Impact of low-*x* resummation on QCD analysis of HERA data

Based on xFitter developers' team and M. Bonvini [arXiv:1802.00064]

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PDF4LHC

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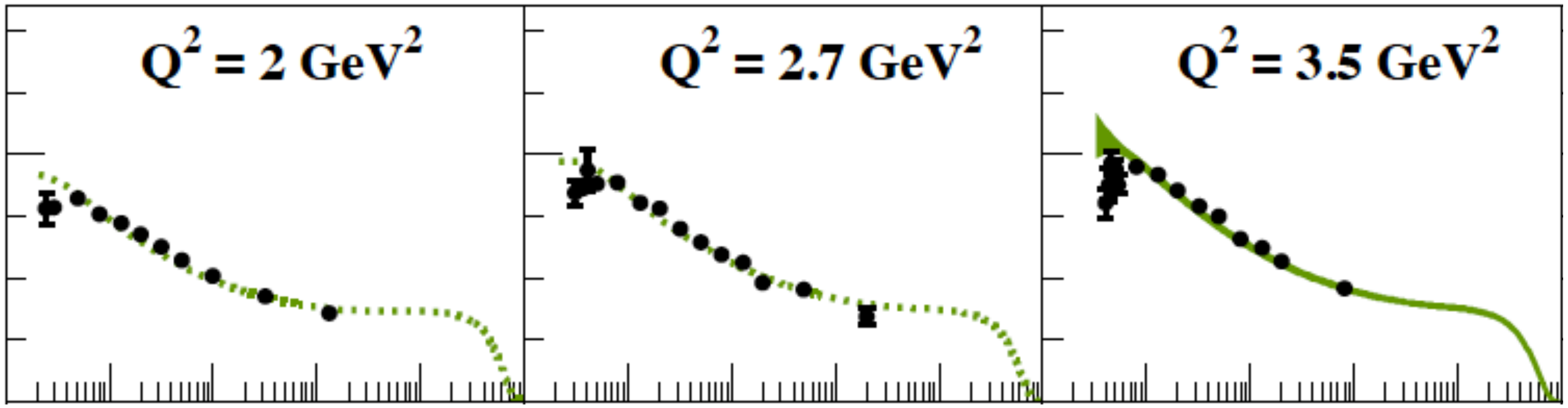
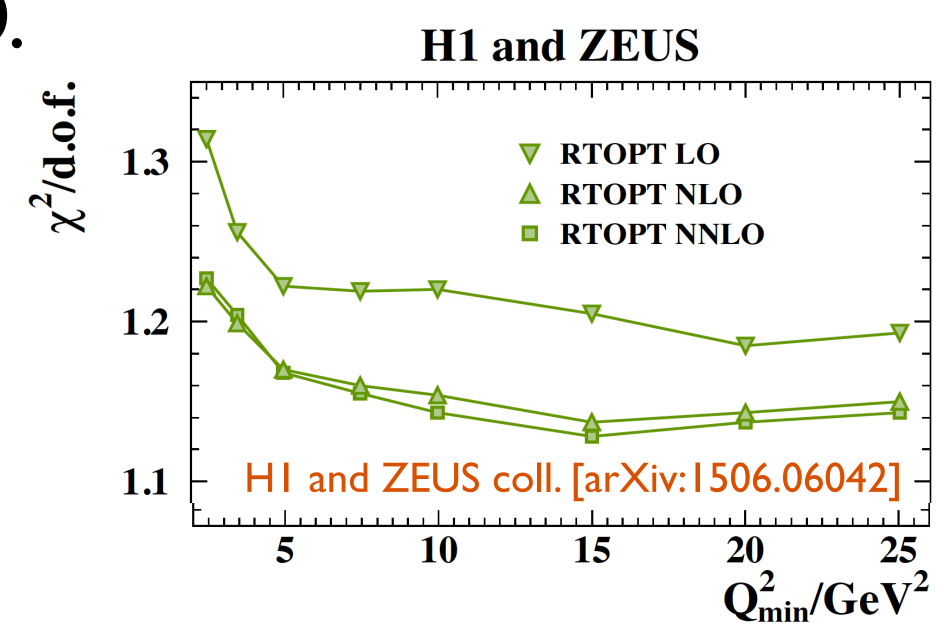
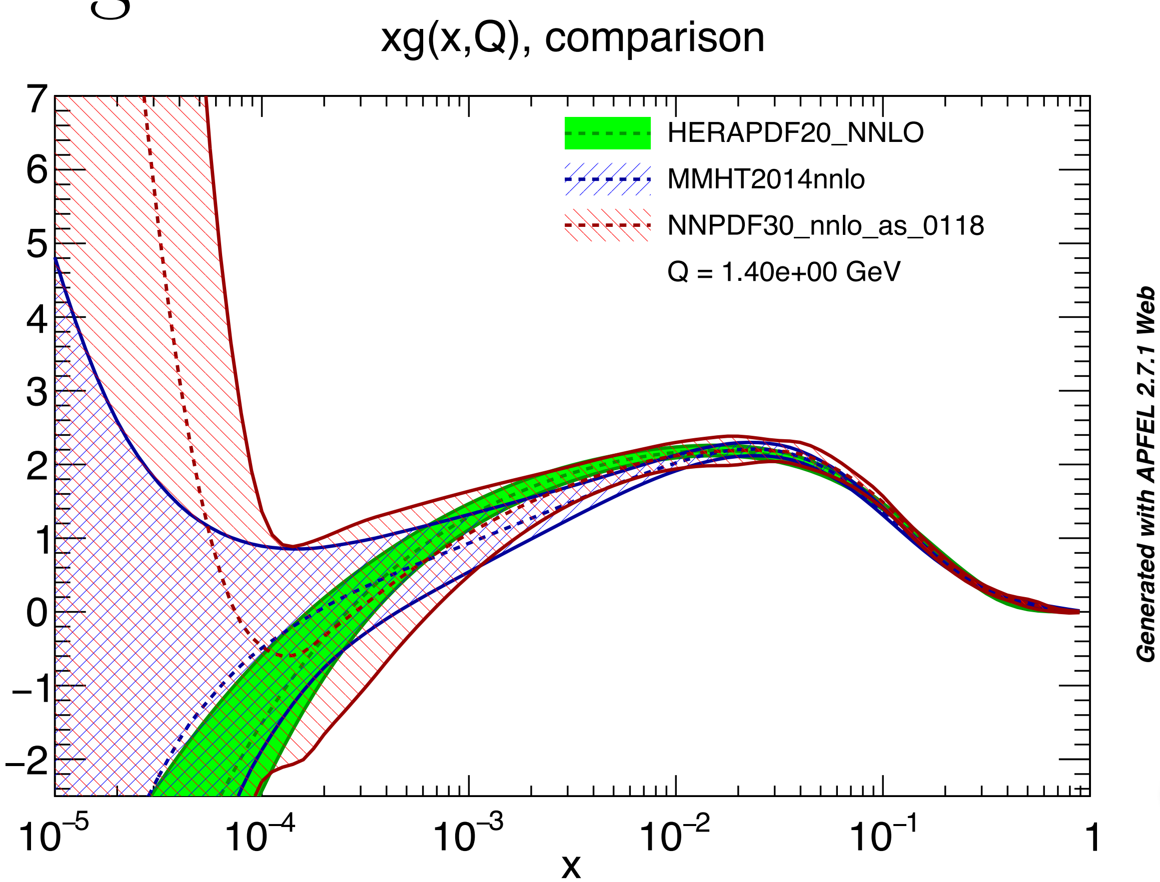
Introduction

- The crucial observation is that **low-x** and **low-Q^2** HERA data are not well-described by fixed-order (FO) QCD.





- Particularly at **NNLO**, this leads to an “unnaturally” suppressed gluon at small-x and small scales.



- Effect driven by $\boldsymbol{F_L}$ required to be large at small Q^2 to describe the turn over of data:

$$\sigma_{\rm red} = F_2 - \frac{y^2}{Y_+} F_L$$

- Larger small-x gluon at small Q^2 but not at large Q^2.

- FO DGLAP evolution too **steep** at small x.

Introduction

- The goal is to fit the combined HERA 1+2 **inclusive** cross sections including **small-x resummation** corrections based on the BFKL formalism up to NLL (NLLx):
  - resummed **evolution**,
  - resummed DIS **structure functions**,
  - resummed PDF **matching conditions**.
- Resummation corrections are properly **matched** to the fixed-order expressions:
  - fixed-order components provided by **APFEL**,
    V. Bertone et *al*. [arXiv:1310.1394]
  - resummed corrections provided by the code **HELL**,
    M. Bonvini et *al*. [arXiv:1708.07510]
    - these include **massless** and **massive** coefficient functions.
  - Implementation of the **FONLL** scheme with small-x corrections.
- This corrections are promptly available in **xFitter** through APFEL.

Introduction

- Recently a more comprehensive PDF analysis was carried out by part of the NNPDF collaboration with M. Bonvini and S. Marzani.

R. D. Ball et *al.* [arXiv:1710.05935]

- Despite based on the same codes for the theoretical predictions, a number of **differences** as compared to this study remain:
    - **global fit** including also hadronic processes,
    - **fitted charm**,
    - well-known fundamental differences in the **methodology**.
- The original purpose of this study was to assess the impact of the small-x resummation on the **HERAPDF2.0 analysis**:
    - gluon PDF parameterisation, Q_{min} cut, charm data, etc.
- However, we **acknowledge** that a direct comparison to NNPDF and the understanding of the possible differences is important:
    - we are currently **revising** the paper to address this point.

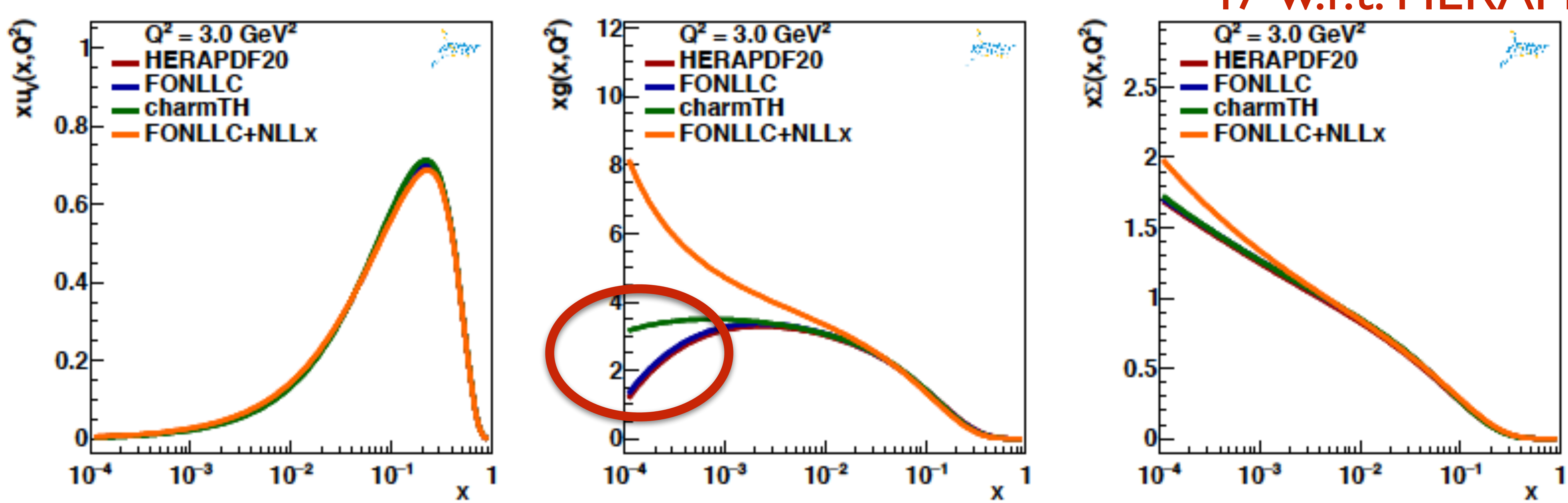
Fit setup

- The aim of this work is to move in steps from **HERAPDF2.0** at **NNLO** to a setup with small-x resummation using APFEL+HELL:

  1. use **FONLL** instead of RT (required to use APFEL),
  2. move up $\boldsymbol{Q_0}$ and displace the **charm** threshold (required by HELL),
  3. turn on the **small-x resummation** at NLLx.

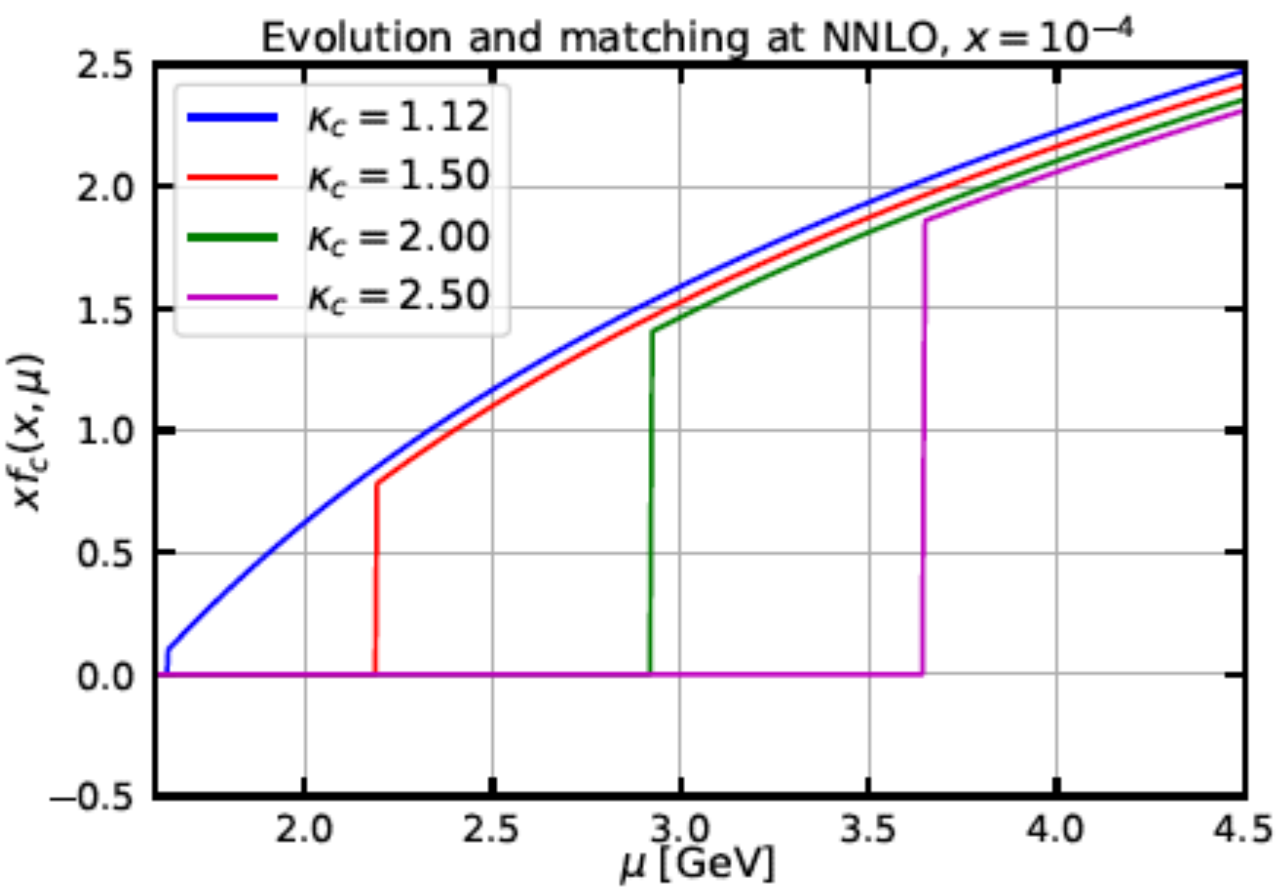
	Step-1	Step-2	Step-3	Step-4
	HERAPDF2.0 NNLO	FONLL-C	Move Q_0^2 and charm threshold	include NLLx resummation
HERA χ^2/d.o.f	1363/1131	1387/1131	1389/1131	1316/1131

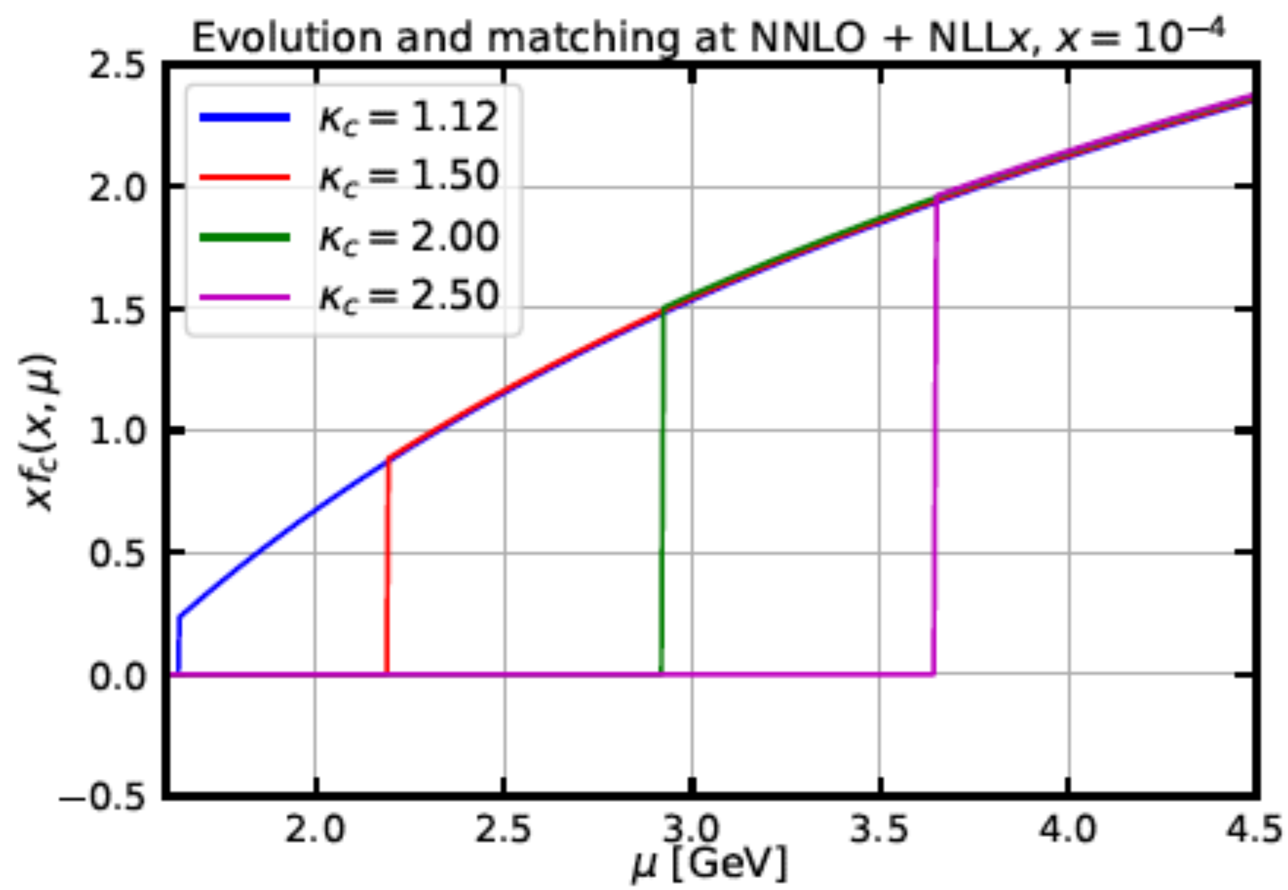
- 47 w.r.t. HERAPDF2.0



Heavy quark threshold matching

- Also the PDF matching conditions are affected by large logs at low x.
- This logs are resummed in HELL:





- Improvement of the **stability** of the (dynamical) charm PDF upon displacement of the charm threshold
- Origin of the difference in the gluon PDF at small x after step 2.

Quality of the fit

- In this analysis we have included also the HERA 1+2 **charm** dataset because it places itself in a region relevant to this study:
  - tune the **charm** mass,
  - we originally included also to the **bottom** data and tuned the bottom mass bust since this dataset is at higher x and Q^2 we finally removed it.

(both fits use FONLL-C)	NNLO fit with new settings	NNLO+NLLx fit with new settings
Total χ^2/d.o.f	1446/1178	1373/1178
subset NC 920 χ^2/n.d.p	446/377	413/377
subset NC 820 χ^2/n.d.p	70/70	65/70
subset charm χ^2/n.d.p	48/47	49/47
correlated shifts inclusive	102	77
correlated shifts charm	15	11
log term inclusive	20	-3
log term charm	-2	-1

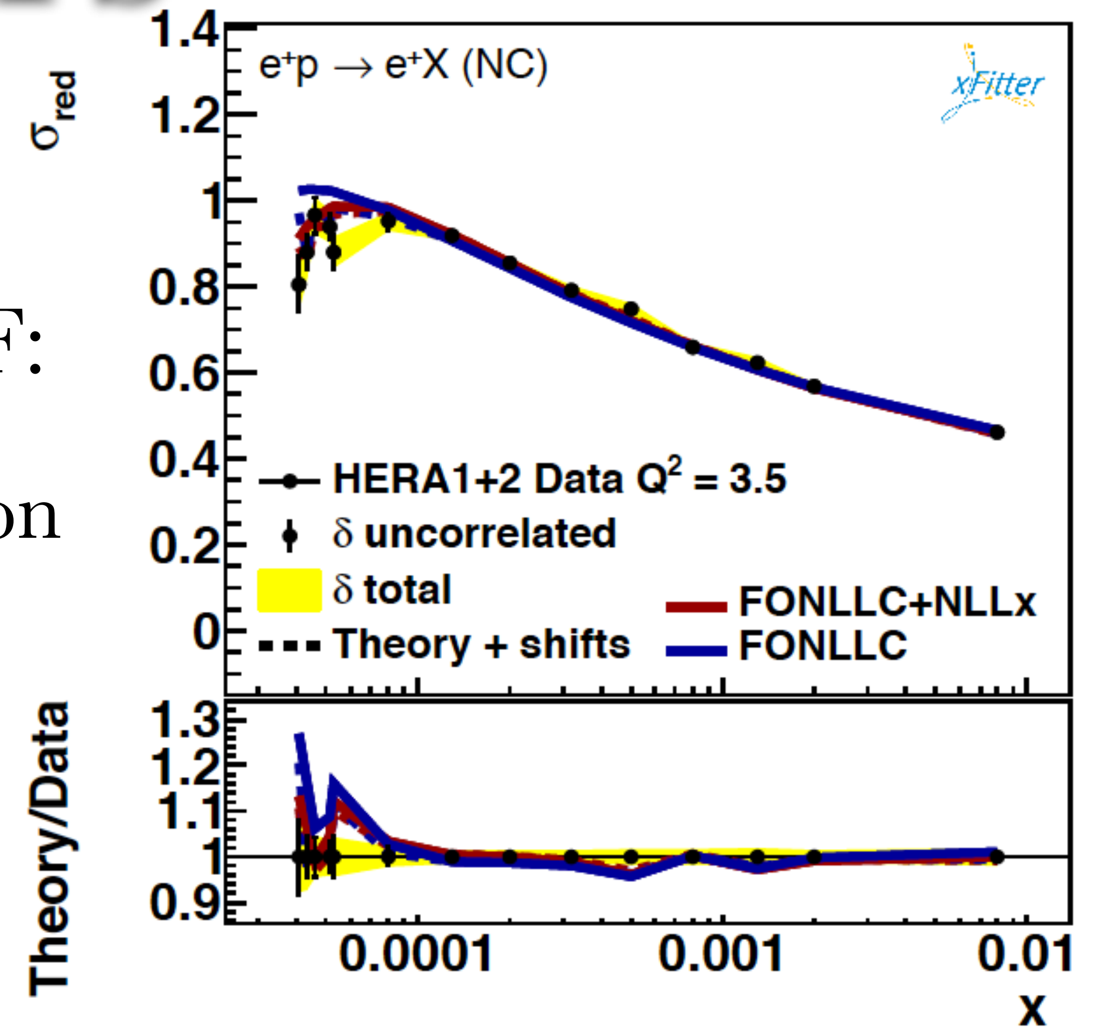
-73 units!

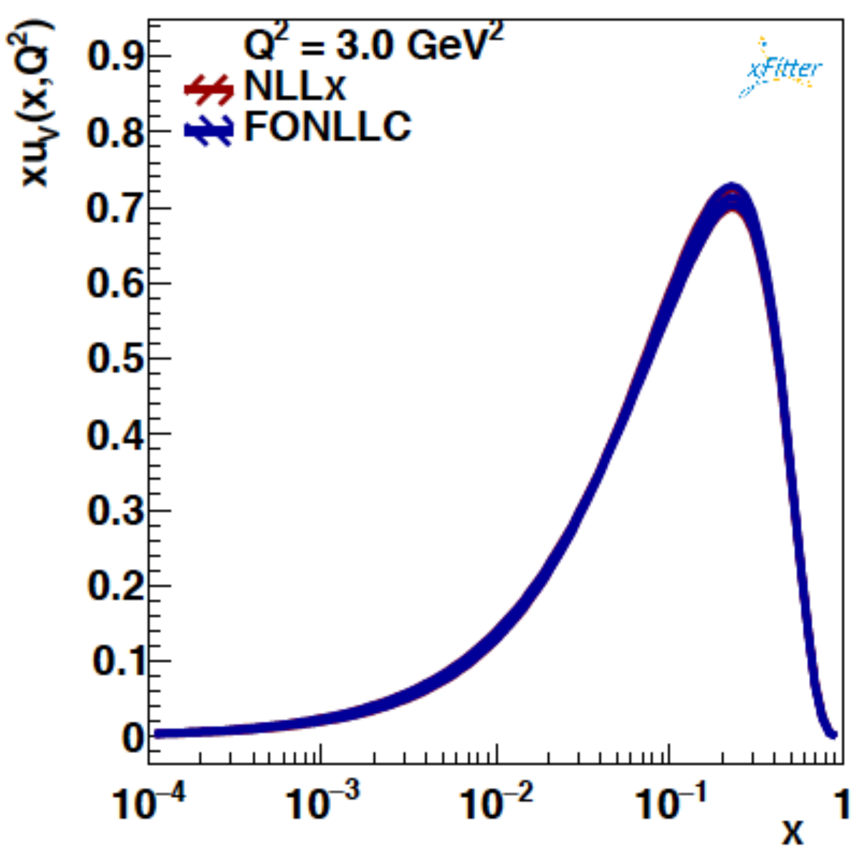
Smaller correlated and log contributions, mostly due to the inclusive data

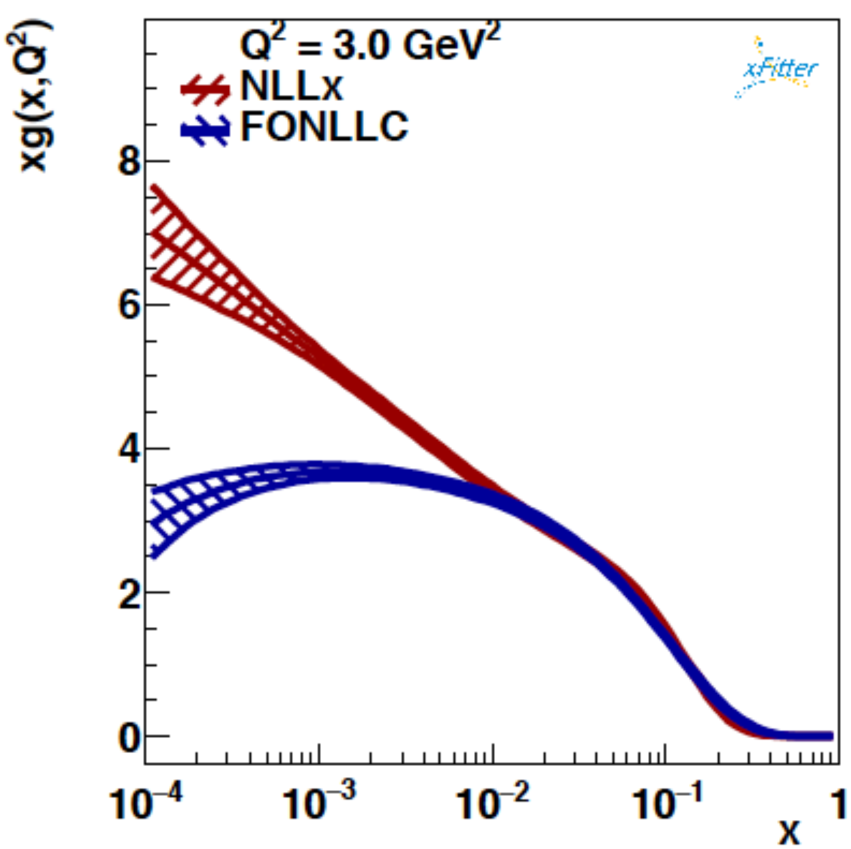
$$\chi^2 = \sum_i \frac{\left[D_i - T_i\left(1 - \sum_j \gamma^i_j b_j\right)\right]^2}{\delta^2_{i,\mathrm{unc}} T_i^2 + \delta^2_{i,\mathrm{stat}} D_i T_i} + \sum_j b_j^2 + \sum_i \ln \frac{\delta^2_{i,\mathrm{unc}} T_i^2 + \delta^2_{i,\mathrm{stat}} D_i T_i}{\delta^2_{i,\mathrm{unc}} D_i^2 + \delta^2_{i,\mathrm{stat}} D_i^2}$$

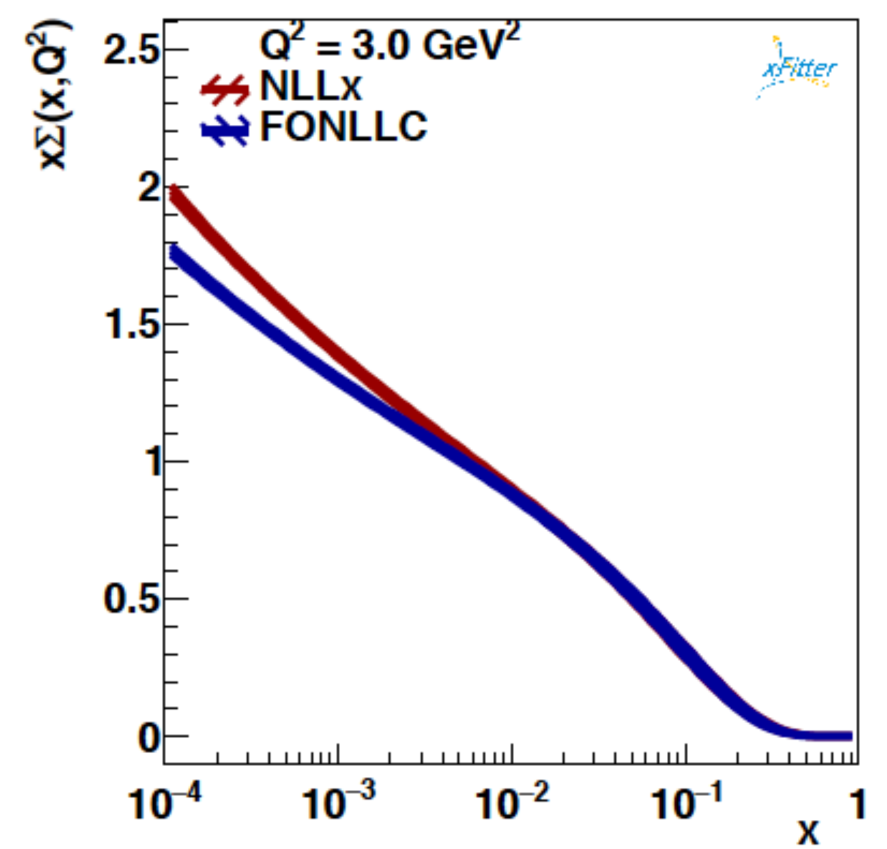
The PDFs

- Better *visual* description of the low-Q^2 bins,
- significant difference on the **gluon** PDF:
  - **no longer negative gluon** distribution at small x.
- Marginal effect on the **singlet** PDF.
- No effect on the **valence** PDFs.

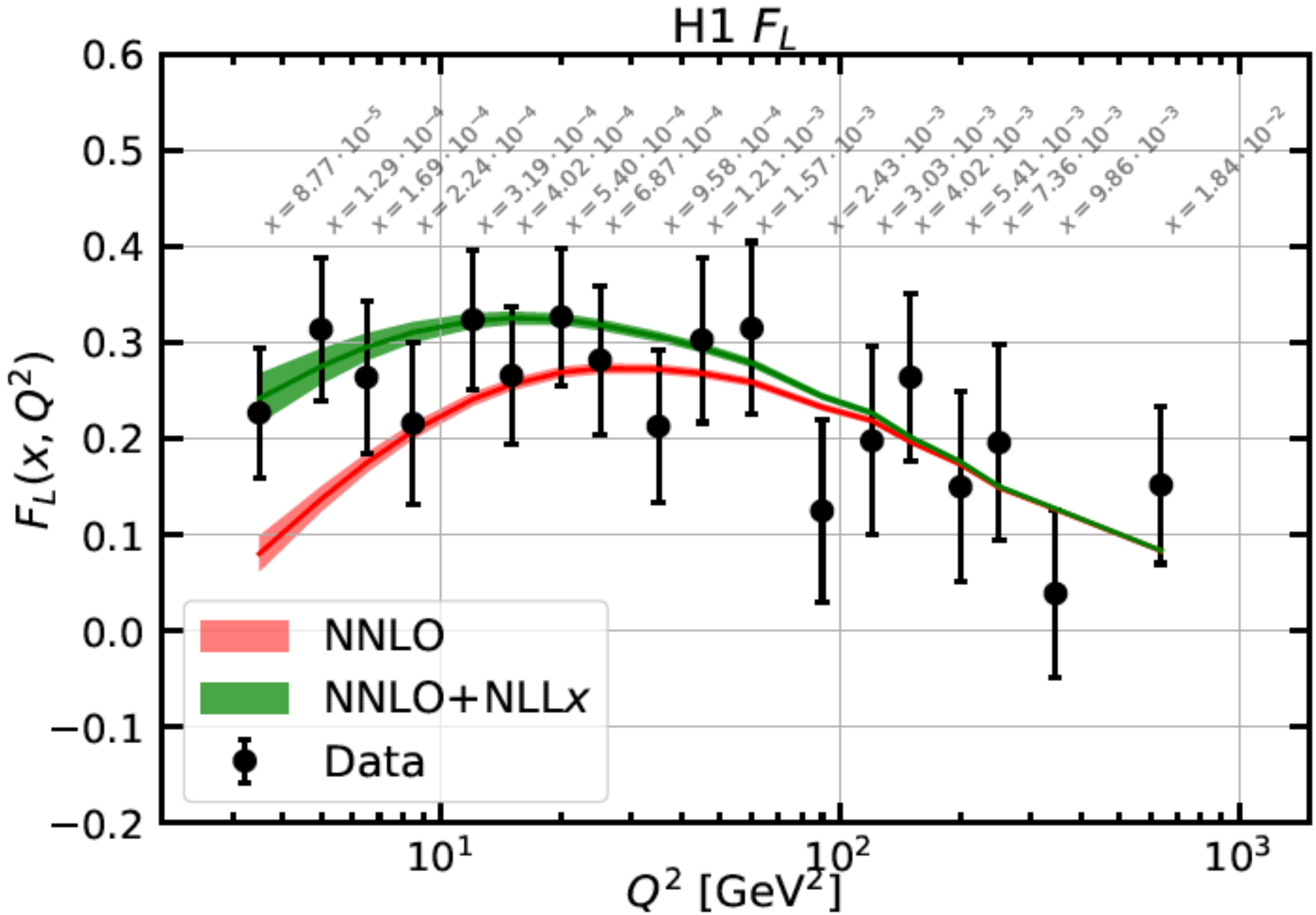








Impact on F_L



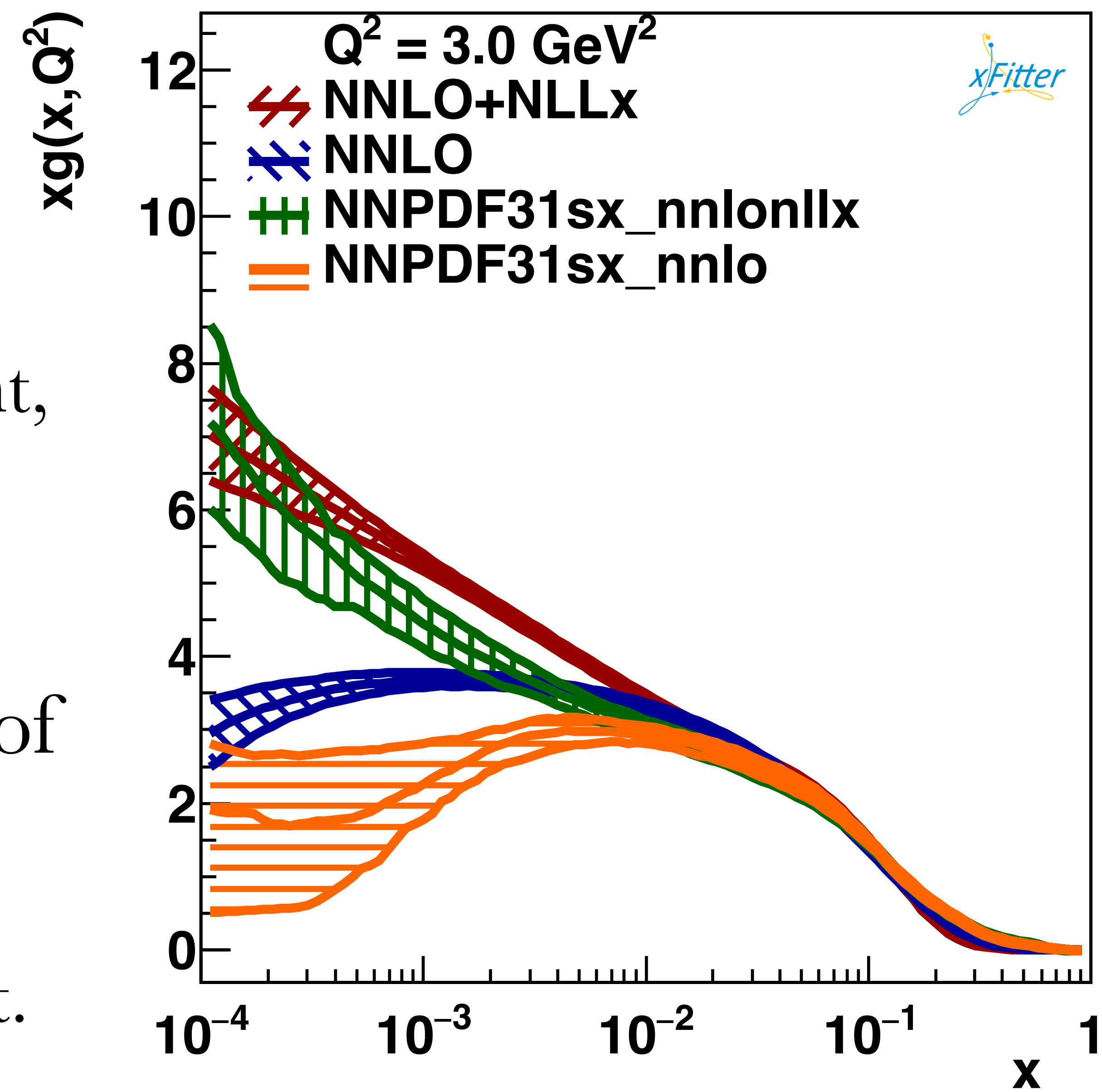
- Better *visual* description of the resummed fit as compared to the fixed order one for the H1 F_L extraction.

Comparison with NNPDF

- Fit with small-x resummation correction by **NNPDF**:
  - fully-fledged PDF analysis,
  - includes **hadronic** data and other DIS experiments,
  - **fitted charm**.

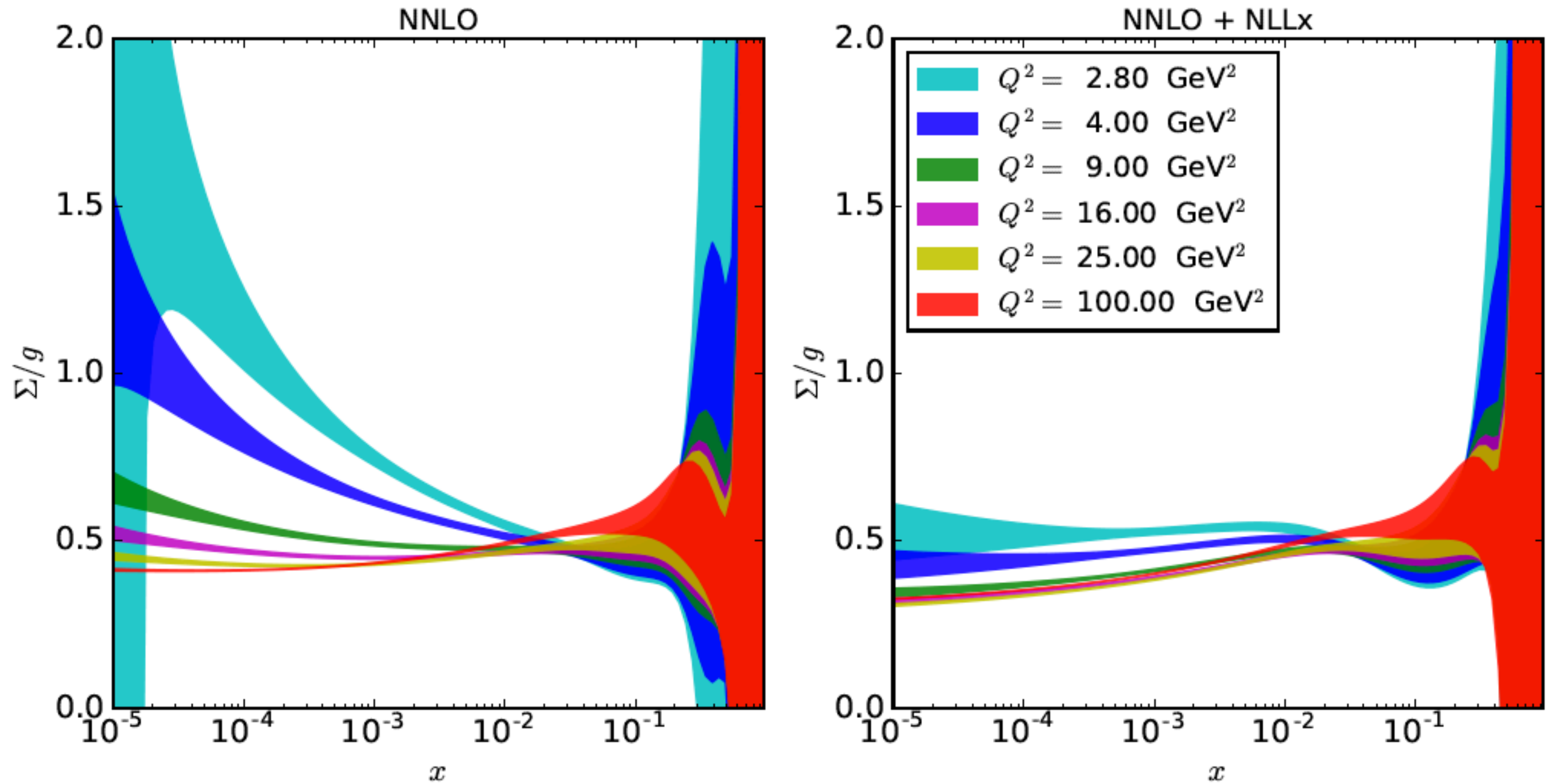
- **No direct comparison** possible with this analysis:
  - no comparison was originally meant,
  - same **qualitative** behaviours.

- We are now investigating the origin of some of the differences:
  - work triggered by the referee report.



The small-x gluon

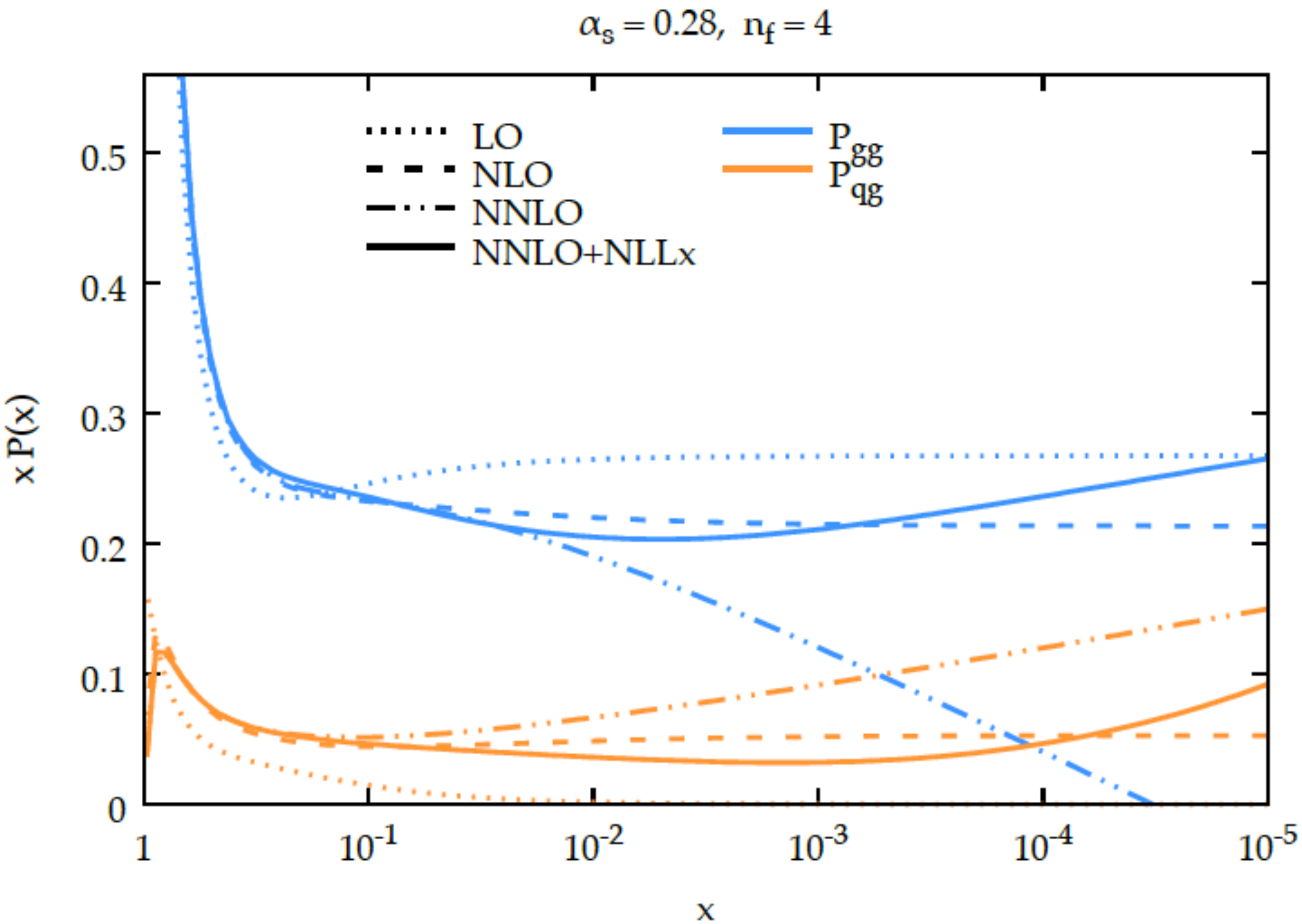
- In the fit with resummation as opposed to the FO one the **rise** of gluon and the singlet distributions at small x becomes similar:
  - this is was “predicted” by the **GRV model** in which low-x gluon and sea PDFs are dynamically generated by low-scale valence distributions.



- Look at the evolution of the Σ / g ratio:
  - large spread at small x for the fixed-order fit,
  - almost constant (~0.5) for the resummed fit.

The small-x gluon

- The behaviour of the Σ / g ratio can be explained by a peculiar feature of P_{gg} and P_{qg} at NNLO.



- For $x < 10^{-3}$ the NNLO curves are such that $P_{gg} < P_{qg}$:
    - suppression of the gluon PDF in favour of the singlet PDF.
- When resummation is introduced $P_{gg} > P_{qg}$ is true at all vales of x:
    - hierarchy between gluon and singlet PDFs is restored.

The $Q^2 = 2.7$ GeV^2 bin

- Motivated by the success in describing the low-Q^2 data, we have tried to include in the fit also the the $Q^2 = 2.7$ GeV^2 bin.

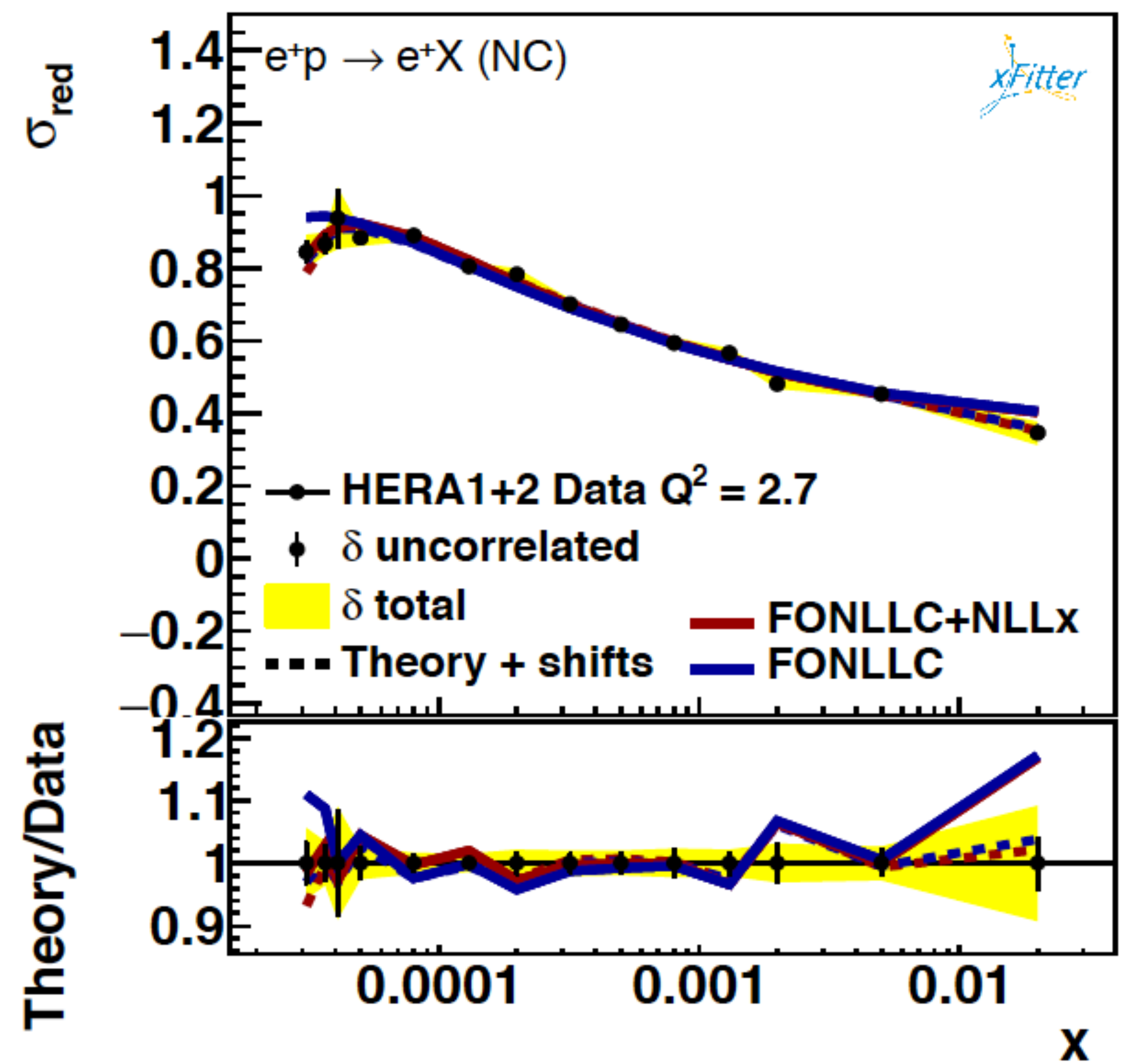
- Visually, small-x resummation helps describe also this bin.

- However, if one looks at the χ^2 this is not quite the case:

  - including 17 more points leads to a worsening in the χ^2 of 41 units at NNLO and 35 at NNLO+NLLx.

- Most probably the large χ^2 is caused by the large-x points.

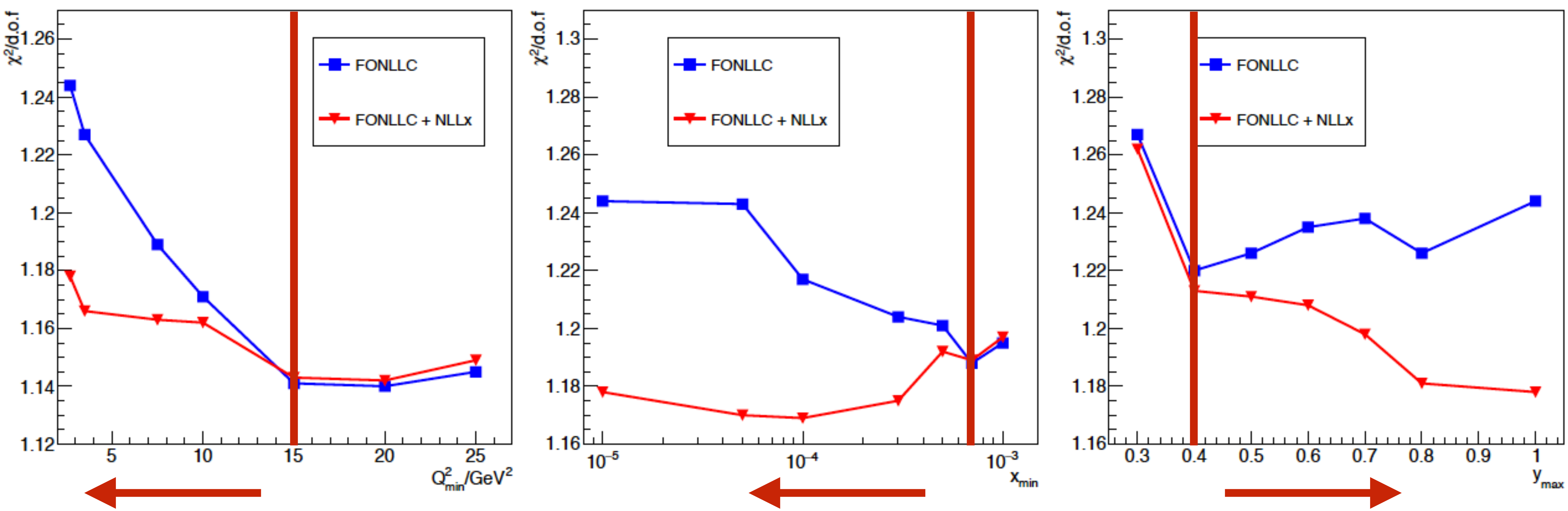
- Nonetheless, we can't conclude that the 2.7 GeV^2 bin is substantially **better described** including small-x resummation.



The relevant kinematic region

- We have tried to **circumscribe** the kinematic region responsible for the improvement when including resummation effects.

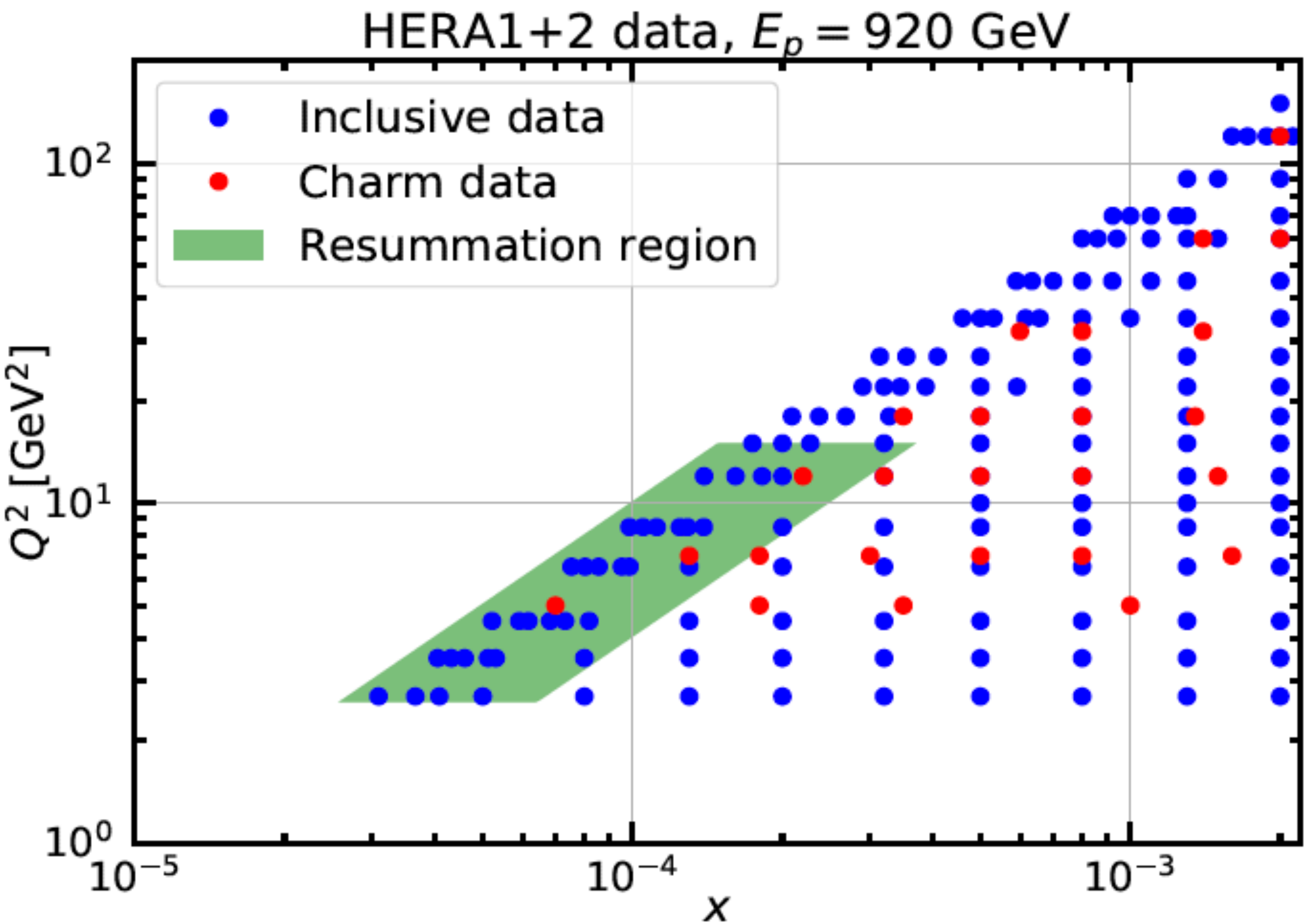
- We have thus performed (independent) χ^2 **scans** as functions of $Q_{\rm min}$, $x_{\rm min}$, and $y_{\rm max}$.



- The arrows indicate the regions in which small-x resummation performs better than fixed order.

The relevant kinematic region

- This allowed us to identify the kinematic region over which the resummation has a beneficial effect:



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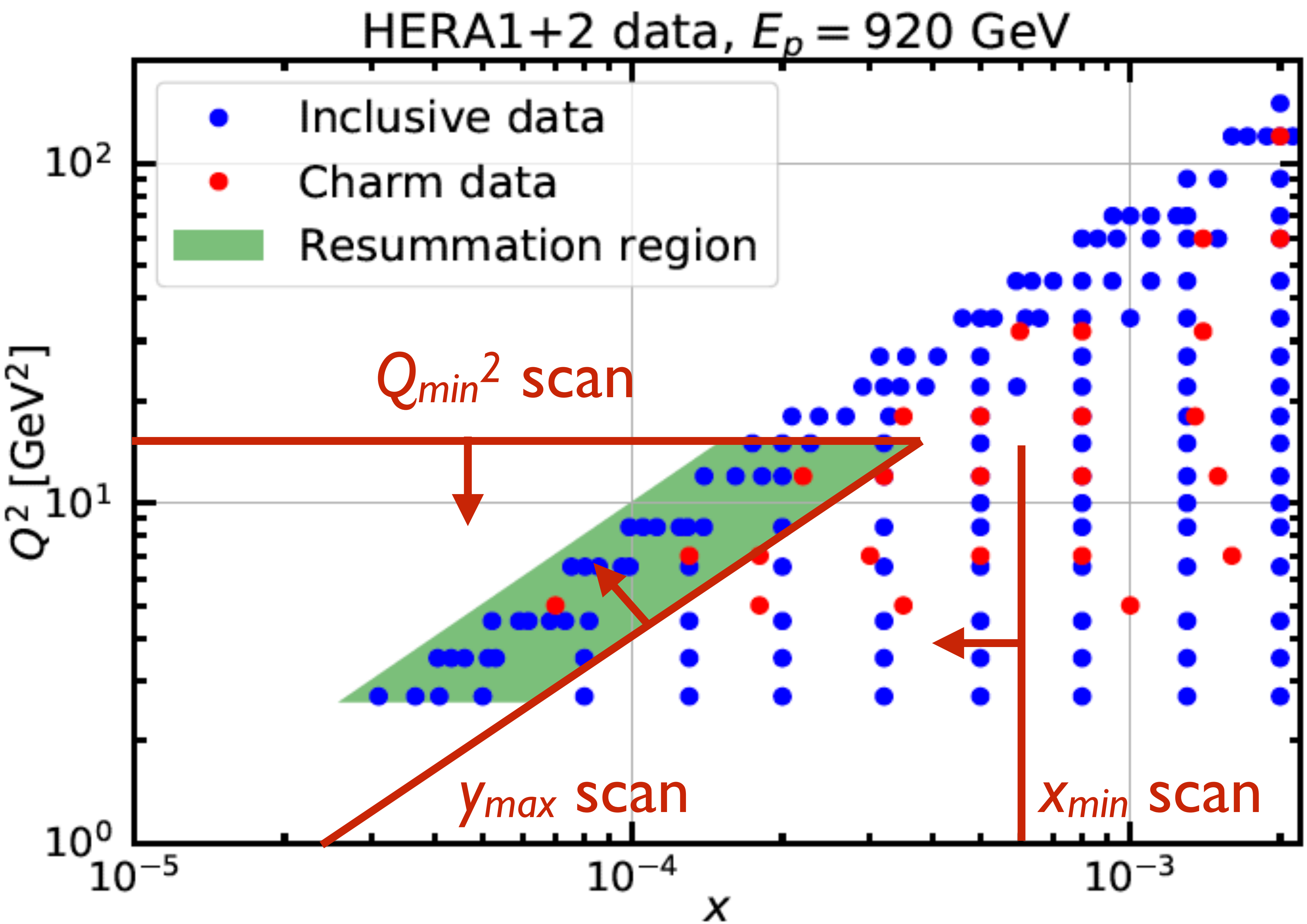
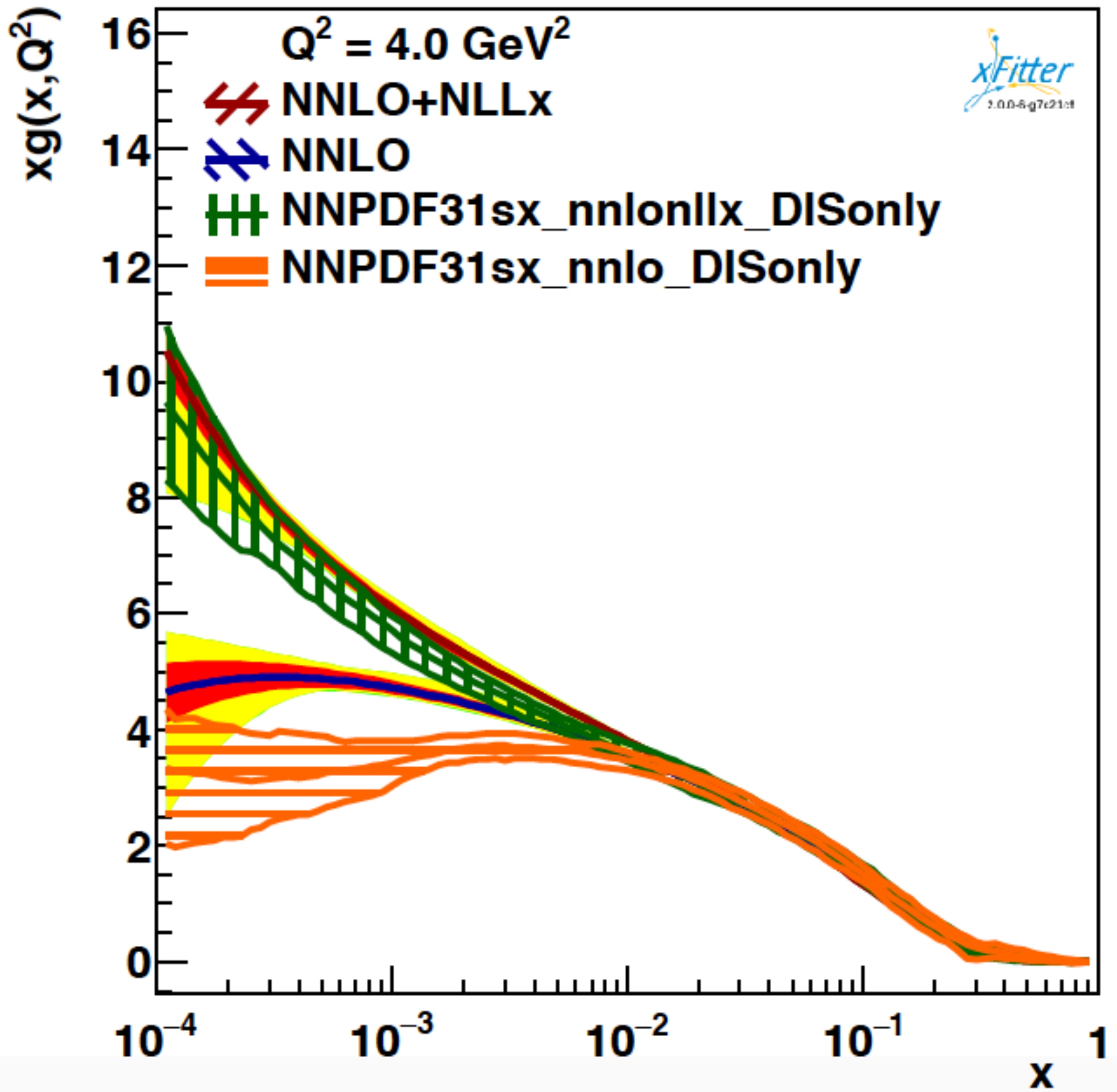


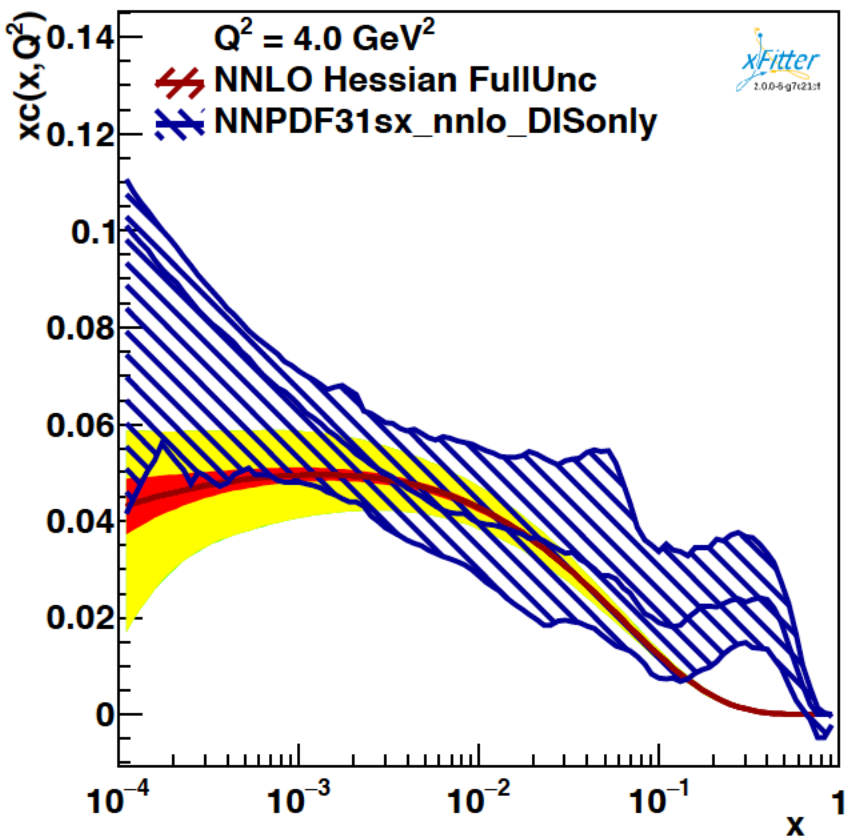
Conclusions

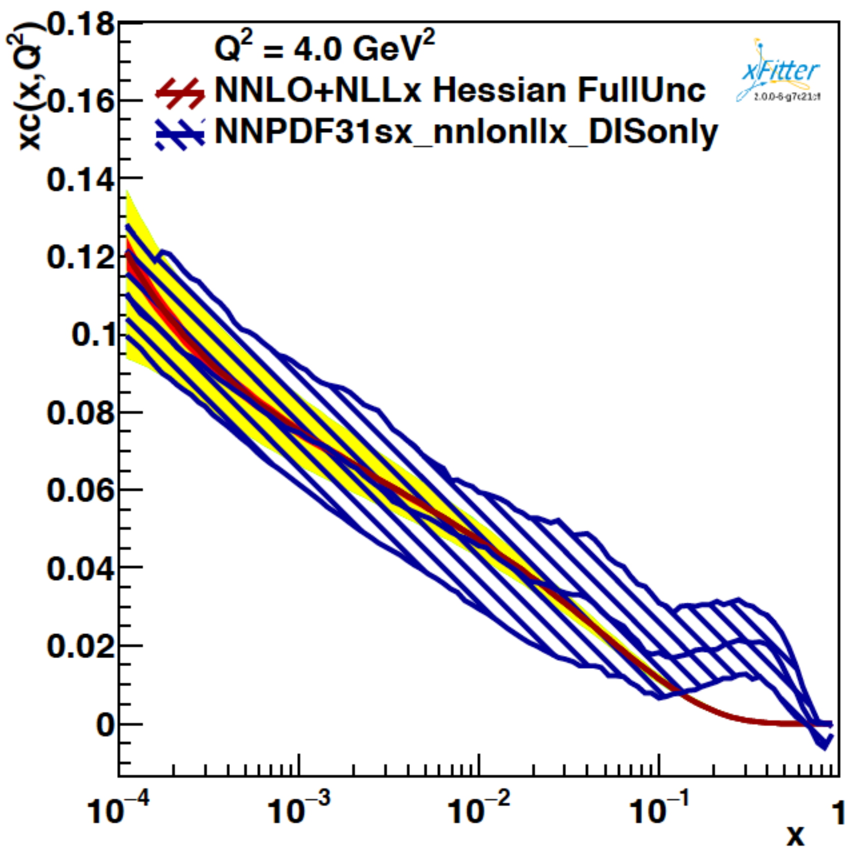
- Recent implementation of small-x **resummation** corrections in the public code **HELL** and its interface to **APFEL** (public as well).
- This has made possible including these effects in PDF analyses up to **NNLO + NLLx** accuracy (*e.g.* the NNPDF31sx global analysis).
- Here we focused on the effect of these corrections on the description of the **HERA data** in the framework of an **HERAPDF** analysis:
  - this was possible thanks to **xFitter** interfaced to **APFEL**.
- Small-x resummation corrections proved to improve the description of HERA data, particularly at small-x and Q^2:
  - driven by F_L whose contribution is particularly relevant at large y.
- Substantial differences also at the level of PDFs:
  - **steeply rising gluon PDF** at low x and Q^2,
  - resemblance to the sea distributions behaviour (dynamical gluon?).

Backup

A more direct comparison to NNPDF

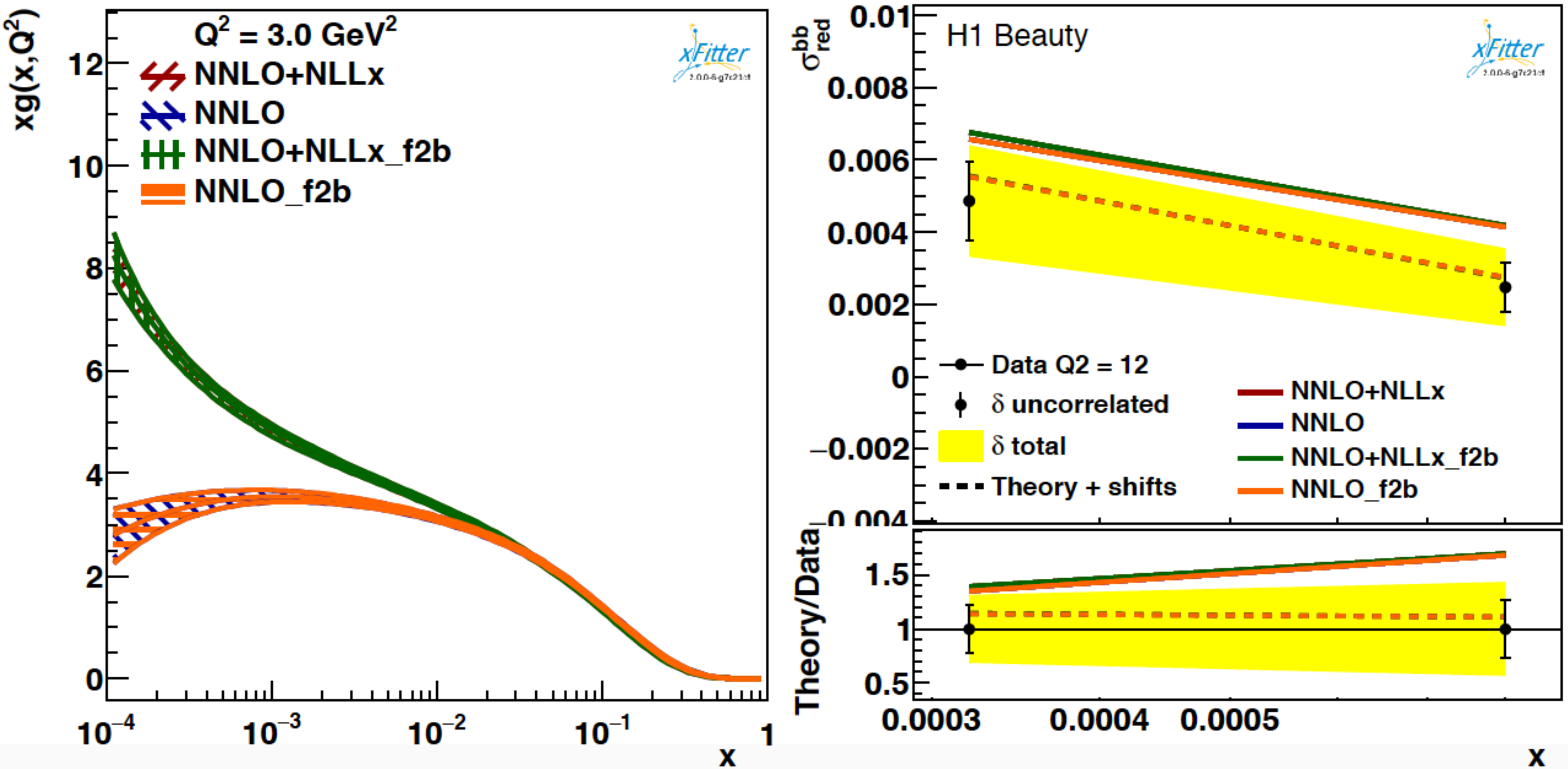






- Including parameterisation uncertainty and comparing to NNPDF DIS-only fits better agreement at NNLO+NLLx.
- Residual difference at NNLO most likely due to fitted charm in NNPDF.

The effect of bottom data



- Bottom data has a very marginal effect on the fit.

The charm data

- This study uses **FONLL with perturbative charm and damping**. No *ad hoc* cut on charm data:

	NNLO fit with new settings	NNLO+NLLx fit with new settings
Total χ^2/d.o.f	1446/1178	1373/1178
subset NC 920 χ^2/n.d.p	446/377	413/377
subset NC 820 χ^2/n.d.p	70/70	65/70
subset charm χ^2/n.d.p	48/47	49/47
correlated shifts inclusive	102	77
correlated shifts charm	15	11
log term inclusive	20	−3
log term charm	−2	−1

- NNPDF3.1 uses **fitted charm and no damping**. A cut $Q^2 > 8$ GeV^2 on the HERA charm data is imposed, otherwise:

	$\chi^2/N_{\rm dat}$ NLO	$\chi^2/N_{\rm dat}$ NLO+NLLx	$\Delta\chi^2$	$\chi^2/N_{\rm dat}$ NNLO	$\chi^2/N_{\rm dat}$ NNLO+NLLx	$\Delta\chi^2$
NMC	1.31	1.32	+5	1.31	1.32	+4
SLAC	1.25	1.28	+2	1.12	1.02	−8
BCDMS	1.15	1.16	+7	1.13	1.16	+14
CHORUS	1.00	1.01	+9	1.00	1.03	+26
NuTeV dimuon	0.66	0.56	−8	0.80	0.75	−4
HERA I+II incl. NC	1.13	1.13	+6	1.16	1.12	−47
HERA I+II incl. CC	1.11	1.09	−1	1.11	1.11	-
HERA $\sigma_c^{\rm NC}$	1.44	1.35	−5	2.45	1.24	−57
HERA F_2^b	1.06	1.14	+2	1.12	1.17	+2
Total	**1.113**	**1.119**	**+17**	**1.139**	**1.117**	**− 70**

- The same cut in the NNPDF3.1sx analysis leads to:

$$\chi^2/N_{\rm dat} = 1.38 \text{ at NNLO and } 1.35 \text{ at NNLO+NLL}x$$