Modification of nPDFs by correlated nucleon pairs

Michael Klasen

ITP, University of Münster

physicsworld TOP 10 BREAKTHROUGH 2024

CERN TH Heavy Ion Coffee, January 27, 2025

A. Denniston, T. Jezo, A. Kusina et al., Phys. Rev. Lett. 133 (2024) 15

nCTEQ nuclear parton distribution functions

DFG

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

Introduction

Short-range nucleon dynamics is fundamental:

- Deficiencies of mean-field model
- Change of nucleon structure in nuclei (EMC effect)
- Related to quark and gluon d.o.f. in nuclei (?)
- Properties of matter under extreme conditions

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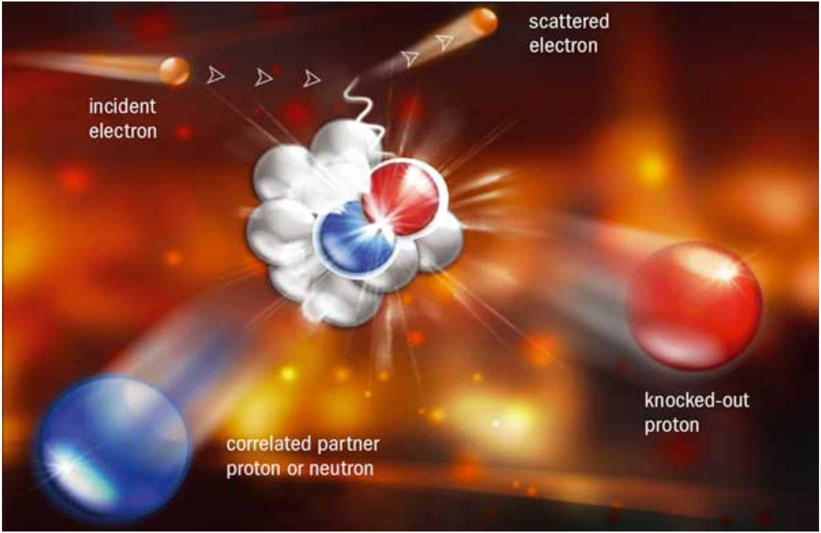
Goal of this work:

- New nPDF ansatz: Single N in mean field + SRC NN pairs
- nCTEQ analysis of DIS, DY, W/Z-boson data at high energy
- Extract SRC fractions and properties of SRC pairs

Nuclei and short-range correlations



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The nuclear many-body problem (1)

C. Ciofi degli Atti, Phys. Rep. 590 (2015) 1

Non-relativistic Schrödinger equation (even though $\frac{v_N}{c} \sim 0.1$):

$$\left[\sum_i \frac{p_i^2}{2m_N} + \sum_{i<j} v_2(x_i, x_j) + \sum_{i<j<k} v_3(x_i, x_j, x_k)\right] \psi_A^f(\{x_A\}) = E_A^f \psi_A^f(\{x_A\})$$

- V_2 dominates, $V_n \simeq (\frac{v_N}{c})^{n-2} V_2$ [H. Primakoff, T. Holstein, PR 55 (1939) 1218]
- V_3 contributes $\leq$ 20 % to BE [S.C. Pieper, R.B. Wiringa, ARNPS 51 (2001) 53]

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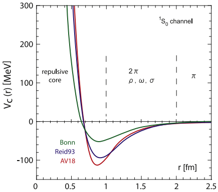
Nuclear NN potentials: [R.J. Furnstahl, K. Ebeler, Rep. Progr. Phys. 76 (2013) 126301]

- Depend on L, S, T ($L + S + T$ odd, Pauli)
- Attractive ($^1S_0$, spin-aligned) for $r \geq 0.7$ fm
- Tensor character for $S = 1$
- Repulsive at small $r \to$ pert. theory fails
- Off-shell effects, important at small r

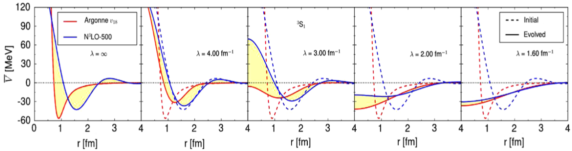


The nuclear many-body problem (2)

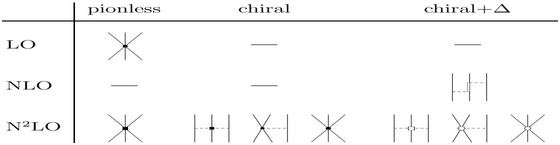
C. Ciofi degli Atti, Phys. Rep. 590 (2015) 1

Chiral perturbation theory: [H.W. Hammer, A. Nogga, A. Schwenk, RMP 85 (2013) 197]

- EFT based on approx., spont. broken chiral symmetry of QCD
- Systematic expansion in local operators and powers of $\Lambda \simeq m_\rho$
- Short range contact int., long range pion exchange ($p_N \simeq m_\pi$)
- Also repulsive at small r, solvable up to $A \leq 12$ with RGEs



- Off-shell NN interactions $\leftrightarrow$ On-shell 3N forces



The nuclear many-body problem (3)

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Nuclear shell model:

- Independent Particle Model: [Jensen et al. PR 75 (1949) 1766; Mayer idib. 1969]

$$\left[-\frac{\hbar^2}{2m_N}\nabla_i^2 + U(\mathrm{x}_i)\right]\phi_\alpha(\mathrm{x}_i) = \epsilon_\alpha\phi_\alpha(\mathrm{x}_i)$$

  with isotropic mean field $U(r_i) = \frac{1}{2}\hbar\omega r_i^2 + D\mathrm{L}_i^2 + CLS$.
  Generated by $V_2 \rightarrow$ Reproduces magic numbers in Z and N
- Motivates "bound" nucleon PDFs
- V_3 modifies monopole, explains e.g. $N = 28$ in ^{20}Ca

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Modern approaches:

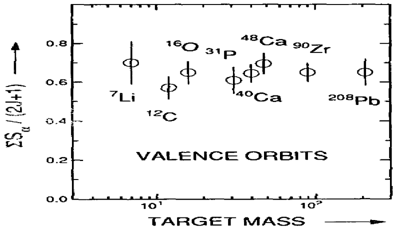
- No-Core Shell Model: [B.R. Barrett, P. Navratil J.P. Vary, PPNP 69 (2013) 131]
  Variational many-body ansatz ($A \leq 12$), also used with ChPT
- Quantum Monte Carlo: [R. Cruz-Torres et al., Nature Phys. 17 (2021) 306]
  Scale separation of short and long distances $\rightarrow$
  A-dependent SRC fractions, A-independent contact terms

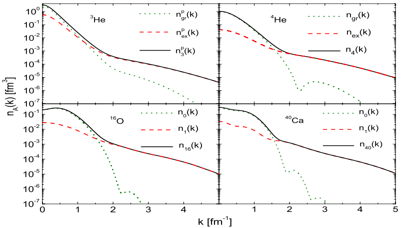
Short-range correlations

O. Hen et al., Rev. Mod. Phys. 89 (2017) 045002 [1611.09768]

Experimental and theoretical evidence:

- QE data show only 65% of single-N strength predicted by IPM





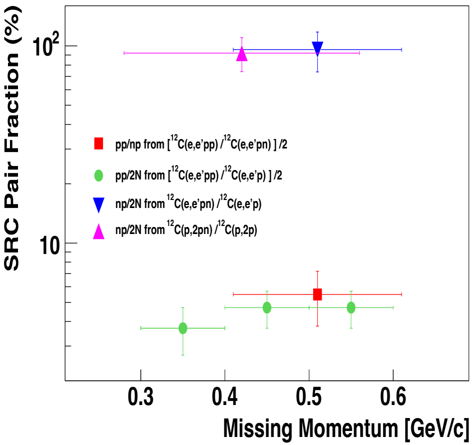
L. Lapikas, Nuclear Physics A 553 (1993) 297c   M. Alvioli et al., PRC 87 (2013) 034603 [1211.0134]

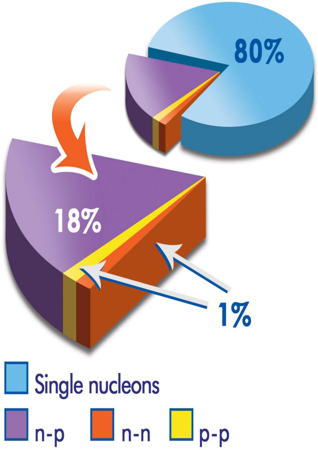
- Remainder in SRC pairs (small p^*, but $p_{\rm rel.} > p_F \sim 250$ MeV)
- Dominated by nodeless rel. S-wave with $S = 1,\ T = 0$ ($\sim d$)
- Typical distance ~ 1 fm $<$ average 1.7 fm $\rightarrow$ Higher density

Exclusive quasi-elastic scattering

R. Subedi et al. (Hall A), Science 320 (2008) 1476 [0908.1514]

^{12}C$(e, e'p, pN)$ ($E_e = 4.627$ GeV, $\theta_e = 19.5°$):

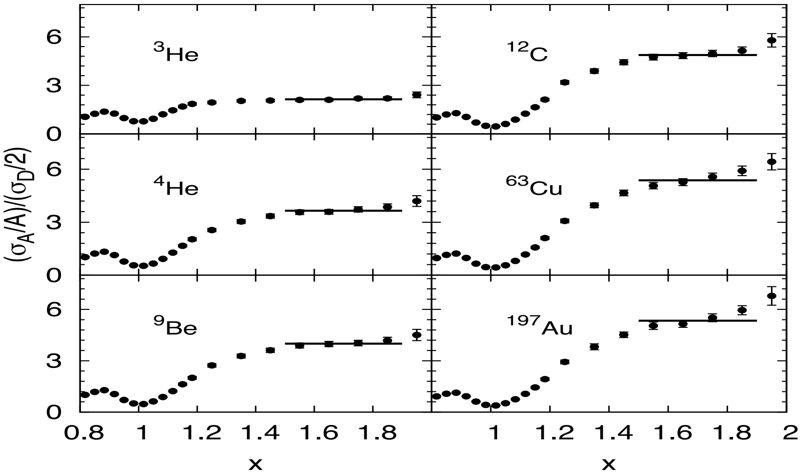




Inclusive quasi-elastic scattering

N. Fomin et al. (Hall C), Phys. Rev. Lett. 108 (2012) 092502 [1107.3583]

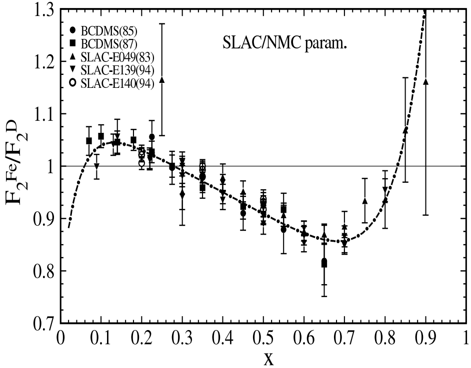
Ratio a_2 = const. for $x > 1.5$ ($E_e = 5.766$ GeV, $\theta_e = 18°$):

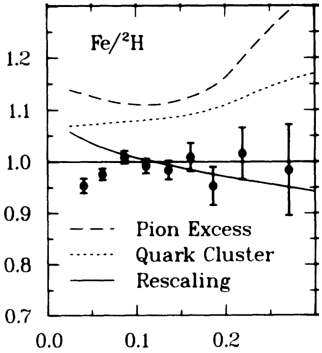


Inclusive deep-inelastic scattering

I. Schienbein et al. [nCTEQ], PRD 80 (2009) 094004 [0907.2357]; D.M. Alde et al., PRL 64 (1990) 2479

Nuclear modification of $F_2^A(x, Q^2)$ ($E_e = 4.5 \ldots 280$ GeV):



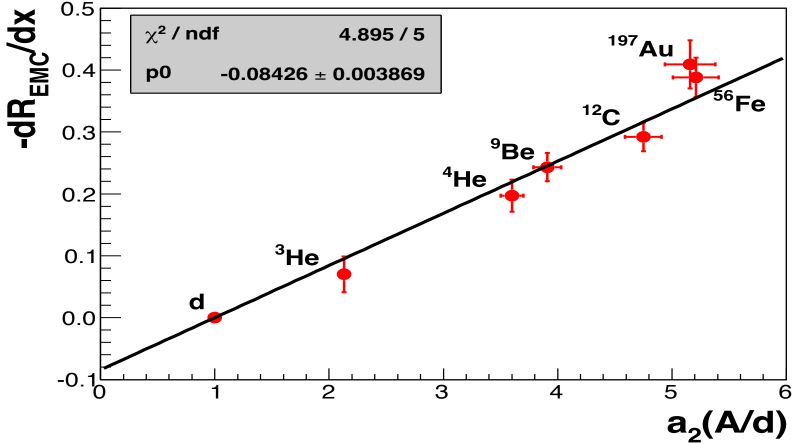


Explanation with N's only violates baryon/momentum sum rules →
Need also π's, but no $\bar{q}$ enhancement seen in nuclear DY.
Partonic? Fewer high-momentum quarks → larger size (e.g. NN^*).

SRCs and the EMC effect

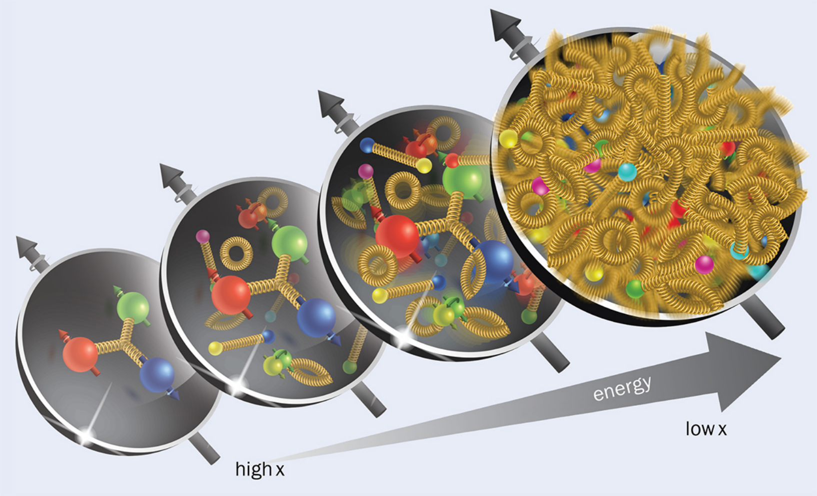
O. Hen, E. Piasetzky, L.B. Weinstein et al., PRL 106 (2011) 052301 and PRC 85 (2012) 047301 [1202.3452]

EMC slope in $0.35 \leq x \leq 0.7$ vs. ratio $a_2 = \sigma_A/\sigma_d$ for $x > 1.5$:



Correlation suggests that EMC effect is of short-distance nature.

Deep-inelastic scattering and nuclear PDFs



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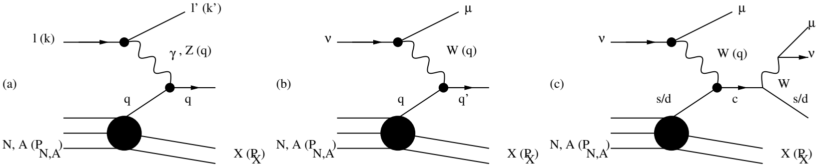
Theoretical foundations

MK, H. Paukkunen, Ann. Rev. Nucl. Part. Sci. 74 (2024) 49 [2311.00450]

Deep-inelastic scattering (NC, CC, dimuon production):



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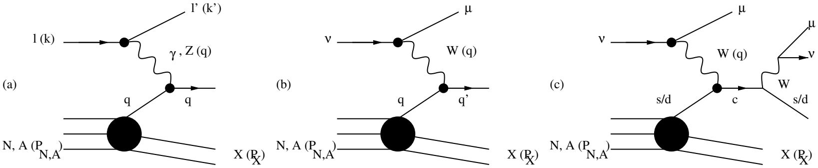
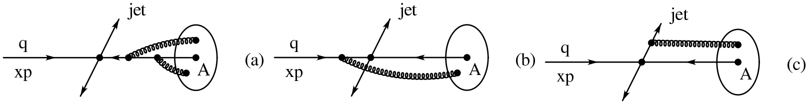


Hadronic collisions: Leading twist, higher-twist [J.w. Qiu, 0305161]



- Transv. size, jet mass, rescattering: $\mathcal{O}\left(r_T^2 \sim \frac{1}{p_T^2}, \frac{m_J^2}{p_T^2}, \frac{\alpha_s(Q^2)\Lambda^2}{Q^2}\right)$
- Enhanced in nuclear collisions by $A^{1/3}$ due to many soft partons

(Perturbative) Quantum Chromodynamics

MK, H. Paukkunen, Ann. Rev. Nucl. Part. Sci. 74 (2024) 49 [2311.00450]

Nuclear structure function(s) in deep-inelastic scattering (DIS):

$$F_2^A(x, Q^2) \;=\; \sum_i f_i^{(A,Z)}(x, Q^2) \otimes C_{2,i}(x, Q^2)$$

QCD factorization theorem, Wilson coefficients $C_{2,i}$ at (N)NLO

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Nuclear parton density functions (nPDFs):

$$f_i^{(A,Z)}(x, Q^2) = \frac{Z}{A} f_i^{p/A}(x, Q^2) + \frac{A-Z}{A} f_i^{n/A}(x, Q^2)$$

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DGLAP evolution equations:

$$\frac{\partial f_i(x, Q^2)}{\partial \log Q^2} = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2)\right) f_j(z, Q^2)$$

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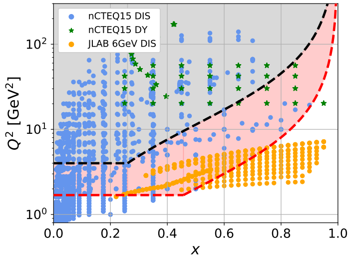
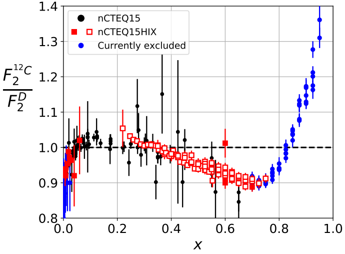
Number and momentum sum rules, but also isospin symmetry:

$$\int_0^1 dx[f^{p/A}_{\{u,d\}} - f^{p/A}_{\{\bar{u},\bar{d}\}}(x)] = \{2,1\} \quad ; \quad f^{n/A}_{d,u}(x,Q^2) = f^{p/A}_{u,d}(x,Q^2)$$

High-x JLab data: Deuteron, TMCs and HT

A. Accardi et al., Phys. Rev. D 93 (2016) 114017 [1602.03154]; E.P. Segarra et al., Phys. Rev. D 103 (2021) 114015 [2012.11566]





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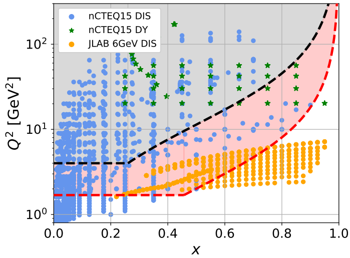

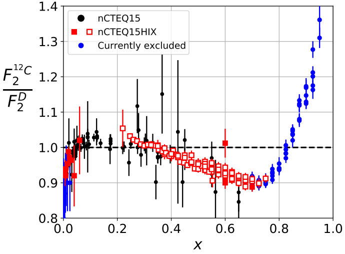

Deuteron:

- Loosely bound → often isoscalar (pn) assumed, fitted with p
- Fermi motion, nucl. binding, off-shell effects (few %) [CJ15,CJ22]

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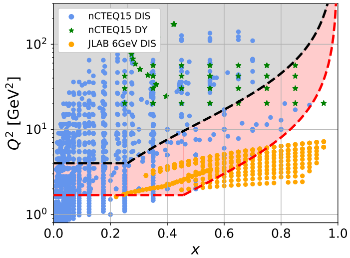

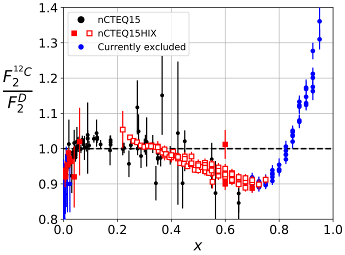

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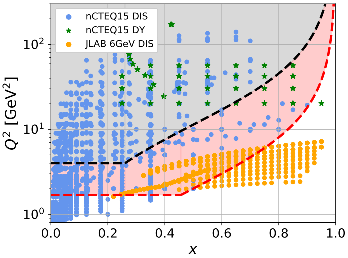

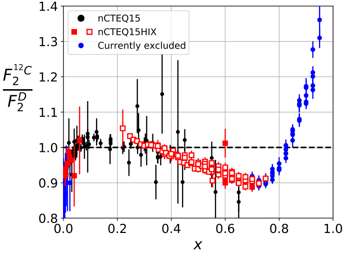

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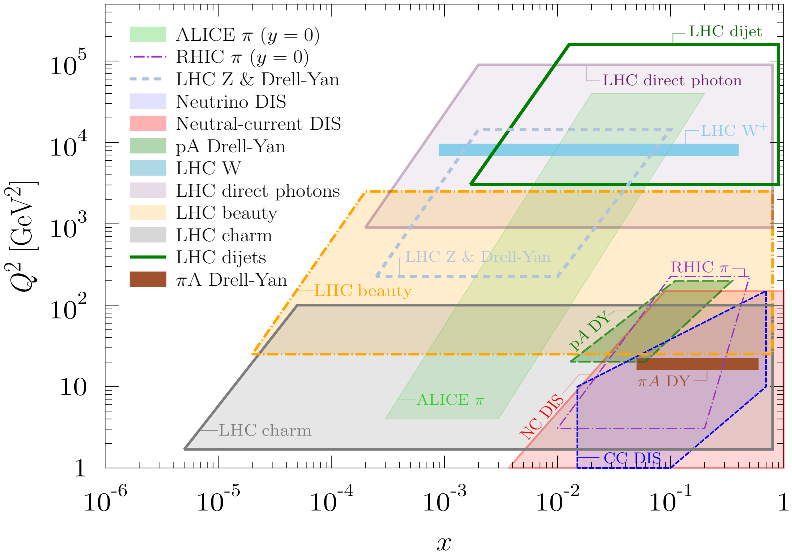
Higher twist (HT) corrections: [CJ15,CJ22]

- $F_2^A(x,Q) \to F_2^A(x,Q)\left[1 + \frac{A^{1/3} h_0 x^{h_1}(1+h_2 x)}{Q^2}\right]$

Experimental kinematic coverage in x and Q^2

MK, H. Paukkunen, Ann. Rev. Nucl. Part. Sci. 74 (2024) 49 [2311.00450]



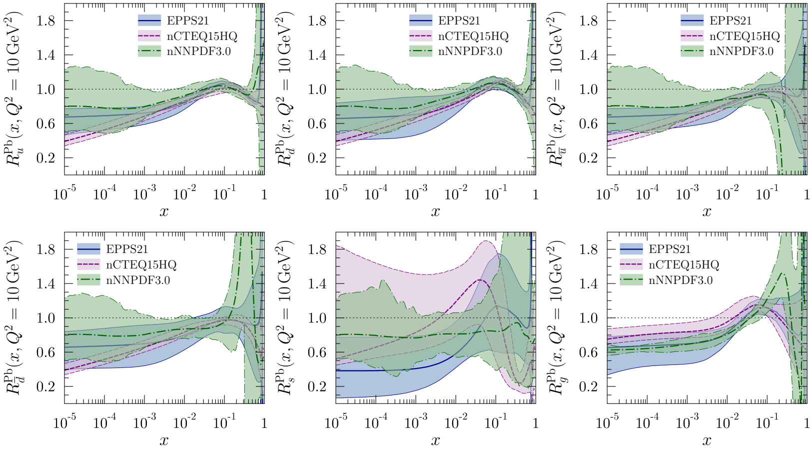
Global analyses of nuclear PDFs

MK, H. Paukkunen, Ann. Rev. Nucl. Part. Sci. 74 (2024) 49 [2311.00450]

ANALYSIS	nCTEQ15HQ	EPPS21	nNNPDF3.0	TUJU21	KSASG20
THEORETICAL INPUT:					
Perturbative order	NLO	NLO	NLO	NNLO	NNLO
Heavy-quark scheme	SACOT$-\chi$	SACOT$-\chi$	FONLL	FONLL	FONLL
Data points	1484	2077	2188	2410	4353
Independent flavors	5	6	6	4	3
Free parameters	19	24	256	16	18
Error analysis	Hessian	Hessian	Monte Carlo	Hessian	Hessian
Tolerance	$\Delta\chi^2 = 35$	$\Delta\chi^2 = 33$	N/A	$\Delta\chi^2 = 50$	$\Delta\chi^2 = 20$
Proton PDF	∼CTEQ6.1	CT18A	∼NNPDF4.0	∼HERAPDF2.0	CT18
Deuteron corrections	$(\checkmark)^{a,b}$	$\checkmark^{c}$	✓	✓	✓
FIXED-TARGET DATA:					
SLAC/EMC/NMC NC DIS	✓	✓	✓	✓	✓
– Cut on Q^2	4 GeV^2	1.69 GeV^2	3.5 GeV^2	3.5 GeV^2	1.2 GeV^2
– Cut on W^2	12.25 GeV^2	3.24 GeV^2	12.5 GeV^2	12.0 GeV^2	
JLab NC DIS	$(\checkmark)^{a}$	✓			✓
CHORUS/CDHSW CC DIS	$(\checkmark/\text{-})^{b}$	✓/-	✓/-	✓/✓	✓/✓
NuTeV/CCFR 2μ CC DIS	$(\checkmark/\checkmark)^{b}$		✓/-		
pA DY	✓	✓	✓		✓
COLLIDER DATA:					
Z bosons	✓	✓	✓	✓	
$W^{\pm}$ bosons	✓	✓	✓	✓	
Light hadrons	✓	$\checkmark^{d}$			
Jets		✓	✓		
Prompt photons			✓		
Prompt D^0	✓	✓	$\checkmark^{e}$		
Quarkonia (J/ψ, ψ', Υ)	✓				

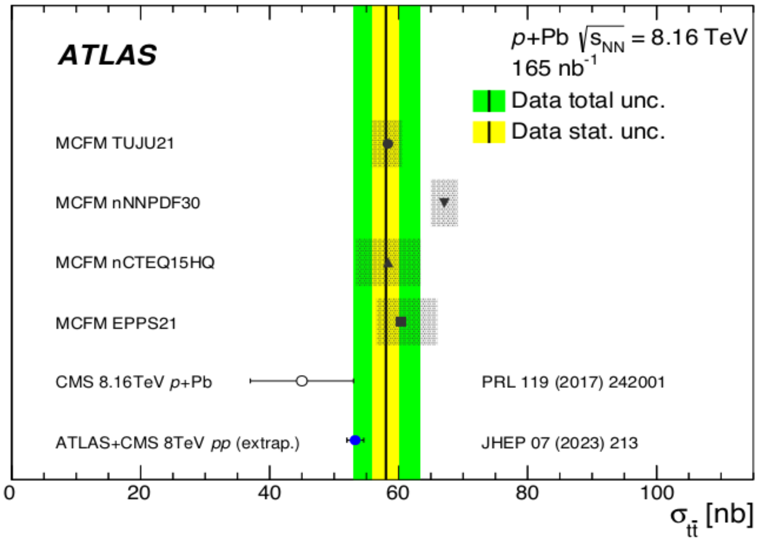
Nuclear PDFs after 10 years of LHC data

MK, H. Paukkunen, Ann. Rev. Nucl. Part. Sci. 74 (2024) 49 [2311.00450]

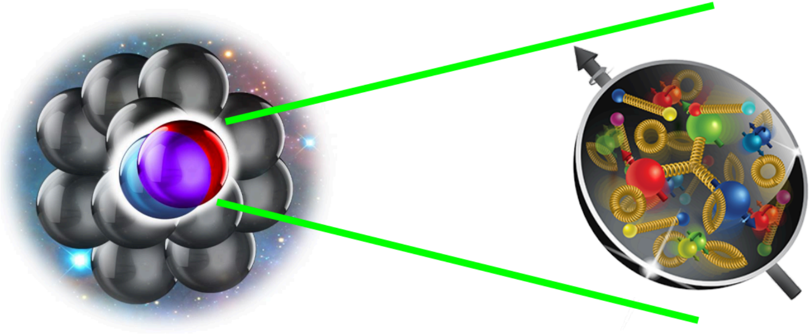


Top pair production in pPb with ATLAS (and CMS)

ATLAS Coll., JHEP 11 (2024) 101 [2405.05078]



Nuclear PDFs from short-range correlations



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Experimental data

A. Denniston, T. Jezo, A. Kusina, MK et al., Phys. Rev. Lett. 133 (2024) 15 [2312.16293]

Inclusive FT (CERN, FNAL, SLAC) and collider (RHIC, LHC) exp.:

- Deep-inelastic scattering:

  Kinematics: $Q^2 = -(p_e - p_{e'})^2,\ y = 1 - E_{e'}/E_e,\ x = Q^2/(sy)$

$$d\sigma(eA \to e'X) = \frac{4\pi\alpha^2}{Q^4}\left[F_2^A(x, Q^2)\left(\frac{y^2}{2} + 1 - y\right) - xy^2 F_L^A\right]$$

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A. Denniston, T. Jezo, A. Kusina, MK et al., Phys. Rev. Lett. 133 (2024) 15 [2312.16293]

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- nCTEQ15HIX/SRC, nCTEQ25: $Q > 1.3$ GeV, $W > 1.7$ GeV

Traditional theoretical approach

E.P. Segarra, T. Jezo, MK et al., Phys. Rev. D 103 (2021) 114015 [2012.11566]

Q^2-dependence calculable to N^3LO QCD [S. Moch et al., PLB 860 (2025) 139194]

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Our traditional parameterisation (e.g. nCTEQ15HIX):

$$xf_i^{p/A}(x, Q_0) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5}$$

where $c_k(A) = p_k + a_k(1 - A^{-b_k})$, $k = \{1, ..., 5\}$,

and $i = \{u_v, d_v, (\bar{u}+\bar{d}), (\bar{d}/\bar{u}), s, g\}$, $s = \bar{s} = \kappa(\bar{u}+\bar{d})/2$, $\kappa = 0.5$.

Reproduces free proton for $A \to 1$, open 19 free parameters.

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χ^2 test function for data set D (3 norm. par. for W/Z production):

$$\chi_D^2 = \sum_{i,j}^N \left(D_i - \frac{T_i}{N_{norm}}\right)(C^{-1})_{ij}\left(D_j - \frac{T_j}{N_{norm}}\right) + \left(\frac{1-N_{norm}}{\sigma_{norm}}\right)^2$$

Covariance matrix: $C_{ij} = \sigma_i^2\,\delta_{ij} + \sum_\alpha^S \bar{\sigma}_{i\alpha}\,\bar{\sigma}_{j\beta}$

Hessian (or Markov Chain Monte Carlo) error analysis

SRC-motivated nuclear PDFs

A. Denniston, T. Jezo, A. Kusina, MK et al., Phys. Rev. Lett. 133 (2024) 15 [2312.16293]

Nuclear spectral function: [C. Ciofi degli Atti, Phys. Rep. 590 (2015) 1]

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

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Parton model translation (nCTEQ15SRC):

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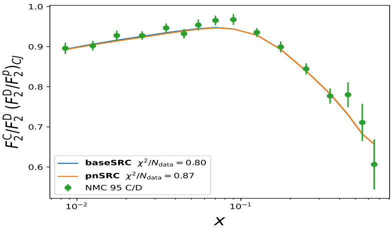
Open 21 parameters ($\sim$ HIX + s) + 30/19 for $C^A_{p,n}$ in base/pn.

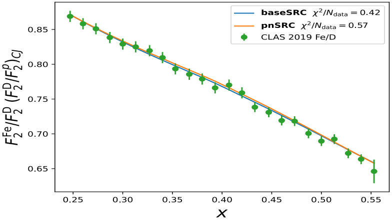
Fitted nuclei and selected comparisons

A. Denniston, T. Jezo, A. Kusina, MK et al., Phys. Rev. Lett. 133 (2024) 15 [2312.16293]

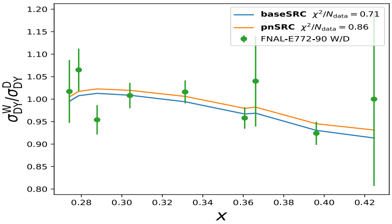
Nuclear A	2	3	4	6	9	12	14	27	40	56	64	84	108	119	131	184	197	208
# data	275	125	66	15	49	196	101	73	92	134	61	84	7	152	4	37	50	163

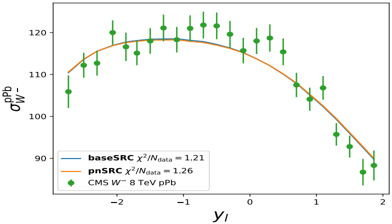


(a)



(b)





Quality of our fits

A. Denniston, T. Jezo, A. Kusina, MK et al., Phys. Rev. Lett. 133 (2024) 15 [2312.16293]

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

- Better overall quality of the SRC fit

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- Slightly worse for W/Z bosons, which probe lower x

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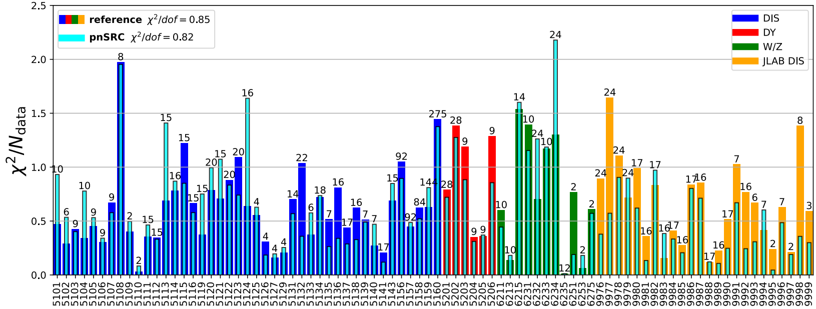
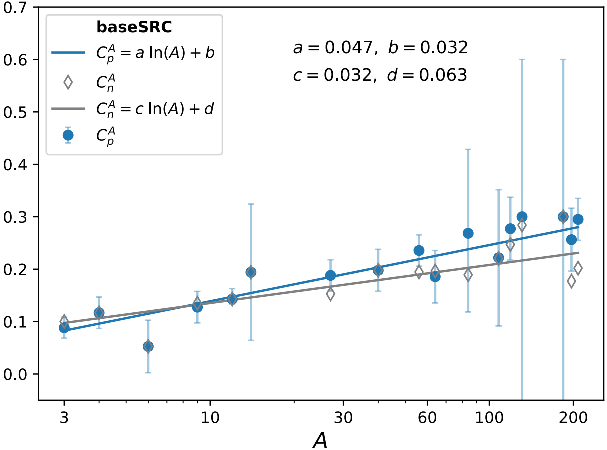


A-dependence of C_p^A and C_n^A

A. Denniston, T. Jezo, A. Kusina, MK et al., Phys. Rev. Lett. 133 (2024) 15 [2312.16293]



Almost equal number of protons and neutrons in SRC pairs:

- $^{197}_{79}$Au ($C_p^A = 0.256,\ C_n^A = 0.178$): $79\ C_p^A \simeq$ 20.2, $118\ C_n^A \simeq$ 21.0
- $^{208}_{82}$Pb ($C_p^A = 0.295,\ C_n^A = 0.202$): $82\ C_p^A \simeq$ 24.2, $126\ C_n^A \simeq$ 25.5

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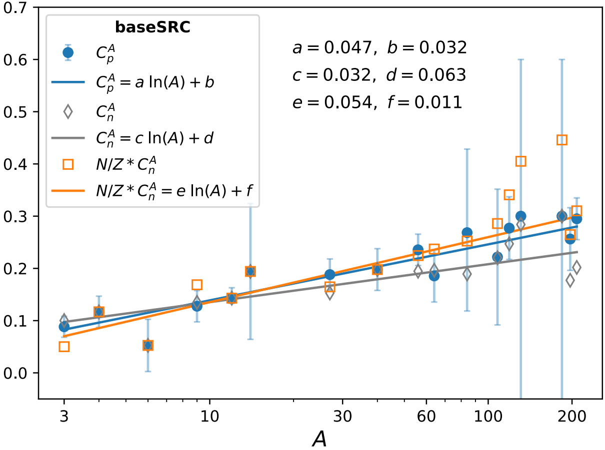
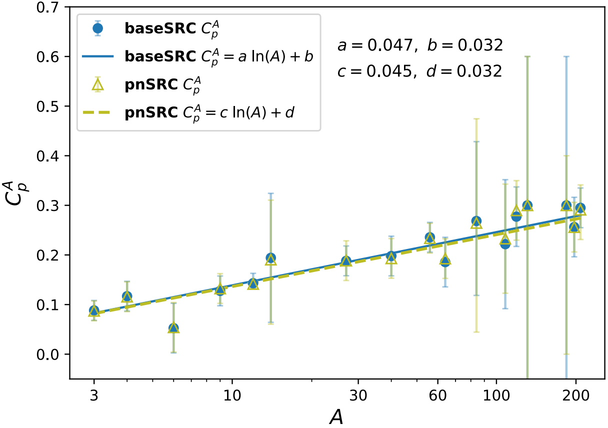


Even better agreement after correcting for neutron excess →
Allows to reduce the number of free parameters: $C_n^A = (Z/N)C_p^A$.
Agrees with exclusive quasi-elastic scattering (pn/NN $\simeq 90 \pm 10\%$).

Comparison of the two fits

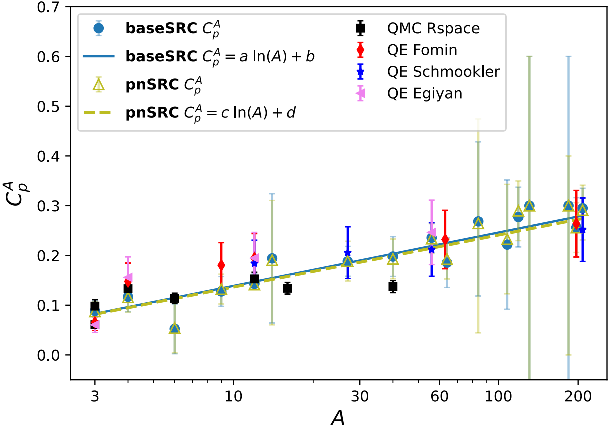
A. Denniston, T. Jezo, A. Kusina, MK et al., Phys. Rev. Lett. 133 (2024) 15 [2312.16293]



pnSRC fit very similar to baseSRC fit: $\chi^2 = 0.82/N_{\rm dof}$ instead of 0.80.

Comparison with QE scattering and QMC calculations

A. Denniston, T. Jezo, A. Kusina, MK et al., Phys. Rev. Lett. 133 (2024) 15 [2312.16293]



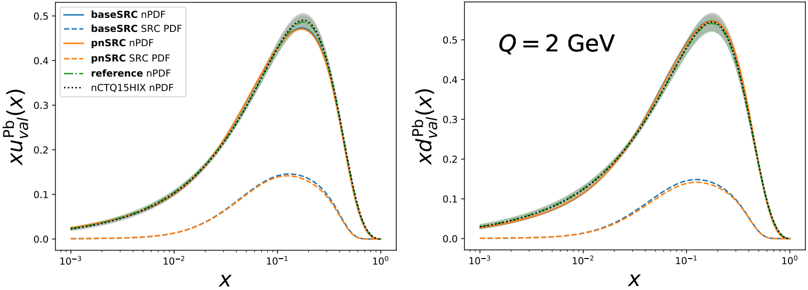
Excellent agreement with

- QE data [Fomin, PRL 108 (2012) 092502; Schmookler, Nature 566 (2019) 354; Egiyan, PRL 96 (2006)]
- QMC theory [R. Cruz-Torres et al., Nature Physics 17 (2021) 306]

Valence quark distributions

A. Denniston, T. Jezo, A. Kusina, MK et al., Phys. Rev. Lett. 133 (2024) 15 [2312.16293]

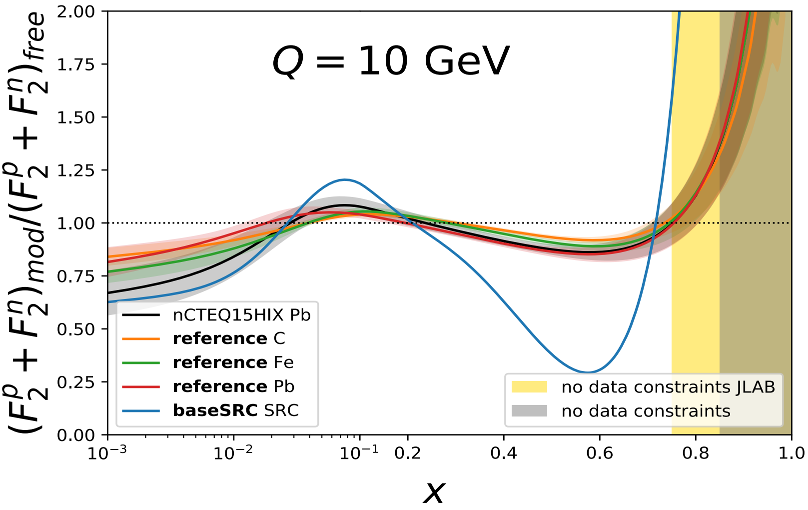
Sanity check:



SRC u, d valence quarks in Pb within previous error bands.
SRC components 20-30% of full nPDFs in agreement with $C_{p,n}^{A}$.

Ratio of bound to free *pn*-pair structure functions

A. Denniston, T. Jezo, A. Kusina, MK et al., Phys. Rev. Lett. 133 (2024) 15 [2312.16293]



Similar, but SRC more pronounced in EMC-region and universal!

Conclusion and outlook

Nuclear binding at low energy:

- Off-shell 2-body $\leftrightarrow$ 3-body interactions $\rightarrow$ Shell model
- Quasi-free nucleons in Mean Field motivate bound N PDFs
- But: Strong experimental and theoretical evidence for SRCs
- Striking correlation of QES and DIS in EMC region

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nCTEQ15SRC:

- nCTEQ15HIX data + W/Z bosons $\rightarrow$ 2 more parameters (s)
- Factorisation of energy scales $\rightarrow$ New SRC ansatz for nPDFs
- Very good fit, in particular to JLab data, and consistent PDFs
- p and n fractions in SRC pairs agree with LE data and theory
- Dominated by pn pairs, again in agreement with LE data
- Partonic structure of SRC pairs universal, large EMC effect

Outlook

Future directions: [O. Hen et al., Rev. Mod. Phys. 89 (2017) 045002]

- Test isospin breaking ($C_n^A \neq \frac{Z}{N} C_p^A$, $f_n \neq f_p$) with QED/PV
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- Separate spin 1 and spin 0 with polarised eA scattering

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Neutrino CC scattering: [C. Ciofi degli Atti, Phys. Rep. 590 (2015) 1]

- π^0 production $>$ baryon resonances [MiniBooNE, PRD 83 (2011) 052009]
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Collective effects in QGP: [C. Ciofi degli Atti, Phys. Rep. 590 (2015) 1]

- Glauber model of individual wounded nucleons (participants)
- SRCs reduce eccentricities [G. Denicol et al., 1406.7792]