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

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- in collaboration with M. Bonvini -

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Motivation

- The **factorisation theorem** for a hadronic cross section reads:

$$d\sigma_{had} = \boxed{W_{ij}} \otimes \boxed{f_i}\, d\phi$$

Partonic cross sections:

- Process dependent
- High-scale objects
- Computable in perturbation theory (LO, NLO, NNLO, N^3LO)

Parton distribution functions (PDFs):

- Universal (process independent)
- Low-scale objects
- Non computable in perturbation theory
- Scale dependence perturbative (DGLAP)

- Once PDFs have been **determined at a given scale**, the **DGLAP** evolution equations can be used to **evolve them to any other scale**

$$\mu^2 \frac{\partial}{\partial \mu^2} f_i(\mu) = \sum_j P_{ij} \otimes f_j(\mu)$$

$$P_{ij}(y) = \frac{\alpha_S(\mu)}{2\pi} P_{ij}^{(0)}(y) + \left(\frac{\alpha_S(\mu)}{2\pi}\right)^2 P_{ij}^{(1)}(y) + \ldots$$

Splitting functions

How do we determine PDFs?

- Presently, the most accurate and reliable way is through **fits to data**

$f_i(x, Q_0^2)$

$x = p_i/p_p$
$0 < x < 1$
$Q_0 \sim 1$ GeV
(initial scale)

DGLAP

$f_i(x, Q^2)$

Q = scale of the fitted data

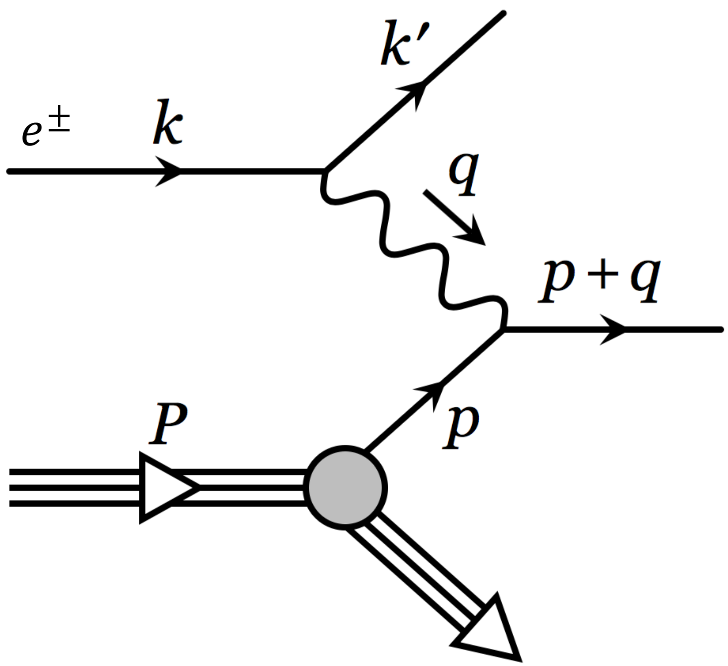
Factorisation theorem

$\sigma = W_{ij} \otimes f_i$

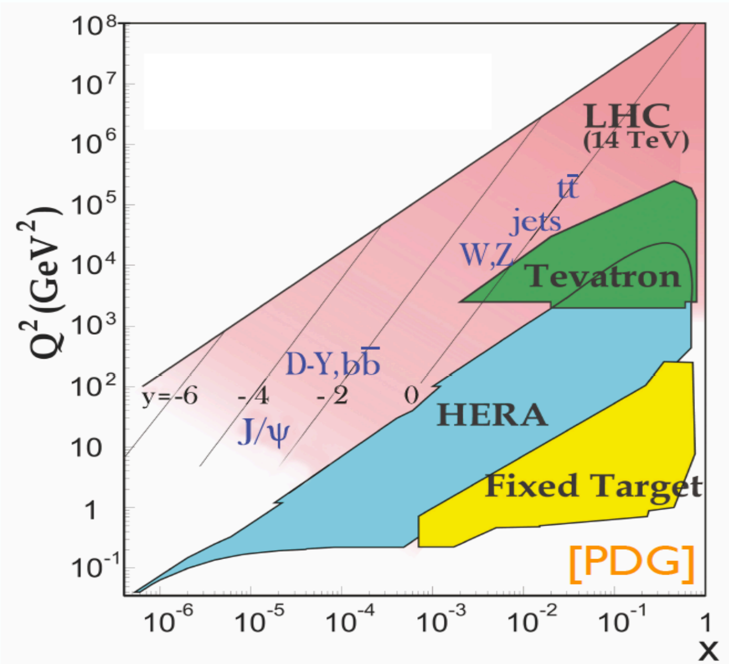
Fitting

Predictions vs data

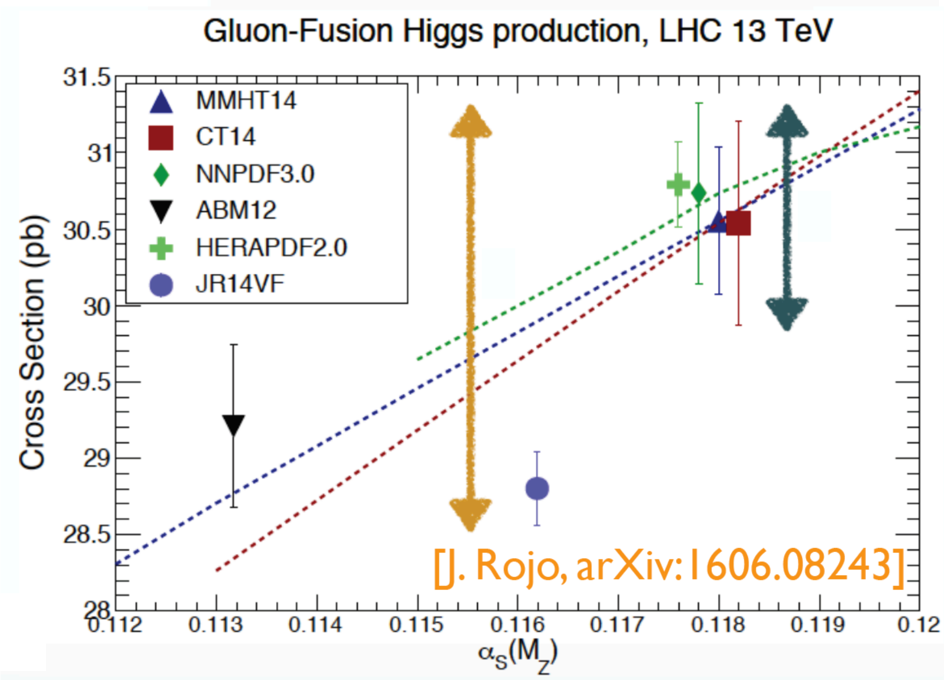
Deep Inelastic Scattering (DIS)



Anyway NOT an easy task



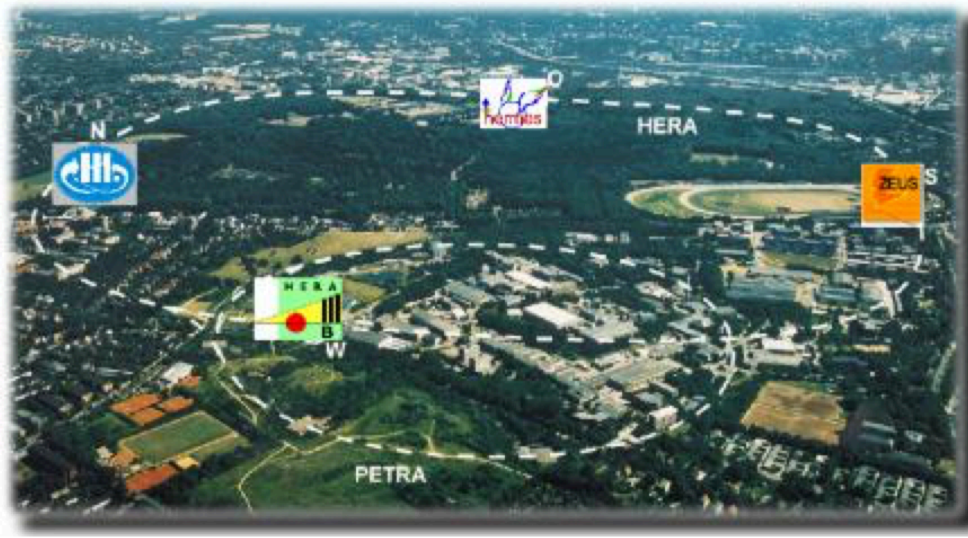
- Fitting PDFs is a **complex** task
- **Datasets**:
  - as large and varied as possible
  - Spanning a wide kinematic range
- Estimate of the **uncertainties**:
  - include full experimental uncertainties
  - ensure a faithful representation
- Choice of the **parameterisation**:
  - avoid parameterisation biases
- **Theoretical inputs**:
  - Higher order (HO) corrections
  - Heavy-quarks mass effect
  - …
- Different choices my lead to different results



Available PDF sets on the market

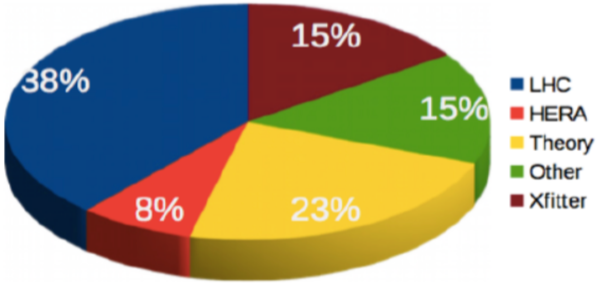
- Several groups working on PDFs and different sets available on the market
  - CTEQ – CT14 – **private code**
    https://arxiv.org/abs/1506.07443
  - MMHT – MMHT14 – **private code**
    https://arxiv.org/abs/1610.04393
  - NNPDF – NNPDF31 – **private code**
    https://arxiv.org/abs/1706.00428
  - ABM – ABMP16 – **private code**
    https://arxiv.org/abs/1609.03327
  - JR – JR14 – **private code**
    https://arxiv.org/abs/1403.1852
  - xFitter – HERAPDF20 – **public code**
    https://arxiv.org/abs/1506.06042

Deutsches Elektronen-SYnchrotron (DESY)



The xFitter Project

- The xFitter project (former HERAFitter) is a **unique open-source QCD fit framework**
- GitLab (CERN) is now the main repository of the project: https://gitlab.cern.ch/fitters/xfitter (open access to download for everyone – read only)
- This code allows users to:
  - **extract PDFs** from a large variety of experimental data
  - assess the **impact** of **new data on PDFs**
  - check the **consistency** of experimental data
  - test different **theoretical assumptions**



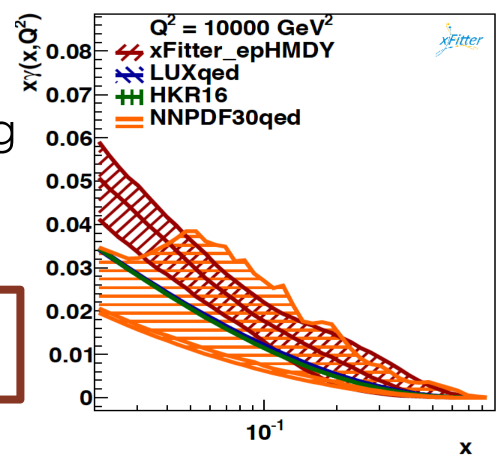
- About 30 active developers between experimentalists and theorists
- More than **60 publications** (**21** just in 2017) obtained using xFitter since the beginning of the project: https://www.xfitter.org/xFitter/xFitter/results
- LHC experiments provide the main developments and usage of the xFitter platform
- List of recent analyses (7 in total) by the xFitter Developers' Team: **MORE IN PREPARATION!**

7	02.2018	xFitter Developers and Marco Bonvini	arXiv:1802.00064	Impact of low-x resummation on QCD analysis of HERA data	
6	07.2017	xFitter Developers	Eur.Phys.J. C77 (2017) no.12 837, arXiv:1707.05343	Impact of the heavy quark matching scales in PDF fits	LHAPDF grids
5	01.2017	F. Giuli, xFitter Developers' team and M. Lisovyi	Eur.Phys.J. C77 (2017) no.6 400, arXiv:1701.08553	The photon PDF from high-mass Drell Yan data at the LHC	
4	03.2016	xFitter and APFEL teams and A. Geiser	JHEP 1608 (2016) 050, arXiv:1605.01946	A determination of mc(mc) from HERA data using a matched heavy flavor scheme	

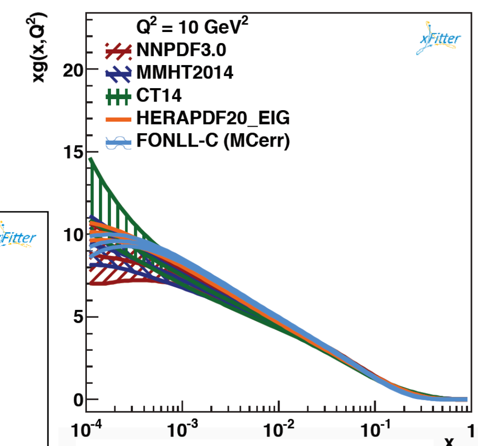
- Latest work: **Impact of low-x resummation on QCD analysis of HERA data** announced on arXiv at the beginning of February - https://arxiv.org/abs/1802.00064

xFitter in a nutshell

- **Parametrise** PDFs at the initial scale:
  - several functional forms available ("standard", Chebyshev,…)
  - define parameters to be fitted
- **Evolve** PDFs to the scales of the fitted data points:
  - DGLAP evolution up to NNLO in QCD and NLO QED (QCDNUM, APFEL, MELA)
  - non-DGLAP evolutions (dipole, CCFM)
- **Compute** predictions for the data points:
  - several mass schemes available in DIS (ZM-VFNS, ACOT, FONLL, TR, FFNS)
  - predictions for hadron-collider data through fast interfaces (APPLgrid, FastNLO)
- **Comparison data-predictions** via χ^2:
  - multiple definitions available
  - consistent treatment of the systematic uncertainties
- **Minimise** the χ^2 w.r.t. the fitted parameters
  - using MINUIT or by Bayesian reweighting
- **Useful drawing tools** – nice and colorful plots

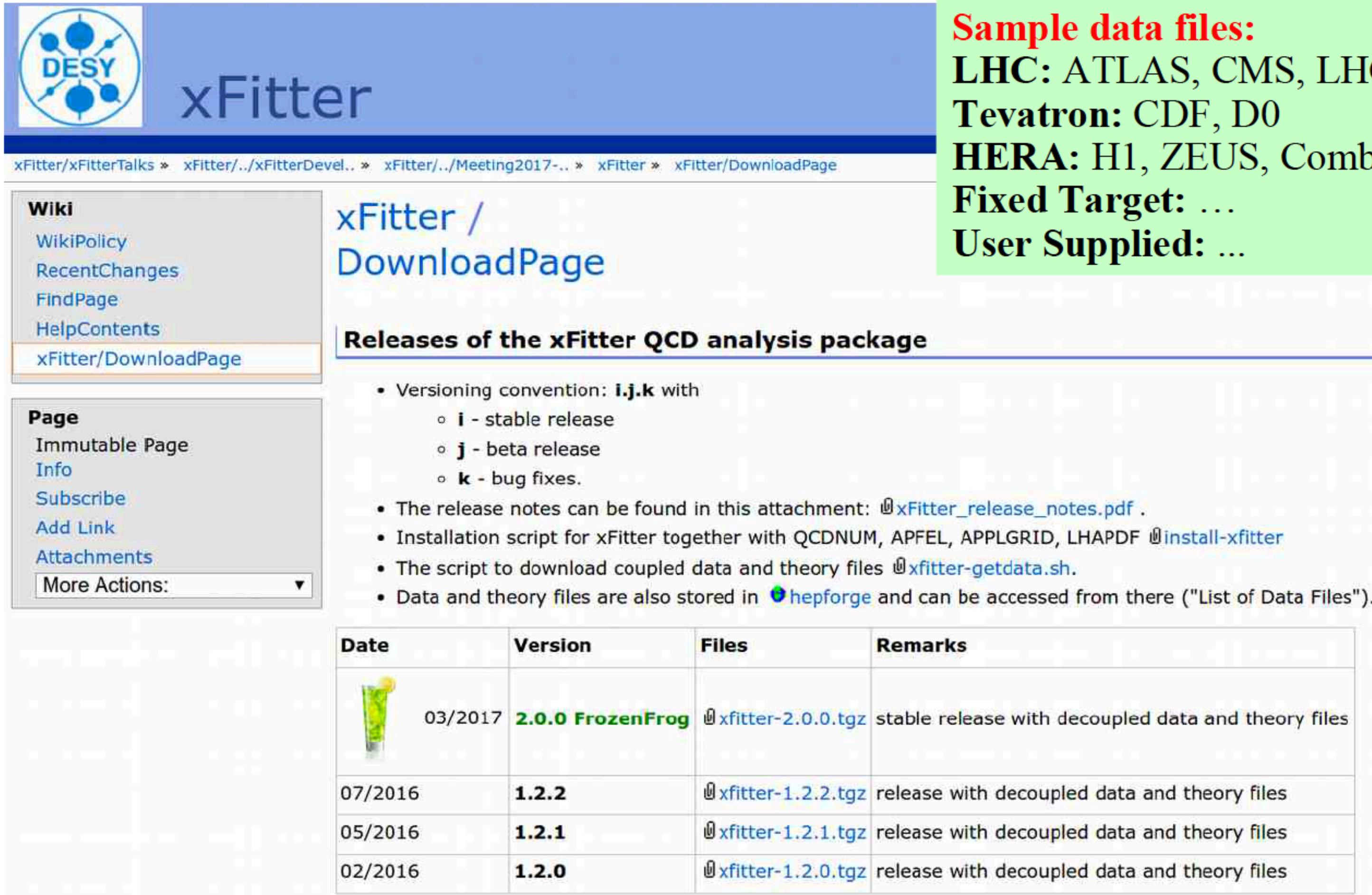


Photon PDF $x\gamma(x,Q^2)$



Gluon PDF $xg(x,Q^2)$

xFitter release 2.0.0



xFitter

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Releases of the xFitter QCD analysis package

- Versioning convention: **i.j.k** with
  - **i** - stable release
  - **j** - beta release
  - **k** - bug fixes.
- The release notes can be found in this attachment: xFitter_release_notes.pdf .
- Installation script for xFitter together with QCDNUM, APFEL, APPLGRID, LHAPDF install-xfitter
- The script to download coupled data and theory files xfitter-getdata.sh.
- Data and theory files are also stored in hepforge and can be accessed from there ("List of Data Files").

Date	Version	Files	Remarks
03/2017	**2.0.0 FrozenFrog**	xfitter-2.0.0.tgz	stable release with decoupled data and theory files
07/2016	**1.2.2**	xfitter-1.2.2.tgz	release with decoupled data and theory files
05/2016	**1.2.1**	xfitter-1.2.1.tgz	release with decoupled data and theory files
02/2016	**1.2.0**	xfitter-1.2.0.tgz	release with decoupled data and theory files

Sample data files:
LHC: ATLAS, CMS, LHCb
Tevatron: CDF, D0
HERA: H1, ZEUS, Combined
Fixed Target: …
User Supplied: …

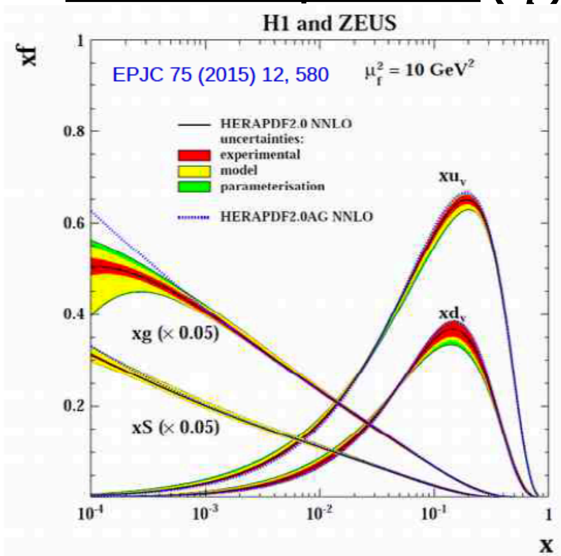
xFitter 2.0.0 FrozenFrog

- By default, only final combined HERAI+II data are distributed
- **getter-xfitter.sh script** to download data with corresponding theory files
- In directory 'datasets' located all available files

https://www.xfitter.org/xFitter/xFitter/DownloadPage

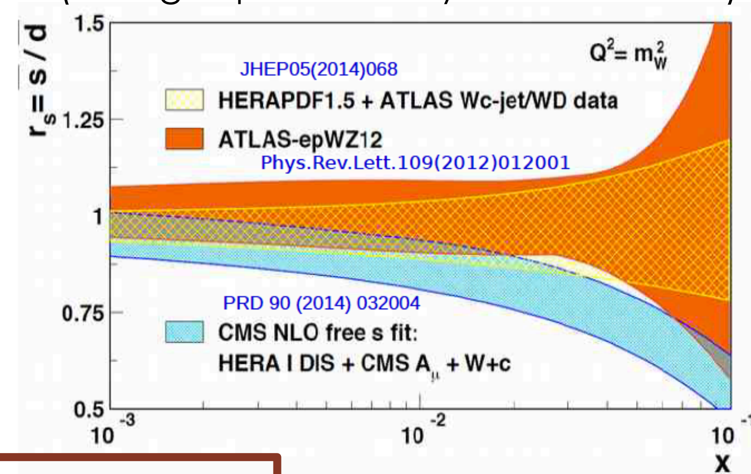
Results obtained with xFitter: Examples (1)

DIS inclusive processes (ep)



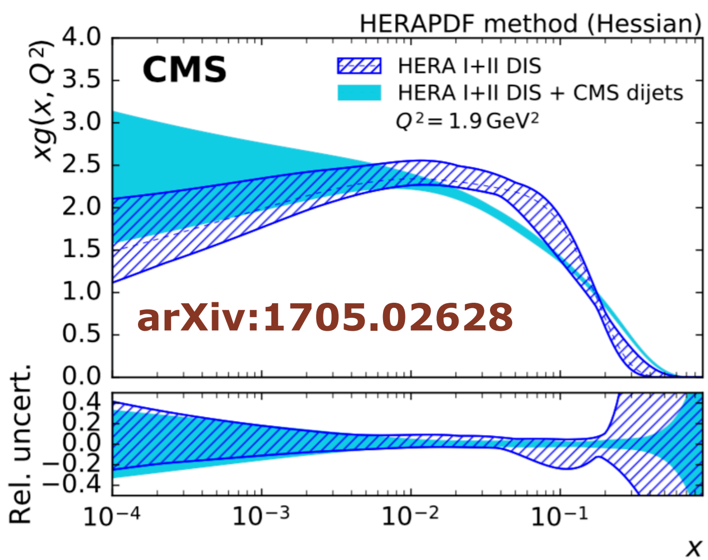
Drell-Yan processes $(pp, p\bar{p})$

(strange quark density determination)

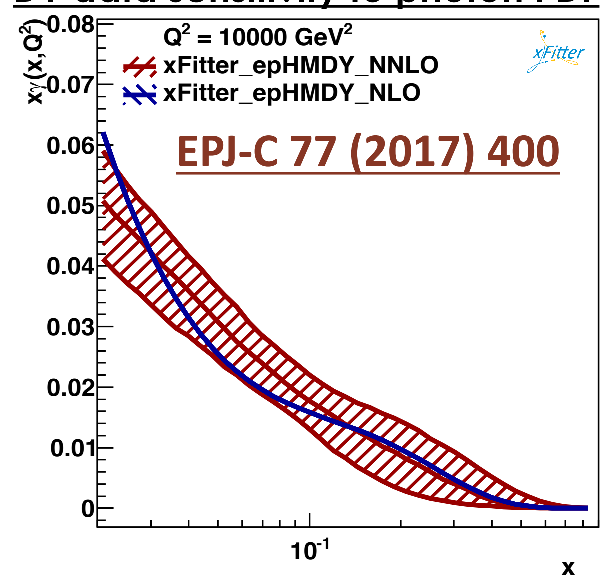


More examples in backup!

Jet production $(ep, pp, p\bar{p})$



DY data sensitivity to photon PDF



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

xFitter Developers' team: Hamed Abdolmaleki [1], Valerio Bertone [2,3], Daniel Britzger [4], Stefano Camarda [5], Amanda Cooper-Sarkar [6], Francesco Giuli [6], Alexander Glazov [7], Aleksander Kusina [8], Agnieszka Luszczak [7,9], Fred Olness [10], Andrey Sapronov [11], Pavel Shvydkin [11], Katarzyna Wichmann [7], Oleksandr Zenaiev [7], and Marco Bonvini [12]

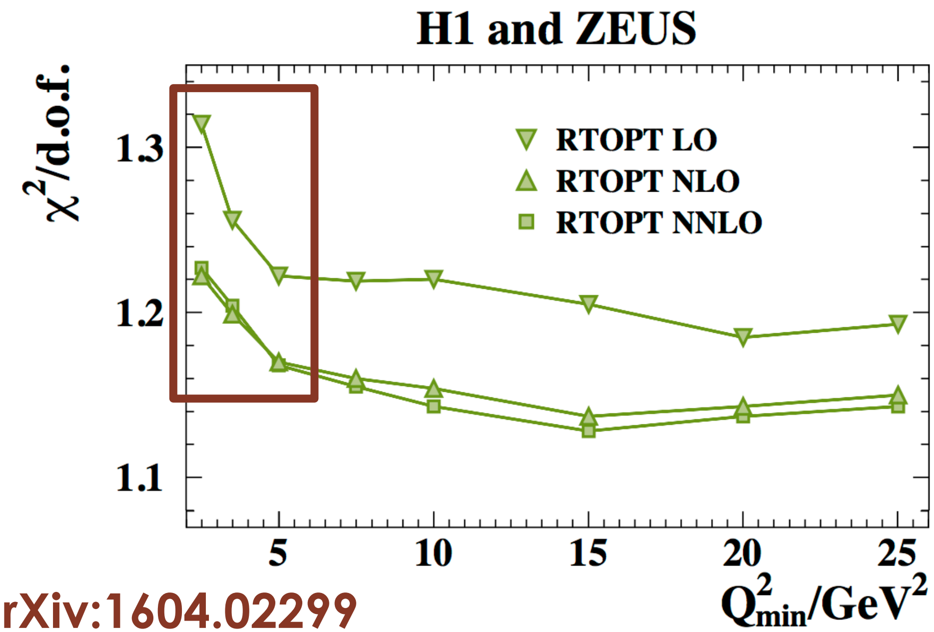
- Introduction
- Theoretical motivations
- Setup
- Fit results
- Comparison to NNPDF31 sets
- Where is small-x resummation relevant?
- LHC phenomenology
- Conclusions

Abstract Fits to the final combined HERA inclusive cross-section data within the conventional DGLAP framework of QCD have shown some tension at low x and low Q^2. A resolution of this tension incorporating $\ln(1/x)$-resummation terms into the HERAPDF fits is investigated using the `xFitter` program. The kinematic region where this resummation is important is delineated. Such high-energy resummation not only gives a better description of the data, particularly of the longitudinal structure function F_L, it also results in a gluon PDF which is steeply rising at low x for low scales, $Q^2 \simeq 2.5$ GeV^2, contrary to the fixed-order NLO and NNLO gluon PDF.

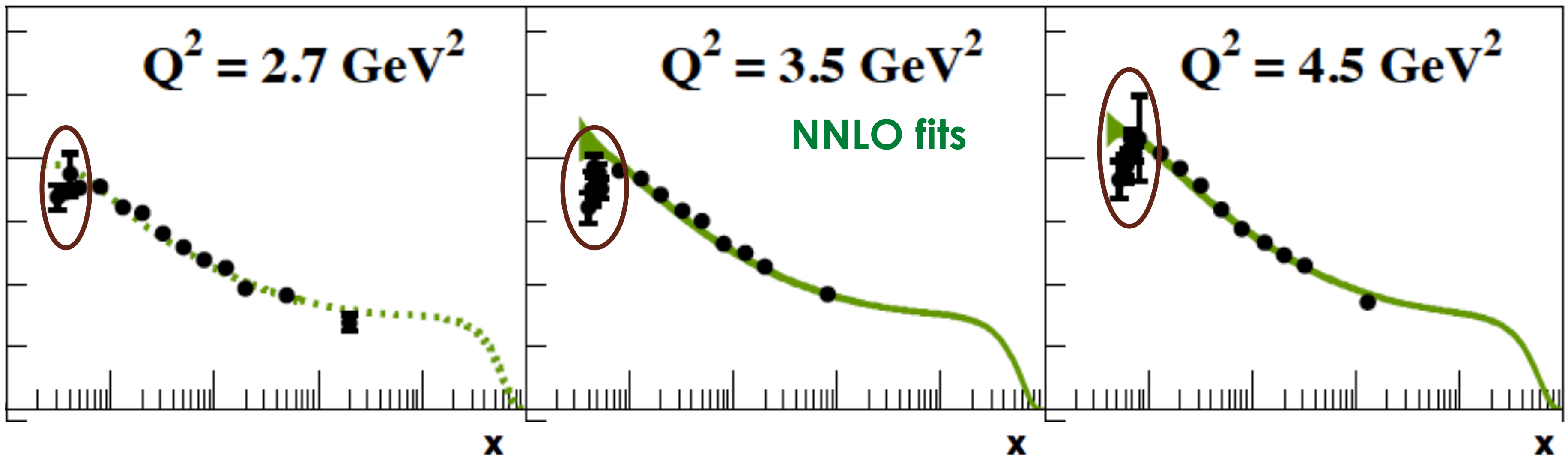
arXiv:1802.00064
Submitted to EPJC

Why are we interested in small-x resummation?

- **Crucial observation**: **low-x** and **low-Q^2** HERA data are not well described by FO pQCD
- Deterioration of χ^2**/ndf** when including data at low-Q^2 at all orders in perturbation theory
- Data turnover at small-x not described by **pQCD fits**



arXiv:1604.02299



Small-x resummation

$$d\sigma_{had} = \underline{W_{ij}} \otimes f_i \, d\phi \longleftrightarrow \mu^2 \frac{\partial}{\partial \mu^2} f_i(\mu) = \sum_j \underline{P_{ij}} \otimes f_j(\mu)$$

Contribution $\frac{1}{x} \alpha_S^n \log^k\left(\frac{1}{x}\right)$ for $0 \leq k \leq (n-1)$

So you have $\frac{1}{x \log\left(\frac{1}{x}\right)}\left[\# \, \alpha_S \log\left(\frac{1}{x}\right) + \# \, \alpha_S^2 \log^2\left(\frac{1}{x}\right) + \# \, \alpha_S^3 \log^3\left(\frac{1}{x}\right) + \ldots\right]$ **(LL)**

If $\boldsymbol{\alpha_S \log\left(\frac{1}{x}\right)}$ **~ 1** → all such terms in the perturbative series are equally important:

All-order resummation

(we do not want to loose predictivity)

Small-x resummation formalism based on **k_T-factorization** and **BFKL**

Developed in the 90s-00s **[Catani,Ciafaloni,Colferai,Hautmann,Salam,Stasto] [Altarelli,Ball,Forte] [Thorne,White]**

Recent developments:

- Improved ABF procedure to resum splitting functions and new formalism for coefficient functions **[Bonvini,Marzani,Peraro][Bonvini,Marzani,Muselli]**
- Resummation matched to NNLO, allowing NNLO+NLLx phenomenology

More info @Room 203 arXiv:1607.02153, arXiv:1708.07510

What's the aim of our work?

- We want to fit the HERAI+II inclusive cross section including **small-x resummation** corrections up to **NLLx**:
  - Resummed PDF evolution
  - Resummed DIS structure functions
  - Resummed PDF matching conditions
- Resummation corrections are properly matched to the fixed-order (FO) expressions:
  - FO components provided by **APFEL** (by V. Bertone, S. Carrazza, J. Rojo) – https://github.com/scarrazza/apfel **arXiv:1310.1394**
  - Resummed corrections available in **HELL** (by M. Bonvini, et al.) – https://www.ge.infn.it/~bonvini/hell/ **arXiv:1708.07510**
    - They include both massless and massive coefficient functions
  - Implementation of the **FONLL heavy-quark scheme** with small-x corrections

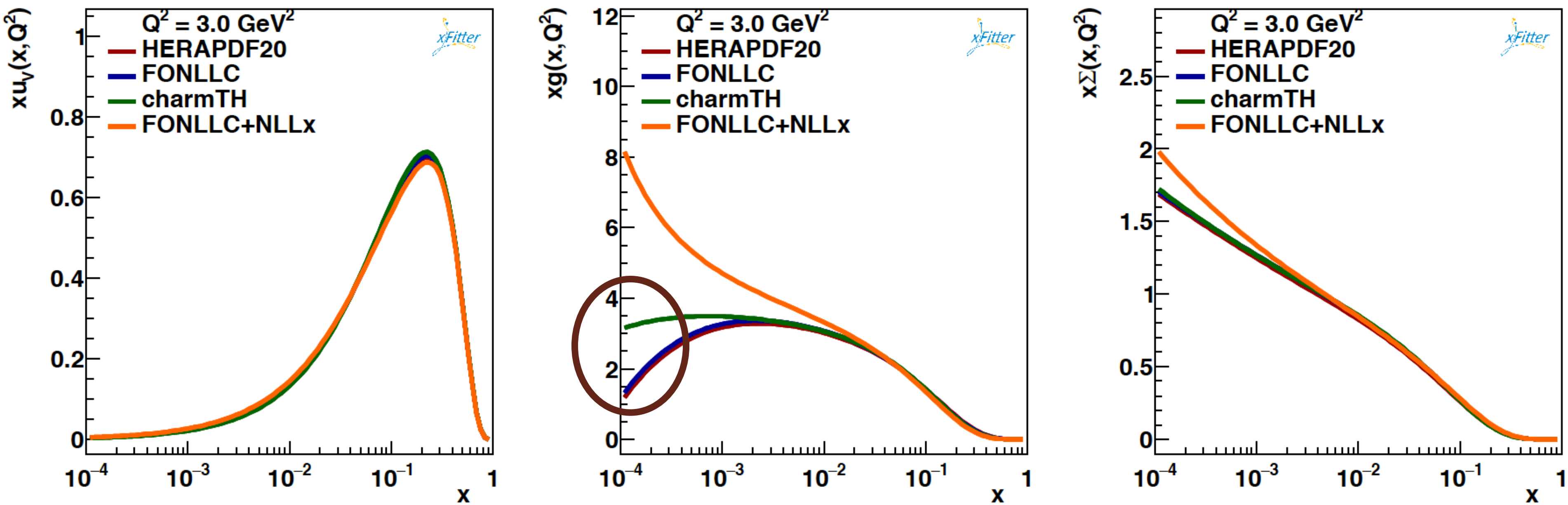
Fit setup

- The aim is to move in small steps from the HERAPDF2.0 NNLO setup (Step-1) to a setup with small-x resummed corrections with APFEL+HELL:
  - Step-2: use FONLL-C instead of TR (required to use APFEL)
  - Step-3: move up Q_0 and displace the charm threshold (required to use HELL)
  - Step-4: Add the small-x resummation at NLLx

Eur. Phys. J. C 77 (2017) 837

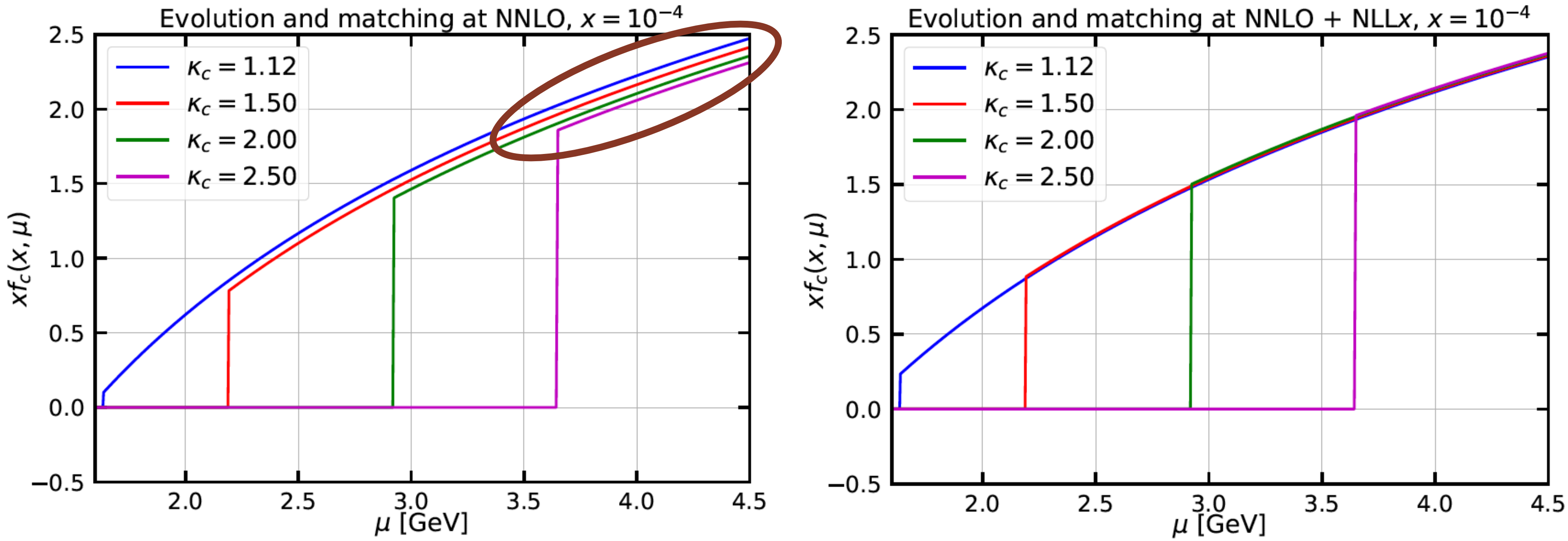
	Step-1	Step-2	Step-3	Step-4
	HERAPDF2.0 NNLO	FONLL-C	Move Q_0^2 and charm threshold	include NLLx resummation
HERA χ^2/d.o.f	1363/1131	1387/1131	1389/1131	1316/1131

-73 units!



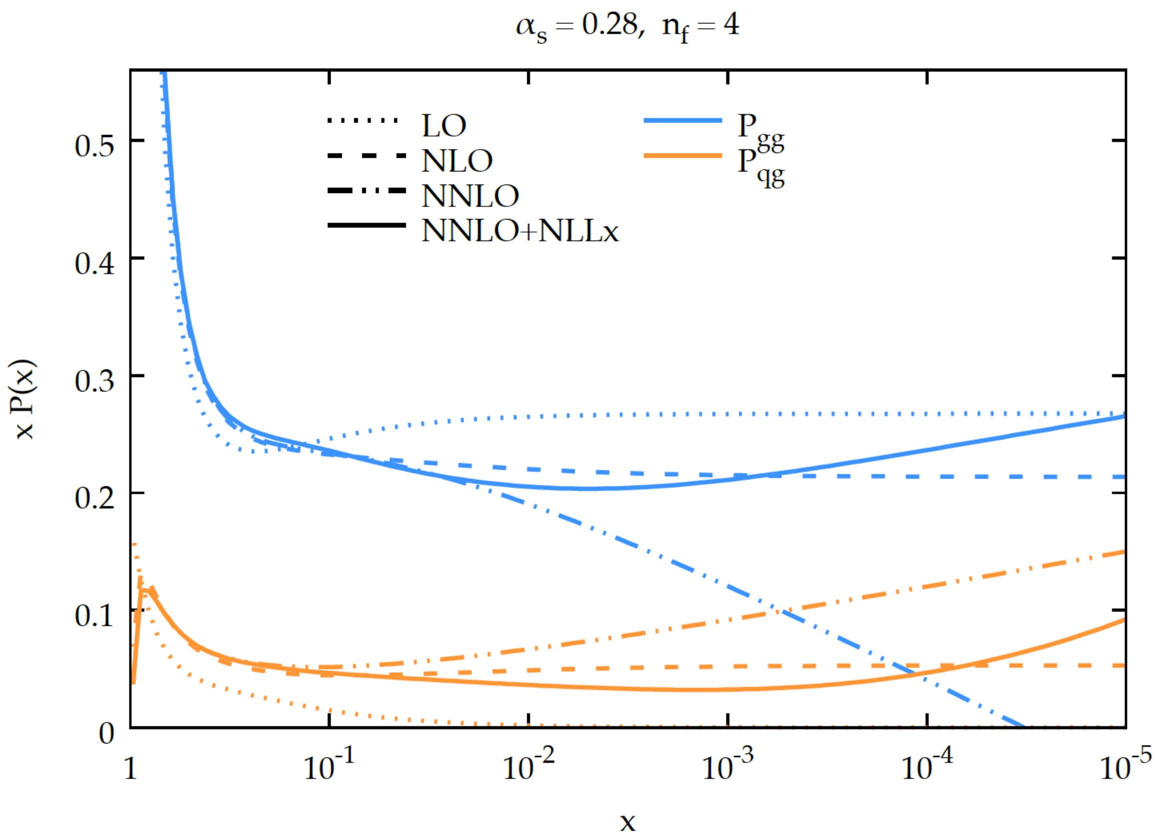
PDF matching conditions

- Also the PDF matching conditions are affected by large logs in the low-x region
- These logs are resummed in HELL



- Charm PDF at x = 10^{-4} as a function of the factorisation scale μ for different values of the charm threshold $\mu_c = \kappa_c \cdot m_c$ (with m_c = 1.46 GeV)
- Moving forward the charm threshold (FO) → **depressed charm PDF** (which needs to be compensated by increased gluon)
  Origin of the difference in the gluon PDF at small x at Step-3 (previous slide)
- Reduced μ_c dependence when resummation included

Splitting functions



Splitting functions for $\mathbf{xP_{gg}(x)}$ and $\mathbf{xP_{qg}(x)}$ at:
- LO (dotted)
- NLO (dashed)
- NNLO (dot-dot-dashed)
- NNLO + NLLx (solid)

$Q^2 \sim 4\ \text{GeV}^2$

At NNLO $xP_{gg}(x) \to -\infty$ when $x \to 0$ → **UNPHYSICAL**

NLLx small correction wrt NLO (better perturbative stability)

- From NLO → NNLO: logs contribution visible and perturbative instability
- At pure NNLO, $xP_{gg}(x)$ falls for $x \to 0$ with $xP_{qg}(x) > xP_{gg}(x)$ for $x \lesssim 10^{-3}$
- When resummation is added:
  - Relation $xP_{qg}(x) < xP_{gg}(x)$ restored
  - **Gain in perturbative stability**

Fit results

- Baseline dataset: combined HERAI+II data
- In this analysis H1/ZEUS charm dataset added as well (it places itself in a region relevant for our study)
- Charm mass tuned:
  - From HERAI+II at NNLO → m_c = 1.43 GeV (optimal value for TR)
  - Scan to find the optimal value of m_c in FONLL → **m_c = 1.46 GeV** (choice compatible with the one in the HERAPDF20NNLO setup within uncertainties)

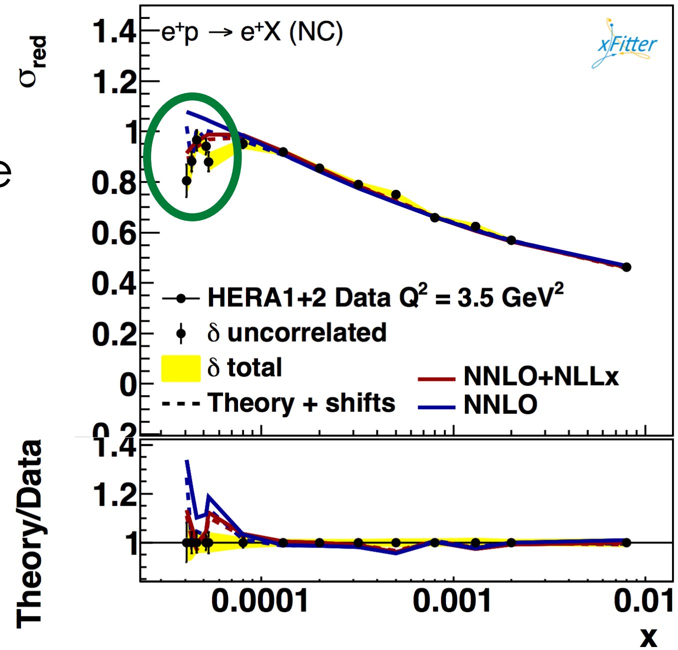
Both using **FONLL-C**	NNLO fit with new settings	NNLO+NLLx fit with new settings	
Total χ^2/d.o.f	1446/1178	1373/1178	**! -73 units!**
subset NC 920 χ^2/n.d.p	446/377	413/377	
subset NC 820 χ^2/n.d.p	70/70	65/70	
subset charm χ^2/n.d.p	48/47	49/47	
correlated shifts inclusive	102	77	**!**
correlated shifts charm	15	11	
log term inclusive	20	−3	**!**
log term charm	−2	−1	

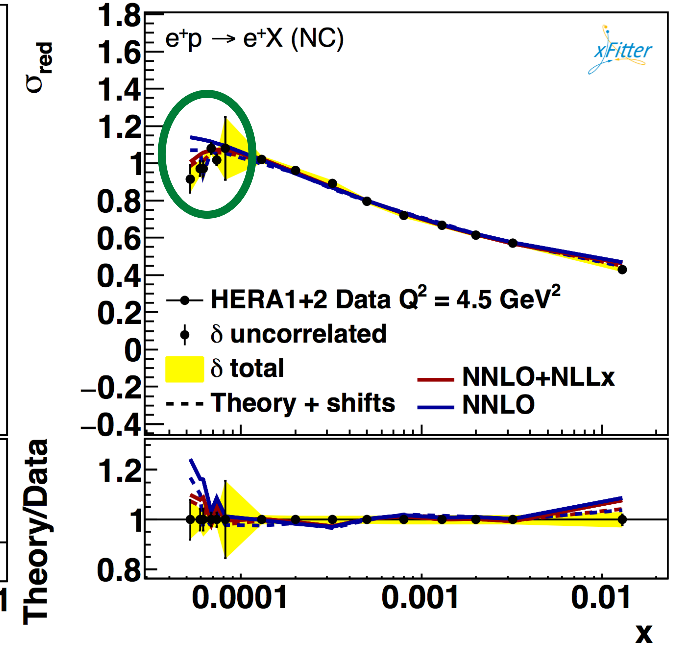
χ^2 formula:

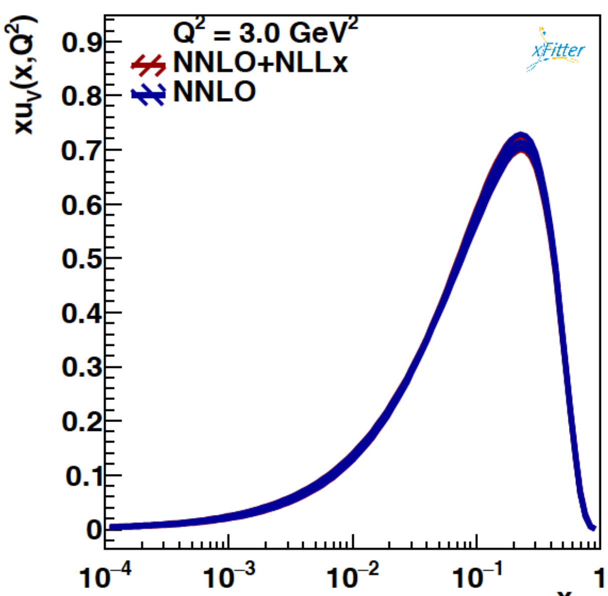
$$\chi^2 = \sum_i \frac{\left[D_i - T_i\left(1 - \sum_j \gamma^i_j b_j\right)\right]^2}{\delta^2_{i,\mathrm{unc}} T_i^2 + \delta^2_{i,\mathrm{stat}} D_i T_i} + \sum_j b_j^2 + \sum_i \ln \frac{\delta^2_{i,\mathrm{unc}} T_i^2 + \delta^2_{i,\mathrm{stat}} D_i T_i}{\delta^2_{i,\mathrm{unc}} D_i^2 + \delta^2_{i,\mathrm{stat}}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

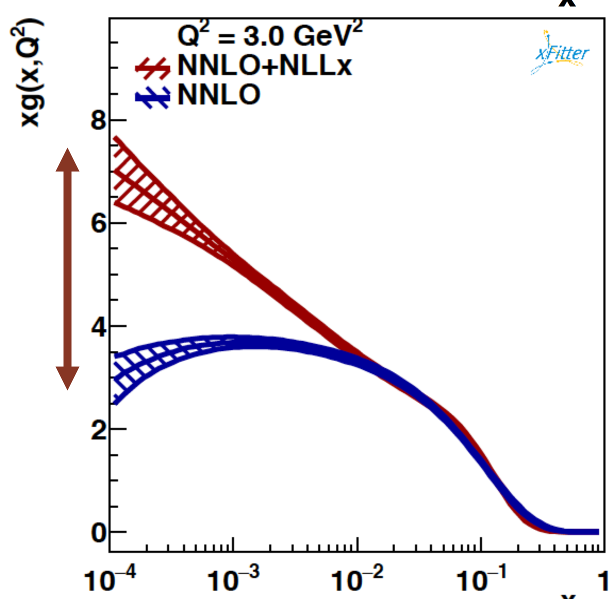
Fit results

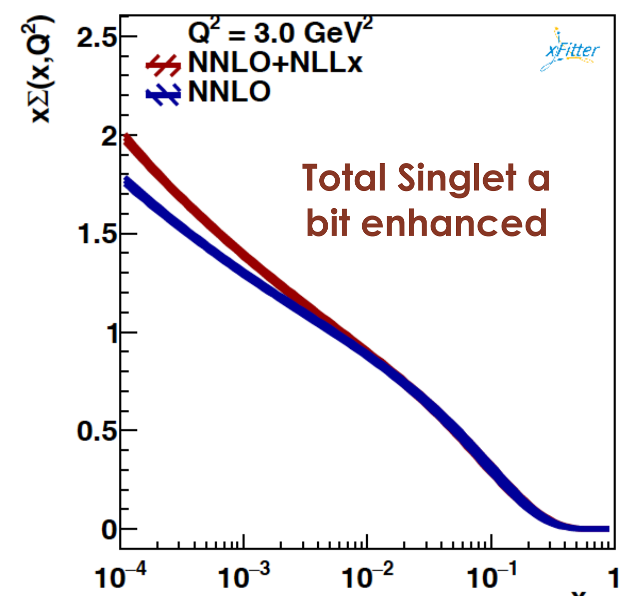
- Better description of the low Q^2 bins
- Significant difference in the gluon PDF
- Other PDFs look about the same
- Experimental uncertainties only



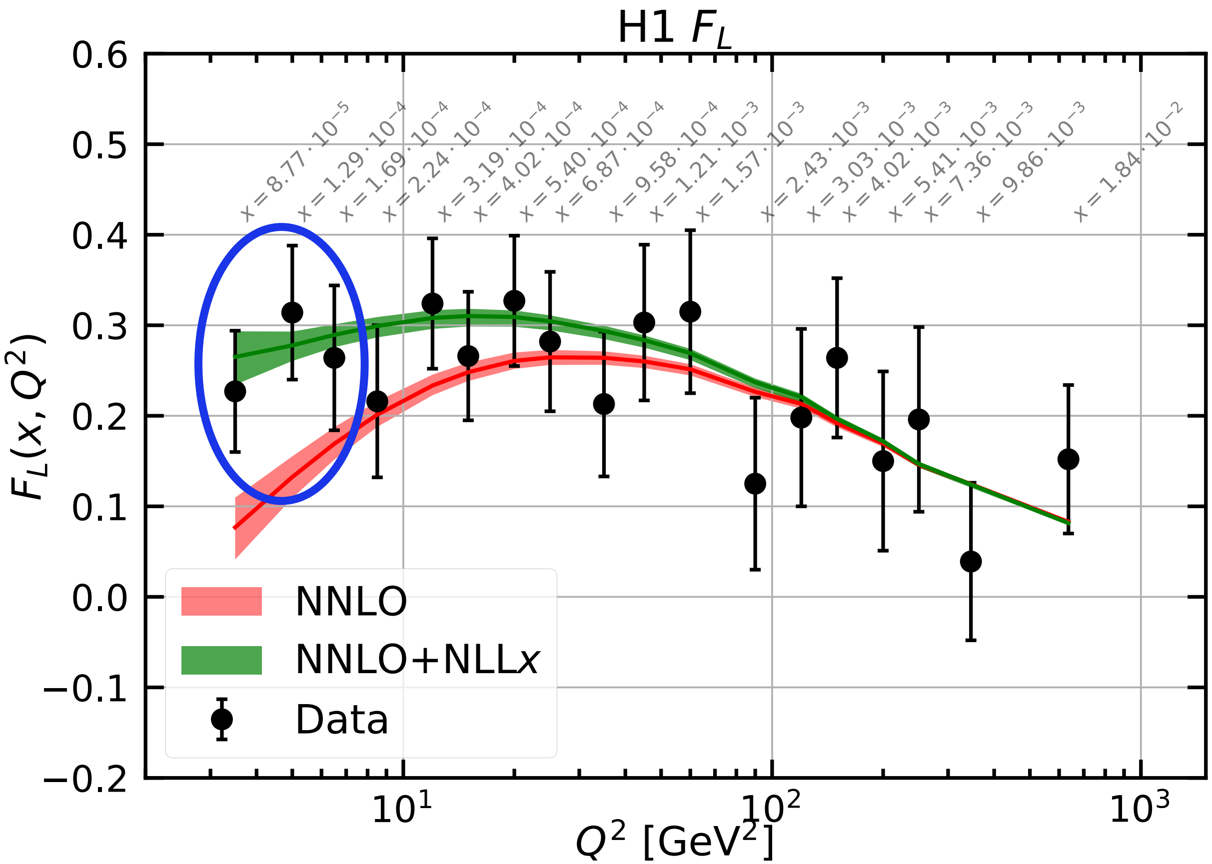








H1 F_L



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

$$Y_+ = (1 + (1-y)^2)$$

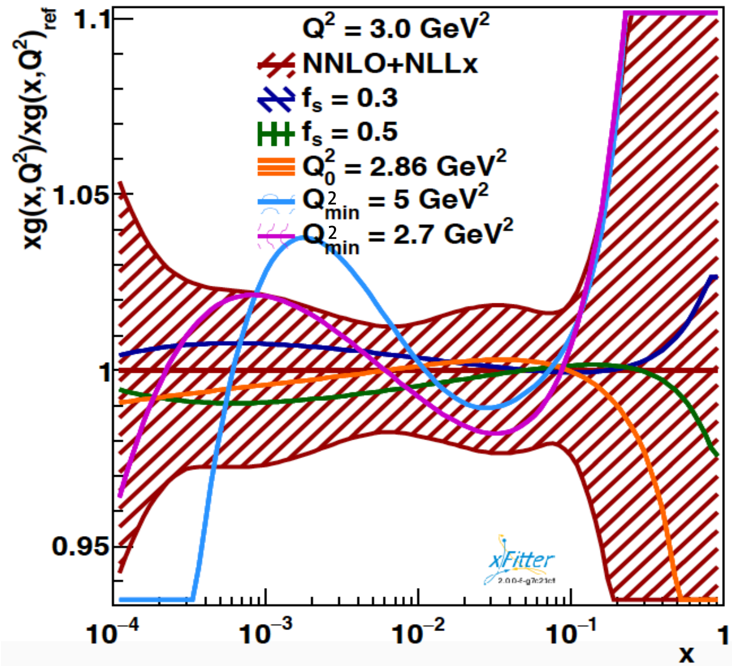
$$y = Q^2/(sx)$$

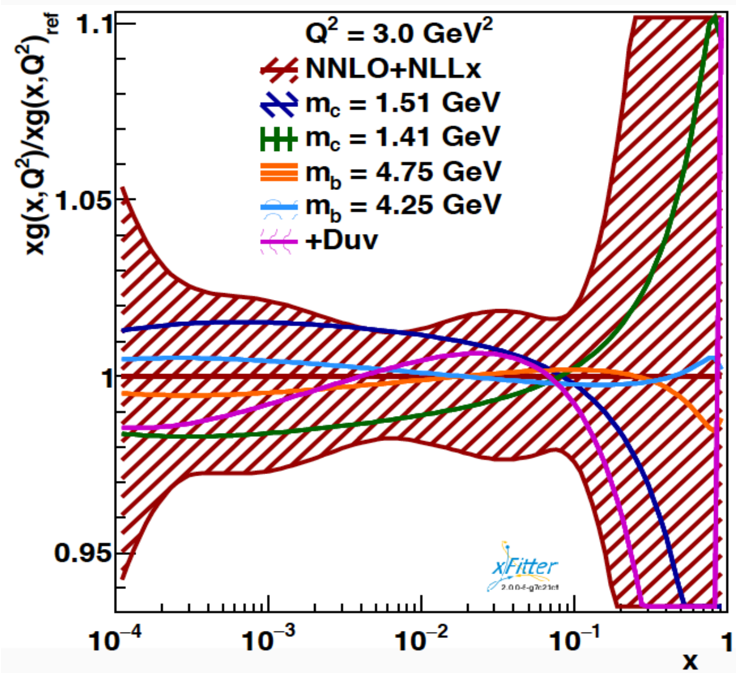
Better description from the **resummed fit** as compared to the FO one for the H1 F_L extraction (**larger F_L**)

- **F_L proportional to the gluon PDF**
- Pretty remarkable because a-posteriori prediction (H1 F_L data not directly included in our fit)

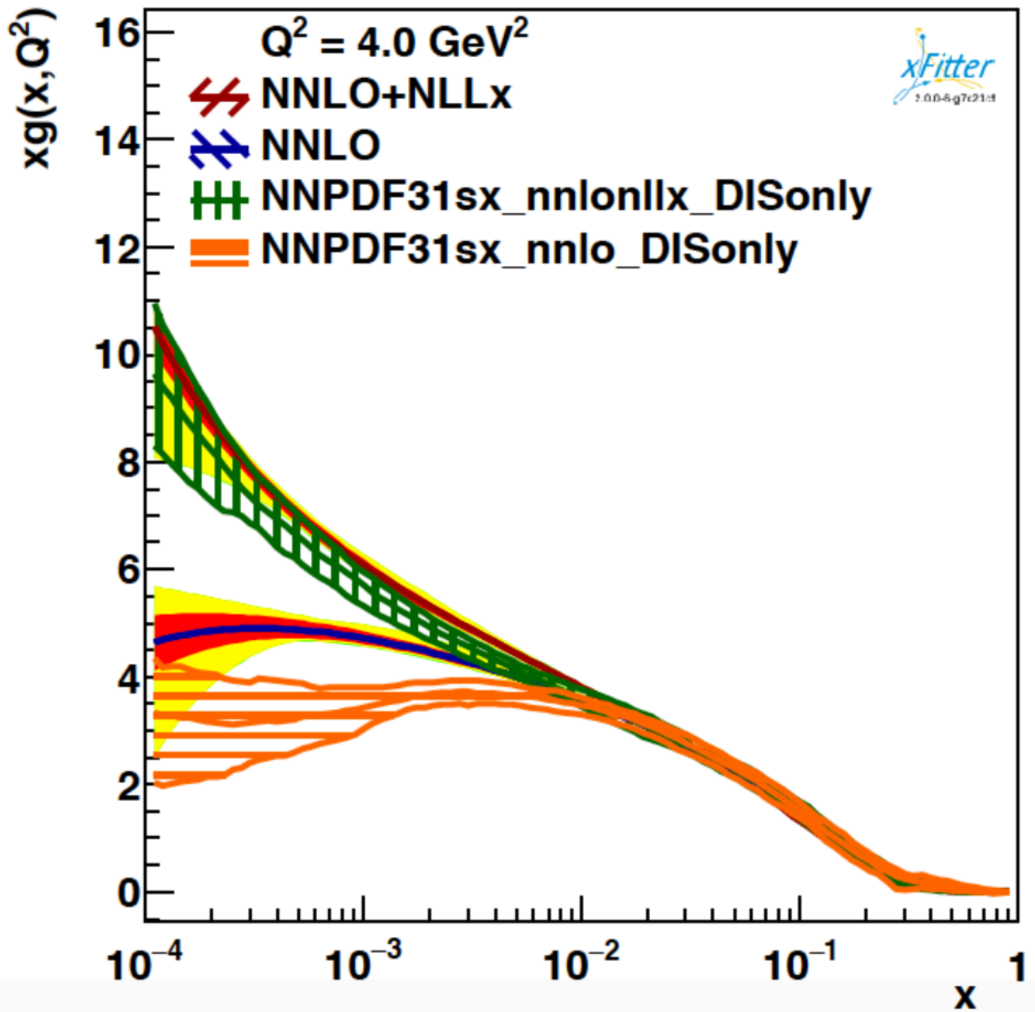
Full uncertainty study

- Full uncertainty study “a-la-HERAPDF” (**new PDF set will be released soon)**
- Model variation:
  - m_c = 1.41 GeV (down variation)
  - m_c = 1.51 GeV (up variation)
  - m_b = 4.25 GeV (down variation)
  - m_b = 4.75 GeV (up variation)
  - f_s = 0.3 (down variation)
  - f_s = 0.5 (up variation)
  - Q^2_{min} = 2.7 GeV^2 (down variation)
  - Q^2_{min} = 5.0 GeV^2 (up variation)
  - Q^2_0 = 2.86 GeV^2
  - α_s = 0.116
- Parameterisation variation:
  - + Duv (15 parameters in the fit) →
    $xu_v(x) = A_{u_v} x^{B_{u_v}} (1+x)^{C_{u_v}} (1 + D_{u_v} x + E_{u_v} x^2)$
- Q^2_{min} up variation affects the fit more
- **NNLO+NLLx becomes more accurate given that it has less tensions with the data**
- Another triumph for small-x resummation



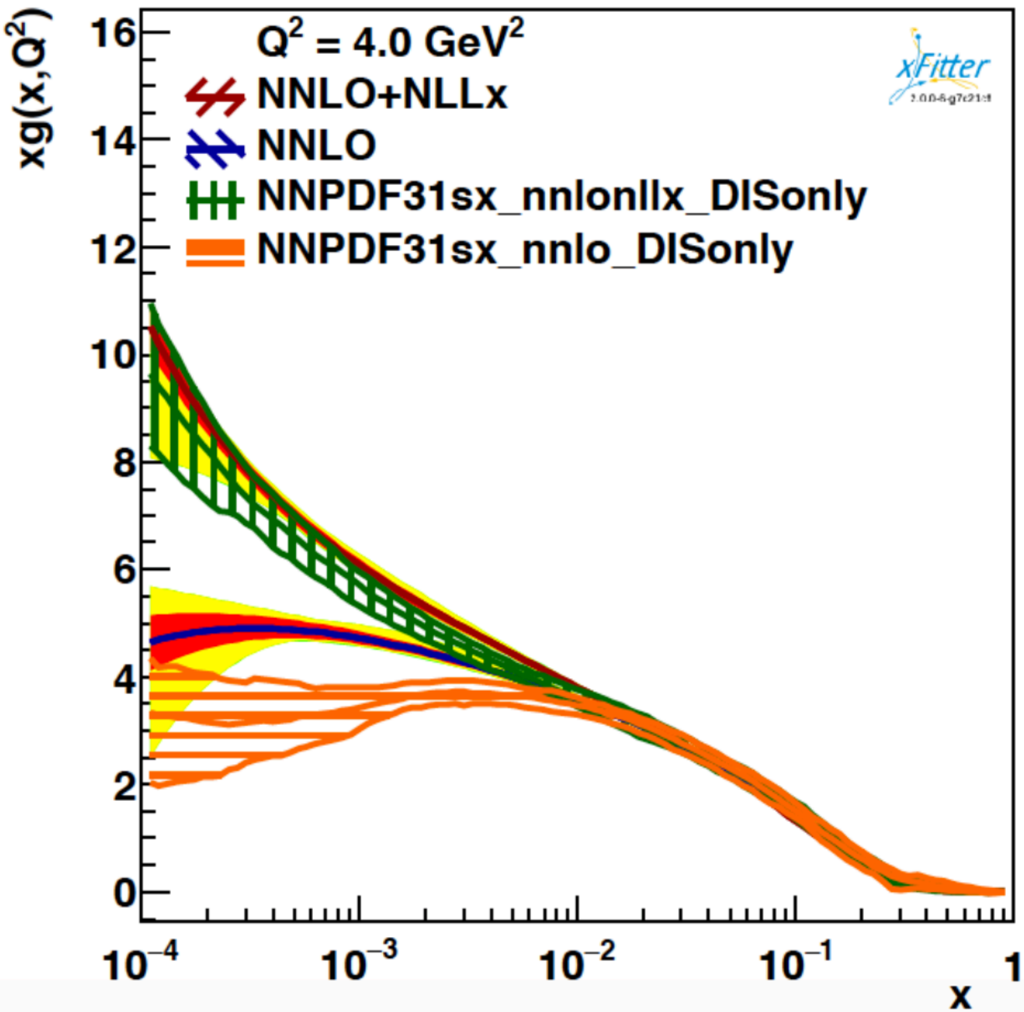


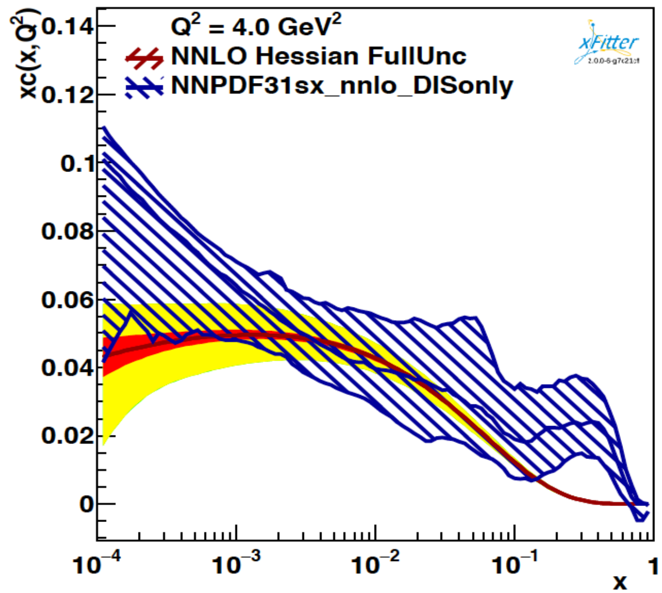
Comparison with NNPDF31 sets

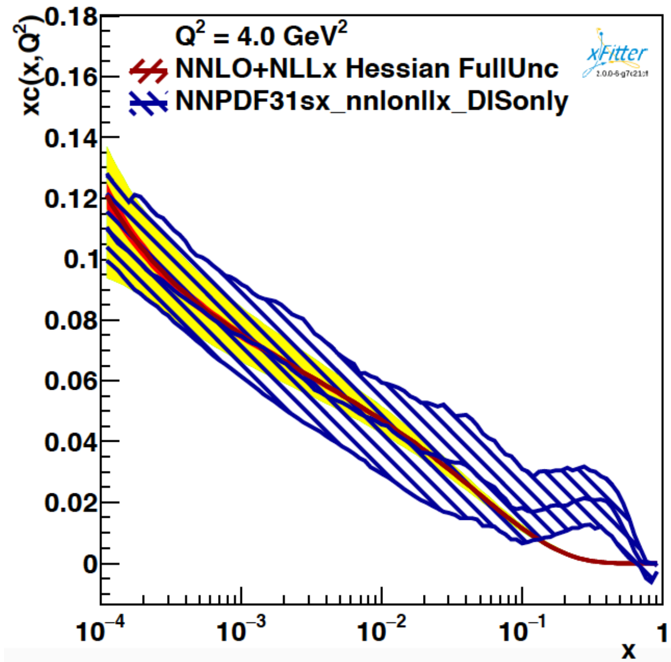


- Fit with small-x resummation corrections by **NNPDF**:
  - Fully-fledged PDF analysis
  - Includes hadronic data and other DIS experiments
  - Fitted charm
- Same qualitative behaviours
- We are now investigating the origin of some of the differences
- Comparison with a NNPDF set with DIS data only (more similar to our datasets)
- **Nice agreement between the two resummed fits**

Comparison with NNPDF31 sets





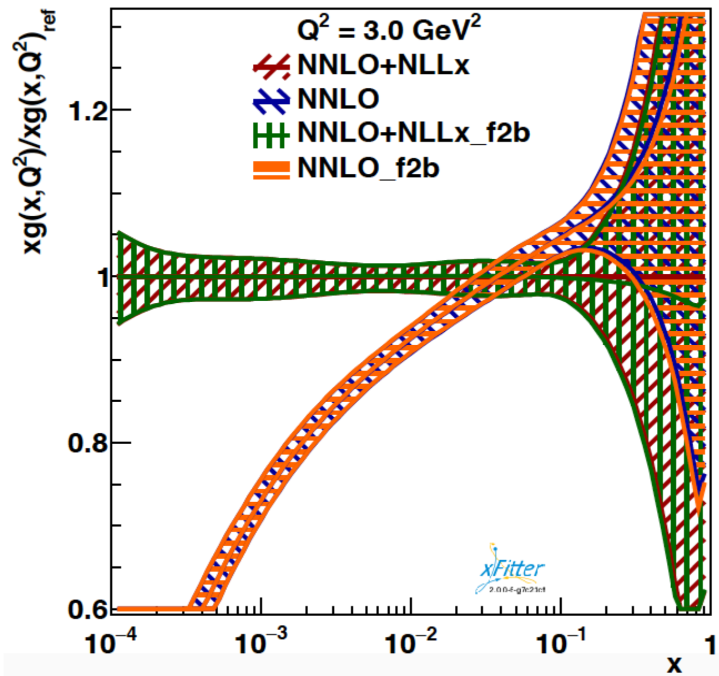


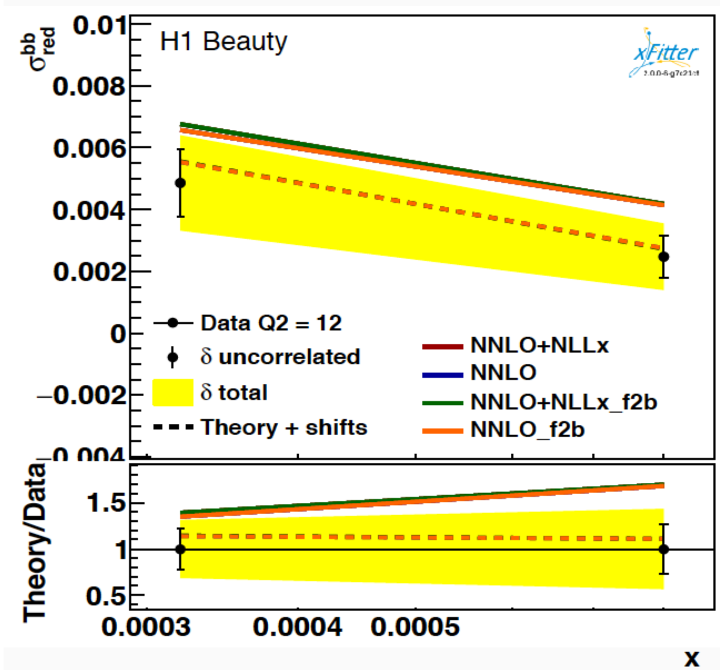
- Bigger difference at NNLO due to a bigger difference in the charm PDF

H1 F_2 beauty data

- We also considered the possibility of including beauty data in our fit
- Scan to identify the optimal m_b mass in the FONLL-C mass scheme with NLLx resummation:
  - m_b = 4.40 GeV —> 1402.95/1207 (1.162)
  - m_b = 4.45 GeV —> 1402.75/1207 (1.162)
  - m_b = 4.50 GeV —> 1402.83/1207 (1.162)
  - m_b = 4.55 GeV —> 1403.09/1207 (1.162)
  - m_b = 4.60 GeV —> 1403.65/1207 (1.163)
- Fit pretty insensitive to this variation so we stuck to our nominal choice (**m_b = 4.50 GeV**)

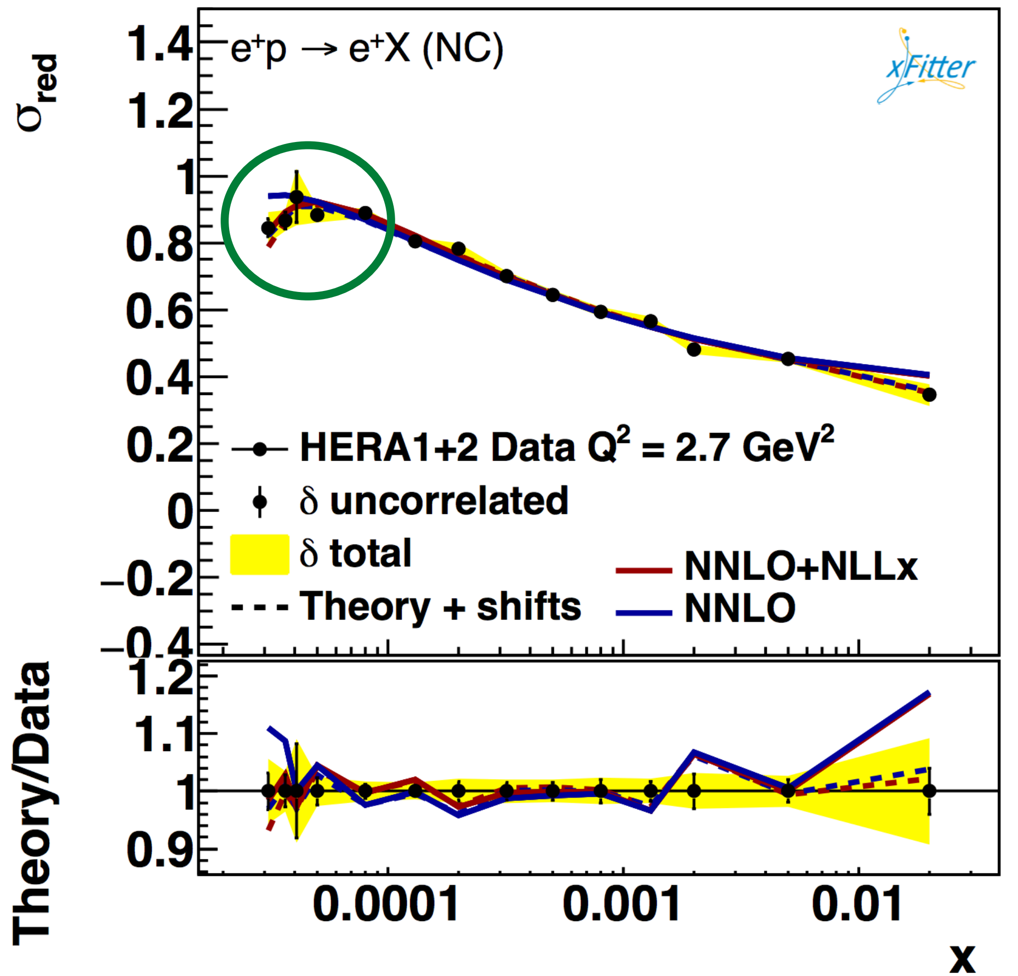
Dataset	NNLO+NLLx	NNLO	NNLO+NLLx f2b	NNLO f2b
Beauty cross section ZEUS Vertex	-	-	13 / 17	13 / 17
Charm cross section H1-ZEUS combined	50 / 47	47 / 47	50 / 47	47 / 47
HERA1+2 CCep	45 / 39	43 / 39	45 / 39	43 / 39
HERA1+2 CCem	53 / 42	57 / 42	53 / 42	57 / 42
HERA1+2 NCem	223 / 159	215 / 159	223 / 159	215 / 159
HERA1+2 NCep 820	65 / 70	67 / 70	65 / 70	67 / 70
HERA1+2 NCep 920	413 / 377	447 / 377	413 / 377	447 / 377
HERA1+2 NCep 460	222 / 204	217 / 204	222 / 204	217 / 204
HERA1+2 NCep 575	217 / 254	219 / 254	217 / 254	219 / 254
H1 F2 Beauty no shift	-	-	3.4 / 12	3.5 / 12
Correlated χ^2	89	116	91	119
Log penalty χ^2	-4.80	+19	-1.86	+22
Total χ^2 / dof	1373 / 1178	1446 / 1178	1394 / 1207	1468 / 1207
χ^2 p-value	0.00	0.00	0.00	0.00





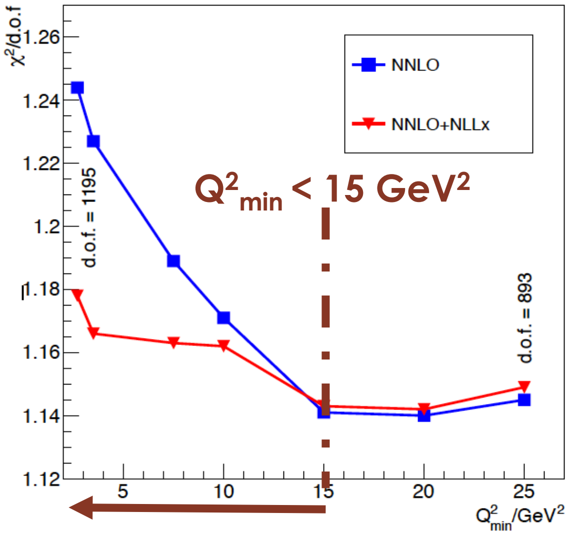
The Q^2 = 2.7 GeV^2 bin

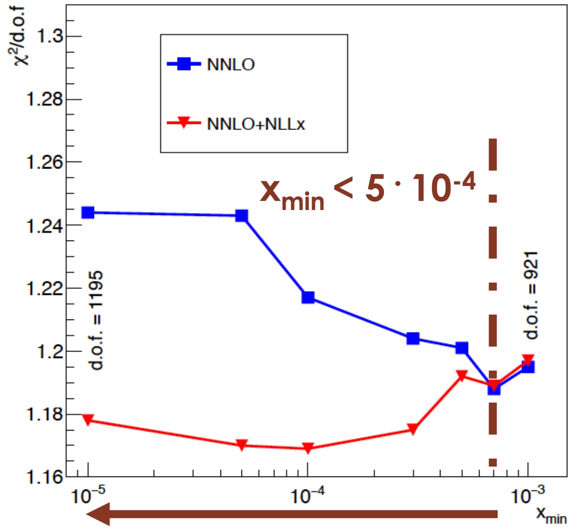
- Motivated by the success in describing the low-Q^2 region, we tried to include Q^2 = 2.7 GeV^2 bin in the fit as well (as in the NNPDF paper) **arXiv:1710.05935**
- The fit with log(1/x) resummation describes these data points better than the FO fit
- The PDFs derived from the fits including this extra Q^2 bin are very similar to those already shown
- **Yet another triumph for small-x resummation**

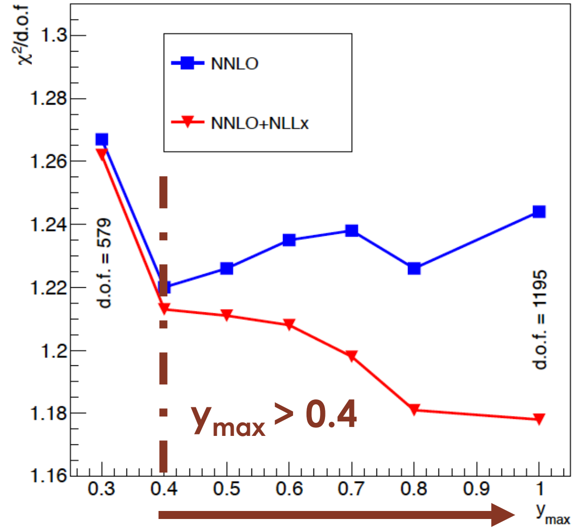


Q^2_{min}, x_{min} and y_{max} scans

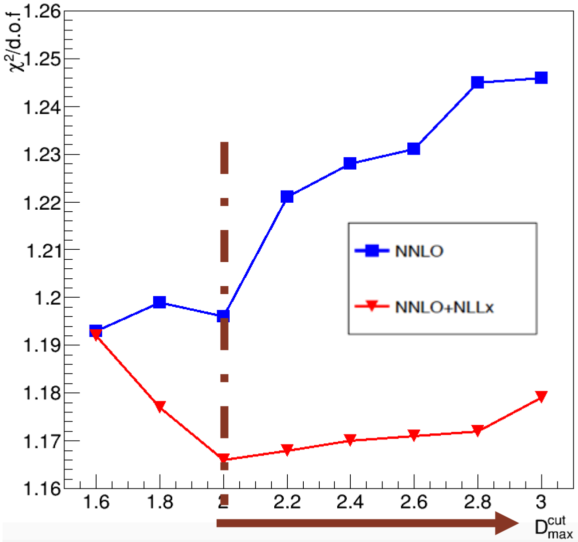
We tried to identify the region where resummation is important:

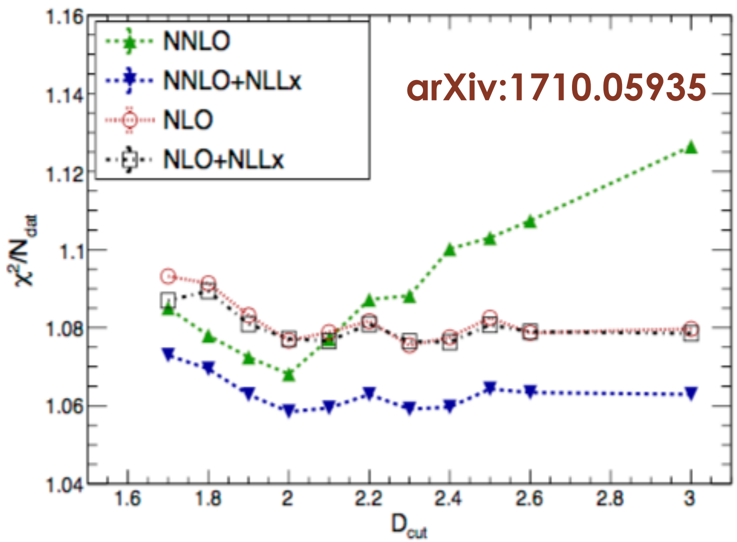






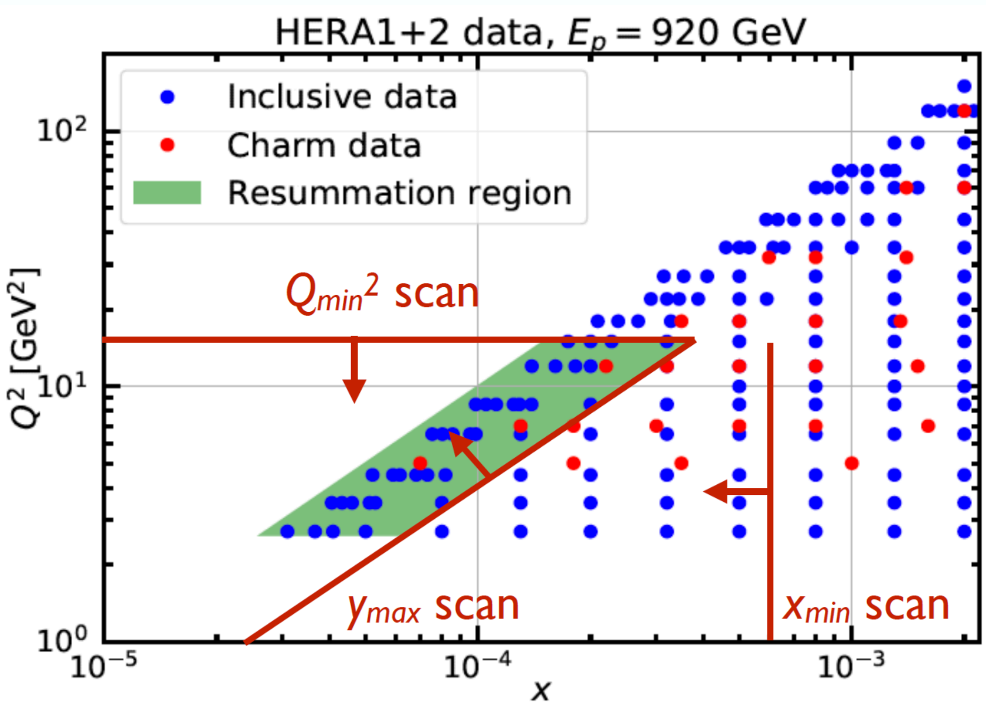
Simultaneous cut on Q^2 and x implemented: $\alpha_s(Q^2)\log\left(\frac{1}{x}\right) \geq D_{cut}$ where:





Consistent with what has been found in the NNPDF paper

Region where resummation has a significant effect

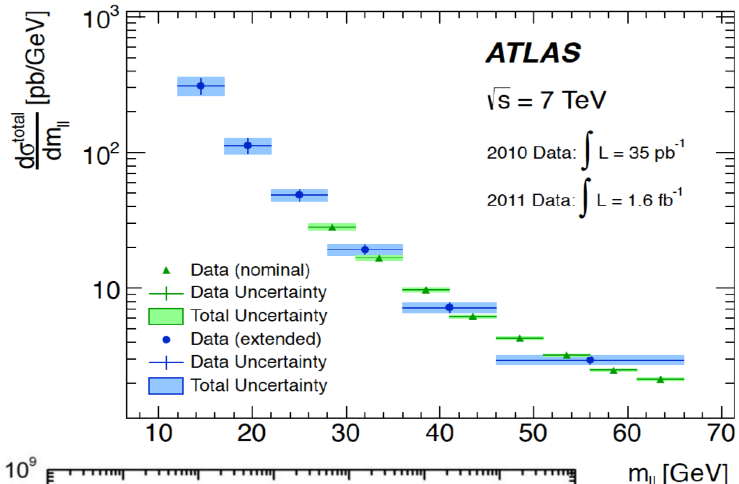


Defined by:
- $x < 5 \cdot 10^{-4}$
- $2.7 < Q^2 < 15$ GeV^2
- $0.4 < y < 1.0$

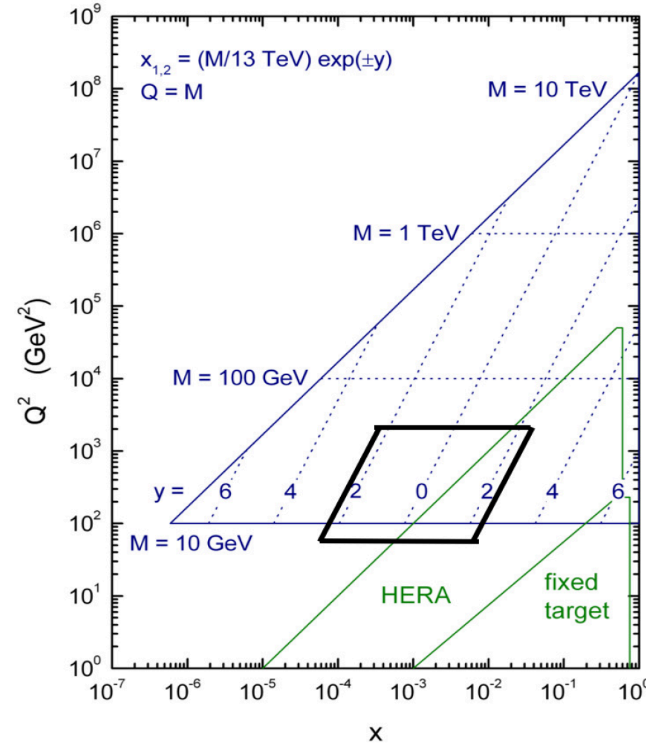
- χ^2 scans have obtained independently from one another - **our estimate reliable?**
- Two additional fits, w/wo resummation, excluding only the data points in the green area
- The total χ^2's of these fits differ by ~15 units in favour of the resummed fit (mostly due to the correlated and logarithmic terms)
- To be compared to the 73 units of when the shaded area is instead included (region corresponds to where low-Q^2 F_L structure function contributes the most)
- This confirms that the shaded area provides **a reliable estimate of the kinematic region in which resummation works significantly better than fixed order**

Low-mass DY @13 TeV – an interesting analysis

- Previous low-mass Drell Yan measurement at 7 TeV here: **JHEP 06 (2014) 112**

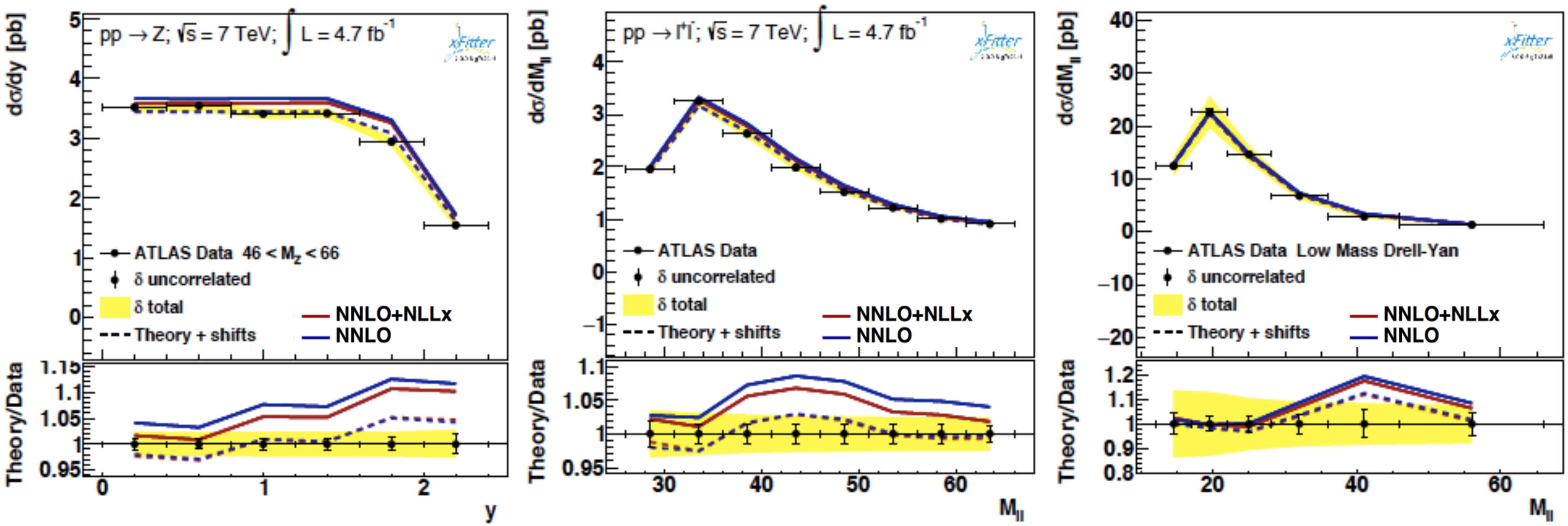


- Performed in the e/μ channels for invariant masses between 26 GeV and 66 GeV using an integrated luminosity of 1.6 fb^{-1} collected in 2011
- The analysis is extended to invariant masses as low as 12 GeV in the muon channel using 35 pb^{-1} of data collected in 2010
- In order to provide information that advances our knowledge of the PDFs – **low-x region**
- For the Run II analysis, **the results will be muon channel-only**
- Right now, just 2015 dataset in use – we might include 2016 dataset as well (triggers and prescales situation to be understood better)
- Cross sections provided both as $d\sigma/dm_{\mu\mu}$ (1D) and $d^2\sigma/dm_{\mu\mu}d|y_{\mu\mu}|$ (2D)
- **First analysis** including the **7-9 GeV bin** for cross section measurements



First look at low-mass DY ATLAS data and low-mass Z sideband @7 TeV

- First look at the description of the following data samples:
  - **JHEP 06 (2014) 112** – low-mass DY, 1.6 fb^{-1}
  - **Eur. Phys. J. C 77(2017) 367** – W,Z precision measurement, 4.7 fb^{-1}



- Description slightly improved when using the small-x resummation for the low mass DY data
- As regards the low mass Z sideband, NLLx resummation doesn't help

First look at low-mass DY ATLAS data and low-mass Z sideband @7 TeV

- First look at the description of the following data samples:
  - **JHEP 06 (2014) 112** – low-mass DY, 1.6 fb^{-1}
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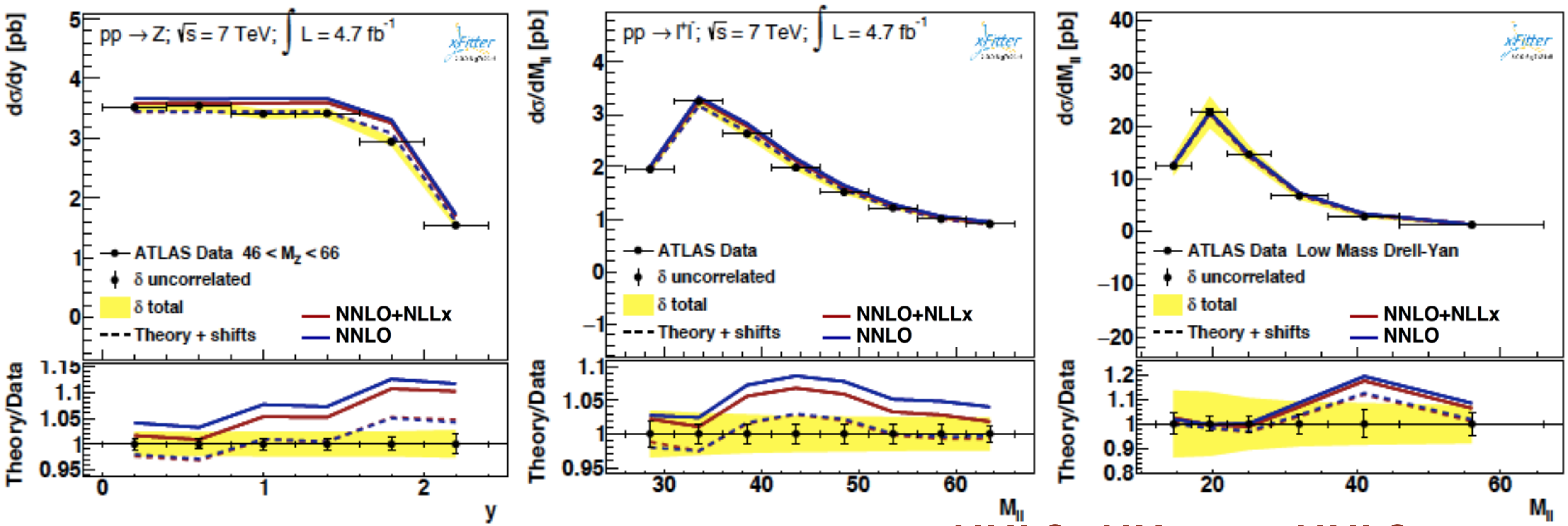

	NNLO+NLLx	NNLO
ATLAS low mass DY 2011	9.5 / 8	11 / 8
ATLAS DY mass 2010 extended data	6.4 / 6	6.9 / 6
ATLAS low mass Z rapidity 2011	31 / 6	31 / 6

First look at low-mass DY ATLAS data and low-mass Z sideband @7 TeV

- First look at the description of the following data samples:
  - **JHEP 06 (2014) 112** – low-mass DY, 1.6 fb^{-1}
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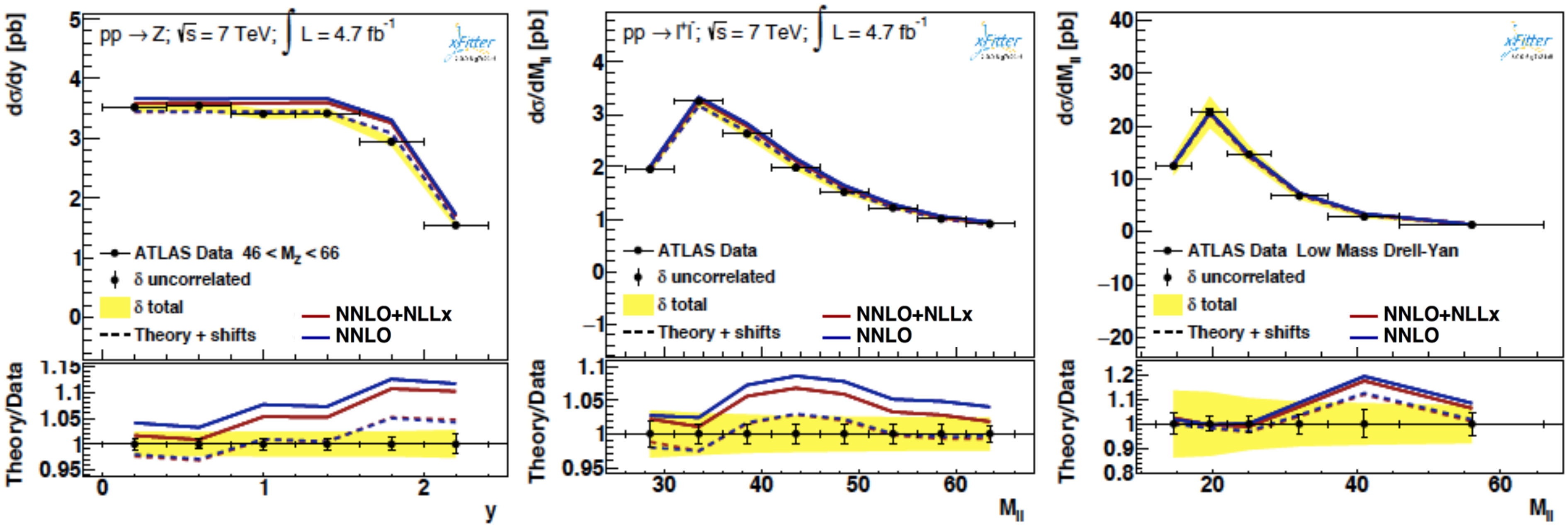
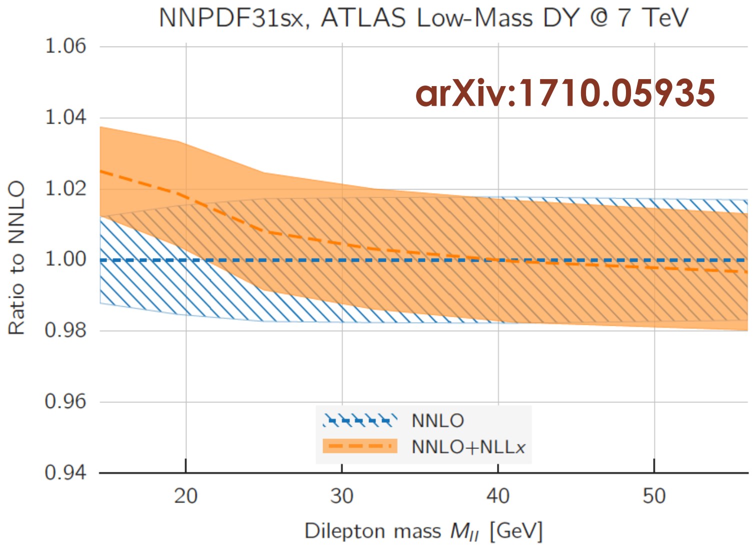


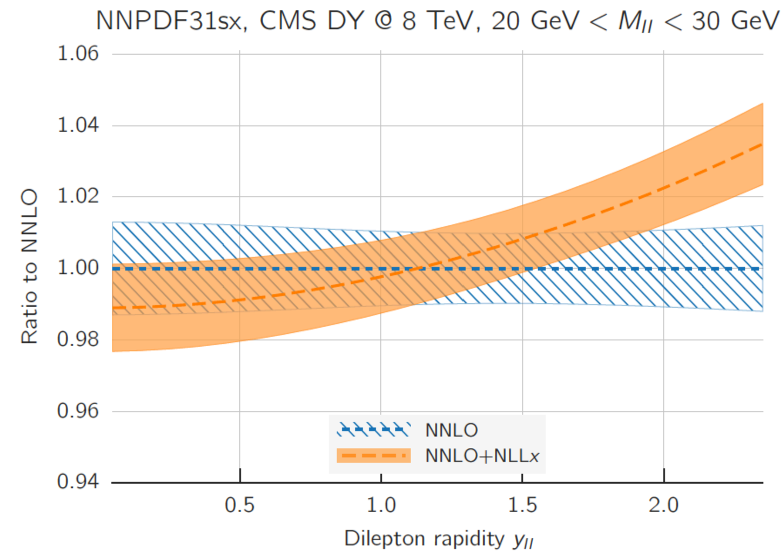
- We cannot perform resummed fit including these data (**resummed hard process cross section not available yet**) – resummation available just in the PDF evolution

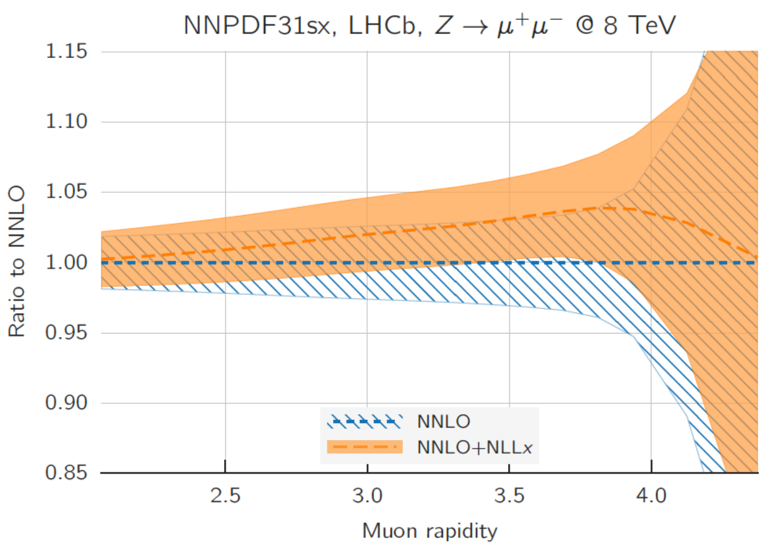
COMPLAIN WITH MARCO BONVINI! @Room 203

Impact of small-x resummation for DY process

- Possible phenomenological consequences of small-x resummation for the DY production process



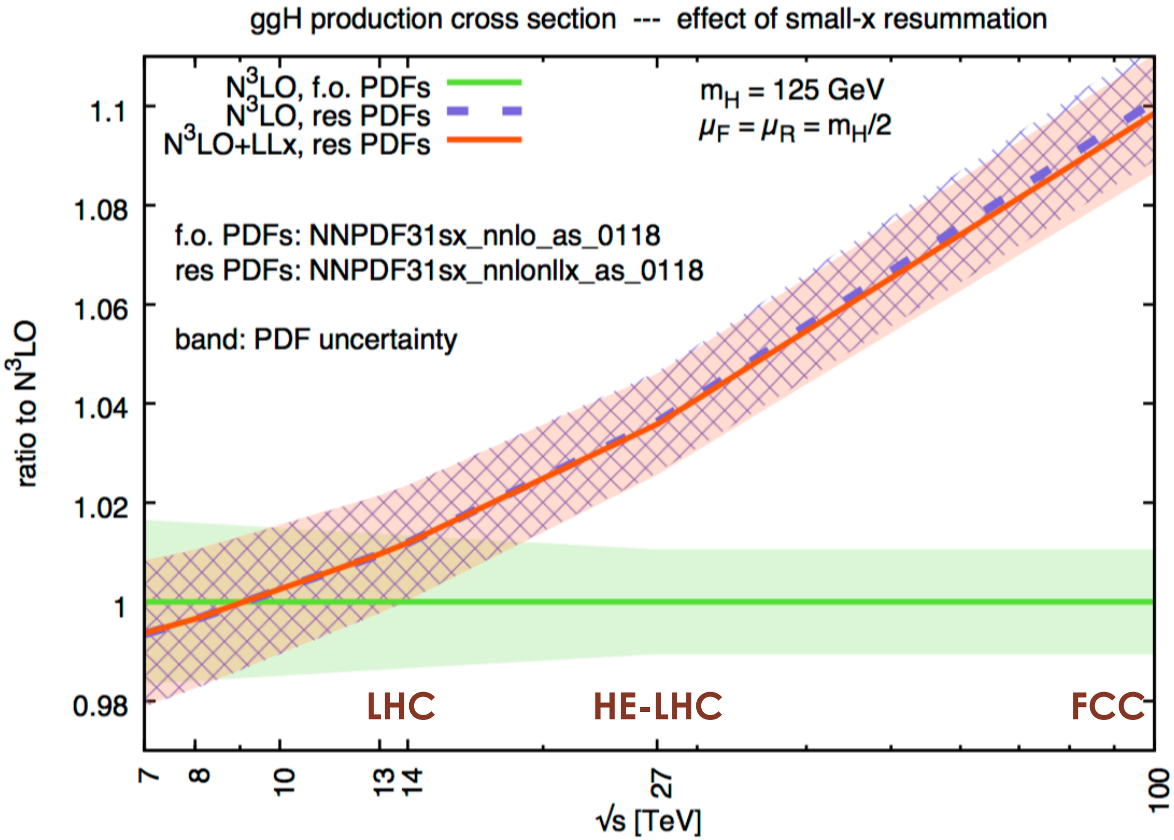




- Comparison between the NNPDF3.1sx NNLO and NNLO+NLLx predictions
- Differences are more marked for the kinematic regions directly sensitive to small-x, e.g. small m_{ll} for ATLAS data or large rapidities in the case of the CMS and LHCb measurements
- Small-x resummation included in the PDF evolution **ONLY**

Impact of resummation: Higgs gF

- Possible phenomenological consequences of resummation for the inclusive gF Higgs production process



https://arxiv.org/abs/1802.07758 **[Bonvini,Marzani]**

- LLx resummed calculation matched to N^3LO FO calculations
- Small-x resummation has a modest impact at current LHC energies
- Its impact grows substantially with the energy, reaching 10% at 100 TeV
- Bulk of the effect: the resummed PDFs and their resummed evolution

Summary

- Study on the impact of small-x resummation on the HERA data **arXiv:1802.00064**
- Small-x resummation available in xFitter through APFEL+HELL
- **Gain of 73 units in χ^2 wrt the FO NNLO fit**
- Significant difference in $xg(x, Q^2)$; **gluon no longer turns over at small x**
- Better description from the resummed fit as compared to the FO NNLO one for the H1 FL extraction and for the low-Q^2 data
- Good agreement with NNPDF31sx study
- We identified the region where resummation has a significant effect:
  - $x < 5 \cdot 10^{-4}$
  - $2.7 < Q^2 < 15$ GeV^2
  - $0.4 < y < 1.0$
- Implications of small-x resummation for physics at LHC
  - Drell-Yan
  - Inclusive gF Higgs production cross section
- Low-mass DY at 13 TeV: new ATLAS measurement coming out soon (**hopefully!**)
- **Small-x resummation crucial for low-x (HERA/LHC) phenomenology**

THANKS FOR YOUR ATTENTION! FG (and MB)

Backup Slides

xFitter on Hepforge: data access

http://xfitter.hepforge.org/

- This website contains complementary information to https://www.xfitter.org/
- Possibility to download data files (including theory)
- Updated automatically with new data added to svn

Your feedback is welcome! ☺
(via email xfitter-help@desy.de)

http://xfitter.hepforge.org/data.html

This page contains the list of publicly available experimental data sets (with corresponding theory grids if available) in the xFitter package.
To download data set please click on the arXiv link (and open/save tar.gz file).

No	Collider	Experiment	Reaction	arXiv	Readme
1	fixedTarget	bcdms	inclusiveDis	cern-ep-89-06	README
2	hera	h1	beautyProduction	0907.2643	
3	hera	h1	inclusiveDis	1012.4355	
4	hera	h1	jets	0706.3722	README
5	hera	h1	jets	0707.4057	README
6	hera	h1	jets	0904.3870	README
7	hera	h1	jets	0911.5678	README
8	hera	h1	jets	1406.4709	README
9	hera	h1zeusCombined	charmProduction	1211.1182	
10	hera	h1zeusCombined	inclusiveDis	0911.0884	
11	hera	h1zeusCombined	inclusiveDis	1506.06042	
12	hera	zeus	beautyProduction	1405.6915	
13	hera	zeus	diffractiveDis	0812.2003	
14	hera	zeus	jets	0208037	
15	hera	zeus	jets	0608048	
16	hera	zeus	jets	1010.6167	
17	lhc	atlas	drellYan	1305.4192	
18	lhc	atlas	drellYan	1404.1212	
19	lhc	atlas	jets	1112.6297	

(more datasets available on the website)

Novelties in xFitter 2.0.0 (1)

Release	Date	Description
`xfitter-2.0.0` (FrozenFrog)	20.03.2017	**Physics related additions:** • Implementation of switching scales for heavy quarks (APFEL) • Fast convolution using APFELGRID ("fk" tables) • Write out top LHAPDF if top mass is below kinematic limit (5 and 6 flavour PDFs) • Extra PDF parameters of the photon parametrisation • Improvements to QED evolution interface (QEDevol) • (optionally) Produce symmetric hessian PDF sets using minuit HESSE covariance matrix computation instead of default ITERATE method. • Updates to dipole steering files, saturation flag added • Extra option to separate statistical uncertainty from total covariance matrix, when it is uncorrelated **Technical improvements:** • Move to QCDNUM 17-01-13 new PDF interfaces. Make use of fast PDF calls. • Update fastNLO to latest version. Switch from APPLGRID → FastNLO to native FastNLO. • `install-xfitter` script uses cvmfs (recommended way to install xFitter) • `xfitter-getdata.sh` script added to download datasets • Added new datasets from LHC and HERA, and LHeC simulated data. • Synchronisation of the lhapdf6 output grid with initialisation from QCDNUM • Restore optional LHAPDFv5 usage

!!

Novelties in xFitter 2.0.0 (2)

Release	Date	Description
xfitter-2.0.0 (FrozenFrog)	20.03.2017	**Physics related additions:**

- Possibility to force PDFs to be positive after processing (`xfitter-process` tool)
- Adjustment of internal systematic arrays to to run with all data. Reduction of other internal arrays to keep memory footprint low
- Improvements in configuration and makefiles to work with different compilers and operation systems
- If `OUTPUTDIR` directory exists when running xfitter, it will be moved to `OUTPUTDIR_OLD`
- Increased the possible length of the output directory name
- Clean up (removing/renaming functions, suppressing unneeded outputs)
- Updates to README, INSTALLATION, steering files, manual, doxygen config
- Add error message if combine utility is used with LHAPDFv 5.x
- Cleanup of warning messages, better indication of potential problems
- Restore `make dist` functionality
- Added extra automatic checks
- Add feature to draw individual sets by using set:ID:dir syntax
- Additional option `--loose-mc-replica-selection`
- Add strict check for second option of MC-replica path matching
- Other small fixes in drawing options (logo, coloured error bands, etc)

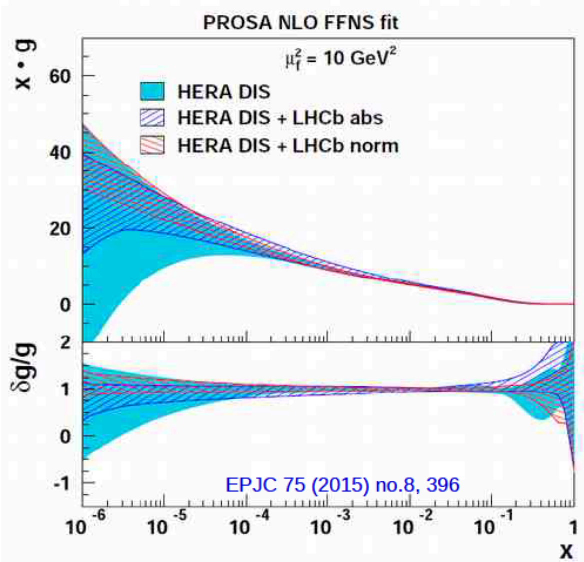
Bug Fixes:

- Fix in the gluon parametrisation (affecting HERAPDF parameterisation sum-rule)
- Enable compilation with LHAPDF6 and without APPLgrid
- Fixes in non-standard parameterisations (e.g. using Chebyshev polynomials)
- Fix few conflicting fortran symbols.

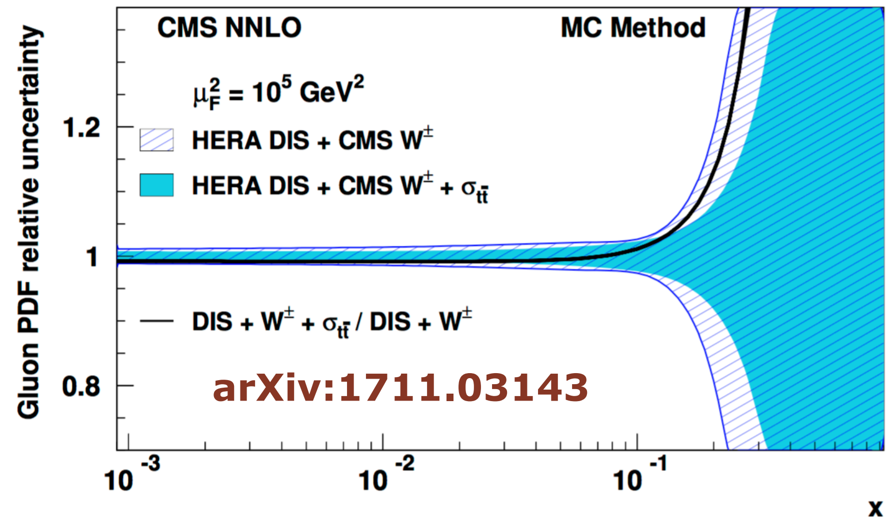
flavour PDFs)
SE covariance
matrix, when
PDF calls.
NLO to native
Fitter)
ta.
QCDNUM

Results obtained with xFitter: Examples (2)

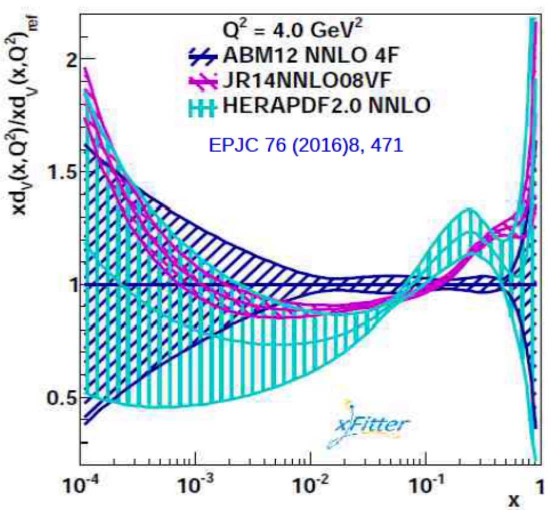
Heavy quark production($ep, pp, p\bar{p}$)



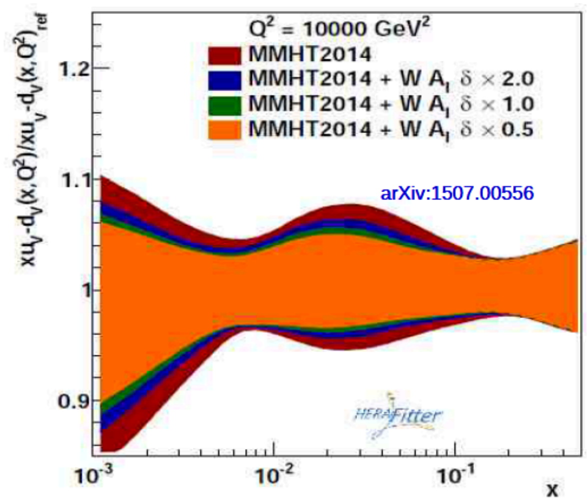
Top-quark production ($pp, p\bar{p}$)



Evolution of moder PDFs (benchmarking)



PDF4LHC report (benchmarking)



Last xFitter Developers Meeting

External xFitter's meeting in Krakow:

- 31 participants
- 3 days workshop with number of talks and many discussions

https://indico.desy.de/indico/event/19213/overview

xFitter External Workshop in Krakow

The third international workshop to bring together users and developers of the xFitter project. The topics will include current status and further developments in accordance with experimental analysis demands.

The programme of the workshop will be from Monday 5th morning till Wednesday 7th lunch time. Participants should arrive Sunday 4th. Welcome reception will be held in the Krakow University of Technology, St. Warszawska 24, Bldg.10-24, room 108, Gallery Gil from 7pm on Sunday. The workshop will end with lunch on Wednesday March 7th. Some limited financial help for attendance at the workshop is available from DESY and Krakow University of Technology.

xFitter workshops

xFitter examples (CTEQ school)

http://qcd2016.desy.de/

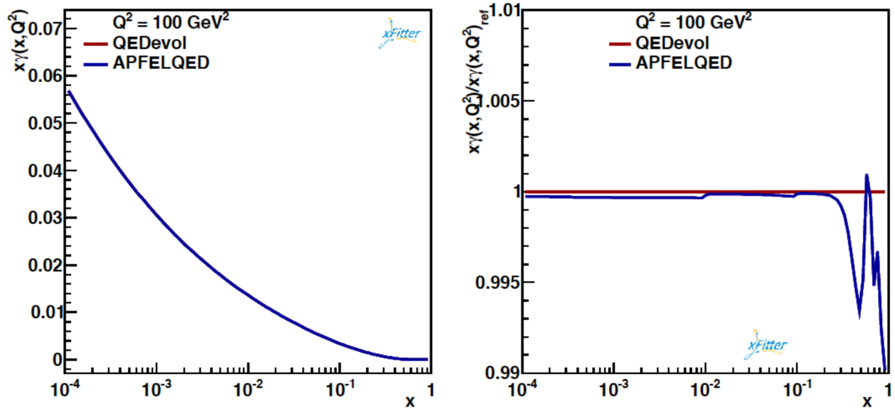
Stefano Camarda
Ringailė Plačakytė

A list of educational examples are provided in the package - prepared for the CTEQ summer school 2016:

- **Exercise 1:** PDF fit
  - learn the basic settings of a QCD analysis, based on HERA data only
- **Exercise 2:** Simultaneous PDF fit and as
  - learn the basic of an as extraction using H1 jet data
- **Exercise 3:** LHAPDF analysis
  - how to estimate impact of a new data without fitting:
  - profiling and reweighting techniques
- **Exercise 4:** Plotting LHAPDF files
  - direct visualisation of PDFs from LHAPDF6 using simple python scripts
- **Exercise 5:** Equivalence of χ^2 representations
  - understand different χ^2 representations (nuisance parameters and covariance matrix χ^2 formulas)

Physics cases in xFitter

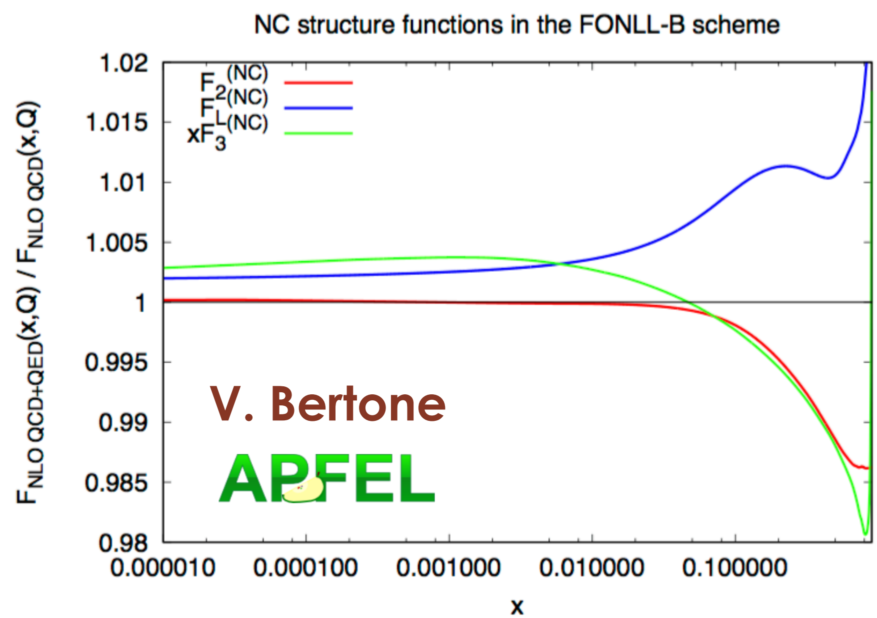
- **New QED PDFs up to NNLO QCD + NLO QED** in FFNS and VFNS are now available via evolutions in:
  - QCDNUM adjusted for DGLAP+QED [R. Sadykov] http://www.nikhef.nl/~h24/qcdnum
  - APFEL DGLAP+QED as used by NNPDF2.3 [V. Bertone et al.] https://apfel.hepforge.org/
  - plan to add NLO QED, interface APPLGRID to SANC https://apfel.hepforge.org/mela.html



[Plots produced by R. Sadykov and V. Bertone]

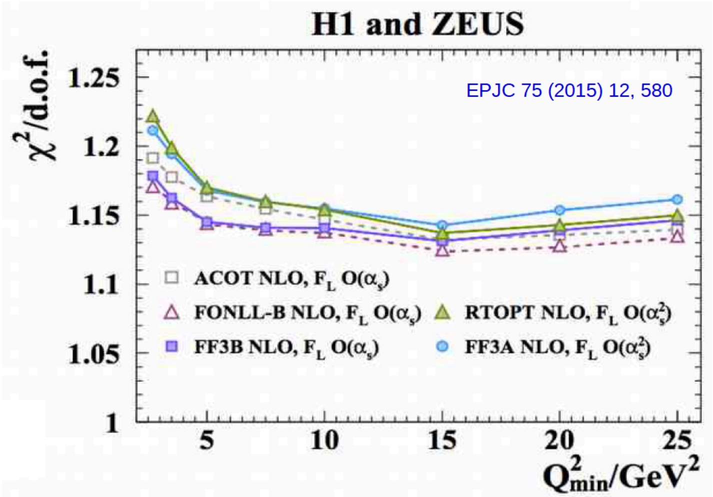
Perfect agreement between QEDEVOL and APFEL

- **NLO QCD + QED via APFEL in xFitter:**
  - implementing the $O(\alpha\alpha_S)$ and the $O(\alpha^2)$ corrections to the DGLAP splitting functions on top of the $O(\alpha)$ ones
  - implementing $O(\alpha\alpha_S^2)$ and the $O(\alpha^2)$, $O(\alpha^2\alpha_S)$ corrections to β functions
  - when including NLO QED corrections, not only the evolution is affected but also the DIS structure functions

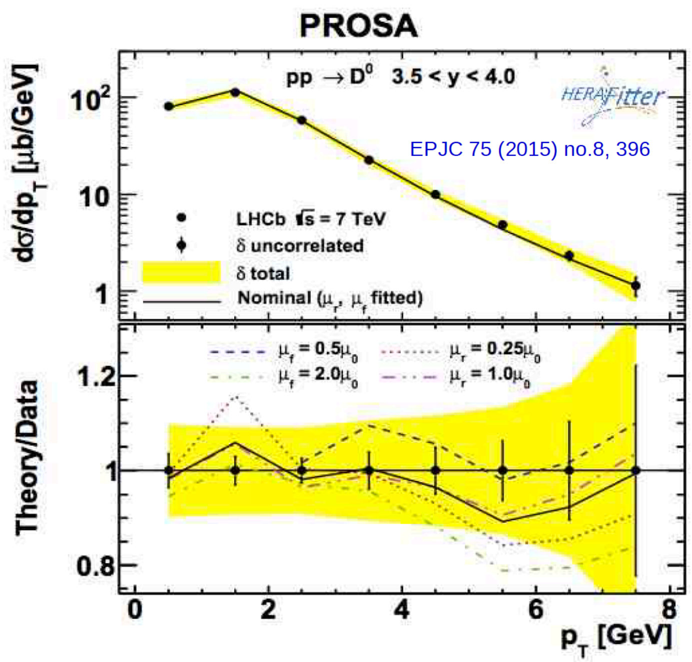


Physics cases in xFitter (2)

- Addition of new Heavy Flavour Scheme: **FONLL VFNS**
  - it is available thanks to collaboration with APFEL
  - various FONLL options available via interface to APFEL https://apfel.hepforge.org/
  - ABM scheme was up-to-dated to OPENQCDRAD v2.0b4 http://www-zeuthen.desy.de/~alekhin/OPENQCDRAD



- **Interface to Mangano-Nason-Ridolfi** (MNR, NPB 373 (1992) 295) theory code added in xFitter:
  - was used for analysing the heavy-flavour production at
  - LHCb and at HERA (via OPENQCDRAD)
  - use of FFNS for accounting of heavy quark masses at NLO
  - added corresponding LHCb data

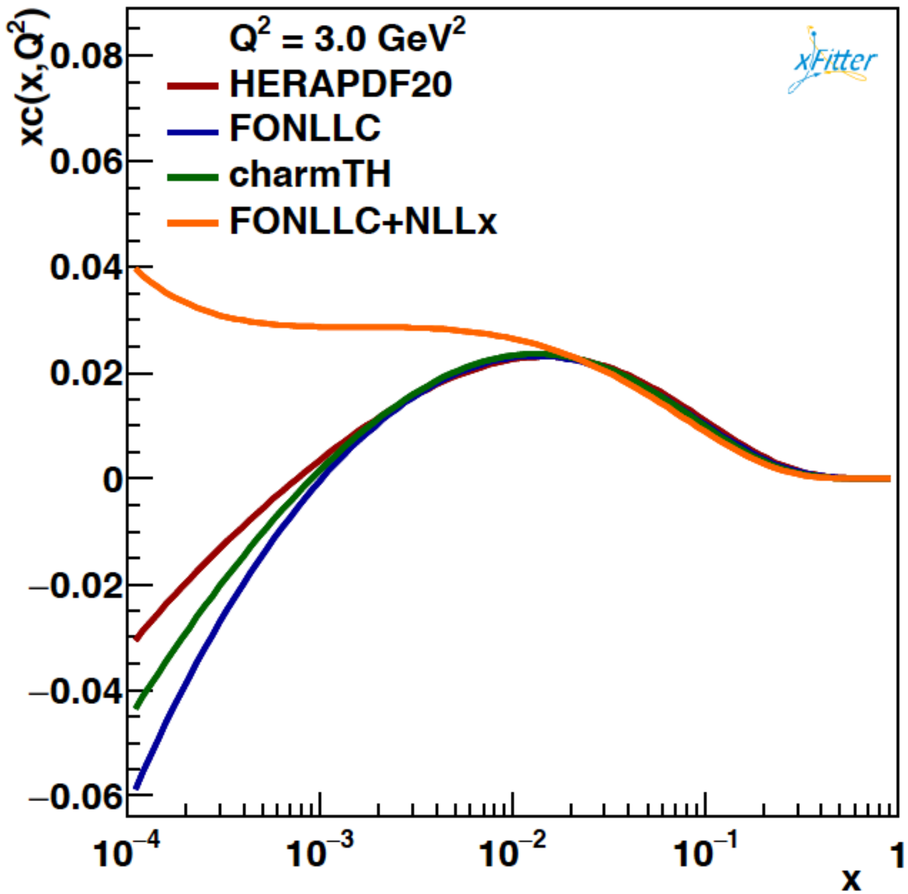


- **Added extra reweighing option** using Giele-Keller weights

Charm PDF

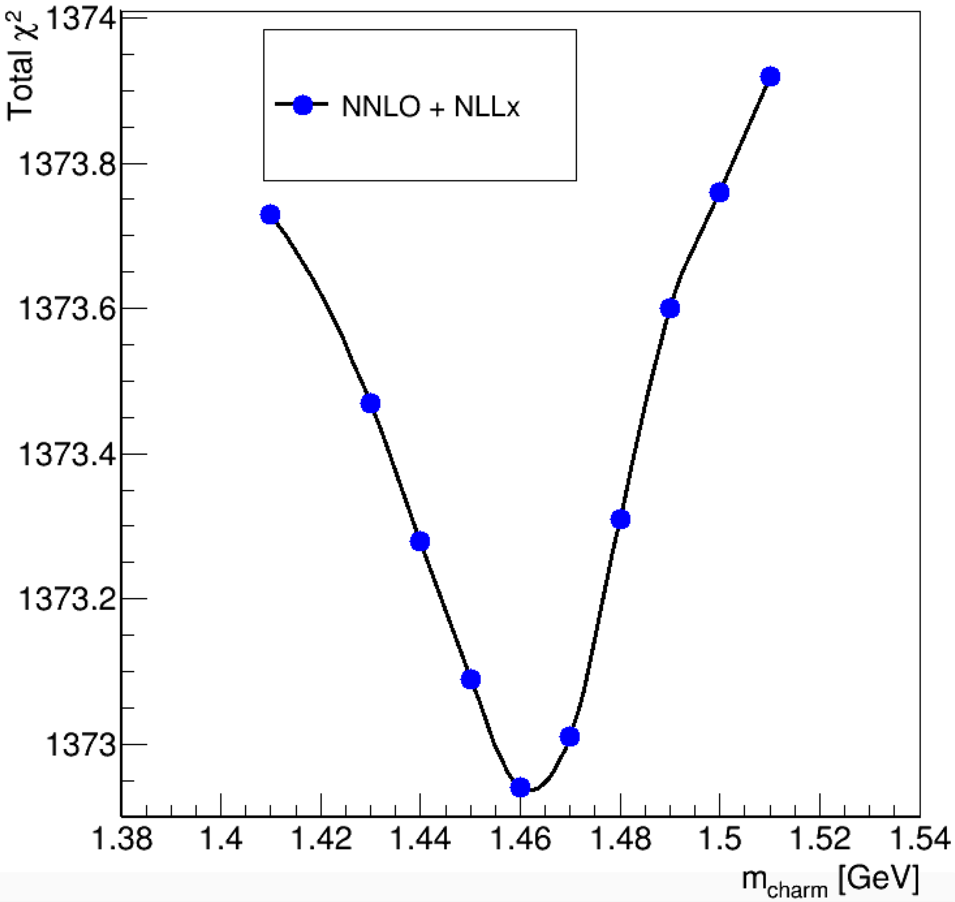
- The aim is to move in small steps from the HERAPDF2.0 NNLO setup (Step-1) to a setup with small-x resummed corrections with APFEL+HELL:
  - Step-2: use FONLL-C instead of TR (required to use APFEL)
  - Step-3: move up Q_0 and displace the charm threshold (required to use HELL)
  - Step-4: Add the small-x resummation at NLLx

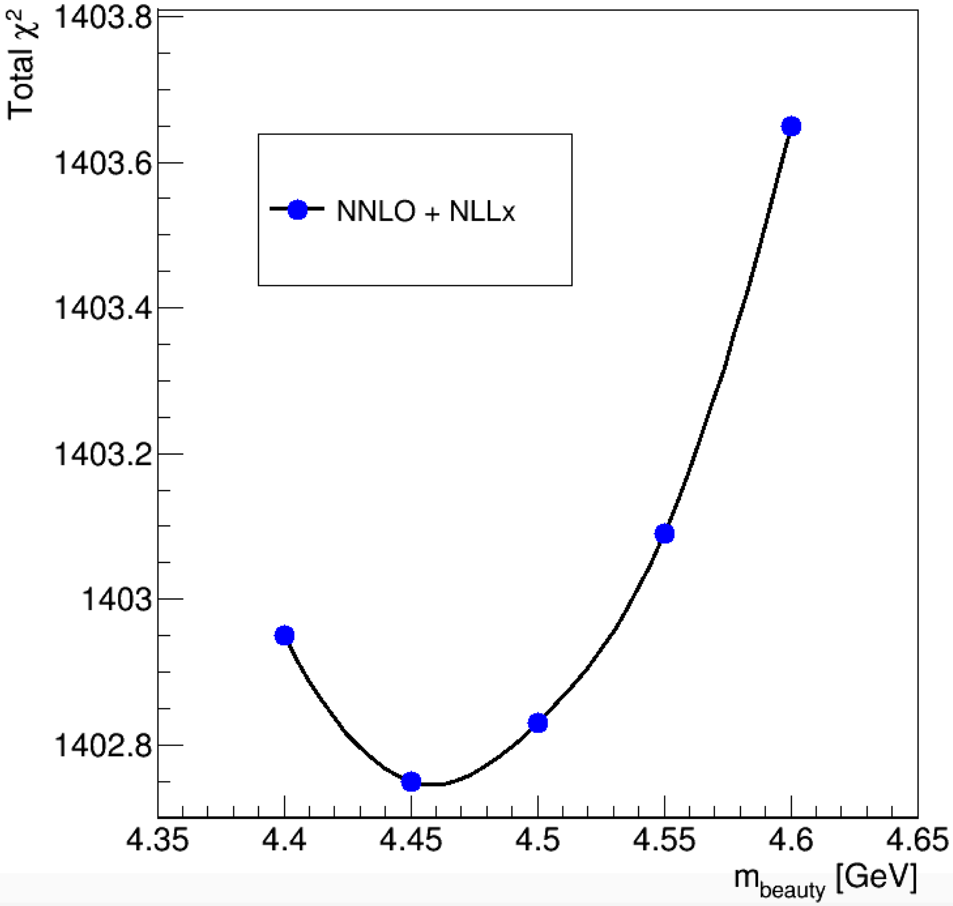
Eur. Phys. J. C 77 (2017) 837



Optimal m_c and m_b values for the fit

Heavy flavour mass scheme: **FONLL-C with small-x corrections included**





N.d.f = 1178

N.d.f = 1207

More detailed comparison to NNPDF31

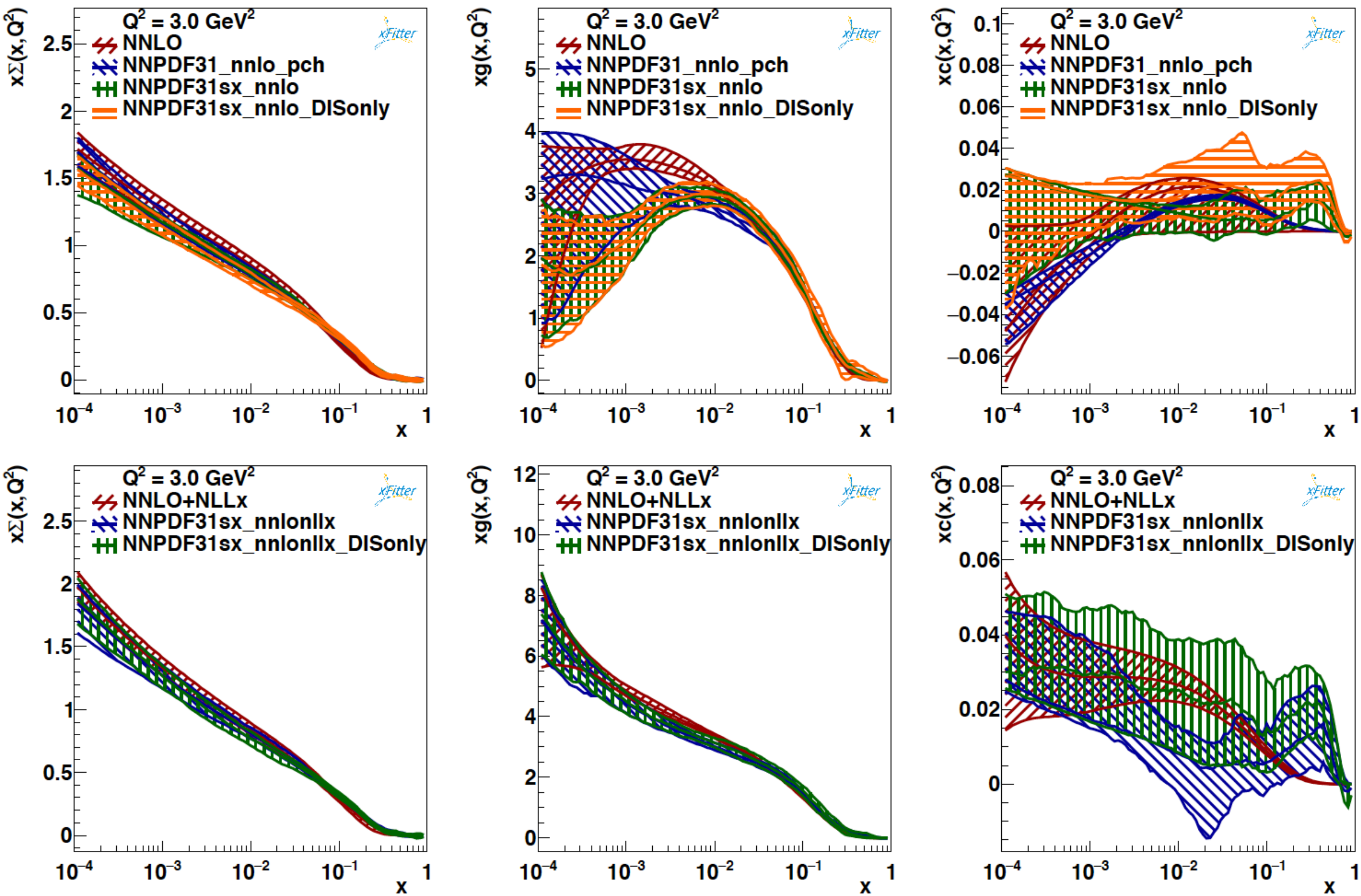


Figure 9 The total singlet, gluon and charm PDFs for the final fits at NNLO (upper plots) and NNLO+NLLx (lower plots) compared to the analogous NNPDF3.1 determinations.

Log term inclusive and log term charm

Standard **NNLO+NLLx vs NNLO fits** (w/o Q^2 = 2.7 GeV^2 bin)

After minimisation 1372.98 1178 1.166

Partial chi2s

413.12(+5.07)	377	HERA1+2 NCep 920
65.25(-0.56)	70	HERA1+2 NCep 820
216.96(-1.46)	254	HERA1+2 NCep 575
221.66(-3.44)	204	HERA1+2 NCep 460
223.20(-0.87)	159	HERA1+2 NCem
45.53(+0.52)	39	HERA1+2 CCep
53.61(-2.43)	42	HERA1+2 CCem
49.50(-1.06)	47	Charm cross section

Correlated Chi2 88.382726246930133
Log penalty Chi2 -4.2267289601319771

HERAonly:
77.0 to the correlated chi2;
-2.9 to the log penalty term
charm data:
11.4 to the correlated chi2;
1.3 to the log penalty term

After minimisation 1445.55 1178 1.227

Partial chi2s

445.57(+13.03)	377	HERA1+2 NCep 920
66.82(+0.99)	70	HERA1+2 NCep 820
218.39(+3.93)	254	HERA1+2 NCep 575
216.46(+1.39)	204	HERA1+2 NCep 460
215.07(+1.63)	159	HERA1+2 NCem
43.50(+0.86)	39	HERA1+2 CCep
56.84(-1.57)	42	HERA1+2 CCem
47.47(-1.50)	47	Charm cross section

Correlated Chi2 116.69776308230242
Log penalty Chi2 18.750060129311155

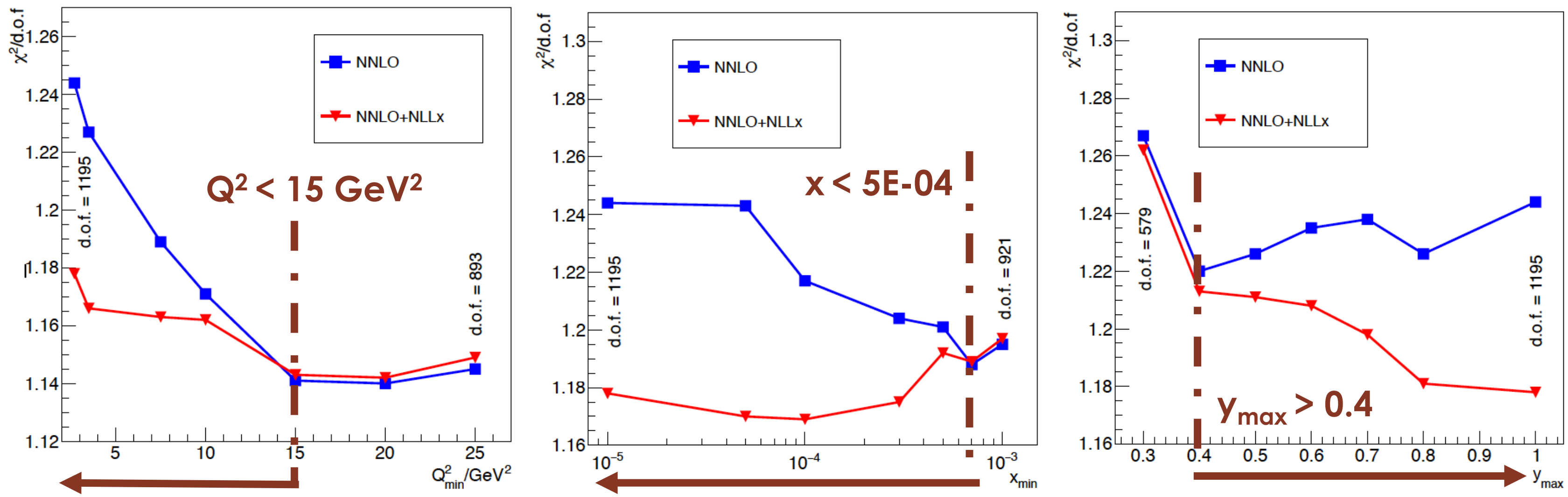
HERAonly:
101.7 to the correlated;
20.4 to the log penalty term
charm data:
15.0 to the correlated chi2;
-1.7 to the log penalty term

Q^2, x_{min} and y_{max} scans

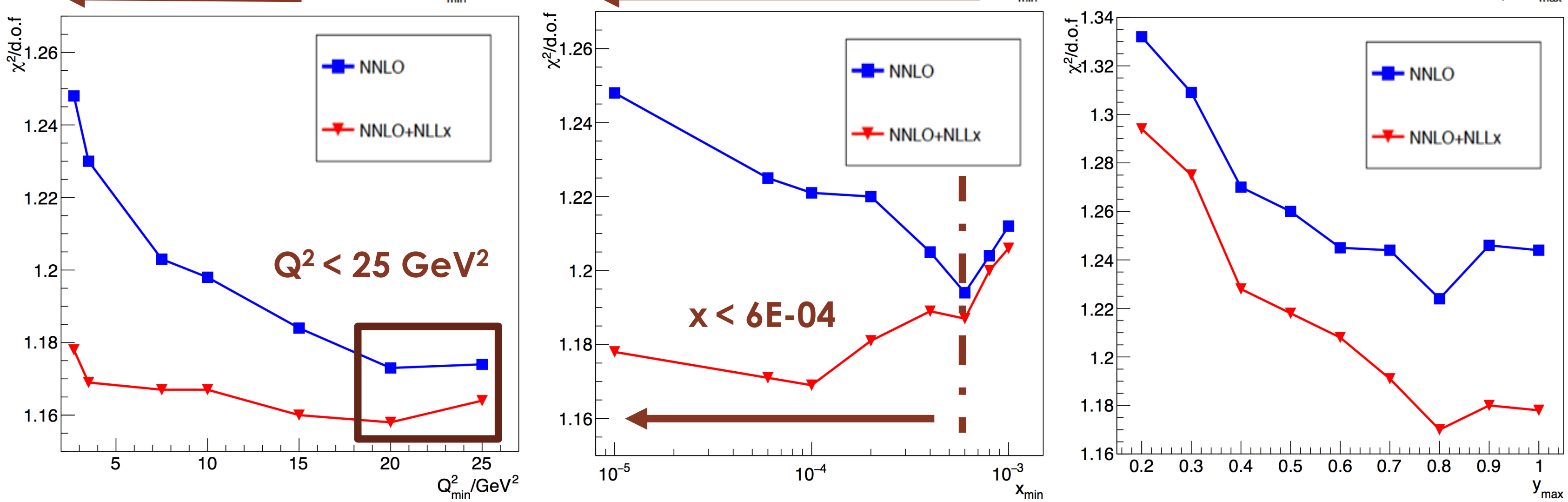
We tried to identify the region where resummation is important:

- Refitting with different cuts on Q^2, x_{min} and y_{max}
- Recomputing χ^2 just varying the cuts on Q^2, x_{min} and y_{max}

Refitting

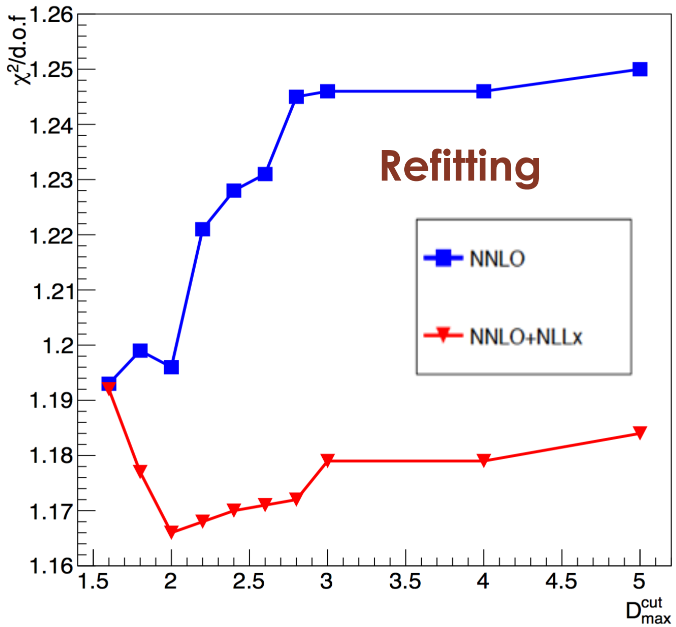


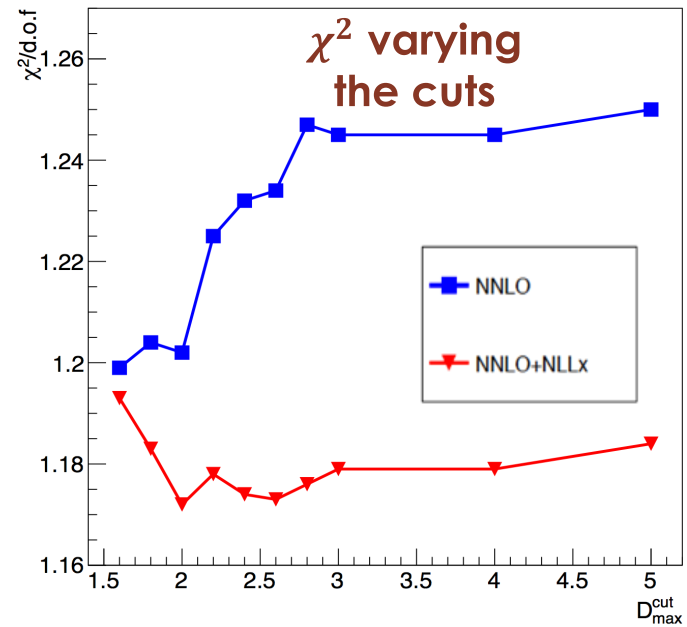
χ^2 varying the cuts

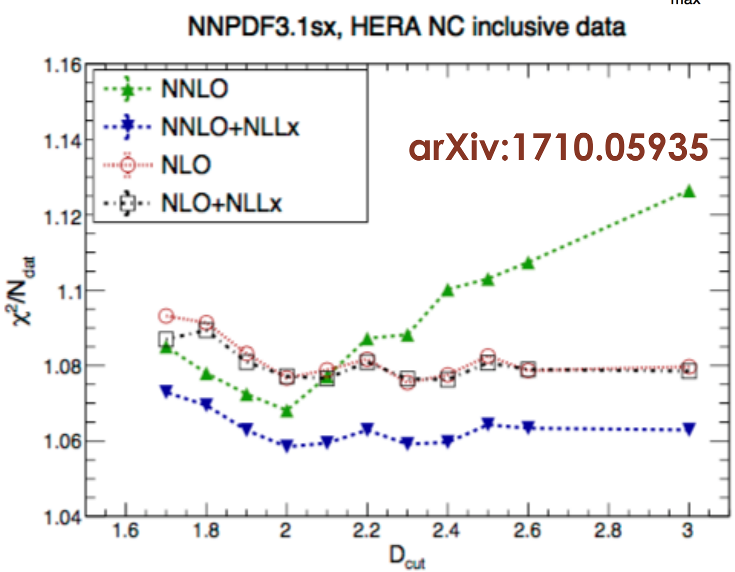


Simultaneous cut on x and Q^2

Simultaneous cut on Q^2 and x implemented: $\ln(1/x) \geq \beta_0 D_{cut} \ln(Q^2/\Lambda^2)$ where $\Lambda \cong 88\ MeV$, $\beta_0 \cong 0.61$







Consistent with what has been found in the NNPDF paper:

- $D_{cut} > 2$ defines the region where resummation is important
- Flat-ish χ^2 distribution for NNLO+NLLx
- Above $D_{cut} = 3$ few data points added even if with huge steps

Region where resummation has a significant effect

——— NNLO+NLLx ———				——— NNLO ———			
After minimisation		1249.20 1064 1.174		After minimisation		1264.22 1064 1.188	
Partial chi2s				Partial chi2s			
395.95(+3.95)	354	HERA1+2 NCep 920		402.82(+7.25)	354	HERA1+2 NCep 920	
51.32(-0.64)	56	HERA1+2 NCep 820		52.23(-0.10)	56	HERA1+2 NCep 820	
179.52(-1.09)	214	HERA1+2 NCep 575		177.53(+1.15)	214	HERA1+2 NCep 575	
179.12(-2.25)	170	HERA1+2 NCep 460		176.67(-0.31)	170	HERA1+2 NCep 460	
222.78(-0.82)	159	HERA1+2 NCem		215.44(+1.04)	159	HERA1+2 NCem	
45.59(+0.57)	39	HERA1+2 CCep		44.30(+0.35)	39	HERA1+2 CCep	
53.88(-2.45)	42	HERA1+2 CCem		54.93(-1.58)	42	HERA1+2 CCem	
44.53(-1.11)	44	Charm cross section		45.39(-1.31)	44	Charm cross	
Correlated Chi2		80.329061352348674		Correlated Chi2		88.418716117383113	
Log penalty Chi2		-3.8395890369565198		Log penalty Chi2		6.4854418695532452	

- The total χ^2's of these fits differ by around 15 units in favour of the resummed fit, mostly due to the correlated and logarithmic terms, to be compared to the 73 units of when the shaded area is instead included.
- This confirms that, the context of DIS, the shaded area in Fig. 11 does provide a reliable estimate of the kinematic region in which resummation works significantly better than fixed order.

Adding the negative gluon term

Do we really need the negative term of gluon? → We produced a version of the **final NNLO+NLLx and NNLO fits without the negative term** just to check this

NNLO+NLLx (standard)

2	'Bg'	-0.074490	0.022636
3	'Cg'	7.039247	0.795647
7	'Aprig'	-0.000320	0.000114
8	'Bprig'	-0.980215	0.017543
9	'Cprig'	25.000000	0.000000
12	'Buv'	0.745665	0.028726
13	'Cuv'	4.959985	0.083442
15	'Euv'	11.636086	1.515132
22	'Bdv'	0.918106	0.089333
23	'Cdv'	4.650377	0.401623
33	'CUbar'	7.607920	1.258096
34	'DUbar'	4.361805	2.421517
41	'ADbar'	0.242674	0.009819
42	'BDbar'	-0.172176	0.004965
43	'CDbar'	8.818216	1.769683

NNLO+NLLx (w/o neg term gluon)

2	'Bg'	-0.138521	0.011161
3	'Cg'	5.593441	0.396115
7	'Aprig'	0.000000	0.000000
8	'Bprig'	0.000000	0.000000
9	'Cprig'	0.000000	0.000000
12	'Buv'	0.754178	0.023272
13	'Cuv'	4.961712	0.082724
15	'Euv'	11.152505	1.351389
22	'Bdv'	0.944546	0.080315
23	'Cdv'	4.778010	0.382632
33	'CUbar'	7.116455	1.610122
34	'DUbar'	2.167268	2.294381
41	'ADbar'	0.263140	0.007530
42	'BDbar'	-0.161943	0.003294
43	'CDbar'	10.132906	1.891836

Similar conclusions can be drawn if considering NNLO-only term

Adding the negative gluon term

Do we really need the negative term of gluon? → We produced a version of the **final NNLO+NLLx and NNLO fits without the negative term** just to check this

NNLO (standard)

2	'Bg'	-0.073354	0.062684
3	'Cg'	6.751494	0.651243
7	'Aprig'	0.068316	0.106861
8	'Bprig'	-0.394262	0.105157
9	'Cprig'	25.000000	0.000000
12	'Buv'	0.807546	0.021963
13	'Cuv'	4.898565	0.086080
15	'Euv'	9.004091	1.152141
22	'Bdv'	1.005596	0.081207
23	'Cdv'	4.943314	0.383313
33	'CUbar'	7.002186	2.155434
34	'DUbar'	0.987550	2.682961
41	'ADbar'	0.286972	0.008839
42	'BDbar'	-0.143059	0.003815
43	'CDbar'	9.599957	1.719759

NNLO(w/o neg term gluon)

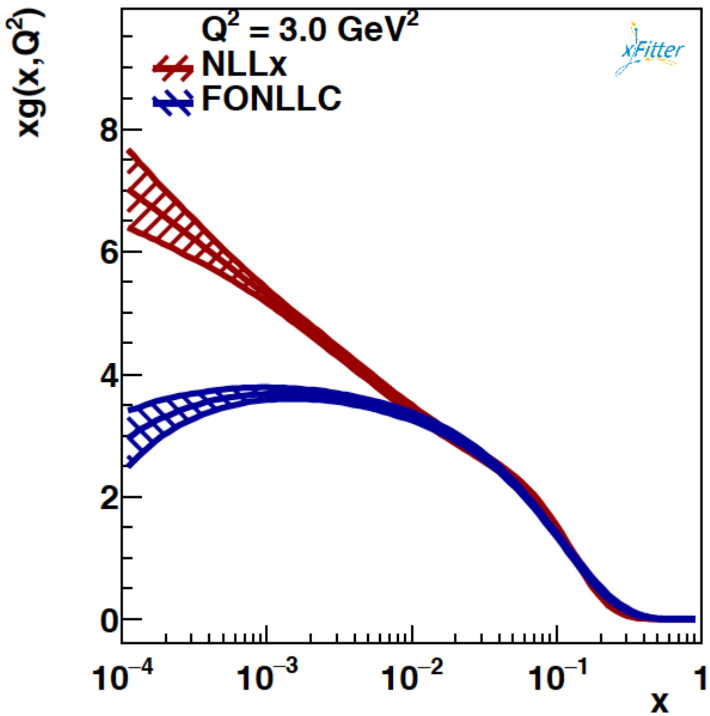
2	'Bg'	-0.004076	0.015425
3	'Cg'	7.440208	0.530265
7	'Aprig'	0.000000	0.000000
8	'Bprig'	0.000000	0.000000
9	'Cprig'	0.000000	0.000000
12	'Buv'	0.813866	0.021348
13	'Cuv'	4.894378	0.086861
15	'Euv'	8.660517	1.098470
22	'Bdv'	1.010196	0.082739
23	'Cdv'	4.970787	0.386256
33	'CUbar'	7.119678	2.129298
34	'DUbar'	1.086109	2.659349
41	'ADbar'	0.284090	0.008164
42	'BDbar'	-0.146533	0.003362
43	'CDbar'	9.315854	1.648179

Here, the output parameters for the the NNLO-only fits

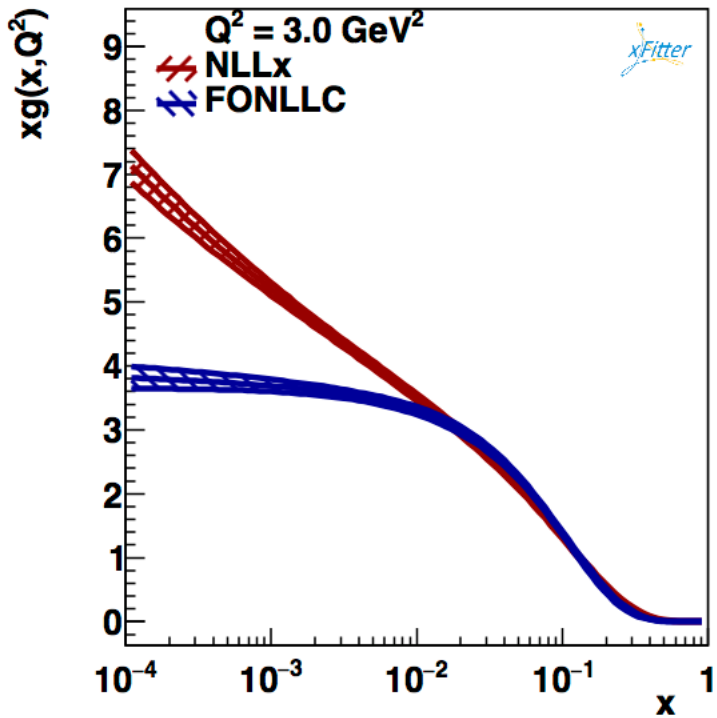
Adding the negative gluon term

Do we really need the negative term of gluon? → We produced a version of the **final NNLO+NLLx and NNLO fits without the negative term** just to check this

NNLO+NLLx (standard)



NNLO+NLLx (w/o neg term gluon)

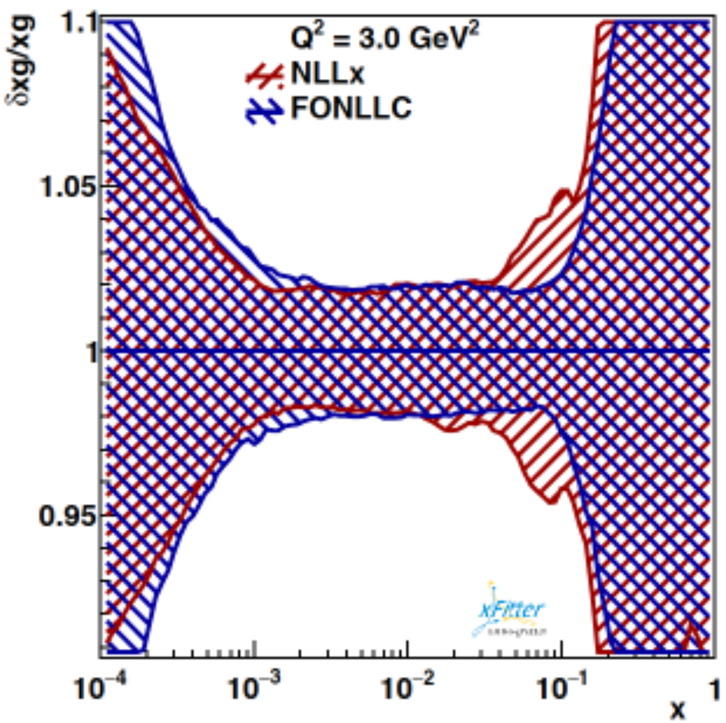


The point is that even without the negative term the gluon for NLLO likes to take a flattish shape at low-x, whereas for NNLO+NLLx it takes a singular shape

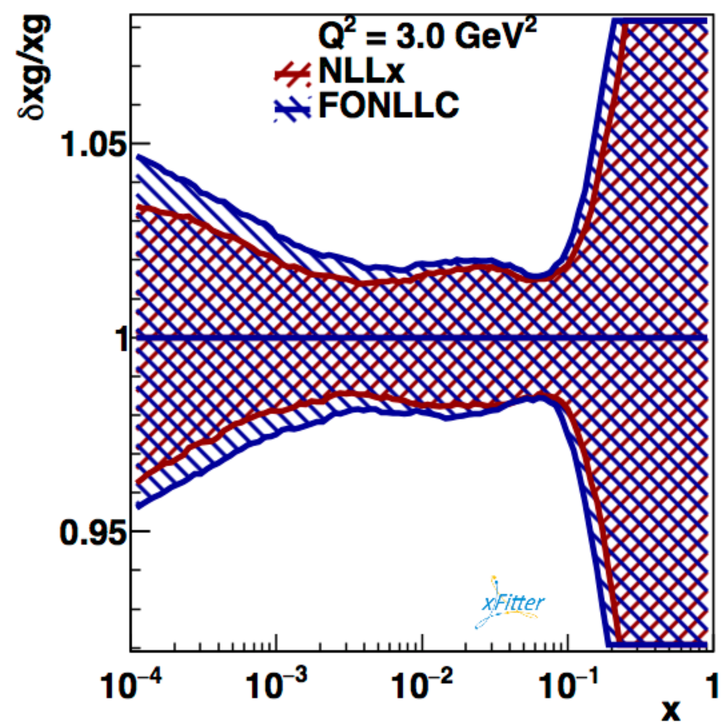
Adding the negative gluon term

Do we really need the negative term of gluon? → We produced a version of the **final NNLO+NLLx and NNLO fits without the negative term** just to check this

NNLO+NLLx (standard)



NNLO+NLLx (w/o neg term gluon)



the uncertainty on the gluon PDF is lower in the low-x region for the fits without the negative term of the gluon added → probably because the gluon description is now so simple.