Determination of quark and gluon distributions in nuclei using correlated nucleon pairs

Dimitrios Daskalas on behalf of Aleksander Kusina

Universite Paris-Saclay, IJCLab, Institute of Nuclear Physics PAN, Krakow, Poland

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

9 Jan 2025

The author acknowledge financial support of the Polish National Agency for Academic Exchange within the **PROM** program.

Figure:

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nCTEQ presentations

- T. Jezo (Thur 12:00)
- N. Derakhshanian (poster)

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Figure:

PDFs and QCD Factorization

- **Collinear Factorization** for hadronic or nuclear inclusive cross sections involving a hard scale $Q^2 \gg \Lambda^2_{\text{QCD}}$

$$\mathrm{d}\sigma^{AB\to k+X} = \sum_{i,j,X'} f_i^A\left(Q^2\right) \otimes f_j^B\left(Q^2\right) \otimes \mathrm{d}\hat{\sigma}^{ij\to k+X'} + \mathcal{O}\left(1/Q^2\right),$$

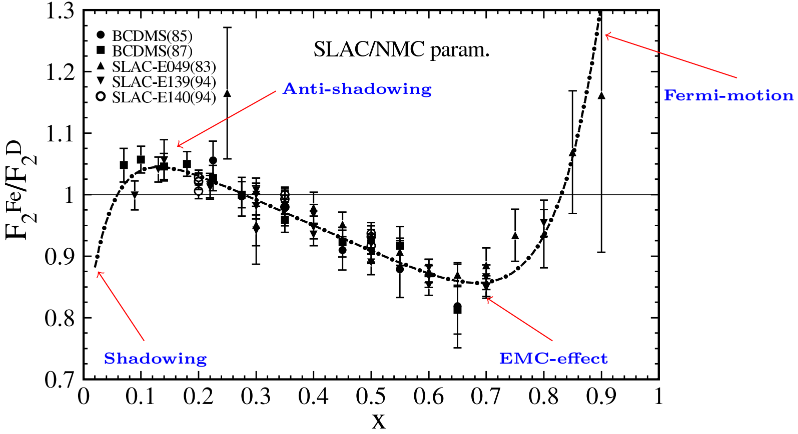
  - Proton PDFs of parton i (**non-perturbative and universal**).
  - $\hat{\sigma}$ – parton level matrix element (**calculable in pQCD**).
  - $\mathcal{O}\left(\frac{1}{Q^2}\right)$ – non-leading terms defining accuracy of factorization formula.

- nPDFs (**PDFs of bound nucleons in nuclei**) not equal to the sum of the free nucleon PDFs
  - Indication of measurable role of Nuclear effects.
  - Added nuclear mass-number (A) dependence, aside with the usual x and Q^2 dependences of free nucleon PDFs.

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**?

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

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

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

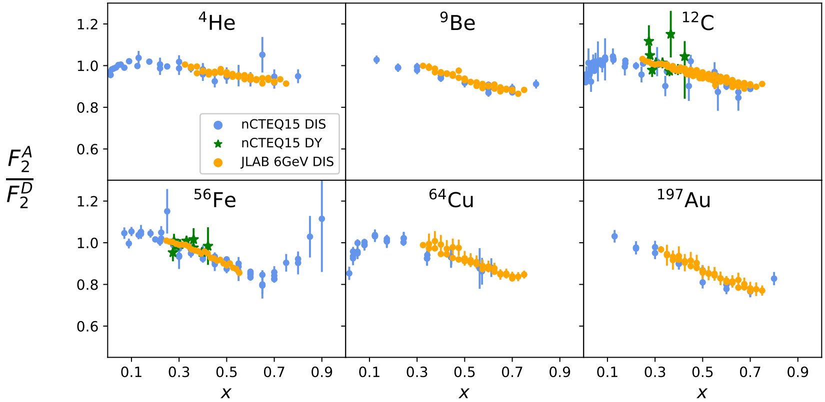
   - bound neutron PDFs are constructed assuming *isospin symmetry*
   - A-dependence

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

3. **Sum rules**

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

JLAB data for different nuclei [nCTEQ15HIX: PRD 103, 114015 (2021)]

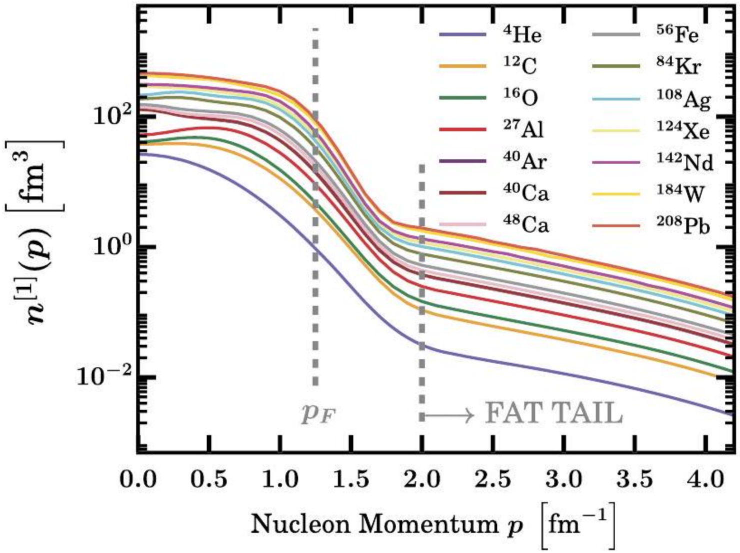


- JLAB data are mostly in EMC region
- The EMC region is directly connected with Short Range Correlatation (SRC) models.

Short Range Correlations (SRCs)

- **Created from nucleon pairs in close proximity**
- **Tensor and Isospin Correlations**: are the main sources of SRC strength, instead of isospin blind central correlations.
- **Mainly close to the centre of nuclei**
- **No momentum constraint**: But in momenta lower than the Fermi momentum, Mean Field contributions are dominant.

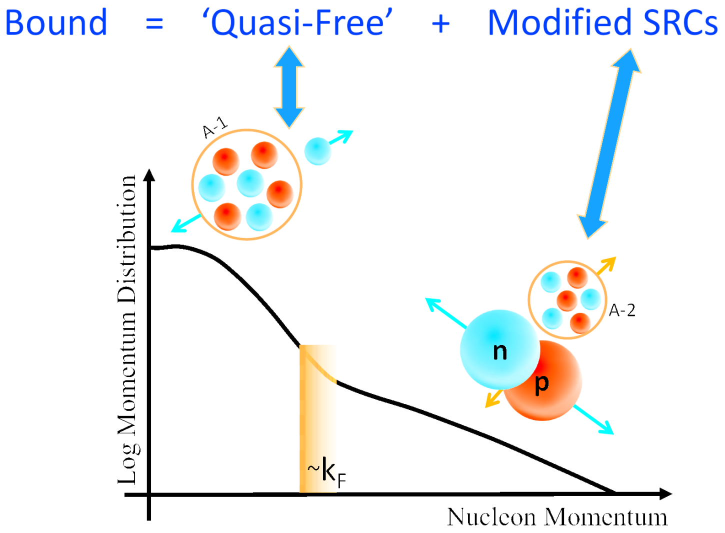
Short Range Correlation (SRC) picture of nuclei



Ryckebusch, Jan and Cosyn, Wim and Stevens, Sam and Casert, Corneel and Nys, Jannes

Short Range Correlation (SRC) picture

- **Scale separation** between low and high momentum regimes.
- **IPM "low momentum" area**: Defined by momenta smaller than the Fermi momentum $p_F = 1.25\text{fm}^{-1}$
- **Fat SRC tail "high momentum' area**: $p \gtrsim 2\text{fm}^{-1}$
- **Universality of SRC**
- **SRC behaviour**; The fat tail of the single-nucleon momentum distributions decreases exponentially with p.



[Or Hen, 4th International Workshop on Quantitative Challenges in SRC & EMC Effect Research, CEA France, 03/02/2023.]

- **Nuclear spectral function**: $S_A(k,E)$, $\int S_A(k,E)k^2dkdE \equiv 1$
- **Probability** for finding a **nucleon** with momentum k and separation energy E in a **nucleus** with mass number A.
- **Unfeasible** calculation for $A > 3$:
  - Approximation (Difference in energy scales associated with the mean-field potential and the interaction energy inside SRC pairs.)

$$S_A(k,E) = S_A^{\mathrm{MF}}(k,E) + S_A^{\mathrm{SRC}}(k,E)$$

  - Approximation (High energies associated with SRCs)

$$S_A^{\mathrm{SRC}}(k,E) \approx \quad \frac{Z}{A}C_A^p \times S_p^{\mathrm{SRC}}(k,E) + \frac{N}{A}C_A^n \times S_n^{\mathrm{SRC}}(k,E)$$

Short-Range Nuclear Structure

$$S_A(k,E) \approx S_A^{\mathrm{MF}}(k,E) + \quad \frac{Z}{A} C_A^p \times S_p^{\mathrm{SRC}}(k,E) + \frac{N}{A} C_A^n \times S_n^{\mathrm{SRC}}(k,E)$$

- $C_A^N (N = p, n)$: Nucleus dependent constants which 'count' the fraction of nucleons in SRC pairs
- $S_N^{\mathrm{SRC}}(k,E)$: Universal pair distributions, dominated by the strong nucleon-nucleon interaction at short-distance.
- $S_A^{\mathrm{MF}}(k,E)$ captures low-energy, single nucleon dynamics
- $C_A^N \times S_N^{\mathrm{SRC}}(k,E)$ captures universal highenergy nucleon-pair dynamics

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:

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

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:

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

We assume that both $f_{i/n}$ and $f_{i/n}^{\text{SRC}}$ 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 $f_{i/p}^{\text{SRC}}(f_{i/n}^{\text{SRC}})$:

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

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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).

Data & Fits

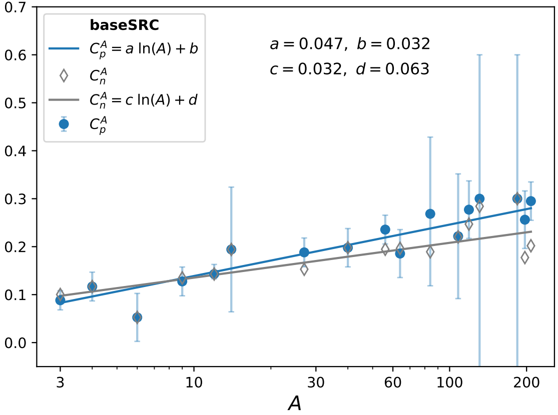
Used data:

- 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.

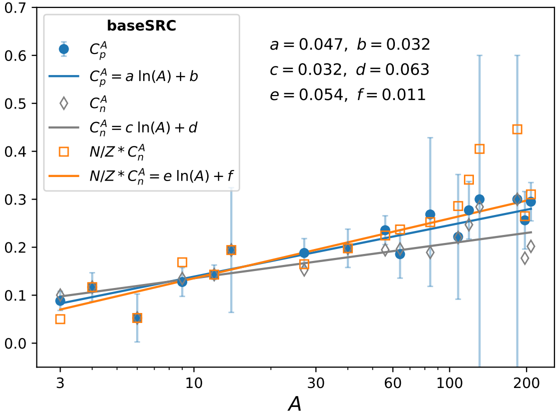
Results: A-dependence of the (C_A^p, C_A^n) parameters



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

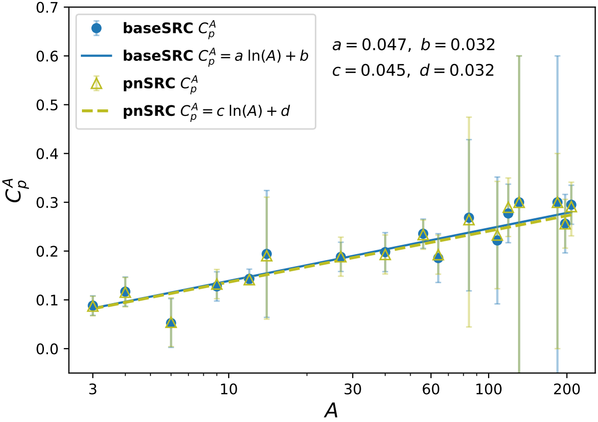
- $^{197}_{79}$Au (C_A^p=0.256, C_A^n=0.178): $79\times C_A^p \simeq$20.2 protons and $118\times C_A^n \simeq$21.0 neutrons.
- $^{208}_{82}$Pb (C_A^p=0.295, C_A^n=0.202): $82\times C_A^p \simeq$24.2 protons and $126\times C_A^n \simeq$25.5 neutrons.

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



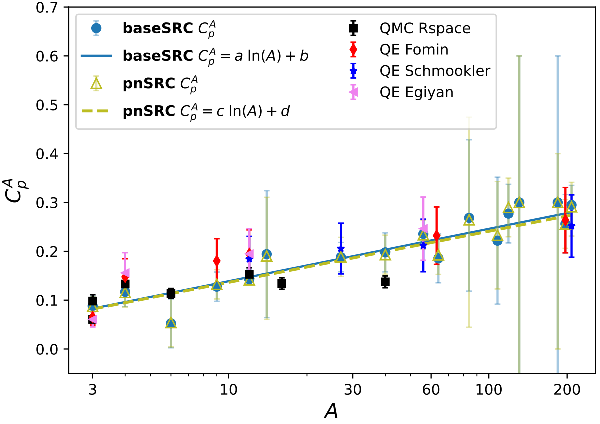
- Correcting for the access of neutrons we obtained a very comparable numbers of protons and neutrons bounded in the SRC pairs.
- This is **consistent** with the hypothesis that the **SRC pairs are dominantly proton-neutron combinations**.
- We can use this observation to restrict number of fit parameters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

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



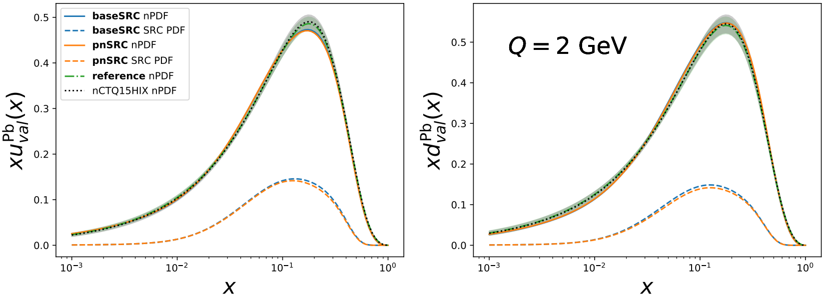
- The obtained C_A^p values are nearly the same as for the baseSRC fit.
- Fit quality is very comparable $\chi^2/N_{\mathrm{DOF}} = 0.82$ (vs $\chi^2/N_{\mathrm{DOF}} = 0.8$).

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



- 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.

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

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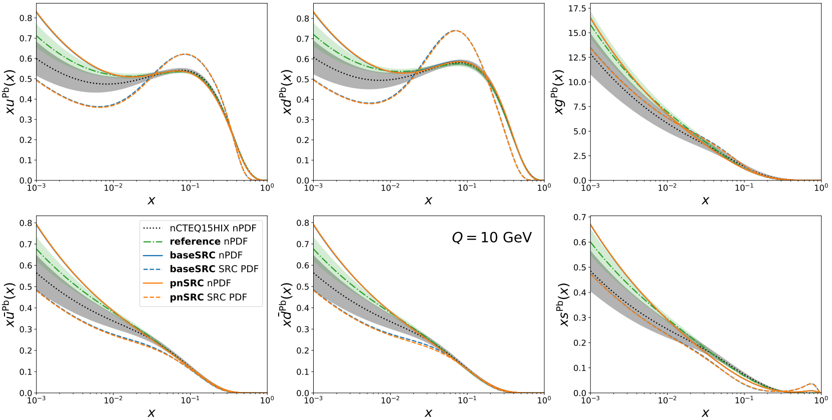
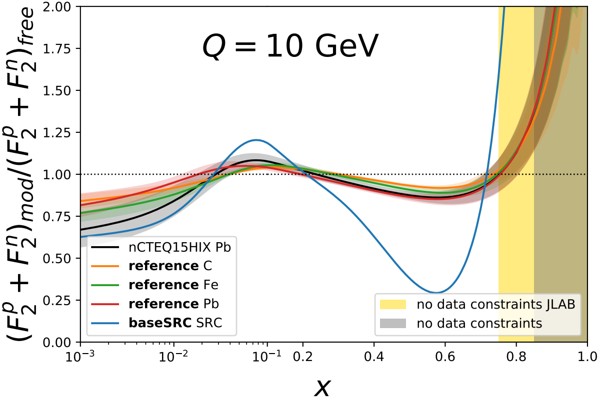


- Clearly "exaggerated" modifications for pure SRC distribution.

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

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.