Evidence for Modified Quark-Gluon Distributions in Nuclei by Correlated Nucleon Pairs

P. Duwentäster

arXiv: 2312.16293

In collaboration with:
A.W. Denniston, T. Jezo, A. Kusina, N. Derakhshanian, P. Duwentäster, O. Hen, C. Keppel, M. Klasen, K. Kovarik, J.G. Morfin, K.F. Muzakka, F.I. Olness, E. Piasetzky, P. Risse, R. Ruiz, I. Schienbein, J.Y. Yu

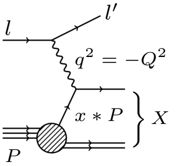
nCTEQ nuclear parton distribution functions

CoE QM

JYVÄSKYLÄN YLIOPISTO UNIVERSITY OF JYVÄSKYLÄ

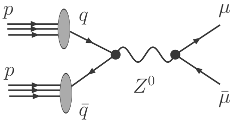
Proton PDFs and QCD Factorization

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



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

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



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

- $f_i(z,\mu)$ – **UNIVERSAL** proton PDFs of parton i (**non-perturbative**).
- $\hat{\sigma}_{ij\to l\bar{l}X}$ – parton level matrix element (**calculable in pQCD**).
- $\mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{Q^2}\right)$ – non-leading terms defining accuracy of factorization formula.

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

$$\mu^2 \frac{d}{d\mu^2} \begin{pmatrix} f_i(x,\mu^2) \\ f_g(x,\mu^2) \end{pmatrix} = \sum_j \frac{\alpha_s}{2\pi} \int_x^1 \frac{dz}{z} \begin{pmatrix} P_{q_i q_j}\left(\frac{x}{z}\right) & P_{q_i g}\left(\frac{x}{z}\right) \\ P_{g q_j}\left(\frac{x}{z}\right) & P_{gg}\left(\frac{x}{z}\right) \end{pmatrix} \begin{pmatrix} f_j(z,\mu^2) \\ f_g(z,\mu^2) \end{pmatrix}$$

Properties of PDFs

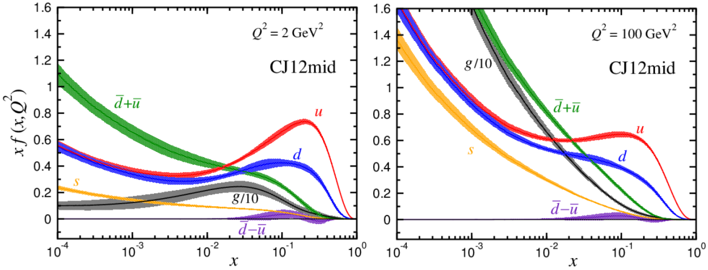
- **Sum rules**
  - **Number sum rules** – connect partons to quarks from SU(3) flavour symmetry of hadrons; proton (uud), neutron (udd). For protons:

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

  - **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

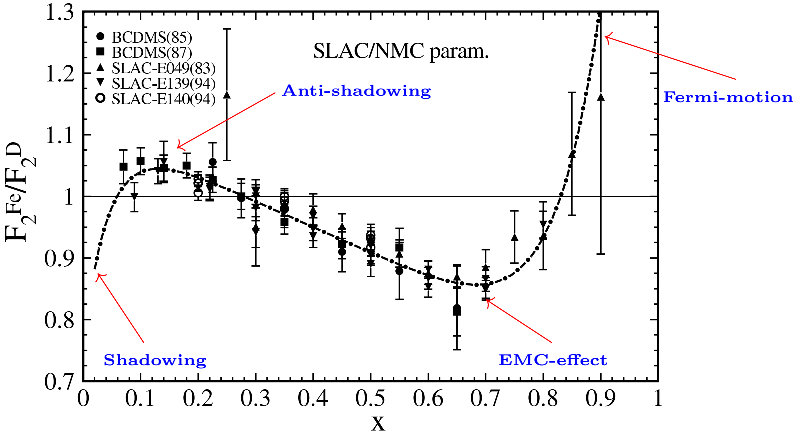


Owens, Accardi, Melnitchouk, PRD 87, 094012 (2013), arXiv:1212.1702

Nuclear collision → nuclear PDFs

- Cross-sections in nuclear collisions are modified

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



- Can we translate this modifications into **universal nuclear PDFs**?

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

Schematics of Global Analysis

1. Choose experimental data (e.g. DIS, DY, inclusive jet prod., etc.)
2. Parametrize **nuclear PDFs** at low initial scale $\mu = Q_0 = 1.3\text{GeV}$:

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

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

   with $c_j = c_j(A) \overset{\text{nCTEQ}}{=} p_k + a_k \left(1 - A^{-b_k}\right)$ depending on the nuclei.
3. Use DGLAP equation to evolve $f_i(x, \mu)$ from $\mu = Q_0$ to $\mu = Q_{\text{max}}$.
4. Calculate theory predictions corresponding to the data (σ_{DIS}, σ_{DY}, etc.).
5. Calculate appropriate χ^2 function – compare data and theory

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

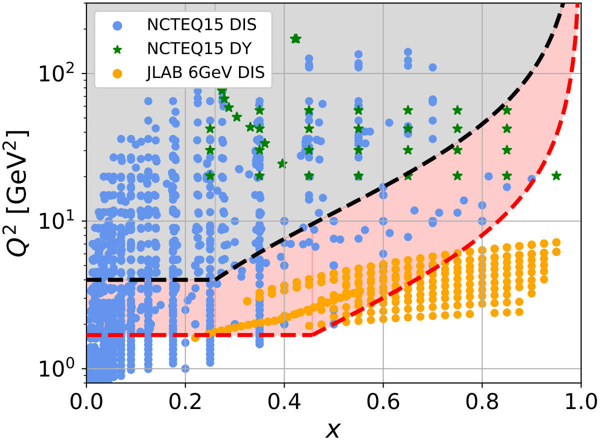
6. Minimize χ^2 function with respect to parameters $c_0, c_1, \dots$

Data in nPDF analyses [nCTEQ15HIX: PRD 103, 114015 (2021)]

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

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

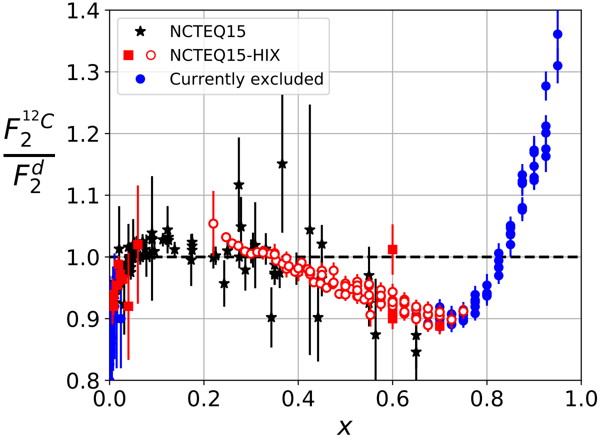
nCTEQ15HIX
$Q > 1.3$ GeV $W > 1.7$ GeV
$N_{\text{data}} = 1679$

Data in nPDF analyses [nCTEQ15HIX: PRD 103, 114015 (2021)]

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

- 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

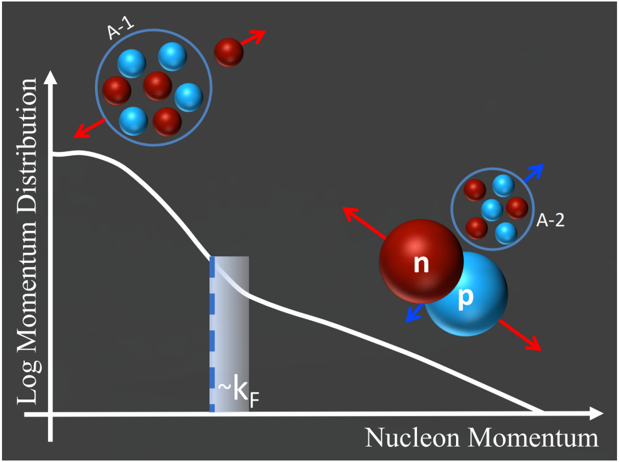
$Q > 2$ GeV
$W > 3.5$ GeV

nCTEQ15HIX

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

Short Range Correlation (SRC) picture of nuclei

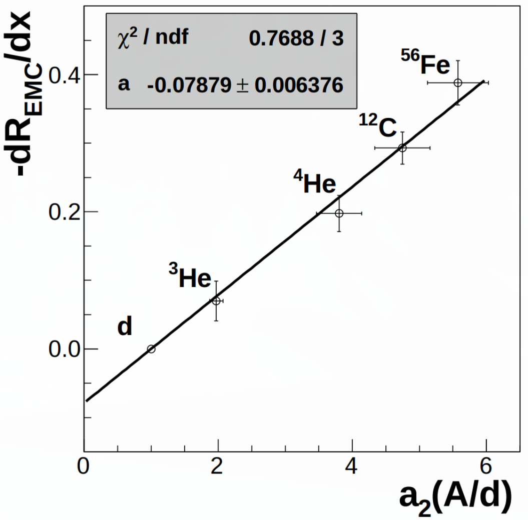
- SRC pairs are nucleon pairs with high relative momentum and small distance
- The center of mass of the pair has a low momentum w.r.t. the nucleus



[Or Hen, https://indico.mit.edu/event/656/contributions/1952/]

Short Range Correlation (SRC) picture of nuclei

- There is a linear correlation between the strength of the EMC effect in different nuclei and the the probability that a nucleon in that nucleus is part of an SRC pair



[Phys.Rev.Lett. 106 (2011) 052301]

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)

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

   - effective bound proton PDFs are parametrized

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

   - effective 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**

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

4. The nucleus is treated as a black box and the microscopic origin of nuclear modification is not addressed.

SRC inspired parametrization

- **Short Range Correlations** (SRC) occur between pairs of nucleons; possible configurations: (pn), (pp), (nn)
  SRCs between more than two nucleons are expected to exist, but have not been experimentally confirmed.
- 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:

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

SRC inspired parametrization

- **Short Range Correlations** (SRC) occur between pairs of nucleons; possible configurations: (pn), (pp), (nn)
  SRCs between more than two nucleons are expected to exist, but have not been experimentally confirmed.
- 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:

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

- For phenomenological purpose we can simplify it assuming:

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

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

SRC inspired parametrization

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

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

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.

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.

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.

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).

Data & Fits

Used data:

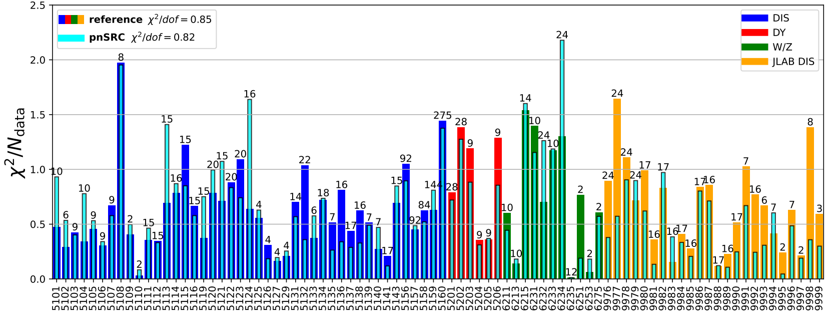
- all DIS & DY data used in the nCTEQ15 analysis [PRD 93, 085037 (2016)]
- high-x DIS data from JLAB which we used in the nCTEQ15hix analysis [PRD 103, 114015 (2021)]
- pPb data for W/Z production from the LHC used in the nCTEQ15WZ analysis [EPJC 80, 968 (2020)]

Performed fits:

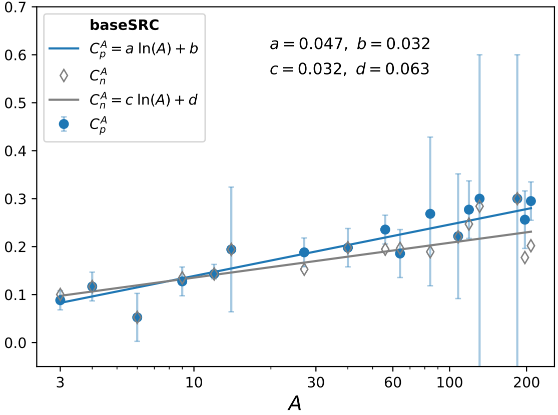
- `Reference`– fit using standard nCTEQ PDF fitting framework
- `baseSRC`– use SRC parametrization, keep C_A^p and C_A^n parameters **independent**
- `pnSRC`– use SRC parametrization, **tie together** C_A^p and C_A^n

Results – very good data description

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
`baseSRC`	0.84	0.75	1.11	0.41	1300	0.80
`pnSRC`	0.85	0.84	1.14	0.49	1350	0.82



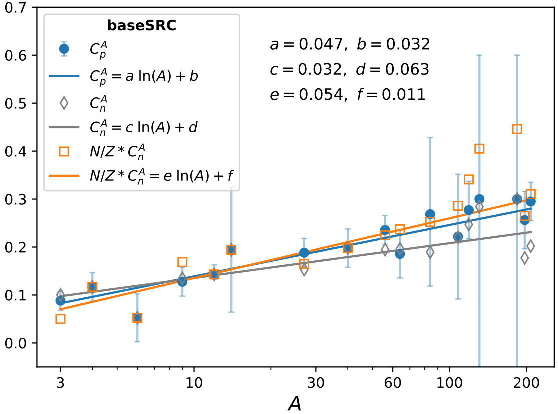
Results: A-dependence of the (C_A^p, C_A^n) parameters



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

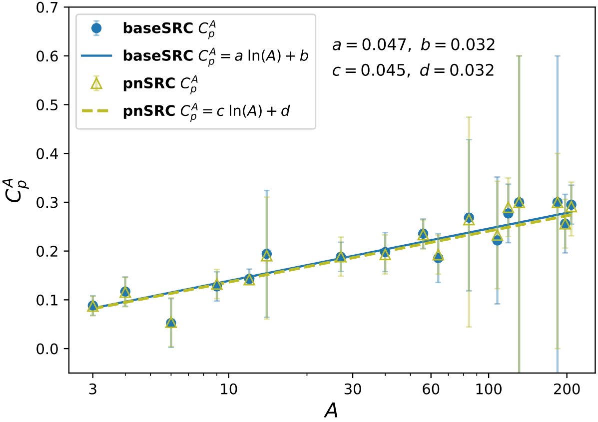
- ${}^{197}_{79}$Au (C_A^p=0.256, C_A^n=0.178): $79\times C_A^p \simeq$20.2 protons and $118\times C_A^n \simeq$21.0 neutrons.
- ${}^{208}_{82}$Pb (C_A^p=0.295, C_A^n=0.202): $82\times C_A^p \simeq$24.2 protons and $126\times C_A^n \simeq$25.5 neutrons.

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



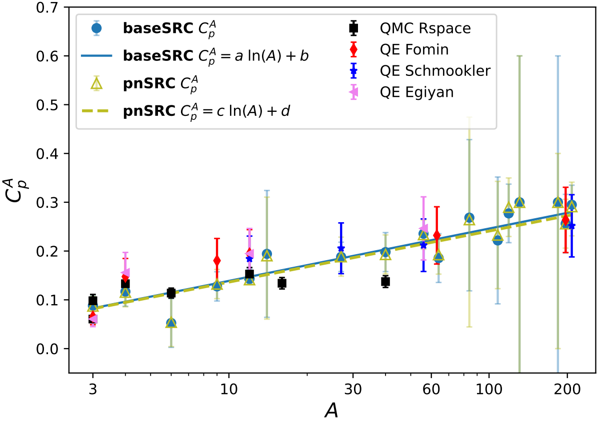
- Correcting for the different absolute amount of neutrons we obtained a very comparable numbers of protons and neutrons bounded in the SRC pairs.
- This is **consistent** with the hypothesis that the **SRC pairs are dominantly proton-neutron combinations**.
- We can use this observation to restrict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

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



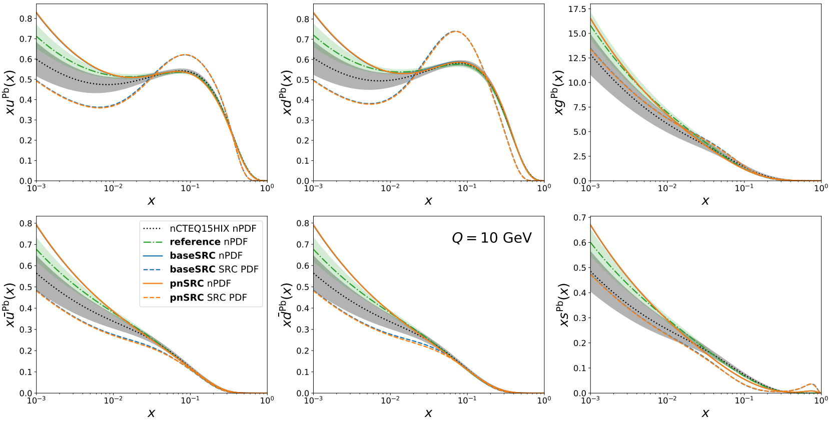
- The obtained C_A^p values are nearly the same as for the baseSRC fit.
- Fit quality is very comparable $\chi^2/N_{\mathrm{DOF}} = 0.82$ (vs $\chi^2/N_{\mathrm{DOF}} = 0.8$).

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)]

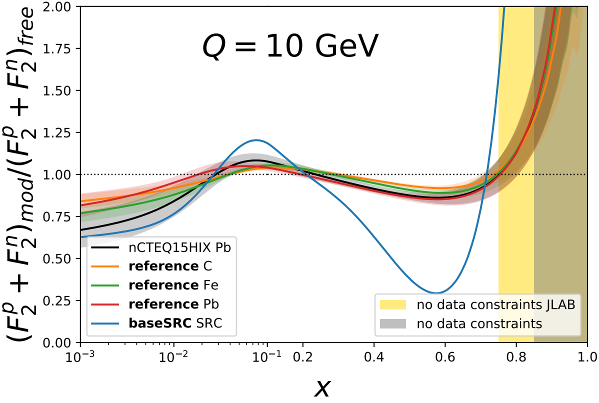
Results: PDFs



- Clearly “exaggerated” modifications for pure SRC distribution.

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

Results: modification of F_2 structure function



- Clearly "exaggerated" modifications for pure SRC distribution.

Summary

- 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.

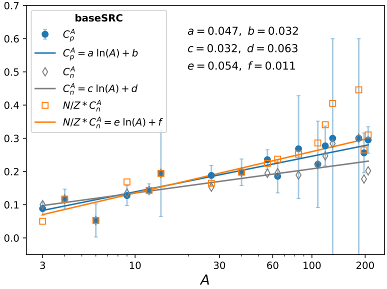
Summary

- The simple SRC-based picture of nPDFs leads to comparable or better data description than the traditional nPDF parameterization.

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

Summary

- The simple SRC-based picture of nPDFs leads to comparable or better data description than the traditional nPDF parameterization.
- The obtained values of $\{C^p_A, C^n_A\}$ suggest approximately equal number of protons and neutrons in the SRC pairings which is consistent with other observations pn-dominance in SRC pairs.



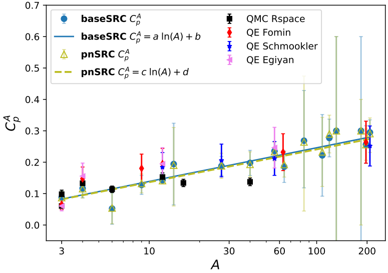
Summary

- 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.

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

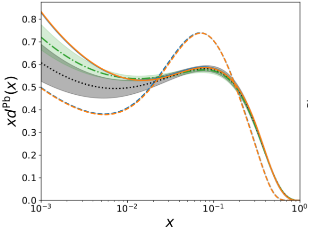
Summary

- 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.



Summary

- 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.



BACKUP SLIDES

Large-x data from JLAB

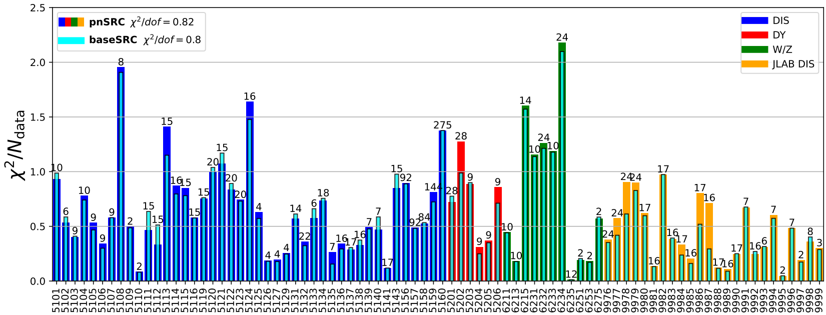
$\mathbf{F_2^A/F_2^D}$: Observable	Experiment	ID	Ref.	# data	#data after cuts
^{208}Pb/D	CLAS	9976	[38]	25	24
^{56}Fe/D	CLAS	9977	[38]	25	24
^{27}Al/D	CLAS	9978	[38]	25	24
^{12}C/D	CLAS	9979	[38]	25	24
^{4}He/D	Hall C	9980	[69]	25	17
		9981	[69]	26	16
^{3}He/D	Hall C	9982	[69]	25	17
		9983	[69]	26	16
^{64}Cu/D	Hall C	9984	[69]	25	17
		9985	[69]	26	16
^{9}Be/D	Hall C	9986	[69]	25	17
		9987	[69]	26	16
^{197}Au/D	Hall C	9988	[69]	24	17
		9989	[69]	26	16
^{12}C/D	Hall C	9990	[69]	25	17
		9991	[69]	17	7
		9992	[69]	26	16
		9993	[69]	18	6
		9994	[69]	17	7
		9995	[69]	15	2
		9996	[69]	19	7
		9997	[69]	16	2
		9998	[69]	21	8
		9999	[69]	18	3
Total				546	336

CLAS [Nature 566 (2019) 7744]

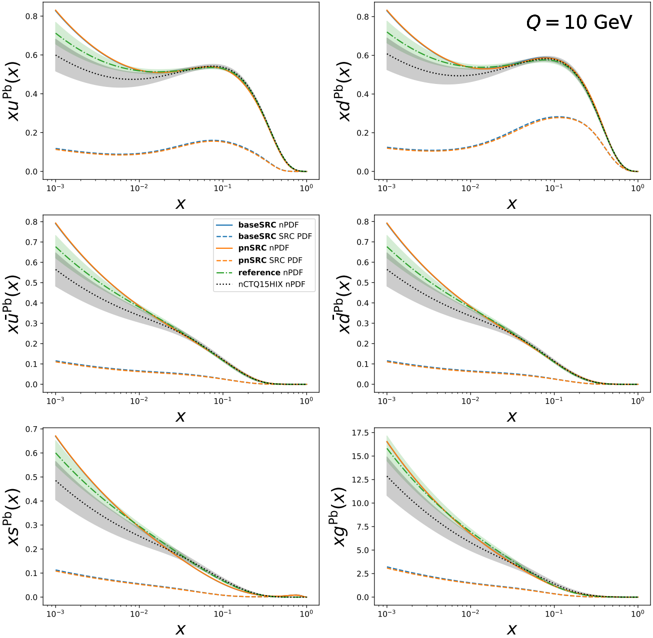
Hall C [PRL 103 (2009) 202301]

Results – very good data description

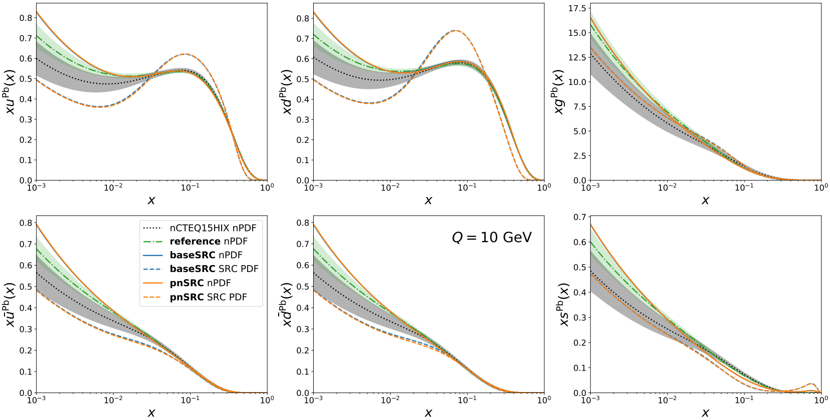
Basically no impact of additional fixing of $C_A^n = (Z/N)C_A^p$



Results

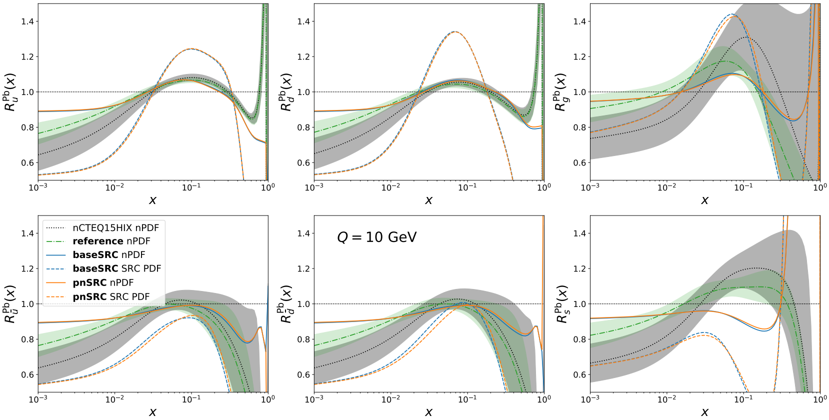

$Q = 10$ GeV
$xu^{\mathrm{Pb}}(x)$
$xd^{\mathrm{Pb}}(x)$
$x\bar{u}^{\mathrm{Pb}}(x)$
$x\bar{d}^{\mathrm{Pb}}(x)$
$xs^{\mathrm{Pb}}(x)$
$xg^{\mathrm{Pb}}(x)$
x
baseSRC nPDF
baseSRC SRC PDF
pnSRC nPDF
pnSRC SRC PDF
reference nPDF
nCTQ15HIX nPDF

Results



$xu^{\mathrm{Pb}}(x)$
$xd^{\mathrm{Pb}}(x)$
$xg^{\mathrm{Pb}}(x)$
$x\bar{u}^{\mathrm{Pb}}(x)$
$x\bar{d}^{\mathrm{Pb}}(x)$
$xs^{\mathrm{Pb}}(x)$
x
nCTEQ15HIX nPDF
reference nPDF
baseSRC nPDF
baseSRC SRC PDF
pnSRC nPDF
pnSRC SRC PDF
$Q = 10$ GeV

Results



$R_u^{\mathrm{Pb}}(x)$
$R_d^{\mathrm{Pb}}(x)$
$R_g^{\mathrm{Pb}}(x)$
$R_{\bar{u}}^{\mathrm{Pb}}(x)$
$R_{\bar{d}}^{\mathrm{Pb}}(x)$
$R_s^{\mathrm{Pb}}(x)$
x
nCTEQ15HIX nPDF
reference nPDF
baseSRC nPDF
baseSRC SRC PDF
pnSRC nPDF
pnSRC SRC PDF
$Q = 10$ GeV

Results

- In order to judge the obtain results in context of nPDFs it is useful to compare them with nPDFs obtained using standard approach.
- We performed a "standard" fit using the same data and nCTEQ15-like parametrization.

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

Table: The `Reference` fit has 19 shape and 3 W/Z normalization parameters. The `baseSRC` and `pnSRC` SRC fits have 21 shape, 3 W/Z normalization, and 30 and 19 SRC parameters, respectively. There are 1684 data points after cuts.

- Better overall quality of the SRC fits.

Results

- In order to judge the obtain results in context of nPDFs it is useful to compare them with nPDFs obtained using standard approach.
- We performed a “standard” fit using the same data and nCTEQ15-like parametrization.

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

Table: The `Reference` fit has 19 shape and 3 W/Z normalization parameters. The `baseSRC` and `pnSRC` SRC fits have 21 shape, 3 W/Z normalization, and 30 and 19 SRC parameters, respectively. There are 1684 data points after cuts.

- Better overall quality of the SRC fits.
- Especially better description of the (precise) high-x JLAB data.

Results

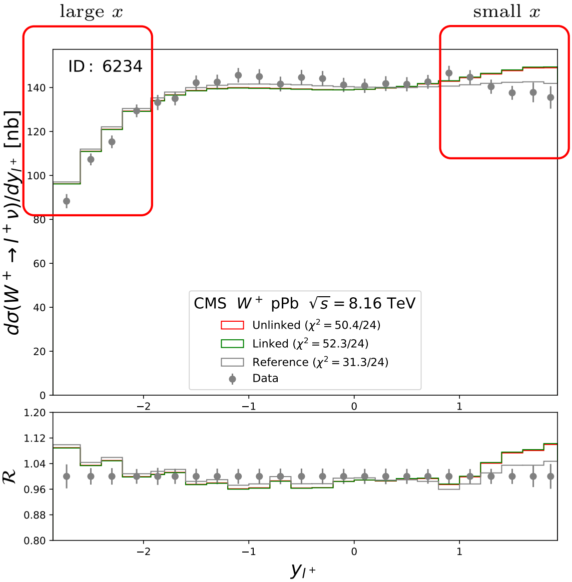
- In order to judge the obtain results in context of nPDFs it is useful to compare them with nPDFs obtained using standard approach.
- We performed a “standard” fit using the same data and nCTEQ15-like parametrization.

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

Table: The `Reference` fit has 19 shape and 3 W/Z normalization parameters. The `baseSRC` and `pnSRC` SRC fits have 21 shape, 3 W/Z normalization, and 30 and 19 SRC parameters, respectively. There are 1684 data points after cuts.

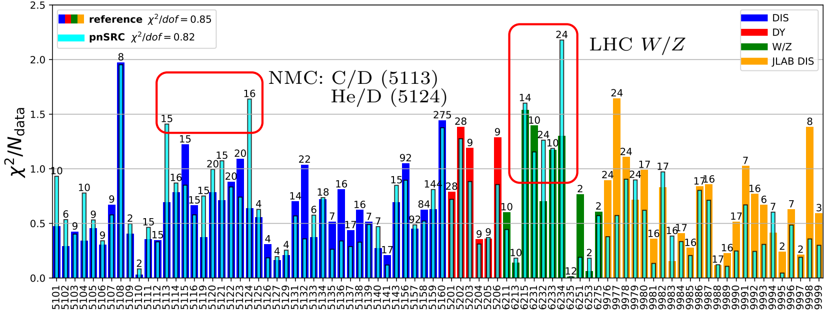
- Better overall quality of the SRC fits.
- Especially better description of the (precise) high-x JLAB data.
- Worse description of the W/Z data from LHC - lowest available x values.

Results



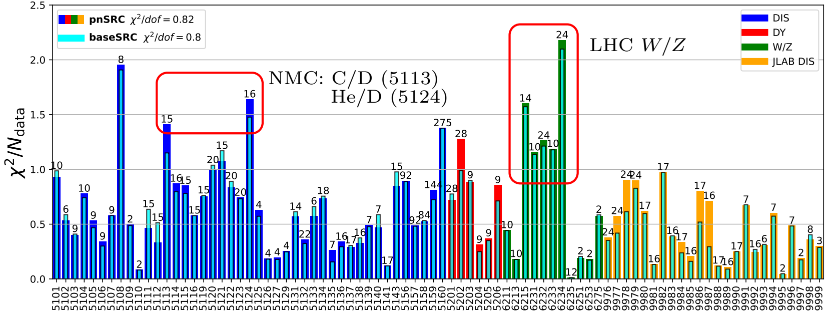
large x
small x
ID : 6234
CMS W^+ pPb $\sqrt{s} = 8.16$ TeV
Unlinked ($\chi^2 = 50.4/24$)
Linked ($\chi^2 = 52.3/24$)
Reference ($\chi^2 = 31.3/24$)
Data
$d\sigma(W^+ \to l^+ \nu)/dy_{l^+}$ [nb]
$\mathcal{R}$
y_{l^+}

Results



- Better overall quality of the SRC fits.
- Especially better description of the (precise) high-x JLAB data.
- Worse description of the W/Z data from LHC - lowest available x values.
- For most of the experiments we observe decrease in χ^2,
  exceptions: 5113 - NMC DIS for C/D, 5124 - NMC DIS for He/D, 6234 & 6232 - CMS $W^\pm$ from Run II.

Results

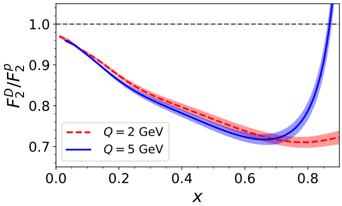

pnSRC $\chi^2/dof = 0.82$
baseSRC $\chi^2/dof = 0.8$
DIS
DY
W/Z
JLAB DIS
NMC: C/D (5113)
He/D (5124)
LHC W/Z
χ^2/N_{data}

Corrections at large-x

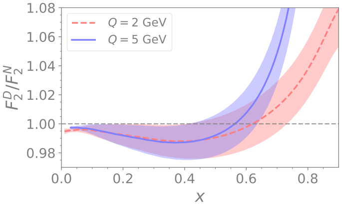
Effects we include:

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

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



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

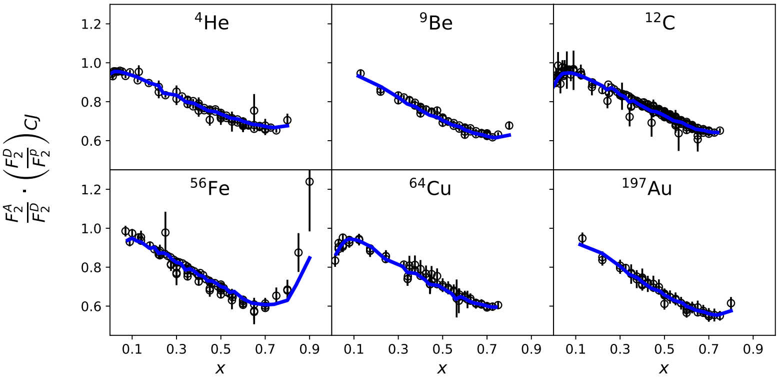


Effects needed when going to even higher-x (lower W):

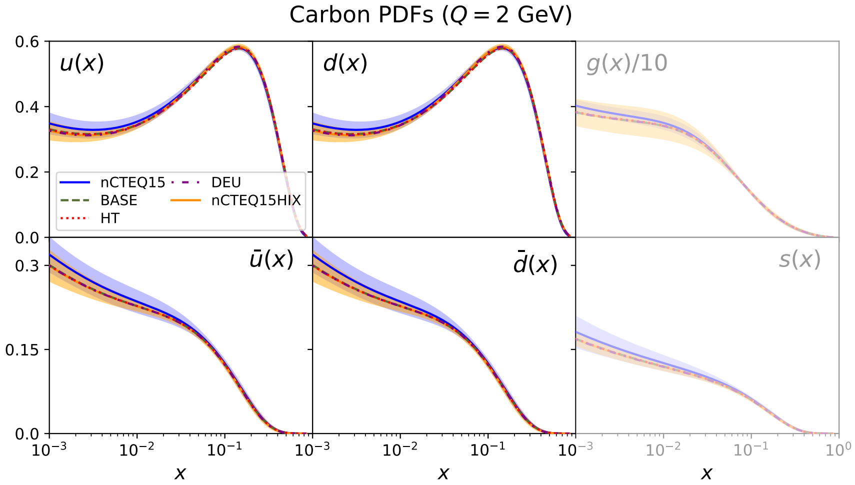
- Non-vanishing structure functions/nPDFs at $x > 1$ and corresponding extension of DGLAP evolution.
- Threshold resummation.

nCTEQ15HIX results

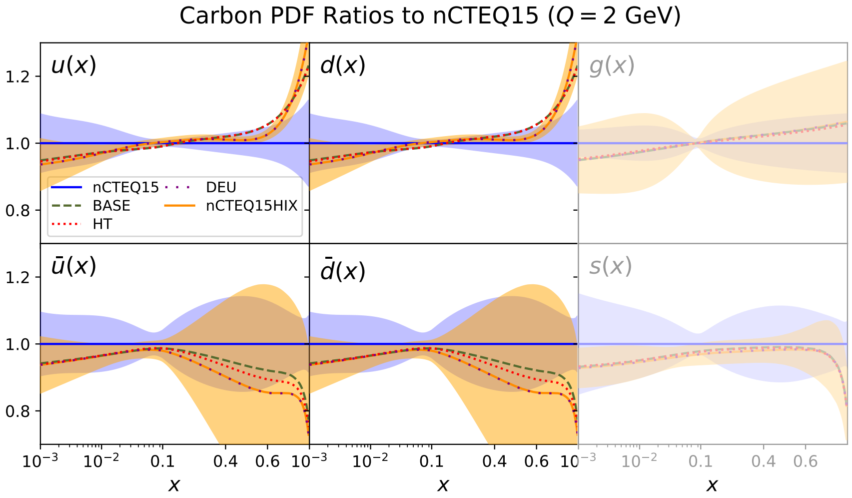
We obtain very good description of the data with $\chi^2 \sim 0.85$



nCTEQ15HIX results: nPDFs



nCTEQ15HIX results: nPDFs

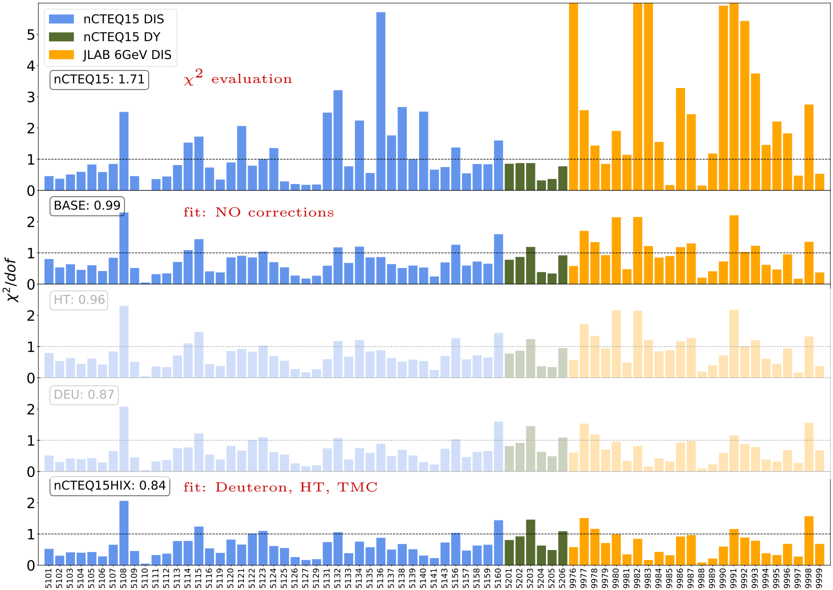


Fits we did

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



Very high-x: Fermi-smearing region

Gaussian smearing:

$$f_A(x,Q) = \int_x^A \frac{dy}{y} S_A(y,Q) f(x/y,Q)$$

with

$$S_A(y) = \frac{1}{\sqrt{2\pi\Delta_A}} \exp\left\{ \frac{-[y-(1-\delta_A)]^2}{2\Delta_A^2} \right\}$$

Very high-x: Fermi-smearing region

Gaussian smearing:

$$f_A(x,Q) = \int_x^A \frac{dy}{y} S_A(y,Q) f(x/y,Q)$$

with

$$S_A(y) = \frac{1}{\sqrt{2\pi\Delta_A}} \exp\left\{ \frac{-[y-(1-\delta_A)]^2}{2\Delta_A^2} \right\}$$

Alternative: x rescaling

$$f_A(x,Q) \longrightarrow f_A(x'_A,Q)$$

with

$$x'_A = x - \epsilon\, x^\kappa \log_{10} A$$

Very high-x: Fermi-smearing region

Gaussian smearing:

$$f_A(x,Q) = \int_x^A \frac{dy}{y} S_A(y,Q) f(x/y,Q)$$

with

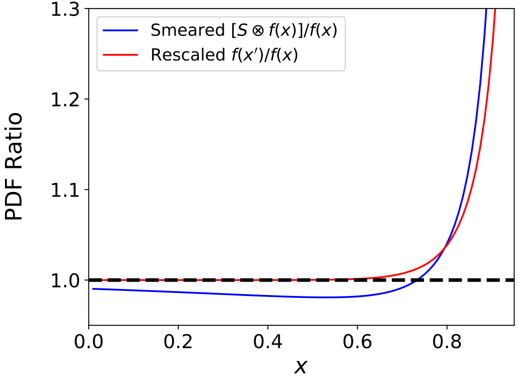
$$S_A(y) = \frac{1}{\sqrt{2\pi\Delta_A}} \exp\left\{ \frac{-[y-(1-\delta_A)]^2}{2\Delta_A^2} \right\}$$

Alternative: x rescaling

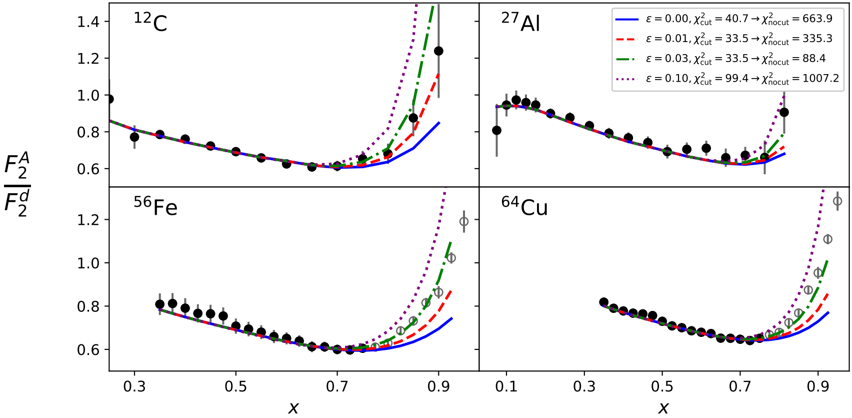
$$f_A(x,Q) \longrightarrow f_A(x'_A,Q)$$

with

$$x'_A = x - \epsilon\, x^{\kappa} \log_{10} A$$



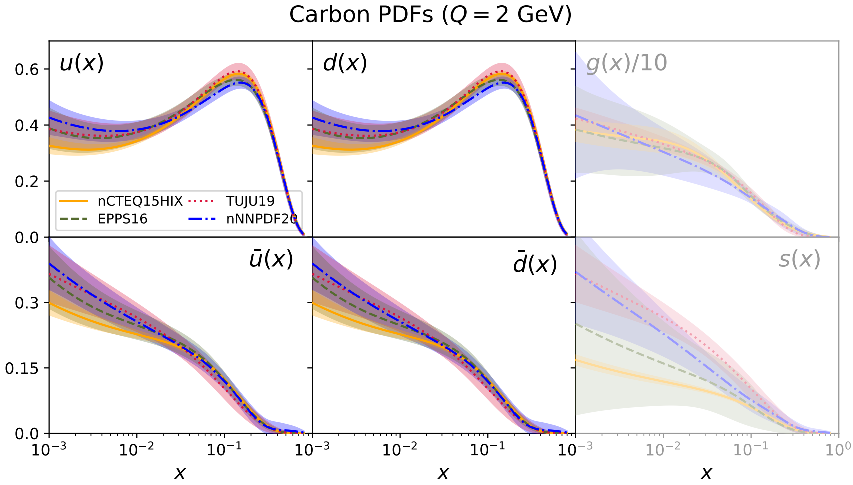
Very high-x: Fermi-smearing region



Possible future options to constrain high-x PDFs

- Electron-ion collider (EIC) [arXiv:2103.05419]
- Fixed target experiment/data at the LHC
  based of AFTER@LHC report [Phys.Rept. 911 (2021) 1-83]

nCTEQ15HIX results: nPDFs



nCTEQ15HIX results: nPDFs