MMHT2014 PDFs - HERA I+II data and new LHC data

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

I will cover a number of topics.

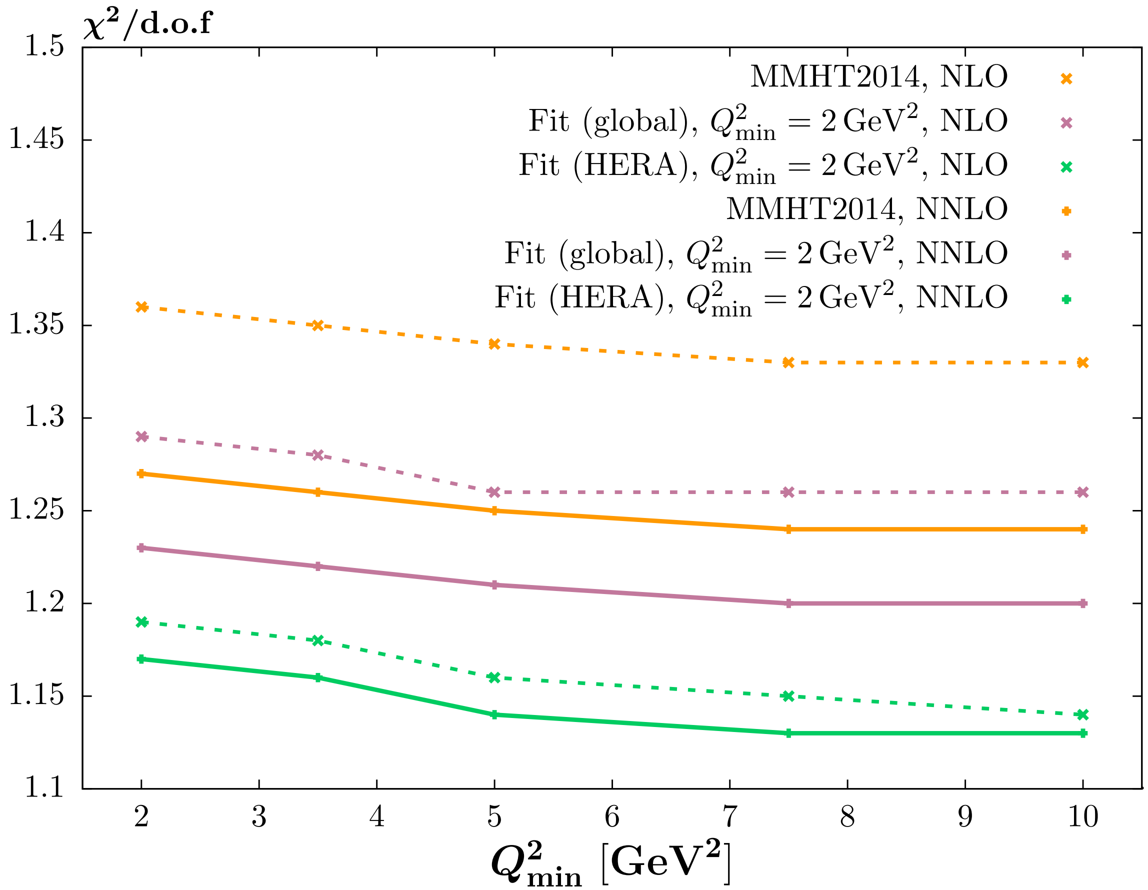
– A review of the fit to final HERA data, with consequences for MMHT PDFs and a study of the fit quality.

– The impact of fitting new LHC and Tevatron data. $\rightarrow$ clear improvements in some PDF uncertainties.

A brief intro to topics just starting investigation. Extension of parameterisation and QED corrections.

HERA II Combined data

Using $Q^2_{\rm min} = 2{\rm GeV}^2$ then 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.



NNLO clearly superior, but less obvious in fit to only HERA II data.

Breakdown of fit quality in subsets of data

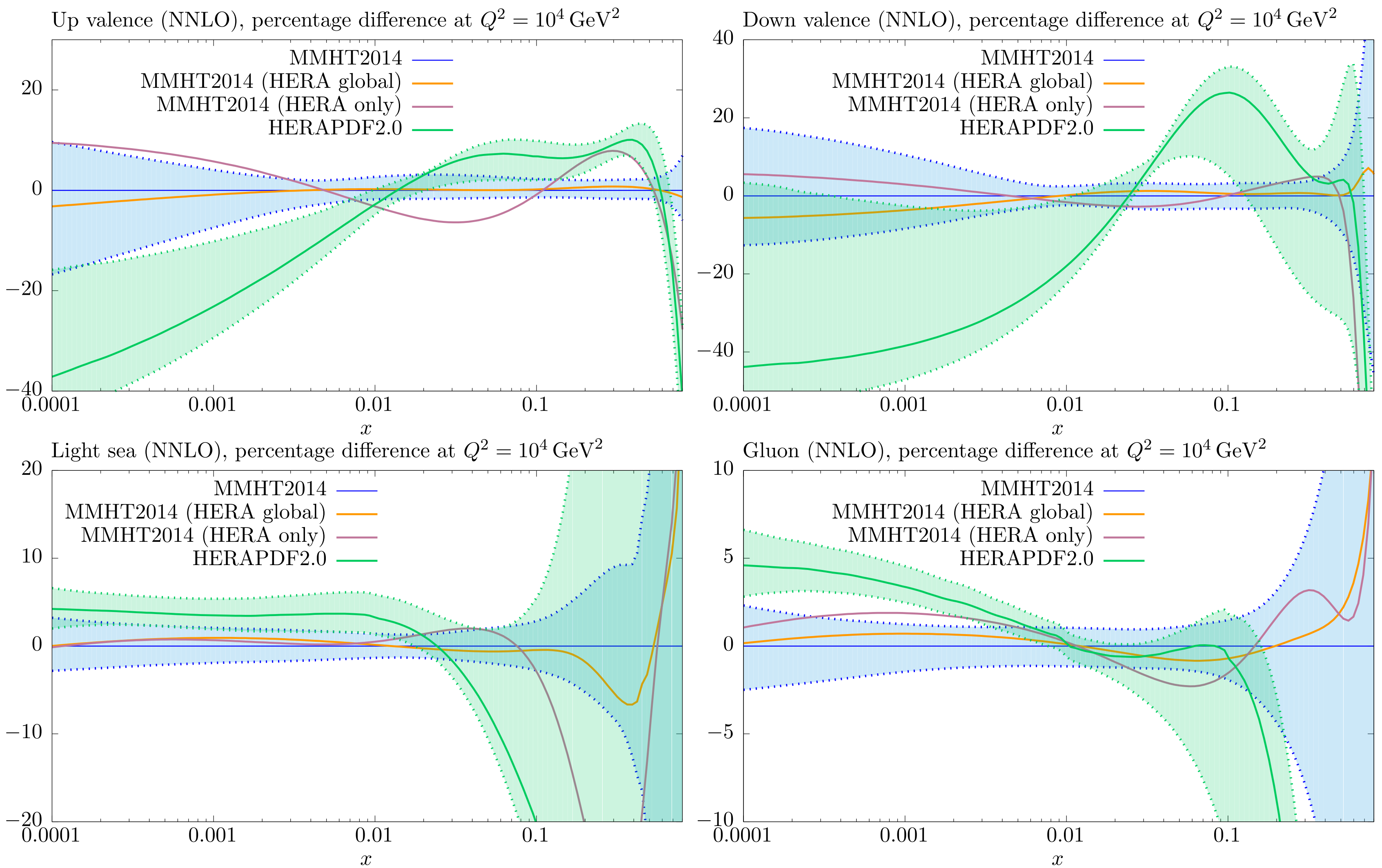
	no. points	NLO χ^2_{HERA}	NLO χ^2_{global}	NNLO χ^2_{HERA}	NNLO χ^2_{global}
correlated penalty		79.9	113.6	73.0	92.1
CC e^+p	39	43.4	47.6	42.2	48.4
CC e^-p	42	52.6	70.3	47.0	59.3
NC e^-p $E_p = 920$ GeV	159	213.6	233.1	213.5	226.7
NC e^+p $E_p = 920$ GeV	377	435.2	470.0	422.8	450.1
NC e^+p $E_p = 820$ GeV	70	67.6	69.8	71.2	69.5
NC e^-p $E_p = 575$ GeV	254	228.7	233.6	229.1	231.8
NC e^-p $E_p = 460$ GeV	204	221.6	228.1	220.2	225.6
total	1145	1342.6	1466.1	1319.0	1403.5

The χ^2 for each subset of HERA I + II data for the four variations of fit for $Q^2_{\rm min} = 3.5~{\rm GeV}^2$.

Large improvement in CC e^-p data when only HERA data fit. Probe of up (valence) quark at high x. Bigger effect at NLO.

$920{\rm GeV}$ NC data also sensitive to whether other data is included.

Other data sets much smaller effect.



HERA II modified PDFs very well within MMHT2014 uncertainties. PDFs from HERA II data only fit in some ways similar to HERAPDF2.0.

When fitted $\alpha_S(M_Z^2)$ =0.1172-3, i.e. no real change from MMHT2014.

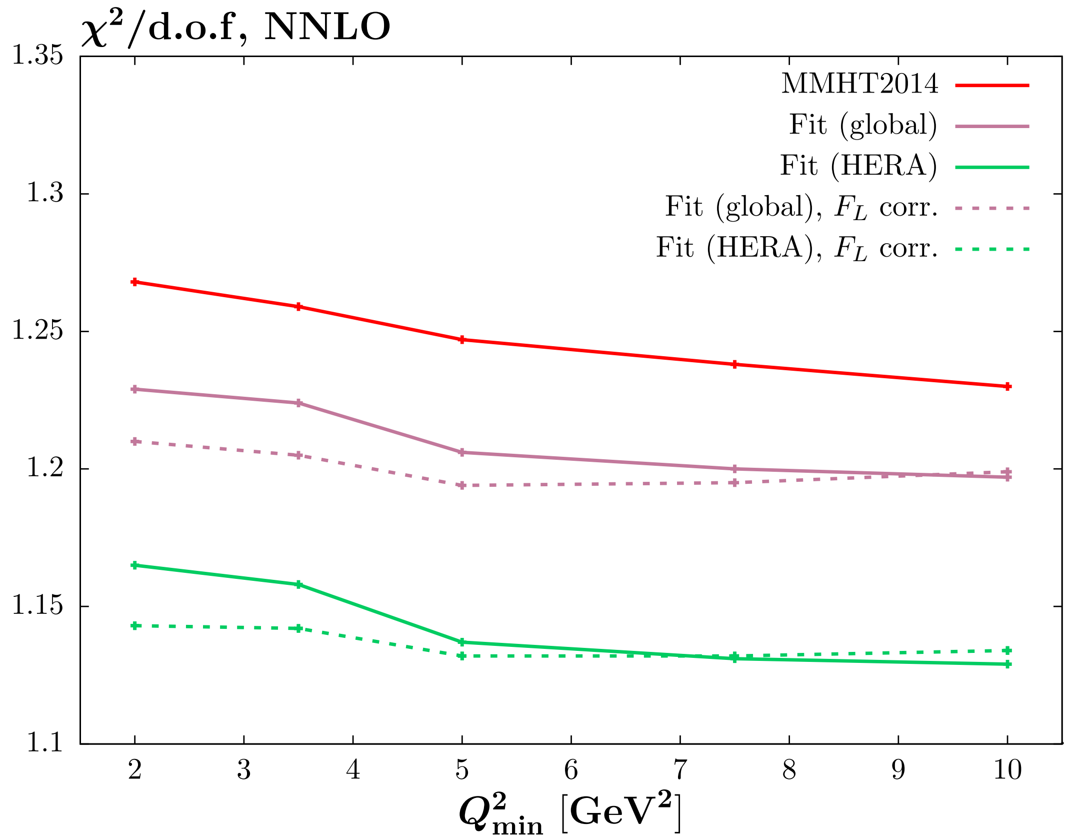
Uncertainties (preliminary) quite similar to MMHT2014.

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

At most a 10% reduction in uncertainties. Very small changes in central values.

Improvement in χ^2 with increasing $Q^2_{\rm min}$. General tendency to overshoot some of the highest y points at low x and Q^2.

Try modification $F_L \to (1 + A/Q^2)F_L$ for $x < 0.01$.



Just about all evidence of a fall of χ^2 per point with $Q^2_{\rm min}$ eliminated. No significant improvement with more complicated models. Very little change in PDFs. At higher x, Q^2 data prefers smaller F_L.

Breakdown of fit quality to new hadron collider data

As well has the combined HERA data we now also fit to high rapidity W, Z data from LHCb at 7 and 8 TeV, $W + c$ jets from CMS, which constrains strange quarks, high precision CMS data on $W^{+,-}$ rapidity distributions which can also be interpreted as an asymmetry measurement, and also the final e asymmetry data from D0 (lepton, not W asymmetry).

	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

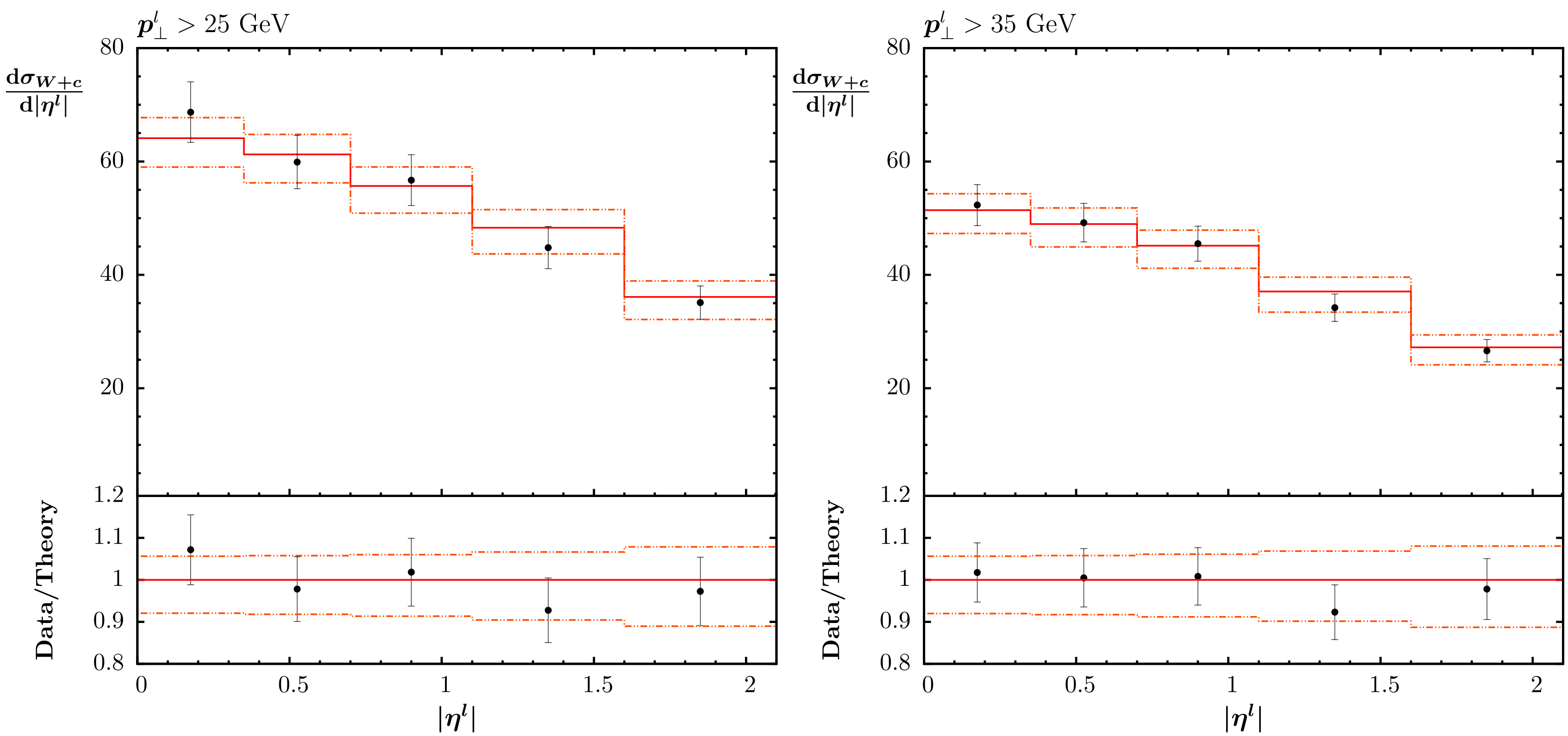
Predictions generally good, and no significant tension with other data when refitting, i.e. changes in PDFs relatively small.

At NLO $\Delta\chi^2 = 9$ for the remainder of the data and at NNLO $\Delta\chi^2 = 15$.

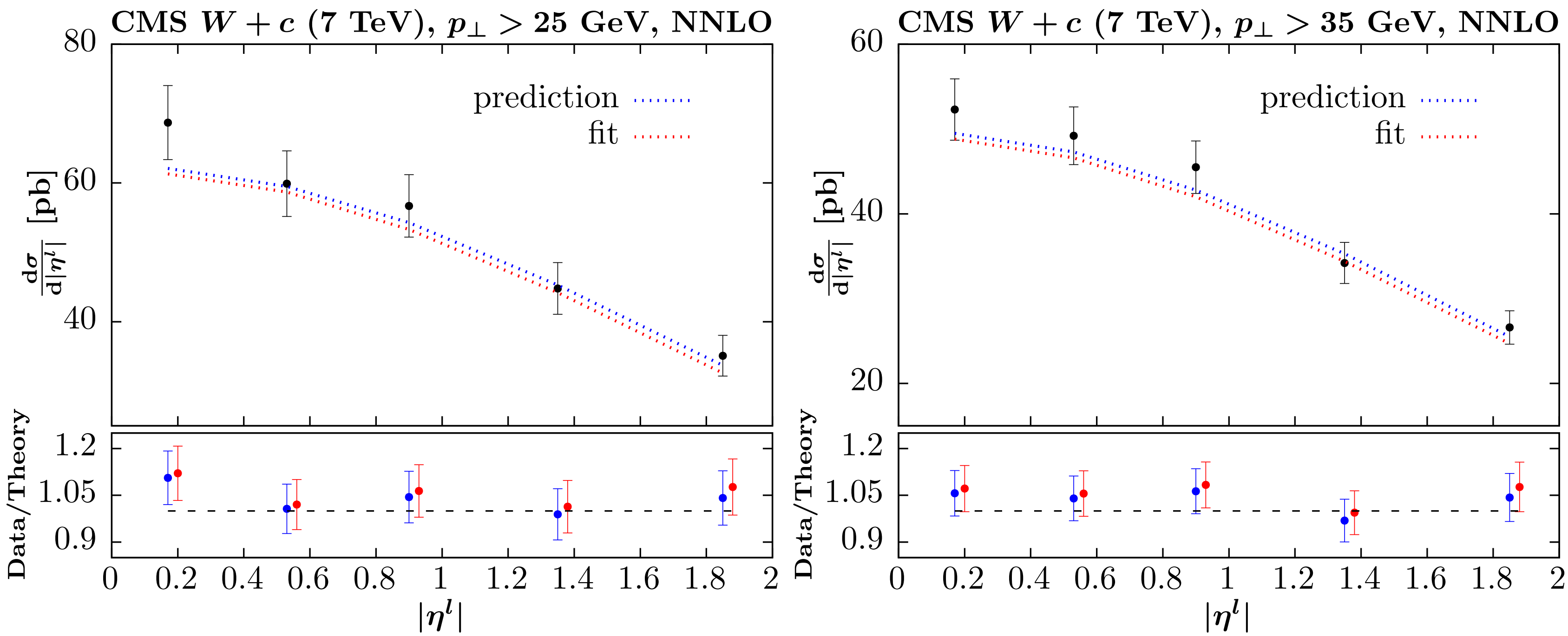
When couplings left free at NLO $\alpha_S(M_Z^2)$ stays very close to 0.120 but at NNLO $\alpha_S(M_Z^2)$ marginally above 0.118, higher than MMHT2014.

New data sets for fit – $W + c$ differential distributions.

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



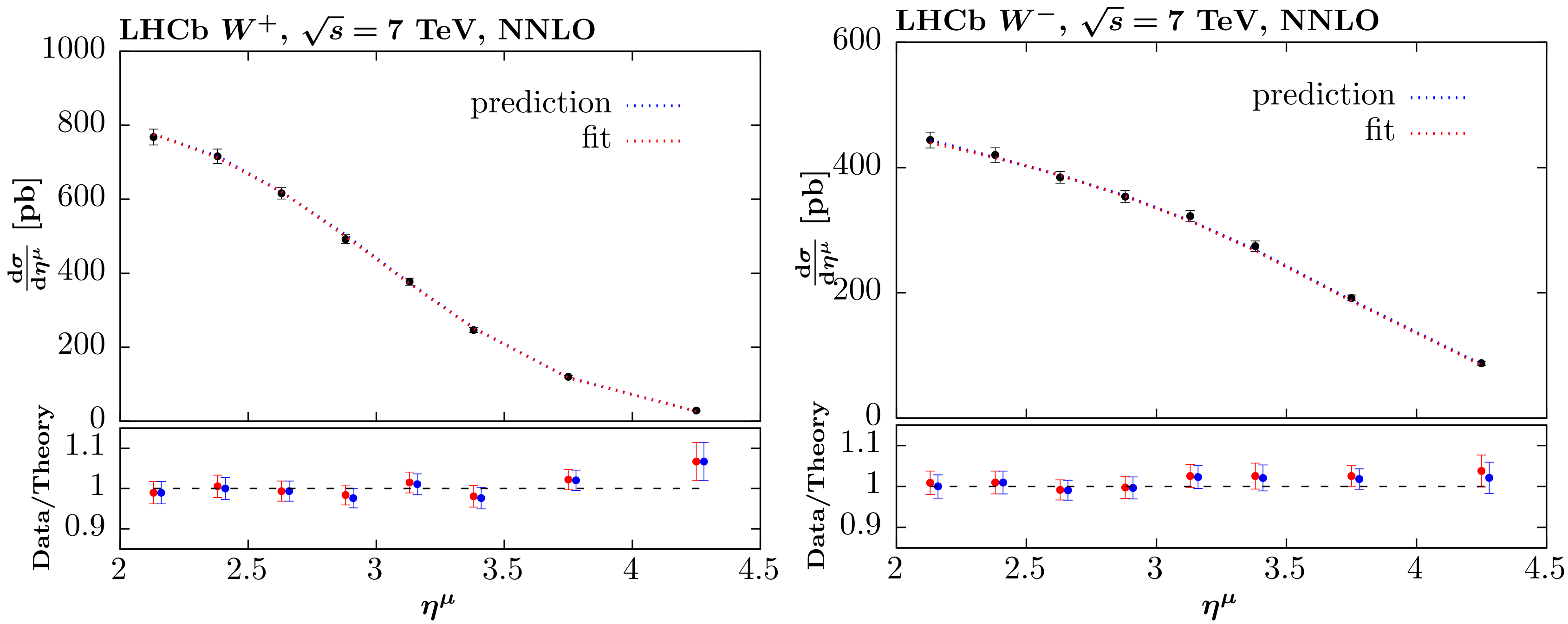
MSTW2008 a bit low (especially for ATLAS), but MMHT2014 seems fine particularly for CMS (shown).



Data on plot use uncertainties added in quadrature.

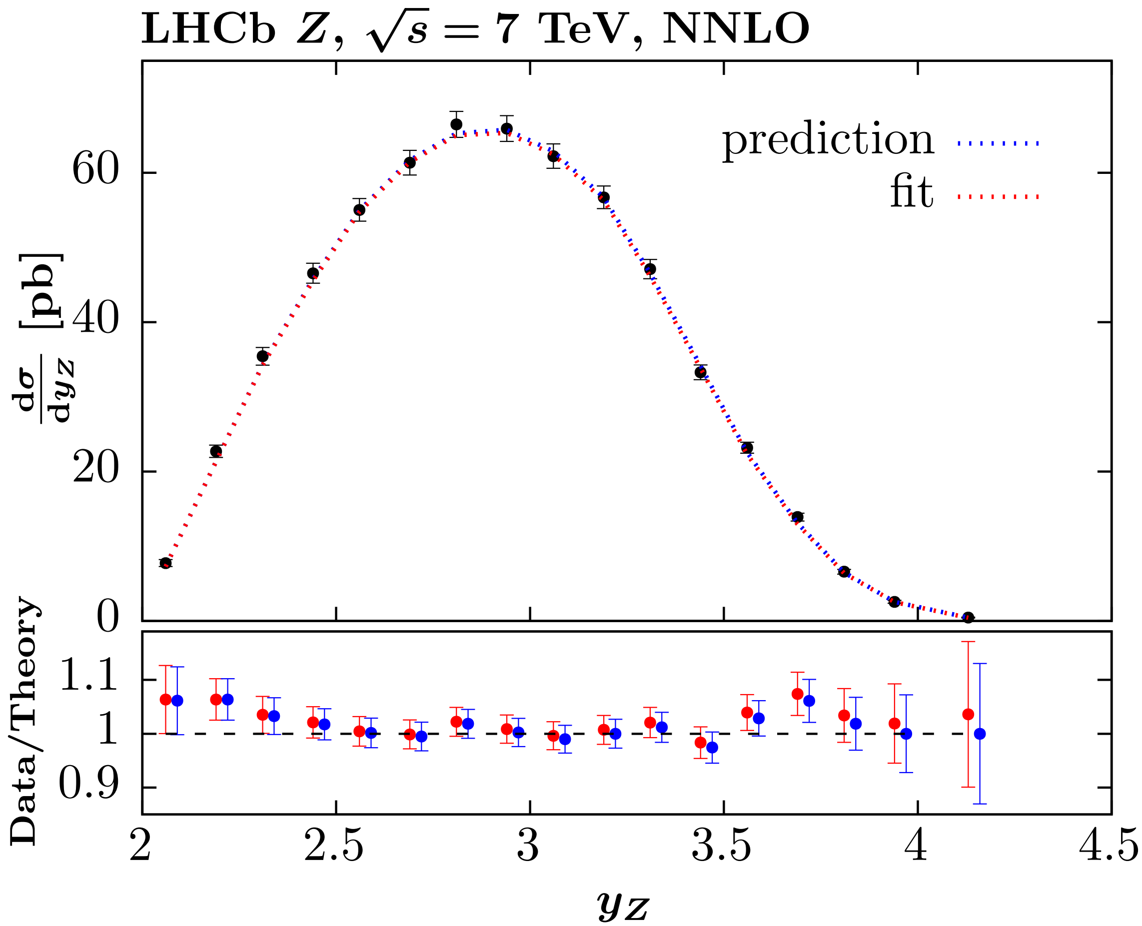
Very little change after fit. By eye comparison looks worse, but slightly better when covariance matrix used (as in fit).

New data on high rapidity W production at LHCb at $7\ \mathrm{TeV}$.



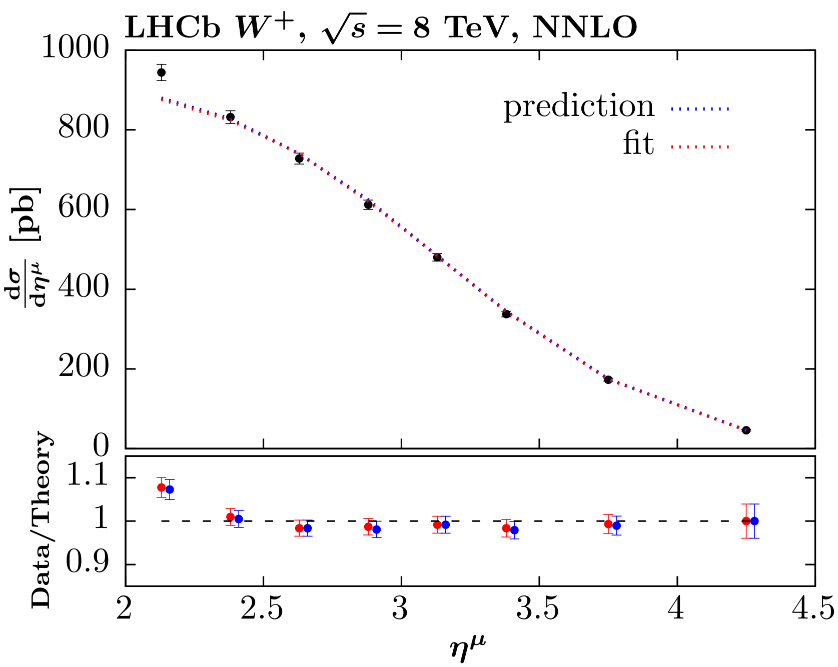
Generally perfectly good agreement using NNLO. Uncertainties added in quadrature on plot, but covariance matrix used in fit.

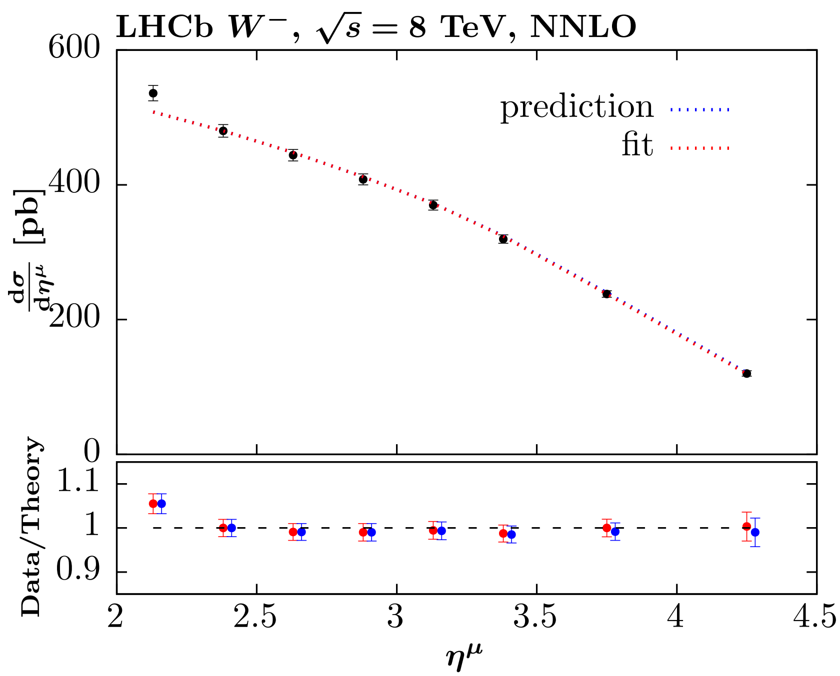
New data on high rapidity Z production at LHCb at $7\ \mathrm{TeV}$.



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

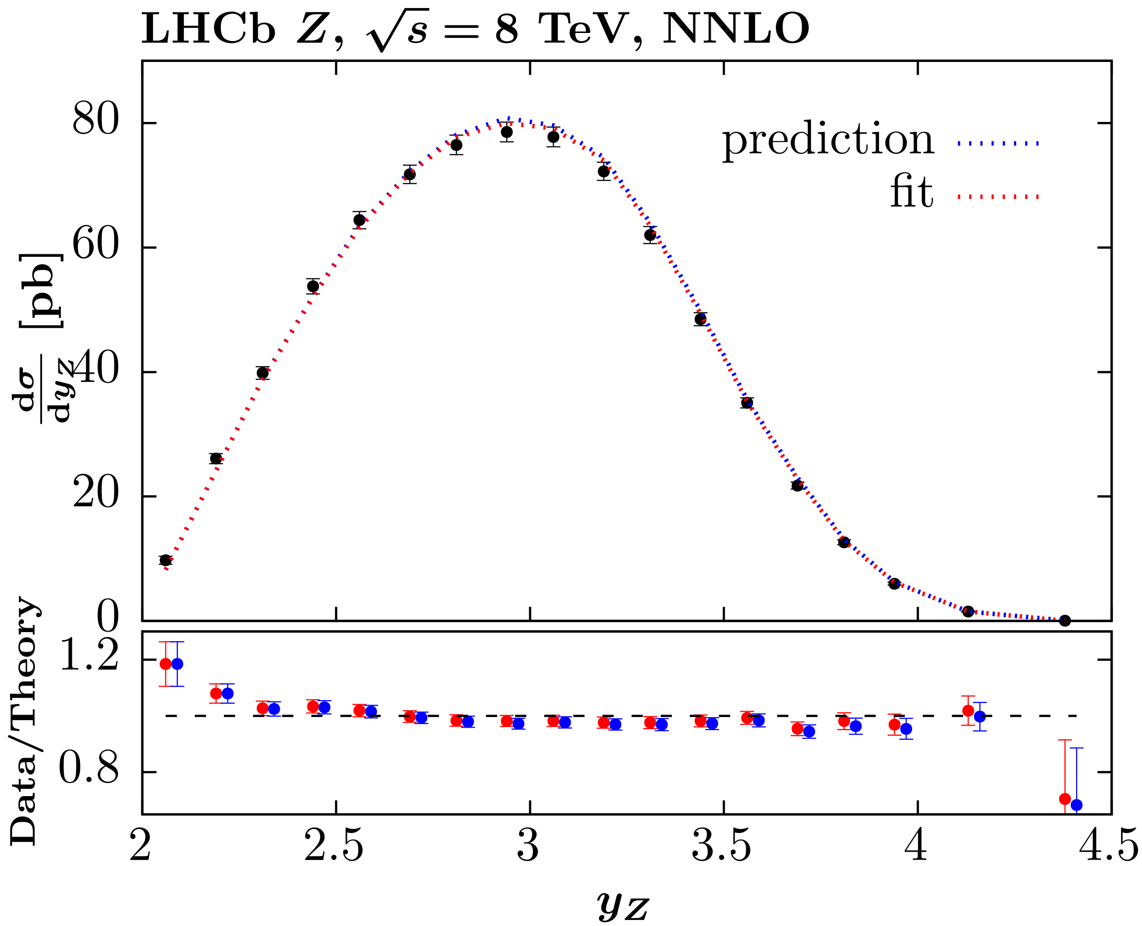
New data on high rapidity W production at LHCb at 8 TeV.





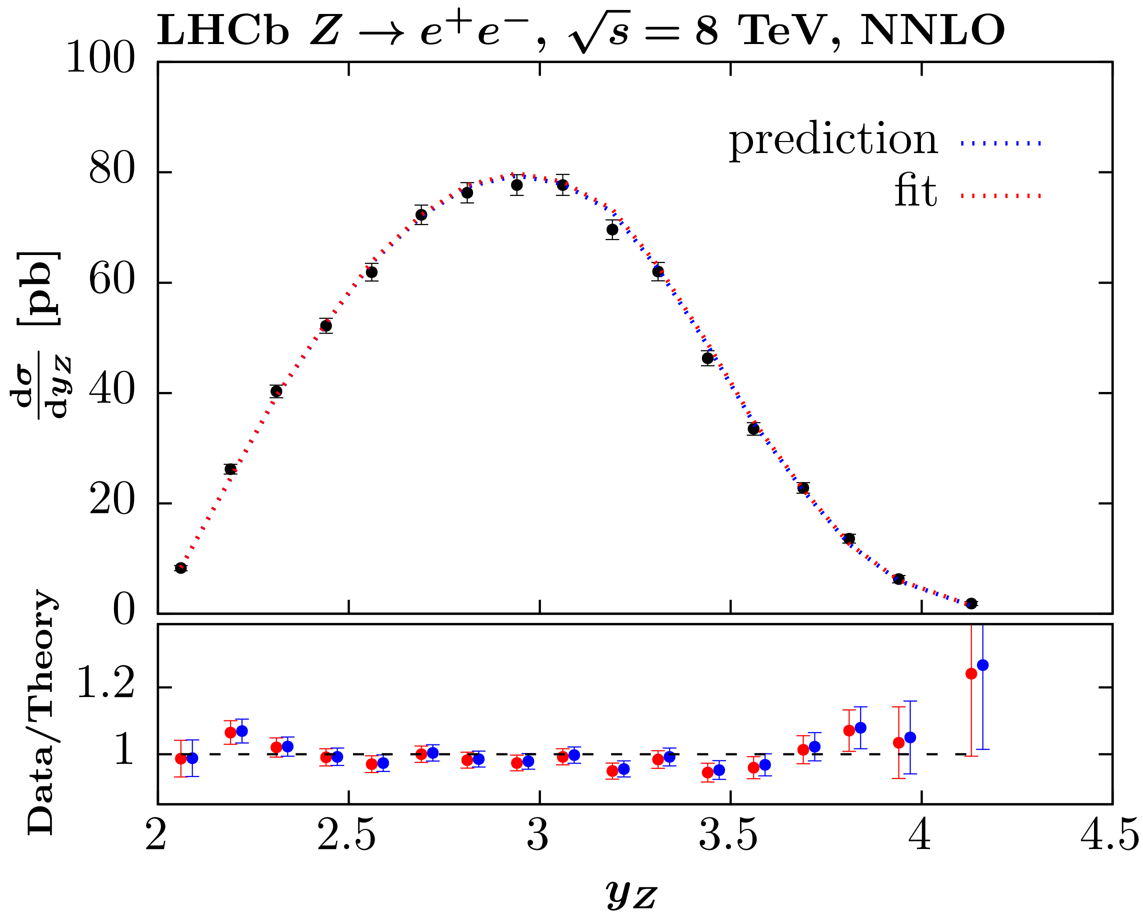
Good fit except at lowest η_μ point in each case.

New data on high rapidity Z production at LHCb at $8\ \mathrm{TeV}$.



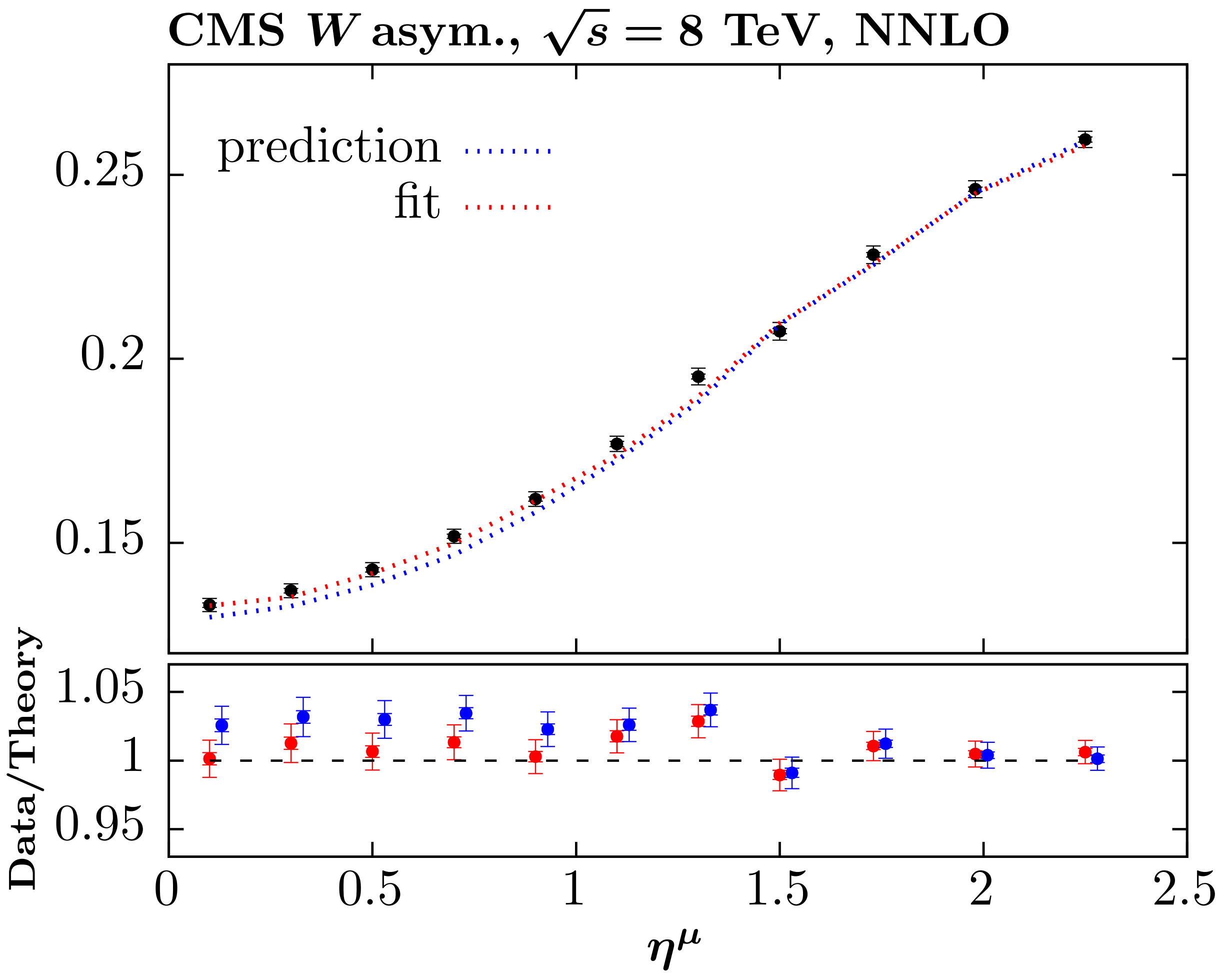
Same issue with lowest y_z point. PDFs at moderate x for these points and well constrained by DIS data.

New data on high rapidity Z production at LHCb at $8\ \mathrm{TeV}$ with electrons.



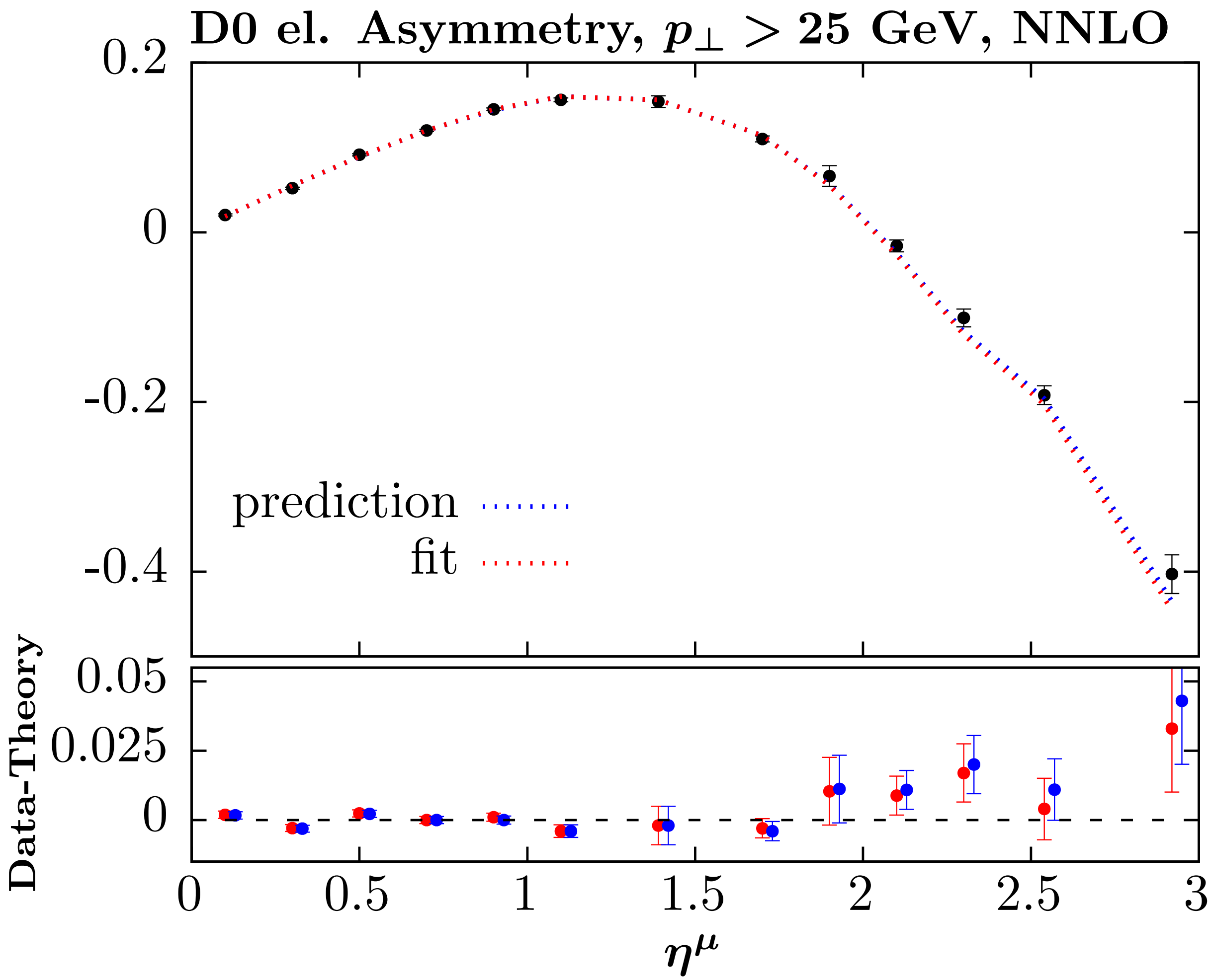
No issue at lowest y_z with these data. Relatively large χ^2 only down to fluctuations.

Good agreement with new 8 TeV CMS $W^{\pm}$ rapidity and asymmetry data (shown). (Fit to individual distributions not asymmetry.)



Small-x valence quarks require some modification of order the size of uncertainty. Scope for reduced uncertainty with new data inclusion.

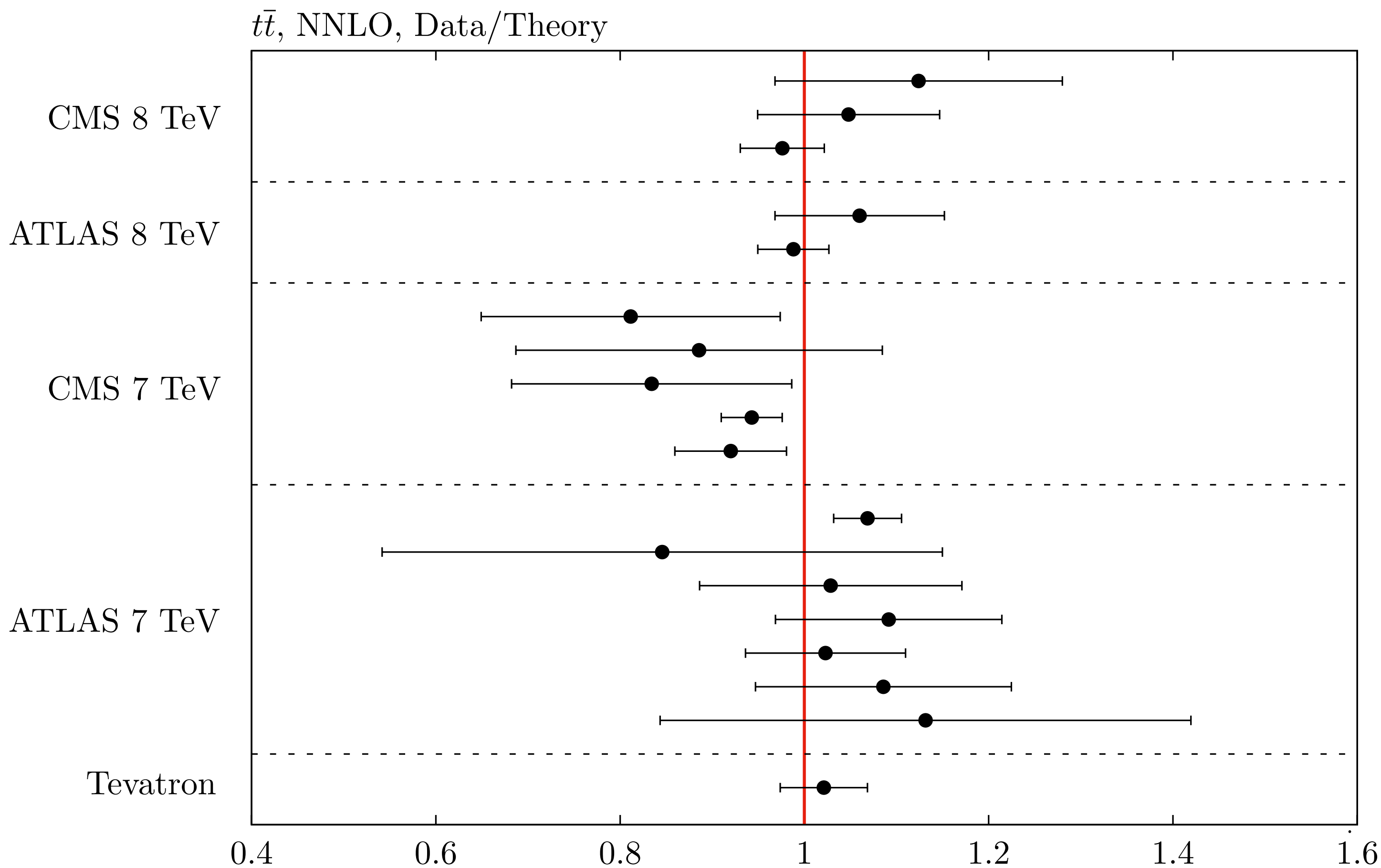
Good agreement with new D0 e asymmetry data



Slight undershooting at highest η_e. Implies slightly smaller down quark, but other data does not prefer this.

(Use the prescription for systematic uncertainties advocated in Eur.Phys.J. C75 (2015) no.9, 458 for these and other Tevatron data.)

Included some more up-to-date results on $\sigma_{\bar{t}t}$.



Fit very good and with $\alpha_S(M_Z^2) = 0.118$ the fitted $m_t^{pole} = 173.4\ \mathrm{GeV}$. At NLO $m_t^{pole} = 170.2\ \mathrm{GeV}$.

Helps drive slight increase in $\alpha_S(M_Z^2)$

PDF sets generated

We generate a preliminary (not for distribution) central set at NLO and NNLO for fit to new data – labelled MMHT (2016 fit).

Also generate PDF eigenvector sets for uncertainties at NNLO.

Use same basis of 25 free PDF parameters as in MMHT2014 (this is subject to possible change in the future).

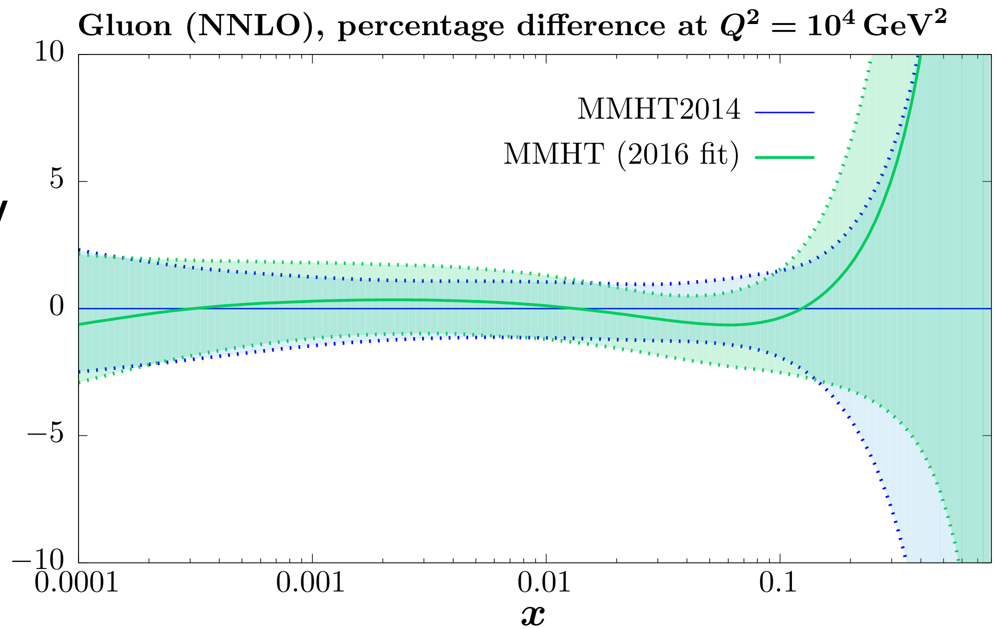
Hence, 50 eigenvector directions.

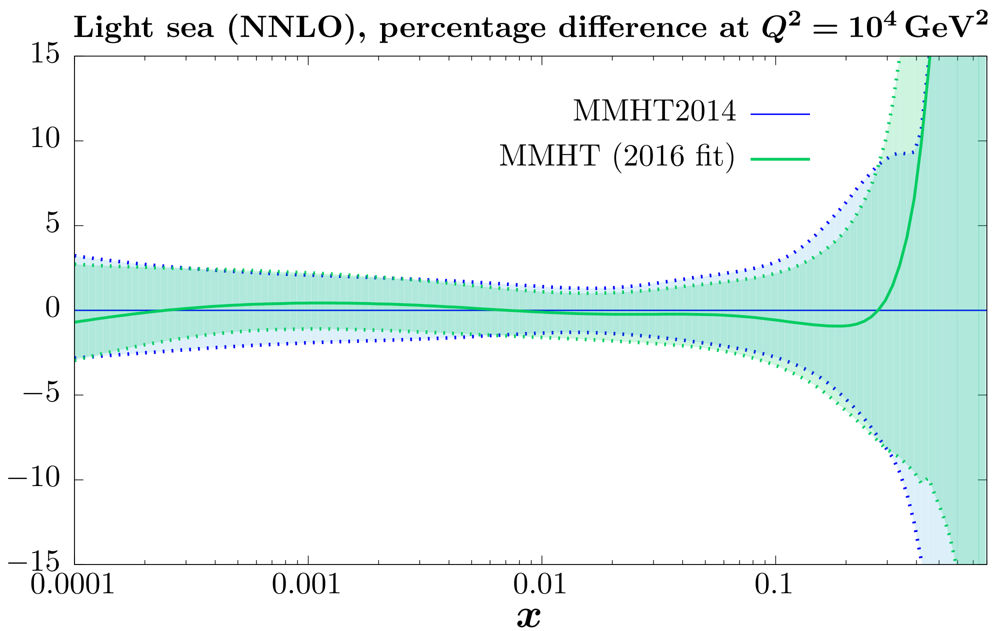
9 of these are best constrained by one of the new (LHC) data sets, CMS $8\ \mathrm{TeV}\ W$ data and $W + c$ jets and the new LHCb data.

Effect on PDFs

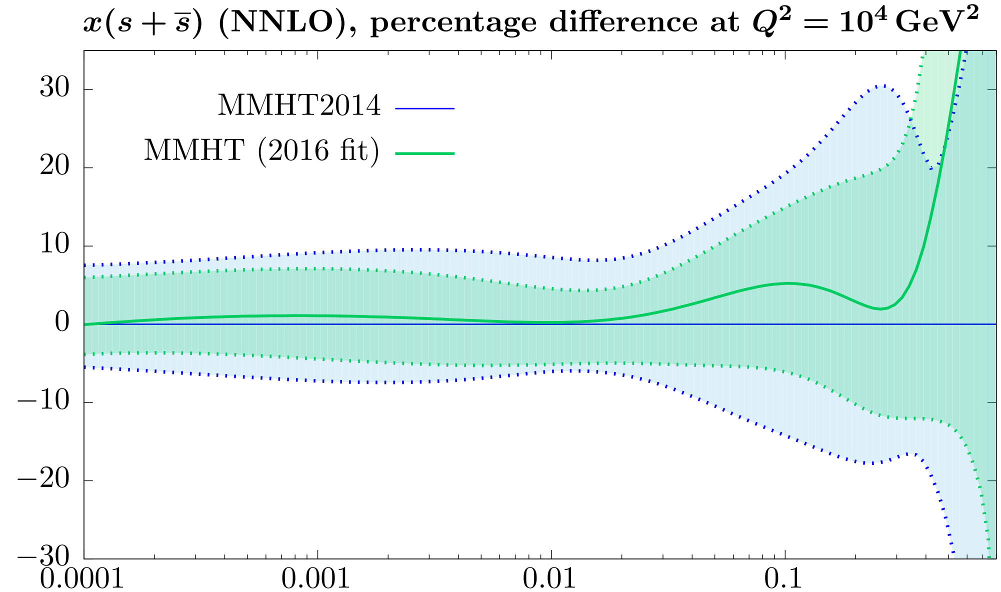
No significant change in gluon or light sea.

Small decrease in uncertainty in some small-x regions due to new HERA data.

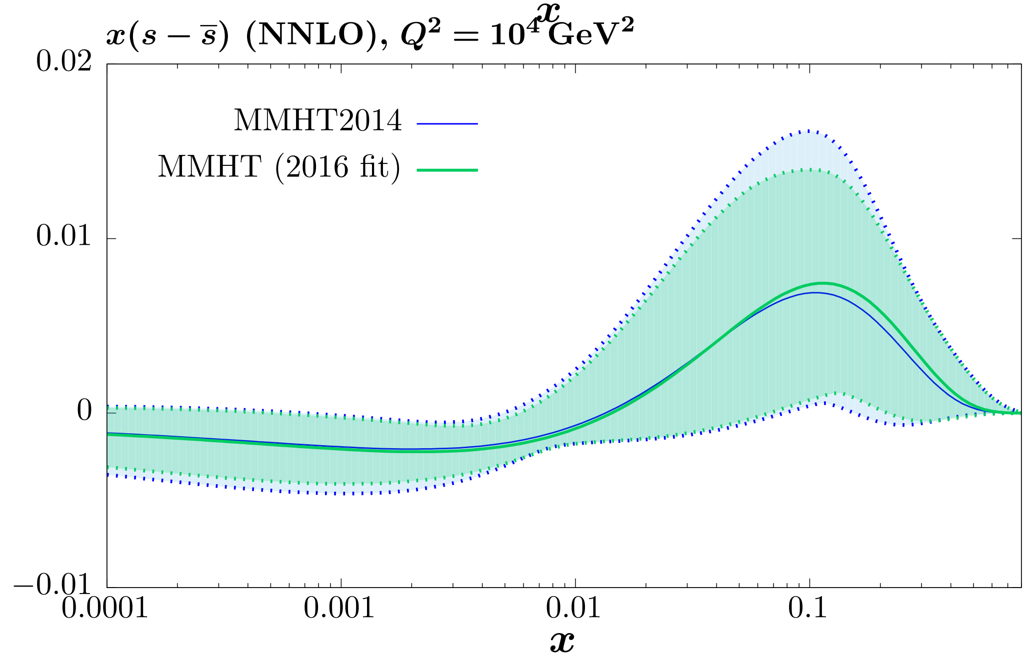




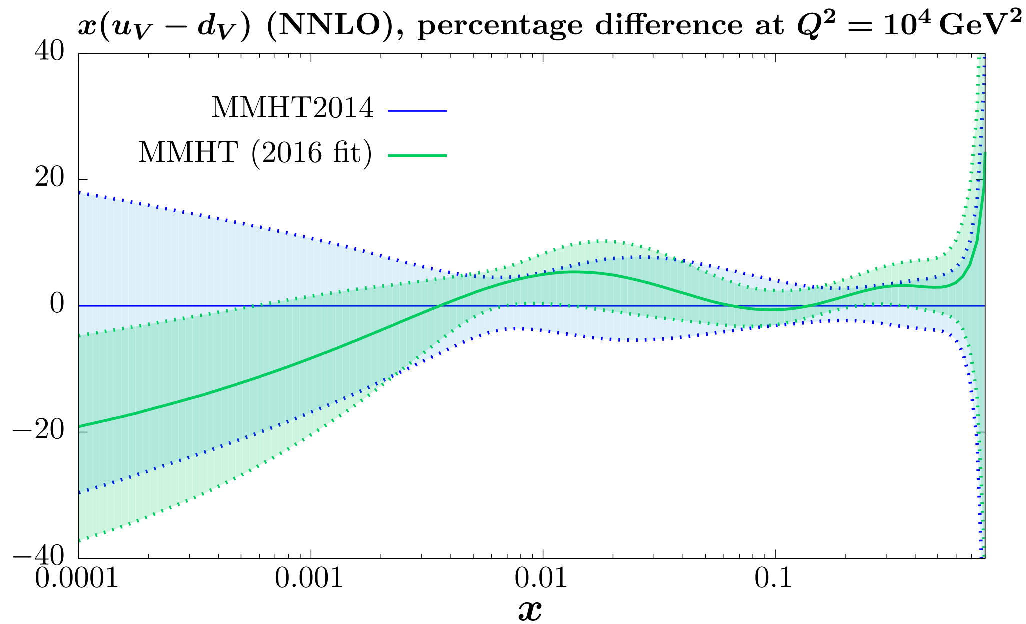
Large reduction in the $s + \bar{s}$ uncertainty, but little change in central value. Due to $W + c$ jets data.

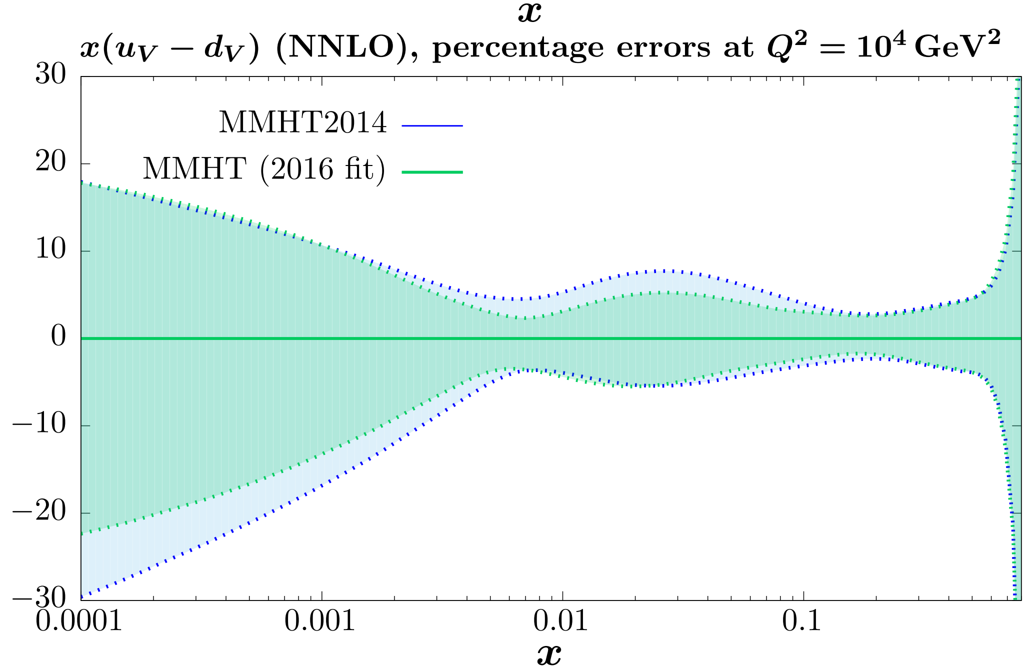


There is some impact on the $s - \bar{s}$ uncertainty, from (effective) asymmetry data.



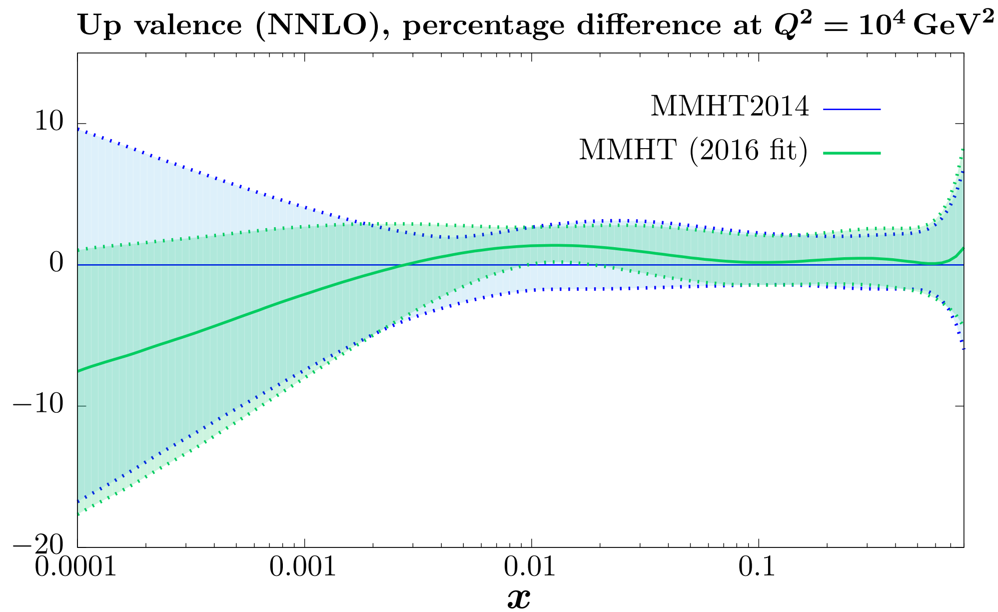
A significant change in $u_v - d_v$, and reduction in the uncertainty, from (effective) CMS asymmetry data.

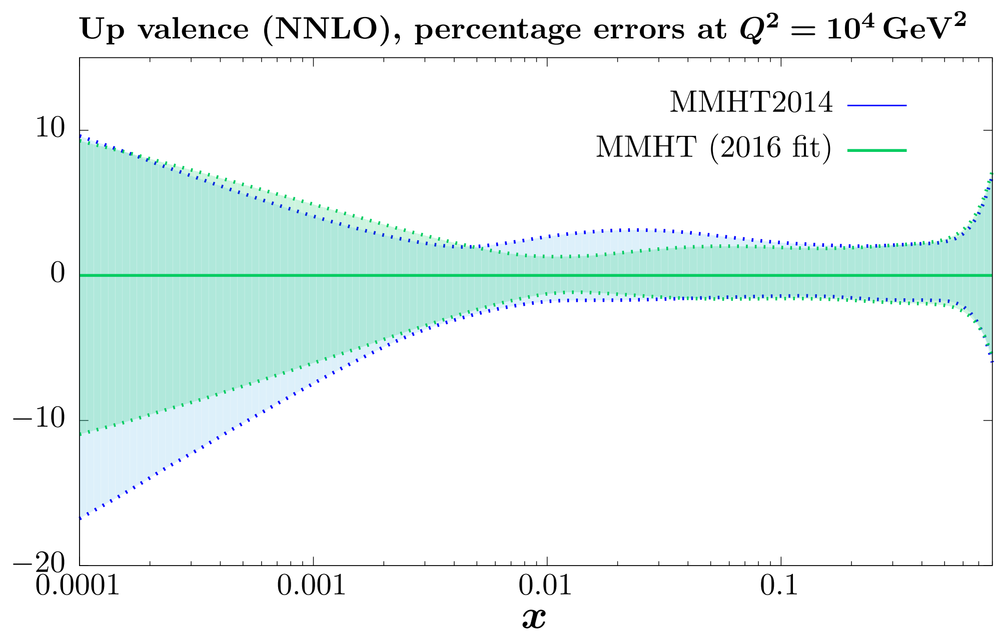




Main change and uncertainty reduction in u_v rather than d_v.

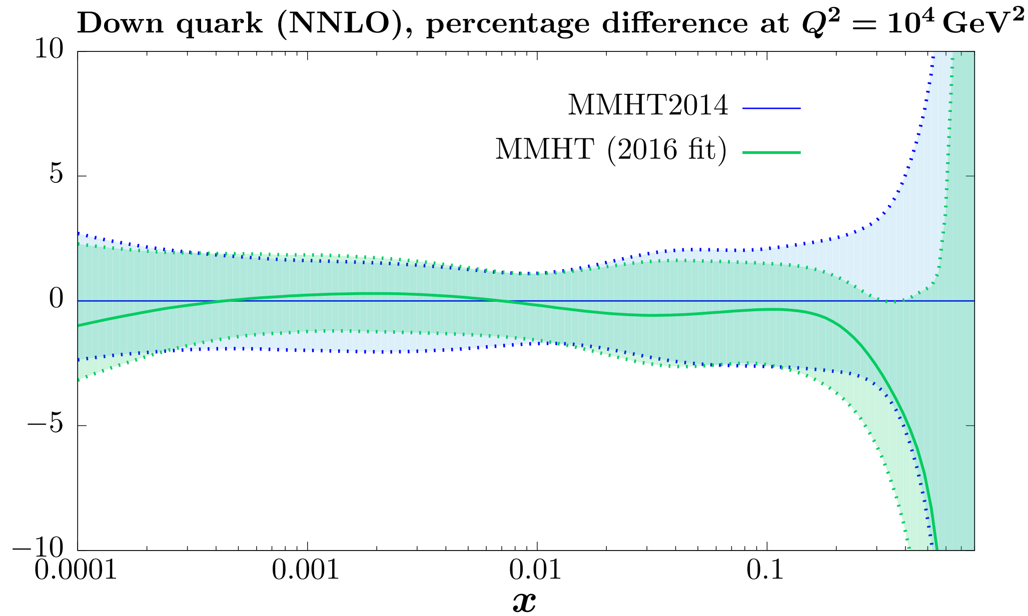
Mainly CMS data, but some impact of new HERA data.

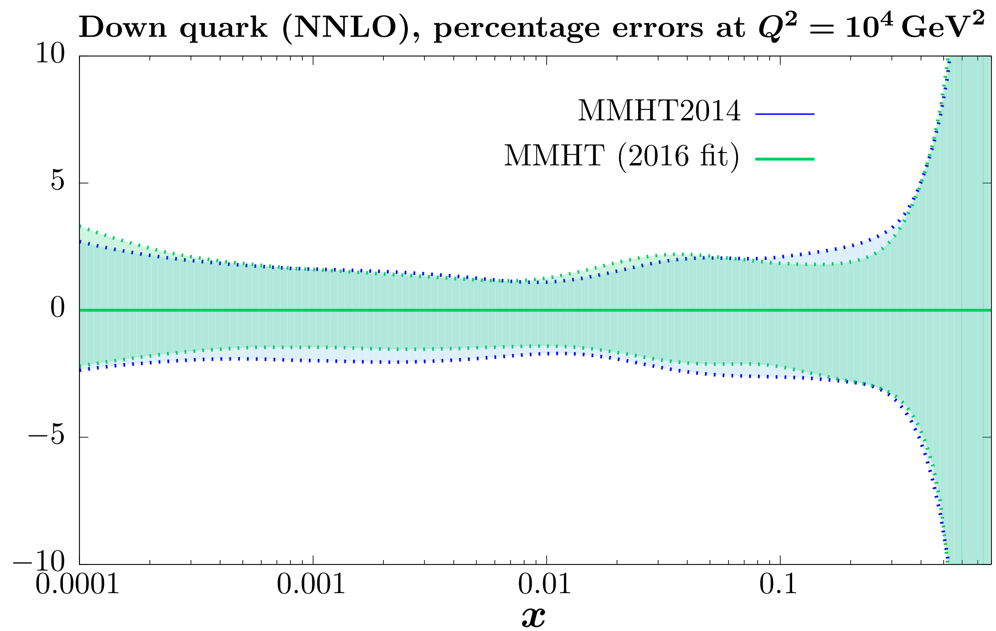


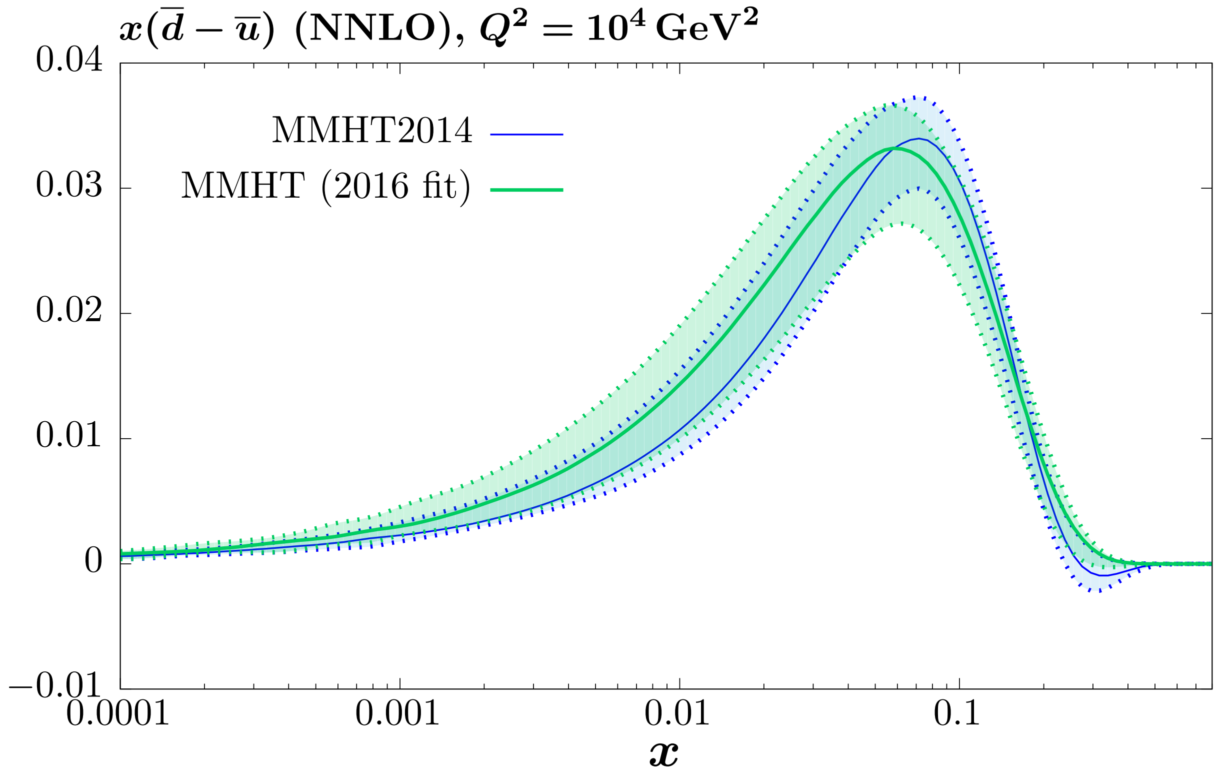


Small change in d at $x \sim 0.01$ and some reduction in uncertainty.

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







No major change in $\bar{d}-\bar{u}$, but even less inclination towards a change in sign at high x which was a feature of earlier sets.

Extension of $\bar{d} - \bar{u}$ parameterisation.

Claim of negative values preferred at small x in arXiv:1508.07923 (ABMP), and marginal preference, with large uncertainty, also from CT14 PDFs.

Currently use 3 free parameters, i.e.

$$(\bar{d} - \bar{u})(x, Q_0^2) = A(1-x)^{\eta_{sea}+2} x^{\delta}(1 + \gamma x + \Delta x^2),$$

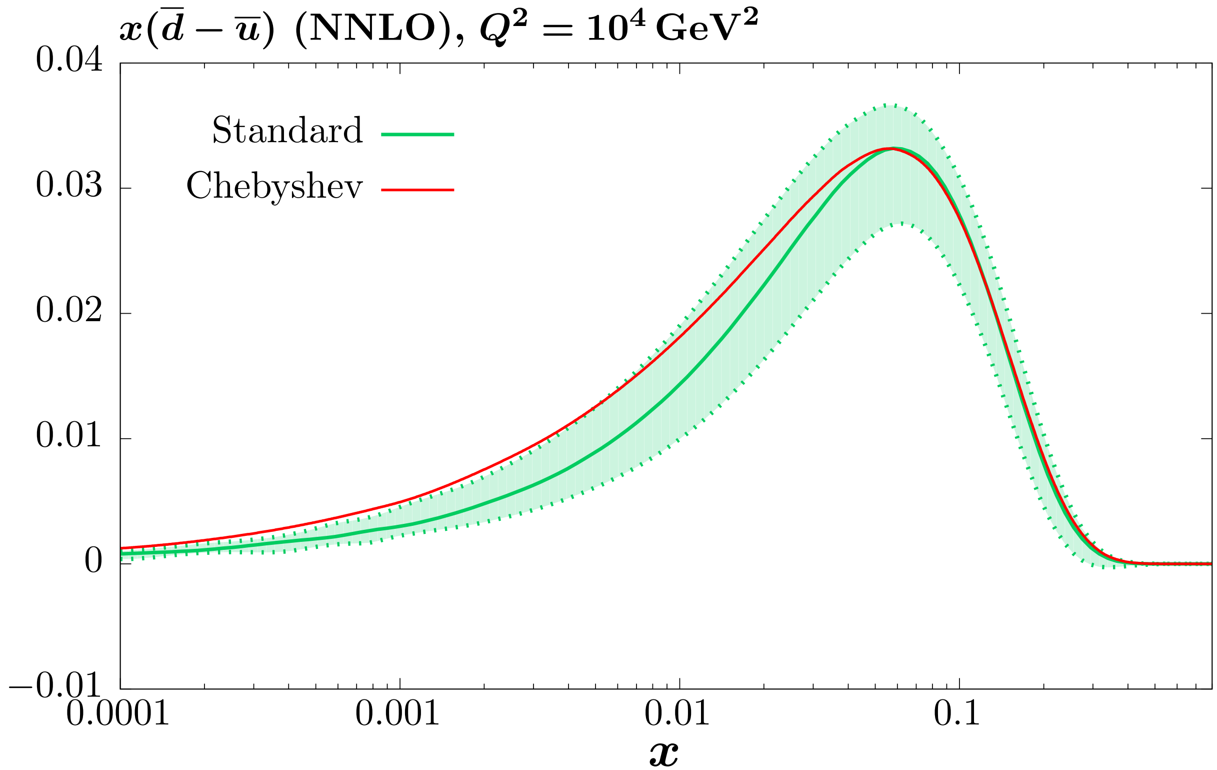
Extend to

$$(\bar{d} - \bar{u})(x, Q_0^2) = A(1-x)^{\eta_{sea}+2} x^{\delta}(1 + \textstyle\sum_{i=1}^{4} a_i T_i(1 - 2x^{\frac{1}{2}})),$$

where $T_i(1 - 2x^{\frac{1}{2}})$ are Chebyshev polynomials. So 5 free parameters. Easily allows multiple turning points (seen in first fit iteration).

Global fit improves by 6 units, relatively minor given 2 extra parameters and size of tolerance criterion.

Improvement of a couple of units in CMS $8\ TeV\ W^{+,-}$ data, newly included LHCb data, E866 total Drell Yan data (not asymmetry) and BCDMS structure function data.



New $(\bar{d}-\bar{u})$ distribution very similar at high x to previous one.

Now a slightly smaller decrease towards zero at low x at edge of previous uncertainty band.

No dramatic change but an improved parameterisation warranted and small-x uncertainty likely to increase due to extra freedom.

Attempted fit to high luminosity ATLAS $7\ \mathrm{TeV}$ inclusive jet data (JHEP 02 (2015) 153)

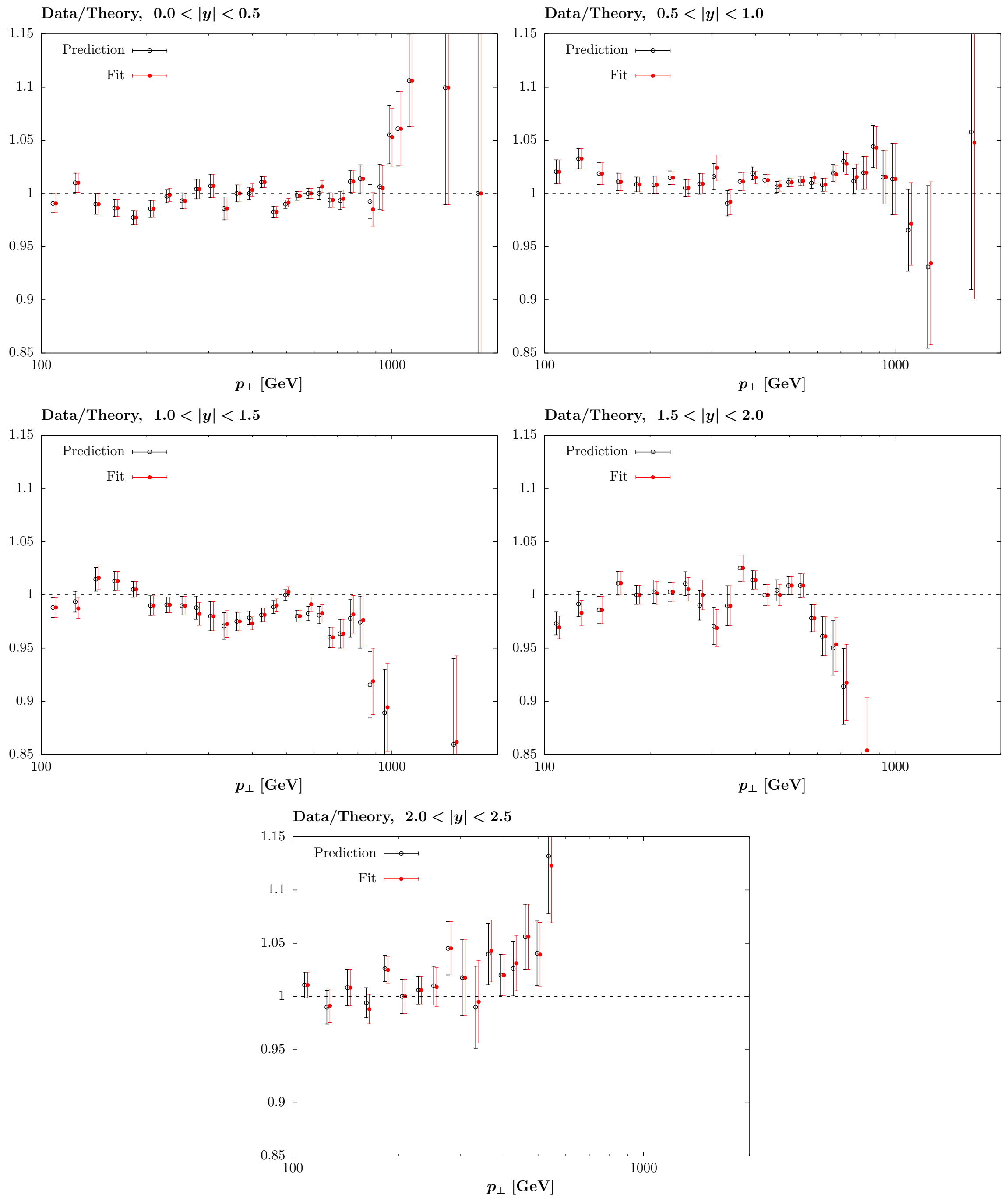
Prediction at NLO gives $\chi^2/N_{pts} = 411.5/140$.

Refit gives improvement only to $\chi^2/N_{pts} = 398.9/140$.

Deterioration in other data only $\Delta\chi^2 = 5.6$, so failure not due to strong tensions.

Cannot simultaneously fit data in all bins. Mismatch in one rapidity bin different in form to neighbouring bins probing PDFs of similar flavour, x and Q^2.

Similar results also seen by other groups.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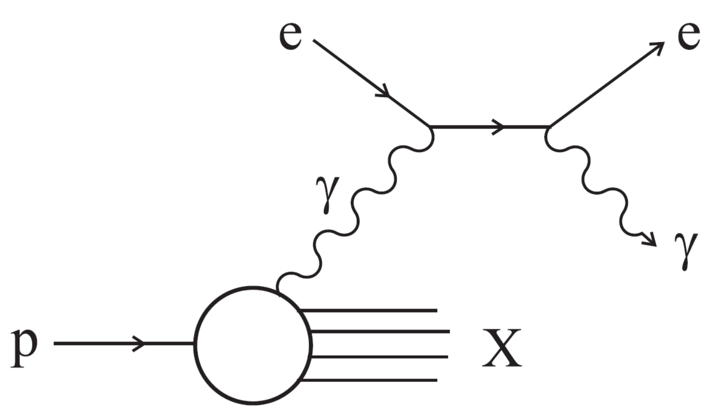
Data/Theory, $0.5 < |y| < 1.0$
Data/Theory, $1.0 < |y| < 1.5$
Data/Theory, $1.5 < |y| < 2.0$
Data/Theory, $2.0 < |y| < 2.5$
Prediction
Fit
$p_\perp$ [GeV]
100
1000
0.85
0.9
0.95
1
1.05
1.1
1.15

PDFs with QED corrections

At the level of accuracy we are now approaching it is important to account for electroweak corrections. At the LHC this can be important for many processes ($W, Z, WH, ZH, WW, jets \ldots$).

For a consistent treatment need PDFS which incorporate QED into the evolution, i.e. the inclusion of the photon PDF $\gamma(x, Q^2)$.

(A. De Rujula *et. al.* Nucl. Phys. B154 (1979) 394, J. Kripfganz and H. Perlt, Zeit. Phys. C41 (1988) 319, J. Blümlein, Zeit. Phys. C47 (1990) 89.)

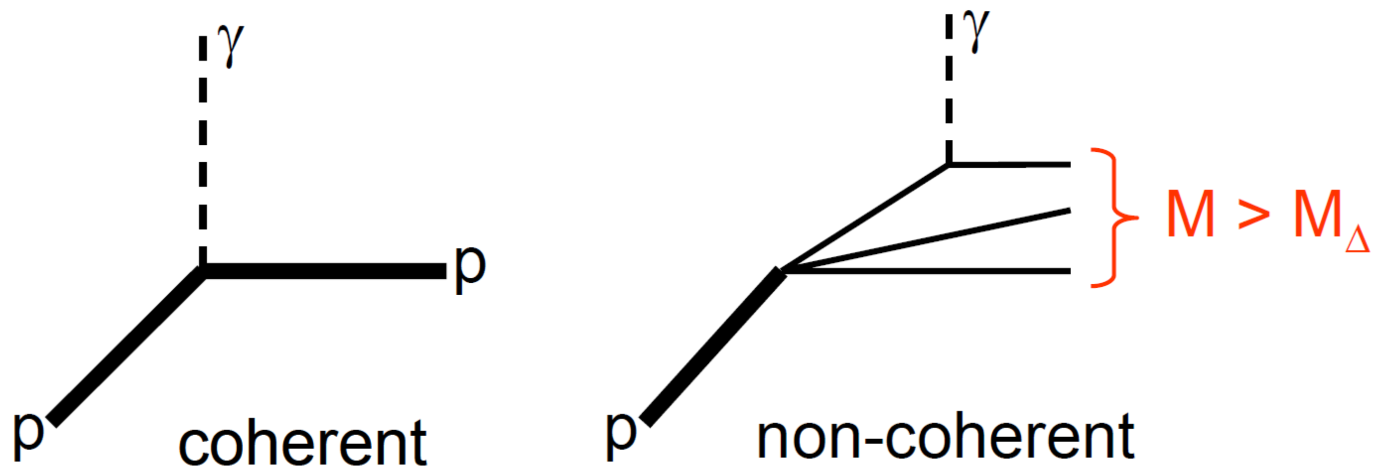


$$\frac{\partial \gamma(x, Q^2)}{\partial \log Q^2} = \frac{\alpha}{2\pi} \int_x^1 \frac{dy}{y} \left(P_{\gamma\gamma} \otimes \gamma + \sum_1 e_i^2 P_{\gamma q} \otimes q_i \right)$$

Set published by NNPDF and recently CT.

Previous sets MRST2004 assumed $\gamma(x, Q^2)$ generated by photon emission off model for valence quarks with QED evolution from $m_q \rightarrow Q_0^2$. Freedom in choice of quark mass, e.g. current mass $\rightarrow$ constituent mass.

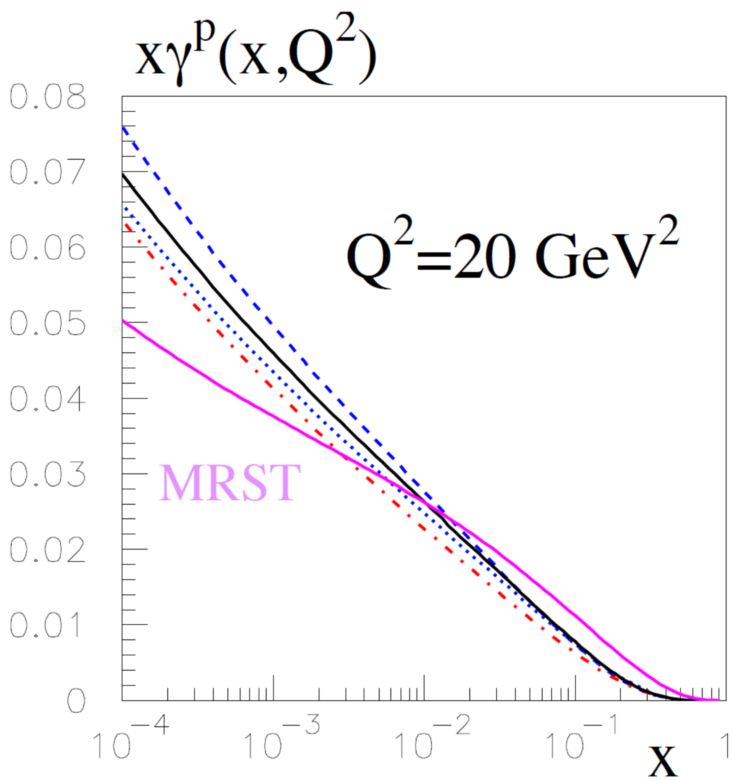
Article by Martin, Ryskin considers separate "coherent" emission and "non-coherent" emission – avoiding double counting.

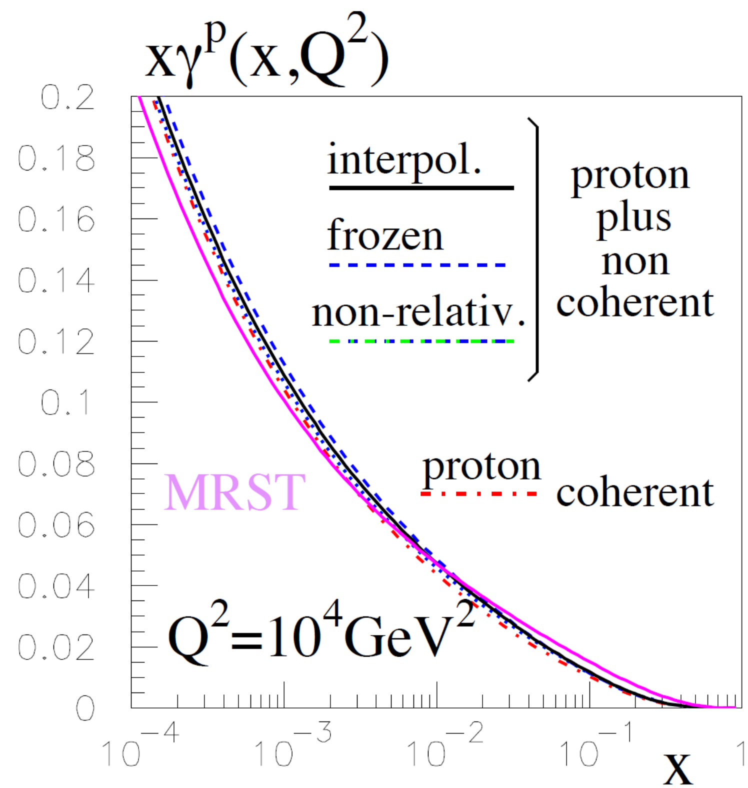


$$\gamma^N(x, Q_0^2) = \gamma^N_{\rm coh} + \gamma^N_{\rm incoh}$$

In practice more constraint on input determination. “Coherent” dies away quickly above Q_0^2, but dominates in input distribution.

Tends to increase $\gamma(x, Q^2)$ at low x, and decrease contribution from incoherent at high x.

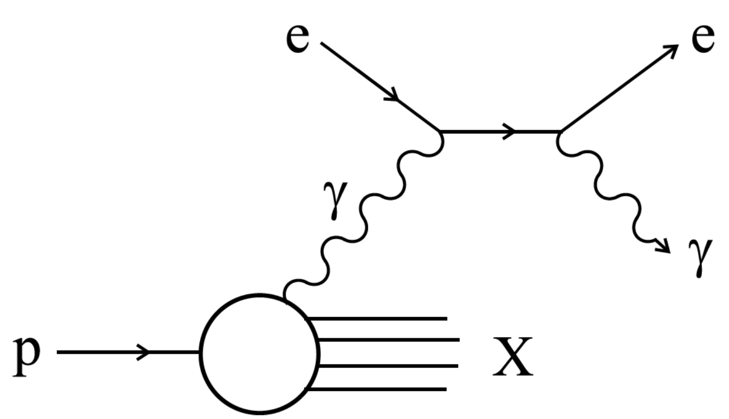


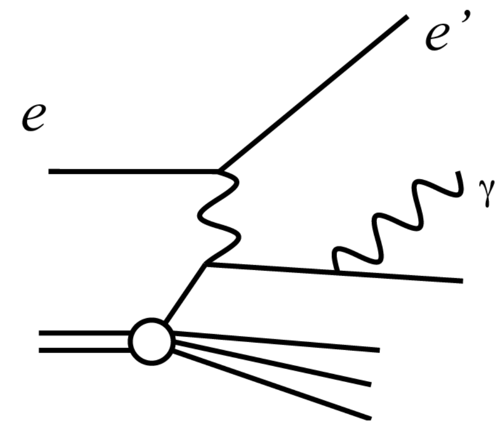


H1 and ZEUS have measurement of isolated photon DIS

$$ep \rightarrow e\gamma + X$$

Important constraint. MRST2004 photon was in good agreement with inclusive ZEUS data for current mass.





Necessary to consider radiation from quark line also - suggests constituent mass assumption (very similar to median NNPDF2.3 photon until very small x) much better (CT14QED). At large negative η and high photon E_T the photon-initiated process dominates.

Detailed study a high priority. Under way with student (Nathvani).

Conclusions

New HERA II combined data studied with context of MMHT2014 PDFs. Fit quality good – better at NNLO. No very significant changes in PDFs or predictions. Slight reduction in uncertainties. Effect of lower χ^2 per point for increased $Q^2_{\rm min}$. Seems to be entirely solved by larger F_L at low x, Q^2. High x, Q^2 data prefers reduced F_L.

Predictions turn out to be good for (most) LHC data previously not included in the fit. Few changes of significance in central values, but some data reduce uncertainties, mainly in strange and low-x valence quarks.

Some new $\sigma_{\bar{t}t}$ data. Fitted m_t^{pole} compatible with world average and there is a small increase in fitted $\alpha_S(M_Z^2)$ at NNLO.

Much extended $\bar{d}-\bar{u}$ parameterisation only leads to very minor changes. Smooth monotonic decrease at small x preferred.

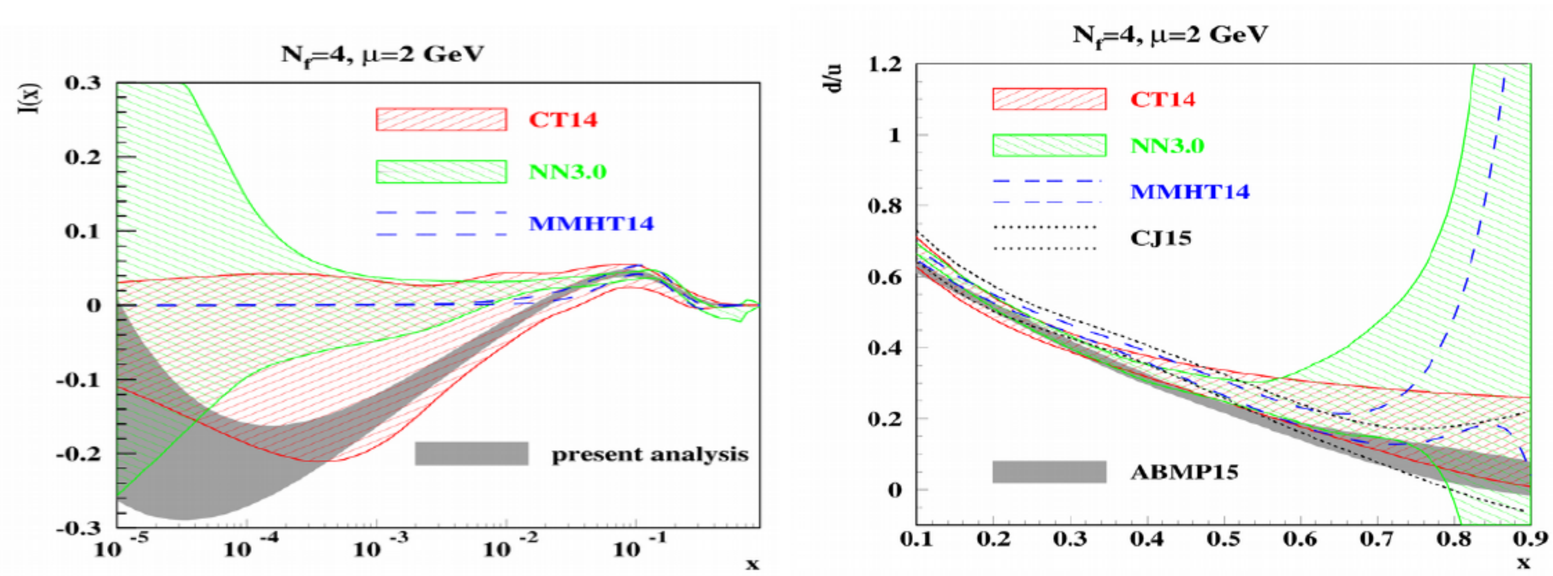
Failure to fit ATLAS $7\ TeV$ jet data at NLO - common with other groups.

Work beginning on updated PDFs with QED corrections. Related issues in talk by Harland-Lang.

Back -up

Open questions on $\bar{d} - \bar{u}$ at small x and d/u as $x \to 1$.

Impact of the forward Drell-Yan data



sa, Blümlein, Moch, Plačakytė, hep-ph/1508.07923

Accardi, et al. hep-ph/1603.08906