Impact of LHC heavy flavour data on nuclear gluon PDF

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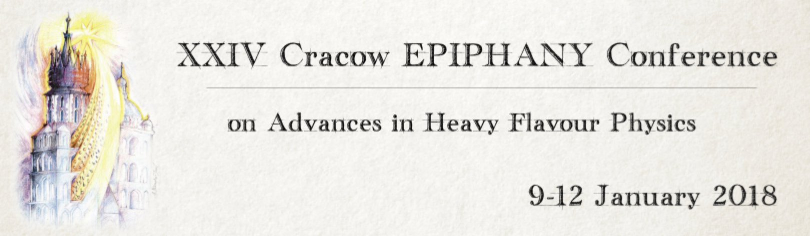
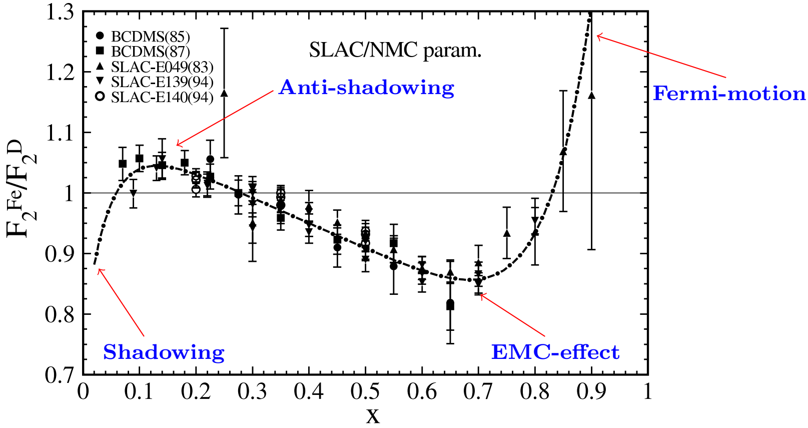
in collaboration with: **J.P. Lansberg**, **I. Schienbein**, **H. Shao**
based on: arXiv:1712.07024



Introduction

- Cross-sections in nuclear collisions are modified



- We translate this modifications into universal quantities: nuclear PDFs (nPDFs)

Introduction

Nuclear PDFs (nPDFs) allow to:

- Get information on the structure of nucleus.
- Description of heavy ion collisions at the LHC and RHIC, and use perturbative probes of the QGP to study its properties.

nPDFs can not be computed and similarly to the proton PDFs are fitted to experimental data.

Differences with the free-proton PDFs

- Theoretical status of Factorization
- Parametrization – more parameters to model A-dependence
- Different data sets – much less data:

  - Less data → less constraining power → **more assumptions** (fixing) about fitting parameters

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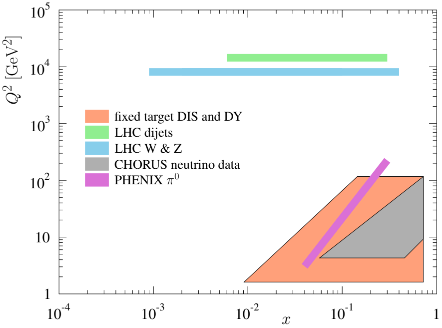
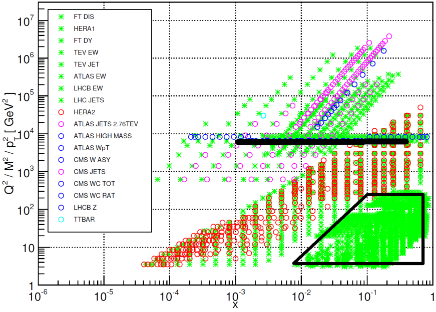
EPPS16 dataset



NNPDF3.0 NLO dataset



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nPDF framework

- **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

nCTEQ15 [arXiv:1509.00792]

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

$$c_k \to c_k(A) \equiv c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right)$$

EPPS16 [arXiv:1612.05741]

$$f_i^{p/A}(x,Q) = R_i^A(x,Q)\, f_i^p(x,Q),$$

$$R_i^A(x,Q_0) = \begin{cases} a_0 + a_1(x-x_a)^2 & x \leq x_a \\ b_0 + b_1 x^{\alpha} + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \leq x \leq \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \leq x \leq \end{cases}$$

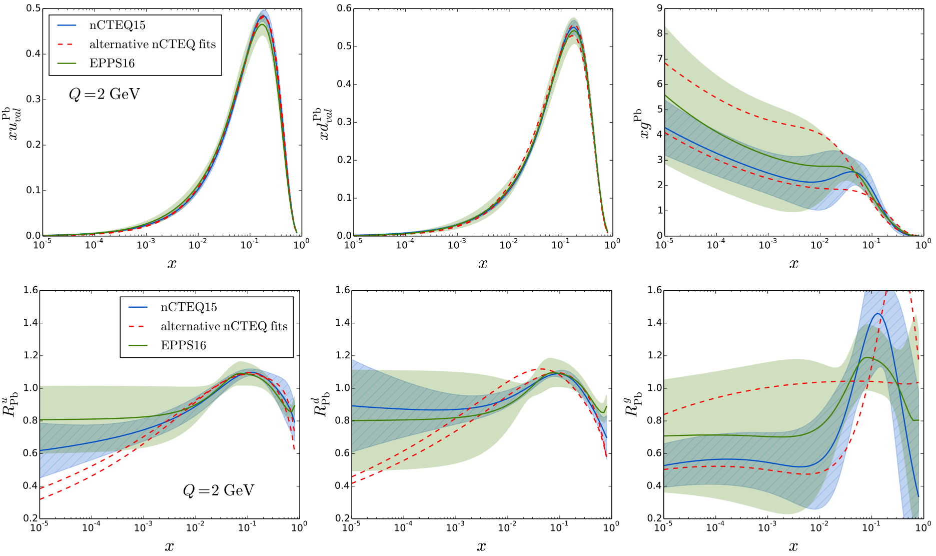
$$d_i \to d_i(A) = d_i(A_{\rm ref}) \left(\frac{A}{A_{\rm ref}}\right)^{\gamma_i [d_i(A_{\rm ref}) - 1]},$$

with $d_i = a_i, b_i, \ldots$ and $A_{\rm ref} = 12$

Current nPDFs

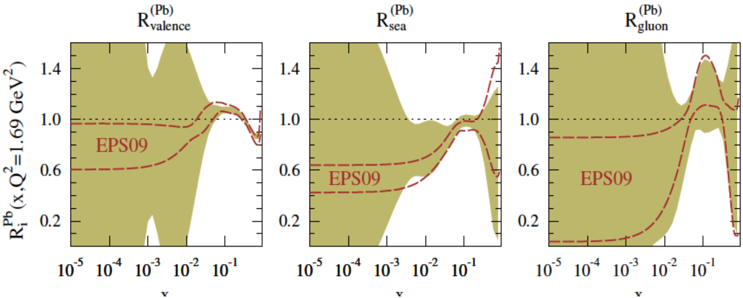
[arXiv:1509.00792, arXiv:1012.1178]

[arXiv:1612.05741]



New fit framework:

The baseline fit using the new fit functions: no control over small x!



The lower bound restricted here by $F_L(Q^2 = 2\,\mathrm{GeV}^2, x > 10^{-5}) > 0$

Maybe against "physical intuition" (small-x theory predicts shadowing, $R_i < 1$), but consistent with the data.

E.g. in EPS09, small-x shadowing was essentially built in

[N. Armesto, 2015 LHeC Workshop, Chavannes-de-Bogis, June 26th 2015]

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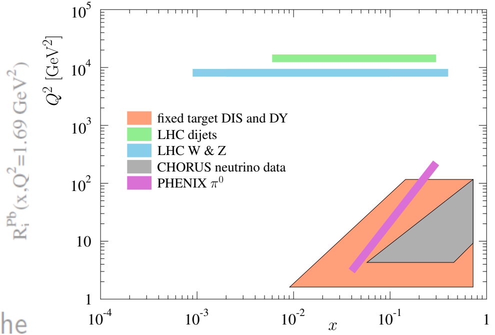

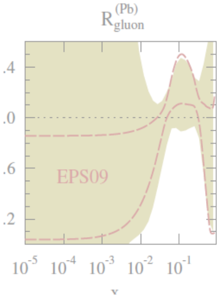

The … $2\ \mathrm{GeV}^2, x > 10^{-5}) > 0$

Gluon nPDFs is particularly badly known (LHC dijet, RHIC π^0)

Maybe …

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E.g. in EPS09, small-x shadowing was essentially built in

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Heavy flavor LHC data

Available heavy-flavor pPb LHC data

	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]

[1] LHCb, R. Aaij et al., JHEP 06, 147 (2017), 1610.02230.
[2] LHCb, R. Aaij et al., Eur. Phys. J. C71, 1645 (2011), 1103.0423.
[3] LHCb, R. Aaij et al., JHEP 06, 064 (2013), 1304.6977.
[4] ALICE, B. B. Abelev et al., Eur. Phys. J. C74, 2974 (2014), 1403.3648.
[5] ATLAS, G. Aad et al., Phys. Rev. D87, 052004 (2013), 1211.7255.
[6] CMS, S. Chatrchyan et al., Phys. Lett. B727, 101 (2013), 1303.5900.
[7] LHCb, R. Aaij et al., Eur. Phys. J. C72, 2025 (2012), 1202.6579.
[8] LHCb, R. Aaij et al., JHEP 11, 103 (2015), 1509.02372.
[9] ALICE, B. B. Abelev et al., Phys. Rev. Lett. 113, 232301 (2014), 1405.3452.
[10] ALICE, J. Adam et al., JHEP 06, 055 (2015), 1503.07179.
[11] ALICE, B. B. Abelev et al., JHEP 02, 073 (2014), 1308.6726.
[12] LHCb, R. Aaij et al., (2017), 1706.07122.
[13] ALICE, B. B. Abelev et al., Phys. Lett. B740, 105 (2015), 1410.2234.
[14] The ATLAS collaboration, (2015), ATLAS-CONF-2015-050.
[15] LHCb, R. Aaij et al., JHEP 1710 (2017) 090, 1707.02750.
[16] LHCb, R. Aaij et al., JHEP 02, 072 (2014), 1308.6729.
[17] LHCb, R. Aaij et al., JHEP 07, 094 (2014), 1405.5152.

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 $Q\bar{Q}$ pairs: initial-state effect
- ...

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

Theoretical predictions

- Theory calculations for heavy quark are done using a data driven method [PRL107, 082002 (2011), 1105.4186; EPJC77, 1 (2017), 1610.05382]
  - partonic matrix elements $|A|^2$ are determined from fits to pp data

$$|\mathcal{A}|^2 = \frac{\lambda^2 \kappa s x_1 x_2}{M_{\mathcal{H}}^2} \exp\left(-\kappa \frac{\min(P_{T,\mathcal{H}}^2, \langle P_T \rangle^2)}{M_{\mathcal{H}}^2}\right) \times \left[1 + \theta\left(P_{T,\mathcal{H}}^2 - \langle P_T \rangle^2\right) \frac{\kappa}{n} \frac{P_{T,\mathcal{H}}^2 - \langle P_T \rangle^2}{M_{\mathcal{H}}^2}\right]^{-n}$$

  with $\kappa, \lambda, \langle P_T \rangle$ and n being fit parameters.

  - Predictions for D^0 and $B \to J/\psi$ have been validated against available perturbative QCD calculations (FONLL, GMVFNS).

- Additional features:
  - ✓ 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.

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Impact on nPDFs: reweighting analysis

Reweighting for Hessian PDFs [arXiv:1310.1089, arXiv:1402.6623]

1. Convert Hessian error PDFs into replicas

$$f_k = f_0 + \sum_i^N \frac{f_i^{(+)} - f_i^{(-)}}{2} R_{ki},$$

2. Calculate weights for each replica

$$w_k = \frac{e^{-\frac{1}{2}\chi_k^2/T}}{\frac{1}{N_{\rm rep}} \sum_i^{N_{\rm rep}} e^{-\frac{1}{2}\chi_k^2/T}}, \qquad \chi_k^2 = \left(\frac{1-f_N}{\sigma^{\rm norm}}\right)^2 + \sum_j^{N_{\rm data}} \frac{(f_N D_j - T_j^k)^2}{\sigma_j^2}$$

3. Calculate observables with new (reweighted) PDFs

$$\langle \mathcal{O} \rangle_{\rm new} = \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} w_k \mathcal{O}(f_k),$$

$$\delta \langle \mathcal{O} \rangle_{\rm new} = \sqrt{\frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} w_k \left(\mathcal{O}(f_k) - \langle \mathcal{O} \rangle\right)^2}.$$

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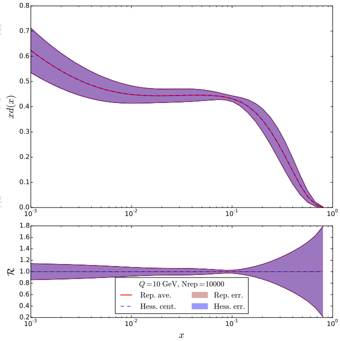

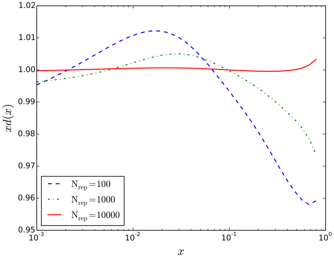

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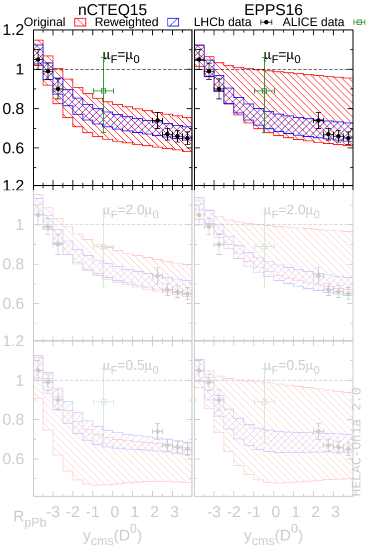
Reweighting with D^0 data



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.

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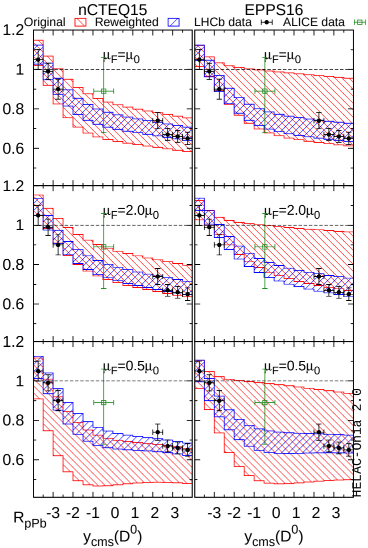

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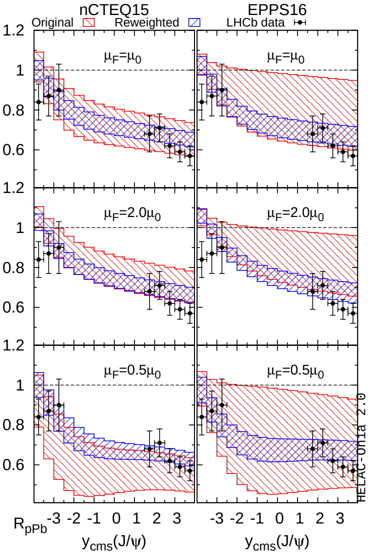
- Initial description of data is good for both nCTEQ15 and EPPS16.
- Substantial reduction of uncertainty especially for EPPS16.
- If we include factorization scale uncertainty errors increase and it can become the dominant uncertainty.

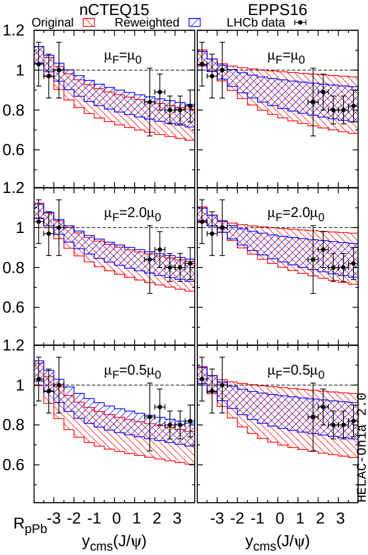
Reweighting with J/ψ data



LHCb [JHEP 02, 072 (2014), 1308.6729; PLB 774 (2017) 159, 1706.07122]
ALICE [JHEP 06, 055 (2015), 1503.07179; JHEP 02, 073 (2014), 1308.6726]

- Again we observe good agreement with the data; the scale uncertainty becomes important.

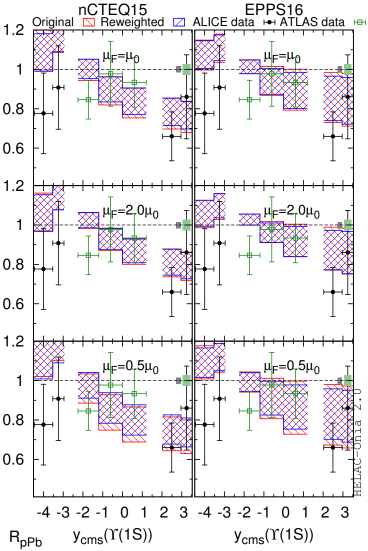
Reweighting with $B \to J/\psi$ data



LHCb [PLB 774 (2017) 159, 1706.07122]

- Scale uncertainty is reduced compared to the D^0 and J/ψ case.
- Data are not yet precise enough to give substantial constraints on nPDFs (but if the precision rises there is big potential).

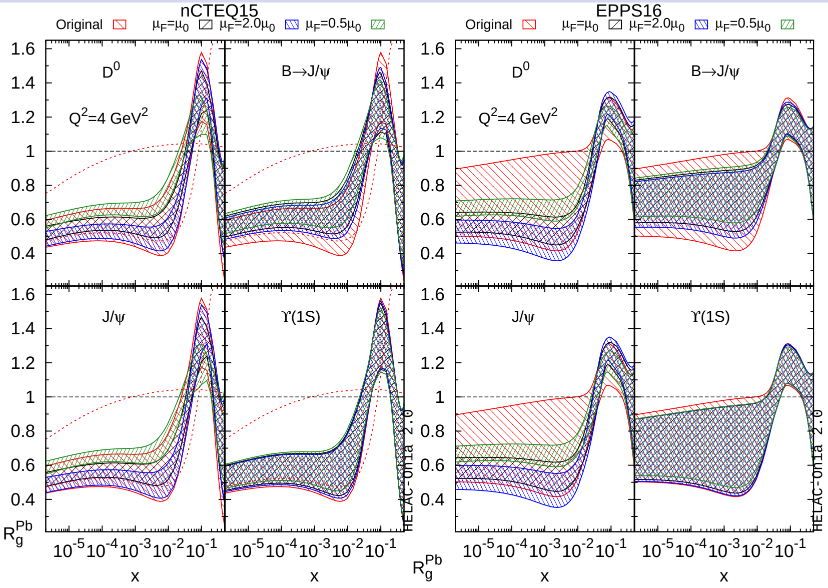
Reweighting with $\Upsilon(1S)$ data



ALICE [PLB 740, 105 (2015), 1410.2234]
ATLAS [ATLAS-CONF-2015-050 (updated in: 1709.03089)]

- With the current precision we don't get any additional constraints on the nPDFs.

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



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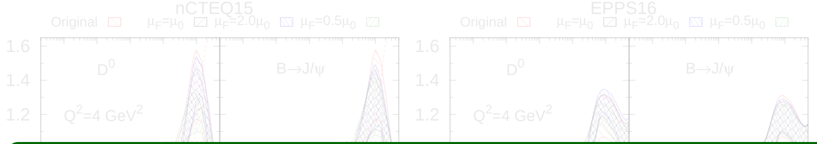


Comments

- We observe global coherence of the data constraints: necessary condition to assume a shadowing-only approach.
- First clear experimental observation on gluon SHADOWING at low x; visible reduction of the EPPS16 uncertainties; confirmation of the extrapolation done in nCTEQ15.
- Confirmation of the existence of a gluon anti-shadowing: $R_g(0.05 \lesssim x \lesssim 0.1) > 1$.
- The scale ambiguity for D^0 and J/ψ production is now the dominant uncertainty.
- Non-prompt J/ψ are really promising if improved data can be obtained.

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].

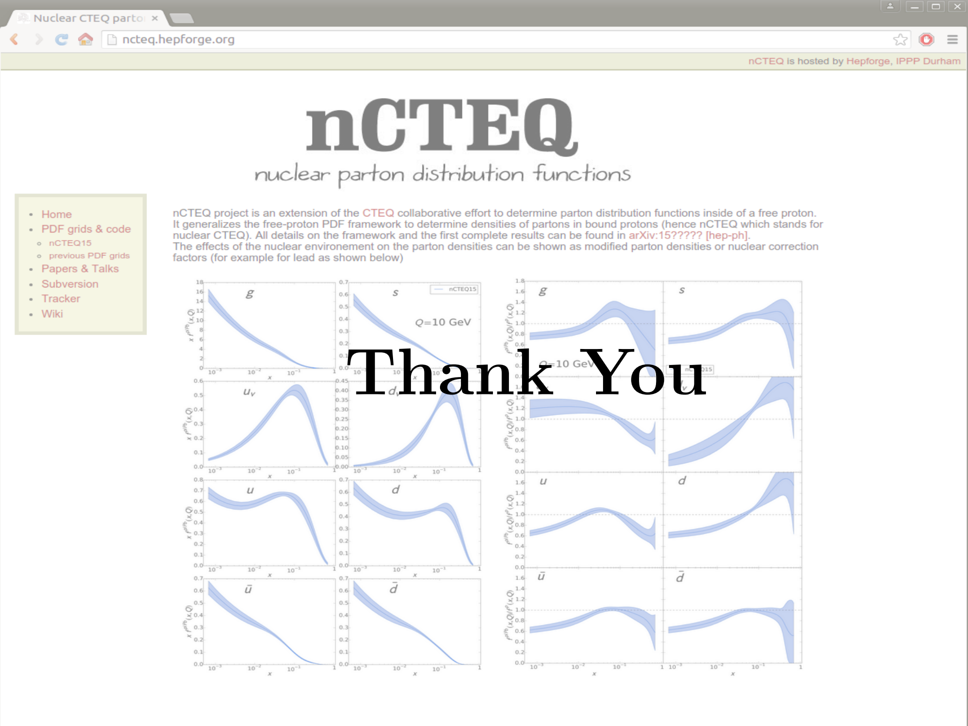
This is very non-trivial and further confirms the "shadowing-only" hypothesis of leading twist factorization is valid within the current data precision!

Summary

Summary

- Gluon nPDFs at low x are extrapolated (no low x data used in fits) $\rightarrow$ need for new constraints at $x \lesssim 10^{-3}$.
- We have proposed a quick and robust method to evaluate effects of heavy-quark data on nPDFs – complementary to full (but time consuming) pQCD computations
  - and used it to analyze D^0, J/ψ, $B \rightarrow J/\psi$ and $\Upsilon(1S)$ data.
- We tested/validated a "shadowing-only" hypothesis based on leading twist factorization.
  - confirmed by the consistency between the used data sets and also with the earlier data.
- Under this hypothesis, the first observation of gluon shadowing was made. Additionally, our analysis corroborates the existance of gluon antishadowing.
- We have showed that the heavy-quark data can improve our knowledge of the nuclear gluon distribution and it should be included in future nPDF fits.

Thank You


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
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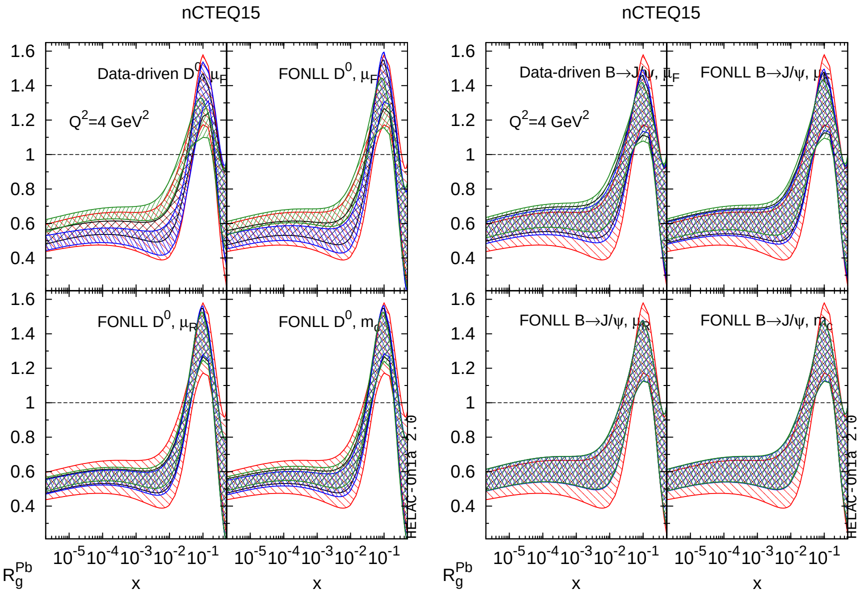
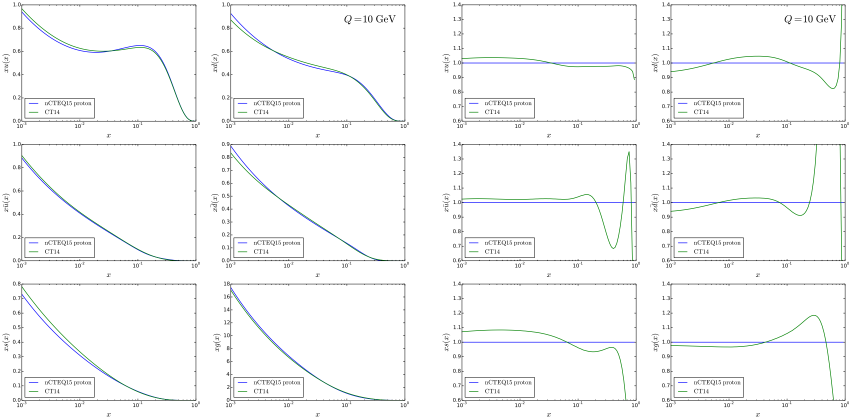
nCTEQ project is an extension of the CTEQ collaborative effort to determine parton distribution functions inside of a free proton. It generalizes the free-proton PDF framework to determine densities of partons in bound protons (hence nCTEQ which stands for nuclear CTEQ). All details on the framework 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)
nCTEQ15
Q=10 GeV

BACKUP SLIDES

Data-driven vs. FONLL



CT10 vs. CTEQ6.1 PDFs



Consistency with other data

Table : $\chi^2/N_{\rm data}$ values for nCTEQ15 nPDFs before and after reweighting using B, D, J/ψ data for different scale choices.

		after reweighting								
	nCTEQ15	B μ_0	B up	B down	D μ_0	D up	D down	J/ψ μ_0	J/ψ up	J/ψ down
W/Z LHC (102)	2.43	2.10	2.15	2.08	2.49	3.11	2.14	2.66	3.25	2.25
NMC F_2^{Sn}/F_2^C (111)	0.58	0.71	0.64	0.77	0.59	0.56	0.84	0.60	0.56	0.88
NMC F_2^{Pb}/F_2^C (14)	0.55	0.51	0.53	0.56	0.50	0.63	0.59	0.44	0.56	0.59
PHENIX J/ψ $R_{\rm dAu}$	1.99							1.93	0.43	3.35

EPS09:

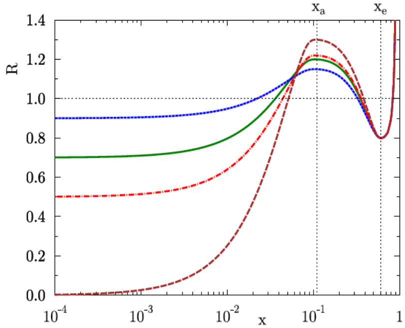
[N. Armesto, 2015 LHeC Workshop, Chavannes-de-Bogis, June 26th 2015]

- Very little freedom at small x.

The fit function in EPS09:

$$R^{\mathrm{EPS09}}(x) = \begin{cases} a_0 + (a_1 + a_2 x)\left(e^{-x} - e^{-x_a}\right) & x \le x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1 \end{cases}$$

(power-law parametrization of A-dependence at x_a, x_e, and $x \to 0$)

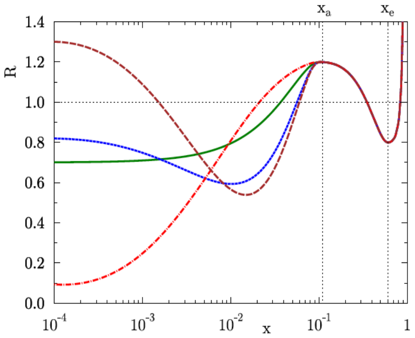


New ICs:

[N. Armesto, 2015 LHeC Workshop, Chavannes-de-Bogis, June 26th 2015]

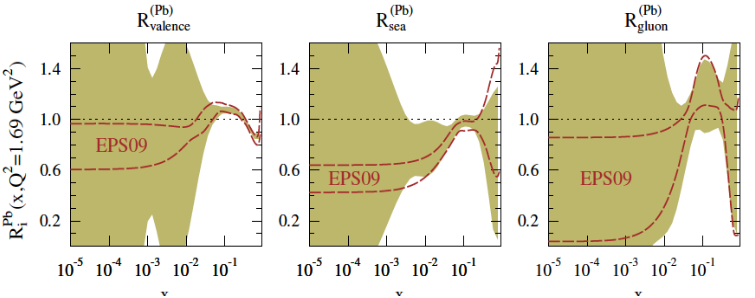
- Use a far more flexible form to reduce the bias at small x:

$$\begin{aligned} R(x \leq x_a) &= a_0 + a_1(x - x_a)^2 \\ &+ \sqrt{x}(x_a - x)\left[a_2 \log\left(\frac{x}{x_a}\right) + a_3 \log^2\left(\frac{x}{x_a}\right) + a_4 \log^3\left(\frac{x}{x_a}\right)\right] \end{aligned}$$



New fit framework:

The baseline fit using the new fit functions: no control over small x!



The lower bound restricted here by $F_L(Q^2 = 2\,\mathrm{GeV}^2, x > 10^{-5}) > 0$

Maybe against "physical intuition" (small-x theory predicts shadowing, $R_i < 1$), but consistent with the data.

E.g. in EPS09, small-x shadowing was essentially built in

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