Nuclear PDFs from the nCTEQ collaboration

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Structure of nuclei

- First approximation: nuclei consist of **free** protons and neutrons **does not work**

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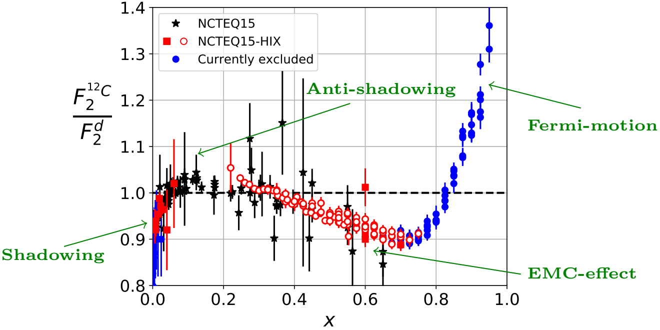

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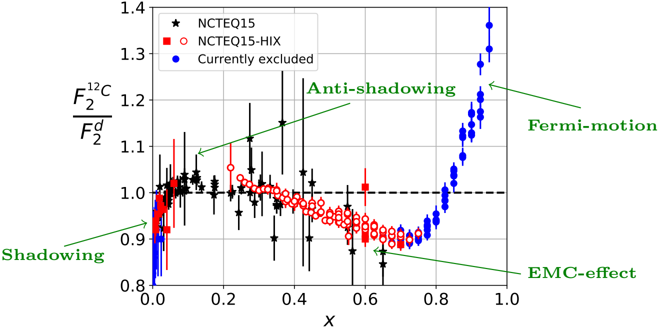


- Can we translate this modifications into ***universal*** quantities – **nuclear PDFs** (nuclear Parton Distribution Functions)?

Collinear factorization

- Can we translate this modifications into ***universal*** **nuclear PDFs**?
- Natural theoretical framework: **collinear factorization**

DY-like processes

$$d\sigma_{pp\to l\bar{l}X} = \sum_{i,j=q,\bar{q},g} f_i(x_1,\mu) \otimes f_j(x_2,\mu) \otimes d\hat{\sigma}_{ij\to l\bar{l}X} + \mathcal{O}\left(\frac{\Lambda^2_{\rm QCD}}{Q^2}\right)$$

DIS-like processes

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

- **Parton-level cross-section**
  - process-dependent
  - perturbative (calculable order by order in α_S)
- **Nuclear PDFs**
  - universal
  - non-perturbative (not calculable)

Assumptions entering nuclear PDF analyses

Factorization

- allow for definition of **universal PDFs**
- **DGLAP** evolution equations
- make the formalism **predictive**
- needed even if it is broken

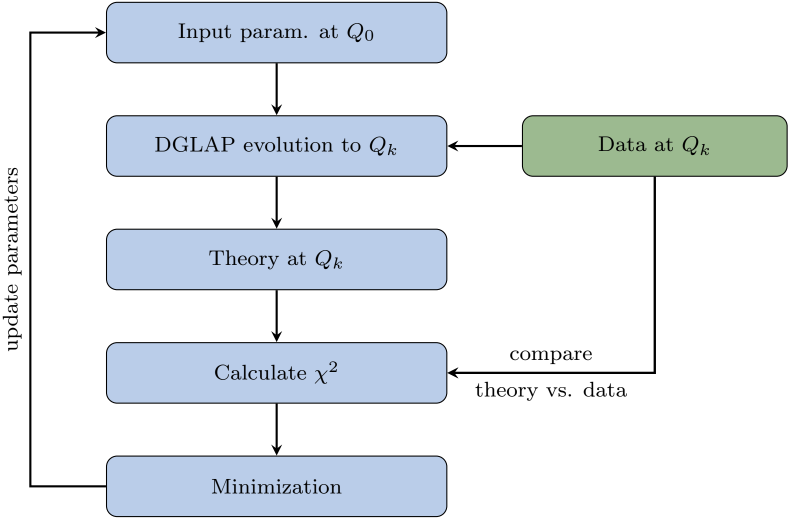
Isospin symmetry

$$\begin{cases} u^{n/A}(x) = d^{p/A}(x) \\ d^{n/A}(x) = u^{p/A}(x) \end{cases} \quad \text{where} \quad f_i^{(A,Z)} = \frac{Z}{A} f_i^{p/A} + \frac{A-Z}{A} f_i^{n/A}$$

Neglect contributions from $x > 1$

- same *evolution equations*
- *sum rules* as the free proton PDFs

Schematics of Global Analysis



Schematics of Global Analysis

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

$$f_i^{(A,Z)}(x,Q) = \frac{Z}{A} f_i^{p/A}(x,Q) + \frac{A-Z}{A} f_i^{n/A}(x,Q)$$
$$f_i^{p/A}(x,Q_0) = f_i^{p/A}(x; c_0, c_1, \ldots) = c_0 x^{c_1} (1-x)^{c_2} P(x; c_3, \ldots)$$

with $c_j = c_j(A) \overset{\text{nCTEQ}}{=} p_k + a_k \left(1 - A^{-b_k}\right)$ depending on the nuclei;
$f_i^{n/A}(x,Q)$ - from isospin symmetry.

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3. Use DGLAP equation to evolve $f_i(x,\mu)$ from $\mu = Q_0$ to $\mu = Q_{\max}$.
4. Calculate theory predictions corresponding to the data (σ_{DIS}, σ_{DY}, etc.).
5. Calculate appropriate χ^2 function – compare data and theory

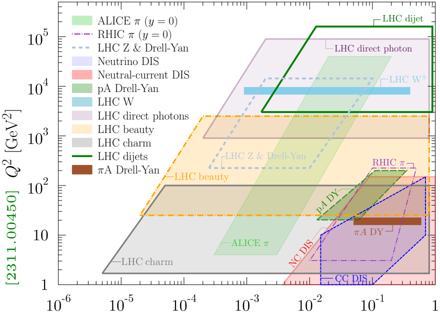
$$\chi^2(\{c_i\}) = \sum_{\text{data points}} \left(\frac{\text{data} - \text{theory}(\{c_i\})}{\text{uncertainty}} \right)^2$$

6. Minimize χ^2 function with respect to parameters $c_0, c_1, \ldots$
7. Compute uncertainties (Hessian, Monte Carlo)

Comparison of available nPDFs

	KSASG20 PRD 104, 034010	TUJU21 PRD 105, 094031	EPPS21 EPJC 82, 413	nNNPDF3.0 EPJC 82, 507	nCTEQ15HQ PRD 105, 114043
lA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓	✓	✓	✓	
pA Drell-Yan	✓		✓	✓	✓
πA Drell-Yan			✓		
RHIC dAu π			✓		✓
LHC pPb π, K					✓
LHC pPb W/Z		✓	✓	✓	✓
LHC pPb dijet			✓	✓	
LHC pPb HQ			✓ GMVFNS	✓ FO+PS(rew)	✓ ME fit
LHC quarkonium					✓ ME fit
LHC pPb γ				✓	

	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15HQ
Kinematic cuts	$Q > 1.3$ (				$Q > 2$GeV $W > 3.5$GeV $p_T^{HQ(SIH)} > 3$ GeV
No data points	4335				1496
No free param.	9				19
χ^2/dof	1.06(1.0				0.86
Error analysis	Hessia				Hessian
$\Delta\chi^2$ tol.	20 (68% (				35
Proton baseline	CT18				~CTEQ6.1
Q_0 ini. scale	1.3 Ge				1.3 GeV
No flavours	3				5
Deuteron treat.	fitted				free
QCD order	**NLO & N**				**NLO**
HQ scheme	FONL				S-ACOT



Towards nCTEQ24/25

Recent nCTEQ results

- Last full nPDF release: **nCTEQ15** [PRD 93, 085037 (2016)]
  - DIS NC data
  - fixed-target DY data
  - pion data from RHIC
- Updates on the way to new release
  - **nCTEQ15WZ** [EPJC 80, 968 (2020)]
    - LHC W/Z data
    - constraints on *gluon* and *strange* nPDFs
  - **nCTEQ15HIX** [PRD 103, 114015 (2021); Prog.Part.Nucl.Phys. 136 (2024) 104096]
    - JLAB DIS data
    - constraints at high-x
    - theoretical corrections: TMC, HT, deuteron
  - **nCTEQ15SIH** [PRD 104 (2021) 9, 094005]
    - LHC & RHIC SIH data
    - constraints on *gluon* nPDF
  - **nCTEQ15neutrino** [PRD 106 (2022) 7, 074004]
    - DIS neutrino data (NuTeV, CHORUS, CDHSW, dimuons)
    - compatibility of NC & CC DIS
    - flavour separation
  - **nCTEQ15HQ** [PRL 121, 052004 (2018); PRD 105 (2022) 11, 114043]
    - LHC & RHIC HF data
    - constraints on low-x *gluon* nPDF
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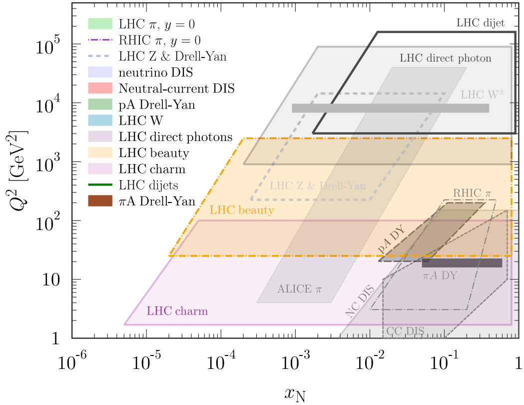
- New data compared to nCTEQ15WZ+SIH ($p_T > 3$ GeV): D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$



	N_{data}	N_{params}	Observables
EPPS21	2029+48	24	(ν)DIS, DY, SIH, W/Z, dijet, D
nNNPDF3.0	2151+37	256	(ν)DIS, DY, W/Z, dijet, γ, D
nCTEQ15HQ	936+548	19	DIS, DY, SIH, W/Z D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$

Heavy Quarks (HQ) - Theoretical approaches

Schemes for the calculation of **Open Heavy Quark** production (D, B mesons):

- **FFNS**: HQ present only in final state. Valid for small p_T.
- **ZM-VFNS**: HQ treated as massless, but included in PDFs. Valid at large p_T.
- Schemes interpolating between the two:
  - **FONLL**: $d\sigma_{\text{FONLL}} = d\sigma_{\text{FFNS}} + (d\sigma_{\text{ZMVFNS}} - d\sigma_{\text{FFNS},0}) \times G(m_Q, p_T)$,
  - **GM-VFNS**: Massive heavy quarks included in the PDFs for $\mu_f > \mu_T$.

Different schemes for the calculation of **Quarkonium** production:

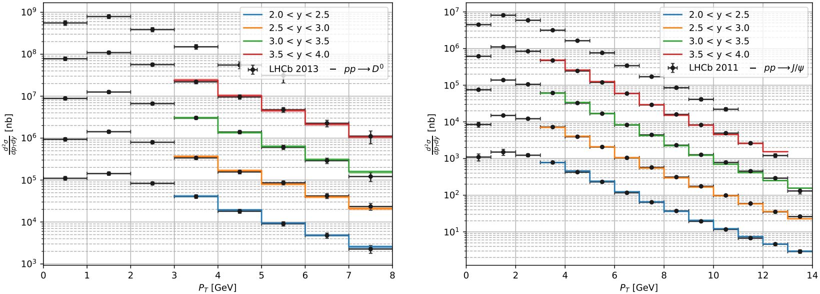
- **Color-evaporation model**: hard scattering creates $Q\bar{Q}$-pair, which radiates gluons until it hadronizes
- **Color-singlet model**: Intermediate state is a color neutral $Q\bar{Q}$-pair
- **Non-relativistic QCD**: separation of short and long distance physics through expansion in velocity

$$\sigma(AB \to \mathcal{Q} + X) = \int \mathrm{d}x_1\, \mathrm{d}x_2 f_{1,g}(x_1)\, f_{2,g}(x_2)\, \frac{1}{2\hat{s}} \overline{|\mathcal{A}_{gg\to Q} + X|^2} \mathrm{dLIPS}$$

- Crystal-Ball parametrization extended to include rapidity dependence (a param.)

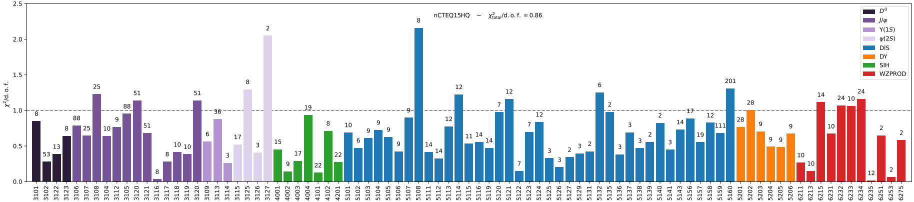
$$\overline{|\mathcal{A}_{gg\to Q+X}|^2} = \frac{\lambda^2 \kappa \hat{s}}{M_{\mathcal{Q}}^2} \begin{cases} e^{-\kappa \frac{p_T^2}{M_Q^2} + a|y|} & \text{if } p_T \leq \langle p_T \rangle \\ e^{-\kappa \frac{\langle p_T \rangle^2}{M_Q^2} + a|y|} \left(1 + \frac{\kappa}{n} \frac{p_T^2 - \langle p_T \rangle^2}{M_Q^2}\right)^{-n}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

- Very good agreement between data and fitted theory

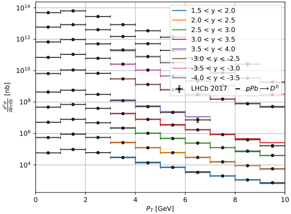


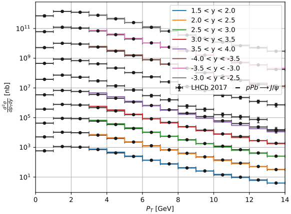
nCTEQ15HQ *p*Pb data description [PRD 105 (2022) 11, 114043]

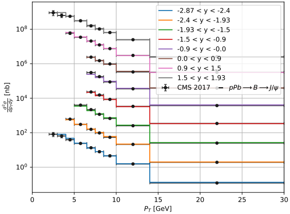
χ^2 for nCTEQ15HQ with 548 new HF data points:



Example *p*Pb data description:







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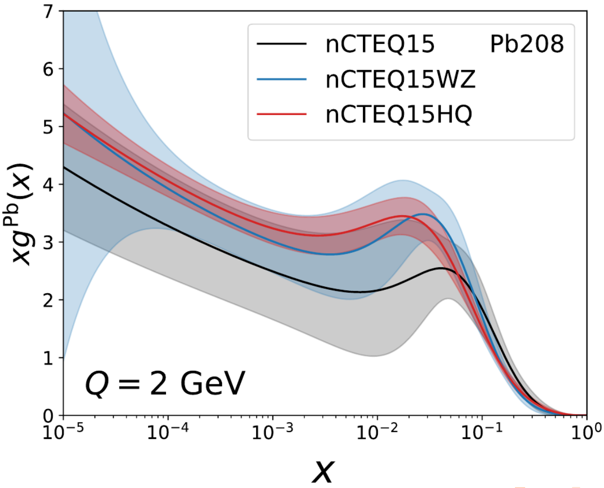
- Predictions for heavy quark(onium) data done with data-driven method [PRL 121 (2018) 052004; PRL107, 082002 (2011); EPJC77, 1 (2017)]



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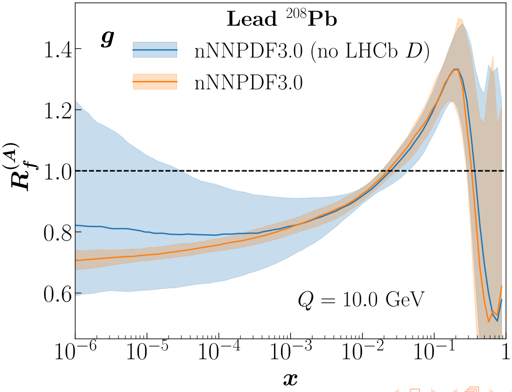
- Similar situation for nNNPDF3.0 [EPJC 82 (2022) 6, 507] where only D data were used



Towards nCTEQ24/25

- New nPDF release: **nCTEQ24/25** will combine the previous analyses:
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    - fixed-target DY data
    - pion data from RHIC
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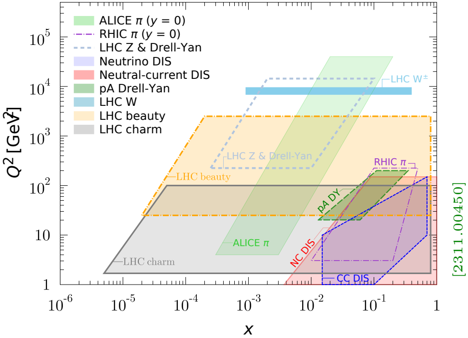
- Data: NC DIS, CC DIS (+dimuon), FT DY, pPb LHC: W/Z, SIH, HQ, RHIC SIH ($\sim$ 3500 data points)



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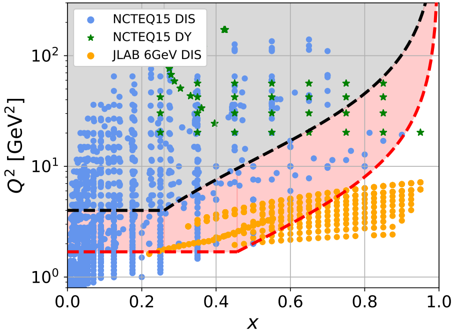

nCTEQ15

$Q > 2$ GeV $W > 3.5$ GeV
$N_{\text{data}} = 708$

nCTEQ15HIX

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

Requires proper treatment of:

- **deuteron corrections**
- **target mass corrections** (TMCs) [Prog.Part.Nucl.Phys. 136 (2024) 104096]
- **higher twist effects**

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- New proton baseline from CJ15 PDFs [PRD 93, 114017 (2016)]

- New PDF parametrization:

$$xf_i(x, Q_0^2) = c_0 x^{c_1} (1-x)^{c_2} \left(1 + c_3\sqrt{x} + c_4 x + c_5 \sqrt{x}^3\right) \qquad i = u_v, d_v, g, \bar{u}+\bar{d}$$

$$\bar{d}/\bar{u}(x, Q_0) = a_0 x^{c_1} (1-x)^{c_2} + 1 + c_3 x (1-x)^{c_4}$$

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$$\bar{d}/\bar{u}(x,Q_0) = a_0 x^{c_1}(1-x)^{c_2} + 1 + c_3 x(1-x)^{c_4}$$

  with updated A-dependence:

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

$$\Downarrow$$

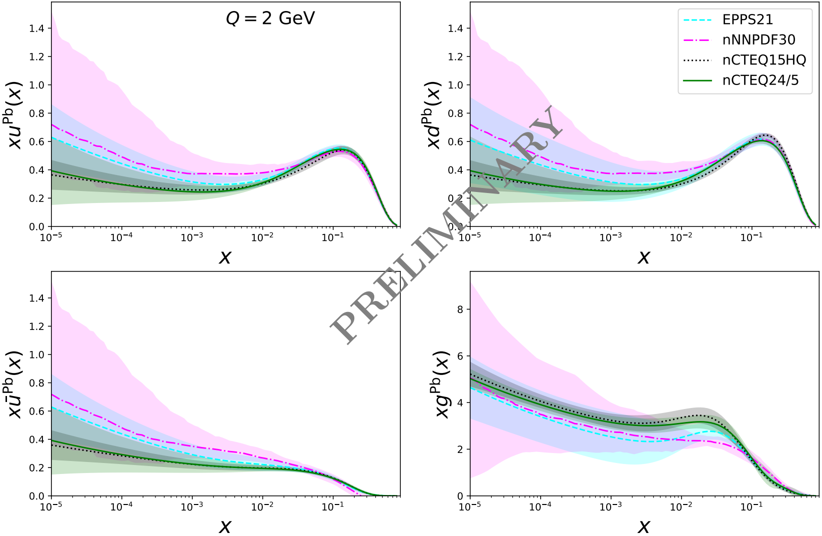
NEW: $c_k(A) \equiv p_k + a_k \ln(A) + b_k \ln^2(A)$

- Other details

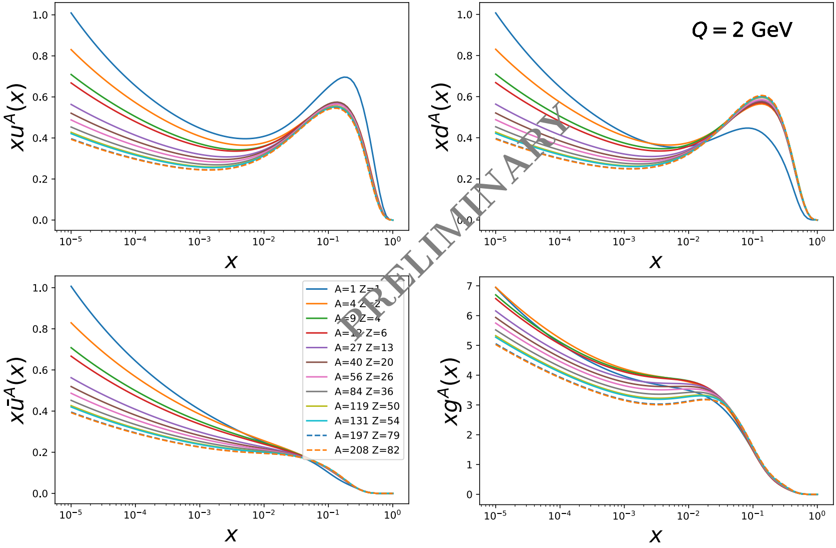
  order: NLO QCD, HQ scheme: SACOT-χ, 30 free parameters, errors: Hessian

Preliminary results: PDFs

- Good agreement with previous nCTEQ PDFs and with EPPS21 & nNNPDF3.0 in the data region.
- Reduced gluon uncertainty (HQ data).



Preliminary results: *A*-dependence



Summary

Summary

- I introduced basics of nPDFs and their determination.
- I reviewed recent nCTEQ results going towards new global release.
- The pPb LHC data have provided crucial information about nPDFs
  - extending kinematic coverage down to $x \sim 10^{-5}$ (before $x \gtrsim 10^{-2}$)
  - gluon distribution (Heavy-quark(-onium), W/Z)
  - flavour separation (W/Z + neutrino DIS)
  - strange quark (W/Z + neutrino DIS, NC DIS)

  but caution is needed as some data can be affected by final state effects.
- I presented preliminary results of new **nCTEQ24/5** nPDF analysis and compared them to other nuclear PDFs.