Parton distributions in nuclei and their connection with correlated nucleon pairs

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

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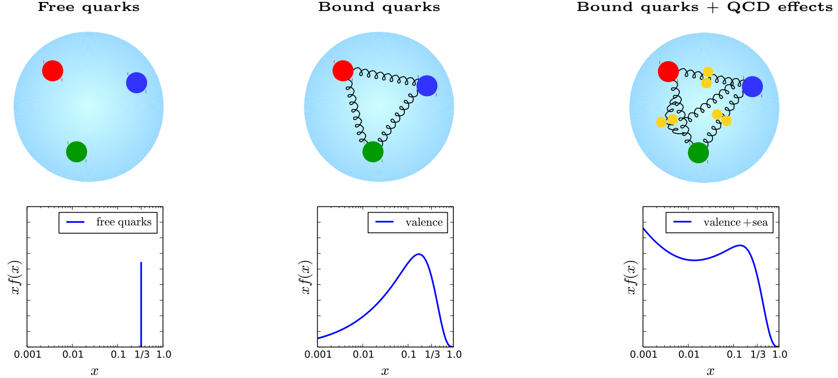
Collinear Parton Distribution Functions (PDFs)

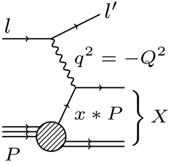
PDF $[f_{a/p}(x,\mu)]$: probability that a parton a carries fraction x of proton's momentum
(valid at leading-order of QCD).



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

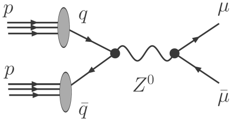
PDFs and QCD Factorization

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



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

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



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

- $f_i(z,\mu)$ – 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**).
- $\mathcal{O}\left(\frac{\Lambda^2_{\text{QCD}}}{Q^2}\right)$ – 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:

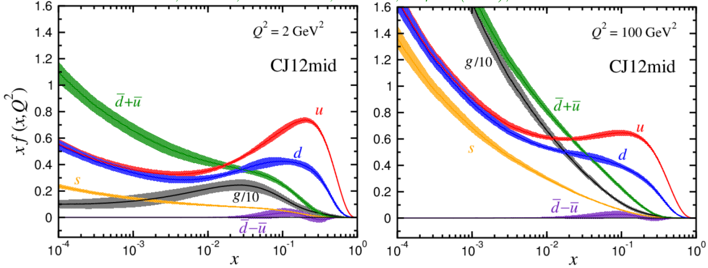
$$\int_0^1 dx[\underbrace{f_u(x) - f_{\bar{u}}(x)}_{u-\text{valence distr.}}] = 2 \qquad \int_0^1 dx[\underbrace{f_d(x) - f_{\bar{d}}(x)}_{d-\text{valence distr.}}] = 1$$

  - **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

Owens, Accardi, Melnitchouk, PRD 87, 094012 (2013), arXiv:1212.1702



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 (σ_{DIS}, σ_{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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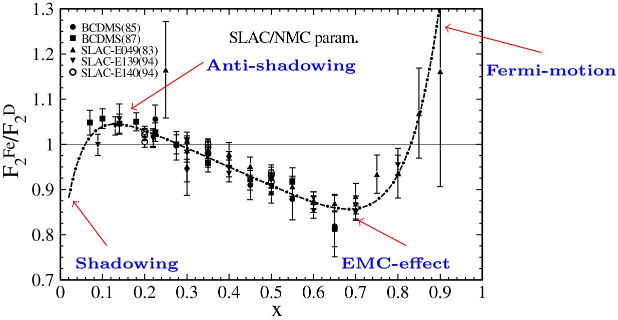
Motivation for nuclear PDFs

- Cross-sections in nuclear collisions are modified

$$F_2^A(x) \neq Z F_2^p(x) + N F_2^n(x)$$



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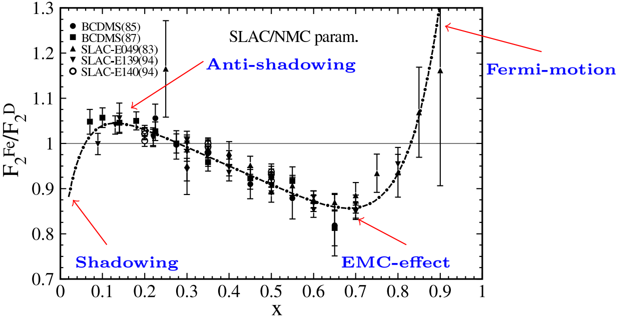
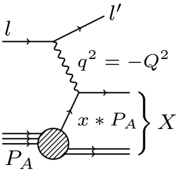


- Working assumption: **factorization** = *universal* **nPDFs**



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

- 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.)
2. Parametrize **nuclear PDFs** at low initial scale $\mu = Q_0 \sim 1\text{GeV}$:

$$f_i^{(A,Z)}(x,Q) = \frac{Z}{A} f_i^{p/A}(x,Q) + \frac{A-Z}{A} f_i^{n/A}(x,Q)$$
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with $c_j = c_j(A) \overset{\text{nCTEQ}}{=} p_k + a_k\left(1 - A^{-b_k}\right)$ depending on the nuclei;
$f_i^{n/A}(x,Q)$ - from isospin symmetry.

3. Use DGLAP equation to evolve $f_i(x,\mu)$ from $\mu = Q_0$ to $\mu = Q_{\text{max}}$.
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nCTEQ framework [PRD 93, 085037 (2016), arXiv:1509.00792]

- **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

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

- **Sum rules**

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

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

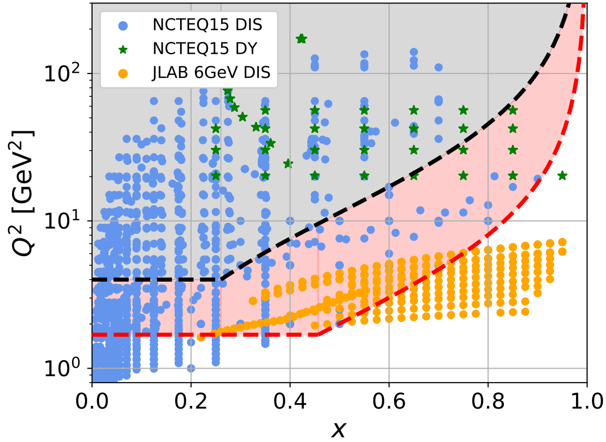
Constraining high-x nPDFs with JLAB data

- **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 $\mathcal{O}\left(\frac{\Lambda^2_{\rm QCD}}{Q^2}\right)$

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

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



nCTEQ15

$Q > 2$ GeV
$W > 3.5$ GeV

$N_{\rm data} = 708$

nCTEQ15HIX

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

$N_{\rm data} = 1679$

Data in nPDF analyses [PRD 103, 114015 (2021)]

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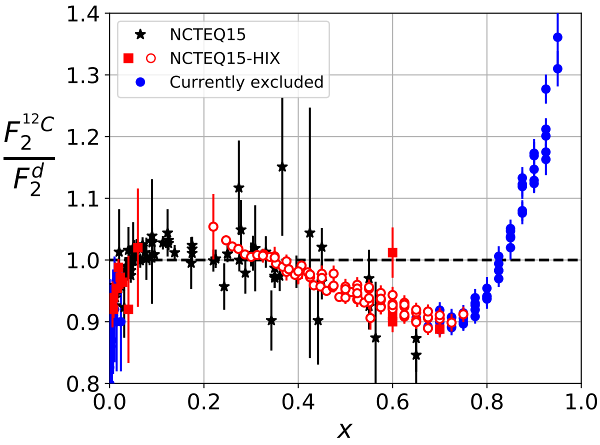


nCTEQ15

$Q > 2$ GeV
$W > 3.5$ GeV

nCTEQ15HIX

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

Large-x data from JLAB

Target	Experiment	ID	Ref.	# data	#data after cuts
^{208}Pb/D	CLAS	9976	[11]	25	24
^{56}Fe/D	CLAS	9977	[11]	25	24
^{27}Al/D	CLAS	9978	[11]	25	24
^{12}C/D	CLAS	9979	[11]	25	24
^{4}He/D	Hall C	9980	[12]	25	17
		9981	[12]	26	16
^{3}He/D	Hall C	9982	[12]	25	17
		9983	[12]	26	16
^{64}Cu/D	Hall C	9984	[12]	25	17
		9985	[12]	26	16
^{9}Be/D	Hall C	9986	[12]	25	17
		9987	[12]	26	16
^{197}Au/D	Hall C	9988	[12]	24	17
		9989	[12]	26	16
^{12}C/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

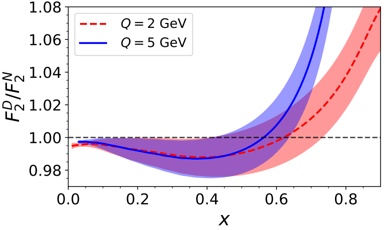
CLAS [Nature 566 (2019) 7744]

Hall C [PRL 103 (2009) 202301]

Effects we include:

- *Target-mass corrections* (OPP) & *dynamic higher-twist* effects
  $\rightarrow$ to good extent cancel in ratio.
- *Deuteron corrections*
  [PRD 93 (2016) 11, 114017]

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



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

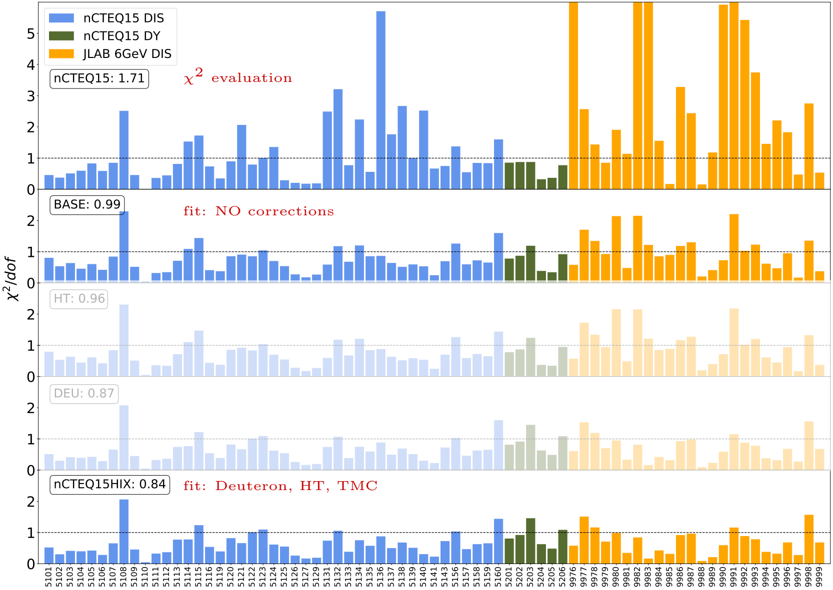
- Non-vanishing structure functions/nPDFs at $x > 1$ and corresponding extension of DGLAP evolution.
- Threshold resummation.

Fits we did

We performed the following fits:

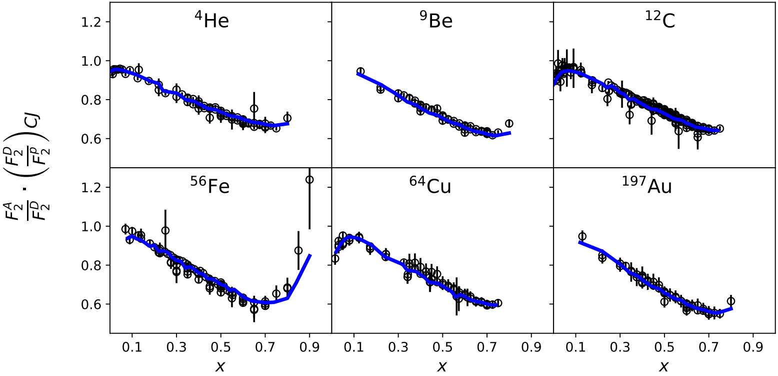
- **nCTEQ15**: for comparison (no fit)
- **BASE**: nCTEQ15 refit including new data & cuts
- **HT**: include HT and TMC corrections
- **DEUT**: include deuteron corrections
- **nCTEQ15HIX**: include both deuteron, HT & TMC corrections

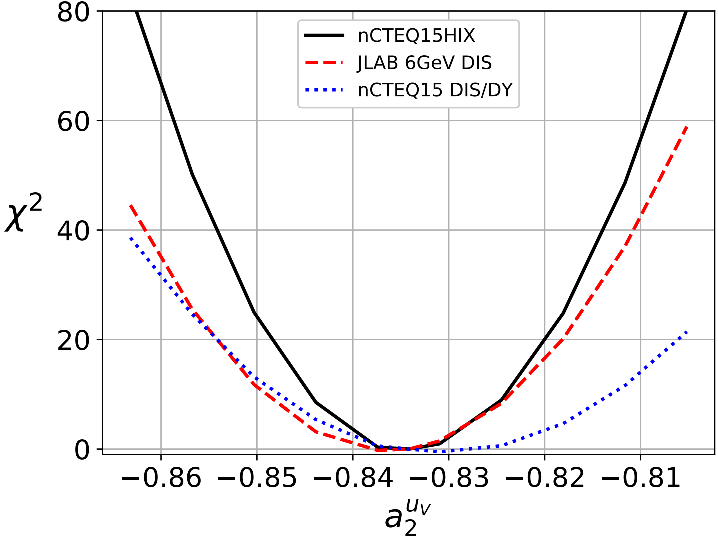
nCTEQ15HIX results



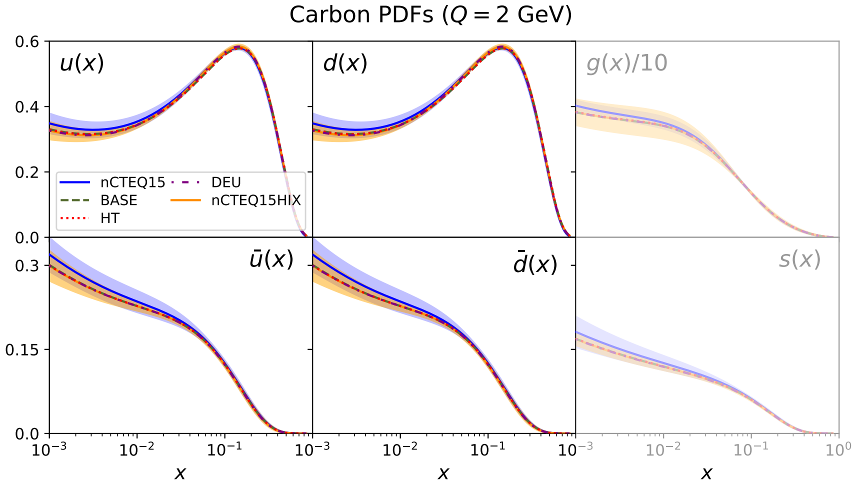
nCTEQ15HIX results

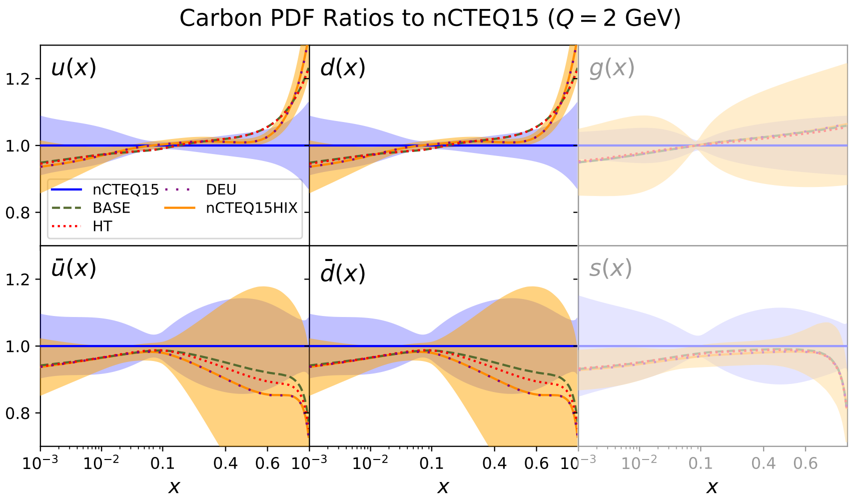
We obtain very good description of the data with $\chi^2 \sim 0.85$



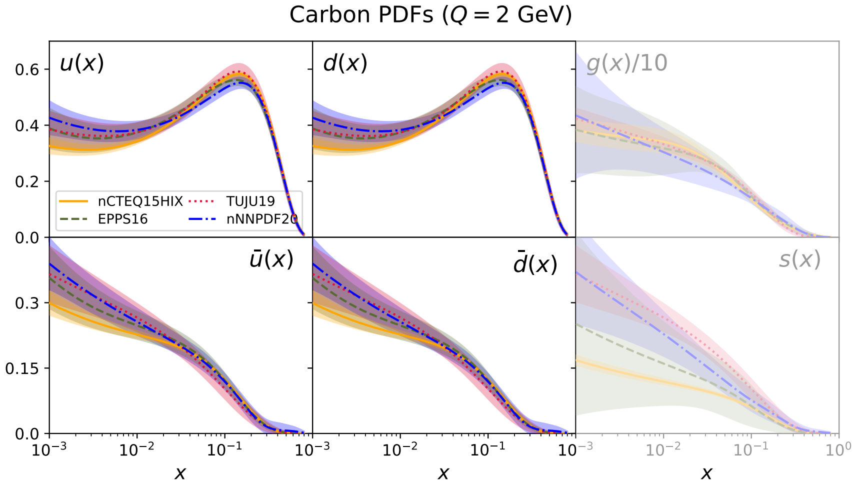

nCTEQ15HIX
JLAB 6GeV DIS
nCTEQ15 DIS/DY
χ^2
80
60
40
20
0
−0.86
−0.85
−0.84
−0.83
−0.82
−0.81
$a_2^{u_V}$

nCTEQ15HIX results: nPDFs




Carbon PDF Ratios to nCTEQ15 ($Q = 2$ GeV)
$u(x)$
$d(x)$
$g(x)$
$\bar{u}(x)$
$\bar{d}(x)$
$s(x)$
nCTEQ15
BASE
HT
DEU
nCTEQ15HIX
1.2
1.0
0.8
10^{-3}
10^{-2}
0.1
0.4
0.6
x

nCTEQ15HIX results: nPDFs



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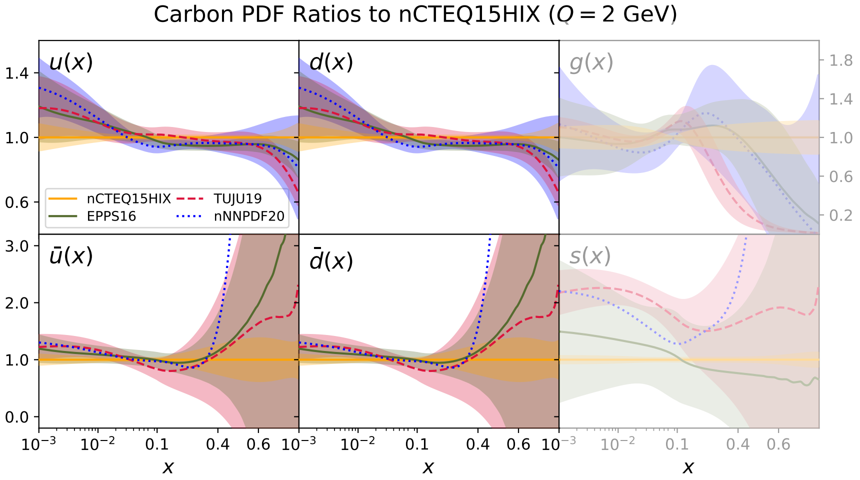

Short Range Correlations (SRC)

- **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)

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

   - bound proton PDFs are parametrized

$$x f_i^{p/A}(x,Q_0) = x^{c_1}(1-x)^{c_2} P(x,\{c_k\})$$

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

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

3. **Sum rules**

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

SRC inspired parametrization

- **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:

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

- For phenomenological purpose we can simplify it assuming:

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

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- As a consequence we will be able to determine only total number of paired neutrons and protons.

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SRC inspired parametrization

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

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

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

The full nPDF f_i^A need to fulfill:

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

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

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

- fulfill DGLAP evolution equation,
- obey the same sum rules as free proton (neutron) distributions.

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

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

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

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

For the purpose of global analysis we:

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

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

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:

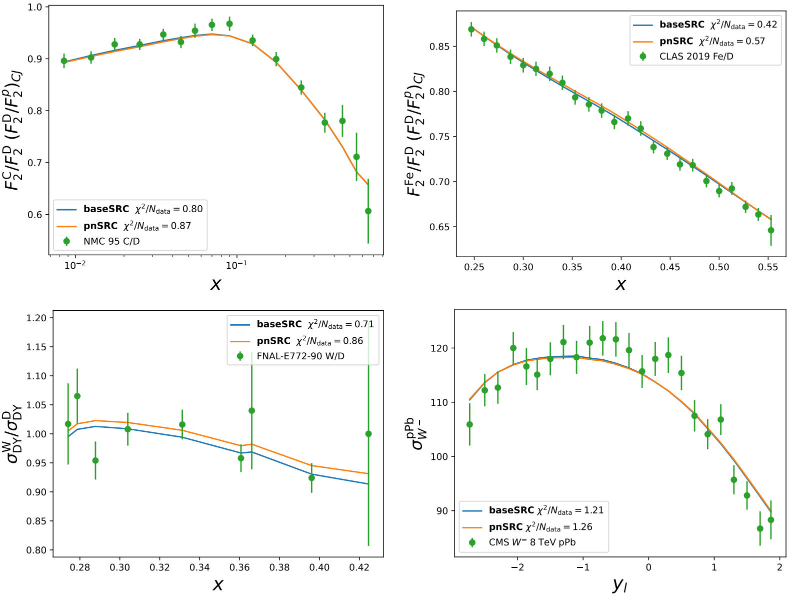
- all DIS & DY data used in the nCTEQ15 analysis [PRD 93, 085037 (2016)],
- high-x DIS data from JLAB which we used in the nCTEQ15hix analysis [PRD 103, 114015 (2021)],
- pPb data for W/Z production from the LHC used in the nCTEQ15WZ analysis [EPJC 80, 968 (2020)].

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.

Results – very good data description



Results – very good data description

- To judge the obtain results in context of nPDFs we compare them with nPDFs obtained from fit using standard approach (`Reference`).

χ^2/N_{data}	DIS	DY	W/Z	JLab	χ^2_{tot}	$\frac{\chi^2_{\text{tot}}}{N_{\text{DOF}}}$
`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
SRC `pnSRC`	0.85	0.84	1.14	0.49	1350	0.82

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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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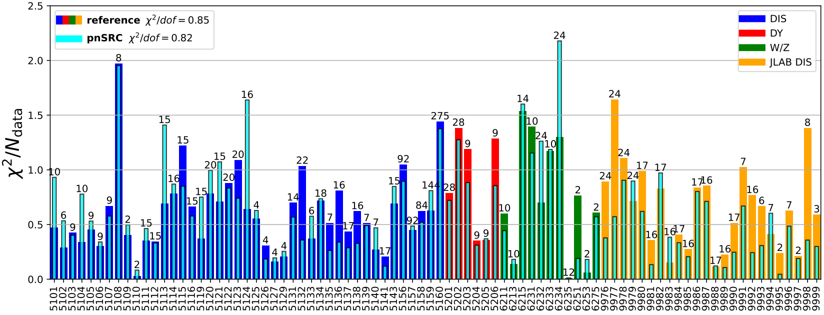
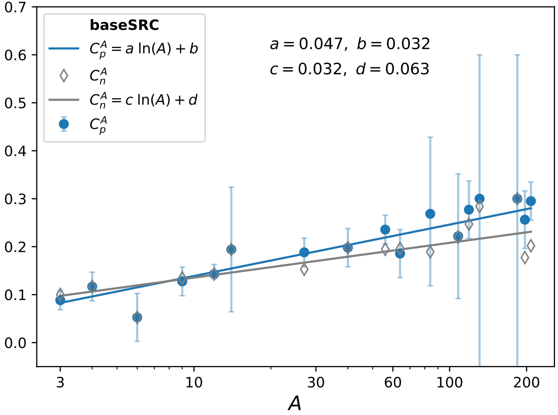


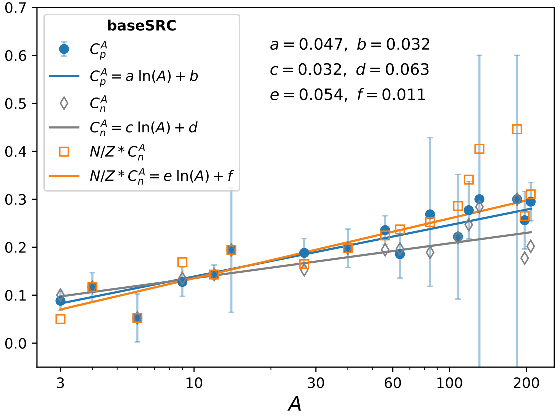
Results: A-dependence of the (C_A^p, C_A^n) parameters



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

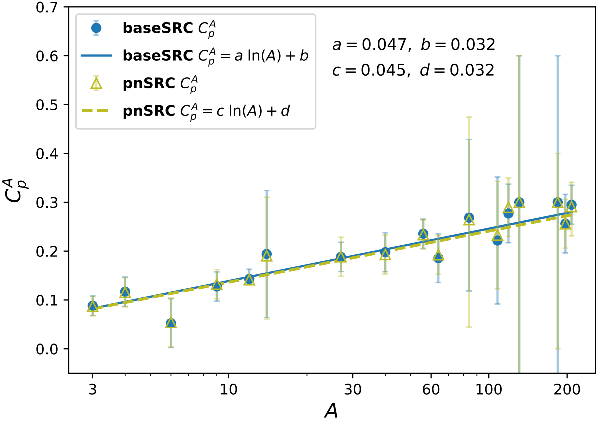
- $^{197}_{79}$Au (C_A^p=0.256, C_A^n=0.178): $79\times C_A^p \simeq$20.2 protons and $118\times C_A^n \simeq$21.0 neutrons.
- $^{208}_{82}$Pb (C_A^p=0.295, C_A^n=0.202): $82\times C_A^p \simeq$24.2 protons and $126\times C_A^n \simeq$25.5 neutrons.

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



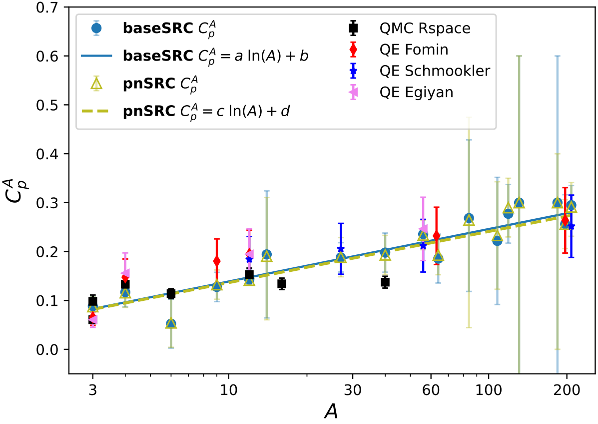
- Correcting for the access of neutrons we obtained a very comparable numbers of protons and neutrons bounded in the SRC pairs.
- This is **consistent** with the hypothesis that the **SRC pairs are dominantly proton-neutron combinations**.
- We can use this observation to restrict number of fit parameters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

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



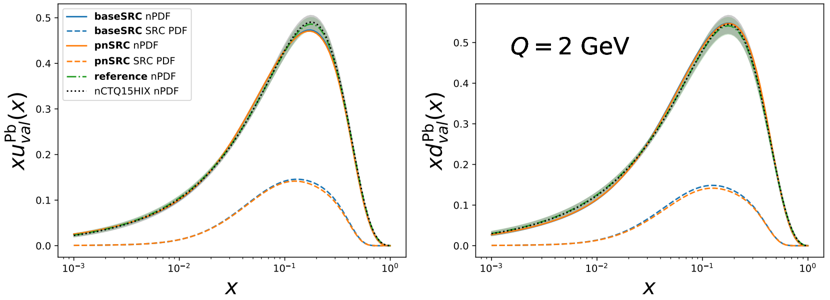
- The obtained C_A^p values are nearly the same as for the baseSRC fit.
- Fit quality is very comparable $\chi^2/N_{\rm DOF} = 0.82$ (vs $\chi^2/N_{\rm DOF} = 0.8$).

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



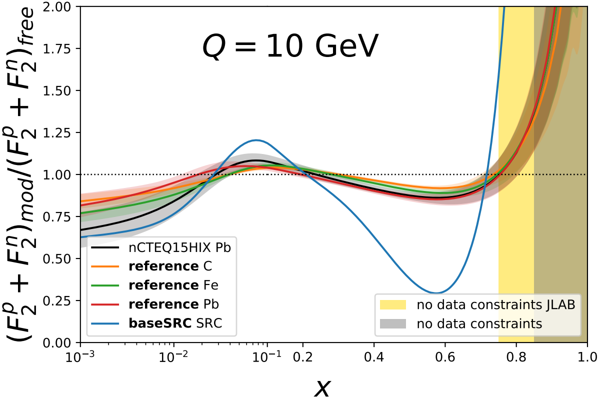
- Results of Quantum Monte Carlo calculations (QMC) [Nature Physics 17, 306-310 (2021)]
- Results of measurements in quasi-elastic region:
  - Fomin [Nature 566, 354-358 (2019)]
  - Schmookler [Phys. Rev. Lett. 96, 082501 (2006)]
  - Egiyan [Phys. Rev. Lett. 108, 092502 (2012)]

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.

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



- Clearly “exaggerated” modifications for pure SRC distribution.

Summary

- 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 rater low energy $\longrightarrow$ 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.