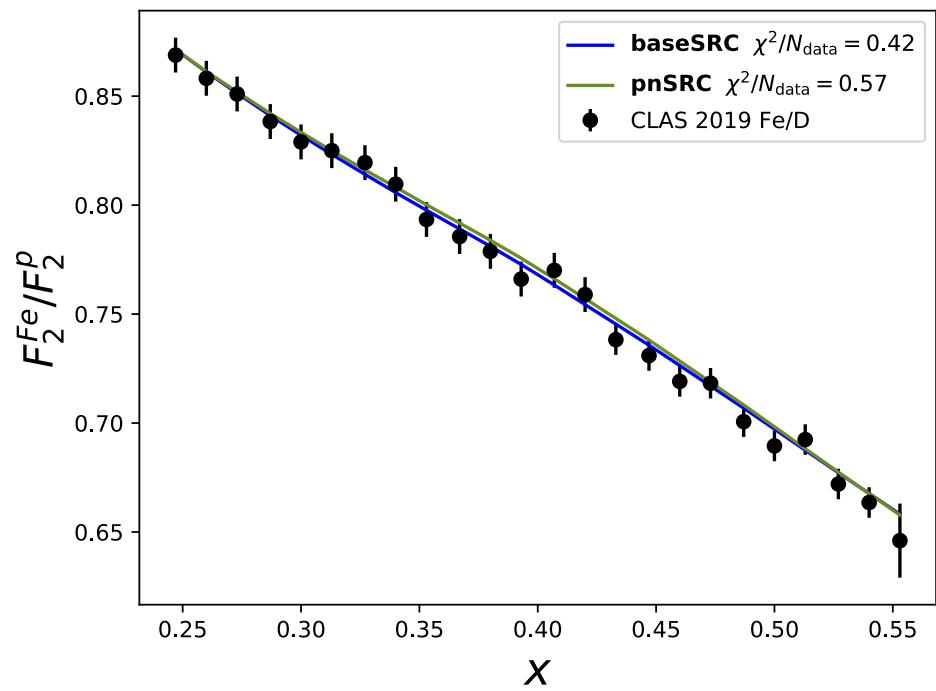
Two Fits:

- Let C_p^A and C_n^A vary independently
- Force pn-dominance:
 $\#Protons\ in\ SRC = \#Neutrons\ in\ SRC$

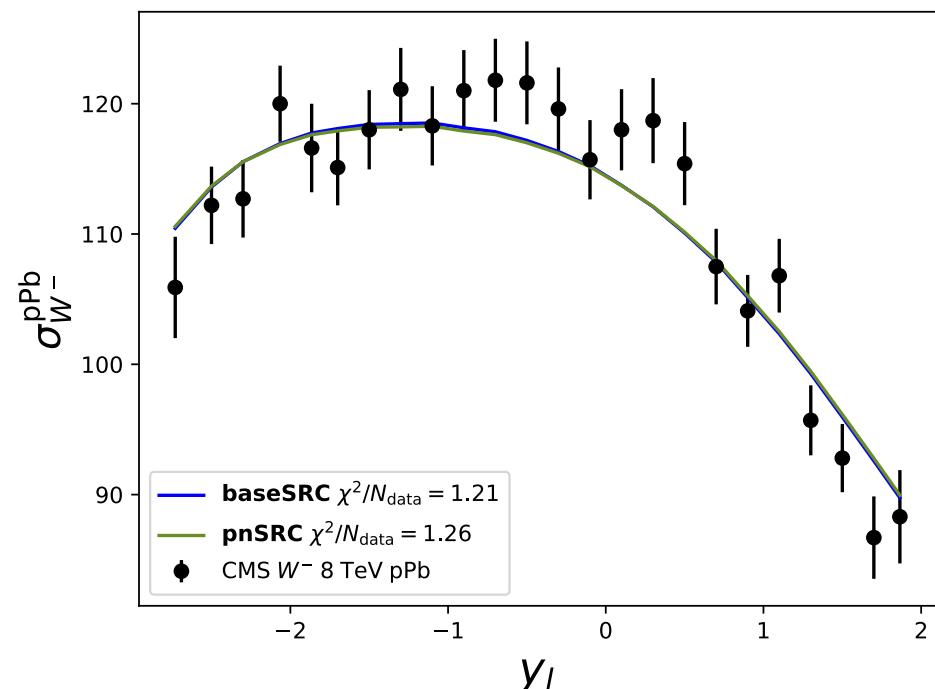
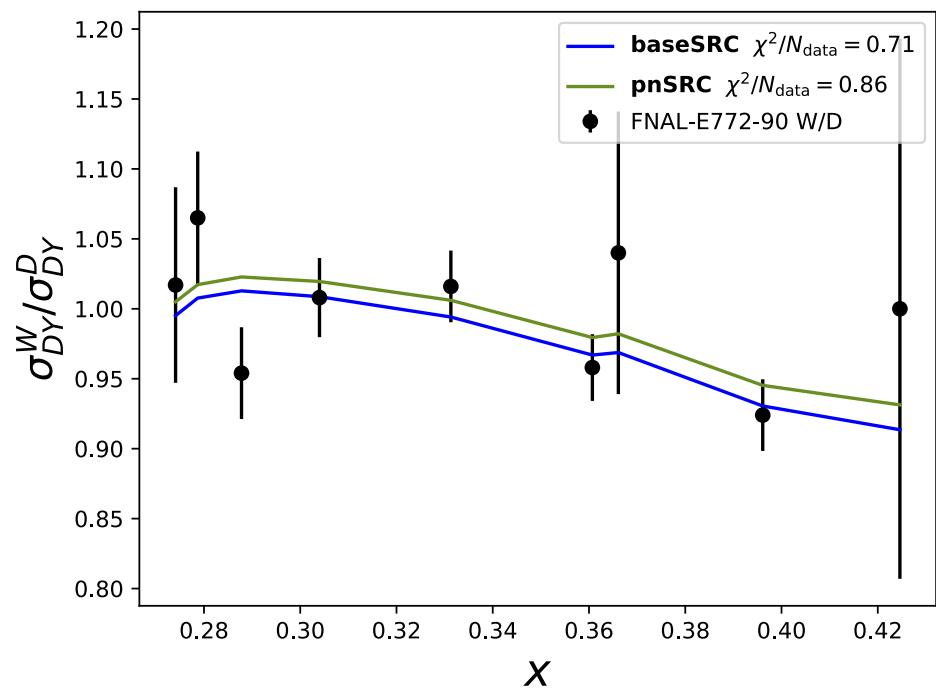
Fits Result:

χ^2/N_{data}	$\frac{\chi^2_{\text{tot}}}{N_{\text{DOF}}}$
reference	0.85
baseSRC	0.80
pnSRC	0.82

Enforcing pn-dominance does not affect the results of the fit.



Enforcing pn-dominance does not affect the results of the fit.



Beyond the SRC-EMC Relation

EMC
 Shadowing
 \leftrightarrow
 SRC Anti-shadowing
 Drell-Yan
 W/Z

