Accessing the high-x content of protons and heavy nuclei in the fixed-target mode at the LHC

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

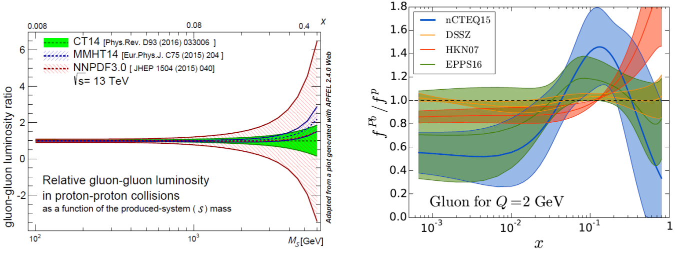
DIS 2019
8-12 April
TORINO

Outline

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

Motivation

- The structure of nucleon and nuclei at high x is poorly known
  - opportunity to advance our knowledge of QCD confinement properties
  - practical implications: improve our knowledge of parton luminosities at colliders (LHC, RHIC, FCC, ...) but also of ultra high energy cosmic rays.



(a) (b)

Figure 1: (a) Gluon-Gluon-luminosity uncertainty computed for 3 sets of proton PDFs as a function of the invariant mass (M_S) of a to-be produced system at $\sqrt{s}$ = 13 TeV. For $y \sim 0$, $x \simeq M_S/\sqrt{s}$ at the LHC (indicated on the upper x axis), whereas the kinematics of the AFTER@LHC program is mainly that of high x where the uncertainties blow up. Plot done thanks to the APFEL program [3]. (b) Compilation of the gluon nuclear PDF uncertainties [4, 5, 6, 7] in a lead nucleus at a factorisation scale (here denoted Q) of 2 GeV.

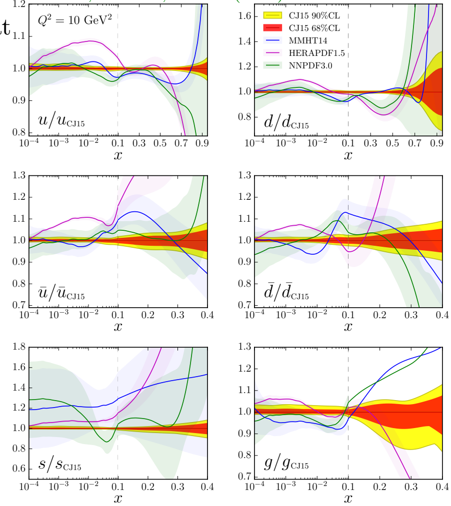
- We still don't know the origin of the nuclear EMC effect.
- We don't know the possible non-perturbative source of charm or beauty quarks in the proton which would carry a big fraction of its momentum.

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

CJ15, PRD 93, 114017 (2016)



Motivation

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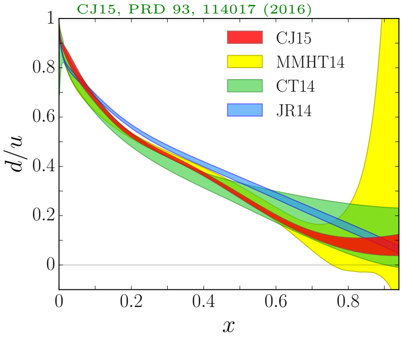
- very large uncertainties on quark sea

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

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

Better understanding important for BSM searches of new heavy states



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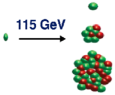
For more details on AFTER@LHC project see:

- A Fixed-Target Programme at the LHC: Physics Case and Projected Performances for Heavy-Ion, Hadron, Spin and Astroparticle Studies, arXiv:1807.00603
- **M. Echevarria** on Tuesday at 10.45: "Unraveling the 3D/spin structure of the nucleons with a fixed-target experiment at the LHC"

Energy range

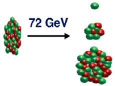
7 TeV proton beam on a fixed target

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



2.76 TeV Pb beam on a fixed target

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



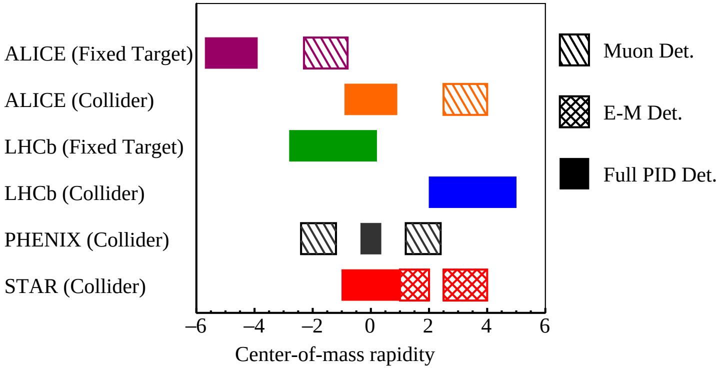
Such $\sqrt{s}$ allow, for the first time, for systematic studies of W boson, bottomonia, p_T spectra, associated production, ..., in the fixed target mode

Effect of boost :

[particularly relevant for high energy beams]

- LHCb and the ALICE muon arm become backward detectors [$y_{\text{c.m.s.}} < 0$]
- 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_{target} ($\equiv x_2$) [uncharted for proton-nucleus; most relevant for p-p$^\uparrow$ with large $x^\uparrow$]

Rapidity coverage



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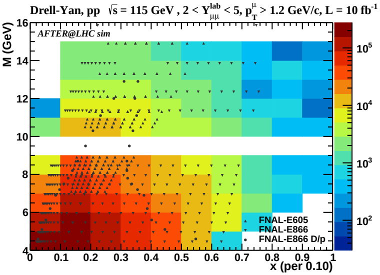
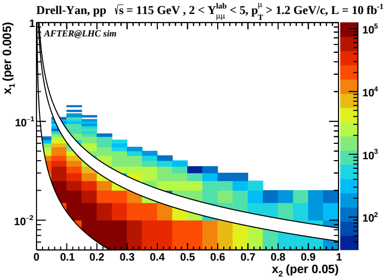
Drell-Yan kinematic coverage

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

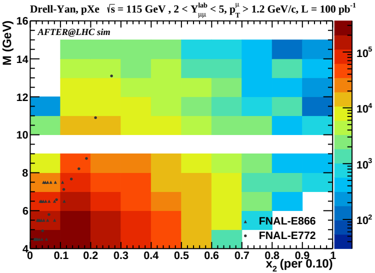


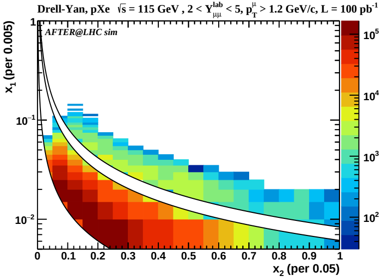


- Access to very large x.
- Much higher statistics in the region covered by NuSea (E866).
- Current data points as used by NNPDF global analysis.

Drell-Yan kinematic coverage

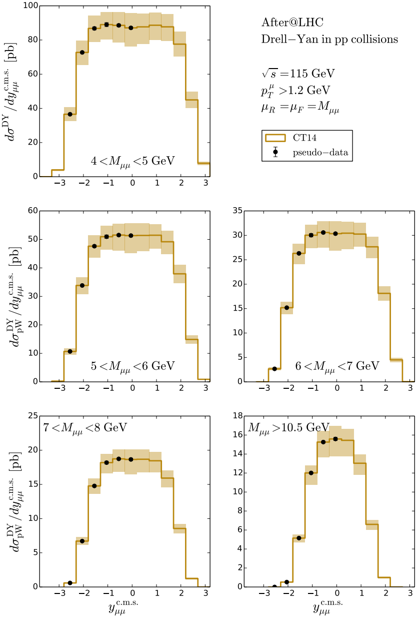
Kinematic plane of DY at AFTER@LHCb in pXe collisions at $\sqrt{s} = 115$ GeV with acceptance: $2 < \eta_\mu^{\text{lab}} < 5$ and $p_T^\mu > 1.2$ GeV.





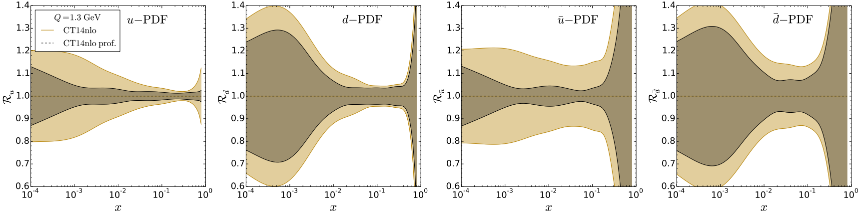
- Unique acceptance: access to large and very large x – region currently lacking data that could be used in global nPDF analysis.
- Extremly large yields up to $x_2 \to 1$.
- Current data points as used by nCTEQ and EPPS global analyses.

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

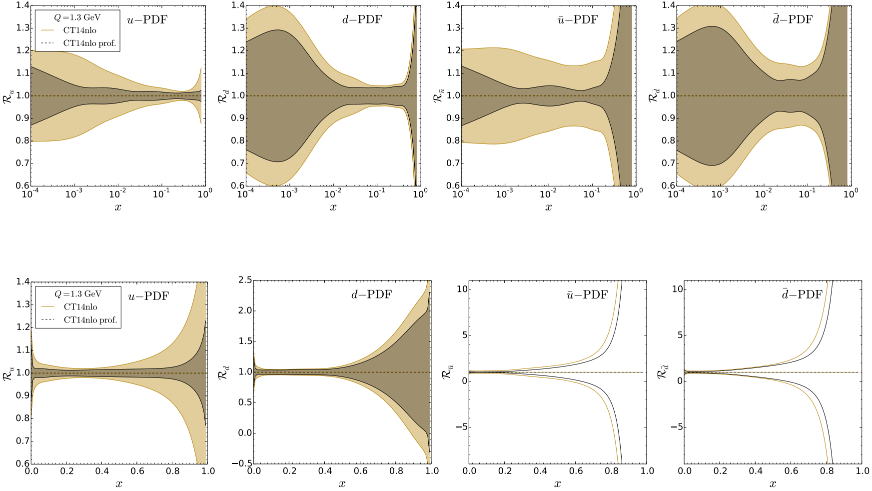


- Pseudo-data produced using MCFM at NLO with CT14 PDFs. (projected experimental uncertainty = statistical uncertainty from the DY yield + uncertainty from the underlying minimum bias event), assuming $\mathcal{L}_{pp} = 10\ \text{fb}^{-1}$.
- To estimate the impact of these pseudo-data on PDFs we use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

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

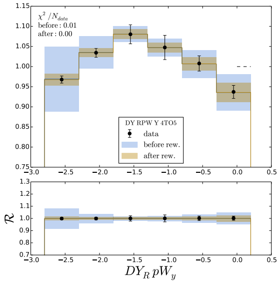


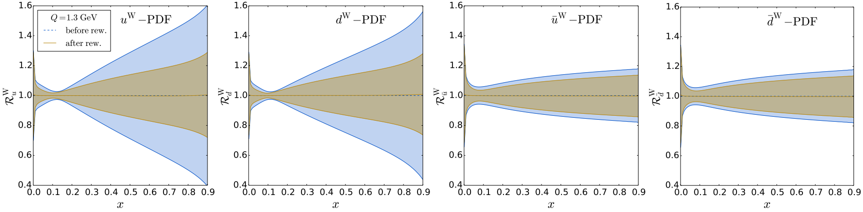
Impact of pp Drell-Yan pseudo-data on proton PDFs



Impact of pXe & pW Drell-Yan pseudo-data on nPDFs

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





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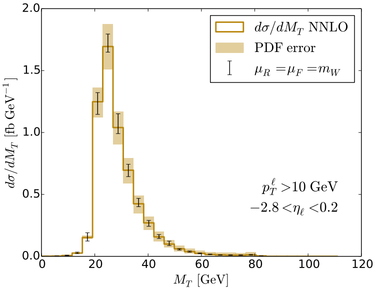
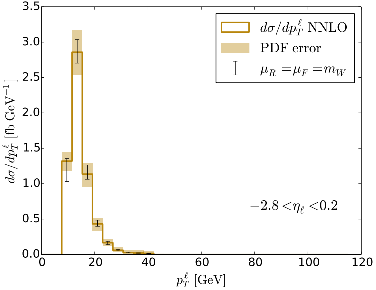
W boson production

- 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.





pp	W^+ NLO	W^+ NNLO	W^+ Counts/year	W^- NLO	W^- NNLO	W^- Counts/year
$p_T^l > 10$ 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
$p_T^l > 20$ 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
$p_T^l > 30$ 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 $2 < \eta_\mu^{\rm lab} < 5$ and imposing a cut $p_T^\mu > 10$ GeV. The results have been obtained for pp collisions at $\sqrt{s} = 115$ 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

$$R^W = \frac{\frac{d\sigma}{dy}(pn \to W^+ + W^-) - \frac{d\sigma}{dy}(pp \to W^+ + W^-)}{\frac{d\sigma}{dy}(pn \to W^+ + W^-) + \frac{d\sigma}{dy}(pp \to W^+ + W^-)} = 1 - 2\frac{\frac{d\sigma}{dy}(pp \to W^+ + W^-)}{\frac{d\sigma}{dy}(pd \to W^+ + W^-)}$$

$$= \frac{[u(x_1) - d(x_1)][\bar{u}(x_2) - \bar{d}(x_2)] + [\bar{u}(x_1) - \bar{d}(x_1)][u(x_2) - d(x_2)]}{[u(x_1) + d(x_1)][\bar{u}(x_2) + \bar{d}(x_2)] + [\bar{u}(x_1) + \bar{d}(x_1)][u(x_2) + d(x_2)]}$$

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

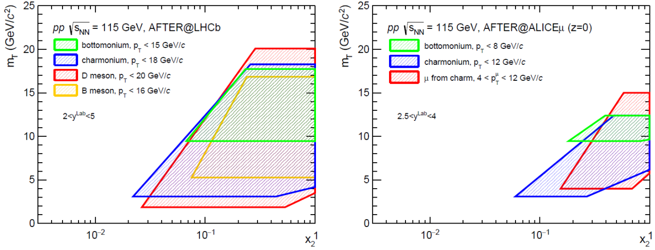
$$R^W(y_{\text{c.m.s.}} = 0) = \frac{(1 - r_v)(1 - r_s)}{(1 + r_v)(1 + r_s)}$$

- 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

Open and hidden heavy flavour mesons

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



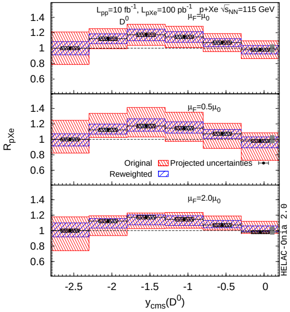
(a) LHCb-like (b) ALICE-like

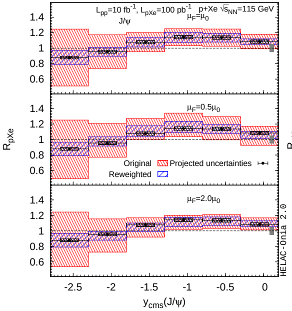
Figure 2: Typical kinematical reach in x_2 and the scale (chosen to be m_T) of the fixed-target mode with a detector acceptance like (a) LHCb and (b) ALICE.

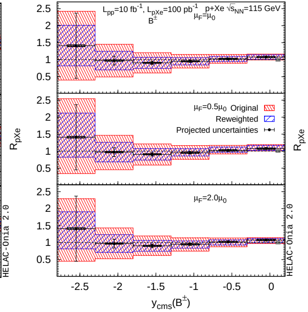
- Possible nuclear effects going beyond modifications of PDFs (e.g. energy loss, break up of quarkonium, ...).
- In the projections we assume that other cold nuclear matter effects are under control or are subtracted.
- This assumptions can be tested by using many heavy flavour probes and extended rapidity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

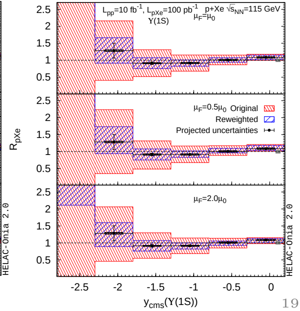
Impact of pXe: D^0, J/ψ, $B^\pm$, $\Upsilon(1S)$ pseudo-data on nPDFs

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

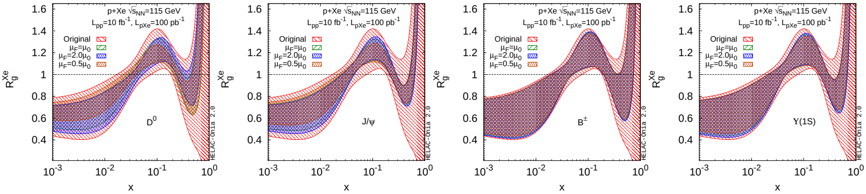








Impact of pXe: D^0, J/ψ, $B^\pm$, $\Upsilon(1S)$ pseudo-data on nPDFs



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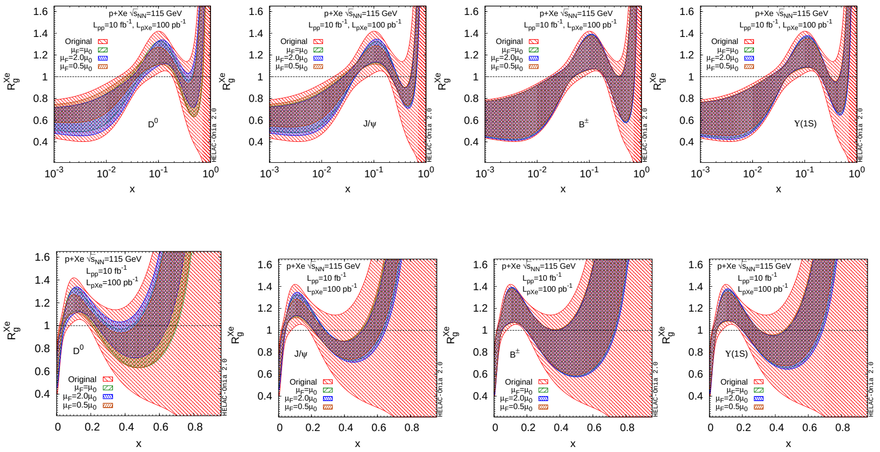
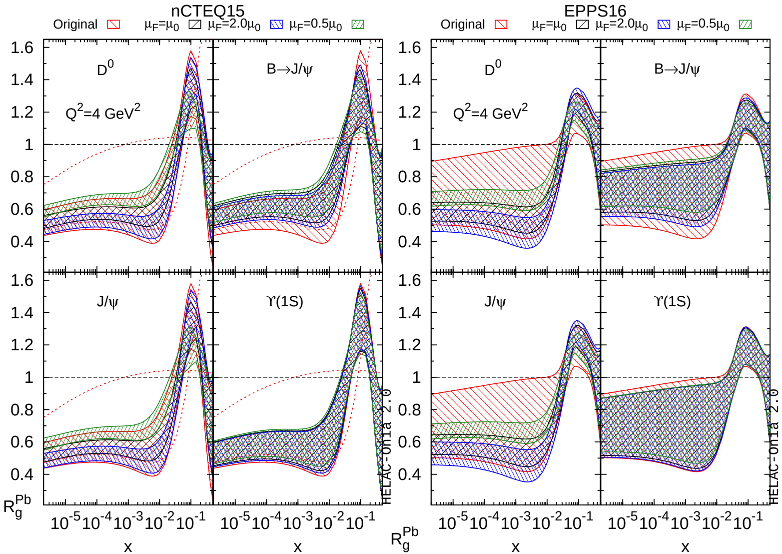


Heavy quarks and low-x nuclear gluon

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



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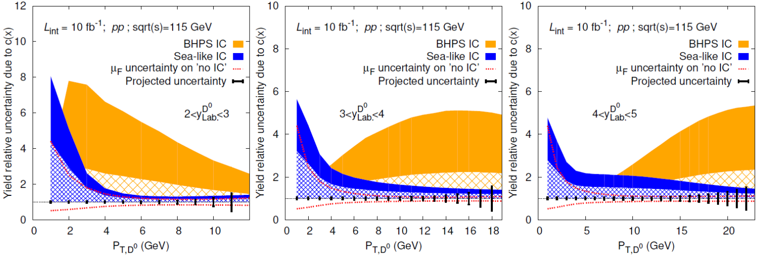
Non-perturbative charm

- Most global analyses of PDFs rely on the assumption that the charm and bottom PDFs are generated perturbatively by gluon splitting $g \to Q\bar{Q}$ 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.



(a) $2 < y_{\text{Lab}} < 3$ (b) $3 < y_{\text{Lab}} < 4$ (c) $4 < y_{\text{Lab}} < 5$

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 $\langle x_{c\bar{c}} \rangle = 2\%$ (2.4%) and the hashed areas up to $\langle x_{c\bar{c}} \rangle = 0.57\%$ (1.1%). The dahed 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 $\mathcal{B}(D^0 \to K\pi) = 3.93\%$.

- 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 AFTER@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

Coherent energy loss effects for J/ψ nad Υ

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

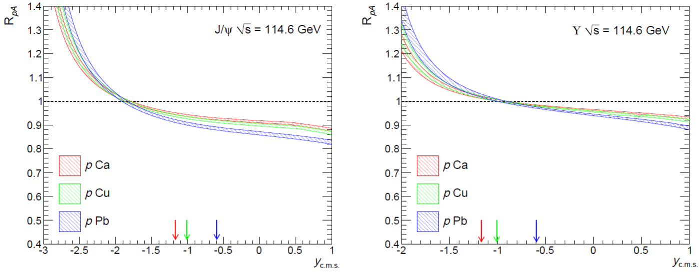
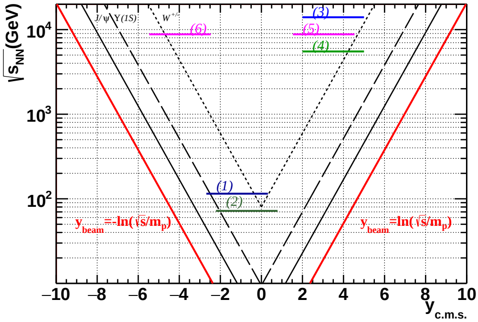


Figure 23: J/ψ (left) and Υ (right) suppression in pPb collisions at $\sqrt{s}$ = 114.6 GeV resulting from the coherent energy loss. The arrow approximately indicates additional break-up effect should be considered. Figure taken from [223].

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

Rapidity coverage

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



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

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

Fixed target mode (1), (2):
Negative $y_{\rm c.m.s.}$: $x_1 < x_2 \Longrightarrow x_F = x_1 - x_2 < 0$

Quite special!

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

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

3. Calculate observables with new (reweighted) PDFs

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

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

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

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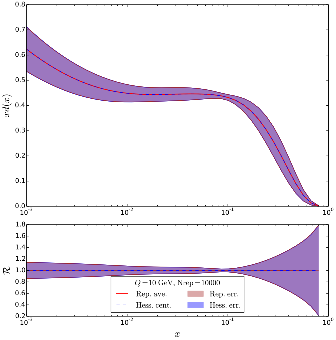

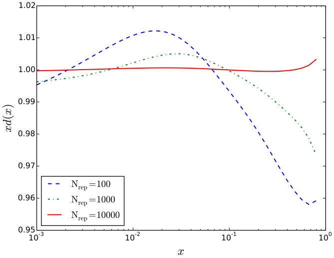

$$\delta \langle \mathcal{O} \rangle_{\text{new}} = \sqrt{\frac{1}{N_{\text{rep}}} \sum_{k=1}^{N_{\text{rep}}} w_k \left(\mathcal{O}(f_k) - \langle \mathcal{O} \rangle \right)^2}.$$

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

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

3. Calculate observables with new (reweighted) PDFs

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

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

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Heavy flavor LHC data

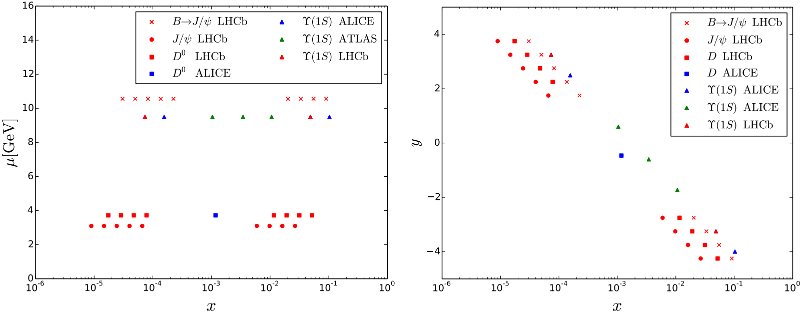
[arXiv:1712.07024]

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.

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

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

  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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$$\times \left[1 + \theta \left(P_{T,\mathcal{H}}^2 - \langle P_T \rangle^2\right.\right.$$

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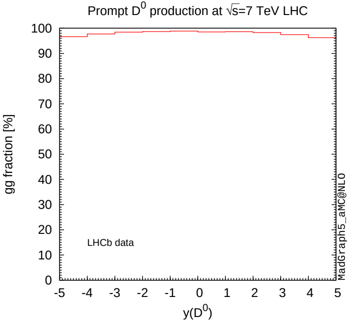

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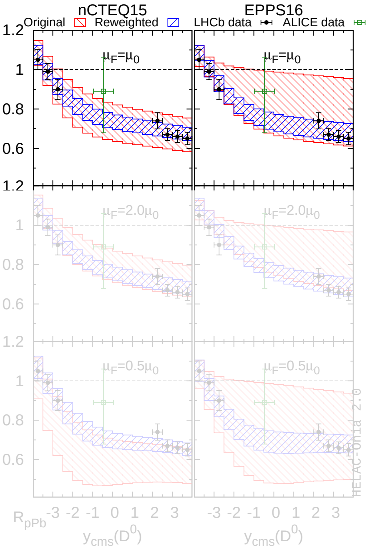
Reweighting with D^0 data



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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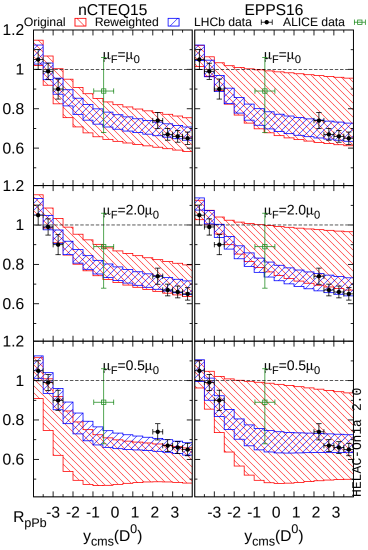

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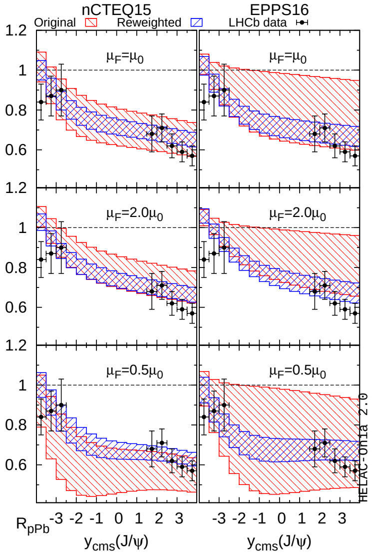
ALICE [PRL113, 232301 (2014), 1405.3452]

- 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.

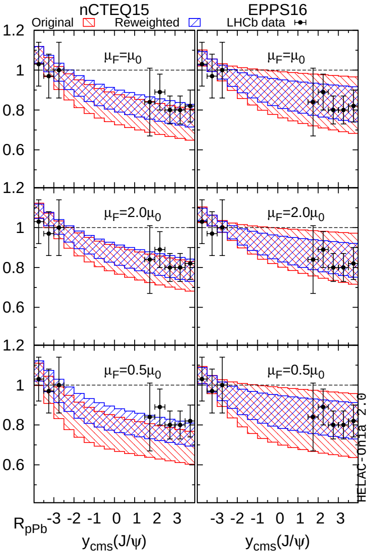
Reweighting with J/ψ data



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.

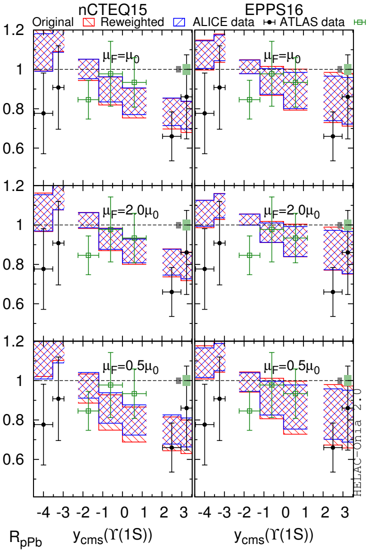
Reweighting with $B \to J/\psi$ data



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).

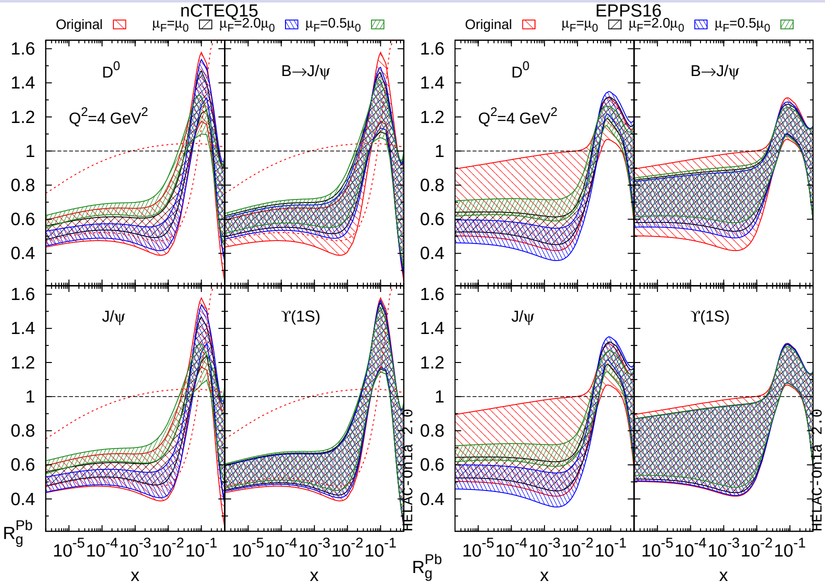
Reweighting with $\Upsilon(1S)$ data



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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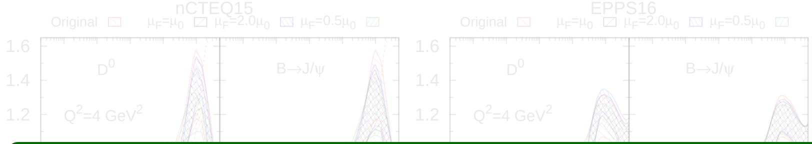


Comments

- 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.

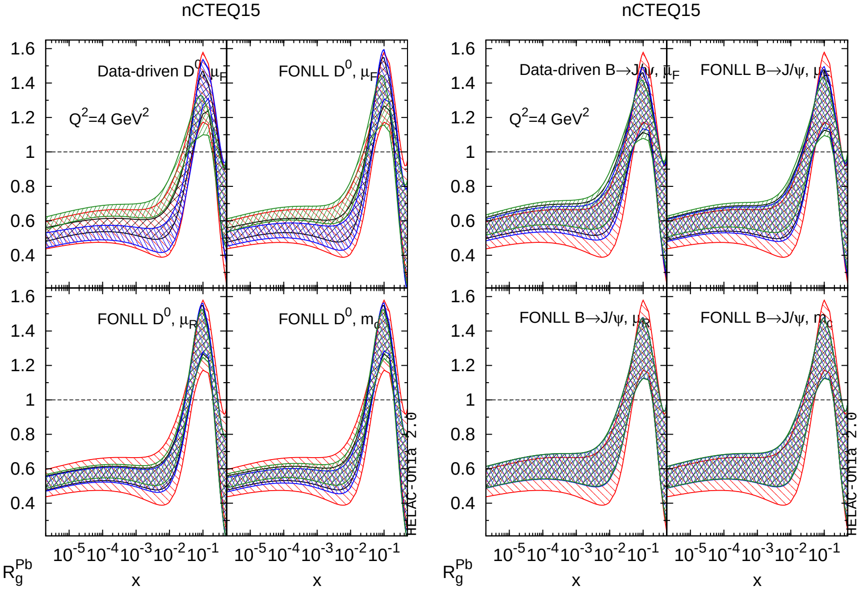
Consistency with other data

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!

Data-driven vs. FONLL



Consistency with other data

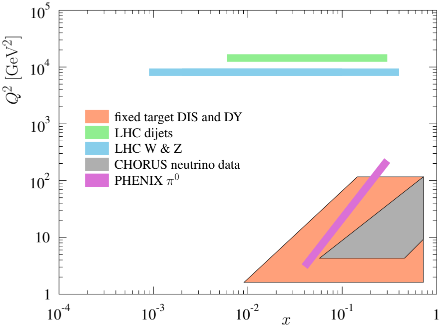
Table : χ^2/N_{data} values for nCTEQ15 nPDFs before and after reweighting using B, D, J/ψ data for different scale choices.

		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_{dAu}	1.99							1.93	0.43	3.35

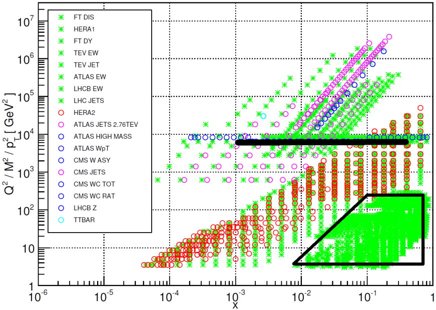
Differences with the free-proton PDFs

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

EPPS16 dataset



NNPDF3.0 NLO dataset



- Less data → less constraining power → more assumptions (fixing) about a_i parameters
- **Assumptions limit/replace uncertainties!**

Available nuclear PDFs

- Multiplicative nuclear correction factors

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

  - **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

$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$
$$f_i(x_N, A=1, \mu_0) \equiv f_i^{free\ proton}(x_N, \mu_0)$$

  - **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]

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

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

EPPS16 [arXiv:1612.05741]

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

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

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

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

Comparison of available nPDFs

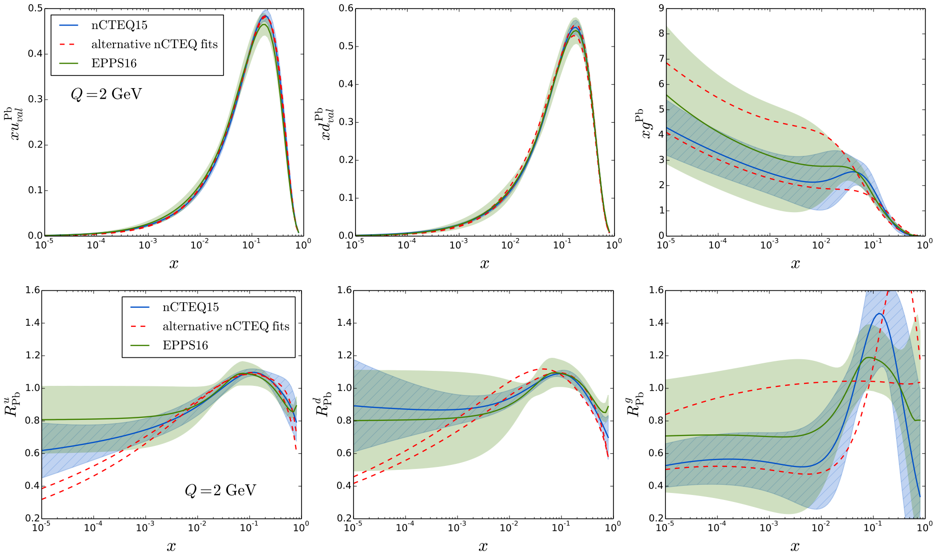
	EPPS16	EPS09	nCTEQ15	DSSZ12	HKN07	KA15
FT NC DIS	✓	✓	✓	✓	✓	✓
FT CC DIS	✓	✗	✗#	✓	✗	✗
FT Drell-Yan	✓	✓	✓	✓	✓	✓
RHIC π^0	✓	✓	✓	✗	✗	✗
LHC W/Z	✓	✗	✗*	✗	✗	✗
LHC dijet	✓	✗	✗	✗	✗	✗
QCD order	NLO	LO & NLO	NLO	NLO	LO & NLO	NNLO
Kinematic cuts	$Q > 1.3$GeV	$Q > 1.3$GeV	$Q > 2$GeV $W > 3.5$GeV	$Q > 1$GeV	$Q > 1$GeV	$Q > 1$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

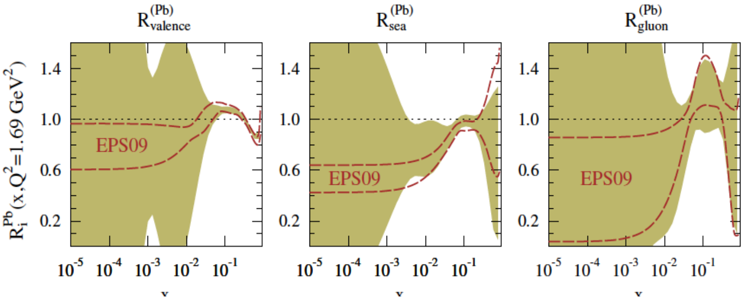
[arXiv:1509.00792, arXiv:1012.1178]

[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 $F_L(Q^2 = 2\,\mathrm{GeV}^2, x > 10^{-5}) > 0$

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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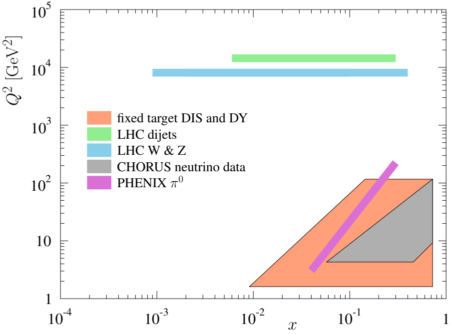

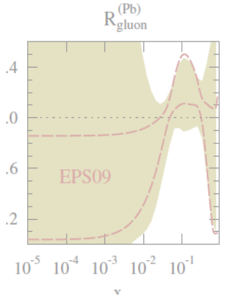

The ... $2\,\mathrm{GeV}^2, x > 10^{-5}) > 0$

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

Maybe ...

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