

AFTER@LHC & LHC (n)PDF reweighting

based on: arXiv:1807.00603

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on behalf of the AFTER@LHC Study Group:
http://after.in2p3.fr/after/index.php/Current_member_list

FTE@LHC & NLOAccess
STRONG 2020 joint kick-off meeting
CERN, 7-8 November 2019

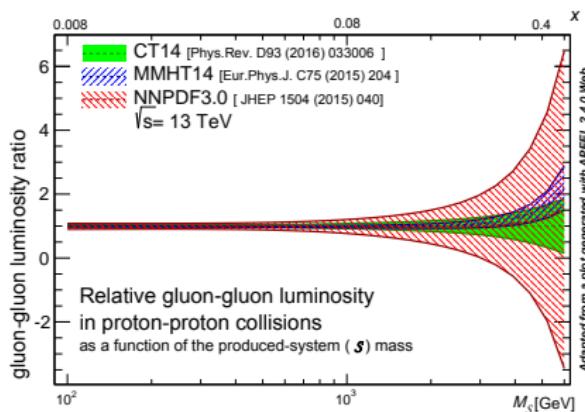
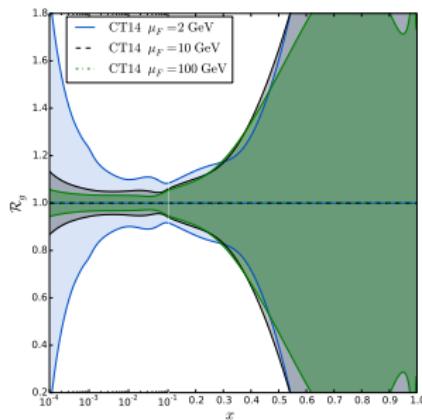


Outline

- ▶ Motivations from PDF perspective
- ▶ AFTER@LHC essentials
- ▶ Projected performances at AFTER@LHC
 - ▶ Drell-Yan lepton pair production
 - ▶ Open and hidden heavy flavour mesons
 - ▶ W boson production
 - ▶ Non-perturbative charm
- ▶ Summary

Motivation

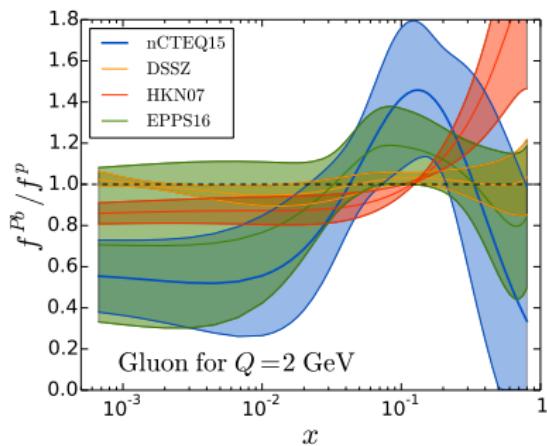
- ▶ The structure of nucleon and nuclei at high x is poorly known
 - ▶ advance knowledge of QCD confinement,
 - ▶ improve knowledge of parton luminosities at colliders (LHC, FCC, ...) and ultra high energy cosmic rays.



- ▶ Origin of the nuclear EMC effect.
- ▶ Possible non-perturbative source of charm or beauty (quarks in the proton which would carry a big fraction of its momentum).

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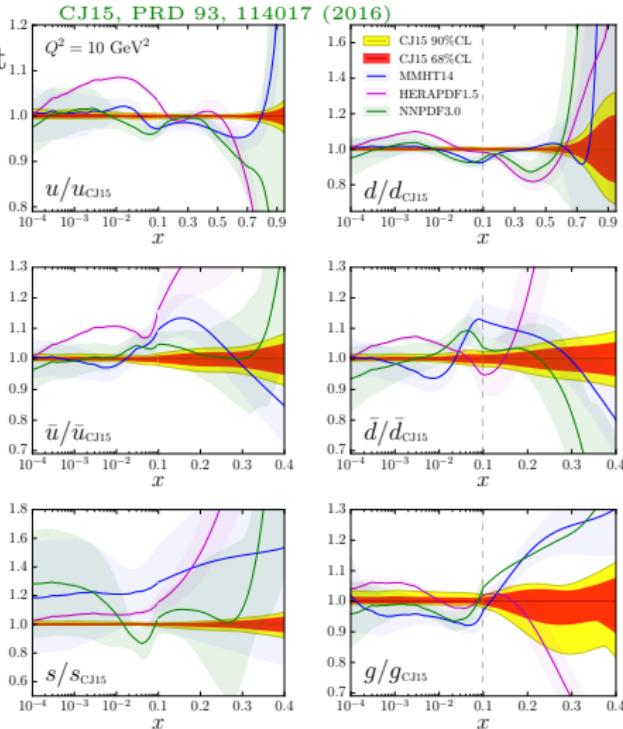


- ▶ Origin of the nuclear EMC effect.
- ▶ Possible non-perturbative source of charm or beauty (quarks in the proton which would carry a big fraction of its momentum).

Motivation

Partonic structure of nucleons and nuclei at high- x ($x > 0.5$) poorly known:

- ▶ > 50% uncertainty on $d(x)$ at $x > 0.6$
- ▶ > 50% uncertainty on $g(x)$ at $x > 0.2$
- ▶ very large uncertainties on quark sea



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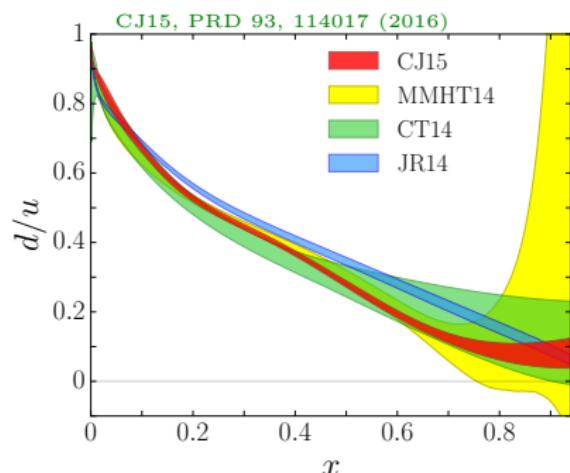
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Better understanding provides tests of models of hadron structure, e.g. for $x \rightarrow 1$:

- ▶ $d/u \rightarrow 1/2$: SU(6) Spin-Flavor symm.
- ▶ $d/u \rightarrow 0$: Scalar diquark dominance
- ▶ $d/u \rightarrow 1/5$: pQCD power counting
- ▶ Local quark hadron duality:
$$d/u \rightarrow \frac{4\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2} \simeq 0.42$$

Better understanding important for BSM searches of new heavy states



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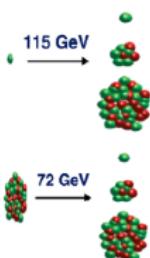


Fixed-target collisions at the LHC: main kinematical features

Energy range similar to RHIC

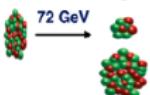
7 TeV proton beam on a fixed target

c.m.s. energy: $\sqrt{s} = \sqrt{2m_N E_p} \approx 115 \text{ GeV}$	Rapidity shift:
Boost: $\gamma = \sqrt{s} / (2m_N) \approx 60$	$y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.8$



2.76 TeV Pb beam on a fixed target

c.m.s. energy: $\sqrt{s_{NN}} = \sqrt{2m_N E_{\text{Pb}}} \approx 72 \text{ GeV}$	Rapidity shift:
Boost: $\gamma \approx 40$	$y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.3$

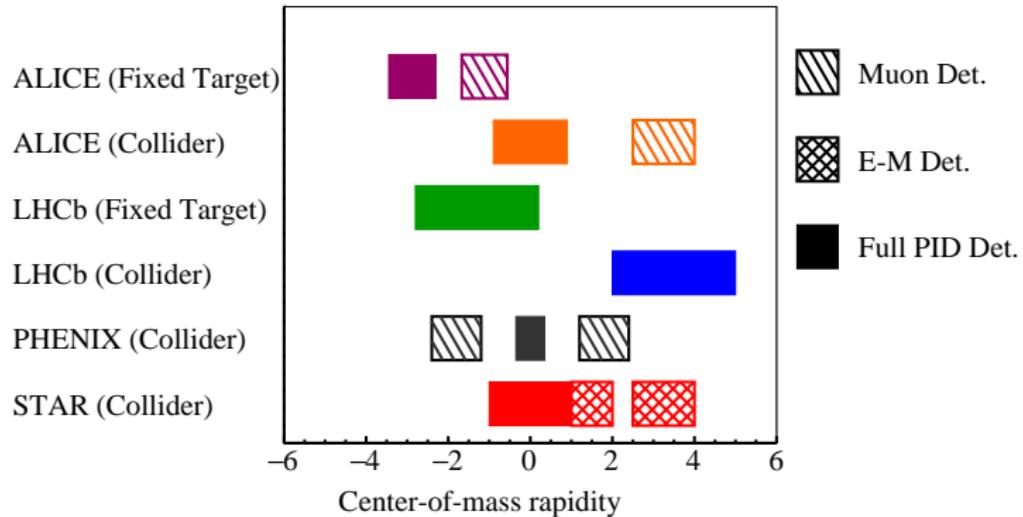


Effect of boost :

[particularly relevant for high energy beams]

- LHCb and the ALICE muon arm become **backward detectors** $[y_{c.m.s.} < 0]$
- The ALICE central barrel becomes an **extreme backward detector**
- With the reduced \sqrt{s} , their **acceptance for physics grows** and nearly covers half of the backward region for most probes $[-1 < x_F < 0]$
- Allows for backward physics up to high x_2
[uncharted for proton-nucleus coll.]; most relevant for pp^\uparrow with large x^\uparrow]

Rapidity coverage

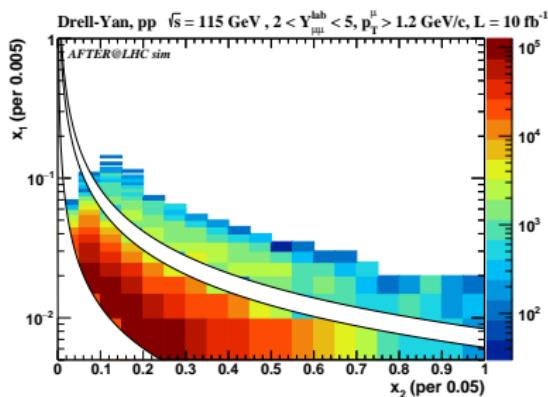
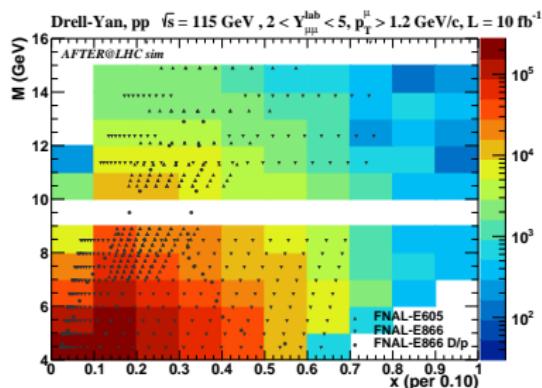


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Drell-Yan kinematic coverage

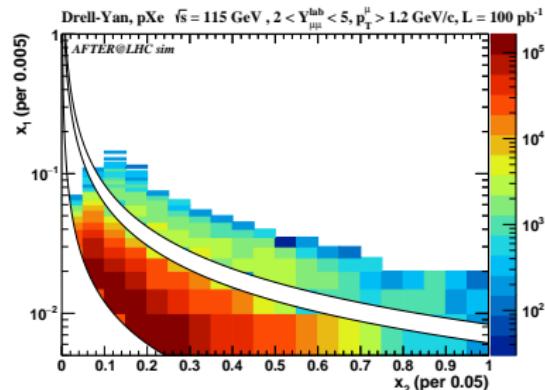
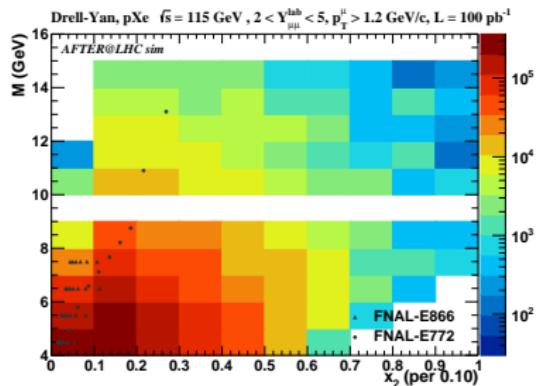
Kinematic plane of DY at AFTER@LHCb in pp collisions at $\sqrt{s} = 115$ GeV with acceptance: $2 < \eta_\mu^{\text{lab}} < 5$ and $p_T^\mu > 1.2$ GeV.



- ▶ Access to very large x .
- ▶ Much higher statistics in the region covered by NuSea (E866).
- ▶ Current data points as used by NNPDF global analysis.

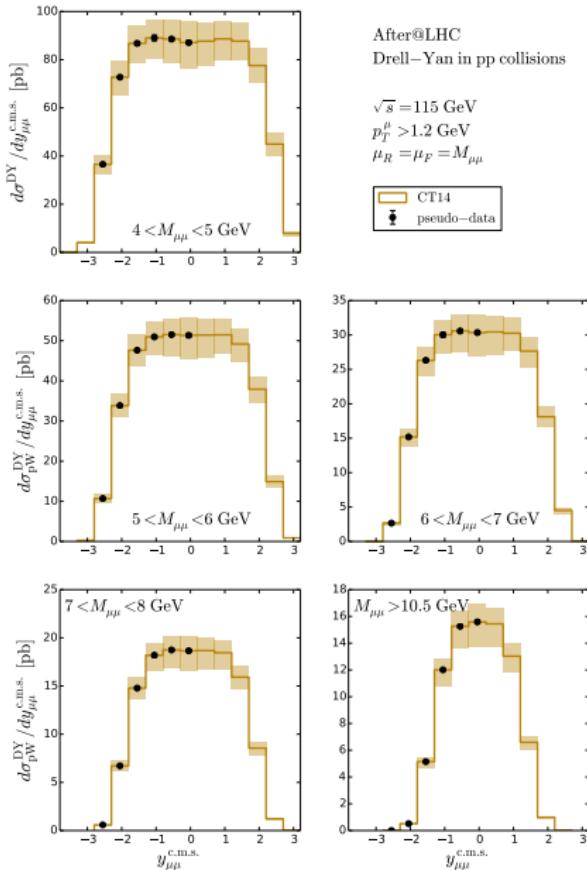
Drell-Yan kinematic coverage

Kinematic plane of DY at AFTER@LHCb in $p\text{Xe}$ collisions at $\sqrt{s} = 115$ GeV with acceptance: $2 < \eta_\mu^{\text{lab}} < 5$ and $p_T^\mu > 1.2$ GeV.



- ▶ **Unique acceptance:** access to large and very large x – region currently lacking data that could be used in global nPDF analysis.
- ▶ **Extremely large yields** up to $x_2 \rightarrow 1$.
- ▶ Current data points as used by nCTEQ and EPPS global analyses.

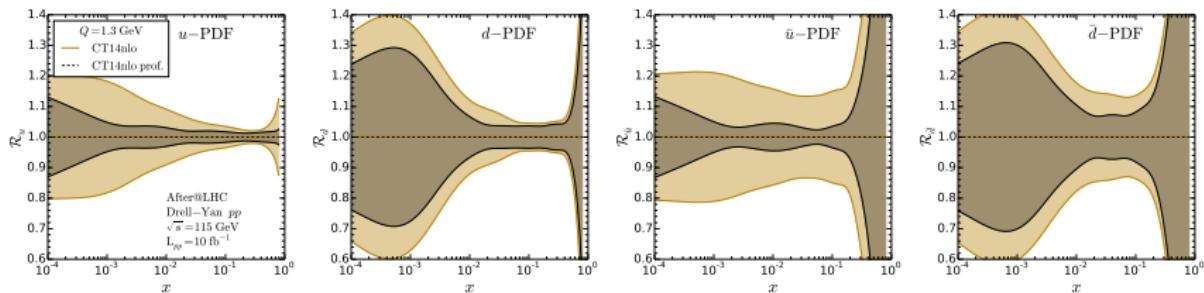
Impact of pp Drell-Yan pseudo-data on proton PDFs



- ▶ Pseudo-data produced using MCFM at NLO with CT14 PDFs. (projected experimental uncertainty = statistical uncertainty from the DY yield + uncertainty from the underlying minimum bias event), assuming $\mathcal{L}_{pp} = 10 \text{ fb}^{-1}$.
- ▶ To estimate the impact of these pseudo-data on PDFs we use reweighting/profiling methods.

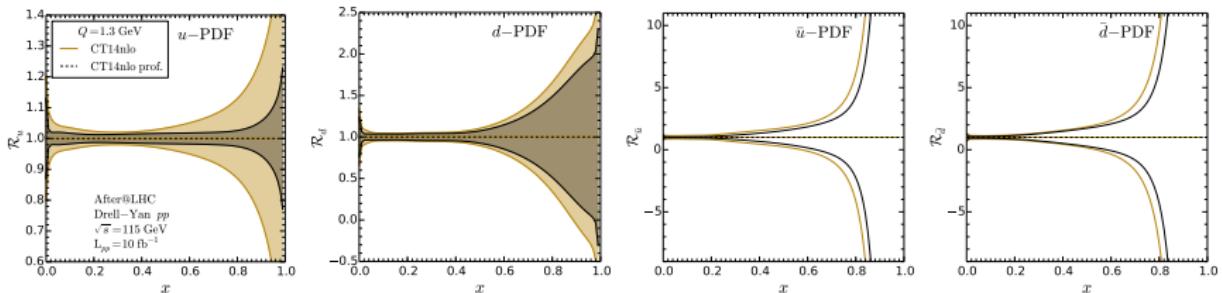
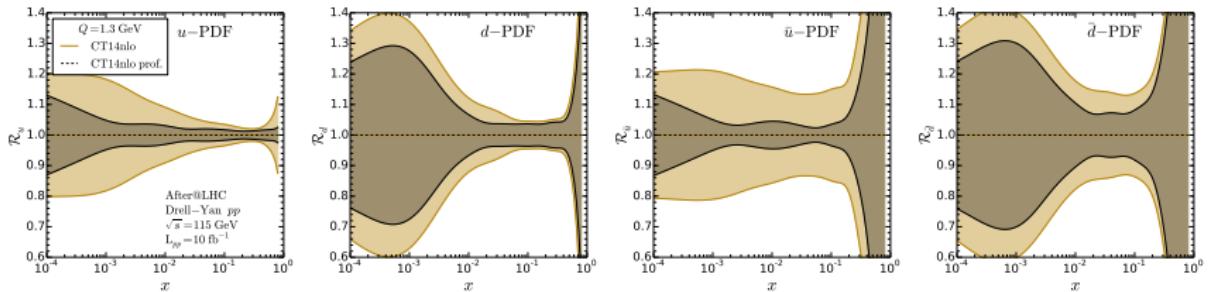
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► $L_{pp} = 10 \text{ fb}^{-1}$



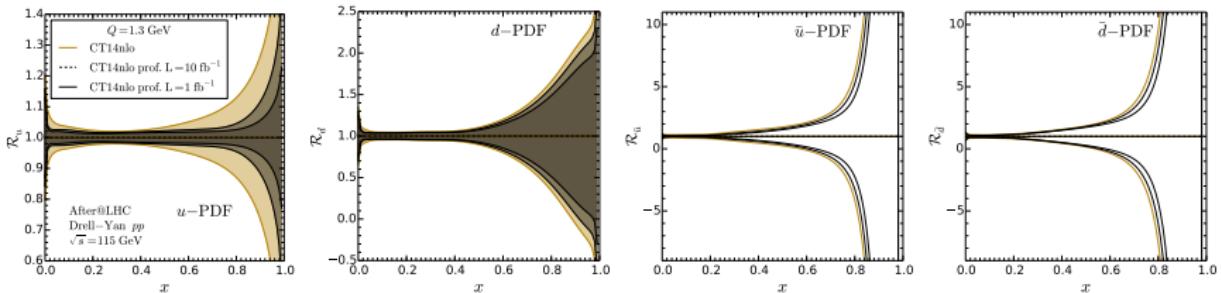
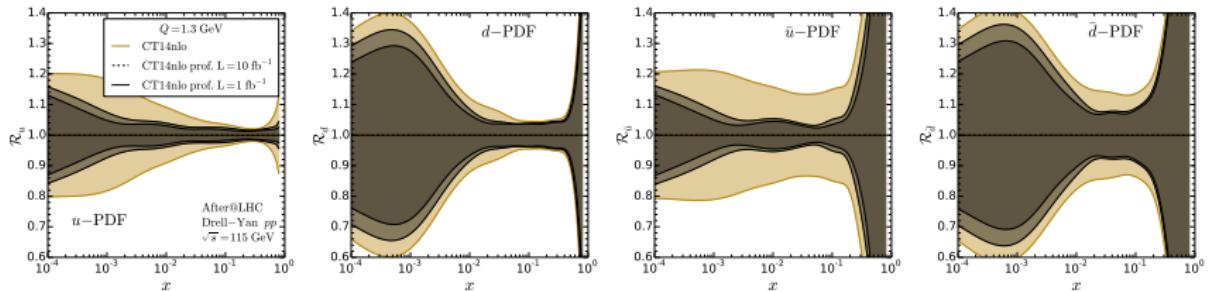
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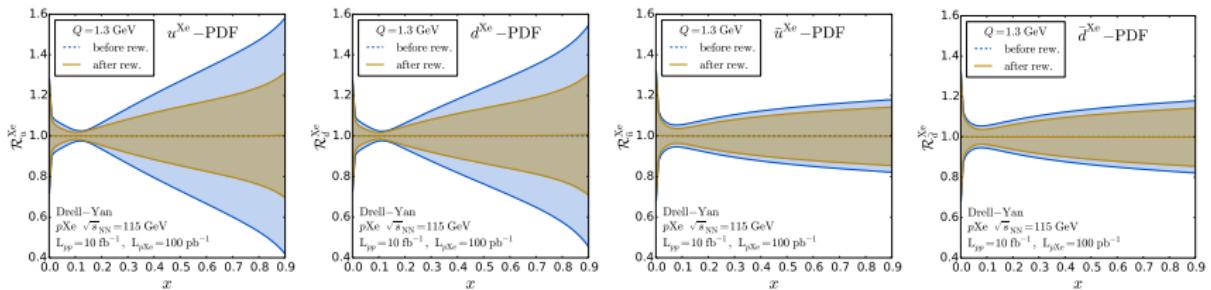
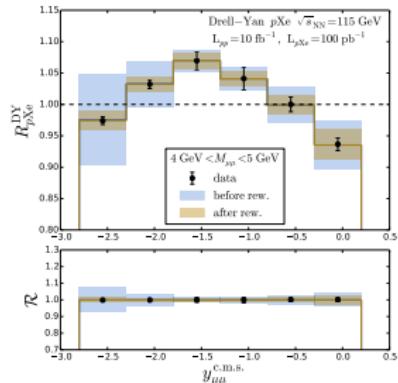
Impact of pp Drell-Yan pseudo-data on proton PDFs

► $L_{pp} = 1 \text{ fb}^{-1}$



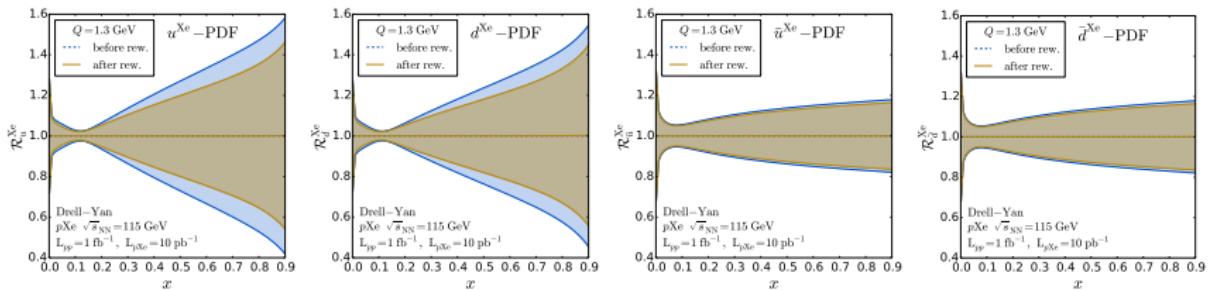
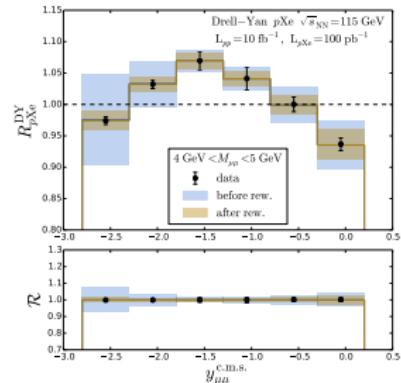
Impact of $p\text{Xe}$ Drell-Yan pseudo-data on nPDFs

- ▶ Pseudo-data for nuclear modifications $R_{p\text{Xe}}$ produced using FEWZ at NLO with nCTEQ15 nPDFs, for 5 bins in the invariant mass of lepton pair:
 - ▶ $4 < M_{\mu\mu} < 5 \text{ GeV}$
 - ▶ $5 < M_{\mu\mu} < 6 \text{ GeV}$
 - ▶ $6 < M_{\mu\mu} < 7 \text{ GeV}$
 - ▶ $7 < M_{\mu\mu} < 8 \text{ GeV}$
 - ▶ $M_{\mu\mu} > 10 \text{ GeV}$
- ▶ Impact of the pseudo-data on nPDFs estimated using reweighting method.
- ▶ $L_{pp} = 10 \text{ fb}^{-1}$, $L_{pXe} = 100 \text{ pb}^{-1}$



Impact of $p\text{Xe}$ Drell-Yan pseudo-data on nPDFs

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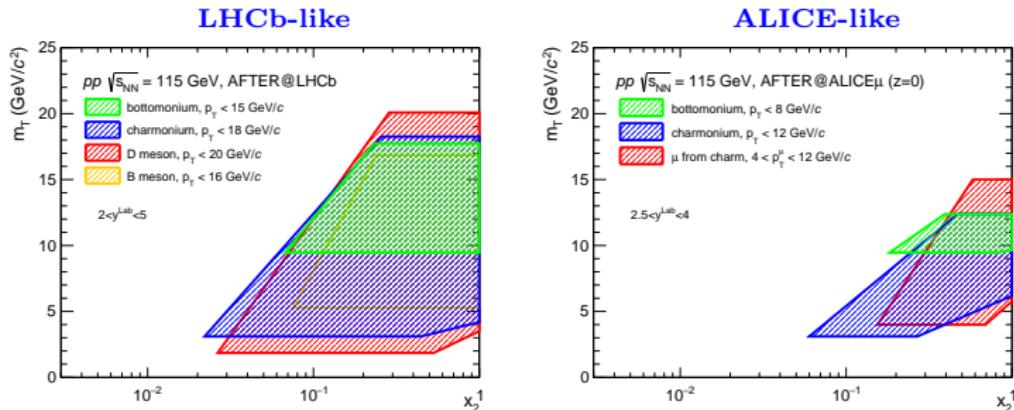


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Open and hidden heavy flavour mesons

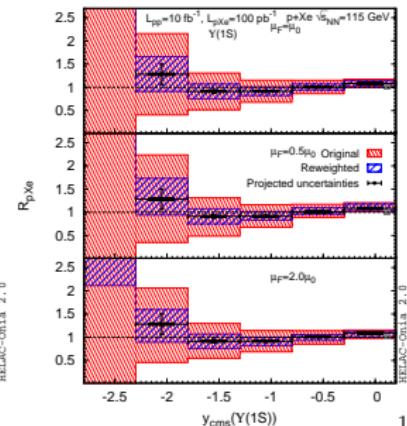
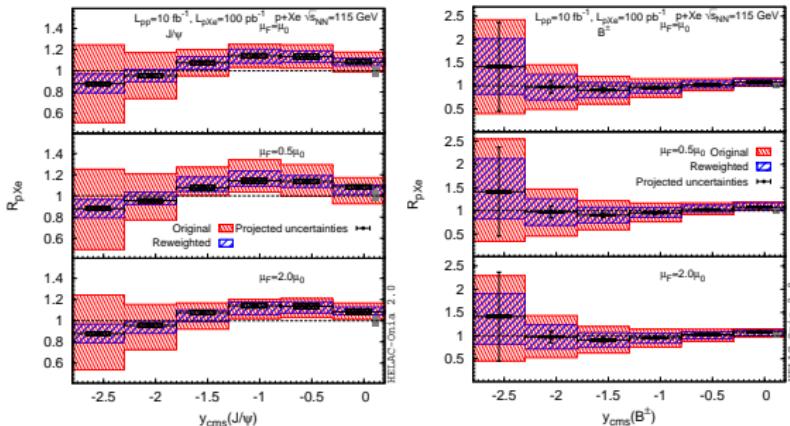
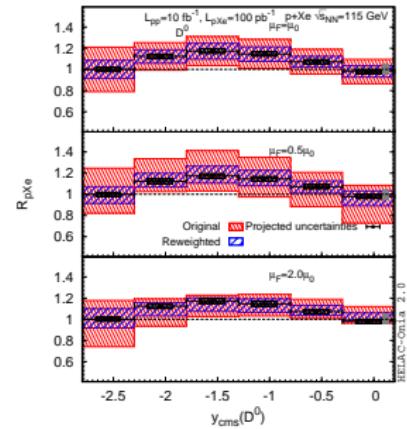
One of the options to constrain **gluon at high- x** are heavy quarks.



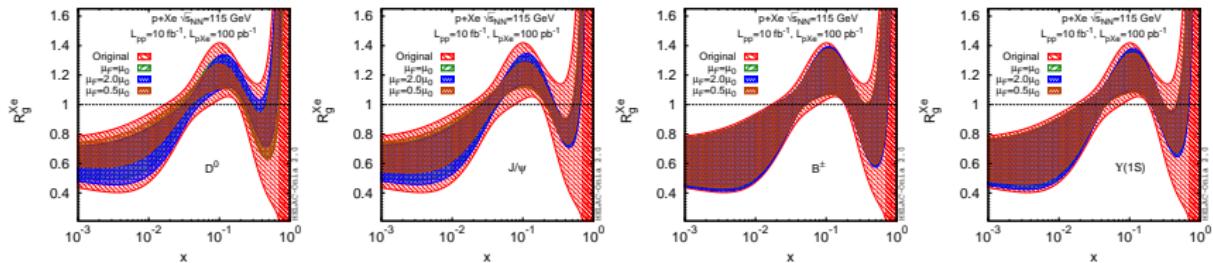
- ▶ Possible nuclear effects going beyond modifications of PDFs (e.g. energy loss, break up of quarkonium, ...).
- ▶ In the projections we assume that other cold nuclear matter effects are under control or are subtracted.
- ▶ This assumptions can be tested by using many heavy flavour probes and extended rapidity coverage.
- ▶ Having a pp baseline is essential allowing to use data driven approach for calculation e.g. for J/ψ .

Impact of $p\text{Xe}$: D^0 , J/ψ , B^\pm , $\Upsilon(1S)$ pseudo-data on nPDFs

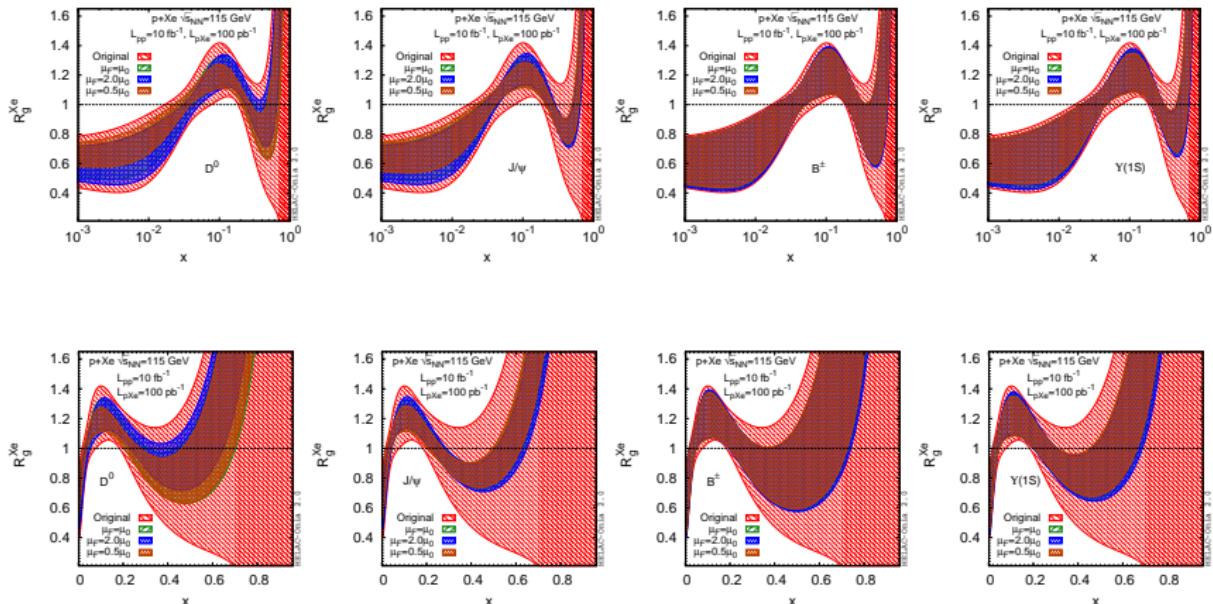
- Pseudo-data for nuclear modifications $R_{p\text{Xe}}$ for D^0 , J/ψ , B^\pm , $\Upsilon(1S)$ production obtained with Helaonia at NLO with nCTEQ15 nPDFs, assuming $\mathcal{L}_{pp} = 10 \text{ fb}^{-1}$, $\mathcal{L}_{p\text{Xe}} = 100 \text{ pb}^{-1}$.
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Impact of $p\text{Xe}$: D^0 , J/ψ , B^\pm , $\Upsilon(1S)$ pseudo-data on nPDFs



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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

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

3. Calculate observables with new (reweighted) PDFs

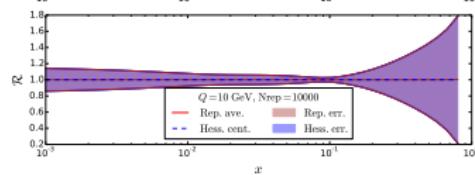
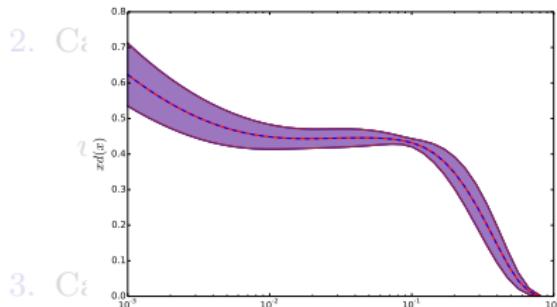
$$\langle \mathcal{O} \rangle_{\text{new}} = \frac{1}{N_{\text{rep}}} \sum_{k=1}^{N_{\text{rep}}} w_k \mathcal{O}(f_k),$$

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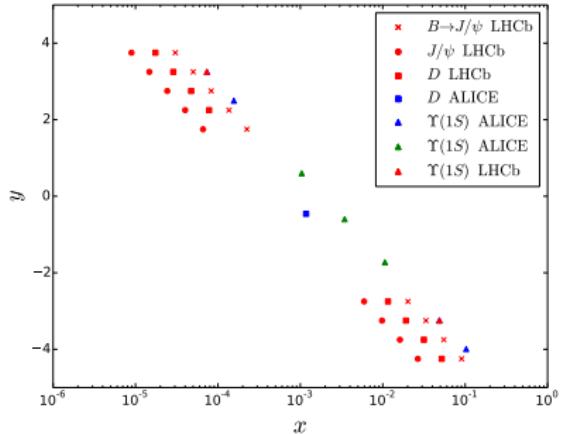
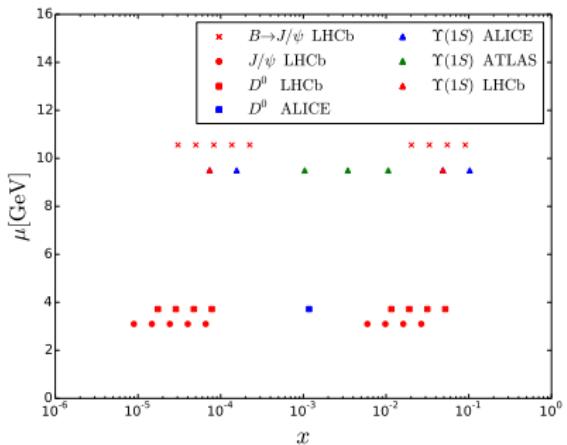
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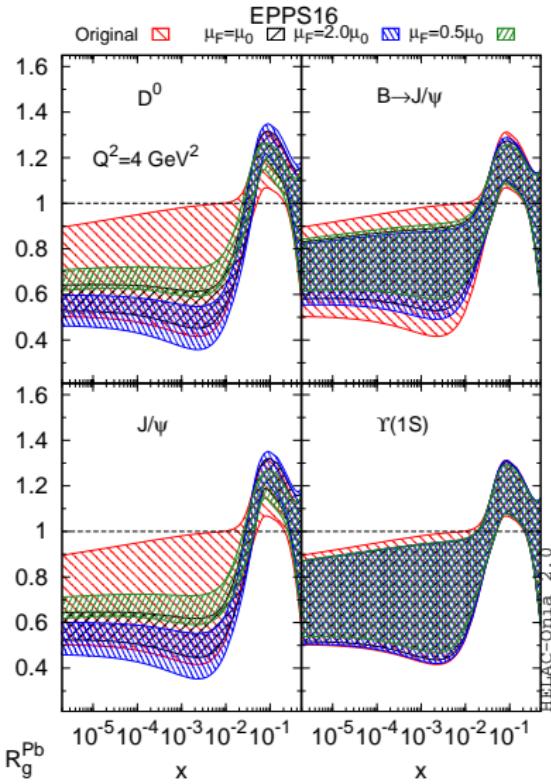
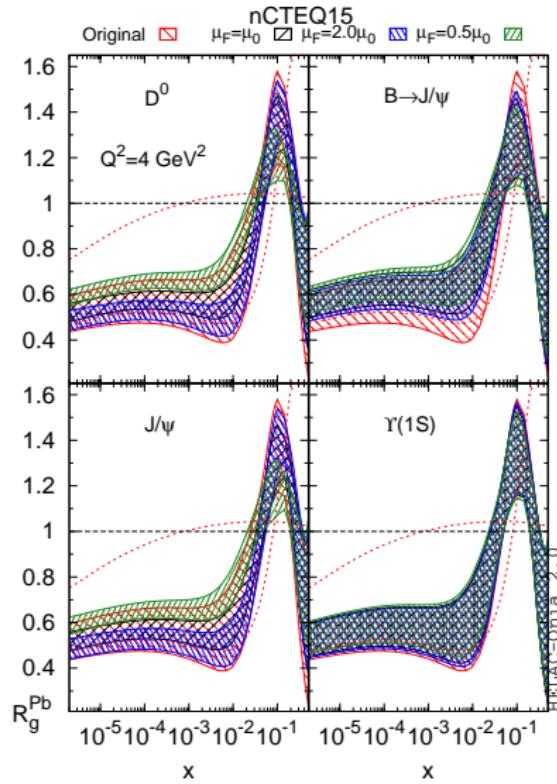
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Heavy quarks at LHC and low- x nuclear gluon



Heavy quarks at LHC and low- x nuclear gluon

Heavy quarks and quarkonium were recently also studied in the context of constraining small- x gluon using current LHC data [PRL 121 (2018), 052004].



Heavy quarks at LHC and low- x nuclear gluon

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

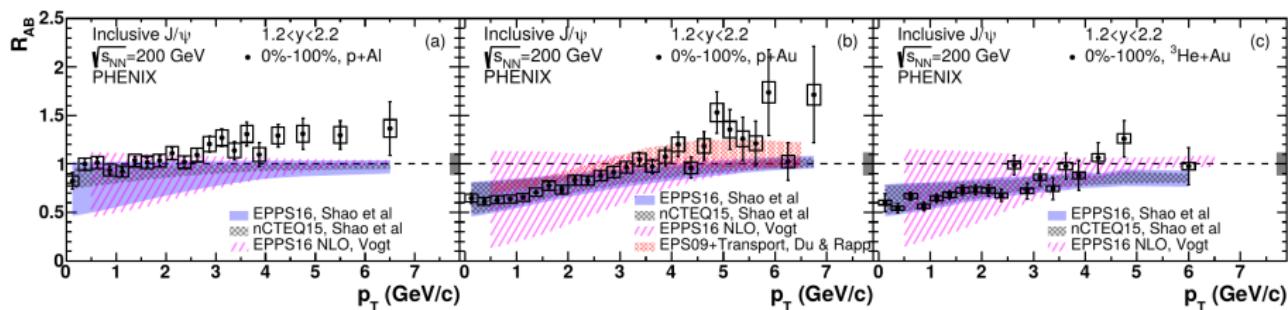


FIG. 10. Nuclear modification factor of inclusive J/ψ as a function of p_T at forward rapidity ($p/{}^3\text{He}$ -going direction) for $0\%-100\%$ $p+A$, $p+Au$, and ${}^3\text{He}+\text{Au}$ collisions. Bars (boxes) around data points represent point-to-point uncorrelated (correlated) uncertainties.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

arXiv:1910.14487

see also: K. Smith, Quark Matter 2019

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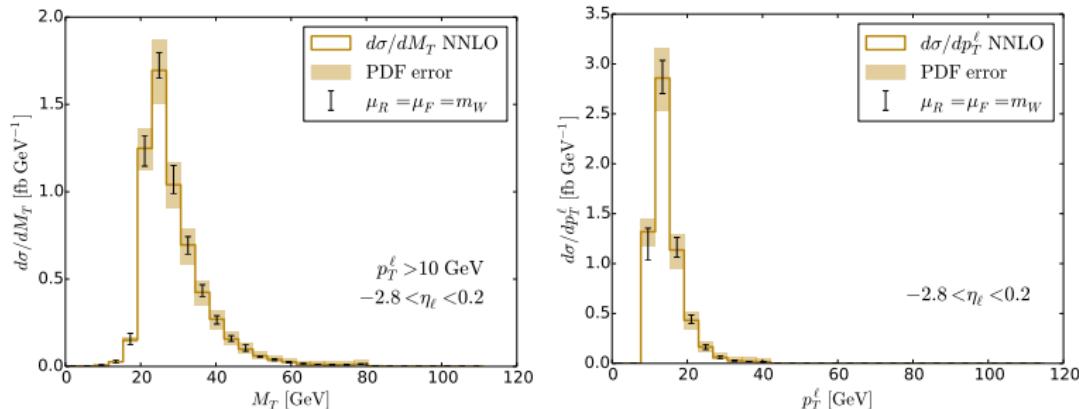
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W boson production

- ▶ W production close to threshold – never measured before.
- ▶ Proxy for heavy resonance searches at the LHC.
- ▶ Potential to provide constraints on light quark sea and the valence quarks (flavor separation).

W boson production

- W bosons at AFTER@LHC will be produced close to threshold.
The production is dominated by off-shell W bosons. $L_{pp} = 10 \text{ fb}^{-1}$



pp	W^+		Counts/year	W^-		Counts/year
	NLO	NNLO		NLO	NNLO	
$p_T^\ell > 10 \text{ GeV}$	$22.5^{+4.8}_{-4.3}$	$25.9^{+4.8}_{-5.0}$	259 ± 49	$5.5^{+1.3}_{-1.3}$	$6.2^{+1.1}_{-1.4}$	62 ± 13
$p_T^\ell > 20 \text{ GeV}$	$1.9^{+1.2}_{-0.7}$	$2.3^{+1.3}_{-1.1}$	23 ± 12	$0.38^{+0.29}_{-0.20}$	$0.50^{+0.25}_{-0.25}$	5 ± 2.5
$p_T^\ell > 30 \text{ GeV}$	$0.28^{+0.91}_{-0.27}$	$0.27^{+0.72}_{-0.24}$	2.7 ± 4.8	$0.035^{+0.091}_{-0.039}$	$0.04^{+0.09}_{-0.04}$	0.4 ± 0.7

Table 13: Cross sections in [fb] at NLO and NNLO integrated over the rapidity range $2 < \eta_\mu^{\text{lab}} < 5$ and imposing a cut $p_T^\mu > 10 \text{ GeV}$. The results have been obtained for pp collisions at $\sqrt{s} = 115 \text{ GeV}$ with FEWZ [168] using the NLO and NNLO CT14 PDFs [167], respectively. The renormalisation and factorisation scales have been set to $\mu_R = \mu_F = M_W$. The asymmetric uncertainties have been calculated using the error PDFs. The expected number of events has been obtained with a yearly luminosity of 10 fb^{-1} .

W boson production

- ▶ At LO, assuming diagonal CKM matrix and neglecting the contribution from the sc -channel

$$\begin{aligned} R^W &= \frac{\frac{d\sigma}{dy}(pn \rightarrow W^+ + W^-) - \frac{d\sigma}{dy}(pp \rightarrow W^+ + W^-)}{\frac{d\sigma}{dy}(pn \rightarrow W^+ + W^-) + \frac{d\sigma}{dy}(pp \rightarrow W^+ + W^-)} = 1 - 2 \frac{\frac{d\sigma}{dy}(pp \rightarrow W^+ + W^-)}{\frac{d\sigma}{dy}(pd \rightarrow W^+ + W^-)} \\ &= \frac{[u(x_1) - d(x_1)][\bar{u}(x_2) - \bar{d}(x_2)] + [\bar{u}(x_1) - \bar{d}(x_1)][u(x_2) - d(x_2)]}{[u(x_1) + d(x_1)][\bar{u}(x_2) + \bar{d}(x_2)] + [\bar{u}(x_1) + \bar{d}(x_1)][u(x_2) + d(x_2)]} \end{aligned}$$

- ▶ At central rapidities $y_{c.m.s.} = 0$ and $x_1 = x_2 = M_{W^*}/\sqrt{s} \simeq 0.25$ we get (with $r_v(x) = d(x)/u(x)$ and $r_s(x) = \bar{d}(x)/\bar{u}(x)$)

$$R^W(y_{c.m.s.} = 0) = \frac{(1 - r_v)(1 - r_s)}{(1 + r_v)(1 + r_s)}$$

- ▶ Therefore, even a rough measurement of this ratio with about 30% precision could provide valuable information on the barely known ratio $r_s = \bar{d}/\bar{u}$ at high x .

Outline

- ▶ Motivations from PDF perspective
- ▶ AFTER@LHC essentials
- ▶ Projected performances at AFTER@LHC
 - ▶ Drell-Yan lepton pair production
 - ▶ Open and hidden heavy flavour mesons
 - ▶ W boson production
 - ▶ Non-perturbative charm
- ▶ Summary

Non-perturbative charm

- ▶ Most global analyses of PDFs rely on the assumption that the charm and bottom PDFs are generated perturbatively by gluon splitting $g \rightarrow Q\bar{Q}$ and do not involve any non-perturbative degrees of freedom.
- ▶ There are indications for charm production at high x (EMC, SELEX) – consistent with the non-perturbative/intrinsic contribution – which are, however, not yet fully conclusive and need to be tested.
- ▶ AFTER@LHC give a great opportunity to test this hypothesis providing access to the high- x region.

Non-perturbative charm

- Relative yield uncertainty for inclusive D^0 meson production at AFTER as a function of D^0 meson transverse momentum.

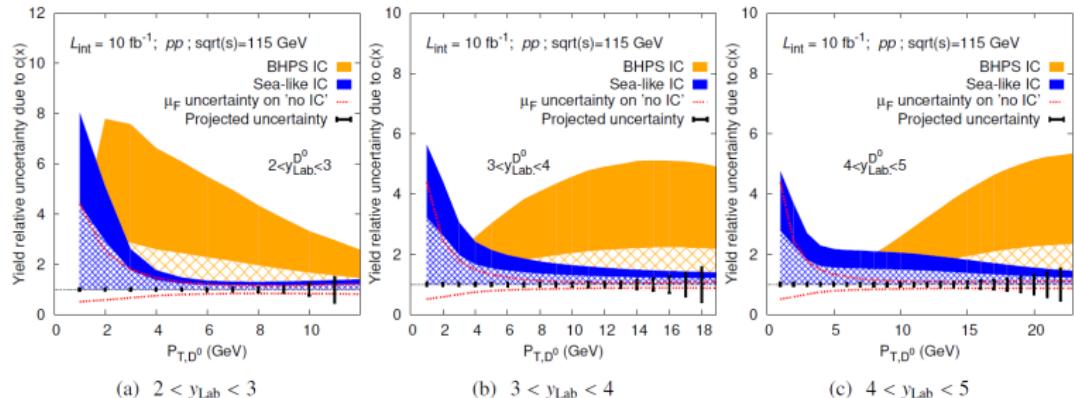


Figure 17: Impact of the uncertainty on the charm content of the proton on the D^0 yield as function of p_T compared to projected uncertainties from the measurement of the D^0 yield in pp collisions at $\sqrt{s} = 115$ GeV in the LHCb acceptance. The orange (blue) zones correspond to yields computed with charm PDFs including BHPS-like (sea-like) IC [190, 191]. The filled areas correspond to yields computed with up to $\langle x_{cc} \rangle = 2\%$ (2.4%) and the hashed areas up to $\langle x_{cc} \rangle = 0.57\%$ (1.1%). The dashed red curves indicate the factorisation scale uncertainty on the 'no-IC' yield. Systematic uncertainties of 5% are included and the statistical uncertainty for the background subtraction is assumed to be negligible which is reasonable assuming LHCb-like performances, see [100]. The rates were computed by assuming an average efficiency of $\langle \varepsilon \rangle = 10\%$ and $\mathcal{B}(D^0 \rightarrow K\pi) = 3.93\%$.

- Even for $p_T \lesssim 15$ GeV the expected precision of the measurement will clearly allow to considerably constrain the intrinsic-charm model, by up to an order magnitude.

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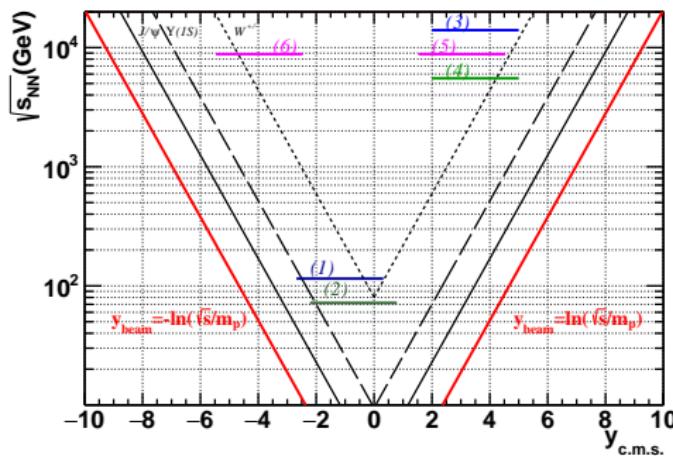
Summary

- ▶ Our current knowledge of high- x structure of nucleons and nuclei is limited and FTE@LHC would bring an opportunity to hugely improve this situation. This is important for different reasons:
 - ▶ Understanding confinement properties of the strong interaction.
 - ▶ Understanding EMC effect.
 - ▶ Discriminating between different models of hadronic structure.
 - ▶ Improve our knowledge of parton luminosities at existing and future hadron colliders (LHC, FCC, ...).
 - ▶ Test existence of non-perturbative/intrinsic heavy quarks in the proton.
 - ▶ Reduce uncertainty on prompt neutrino fluxes,
 - ▶ Help identify mechanism responsible for production of Ultra High-Energy CRs.

BACKUP SLIDES

Rapidity coverage

Example of acceptance for **LHCb-like** detector: $2 < \eta_{\text{lab}} < 5$



(1) pA fixed target mode $\sqrt{s_{\text{NN}}} = 115$ GeV
(2) PbA fixed target mode $\sqrt{s_{\text{NN}}} = 72$ GeV

(3) pp collider mode $\sqrt{s_{\text{NN}}} = 14$ TeV
(4) PbPb collider mode $\sqrt{s_{\text{NN}}} = 5.5$ TeV
(5) pPb collider mode $\sqrt{s_{\text{NN}}} = 8.8$ TeV
(6) Pbp collider mode $\sqrt{s_{\text{NN}}} = 8.8$ TeV

Fixed target mode (1), (2):

Negative $y_{\text{c.m.s.}}$: $x_1 < x_2 \implies x_F = x_1 - x_2 < 0$

Quite special!

Coherent energy loss effects for J/ψ nad Υ

[Adv. High Energy Phys. 2015 (2015) 961951]

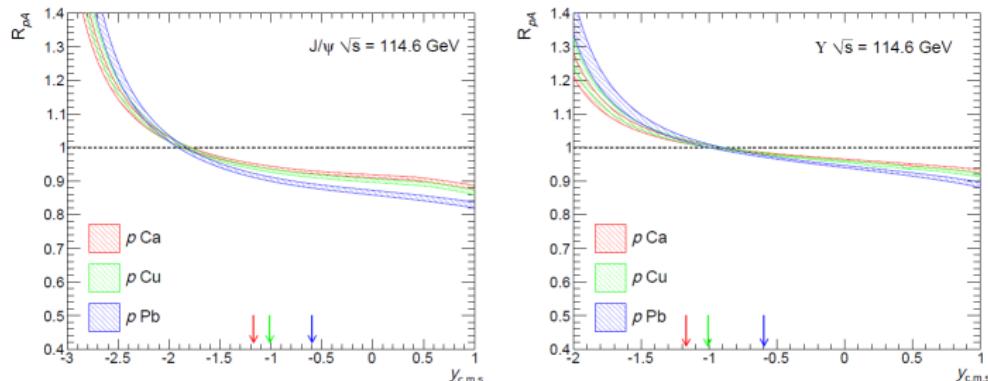


Figure 23: J/ψ (left) and Υ (right) suppression in $p\text{Pb}$ collisions at $\sqrt{s} = 114.6$ GeV resulting from the coherent energy loss. The arrow approximately indicates additional break-up effect should be considered. Figure taken from [223].

- AFTER@LHC should be able to discriminate between different kind of nuclear effects like: energy loss, break-up effects, nuclear PDFs, etc.

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

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

3. Calculate observables with new (reweighted) PDFs

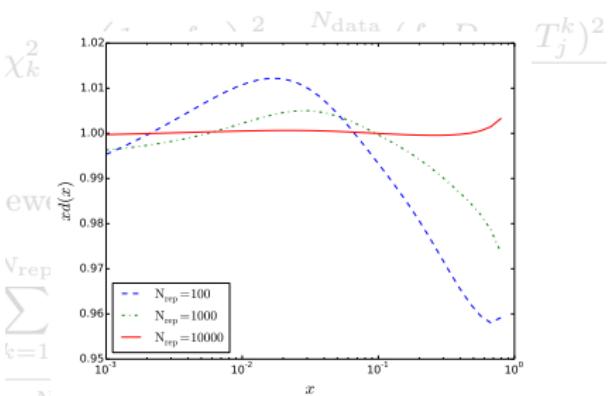
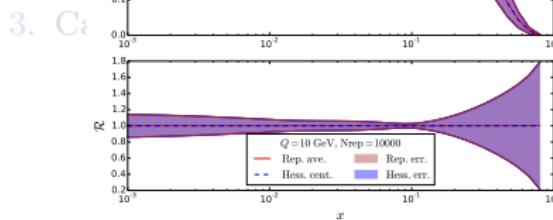
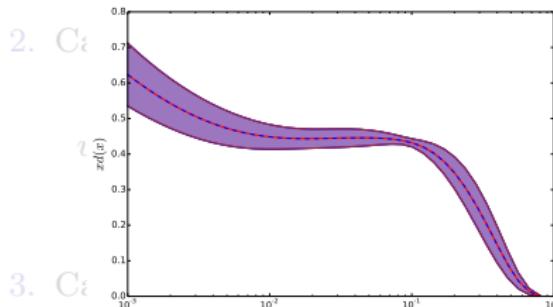
$$\langle \mathcal{O} \rangle_{\text{new}} = \frac{1}{N_{\text{rep}}} \sum_{k=1}^{N_{\text{rep}}} w_k \mathcal{O}(f_k),$$

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

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Heavy flavor LHC data

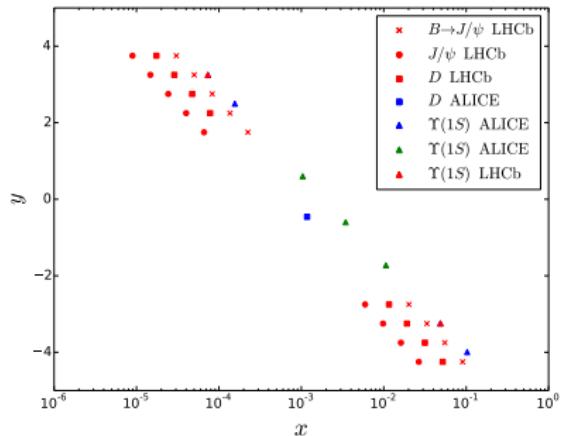
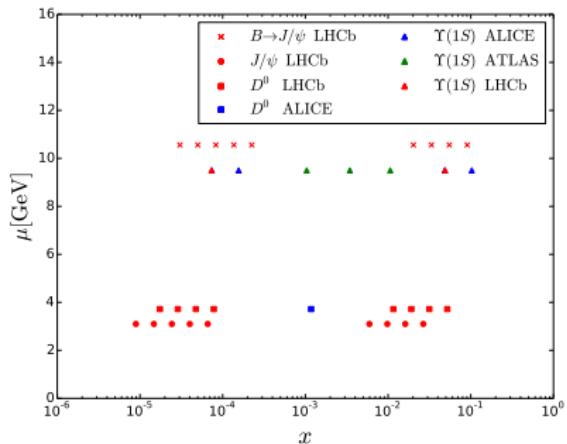
[arXiv:1712.07024]

Available heavy-flavor pPb LHC data

	D^0	J/ψ	$B \rightarrow J/\psi$	$\Upsilon(1S)$
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.

Kinematic reach of the data



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.

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

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

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

- ▶ Predictions for D^0 and $B \rightarrow J/\psi$ 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 $2 \rightarrow 2$ partonic processes dominated by single partonic channel ($gg, q\bar{q}, \dots$)
 - In our case ($D^0, J/\psi, B \rightarrow J/\psi, \Upsilon(1S)$ production) *gg* dominated.

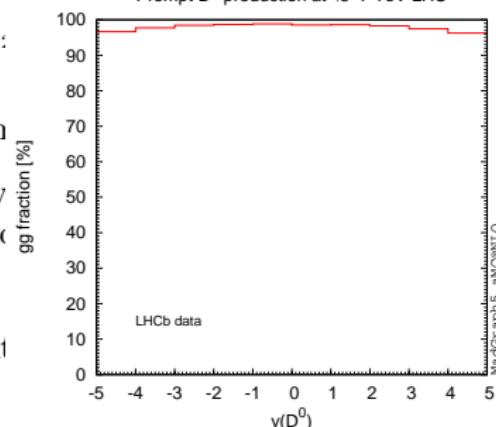
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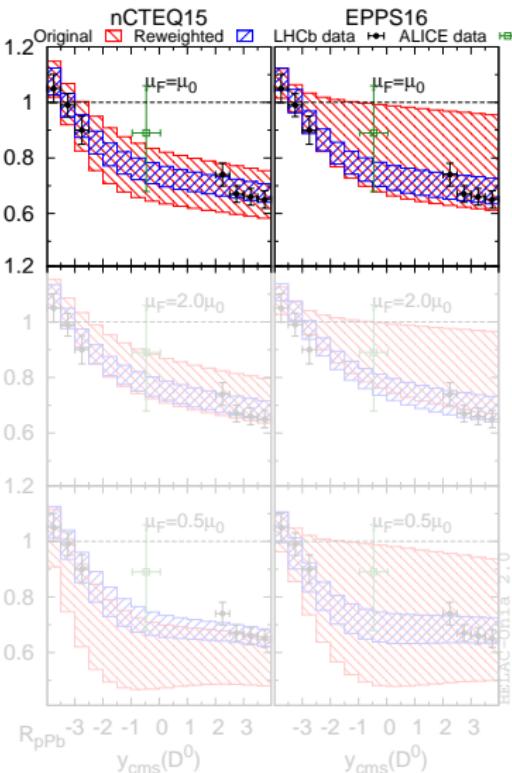
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→ In our case ($D^0, J/\psi, B \rightarrow J/\psi, \Upsilon(1S)$ production) **gg dominated**.



Reweighting with D^0 data

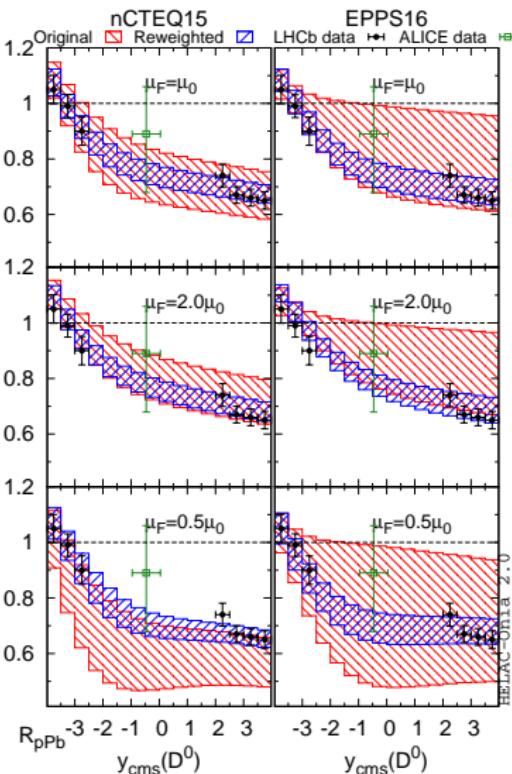


LHCb [JHEP 1710 (2017) 090, 1707.02750]

ALICE [PRL113, 232301 (2014), 1405.3452]

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

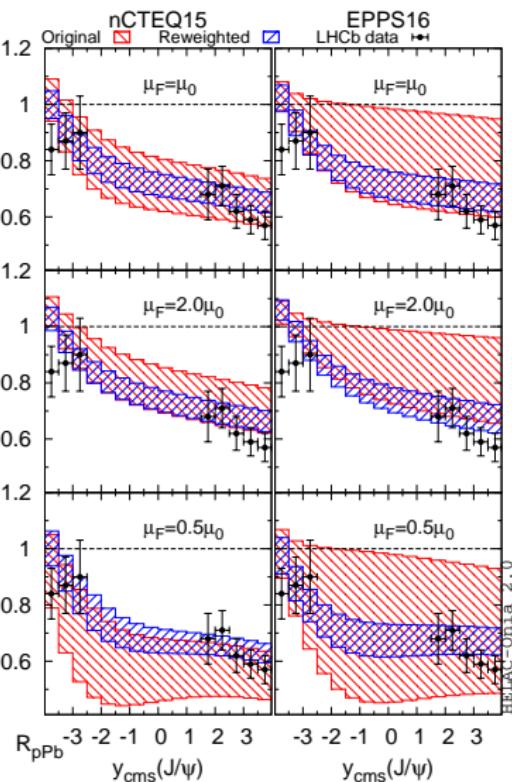
Reweighting with D^0 data



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ALICE [PRL113, 232301 (2014), 1405.3452]

- ▶ 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.

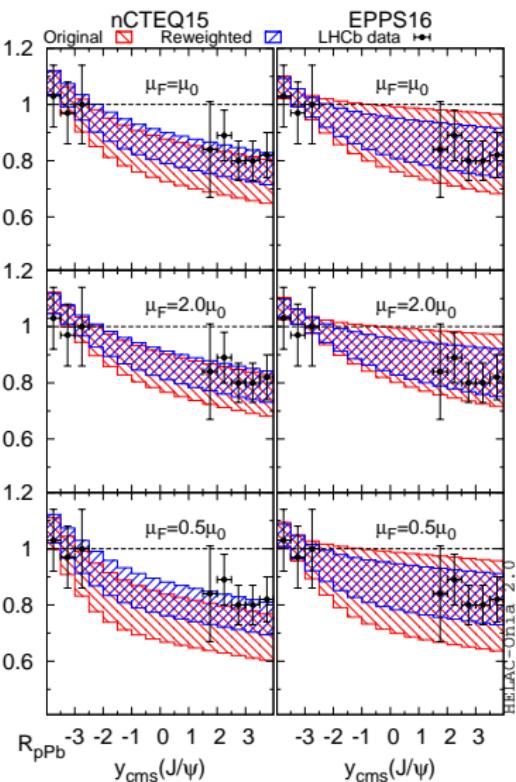
Reweighting with J/ψ data



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.

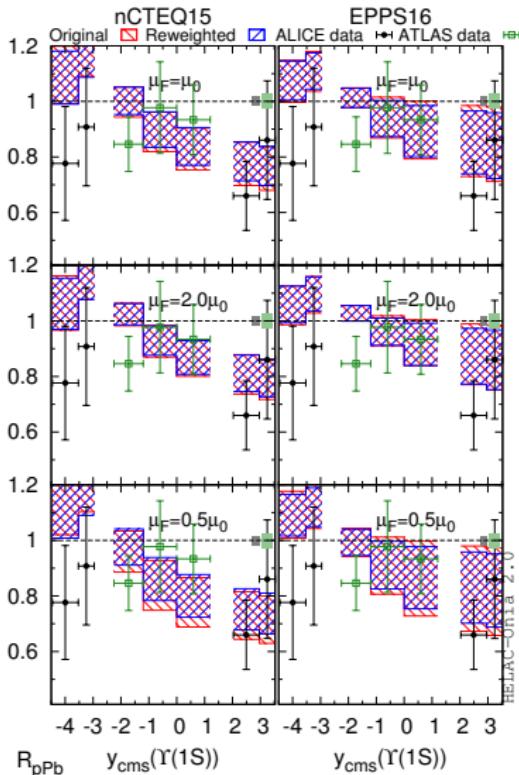
Reweighting with $B \rightarrow J/\psi$ data



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

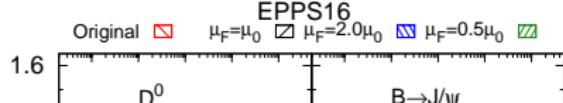
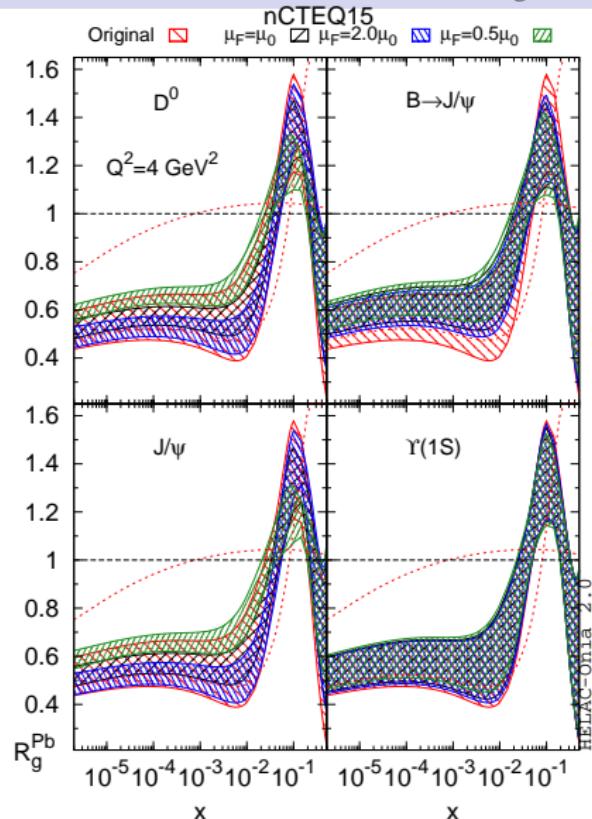


ALICE [PLB 740, 105 (2015), 1410.2234]

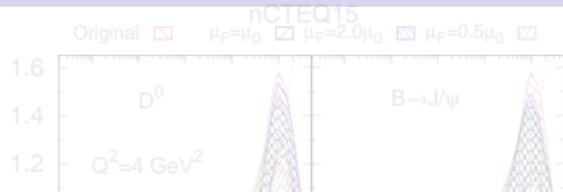
ATLAS [ATLAS-CONF-2015-050 (updated in: 1709.03089)]

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

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



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



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.

R



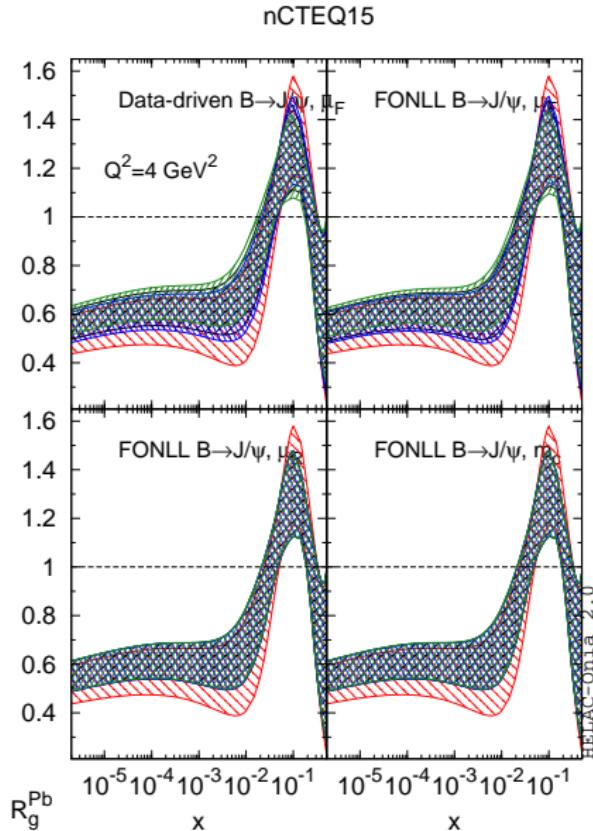
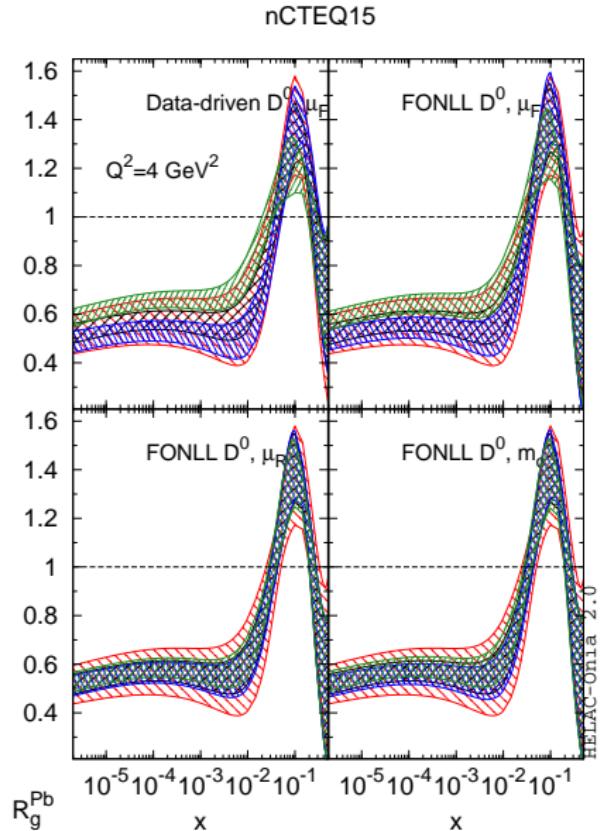
Consistency with other data

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 $R_{d\text{Au}}$ 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!

Data-driven vs. FONLL



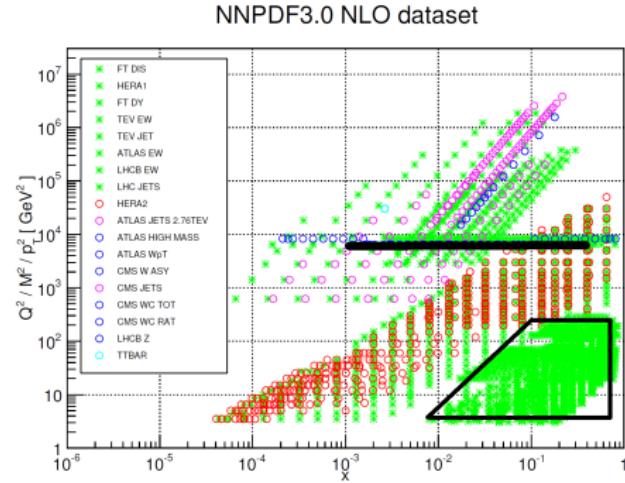
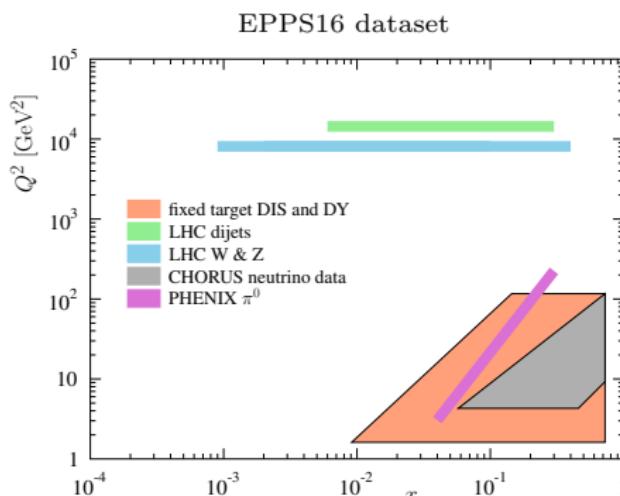
Consistency with other data

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

	nCTEQ15	after reweighting								
		$B \mu_0$	B up	B down	$D \mu_0$	D up	D down	$J/\psi \mu_0$	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 $J/\psi R_{d\text{Au}}$	1.99							1.93	0.43	3.35

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 a_i parameters
- ▶ **Assumptions limit/replace uncertainties!**

Available nuclear PDFs

► Multiplicative nuclear correction factors

$$f_i^{p/A}(x_N, \mu_0) = R_i(x_N, \mu_0, A) f_i^{\text{free proton}}(x_N, \mu_0)$$

- **HKN:** Hirai, Kumano, Nagai [PRC 76, 065207 (2007)]
- **DSSZ:** de Florian, Sassot, Stratmann, Zurita [PRD 85, 074028 (2012)]
- **EPS09:** Eskola, Paukkunen, Salgado [JHEP 04 (2009) 065]
- **EPPS16:** Eskola, Paakkinen, Paukkunen, Salgado [EPJC 77 (2017) 163]
- **KT16:** Khanpour, Tehrani [PRD 93, 014026 (2016)]

► Convolution relation

$$f_i^{p/A}(x_N, Q_0^2) = \int_{x_N}^A \frac{dy}{y} W_i(y, A, Z) f_i\left(\frac{x_N}{y}, Q_0^2\right)$$

- **DS04:** de Florian, Sassot [PRD 69, 074028 (2004)]

► Native nuclear PDFs

$$\begin{aligned} f_i^{p/A}(x_N, \mu_0) &= f_i(x_N, A, \mu_0) \\ f_i(x_N, A = 1, \mu_0) &\equiv f_i^{\text{free proton}}(x_N, \mu_0) \end{aligned}$$

- **nCTEQ15:** Kovarik, Kusina, Jezo, Clark, Keppel, Lyonnet, Morfin, Olness, Owens, Schienbein, Yu [PRD 93, 085037 (2016), arXiv:1509.00792]

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 neutron PDFs, $f_i^{n/A}$, constructed assuming iso-spin symmetry
- bound proton PDFs parametrized:

nCTEQ15 [[arXiv:1509.00792](#)]

EPPS16 [[arXiv:1612.05741](#)]

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

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

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

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

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

Comparison of available nPDFs

	EPPS16	EPS09	nCTEQ15	DSSZ12	HKN07	KA15
FT NC DIS	✓	✓	✓	✓	✓	✓
FT CC DIS	✓	✗	✗ [#]	✓	✗	✗
FT Drell-Yan	✓	✓	✓	✓	✓	✓
RHIC π^0	✓	✓	✓	✗	✗	✗
LHC W/Z	✓	✗	✗ [*]	✗	✗	✗
LHC dijet	✓	✗	✗	✗	✗	✗
QCD order	NLO	LO & NLO	NLO	NLO	LO & NLO	NNLO
Kinematic cuts	$Q > 1.3\text{GeV}$	$Q > 1.3\text{GeV}$	$Q > 2\text{GeV}$ $W > 3.5\text{GeV}$	$Q > 1\text{GeV}$	$Q > 1\text{GeV}$	$Q > 1\text{GeV}$
No data points	1811	929	740	1579	1241	1479
No free param.	20	15	16	25	12	16
χ^2/dof	1.00	0.79	0.81	0.99	1.21	1.15
Error analysis	Hessian	Hessian	Hessian	Hessian	Hessian	Hessian
Tolerance $\Delta\chi^2$	52	50	35	30	13.7	1?
Proton baseline	CT14NLO	CTEQ6.1	CTEQ6.1-like	MSTW2008	MRST1998	JR09
Heavy-quark eff.	✓	✗	✓	✓	✗	✗
Flavour sep.	✓	✗	✓	✗	✗	✗
Reference	[1612.05741]	[0902.4154]	[1509.00792]	[1112.6324]	[0709.3038]	[1601.00939]

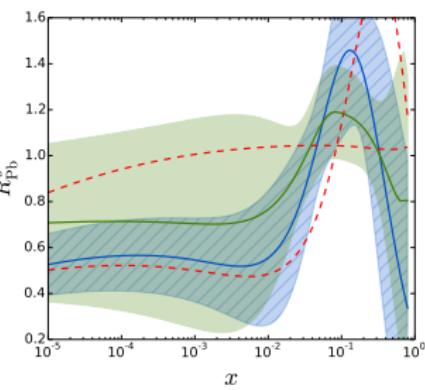
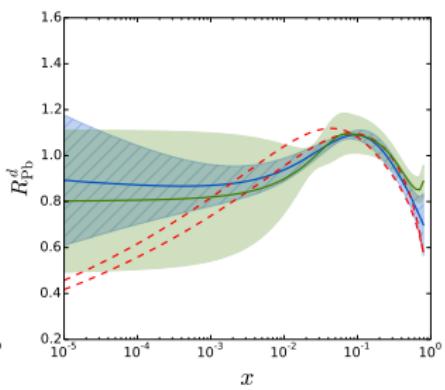
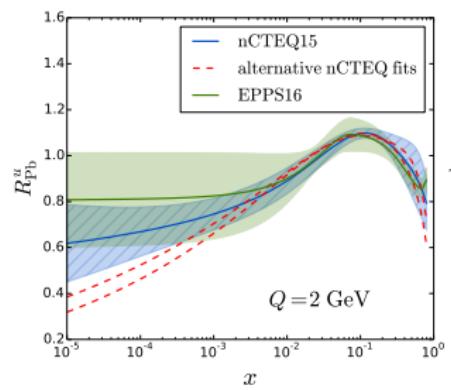
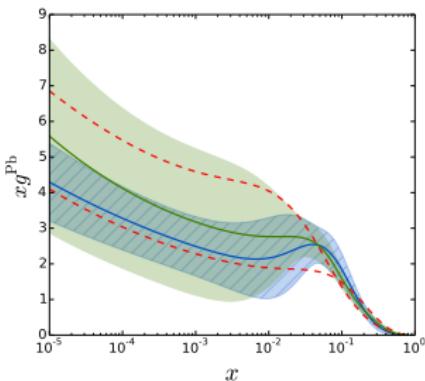
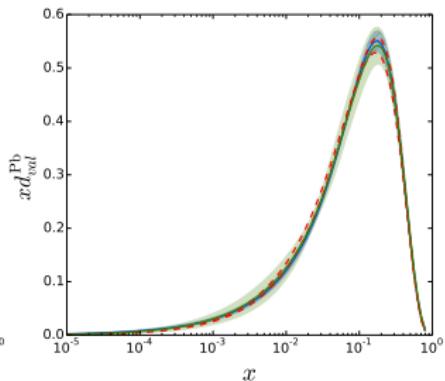
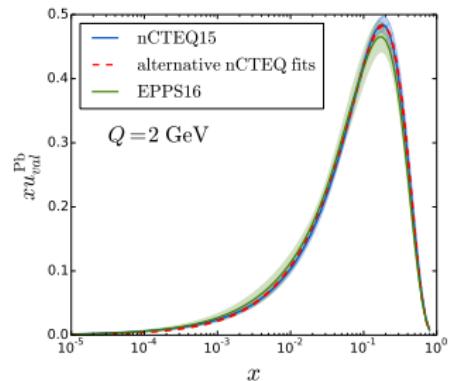
[#] In a separate dedicated analysis [PRL106, 122301, (2011), 1012.0286; PRD80, 094004, (2009), 0907.2357]

^{*} See a reweighting study [EPJC77, 488 (2017), 1610.02925]

Current nPDFs

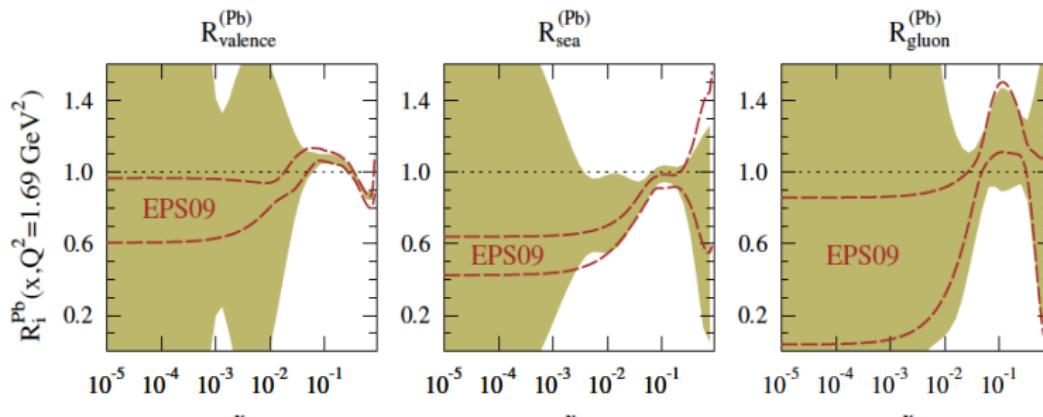
[arXiv:1509.00792, arXiv:1012.1178]

[arXiv:1612.05741]



New fit framework:

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



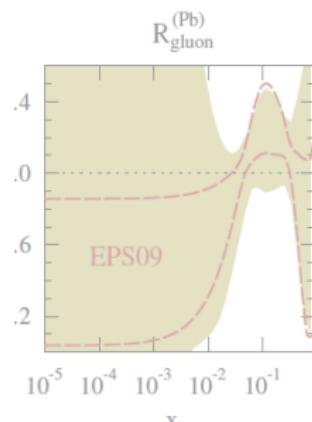
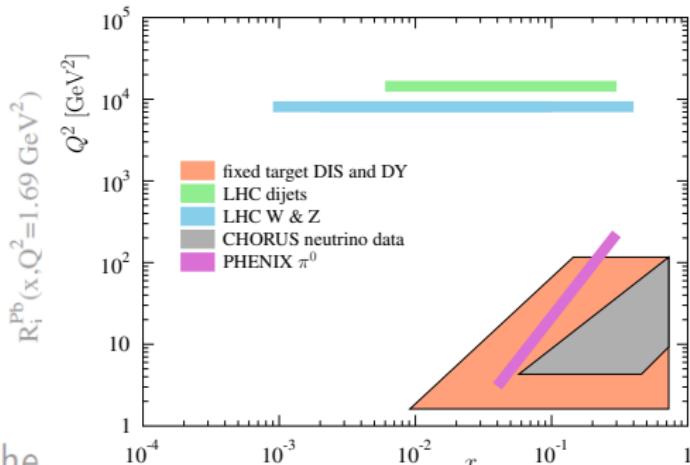
The lower bound restricted here by $F_L(Q^2 = 2 \text{ GeV}^2, x > 10^{-5}) > 0$

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

New fit framework:

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



The $\int_{x=10^{-5}}^{x=10^{-1}} R_i^{Pb}(x, Q^2=1.69 \text{ GeV}^2) dx > 0$

Maybe Gluon nPDFs is particularly badly known (LHC dijet, RHIC π^0)
 $R_i < 1$), but consistent with the data.

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