MMHT PDFs: updates and outlook

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Precise theory for precise measurements at LHC and future colliders, Quy Nhon, Vietnam, 26 Sep 2016

In collaboration with Alan Martin and Robert Thorne

and thanks to Patrick Motylinski, Ben Watt, Graeme Watt and James Stirling

Outline

- Fit to final HERA combined data set, consequences for MMHT and variation of fit quality with $Q^2_{\rm min}$.

- Impact of new post-MMHT14 LHC and Tevatron data on the PDFs $\longrightarrow$ clear improvements for some PDFs.

- Very briefly : MMHT + QED corrections - the photon PDF.

Fit to HERA combined data

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The impact of the final HERA combined data on PDFs obtained from a global fit

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Abstract

We investigate the effect of including the HERA run I + II combined cross section data on the MMHT2014 PDFs. We present the fit quality within the context of the global fit and when only the HERA data are included. We examine the changes in both the central values and uncertainties in the PDFs. We find that the prediction for the data is good, and only relatively small improvements in χ^2 and changes in the PDFs are obtained with a refit at both NLO and NNLO. PDF uncertainties are slightly reduced. There is a small dependence of the fit quality on the value of $Q^2_{\rm min}$. This can be improved by phenomenologically motived corrections to $F_L(x,Q^2)$ which parametrically are largely in the form of higher–twist type contributions.

1 Introduction

The MSTW2008 PDFs [1] have been widely used in the analyses of hadron collider data. They were recently updated with an analysis performed in the same general framework, resulting in

HERA II combined data

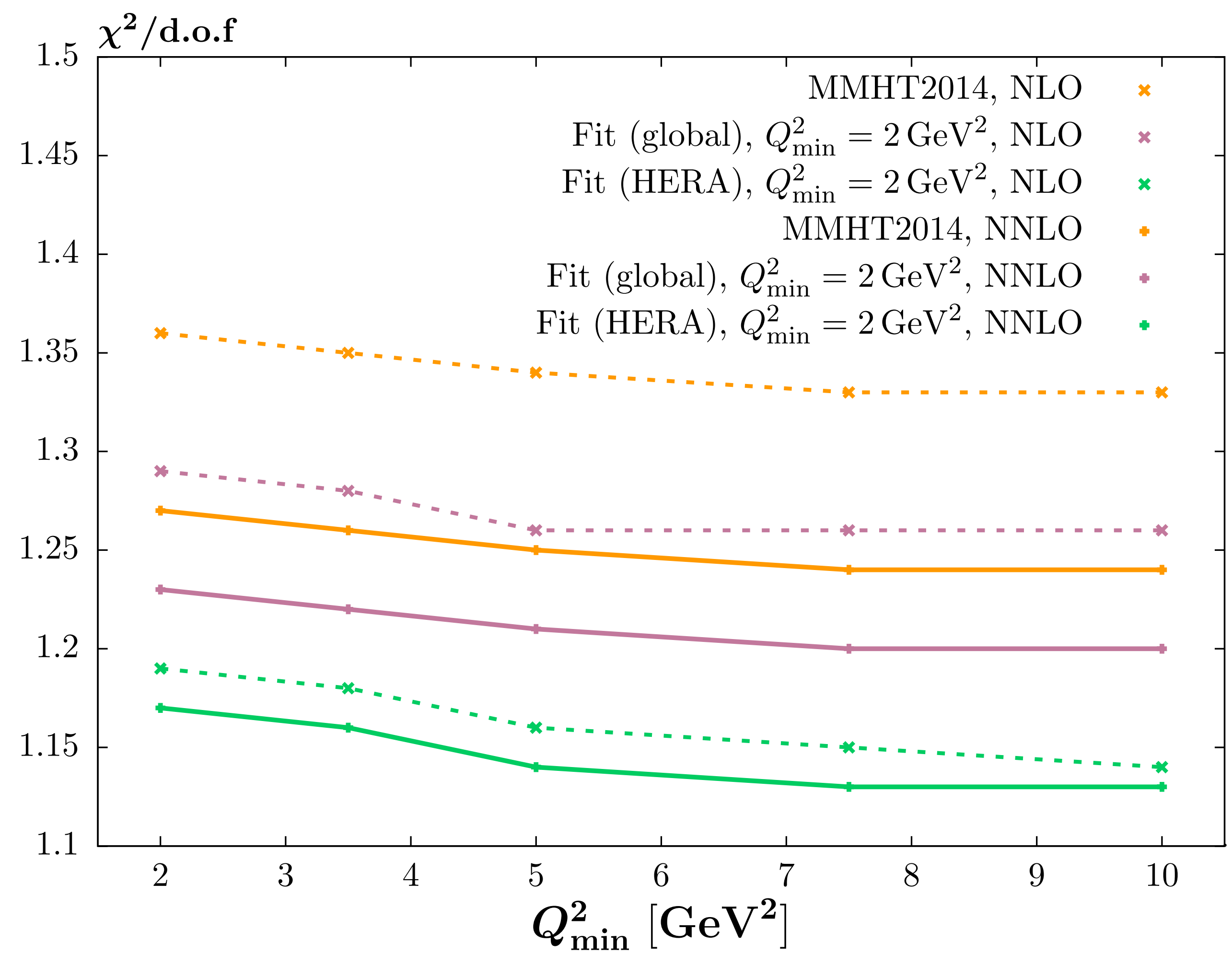
- Using $Q^2_{\rm min} = 2\,{\rm GeV}^2$ there are 1185 data points with 162 correlated systematics. 7 procedural uncertainties and luminosity uncertainty. Separated into 7 subsets, depending on whether e^+or e^-, neutral or charged current and on E_p .

  - Fit quality at NNLO:

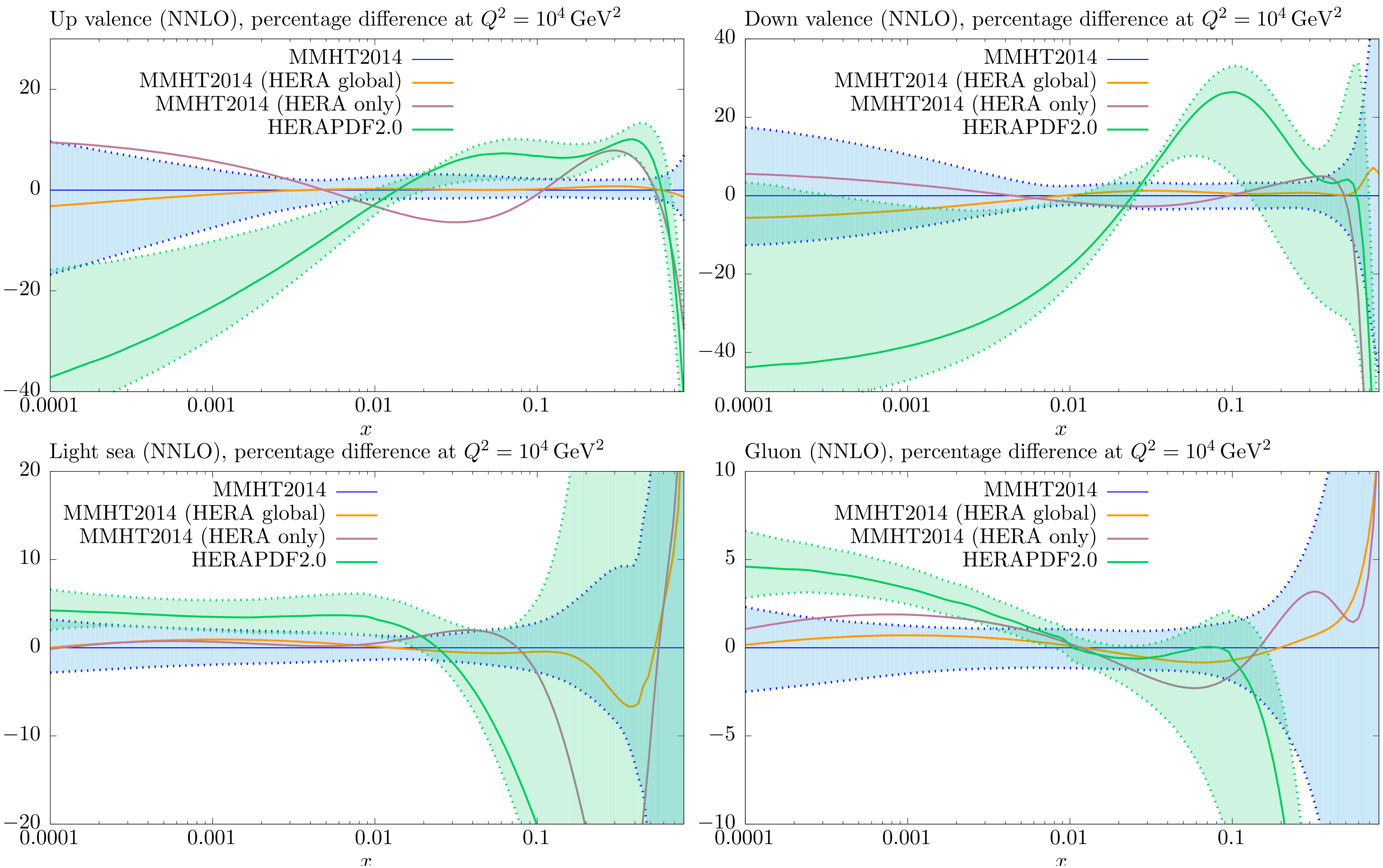
    $Q^2 > 2.5 \sim 1435/1168$

    $Q^2 > 5 \sim 1310/1092$

    $Q^2 > 10 \sim 1200/1007$



- Find NNLO clearly superior, but less pronounced in fit to HERA only.



- HERA-II modified PDFs well within MMHT2014 uncertainties. PDFs from HERA-II only fits in some ways similar to HERAPDF2.0.
- When fitted $\alpha_s(M_Z^2) = 0.1172 - 3$, i.e. very similar to MMHT14.

	MMHT14	MMHT14 (HERA global)
W Tevatron (1.96 TeV)	$2.782^{+0.056}_{-0.056}$ $\binom{+2.0\%}{-2.0\%}$	$2.789^{+0.050}_{-0.050}$ $\binom{+1.8\%}{-1.8\%}$
Z Tevatron (1.96 TeV)	$0.2559^{+0.0052}_{-0.0046}$ $\binom{+2.0\%}{-1.8\%}$	$0.2563^{+0.0047}_{-0.0047}$ $\binom{+1.8\%}{-1.8\%}$
W^+ LHC (7 TeV)	$6.197^{+0.103}_{-0.092}$ $\binom{+1.7\%}{-1.5\%}$	$6.221^{+0.100}_{-0.096}$ $\binom{+1.6\%}{-1.5\%}$
W^- LHC (7 TeV)	$4.306^{+0.067}_{-0.076}$ $\binom{+1.6\%}{-1.8\%}$	$4.320^{+0.064}_{-0.070}$ $\binom{+1.5\%}{-1.6\%}$
Z LHC (7 TeV)	$0.964^{+0.014}_{-0.013}$ $\binom{+1.5\%}{-1.3\%}$	$0.966^{+0.015}_{-0.013}$ $\binom{+1.6\%}{-1.3\%}$
W^+ LHC (14 TeV)	$12.48^{+0.22}_{-0.18}$ $\binom{+1.8\%}{-1.4\%}$	$12.52^{+0.22}_{-0.18}$ $\binom{+1.8\%}{-1.4\%}$
W^- LHC (14 TeV)	$9.32^{+0.15}_{-0.14}$ $\binom{+1.6\%}{-1.5\%}$	$9.36^{+0.14}_{-0.13}$ $\binom{+1.5\%}{-1.4\%}$
Z LHC (14 TeV)	$2.065^{+0.035}_{-0.030}$ $\binom{+1.7\%}{-1.5\%}$	$2.073^{+0.036}_{-0.026}$ $\binom{+1.7\%}{-1.3\%}$
Higgs Tevatron	$0.874^{+0.024}_{-0.030}$ $\binom{+2.7\%}{-3.4\%}$	$0.866^{+0.019}_{-0.023}$ $\binom{+2.2\%}{-2.7\%}$
Higgs LHC (7 TeV)	$14.56^{+0.21}_{-0.29}$ $\binom{+1.4\%}{-2.0\%}$	$14.52^{+0.19}_{-0.24}$ $\binom{+1.3\%}{-1.7\%}$
Higgs LHC (14 TeV)	$47.69^{+0.63}_{-0.88}$ $\binom{+1.3\%}{-1.8\%}$	$47.75^{+0.59}_{-0.72}$ $\binom{+1.2\%}{-1.5\%}$
$t\bar{t}$ Tevatron	$7.51^{+0.21}_{-0.20}$ $\binom{+2.8\%}{-2.7\%}$	$7.57^{+0.18}_{-0.18}$ $\binom{+2.4\%}{-2.4\%}$
$t\bar{t}$ LHC (7 TeV)	$175.9^{+3.9}_{-5.5}$ $\binom{+2.2\%}{-3.1\%}$	$174.8^{+3.3}_{-5.3}$ $\binom{+1.9\%}{-3.0\%}$
$t\bar{t}$ LHC (14 TeV)	970^{+16}_{-20} $\binom{+1.6\%}{-2.1\%}$	964^{+13}_{-19} $\binom{+1.3\%}{-2.0\%}$

Table 2: The values of various cross sections (in nb) obtained with the NNLO MMHT 2014 sets, with and without the final HERA combination data set included. PDF uncertainties only are shown.

- At most 10% change in uncertainties. Very little change in central values.

Low Q^2 study (1)

- See improvement in χ^2 with $Q^2_{\rm min}\uparrow$. Higher twist/low x effect?
- General tendency to overshoot some of the highest y points at low and x and Q^2. Recall:

$$\tilde{\sigma}(x,Q^2)=F_2(x,Q^2)-\frac{y^2}{1+(1-y^2)}F_L(x,Q^2)$$

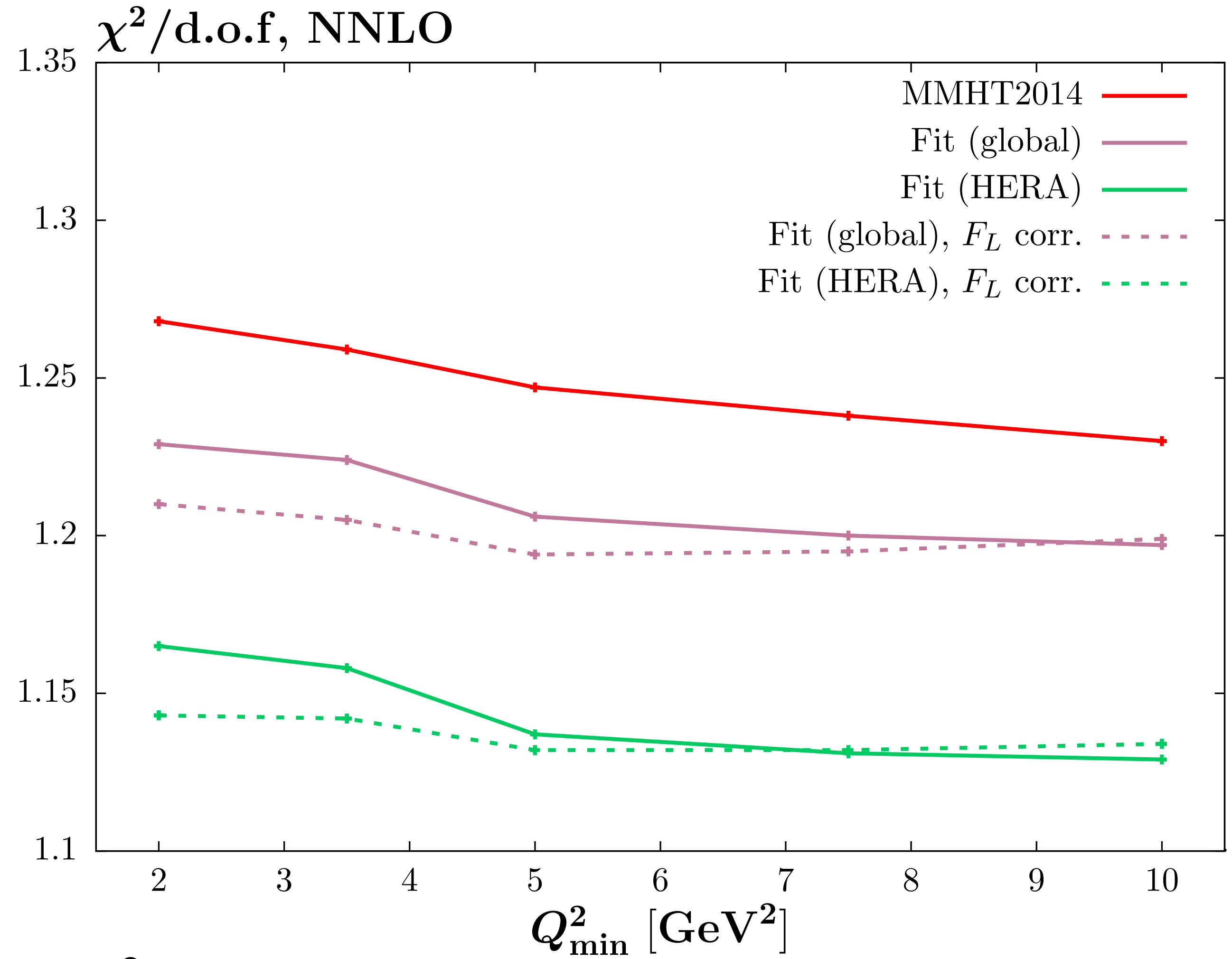
$\longrightarrow$ Try modification:

$$F_L \to F_L\left(1+\frac{a}{Q^2}\right)$$

with a free in fit.

$a_{\rm fit}=4.3\,{\rm GeV}^2$

- Find almost almost entire fall in χ^2 with $Q^2_{\rm min}\uparrow$ gone.
- Small effect on PDFs.



Low Q^2 study (2)

- If we try instead:

$$F_2(x,Q^2) \to F_2(x,Q^2)\left(1+\frac{a_i}{Q^2}\right), \qquad x < 0.01$$

find little effect on comparison. More complicated modifications (e.g. extra $1/Q^4$ term in F_L) give marginal improvements.

- Might take as clear evidence for higher twist. Caveat: for (fixed) higher $y = Q^2/sx$ correlation between x and Q^2. If we try instead

$$F_L^{(1)}(x,Q^2) = F_L(x,Q^2)\left(1+\frac{\alpha_S(Q^2)}{4\pi}\frac{b_1}{x^{b_2}}\right)$$

again find fall in χ^2 with $Q^2_{\min}\uparrow$ is gone (fitted powers of b_1, b_2 effectively mimic $1/Q^2$).

New collider data in fit

New data sets

- In addition to combined HERA data, we have included:
  - Latest total $t\bar{t}$ cross sections (Tevatron, ATLAS/CMS)
  - LHCb $W + Z$ 7 TeV (1505.07024)
  - LHCb $W + Z$ 8 TeV (1511.08039)
  - LHCb $Z \to e^+e^-$ 8 TeV (1503.00963)
  - CMS W^+/W^- 8 TeV (1603.01803)
  - CMS $W + c$ 7 TeV (1310.1138)
  - D0 $W \to e\nu$ asymmetry (1412.2862)
- Have also included ATLAS 7 TeV jet data (1410.8857), but some issues- see later.
- Fit to CMS double differential Drell-Yan 8 TeV (1412.1115) so far poor - in communication with CMS.

New data sets - fit quality

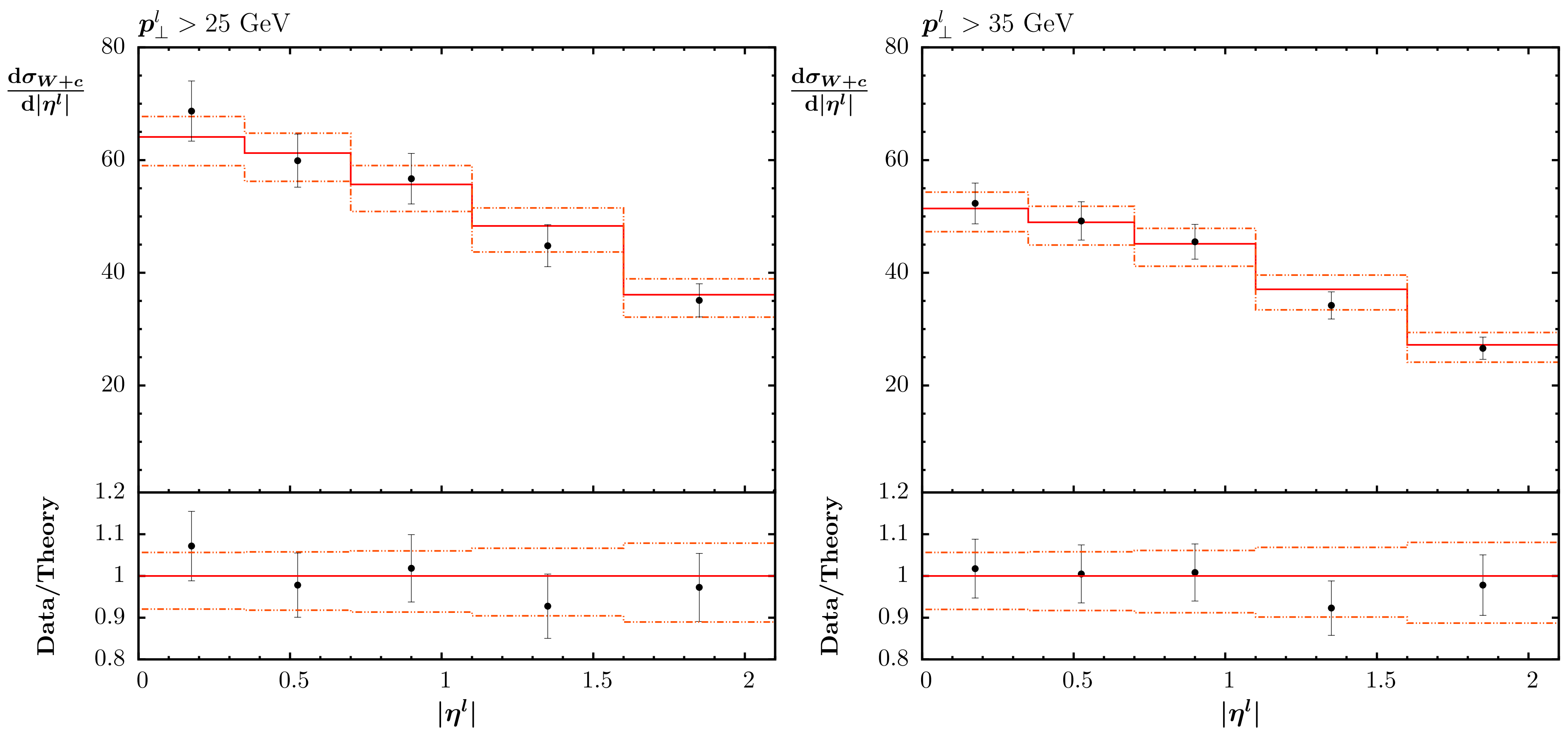
	no. points	NLO χ^2_{pred}	NLO χ^2_{new}	NNLO χ^2_{pred}	NNLO χ^2_{new}
$\sigma_{t\bar{t}}$ Tevatron +CMS+ATLAS	18	19.6	20.5	14.7	15.5
LHCb 7 TeV $W+Z$	33	50.1	45.4	37.1	36.7
LHCb 8 TeV $W+Z$	34	77.0	58.9	76.1	67.2
LHCb 8TeV e	17	37.4	33.4	30.0	27.8
CMS 8 TeV W	22	32.6	18.6	57.6	29.4
CMS 7 TeV $W+c$	10	8.5	10.0	8.7	8.0
D0 e asymmetry	13	22.2	21.5	27.3	22.9
total	3738/3405	4375.9	4336.1	3768.0	3739.3

- Predictions generally good, no significant tension with other data when refitting, i.e. changes in PDFs relatively small.
- Some issue for LHCb $W+Z$ 8 TeV (see later).
- At NLO(NNLO) find $\Delta\chi^2 = 9(15)$ for rest of data.
- Allowing couplings free, $\alpha_S(M_Z^2)$ very close to 0.120 at NLO but now marginally above 0.118 at NNLO - higher than MMHT14 (= 0.1172).

New data - $W + c$

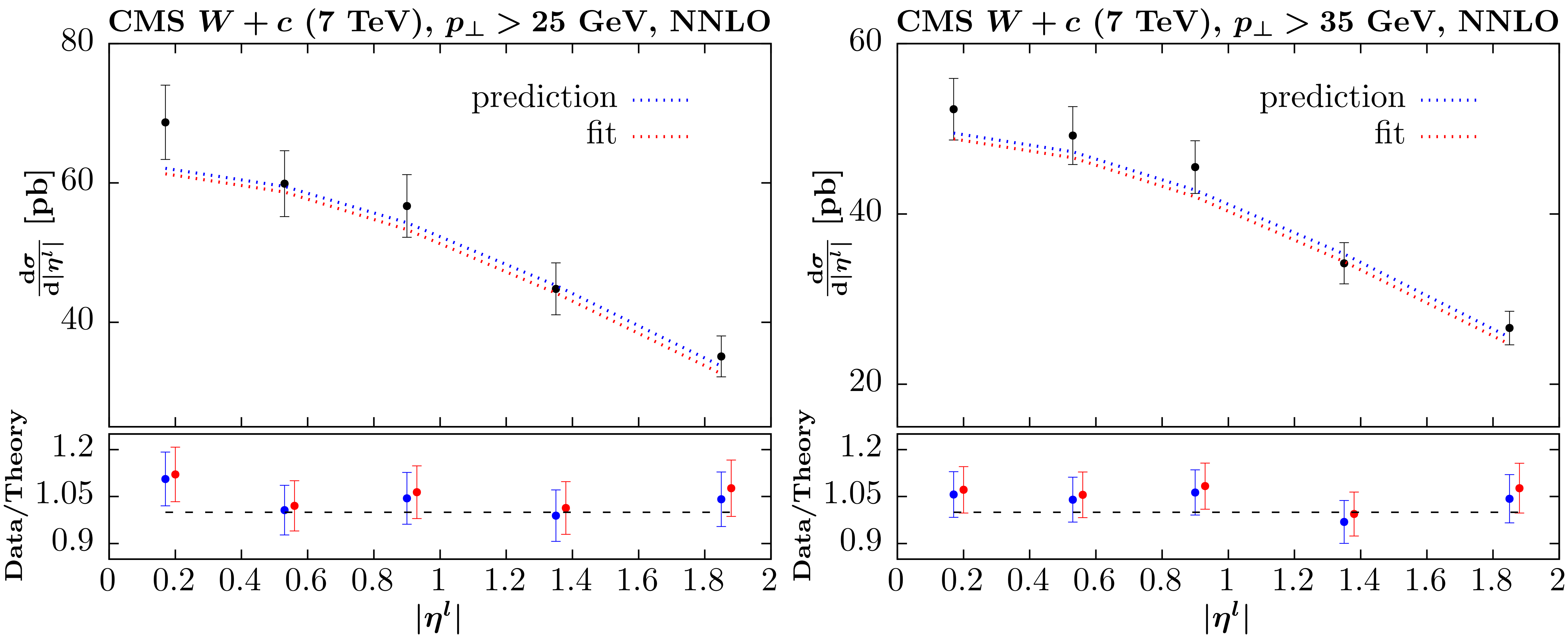
- Previously - compared only to this :

	GeV	data	MSTW2008	MMHT2014
$\sigma(W+c)$	$p_T^{\rm lep} > 25$	$107.7 \pm 3.3(\rm stat.) \pm 6.9(\rm sys.)$	102.8 ± 1.7	110.2 ± 8.1
$\sigma(W+c)$	$p_T^{\rm lep} > 35$	$84.1 \pm 2.0(\rm stat.) \pm 4.9(\rm sys.)$	80.4 ± 1.4	86.5 ± 6.5
$R_c^{\pm}$	$p_T^{\rm lep} > 25$	$0.954 \pm 0.025(\rm stat.) \pm 0.004(\rm sys.)$	0.937 ± 0.029	0.924 ± 0.026
$R_c^{\pm}$	$p_T^{\rm lep} > 35$	$0.938 \pm 0.019(\rm stat.) \pm 0.006(\rm sys.)$	0.932 ± 0.030	0.904 ± 0.027



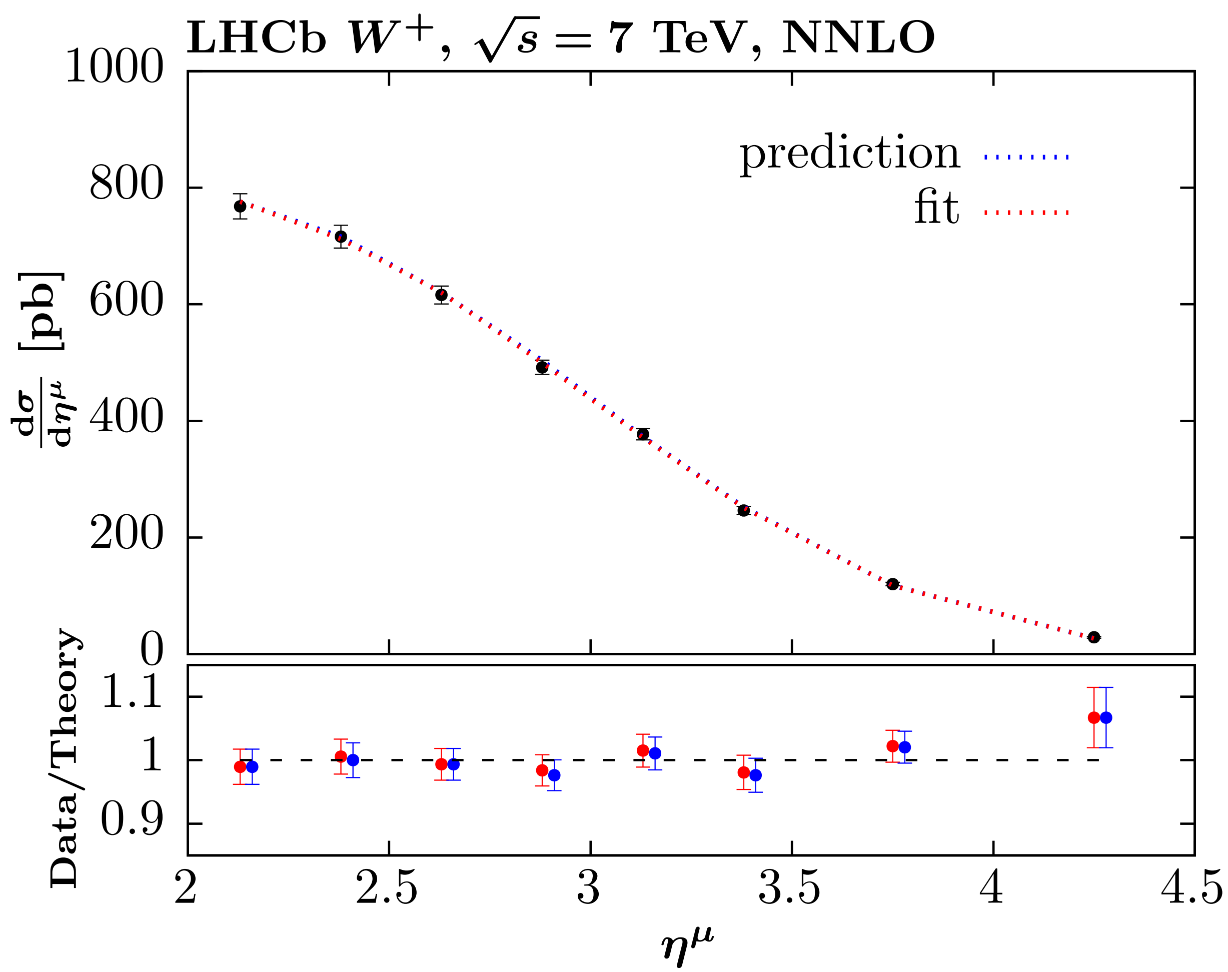
- MSTW08 a bit low (esp. for ATLAS), but MMHT14 seems fine for CMS (shown).

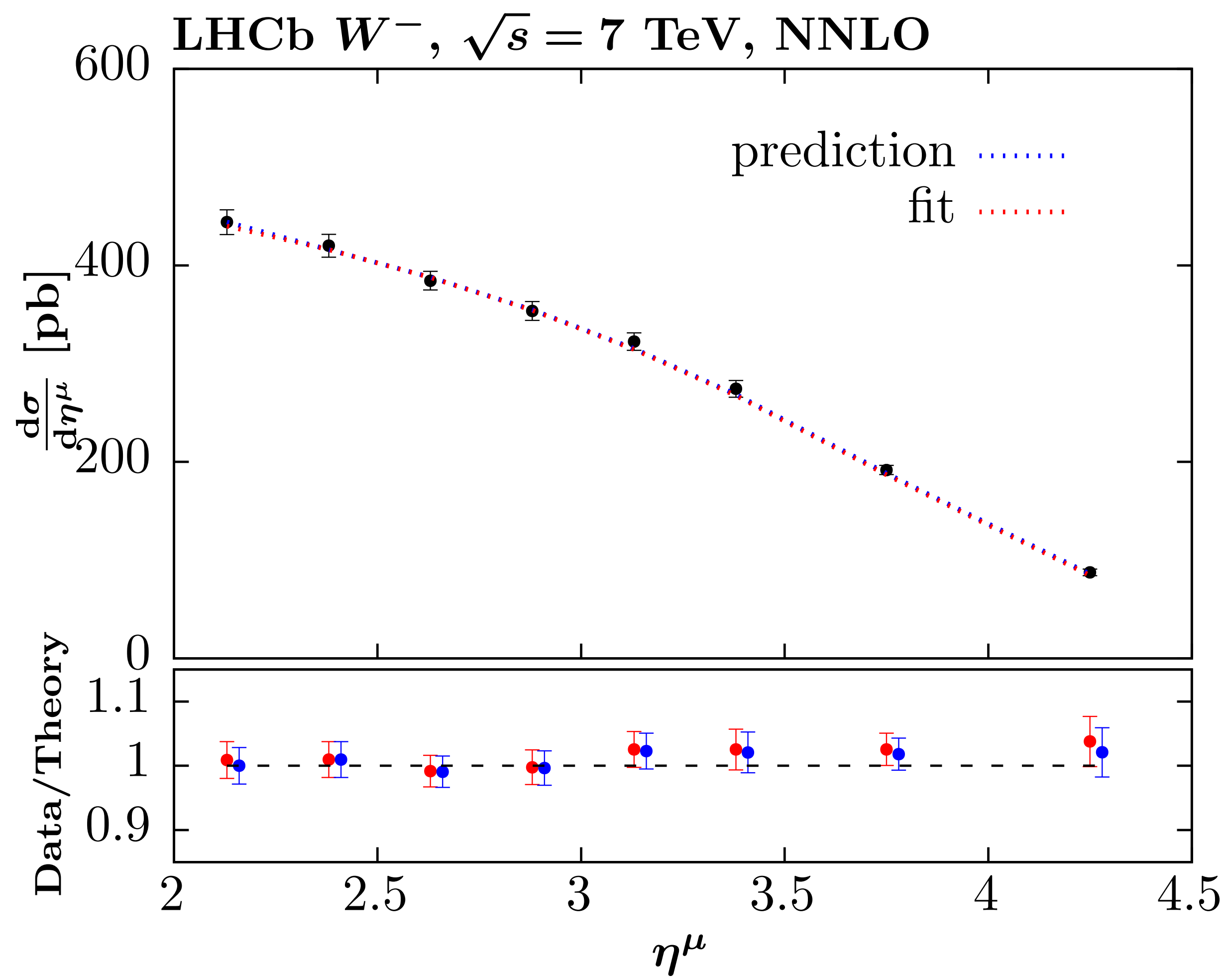
New data - $W + c$



- Data on plot - uncertainties added in quadrature.
- Very little change after fit. By eye looks worse but covariance matrix used for systematics $\longrightarrow$ cannot display on plot. In fact description slightly better after fit.

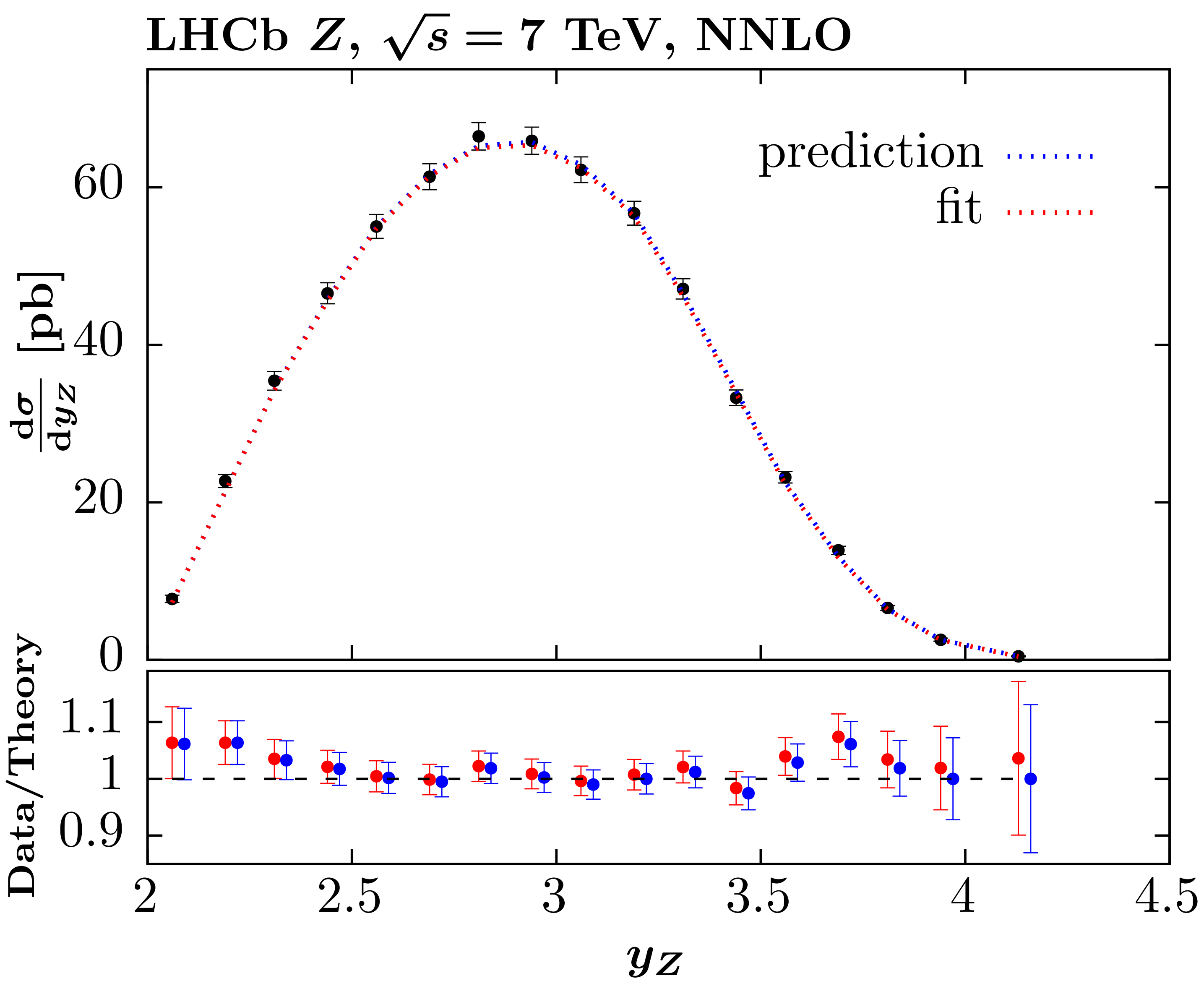
LHCb forward W at 7 TeV





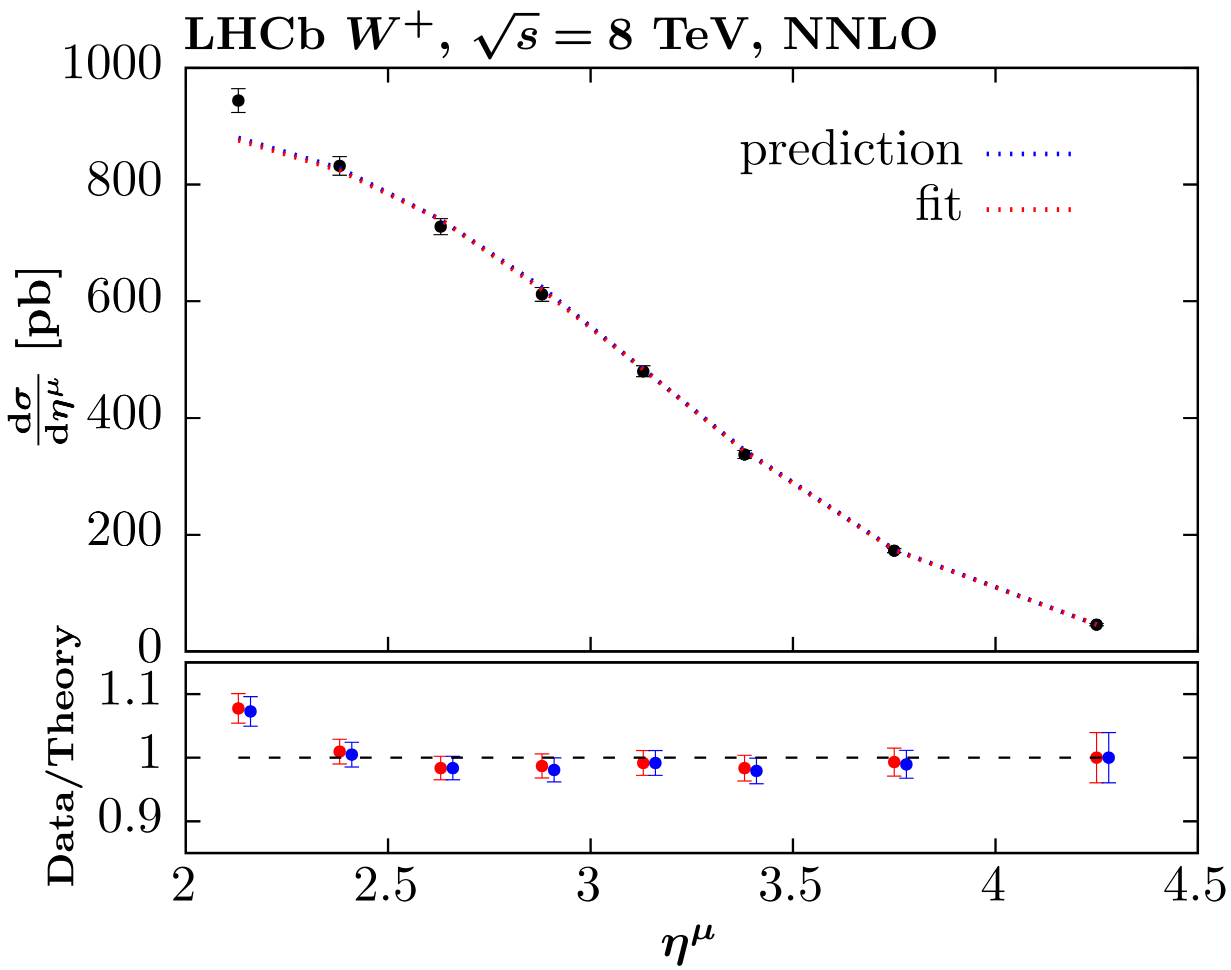
- Generally good agreement using NNLO. Uncertainties in quadrature on plot, but covariance matrix used in fit.

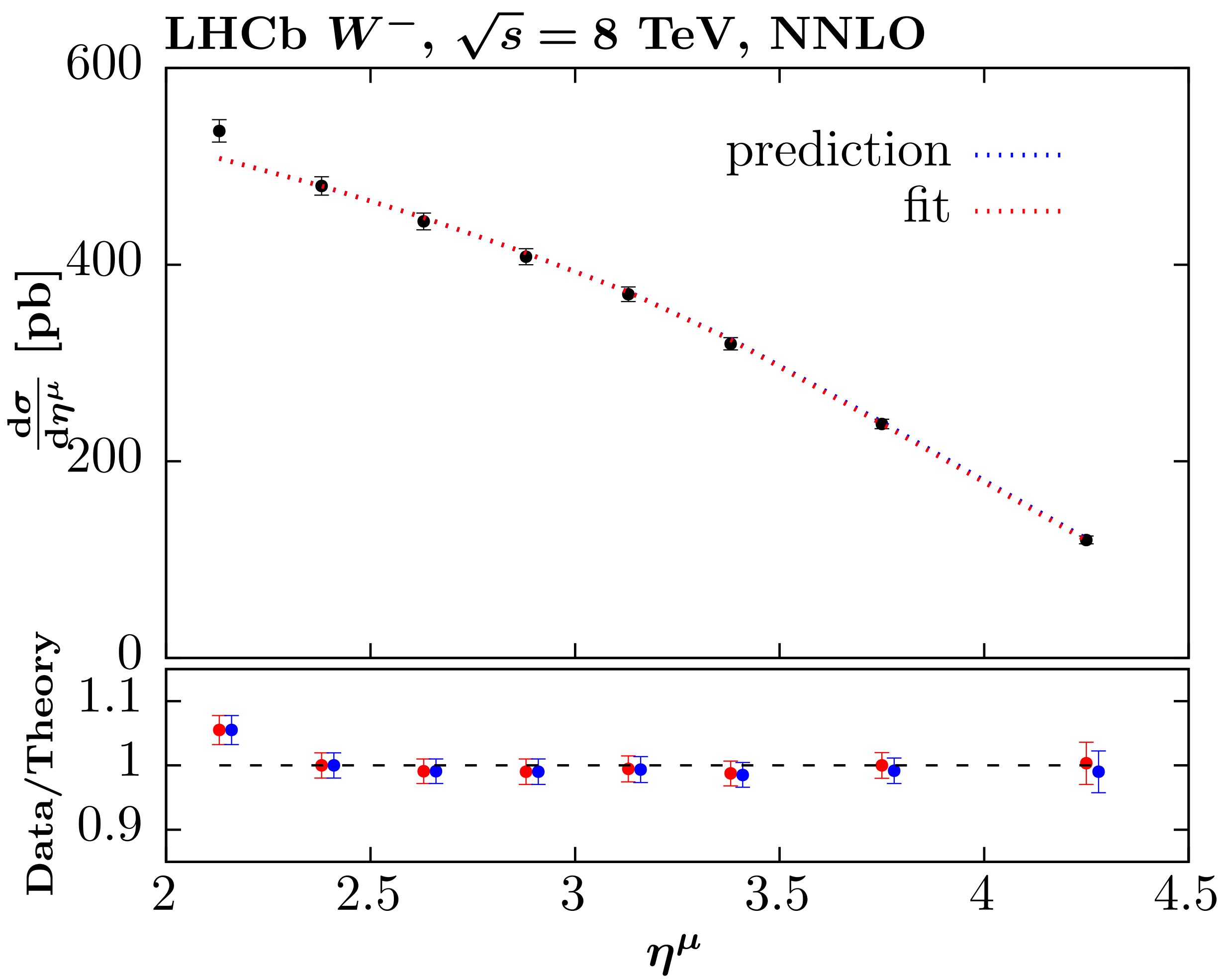
LHCb forward Z at 7 TeV



- Generally good agreement using NNLO. A little low at low y_Z .

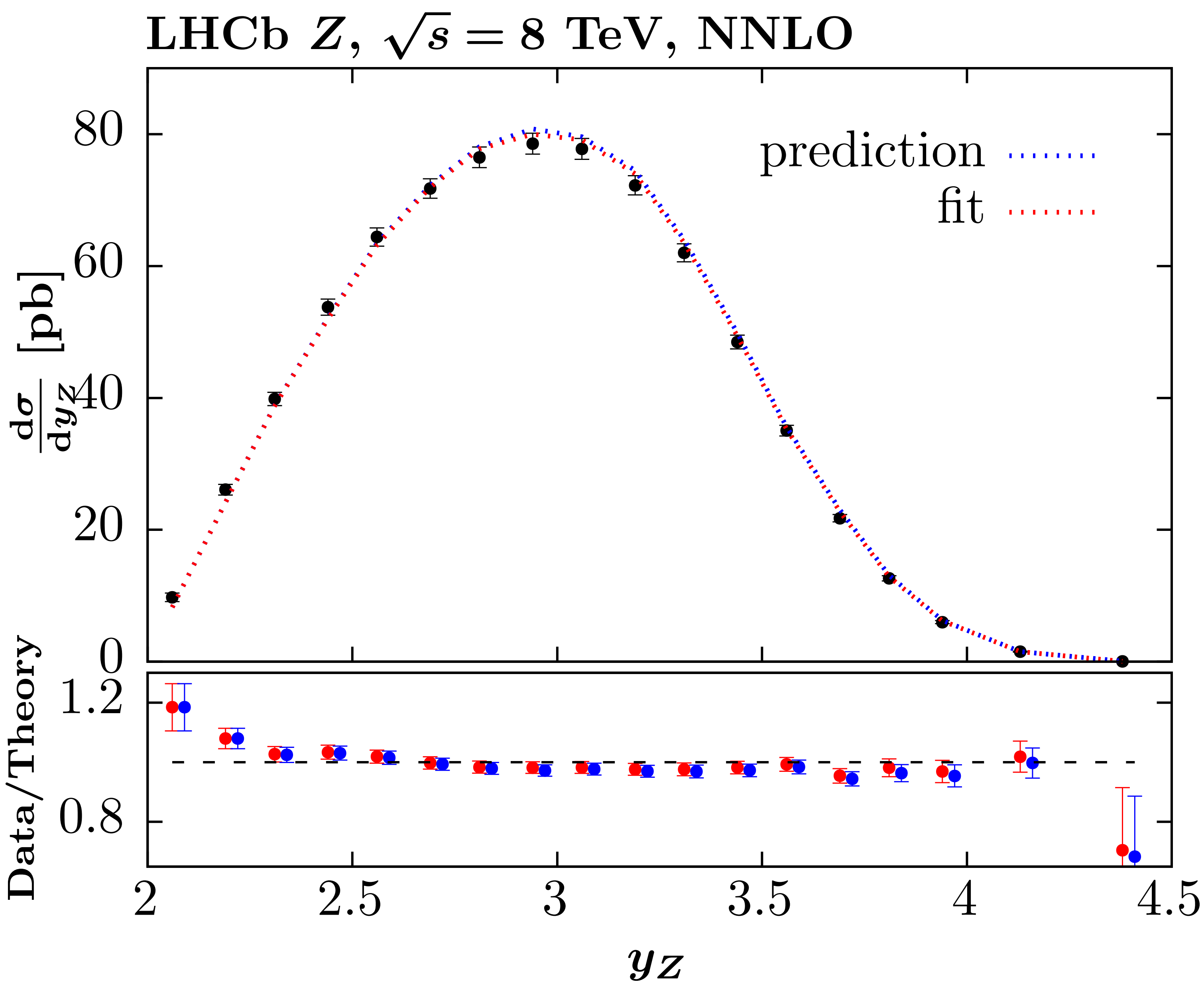
LHCb forward W at 8 TeV





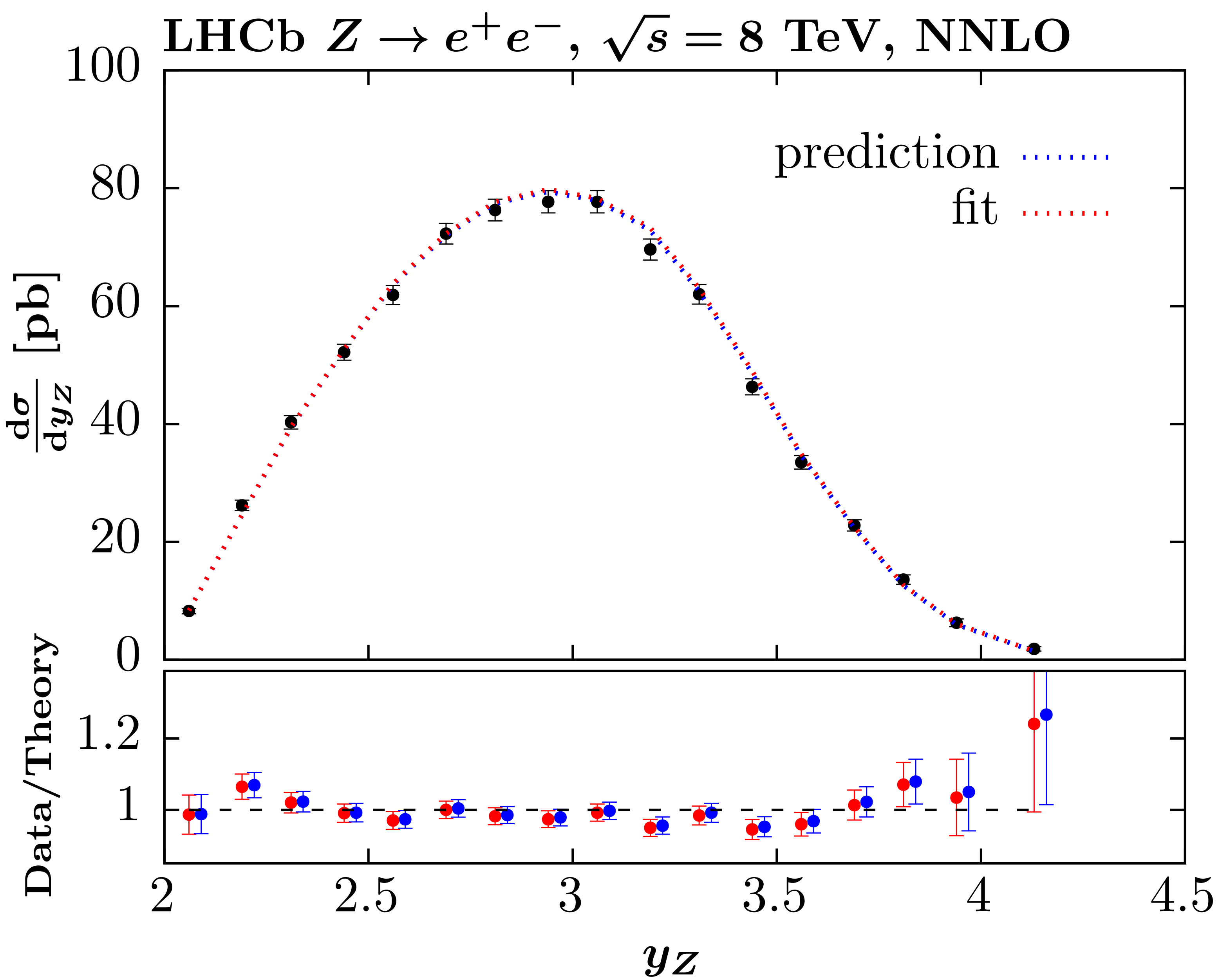
- Generally good fit but lowest η^μ bin in both cases below data $\longrightarrow$ overall relatively poor.

LHCb forward $Z(\to \mu^+\mu^-)$ at 8 TeV



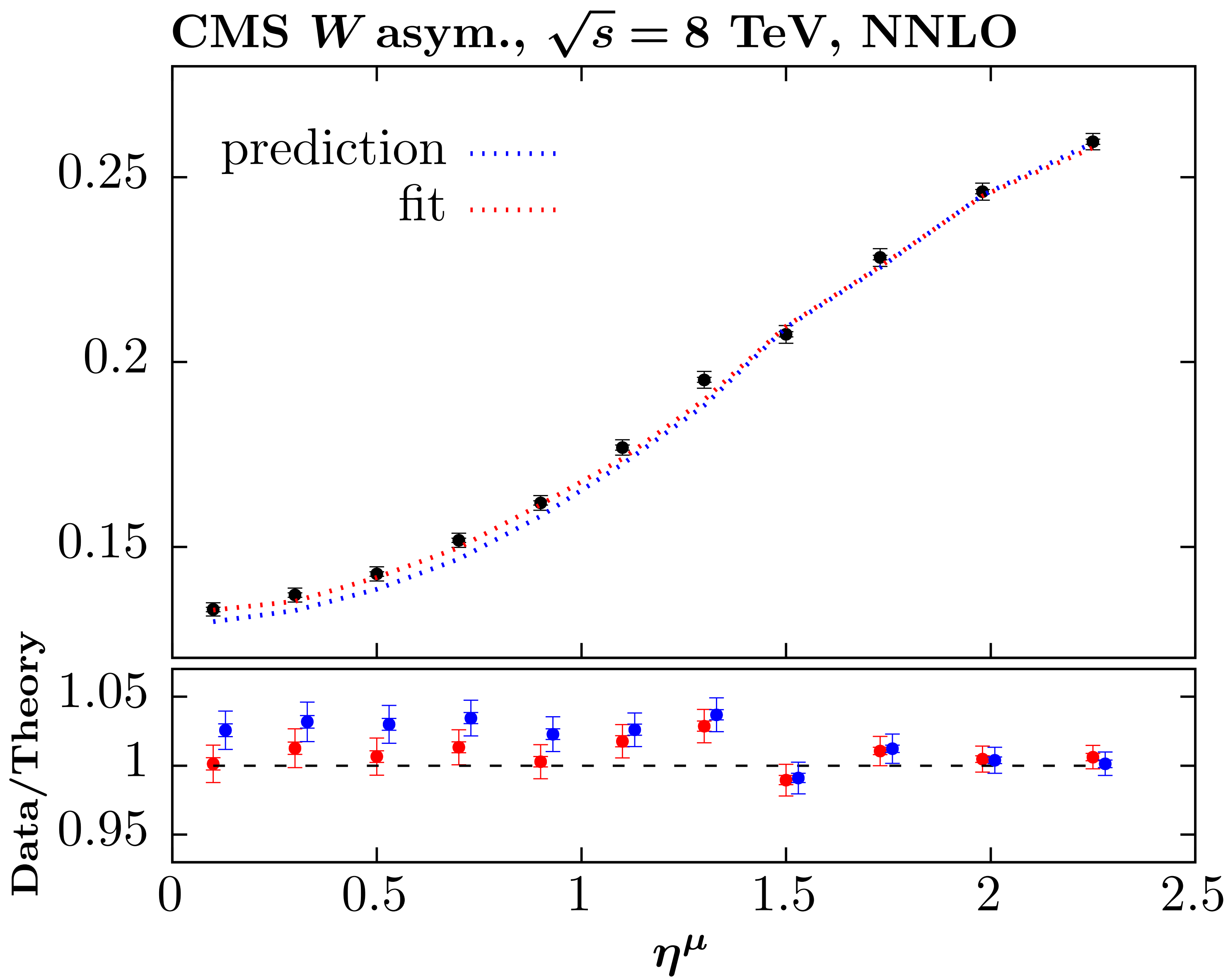
- Again generally good fit but lowest bin below data. PDFs at moderate x for this point $\Rightarrow$ well constrained by DIS data.

LHCb forward $Z(\rightarrow e^+e^-)$ at 8 TeV



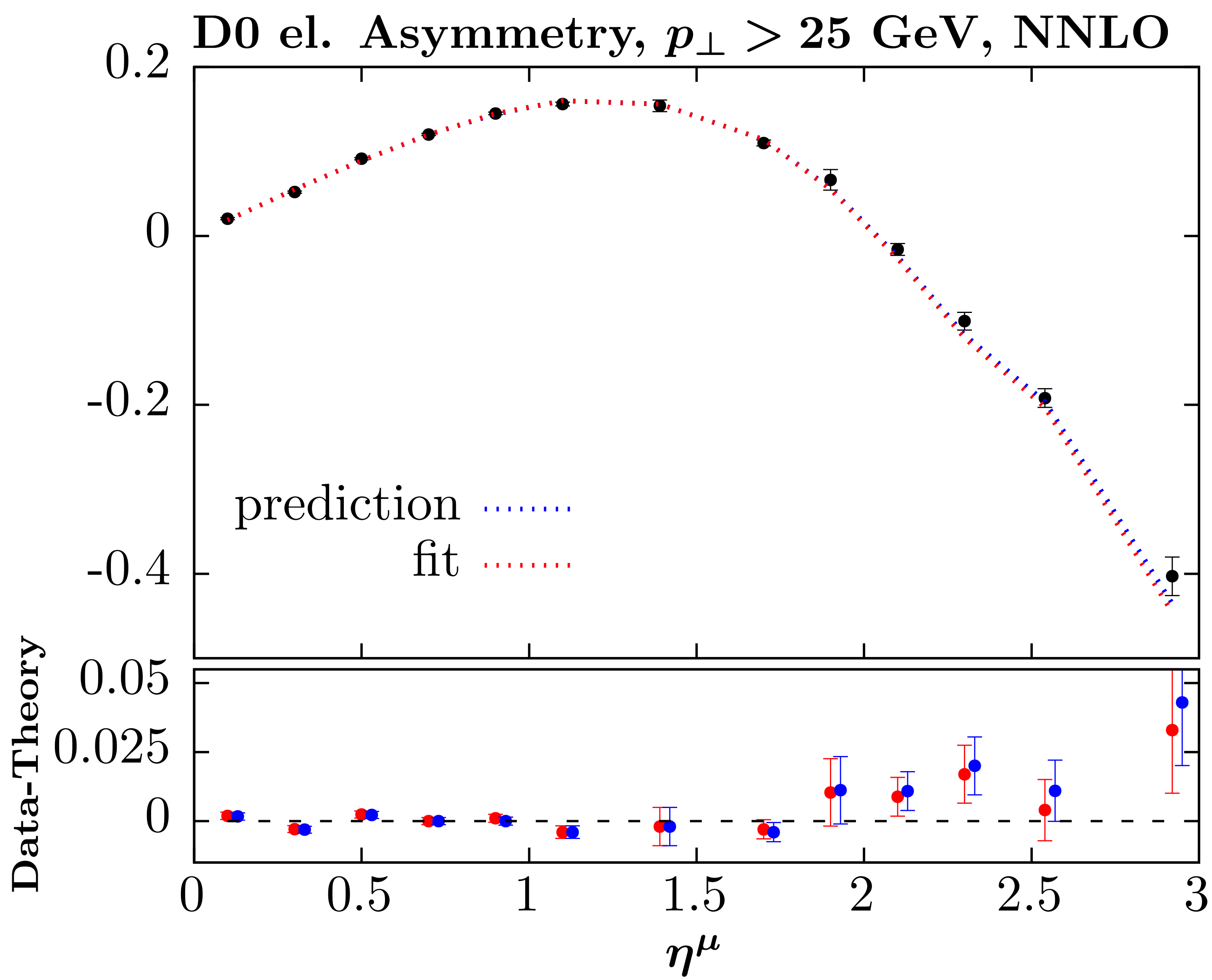
• Issue seen in $\mu^+\mu^-$ data not evident here. Relatively large χ^2 due to fluctuations.

CMS W^+/W^- at 8 TeV



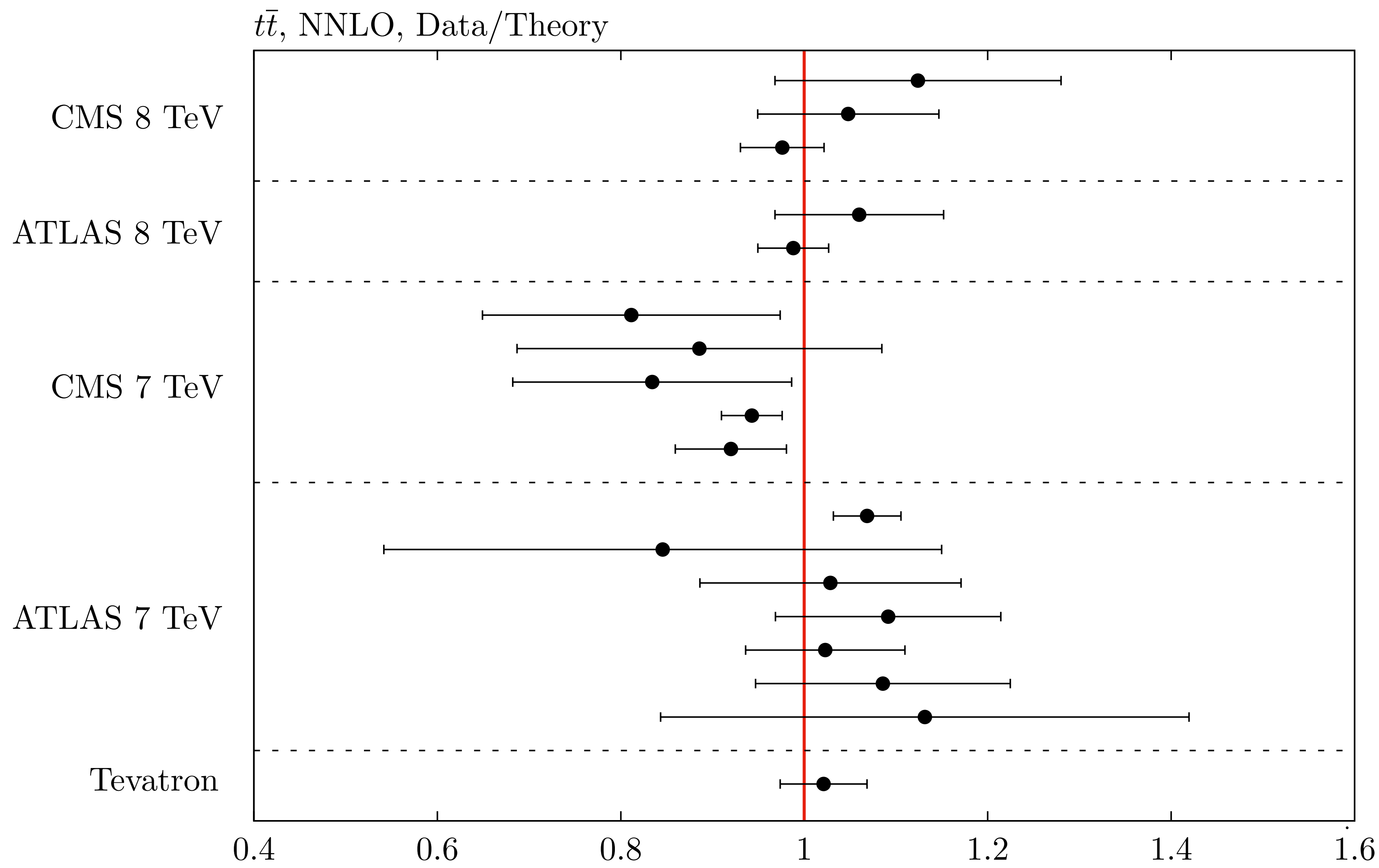
- Fit to distributions not asymmetry.
- Shift after fitting clear: small x valence quarks require some modification of $\sim$ the uncertainty. Scope for reduced PDF errors from fit.

D0 e asymmetry data



- Slight undershoot at highest η^μ $\Rightarrow$ slightly smaller down quark. But other data do no prefer this.

Updated $t\bar{t}$ data



- Fit very good, with larger $\sigma_{t\bar{t}}$ then before.
- Find $m_t \downarrow$ and $\alpha_S \uparrow$: with $\alpha_S(M_Z^2) = 0.118$ find $m_t = 170.2(173.4)$ GeV at NLO(NNLO). Previous MMHT14 values $m_t = 171.7(174.2)$ GeV .
- Helps drive increase in α_S.

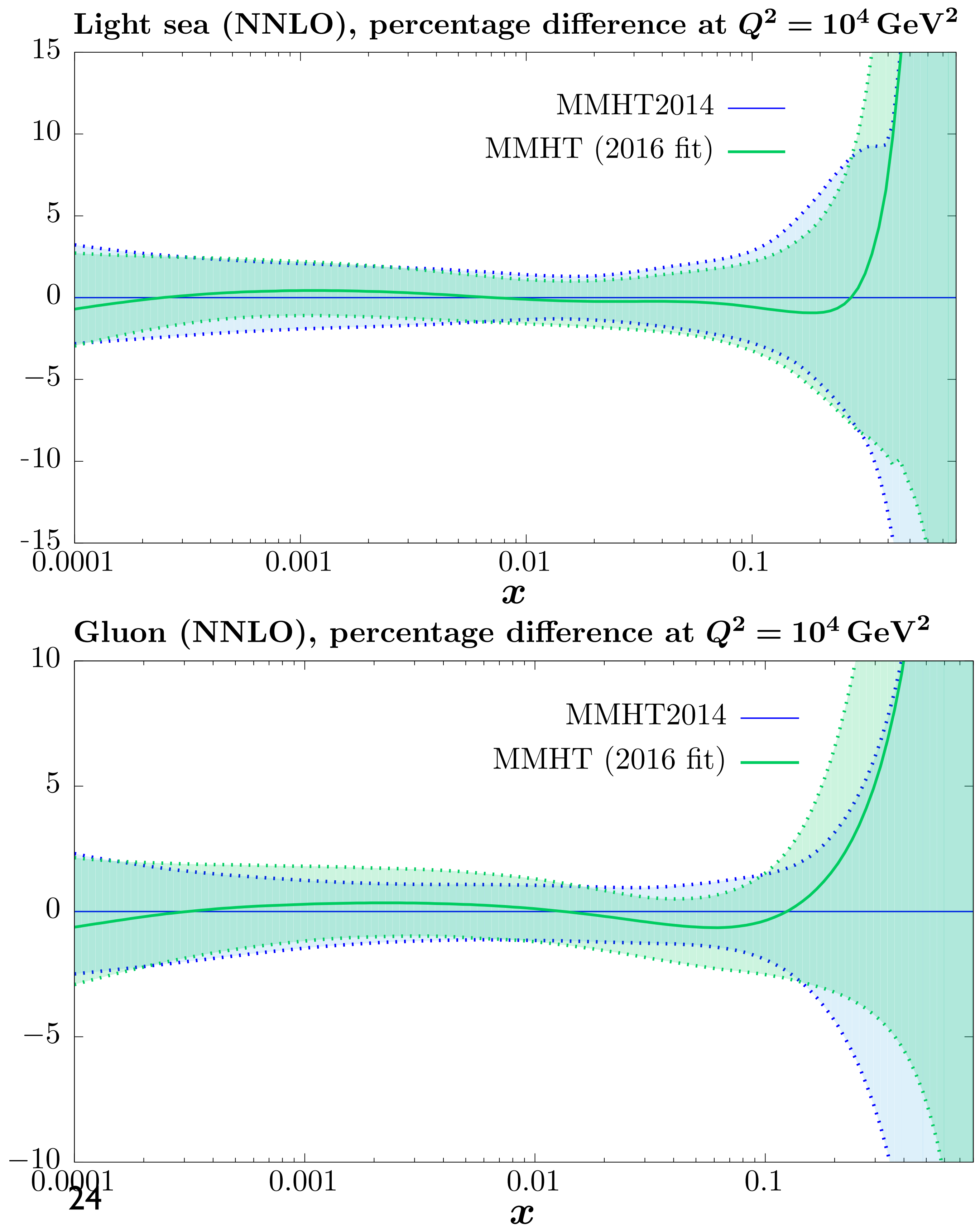
PDF update

- Generate preliminary (not for distribution) PDF sets at NLO and NNLO - labelled MMHT (2016 fit).
- In addition have generated PDF eigenvector sets for uncertainties at NNLO.
- Use same basis as in MMHT14 (subject to change in future): 25 free PDF parameters, hence 50 eigenvector directions.

$\longrightarrow$ Find new data has quite significant effect. 9 directions now constrained by new LHC data - in particular the 8 TeV CMS W data, but also the CMS $W+c$ and the LHCb W, Z.

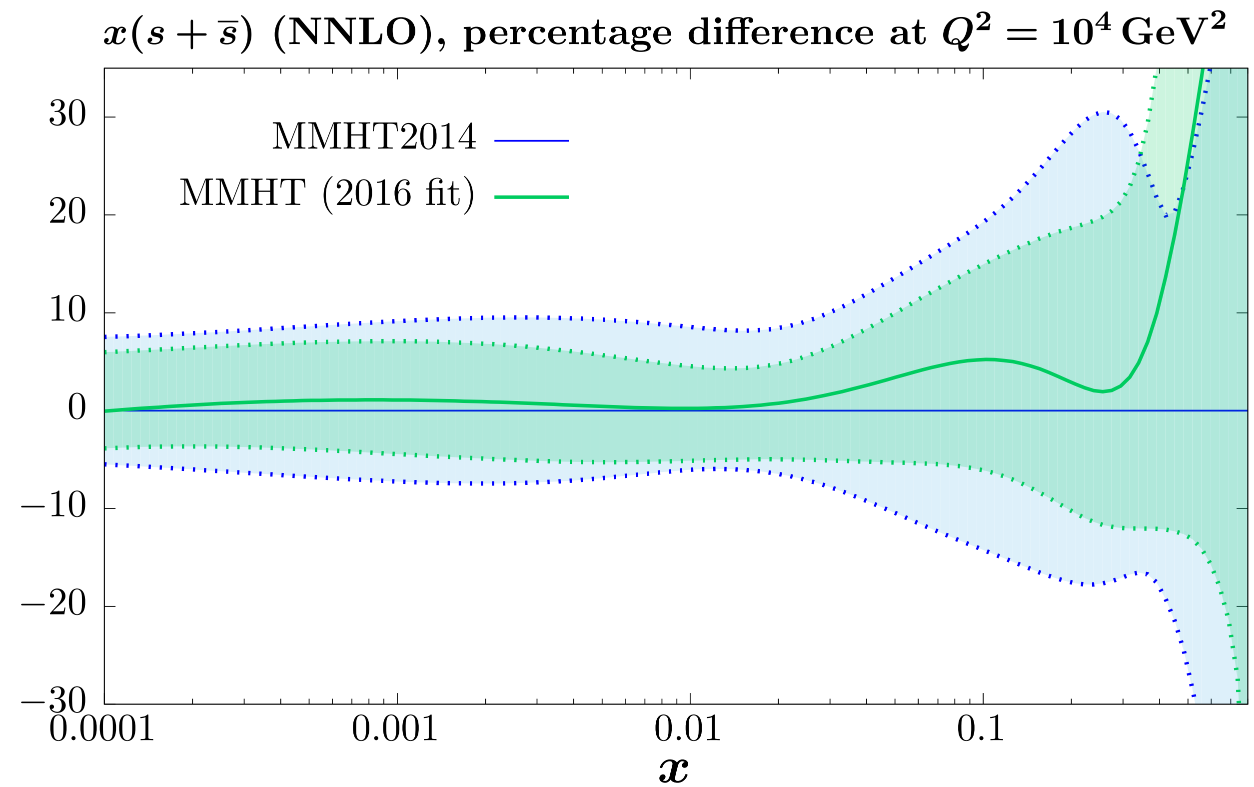
Changes in PDFs (1)

- No significant change in gluon or light sea. Some decrease in some small x regions due to new HERA data.

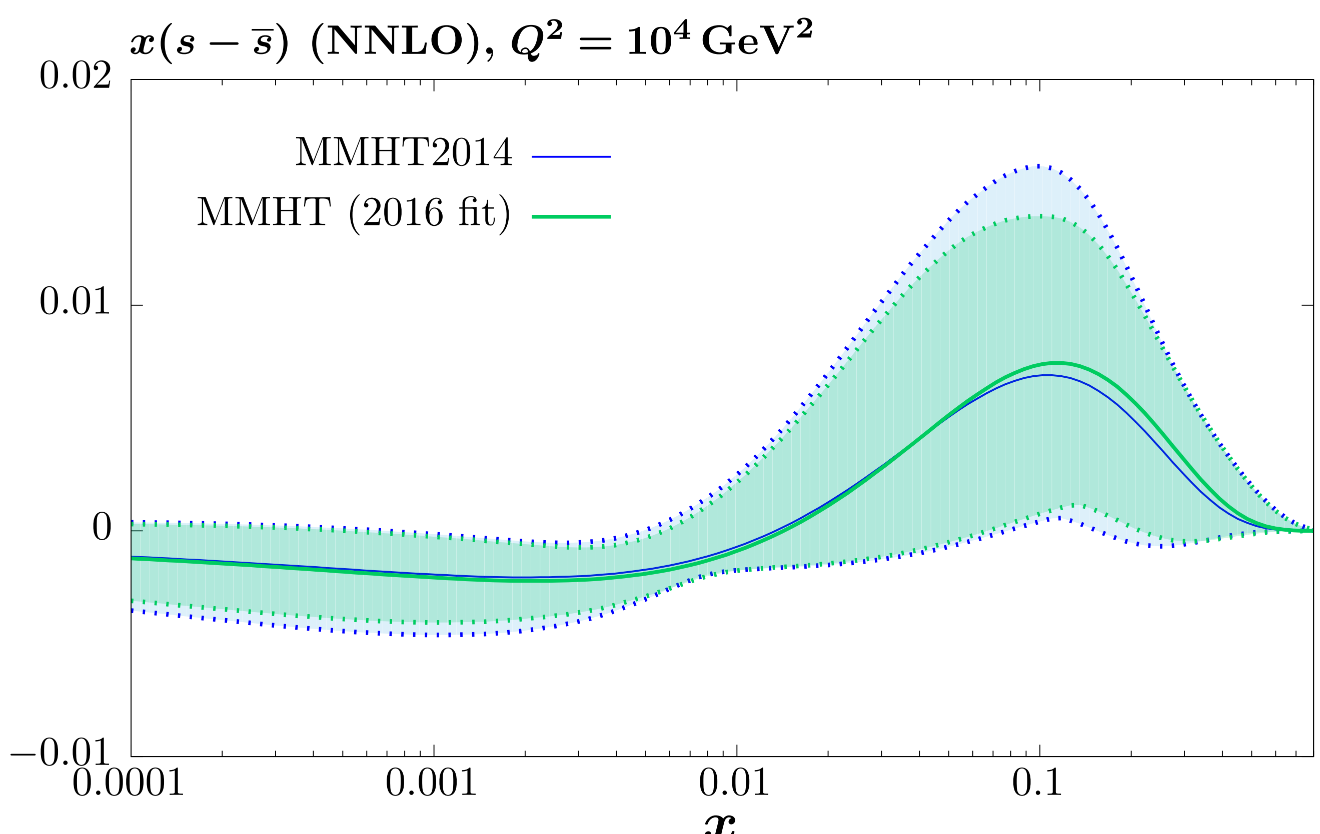


Changes in PDFs (2)

- Large reduction in $s+\bar{s}$ uncertainty, but little change in central value. Due to $W+c$ data.

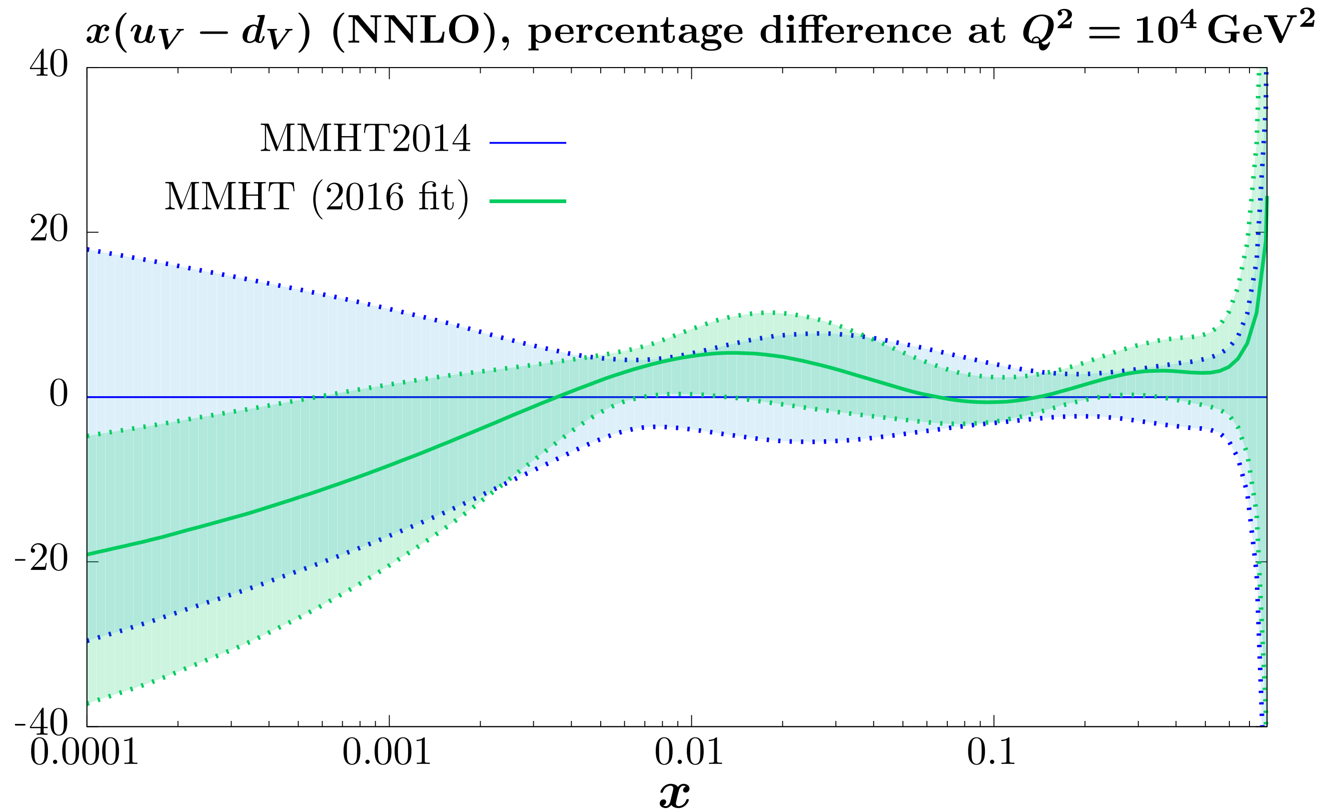


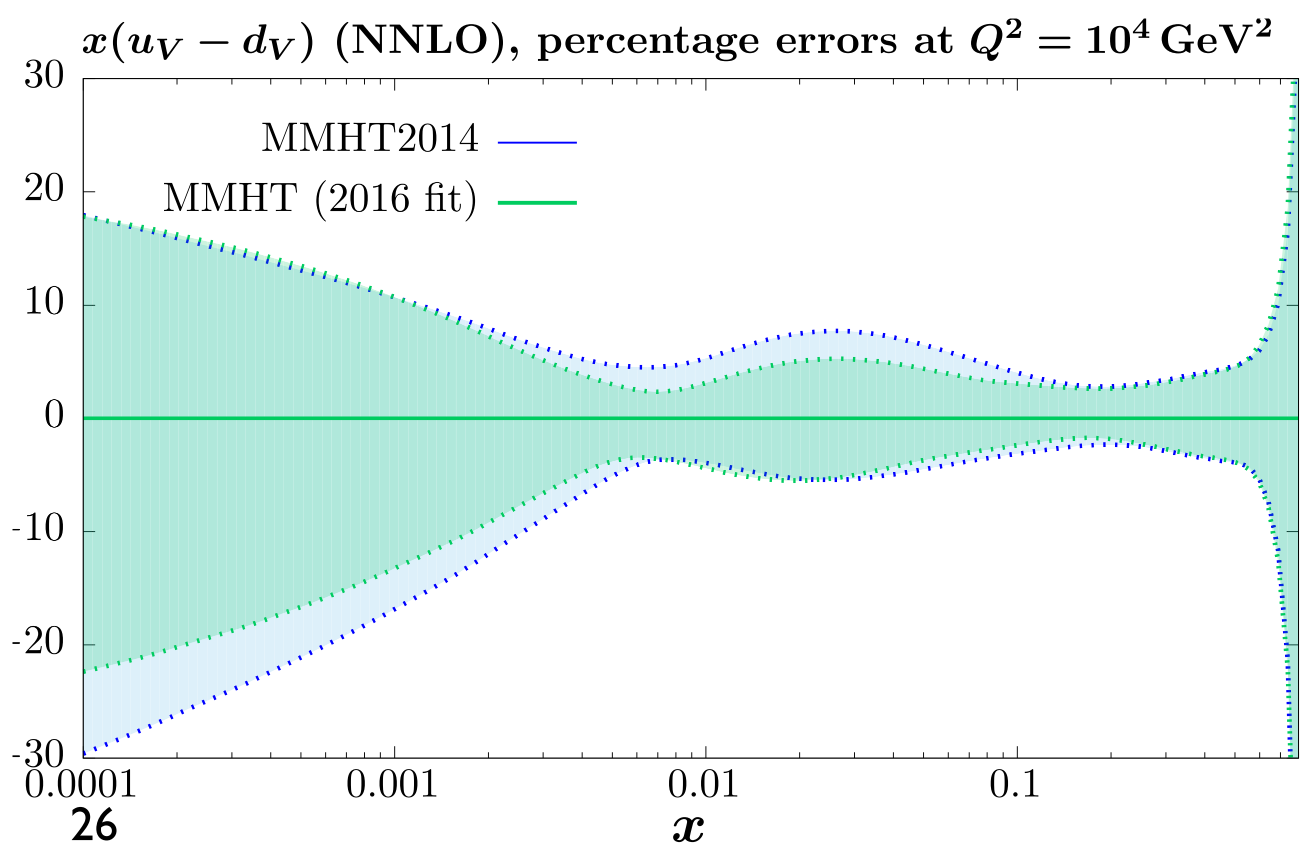
- Some impact on $s-\bar{s}$ as well due to CMS (effective) W asymmetry data.



Changes in PDFs (3)

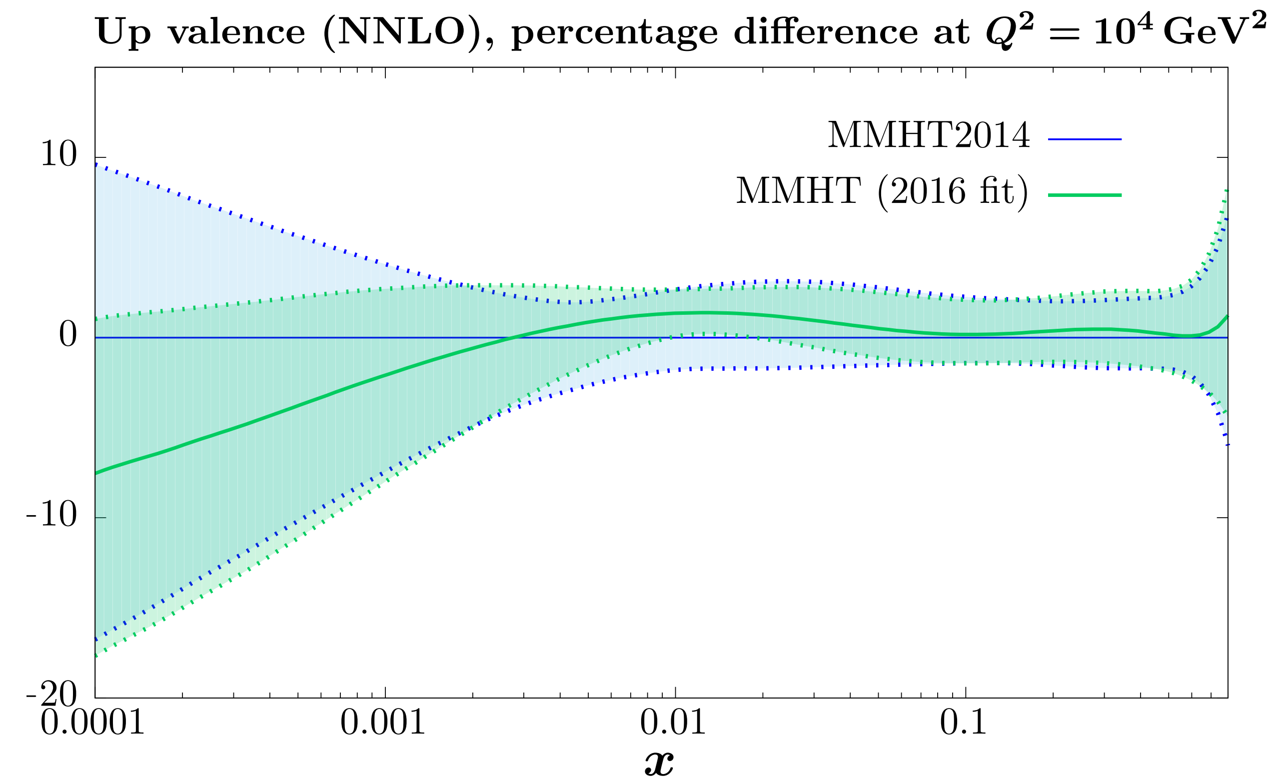
• Significant change in central value and reduction in uncertainty for $u_V - d_V$. Due to CMS W (effective) asymmetry.

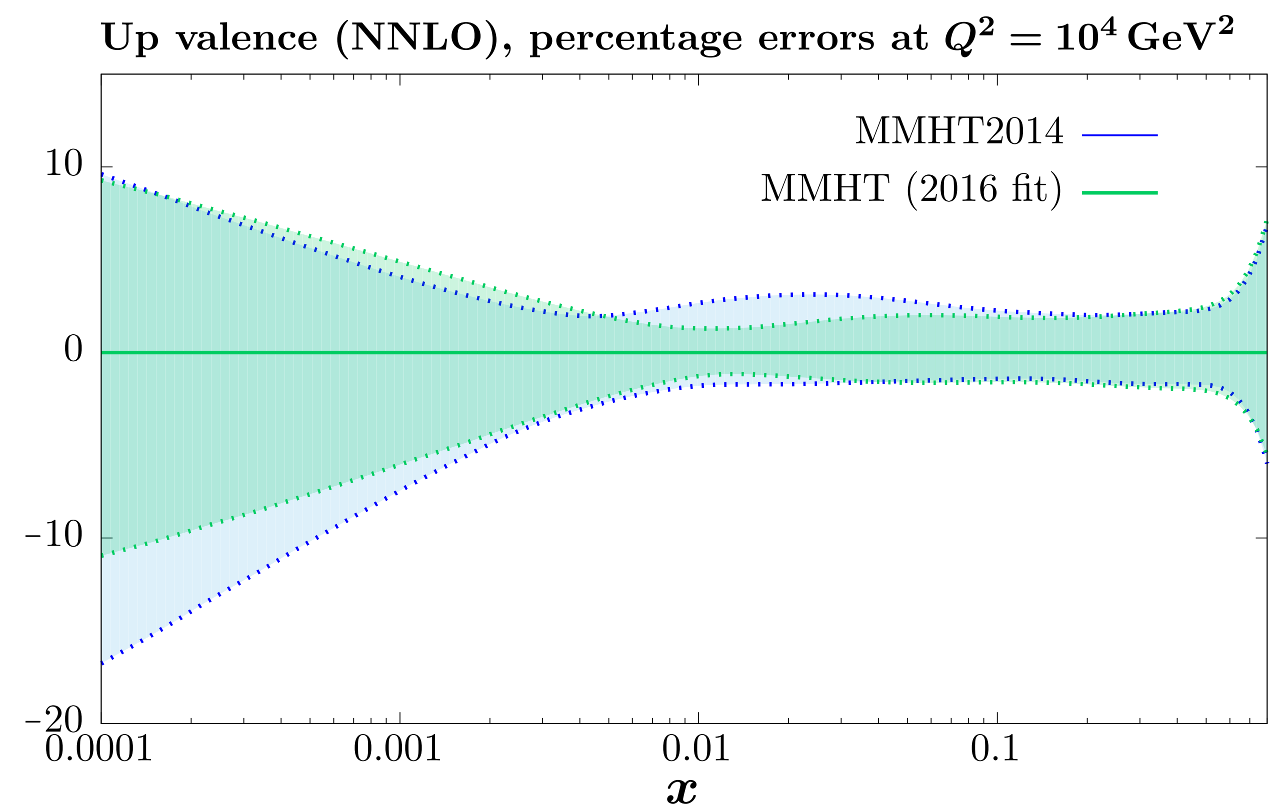




Changes in PDFs (4)

- Main uncertainty reduction in u_V rather than d_V. Mainly from CMS W data, but some impact from HERA combined set.

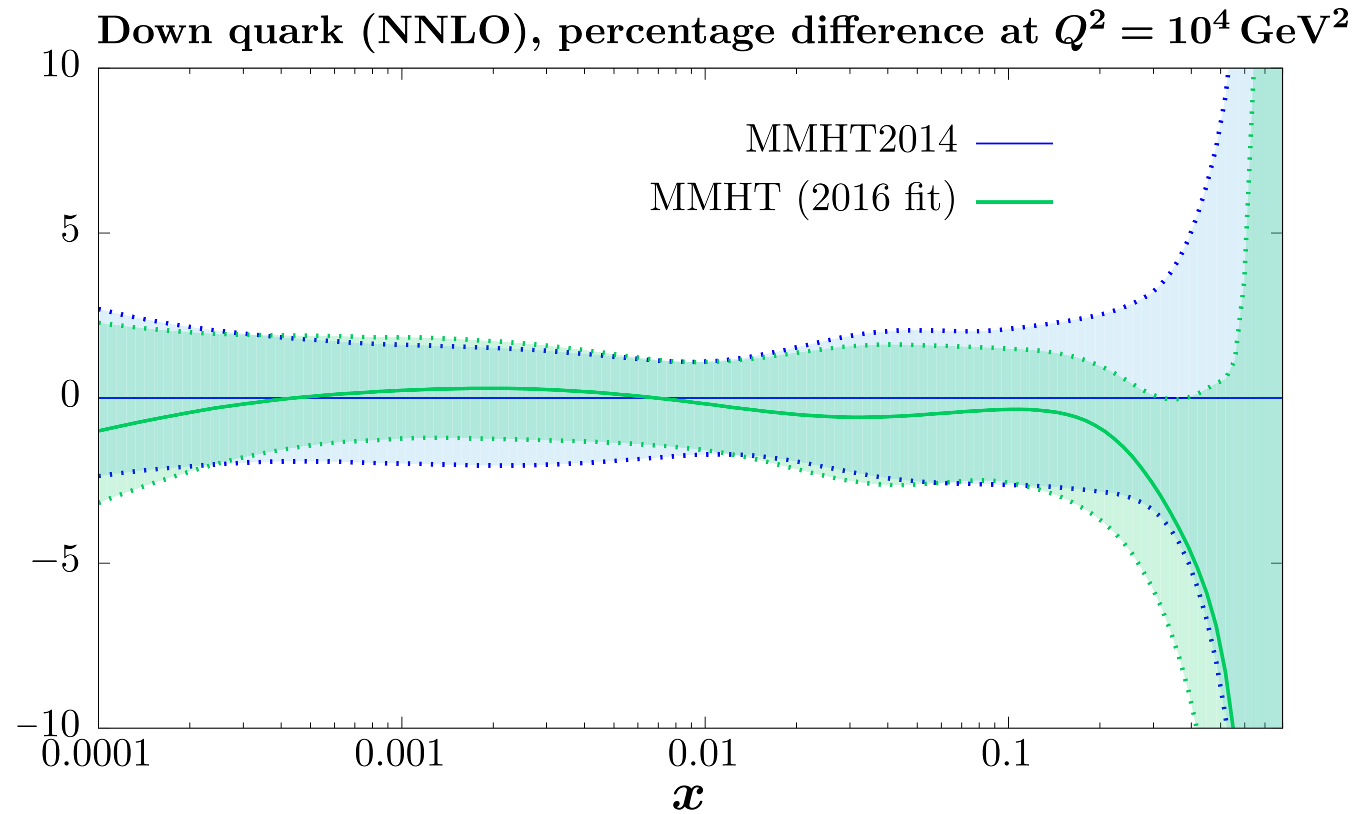


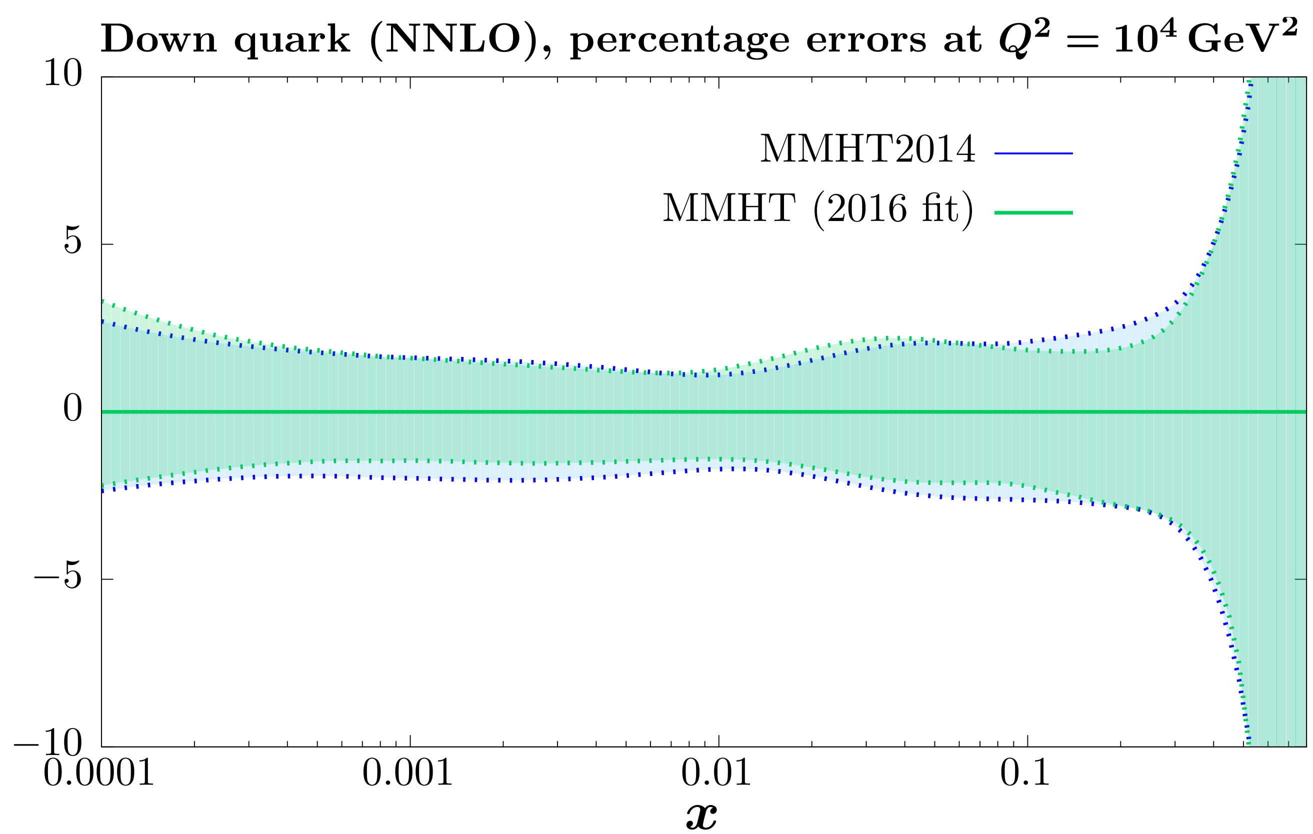


Changes in PDFs (5)

- Small change in d at $x \sim 0.01$ and some reduction in uncertainty.

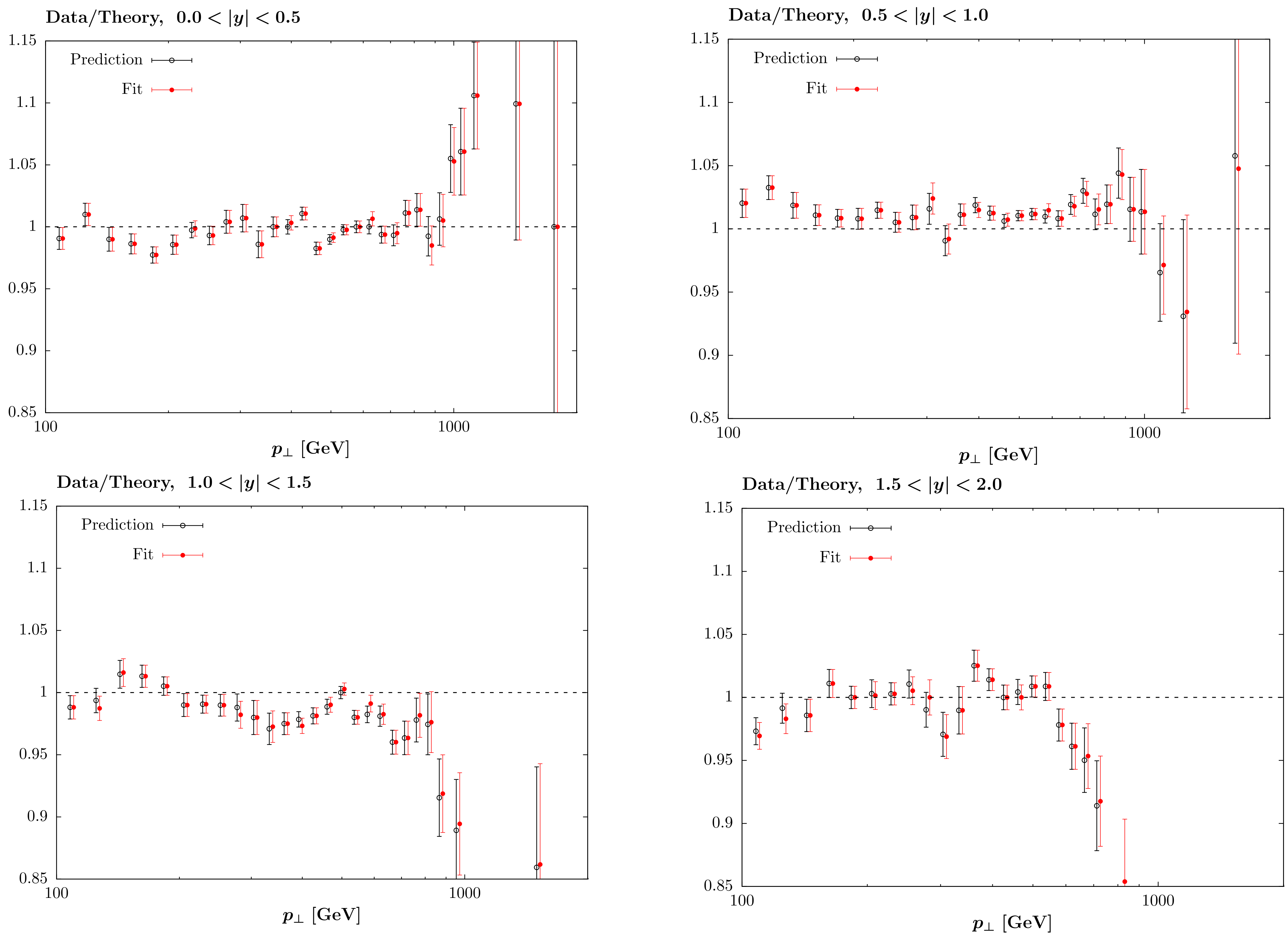
- Significant change in d at high x and some reduction in uncertainty for $x \sim 0.2$.





ATLAS jet data (1)

- Also attempt to fit ATLAS 7 TeV jet data (1410.8857).
- Prediction very poor: $\chi^2/N_{\rm pts} = 411.5/140$ at NLO.
- Refit gives marginal improvement: $\chi^2/N_{\rm pts} = 389.9/140$.
- Deterioration only $\Delta\chi^2 = 5.6$ in other data sets so not due to strong tensions.
- Why is fit so bad?



$\longrightarrow$ Cannot simultaneously fit data in all bins. Mismatch in one rapidity bin different in form to neighbouring bins but these are sensitive to PDFs of same flavour at very similar x and Q^2.

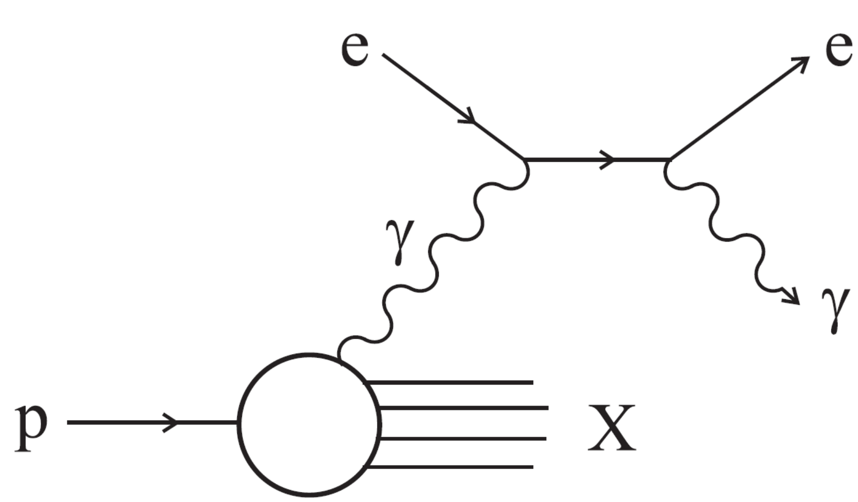
The photon PDF

The photon PDF

• At the level of QCD accuracy we are working, important to account for electroweak effects including initial state photons - introduce a photon PDF.

• My talk tomorrow: due to contribution from ‘coherent’ emission, photon PDF already quite well determined.

• Work ongoing on including within MMHT framework. Aim to include both LHC and low Q^2 structure function data $\longrightarrow$ physical approach to photon PDF.



$$\frac{\partial\gamma(x,Q^2)}{\partial\log Q^2} = \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\left(P_{\gamma\gamma}\otimes\gamma + \sum_1 e_i^2 P_{\gamma q}\otimes q_i\right)$$

Conclusions

- Have studied final combined HERA data within MMHT approach:
  - Effect on PDFs/predictions not too large, slight reduction in uncertainties.
  - Decreasing χ^2 with $Q^2_{\rm min} \uparrow$ studied. Find a simple phenomenological change in F_L (reducing size at low x, Q^2) removes this effect entirely.
- Range of new LHC (Tevatron) data included in fit. Have studied impact on PDFs and uncertainties. Non-negligible reduction in uncertainties for some PDFs, in particular strange and low x valence.
- Failure to fit ATLAS 7 TeV jet data - common with other groups.
- Work to include photon PDF in MMHT framework ongoing.