Nuclear Parton Distribution Functions

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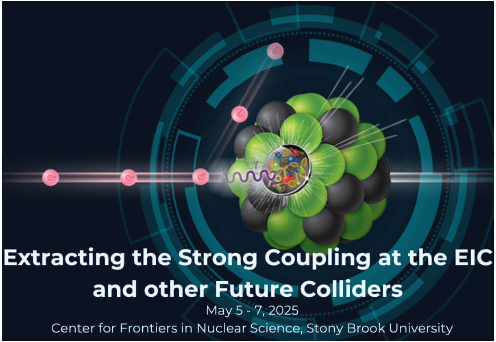
Thanks to: K. Greve, T. Jezo, M. Klasen, F.I. Olness, J. Wissmann



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Structure of nuclei

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

$$F_2^A(x) \neq Z F_2^p(x) + N F_2^n(x)$$

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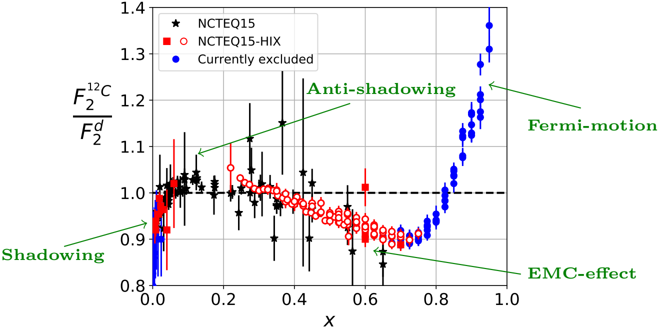

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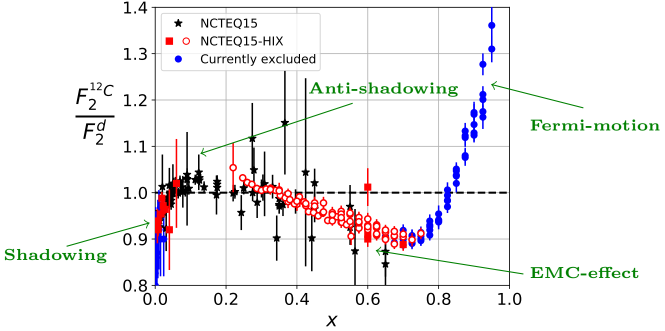


- Can we translate this modifications into ***universal*** quantities – **nuclear PDFs** (nuclear Parton Distribution Functions)?

Collinear factorization

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

DY-like processes

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

DIS-like processes

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

- **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

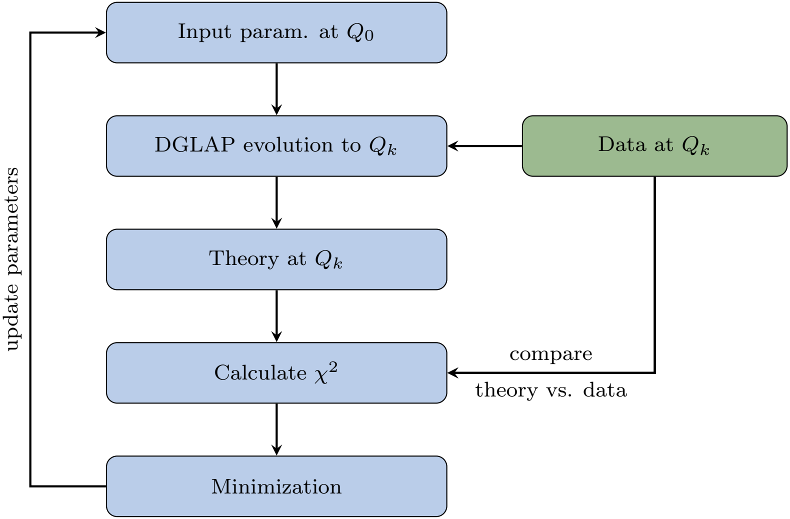
Isospin symmetry

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

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 $\mu = Q_0 \sim 1\text{GeV}$:

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

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 $\mu = Q_{\text{max}}$.
4. Calculate theory predictions corresponding to the data (σ_{DIS}, σ_{DY}, etc.).
5. Calculate appropriate χ^2 function – compare data and theory

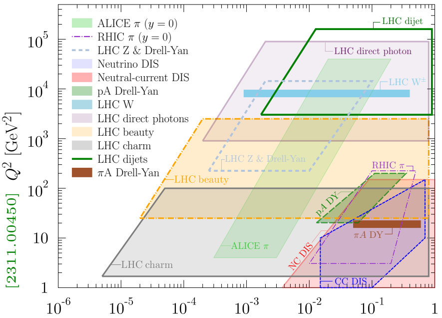
$$\chi^2(\{c_i\}) = \sum_{\text{data points}} \left(\frac{\text{data} - \text{theory}(\{c_i\})}{\text{uncertainty}}\right)^2$$

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				✓	

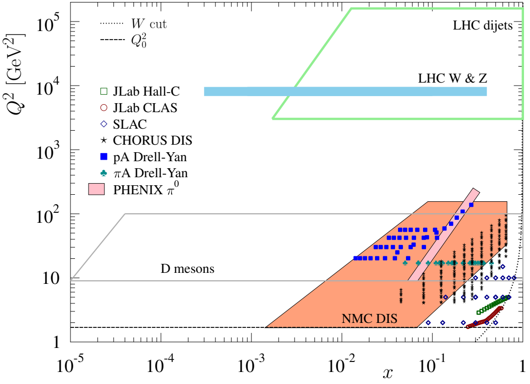
	KSASG20	nCTEQ15HQ
Kinematic cuts	$Q > 1.3$ (	$Q > 2$GeV $W > 3.5$GeV $p_T^{HQ(SIH)} > 3$ GeV
No data points	4335	1496
No free param.	9	19
χ^2/dof	1.06(1.0	0.86
Error analysis	Hessiar	Hessian
$\Delta\chi^2$ tol.	20 (68% (	35
Proton baseline	CT18	~CTEQ6.1
Q_0 ini. scale	1.3 Ge'	1.3 GeV
No flavours	3	5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



Updates from EPPS

EPPS21 vs. EPPS16

- New data compared to EPPS16:
  - LHC pPb D-meson data from LHCb (Run I)
  - LHC pPb $W^{\pm}$ data from CMS (Run II)
  - LHC pPb double-differential dijet data from CMS (Run I)
  - JLAB DIS data from Hall C and CLAS



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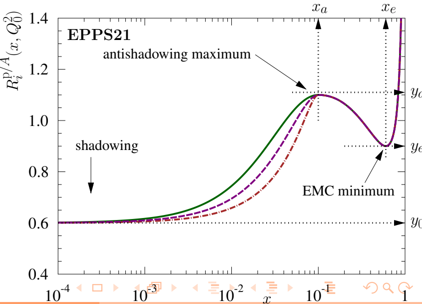
- New parametrization (24 free parameters vs. 20)

$$R_i^A(x, Q_0^2) = \begin{cases} a_0 + a_1(x - x_a)\left[e^{-xa_2/x_a} - e^{-a_2}\right], & x \le x_a \\ b_0 x^{b_1}(1-x)^{b_2} e^{xb_3}, & x_a \le x \le x_e \\ c_0 + c_1(c_2 - x)(1-x)^{-\beta}, & x_e \le x \le 1 \end{cases}$$

$$y_i(A) = 1 + \left[y_i(A_{\mathrm{ref}}) - 1\right]\left(\frac{A}{A_{\mathrm{ref}}}\right)^{\gamma_i}$$



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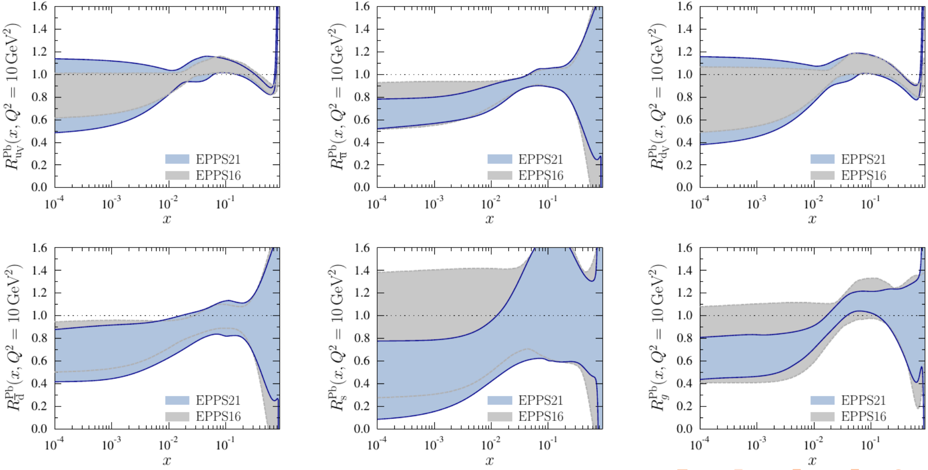
- Account for the uncertainties of the proton baseline

- Tolerance criterion $\Delta\chi^2 \simeq 33$ (compared to 50)

- Inclusion of $W > 1.8$ GeV cut for DIS data

EPPS21 vs. EPPS16 [EPJC 82 (2022) 5, 413]

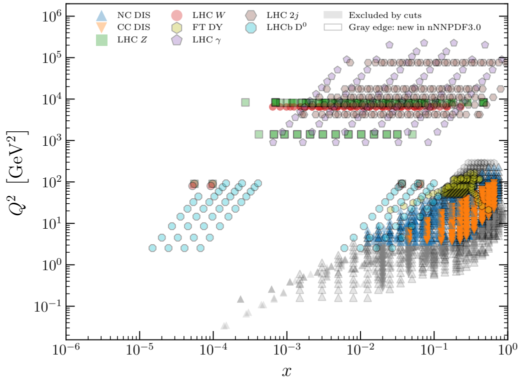
- New data compared to EPPS16:
  JLAB DIS, CMS W from pPb @8TeV, CMS dijet, LHCb D^0
- D meson data from LHCb at $\sqrt{s} = 5$ TeV [JHEP 1710 (2017) 090]
- Predictions for D meson (double differential in p_T and y) calculated in version of GM-VFNS scheme [JHEP 05 (2018) 196]



Updates from nNNPDF

nNNPDF3.0 vs. nNNPDF2.0

- New data compared to nNNPDF2.0:
  - LHC pPb D-meson data from LHCb (Run I)
  - LHC pPb prompt γ from ATLAS (Run II)
  - LHC pPb Z data from CMS (Run II), ALICE (Run I, Run II), LHCb (Run I)
  - LHC pPb $W^{\pm}$ data from ALICE (Run I)
  - LHC pPb dijet data from CMS (Run I)
  - NC DIS data for deuteron



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- Methodological updates
  - Proton boundary condition imposed at $x = 10^{-6}$ (instead of $x = 10^{-3}$)
  - New proton baseline
  - Hyperparameter optimisation (NN architecture, etc.)

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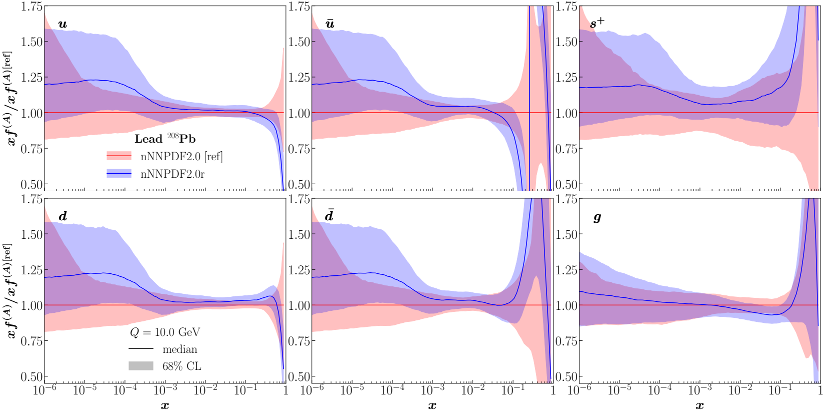

nNNPDF3.0 [EPJC 82 (2022) 6, 507]

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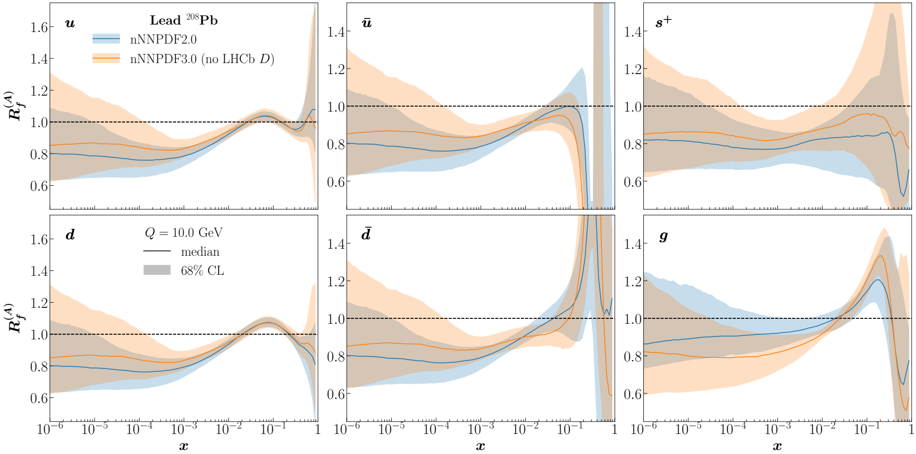
- D meson data from LHCb at $\sqrt{s} = 5$ TeV [JHEP 1710 (2017) 090]
- Predictions for D meson in FFNS done in POWHEG+PYTHIA included using **PDF reweighting**



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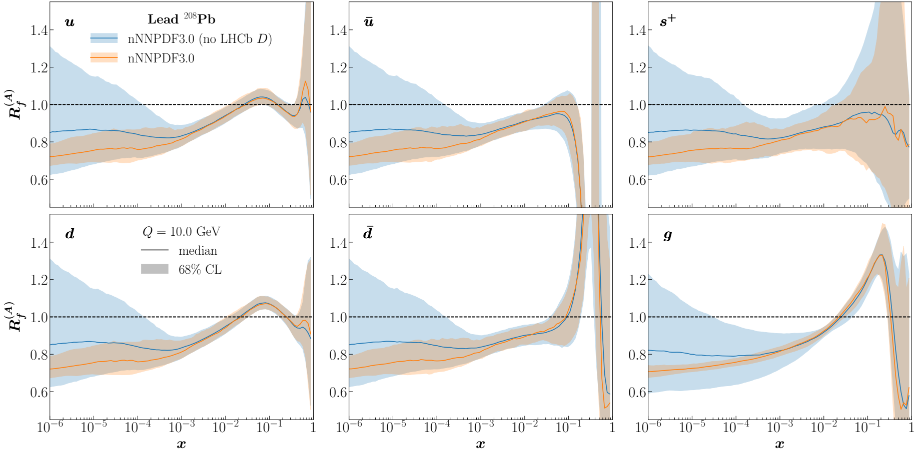

Updates from nCTEQ

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
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  - **nCTEQ15neutrino** [PRD 106 (2022) 7, 074004]
    - DIS neutrino data (NuTeV, CHORUS, CDHSW, dimuons)
    - compatibility of NC & CC DIS
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  - **nCTEQ15HQ** [PRL 121, 052004 (2018); PRD 105 (2022) 11, 114043]
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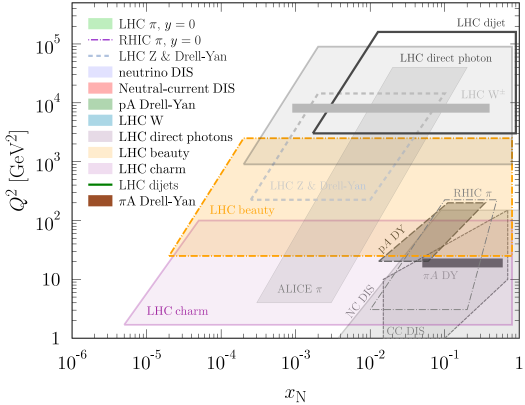
- New data compared to nCTEQ15WZ+SIH ($p_T > 3$ GeV): D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$



	$N_{\rm data}$	$N_{\rm params}$	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**: $d\sigma_{\mathrm{FONLL}} = d\sigma_{\mathrm{FFNS}} + (d\sigma_{\mathrm{ZMVFNS}} - d\sigma_{\mathrm{FFNS},0}) \times G(m_Q, p_T)$,
  - **GM-VFNS**: Massive heavy quarks included in the PDFs for $\mu_f > \mu_T$.

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

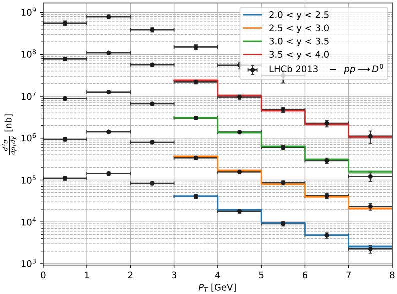
- **Color-evaporation model**: hard scattering creates $Q\bar{Q}$-pair, which radiates gluons until it hadronizes
- **Color-singlet model**: Intermediate state is a color neutral $Q\bar{Q}$-pair
- **Non-relativistic QCD**: separation of short and long distance physics through expansion in velocity

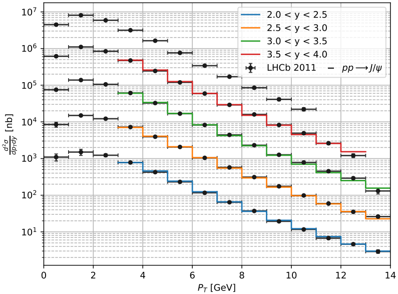
$$\sigma(AB \to \mathcal{Q} + X) = \int \mathrm{d}x_1\, \mathrm{d}x_2 f_{1,g}(x_1)\, f_{2,g}(x_2)\, \frac{1}{2\hat{s}} \overline{\left|\mathcal{A}_{gg\to Q} + X\right|^2} \mathrm{dLIPS}$$

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

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

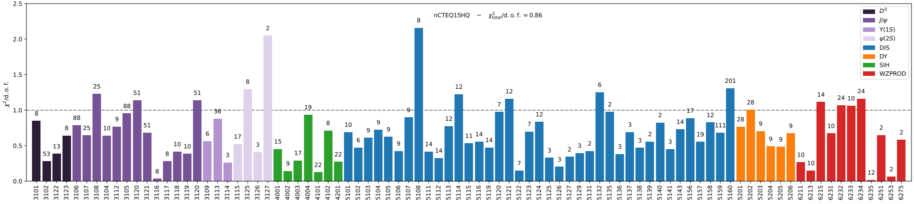
- Very good agreement between data and fitted theory



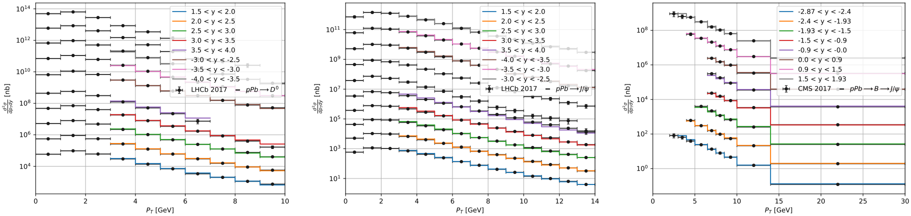


nCTEQ15HQ *p*Pb data description [PRD 105 (2022) 11, 114043]

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



Example *p*Pb data description:



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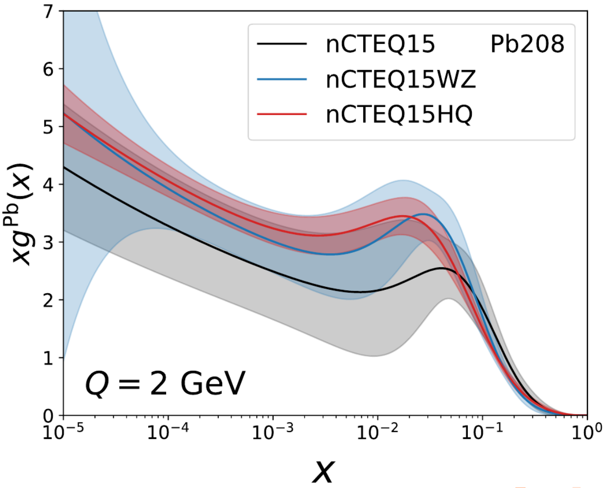
- New data compared to nCTEQ15WZ+SIH:
  D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$
- Predictions for heavy quark(onium) data done with data-driven method [PRL 121 (2018) 052004; PRL107, 082002 (2011); EPJC77, 1 (2017)]



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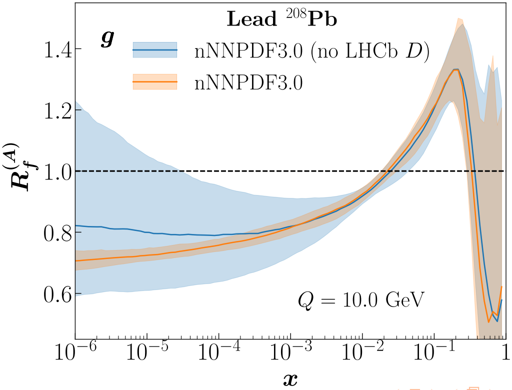
- Similar situation for nNNPDF3.0 [EPJC 82 (2022) 6, 507] where only D data were used



Towards nCTEQ25

- New nPDF release: **nCTEQ25** will combine the previous analyses:
  - **nCTEQ15** [PRD 93, 085037 (2016)]
    - DIS NC data
    - fixed-target DY data
    - pion data from RHIC
  - **nCTEQ15WZ** [EPJC 80, 968 (2020)]
    - LHC W/Z data
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  - **nCTEQ15HIX** [PRD 103, 114015 (2021); Prog.Part.Nucl.Phys. 136 (2024) 104096]
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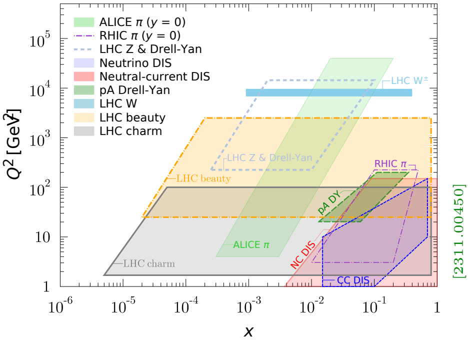
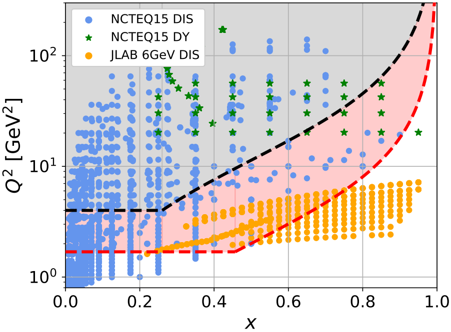
- Data: NC DIS, CC DIS (+dimuon), FT DY, *p*Pb LHC: W/Z, SIH, HQ, RHIC SIH ($\sim$ 3500 data points)



Towards nCTEQ25

- Data: NC DIS, CC DIS (+dimuon), FT DY, pPb LHC: W/Z, SIH, HQ, RHIC SIH ($\sim$ 3500 data points)
- Extended kinematic cuts on Q^2 and $W^2 = Q^2 \frac{1-x}{x} + M_N^2$: $Q > 1.3$ GeV $W > 1.7$ GeV (earlier cuts: $Q > 2$ GeV $W > 3.5$ GeV)



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**

Towards nCTEQ25

- Data: NC DIS, CC DIS (+dimuon), FT DY, pPb LHC: W/Z, SIH, HQ, RHIC SIH ($\sim$ 3500 data points)

- Extended kinematic cuts on Q^2 and $W^2 = Q^2 \frac{1-x}{x} + M_N^2$: $Q > 1.3$ GeV $W > 1.7$ GeV (earlier cuts: $Q > 2$ GeV $W > 3.5$ GeV)

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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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  with updated A-dependence:

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

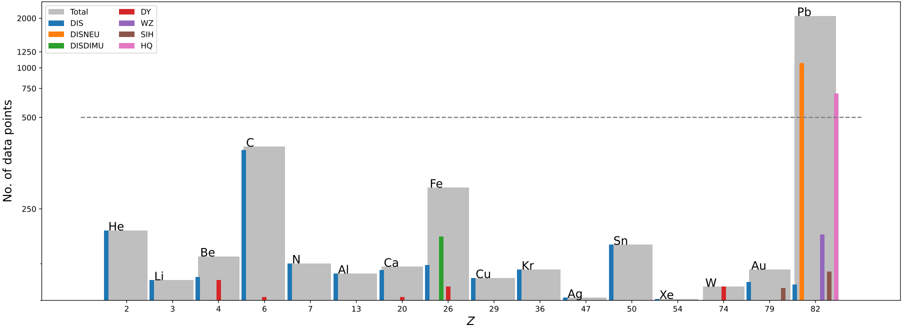
$$\Downarrow$$

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

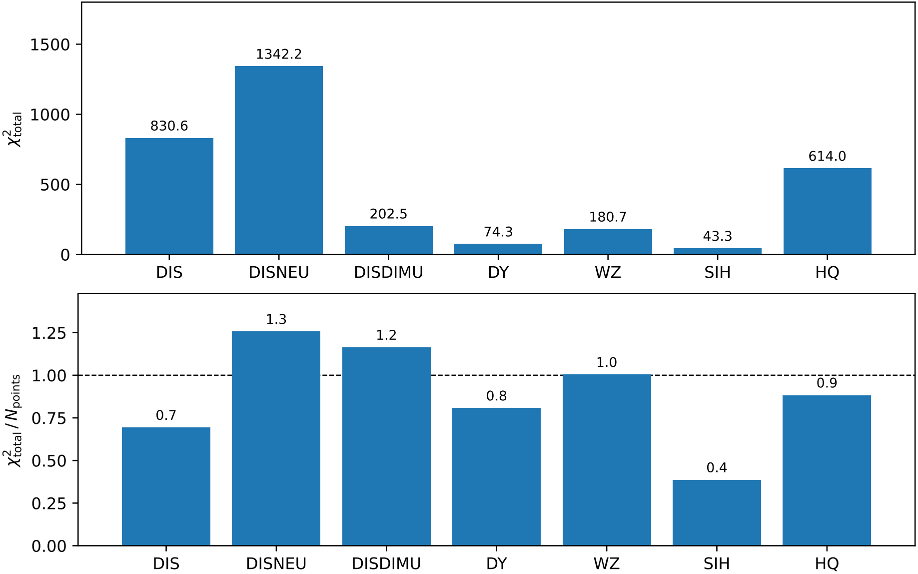
- Other details

  order: NLO QCD, HQ scheme: SACOT-χ, 32 free parameters, errors: Hessian ($T = 40$)

Experimental data

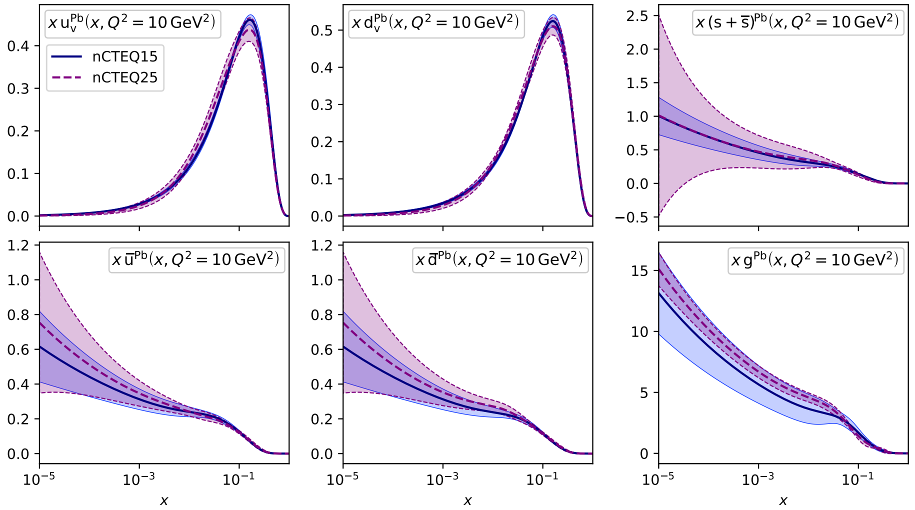


Preliminary results: χ^2 per experiment

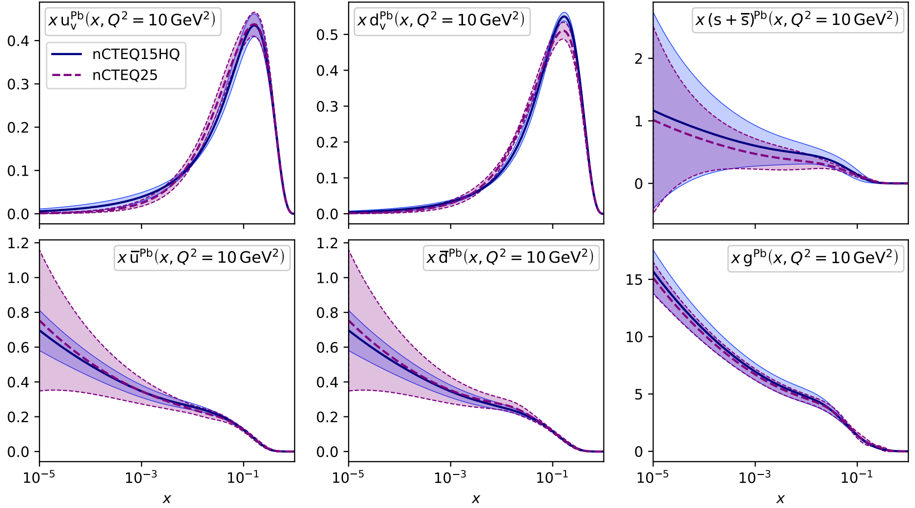


Fit quality: $N_{\text{data}} = 3518$, $\chi^2 = 3413$, $\chi^2/N_{\text{data}} = 0.98$

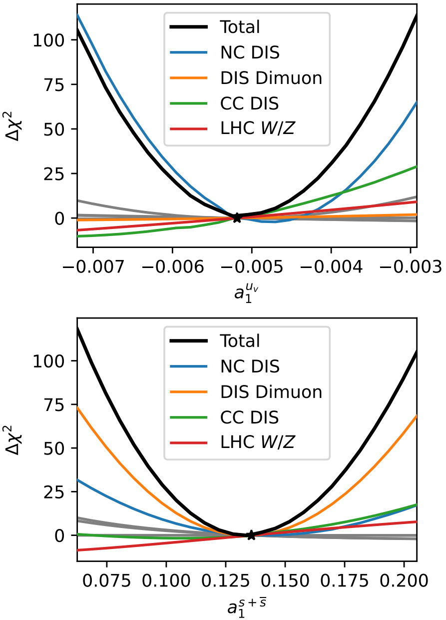
Preliminary results: Comparison with nCTEQ15



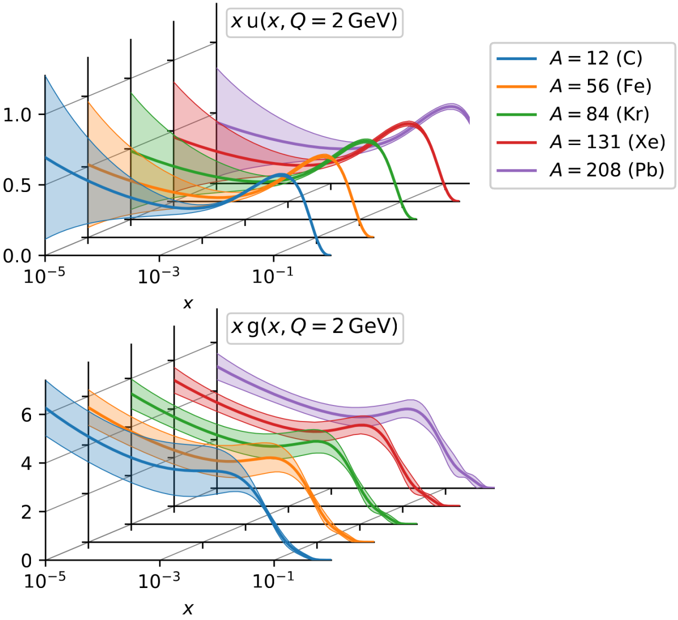
Preliminary results: Comparison with nCTEQ15HQ



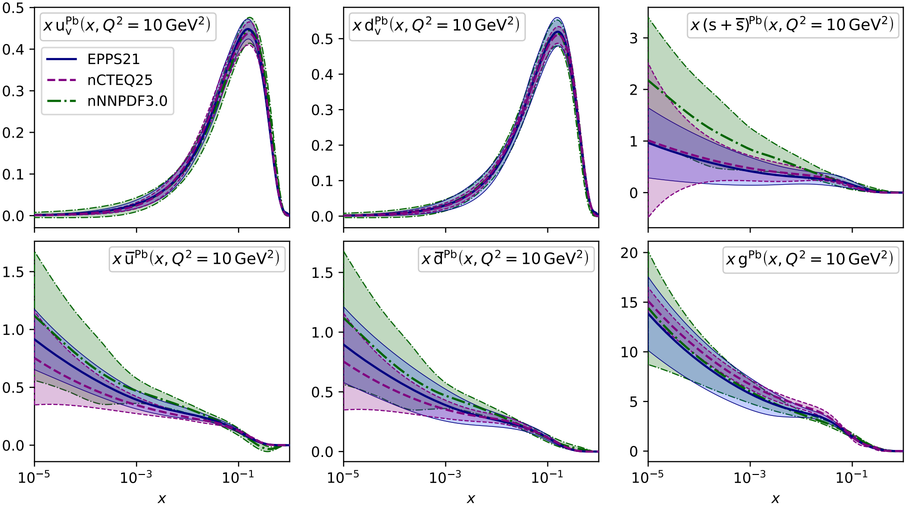
Preliminary results: χ^2 scans



Preliminary results: *A*-dependence



Preliminary results: Comparison with other global analyses



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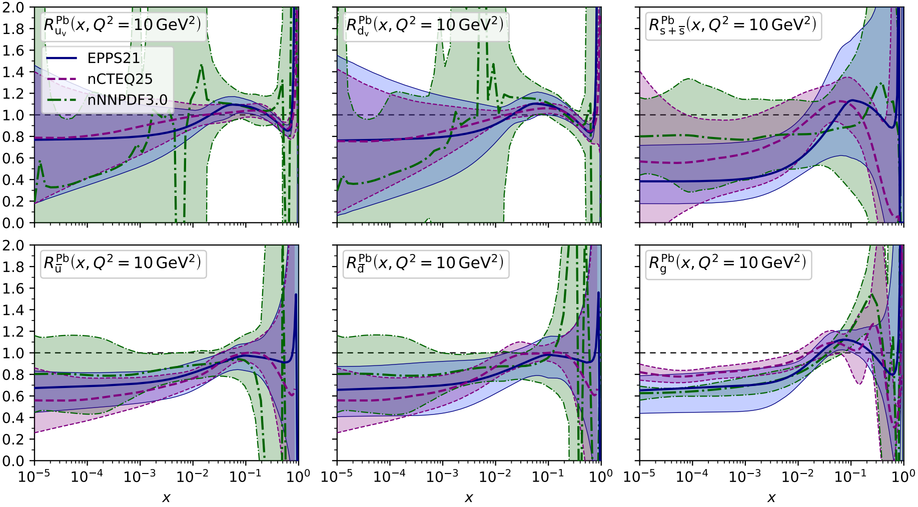

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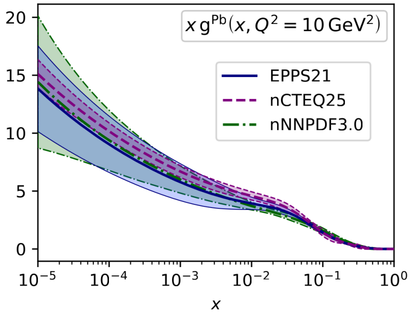

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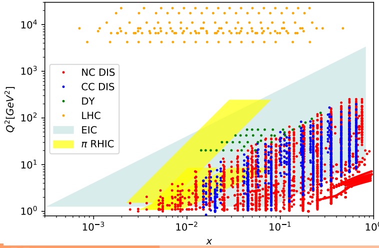

[NPA 1026 (2022) 122447]