Constraining the gluon nuclear content with heavy-flavour production at the LHC

J.P. Lansberg
IPN Orsay – Paris-Sud U. –CNRS/IN2P3 – Université Paris-Saclay

EPS-HEP 2019, Ghent, Belgium

in collaboration with A. Kusina, I. Schienbein and H.S. Shao

based on PRL 121 (2018) 052004 & EPJC 77 (2017) 1 & more to appear

Introduction

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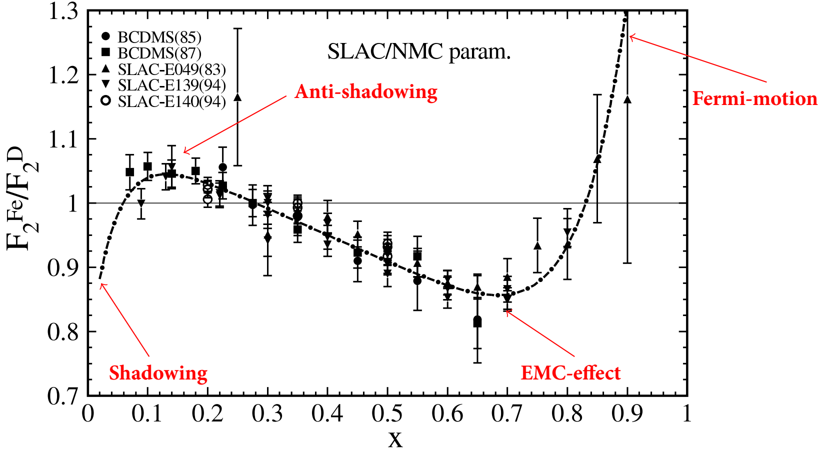
- Cross-sections in nuclear collisions are modified



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

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Nuclear PDFs (nPDFs) allow one to get information on:

- the structure of the nuclei in terms of quarks and gluons;
- the initial state of heavy-ion collisions at the LHC and RHIC
  esp. to use perturbative probes of the QGP to study its properties.

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fit to experimental data. Only the evolution is perturbative

→ Can heavy-flavour data help us better constrain the nPDFs ?

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Differences with the free-proton PDFs

- Theoretical status of Factorisation
- Parametrisation – more parameters to model the A-dependence
- Different data sets – much less data:

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

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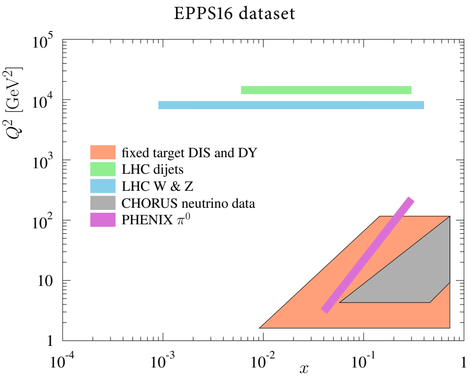

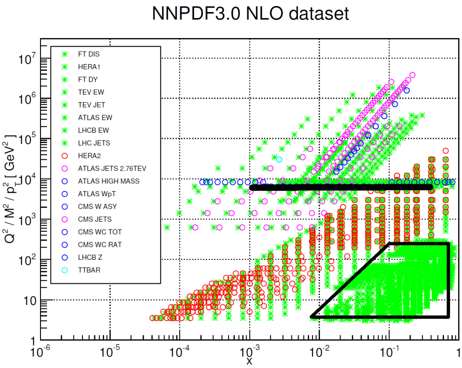

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Current nPDFs

N. Armesto, DIS 2019

SET		EPS09 JHEP 0904 (2009) 065	DSSZ PRD85 (2012) 074028	nCTEQ15 PRD93 (2016) 085037	KA15 PRD93 (2016) 014036	EPPS16 EPJC C77 (2017)163	nNNPDF1.0 1904.00018
data	eDIS	✔	✔	✔	✔	✔	✔
	DY	✔	✔	✔	✔	✔	✘
	π^0	✔	✔	✔	✘	✔	✘
	νDIS	✘	✔	✘	✘	✔	✘
	pPb	✘	✘	✘	✘	✔	✘
# data		929	1579	740	1479	1811	451
order		NLO	NLO	NLO	NNLO	NLO	NNLO
proton PDF		CTEQ6.1	MSTW2008	~CTEQ6.1	JR09	CT14NLO	NNPDF3.1
mass scheme		ZM-VFNS	GM-VFNS	GM-VFNS	ZM-VFNS	GM-VFNS	FONLL-B
comments		$\Delta\chi^2$=50, ratios, huge shadowing-antishadowing	$\Delta\chi^2$=30, ratios, medium-modified FFs for π^0	$\Delta\chi^2$=35, PDFs, valence flavour sep., not enough sensitivity	PDFs, deuteron data included	$\Delta\chi^2$=52, flavour sep., ratios, LHC pPb data	NNPDF methodology, isoscalarity assumed

Current nPDFs

[arXiv:1509.00792, arXiv:1012.1178]

[arXiv:1612.05741,arXiv:1904.00018

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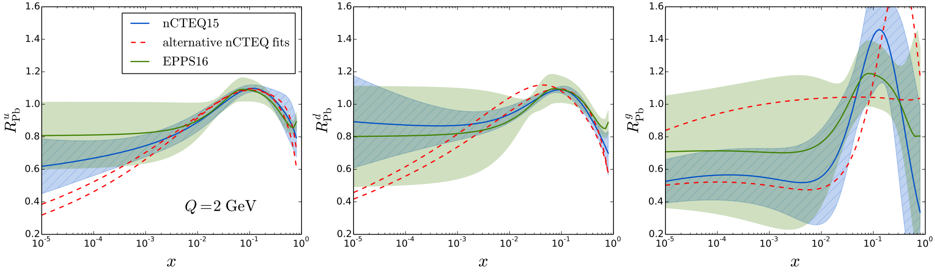

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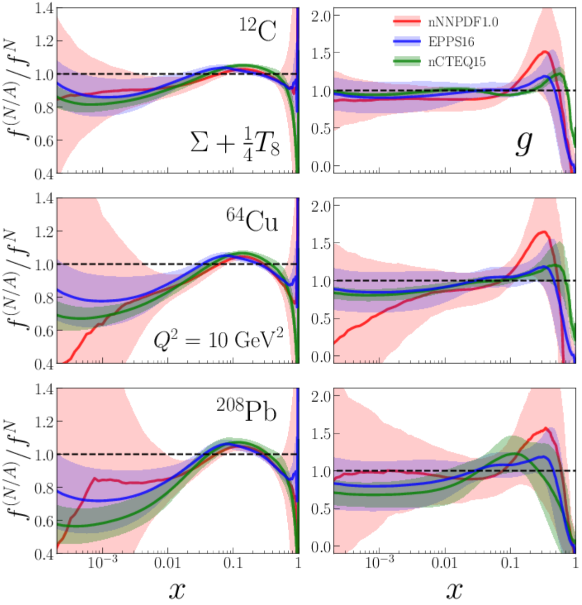

Heavy-flavour LHC data

Available heavy-flavour pPb LHC data*

	D^0	J/ψ	$B \to J/\psi$	$\Upsilon(1S)$
μ_0	$\sqrt{4M^2_{D^0} + P^2_{T,D^0}}$	$\sqrt{M^2_{J/\psi} + P^2_{T,J/\psi}}$	$\sqrt{4M^2_B + \left(\frac{M_B}{M_{J/\psi}} P_{T,J/\psi}\right)^2}$	$\sqrt{M^2_{\Upsilon(1S)} + P^2_{T,\Upsilon(1S)}}$
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.

* : **At the time we performed our study (→ we can add more in the future; see the talks in this session)**

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 that the leading twist factorisation is valid – ONLY modifications of PDFs are present → "shadowing-only" hypothesis.

→ we de facto do not consider excited quarkonium data.

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Automating the computation of nuclear PDF effects on HF production

An automated code to evaluate the impact of nuclear PDF I

JPL, H.S. Shao Eur.Phys.J. C77 (2017) 1

- **Partonic** scattering cross section fit from *pp* data with a Crystal Ball function parametrising $|\mathcal{A}_{gg\to\mathcal{H}X}|^2$ **C.H. Kom, A. Kulesza, W.J. Stirling PRL 107 (2011) 082002**
- A way to evade the quarkonium-production-mechanism controversy ?

  for a recent review: JPL, 1903.09185, submitted to Phys. Rept.

  To some extent, I would say "yes".
- Applied to J/ψ, Υ, D and B: it can be extended to all the probes produced in $2 \to 2$ partonic processes with a single partonic contribution
- The key point to compute nPDF effect is to have a **partonic** cross section
- Validated (for D^0) by the state-of-the-art pQCD code FONLL
- Any nPDF set available in LHAPDF5 or 6 can be used
- Currently limited to processes dominated by a single partonic channel

  (gg or $q\bar{q}$, ...)
- Not yet interfaced to a Glauber model

  [no centrality and no combination with other nuclear effects]

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  which make sense if nPDFs are the only nuclear effect
- Conversely, one can test this hypothesis by comparing our curves to data
  Global agreement $\overset{?}{\Rightarrow}$ only nPDFs matter
- One can go further in the data comparison with reweighting (see later)
  and then HF-data inclusion in nPDF fits
- Last but not least: the automation of the evaluation allows one to study different nPDF sets AND the scale uncertainties: better control of the theory uncertainties

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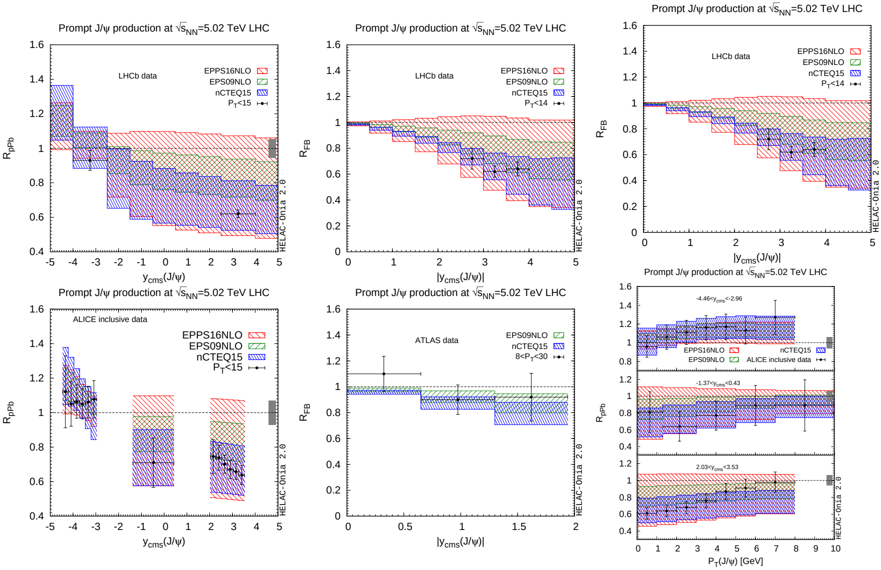
Results for pA collisions using nCTEQ15 & EPPS16 out-of-the-box

Some J/ψ comparisons



More results: $\Upsilon(1S)$ and ... η_c

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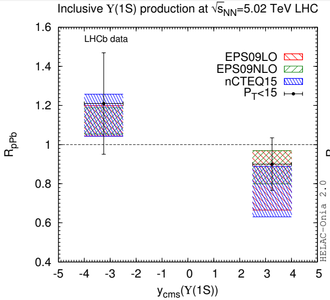
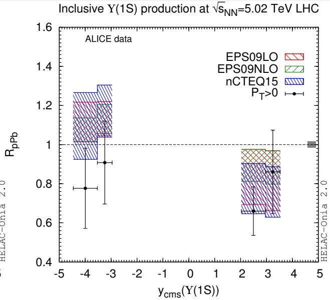
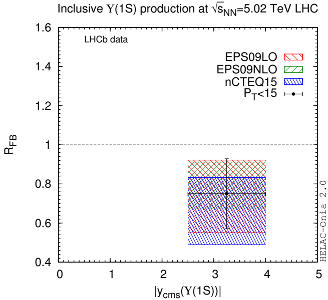




Our 8 TeV predictions in J.L. Albacete, *et al.*. NPA 972 (2018) 18



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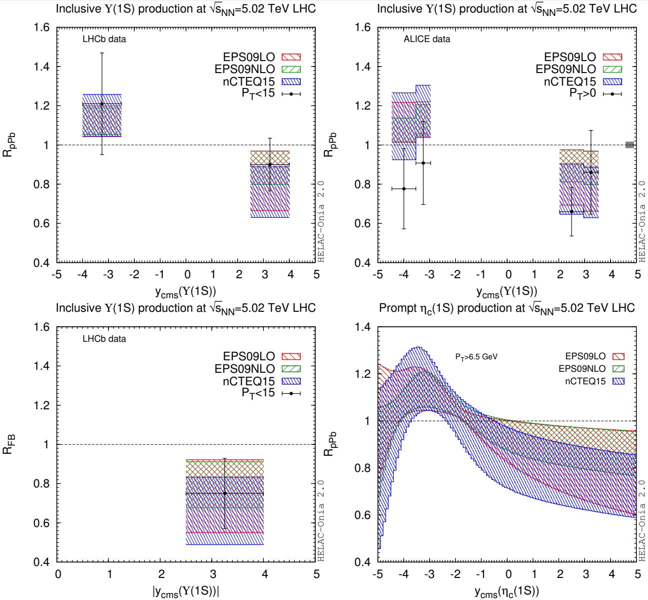

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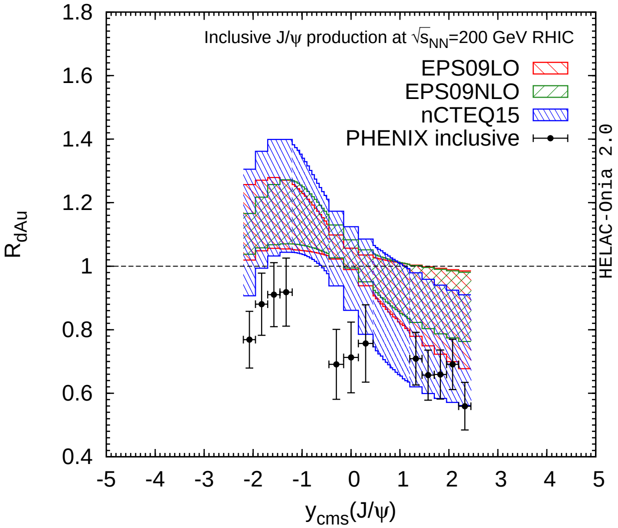
J/ψ's at RHIC: no more tension with forward J/ψ data !



→ : Backward data likely affected by break-up or comover interactions;

→ : Question mark on the $y \sim 0$ data: no antishadowing ?

Impact on nPDFs: reweighting analysis[1]

[1] From now on, all nPDF uncertainties are 68%CL

Reweighting: the principle behind

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

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

3. Calculate observables with new (reweighted) PDFs

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

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

- N is the # of eigensets, N_{rep} is the # of constructed replicas
- f_0 is the "central-value" of the nPDF vector (*i.e.* of functions of x) in $N_{\rm flavour}$ dimension
- $f_i^{(\pm)}$ ($i \in [1:N]$) is the "upper/lower value" function of a given eigenset i
- R_{ki} is a number randomly choosen for each set of (k, i) (thus fixed for all $N_{\rm flavour}$) according to a standard Normal distribution
- f_k is the constructed vector
- T_j^k is the predicted theory for data j and replica k
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Reweighting: the principle behind

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

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

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* N is the # of eigensets, N_{rep} is the # of constructed replicas
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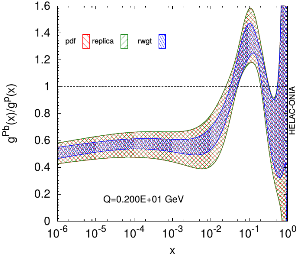
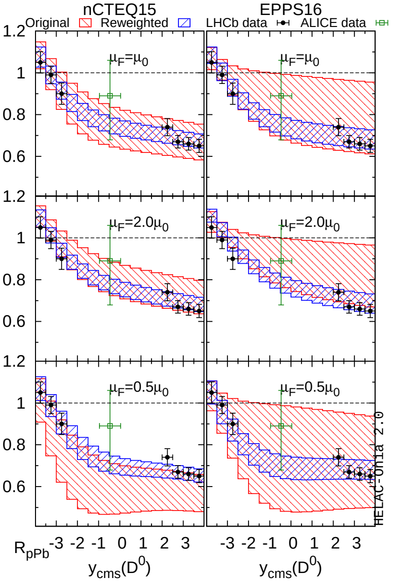


Reweighting with D^0 data



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

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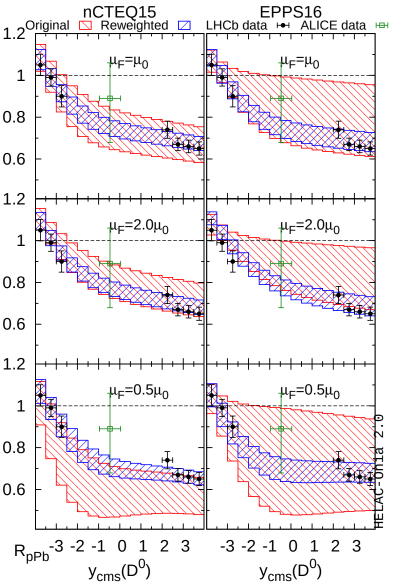

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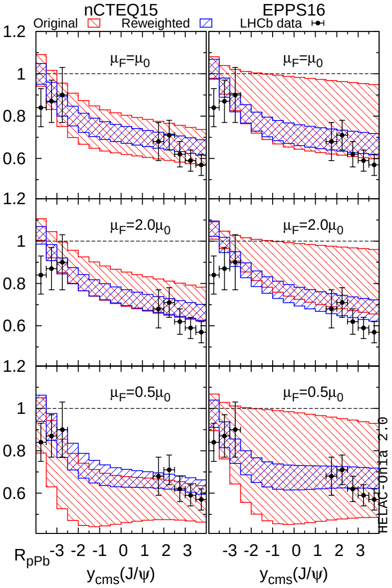
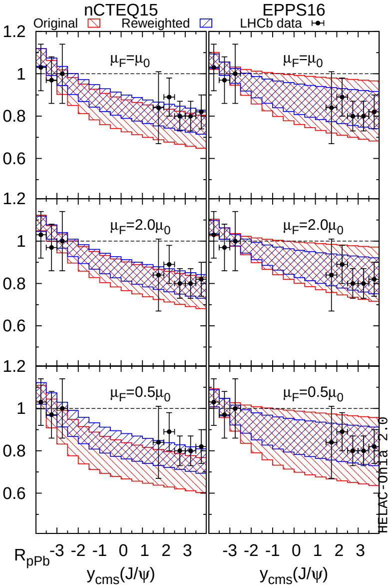
Reweighting with J/ψ data



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 a good agreement with the data; the **scale uncertainty** becomes important.

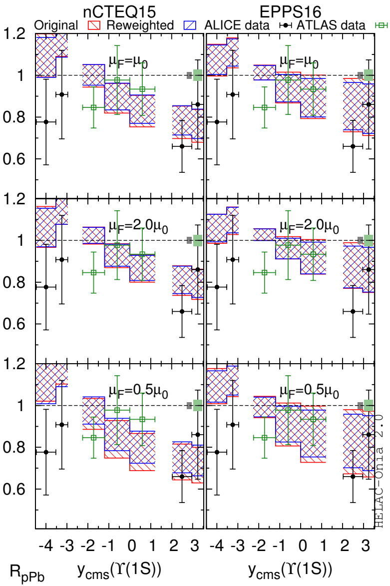
Reweighting with $B \to J/\psi$ data



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

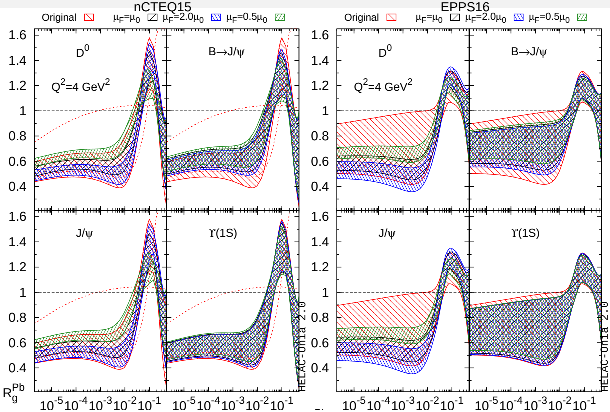


ALICE [PLB 740, 105 (2015), 1410.2234]

ATLAS [ATLAS-CONF-2015-050 (updated in: 1709.03089)]

- With the current precision we do not get any additional constraints on the nPDFs.

Results of the reweighting process



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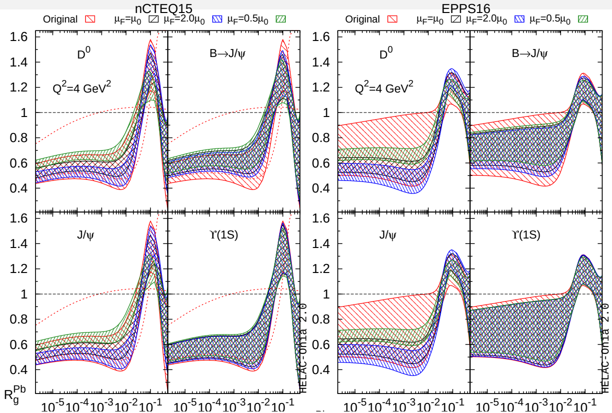

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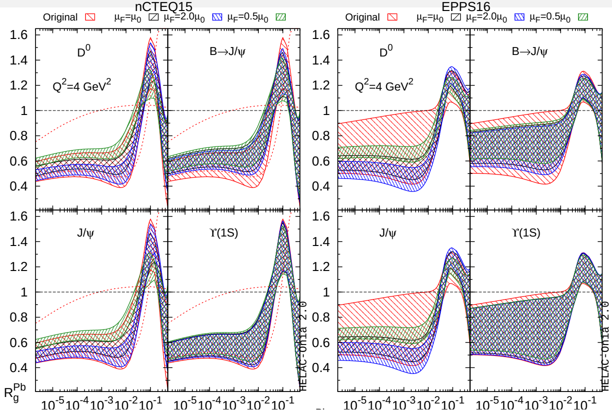

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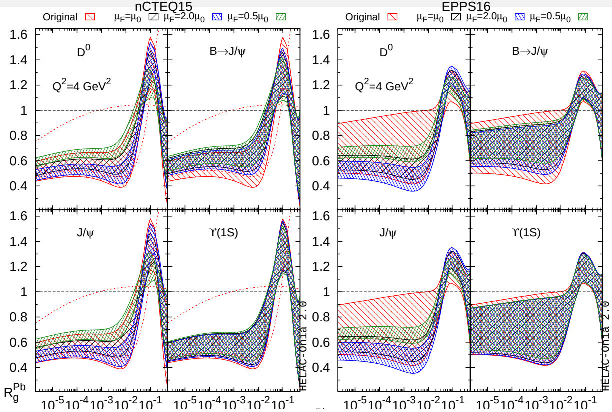

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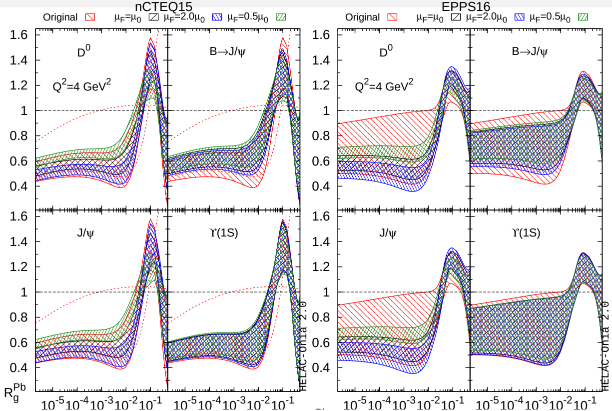

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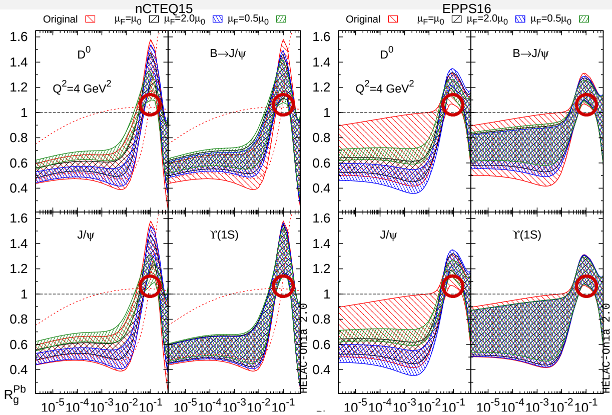

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Consistency with other data

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

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

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

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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
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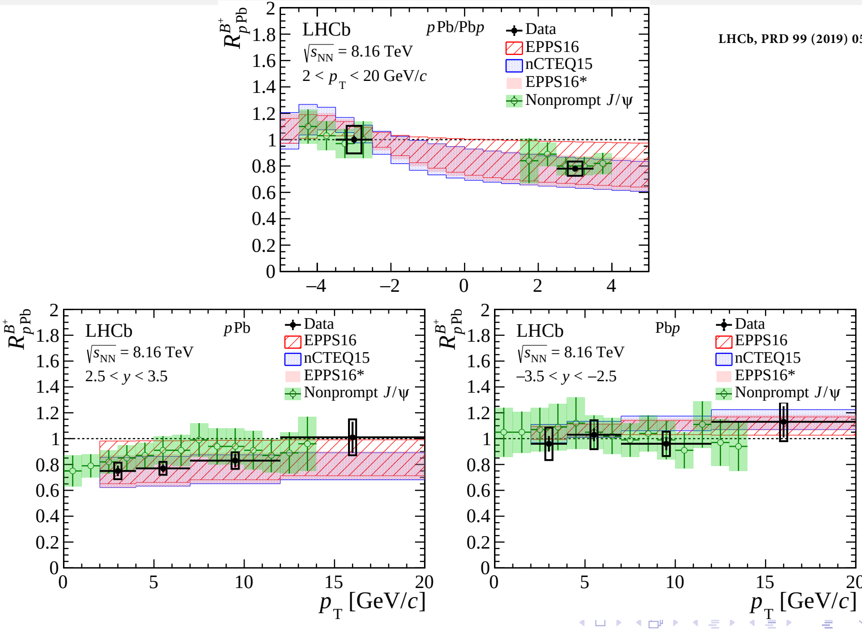
Predictions using the reweighted nPDFs

Improved agreement with the reweighted nPDFs for B^+

LHCb, PRD 99 (2019) 052011



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  $\rightarrow$ 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

  $\rightarrow$ we used it to analyse D^0, J/ψ, $B \rightarrow J/\psi$ and $\Upsilon(1S)$ data.
- We proposed a "shadowing-only" hypothesis based on the leading twist factorisation

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- Under this hypothesis, we made, using a Bayesian reweighting, the first direct observation of gluon shadowing. Additionally, our analysis corroborates the existence of gluon antishadowing.
- Studying the coherence with AA UPC J/ψ data is in our to do list BUT
  (i) the nuclear GPDs are unknown (likely not directy connected to nPDFs) &
  (ii) the scale uncertainties is likely huge (cf. NLO $\gamma p \rightarrow J/\psi p$ analyses)
- We will release very soon the LHAPDF grids of the reweighted nPDFs presented here.
- Overall, the heavy-quark data can improve our knowledge of the nuclear gluon distribution and it should be included in future nPDF fits.
- Our work is part of a clear renewal our interest for HF data for (n)PDF studies

  [EPJC 75 (2015) 396, JHEP 1704 (2017) 044, PRL 118 (2017) 072001, 1906.06971, 1906.02512, 1907.01400, ...].
- and will contribute to the elaboration of NLOAccess within the EU network STRONG-2020.

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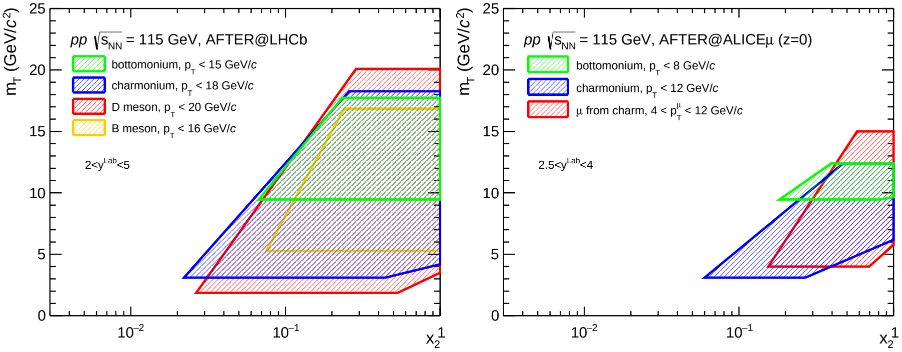
BACKUP SLIDES

Application to the LHC in the fixed-target mode (AFTER@LHC)

HF kinematical coverage of LHCb and ALICE in the fixed-target mode [arXiv:1807.00603]



ALICE could cover $\eta \sim 1-2$ for quarkonium into dileptons with one muon in the muon arm and another in the central barrel

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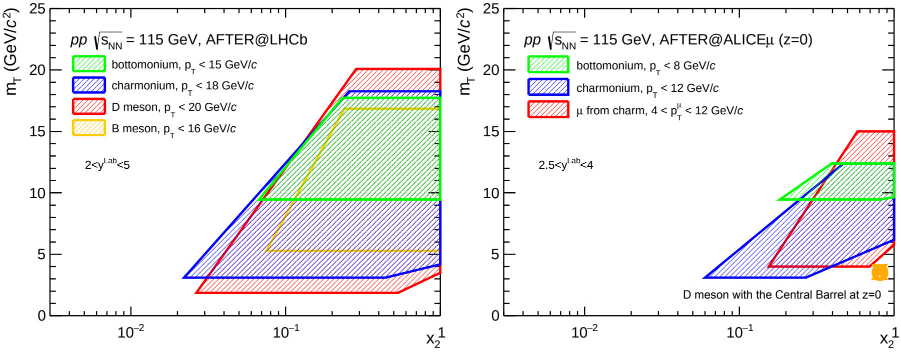

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- This is the realm of the FT LHC experiments
- First projections are extremely promising
  [NB: initial nPDF uncertainties for $x > 0.1$ are underestimated;
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- This assumes that we control other potential CNM effects: global study required !
- Similar studies for the *proton* PDFs are yet to be done along the lines of the studies carried out for low-x gluon at the LHC
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Reward: unique constraints on gluon PDFs at high x and low scales

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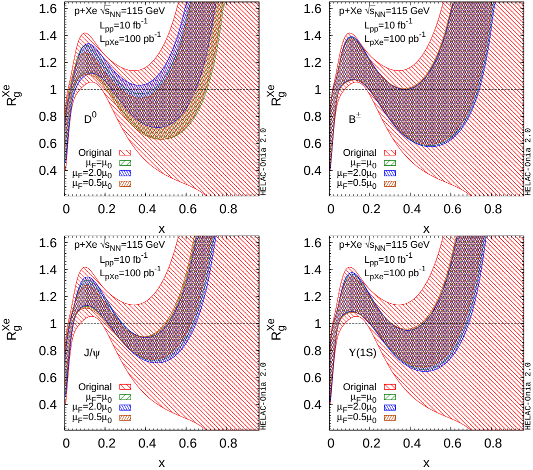

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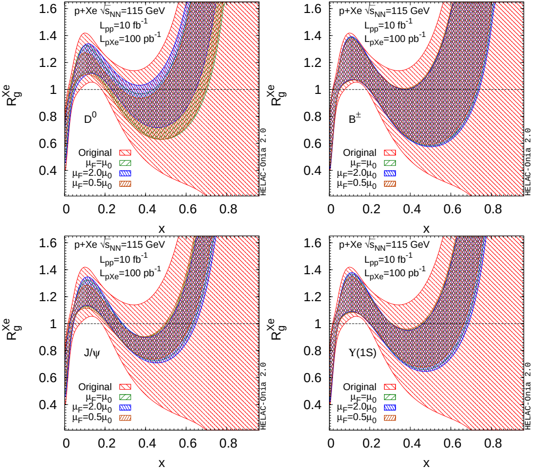

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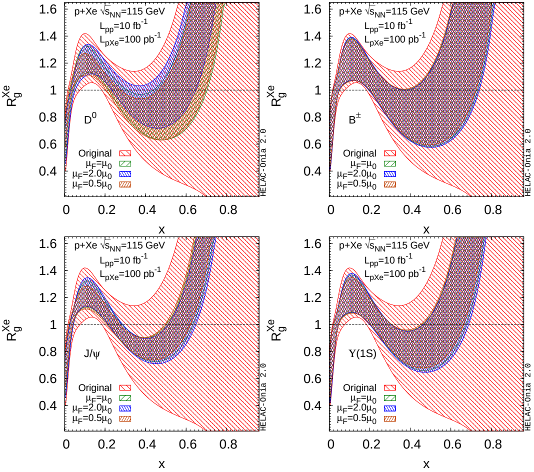

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A quick comparison between nCTEQ15 and EPPS16

- **Parametrisation**
  - 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]

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

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

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

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

Data-driven vs. FONLL