MMHT2014 PDFs - Heavy Quarks and HERA I+II data

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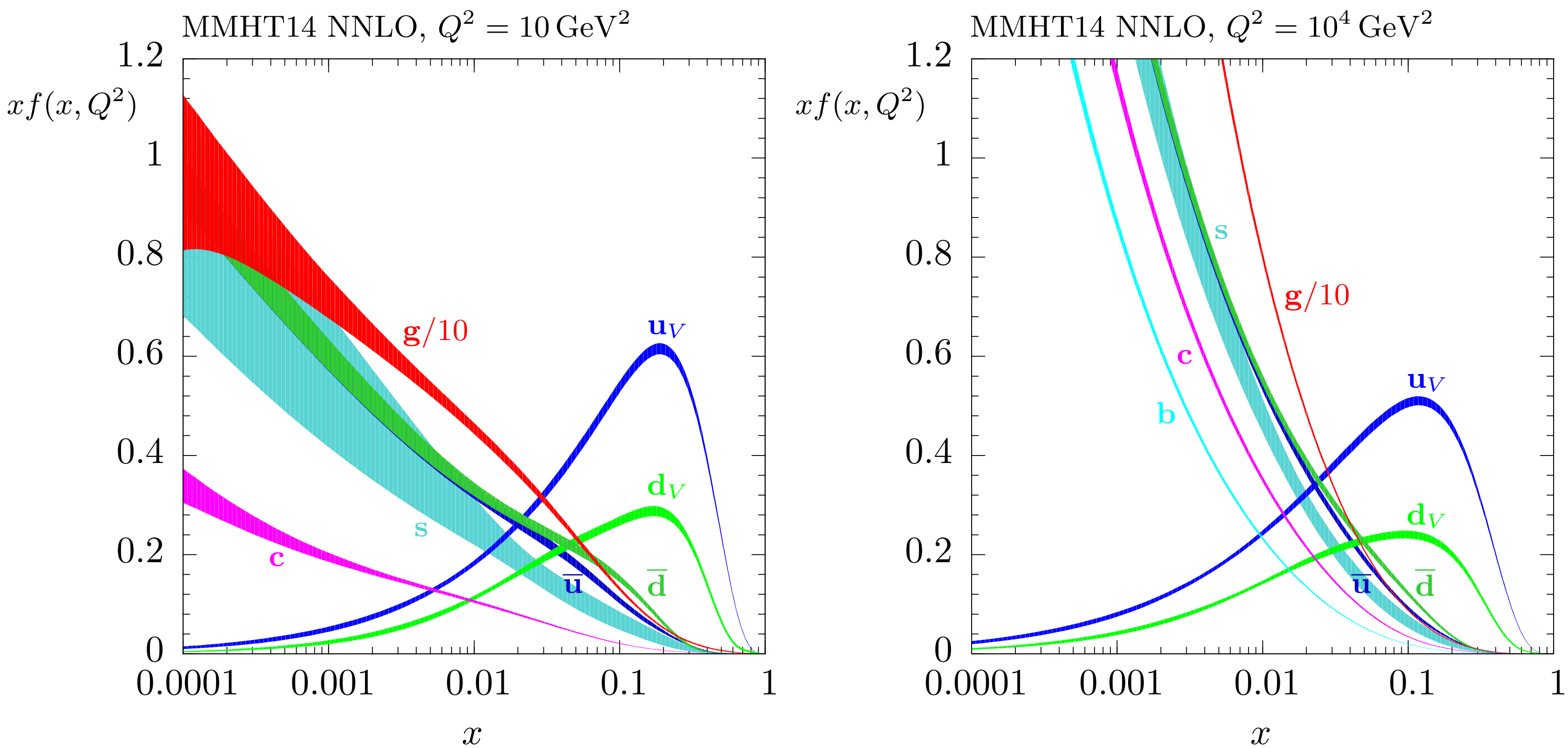
and thanks to Ben Watt, Graeme Watt and James Stirling

MMHT 2014 PDFs



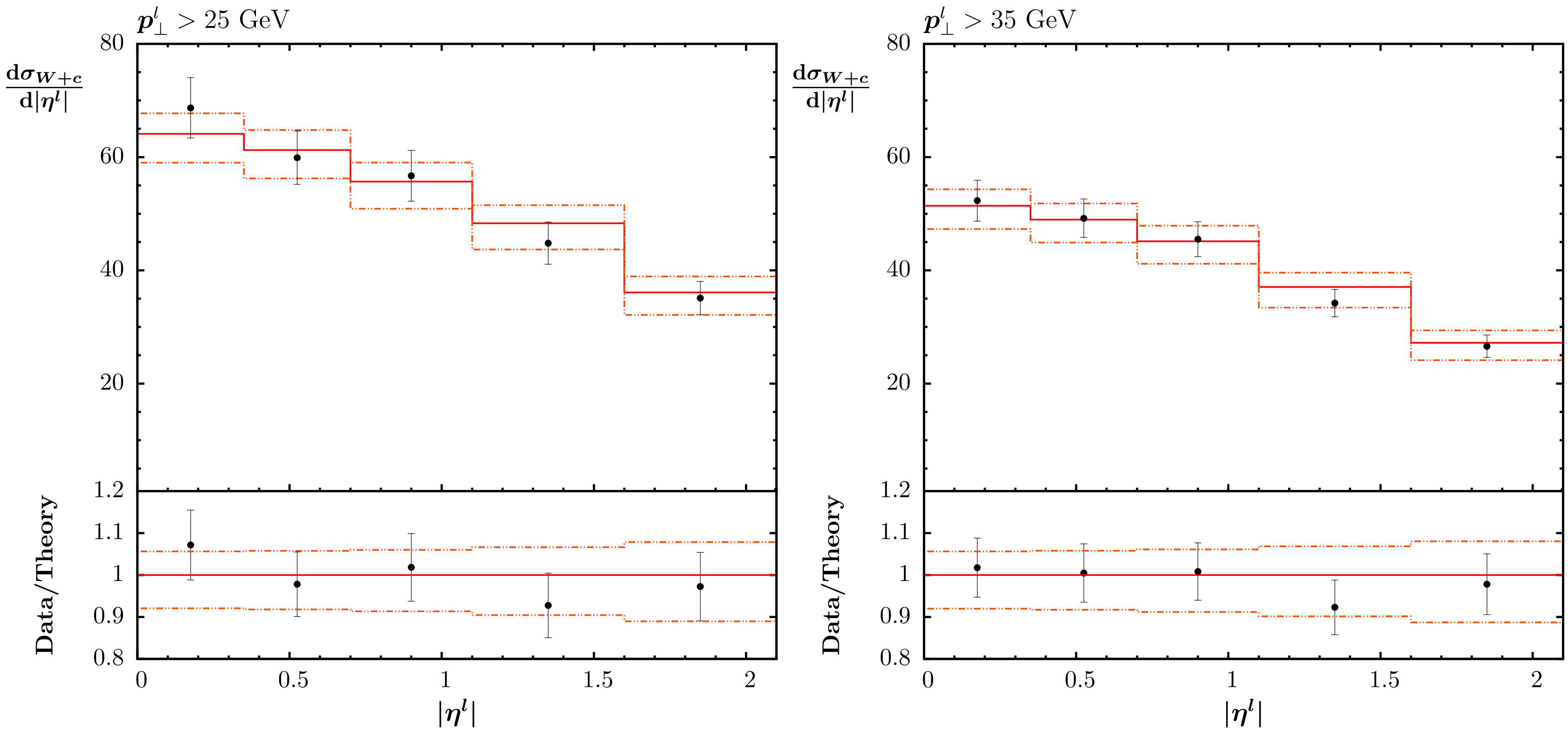
Available in LHAPDF5 and LHAPDF6.

Also at http://www.hep.ucl.ac.uk/mmht where there is stand-alone Fortran code, a C++ wrapper and Mathematica implementations as well as grids in LHAPDF5 and LHAPDF6 format.

Now also with $\alpha_S(M_Z^2)$ variations, range of m_c and m_b and in 3 and 4 flavour schemes.

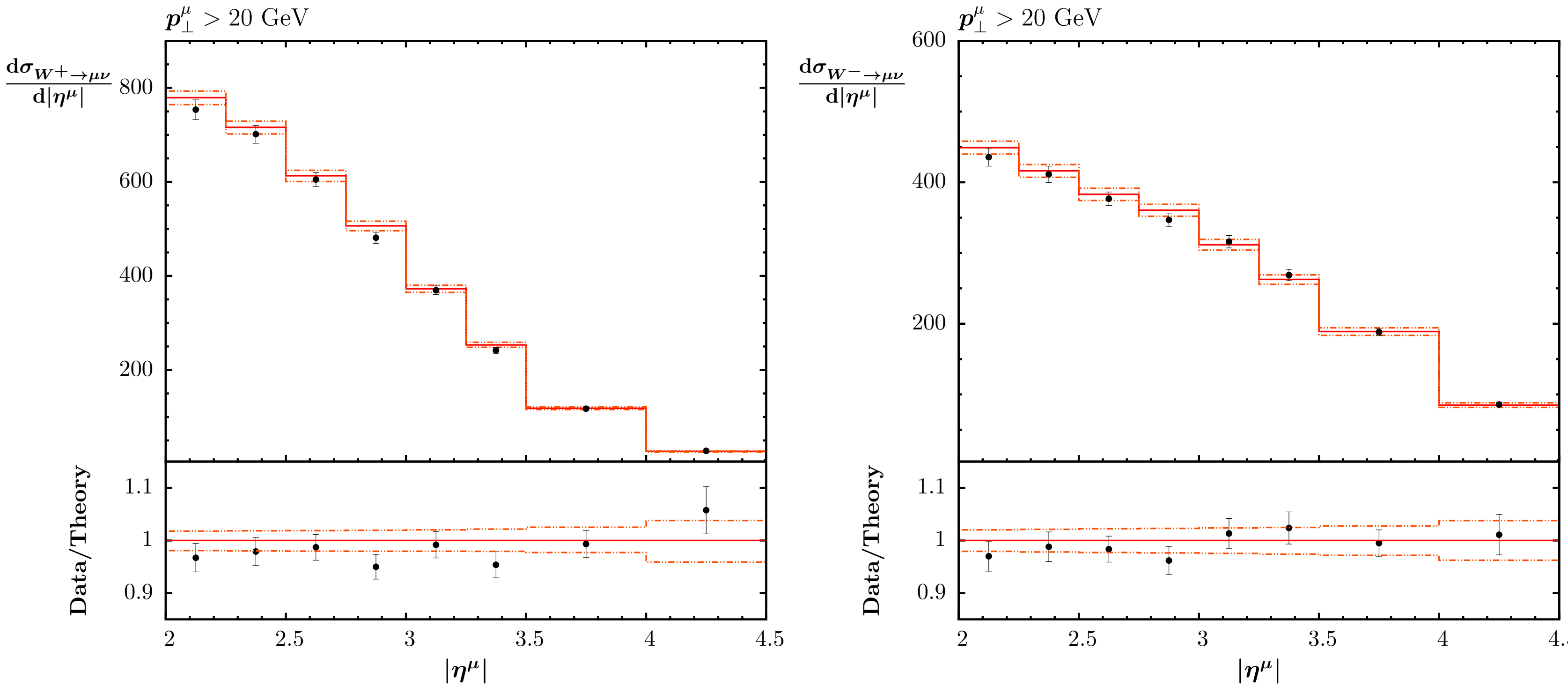
New data sets for fit – $W + c$ differential distributions.

	GeV	data	MSTW2008	MMHT2014
$\sigma(W+c)$	$p_T^{\rm lep} > 25$	$107.7 \pm 3.3({\rm stat.}) \pm 6.9({\rm sys.})$	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



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 LHCb at 7 TeV.

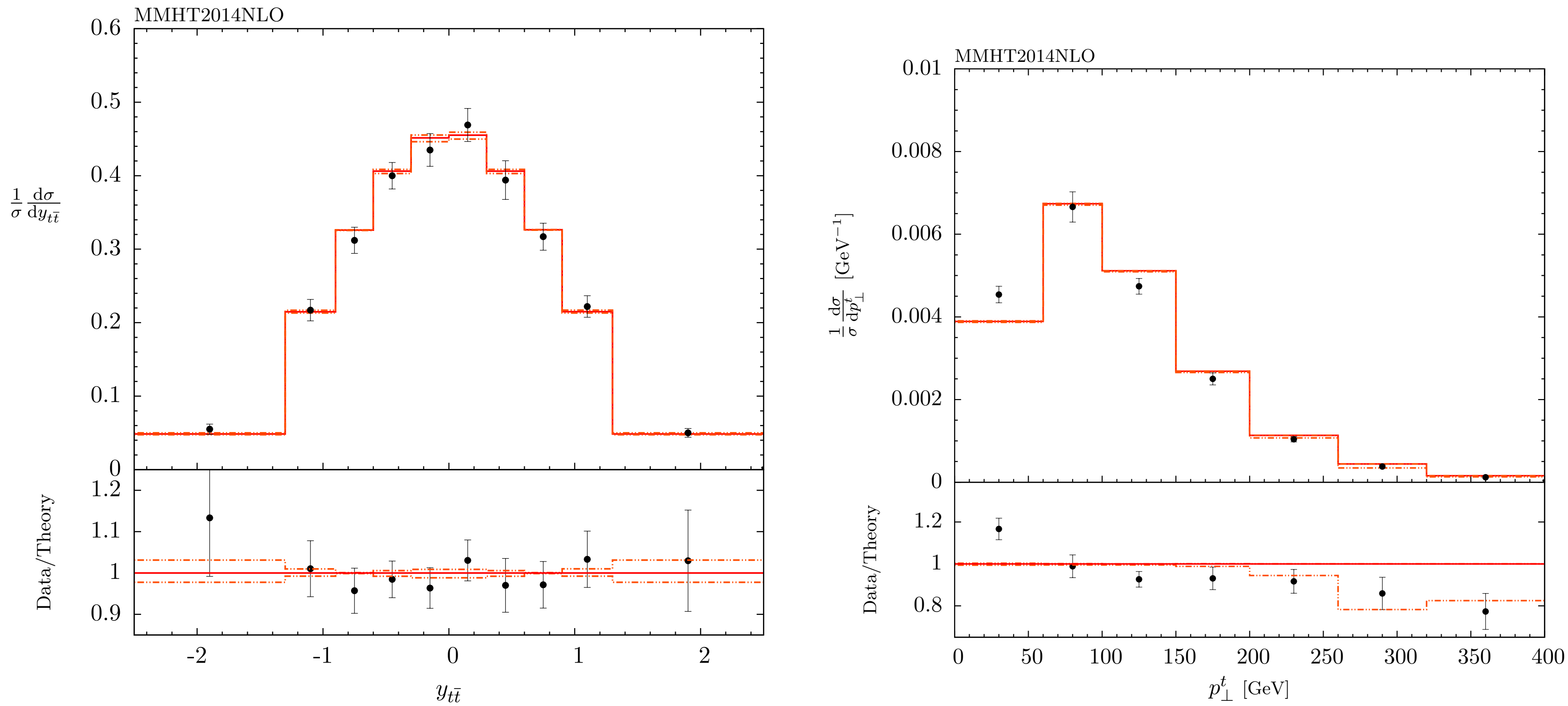


Generally perfectly good agreement using NNLO.

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).



Interesting to now see NNLO corrections (Czakon *et al.* which improve p_t distribution, with MSTW distributions.

PDFs and Heavy Quarks

As before we make the same 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).

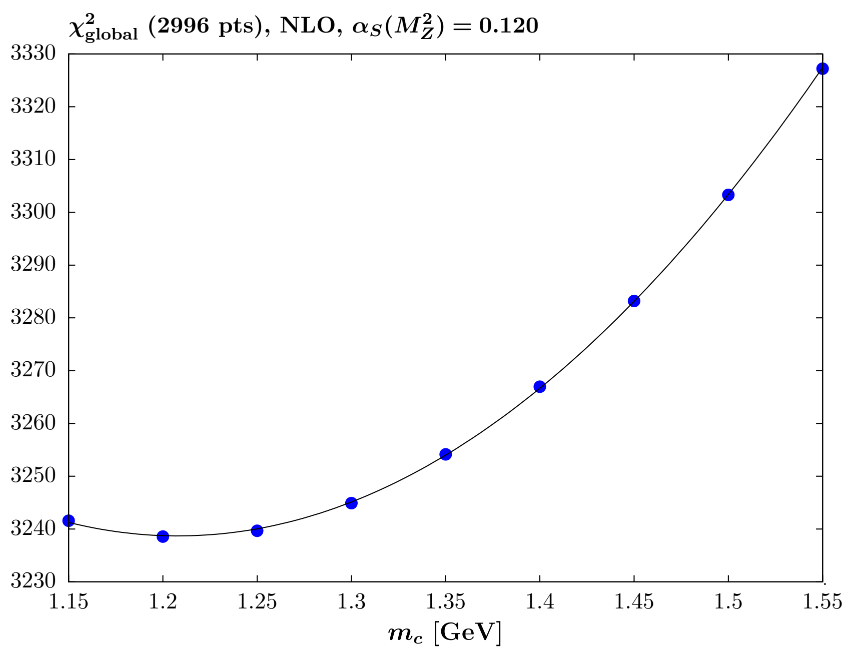
As default fix the number of flavours in α_S, but we also provide analogous sets with variable flavour α_S for $n_f = 4$ as there were some requests for this for MSTW2008.

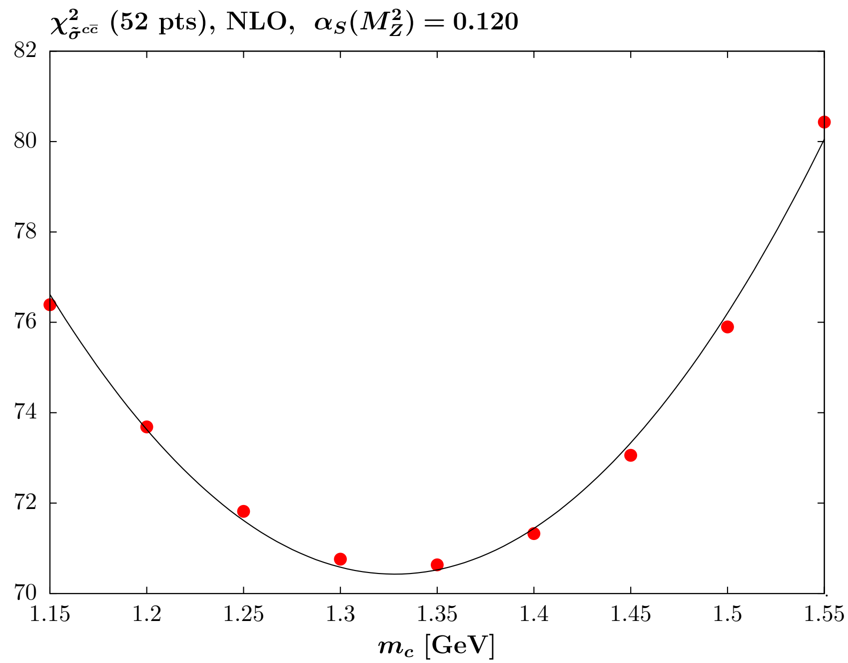
Now also make available sets with fits done for m_c and m_b (defined in pole scheme) varying from default values of $m_c = 1.40\ \mathrm{GeV}$ and $m_b = 4.75\ \mathrm{GeV}$ in steps of $0.05\ \mathrm{GeV}$ and $0.25\ \mathrm{GeV}$ respectively.

Not as wide a range as last time – i.e. now $m_c = 1.15 - 1.55\ \mathrm{GeV}$ and $m_b = 4.25 - 5.25\ \mathrm{GeV}$.

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 NLO in fits at fixed $\alpha_s(M_Z^2) = 0.120$.



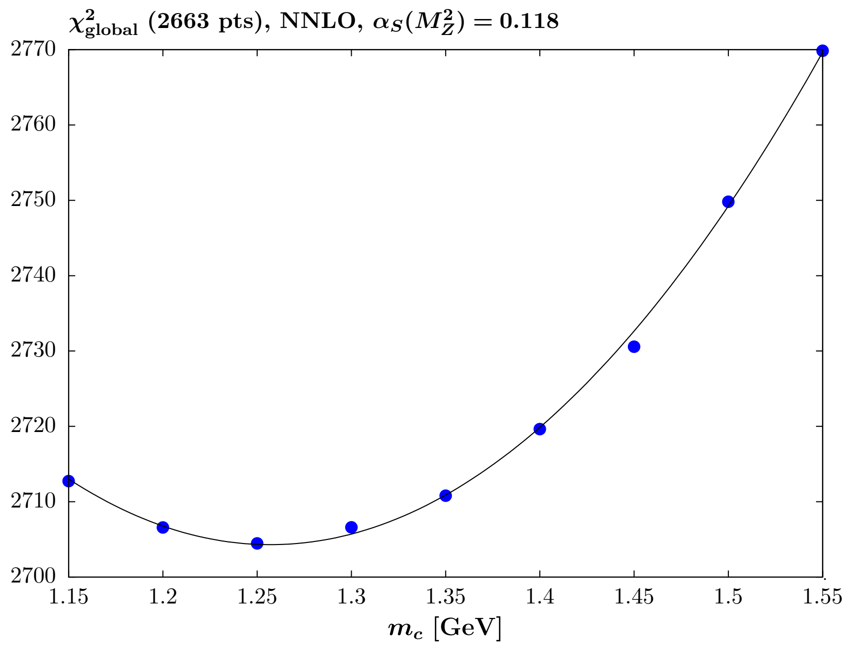


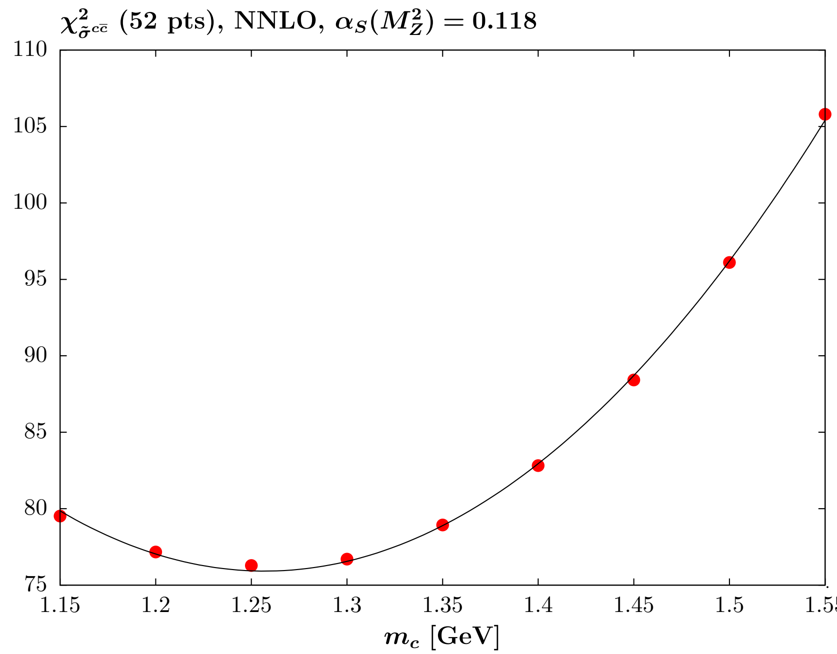
Similar variation with m_c for varying $\alpha_S(M_Z^2)$. For $0.13\ \mathrm{GeV} < m_c < 1.5\ \mathrm{GeV}$ difference compared to free coupling negligible.

Preference for $m_c \sim 1.20\mathrm{GeV}$, or marginally higher.

Slight tension between global fit and charm data.

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



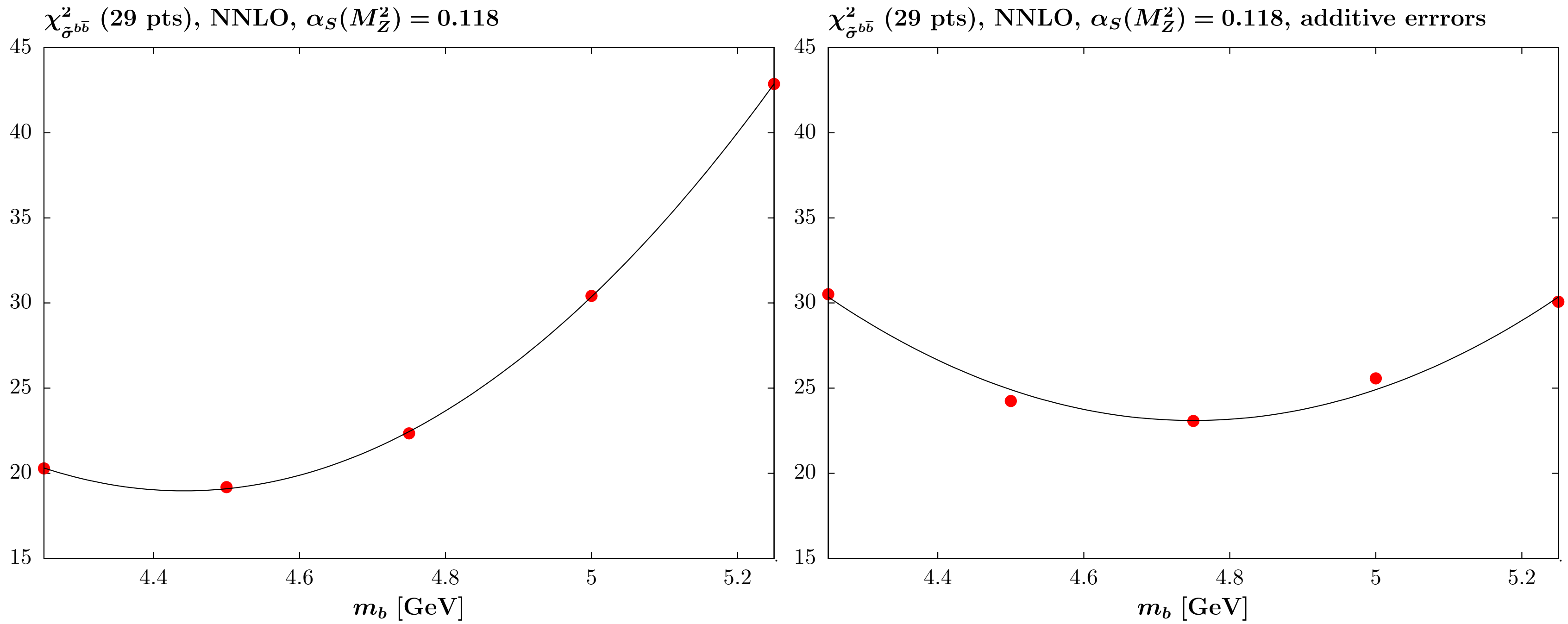


Similar variation with m_c for varying $\alpha_S(M_Z^2)$.

Less tension between global fit and charm.

Again preference for $m_c \sim 1.25\text{GeV}$.

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

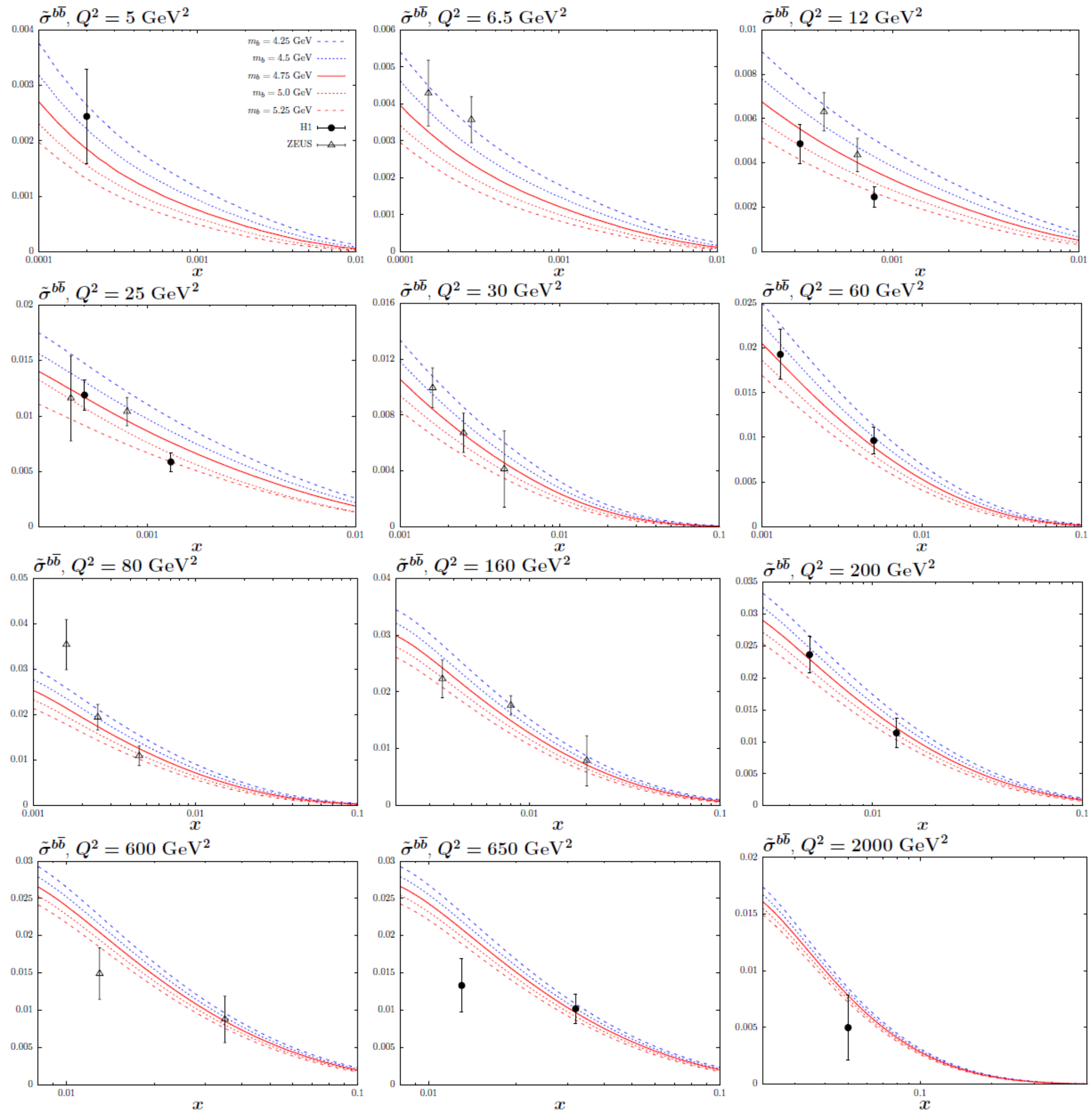


Global fit very weakly prefers $m_b \sim 4.25\mathrm{GeV}$

Beauty data prefer $m_b \sim 4.25\mathrm{GeV}$ for multiplicative error treatment and $m_b \sim 4.75\mathrm{GeV}$ for additive error treatment

Fit to (unshifted) beauty cross section data.

Large fluctuations in both directions on scale of statistical uncertainties



Variation of Cross Sections with quark masses

Use $\Delta m_c = \pm 0.15$ GeV and $\Delta m_b = \pm 0.5$ GeV.

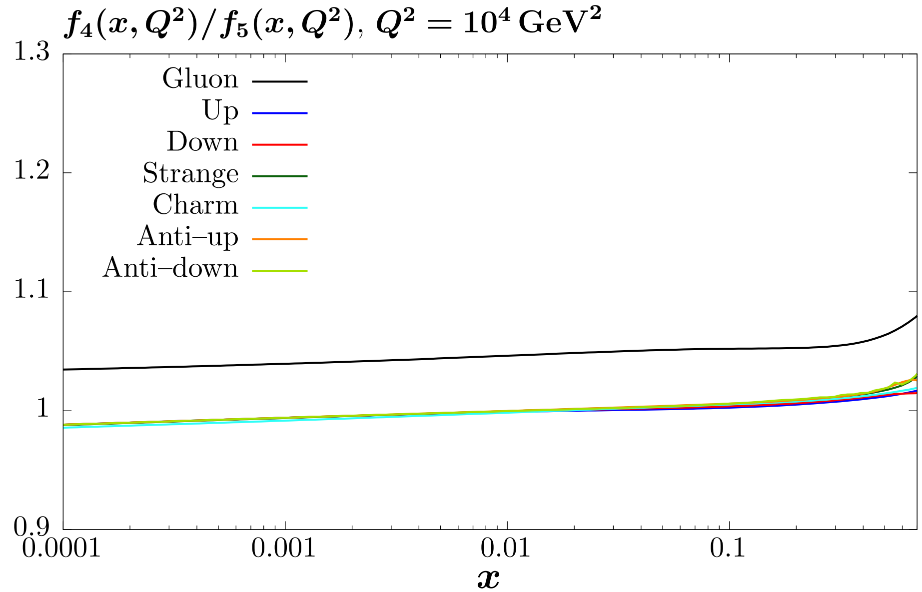
	σ	PDF unc.	m_c var.	m_b var.
W Tevatron (1.96 TeV)	2.78	$^{+0.0017}_{-0.056}$ $\left(^{+2.0\%}_{-2.0\%}\right)$	$^{+0.0017}_{-0.0086}$ $\left(^{+0.061\%}_{-0.31\%}\right)$	$^{-0.00092}_{-0.0015}$ $\left(^{-0.033\%}_{-0.052\%}\right)$
Z Tevatron (1.96 TeV)	0.256	$^{+0.0052}_{-0.0046}$ $\left(^{+2.0\%}_{-1.8\%}\right)$	$^{+0.00042}_{-0.0011}$ $\left(^{+0.16\%}_{-0.43\%}\right)$	$^{-0.00029}_{-0.000016}$ $\left(^{-0.11\%}_{-0.0059\%}\right)$
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	$^{+0.035}_{-0.030}$ $\left(^{+1.7\%}_{-1.5\%}\right)$	$^{+0.021}_{-0.025}$ $\left(^{+1.03\%}_{-1.2\%}\right)$	$^{-0.0035}_{-0.0013}$ $\left(^{-0.17\%}_{-0.062\%}\right)$

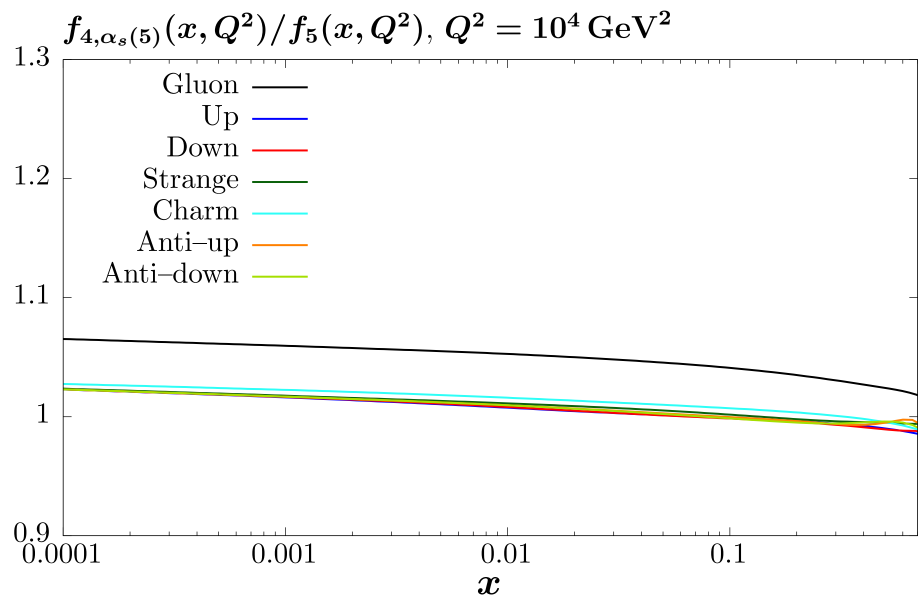
	σ	PDF unc.	m_c var.	m_b var.
$t\bar{t}$ Tevatron (1.96 TeV)	7.5	$^{+0.21}_{-0.20}$ $\left(^{+2.8\%}_{-2.7\%}\right)$	$^{-0.059}_{+0.077}$ $\left(^{-0.78\%}_{+1.0\%}\right)$	$^{+0.0088}_{+0.0015}$ $\left(^{+0.12\%}_{+0.20\%}\right)$
$t\bar{t}$ LHC (7 TeV)	176	$^{+3.9}_{-5.5}$ $\left(^{+2.2\%}_{-3.1\%}\right)$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

PDFs in 4-flavour Scheme





4- flavour coupling (left) and full variable flavour coupling (right).

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.

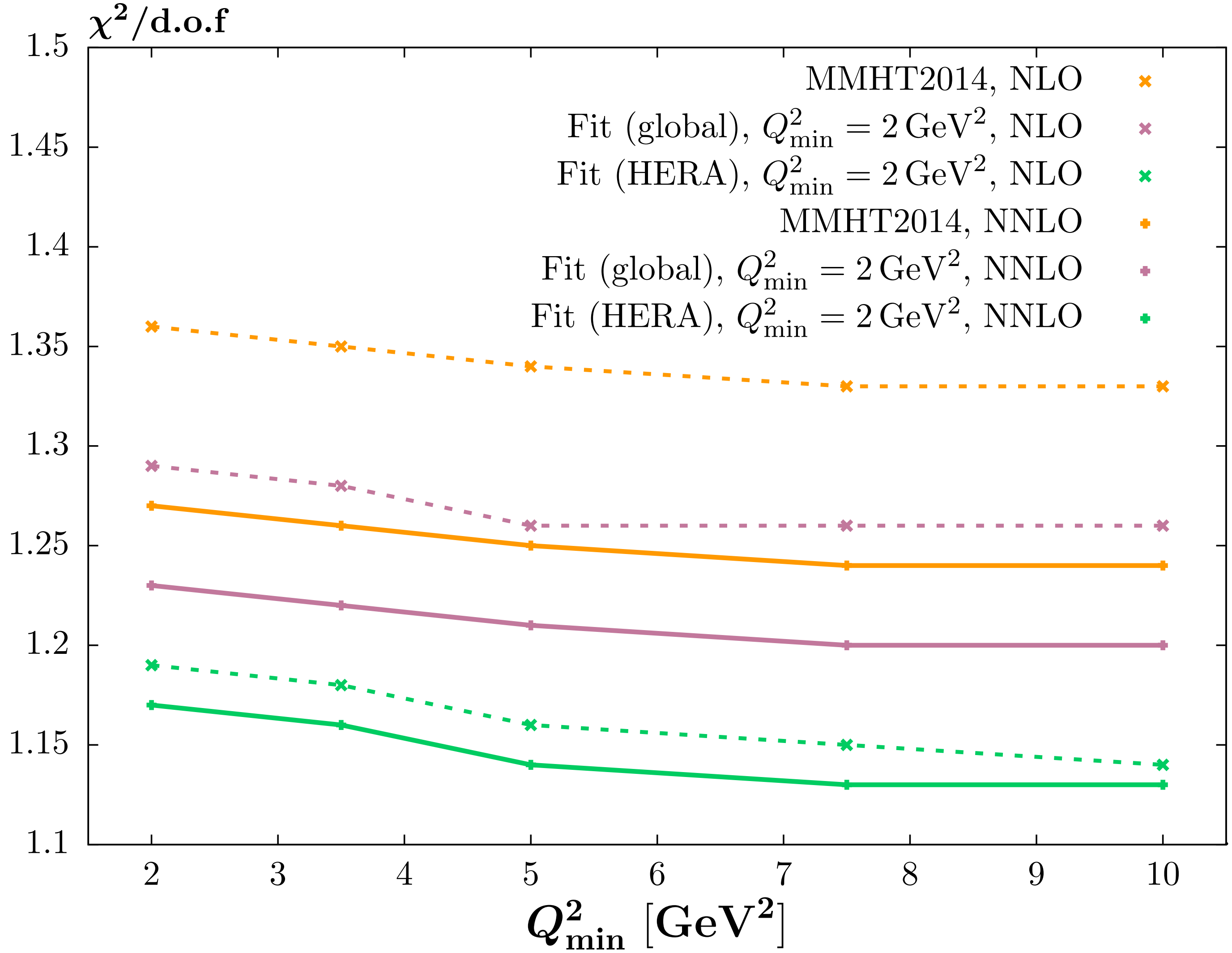
Also trying fitting only HERA II data, with 4 parameters fixed to avoid particularly unusual PDFs.

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 $Q^2_{\rm min}$ without refitting.

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

Breakdown of fit quality in subsets of data

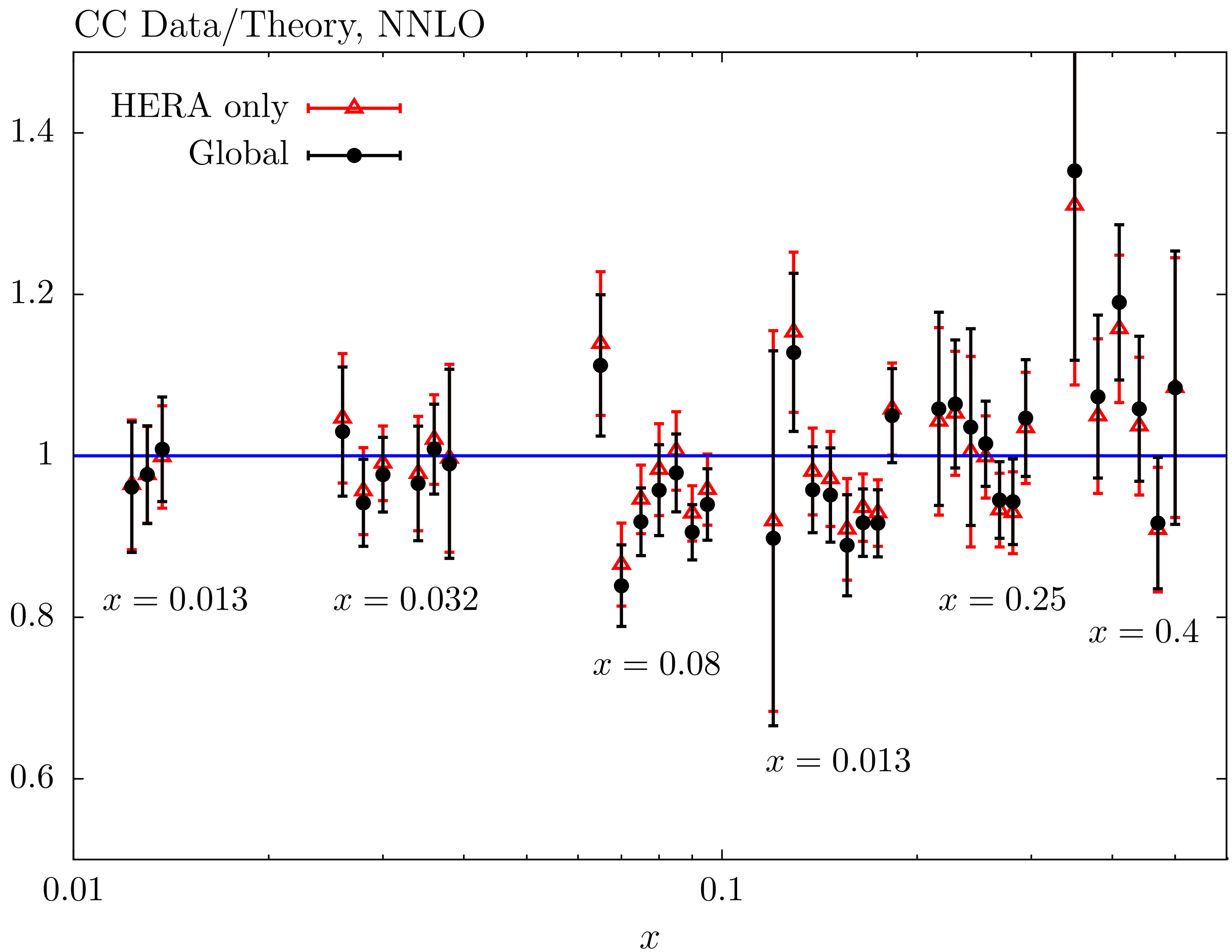
	no. points	NLO χ^2_{HERA}	NLO χ^2_{global}	NNLO χ^2_{HERA}	NNLO χ^2_{global}
correlated penalty		79.9	113.6	73.0	92.1
CC e^+p	39	43.4	47.6	42.2	48.4
CC e^-p	42	52.6	70.3	47.0	59.3
NC e^-p $E_p = 920$ GeV	159	213.6	233.1	213.5	226.7
NC e^+p $E_p = 920$ GeV	377	435.2	470.0	422.8	450.1
NC e^+p $E_p = 820$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

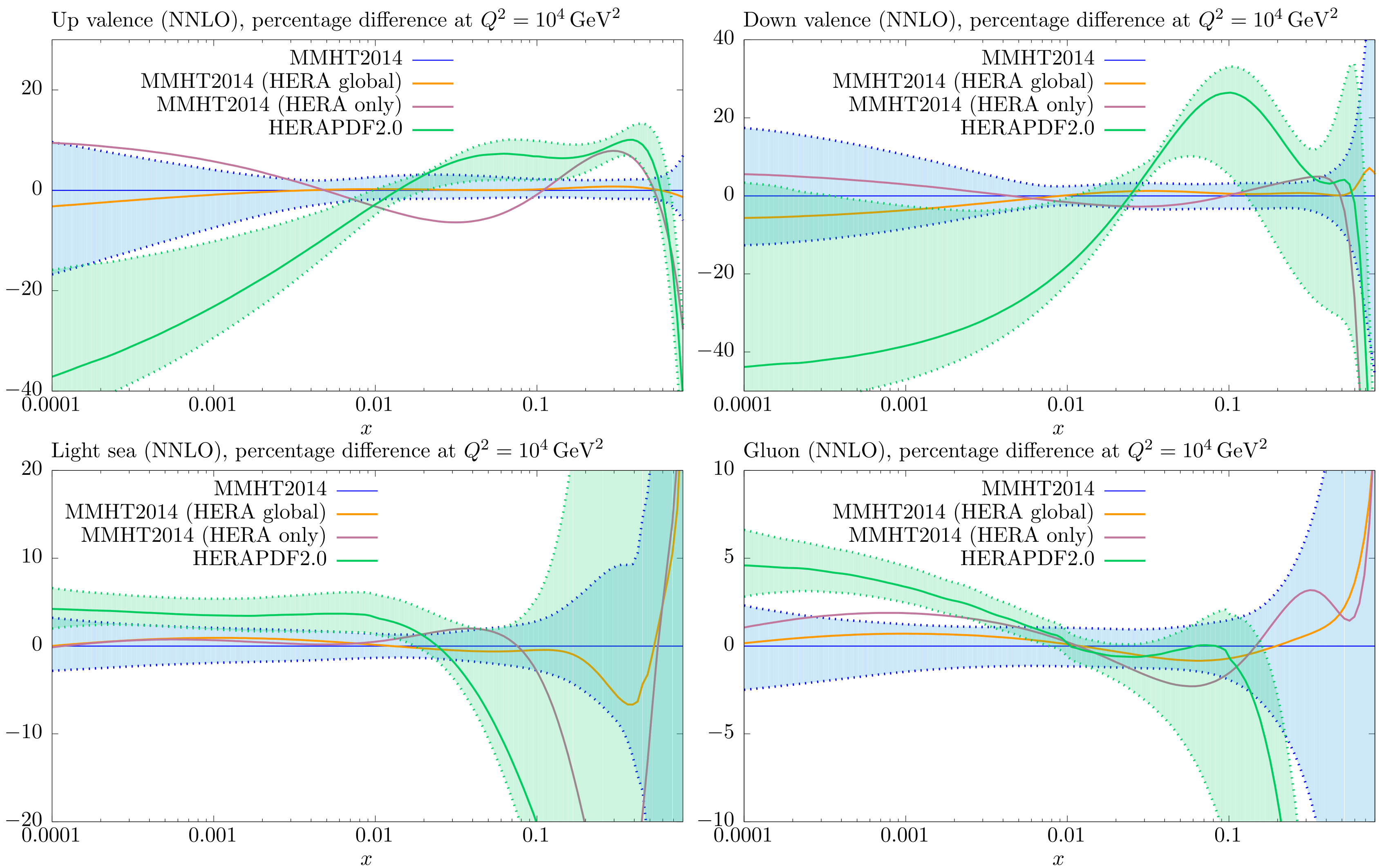
Large improvement in CC e^-p data when only HERA data fit. Probe of up (valence) quark at high x. Bigger effect at NLO.

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

Other data sets much smaller effect.

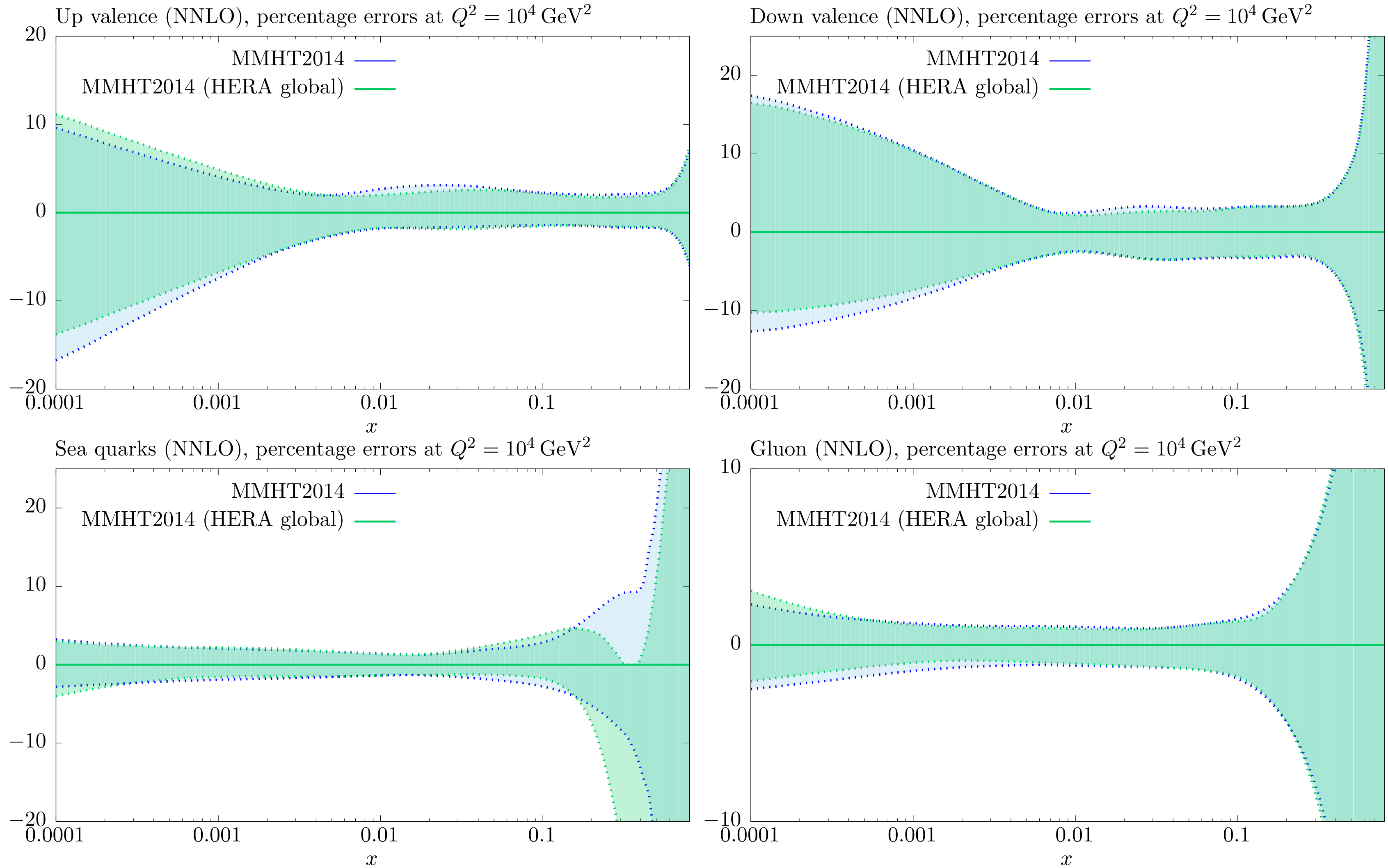


Clearly a different shape for the CC $e^{-}p$ data against theory in global and HERA-only fits. Affects up quark which is constrained by lots of other data.



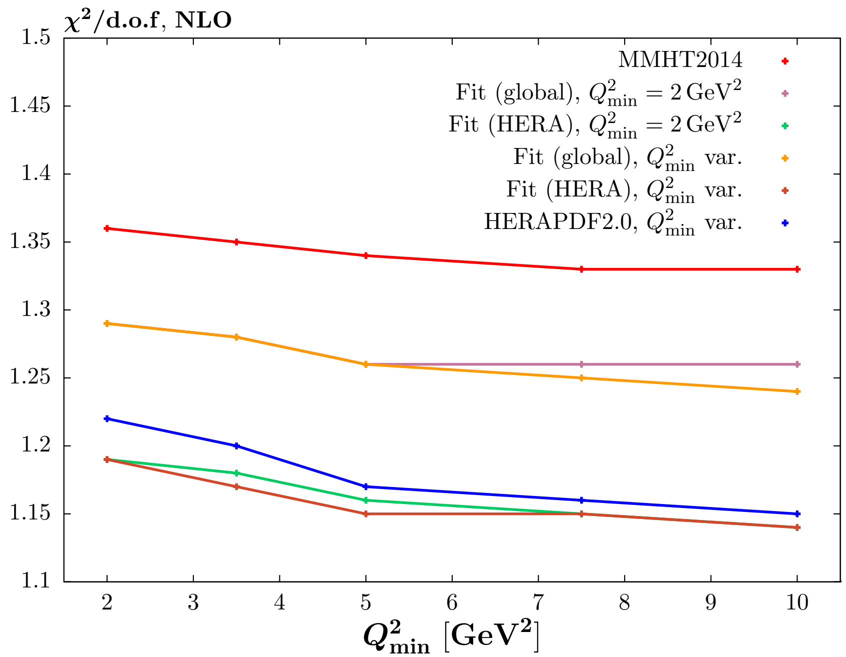
HERA II modified PDFs very well within MMHT2014 uncertainties. PDFs from HERA II data only fit in some ways similar to HERAPDF2.0.

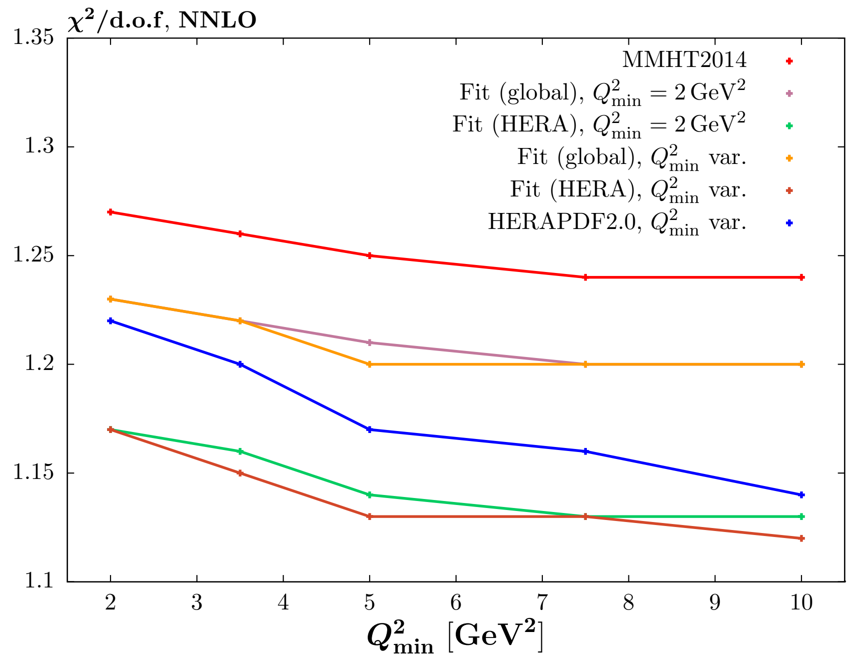
Predictions for e.g. $gg \to H$ change by $< 0.2\%$ for full range of LHC energies.



Uncertainties (preliminary) quite similar to MMHT2014.

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



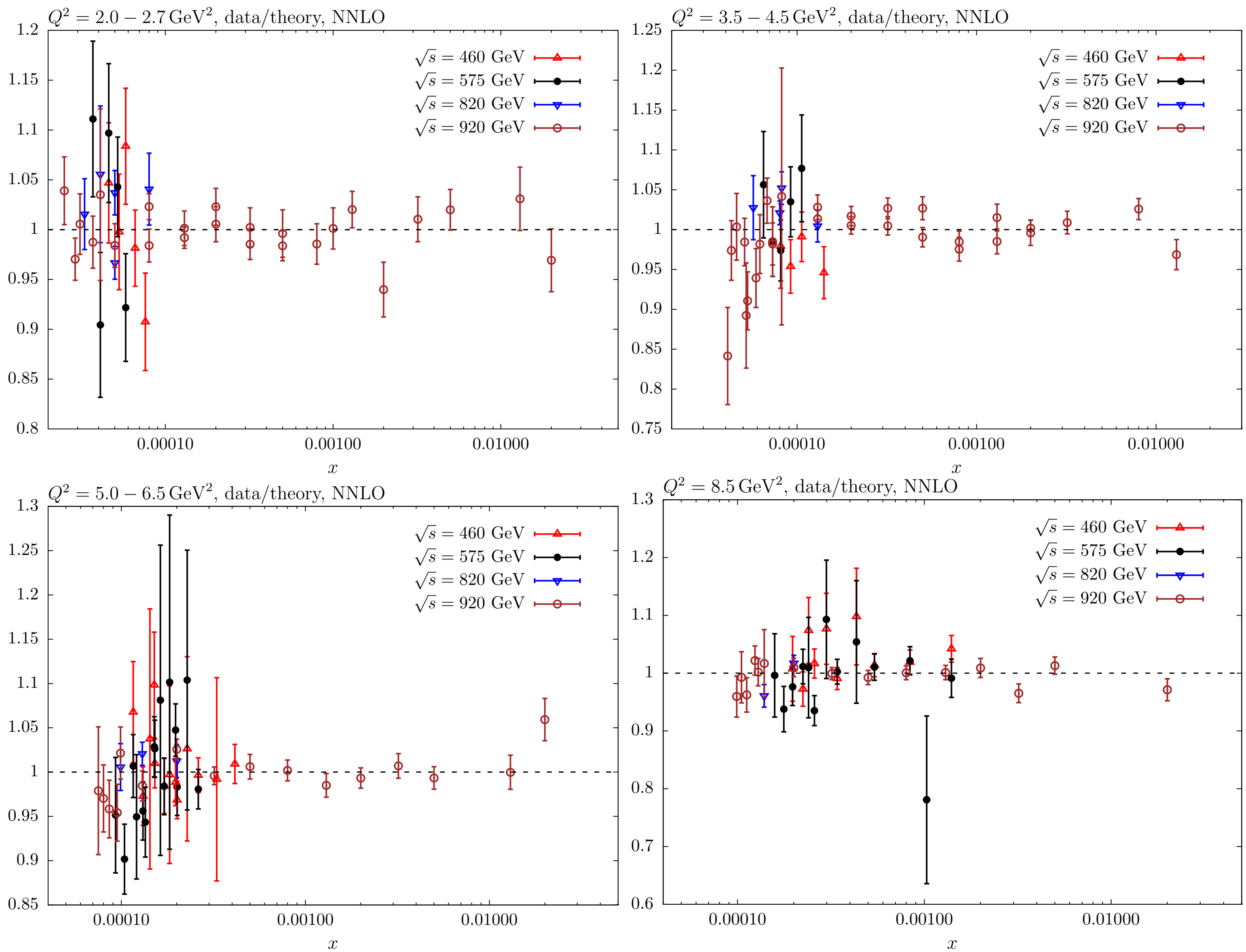


Also look at effect of changing the Q^2 cut, on only HERA II data, at both NLO and NNLO (note – definition of χ^2 for HERAPDF2.0 not identical.

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.

Quite large fluctuations in theory/data at low Q^2 rather than obvious systematic issue.



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 $F_L \rightarrow (1 + A/Q^2)F_L$ 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 $\rightarrow$ $\Delta\chi^2 = -23$ for $Q^2_{\rm min} = 2\ {\rm GeV}^2$. $A \approx 4$. Very similar in fit to only HERA data.

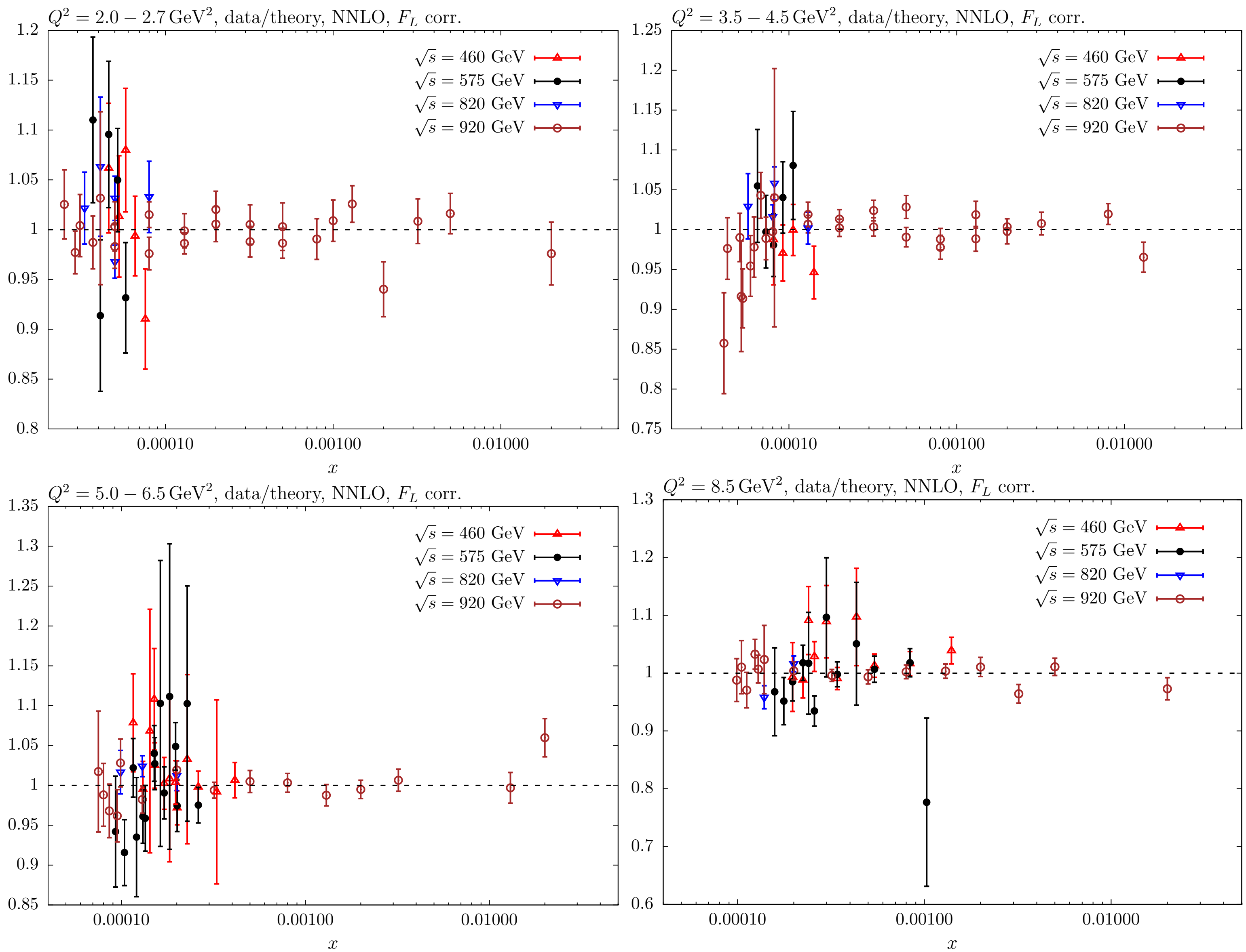
Try additionally corrections $F_2 \rightarrow (1 + A_i/Q^2)F_2$ in 6 bins for $x < 0.01$.

$A_i \sim 0.1$, but with little significance and $\rightarrow \Delta\chi^2 = -10$ almost all in non HERA data. Very little effect in fit to only HERA data.

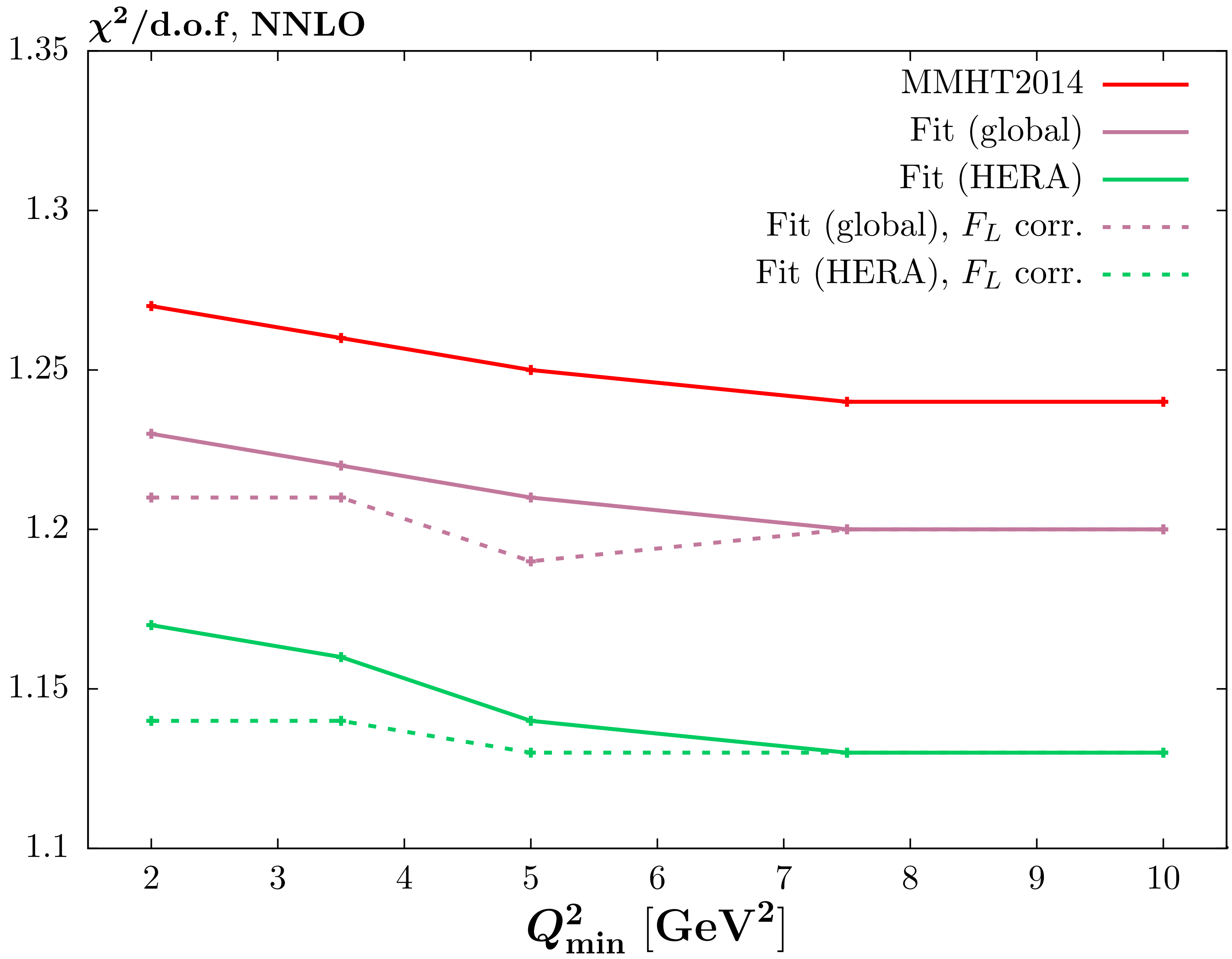
Flattens $\chi^2_{Q^2_{\rm min}}$ curve almost entirely.

Extremely little change in PDFs.

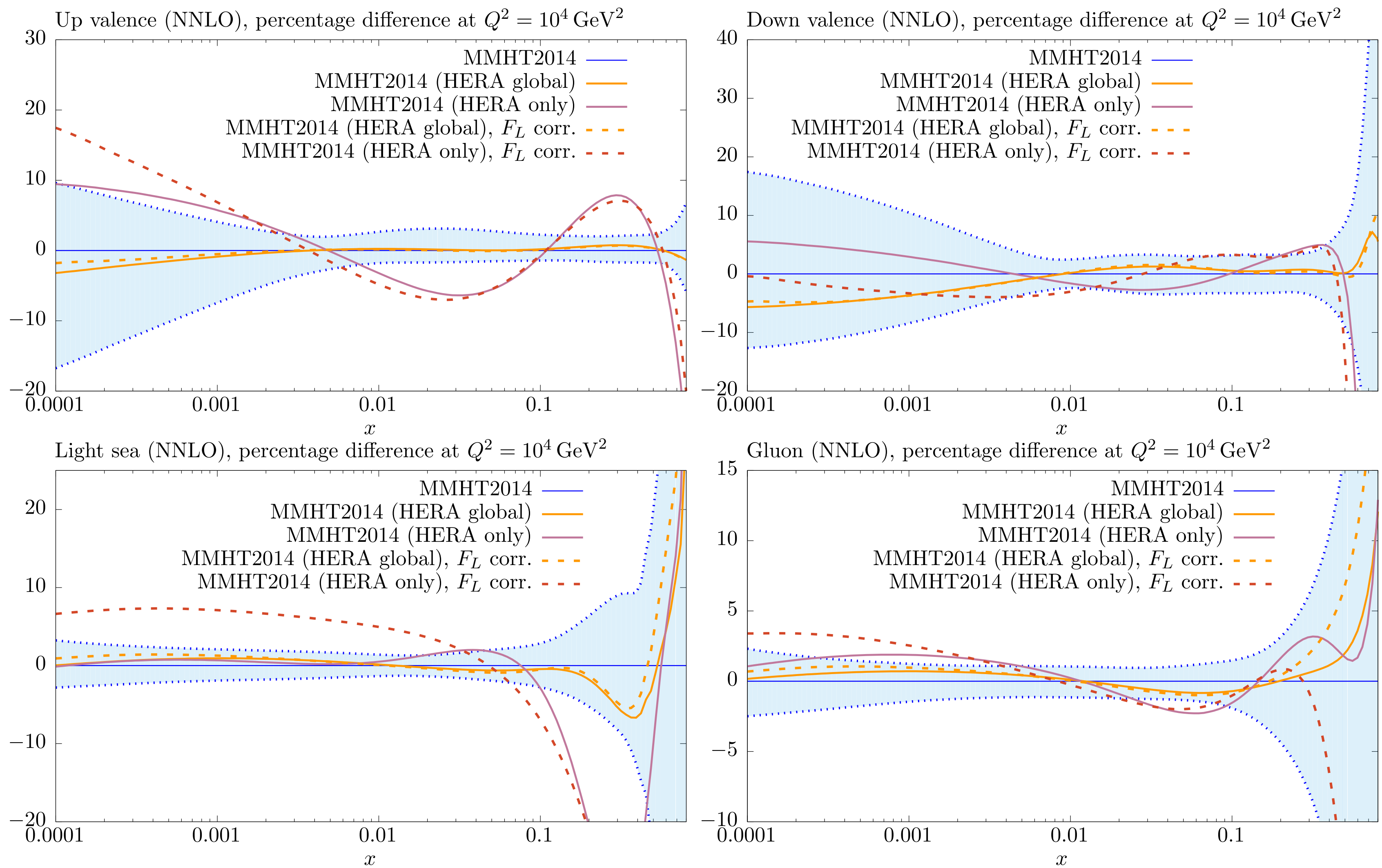
Best fit a big proportional change in $F_L(x, Q^2)$ at small x, Q^2 (high y requirement leads to strong correlation), but this is a region where $F_L(x, Q^2)$ in NLO, NNLO fits varies quickly and is sensitive to many potential corrections.



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 $Q^2_{\rm min}$ 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.

Conclusions

MMHT2014 PDFs recently released now with variations in both $\alpha_S(m_Z^2)$, heavy quark masses and active flavour number.

Few dramatic 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.

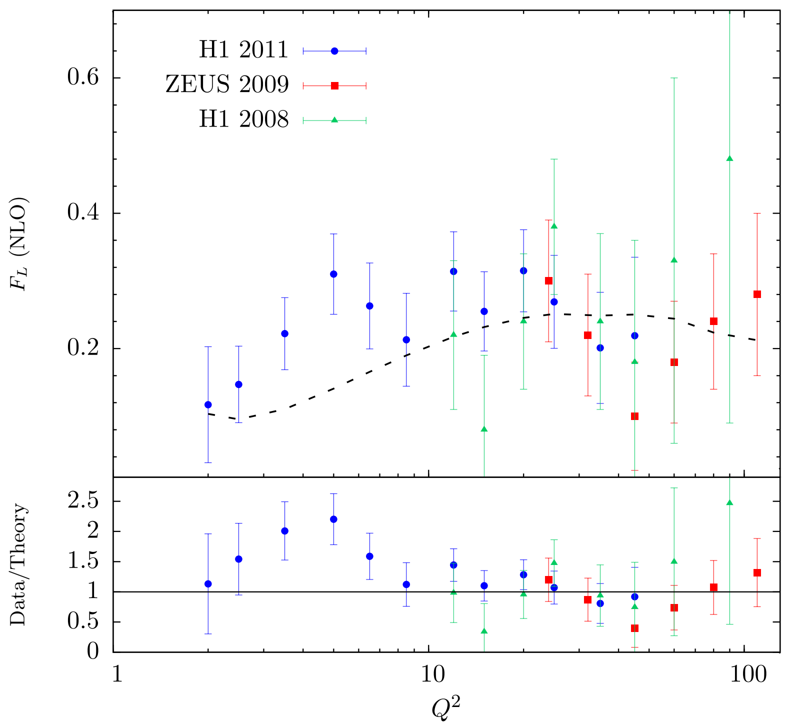
Predictions appear to be good for data not included in fit (including now, it seems, differential top at NNLO).

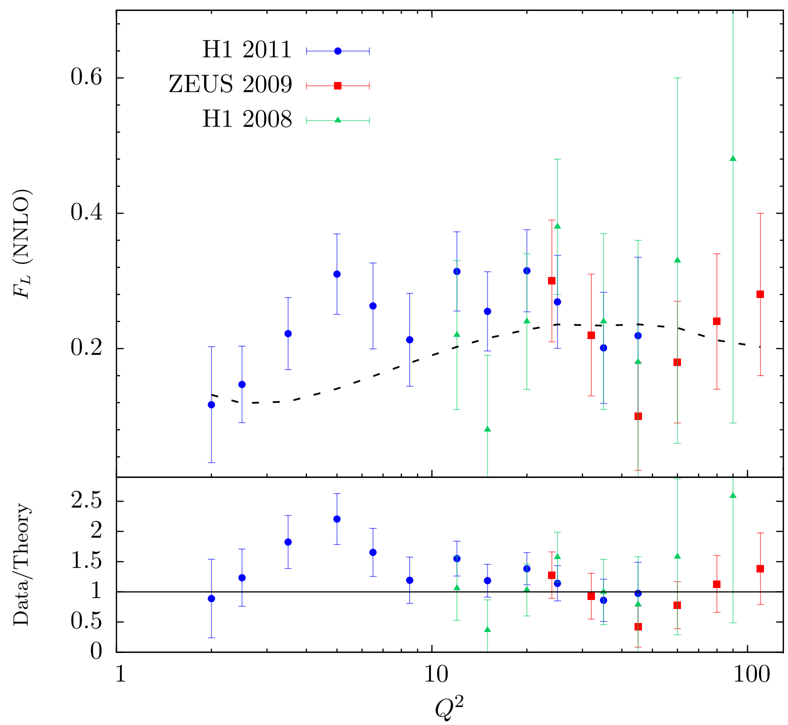
New HERA II combined data studied. Fit quality good – better at NNLO. No very significant changes in PDFs or predictions.

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.

Back -up

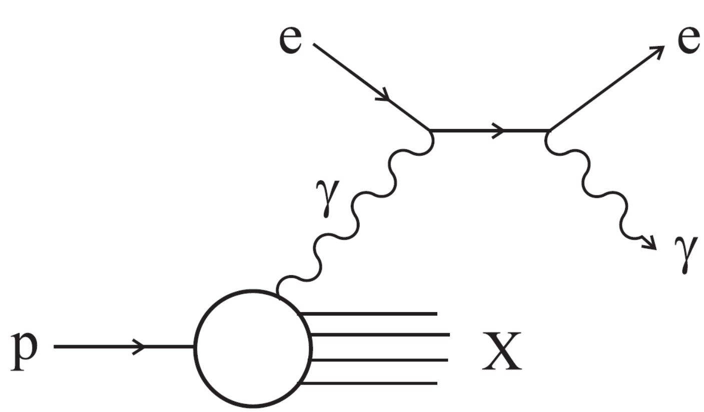

H1 2011
ZEUS 2009
H1 2008
F_L (NLO)
Data/Theory
Q^2


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

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 ($W, Z, WH, ZH, WW, jets\ldots$).

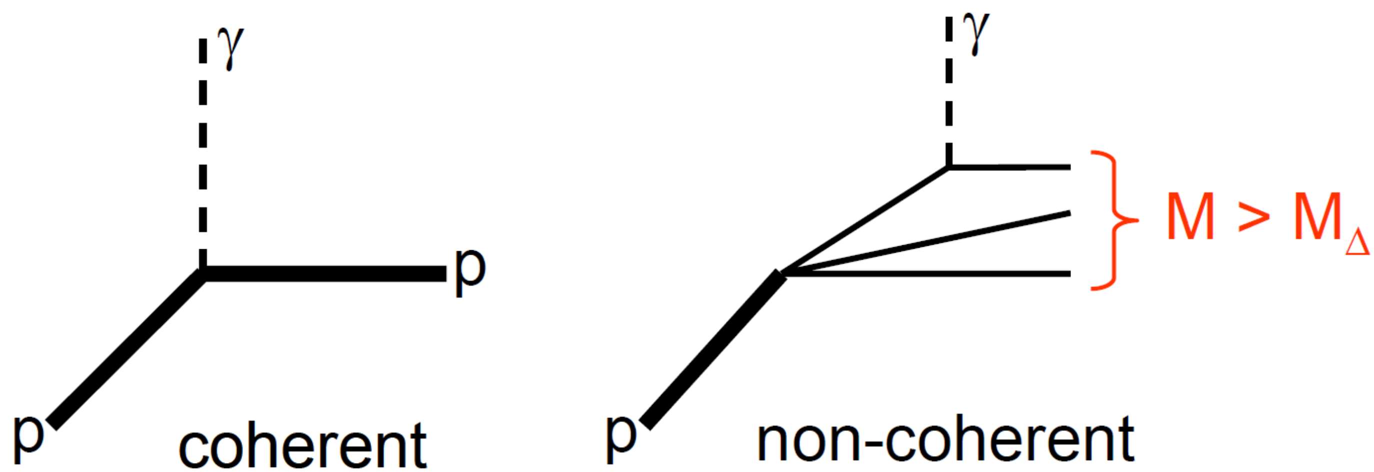
For a consistent treatment need PDFS which incorporate QED into the evolution, i.e. the inclusion of the photon PDF $\gamma(x, Q^2)$. (Set published by NNPDF and recently CT.)



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

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.

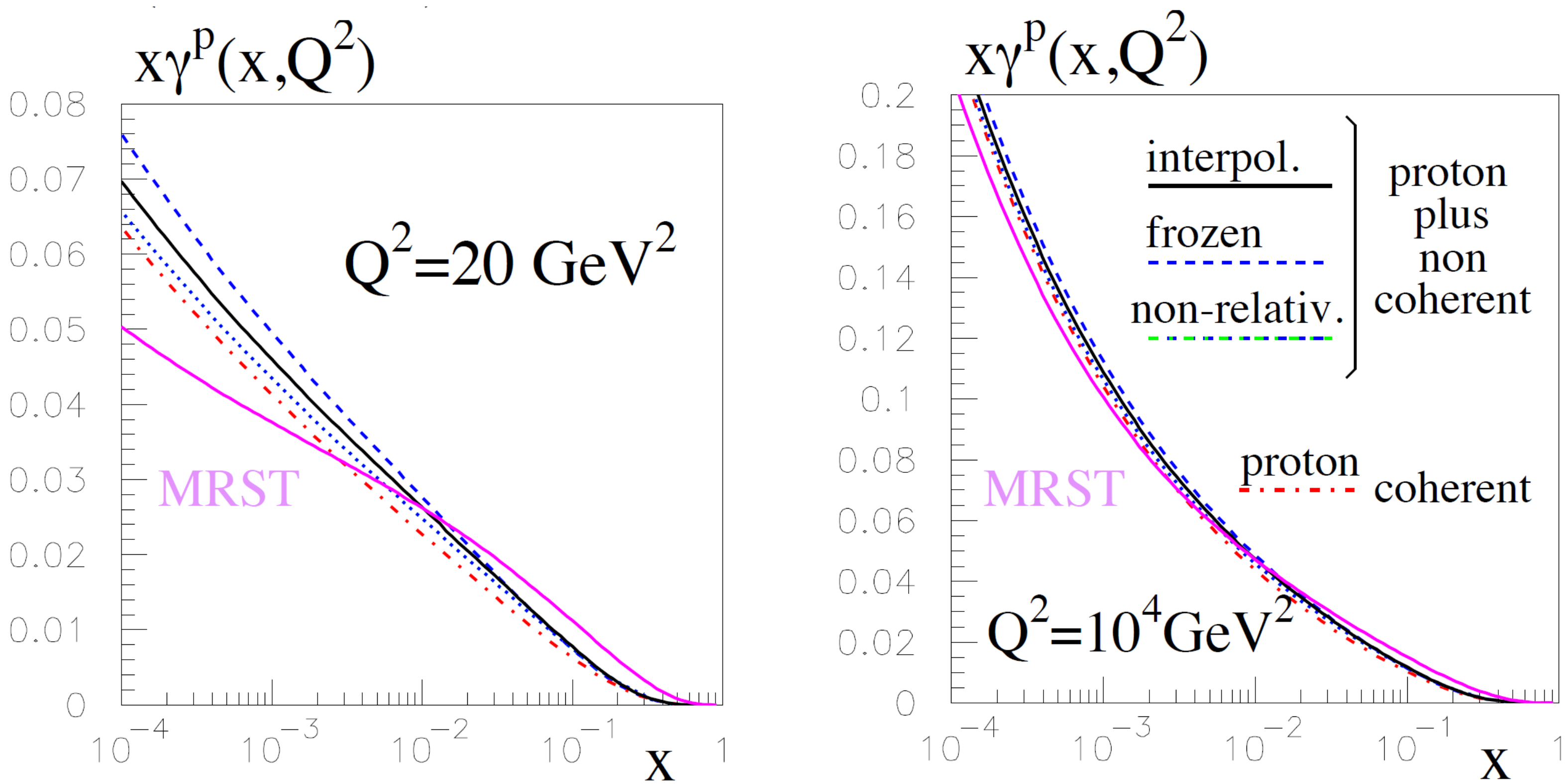
Article by Martin, Ryskin considers separate "coherent" emission and "non-coherent" emission.



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

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

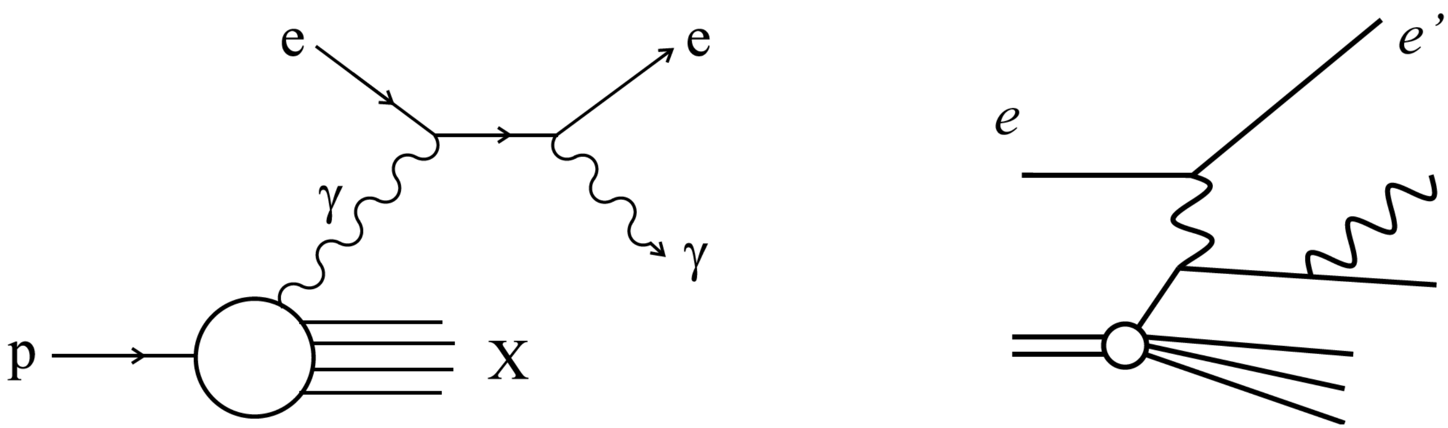
Tends to increase $\gamma(x, Q^2)$ at low x. (MRST2004 larger than NNPDF2.3 for $x < 0.01$).



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.



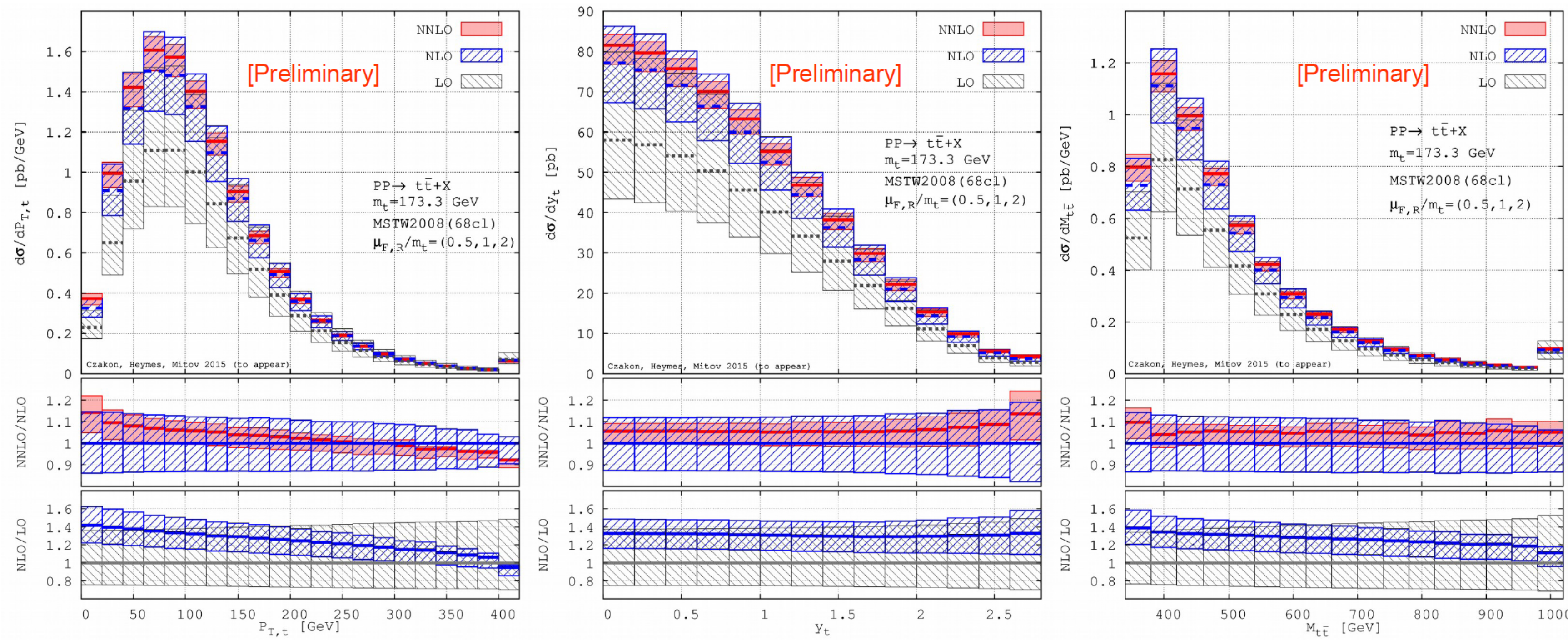
Necessary to consider radiation from quark line also - suggests constituent mass assumption better (CT14QED). At large negative η and high photon E_T the photon-initiated process dominates.

Detailed study a high priority.

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

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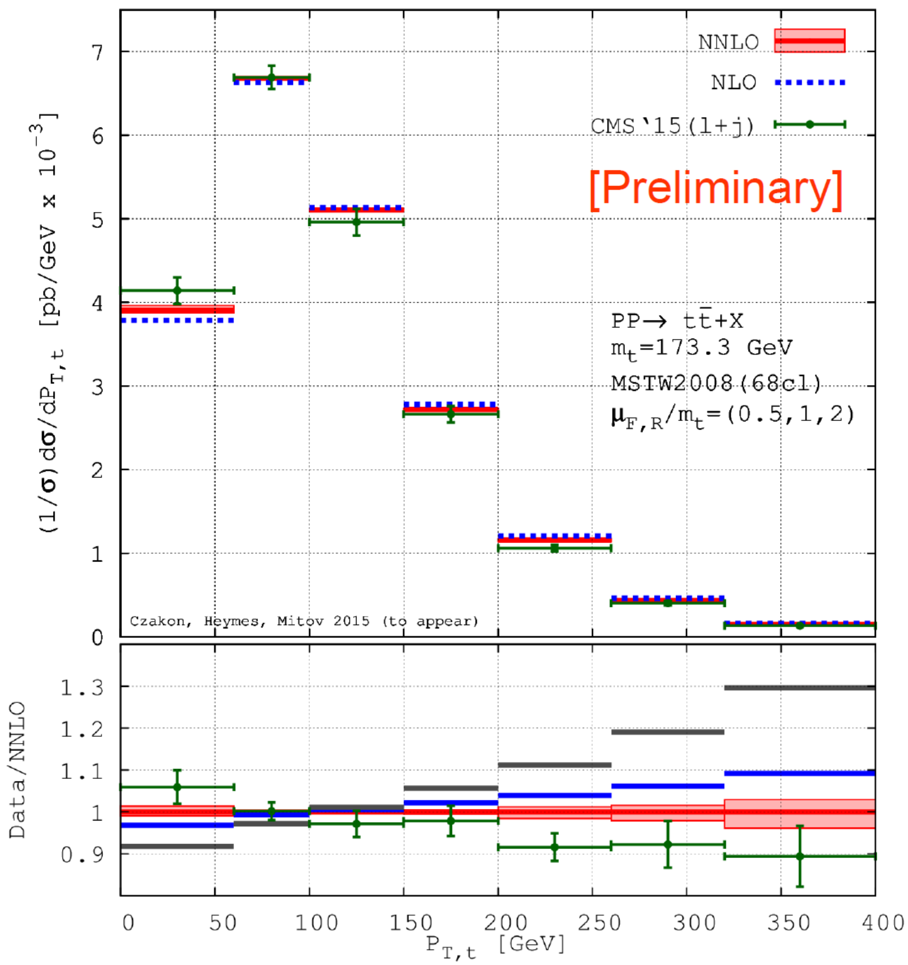
P_T-distribution LHC 8TeV (preliminary)

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

- NNLO prediction vs. measurement



- No overflow bin included
- Good convergence of series
- ATLAS data has been shown

→ [see talk by: B. Tannenwald]

appears to be in perfect agreement with NNLO

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