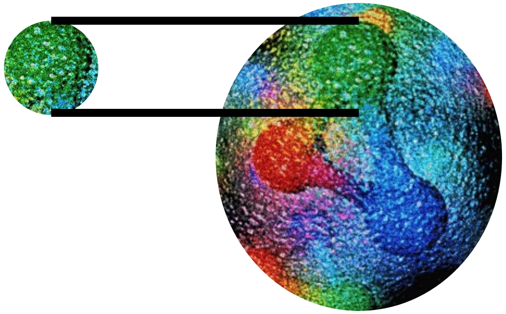
Modification of Quark-Gluon Distributions in Nuclei by Correlated Nucleons Pairs

Andrew Denniston (MIT)

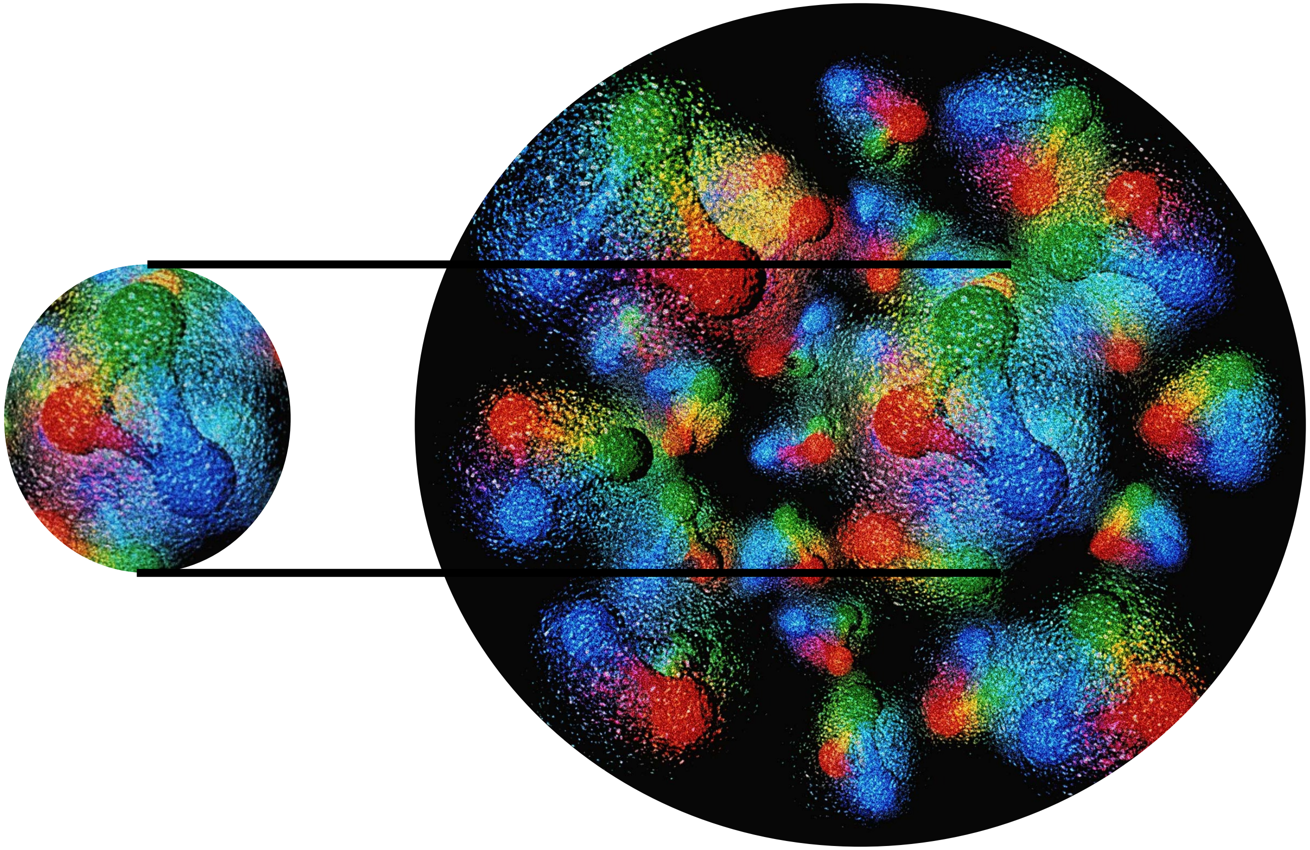
In Collaboration with: Tomas Jezo, Aleksander Kusina, Fred Olness, Or Hen

August 8th, 2024

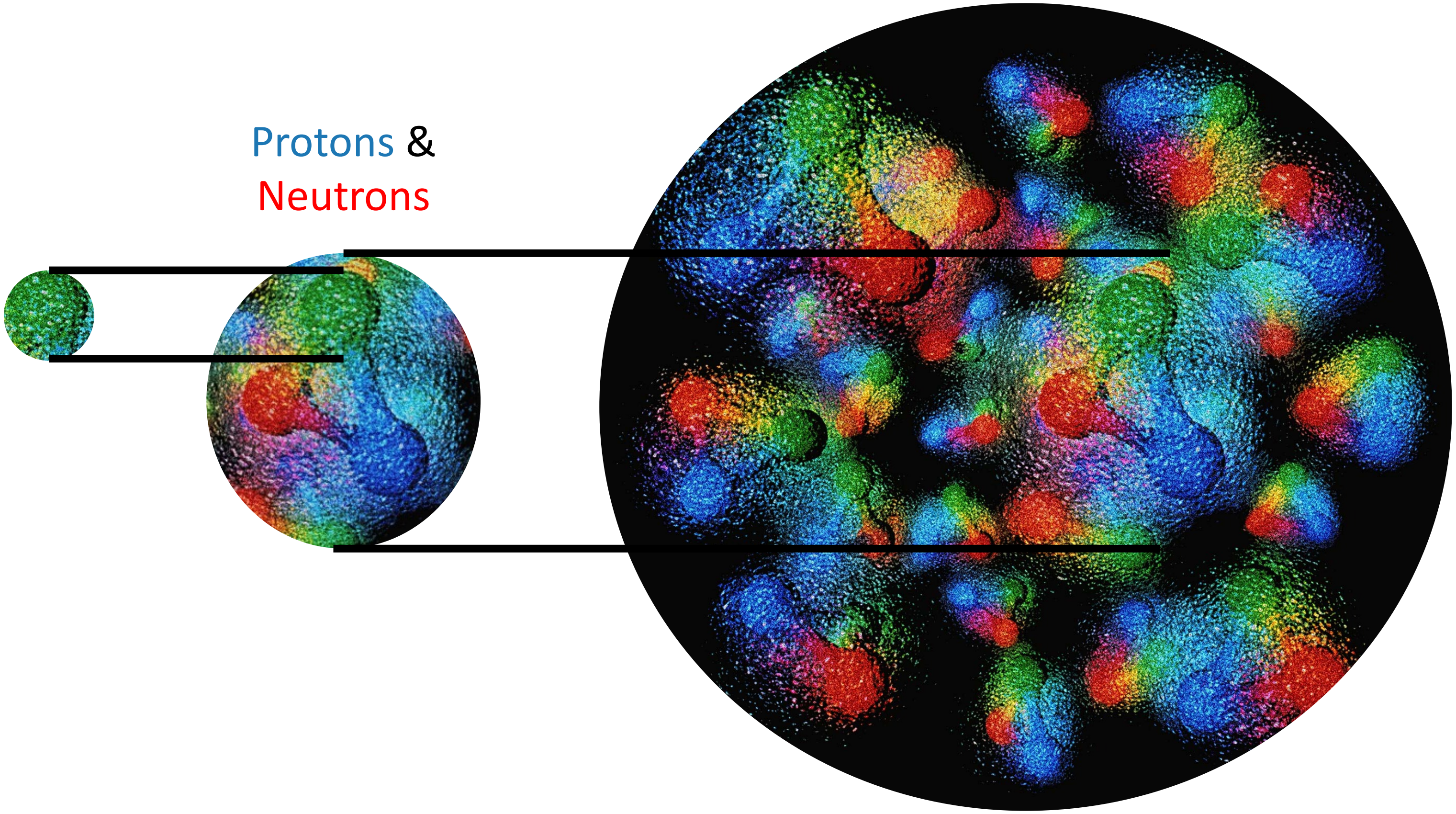
Partons in Hadrons



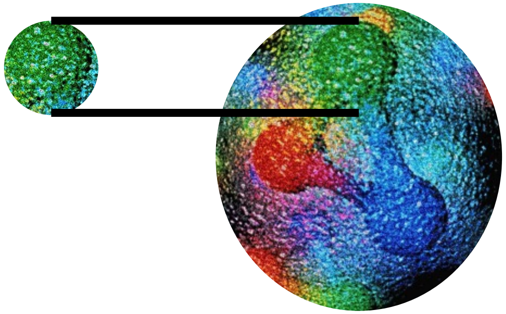
Hadrons in the Nucleus



Partons in the Nucleus



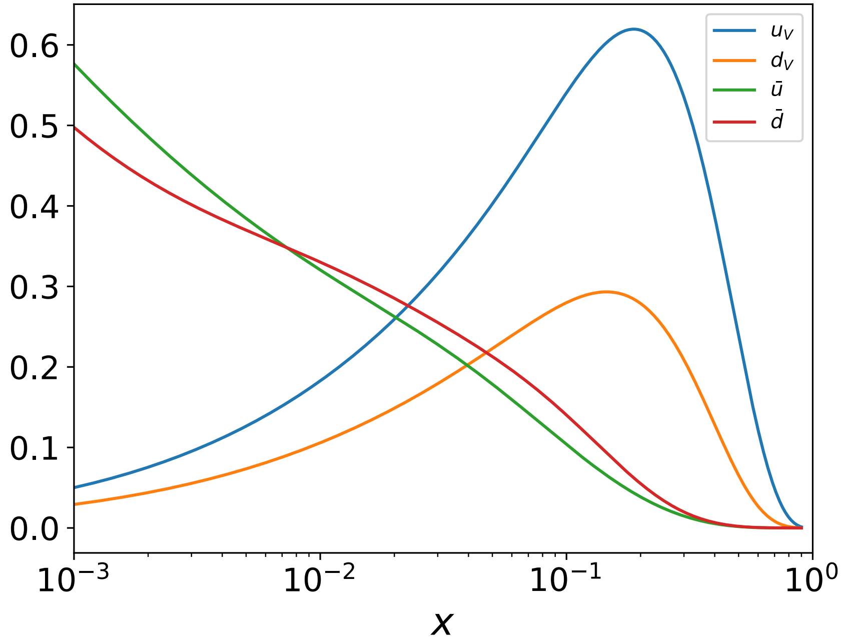
Partons in Hadrons



Proton PDF

$$F_2^A(x,Q) \sim x \sum_i Q_{q,i}^2 f_i^A(x,Q)$$

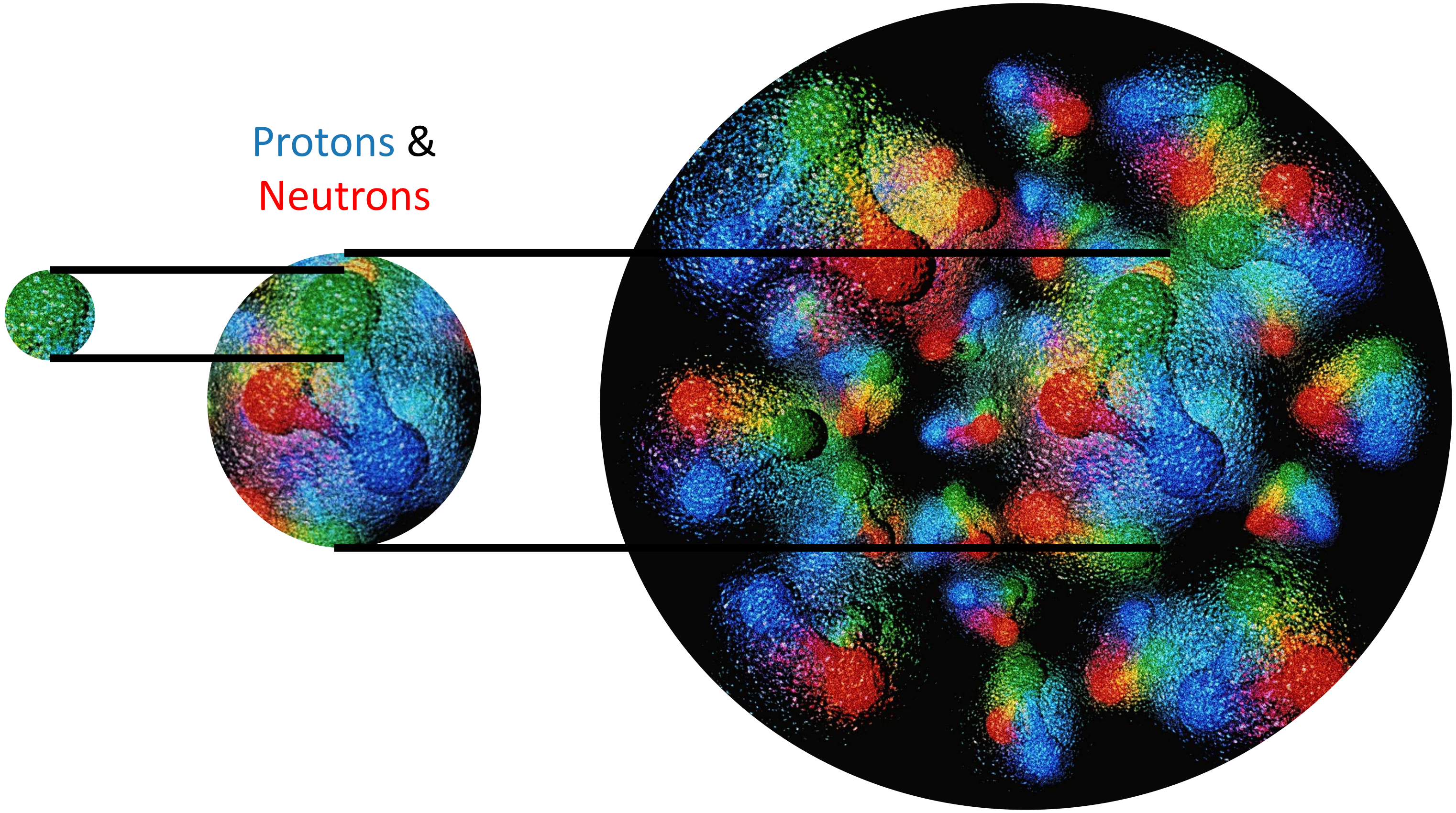
$xf_i^{p(A)}(x)$



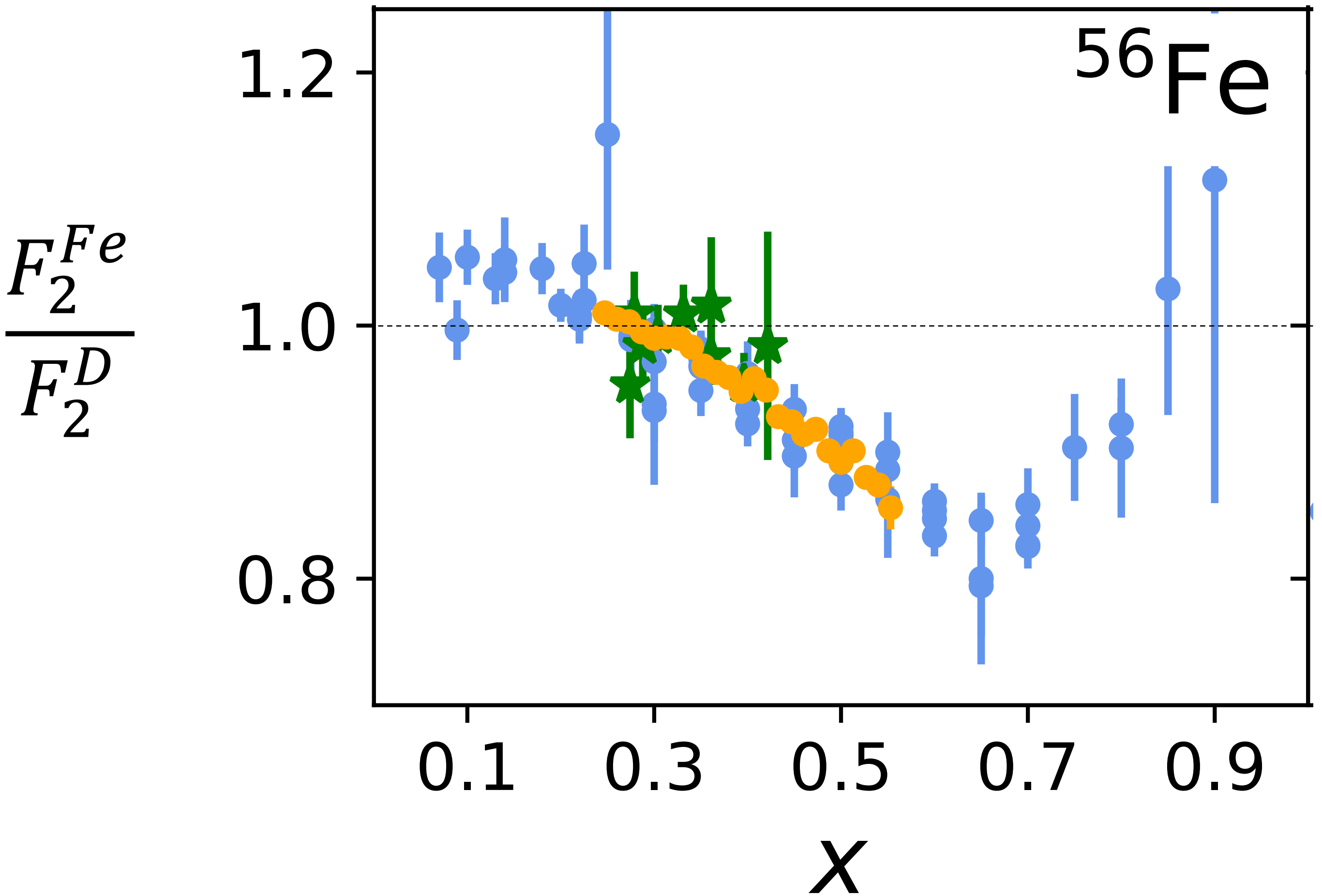
$$xf_i^{p(A)}(x\ ) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5}$$

Kovarik PRD (2015)

Partons in the Nucleus

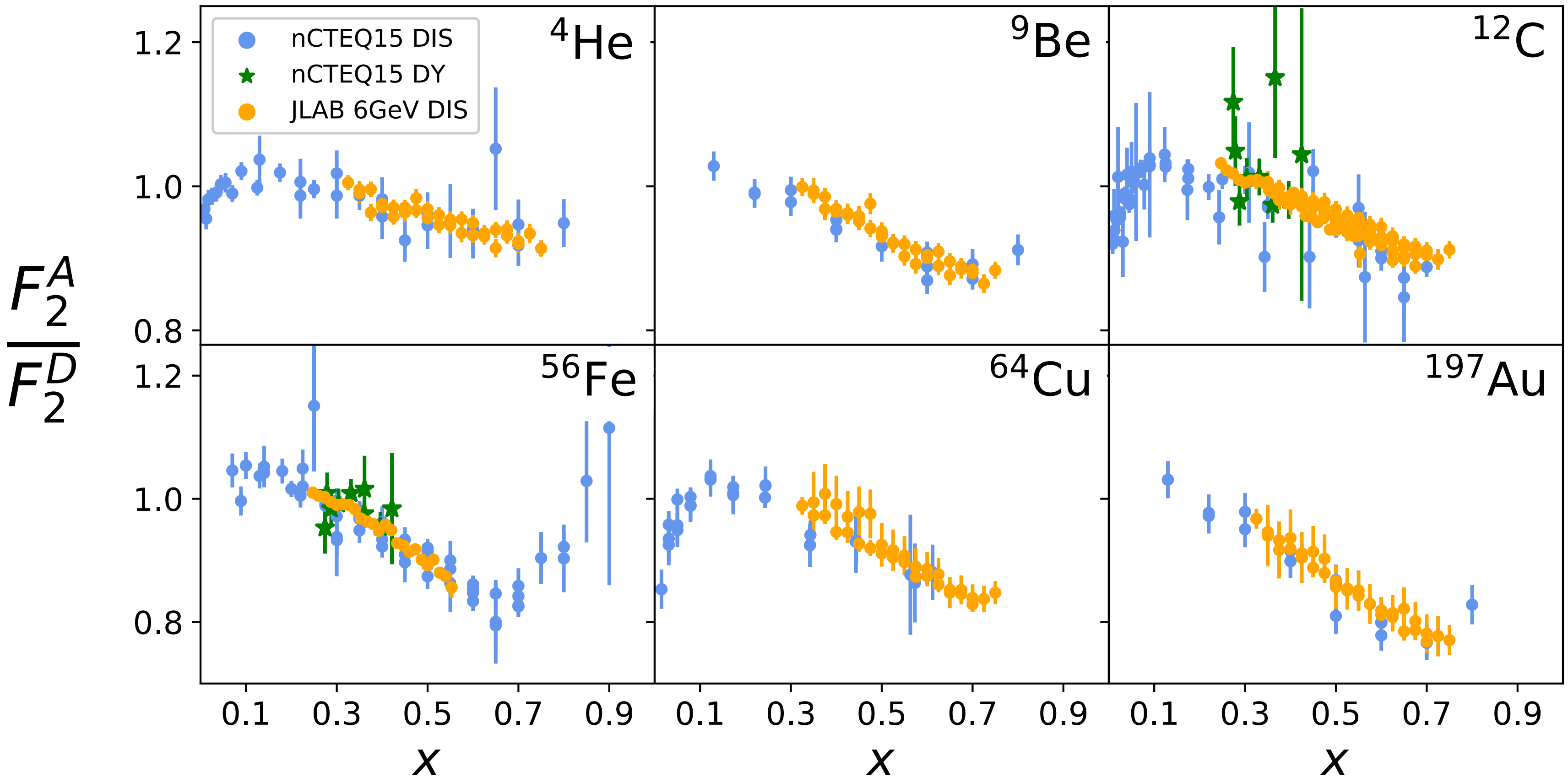


The EMC Effect



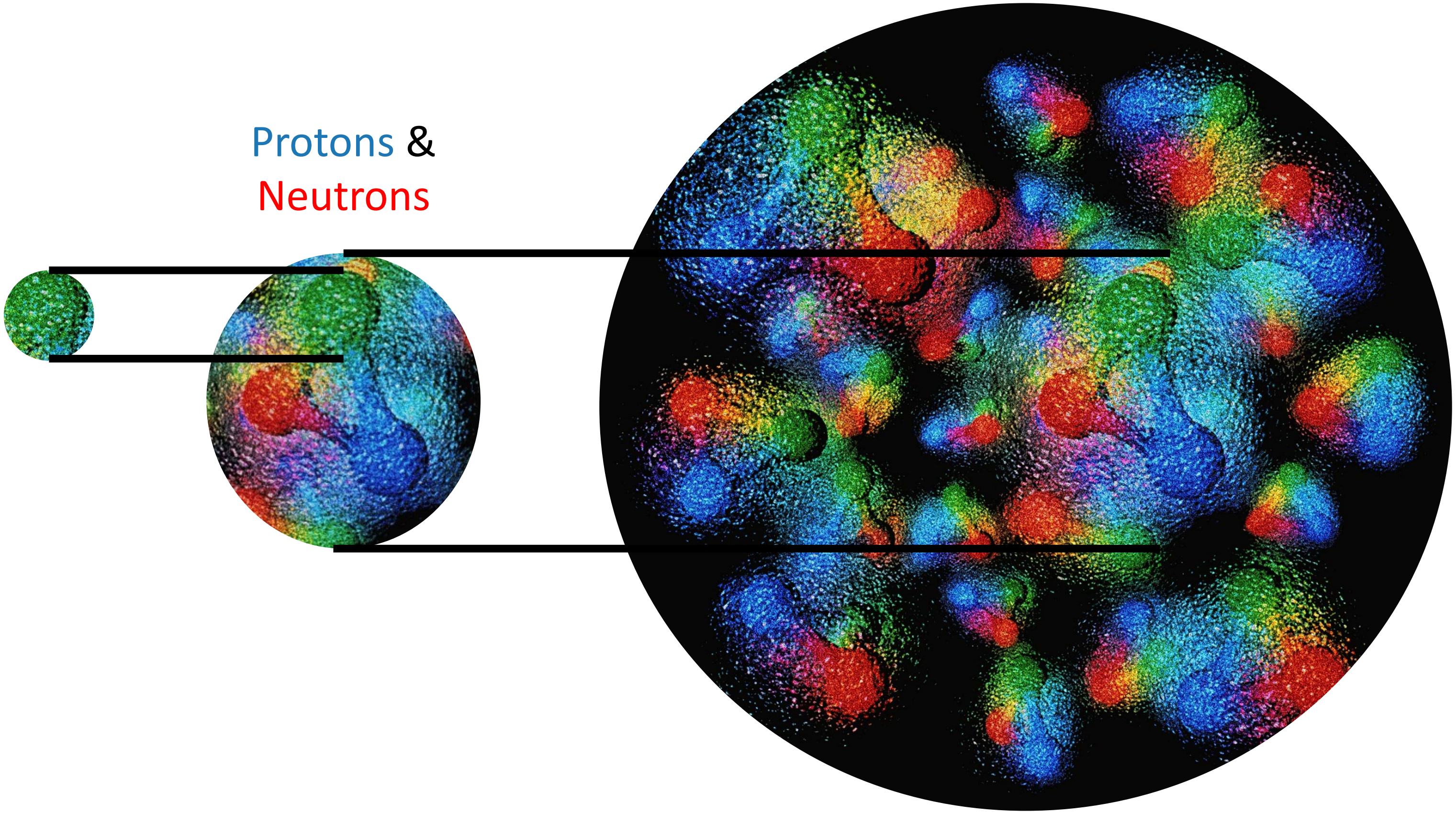
Segarra PRD (2021)

Nuclear Dependance



Segarra PRD (2021)

Partons in the Nucleus



Cause of the EMC Effect?

Traditional Nuclear Effects

Medium Modification

Cause of the EMC Effect?

~~Traditional Nuclear Effects~~

Drell-Yan Reactions

Medium Modification

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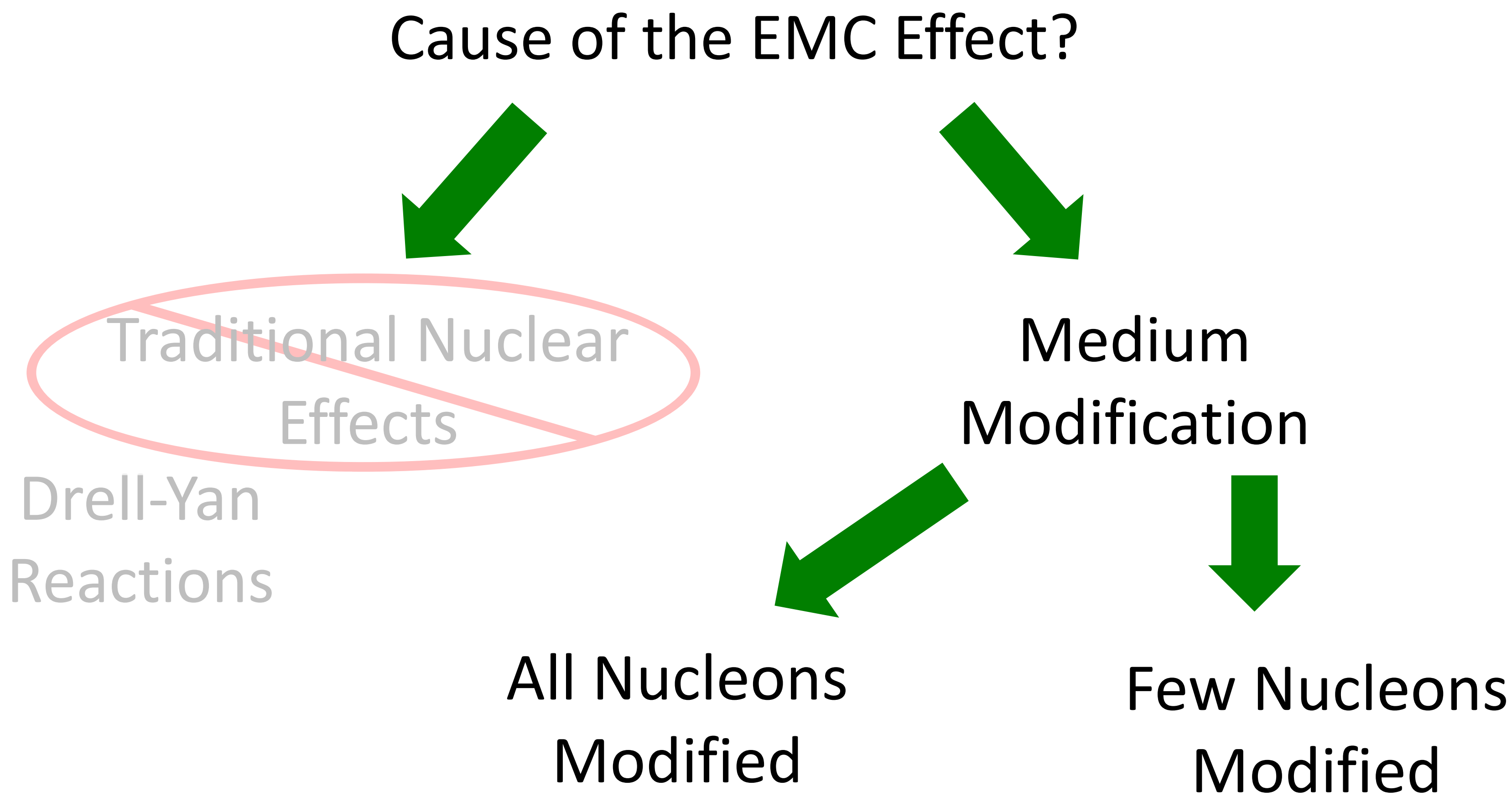

Cause of the EMC Effect?
Traditional Nuclear Effects
Drell-Yan Reactions
Medium Modification
All Nucleons Modified
Few Nucleons Modified

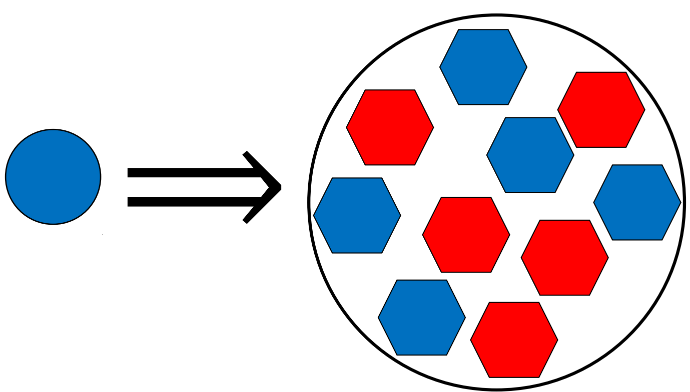
Cause of the EMC Effect?

~~Traditional Nuclear Effects~~

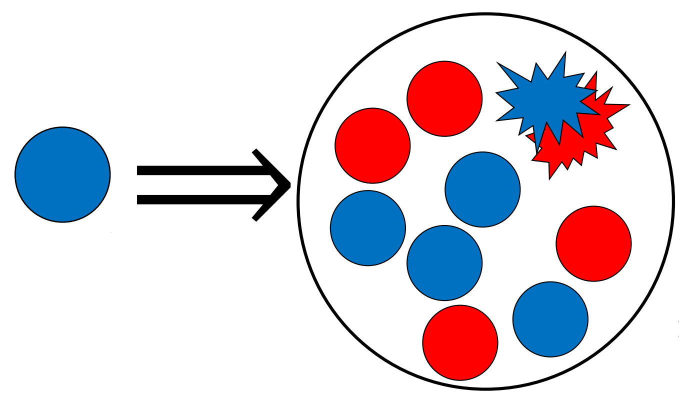
Drell-Yan Reactions

Medium Modification

All Nucleons Modified



Few Nucleons Modified



Cause of the EMC Effect?

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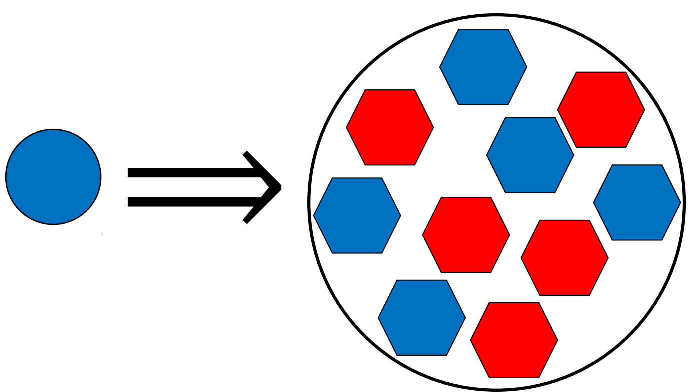
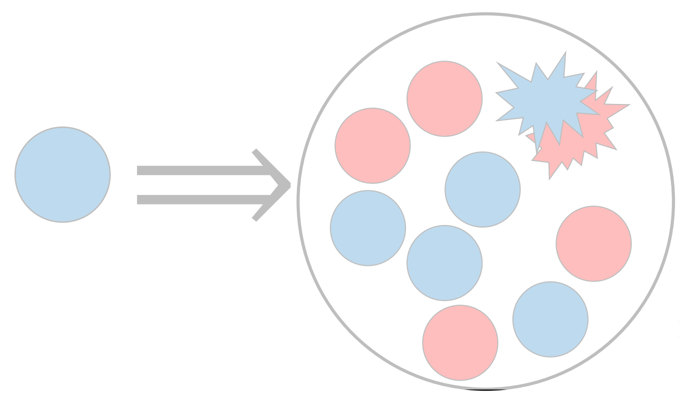
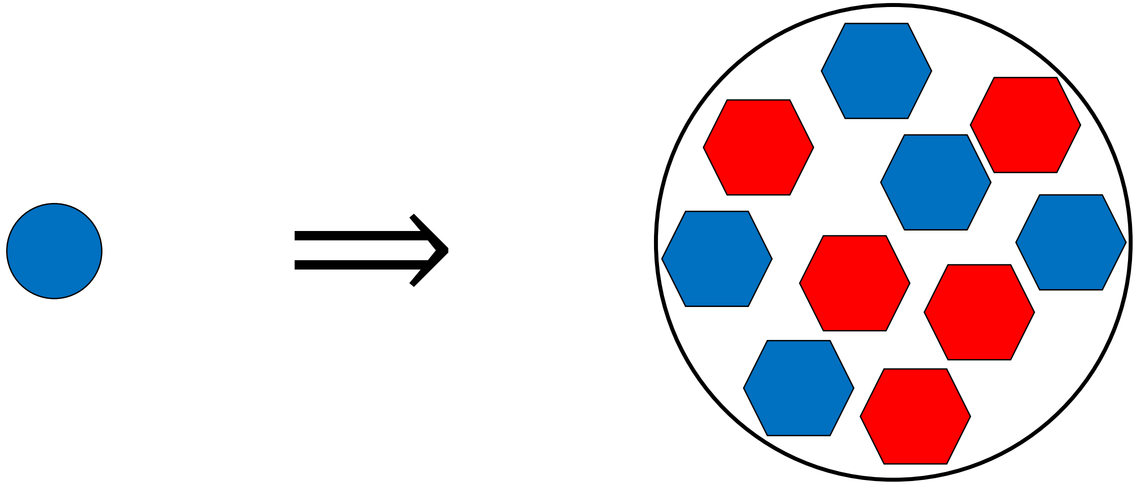
Few Nucleons Modified





All Nucleons Modified Approach

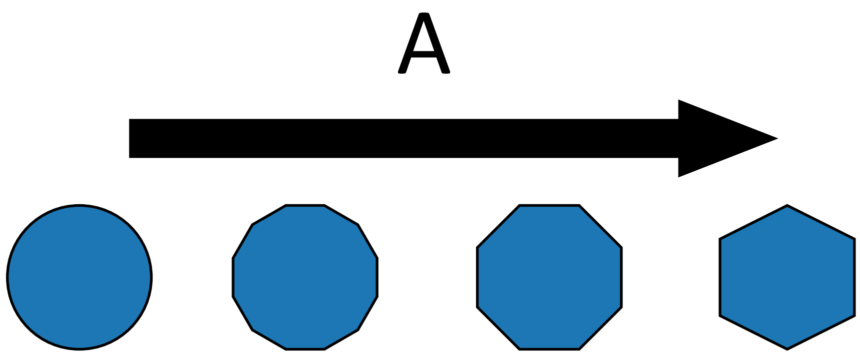
$$f_i^A(x) = \frac{Z}{A} f_i^{p(A)}(x) + \frac{A - Z}{A} f_i^{n(A)}(x)$$



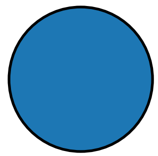
All Nucleons Modified Approach

Depend on A

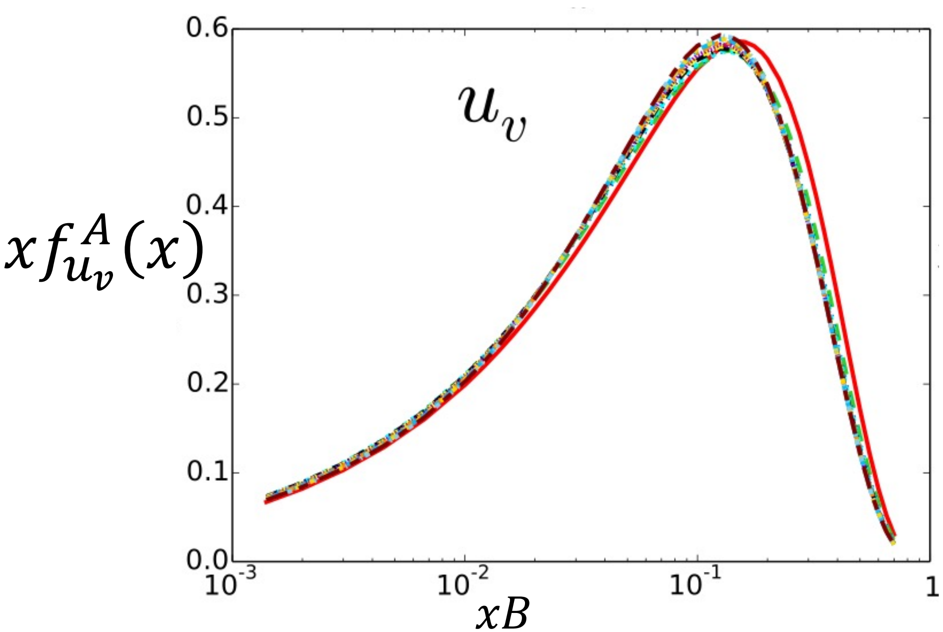
$$f_i^A(x) = \frac{Z}{A} f_i^{p(A)}(x) + \frac{A-Z}{A} f_i^{n(A)}(x)$$



All Nucleons Modified Approach

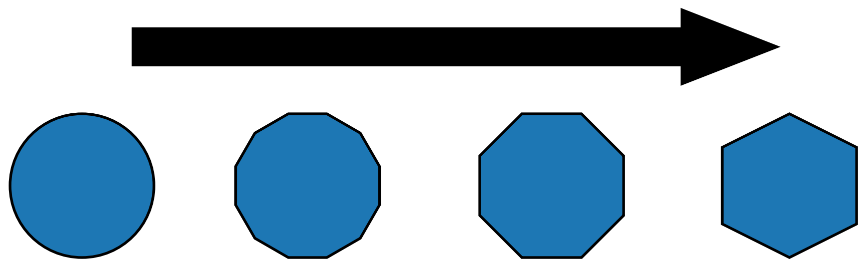


$$xf_i^{p(A)}(x\ ) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5}$$

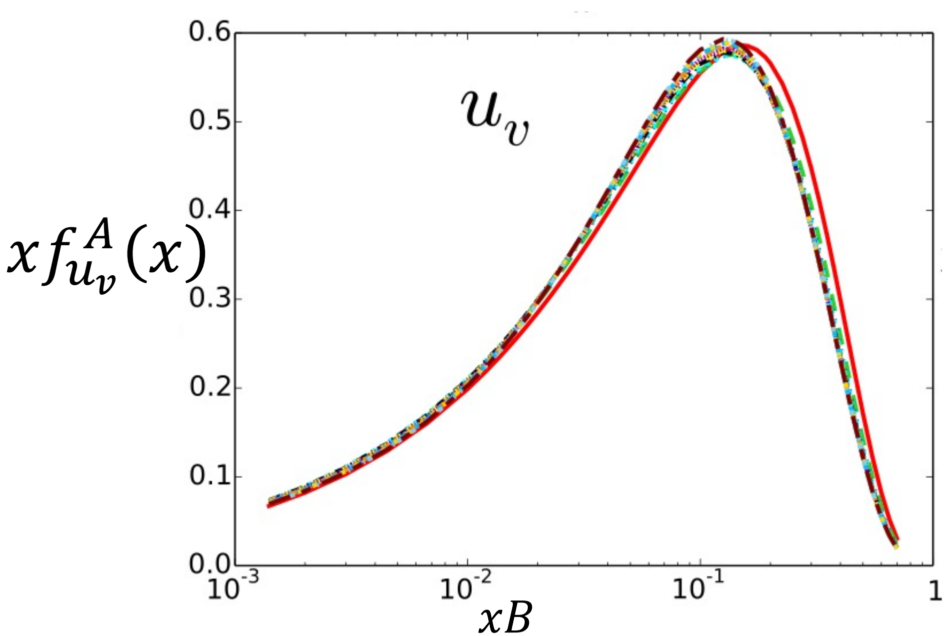


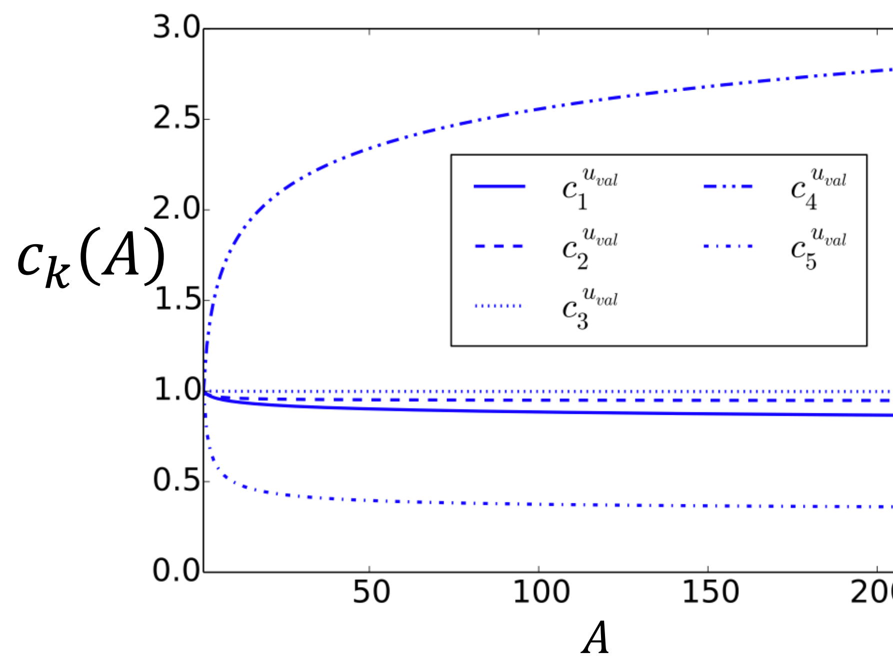
Kovarik PRD (2015)

All Nucleons Modified Approach



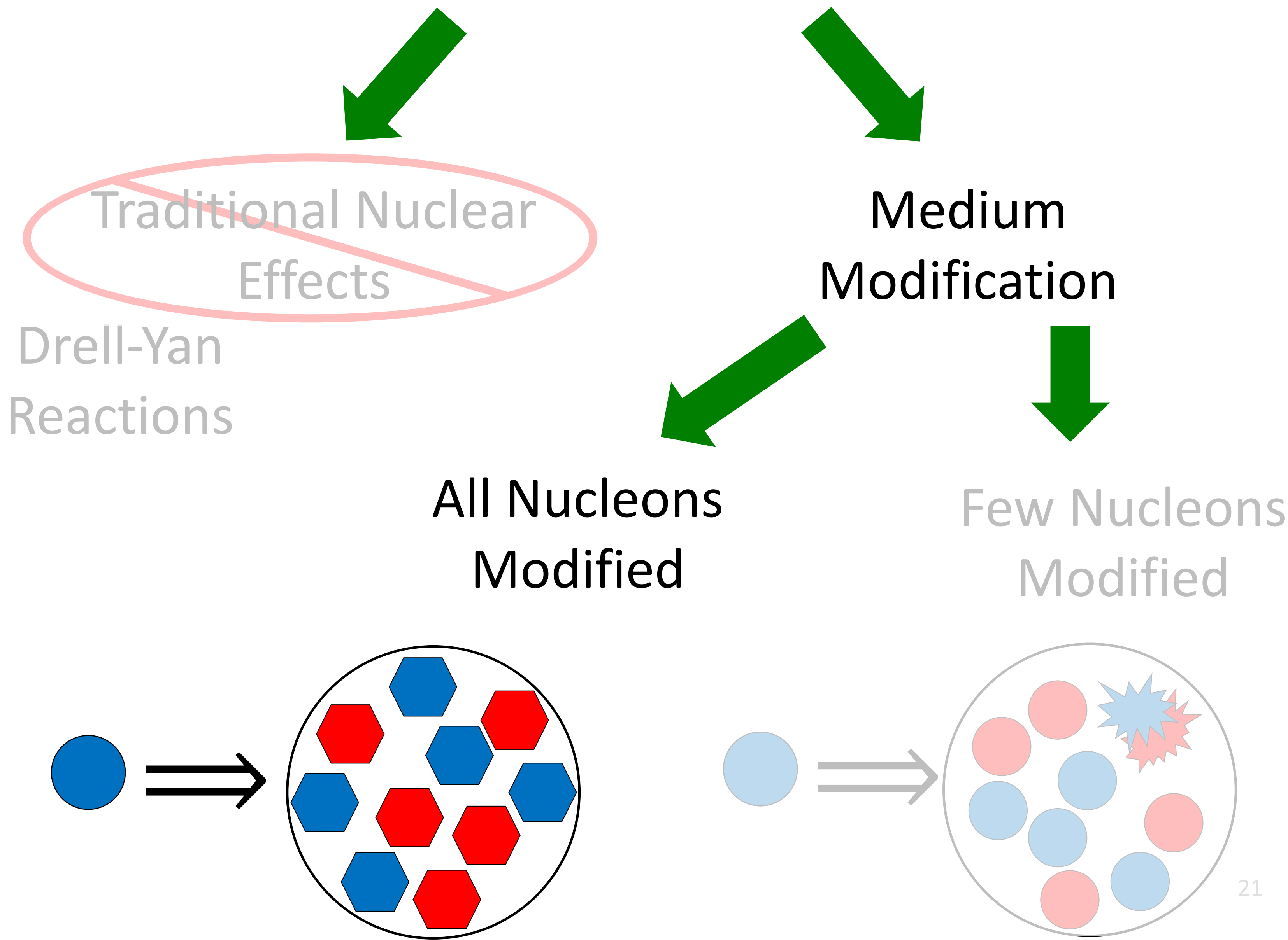
$$xf_i^{p(A)}(x) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5} \qquad c_k(A) = c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$$





Kovarik PRD (2015)

Cause of the EMC Effect?



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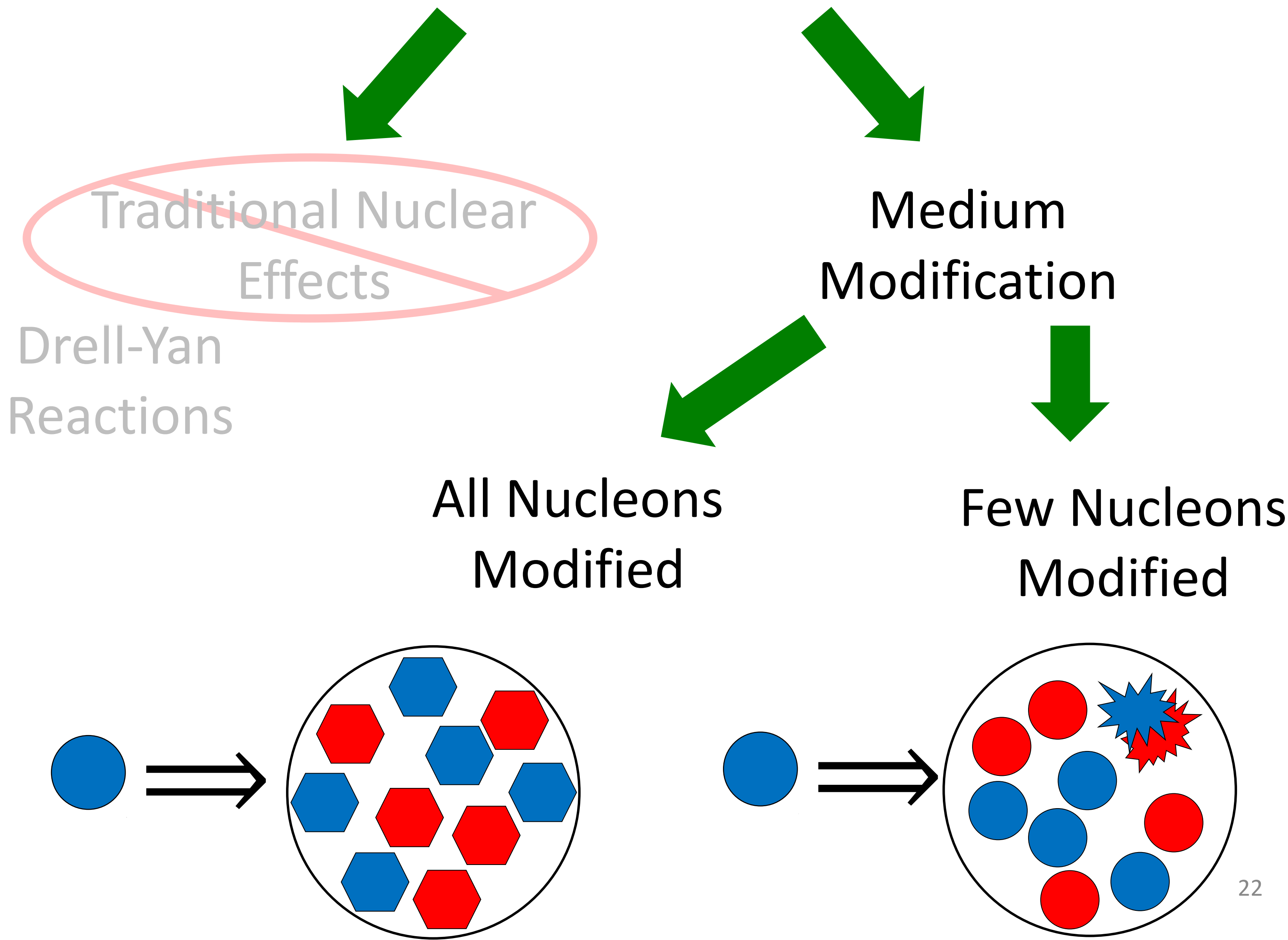
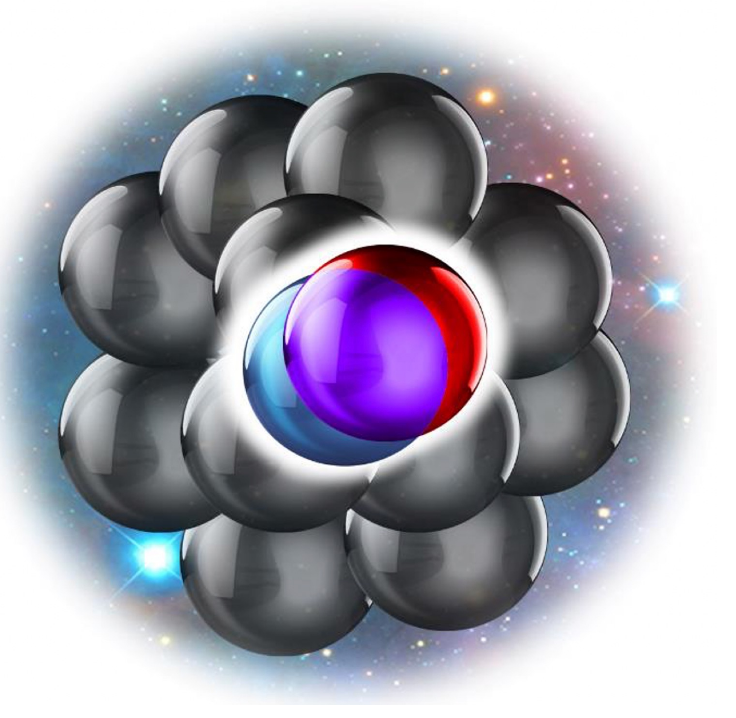


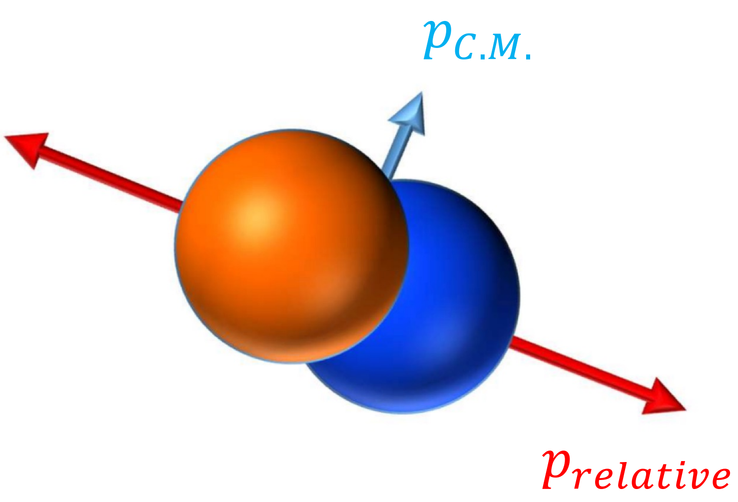
Nuclear Short-Range Correlations

- Pairs with small separation



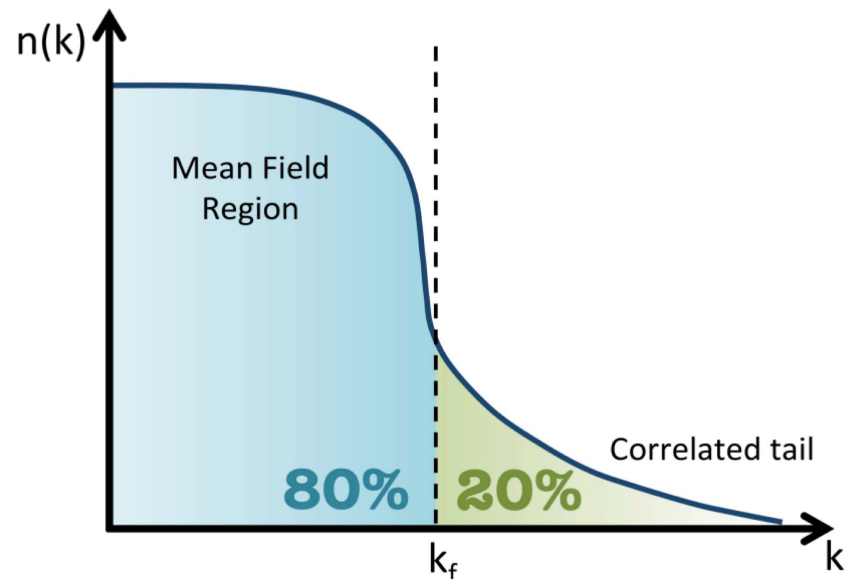
Nuclear Short-Range Correlations

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



Nuclear Short-Range Correlations

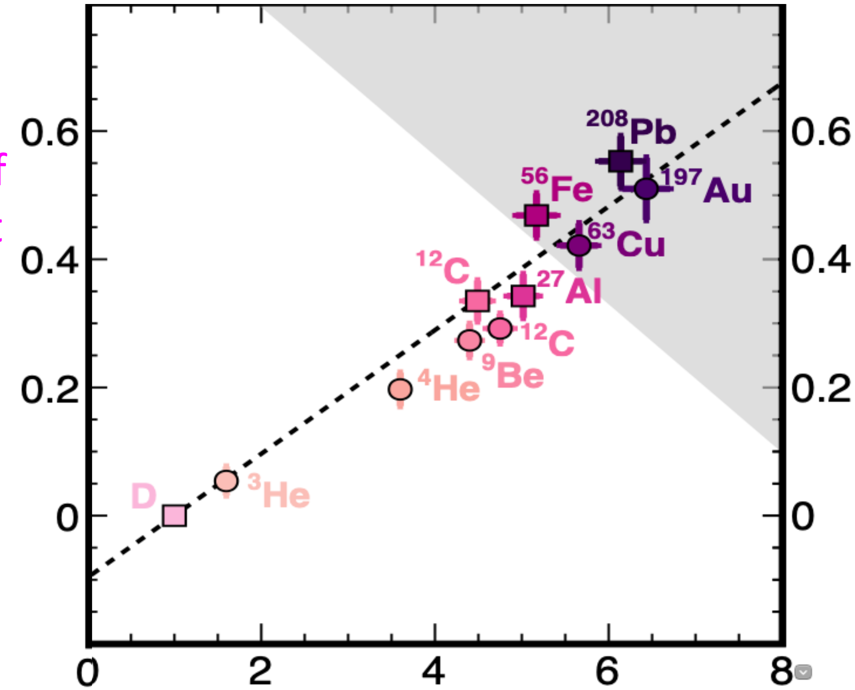
- Pairs with small separation
- High relative momentum compared to k_F
- Significant fraction of the nuclear spectral function



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

Strength of EMC Effect

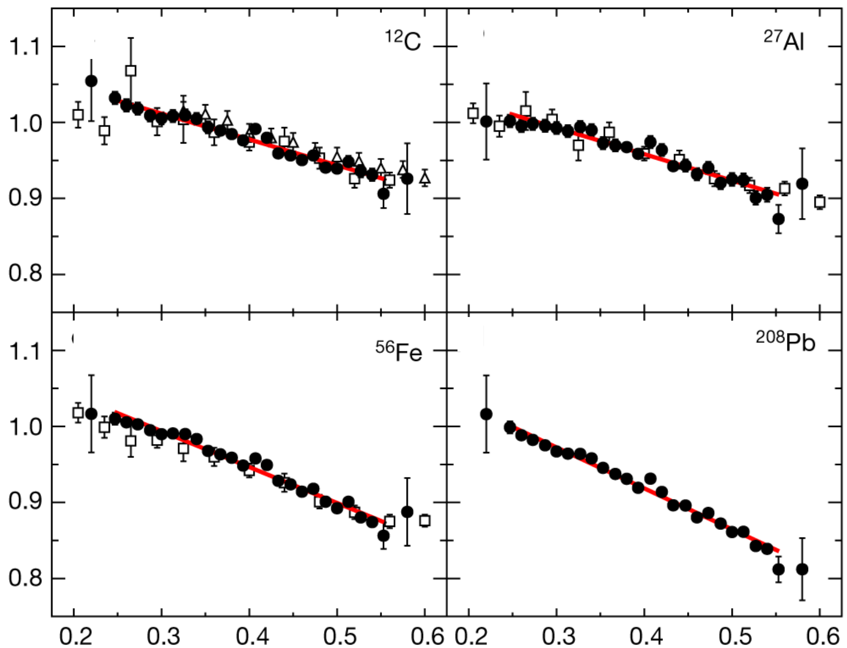


Abundance of SRCs

Schmookler Nature (2019)

Comparing SRCs with the EMC Effect

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

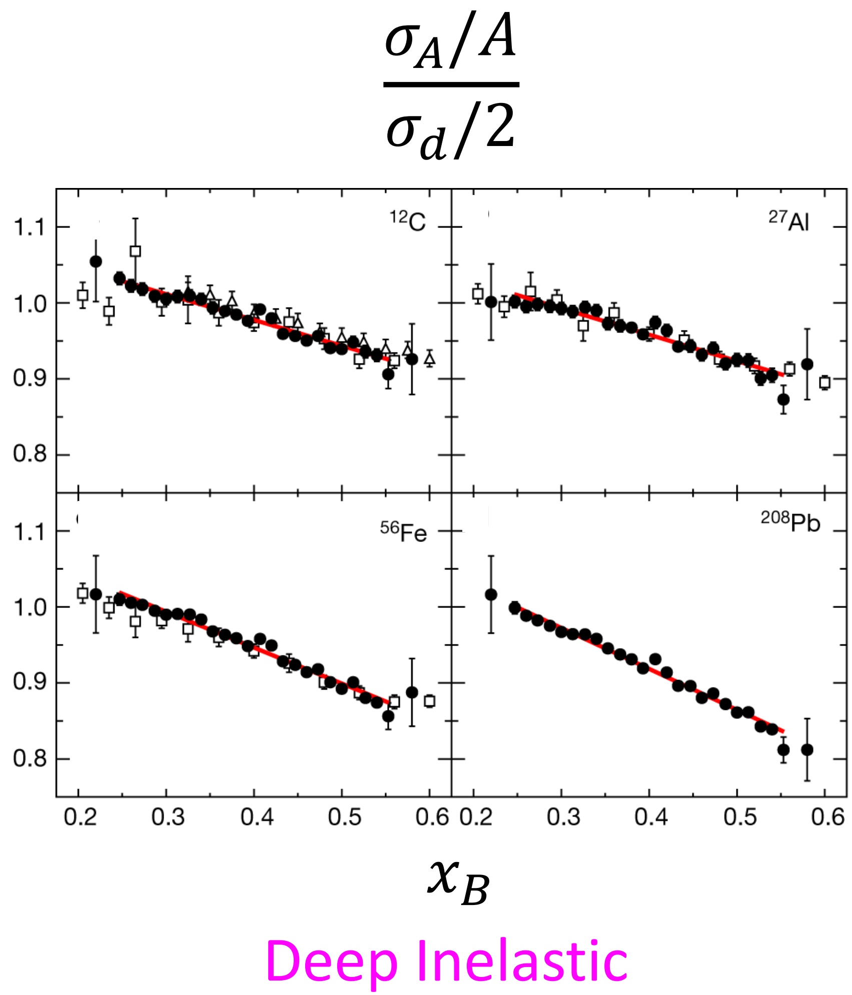


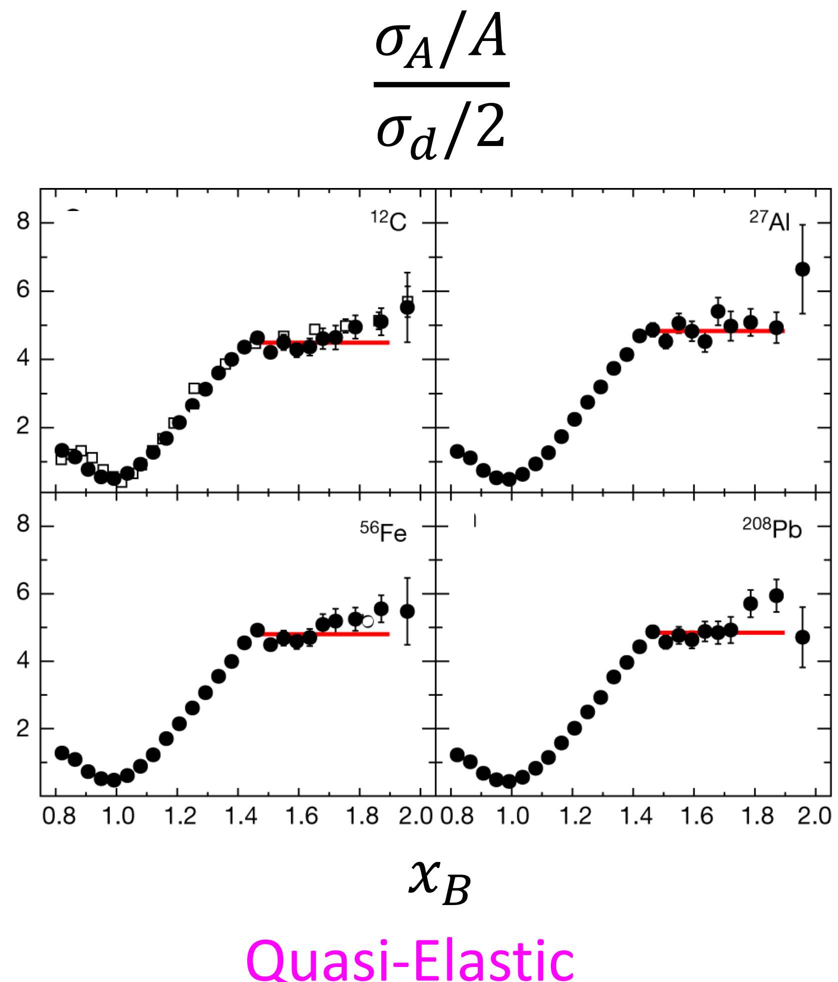
$$x_B$$

Deep Inelastic

Schmookler Nature (2019)

Comparing SRCs with the EMC Effect



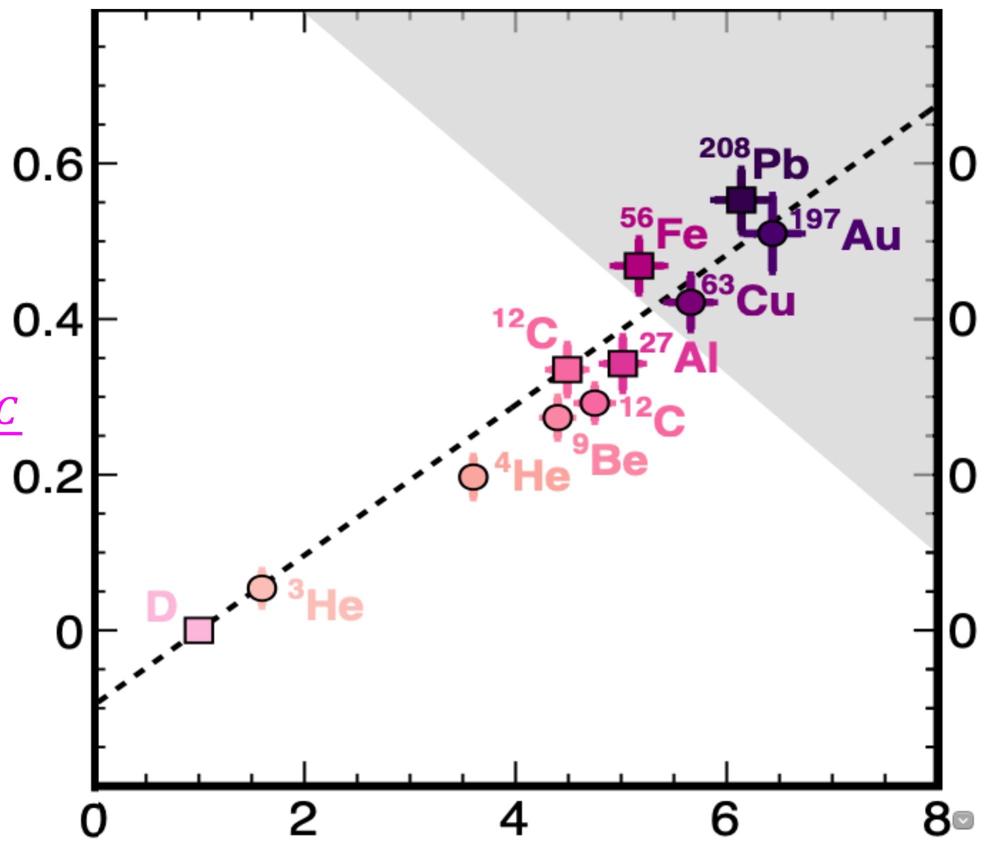


Schmookler Nature (2019)

Comparing SRCs with the EMC Effect

Strength of EMC Effect

$$-\frac{dR^{p}_{EMC}}{dx_B}$$



a_2^p Abundance of SRCs

Schmookler Nature (2019)

Cause of the EMC Effect?

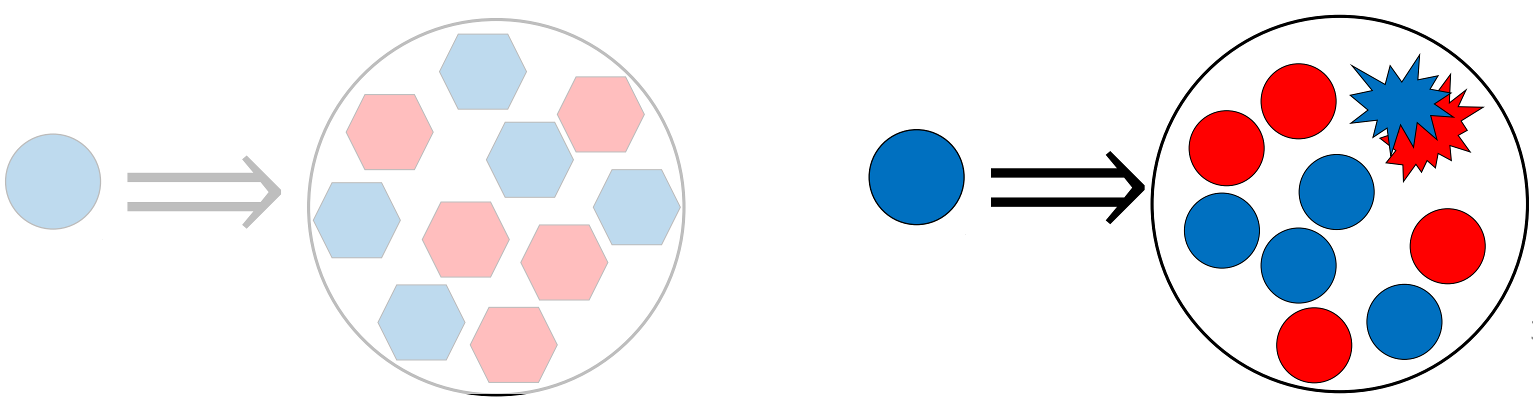
Traditional Nuclear Effects

Drell-Yan Reactions

Medium Modification

All Nucleons Modified

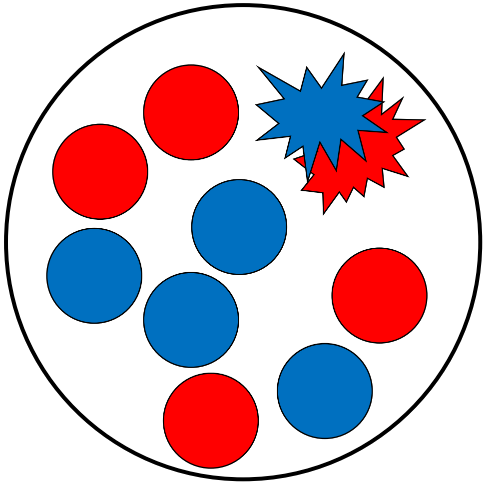
Few Nucleons Modified



Incorporating SRCs

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

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



Incorporating SRCs

Free Nucleons SRC Nucleons

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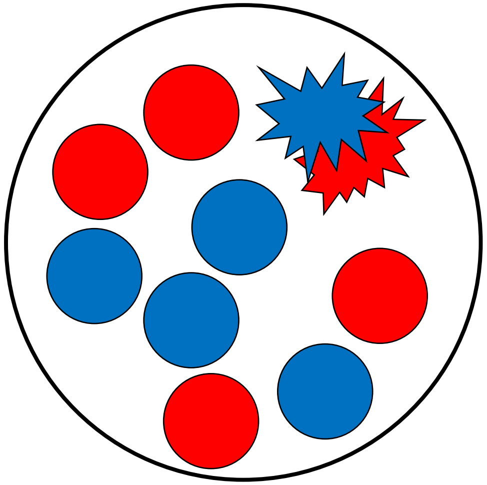


Incorporating SRCs

Free Nucleons SRC Nucleons

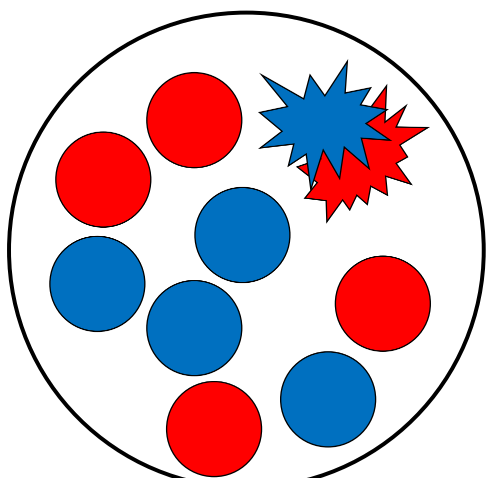
$$f_i^A(x) = \frac{Z}{A}\left[(1-C_p^A)\, f_i^p(x) + C_p^A\, f_i^{SRC\,p}(x)\right] +$$

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

Independent of A

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

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



Incorporating SRCs

Free Nucleons SRC Nucleons

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Independent of A

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

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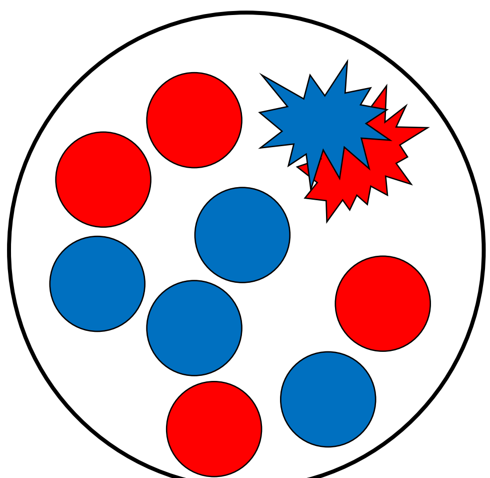

Incorporating SRCs

Free Nucleons SRC Nucleons

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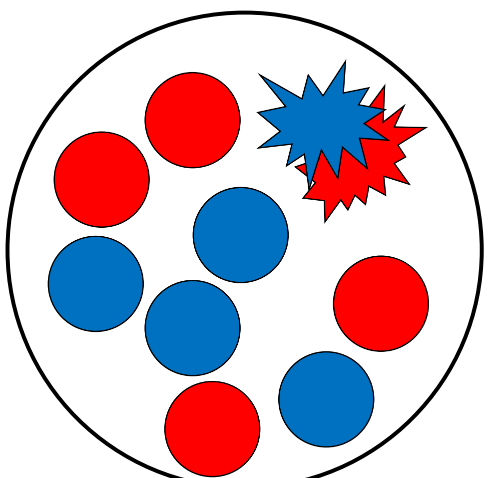
Independent of A

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

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



Depend on A

SRC Abundancies

C_p^A, C_n^A

Incorporating SRCs

Free Nucleons SRC Nucleons

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

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

Inputs of SRC Fit

$f_i^p(x)$ $f_i^n(x)$: **Fixed** from Free Proton PDF

Inputs of SRC Fit

$f_i^p(x)$ $f_i^n(x)$: **Fixed** from Free Proton PDF

$f_i^{SRC\,p}(x)$ $f_i^{SRC\,n}(x)$: **Fitted** Independent of A

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

Inputs of SRC Fit

$f_i^p(x)$ $f_i^n(x)$: **Fixed** from Free Proton PDF

$f_i^{SRC\,p}(x)$ $f_i^{SRC\,n}(x)$: **Fitted** Independent of A

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

C_p^A C_n^A: **Fitted** Dependent on A

Details of Fit:

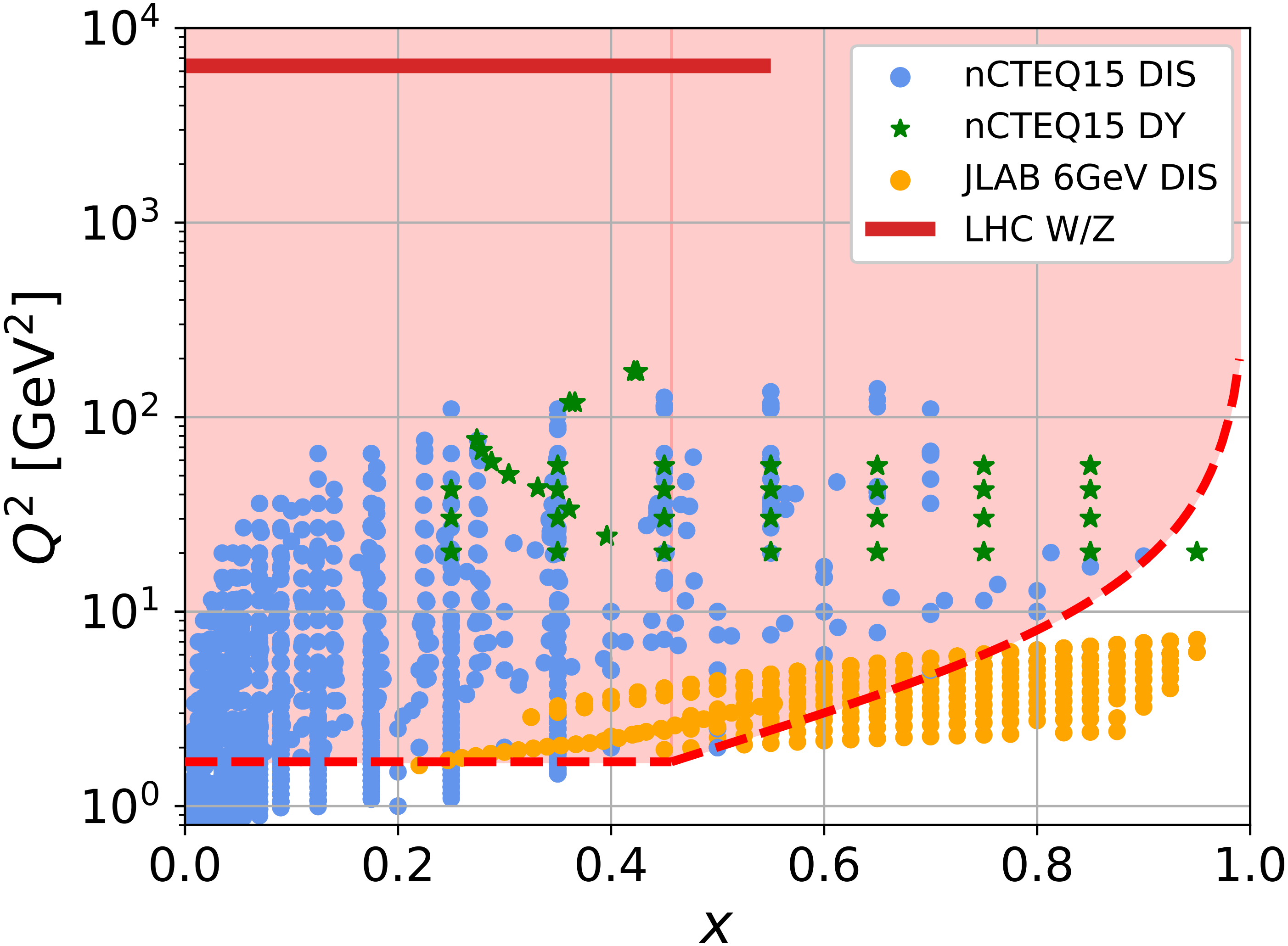
1. Minimize χ^2
2. Cut out non-DIS kinematics
3. Satisfy Sum Rules
4. Full Theoretical Calculations
5. DGLAP Evolve PDFs
6. All PDFs are defined for $x \in (0,1)$

$$\int_0^1 dx\, x f_i^A(x,Q) = 1 \qquad \int_0^1 dx\, f_{u_v}^A(x,Q) = \frac{A+Z}{A} \qquad \int_0^1 dx\, f_{d_v}^A(x,Q) = \frac{A+N}{A}$$

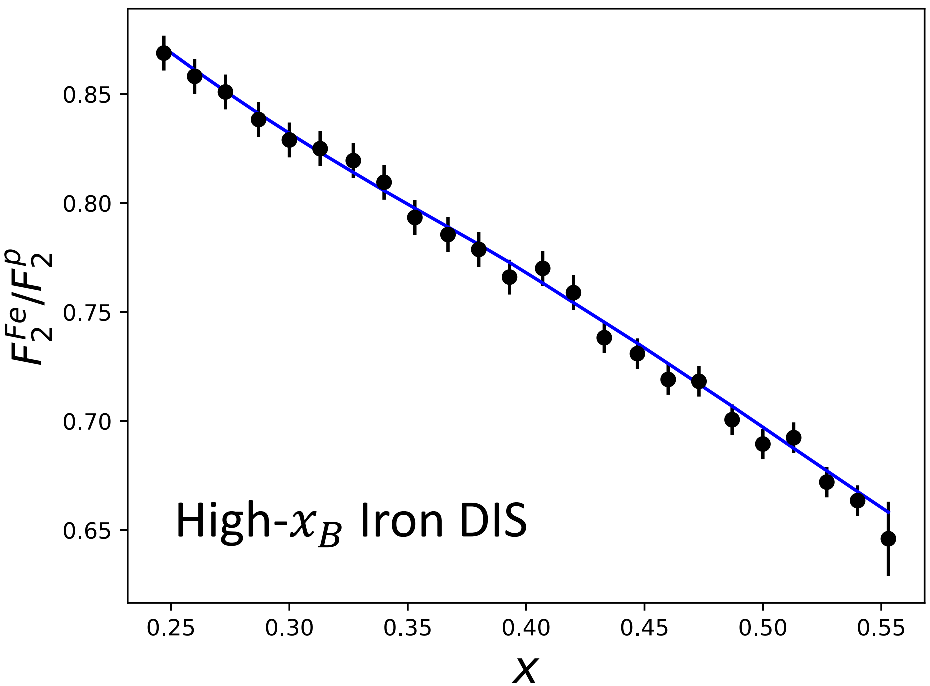
$$F_2^{A,Z}(x,Q) = \sum_i C_i\,(x,Q) \otimes f_{\mathrm{i}}^{A,Z}(x,Q)$$

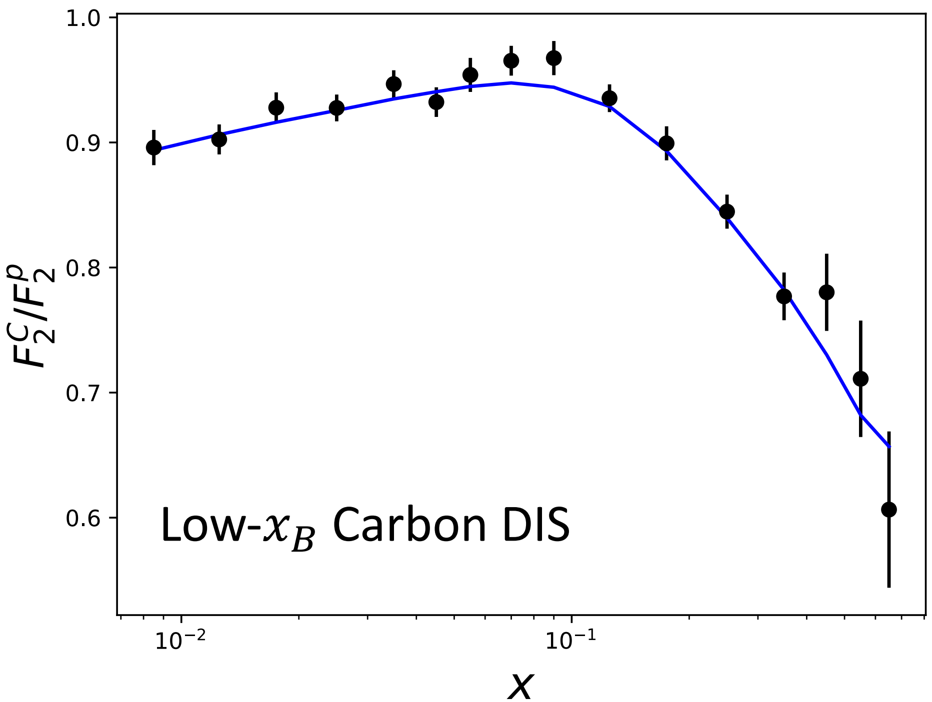
World Data to Fit:

$Q > 1.3\ GeV$
$W > 1.7\ GeV$

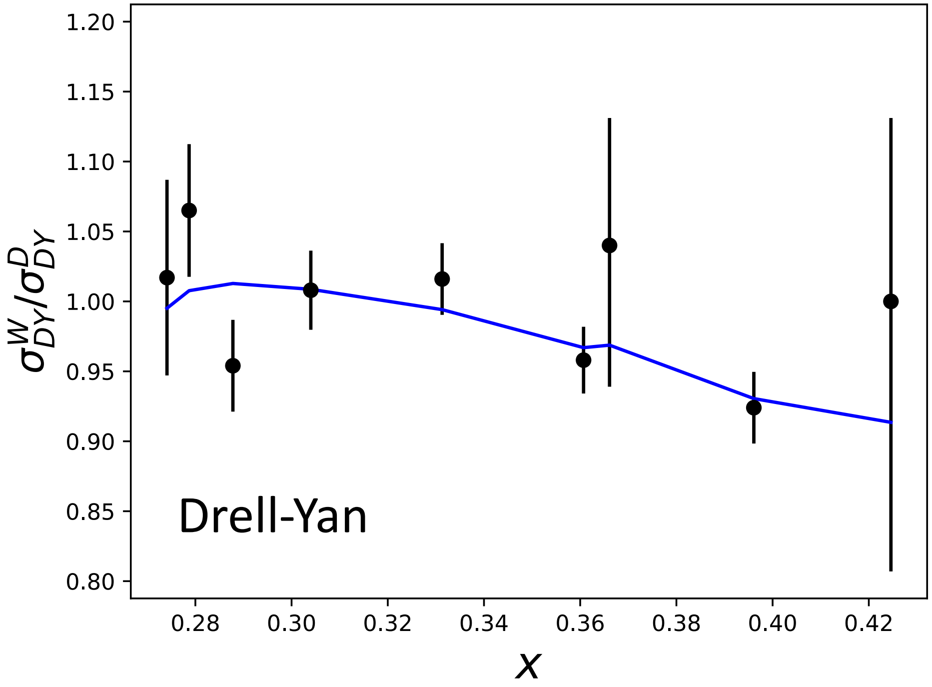


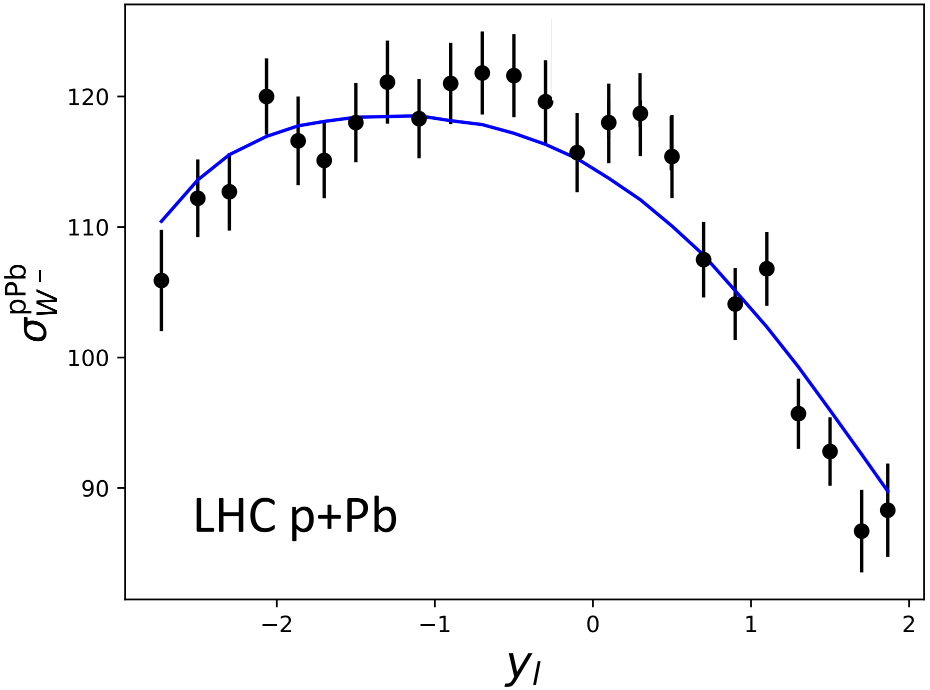
Fit Over Wide x_B Range





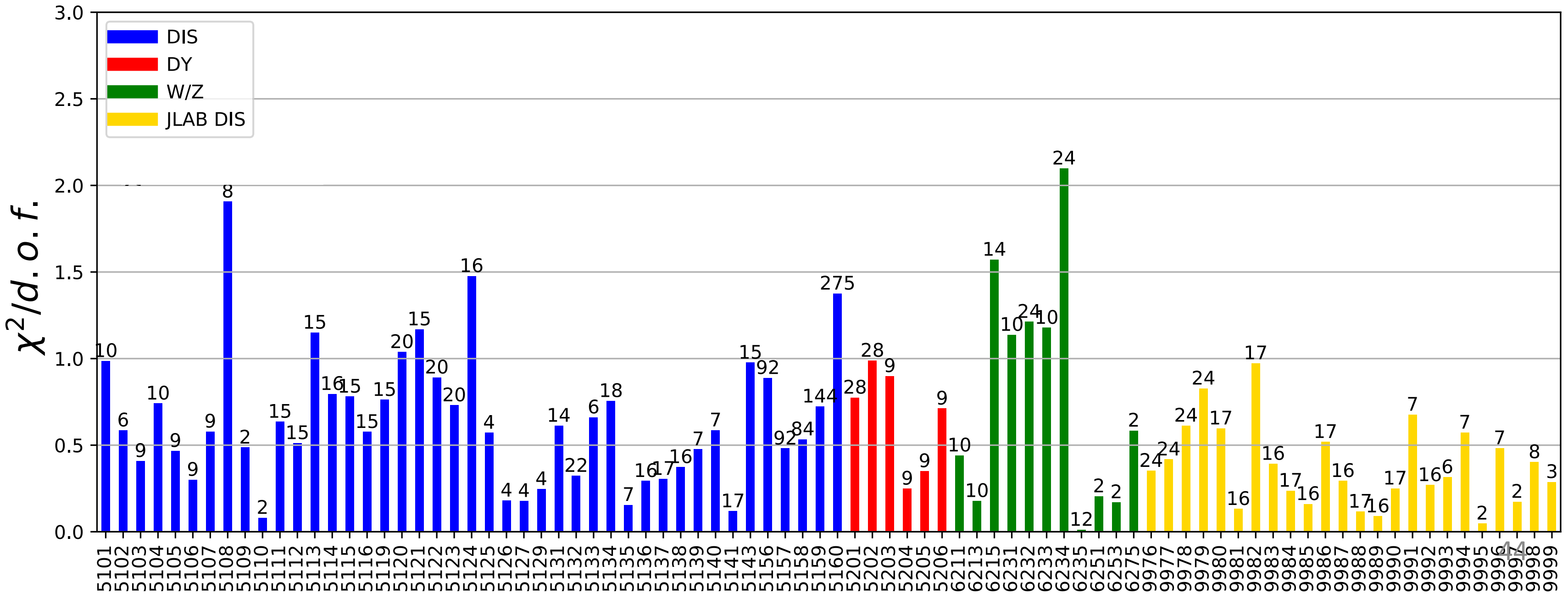
Drell-Yan and W Production are Well Described





Fit Result:

χ^2/N_{data}	$\frac{\chi^2_{\text{tot}}}{N_{\text{DOF}}}$
All Modified	0.85
SRC	0.80



Inputs of SRC Fit

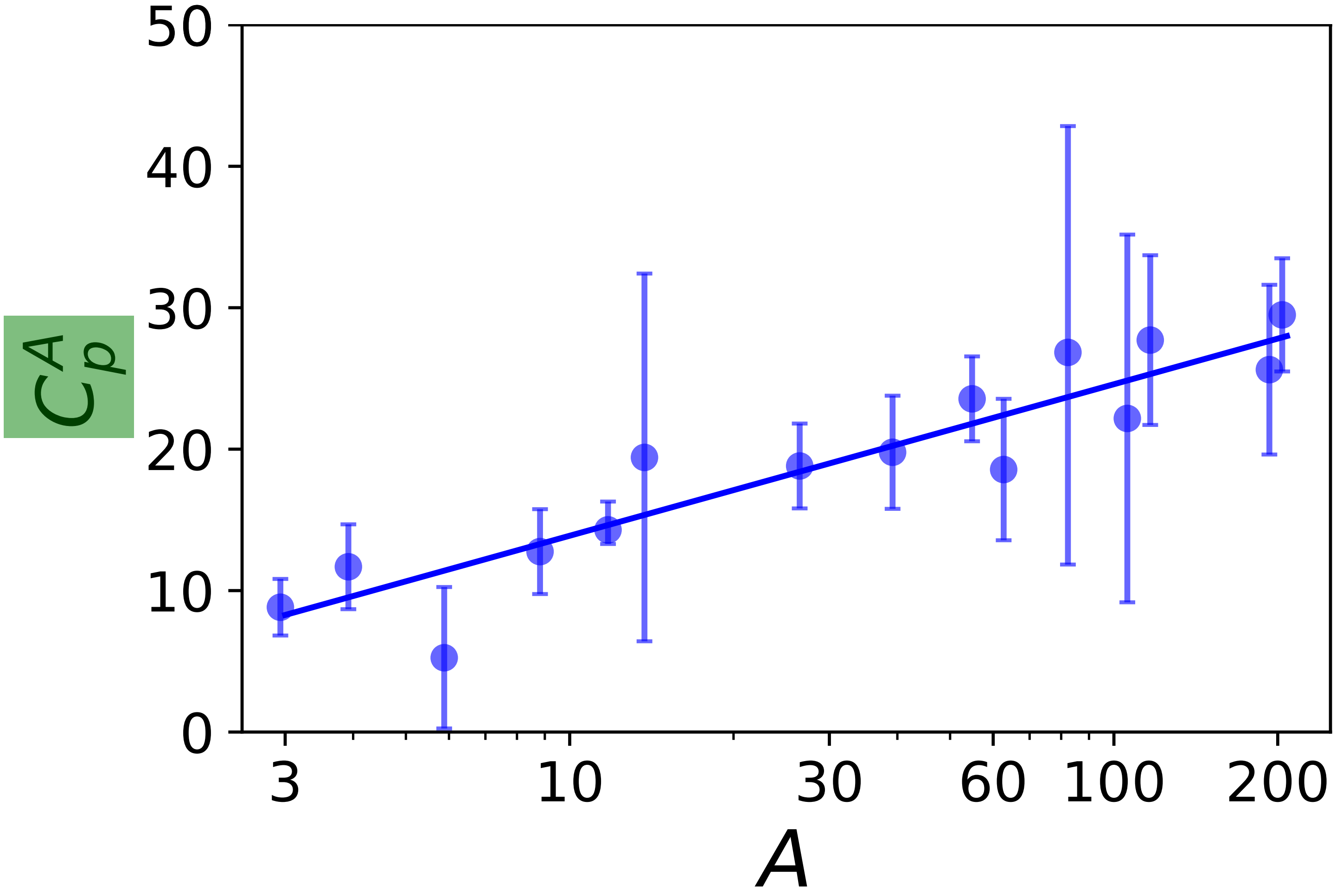
$f_i^p(x)$ $f_i^n(x)$: **Fixed** from Free Proton PDF

$f_i^{SRC\,p}(x)$ $f_i^{SRC\,n}(x)$: **Fitted** Independent of A

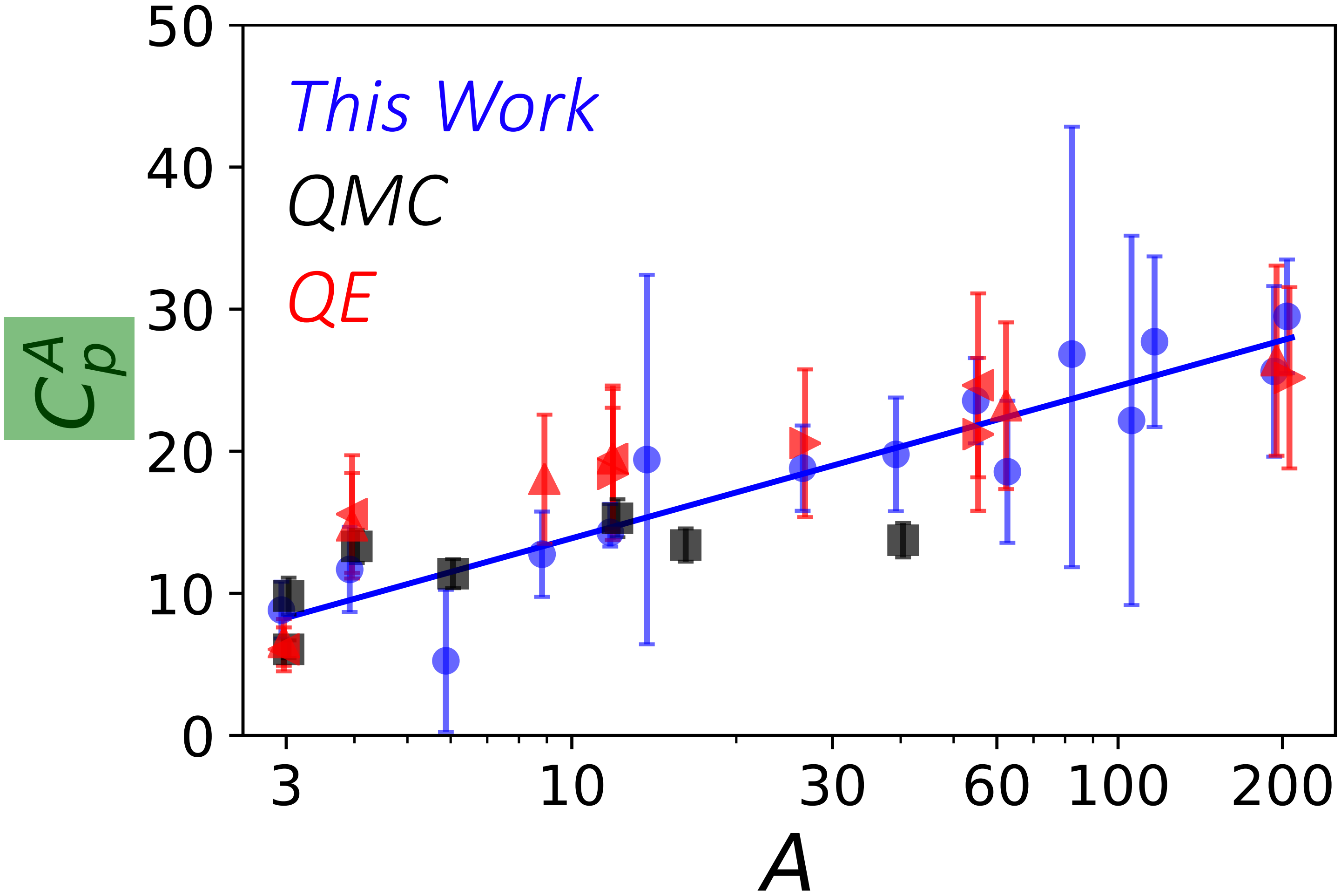
$$x f_i^{p(A)}(x) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4} x)^{c_5}$$

C_p^A C_n^A: **Fitted** Dependent on A

How Many SRCs do we expect?



Nuclear Physics Extracted from Parton Measurements



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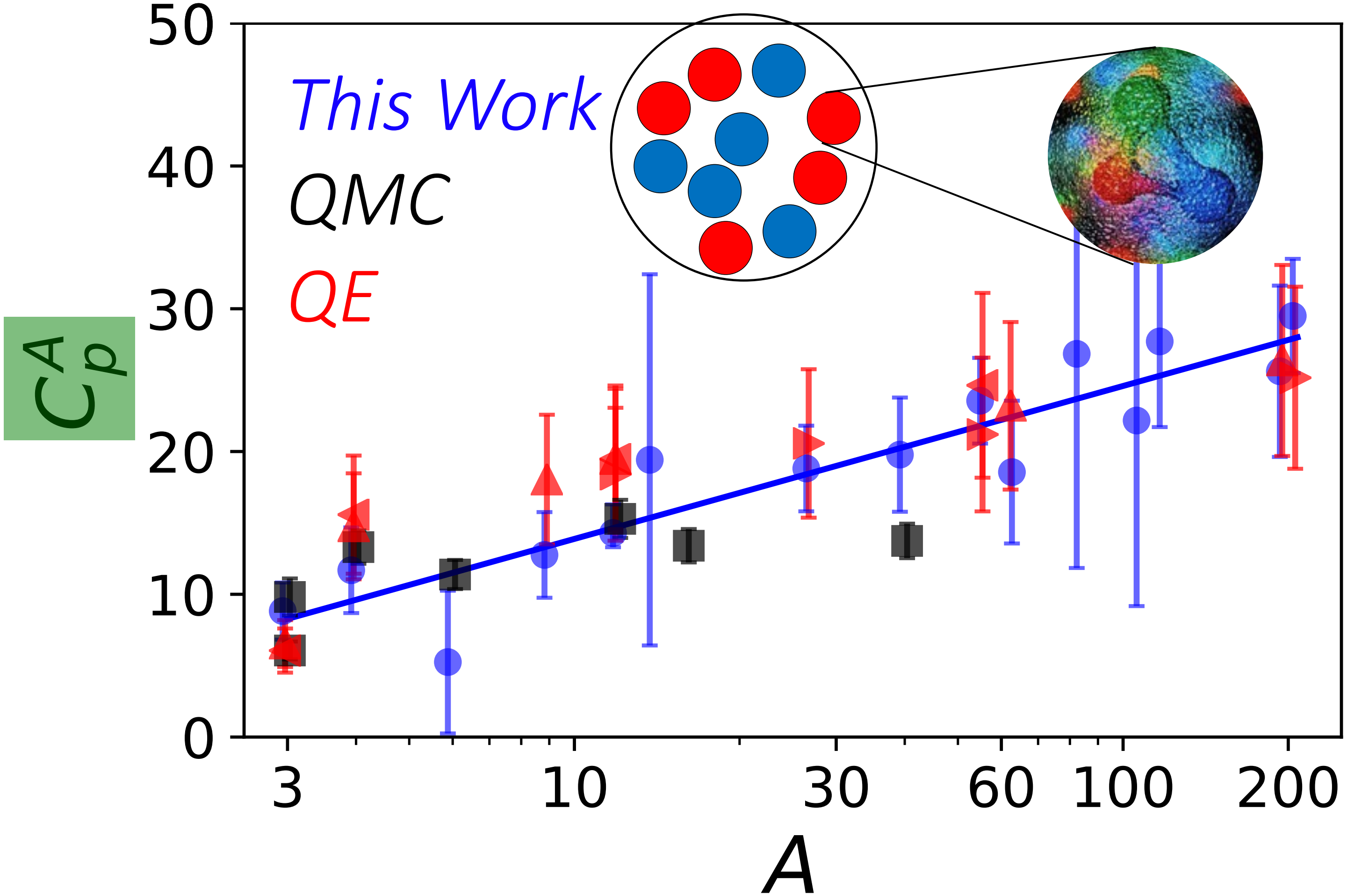
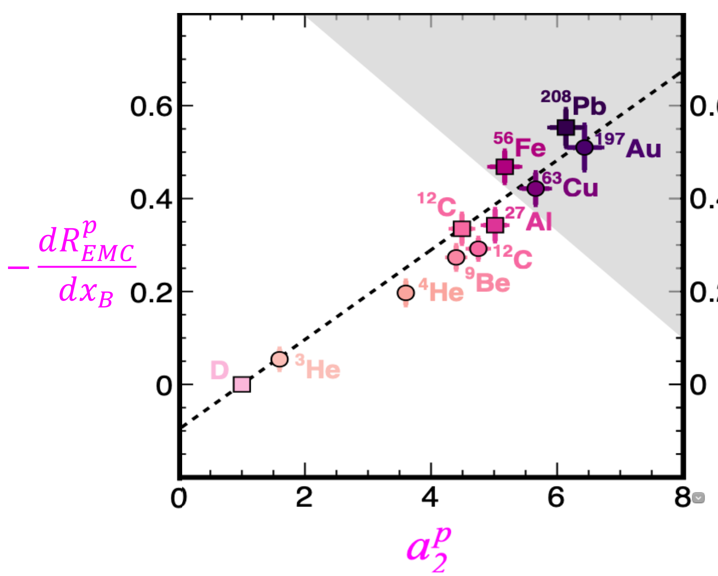


Beyond the SRC-EMC Relation

SRC ⟺ EMC



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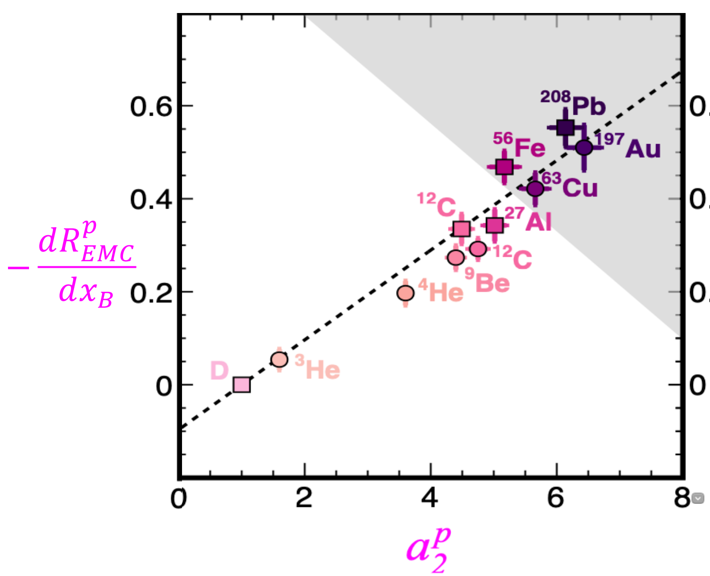
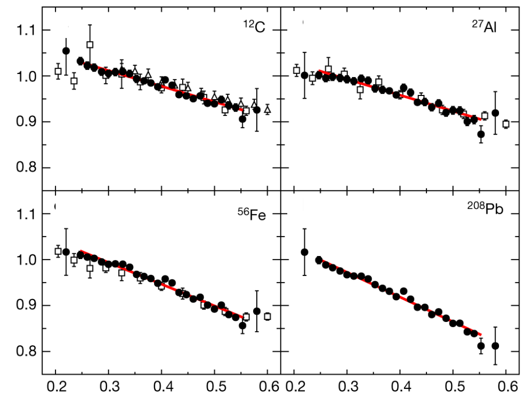
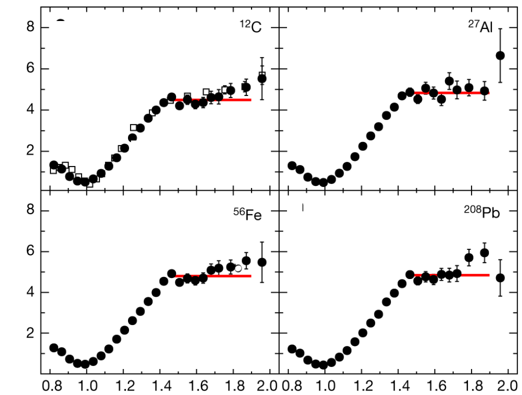


$\frac{\sigma_A/A}{\sigma_d/2}$



x_B

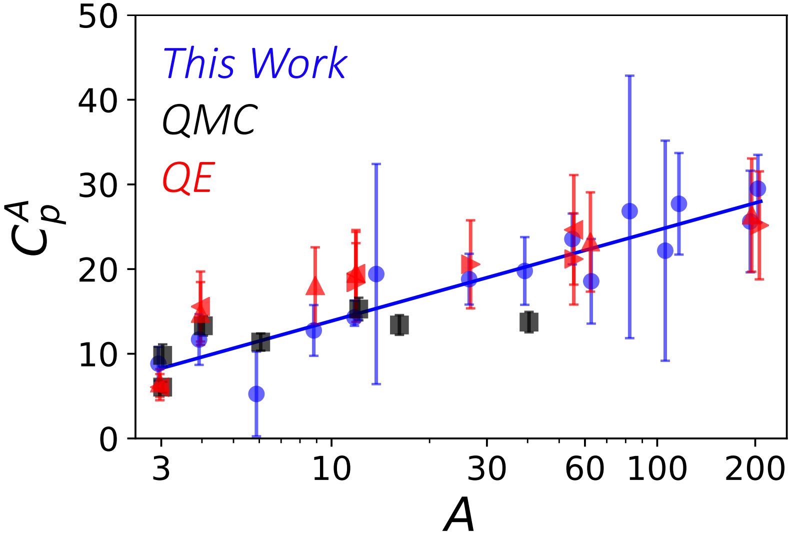
$\frac{\sigma_A/A}{\sigma_d/2}$

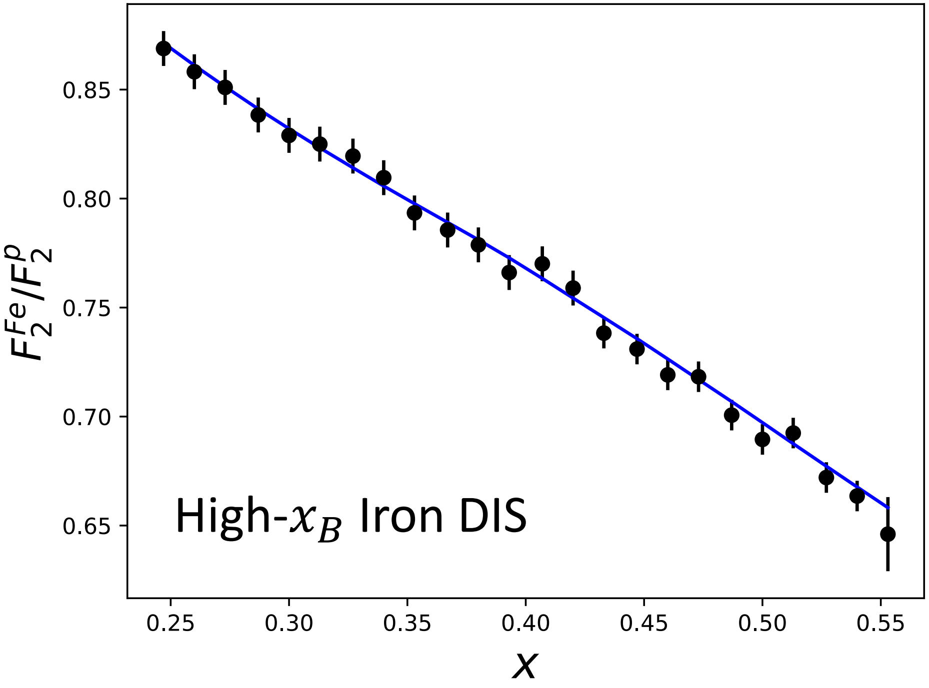


x_B

Beyond the SRC-EMC Relation

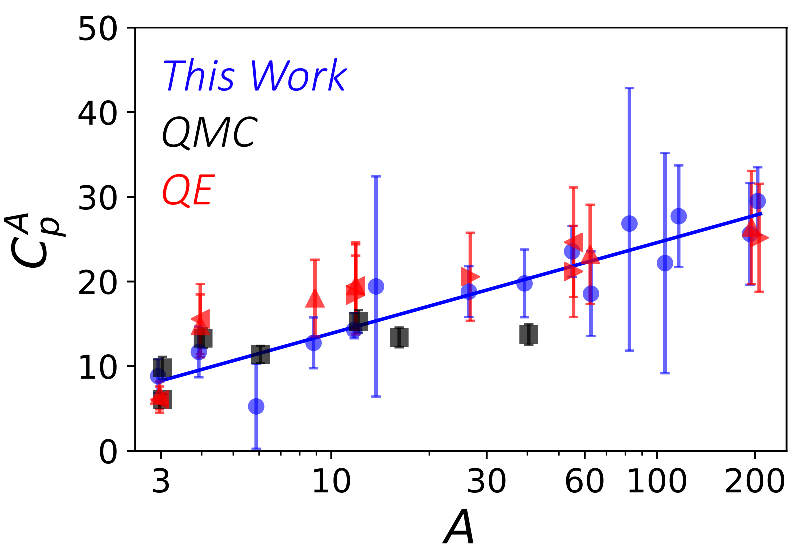
SRC ⟺ EMC

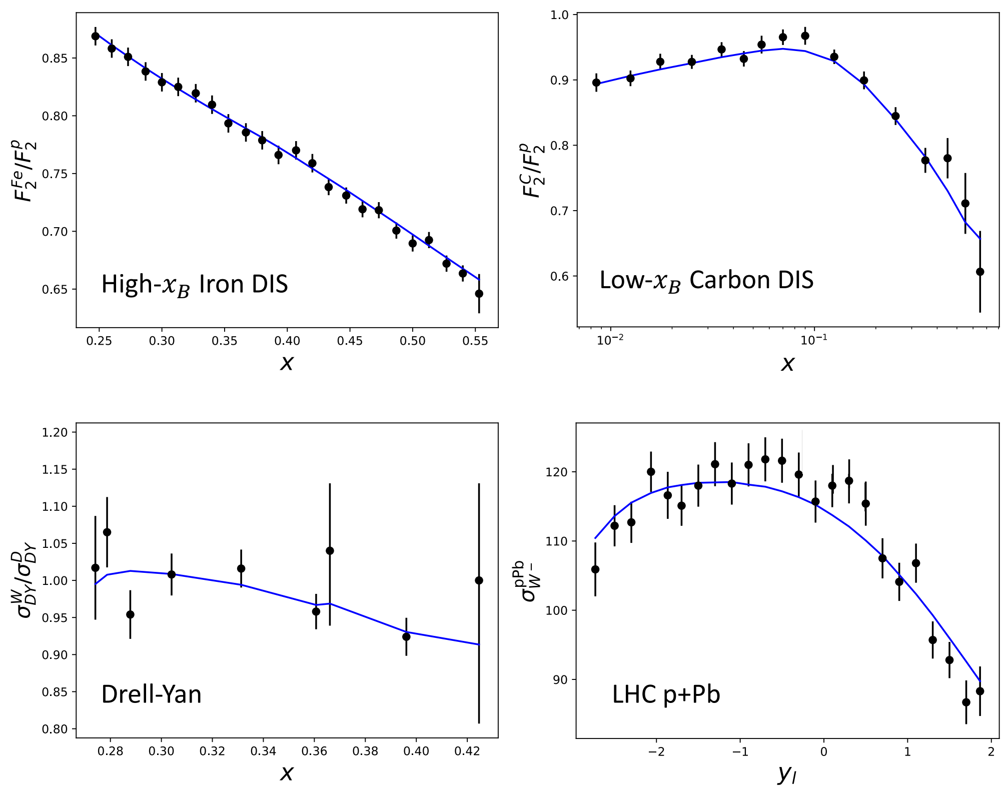




Beyond the SRC-EMC Relation

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





Inputs of SRC Fit

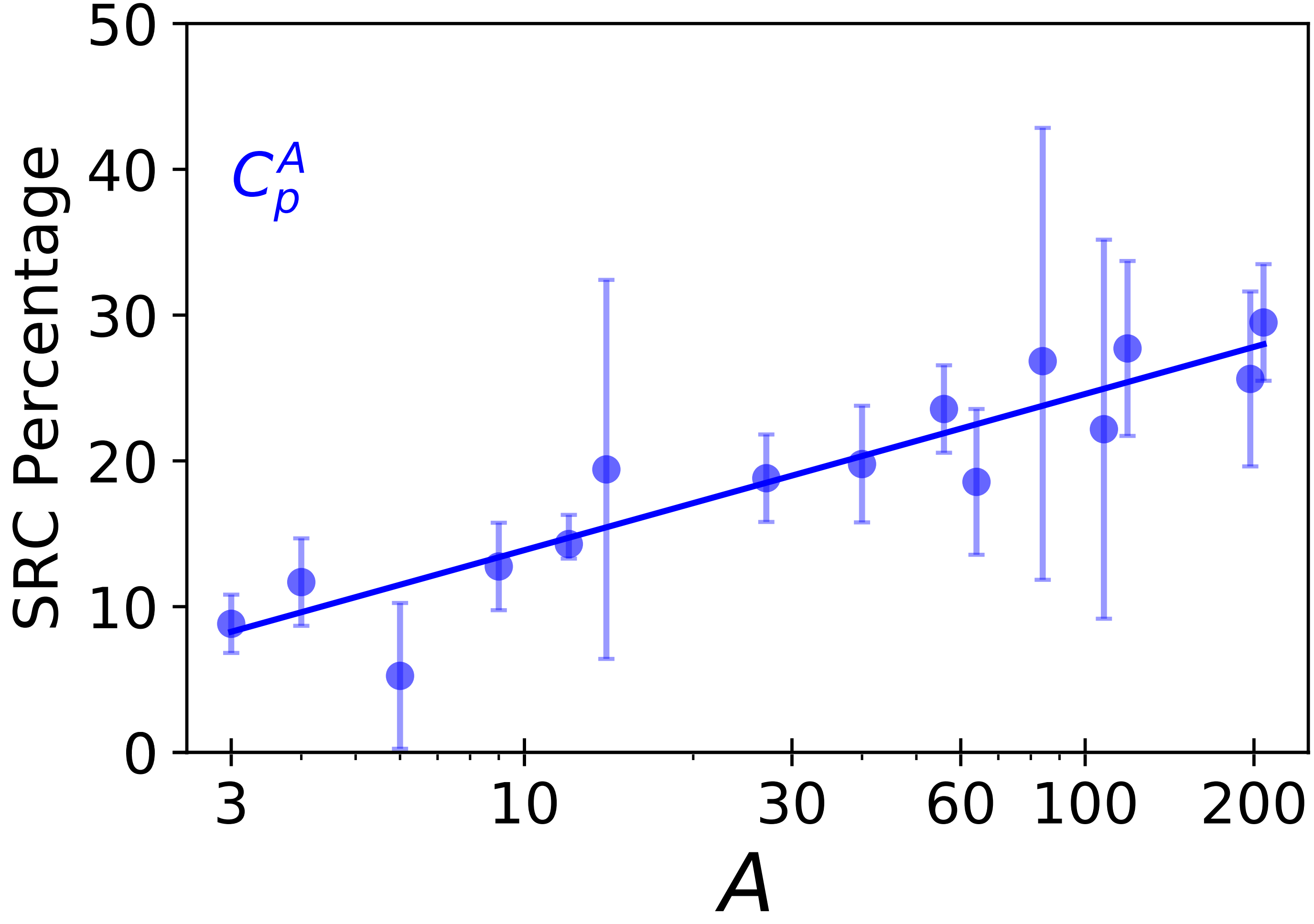
$f_i^p(x)$ $f_i^n(x)$: **Fixed** from Free Proton PDF

$f_i^{SRC\,p}(x)$ $f_i^{SRC\,n}(x)$: **Fitted** Independent of A

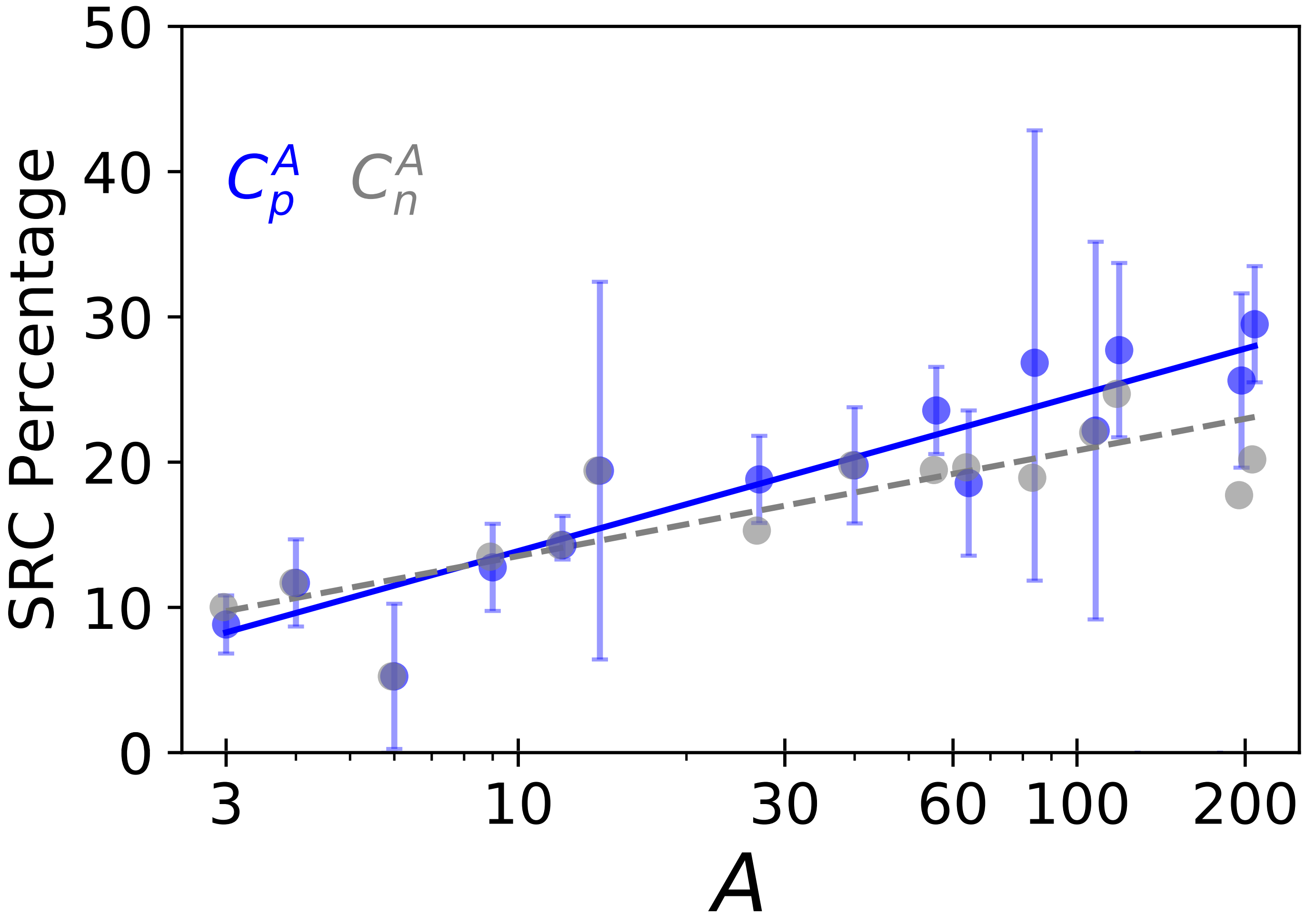
$$xf_i^{p(A)}(x) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5}$$

C_p^A C_n^A: **Fitted** Dependent on A

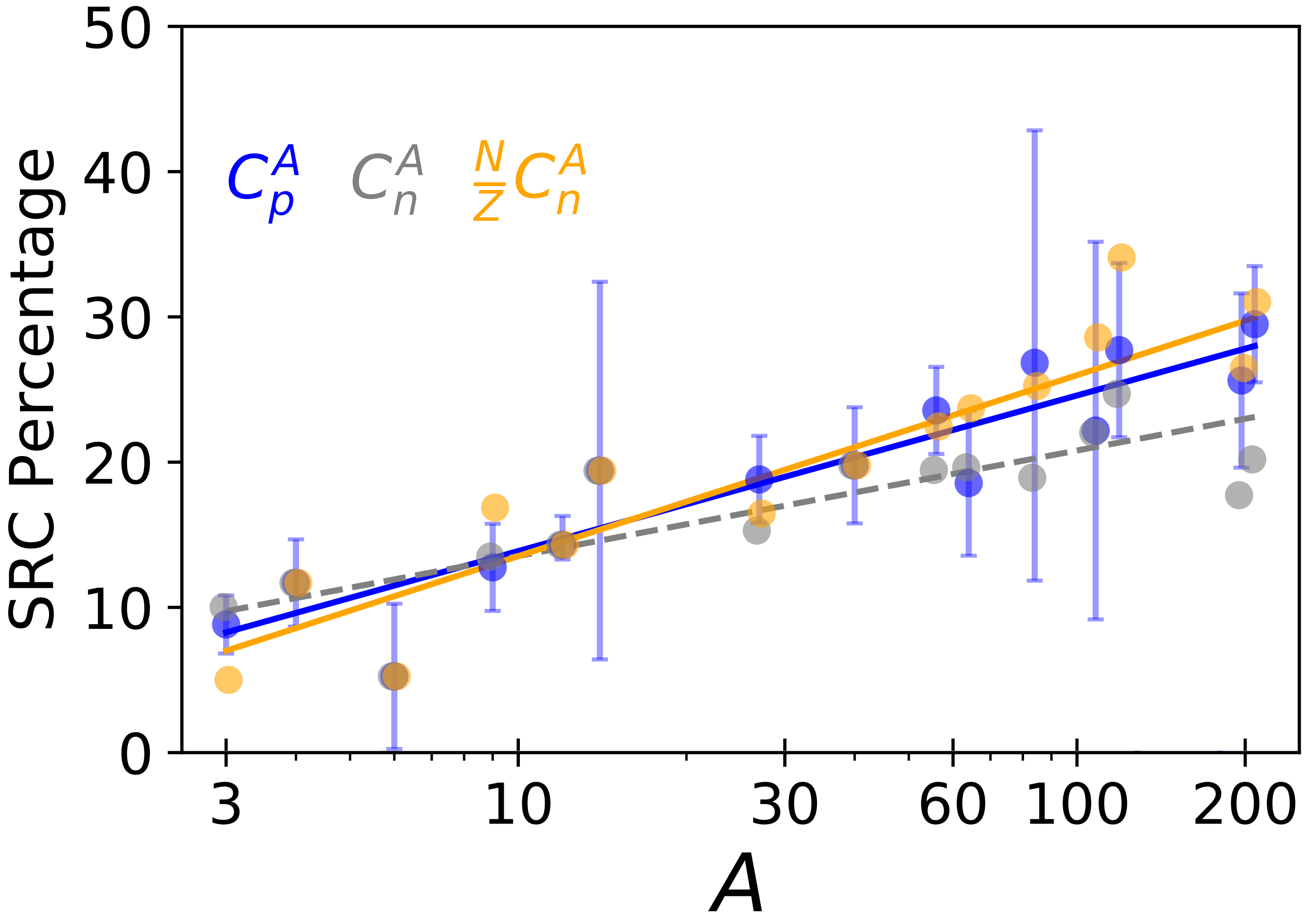
Neutron Abundance? C_n^A



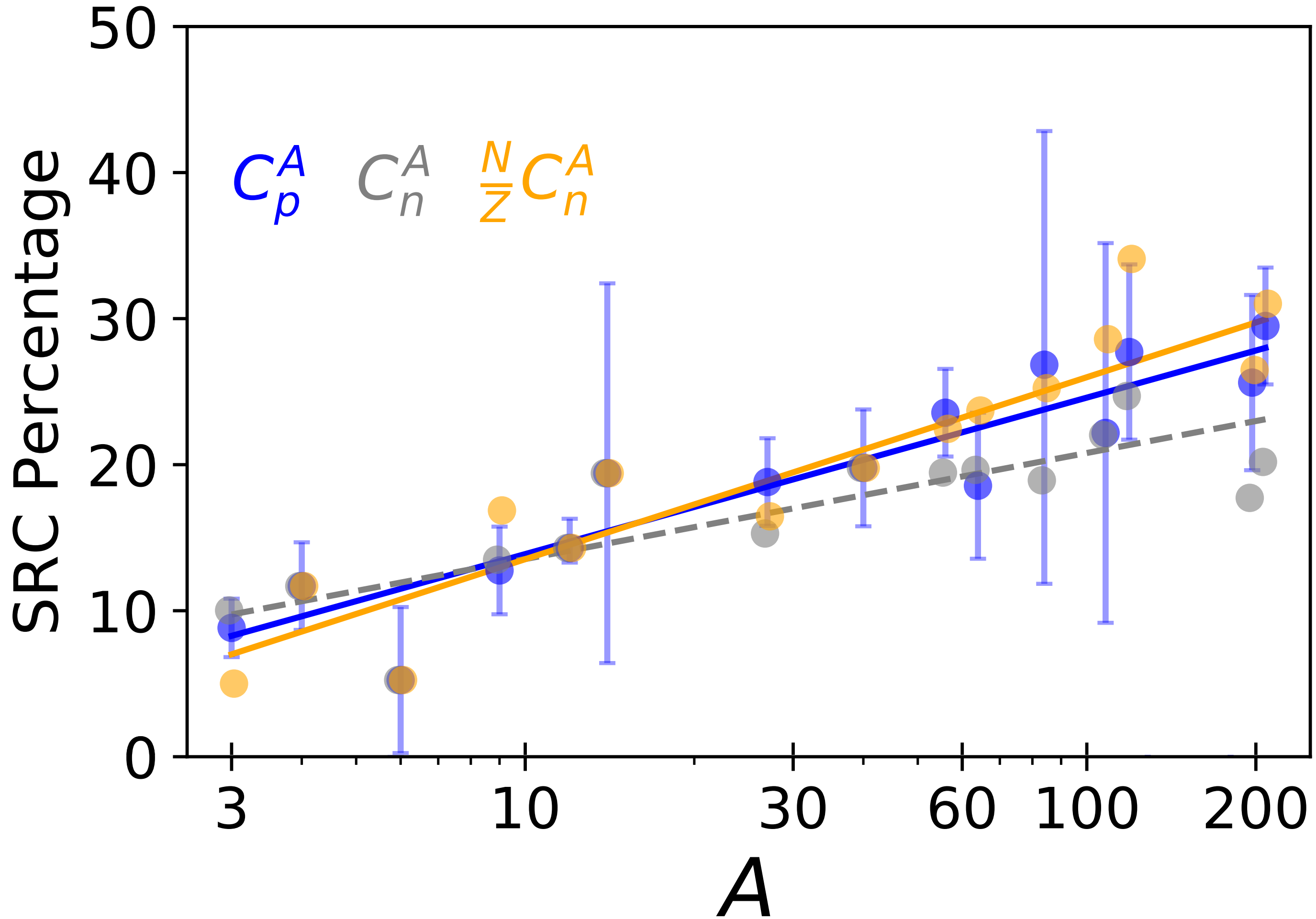
Neutron Abundance? C_n^A



Neutron Abundance? C_n^A

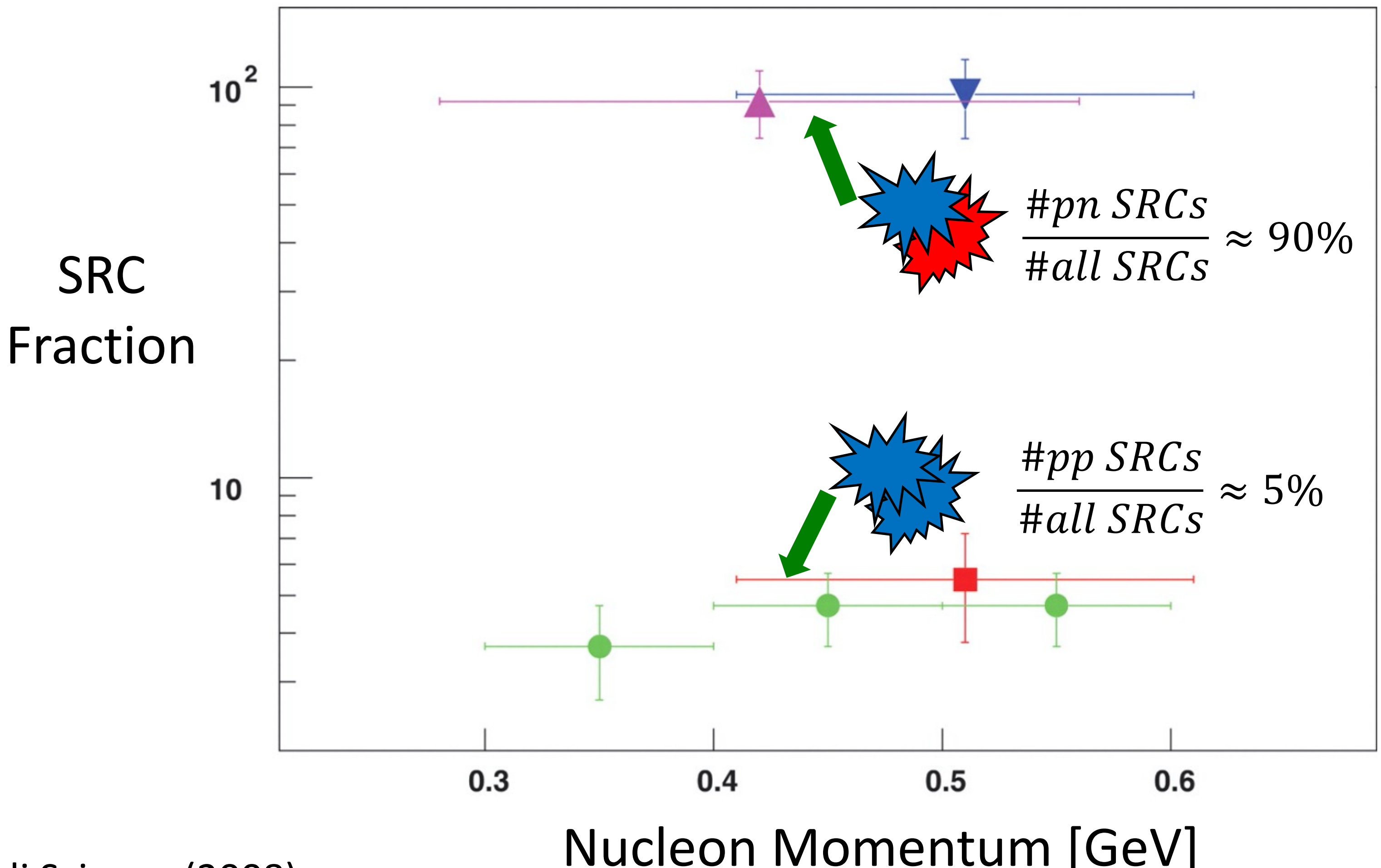


Neutron Abundance? C_n^A



$\#SRC\ Protons = \#SRC\ Neutrons$

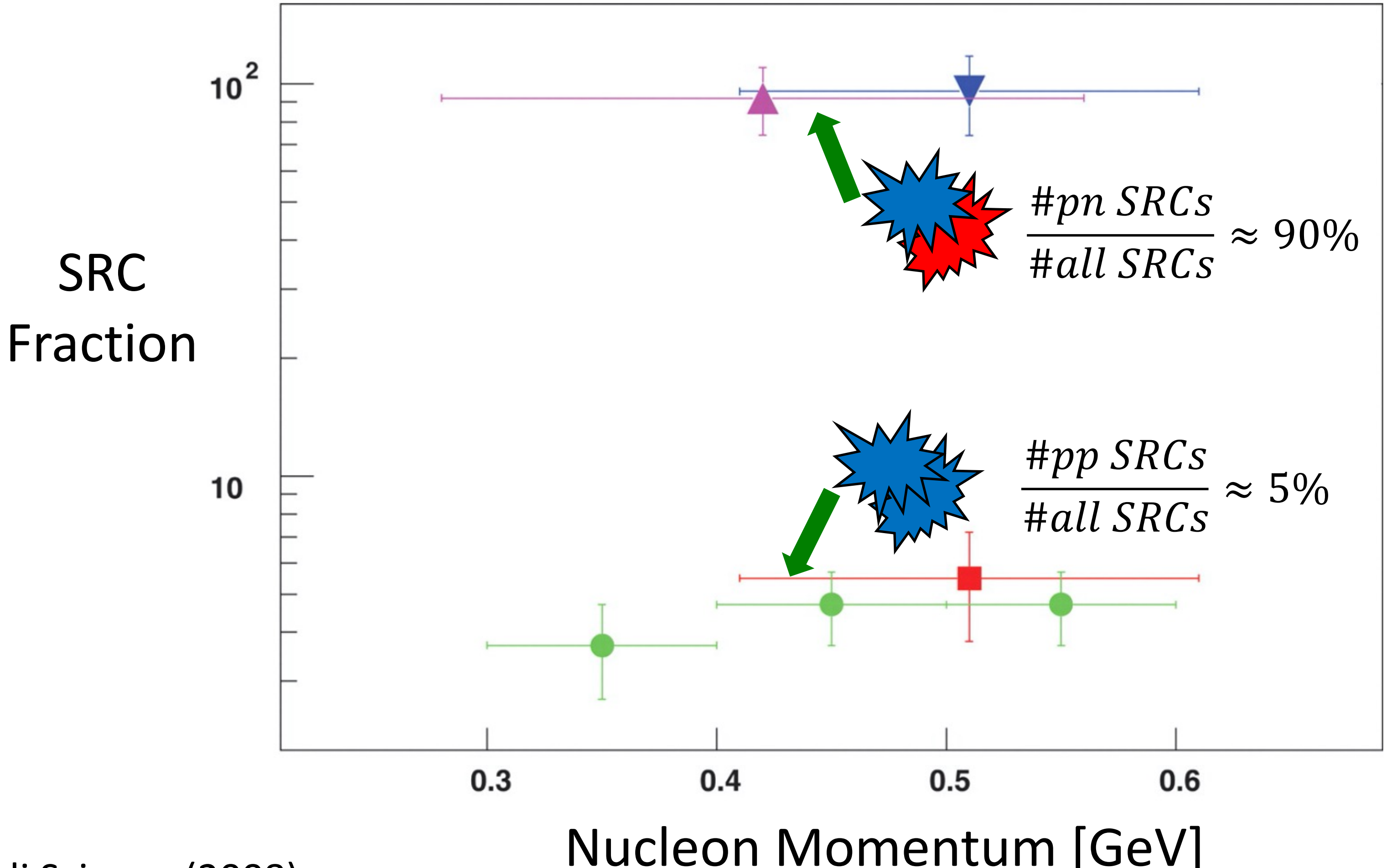
Proton-Neutron Pairs Dominate



Subedi Science (2008)

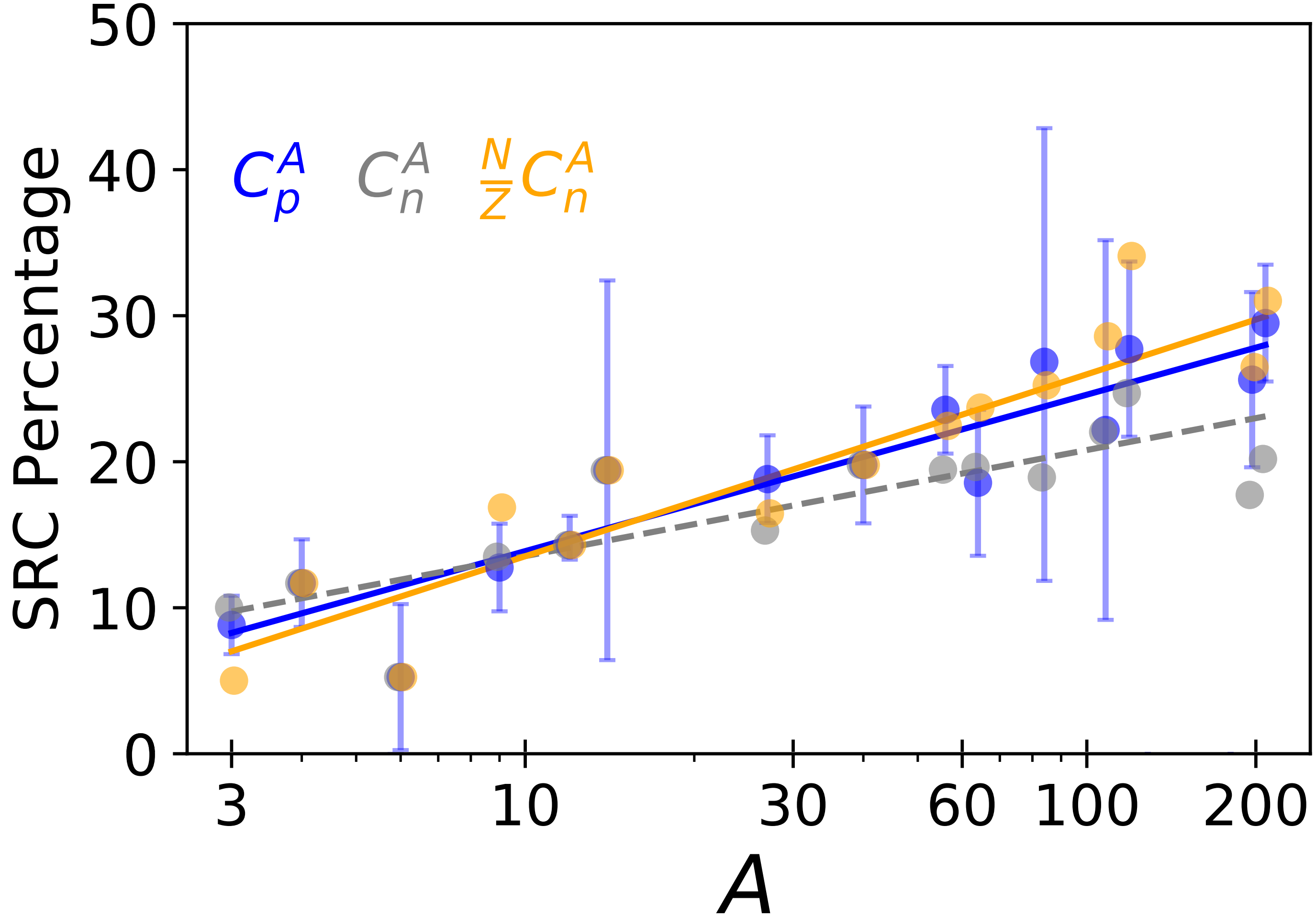
Proton-Neutron Pairs Dominate

Equal number of SRC protons and neutrons.



Subedi Science (2008)

Neutron abundance is consistent with SRC pn-dominance



$\#SRC\ Protons = \#SRC\ Neutrons$

Inputs of SRC Fit

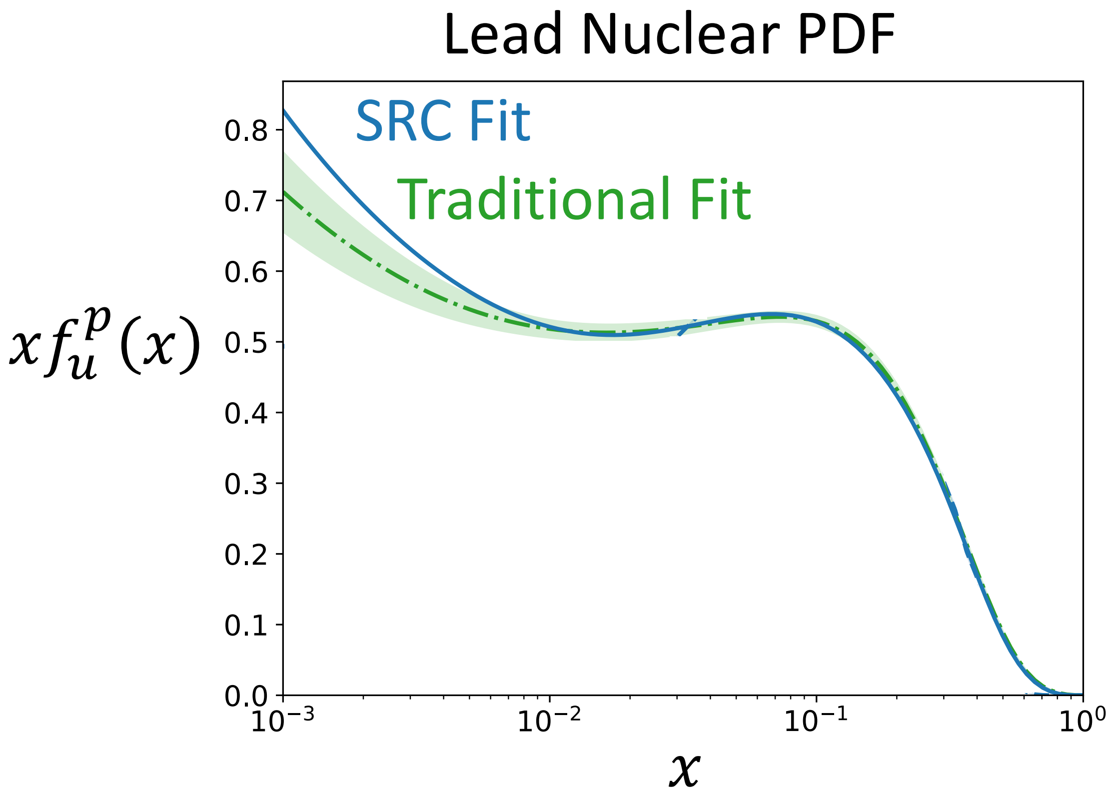
$f_i^p(x)$ $f_i^n(x)$: **Fixed** from Free Proton PDF

$f_i^{SRC\,p}(x)$ $f_i^{SRC\,n}(x)$: **Fitted** Independent of A

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

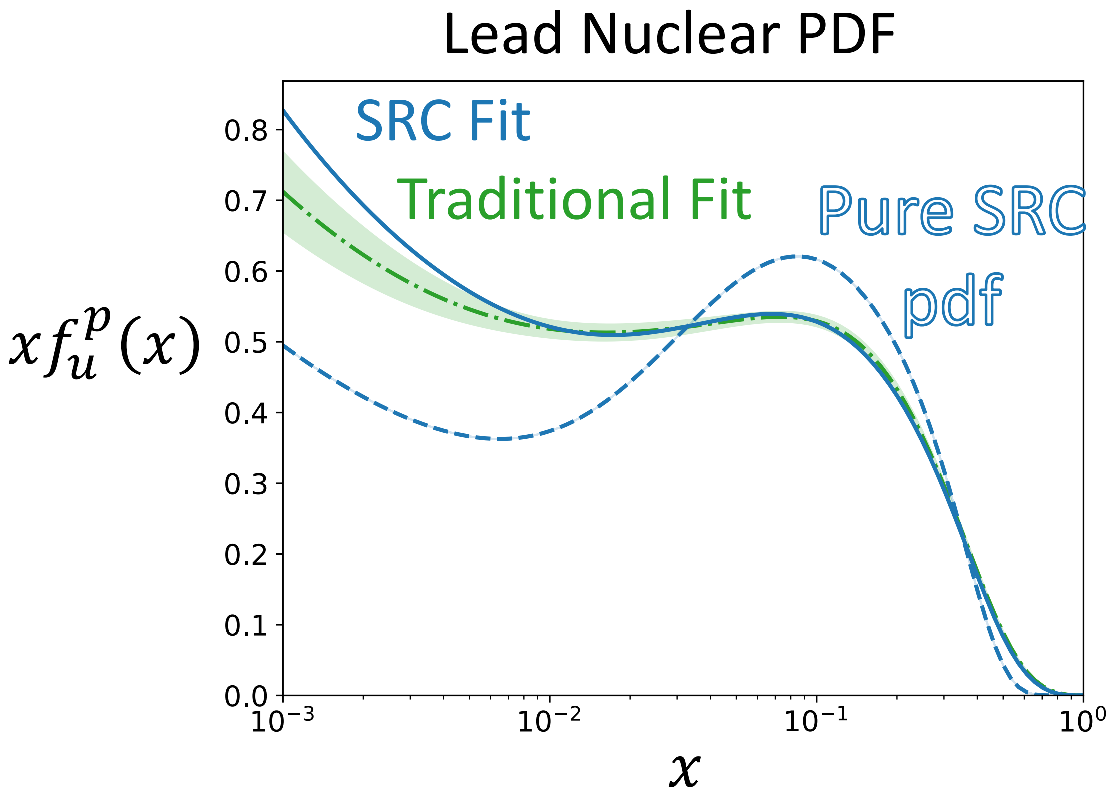
C_p^A C_n^A: **Fitted** Dependent on A

Nuclear PDF and SRC PDF



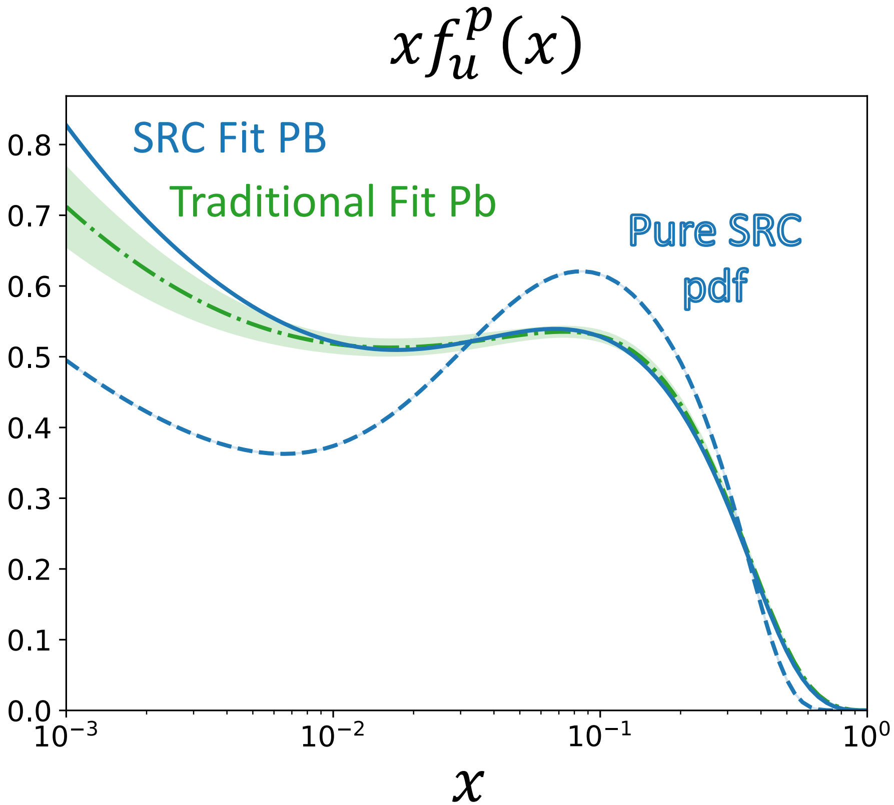
$Q^2 = 10\ GeV^2$

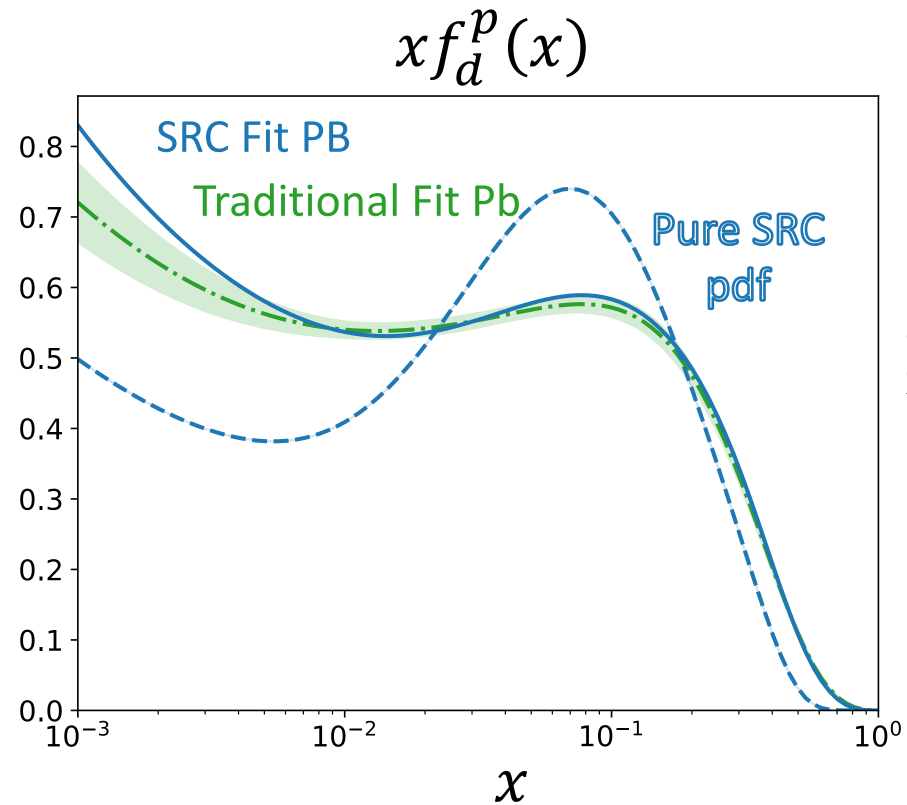
Nuclear PDF and SRC PDF



$Q^2 = 10\ GeV^2$

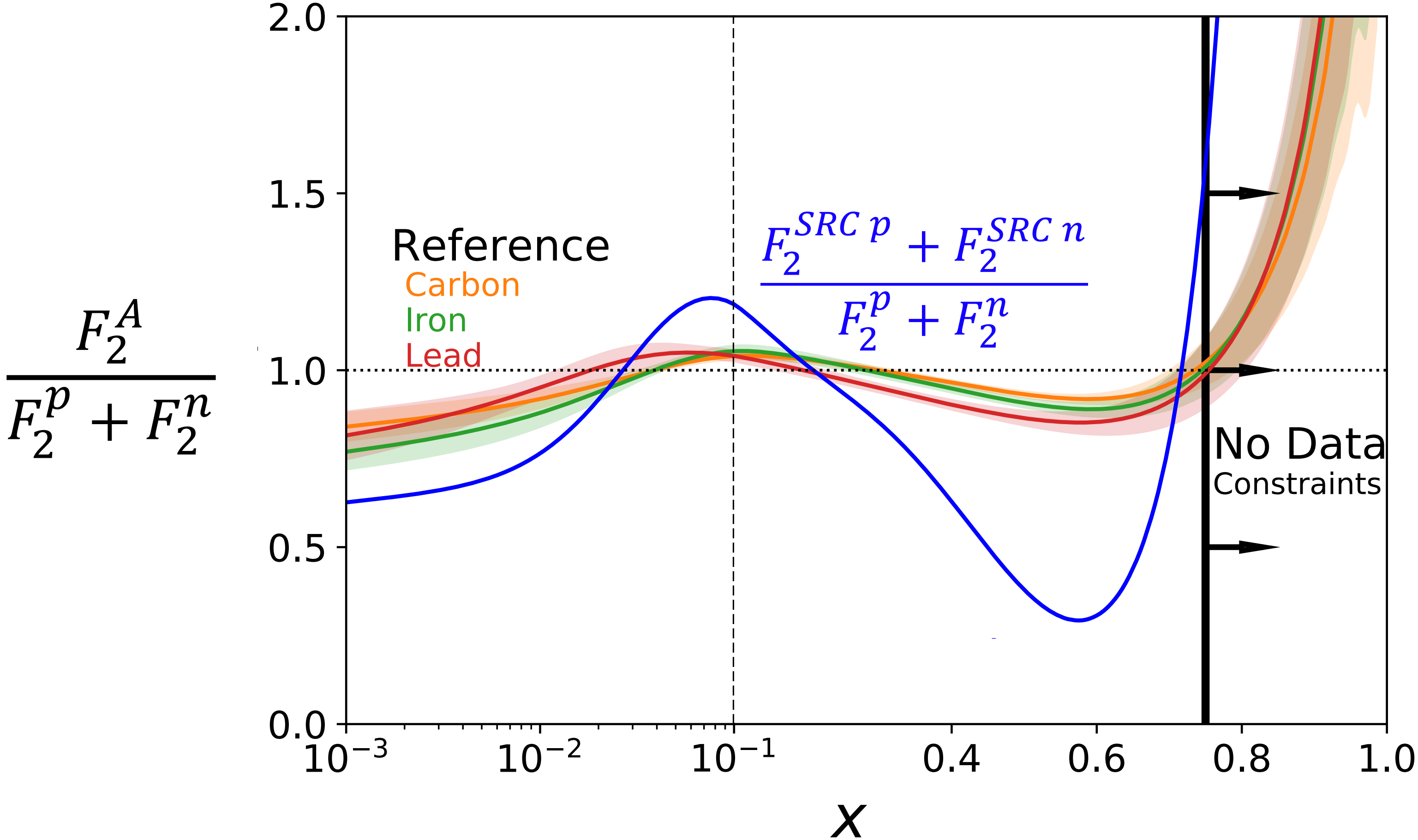
Nuclear PDF and SRC PDF





$Q^2 = 10\ GeV^2$

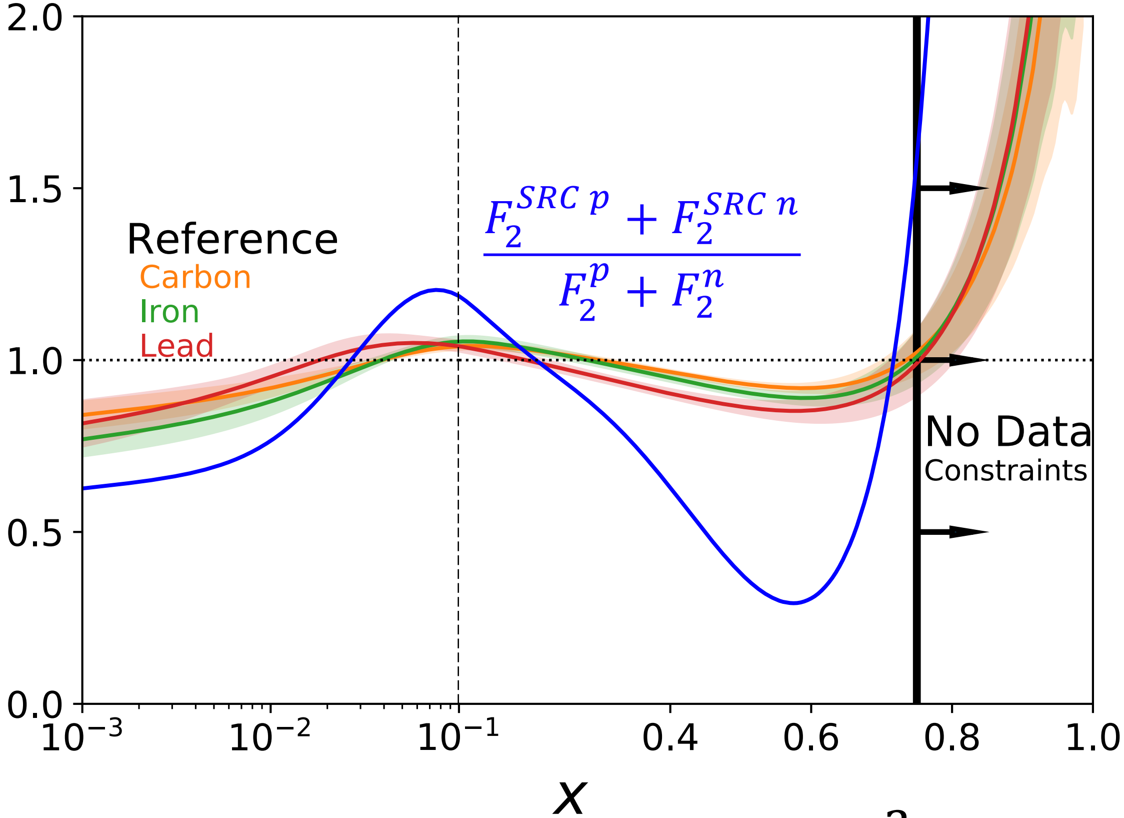
Structure of SRC Nucleons

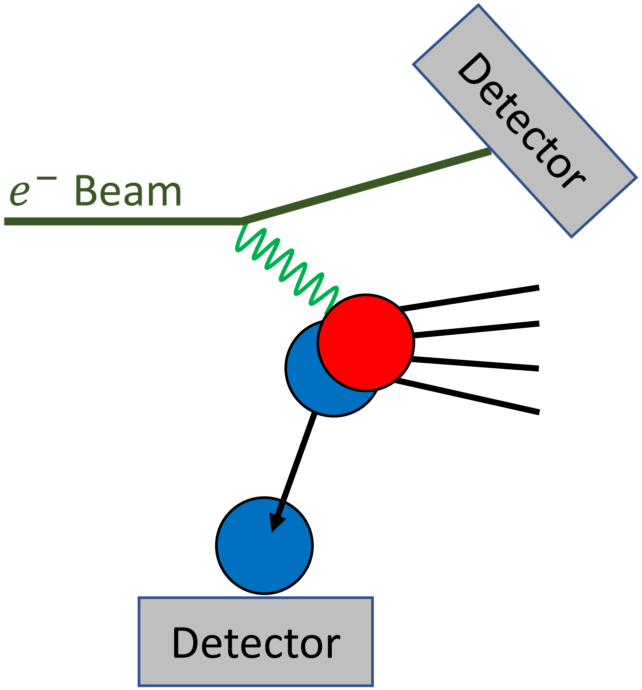


$Q^2 = 10\ GeV^2$

Tagged Experiments Might Measure this Observable

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





Eg. BAND, LAD

$Q^2 = 10\ GeV^2$

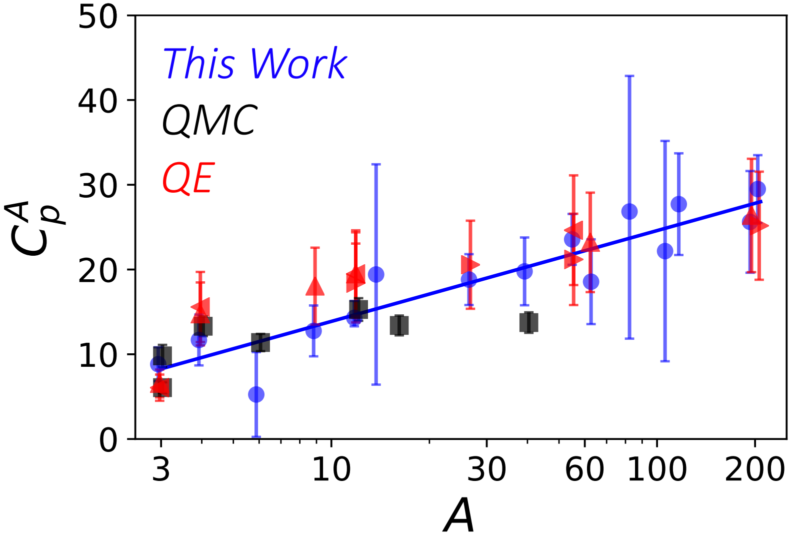
Summary

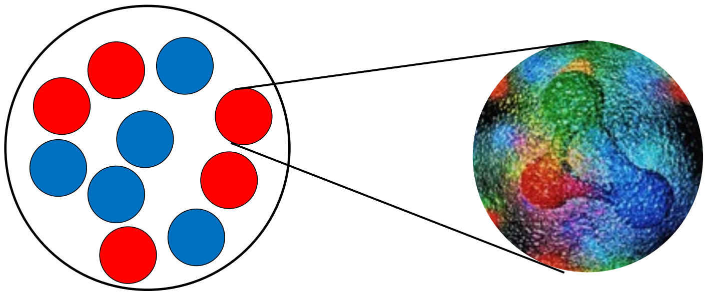
- SRC Parameterization produces a good fit.

χ^2/N_{data}	$\frac{\chi^2_{\text{tot}}}{N_{\text{DOF}}}$
All Modified	0.85
SRC	0.80

Summary

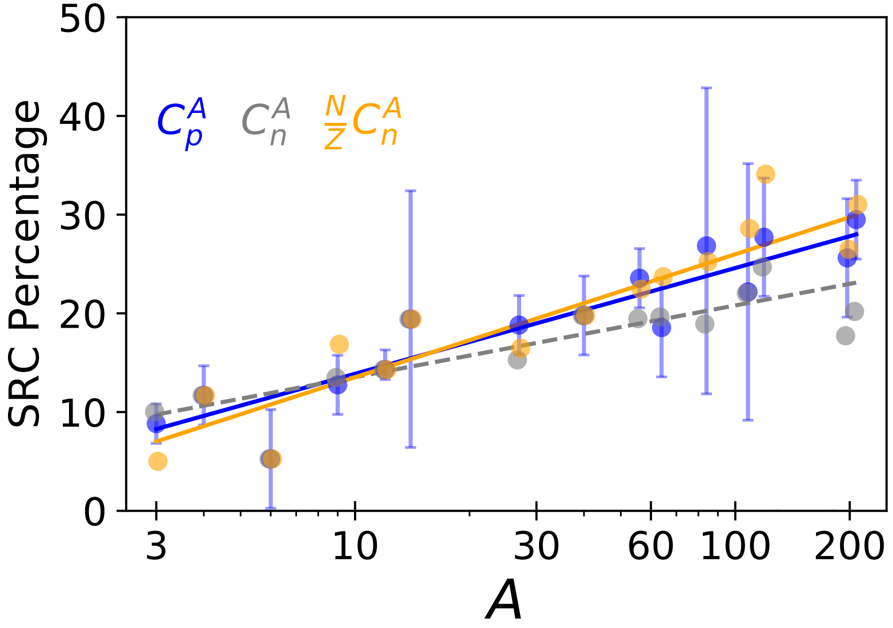
- SRC Parameterization produces a good fit.
- Nuclear physics extracted from parton measurements.





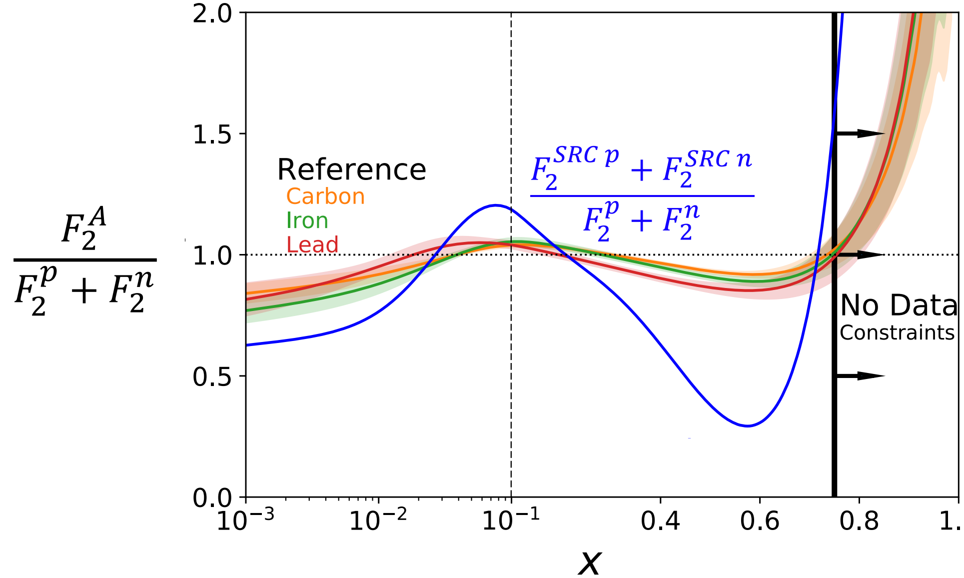
Summary

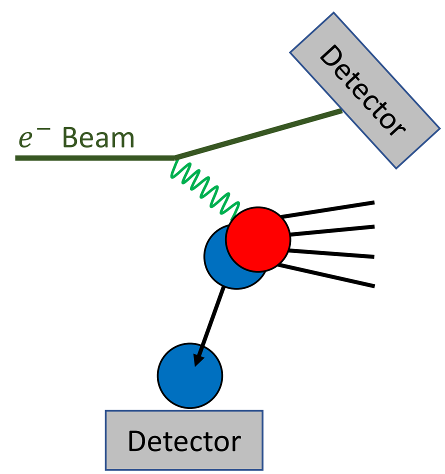
- SRC Parameterization produces a good fit.
- Nuclear physics extracted from parton measurements.
- pn-dominance naturals emerges from the fit.



Summary

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

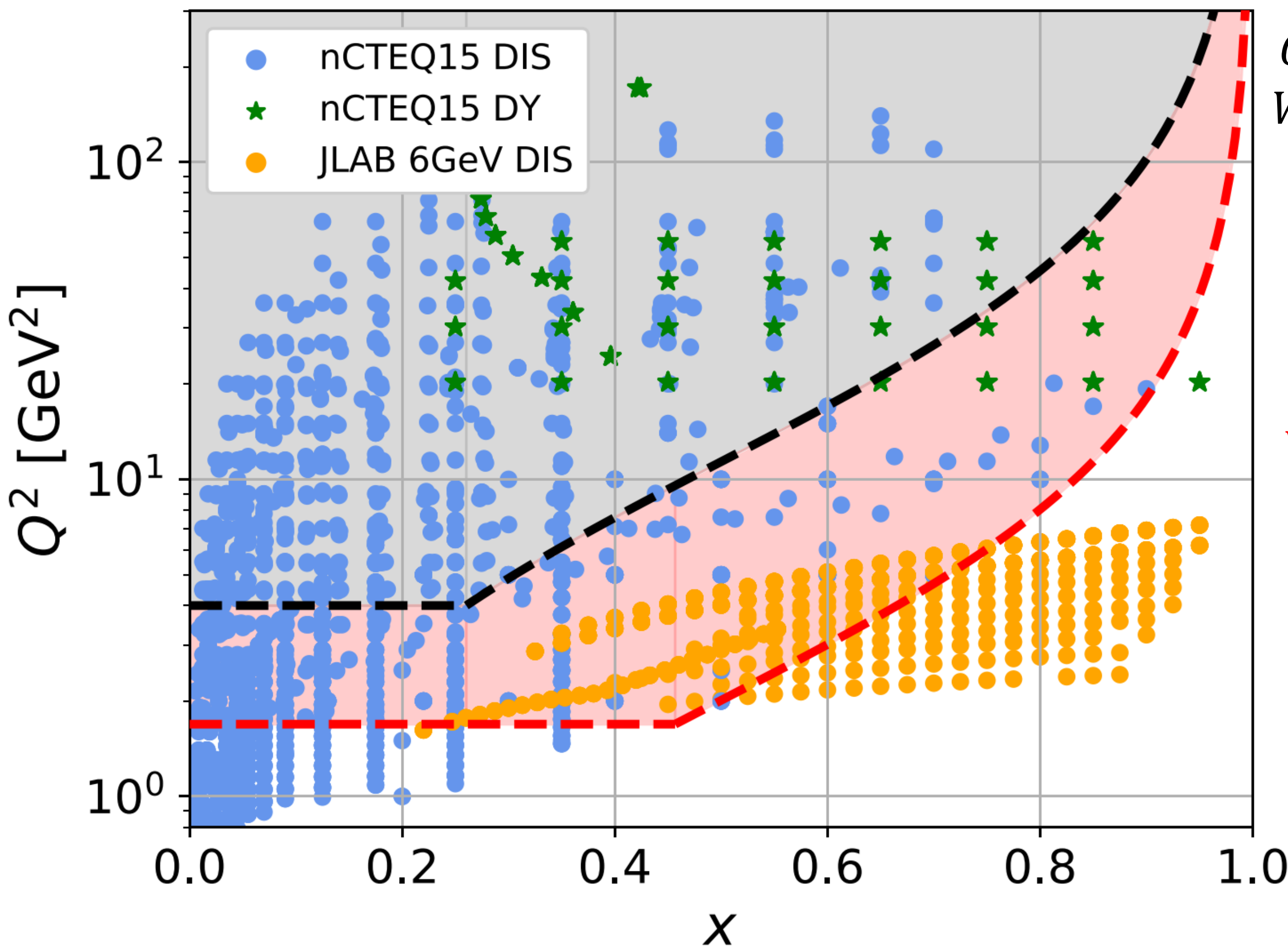




End

Extra

Cut out data with non-DIS Kinematics

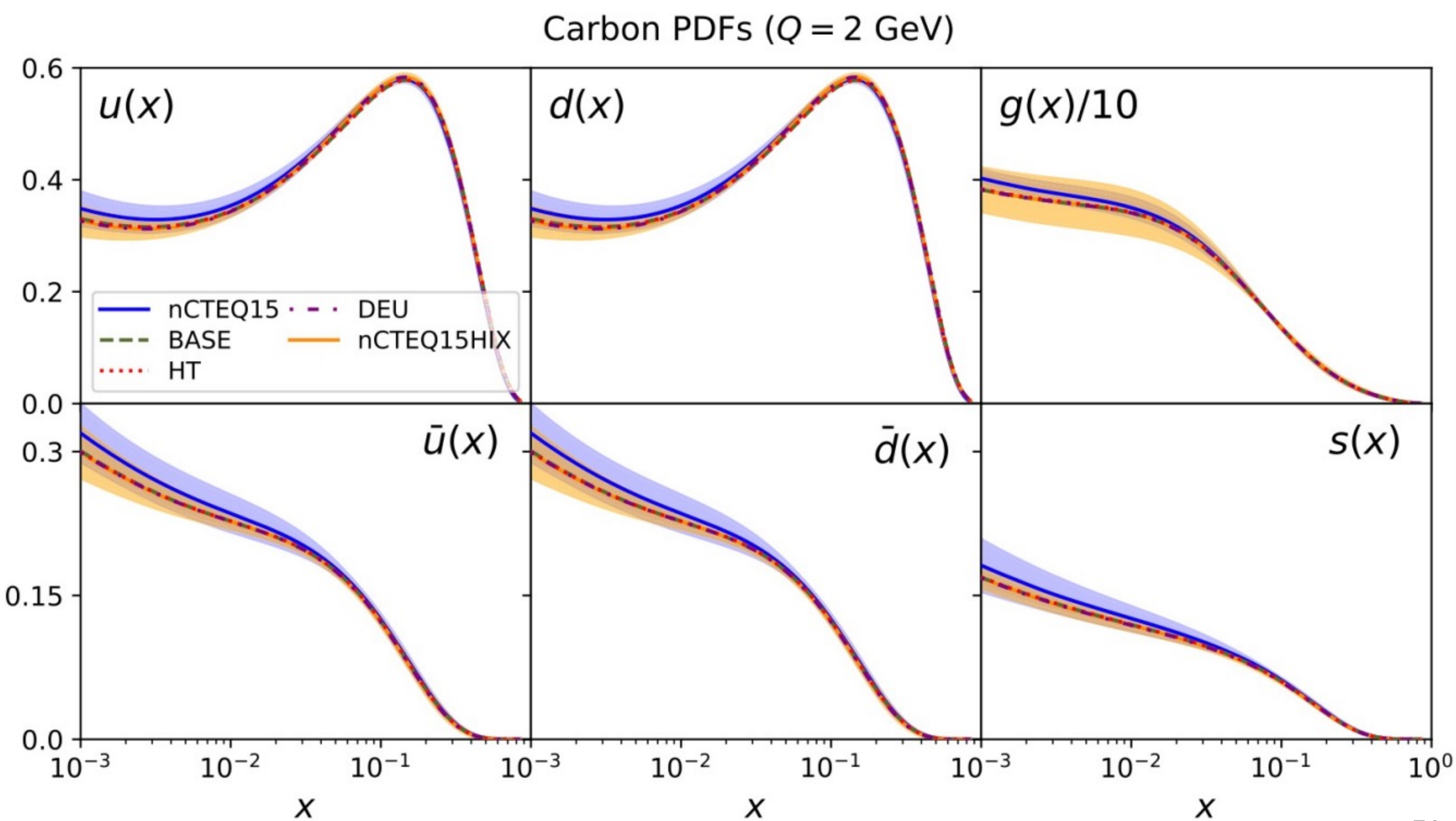


$Q > 2.0\ GeV$
$W > 3.5\ GeV$

$Q > 1.3\ GeV$
$W > 1.7\ GeV$

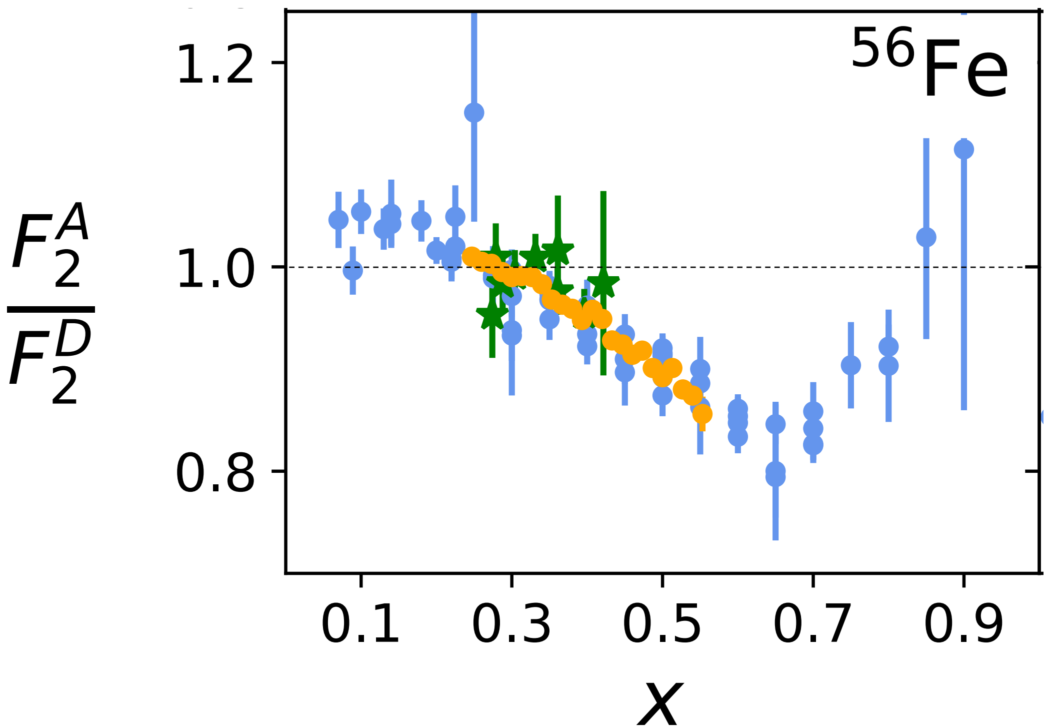
Segarra PRD (2021)

Previous PDF fits



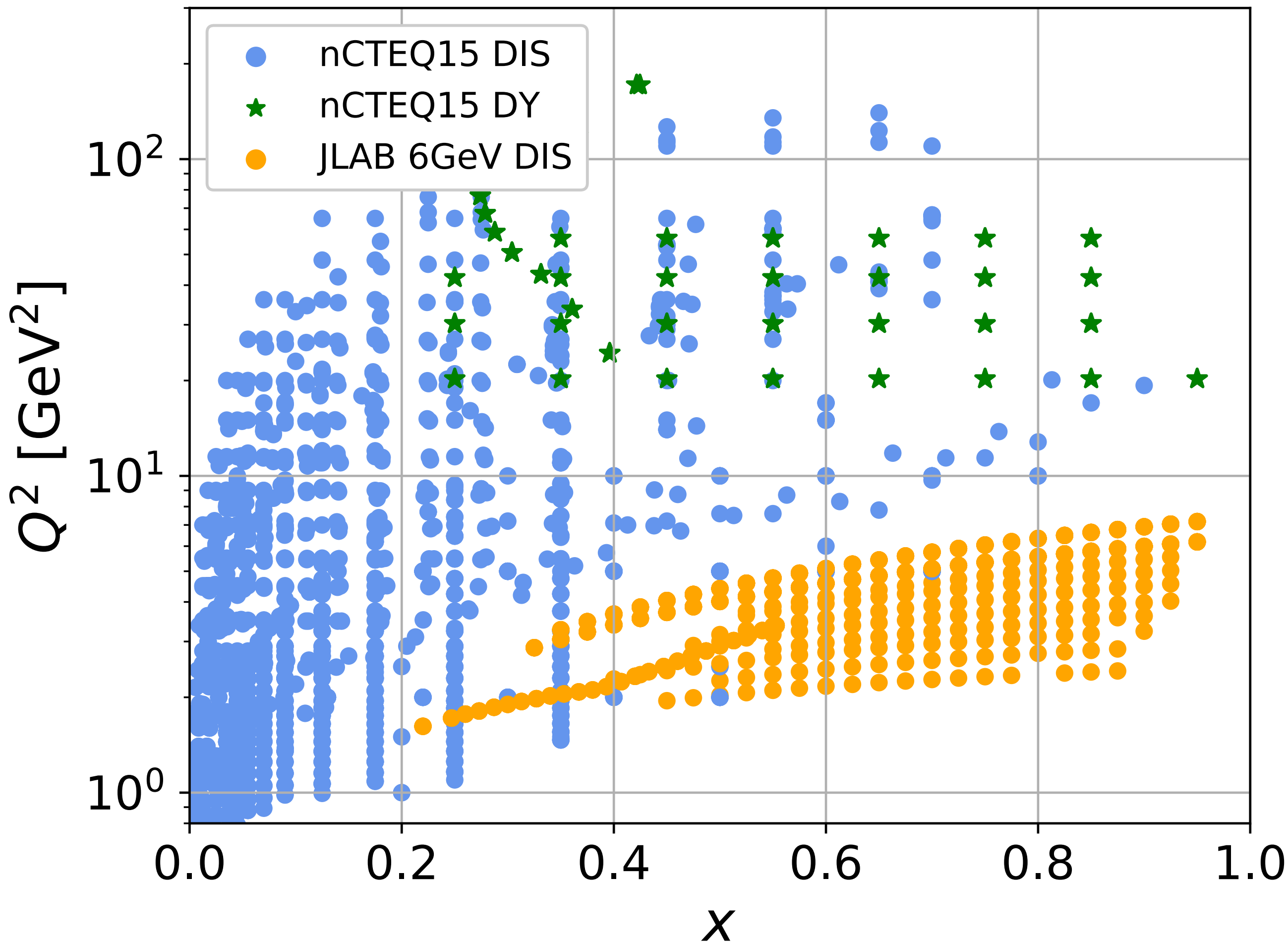
Segarra PRD (2021)

Medium Modification and nPDFs



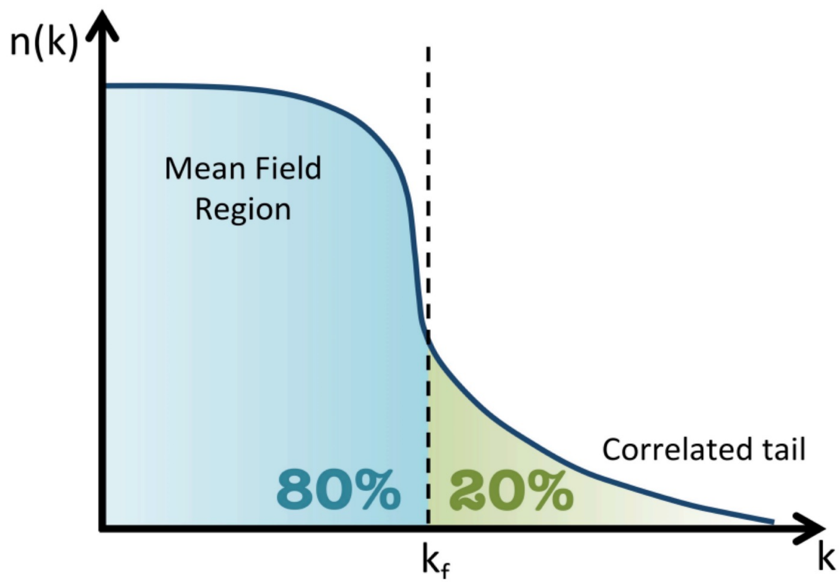
$$F_2^{A,Z}(x,Q) \sim x \sum_i C_i^2 \, f_\mathrm{i}^{A,Z}(x)$$

World Data of Medium Modification



Segarra PRD (2021)

Spectral Function

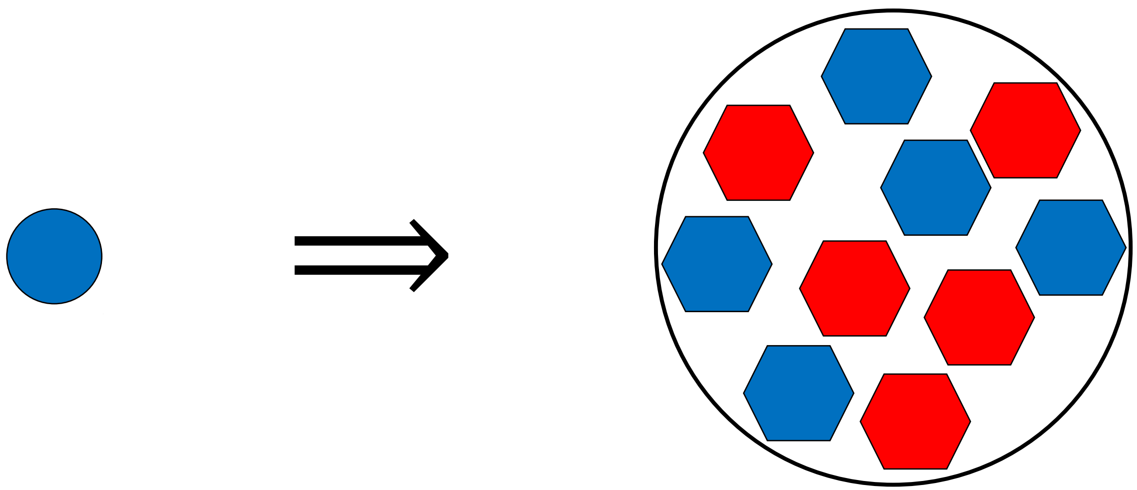


$$S_A(k,E) = S_A^{MF}(k,E) + S_A^{SRC}(k,E)$$

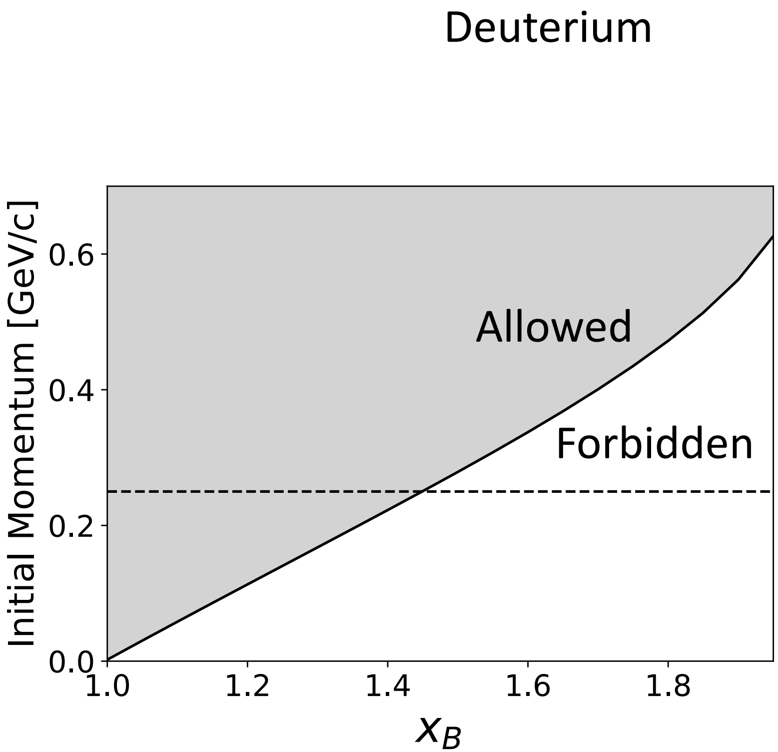
Original Parametrization

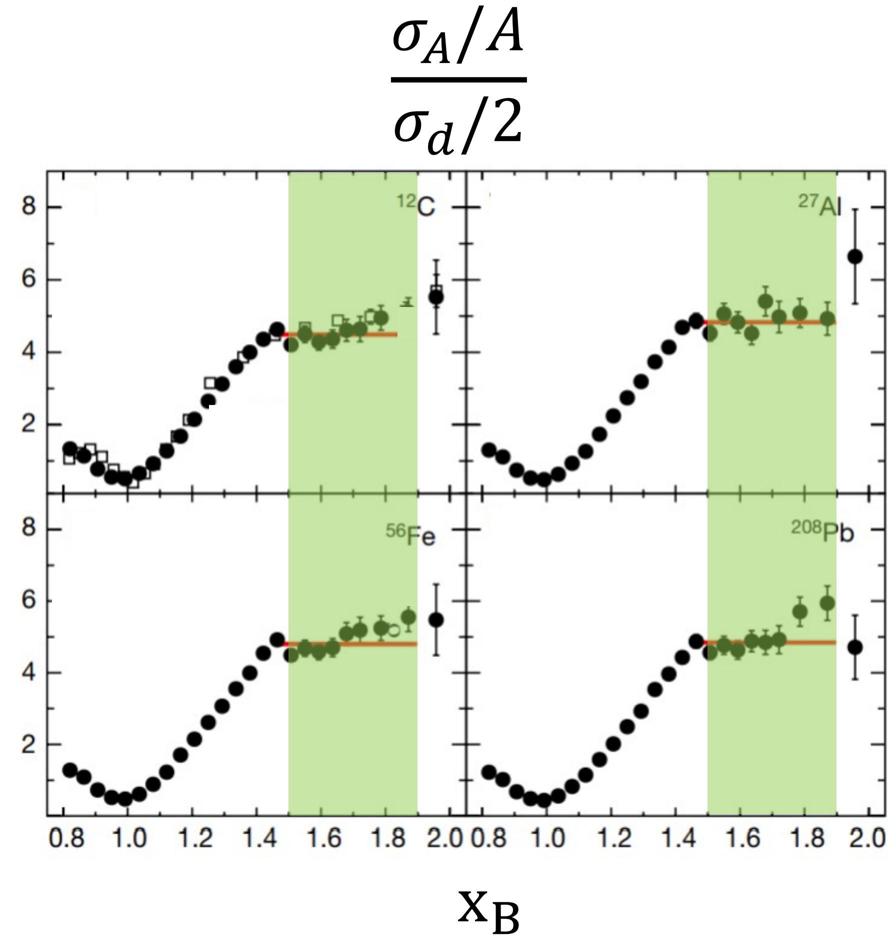
Depend on A

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



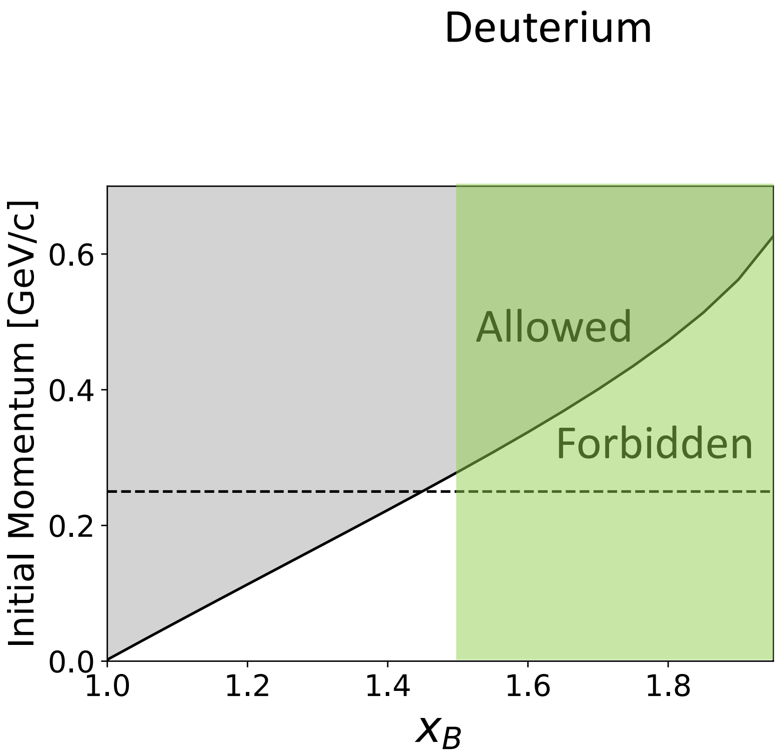
SRC Measurements

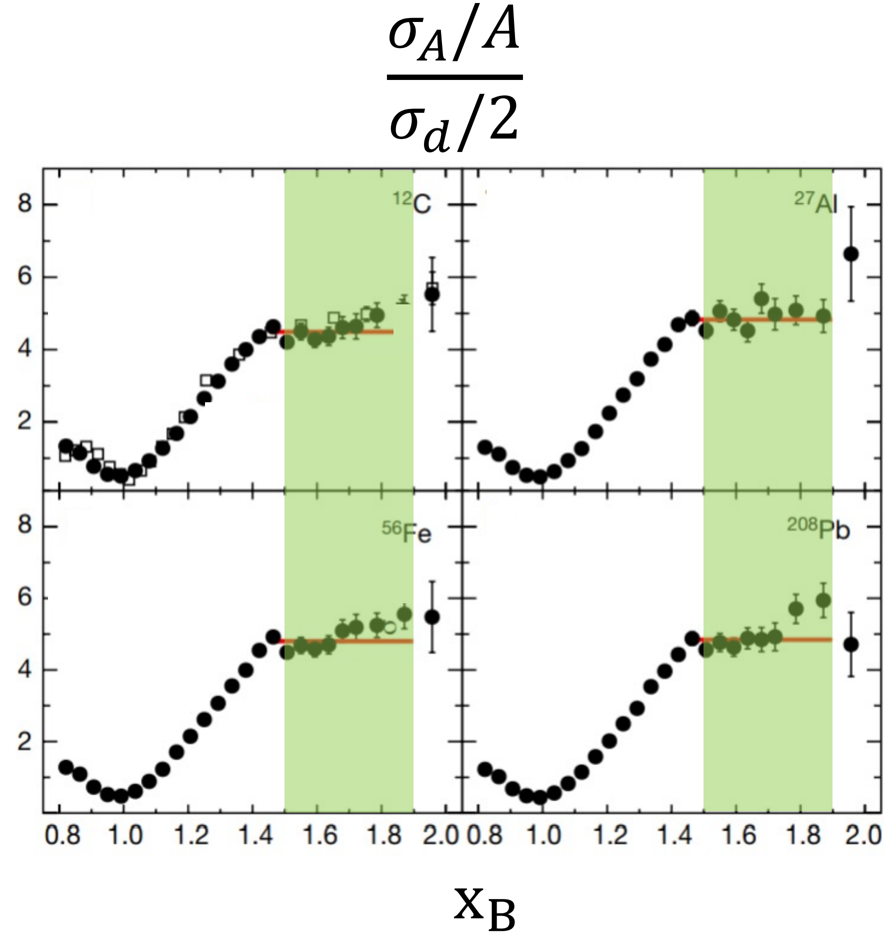




- Schmookler Nature (2019)

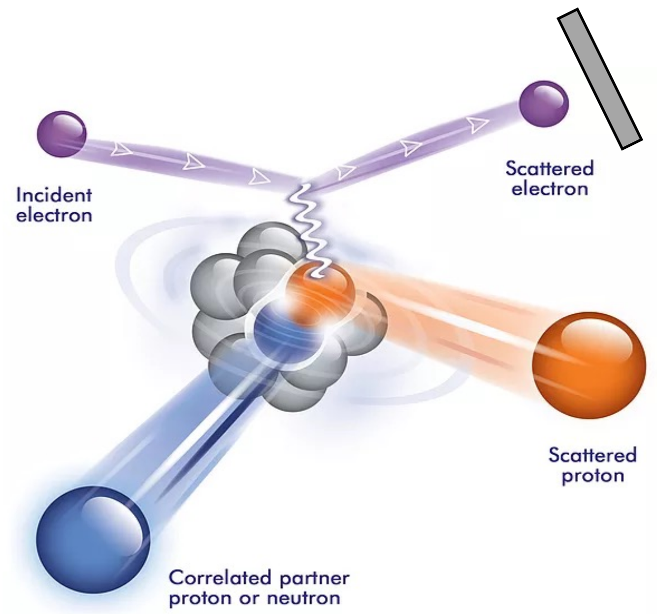
SRC Measurements



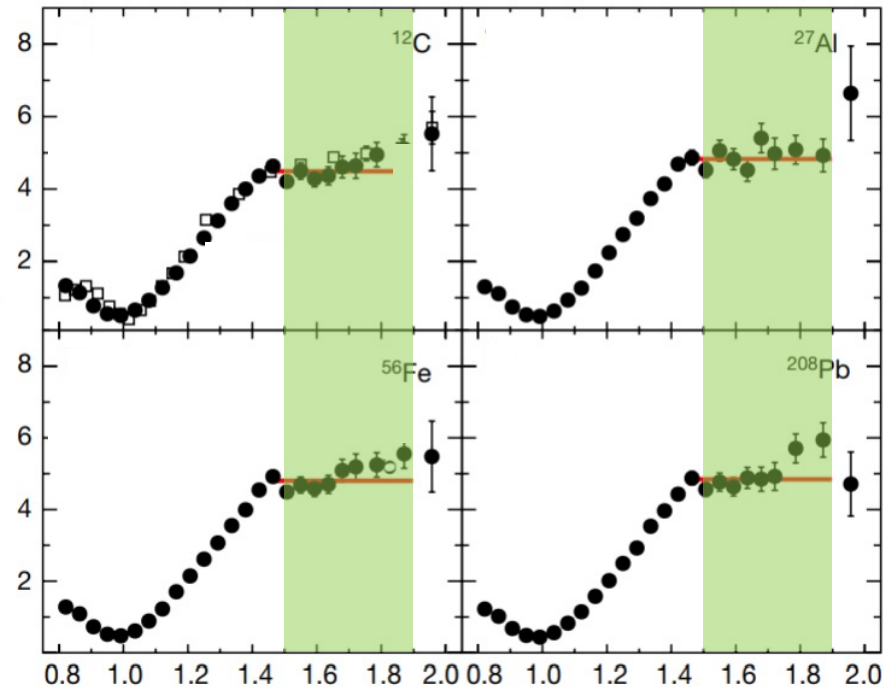


Schmookler Nature (2019)

SRC Measurements



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



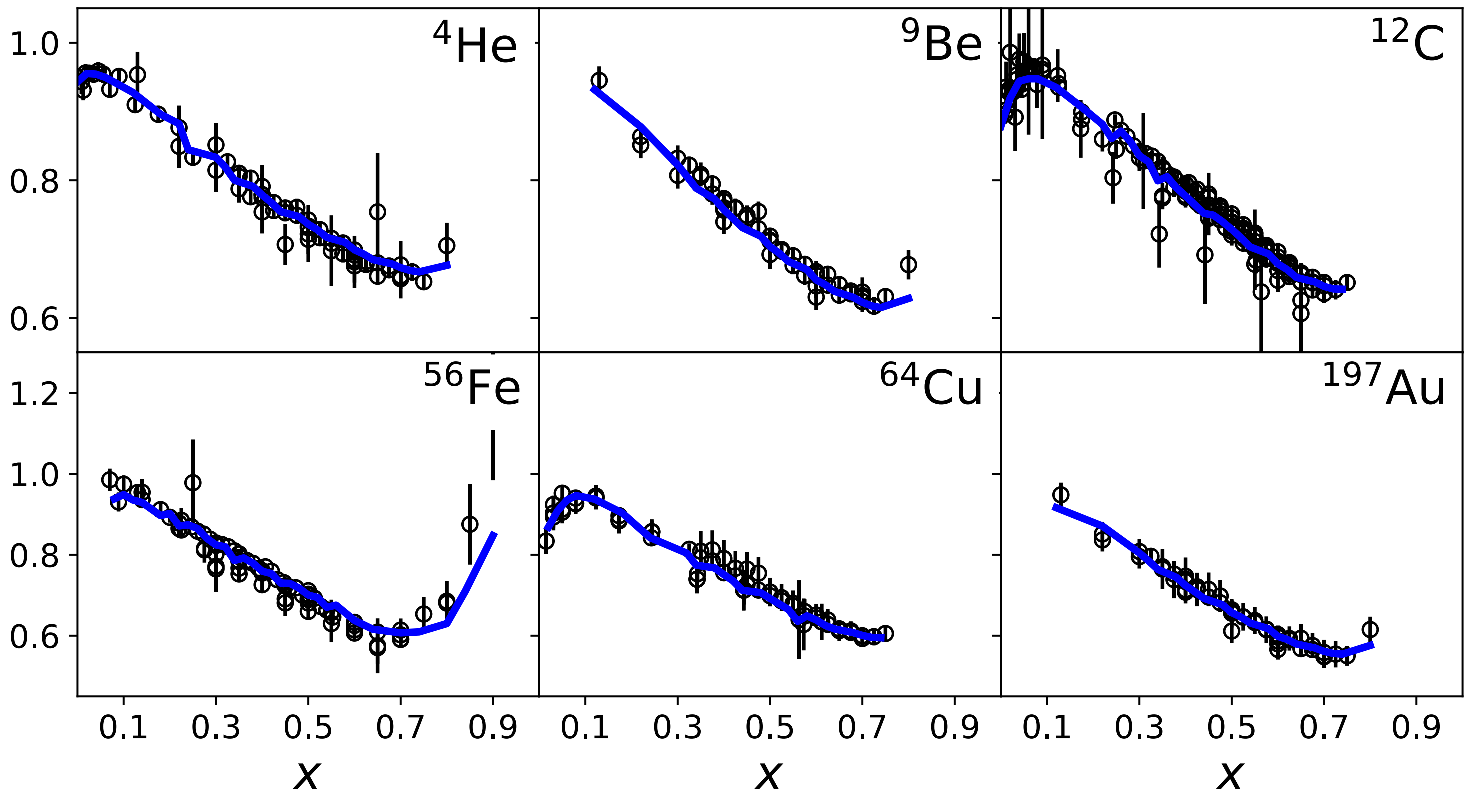
x_B

Schmookler Nature (2019)

Fitting to World Data

$$\frac{\chi^2_{Tot}}{DOF} = 0.85$$

$$\frac{F_2^A}{F_2^D}\left(\frac{F_2^D}{F_2^p}\right)_{CJ}$$



Segarra PRD (2021)

Fit using pn-dominance

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

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

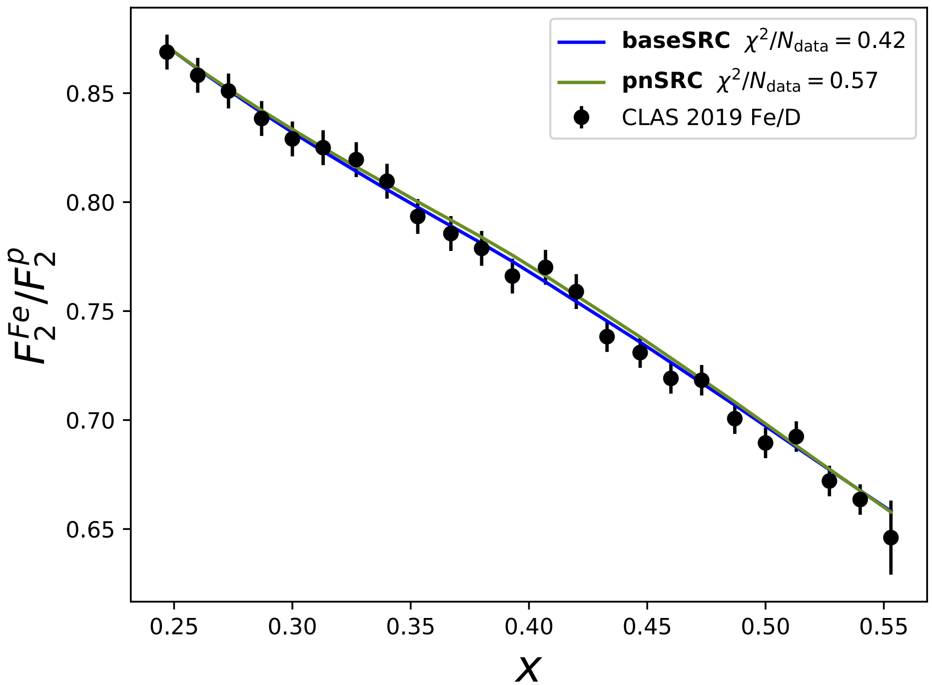
Two Fits:

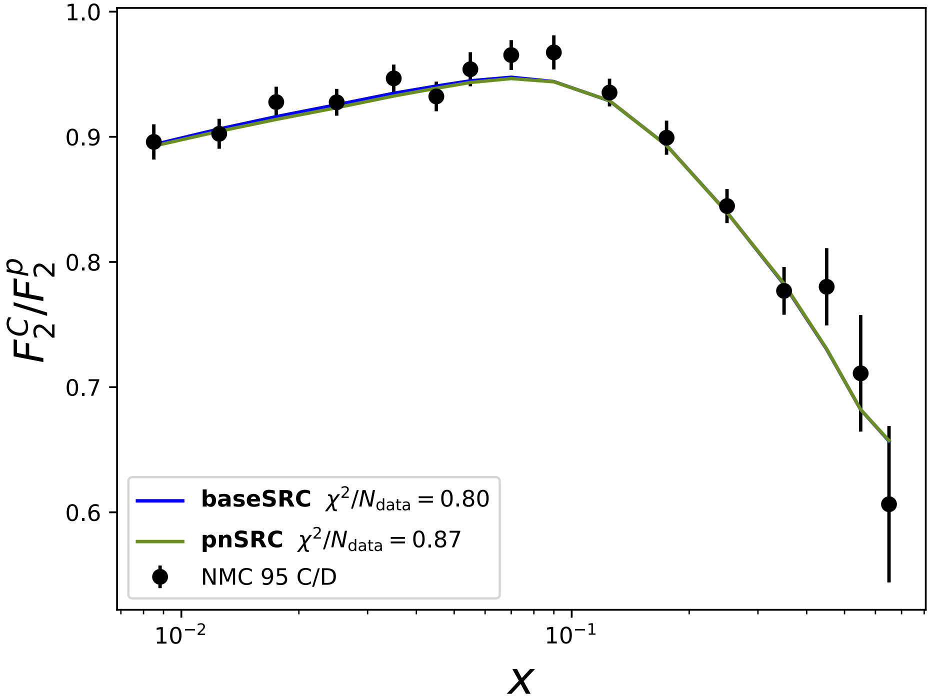
- Let C_p^A and C_n^A vary independently
- Force pn-dominance:
  #Protons in SRC = #Neutrons in SRC

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.





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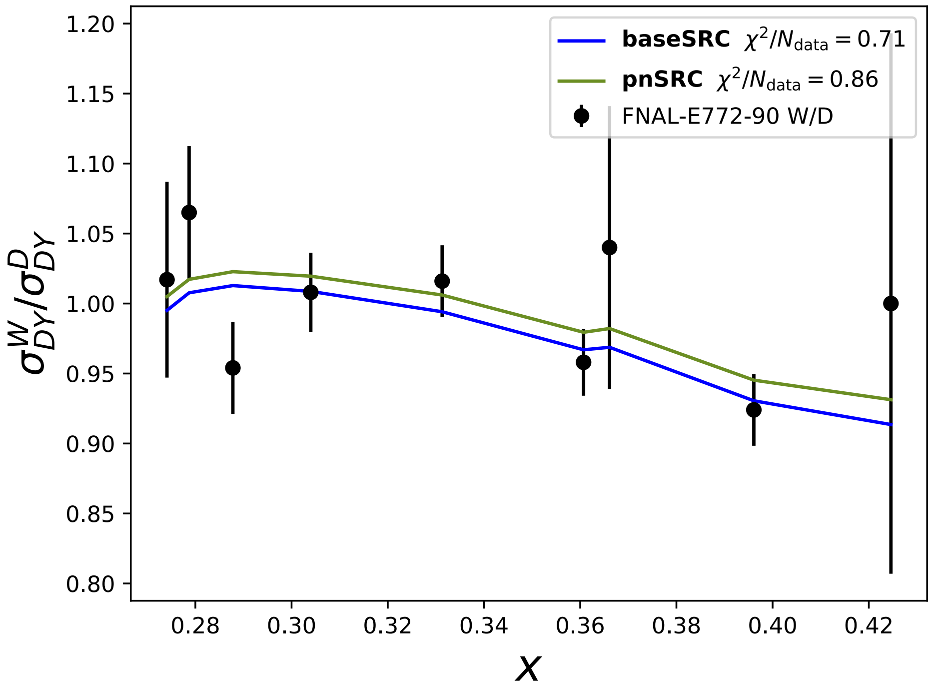
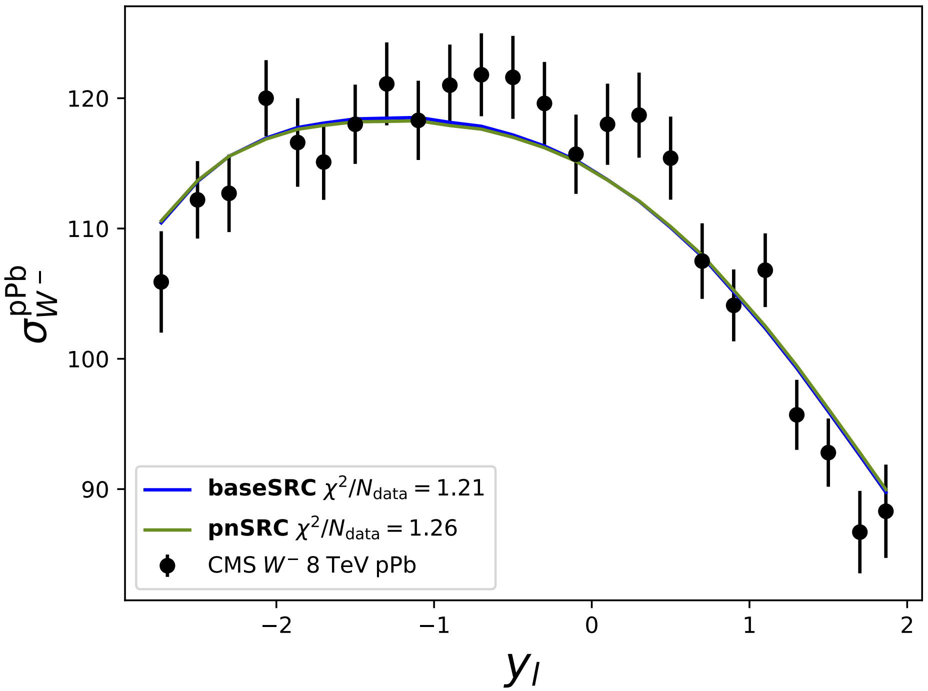
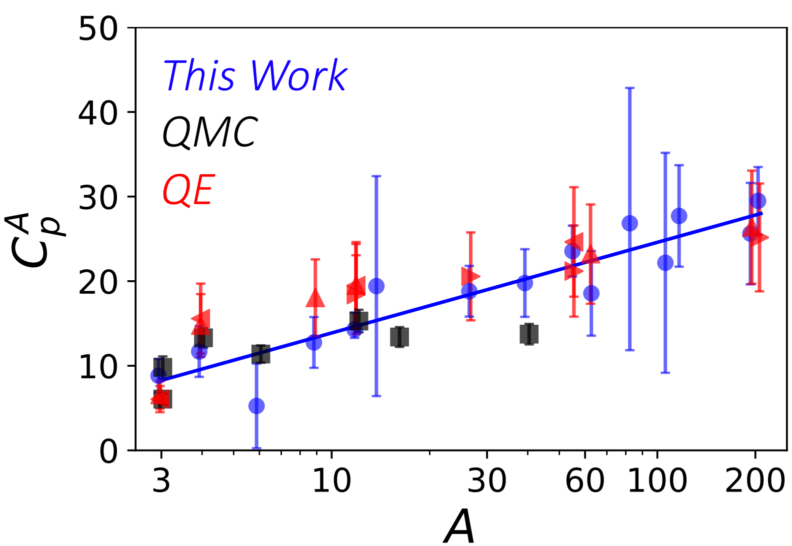


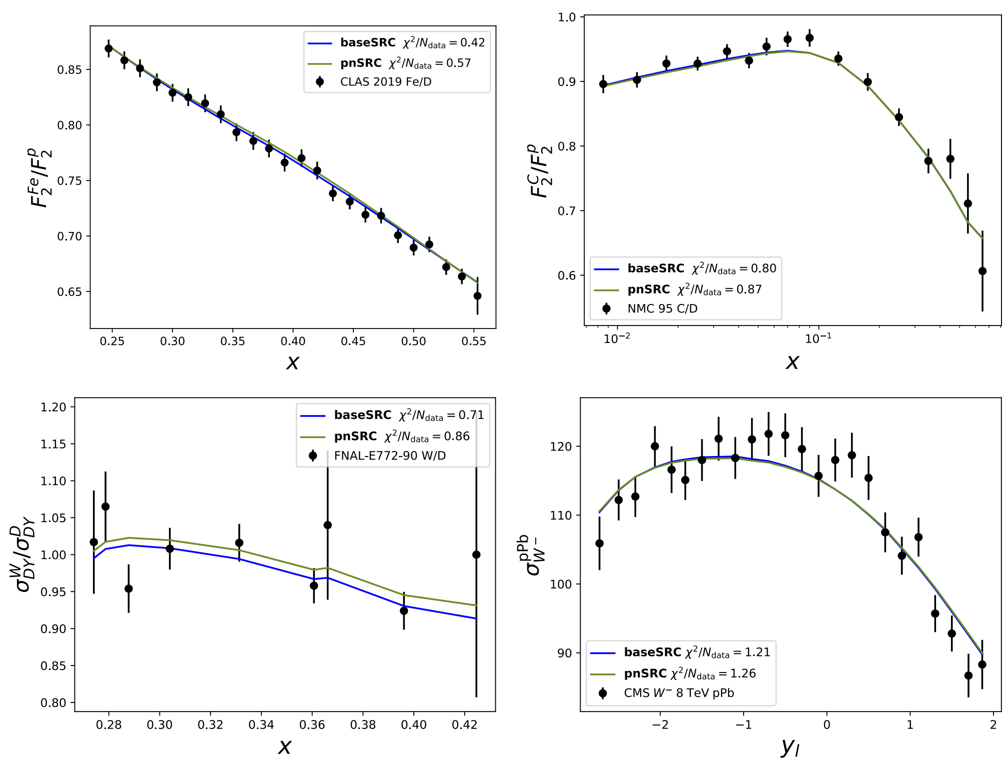


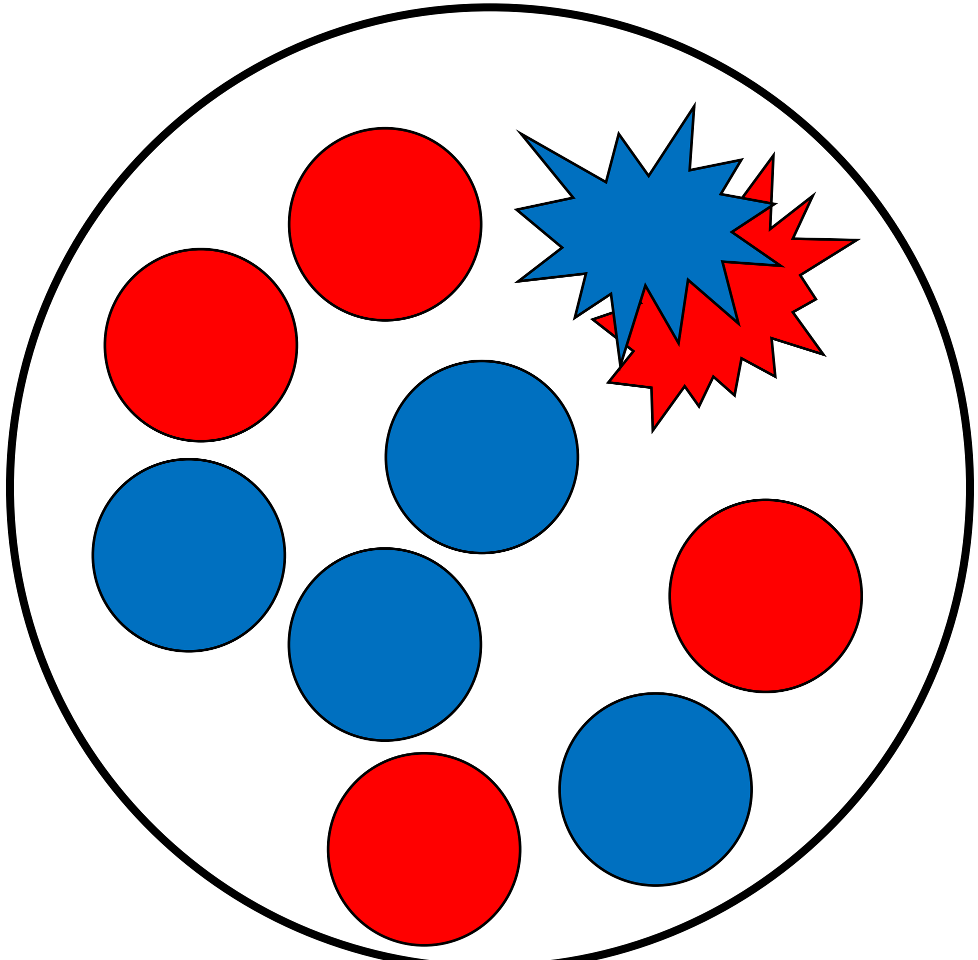
Beyond the SRC-EMC Relation

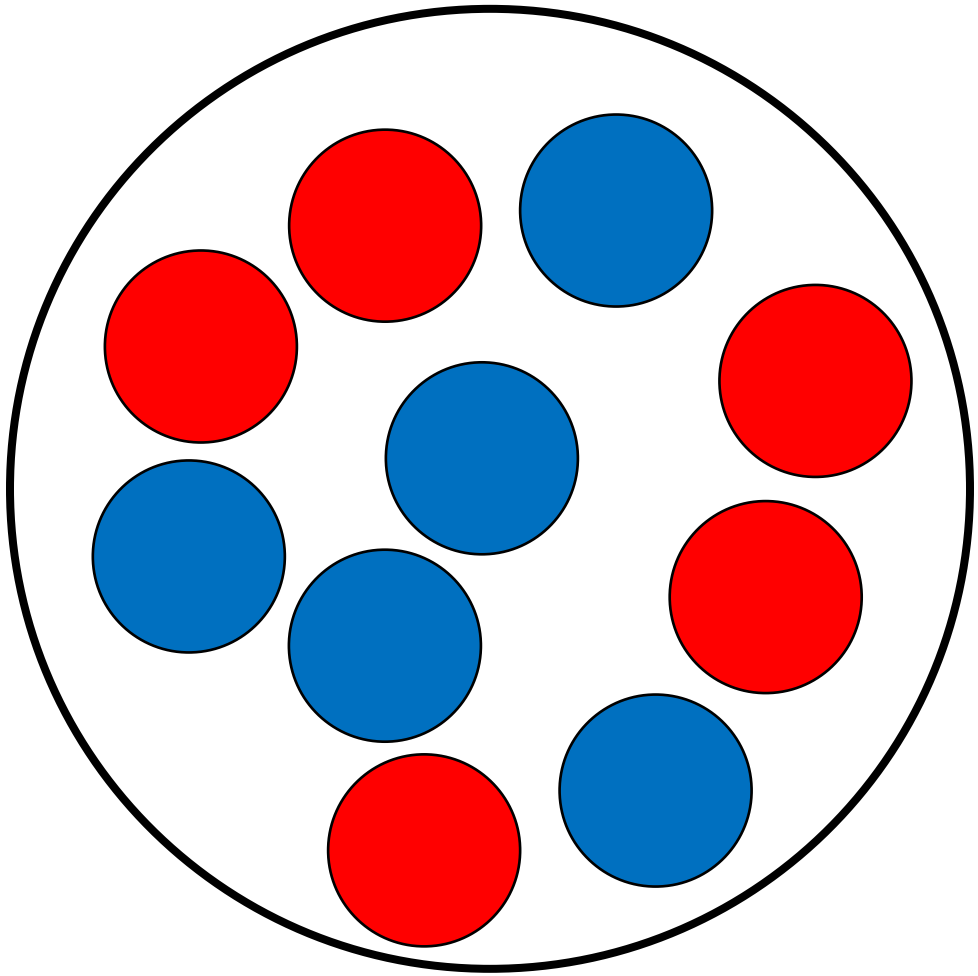
SRC ⟺ EMC, Shadowing, Anti-shadowing, Drell-Yan, W/Z

- EMC
- Shadowing
- Anti-shadowing
- Drell-Yan
- W/Z





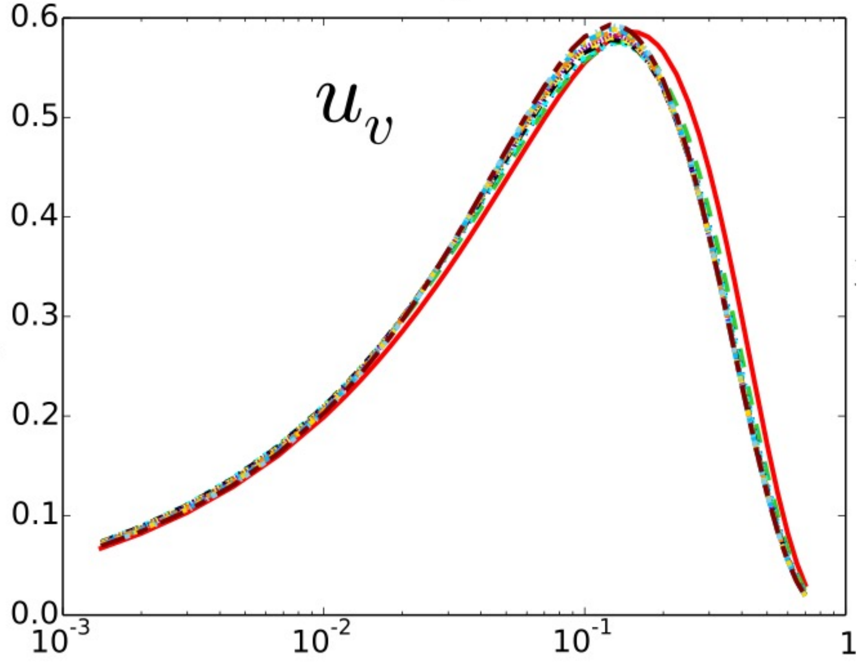




All Nucleons Modified Approach

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

$xf_{u_v}^{A}(x)$



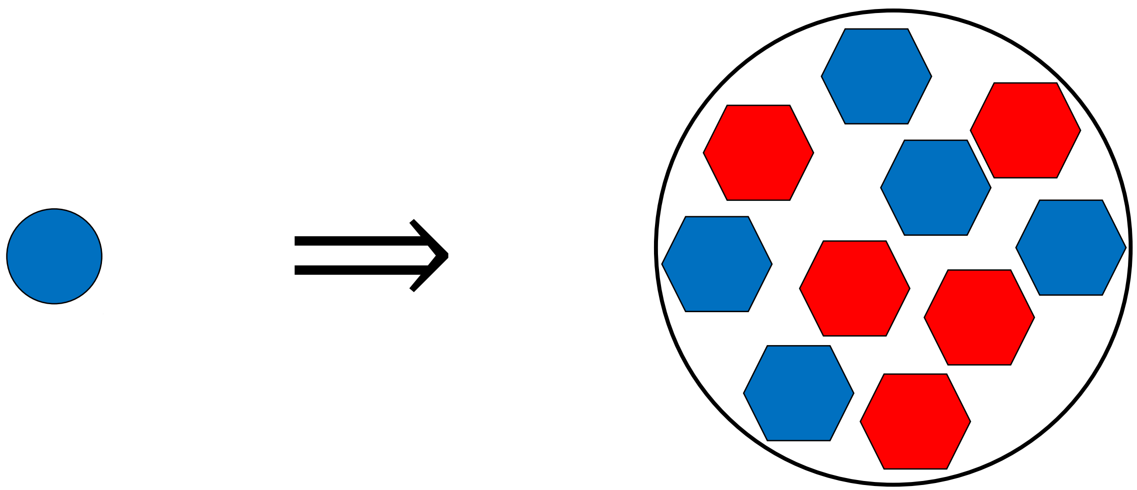
xB

Kovarik PRD (2015)

All Nucleons Modified Approach

Depend on A

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

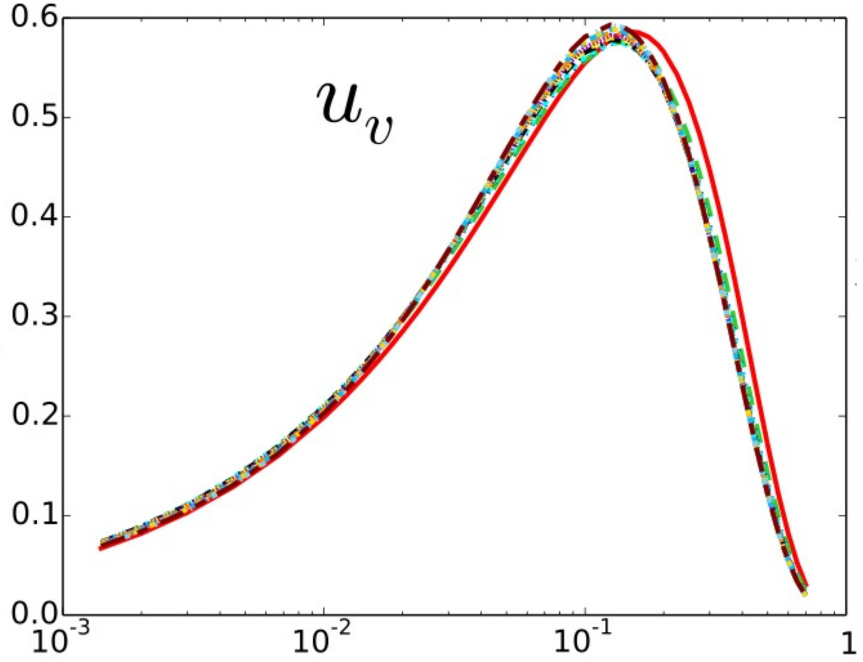


All Nucleons Modified Approach

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

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

$xf_{u_v}^{A}(x)$



xB

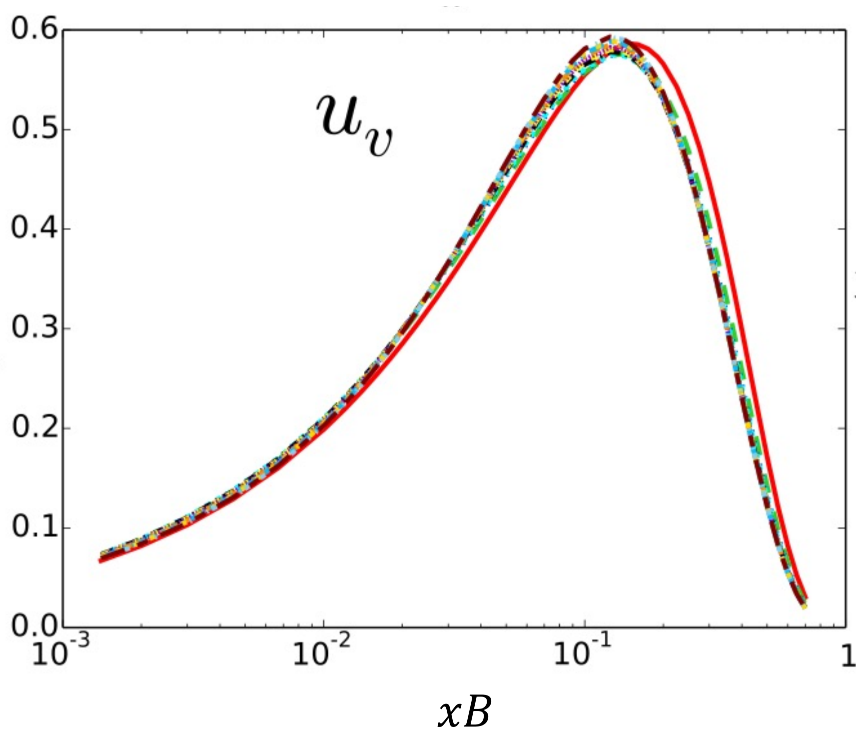
Kovarik PRD (2015)

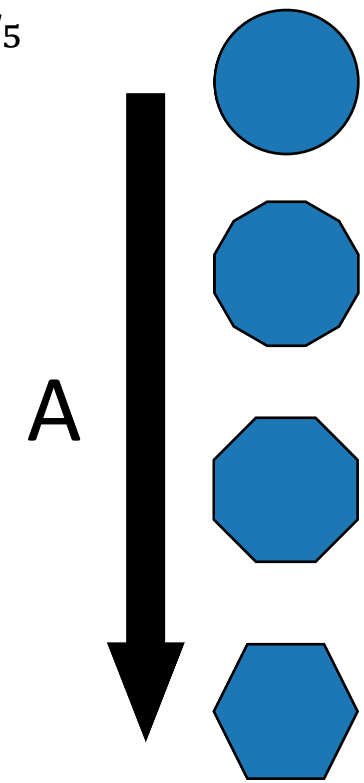
All Nucleons Modified Approach

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

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

$xf_{u_v}^A(x)$





Kovarik PRD (2015)

All Nucleons Modified Approach

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

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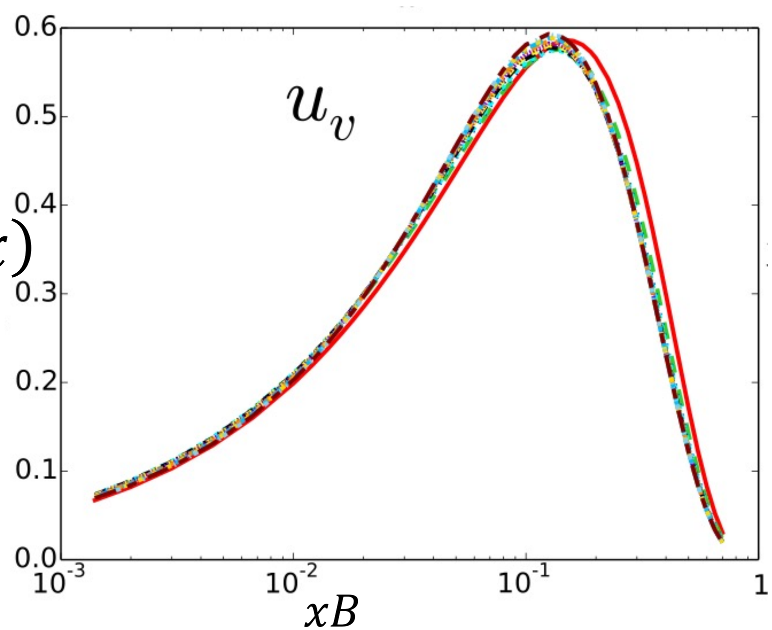
$xf_{u_v}^A(x)$



$c_k(A)$

Kovarik PRD (2015)

A

Incorporating SRCs

Free Nucleons SRC Nucleons

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

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

New Fit:

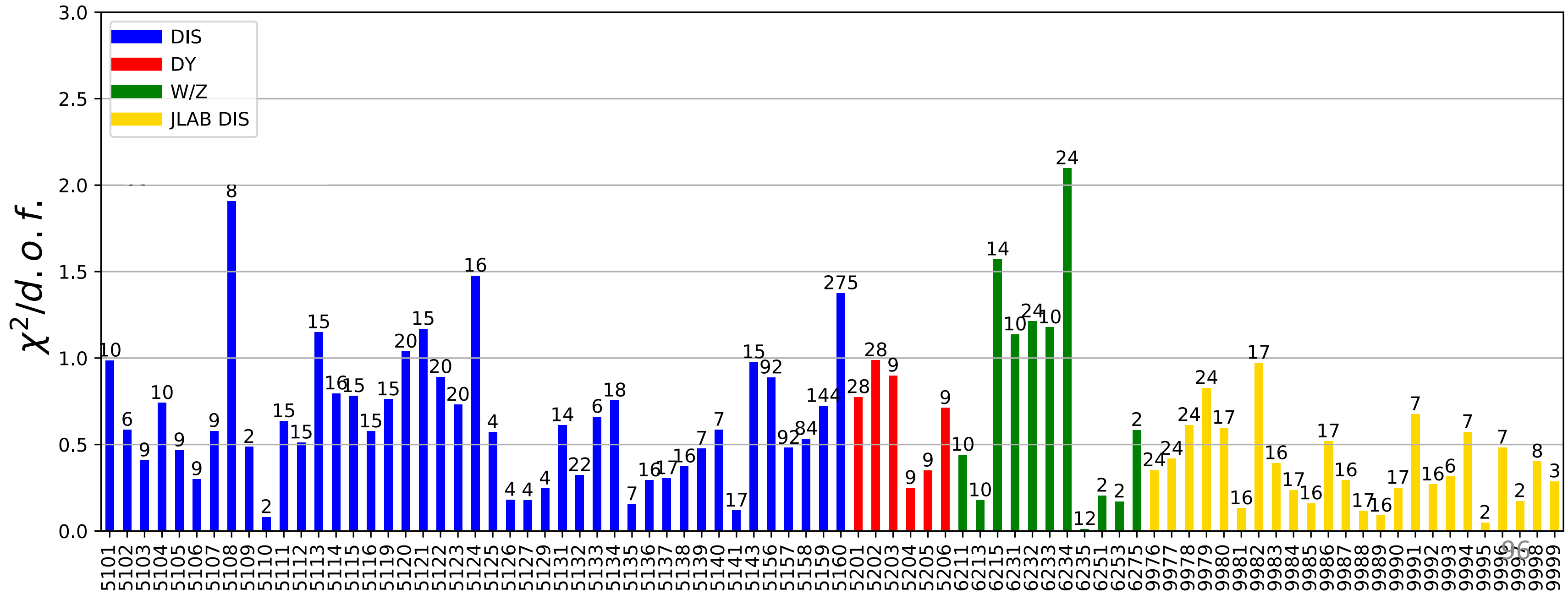
- $f_i^p(x)$ comes from nCTEQ15 free proton
- $f_i^{SRC\,p}(x)$ is fit without A dependence:

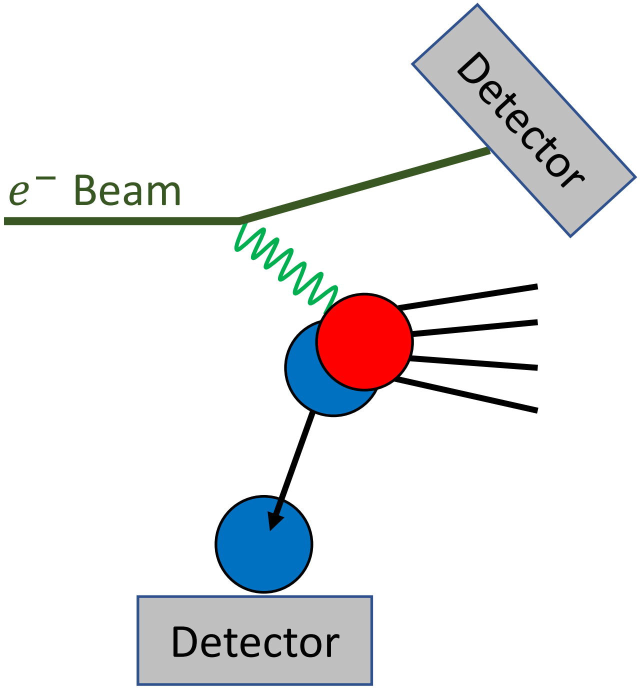
$$x f_i^{SRC\,p}(x) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1 + e^{c_4} x)^{c_5}$$

- 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

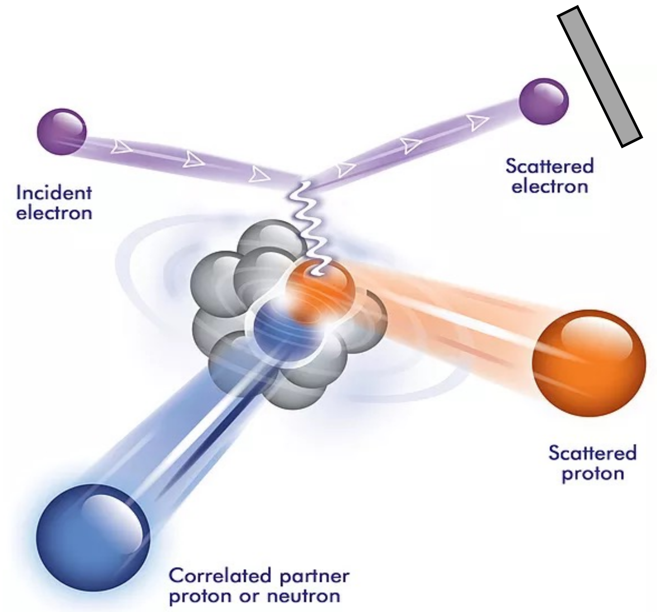
Fit Result:

χ^2/N_{data}	DIS	DY	W/Z	JLab	χ^2_{tot}	$\frac{\chi^2_{\mathrm{tot}}}{N_{\mathrm{DOF}}}$
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



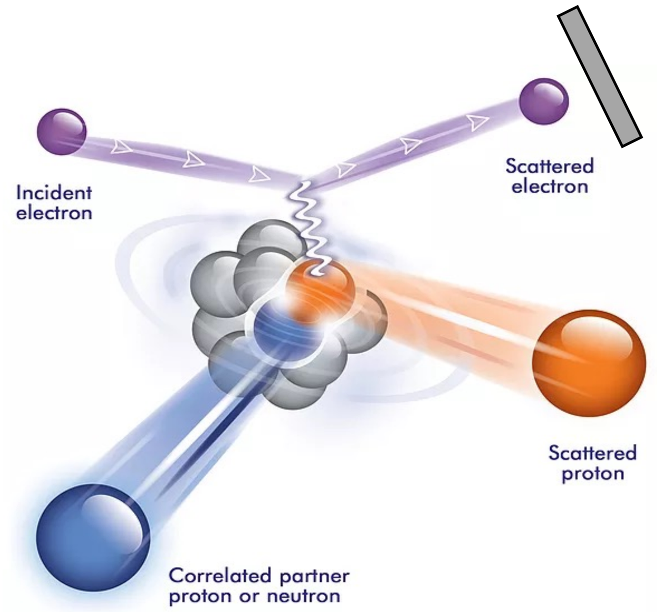

e^- Beam
Detector
Detector

SRC Measurements

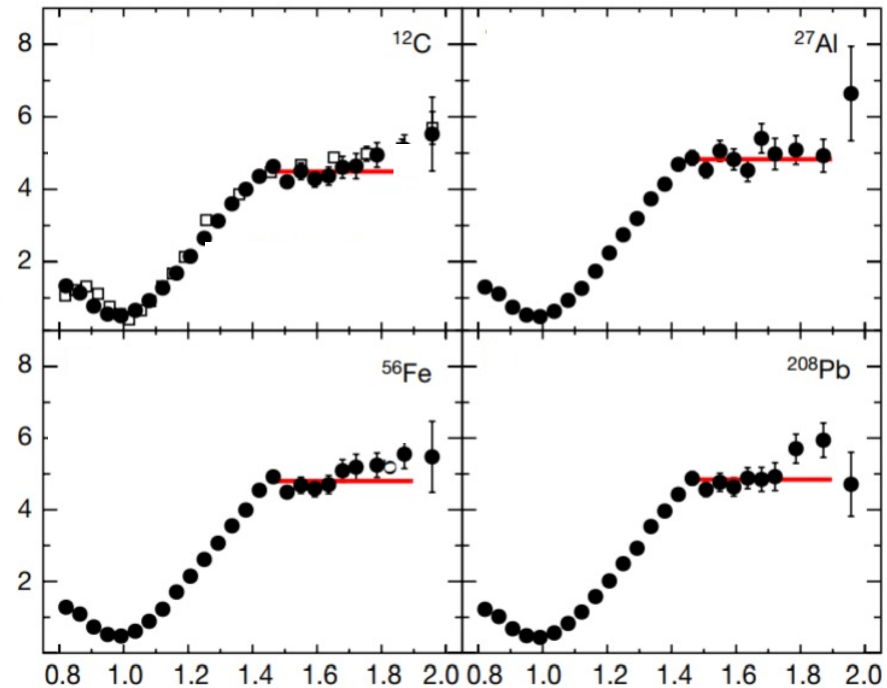


Schmookler Nature (2019)

SRC Measurements



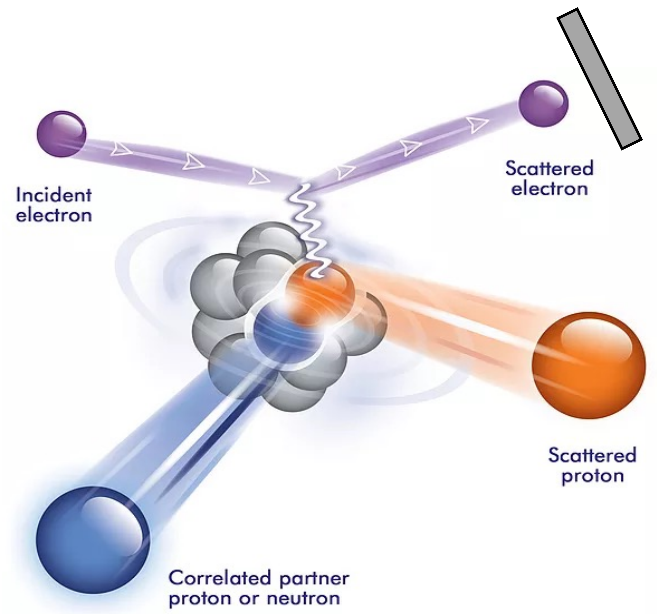
$$\frac{\sigma_A/A}{\sigma_d/2}$$



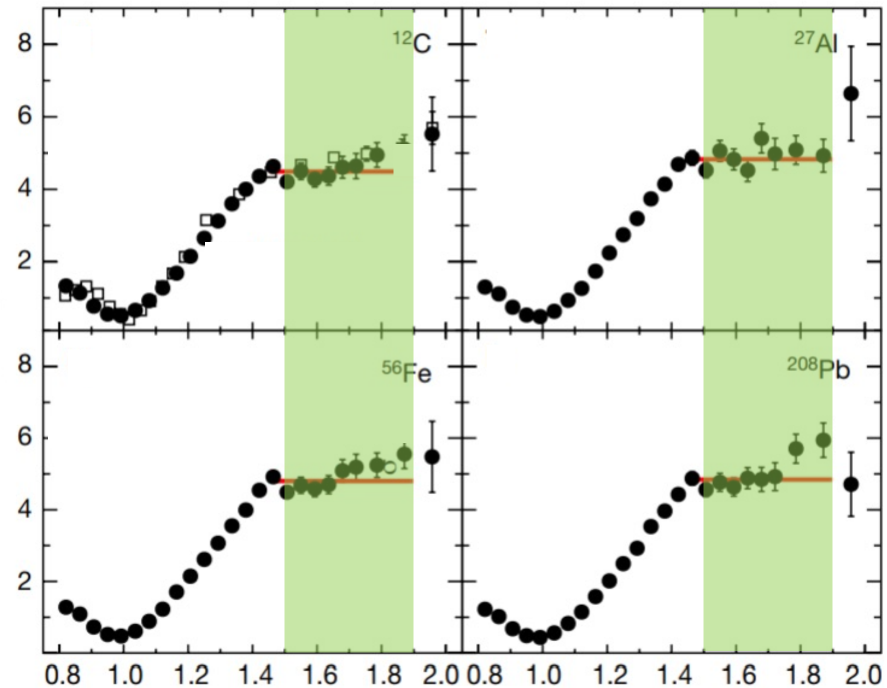
x_B

Schmookler Nature (2019)

SRC Measurements



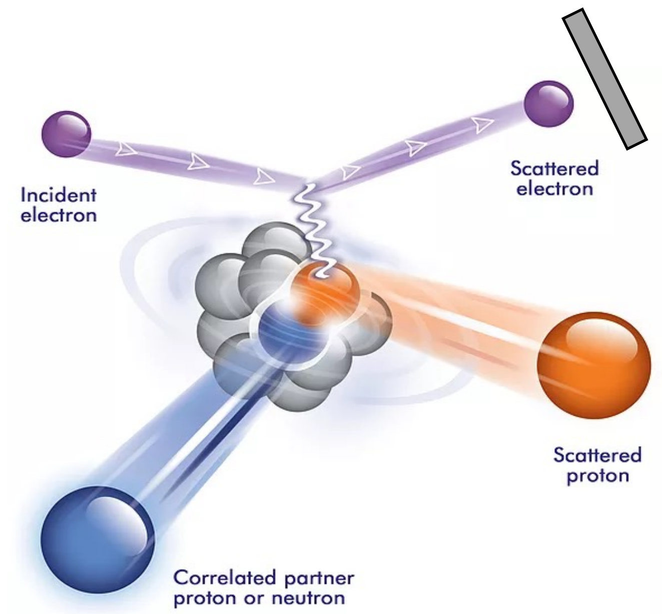
$$\frac{\sigma_A/A}{\sigma_d/2}$$



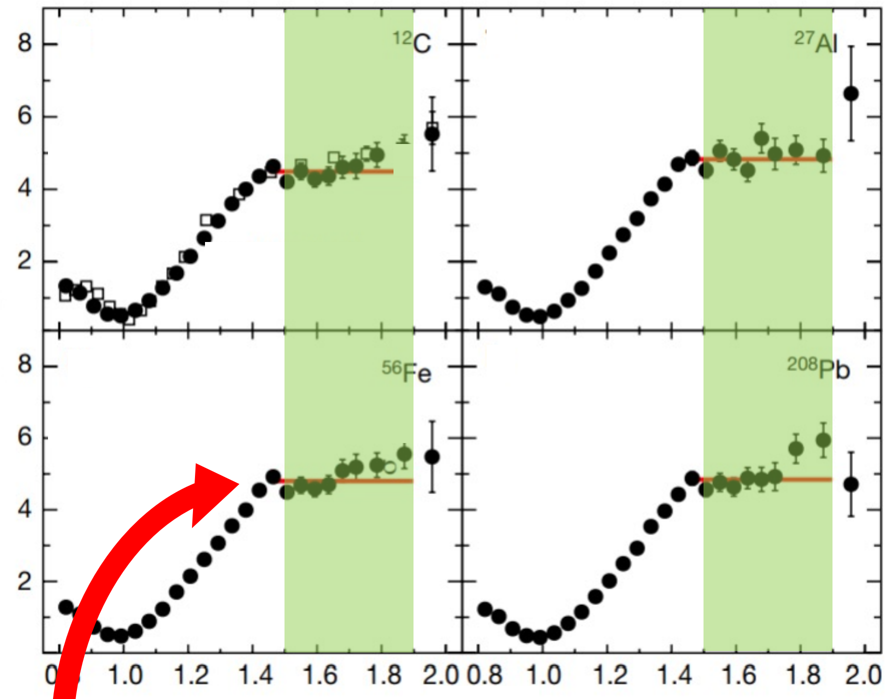
x_B

Schmookler Nature (2019)

SRC Measurements



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

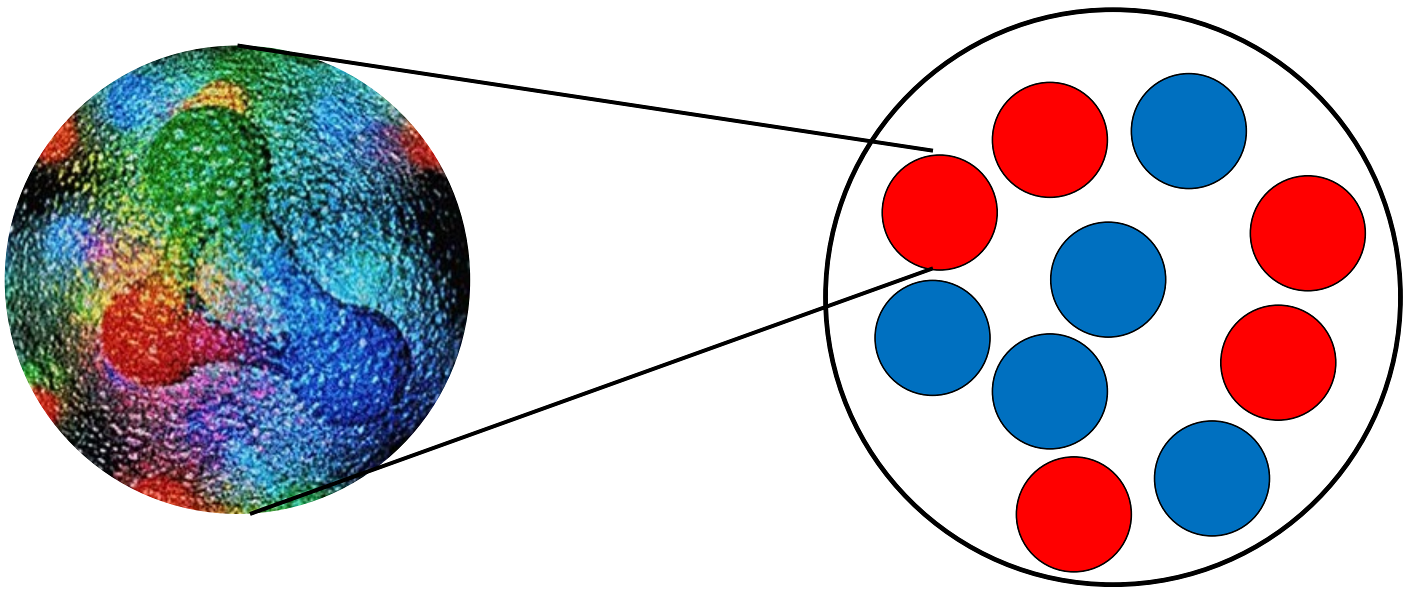


x_B

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

Schmookler Nature (2019)

Partons in the Nucleus



Incorporating SRCs

Modified Protons

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

Modified Neutrons

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