Short-range correlations and the phenomenological determination of nuclear PDFs

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Introduction

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**

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

Introduction

Let's consider a parametrization inspired by nuclear dynamics, one option are models based on: **Short Range Correlations** (SRC).

- 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:

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

- For phenomenological purpose we can simplify it assuming:

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

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

SRC parametrization

Our phenomenological SRC inspired parametrization takes form:

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

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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For the purpose of global analysis we:

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

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

Free parameters:

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

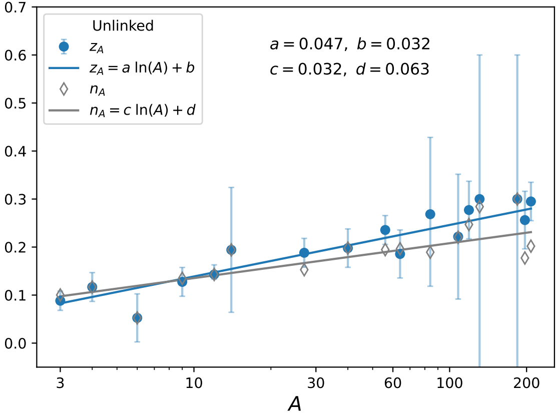
Data

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)].

Results: A-dependence of the (z_A, n_A) parameters

With such a setup we are able to obtain a very good fit to data with $\chi^2/N_{\text{DOF}} = 0.8$.



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

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

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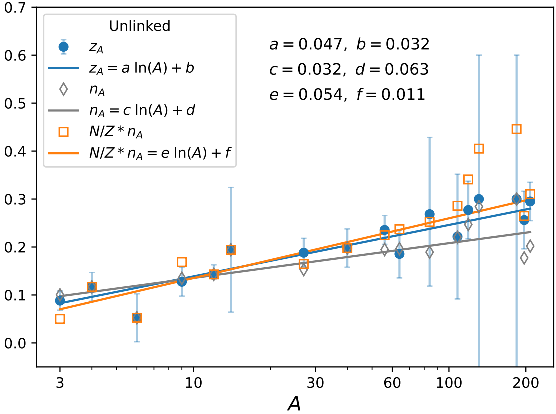
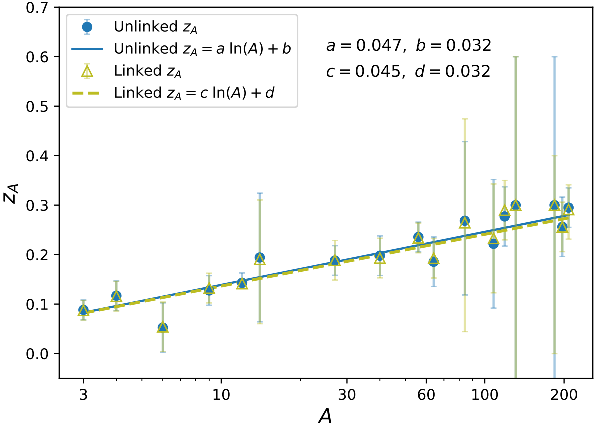


- Correcting for the access of neutrons we obtained a very comparable numbers of protons and neutrons bounded in the SRC pairs.
- This is consistent with the hypothesis that the SRC pairs are dominantly proton-neutron combinations.
- We can use this observation to restrict number of fit parameters by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

Results - **Linked** fit $n_A = (Z/N) z_A$



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

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 **Unlinked**	0.84	0.75	1.11	0.41	1300	0.80
SRC **Linked**	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 **Unlinked** and **Linked** SRC fits have 21 shape, 3 W/Z normalization, and 30 and 19 SRC parameters, respectively. There are 1684 data points after cuts.

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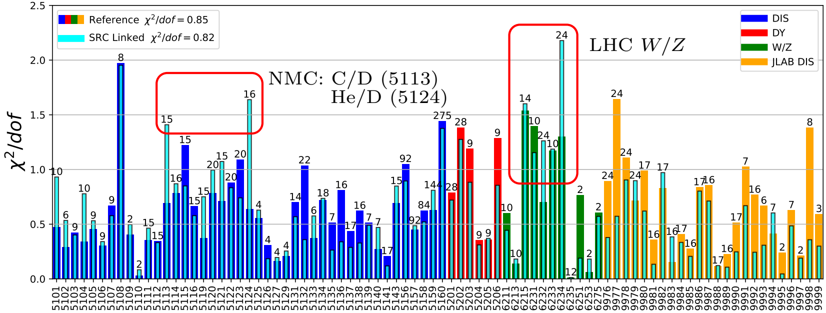

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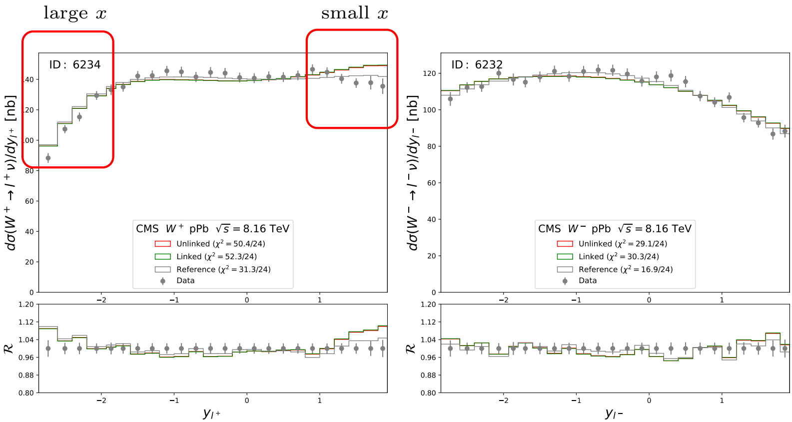
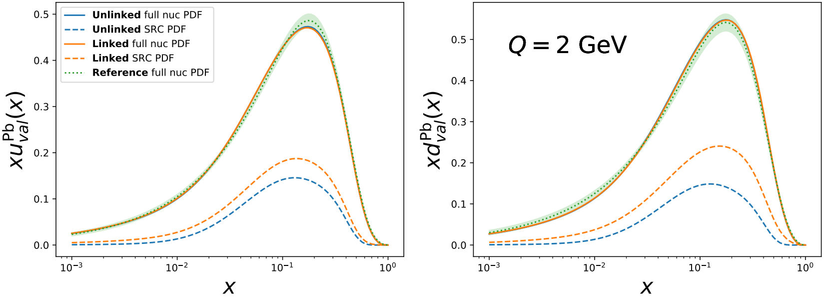
- Especially better description of the (precise) high-x JLAB data.
- Worse description of the W/Z data from LHC - lowest available x values.
- For most of the experiments we observe decrease in χ^2, exceptions: 5113 - NMC DIS for C/D, 5124 - NMC DIS for He/D, 6234 & 6232 - CMS $W^{\pm}$ from Run II.

Results


large x
small x
ID: 6234
ID: 6232
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
CMS W^- pPb $\sqrt{s} = 8.16$ TeV
Unlinked ($\chi^2 = 29.1/24$)
Linked ($\chi^2 = 30.3/24$)
Reference ($\chi^2 = 16.9/24$)
Data
$d\sigma(W^+ \to l^+\nu)/dy_{l^+}$ [nb]
$d\sigma(W^- \to l^-\nu)/dy_{l^-}$ [nb]
$\mathcal{R}$
y_{l^+}
y_{l^-}

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 $\{z_A, n_A\}$ values.

Summary

- The simple SRC-based picture of nPDFs leads to comparable or better data description than the traditional nPDF parameterization.
- The $\{z_A, n_A\}$ parameters increase logarithmically in a uniform pattern with the nuclear A values from $\sim 10\%$ to $\sim 30\%$.
- For the `Unlinked` fit the obtained values of $\{z_A, n_A\}$ suggest approximately equal number of protons and neutrons in the SRC pairings. While this is consistent with other observations suggesting the SRC pairs are predominantly *pn* further analysis is required to confirm it.
- Even when the $\{z_A, n_A\}$ parameters are constrained in the `Linked` fit, we obtain a very good fit to the data, yielding lower χ^2 than in the `Reference` fit. This should be tested with more data and/or can be used to further constrain the used parametrization.
- The improvement of the JLab data at the expense of the W/Z data suggests this approach may be more appropriate for larger x than for smaller x.
- It is notable that all the above results, obtained from purely data driven fits, seem to support the SRC-based description of nuclei.