



nCTEQ
nuclear parton distribution functions

Nuclear parton distribution functions with nCTEQ

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nCTEQ collaboration

ITP, WWU

SFB 1225 isoQuant



Nuclear structure with nCTEQ

Periodic Table of the Elements

Nuclei with DIS data included in nCTEQ15 (Fig. by E. Godat)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA	IIA	IIIB	IVB	VB	VI	VII	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VVA	VIA	VIIA	VIIIA
H Hydrogen 1.008	He Helium 4.003																
Li Lithium 6.941	Be Beryllium 9.012											B Boron 10.811	C Carbon 12.011	N Nitrogen 14.007	O Oxygen 15.999	F Fluorine 18.998	Ne Neon 20.180
Na Sodium 22.990	Mg Magnesium 24.305											Al Aluminum 26.982	Si Silicon 28.086	P Phosphorus 30.974	S Sulfur 32.066	Cl Chlorine 35.453	Ar Argon 39.948
K Potassium 39.098	Ca Calcium 40.078	Sc Scandium 44.956	Ti Titanium 47.88	V Vanadium 50.942	Cr Chromium 51.996	Mn Manganese 54.938	Fe Iron 55.933	Co Cobalt 58.933	Ni Nickel 58.693	Cu Copper 63.546	Zn Zinc 65.39	Ga Gallium 69.723	Ge Germanium 72.63	As Arsenic 74.922	Se Selenium 78.972	Br Bromine 79.904	Kr Krypton 83.798
Rb Rubidium 84.468	Sr Strontium 87.62	Y Yttrium 88.906	Zr Zirconium 91.224	Nb Niobium 92.906	Mo Molybdenum 95.94	Tc Technetium 98.906	Ru Ruthenium 101.07	Rh Rhodium 102.905	Pd Palladium 106.42	Ag Silver 107.868	Cd Cadmium 112.411	In Indium 114.818	Sn Tin 118.710	Sb Antimony 121.757	Te Tellurium 127.6	I Iodine 126.905	Xe Xenon 131.29
Cs Cesium 132.905	Ba Barium 137.327		Hf Hafnium 178.49	Ta Tantalum 180.948	W Tungsten 183.85	Re Rhenium 186.207	Os Osmium 190.23	Ir Iridium 192.22	Pt Platinum 195.08	Au Gold 196.967	Hg Mercury 200.59	Tl Thallium 204.383	Pb Lead 207.2	Bi Bismuth 208.980	Po Polonium [209]	At Astatine [209]	Rn Radon [222]
Fr Francium [223]	Ra Radium [226]		Rf Rutherfordium [261]	Db Dubnium [262]	Sg Seaborgium [266]	Bh Bohrium [264]	Hs Hassium [269]	Mt Meitnerium [268]	Ds Darmstadtium [271]	Rg Roentgenium [272]	Cn Copernicium [285]	Uut Ununtrium [288]	Fl Flerovium [289]	Uup Ununpentium [294]	Lv Livermorium [293]	Uus Ununseptium [294]	Uuo Ununoctium [294]

- nCTEQ's fundamental quest: study structure of nuclei from high energy perspective
- Highlights for today:
 - ▶ Nuclear structure from heavy quark production [a]
 - ▶ Short-range-correlation inspired atomic number dependence [b]

[a] Düwentester, TJ, Klasen et al., '22

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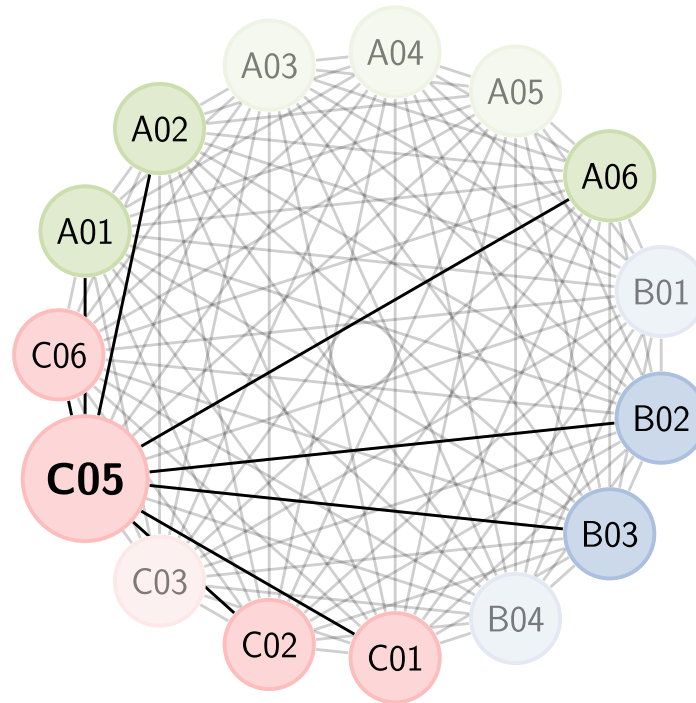
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Nuclear structure with nPDFs in isoQuquant

- C05: Probing the QCD phase structure with heavy quarks



Nuclear structure with nPDFs in isoQuaant

- C05: Probing the QCD phase structure with heavy quarks
- Connections to other projects:
 - A01: Initial state and thermalisation in HI collisions [Berges, Reygers, Stachel]
 - Jet quenching: T_I dependence vs. nPDF uncertainty
 - Low- p_T photons: Subtraction of direct/fragmentation photons
 - A02: From QCD transport to particle yields [Masciocchi, Pawlowski, Stachel]
 - Low- p_T π, K, p, D : Transport coefficient vs. nPDF uncertainty
 - B02: NP QED theory in strong EM fields [Harman, Keitel, Di Piazza]
 - J/ψ in UPCs: Photoproduction, diffraction and shadowing
 - B03: Quantum dynamics of strong gauge fields and condensates [Berges, Pawlowski, Wienhard]
 - Test BE enhan. in BFKL with J/ψ 's [Gotsman, Levin, 1804.02561, 1808.04982]
 - C02: From few to many – ultracold atoms in recuded dimensions [Enss, Jochim]
 - Fermi gas correlations at large x (EMC eff.) [Arrington et al., 1206.06343]
 - C06: Flow and fluctuations in relativ. HI collisions [Flörchinger, Masciocchi]
 - Small- x region of nPDFs determines initial state fluctuations

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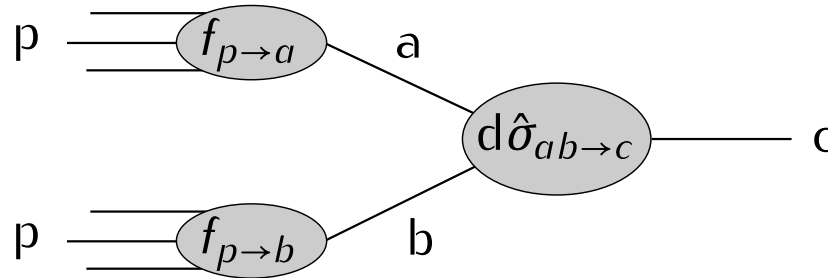
- Fermi gas correlations at large x (EMC eff.) [Arrington et al., 1206.06343]

C06: Flow and fluctuations in relativ. HI collisions [Flörchinger, Masciocchi]

- Small- x region of nPDFs determines initial state fluctuations

High energy particle collisions

- Take for example proton-proton (pp) collisions in picture:



- Or in formula, in the collinear factorization framework:

$$d\sigma_{pp \rightarrow c} = \sum_{a,b} f_{p \rightarrow a}(x_a, \mu) \otimes f_{p \rightarrow b}(x_b, \mu) \otimes d\hat{\sigma}_{ab \rightarrow c}(\mu)$$
$$\mu \gtrsim 1 \text{ GeV}, x \in (0, 1)$$

- With μ : factorization scale, x : fraction of parton $a(b)$ momentum in proton p

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- Parton Distribution Functions (PDFs)
 $f_{p \rightarrow a}(x, \mu)$
 - ▶ Universal
 - ▶ Not calculable from first principles (not yet)
- Similarly for lp , νp and one-particle inclusive^a processes

- Hard cross section
 $d\hat{\sigma}_{ab \rightarrow c}(\mu)$
 - ▶ Process specific
 - ▶ Calculable in perturbative QCD (pQCD)

^aWhich involve second factorization scale and convolution with fragmentation functions.

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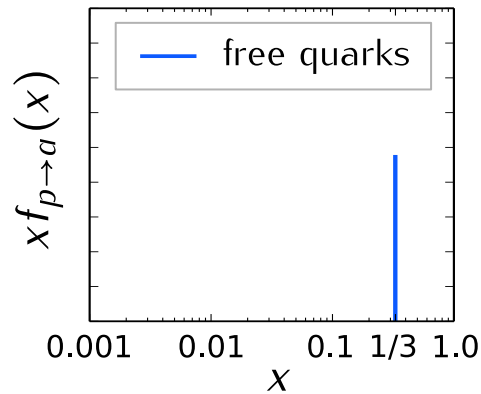
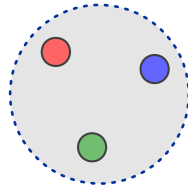
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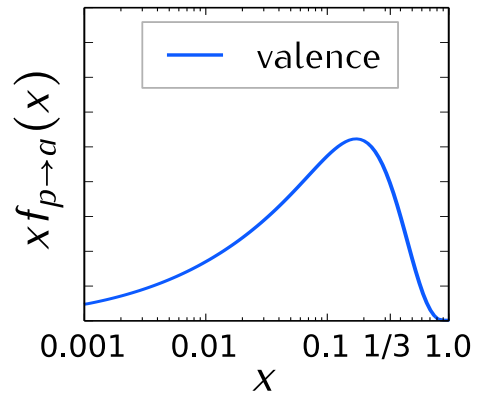
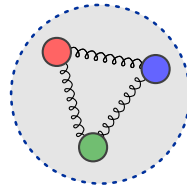
Parton Distribution Functions (PDFs)

- PDF[$f_{p \rightarrow a}(x, \mu)$]: probability that parton a carries fraction^a x of proton p momentum

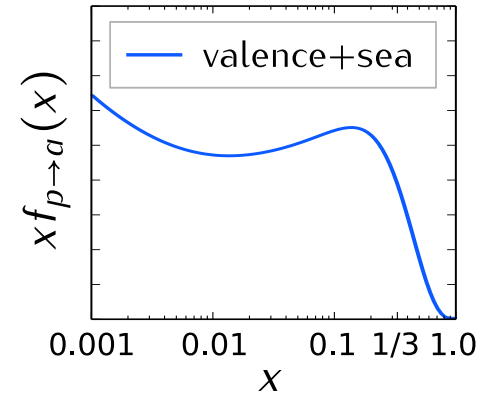
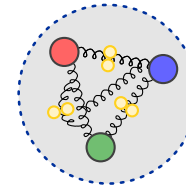
Free partons



Bound partons



Bound partons
& QCD effects



^aLongitudinal.

Parton Distribution Functions (PDFs)

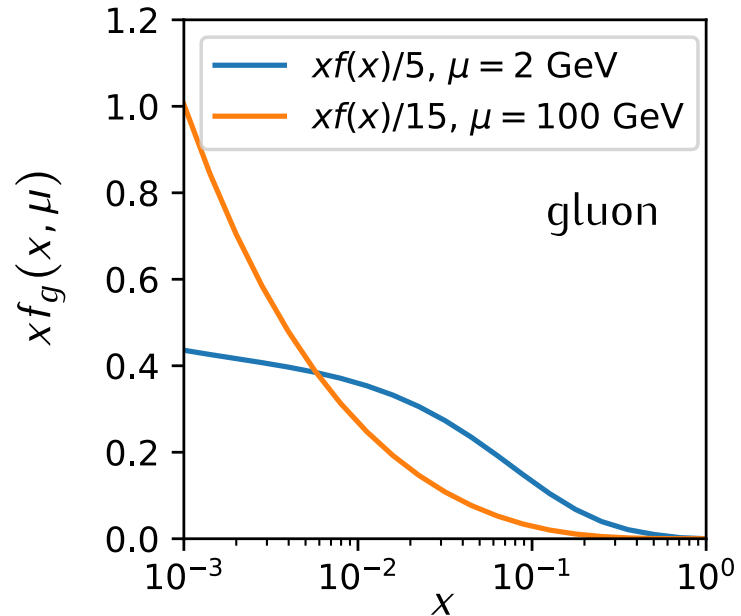
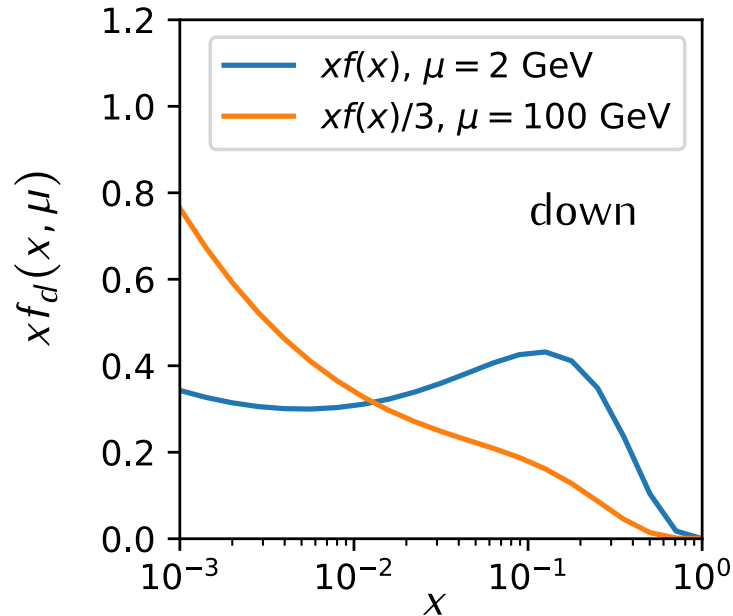
- Universal: same PDF enters different processes (DIS, DY, SIH, HQ, ...)
- x dependence not calculable in pQCD
- μ dependence governed by DGLAP evolution equations

$$\frac{df_q(x, \mu^2)}{d \log \mu^2} = \frac{\alpha_S(\mu^2)}{2\pi} \int_x^1 \frac{dy}{y} \left[P_{qq}\left(\frac{x}{y}\right) f_q(y, \mu^2) + P_{qg}\left(\frac{x}{y}\right) f_g(y, \mu^2) \right]$$
$$\frac{df_g(x, \mu^2)}{d \log \mu^2} = \frac{\alpha_S(\mu^2)}{2\pi} \int_x^1 \frac{dy}{y} \left[P_{gg}\left(\frac{x}{y}\right) f_g(y, \mu^2) + P_{gq}\left(\frac{x}{y}\right) f_q(y, \mu^2) \right]$$

- ▶ Describe violations of Bjorken x scaling
- ▶ Different PDFs mix: set of $(2n_f + 1)$ coupled integro-differential equations.

Parton Distribution Functions (PDFs)

- μ dependence governed by DGLAP evolution equations:



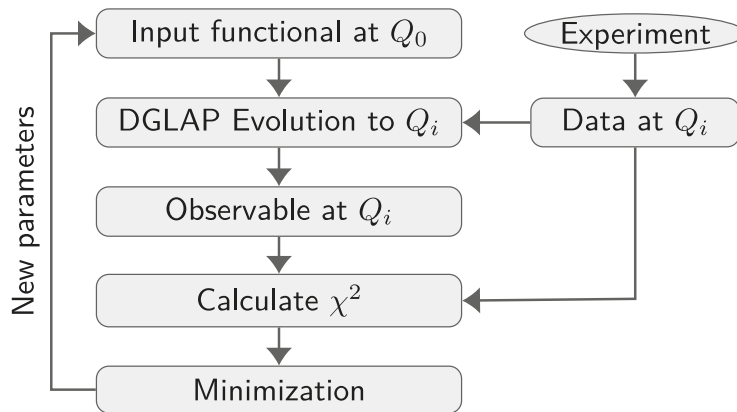
- ▶ Reduces valence and increases sea
- ▶ Mixes flavours

Parton Distribution Functions (PDFs)

- x dependence not calculable in pQCD^a:
 - ▶ assume parametrization in x^b at a chosen input scale Q_0 :

$$xf_i(x, Q_0) = N(1-x)^{p_{i,1}} P(x, p_{i,2}, \dots)$$

- ▶ set $p_{i,j}$, calculate theoretical predictions, compare to data, iterate:



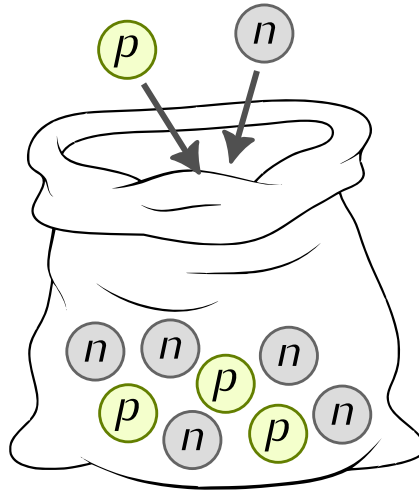
$$\chi^2 = \sum_{ij}^N (D_i - T_i) (C^{-1})_{ij} (D_j - T_j)$$

^aCalculable in lattice QCD in near future?

^bNNPDF collaboration use NN to avoid parametrization bias.

Nuclear Parton Distribution Functions (nPDFs)

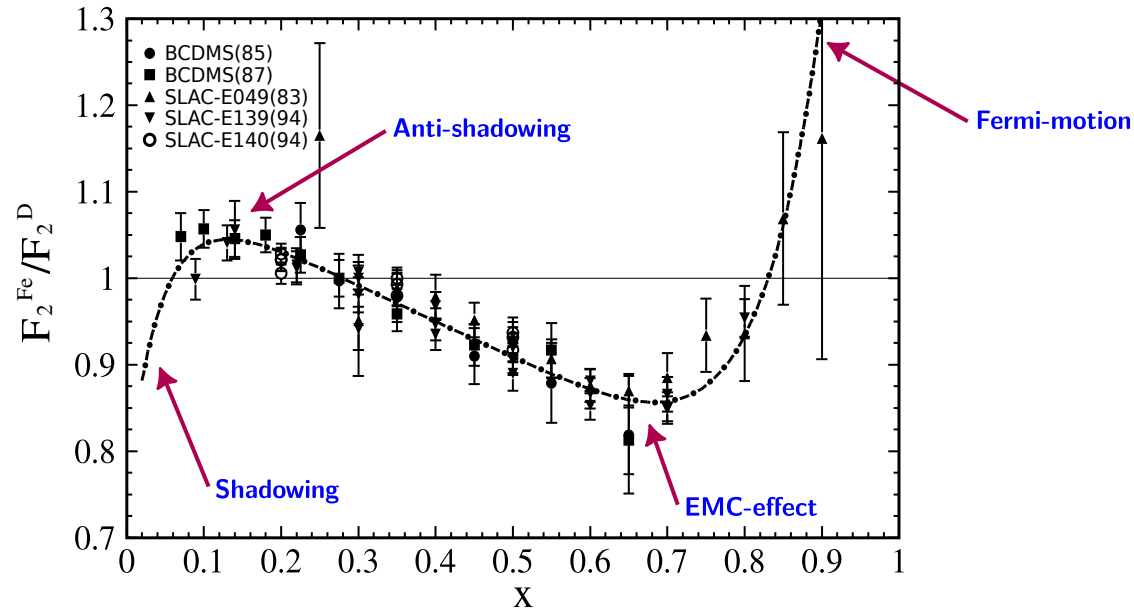
- Free nucleon approximation:



$$Af^A(x, \mu) = Zf^p(x, \mu) + Nf^n(x, \mu)$$

Nuclear Parton Distribution Functions (nPDFs)

- Nuclear modification:



$$Af^A(x, \mu) \neq Zf^p(x, \mu) + Nf^n(x, \mu)$$

Nuclear Parton Distribution Functions (nPDFs)

- Nuclear modification can be incorporated into the PDF framework^a:

1. nucleon PDF \times A-dependent nuclear modification: $f_i^{p/A} = f_i^p(x, \mu) \times R_i(x, \mu, A)$
2. A-dependent bound nucleon PDF: $f_i^{p/A} = f_i(x, \mu, A)$, $f_i(x, \mu, A=1) = f_i^p(x, \mu)$

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

- ▶ bound proton PDF fulfils the usual evolution equations and sum rules
- ▶ bound neutron PDF from isospin symmetry, i.e. $f_{d,u}^{p/A} = f_{u,d}^{p/A}$
- ▶ nPDFs replace PDFs in the factorization formula^b
- ▶ momentum fraction now $x \in (0, A)$ but $x > 1$ region negligible

^aUnderlying dynamics of nuclear modifications remains to be theoretically understood.

^bProof of factorization for collisions of nuclei not yet available.

nCTEQ nPDFs

- nCTEQ nPDFs:

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5}$$
$$c_k \rightarrow c_k(A) \equiv p_k + a_k (1 - A^{-b_k})$$

- ▶ NLO QCD; $Q_0 = 1.3$ GeV; $f_i^{p/A}(x, Q, A = 1) \equiv$ CTEQ6 w/o nuclear data
- ▶ A dependence: not from first principles; constraint for A's with few data pts
- ▶ data: DIS NC (1472) & CC (974/4644), DY (92), LHC W/Z (86), SIH (112), HQ (965); no jet or direct photon yet
- ▶ NEW!: High- x vs. JLAB DIS data [a], Impact of HQ data [b], Compatibility of ν -DIS data [c]

[a] Segarra, TJ, Klasen et al., '21

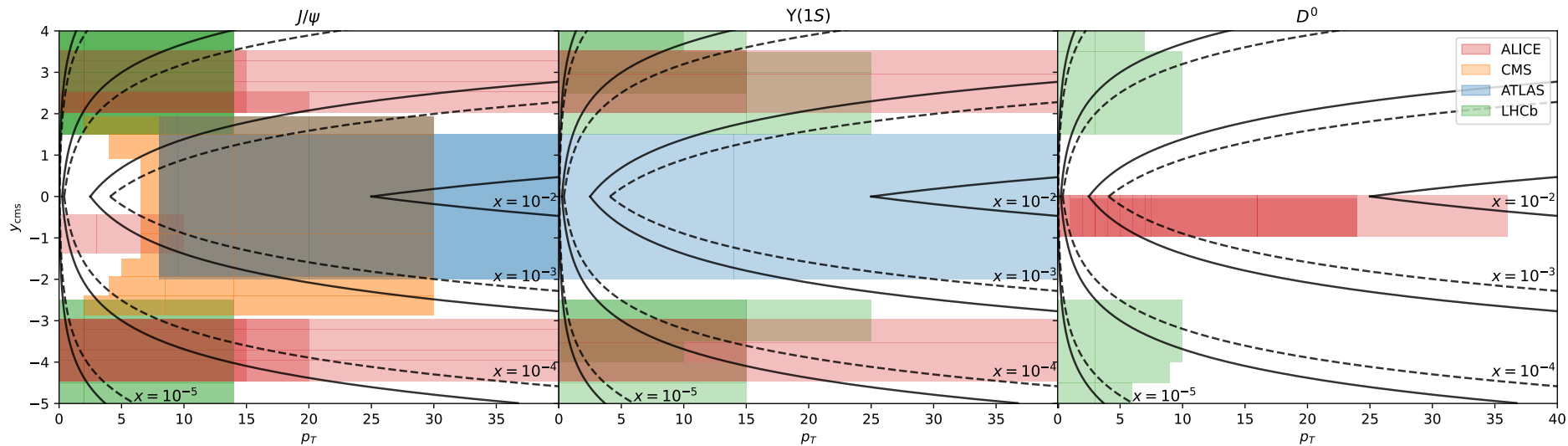
[b] Düwentester, TJ, Klasen et al., '22

[c] Muzakka, TJ, Kovařík, Klasen et al., '22

Impact of heavy quark(-onia) production

[Düwentester, T], Klasen et al., '22]

- Heavy Quarks reach down to $x \simeq 10^{-5}$ ($x \approx 2p_T e^{-|y|} / \sqrt{s}$):



Impact of heavy quark(-onia) production

[Düwentester, T], Klasen et al., '22]

- Heavy quarks and quarkonia production modelled using a data driven approach:
 - ▶ dominated by gg channel

$$\sigma(AB \rightarrow Q + X) = \int dx_1 dx_2 f_{1,g}(x_1, \mu) f_{2,g}(x_2, \mu) \frac{1}{2\hat{s}} \overline{|\mathcal{A}_{gg \rightarrow Q+X}|^2} dPS$$

- ▶ effective amplitude parametrized by CB-like model

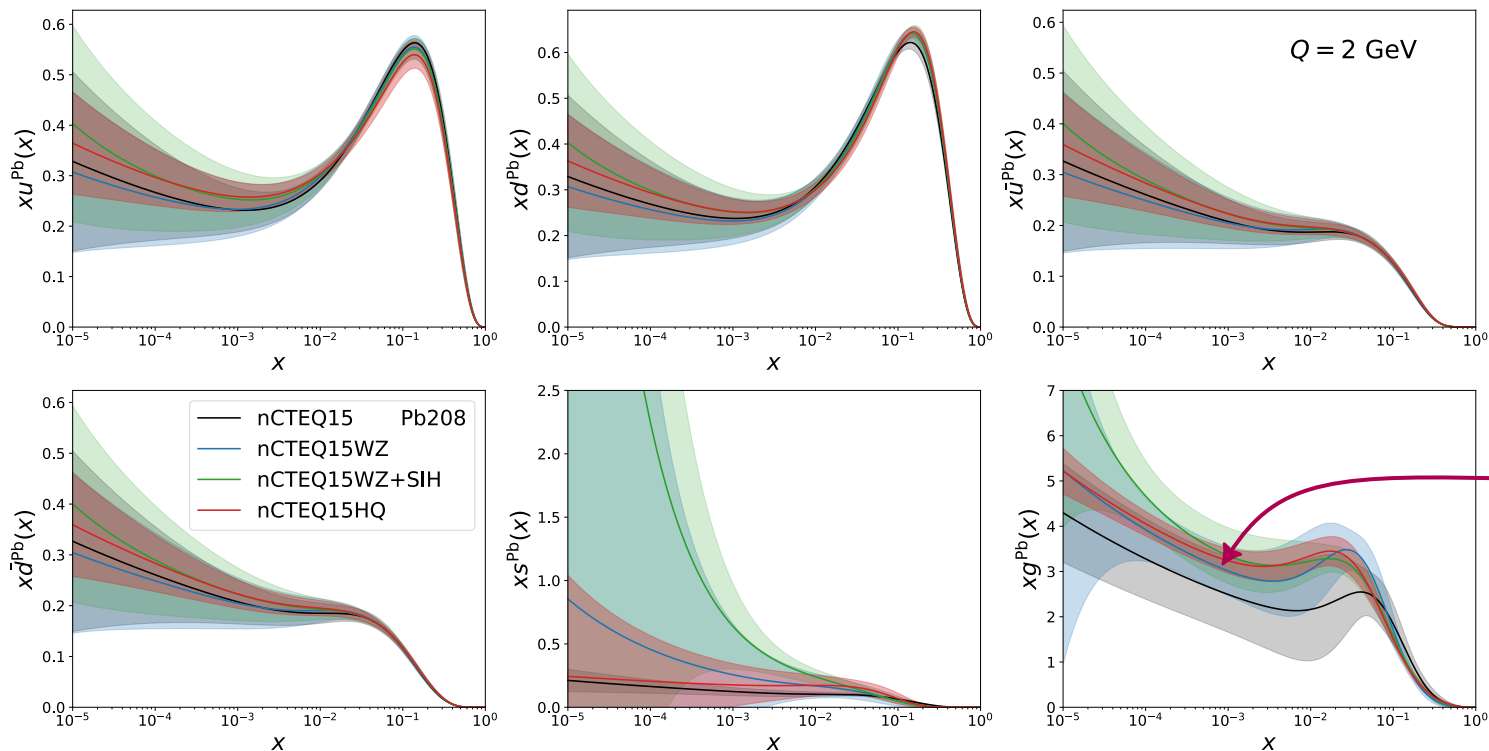
$$\overline{|\mathcal{A}_{gg \rightarrow Q+X}|^2} = \frac{\lambda^2 \kappa \hat{s}}{M_Q^2} e^{a|y|} \begin{cases} e^{-\kappa \frac{p_T^2}{M_Q^2}} & \text{if } p_T \leq \langle p_T \rangle \\ e^{-\kappa \frac{\langle p_T \rangle^2}{M_Q^2}} \left(1 + \frac{\kappa}{n} \frac{p_T^2 - \langle p_T \rangle^2}{M_Q^2} \right)^{-n} & \text{if } p_T > \langle p_T \rangle \end{cases}$$

- ▶ κ , λ , $\langle p_T \rangle$, n and a fitted to pp data for each final state separately and fixed in an nuclear PDF fit

Impact of heavy quark(-onia) production

[Düwentester, T], Klasen et al., '22]

- Pb^{208} results compared to our previous results

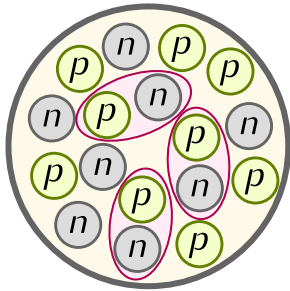


Impressive
reduction of
gluon PDF
uncertainty

Short-Range–Correlation inspired A dependence

[Deniston, TJ, Kusina et al., '22/23]

- Short-Range–Correlation (SRC) model of the nuclear structure:



$$f_i^{p/A}(x, \mu, A) = z(A)(f_i^p)^{\text{src}}(x, Q) + [1 - z(A)]f_i^p(x, Q)$$

$$f_i^{n/A}(x, \mu, A) = n(A)(f_i^n)^{\text{src}}(x, Q) + [1 - n(A)]f_i^n(x, Q)$$

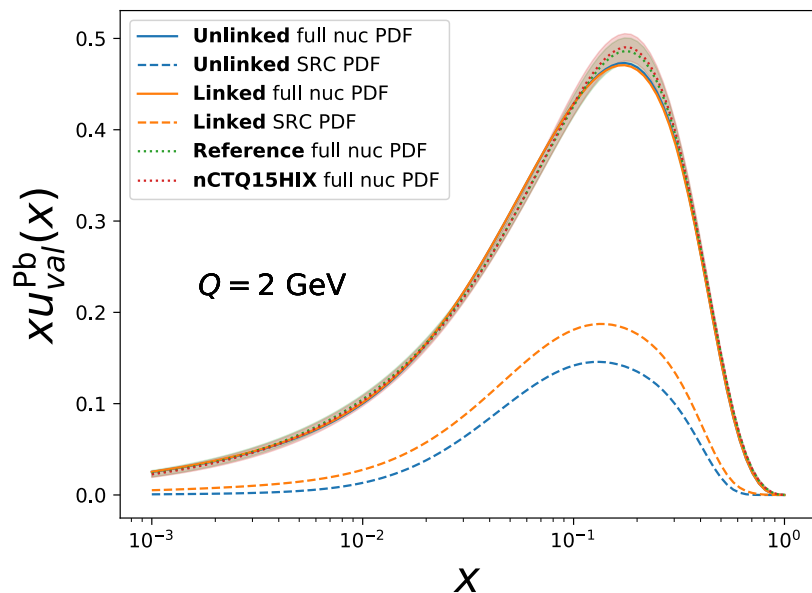
$$f_i(x, \mu, A) = \frac{Z}{A}f_i^{p/A}(x, \mu, A) + \frac{N}{A}f_i^{n/A}(x, \mu, A)$$

- ▶ $f^{p(n)}$: proton (neutron) PDF (fixed)
- ▶ $(f^{p(n)})^{\text{src}}$: SRC pair PDF and its isopartner (p fitted, n tied)
- ▶ $z(A)$ and $n(A)$ fractions of SRC pairs (fitted independently or tied)
- ▶ There is only one and universal $(f^p)^{\text{src}}$ PDF (x dep., no A dep.)
- ▶ One z (and opt. one n) fraction per nucleus (A dep., no x dep.)
- ▶ In the original nCTEQ parametrization x and A dependences do not factorize

Short-Range–Correlation inspired A dependence

[Deniston, TJ, Kusina et al., '22/23]

- Fit with the new parametrization obtains a very good description of data:



preliminary

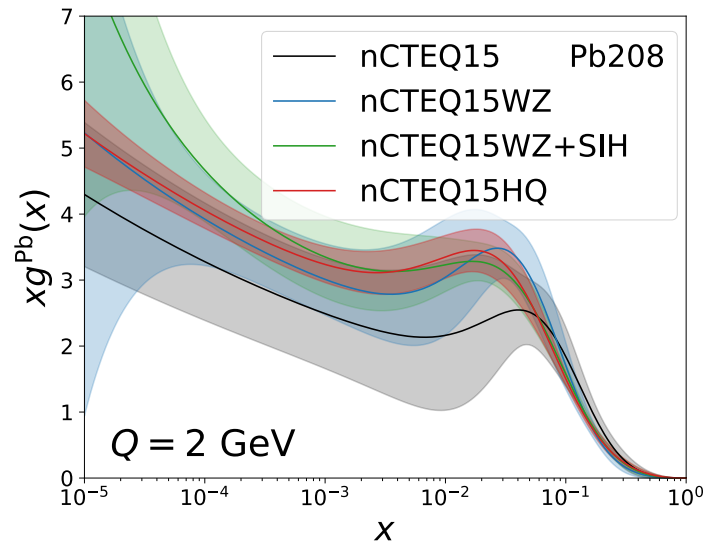
- Same nuclear PDFs as before, but ...
- Now we also extract z fractions and compare them to quasi elastic scattering data
- How does this affect low x ?

Summary

- Introduced collinear factorization & PDFs as measure of proton structure
- Discussed some basic properties of PDFs
- Shown the nuclear modification fractions & how to incorporate it into nPDFs
- Selection of recent global nPDF analyses:

[Düwentester, TJ, Klasen et al., '22]

[Deniston, TJ, Kusina et al., '2X]

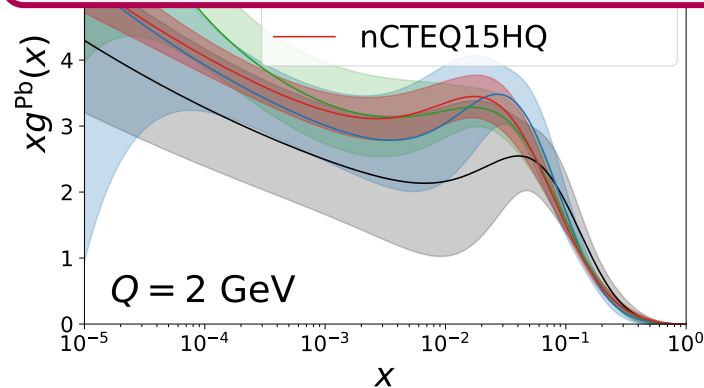


preliminary

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preliminary