Universität Münster
SMU
Jefferson Lab

Progress and Opportunities for nuclear PDFs & the EIC

POETIC25 – FIU – Miami

Peter Risse

nCTEQ
nuclear parton distribution functions

Structure of nuclei

- Nuclear binding energy $\sim 1\%$ of mass
- First approximation:
  nuclei consist of free protons & neutrons

$$F_2^A(x) \approx Z F_2^{p,free}(x) + N F_2^{n,free}(x)$$

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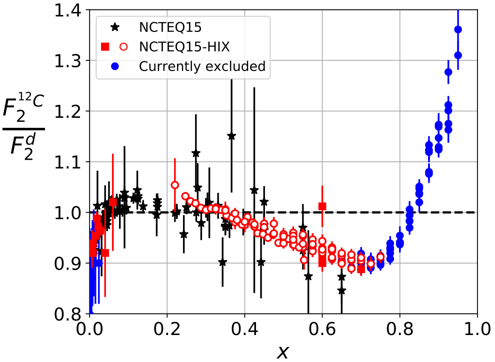
$$F_2^A(x) \neq Z F_2^{p,free}(x) + N F_2^{n,free}(x)$$

$\Rightarrow$ **does not work**



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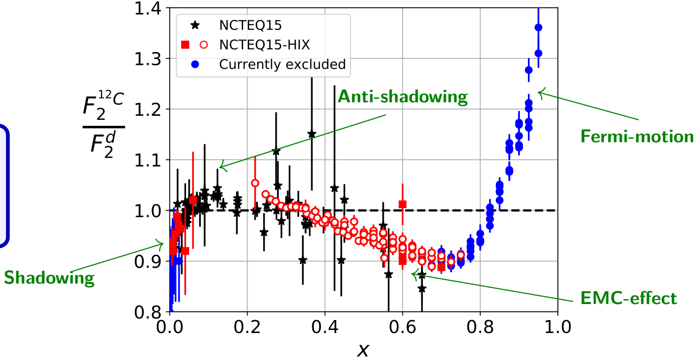
- Cross-sections in nuclear collisions are modified
- Can we translate these modifications into **universal** quantities?



$\Rightarrow$ **nuclear PDFs**

Theoretical foundation and assumptions

- Natural theoretical framework: **Collinear Factorization**

DIS-like Process

$$d\sigma_{lA\to lX} = \sum_i^{q,\bar{q},g} f_i^{(A,Z)} \otimes d\hat{\sigma}_{il\to l'X}$$

DY-like Process

$$d\sigma_{pA\to l\bar{l}X} = \sum_{i,j}^{q,\bar{q},g} f_i^{p} \otimes f_j^{(A,Z)} \otimes d\hat{\sigma}_{ij\to l\bar{l}X}$$

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- Assumptions

Averaged proton/neutron with isospin symmetry

$$f_i^{(A,Z)} = \frac{Z}{A} f_i^{p/A} + \frac{A-Z}{A} f_i^{n/A} \quad \text{where} \quad \begin{array}{l} u^{n/A}(x) = d^{p/A}(x) \\ d^{n/A}(x) = u^{p/A}(x) \end{array}$$

Problems:

- difficult flavor separation
- need more isospin-asymetric nuclei

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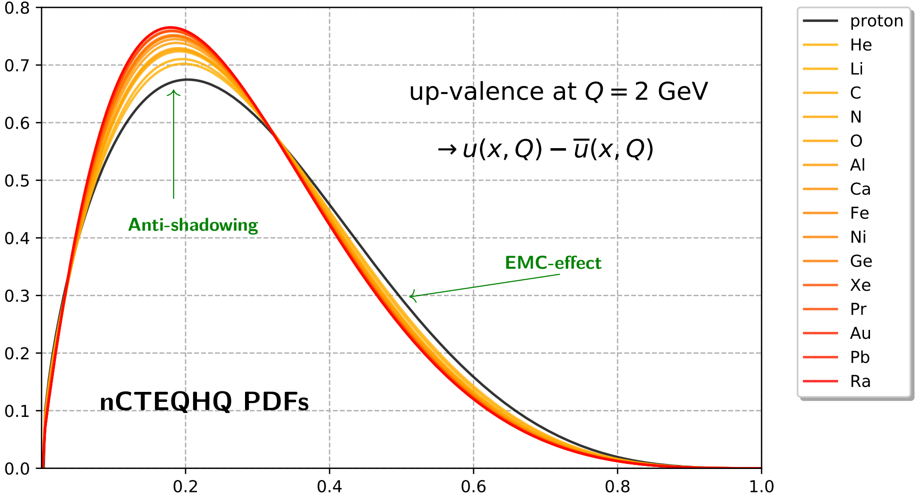
Problems:

- difficult flavor separation
- need more isospin-asymetric nuclei

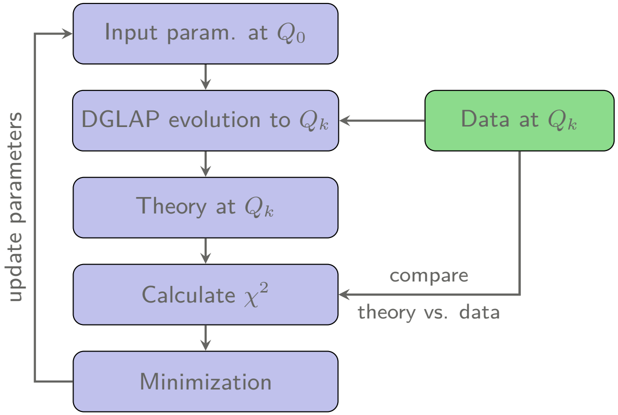
Neglect contributions from $x > 1$

- DGLAP evolution equations
- free proton PDFs sum rules
- under investigation at JLab/EIC

Nuclear modification: free proton vs bound proton



Methodology and experimental data



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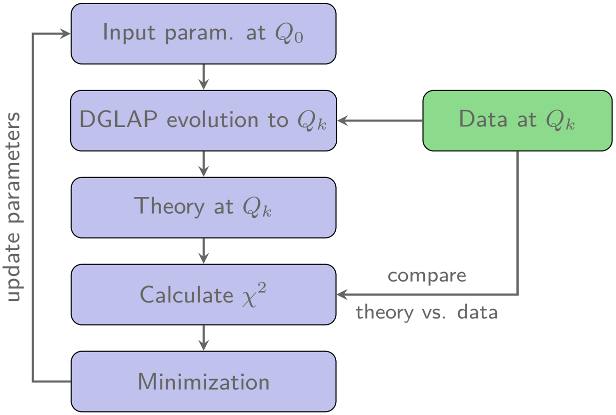
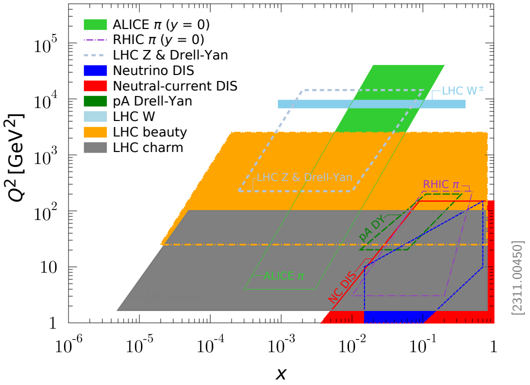


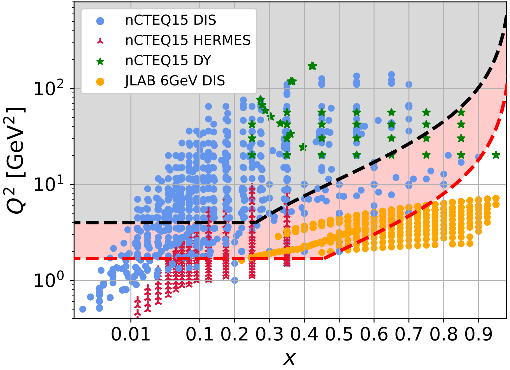


- utilized data points: $\mathcal{O}(3000)$
- experimental precision lower than for proton

Enlarged kinematic cuts

Kinematic variables:

$$Q^2 \quad \& \quad W^2 = Q^2 \frac{1-x}{x} + M_N$$



nCTEQ15

$Q > 2$ GeV
$W > 3.5$ GeV
$N_{\text{data}} = 708$

nCTEQ15HIX

$Q > 1.3$ GeV
$W > 1.7$ GeV
$N_{\text{data}} = 1679$

[PRD 103, 114015 (2021)]

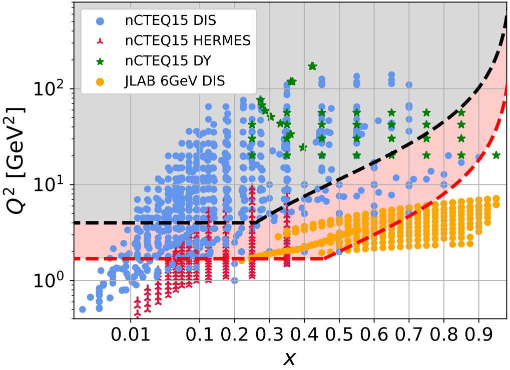
Enlarged kinematic cuts

Kinematic variables:

$$Q^2 \quad \& \quad W^2 = Q^2 \frac{1-x}{x} + M_N$$

Requires proper treatment of:

- deuteron corrections
  [PRD 93, 114017 (2016)]
- target mass corrections (TMCs)
  [Prog.Part.Nucl.Phys. 136 (2024) 104096]
- higher twist effects
  [PRD 93, 114017 (2016)]



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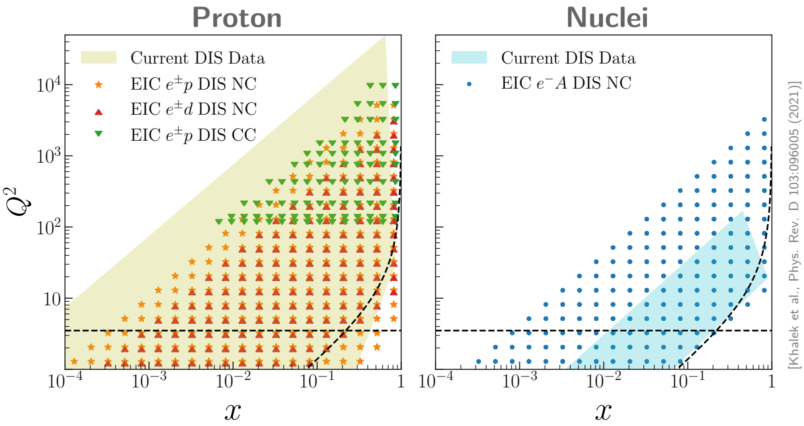
[PRD 103, 114015 (2021)]

EIC: projected neutral current DIS data



- kinematic coverage more than doubles
- "EIC will be the nuclear HERA"

Comparison of available nPDFs

	KSASG20 PRD 104, 034010	TUJU21 PRD 105, 094031	EPPS21 EPJC 82, 413	nNNPDF3.0 EPJC 82, 507	nCTEQ15HQ PRD 105, 114043
lA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓	✓	✓	✓	
pA Drell-Yan	✓		✓	✓	✓
πA Drell-Yan			✓		
RHIC dAu π			✓		✓
LHC pPb π, K					✓
LHC pPb W/Z		✓	✓	✓	✓
LHC pPb dijet			✓	✓	
LHC pPb HQ			✓ GMVFNS	✓ FO+PS(rew)	✓ ME fit
LHC quarkonium					✓ ME fit
LHC pPb γ				✓	
Kinematic cuts	$Q > 1.3$ GeV	$Q > 1.87$ GeV $W > 3.5$ GeV	$Q > 1.3$ GeV $W > 1.8$ GeV $p_T^{HQ} > 3$ GeV	$Q > 1.87$ GeV $W > 3.5$ GeV	$Q > 2$GeV $W > 3.5$GeV $p_T^{HQ(SIH)} > 3$ GeV
No data points	4335	2410	2077	2188	1496
No free param.	9	16	24	256 (NN)	19
χ^2/dof	1.06(1.05)	0.94(0.84)	1.00	1.10	0.86
Error analysis	Hessian	Hessian	Hessian	Monte Carlo	Hessian
$\Delta\chi^2$ tol.	20 (68% CL)	50	35	N/A	35
Proton baseline	CT18	custom	CT18A	∼NNPDF4.0	∼CTEQ6.1
Q_0 ini. scale	1.3 GeV	1.3 GeV	1.3 GeV	1.0 GeV	1.3 GeV
No flavours	3	4	6	6	5
Deuteron treat.	fitted	fitted	free	fitted	free
QCD order	**NLO & NNLO**	**NLO & NNLO**	**NLO**	**NLO**	**NLO**
HQ scheme	FONLL	FONLL	S-ACOT	FONLL	S-ACOT

[2311.00450]

EPPS21 parametrization

Bound Proton

$$f_i^{p/A}(x, Q_0^2) = R_i^{p/A}(x, Q_0^2) f_i^p(x, Q_0^2)$$

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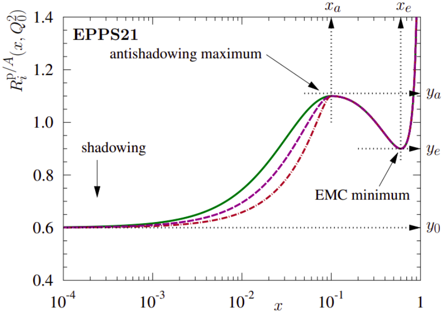
with Nuclear ratio

$$R_i^{p/A}(x, Q_0^2) = \begin{cases} a_{0i} + a_{1i}(x - x_{ai})\left[e^{-xa_{2i}/x_{ai}} - e^{-a_{2i}}\right], & x \leq x_{ai} \\ b_{0i} x^{b_{1i}} (1-x)^{b_{2i}} e^{xb_{3i}}, & x_{ai} \leq x \leq x_{ei} \\ c_{0i} + c_{1i}(c_{2i} - x)(1-x)^{-\beta_i}, & x_{ei} \leq x \leq 1, \end{cases}$$



[EPJC 82, 413]

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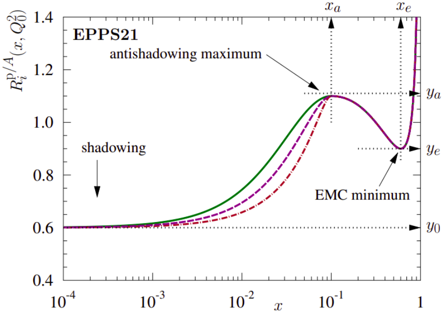
and A-dependence through scaling

$$R_i^{p/A}(x, Q_0^2) = 1 + \left[R_i^{p/A_{\mathrm{ref}}}(x, Q_0^2) - 1\right]\left(\frac{A}{A_{\mathrm{ref}}}\right)^{\gamma_i}, \ \gamma_i > 0, \ A_{\mathrm{ref}} = 12$$



[EPJC 82, 413]

nNNPDF3.0 parametrization

Bound Proton

$$xf_k^{A}(x, Q_0; \theta) = \eta_k^{A} x^{1-\alpha_k^{A}} (1-x)^{\beta_k^{A}} \mathrm{NN}_k^{A}(x, Q_0; \theta)$$

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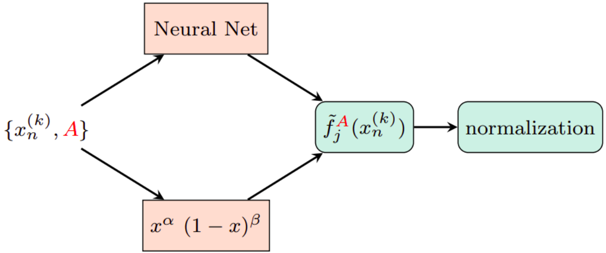
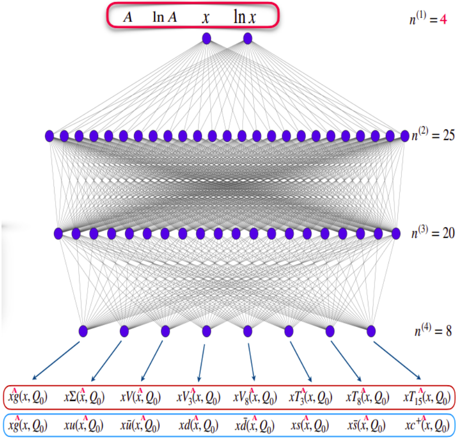
Neural Network with explicit A-dependence





[T. Rabemananjara]

nCTEQ parametrization (incl. an update for the upcoming release)

Proton baseline

CTEQ6M [PRD 75,054030 (2007)] ⇒ CJ15 [PRD 93, 114017 (2016)]

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PDF parametrization:

$$xf_i(x,Q_0^2) = \mathbf{c_0} x^{\mathbf{c_1}} (1-x)^{\mathbf{c_2}} \left(1 + \mathbf{c_3}\sqrt{x} + \mathbf{c_4} x + \mathbf{c_5}\sqrt{x}^3\right) \qquad i = u_v, d_v, g, \bar{u}+\bar{d}, s+\bar{s}$$

$$\bar{d}/\bar{u}(x,Q_0) = \mathbf{c_0} x^{\mathbf{c_1}} (1-x)^{\mathbf{c_2}} + 1 + \mathbf{c_3} x (1-x)^{\mathbf{c_4}} \qquad Q_0 = 1.3\,\mathrm{GeV}$$

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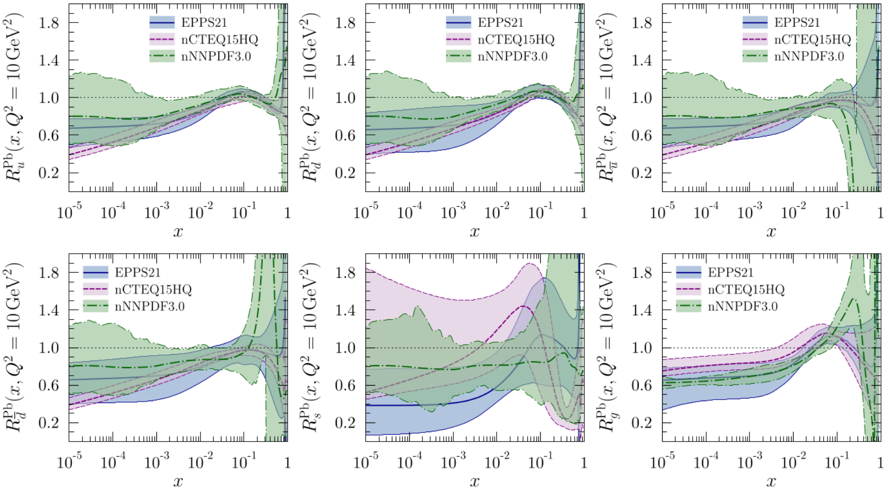
with updated A-dependence:

Currently: $c_k(A) \equiv p_k + a_k \left(1 - A^{-b_k}\right)$

$\Downarrow$

Future: $c_k(A) \equiv p_k + a_k \ln(A) + b_k \ln^2(A)$

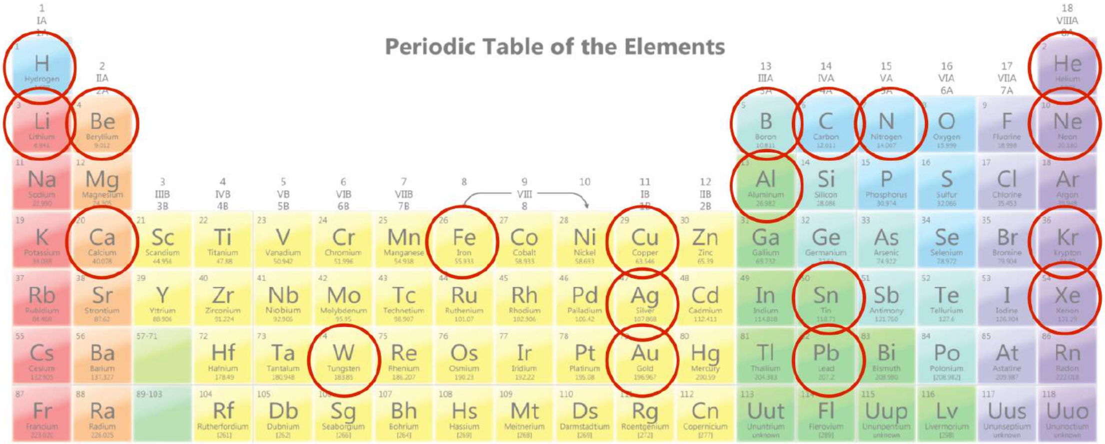
Nuclear ratio of EPPS21 vs. nNNPDF3.0 vs. nCTEQ15HQ



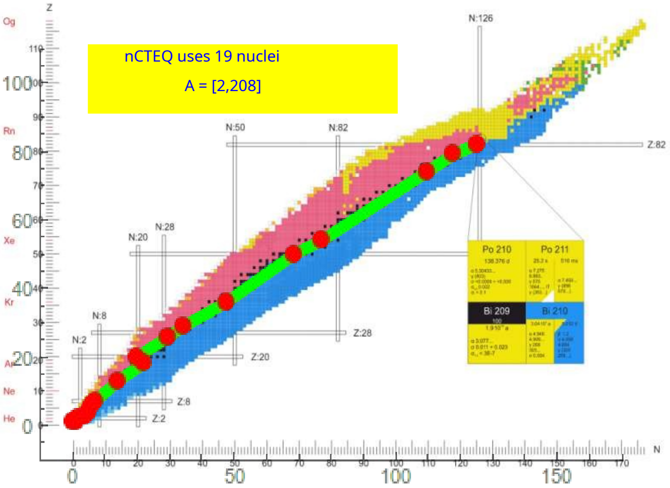
[2311.00450]

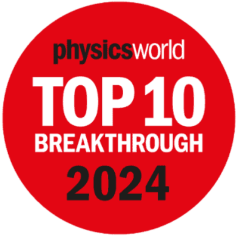
What else can the EIC do for nPDFs?

Nuclei currently included

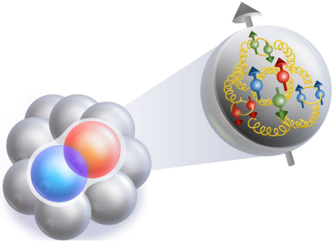


Isotope chart





Short Range Correlations & nuclear PDFs



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

A.W. Denniston[1,*] T. Ježo[2,†] A. Kusina[3] N. Derakhshanian[3] P. Duwentäster[2,4,5]
O. Hen[1] C. Keppel[6] M. Klasen[2,7] K. Kovařík[2] J.G. Morfín[8] K.F. Muzakka[2,9]
F.I. Olness[10] E. Piasetzky[11] P. Risse[2] R. Ruiz[3] I. Schienbein[12] and J.Y. Yu.[12]

New SRC-motivated parametrization

Modeling of short-ranged nuclear structure suggests separation of single nucleons from SRC nucleon pairs.

$\Downarrow$

Translation to parton model

$$f_i^A(x,Q_0) = \frac{Z}{A}\left[(1-\boldsymbol{C_p^A})f_i^p(x,Q_0) + \boldsymbol{C_p^A} f_i^{p,SRC}(x,Q_0)\right] + \frac{N}{A}\left[(1-\boldsymbol{C_n^A})f_i^n(x,Q_0) + \boldsymbol{C_n^A} f_i^{n,SRC}(x,Q_0)\right]$$

$f_i^{p/n}(x,Q_0)$	$\boldsymbol{C_p^A}, \boldsymbol{C_n^A}$	$f_i^{p,SRC}(x,Q_0), f_i^{n,SRC}(x,Q_0)$
free nucleon PDFs	fraction of nucleon in SRC pairs	modified nucleon in SRC pair
***A*-independent**	***A*-dependent**	***A*-independent**

Quality of the fit

χ^2/N_{data}	DIS	DY	W/Z	JLab	χ^2_{tot}	$\frac{\chi^2_{\text{tot}}}{N_{\text{DOF}}}$
`traditional`	0.85	0.97	0.88	0.72	1408	0.85
`baseSRC`	0.84	0.75	1.11	0.41	1300	0.80
`pnSRC`	0.85	0.84	1.14	0.49	1350	0.82
N_{data}	1136	92	120	336	1684	

- three fits: one with traditional parametrization, two fits SRC inspired

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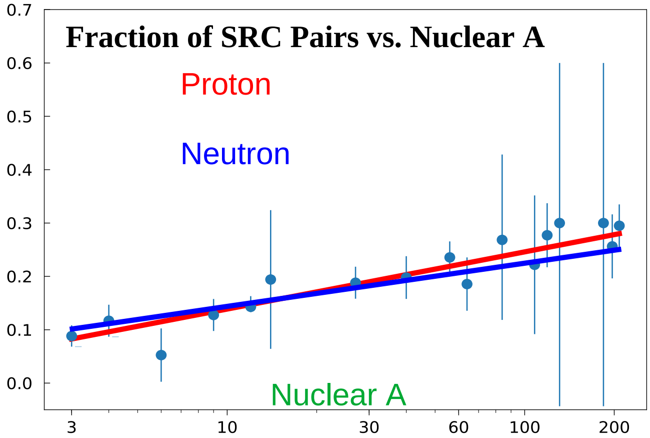
- **better overall** quality for the SRC inspired fit
- particularly pronounced for high-x JLab data
- worse description of W/Z data, which probe lower x-values

SRC fractions

Fit proton & neutron fractions independently: `baseSRC`

- both proton and neutron fraction have simple logarithmic A-dependence
- C_p^A & C_n^A unconstrained for nuclei with sparse data



Nuclear A	2	3	4	6	9	12	14	27	40	56	64	84	108	119	131	184	197	208
# data	275	125	66	15	49	196	101	73	92	134	61	84	7	152	4	37	50	163

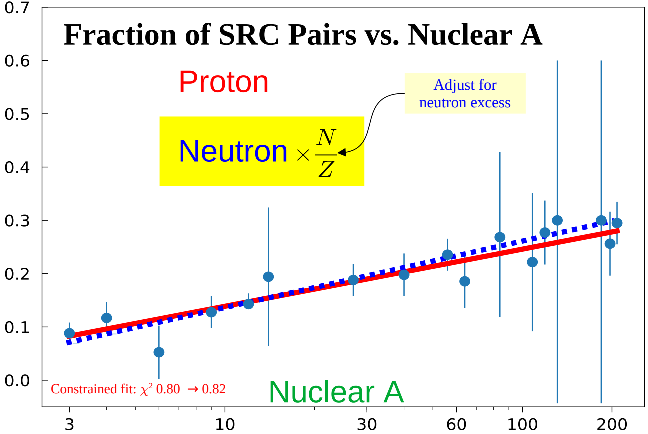
SRC fractions adjusted for neutron excess

Fit proton & neutron fractions independently: `baseSRC`

- both proton and neutron fraction have simple logarithmic A-dependence
- C_p^A & C_n^A unconstrained for nuclei with sparse data

New fit with $C_n^A = Z/N\, C_p^A$: `pnSRC`

- neutron fractions adjusted for excess
- better agreement with proton fractions
- small χ^2/N_{DOF} increase, but less parameters to fit!



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Thank you!

Preliminary results: A-dependence