

Quark and gluon distributions in nuclei at high energy and their connection with correlated nucleon pairs

[PRL 133 (2024) 15, 152502]
[PRD 103, 114015 (2021)]

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Seminarium Fizyki Jadra Atomowego
Uniwersytet Warszawski, 6 Marca 2025

Work supported by:



NARODOWE CENTRUM NAUKI

SONATA BIS grant No 2019/34/E/ST2/00186

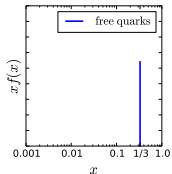
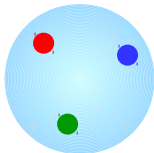
OPUS grant No 2023/49/B/ST2/03862



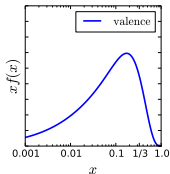
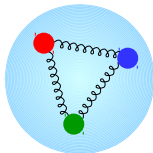
Collinear Parton Distribution Functions (PDFs)

PDF [$f_{a/p}(x, \mu)$]: probability that a parton a carries fraction x of proton's momentum
(valid at leading-order of QCD).

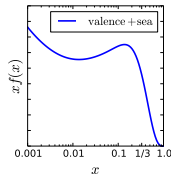
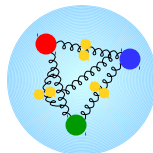
Free quarks



Bound quarks

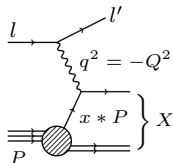


Bound quarks + QCD effects



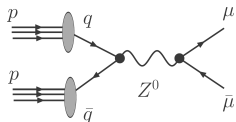
$$x = \frac{\text{longitudinal parton momentum}}{\text{longitudinal nucleon momentum}} = \frac{p_{\text{parton}}^+}{p_{\text{nucleon}}^+}, \quad \text{where } p^\pm = (p^0 \pm p^3)/\sqrt{2}$$

- **Factorization** in case of **Deep Inelastic Scattering** (DIS)



$$\frac{d^2\sigma}{dx dQ^2} = \sum_{i=q,\bar{q},g} \int_x^1 \frac{dz}{z} f_i(z, \mu) d\hat{\sigma}_{il \rightarrow l' X} \left(\frac{x}{z}, \frac{Q}{\mu} \right) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{Q^2}\right)$$

- **Factorization** in case of **Drell-Yan lepton pair production** (DY)



$$\sigma_{pp \rightarrow l\bar{l}X} = \sum_{i,j=q,\bar{q},g} \int_{x_1}^1 dz_1 \int_{x_2}^1 dz_2 \times f_i(z_1, \mu) f_j(z_2, \mu) \hat{\sigma}_{ij \rightarrow l\bar{l}X} \left(\frac{x_1}{z_1}, \frac{x_2}{z_2}, \frac{Q}{\mu} \right) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{Q^2}\right)$$

- $f_i(z, \mu)$ – proton PDFs of parton i (**non-perturbative**).

PDFs are **UNIVERSAL** – do not depend on the process!!!

- $\hat{\sigma}$ – parton level matrix element (**calculable in pQCD**).
- $\mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{Q^2}\right)$ – non-leading terms defining accuracy of factorization formula.
- μ – factorization scale, naturally set to be of order $\sim Q$

Properties of PDFs

► Sum rules

- **Number sum rules** – connect partons to quarks from SU(3) flavour symmetry of hadrons; proton (uud), neutron (udd). For protons:

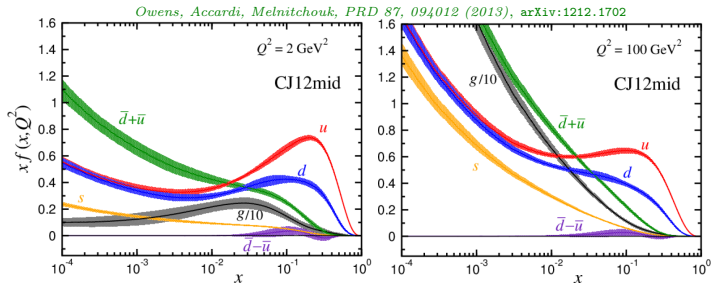
$$\int_0^1 dx \underbrace{[f_u(x) - f_{\bar{u}}(x)]}_{u\text{-valence distr.}} = 2 \qquad \int_0^1 dx \underbrace{[f_d(x) - f_{\bar{d}}(x)]}_{d\text{-valence distr.}} = 1$$

- **Momentum sum rule** – momentum conservation connecting all flavours

$$\sum_{i=q,\bar{q},g} \int_0^1 dx x f_i(x) = 1$$

► Scale dependence

- **x -dependence** of PDFs is NOT calculable in pQCD
- **μ^2 -dependence** is calculable in pQCD – given by **DGLAP** equations



Schematics of Global Analysis

1. Choose experimental data (e.g. DIS, DY, inclusive jet prod., etc.)
2. Parametrize PDFs at low initial scale $\mu = Q_0 \sim 1\text{GeV}$:

$$f_i(x, Q_0) = f_i(x; c_0, c_1, \dots) = c_0 x^{c_1} (1-x)^{c_2} P(x; c_3, \dots)$$

3. Use DGLAP equation to evolve $f_i(x, \mu)$ from $\mu = Q_0$ to $\mu = Q_{\max}$.
4. Calculate theory predictions corresponding to the data ($\sigma_{\text{DIS}}, \sigma_{\text{DY}}$, etc.).
5. Calculate appropriate χ^2 function – compare data and theory

$$\chi^2(\{c_i\}) = \sum_{\text{experiments}} \chi_n^2(\{c_i\})$$
$$\chi_n^2(\{c_i\}) = \sum_{\text{data points}} \left(\frac{\text{data} - \text{theory}(\{c_i\})}{\text{uncertainty}} \right)^2$$

6. Minimize χ^2 function with respect to parameters c_0, c_1, \dots
7. Compute uncertainties (Hessian, Monte Carlo)

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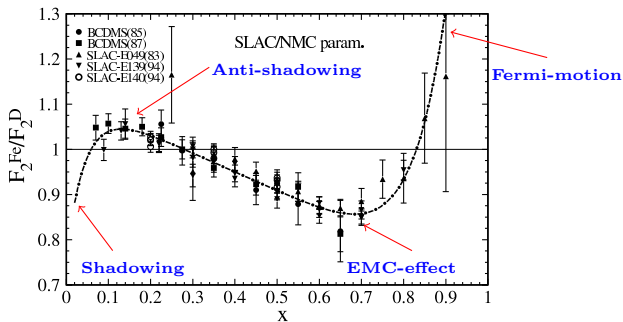
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Motivation for nuclear PDFs

- ▶ Cross-sections in nuclear collisions are modified

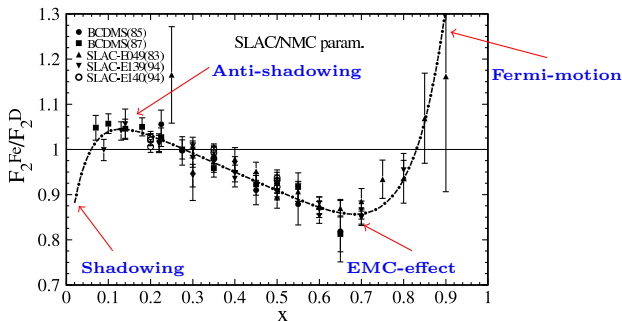
$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$



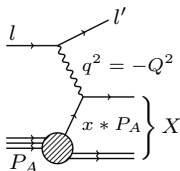
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- Working assumption: **factorization** = *universal* nPDFs



$$\frac{d^2\sigma}{dx dQ^2} = \sum_i f_i^A(x, Q^2) \otimes d\hat{\sigma}_{il \rightarrow l'X}$$

- Do not consider any cold nuclear matter effects (e.g. energy loss).

Schematics of Global Analysis

1. Choose experimental data (e.g. DIS, DY, inclusive jet prod., etc.)
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with $c_j = c_j(A) \stackrel{\text{nCTEQ}}{=} p_k + a_k (1 - A^{-b_k})$ depending on the nuclei;
 $f_i^{n/A}(x, Q)$ - from isospin symmetry.

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► **Parametrization**

- *PDF of nucleus* (A - mass, Z - charge)

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

- bound proton PDFs are parametrized

$$x f_i^{p/A}(x, Q_0) = x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5}$$

- bound neutron PDFs are constructed assuming *isospin symmetry*
- A -dependence

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

► **Sum rules**

$$\int_0^1 dx f_{u_v}^{p/A}(x, Q) = 2, \quad \int_0^1 dx f_{d_v}^{p/A}(x, Q) = 1, \quad \int_0^1 dx \sum_i x f_i^{p/A}(x, Q) = 1.$$

- **Error analysis** using *Hessian* method

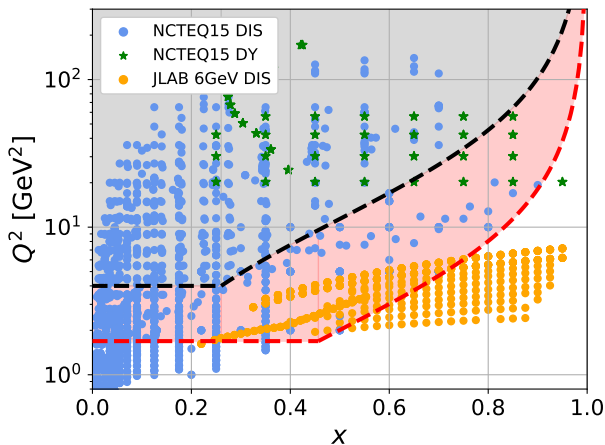
- ▶ **nCTEQ15HIX** [PRD 103, 114015 (2021)]
 - ▶ based on nCTEQ15 analysis
 - ▶ include JLAB DIS data
 - ▶ covers broad range of nuclei: He, Be, C, Al, Fe, Cu, Au, Pb
 - ▶ constraints at high- x
 - ▶ theoretical corrections needed: TMC, HT, deuteron

In (n)PDF analyses we use kinematic cuts to exclude data that are

- ▶ in *non-perturbative region*
- ▶ have significant *higher-twist corrections*

$$\mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{Q^2}\right)$$

This is typically done by *kinematic cuts* on Q^2 and $W^2 = Q^2 \frac{1-x}{x} + M_N^2$



nCTEQ15

$Q > 2 \text{ GeV}$
 $W > 3.5 \text{ GeV}$

$N_{\text{data}} = 708$

nCTEQ15HIX

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

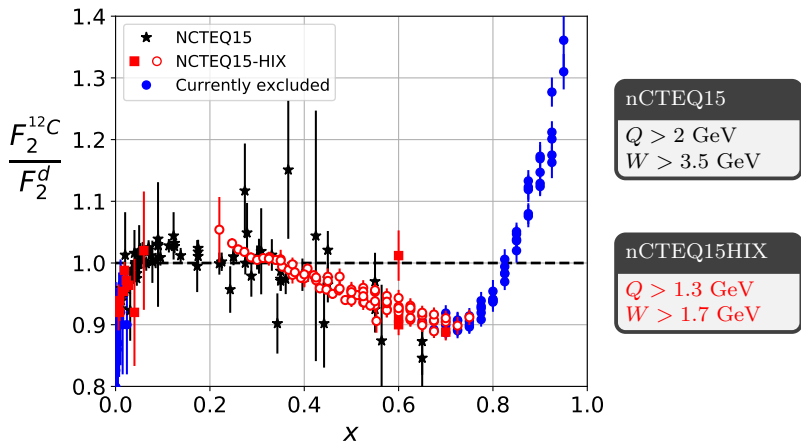
$N_{\text{data}} = 1679$

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Large- x data from JLAB

Target	Experiment	ID	Ref.	# data	#data after cuts
$^{208}\text{Pb}/\text{D}$	CLAS	9976	[11]	25	24
$^{56}\text{Fe}/\text{D}$	CLAS	9977	[11]	25	24
$^{27}\text{Al}/\text{D}$	CLAS	9978	[11]	25	24
$^{12}\text{C}/\text{D}$	CLAS	9979	[11]	25	24
$^4\text{He}/\text{D}$	Hall C	9980	[12]	25	17
		9981	[12]	26	16
$^3\text{He}/\text{D}$	Hall C	9982	[12]	25	17
		9983	[12]	26	16
$^{64}\text{Cu}/\text{D}$	Hall C	9984	[12]	25	17
		9985	[12]	26	16
$^9\text{Be}/\text{D}$	Hall C	9986	[12]	25	17
		9987	[12]	26	16
$^{197}\text{Au}/\text{D}$	Hall C	9988	[12]	24	17
		9989	[12]	26	16
$^{12}\text{C}/\text{D}$	Hall C	9990	[12]	25	17
		9991	[12]	17	7
		9992	[12]	26	16
		9993	[12]	18	6
		9994	[12]	17	7
		9995	[12]	15	2
		9996	[12]	19	7
		9997	[12]	16	2
		9998	[12]	21	8
		9999	[12]	18	3
Total				546	428

CLAS [[Nature 566 \(2019\) 7744](#)]

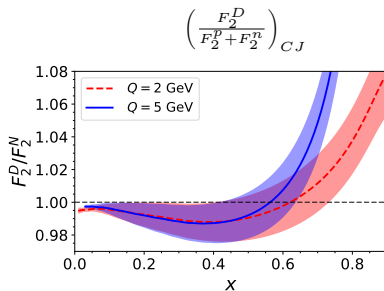
Hall C [[PRL 103 \(2009\) 202301](#)]

Corrections at large- x

Effects we include:

- ▶ *Target-mass corrections* (OPP) & *dynamic higher-twist* effects
→ to good extent **cancel in ratio**.
- ▶ *Deuteron corrections*

[PRD 93 (2016) 11, 114017]



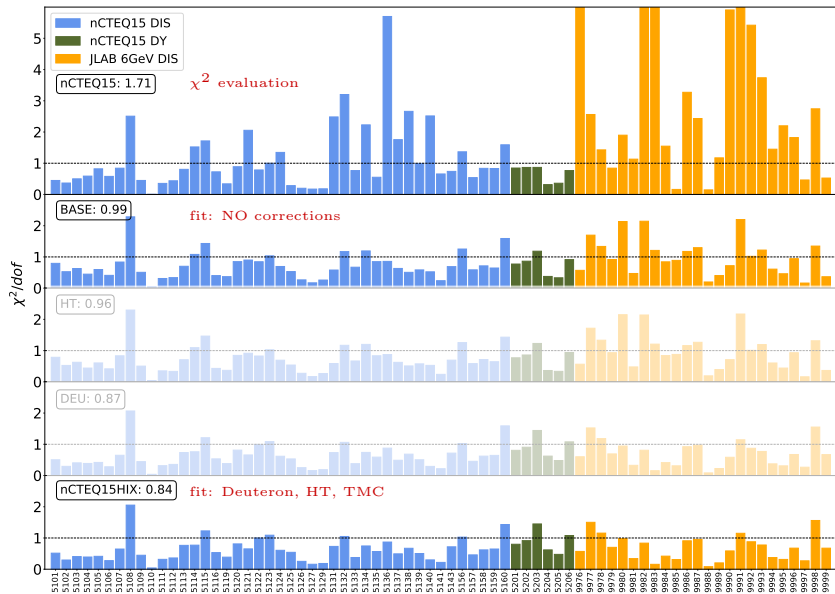
Effects needed when going to even higher- x (lower W):

- ▶ Non-vanishing structure functions/nPDFs at $x > 1$ and corresponding extension of DGLAP evolution.
- ▶ Threshold resummation.

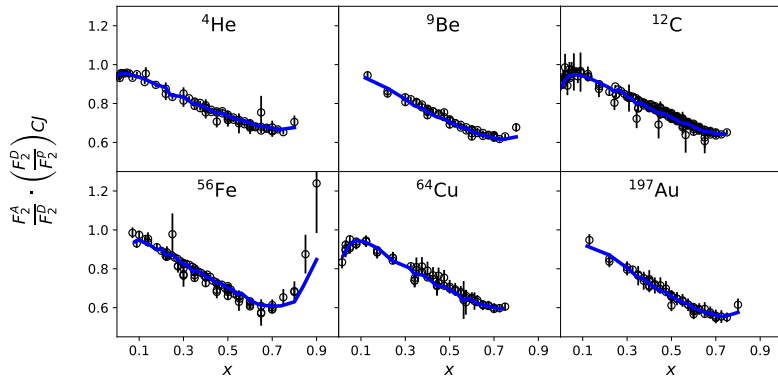
We performed the following fits:

- ▶ **nCTEQ15**: for comparison (no fit)
- ▶ **BASE**: nCTEQ15 refit including new data & cuts
- ▶ **HT**: include HT and TMC corrections
- ▶ **DEUT**: include deuteron corrections
- ▶ **nCTEQ15HIX**: include both deuteron, HT & TMC corrections

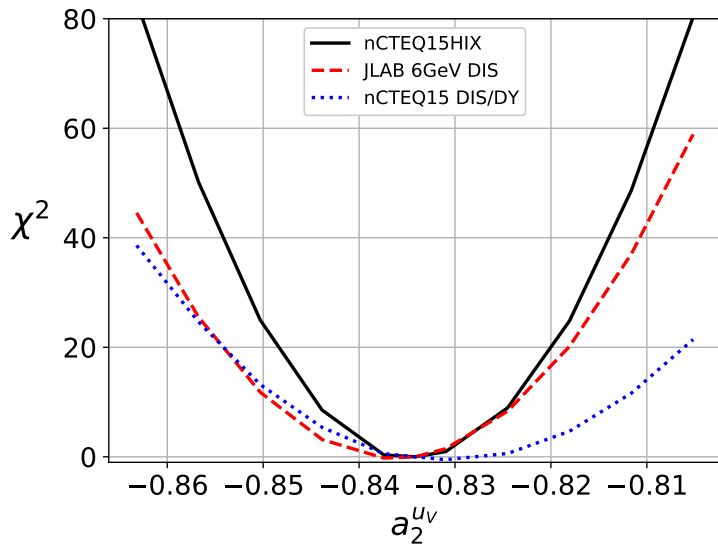
nCTEQ15HIX results

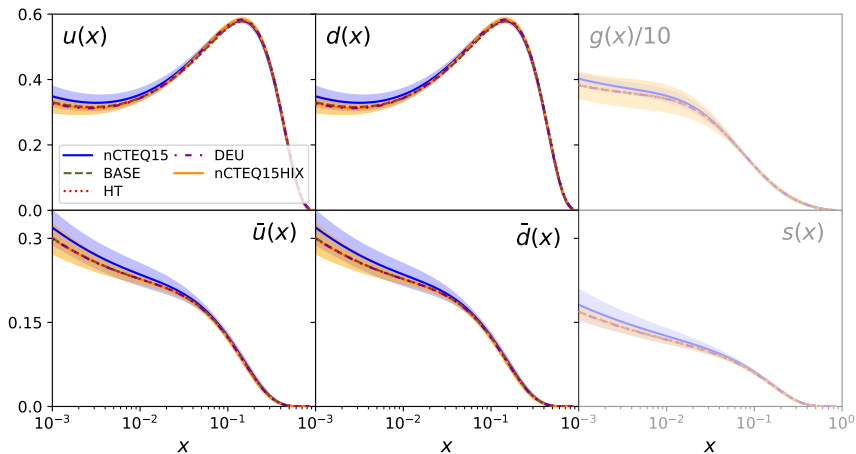


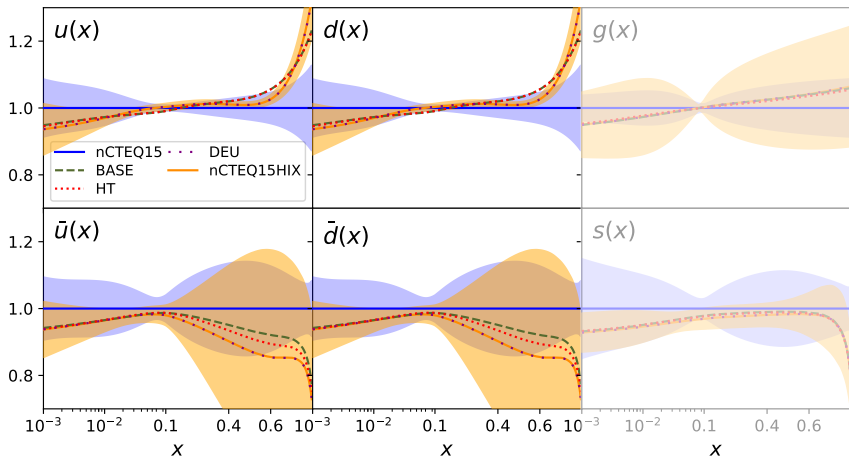
We obtain very good description of the data with $\chi^2 \sim 0.85$

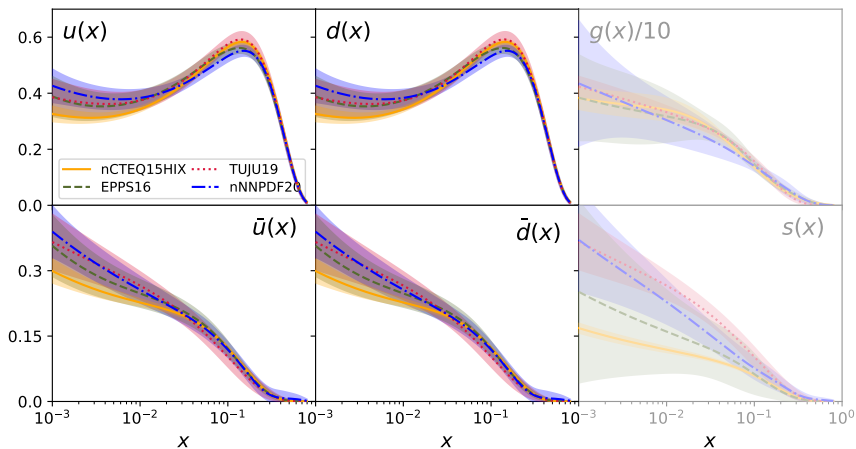


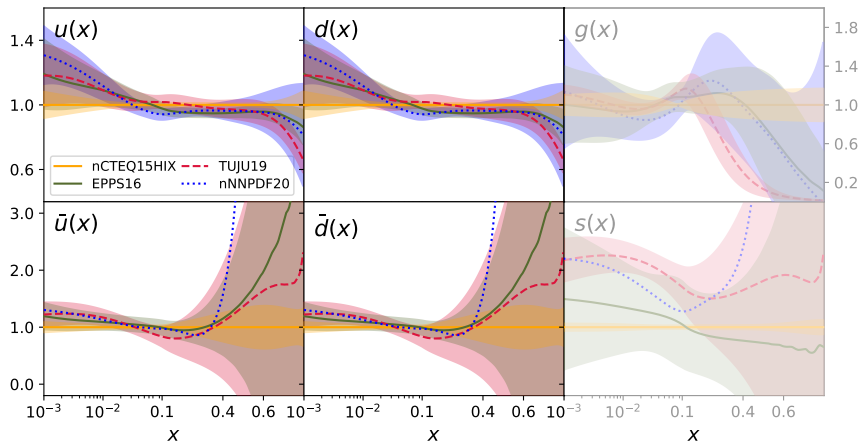
JLAB data constraints mostly valence region



Carbon PDFs ($Q = 2$ GeV)

Carbon PDF Ratios to nCTEQ15 ($Q = 2$ GeV)

Carbon PDFs ($Q = 2$ GeV)

Carbon PDF Ratios to nCTEQ15HIX ($Q = 2$ GeV)

- ▶ **nCTEQ15HIXsrc** [PRL 133 (2024) 15, 152502]
 - ▶ based on same data as nCTEQ15HIX
 - ▶ include JLAB DIS data + W/Z from LHC
 - ▶ look especially at the EMC region (high- x)
 - ▶ parametrization inspired by SRC models

Standard nPDF parametrization

1. One of the standard ways of parametrizing nuclear PDFs (nPDFs) is by extending the proton PDF parametrizations to account for A -dependence.
2. E.g. in the nCTEQ group:
 - ▶ *PDF of nucleus* (A - mass, Z - charge, N - number of neutrons)

$$f_i^{(A,Z)}(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{N}{A} f_i^{n/A}(x, Q)$$

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$$c_k \rightarrow c_k(A) \equiv p_k + a_k (1 - A^{-b_k})$$

3. Sum rules

$$\int_0^1 dx f_{u_v}^{p/A}(x, Q) = 2, \quad \int_0^1 dx f_{d_v}^{p/A}(x, Q) = 1, \quad \int_0^1 dx \sum_i x f_i^{p/A}(x, Q) = 1.$$

- ▶ **Short Range Correlations** (SRC) pairs can have isospin $I = 0, 1$, possible configurations: (pn) , (pp) , (nn)
- ▶ Partonic content of SRC pairs could be expressed as a convolution of distributions of a parton inside a nucleon and a nucleon inside a pair, then the distribution of the full nucleus:

$$f_i^A = \frac{Z}{A} \left[(1 - [C_A^{(pp)} + C_A^{(pn)}]) f_{i/p} + C_A^{(pp)} f_{\text{SRC}}^{p/(pp)} \otimes f_{i/p} + C_A^{(pn)} f_{\text{SRC}}^{p/(pn)} \otimes f_{i/p} \right] \\ + \frac{N}{A} \left[(1 - [C_A^{(nn)} + C_A^{(pn)}]) f_{i/n} + C_A^{(nn)} f_{\text{SRC}}^{n/(nn)} \otimes f_{i/n} + C_A^{(pn)} f_{\text{SRC}}^{n/(pn)} \otimes f_{i/n} \right]$$

- ▶ For phenomenological purpose we can simplify it assuming:

$$f_{i/p}^{\text{SRC}} \equiv [f_{\text{SRC}}^{p/(pp)} + f_{\text{SRC}}^{p/(pn)}] \otimes f_{i/p} \qquad C_A^p \equiv C_A^{(pp)} + C_A^{(pn)}$$

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Our **phenomenological SRC inspired parametrization** takes form:

$$f_i^A(x, Q) = \frac{Z}{A} \left[(1 - C_A^p) f_{i/p}(x, Q) + C_A^p f_{i/p}^{\text{SRC}}(x, Q) \right] \\ + \frac{N}{A} \left[(1 - C_A^n) f_{i/n}(x, Q) + C_A^n f_{i/n}^{\text{SRC}}(x, Q) \right]$$

with $f_{i/p}(f_{i/n})$ being the free proton (neutron) PDFs and $f_{i/p}^{\text{SRC}}(f_{i/n}^{\text{SRC}})$ the effective SRC proton (neutron) distributions.

The full nPDF f_i^A need to fulfill:

1. DGLAP evolution.
2. Momentum and number sum rules:

$$\int_0^1 dx x f_i^A(x, Q) = 1, \quad \int_0^1 dx f_{uv}^A(x, Q) = \frac{A+Z}{A}, \quad \int_0^1 dx f_{dv}^A(x, Q) = \frac{A+N}{A}.$$

We assume that both $f_{i/n}$ and $f_{i/n}^{\text{SRC}}$ can be determined using isospin symmetry. We also restrict $f_{i/p}^{\text{SRC}}(f_{i/n}^{\text{SRC}})$ (and f_i^A) to be define on $x \in (0, 1)$, then $f_{i/p}^{\text{SRC}}(f_{i/n}^{\text{SRC}})$:

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For the purpose of global analysis we:

- ▶ fix the free proton PDFs to the nCTEQ15 proton,
- ▶ parametrize the SRC PDFs as:

$$x f_{i/p}^{\text{SRC}}(x, Q_0) = x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5}$$

Free parameters:

- ▶ x -shape: set of $\{c_k\}$ parameters for each flavour (total of 21),
- ▶ A -dependence: pairs of (C_A^p, C_A^n) parameters which are independent for each nuclei (instead we could use nuclear model to constrain them).

Used data:

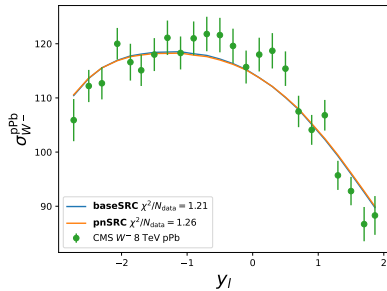
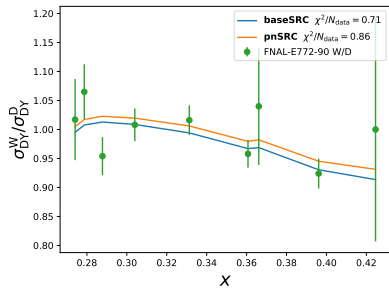
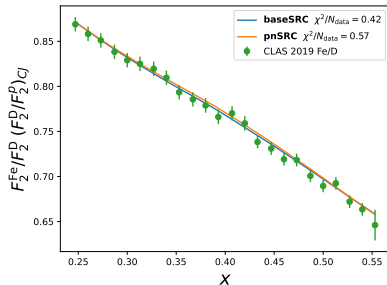
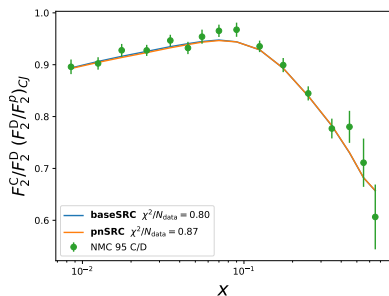
- ▶ all DIS & DY data used in the nCTEQ15 analysis [PRD 93, 085037 (2016)],
- ▶ high- x DIS data from JLAB which we used in the nCTEQ15hix analysis [PRD 103, 114015 (2021)],
- ▶ p Pb data for W/Z production from the LHC used in the nCTEQ15WZ analysis [EPJC 80, 968 (2020)].

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

Performed fits:

- ▶ **Reference**– fit using standard nCTEQ PDF fitting framework,
- ▶ **baseSRC**– use SRC parametrization, keep C_A^p and C_A^n parameters **independent**,
- ▶ **pnSRC**– use SRC parametrization, **tie together** C_A^p and C_A^n .

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Reference	0.85	0.97	0.88	0.72	1408	0.85
SRC baseSRC	0.84	0.75	1.11	0.41	1300	0.80
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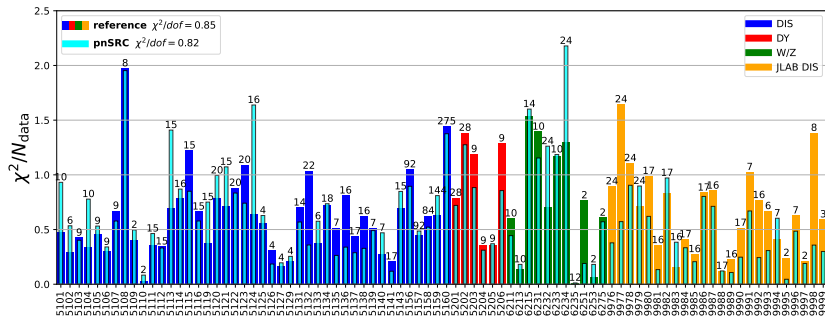
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- ▶ Especially better description of the (precise) high- x JLAB data.
- ▶ Worse description of the W/Z data from LHC - lowest available x values.

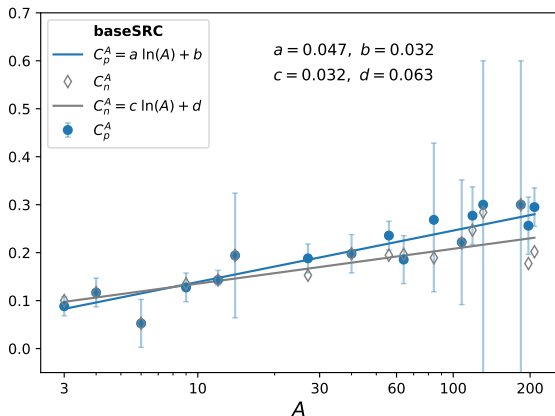
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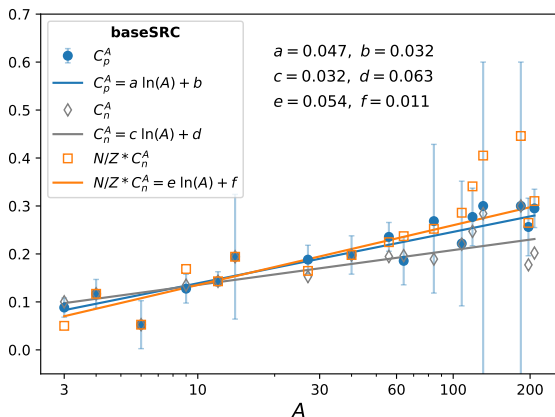
Results: A -dependence of the (C_A^p, C_A^n) parameters



The number of protons and neutrons in SRC pairs is approximately equal, e.g.

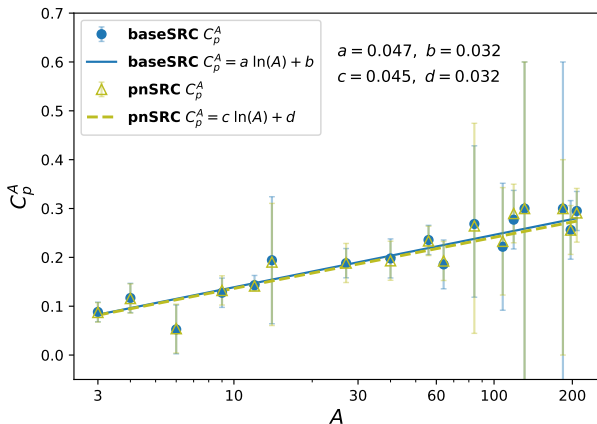
- ▶ $^{197}_{79}\text{Au}$ ($C_A^p=0.256, C_A^n=0.178$): $79 \times C_A^p \simeq 20.2$ protons and $118 \times C_A^n \simeq 21.0$ neutrons.
- ▶ $^{208}_{82}\text{Pb}$ ($C_A^p=0.295, C_A^n=0.202$): $82 \times C_A^p \simeq 24.2$ protons and $126 \times C_A^n \simeq 25.5$ neutrons.

Results: A -dependence of the (C_A^p, C_A^n) parameters



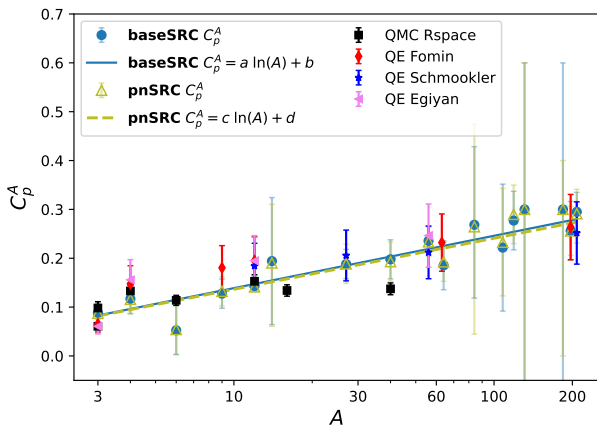
- ▶ Correcting for the access of neutrons we obtained a very comparable numbers of protons and neutrons bounded in the SRC pairs.
- ▶ This is **consistent** with the hypothesis that the **SRC pairs are dominantly proton-neutron combinations**.
- ▶ We can use this observation to restrict number of fit parameters by linking $C_A^n = (Z/N)C_A^p$.

Results - pnSRC fit with $C_A^n = (Z/N)C_A^p$



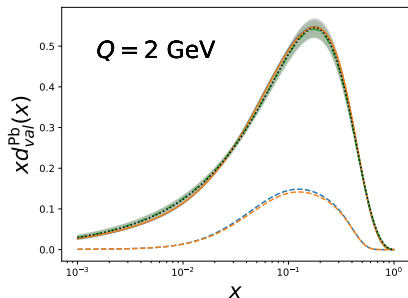
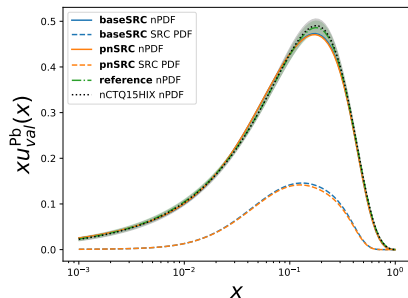
- ▶ The obtained C_A^p values are nearly the same as for the **baseSRC** fit.
- ▶ Fit quality is very comparable $\chi^2/N_{\text{DOF}} = 0.82$ (vs $\chi^2/N_{\text{DOF}} = 0.8$).

Results - pnSRC fit with $C_A^n = (Z/N)C_A^p$



- ▶ Results of Quantum Monte Carlo calculations (QMC) [Nature Physics 17, 306-310 (2021)]
- ▶ Results of measurements in quasi-elastic region:
 - ▶ Fomin [Nature 566, 354-358 (2019)]
 - ▶ Schmookler [Phys. Rev. Lett. 96, 082501 (2006)]
 - ▶ Egiyan [Phys. Rev. Lett. 108, 092502 (2012)]

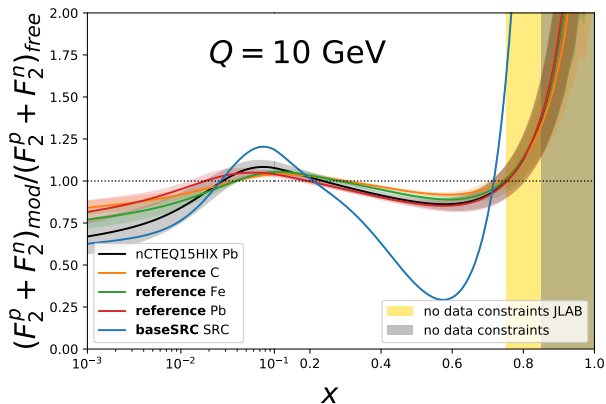
Results: PDFs



- ▶ nPDFs obtained from SRC fits lie within the error bands of the **Reference** fit.
- ▶ The SRC components of the full nPDFs are in the range 20% to 30% – in agreement with the $\{C_A^p, C_A^n\}$ values.

$$f_i^A(x, Q) = \frac{Z}{A} \left[(1 - C_A^p) f_{i/p}(x, Q) + C_A^p f_{i/p}^{\text{SRC}}(x, Q) \right] + \frac{N}{A} \left[(1 - C_A^n) f_{i/n}(x, Q) + C_A^n f_{i/n}^{\text{SRC}}(x, Q) \right]$$

Results: modification of F_2 structure function



- ▶ Clearly “exaggerated” modifications for pure SRC distribution.

- ▶ **JLAB data** provides very interesting **constraints in the high- x** region:
 - ▶ covers a range of nuclei: He, Be, C, Al, Fe, Cu, Au, Pb,
 - ▶ very precise,
 - ▶ unfortunately rather low energy \rightarrow require corrections: HT, TMC, deuteron.
- ▶ The simple **SRC-based picture** of nPDFs leads to **comparable or better data description** than the traditional nPDF parameterization.
- ▶ The obtained values of $\{C_A^p, C_A^n\}$ suggest approximately equal number of protons and neutrons in the SRC pairings which is consistent with other observations ***pn*-dominance in SRC pairs**.
- ▶ Even when the $\{C_A^p, C_A^n\}$ parameters are constrained in the **pnSRC** fit, we obtain a very good fit to the data, yielding lower χ^2 than in the **Reference** fit. This can be used to further constrain the used parametrization.
- ▶ It is notable that all the above results, obtained from purely **data driven fits**, seem to support the **SRC-based description of nuclei**.
- ▶ The obtained SRC distributions feature “exaggerated” modifications compared to the full nPDFs.