MMHT2014 PDFs - HERA I+II data and other updates.

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In collaboration with Lucian Harland-Lang, Patrick Motylinski and Alan Martin

and thanks to Ben Watt, Graeme Watt and James Stirling

I will cover a number of topics.

– Some clarifications on MMHT PDFs with varying quark masses.

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

– A brief intro to topics just starting investigation.

PDFs and Heavy Quarks

As before we made the standard PDFs sets (i.e. exactly the same input at $Q_0^2 = 1\ \mathrm{GeV}^2$) available for three flavour and four flavour fixed-flavour number schemes (FFNS).

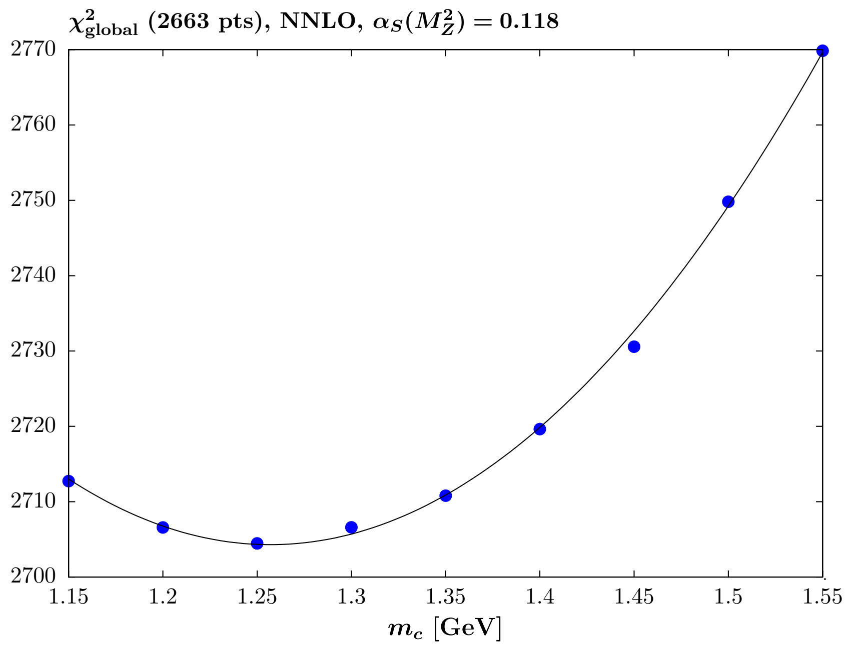
As default fix the number of flavours in α_S, but we also provide analogous sets with variable flavour α_S for $n_f = 4$ as there were some requests for this for MSTW2008.

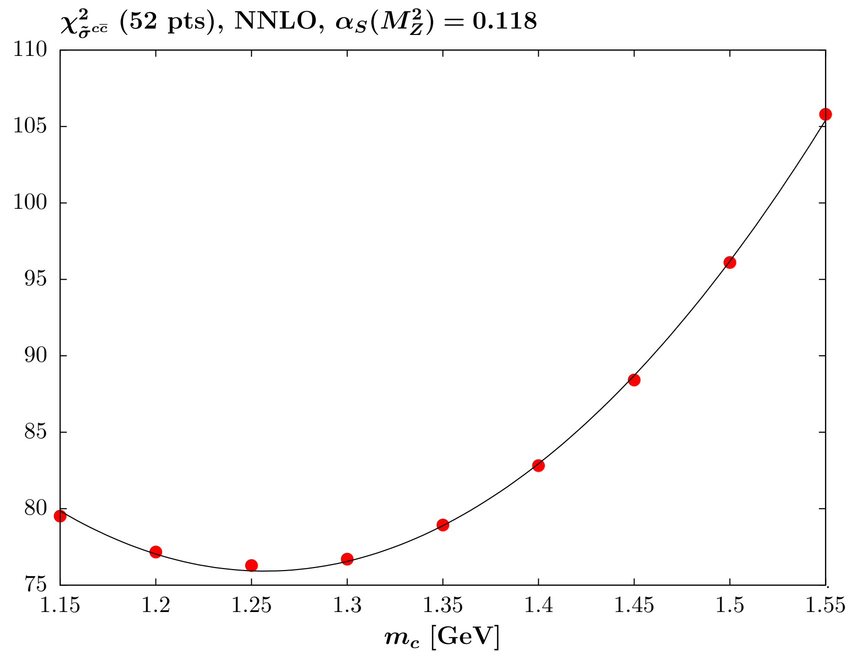
We have also made available sets with fits done for m_c and m_b (defined in pole scheme) varying from default values of $m_c = 1.40\ \mathrm{GeV}$ and $m_b = 4.75\ \mathrm{GeV}$ in steps of $0.05\ \mathrm{GeV}$ and $0.25\ \mathrm{GeV}$ respectively.

Might expect $m_c^{\mathrm{pole}} = 1.5 \pm 0.2\ \mathrm{GeV} \quad \mathrm{and} \quad m_b^{\mathrm{pole}} = 4.9 \pm 0.2\ \mathrm{GeV}$ from conversion of m_b from $\overline{MS}$ definition and $m_b^{\mathrm{pole}} - m_c^{\mathrm{pole}} = 3.4\ \mathrm{GeV}$ with a very small uncertainty (hep-ph/0509195, hep-ph/0408002), where renormalon ambiguity cancels.

m_b constrained to fairly close to $m_b = 4.75\ \mathrm{GeV}$ from direct $F_2^{\bar{b}b}(x, Q^2)$ data from HERA and m_c also constrained far better than previous range from various sources.

Dependence on m_c at NNLO in fits at fixed $\alpha_s(M_Z^2) = 0.118$.





Preference for $m_c \sim 1.25\text{GeV}$ - low but not inconsistent.

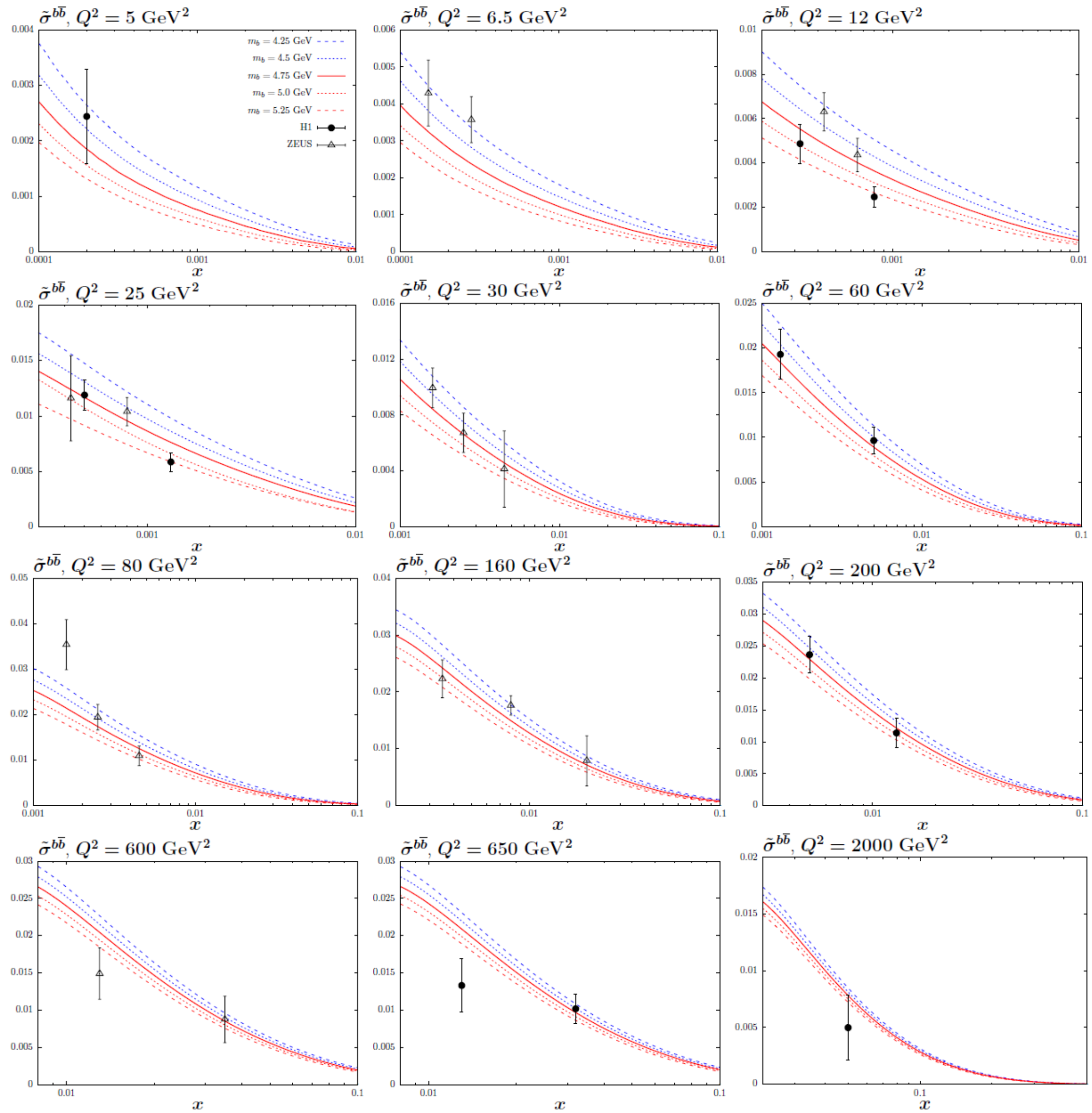
Variation with m_c for varying $\alpha_S(M_Z^2)$, e.g at NNLO.

m_c (GeV)	$\chi^2_{\rm global}$ 2663 pts	$\chi^2_{\tilde{\sigma}^{c\bar{c}}}$ 52 pts	$\alpha_s(M_Z^2)$
1.15	2703	78	0.1164
1.2	2699	76	0.1166
1.25	2698	75	0.1167
1.3	2701	76	0.1169
1.35	2707	78	0.1171
1.4	2717	82	0.1172
1.45	2729	88	0.1173
1.5	2749	96	0.1173
1.55	2769	105	0.1175

Weak dependence on $\alpha_S(M_Z^2)$, i.e. only 0.0005 from best to default m_c value, and PDFs change in largely anti-correlated manner to small-x gluon.

Fit to (unshifted) beauty cross section data.

Large fluctuations in both directions on scale of statistical uncertainties



Note that for both $\sigma^{c\bar{c}}$ and $\sigma^{b\bar{b}}$ details on mass dependence and absolute values of χ^2 depend on choice of multiplicative or additive definition of correlated uncertainties.

For $\sigma^{c\bar{c}}$ the χ^2 is lower and difference between NLO and NNLO less if the additive rather than multiplicative definition is used.

For both sets of data the additive definition pushes the preferred mass a little higher.

Variation of Cross Sections with quark masses Use $\Delta m_c = \pm 0.15$ GeV and $\Delta m_b = \pm 0.5$ GeV.

	σ	PDF unc.	m_c var.	m_b var.
W Tevatron (1.96 TeV)	2.78	$^{+0.0017}_{-0.056}$ $\left(^{+2.0\%}_{-2.0\%}\right)$	$^{+0.0017}_{-0.0086}$ $\left(^{+0.061\%}_{-0.31\%}\right)$	$^{-0.00092}_{-0.0015}$ $\left(^{-0.033\%}_{-0.052\%}\right)$
Z Tevatron (1.96 TeV)	0.256	$^{+0.0052}_{-0.0046}$ $\left(^{+2.0\%}_{-1.8\%}\right)$	$^{+0.00042}_{-0.0011}$ $\left(^{+0.16\%}_{-0.43\%}\right)$	$^{-0.00029}_{-0.000016}$ $\left(^{-0.11\%}_{-0.0059\%}\right)$
W^+ LHC (7 TeV)	6.20	$^{+0.103}_{-0.092}$ $\left(^{+1.7\%}_{-1.5\%}\right)$	$^{+0.029}_{-0.040}$ $\left(^{+0.48\%}_{-0.64\%}\right)$	$^{+0.0043}_{-0.014}$ $\left(^{+0.070\%}_{-0.22\%}\right)$
W^- LHC (7 TeV)	4.31	$^{+0.067}_{-0.076}$ $\left(^{+1.6\%}_{-1.8\%}\right)$	$^{+0.019}_{-0.022}$ $\left(^{+0.44\%}_{-0.51\%}\right)$	$^{+0.0059}_{-0.0091}$ $\left(^{+0.14\%}_{-0.21\%}\right)$
Z LHC (7 TeV)	0.964	$^{+0.014}_{-0.013}$ $\left(^{+1.5\%}_{-1.3\%}\right)$	$^{+0.0074}_{-0.0088}$ $\left(^{+0.77\%}_{-0.92\%}\right)$	$^{-0.00096}_{-0.00038}$ $\left(^{-0.10\%}_{-0.039\%}\right)$
W^+ LHC (14 TeV)	12.5	$^{+0.22}_{-0.18}$ $\left(^{+1.8\%}_{-1.4\%}\right)$	$^{+0.091}_{-0.12}$ $\left(^{+0.73\%}_{-0.93\%}\right)$	$^{+0.0087}_{-0.037}$ $\left(^{+0.069\%}_{-0.30\%}\right)$
W^- LHC (14 TeV)	9.3	$^{+0.15}_{-0.14}$ $\left(^{+1.6\%}_{-1.5\%}\right)$	$^{+0.064}_{-0.075}$ $\left(^{+0.69\%}_{-0.81\%}\right)$	$^{+0.012}_{-0.029}$ $\left(^{+0.13\%}_{-0.31\%}\right)$
Z LHC (14 TeV)	2.06	$^{+0.035}_{-0.030}$ $\left(^{+1.7\%}_{-1.5\%}\right)$	$^{+0.021}_{-0.025}$ $\left(^{+1.03\%}_{-1.2\%}\right)$	$^{-0.0035}_{-0.0013}$ $\left(^{-0.17\%}_{-0.062\%}\right)$

	σ	PDF unc.	m_c var.	m_b var.
$t\bar{t}$ Tevatron (1.96 TeV)	7.5	$^{+0.21}_{-0.20}$ $\left(^{+2.8\%}_{-2.7\%}\right)$	$^{-0.059}_{+0.077}$ $\left(^{-0.78\%}_{+1.0\%}\right)$	$^{+0.0088}_{+0.0015}$ $\left(^{+0.12\%}_{+0.20\%}\right)$
$t\bar{t}$ LHC (7 TeV)	176	$^{+3.9}_{-5.5}$ $\left(^{+2.2\%}_{-3.1\%}\right)$	$^{-1.1}_{+1.4}$ $\left(^{-0.60\%}_{+0.77\%}\right)$	$^{+0.77}_{-0.009}$ $\left(^{+0.44\%}_{-0.0051\%}\right)$
$t\bar{t}$ LHC (14 TeV)	970	$^{+16}_{-20}$ $\left(^{+1.6\%}_{-2.1\%}\right)$	$^{-3.0}_{+3.1}$ $\left(^{-0.31\%}_{+0.32\%}\right)$	$^{+3.1}_{-1.7}$ $\left(^{-0.32\%}_{+0.17\%}\right)$

	σ	PDF unc.	m_c var.	m_b var.
Higgs Tevatron (1.96 TeV)	0.87	$^{+0.024}_{-0.030}$ $\left(^{+2.7\%}_{-3.4\%}\right)$	$^{-0.0060}_{+0.0070}$ $\left(^{-0.68\%}_{+0.79\%}\right)$	$^{+0.0042}_{-0.0011}$ $\left(^{+0.48\%}_{-0.13\%}\right)$
Higgs LHC (7 TeV)	14.6	$^{+0.21}_{-0.29}$ $\left(^{+1.4\%}_{-2.0\%}\right)$	$^{+0.025}_{-0.019}$ $\left(^{+0.17\%}_{-0.13\%}\right)$	$^{+0.049}_{-0.044}$ $\left(^{+0.34\%}_{-0.30\%}\right)$
Higgs LHC (14 TeV)	47.7	$^{+0.63}_{-0.88}$ $\left(^{+1.3\%}_{-1.8\%}\right)$	$^{+0.27}_{-0.22}$ $\left(^{+0.57\%}_{-0.48\%}\right)$	$^{+0.16}_{-0.16}$ $\left(^{+0.34\%}_{-0.33\%}\right)$

Variations small but not insignificant. Easily understood from PDF behaviour. Suggest adding in quadrature.

$\sigma_{gg\rightarrow H}$ for $m_c = 1.15 - 1.55$ GeV and free α_S is $41.01 - 42.28$pb not the $40.48 - 42.08$pb (ignoring α_S-PDF correlation) appearing elsewhere.

HERA II **Combined data**

Recently released in arXiv:1506.06042.

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.

Compared to 621 data points, separated into 5 subsets, with generally larger uncertainties from HERA I (but fewer systematics) combined data used previously.

Prediction with MMHT2014 PDFs already fairly good.

NLO – $\chi^2 = 1611/1185 = 1.36$ per point

NNLO – $\chi^2 = 1503/1185 = 1.27$ per point

(HERAPDF2.0 get ~ 1.20 with $Q^2_{\rm min} = 2~{\rm GeV}^2$ at NLO and NNLO).

Under refitting in global fit

NLO – $\chi^2 = 1533/1185 = 1.29$ per point, with deterioration $\Delta\chi^2 = 29$ in other data.

NNLO – $\chi^2 = 1457/1185 = 1.23$ per point, with deterioration $\Delta\chi^2 = 12$ in other data.

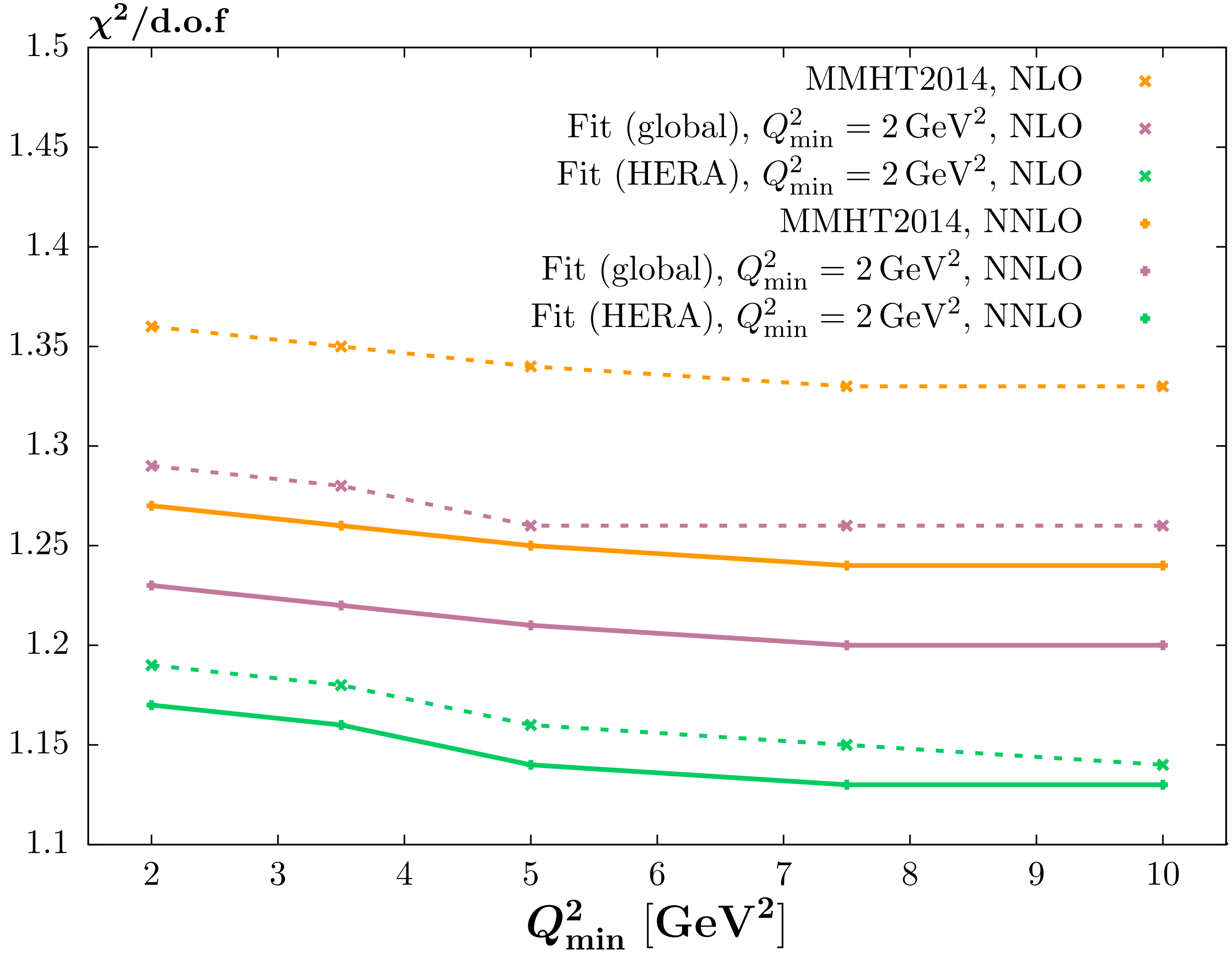
Also trying fitting only HERA II data, with 4 parameters fixed to avoid particularly unusual PDFs.

NLO – $\chi^2 = 1416/1185 = 1.19$ per point

NNLO – $\chi^2 = 1381/1185 = 1.17$ per point

NNLO definitely better than NLO.

Charged current χ^2 over 20 units better in HERA II only fit, and over 10 units better at NNLO.



Look at NLO compared to NNLO with different $Q^2_{\min}$ without refitting.

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

Breakdown of fit quality in subsets of data

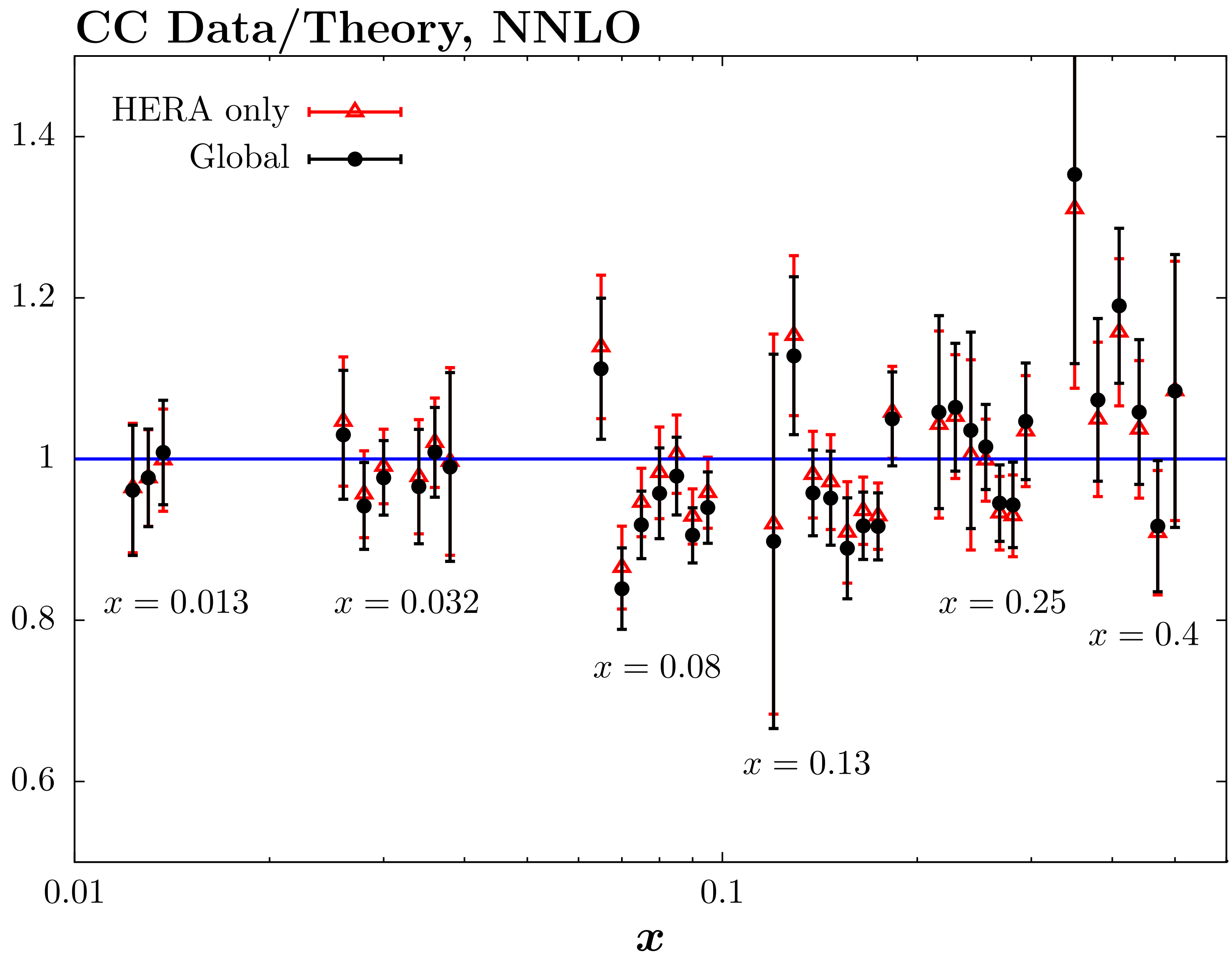
	no. points	NLO χ^2_{HERA}	NLO χ^2_{global}	NNLO χ^2_{HERA}	NNLO χ^2_{global}
correlated penalty		79.9	113.6	73.0	92.1
CC e^+p	39	43.4	47.6	42.2	48.4
CC e^-p	42	52.6	70.3	47.0	59.3
NC e^-p $E_p = 920$ GeV	159	213.6	233.1	213.5	226.7
NC e^+p $E_p = 920$ GeV	377	435.2	470.0	422.8	450.1
NC e^+p $E_p = 820$ 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 $Q^2_{\rm min} = 3.5\ {\rm GeV}^2$.

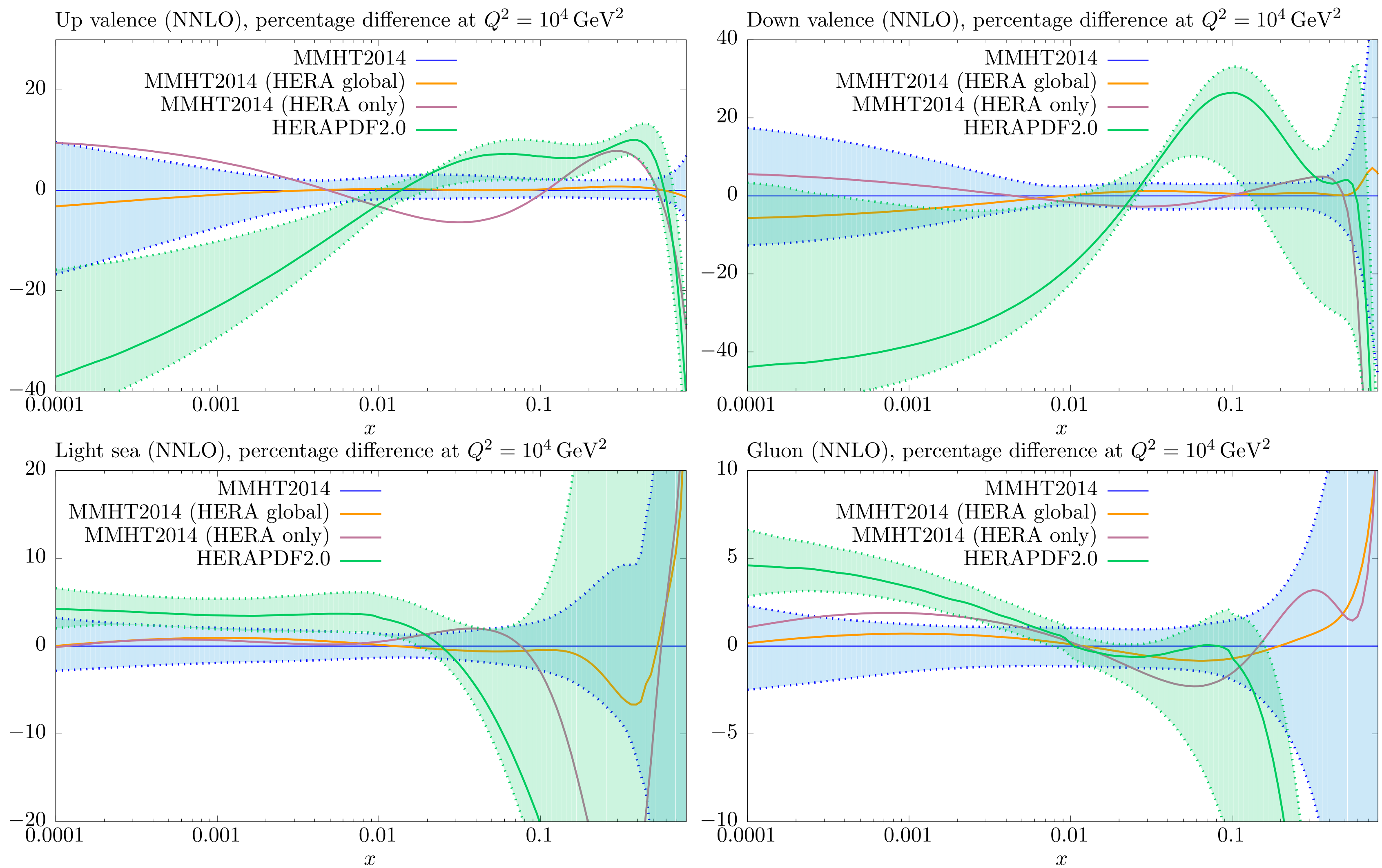
Large improvement in CC e^-p data when only HERA data fit. Probe of up (valence) quark at high x. Bigger effect at NLO.

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

Other data sets much smaller effect.

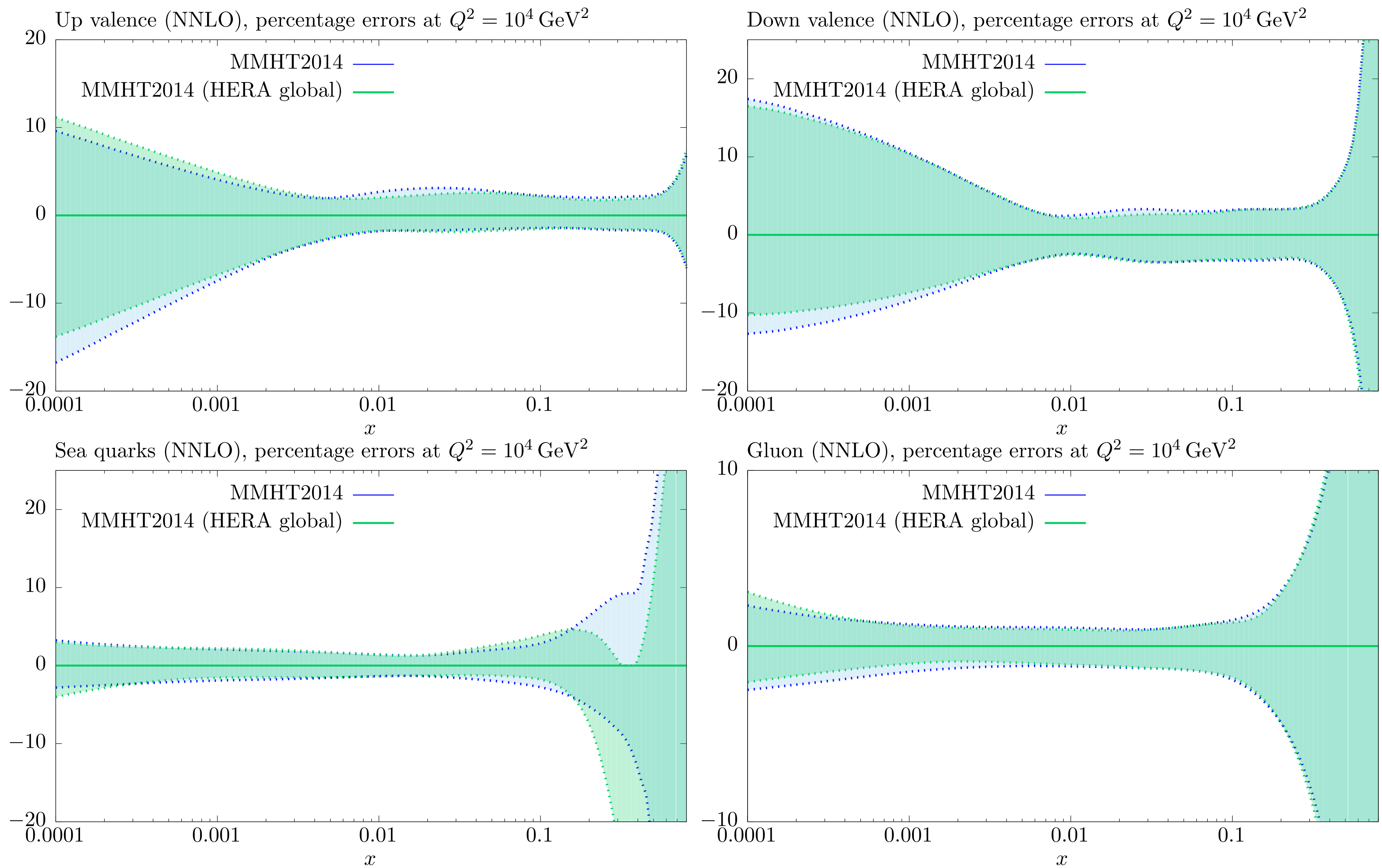


Clearly a different shape for the CC $e^{-}p$ data against theory in global and HERA-only fits. Affects up quark which is constrained by lots of other data.



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

Predictions for e.g. $gg \to H$ change by $< 0.3\%$ for LHC energies. When fitted $\alpha_S(M_Z^2)$ =0.1172-3, i.e. no real change from MMHT2014.



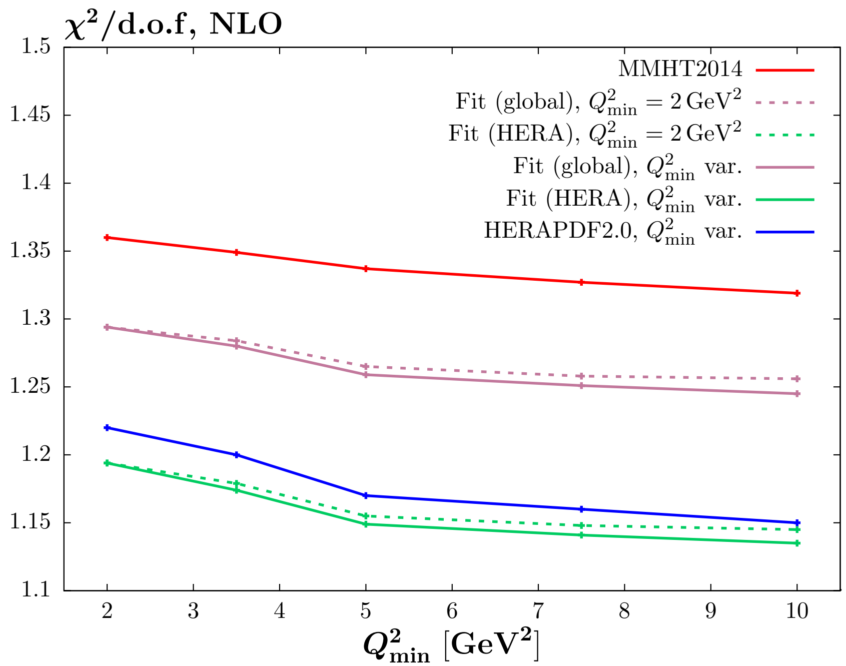
Uncertainties (preliminary) quite similar to MMHT2014.

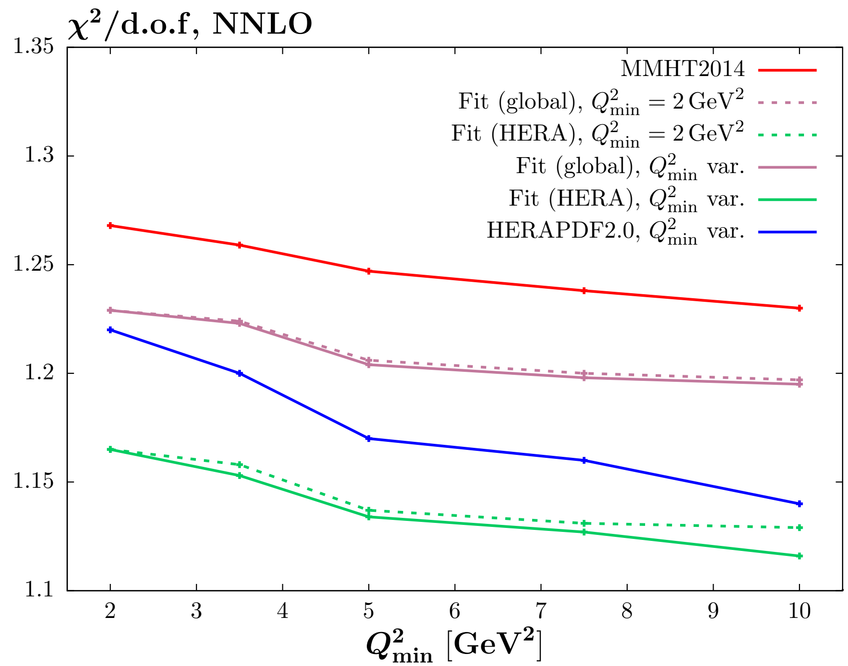
Most obvious improvement in gluon for $x \sim 0.001$.

Effect more obvious when looking at predictions.

	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.

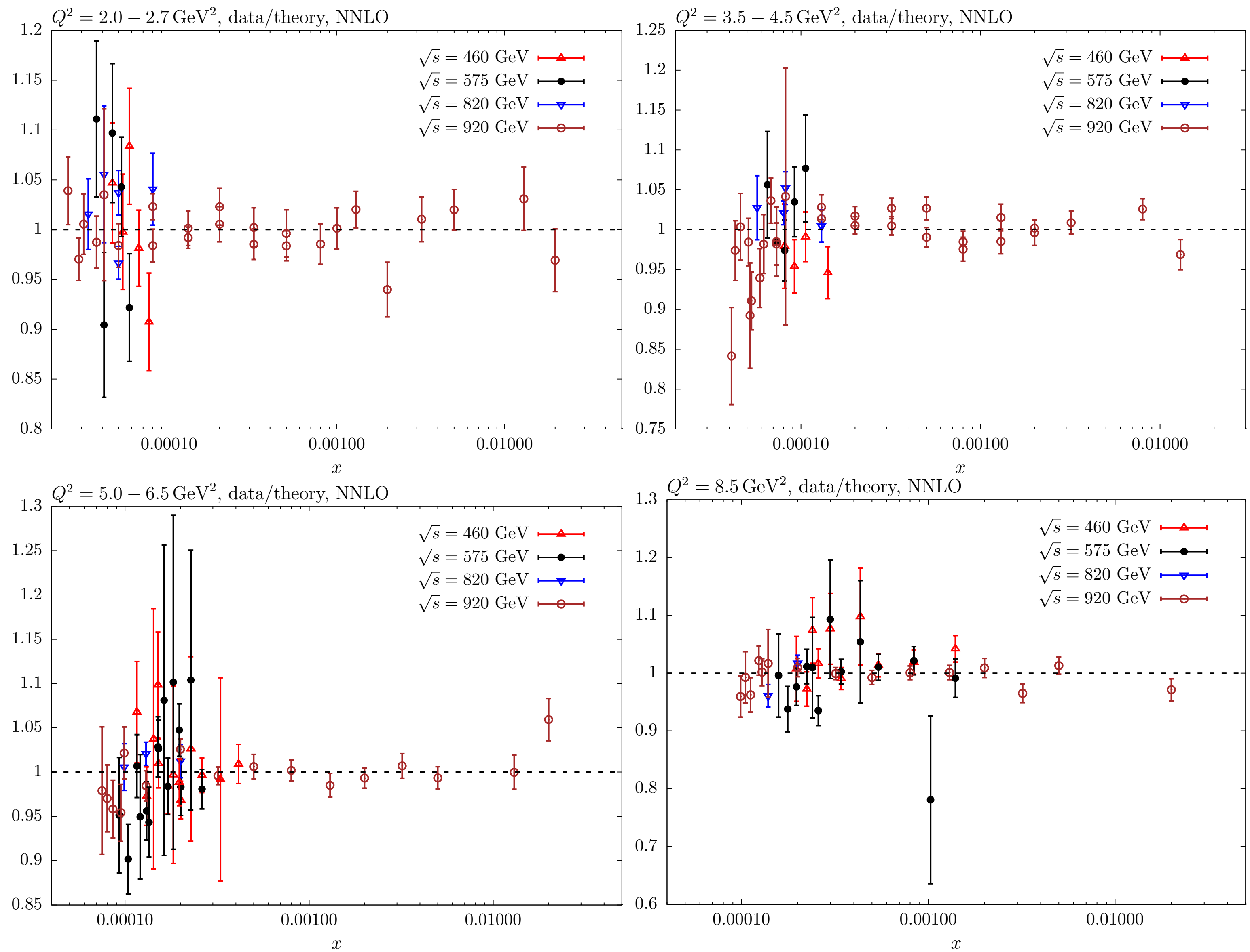




Also look at effect of changing the Q^2 cut, on only HERA II data, at both NLO and NNLO (note – definition of χ^2 for HERAPDF2.0 not identical.

Improvement in χ^2 with $Q^2_{\rm min}$ largely achieved without refitting.

Less improvement than for HERAPDF2.0 particularly in global fit and at NNLO.



Main obvious systematic trend in $2.5\ \mathrm{GeV}^2 \leq Q^2 < 5\ \mathrm{GeV}^2$ bin. Change in shift $\propto \delta_1$ procedural uncertainty when moving to $Q^2_{\mathrm{min}} = 3.5\ \mathrm{GeV}^2$.

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 $x < 0.01$.

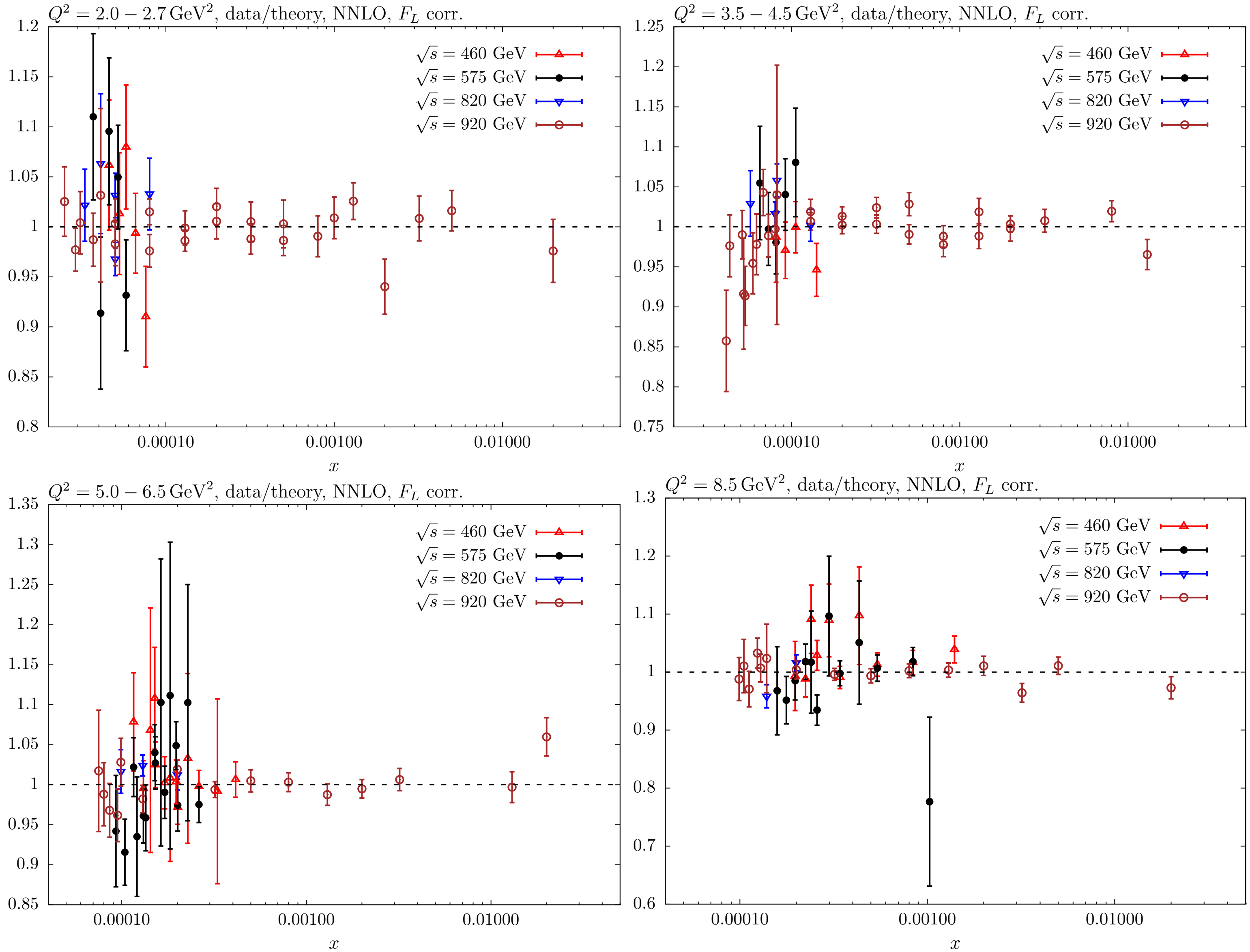
Just “guessing” $A = 1$ with no refit improves χ^2 by a few units.

Refit and leaving A as a free parameter $\to$ $\Delta\chi^2 = -24$ for $Q^2_{\rm min} = 2\ {\rm GeV}^2$. $A \approx 4$. Very similar in fit to only HERA data.

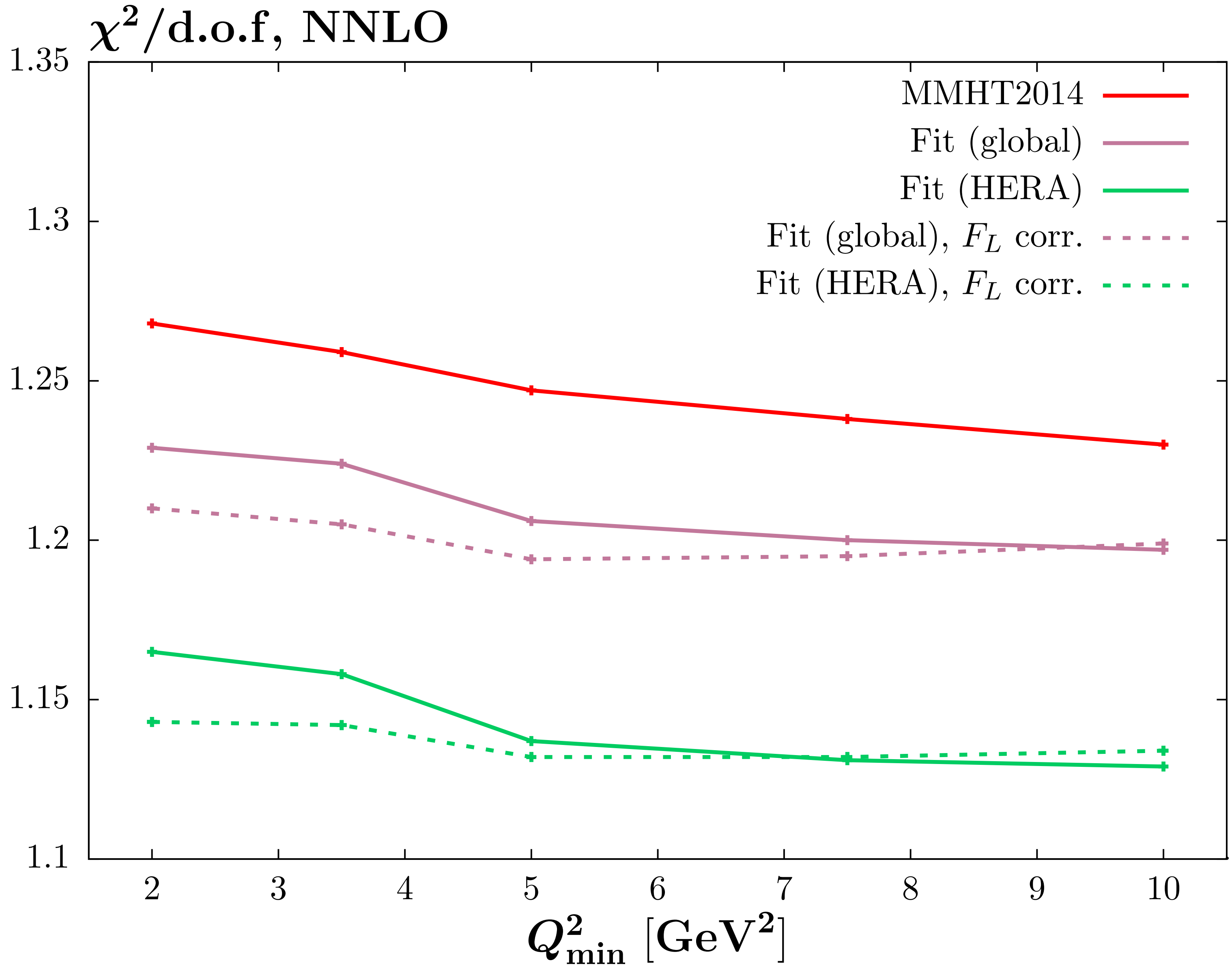
Also adding $(B/Q^4)F_L$ leads to little further improvement.

Try additionally corrections $F_2 \to (1 + A_i/Q^2)F_2$ in 6 bins for $x < 0.01$. $A_i \sim 0.1$, but with little significance and $\to \Delta\chi^2 = -10$ almost all in non HERA data. Very little effect in fit to only HERA data.

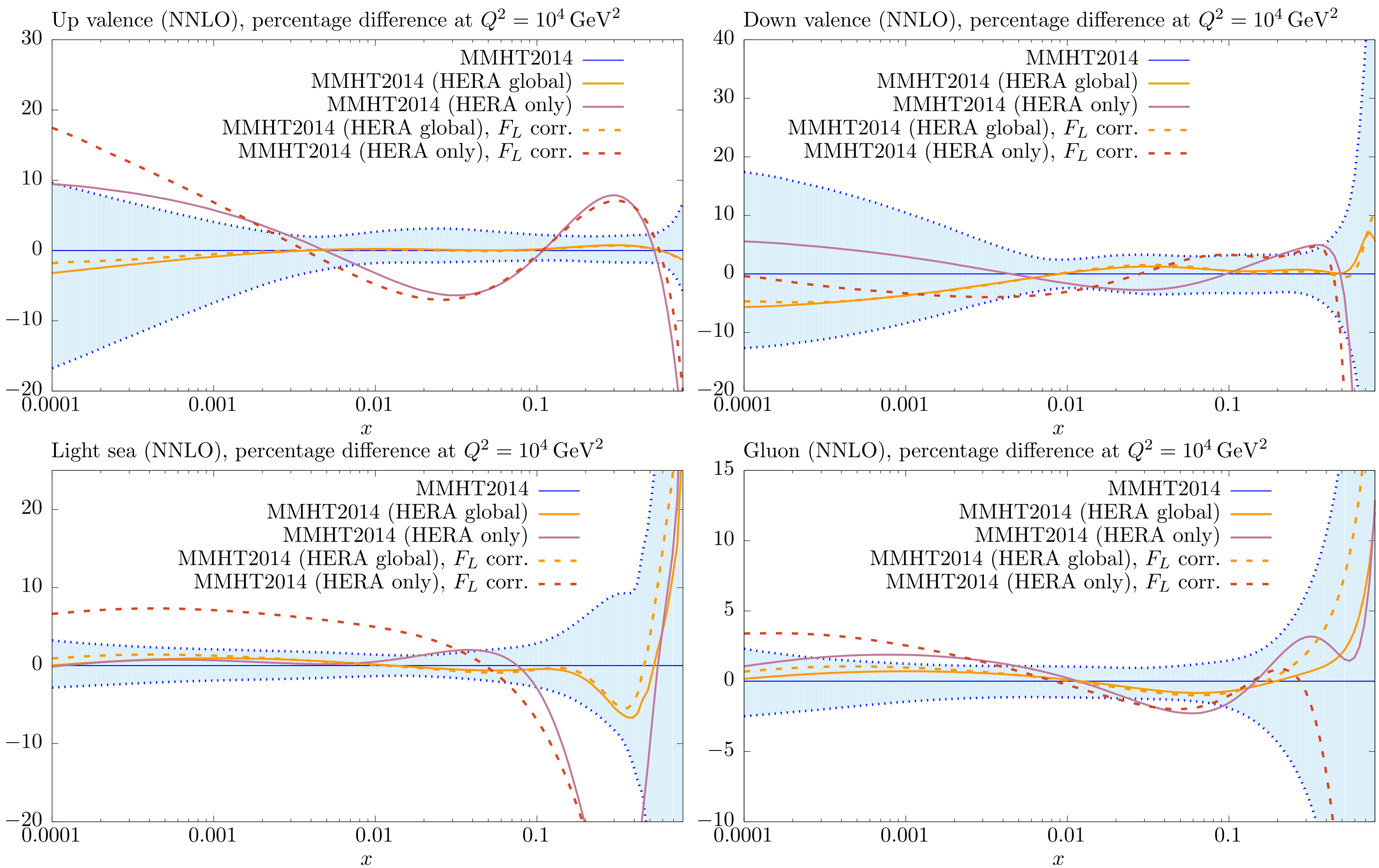
Best fit a big proportional change in $F_L(x, Q^2)$ at small x, Q^2 (high y requirement leads to strong correlation), but this is a region where $F_L(x, Q^2)$ in NLO, NNLO fits varies quickly and is sensitive to many potential corrections.



Some tightening of (data/theory) evident. Less evident "lowest x" overshoot. Still outliers to some extent despite much improved fit quality.



Just about all evidence of a fall of χ^2 per point with $Q^2_{\min}$ eliminated.



HERA II modified PDFs with allowed higher twist $F_L(x, Q^2)$ corrections very similar to those without, except up, down strange fractions in sea at small x, which have little constraint. More general small-x higher twist leads to no significant differences.

Try an alternative correction of the form $= F_L(x,Q^2)\left(1+\frac{\alpha_S(Q^2)}{4\pi}\frac{b_1}{x^{b_2}}\right)$.

Leads to $\rightarrow \Delta\chi^2 = -28$ with $b_1 = 0.014$ and $b_2 = 0.82$.

However, as at fixed y we have $x \propto Q^2$, the power of $b_2 \lesssim 1$in combination with the slow falling of α_S with Q^2 leads to the correction being effectively $\sim 1/Q^2$.

$\ln(1/x)$ terms less successful than the power term.

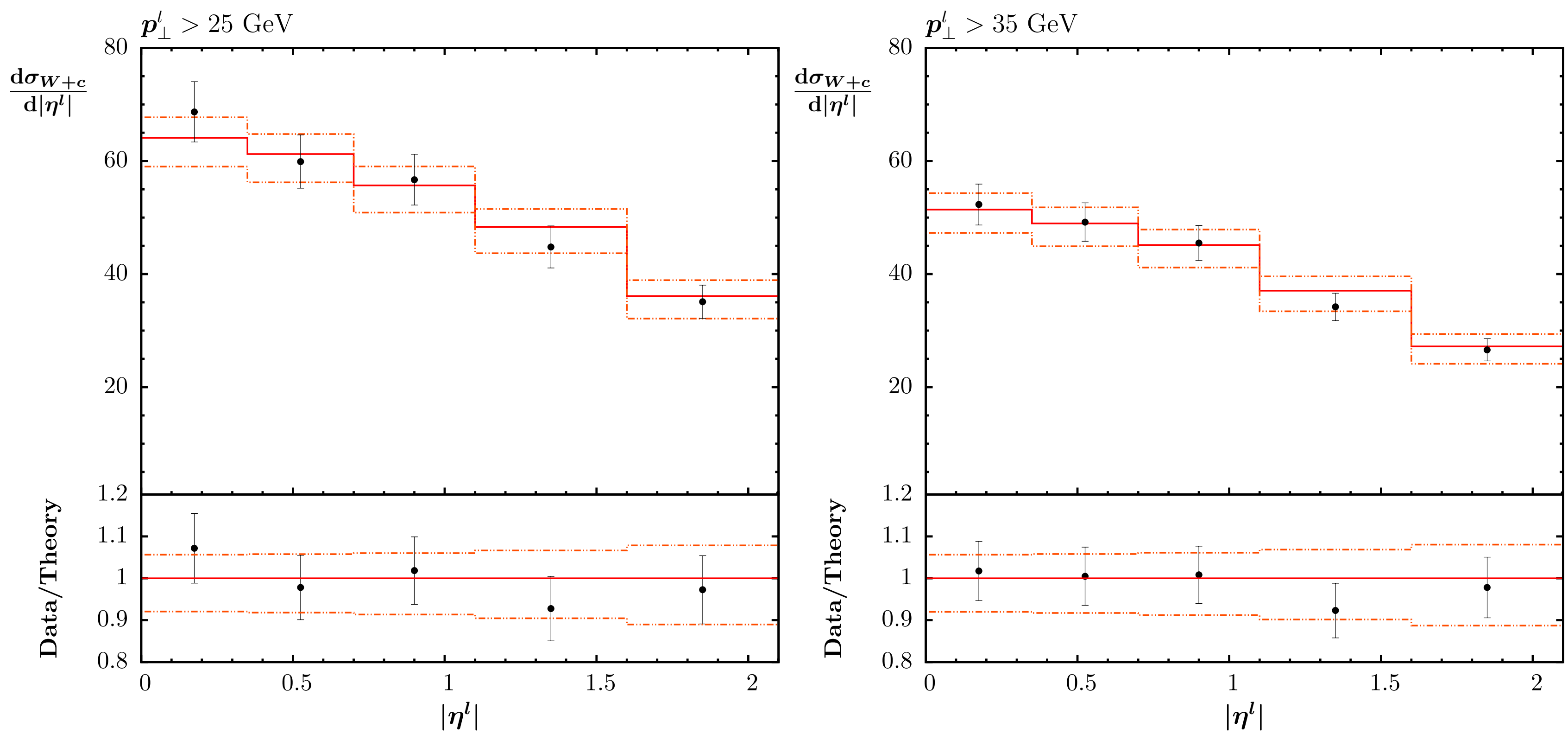
If we try an alternative correction of the form $F_L(x,Q^2)\,(1+c_1x^{c_2})$, then $\rightarrow \Delta\chi^2 = -13$ with $c_1 = -1.97$ and $c_2 = 0.42$, i.e. a negative correction to $F_L(x,Q^2)$ concentrated at high x, and hence high Q^2.

A detailed examination of data against theory show that the theory predictions at high Q^2 and high y show a tendency to undershoot the data, i.e. the opposite trend to the low Q^2 case.

An addition of both type of terms allows an overall $\rightarrow \Delta\chi^2 = -42$, even better than the sum of the two independent effects.

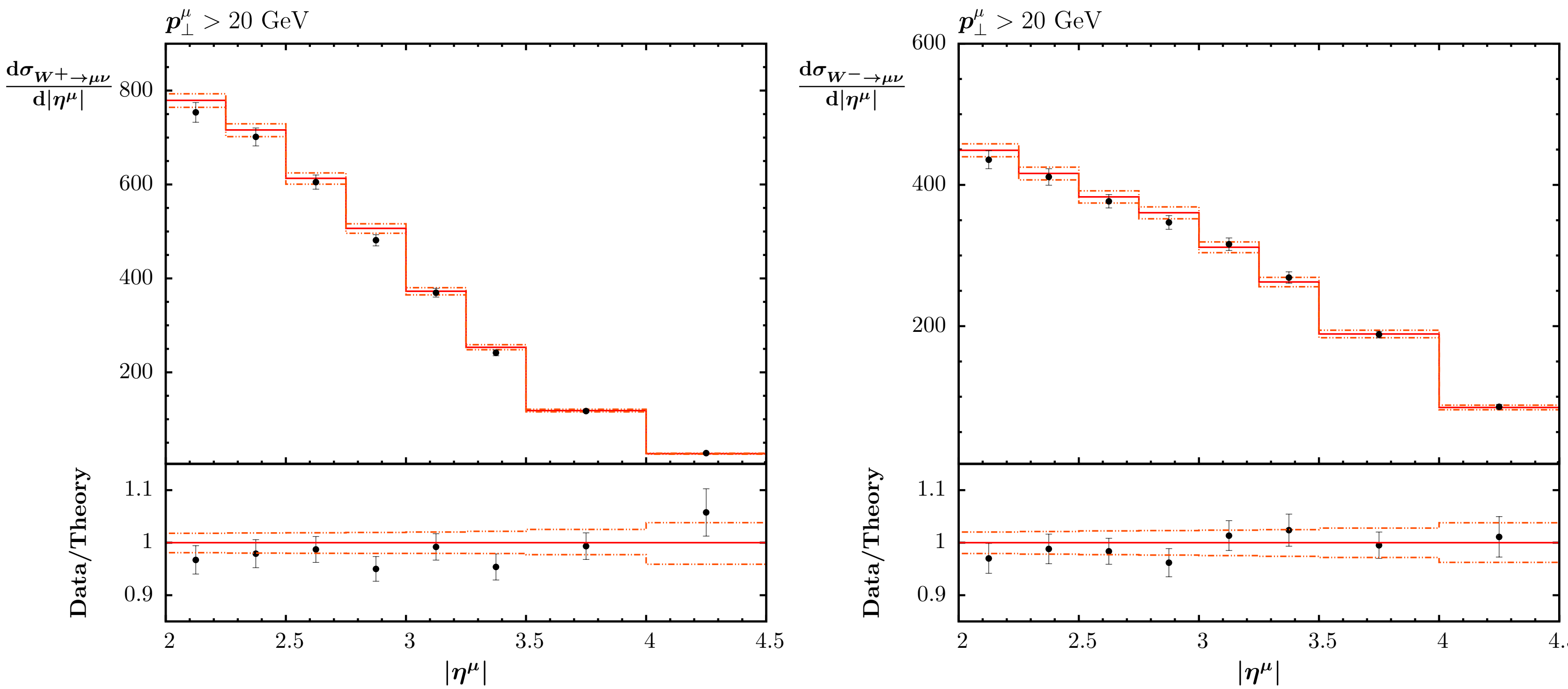
New data sets for fit – $W + c$ differential distributions.

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



MSTW2008 a bit low (especially for ATLAS), but MMHT2014 seems fine particularly for CMS (shown). Data will add some constraint.

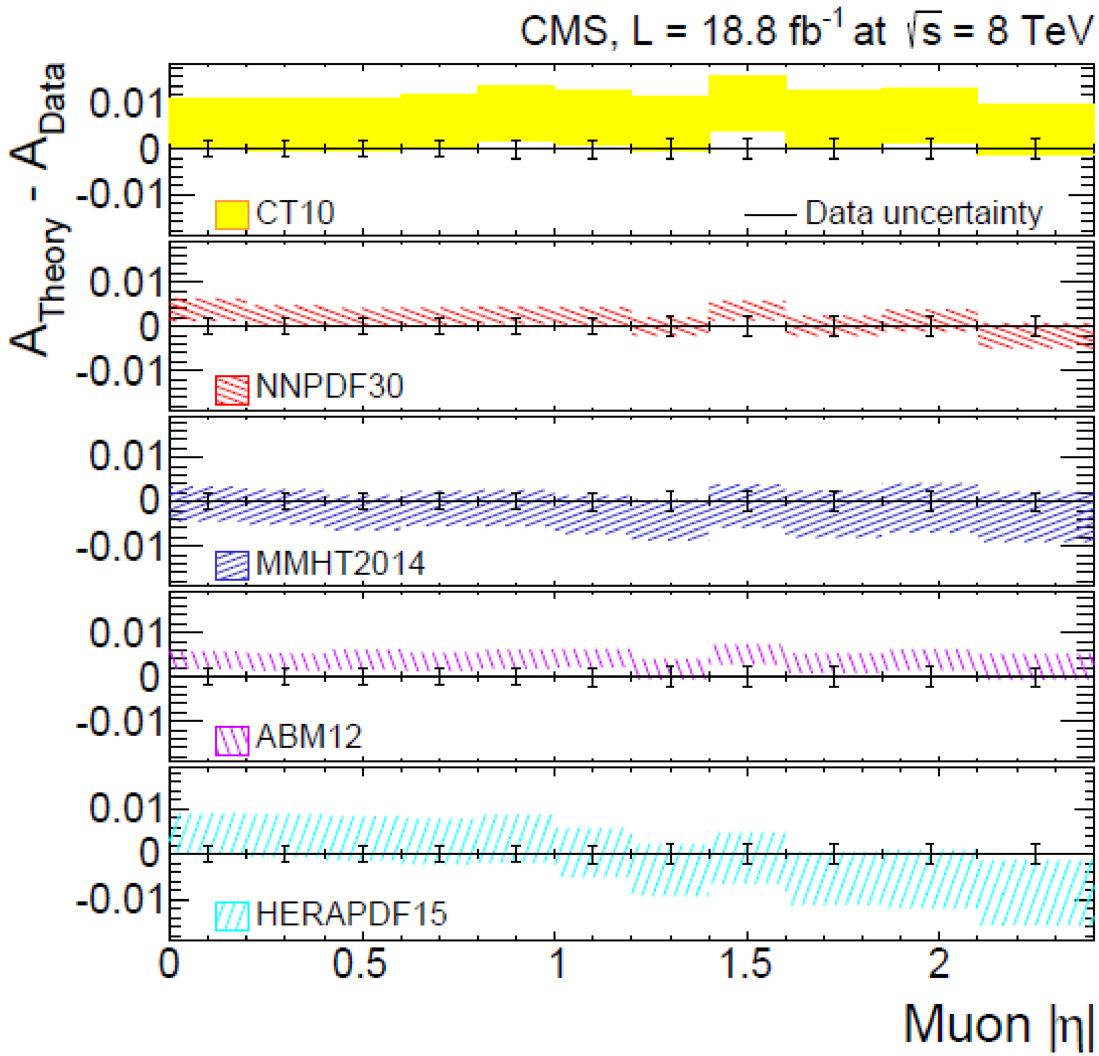
New data on high rapidity W production at LHCb at 7 TeV.



Generally perfectly good agreement using NNLO.

Also excellent agreement with high rapidity W production at LHCb at 8 TeV and recent W production data from CMS at 8 TeV, including asymmetry data.

Excellent agreement with new 8 TeV CMS $W^{\pm}$ rapidity and asymmetry data (shown).

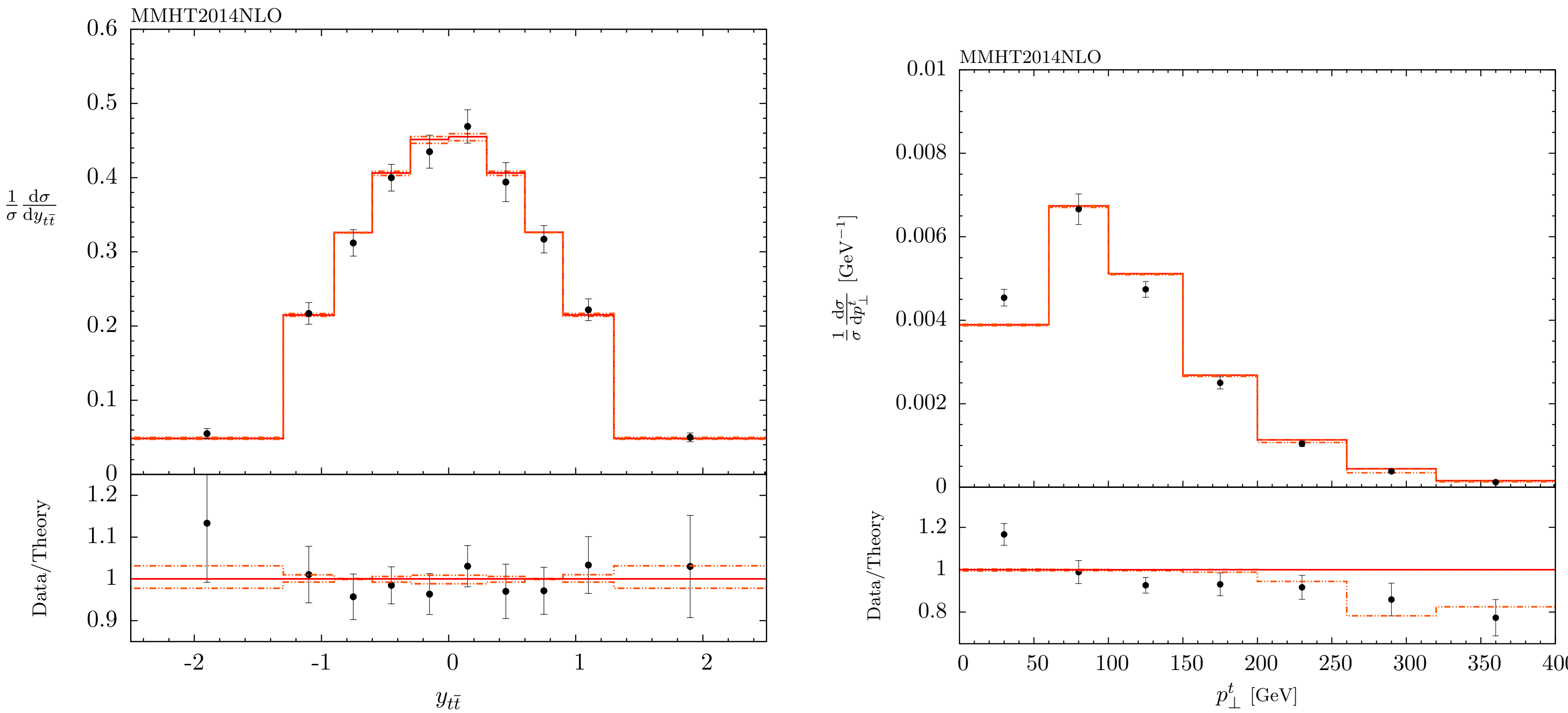


Small-x valence quarks appear to be working perfectly, but some scope for reduced uncertainty with new data inclusion.

New data sets for fit – $t\bar{t}$ differential distributions.

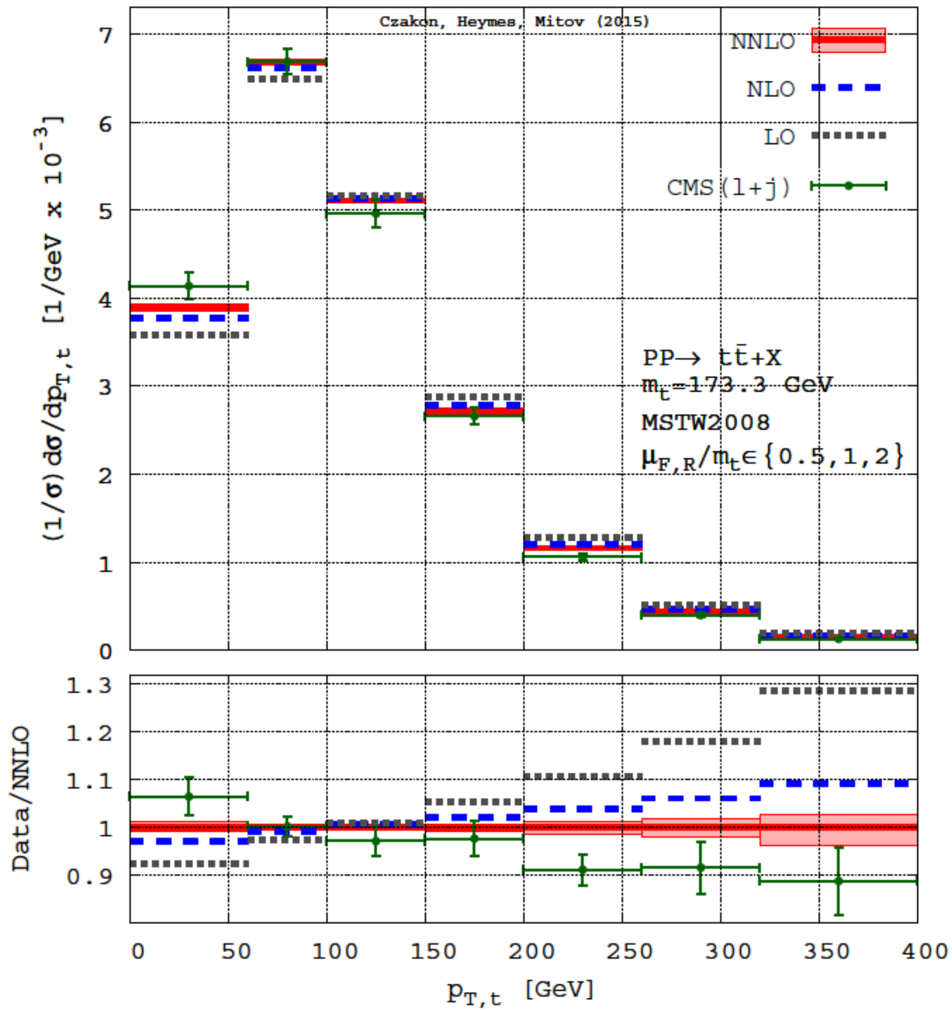
Variety of data sets not in PDF determination as they did not meet cut-off date and/or missing NNLO corrections.

For example, differential $\bar{t}t$ production (show CMS below). $y_{\bar{t}t}$ distribution at NLO very good, p_t distribution off in shape ($m_{\bar{t}t}$ somewhere in between).

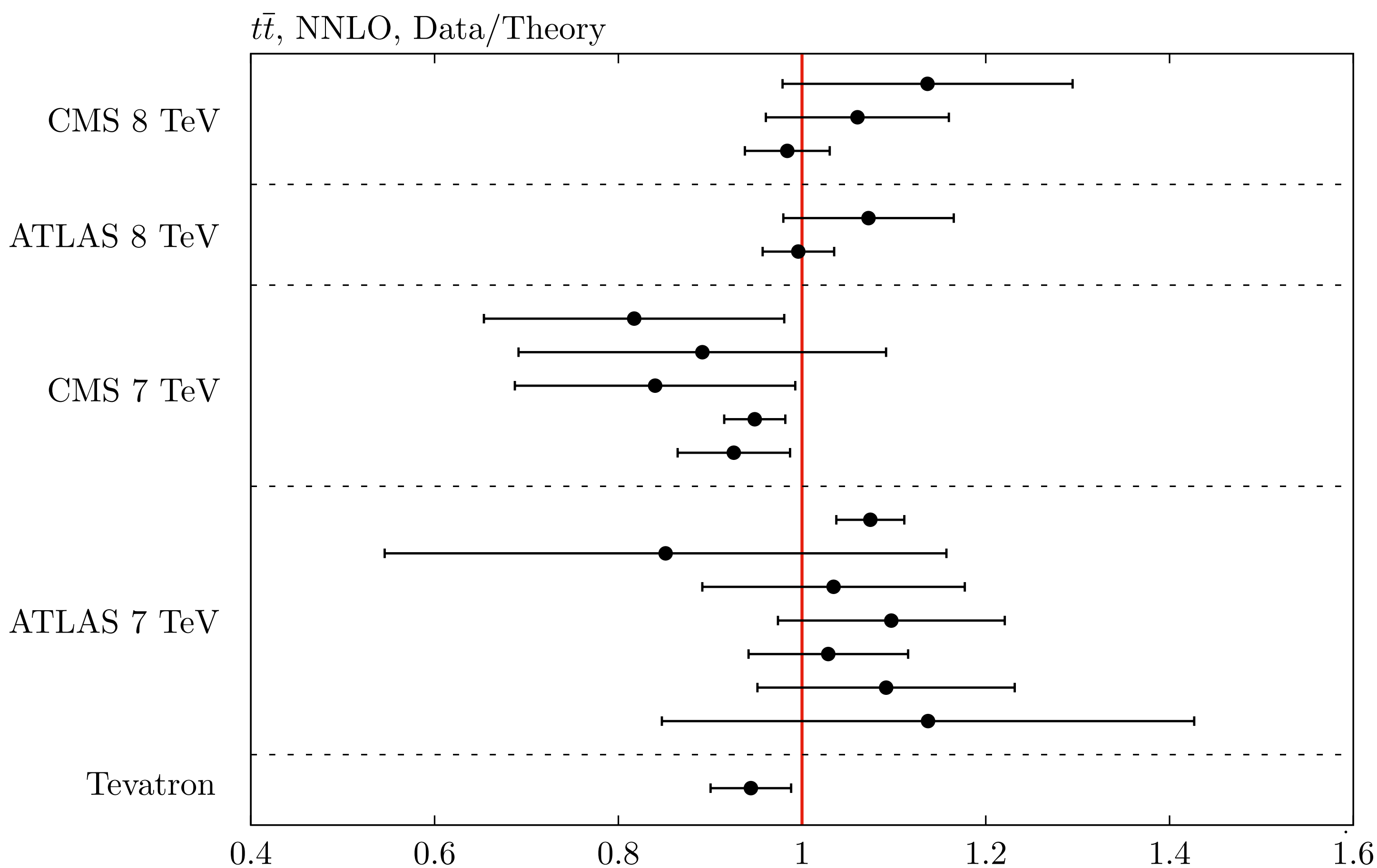


Full NNLO correction (Czakon, Heymes and Mitov) improved comparison with p_t data considerably.

Little change in $y_{\bar{t}t}$, and some in $m_{\bar{t}t}$.



Included provisionally some more up-to-date results on $\sigma_{\bar{t}t}$ along with final HERA data.



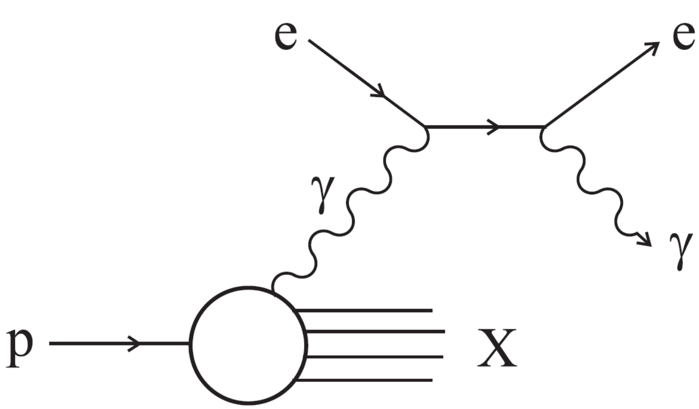
Fit very good and with $\alpha_S(M_Z^2) = 0.118$ the fitted $m_t^{pole} = 173.9$ GeV. When fitted $\alpha_S(M_Z^2) = 0.1174$ with $m_t^{pole} = 173.5$ GeV.

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.)

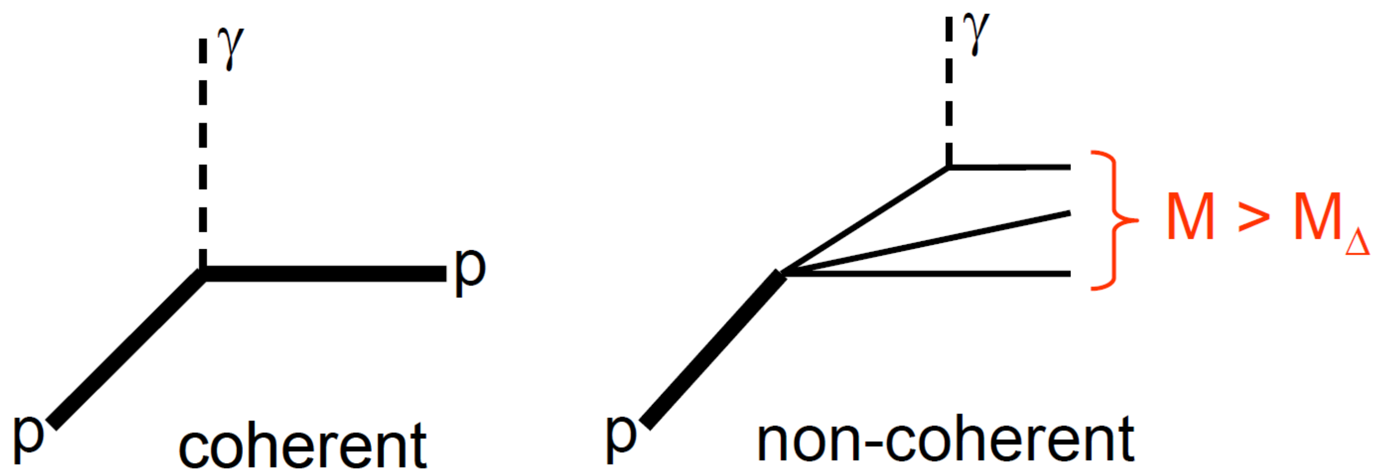


$$\frac{\partial \gamma(x, Q^2)}{\partial \log Q^2} = \frac{\alpha}{2\pi} \int_x^1 \frac{dy}{y} \left(P_{\gamma\gamma} \otimes \gamma + \sum_{1} e_i^2 P_{\gamma q} \otimes q_i \right)$$

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 $m_q \to Q_0^2$. Freedom in choice of quark mass, e.g. current mass $\to$ constituent mass.

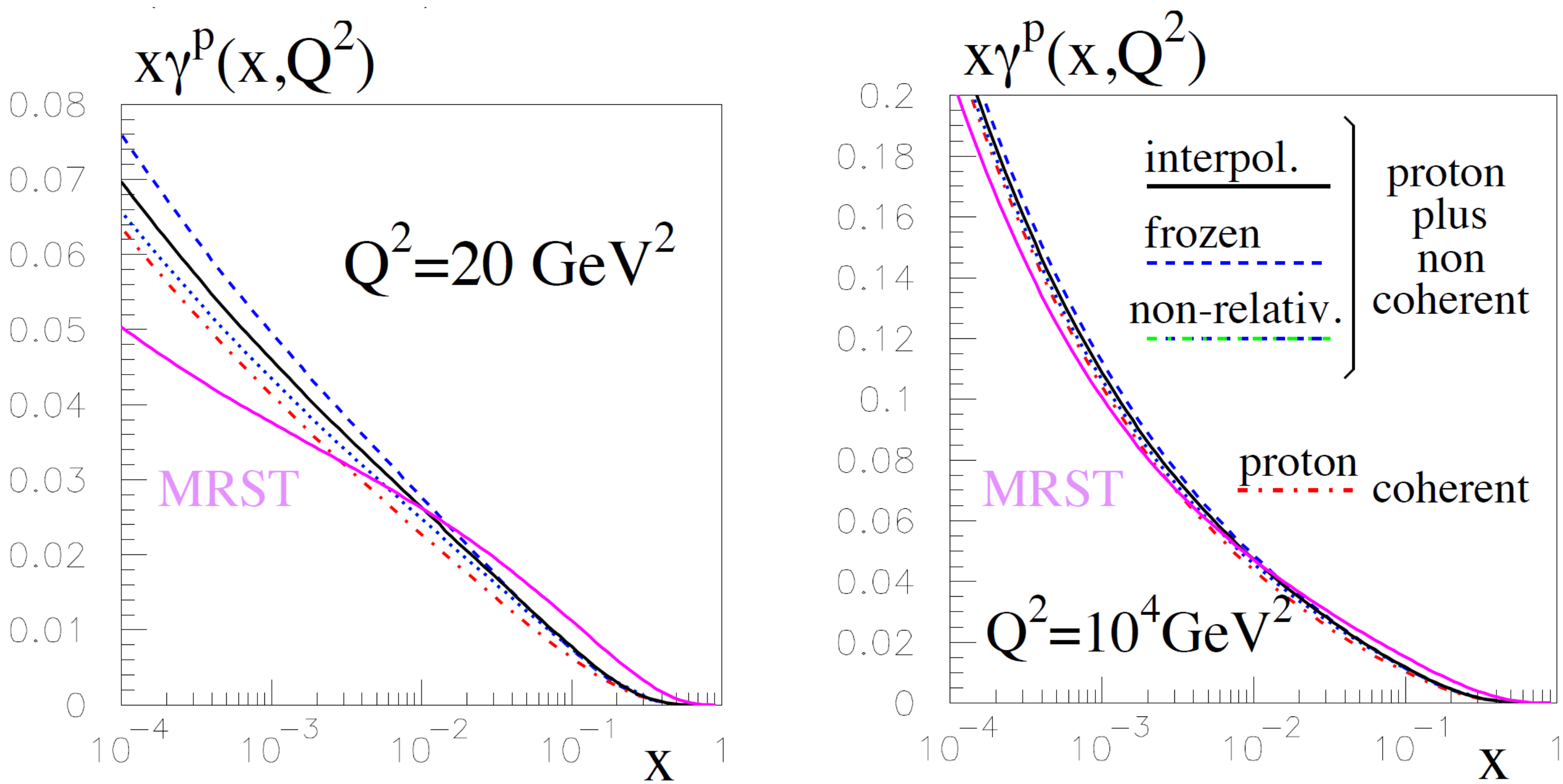
Article by Martin, Ryskin considers separate "coherent" emission and "non-coherent" emission.



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

Additional possible flexibility in input determination. “Coherent” dies away quickly above Q_0^2, but dominates in input distribution.

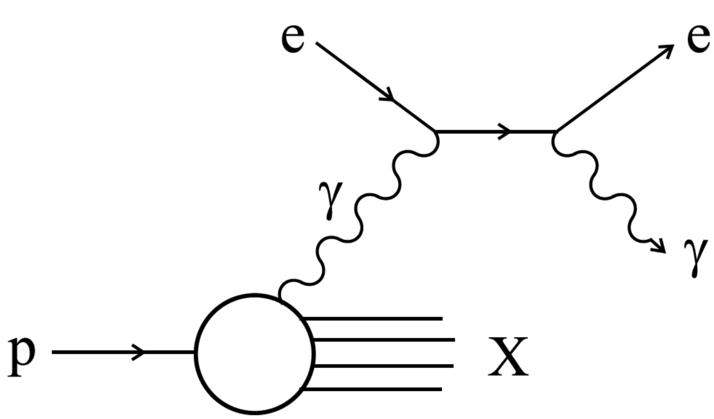
Tends to increase $\gamma(x, Q^2)$ at low x. (MRST2004 larger than NNPDF2.3 for $x < 0.01$, but mainly due to evolution differences not input).

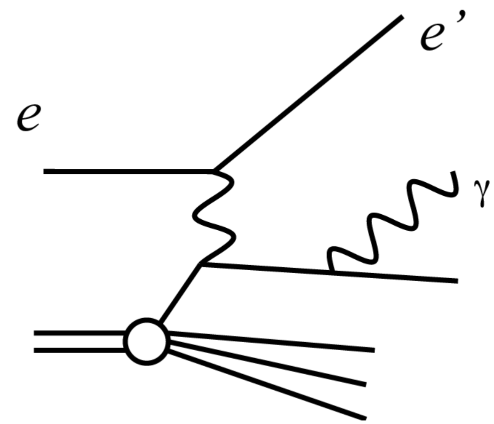


H1 and ZEUS have measurement of isolated photon DIS

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

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.

Conclusions

MMHT2014 PDFs now with variations in heavy quark masses and active flavour number. Few significant effects on PDFs. In general predictions remain very close to those with MSTW2008 PDFs. Slightly less variation in PDFs with $m_{c,b}$ variation than previously, and much smaller than PDF uncertainties.

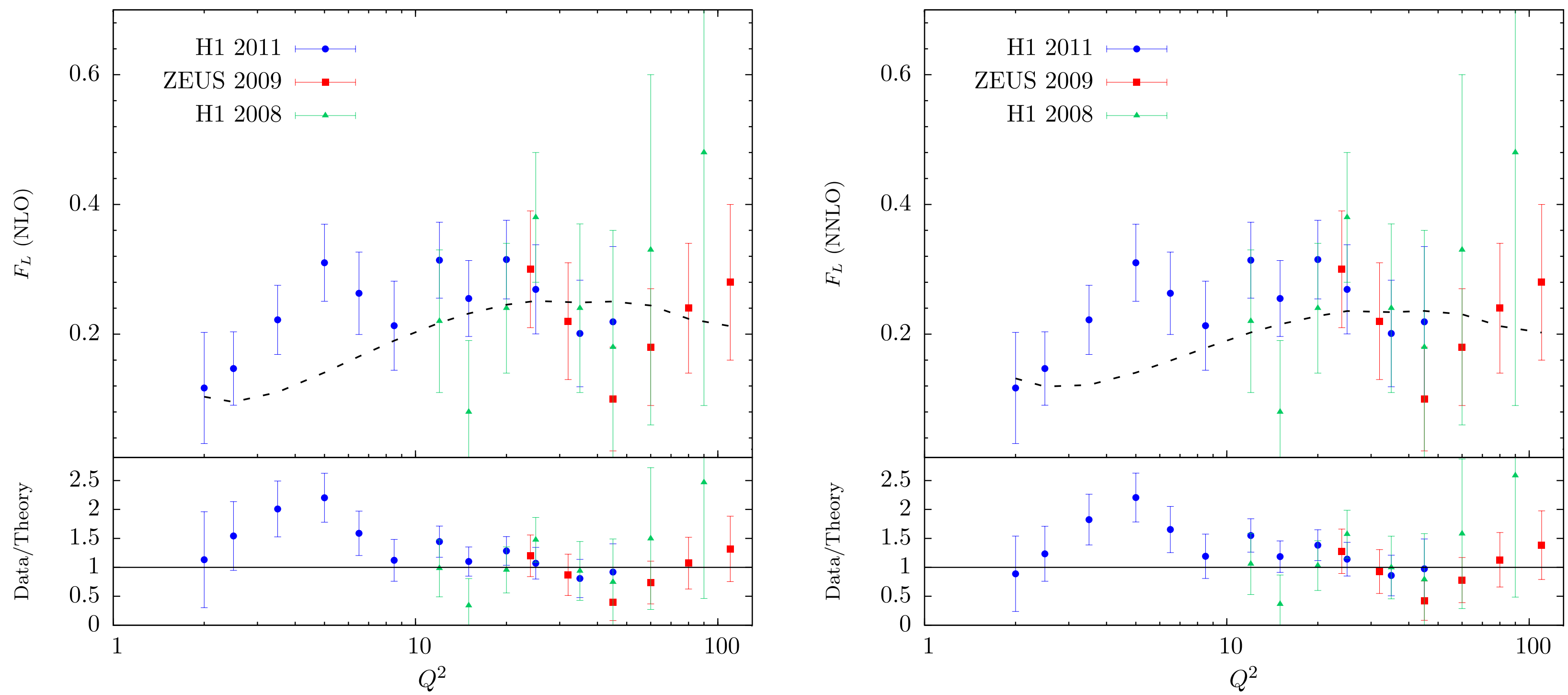
New HERA II combined data studied. Fit quality good – better at NNLO. No very significant changes in PDFs or predictions. Slight reduction in uncertainties.

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. Higher twist parameterisation successful, but strong correlation between Q^2 and x at high y. At higher x, Q^2 data defiitely prefers smaller F_L.

Predictions continue to appear to be good for LHC data not yet included in the fit. No obvious sign of need for change in central values, but some data will clearly reduce uncertainties. Some new $\sigma_{\bar{t}t}$ data. Fitted m_t^{pole} compatible with world average and tiny increase in fitted $\alpha_S(M_Z^2)$.

Work beginning on updated PDFs with QED corrections.

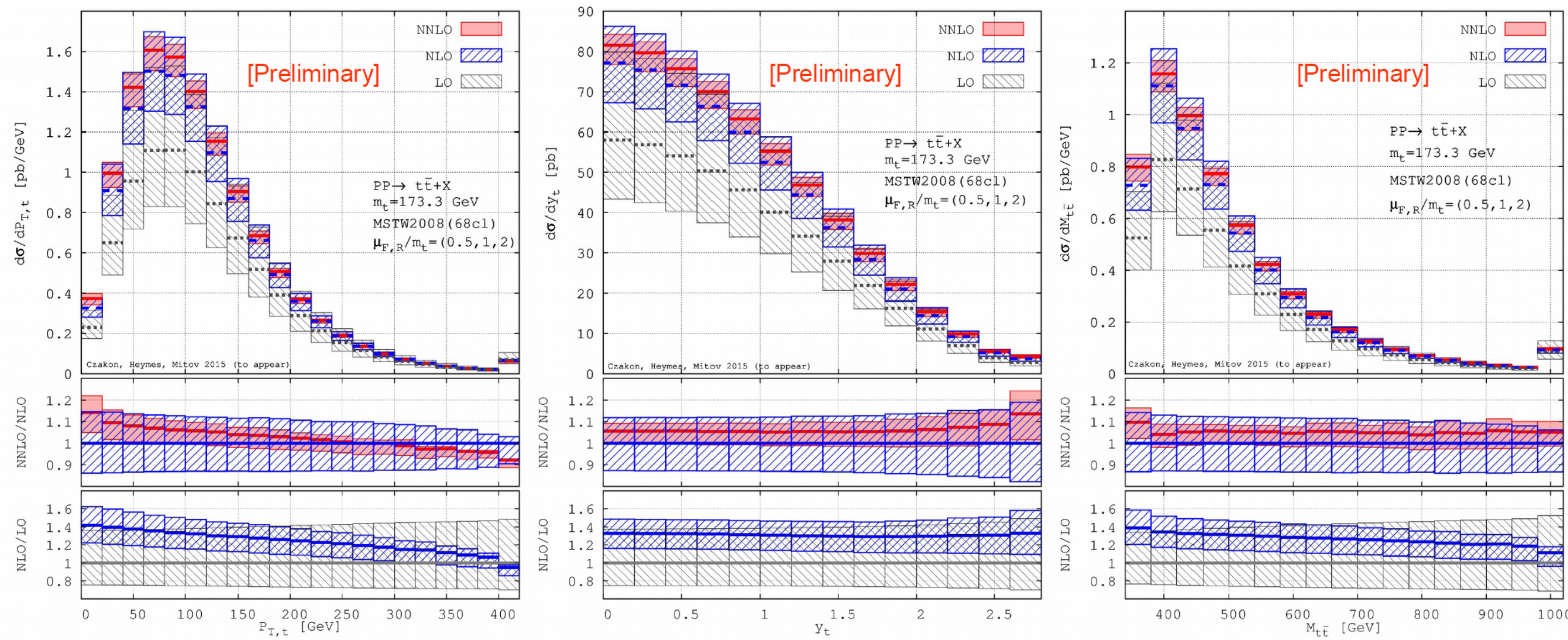
Back -up


H1 2011
ZEUS 2009
H1 2008
F_L (NLO)
Data/Theory
Q^2
F_L (NNLO)

LHC 8TeV (preliminary)

[Czakon, Fiedler, DH, Mitov.; in preperation]

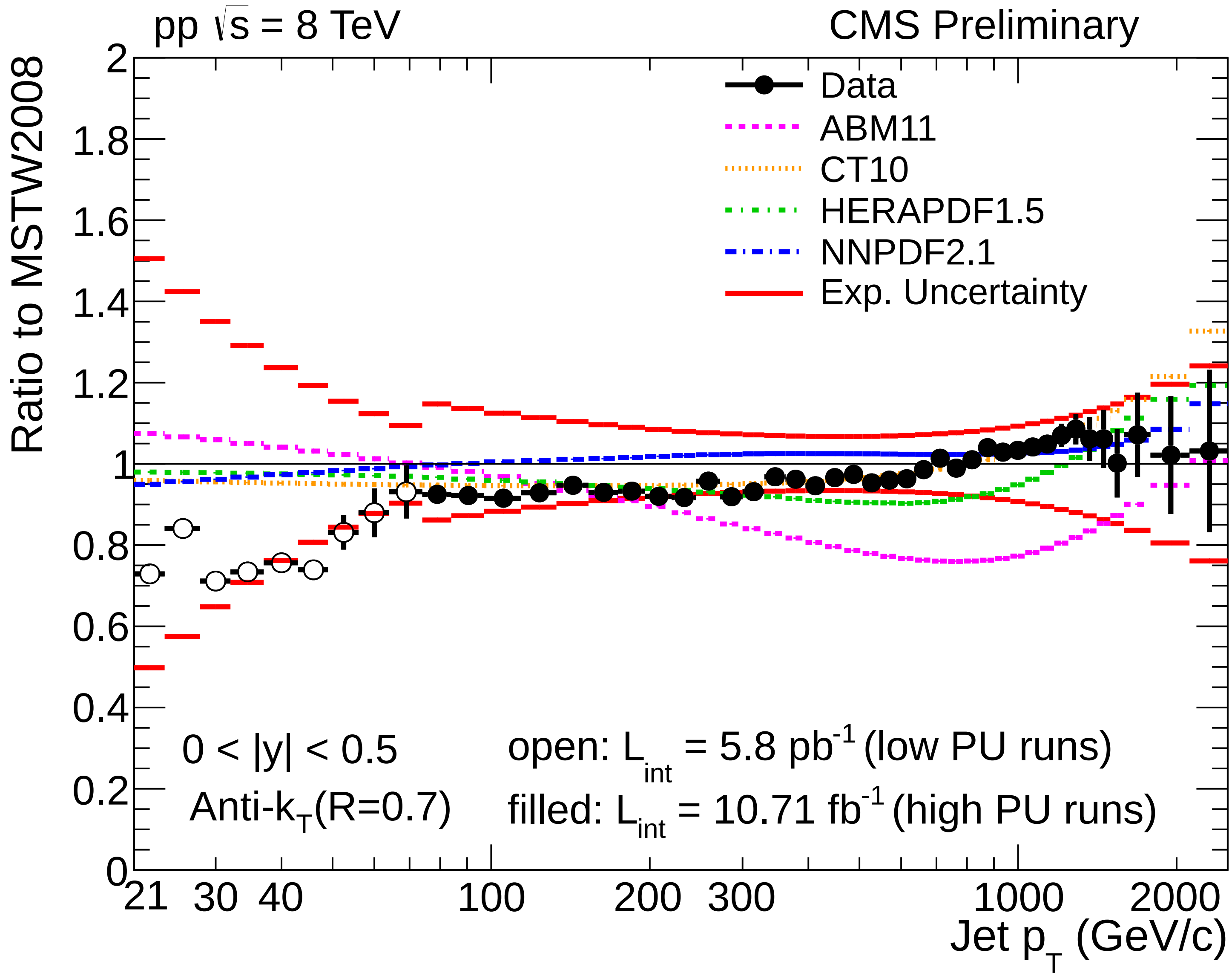
P_T of t | Rapidity of t | Invariant mass



- Absolute normalization
- Last bin is overflow bin
- Fixed scale variation
- Good convergence of the perturbative series in each bin

10

Comparison to CMS jet data at NLO



NNLO corrections consistent with (particularly MSTW/NNPDF) NLO comparison.