Nuclear PDFs

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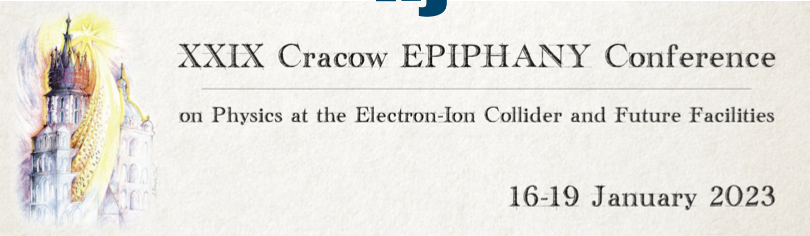

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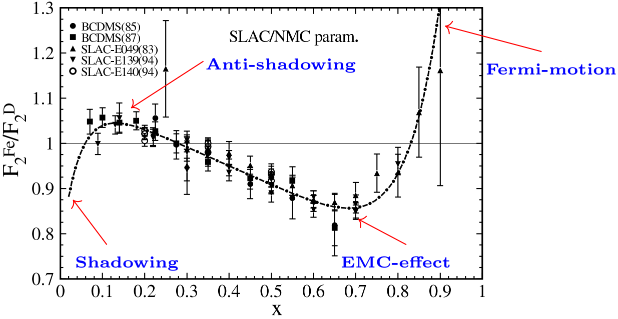
Introduction

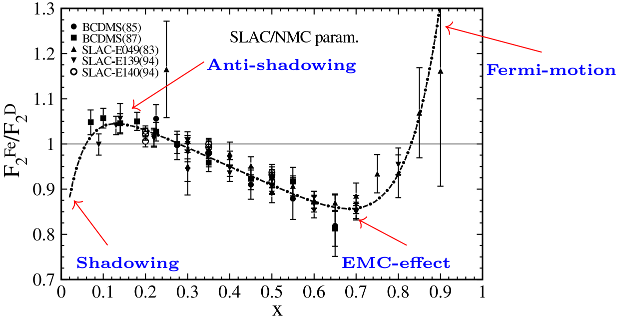
- Cross-sections in nuclear collisions are modified

$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$

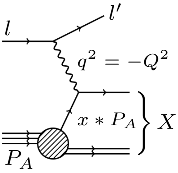


- Cross-sections in nuclear collisions are modified

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



- Working assumption: **factorization** = *universal* **nPDFs**



$$\frac{d^2\sigma}{dx dQ^2} = \sum_i f_i^A(x, Q^2) \otimes d\hat{\sigma}_{il\to l'X} + \mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{Q^2}\right)$$

- Do not consider any cold nuclear matter effects (e.g. energy loss).

Assumptions entering nuclear PDF analyses

Factorization & DGLAP evolution

- allow for definition of **universal PDFs**
- 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

1. Choose experimental data (e.g. DIS, DY, inclusive jet prod., etc.)
2. Parametrize **nuclear PDFs** at low initial scale $\mu = Q_0 = 1.3\text{GeV}$:

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

$$f_i^{p/A}(x, Q_0) = f_i^{p/A}(x; a_0, a_1, \dots) = a_0 x^{a_1}(1-x)^{a_2} P(x; a_3, \dots)$$

with $a_j = a_j(A) \overset{\text{nCTEQ}}{=} p_k + a_k\left(1 - A^{-b_k}\right)$ depending on the nuclei.

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_{DIS}, etc.).
5. Calculate appropriate χ^2 function – compare data and theory

$$\chi^2(\{a_i\}) = \sum_{\text{experiments}} w_n \chi_n^2(\{a_i\})$$

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

(by default $w_n = 1$)

6. Minimize χ^2 function with respect to parameters $a_0, a_1, \dots$

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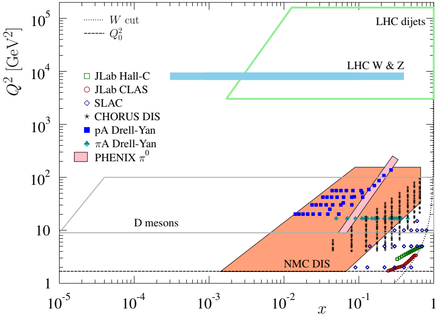
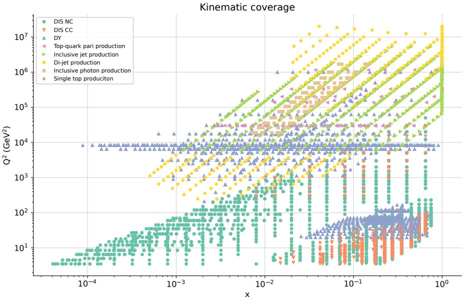
Differences with the free-proton PDFs

- Theoretical *status* of Factorization (no proof for pA or AA, final state effects)
- Higher-twists potentially enhanced
- Parametrization – more parameters to model A-dependence
- Fewer, less precise data with more restrictive kinematic coverage (no HERA, LHC very important):

EPPS21 $\sim$ 2000 **points**



NNPDF4.0 $\sim$ 5000 **points**



Recent data important for nPDF analyses

- LHC pPb $W/Z/DY$ production
- LHC pPb dijets
- LHC pPb heavy-quark(onia): D, B, J/ψ, ...
- LHC pPb SIH: inclusive pions, kaons, ...
- LHC pPb prompt γ
- JLAB DIS data from Hall C and CLAS

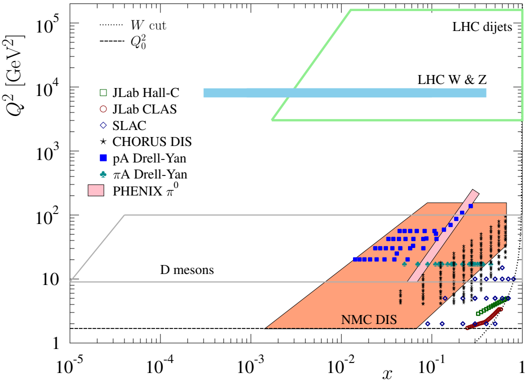
Comparison of available nPDFs

	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				✓	
Kinematic cuts	$Q > 1.3$ GeV	$Q > 1.87$ GeV $W > 3.5$ GeV	$Q > 1.3$ GeV $W > 1.8$ GeV $p_T^{HQ} > 3$ GeV	$Q > 1.87$ GeV $W > 3.5$ GeV	$Q > 2$GeV $W > 3.5$GeV $p_T^{HQ(SIH)} > 3$ GeV
No data points	4335	2410	2077	2188	1496
No free param.	9	16	24	256 (NN)	19
χ^2/dof	1.06(1.05)	0.94(0.84)	1.00	1.10	0.86
Error analysis	Hessian	Hessian	Hessian	Monte Carlo	Hessian
$\Delta\chi^2$ tol.	20 (68% CL)	50	35	N/A	35
Proton baseline	CT18	custom	CT18A	~NNPDF4.0	~CTEQ6.1
Q_0 ini. scale	1.3 GeV	1.3 GeV	1.3 GeV	1.0 GeV	1.3 GeV
No flavours	3	4	6	6	5
Deuteron treat.	fitted	fitted	free	fitted	free
QCD order	NLO & NNLO	NLO & NNLO	NLO	NLO	NLO
HQ scheme	FONLL	FONLL	S-ACOT	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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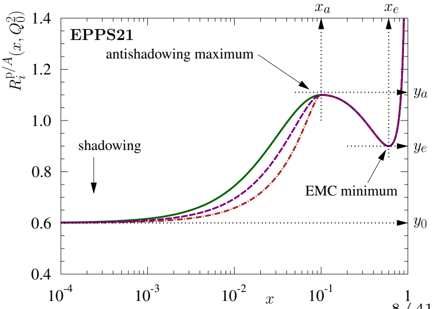
- New parametrization (24 free parameters vs. 20)

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

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



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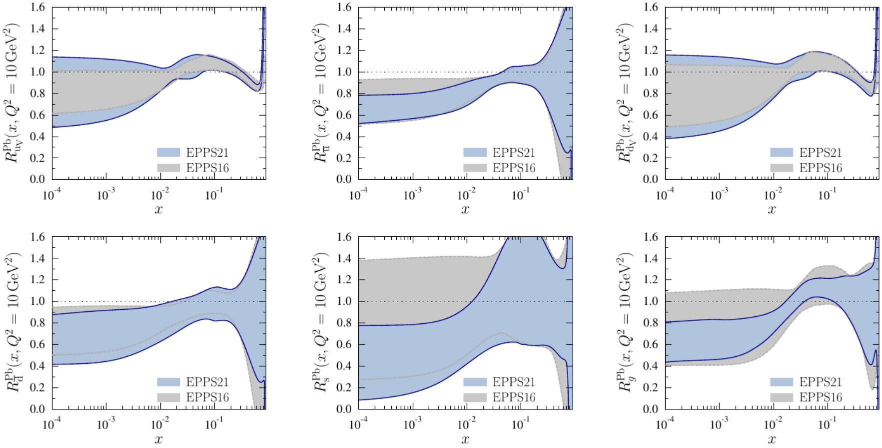
- Account for the uncertainties of the proton baseline
- Tolerance criterion $\Delta\chi^2 \simeq 33$ (compared to 50)
- Inclusion of $W > 1.8$ GeV cut for DIS data

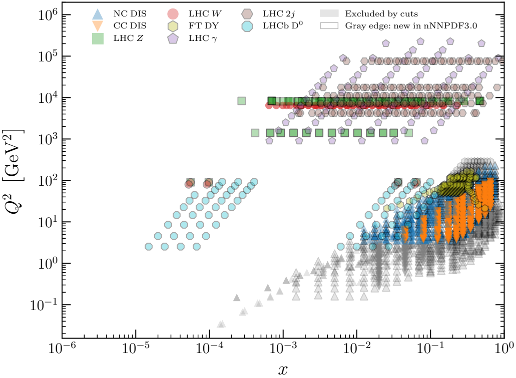
EPPS21 vs. EPPS16 [EPJC 82 (2022) 5, 413]

- 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

- 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



nNNPDF3.0 vs. nNNPDF2.0

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

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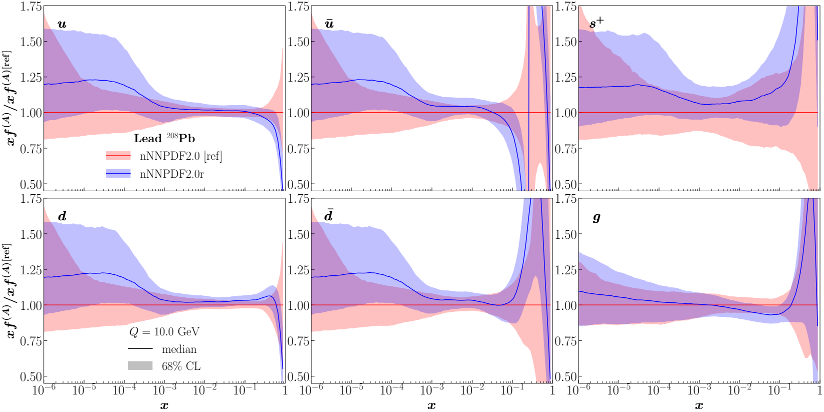

nNNPDF3.0 [EPJC 82 (2022) 6, 507]

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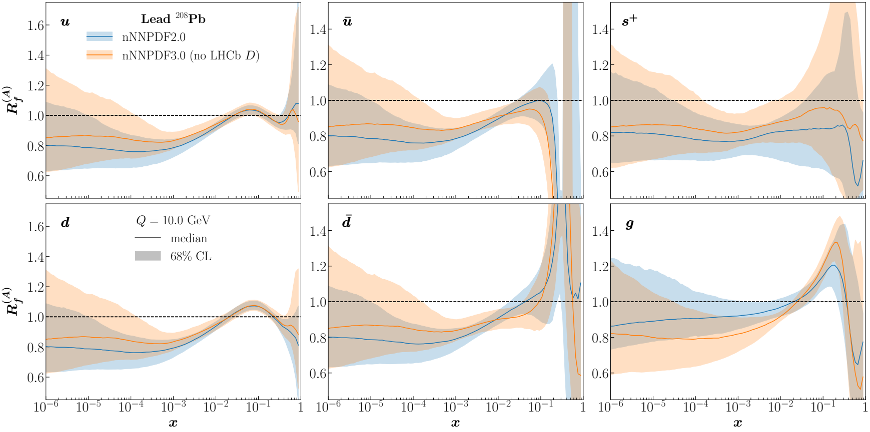
- D meson data from LHCb at $\sqrt{s} = 5$ TeV [JHEP 1710 (2017) 090]
- Predictions for D meson in FFNS done in POWHEG+PYTHIA included using **PDF reweighting**



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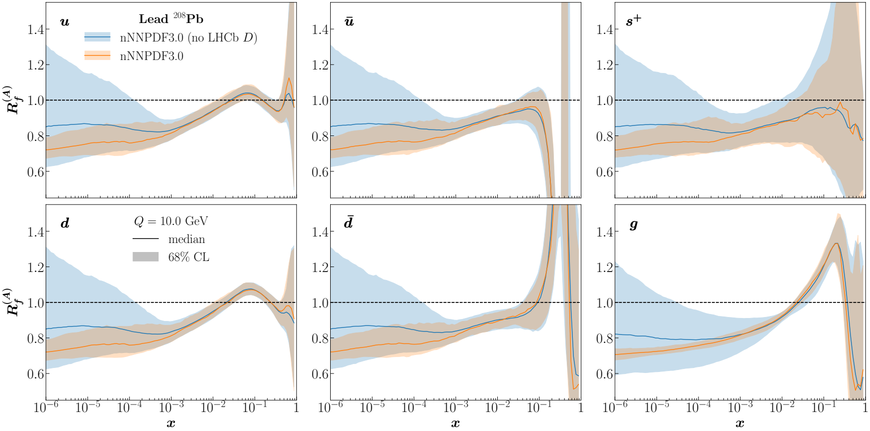

Updates from nCTEQ

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)]
    - 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
    - currently in form of PDF-reweighting

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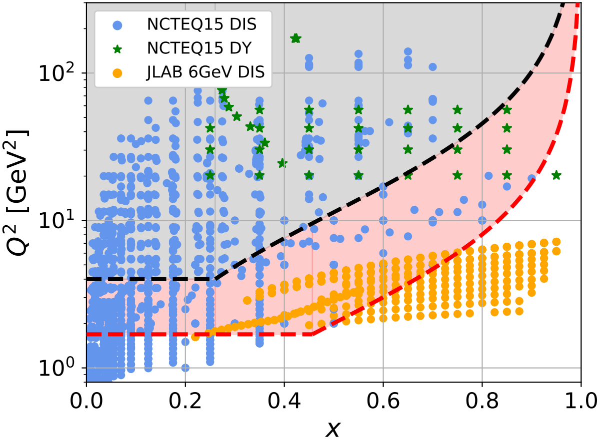
Large-x data from JLAB

In (n)PDF analyses we use kinematic cuts to exclude data that are

- in *non-perturbative region*
- have significant *higher-twist corrections*

This is typically done by *kinematic cuts* on Q^2 and $W^2 = Q^2 \frac{1-x}{x} + M_N^2$



nCTEQ15
$Q > 2$ GeV $W > 3.5$ GeV
$N_{\text{data}} = 708$

nCTEQ15HIX
$Q > 1.3$ GeV $W > 1.7$ GeV
$N_{\text{data}} = 1679$

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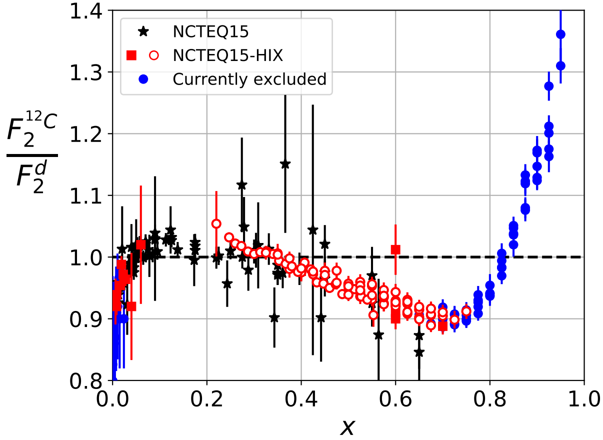


nCTEQ15

$Q > 2$ GeV
$W > 3.5$ GeV

nCTEQ15HIX

$Q > 1.3$ GeV
$W > 1.7$ GeV

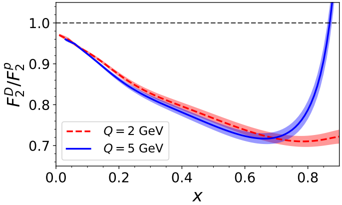
Large-x data from JLAB

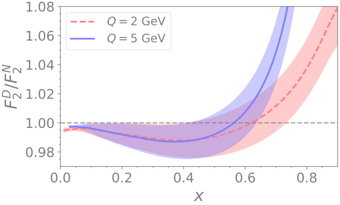
Target	Experiment	ID	Ref.	# data	#data after cuts
^{208}Pb/D	CLAS	9976	[11]	25	24
^{56}Fe/D	CLAS	9977	[11]	25	24
^{27}Al/D	CLAS	9978	[11]	25	24
^{12}C/D	CLAS	9979	[11]	25	24
^{4}He/D	Hall C	9980	[12]	25	17
		9981	[12]	26	16
^{3}He/D	Hall C	9982	[12]	25	17
		9983	[12]	26	16
^{64}Cu/D	Hall C	9984	[12]	25	17
		9985	[12]	26	16
^{9}Be/D	Hall C	9986	[12]	25	17
		9987	[12]	26	16
^{197}Au/D	Hall C	9988	[12]	24	17
		9989	[12]	26	16
^{12}C/D	Hall C	9990	[12]	25	17
		9991	[12]	17	7
		9992	[12]	26	16
		9993	[12]	18	6
		9994	[12]	17	7
		9995	[12]	15	2
		9996	[12]	19	7
		9997	[12]	16	2
		9998	[12]	21	8
		9999	[12]	18	3
Total				546	428

Corrections at large-x

Effects we include:

- *Target-mass corrections* (OPP) & *dynamic higher-twist* effects
  $\rightarrow$ to good extent cancel in ratio.
- *Deuteron corrections* (taken from CJ15 [PRD 93 (2016) 11, 114017])

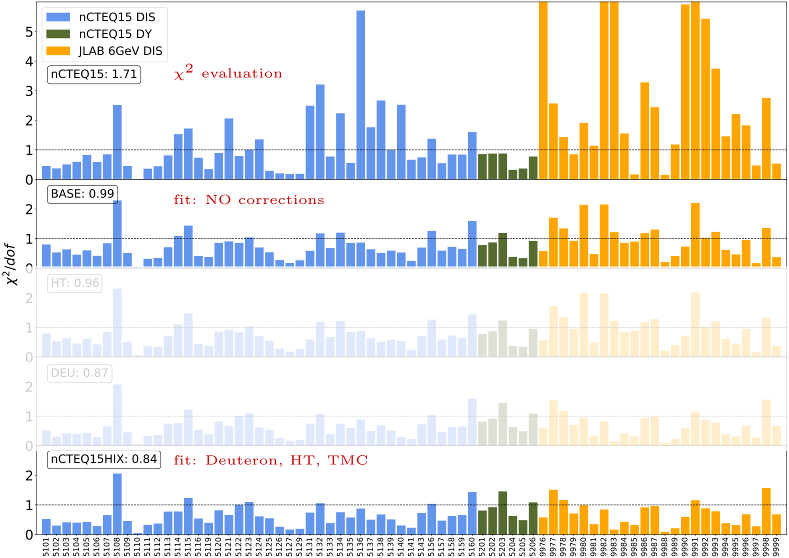




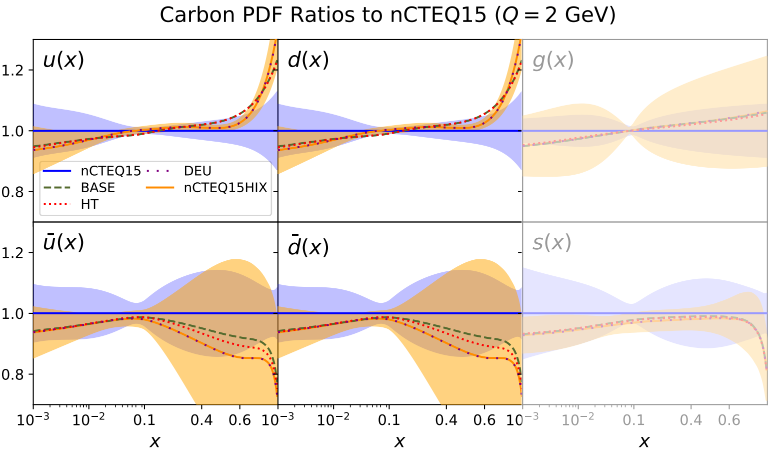
Effects needed when going to even higher-x (lower W):

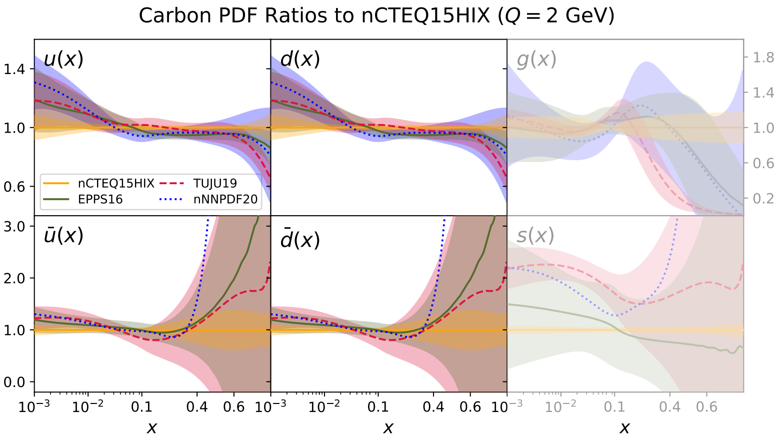
- Non-vanishing structure functions/nPDFs at $x > 1$ and corresponding extension of DGLAP evolution.
- Threshold resummation.

nCTEQ15HIX results



nCTEQ15HIX results: nPDFs





Carbon PDF Ratios to nCTEQ15HIX ($Q = 2$ GeV)
$u(x)$
$d(x)$
$g(x)$
$\bar{u}(x)$
$\bar{d}(x)$
$s(x)$
nCTEQ15HIX
TUJU19
EPPS16
nNNPDF20
1.4
1.0
0.6
3.0
2.0
1.0
0.0
1.8
1.4
1.0
0.6
0.2
10^{-3}
10^{-2}
0.1
0.4
0.6
x

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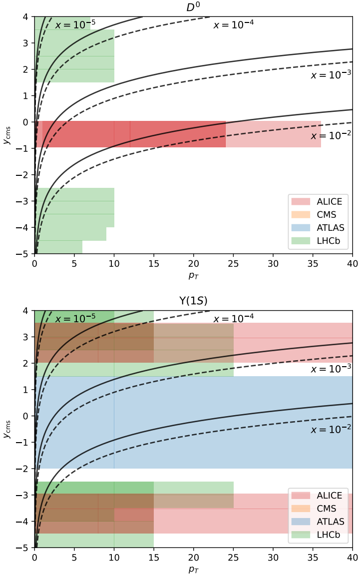
Available nPDFs including heavy quark(onium) data

	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, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$

- New data compared to nCTEQ15WZ+SIH ($p_T > 3$ GeV):
  D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$



Different schemes for the calculation of open **heavy quark** production (D, B mesons):

- **FFNS**: heavy quarks present only in final state. Valid for small p_T.
- **ZM-VFNS**: heavy quarks treated as massless, but included in PDFs for $\mu_f > \mu_T$. Valid at large p_T.
- Schemes interpolating between the two:
  - **FONLL**:

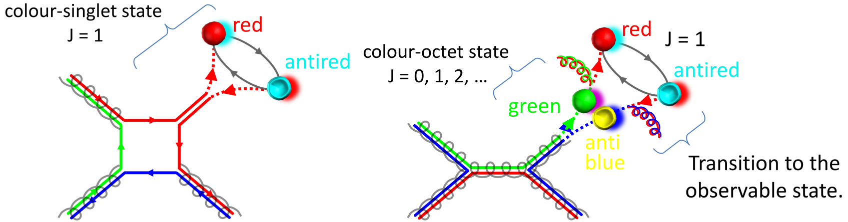
$$d\sigma_{\text{FONLL}} = d\sigma_{\text{FFNS}} + (d\sigma_{\text{ZMVFNS}} - d\sigma_{\text{FFNS},0}) \times G(m_Q, p_T),$$

  - **GM-VFNS**: Massive heavy quarks included in the PDFs for $\mu_f > \mu_T$.

All schemes introduce dependence on non-perturbative final-state fragmentation functions

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

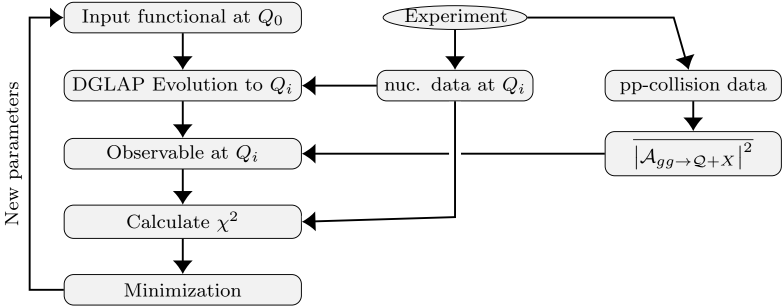
- **Color-evaporation model**: hard scattering creates $Q\bar{Q}$-pair, which radiates gluons until it hadronizes
- **Color-singlet model**: Intermediate state is a color neutral $Q\bar{Q}$-pair
- **Non-relativistic QCD**: separation of short and long distance physics through expansion in velocity



Illustrations by Pietro Faccioli (https://idpasc.lip.pt/uploads/talk/file/530/LIP_curso_polarization.pdf)

Data-driven Approach

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



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

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

Data-driven Approach: Proton-proton baseline

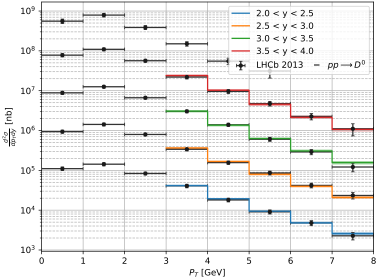
$$\overline{\left|\mathcal{A}_{gg\to Q+X}\right|^2} = \frac{\lambda^2\kappa\hat{s}}{M_Q^2}\begin{cases} e^{-\kappa\frac{p_T^2}{M_Q^2}+a|y|} & \text{if } p_T \leq \langle p_T\rangle \\ e^{-\kappa\frac{\langle p_T\rangle^2}{M_Q^2}+a|y|}\left(1+\frac{\kappa}{n}\frac{p_T^2-\langle p_T\rangle^2}{M_Q^2}\right)^{-n}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

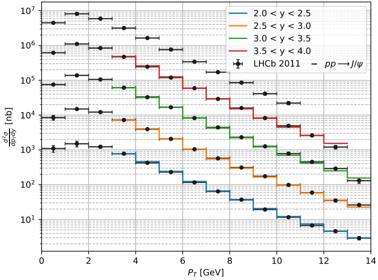
- Impose cuts to remove data with $p_T < 3\,\text{GeV}$ and outside of $-4 \leq y_{cms} \leq 4$

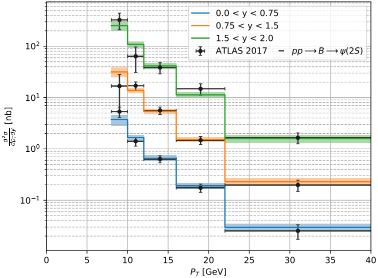
	D^0	J/ψ	$B \to J/\psi$	$\Upsilon(1S)$	$\psi(2S)$	$B \to \psi(2S)$
κ	0.3345	0.4789	0.1548	0.9452	0.2158	0.4527
λ	1.8259	0.3037	0.1213	0.0656	0.0752	0.1385
$\langle p_T\rangle$	2.4009	5.2931	-7.6502	8.6378	8.9881	7.8052
n	2.0007	2.1736	1.5553	1.9323	1.0720	1.6479
a	-0.0329	0.0281	-0.0808	0.2238	-0.1061	0.0617
N_{points}	34	501		375	55	
χ^2/N_{dof}	0.25	0.88		0.92	0.77	

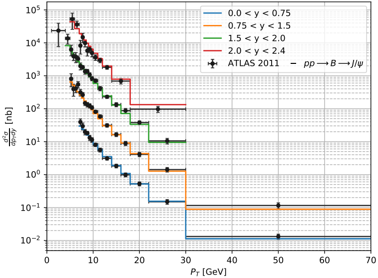
- Very good agreement between data and fitted theory

Data-driven Approach: Proton-proton baseline



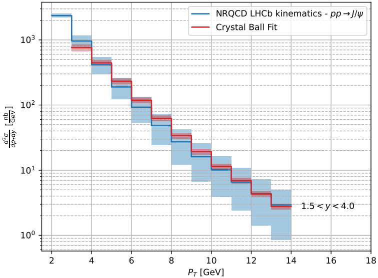


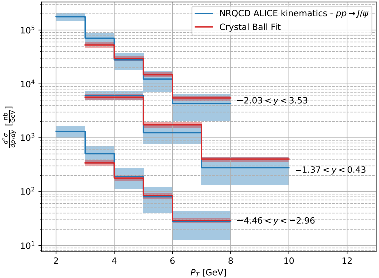




Baseline - comparison with NRQCD for J/ψ

Calculations by Mathias Butenschoen, Bernd Kniehl [M. Butenschoen et al., Nucl.Phys.B Proc.Suppl. 222-224 (2012) 151-161]

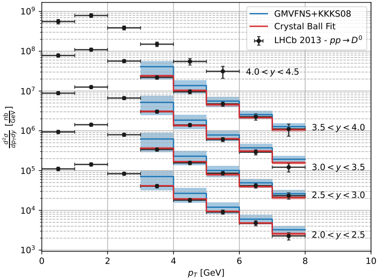


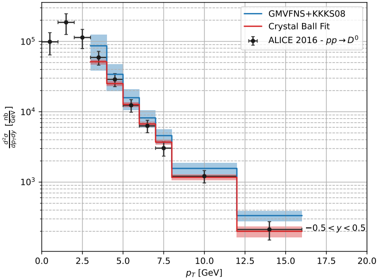


- NRQCD Uncertainties due to scale variations: $1/2 < \mu_r/\mu_{r,0} = \mu_i/\mu_{i,0} = \mu_{\text{NRQCD}}/\mu_{\text{NRQCD},0} < 2$
- Base scale $\mu_{r,0} = \mu_{i,0} = \sqrt{p_T^2 + 4m_c^2}$ and $m_{\text{NRQCD},0} = m_c$

Baseline - comparison with GMVFNS for D^0

Calculations in the GMVFNS using KKKS08 fragmentation functions





- GMVFNS Uncertainties due to scale variations: $1/2 < \mu_r/\mu_{r,0}, \mu_i/\mu_{i,0}, \mu_f/\mu_{f,0} < 2$
- Base scale $\mu_{r,0} = \mu_{i,0} = \mu_{f,0} = \sqrt{p_T^2 + 4m_c^2}$ and $m_c = 1.3$ GeV

nCTEQ15HQ fit setup [PRD 105 (2022) 11, 114043]

- Include all data from nCTEQ15WZ+SIH (936 points) [PRD 104 (2021) 094005] + 548 Heavy Quark(onia) data points
- Use the same open parameters and settings as nCTEQ15WZ+SIH

PDF of nucleus:

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

bound proton PDFs:

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

A-dependence:

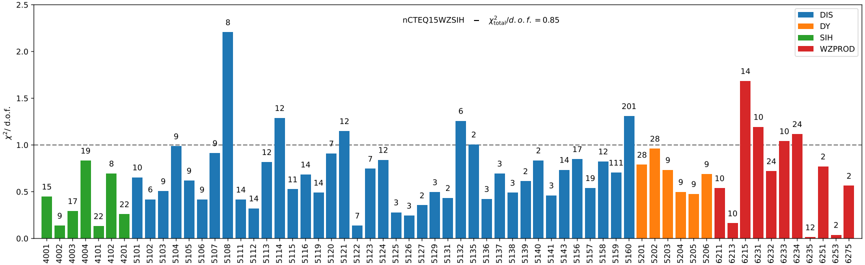
$$c_k \to c_k(A) \equiv p_k + a_k\left(1 - A^{-b_k}\right)$$

Open parameters: $\{a_1^{u_v},\ a_2^{u_v},\ a_4^{u_v},\ a_5^{u_v},\ a_1^{d_v},\ a_2^{d_v},\ a_5^{d_v},\ a_1^{\bar{u}+\bar{d}},\ a_5^{\bar{u}+\bar{d}},$
$a_1^g,\ a_4^g,\ a_5^g,\ b_0^g,\ b_1^g,\ b_4^g,\ b_5^g,\ a_0^{s+\bar{s}},\ a_1^{s+\bar{s}},\ a_2^{s+\bar{s}}\}$

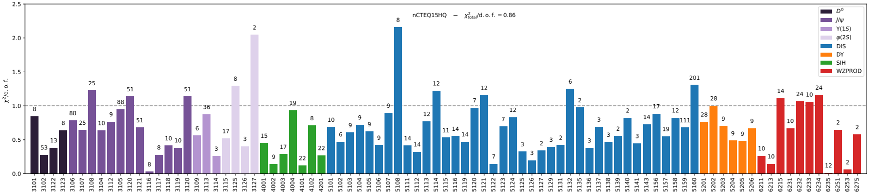
- Add uncertainties of the CB fit to data systematic uncertainties
- Repeat full procedure with different scale choices $\mu_f/\mu_{f,0} = \{\frac{1}{2}, 1, 2\}$

nCTEQ15HQ data description χ^2 [PRD 105 (2022) 11, 114043]

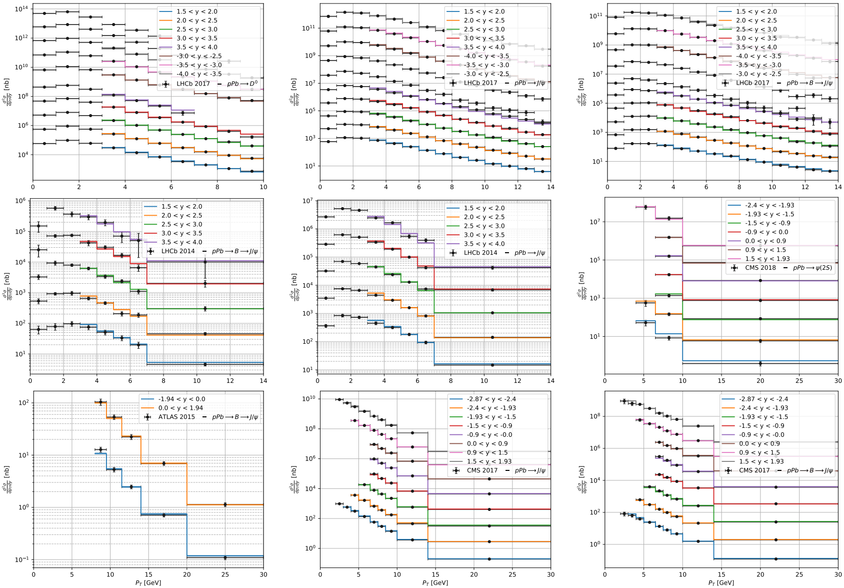
Earlier nCTEQ15WZ+SIH fit:



Now with 548 new HF data points nCTEQ15HQ:

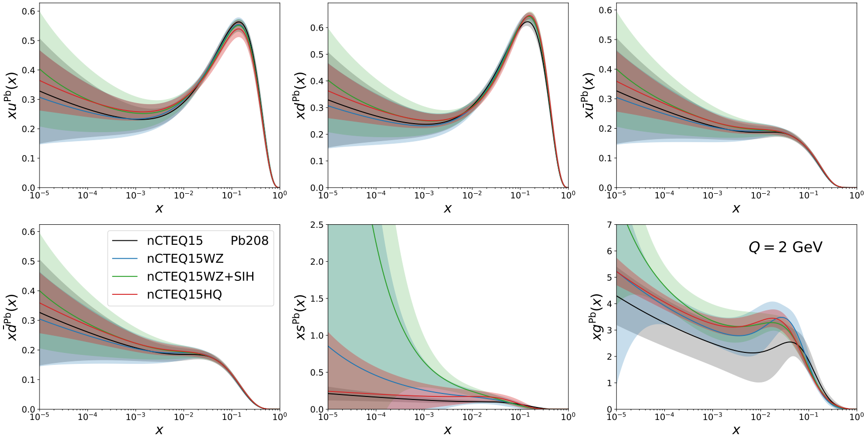


nCTEQ15HQ data description [PRD 105 (2022) 11, 114043]

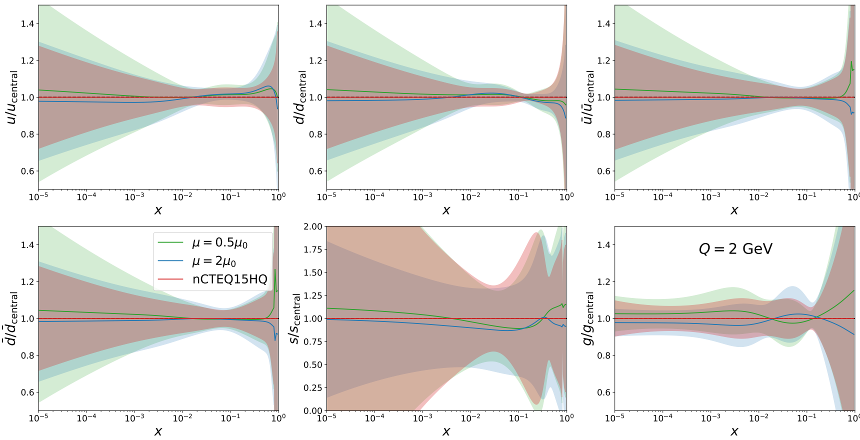


nCTEQ15HQ nPDFs [PRD 105 (2022) 11, 114043]

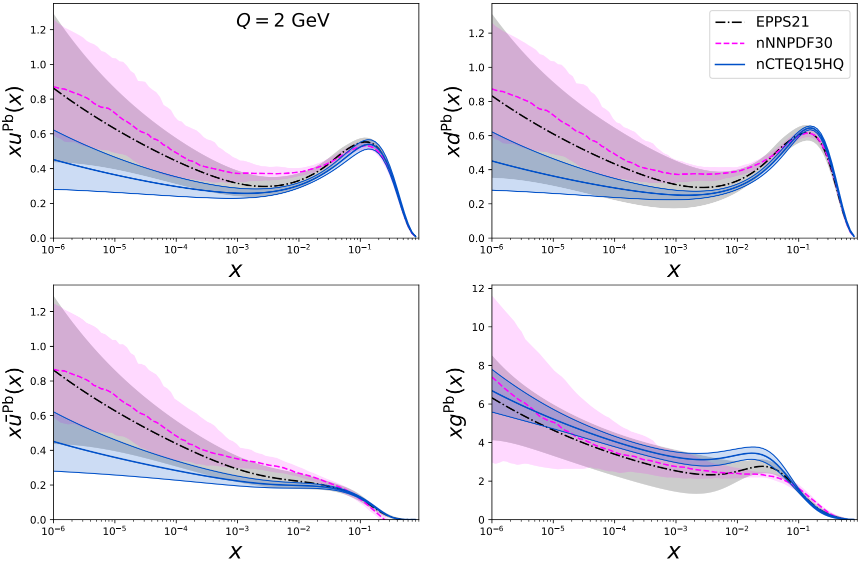
- New data compared to nCTEQ15WZ+SIH: D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$
- Predictions for heavy quark(onium) data done with data-driven method [PRL 121 (2018) 052004; PRL107, 082002 (2011); EPJC77, 1 (2017)]

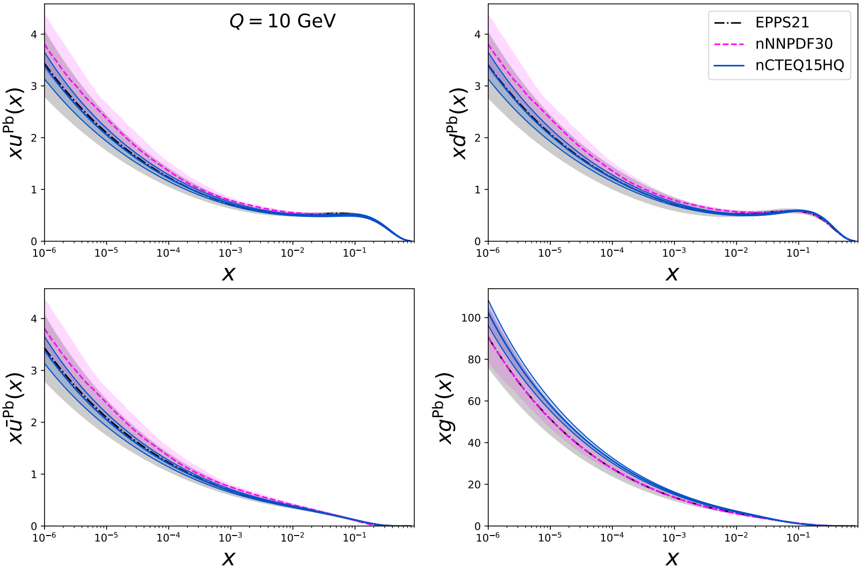


nCTEQ15HQ nPDFs scale dependence [PRD 105 (2022) 11, 114043]



Comparison of nPDFs using HF data





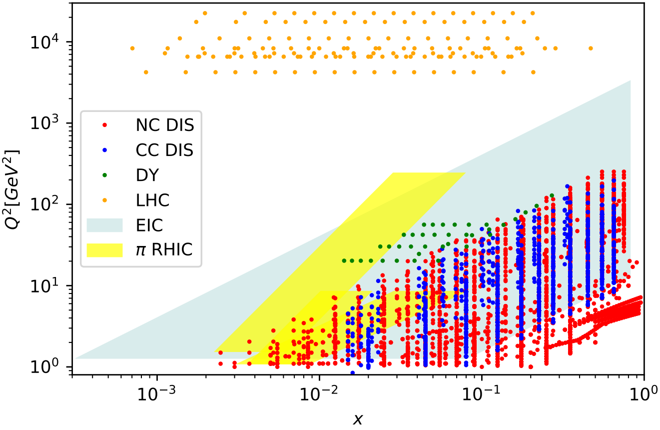
$Q = 10$ GeV
EPPS21
nNNPDF30
nCTEQ15HQ
$xu^{Pb}(x)$
$xd^{Pb}(x)$
$x\bar{u}^{Pb}(x)$
$xg^{Pb}(x)$
x
0
1
2
3
4
20
40
60
80
100
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

Summary

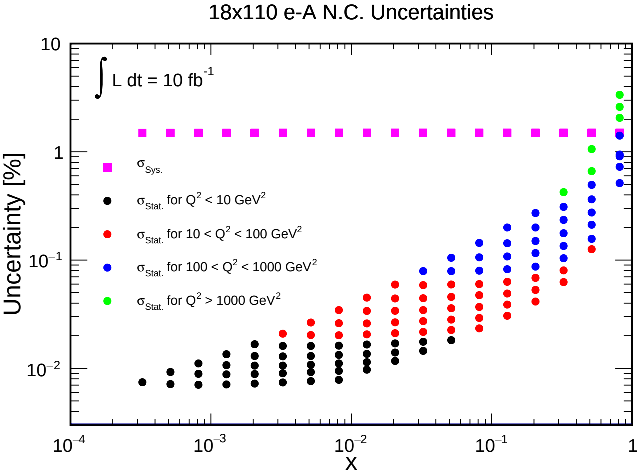
- The pPb LHC data have provided crucial information about nPDFs
  - extending kinematic coverage down to $x \sim 10^{-5}$ (before $x \gtrsim 10^{-2}$)
  - gluon distribution (HQ(-onium), dijets, prompt photon, W/Z)
  - flavour separation (W/Z)
  - strange quark (W/Z)
- Good starting point for EIC but
  - factorization in pA collisions is not proven
  - there can be other effects like energy loss [JHEP 01 (2022) 164]
- EIC will give opportunity to test what we learned at the LHC (and not only e.g. resolve questions about CC DIS)
  - become new "HERA" for nucleus structure: giving access to precise measurements in broad kinematic range for a spectrum of nuclei

Electron-Ion Collider opportunities for nPDFs [Nucl.Phys.A 1026 (2022) 122447]

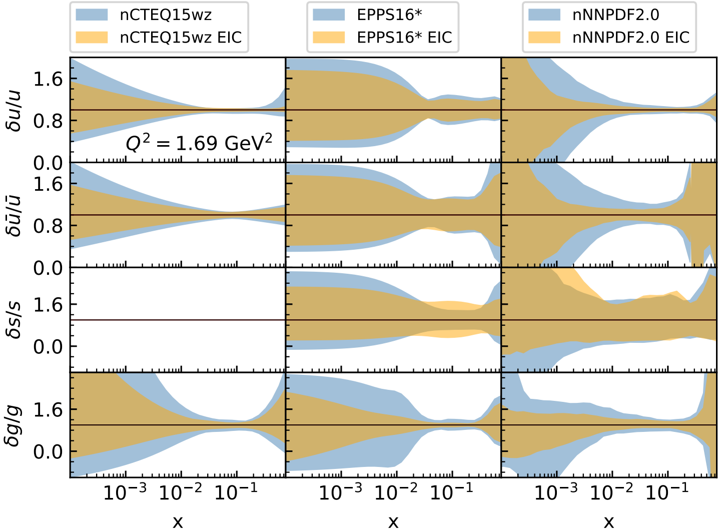
- Range of nuclei: Au, Cu, Fe, C, He, ...
- CM energy $\sqrt{s} \sim 40 - 140\sqrt{Z/A}$ GeV
- Very large luminosity $\sim 10^{33} - 10^{34}$ cm^{-2} s^{-1}
  ($\sim 100 - 1000$ times higher than HERA)
- Wide kinematic coverage



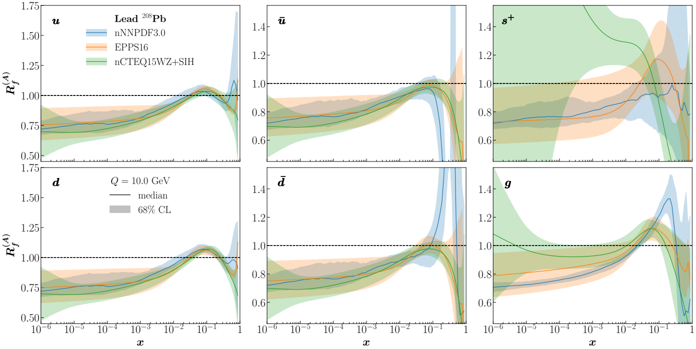
- Small uncertainties



- Great prospects for understanding nuclear structure in particular nPDFs



- The LHC brought a new era for nuclear PDFs
  - pre-LHC nPDFs were very weakly constrained, with hardly any flavor separation, including a lot of assumptions.
  - Finally we are in the stage were newer nPDFs from different groups are in quite a good agreement.



- Nevertheless we are still far away from the precision of proton PDFs

- EIC will allow to test what we learn at the LHC and should bring us to a era of precision in nPDFs.

Nuclear CTEQ parto ×

ncteq.hepforge.org

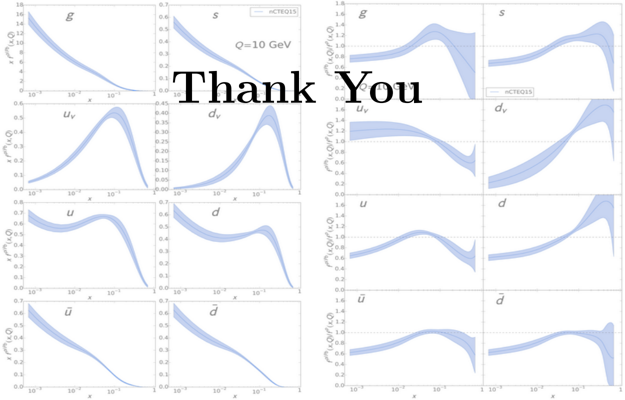
nCTEQ is hosted by Hepforge, IPPP Durham

nCTEQ

nuclear parton distribution functions

- Home
- PDF grids & code
  - nCTEQ15
  - previous PDF grids
- Papers & Talks
- Subversion
- Tracker
- Wiki

nCTEQ project is an extension of the CTEQ collaborative effort to determine parton distribution functions inside of a free proton. It generalizes the free-proton PDF framework to determine densities of partons in bound protons (hence nCTEQ which stands for nuclear CTEQ). All details on the framework and the first complete results can be found in arXiv:15????? [hep-ph].
The effects of the nuclear environement on the parton densities can be shown as modified parton densities or nuclear correction factors (for example for lead as shown below)

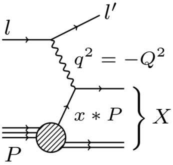


Thank You

BACKUP SLIDES

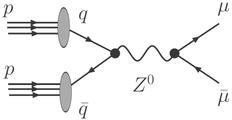
PDFs and QCD Factorization

- **Factorization** in case of **Deep Inelastic Scattering** (DIS)



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

- **Factorization** in case of **Drell-Yan lepton pair production** (DY)



$$\sigma_{pp\to l\bar{l}X} = \sum_{i,j=q,\bar{q},g} \int_{x_1}^1 dz_1 \int_{x_2}^1 dz_2$$

$$\times f_i(z_1,\mu) f_j(z_2,\mu) \hat{\sigma}_{ij\to l\bar{l}X}\left(\frac{x_1}{z_1}, \frac{x_2}{z_2}, \frac{Q}{\mu}\right) + \mathcal{O}\left(\frac{\Lambda^2_{\text{QCD}}}{Q^2}\right)$$

- $f_i(z,\mu)$ – proton PDFs of parton i (**non-perturbative**).

PDFs are **UNIVERSAL** – do not depend on the process!!!

- $\hat{\sigma}$ – parton level matrix element (**calculable in pQCD**).
- $\mathcal{O}\left(\frac{\Lambda^2_{\text{QCD}}}{Q^2}\right)$ – non-leading terms defining accuracy of factorization formula.

- **Sum rules**
  - **Number sum rules** – connect partons to quarks from SU(3) flavour symmetry of hadrons; proton (uud), neutron (udd). For protons:

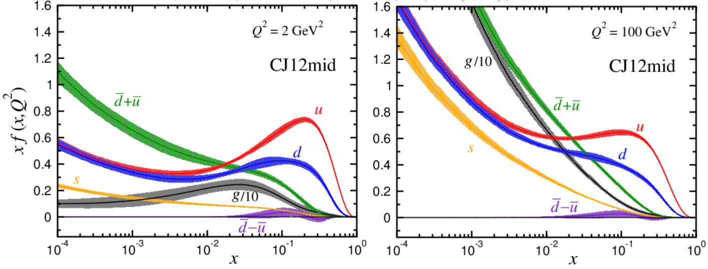
$$\int_0^1 dx[\underbrace{f_u(x) - f_{\bar{u}}(x)}_{u-\text{valence distr.}}] = 2 \qquad \int_0^1 dx[\underbrace{f_d(x) - f_{\bar{d}}(x)}_{d-\text{valence distr.}}] = 1$$

  - **Momentum sum rule** – momentum conservation connecting all flavours

$$\sum_{i=q,\bar{q},g} \int_0^1 dx\, x f_i(x) = 1$$

- **Scale dependence**
  - x-**dependence** of PDFs is NOT calculable in pQCD
  - μ^2-**dependence** is calculable in pQCD – given by **DGLAP** equations

Owens, Accardi, Melnitchouk, PRD 87, 094012 (2013), `arXiv:1212.1702`



Schematics of Global Analysis

1. Choose experimental data (e.g. DIS, DY, inclusive jet prod., etc.)
2. Parametrize PDFs at low initial scale $\mu = Q_0 = 1.3\text{GeV}$:

$$f_i(x, Q_0) = f_i(x; a_0, a_1, \dots) = a_0 x^{a_1}(1-x)^{a_2} P(x; a_3, \dots)$$

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_{DIS}, etc.).
5. Calculate appropriate χ^2 function – compare data and theory

$$\chi^2(\{a_i\}) = \sum_{\text{experiments}} w_n \chi_n^2(\{a_i\})$$

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

(by default $w_n = 1$)

6. Minimize χ^2 function with respect to parameters $a_0, a_1, \dots$

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$$f_i(x, Q_0) = f_i(x; a_0, a_1, \dots) = a_0 x^{a_1} (1-x)^{a_2} P(x; a_3, \dots)$$

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_{DIS}, etc.).
5. Calculate appropriate χ^2 function – compare data and theory

$$\chi^2(\{a_i\}) = \sum_{\text{experiments}} w_n \chi_n^2(\{a_i\})$$

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

(by default $w_n = 1$)

6. Minimize χ^2 function with respect to parameters $a_0, a_1, \dots$

Recent nCTEQ results

- Last full nPDF release: **nCTEQ15**
  - DIS NC data
  - fixed-target DY data
  - pion data from RHIC
- Updates on the way to new release
  - **nCTEQ15WZ**
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  - **nCTEQ15neutrino**
    - 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
    - currently in form of PDF-reweighting

nPDF constrains

To better constrain (n)PDFs we need precise data for different process

- more process give access to more flavour combination - better flavour separation
- caveat: use processes where factorization works

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For nPDFs we generally lack good constraints on **gluon**:

- 😐 **DIS** (from Q^2 evolution): not large enough lever arm
- 🙂 W/Z from pPb in LHC: good for $x \geq 10^{-3}$
- 🙁 **Dijets** from pPb in LHC: problematic NLO doesn't work
- 😐 **Direct photon** from pPb in LHC: not very precise
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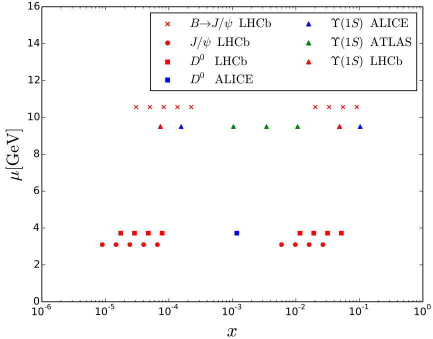
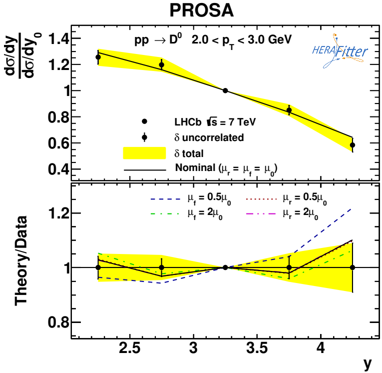
- 😐 **SIH** (Single Inclusive Hadron) from LHC & RHIC: FF-dependent + $x \geq 10^{-2}$

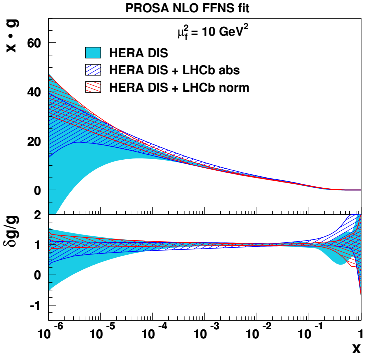
? **Heavy quark(onia)**: precise + access to very small $x \leq 10^{-5}$ but...



First use of HF data to constrain (n)PDFs

- PROSA [EPJC 75, 396 (2015)] first use of D and B data to constrain proton PDFs
  - use ratio to central bin to reduce scale uncertainty





First use of HF data to constrain (n)PDFs

- First use in nPDFs [PRL 121 (2018) 052004; PRD 104 (2021) 014010]: pPb data for D, B, J/ψ, Υ

- Use PDF reweighting
- Data-driven approach for theory calculations
  [PRL107, 082002 (2011); EPJC77, 1 (2017)]

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

✓ removes model dependence
✓ fast to generate events
✗ currently limited to probes produced in $2\to 2$ partonic processes dominated by single partonic channel (gg, $q\bar{q}$, ...)
$\to$ In our case (D^0, J/ψ, $B\to J/\psi$, $\Upsilon(1S)$ production) gg dominated.
✗ not a fixed order calculation

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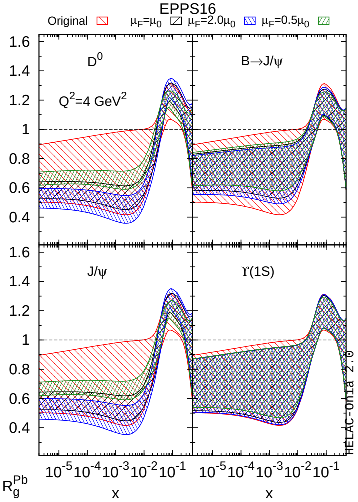
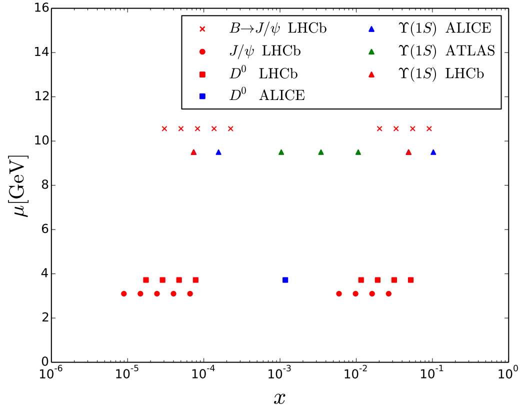


- Use PDF reweighting
- Data-driven approach for theory calculations [PRL107, 082002 (2011); EPJC77, 1 (2017)]
- Predictions for D and B validated against available pQCD calculations (FONLL, GMVFNS).
- Additional features:
  - ✓ large available data sets from multiple LHC experiments
  - ✓ uncertainty in pp collision is well controlled by the data
  - ✓ removes model dependence
  - ✓ fast to generate events
  - ✗ currently limited to probes produced in $2 \to 2$ partonic processes dominated by single partonic channel (gg, $q\bar{q}$, ...)
    $\to$ In our case ($D^0, J/\psi, B \to J/\psi, \Upsilon(1S)$ production) gg dominated.
  - ✗ not a fixed order calculation

pPb LHC heavy-flavour data [PRL 121 (2018) 052004; PRD 104 (2021) 014010]

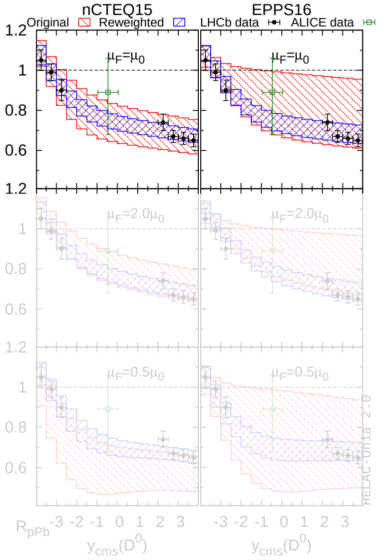
	D^0	J/ψ	$B \to J/\psi$	$\Upsilon(1S)$
μ_0	$\sqrt{4M_{D^0}^2 + P_{T,D^0}^2}$	$\sqrt{M_{J/\psi}^2 + P_{T,J/\psi}^2}$	$\sqrt{4M_B^2 + \left(\frac{M_B}{M_{J/\psi}} P_{T,J/\psi}\right)^2}$	$\sqrt{M_{\Upsilon(1S)}^2 + P_{T,\Upsilon(1S)}^2}$
p+p data	LHCb [1]	LHCb [2,3]	LHCb [2,3]	ALICE [4], ATLAS [5], CMS [6], LHCb [7,8]
R_{pPb} data	ALICE [9], LHCb [15]	ALICE [10,11], LHCb [16,12]	LHCb [12]	ALICE [13], ATLAS [14], LHCb [17]



Expected nuclear effects on heavy quark(onium) production in pA collisions

- Nuclear modification of PDFs: initial-state effect
- Energy loss (w.r.t. pp collisions): initial-state or final-state effect
- Break up of the quarkonium in the nuclear matter: final-state effect
- Break up by comoving particles: final-state effect
- Colour filtering of intrinsic QQ pairs: initial-state effect
- ...

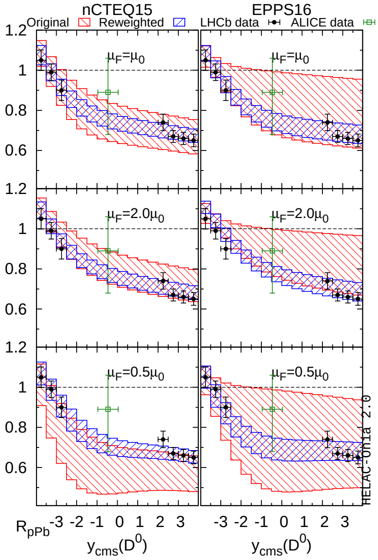
- We assume leading twist factorization is valid – ONLY modifications of PDFs are present → “shadowing-only” hypothesis.



LHCb [JHEP 1710 (2017) 090, 1707.02750]
ALICE [PRL113, 232301 (2014), 1405.3452]

- Initial description of data is good for both nCTEQ15 and EPPS16.
- Substantial reduction of uncertainty especially for EPPS16.

Reweighting with D^0 data



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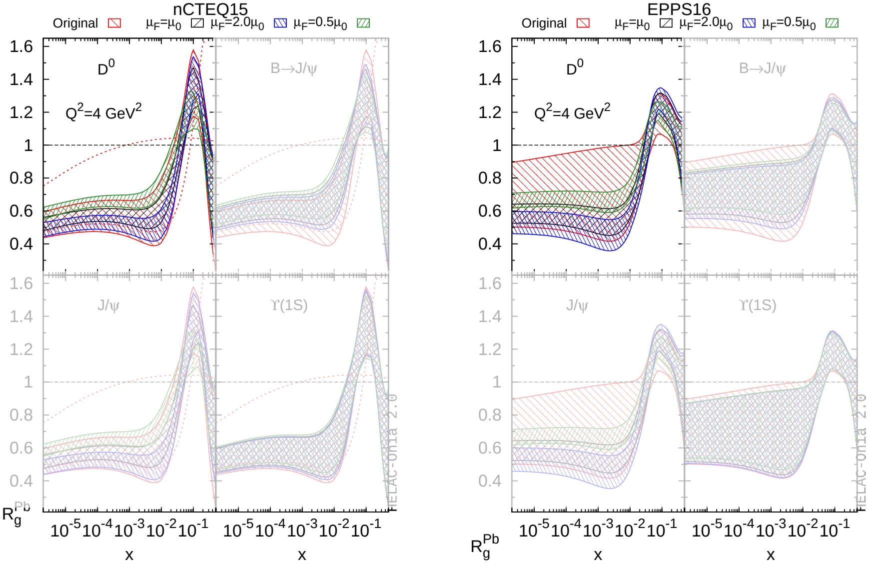
- Initial description of data is good for both nCTEQ15 and EPPS16.
- Substantial reduction of uncertainty especially for EPPS16.
- If we include factorization scale uncertainty errors increase and it can become the dominant uncertainty.

Reweighting results: $R_g^{\mathrm{Pb}} = f_g^{\mathrm{Pb}}/f_g^{p}$



Consistency with other data

We checked the consistency of the reweighted (**nCTEQ15**) nPDFs with other data sets entering global analysis:

- DIS data (the most precise set NMC Sn/C [NPB 481 (1996) 23]).
- LHC W/Z boson production data [EPJC 77, (2017) 488].
- PHENIX J/ψ $R_{d\mathrm{Au}}$ data [PRL 107 (2011) 142301; PRC 87, (2013) 034904].

This is very non-trivial and further confirms the “shadowing-only” hypothesis of leading twist factorization is valid within the current data precision!

Consistency with other data

- The results of the [PRL 121 (2018), 052004] study were successfully used e.g. to describe data at RHIC.

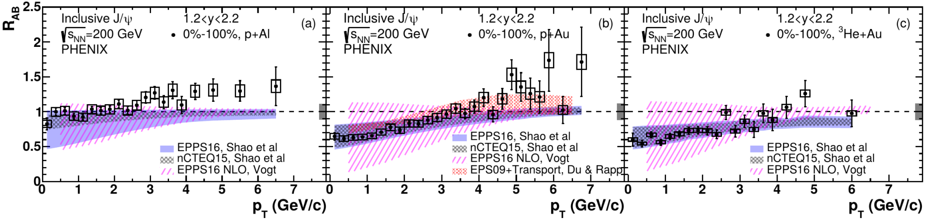
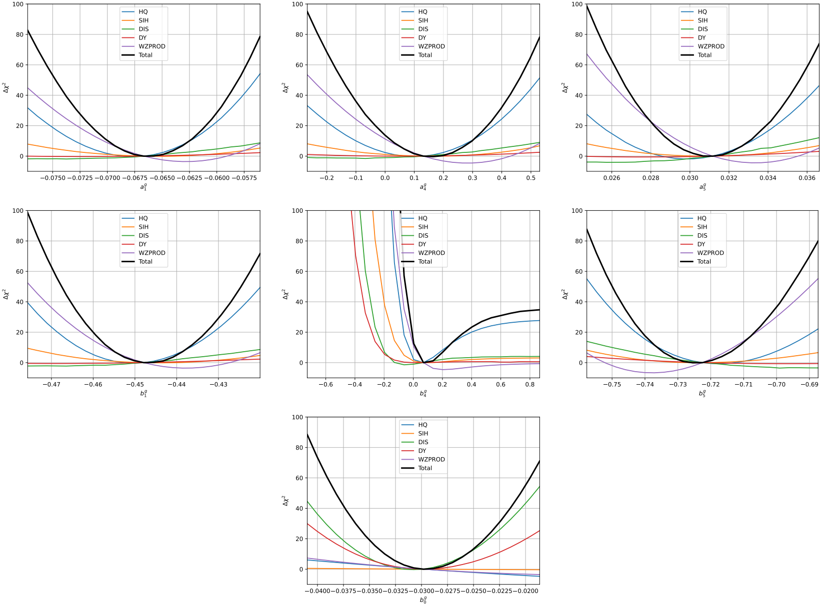


FIG. 10. Nuclear modification factor of inclusive J/ψ as a function of p_T at forward rapidity ($p/^3$He-going direction) for 0%–100% p+Al, p+Au, and ^{3}He+Au collisions. Bars (boxes) around data points represent point-to-point uncorrelated (correlated) uncertainties. The theory bands are discussed in the text.

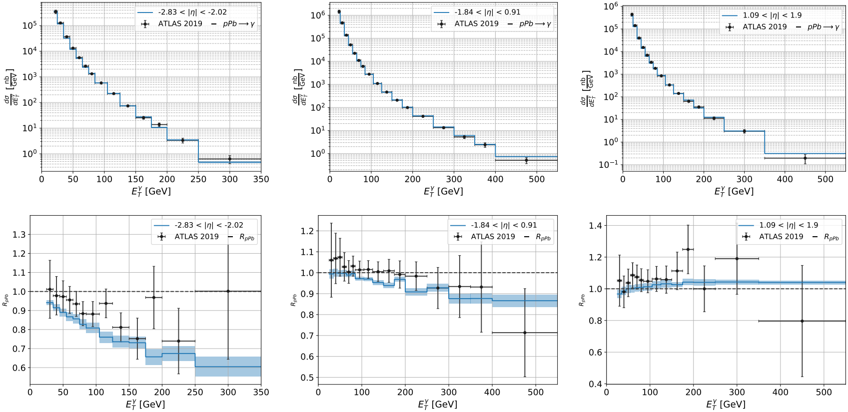
arXiv:1910.14487

see also: K. Smith, Quark Matter 2019

nCTEQ15HQ: gluon parameters χ^2 scans

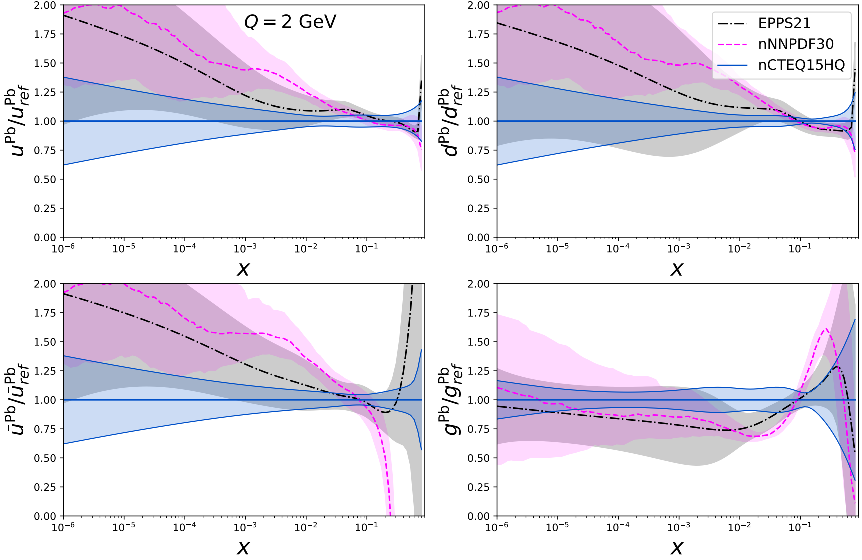


nCTEQ15HQ: description of prompt photons (NOT fitted)



- $\frac{d\sigma}{dE_T}$: $\chi^2/N_{dof} = 1.66$ (0.99 with free normalization)
- R_{pPb}: $\chi^2/N_{dof} = 0.53$

Comparison of nPDFs using HF data: nuclear modification



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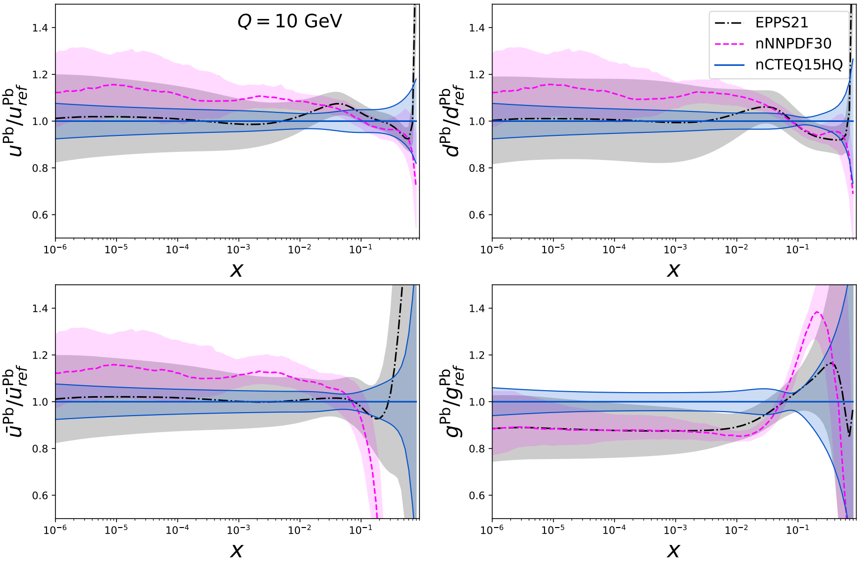

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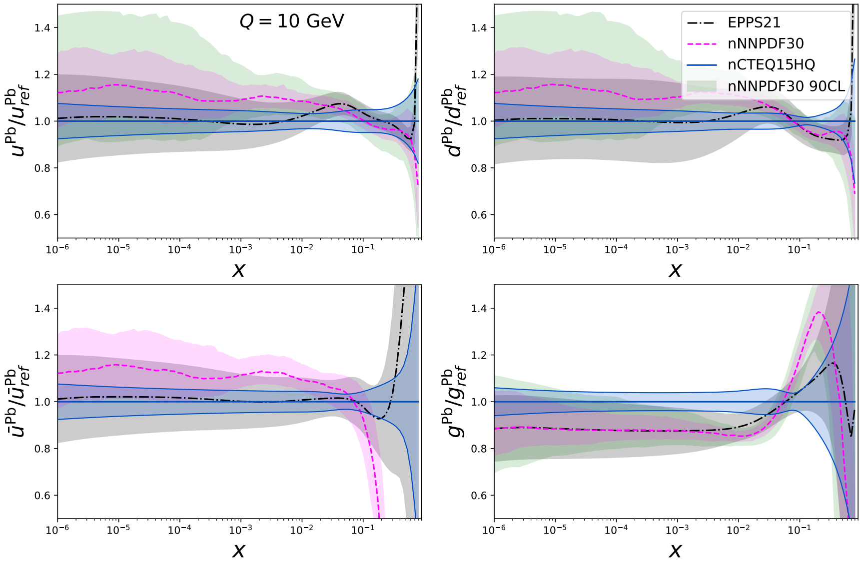
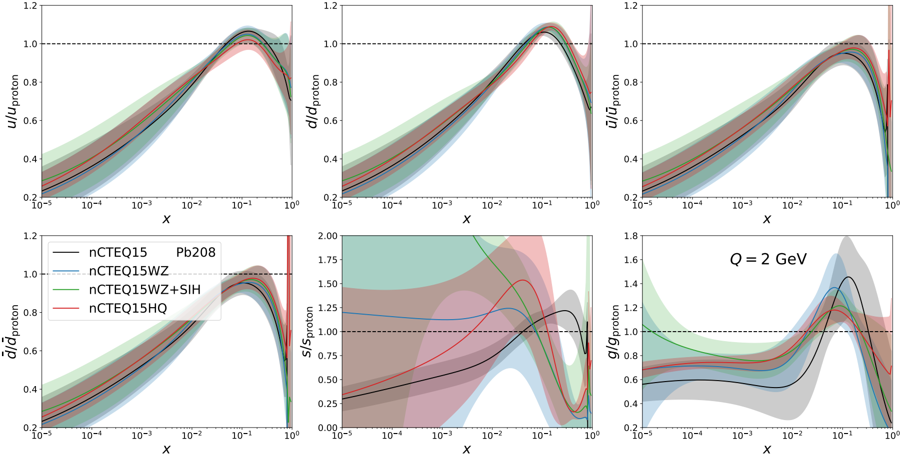


nCTEQ15HQ [PRD 105 (2022) 11, 114043] nuclear modification



Summary

- **Heavy Quark(onia)** data can constrain low-x gluon nPDFs in a region unconstrained by any other data but should we use them???
  - ✓ data-driven approach reduces uncertainties
  - ✓ compatible with data of other processes
  - ✗ but does it mean the collinear factorization is work?
  - ✗ possible other effects like energy loss
  - ✗ large scale uncertainties for charm
  - ✗ very low-x possible saturation region
  - ✗ dependence on fragmentation functions
- Maybe better to restrict to open heavy flavour especially B meson?
  - ✓ pQCD calculations should be reliable
  - ✓ scale uncertainties reduced compared to charm
  - ✗ there still can be other effects [JHEP 01 (2022) 164] (could be removed by cuts?)
  - ✗ removes a lot of data

Recent nCTEQ results

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  - **nCTEQ15SIH** [arXiv:2105.09873]
    - LHC & RHIC SIH data
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  - **nCTEQ15neutrino [in progress]**
    - DIS neutrino data (NuTeV, CHORUS, CDHSW, dimuons)
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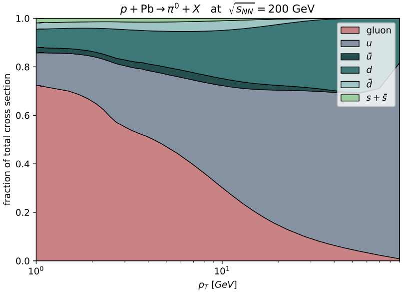
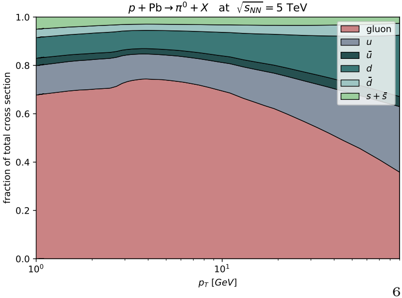
Single Inclusive Hadron (SIH): motivation

- ✓ SIH data is *sensitive to gluon PDF*
- ✓ New precise data from ALICE
- ✗ dependence on fragmentation functions (FFs)





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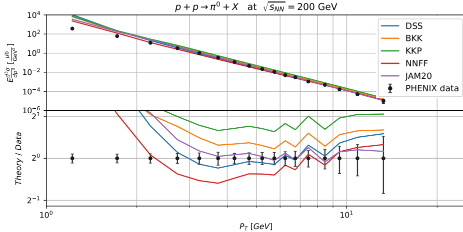
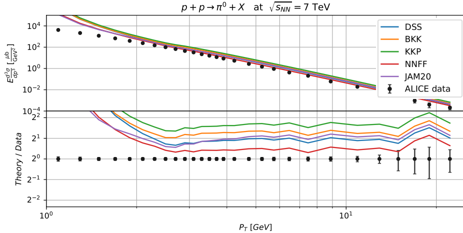
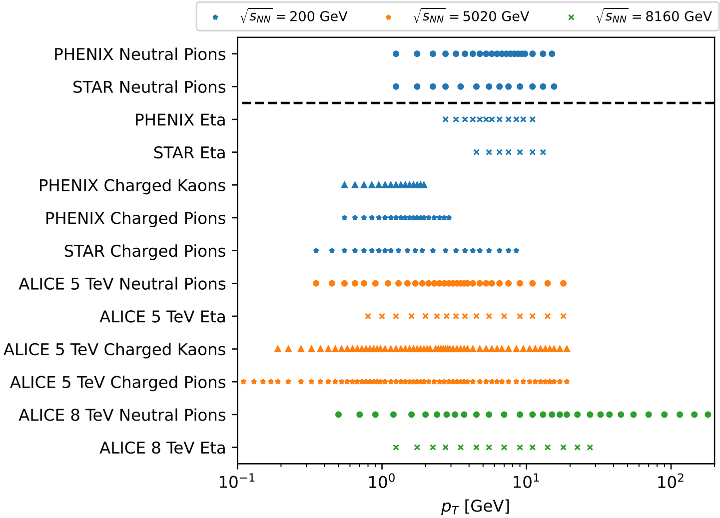





$\sqrt{s_{NN}} = 200$ GeV
$\sqrt{s_{NN}} = 5020$ GeV
$\sqrt{s_{NN}} = 8160$ GeV
PHENIX Neutral Pions
STAR Neutral Pions
PHENIX Eta
STAR Eta
PHENIX Charged Kaons
PHENIX Charged Pions
STAR Charged Pions
ALICE 5 TeV Neutral Pions
ALICE 5 TeV Eta
ALICE 5 TeV Charged Kaons
ALICE 5 TeV Charged Pions
ALICE 8 TeV Neutral Pions
ALICE 8 TeV Eta
10^{-1}
10^{0}
10^{1}
10^{2}
p_T [GeV]

nCTEQ15SIH: data selection

- Used data: same as in nCTEQ15WZ (NC DIS, DY, W/Z) + **SIH** (π^0, $\pi^\pm$, $K^\pm$ from RHIC & LHC)
- *Kinematic cut* for SIH data: $p_T > 3$ GeV
- *Normalization* of SIH data *fitted* (uncertainty $\sim 5\%$)
- Use *DSS fragmentation*
- FFs uncertainties added to the data sys. uncert.

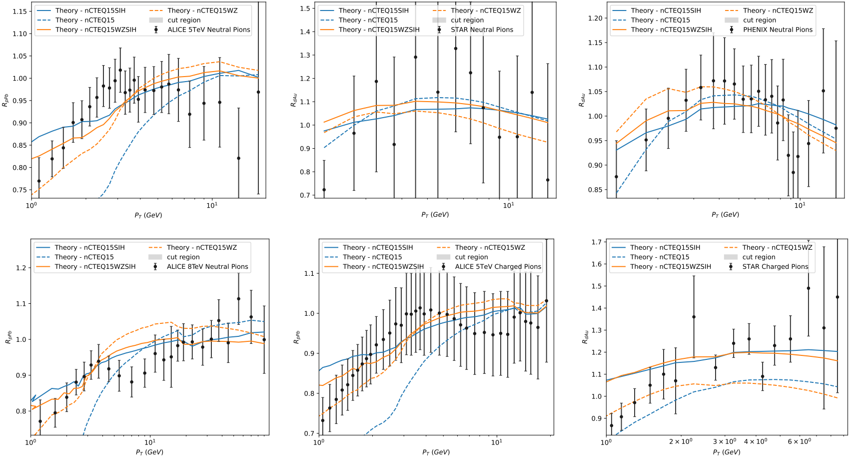
Comparison of Main fits

$\chi^2/N_{d.o.f.}$ for individual processes					
	DIS	DY	WZ	SIH	**Total**
nCTEQ15	0.86	0.78	(3.74)	(1.23)	**1.28**
nCTEQ15+SIH	0.87	0.72	(2.32)	0.38	**1.00**
nCTEQ15WZ	0.90	0.78	0.90	(0.81)	**0.90**
nCTEQ15WZ+SIH	0.91	0.77	1.02	0.41	**0.85**

χ^2 values of the Single Inclusive Hadron data obtained by using different fragmentation functions

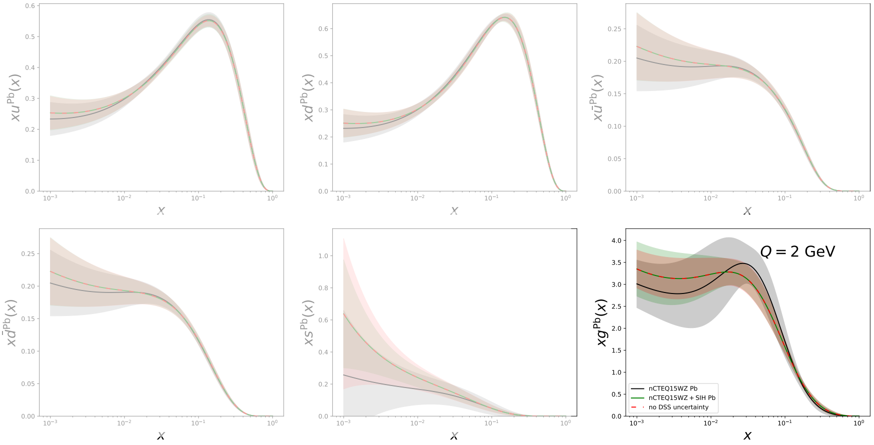
DSS (unmodified data)	DSS	KKP	BKK	NNFF	JAM20
0.461	0.412	0.401	0.420	0.456	0.553

Theory predictions



Resulting lead nPDFs

Based on nCTEQ15WZ (951 total data points, 120 of them SIH)



nCTEQ framework [PRD 93, 085037 (2016), arXiv:1509.00792]

- **Parametrization**
  - *PDF of nucleus* (A - mass, Z - charge)

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

  - bound proton PDFs are parametrized

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

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

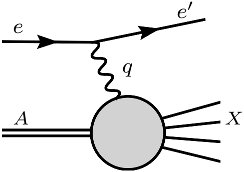
$$c_k \to c_k(A) \equiv p_k + a_k \left(1 - A^{-b_k}\right)$$

- **Sum rules**

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

- **Error analysis** using *Hessian* method

Variables: DIS of nuclear target $eA \to e'X$



- DIS variables in case on nucleons
  in nucleus $\begin{cases} Q^2 \equiv -q^2 \\ x_A \equiv \frac{Q^2}{2\, p_A \cdot q} \end{cases}$
  - p^A – nucleus momentum
  - $x_A \in (0, 1)$ – analog of Bjorken variable
    (fraction of the nucleus momentum carried by a nucleon)

- Analogue variables for partons:
  - $p_N = \frac{p_A}{A}$ – *average* nucleon momentum
  - $x_N \equiv \frac{Q^2}{2\, p_N \cdot q} = A\, x_A$ – parton momentum fraction with respect to the average nucleon momentum p_N
  - $x_N \in (0, A)$ – parton can carry more than the average nucleon momentum p_N.