An update on nuclear PDFs at the LHeC

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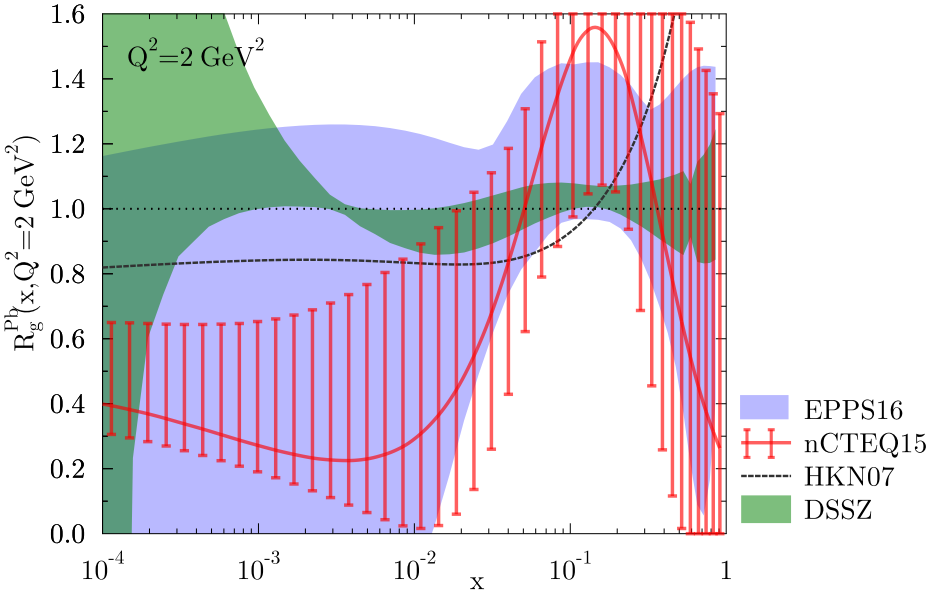
Introduction

- Significant uncertainties in the nuclear PDFs (nPDFs)

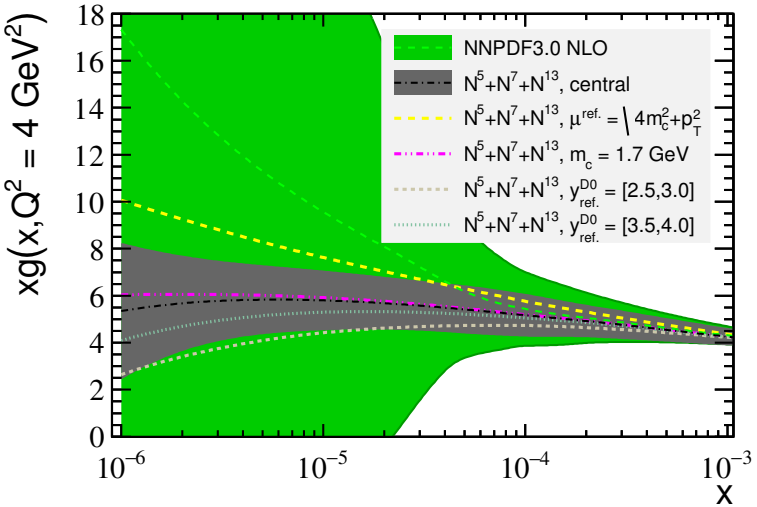
$$R_g^A(x, Q^2) = f_g^{\mathrm{p},A}(x, Q^2)/f_g^{\mathrm{p}}(x, Q^2),$$



- Especially the small-x (here, $x \lesssim 10^{-2}$) behaviour of nPDFs at smallish Q^2 are largely unknown — may become a bottleneck e.g. in
  - distinguishing effects of non-linear evolution
  - precision studies of phenomena in heavy-ion collisions
  - calculations of cosmic-ray interactions in the air

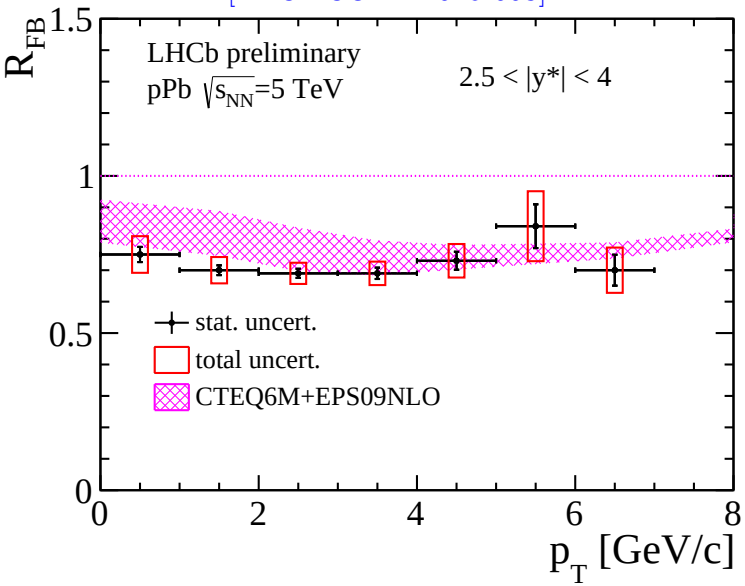
Capabilities of LHC in constraining small x

- The potential of D (and B) meson production has been demonstrated in p-p case [PRL 118 072001 & EPJ C75 396]



- Analogous measurements also in p-Pb. The impact on nuclear PDFs?

[LHCb CONF-2016-003]

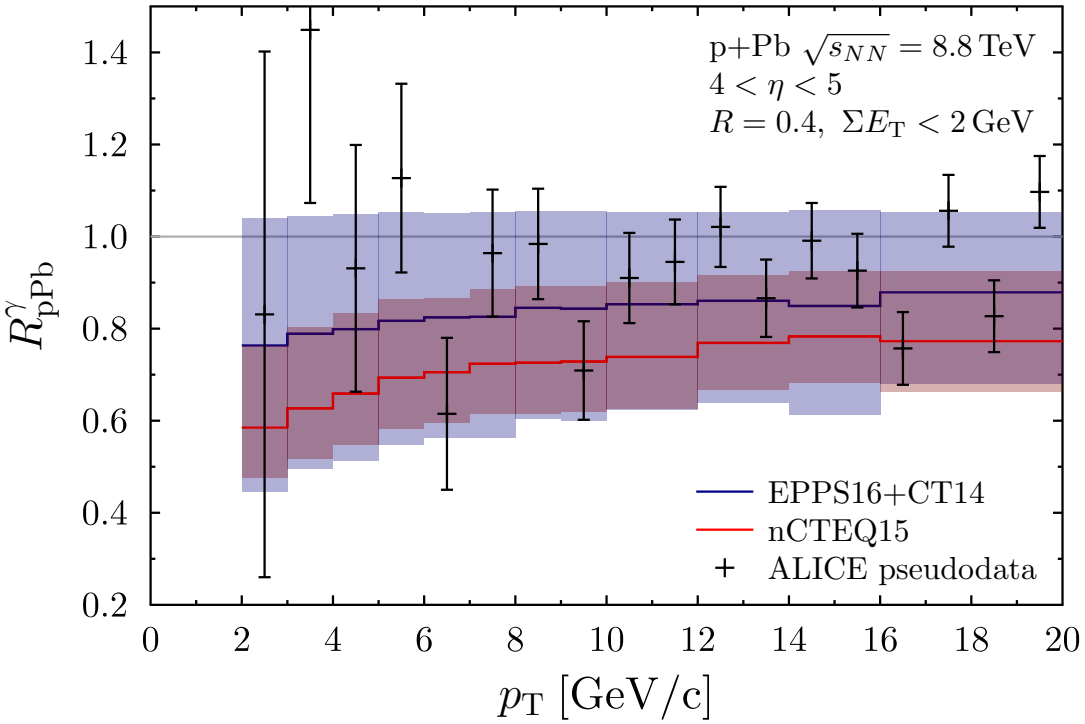


- Theoretical treatment (e.g. heavy-quark hadronization) not unique.
  - In ratios (R_{pPb}, forward-to-bacward) effects like these may largely cancel.
  - May still hamper the **precision** determination of PDFs

Capabilities of LHC in constraining small x

- Isolated photons at forward direction (e.g. LHCb, ALICE FOCAL)
- Simulated FOCAL pseudodata vs. EPPS16 & nCTEQ15:

FIGURE BY I. HELENIUS



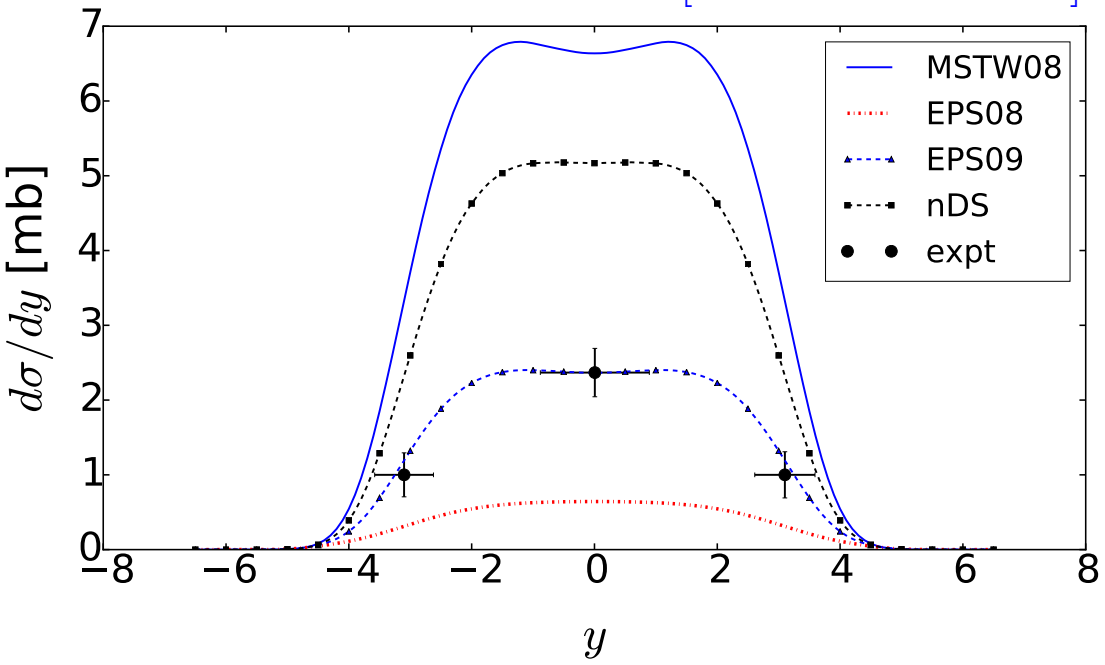
- The impact to be estimated — the x distributions are typically rather broad though [JHEP 1409 (2014) 138].

Capabilities of LHC in constraining small x

- It has been argued that ultraperipheral vector meson (e.g. J/ψ) production in Pb-Pb collisions is particularly sensitive to nuclear gluon

$$\sigma^{\gamma A \to V} \propto \left[g^A(x, Q^2) \right]^2$$

[arXiv:1603.01919]



- How accurately the distributions probed by this process correspond to the inclusive NLO (and beyond) PDFs?

The LHeC pseudodata

- Assume $\mathcal{L}_{\rm ep} = 10\,{\rm fb}$, $\mathcal{L}_{\rm ePb} = 1\,{\rm fb}$ (per nucleon)
- Considered energy configs: $\sqrt{s_{\rm p}} = 7\,{\rm TeV}$, $\sqrt{s_{\rm Pb}} = 2.75\,{\rm TeV}$ (per nucleon) on $E_e = 60\,{\rm GeV}$ electrons.
- The pseudodata are here obtained from ratios of reduced cross sections $\sigma^i_{\rm ePb}$, $\sigma^i_{\rm ep}$ and relative point-to-point ($\delta^i_{\rm uncor.}$) and normalization ($\delta^i_{\rm uncor.}$) uncertainties as

$$R_i = R_i(EPS09) \times \left[1 + \delta^i_{\rm uncor.} r^i + \delta_{\rm norm.} r^{\rm norm.}\right]$$

where

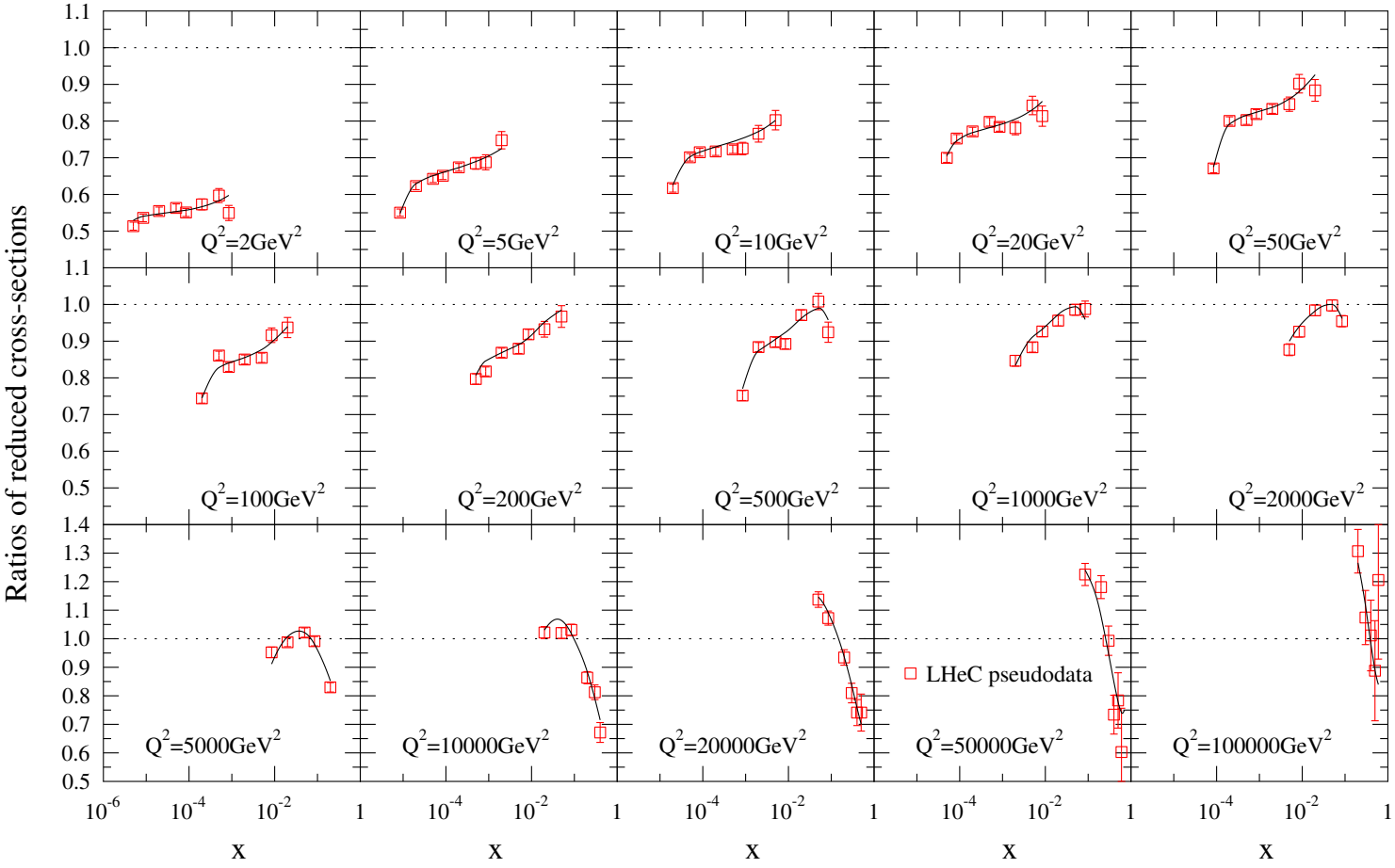
$$R_i(EPS09) = \frac{\sigma^i_{\rm ePb}(CTEQ6.6 + EPS09)}{\sigma^i_{\rm ep}(CTEQ6.6)},$$

and r^i and $r^{\rm norm.}$ are Gaussian random numbers.

- In EPS09 $R_{u_{\rm V}} \approx R_{d_{\rm V}}$, $R_{\overline{u}} \approx R_{\overline{d}} \approx R_{\overline{s}}$ (free in EPPS16, but would not expect large deviations from this)
- EPS09 and CTEQ6.6 used only in generating the pseudodata.

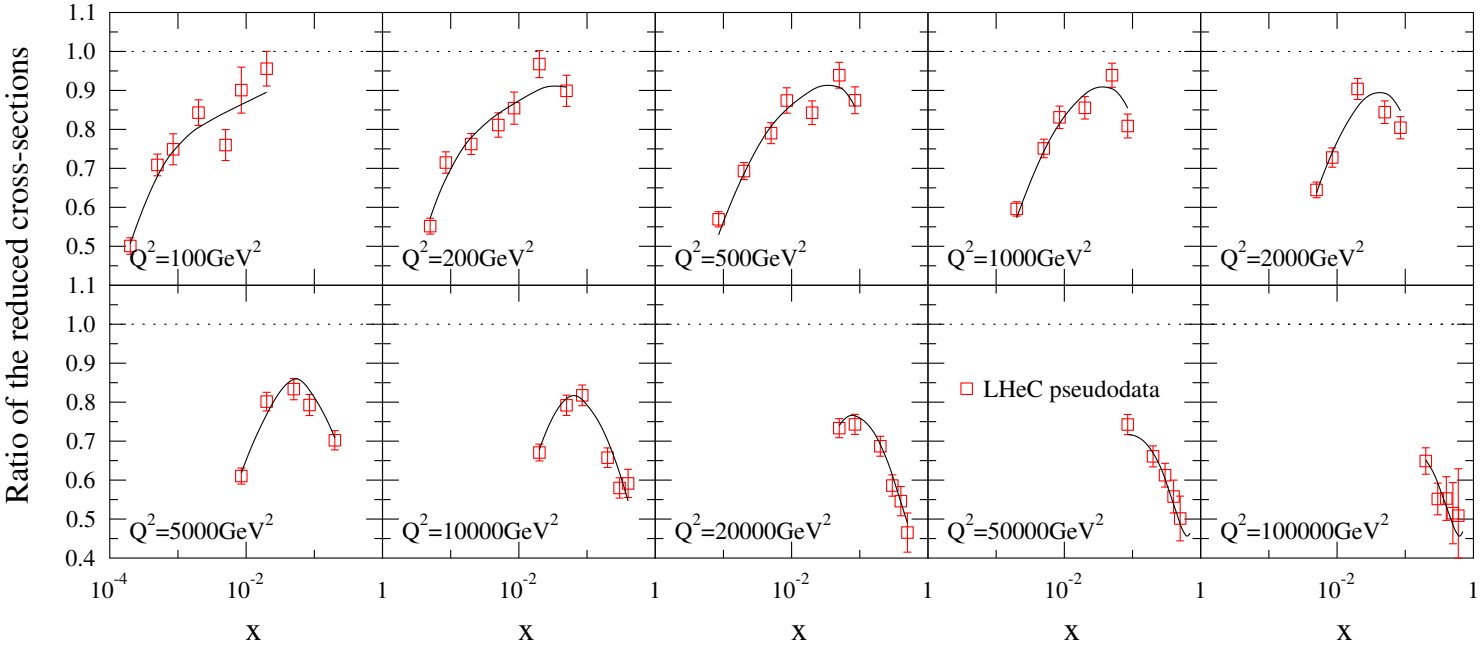
The LHeC Pseudodata

- The neutral-current pseudodata:



The LHeC Pseudodata

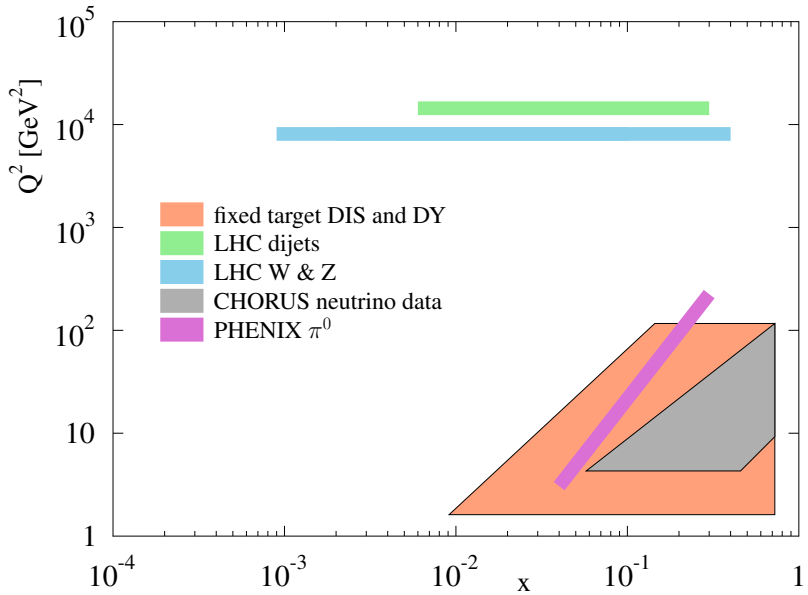
- The charged-current pseudodata:

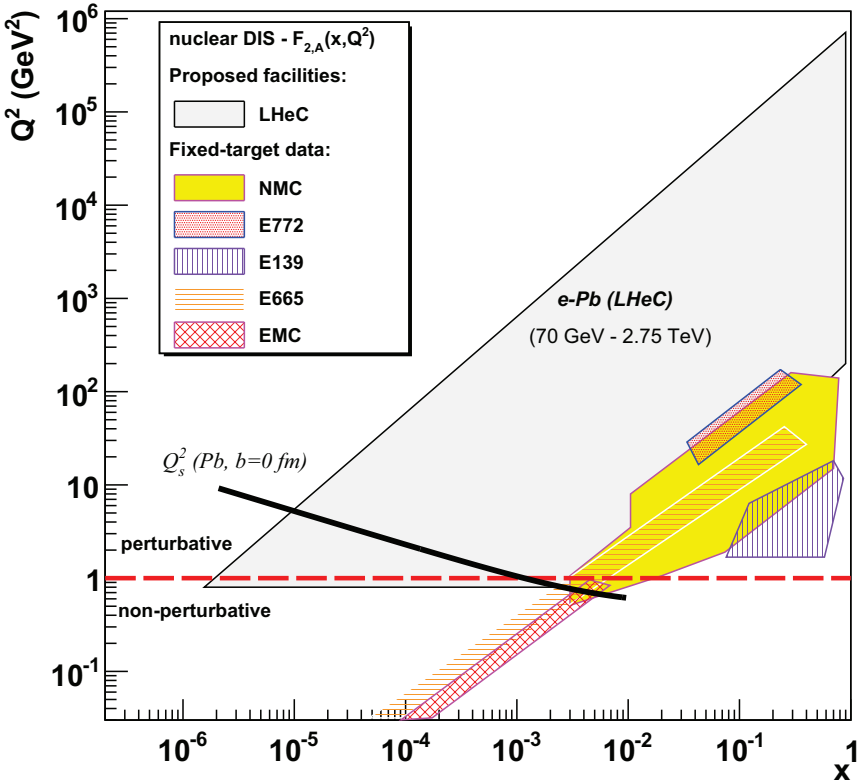


- Neutral- & charged-current cross sections probe different partonic combinations — a better control over the flavour separation?

The analysis framework

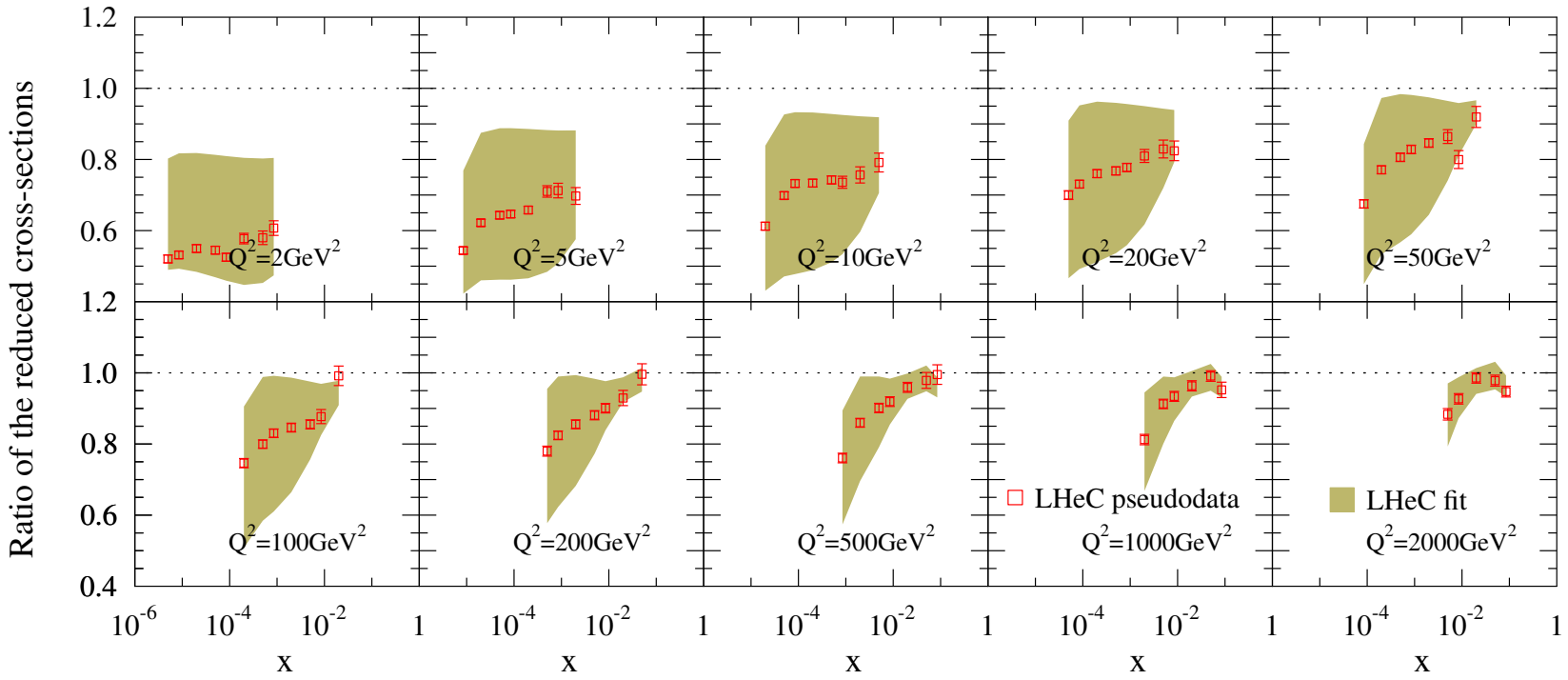
- The fit framework same as in the EPPS16 analysis [EPJ C77, 163]
- Include the same data as in EPPS16 plus LHeC (NC and CC) pseudo data.
- Hessian uncertainty analysis with $\Delta\chi^2 = 52$ (as in EPPS16)





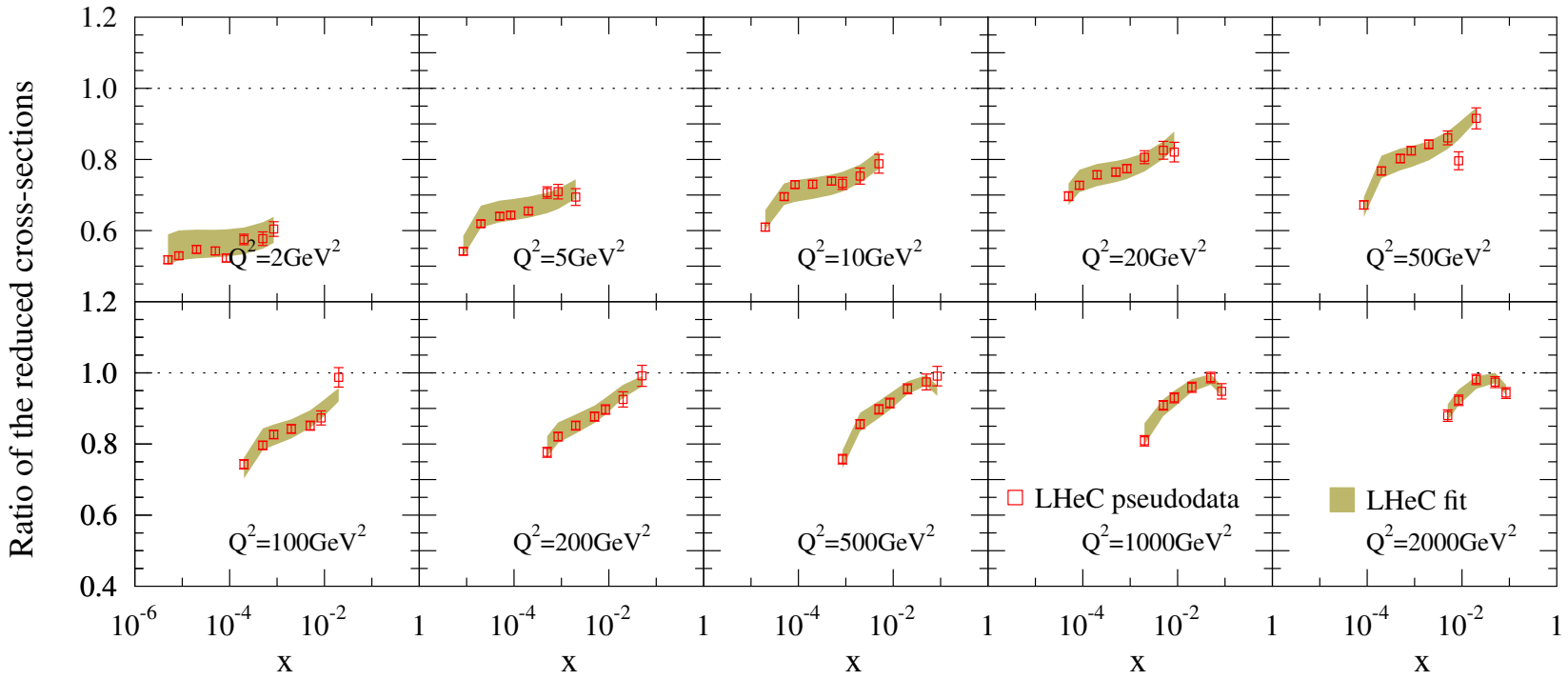
The effect of LHeC pseudodata

The NC data vs. EPPS16



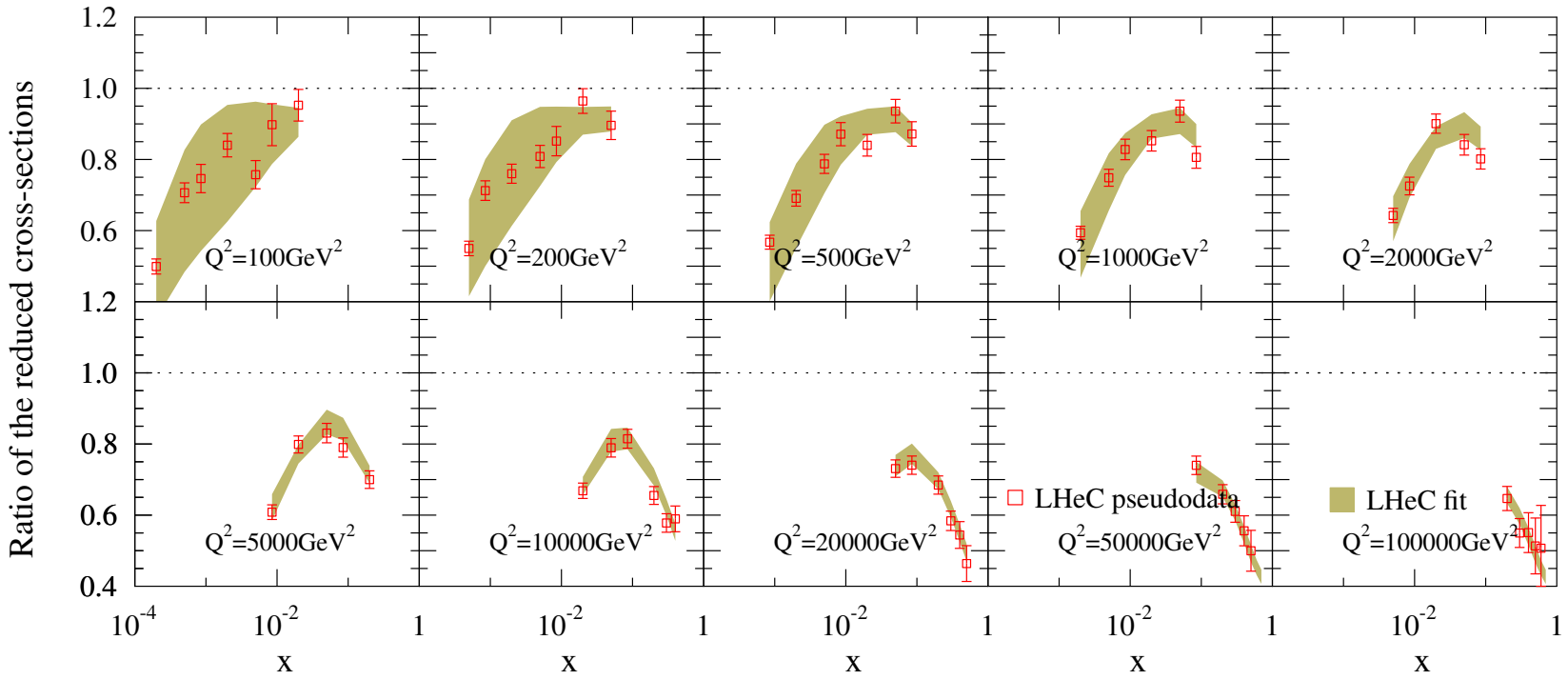
The effect of LHeC pseudodata

The NC data after including NC+CC data into the analysis



The effect of LHeC pseudodata

The CC data vs. EPPS16



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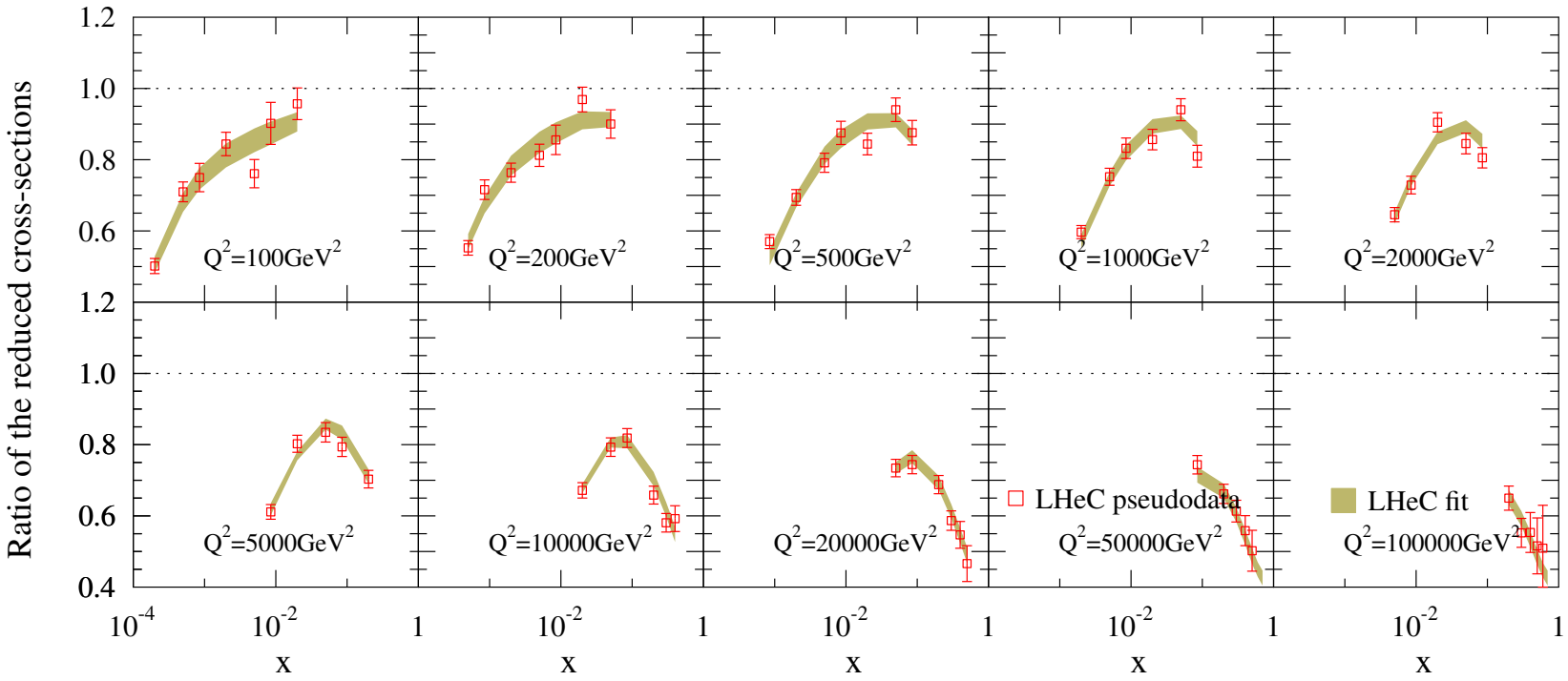
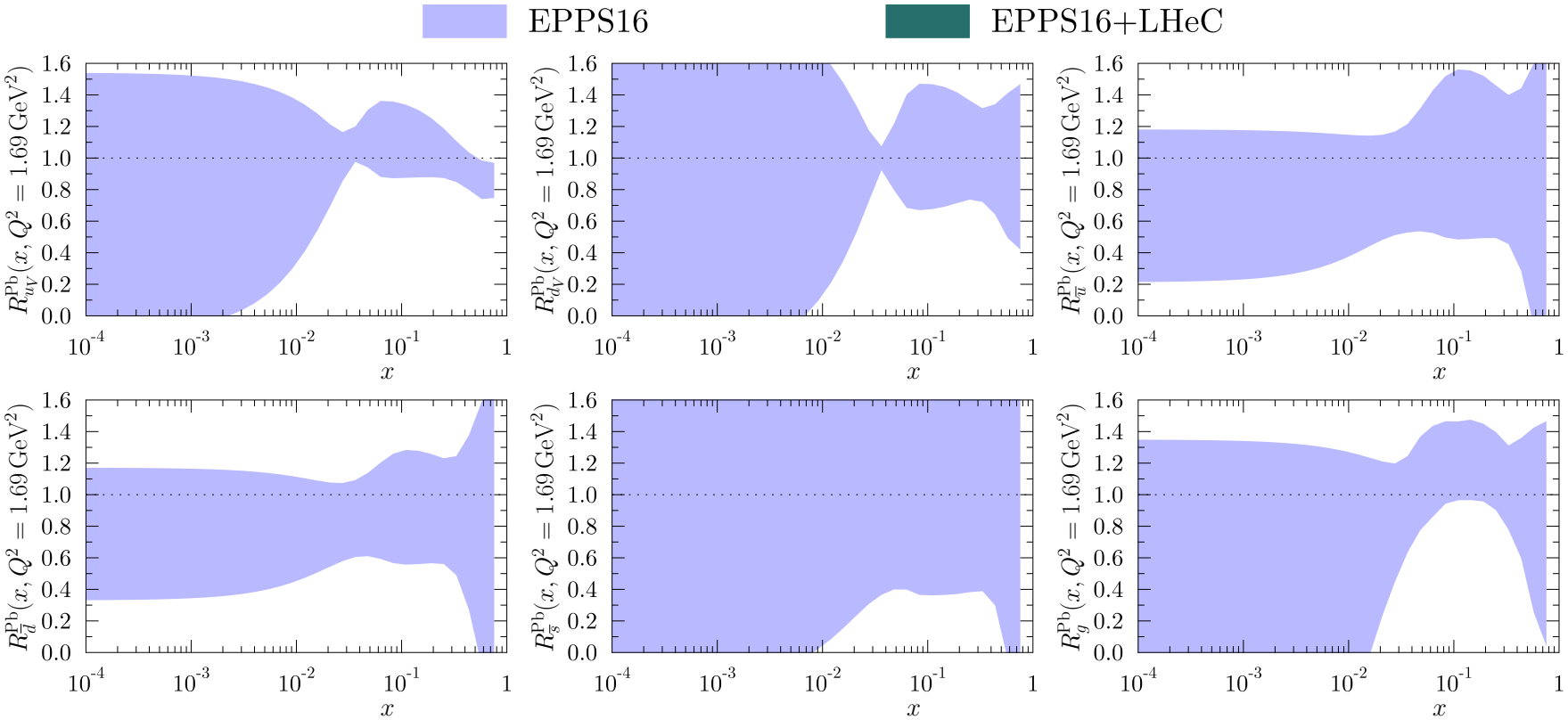
The CC data after including NC+CC data into the analysis



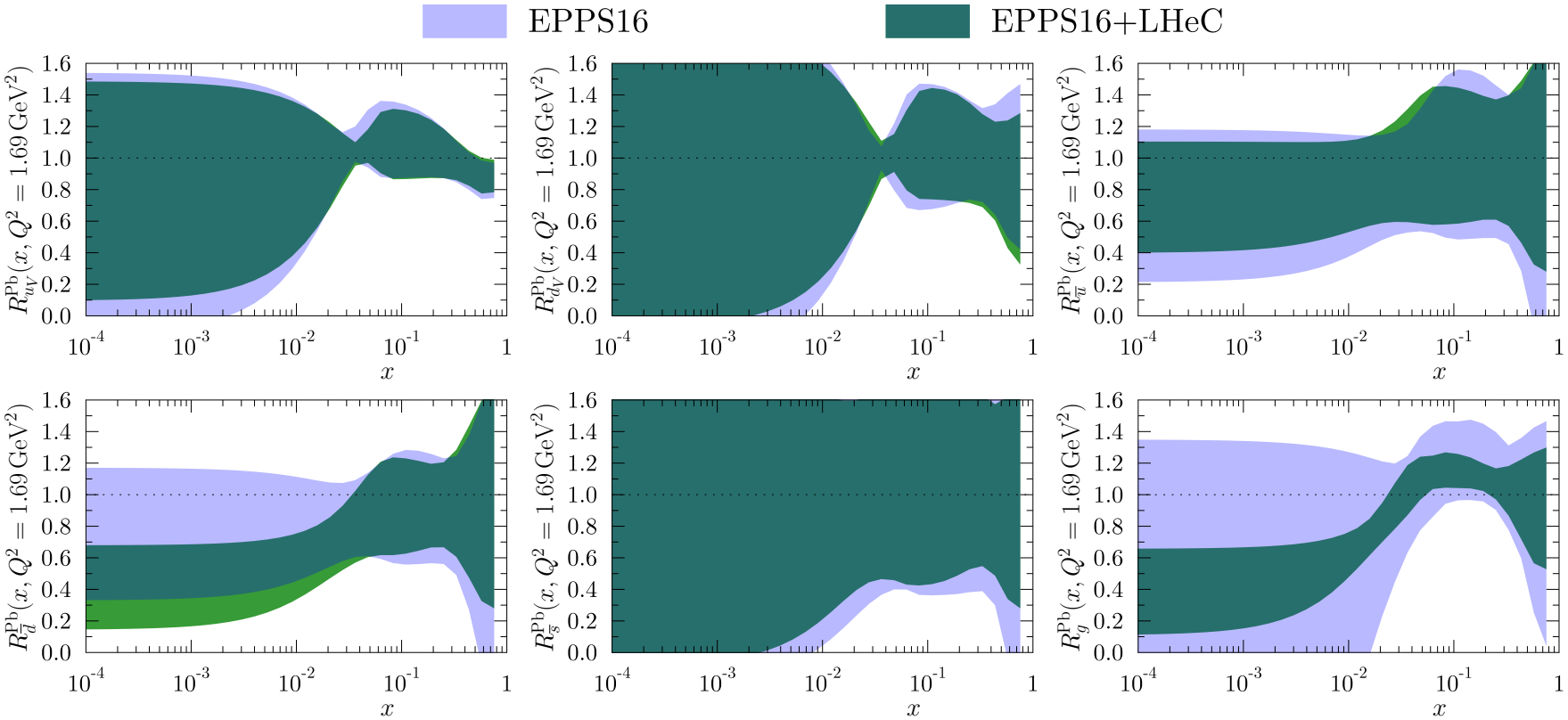
The effect of LHeC pseudodata

- The EPPS16 errorbands at $Q^2 = 1.69\,\mathrm{GeV}^2$



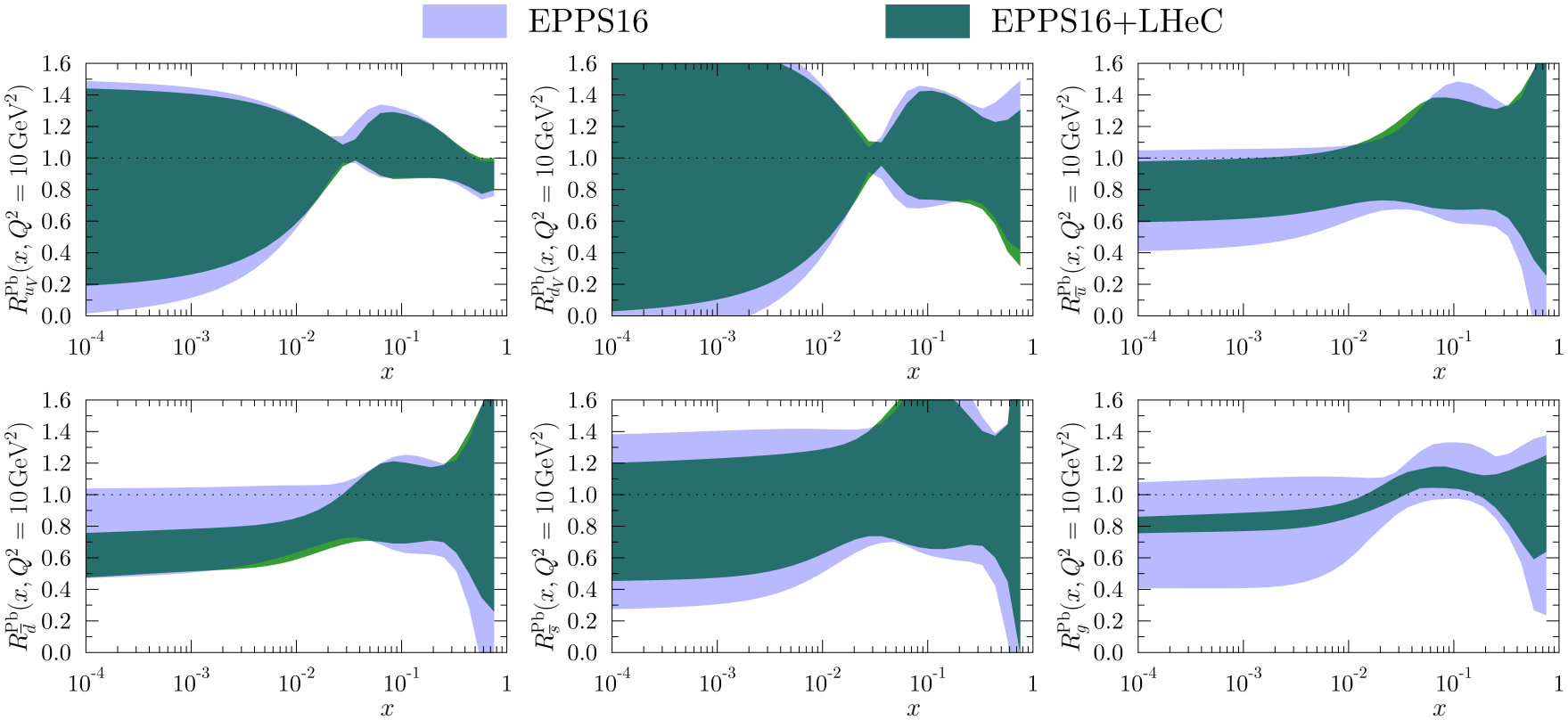
The effect of LHeC pseudodata

- The improvement after adding the LHeC data ($Q^2 = 1.69\,\mathrm{GeV}^2$)



The effect of LHeC pseudodata

- The improvement after adding the LHeC data ($Q^2 = 10\,\mathrm{GeV}^2$)



The effect of LHeC pseudodata

- Why it is so hard to pin down the flavor dependence?
- Take the valence up-quark distribution u_V^A as an example:

$$u_V^A = \frac{Z}{A} R_{u_\mathrm{V}} u_\mathrm{V}^{\mathrm{proton}} + \frac{A-Z}{A} R_{d_\mathrm{V}} d_\mathrm{V}^{\mathrm{proton}}$$

- Write this in terms of average modification R_V and the difference δR_V

$$R_V \equiv \frac{R_{u_\mathrm{V}} u_\mathrm{V}^{\mathrm{proton}} + R_{d_\mathrm{V}} d_\mathrm{V}^{\mathrm{proton}}}{u_\mathrm{V}^{\mathrm{proton}} + d_\mathrm{V}^{\mathrm{proton}}}, \qquad \delta R_\mathrm{V} \equiv R_{u_\mathrm{V}} - R_{d_\mathrm{V}}$$

$$u_V^A = \underbrace{R_\mathrm{V}\left(\frac{Z}{A} u_\mathrm{V}^{\mathrm{proton}} + \frac{A-Z}{A} d_\mathrm{V}^{\mathrm{proton}}\right)}_{\text{Leading term}} + \underbrace{\delta R_\mathrm{V}\left(\frac{2Z}{A} - 1\right) \frac{u_\mathrm{V}^{\mathrm{proton}}}{1 + u_\mathrm{V}^{\mathrm{proton}}/d_\mathrm{V}^{\mathrm{proton}}}}_{\text{“Correction term”}}$$

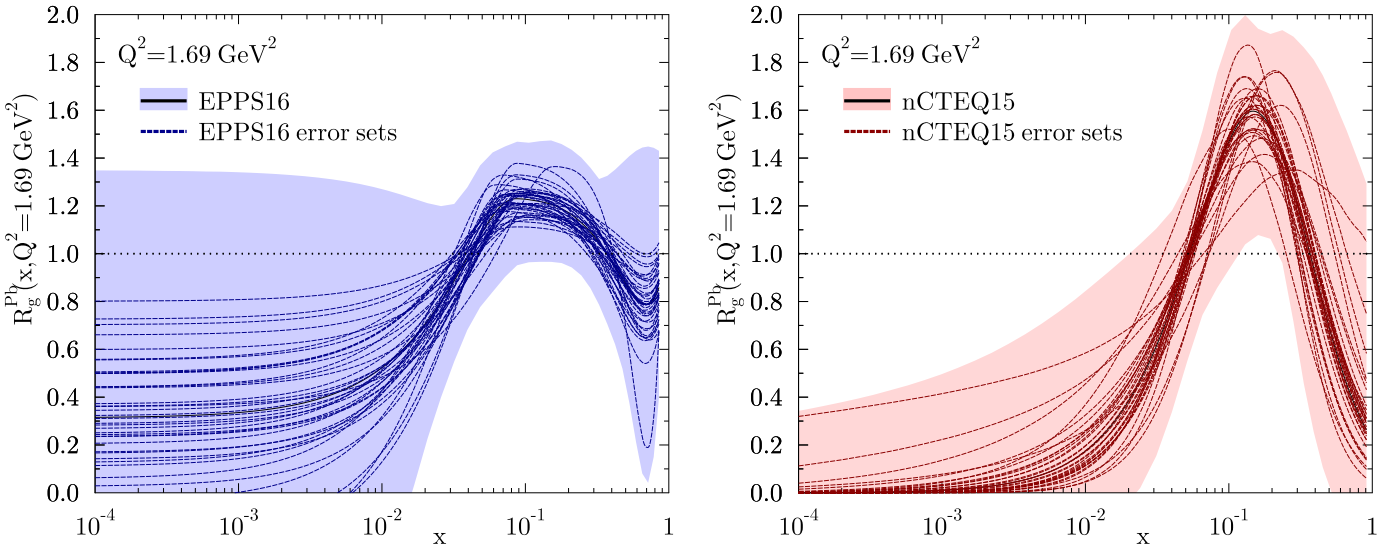
- The effects of flavour separation (i.e. δR_V here) are suppressed in cross sections — but also so in most of the nPDF applications.

About the functional forms

- The fit functions in EPPS16 & nCTEQ15:

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

$$R^{\mathrm{nCTEQ15}}(x) = \left[c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5}\right] / f^p(x)$$



- Very little freedom at small x — both (as well as the fit shown here) do significantly underestimate the true uncertainties.

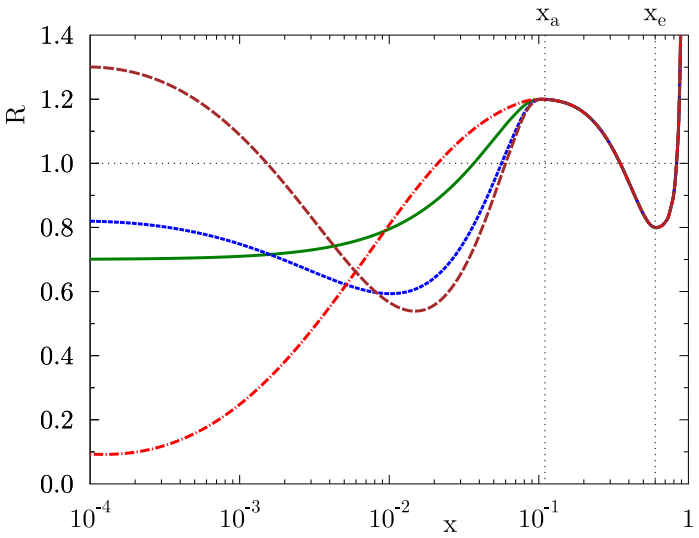
About the functional forms

In principle, one can replace the small-x fit function by a more flexible form

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

or

$$R(x \leq x_a) = a_0 + (x - x_a)^2 \left[a_1 + a_2 x^{\alpha} + a_3 x^{2\alpha} + a_4 x^{3\alpha} + \ldots\right], \ \alpha \ll 1$$

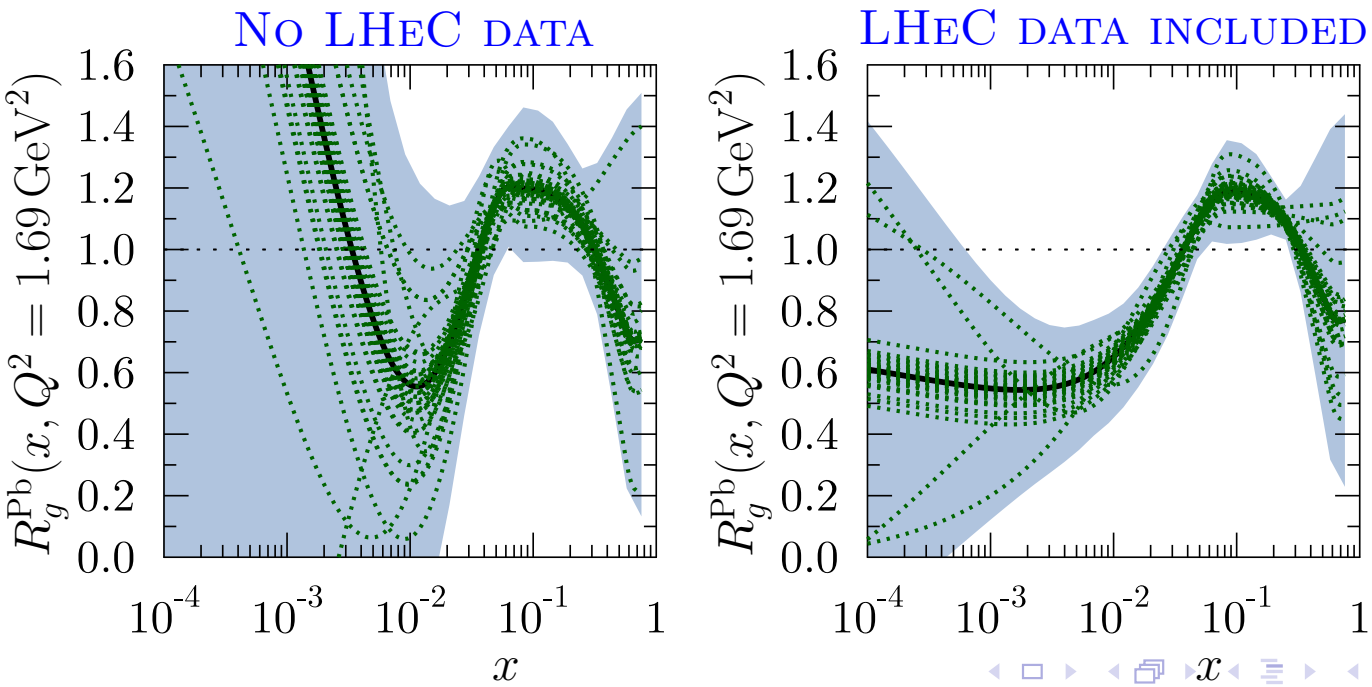


$\Longrightarrow$ The bias at small x can be significantly reduced

About the functional forms

- However, the Hessian method used e.g. in EPPS16 is not particularly accurate when there's no, or only very weak constraints
  - Significant non-quadratic components in the global χ^2 function
  - Large correlations among the fit parameters
- Would need Monte-Carlo methods to more reliably map the uncertainties

  $\Longrightarrow$ Further work needed
- Despite all the shortcomings, a typical result using a more flexible form (the red one in the previous slide) for the gluons:



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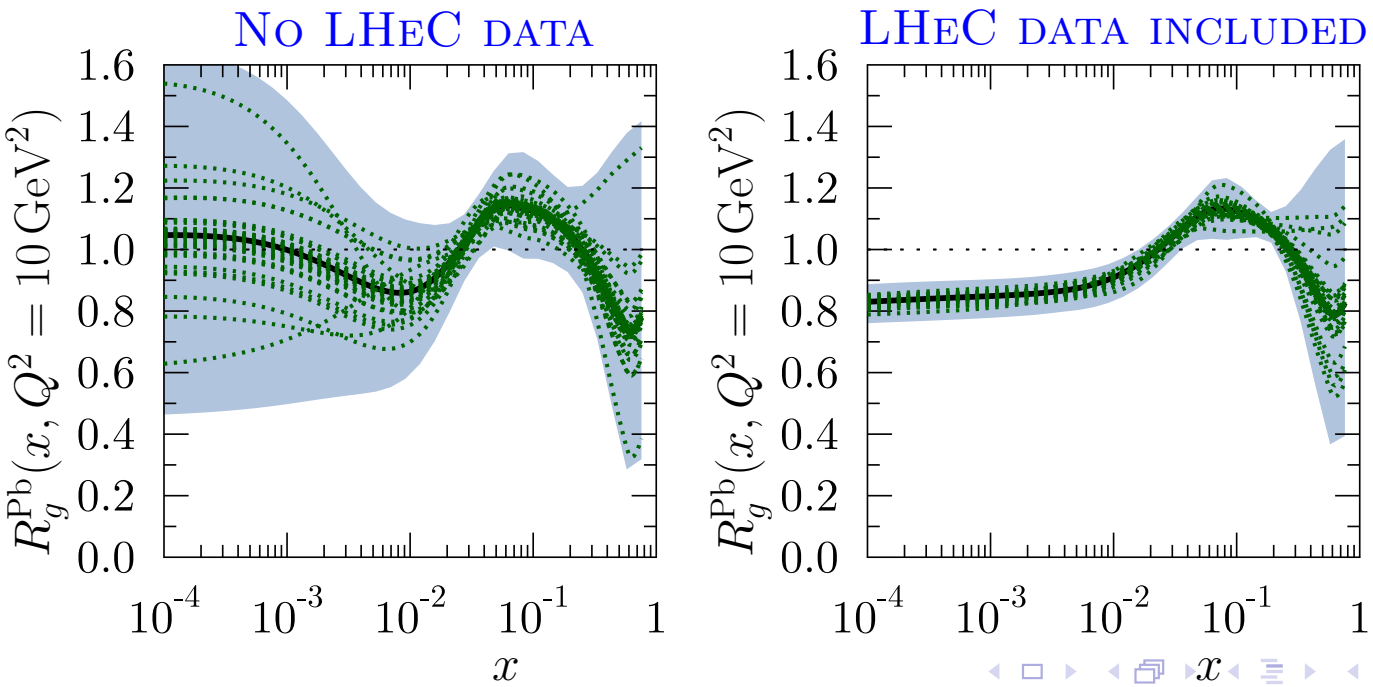

Summary

- Nuclear PDFs at small-x still largely unconstrained — may limit the physics output of e.g. the LHC Pb-Pb program and neutrino telescopes.
  - The capabilities of LHC may be limited by theoretical uncertainties
  - DIS theoretically much cleaner — LHeC would significantly increase our knowledge on nPDFs
- The effect of LHeC on EPPS16 global fit studied by a fit on a sample of NC and CC pseudodata.
  - significant reduction especially on the gluon uncertainty
- Briefly discussed the sizable small-x parametrization bias
  - a workaround within EPPS16 is to increase the flexibility of the fit functions at small x
  - doesn't work well with the Hessian method used in EPPS16 fit
  - Monte-Carlo methods required