MMHT2014 PDFs -- updates

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Introduction

Determination of α_S

PDFs and heavy quarks (see, 1510.02332)

Inclusion of combined HERA data

Impact of recent LHC data &

MMHT2016 PDFs (prelim.)

Photon PDF

Diffraction 2016
Sept 2-8th , Acireale
Catania, Sicily

MMHT14 PDFs (successor to MSTW08)

1412.3989

Theoretical updates:

well behaved

1211.1215
MSTWCPdeut

- Parameterization in terms of Chebyshev polynominals

$$(1+\epsilon x^{0.5}+\gamma x) \rightarrow (1+\sum a_i T_i(y)) \text{ with } y=1-2\sqrt{x}$$

- Parameteriz^n of deuteron correct^{ns}—parameters determined by fit
- Multiplicative error treatment
- Updated nuclear corrections
- Optimal GM-VFNS used
- Expt^{al} value of $B_\mu \equiv B(D \rightarrow \mu)$ now input (with error) in fit

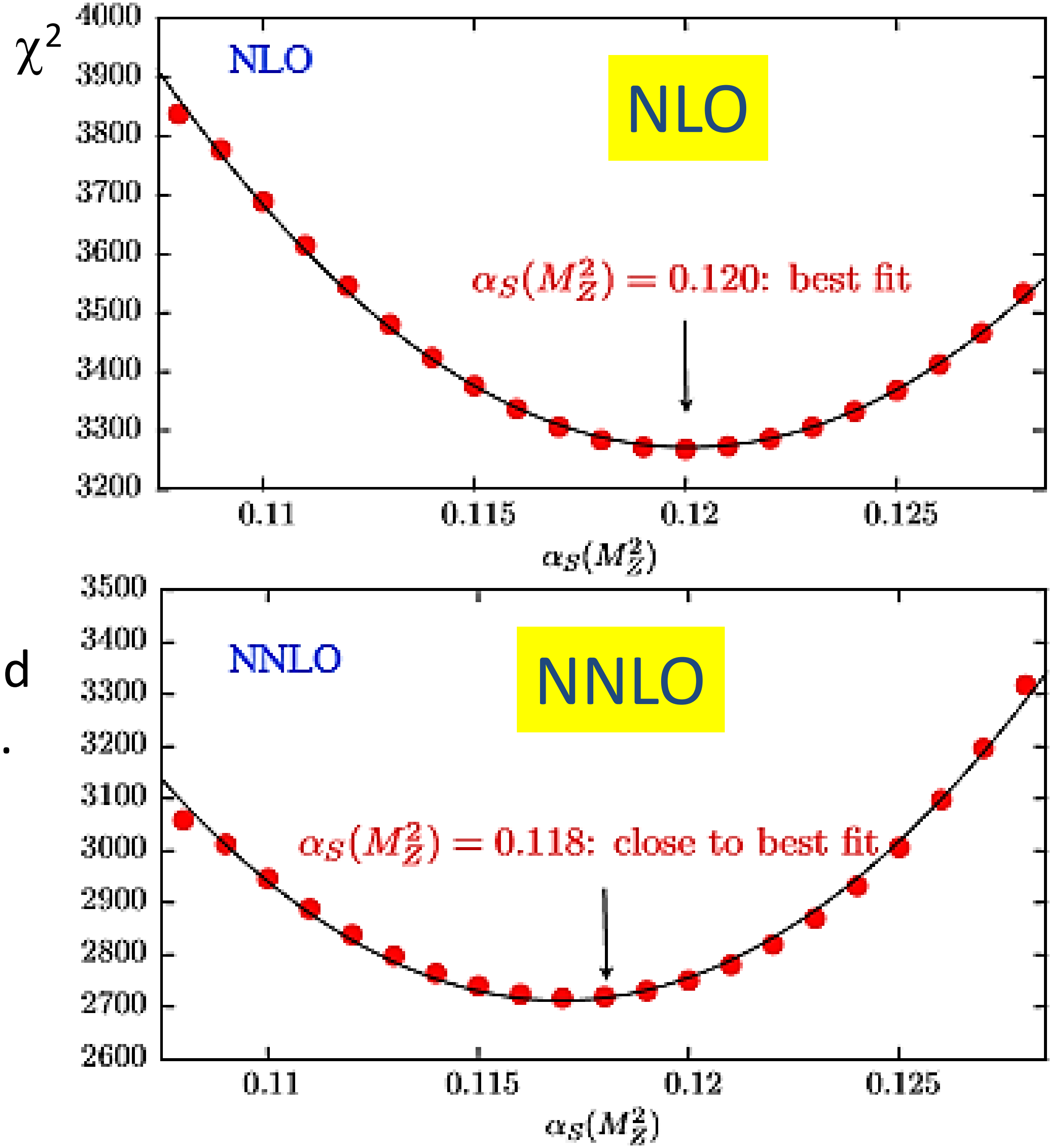
New data: HERA I combined, Tevatron W,Z updates, LHC data

MSTW08/MMHT14 differences small--an exception is **(u_V-d_V)** at low x

"MMHT16": -- HERA I+II, recent LHC data

Further study of α_S

see, 1506.05682



PDFs sets in extended range of α_S available. Allows error due to α_S to be added in quadrature

Impact of final HERA combined data

1601.03413

Prediction of HERA II by MMHT2014 PDFs (which fitted HERA I)

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

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

HERAPDF2.0 (fitting **only** comb.HERA data) with $Q^2(\text{min})=2\ \text{GeV}^2$ find

$\chi^2 \sim 1.20$ per point at NLO and NNLO

Refitting with HERA II by MMHT2014 PDFs gives

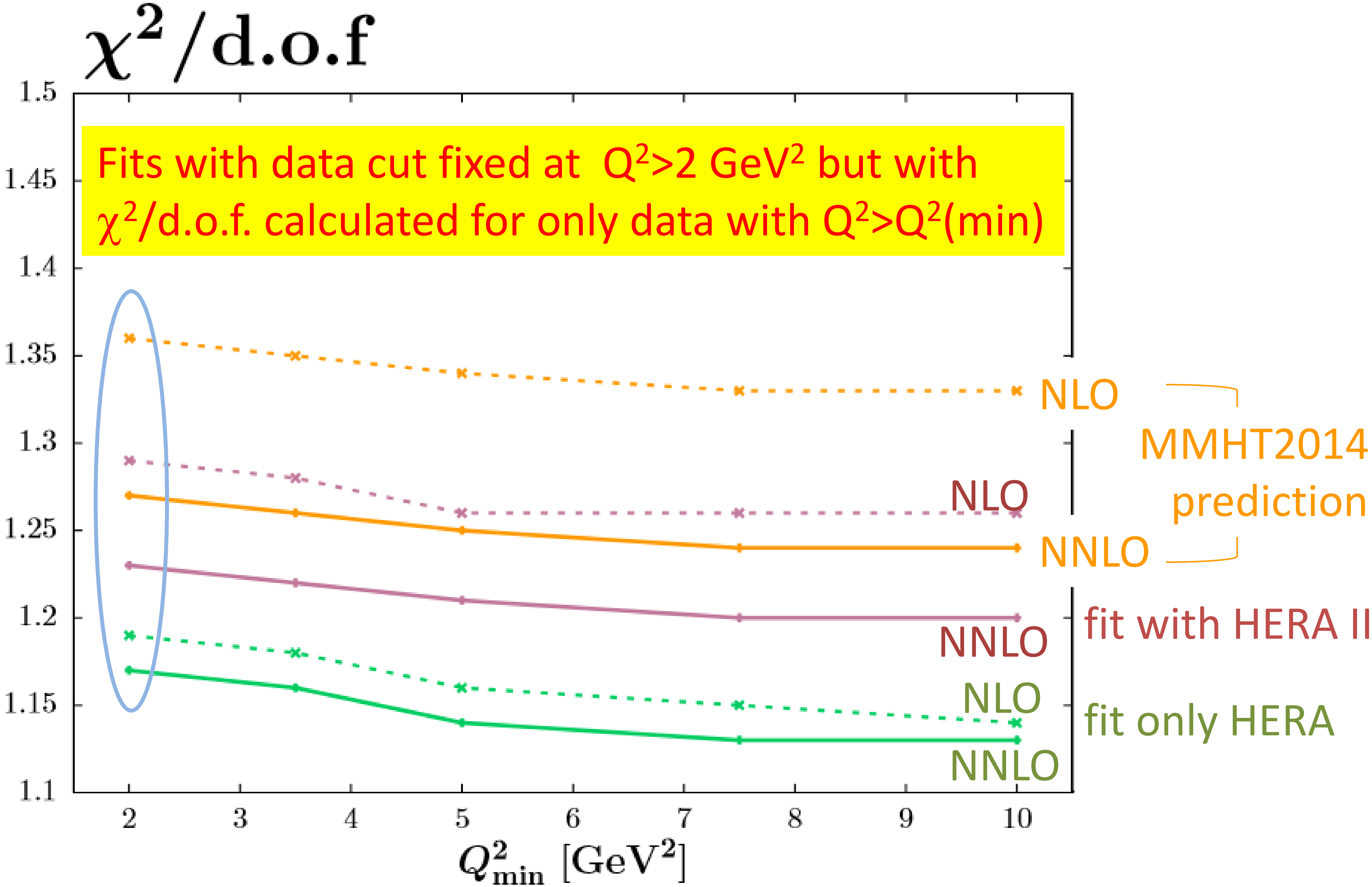
NLO – $\chi^2 = 1533/1185 = 1.29$ /pt with $\Delta\chi^2=29$ due to other data

NNLO – $\chi^2 = 1457/1185 = 1.23$ / pt with $\Delta\chi^2=12$ due to other data

Also tried fitting **only** HERA II data (with 4 parameters fixed to avoid spurious PDFs)

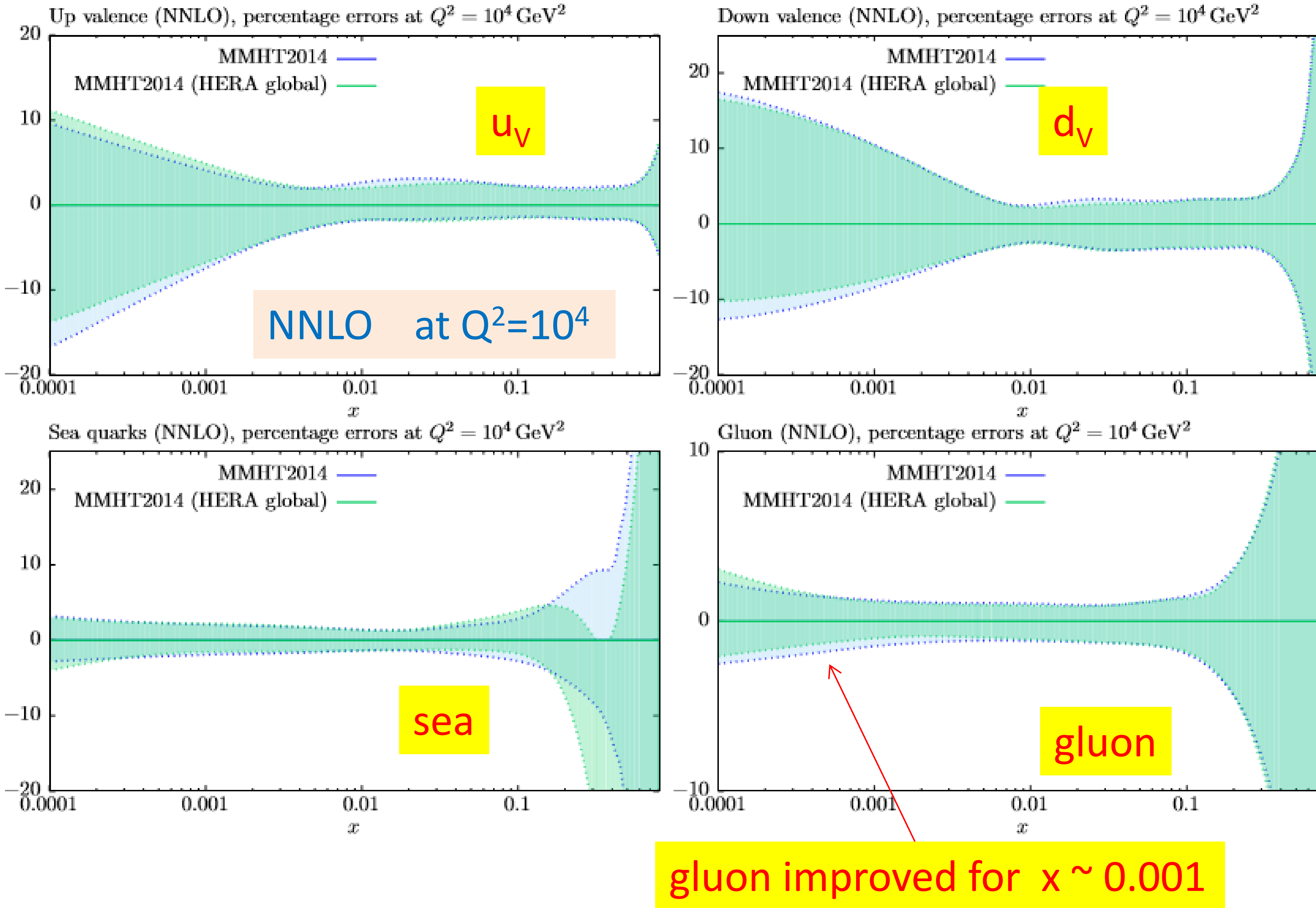
NLO – $\chi^2 = 1416/1185 = 1.19$ per point

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



NNLO always better than NLO fit

PDF uncertainties little improved from MMHT2014



HERA II effect more obvious when looking at predictions

	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} $\binom{+1.3\%}{-2.0\%}$

Up to about 10% reduction in uncertainties.

Very small change in central values

Impact of LHC data

NNLO

	no.pts	MMHT14 χ^2(pred.)	MMHT16 χ^2(fit)
$\sigma_{t\bar{t}}$ Tevatron +CMS+ATLAS	18	14.7	15.5
LHCb 7 TeV $W+Z$	33	37.1	36.7
LHCb 8 TeV $W+Z$	34	76.1	67.2
LHCb 8TeV e	17	30.0	27.8
CMS 8 TeV W	22	57.6	29.4
CMS 7 TeV $W+c$	10	8.7	8.0
D0 7 e asymmetry	13	27.3	22.9
total	3405	3768.0	3739.3

MMHT14 predictions generally v.good.

MMHT16 fit – no tension – so PDFs v.similar

$\Delta\chi^2$=15 for remainder of data

If coupling free $\alpha_S(M_Z^2)$=0.118 (from 0.1172)

look at data in turn →

W+c data and s PDF

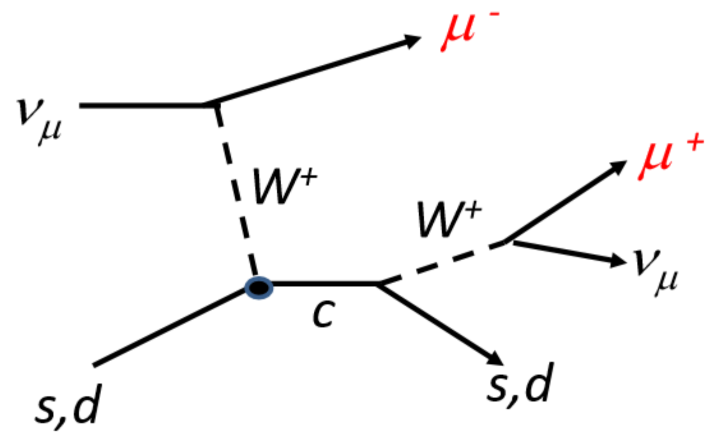
Recall need

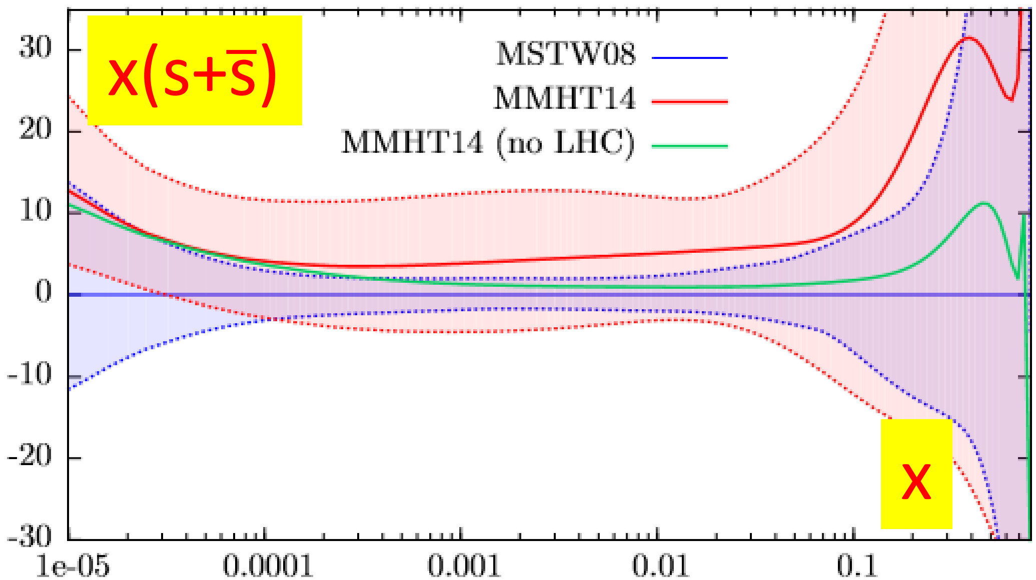
$B_\mu \equiv B(D \to \mu)$ for s PDF from ν→μμ evts

MSTW used fixed B_μ =0.099 (NuTeV value)

whereas **MMHT** fitted $B_\mu = 0.092 \pm 10\%$

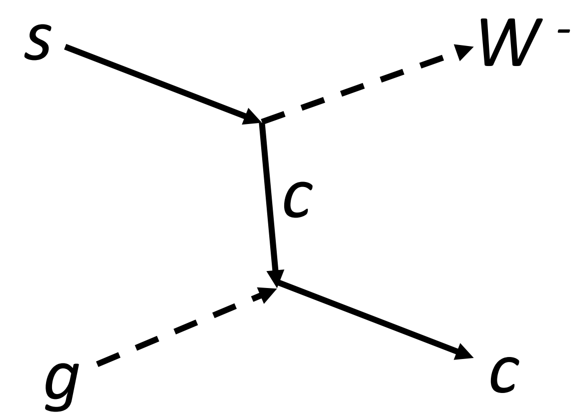
and found $B_\mu = (0.085 - 0.091) \pm 15\%$



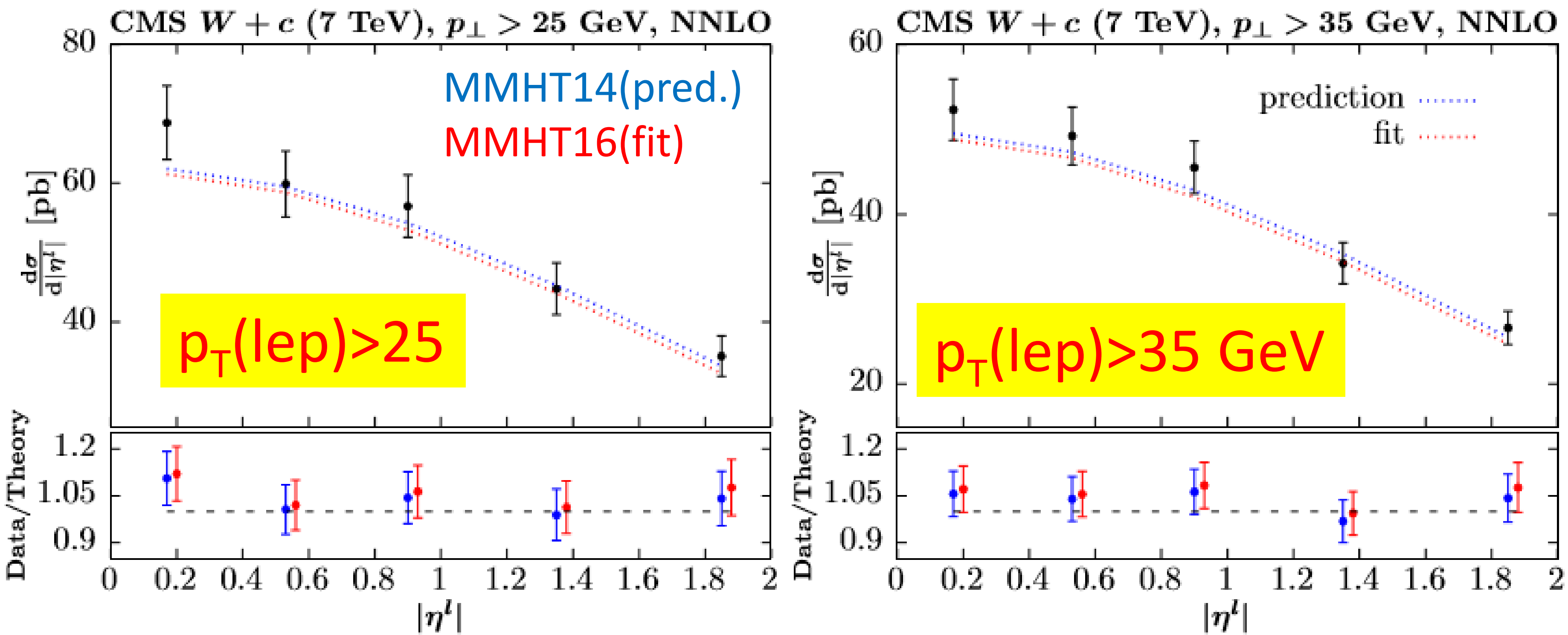


Uncertainty & value of *s* increased

W+c data and s PDF



$$\frac{d\sigma_{W+c}}{d|\eta^l|}$$



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.

W^+, W^- production

very naïve:

$u = u_V + q$

$d = d_V + q$

u(bar) ~ d(bar) ~ q

$A(y=0) = \sigma(W^+) - \sigma(W^-)$

$= u\,\bar{d} - \bar{u}\,d$

$\sim (u_V+q)q - q(d_V+q)$

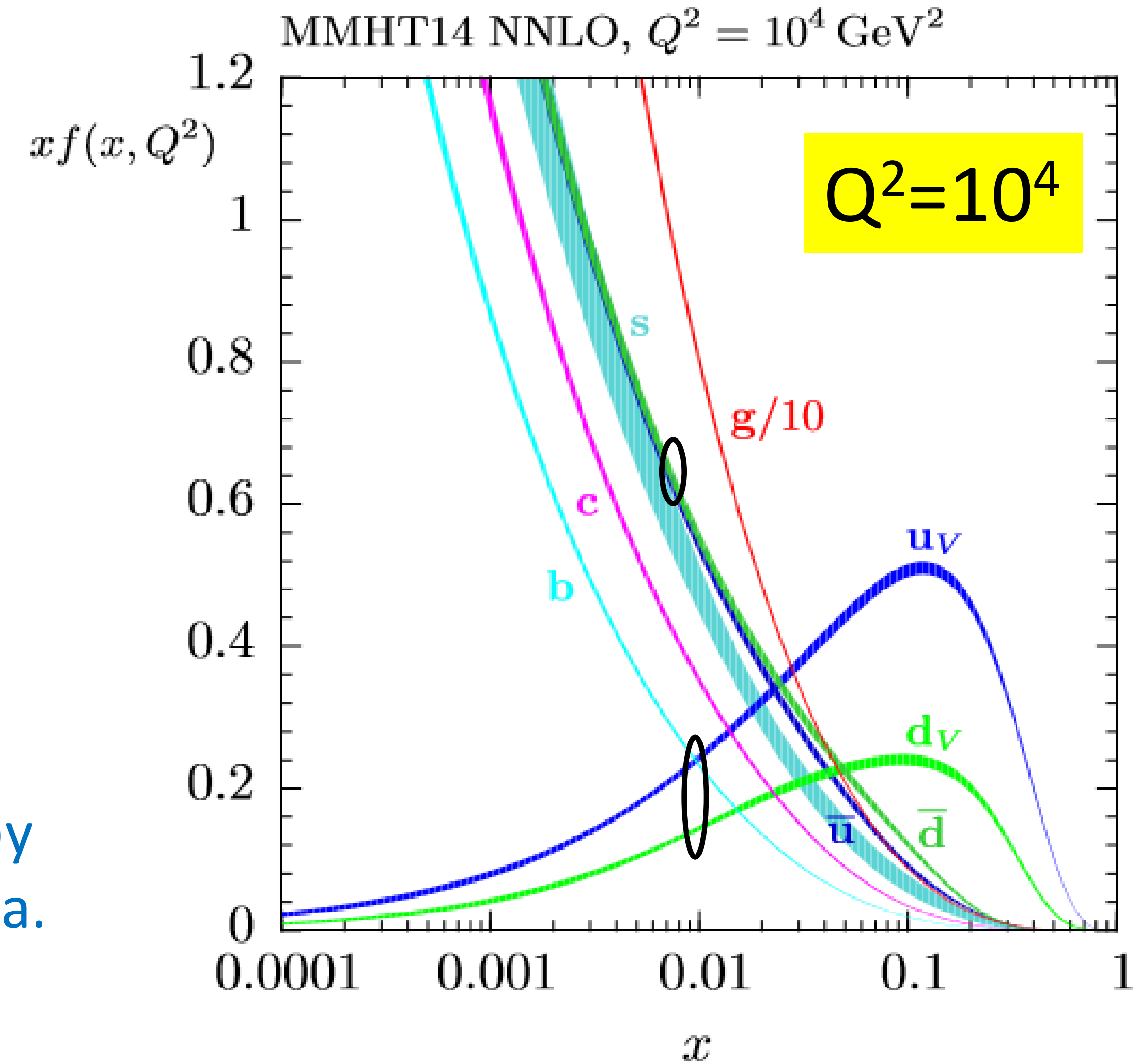
$= (u_V-d_V)q$

in practice with y dep.

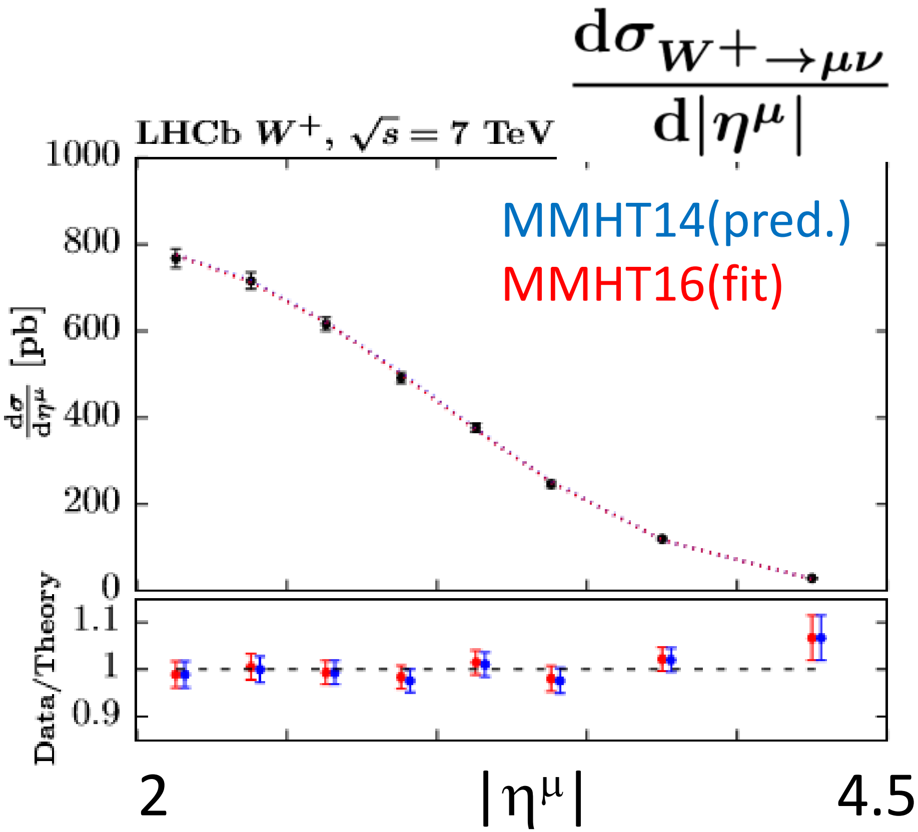
very rich structure

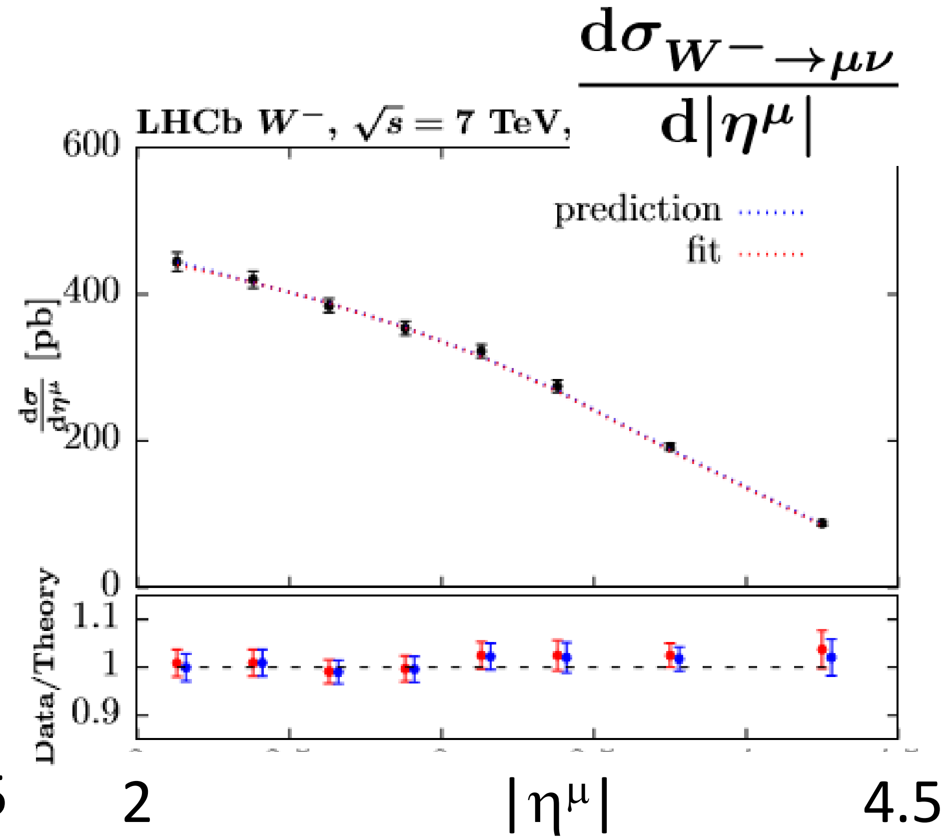
$x_{1,2} = M_W/\mathrm{sqrt}(s)*\exp(+/-)y$

and also Z prod.& D-Y data.



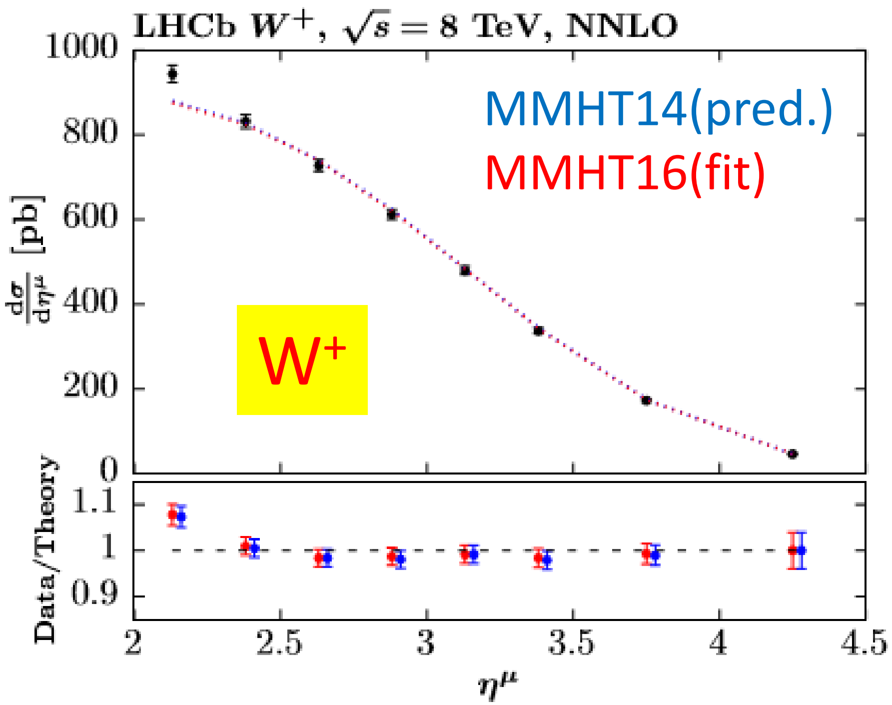
High rapidity W production at LHCb at 7 TeV

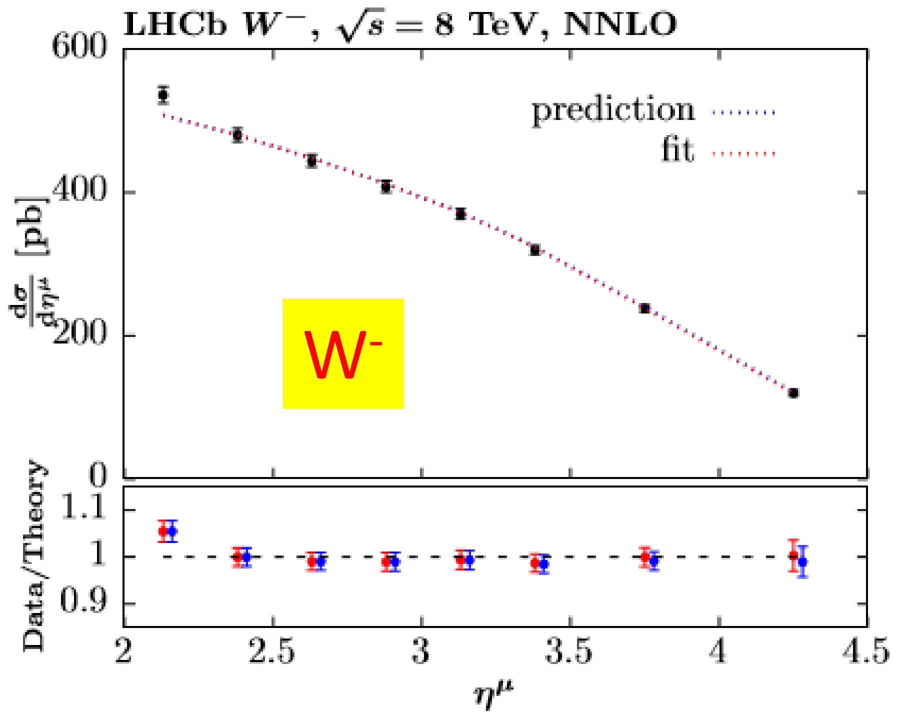




Generally perfectly good agreement using NNLO. Uncertainties added in quadrature on plot, but covariance matrix used in fit.

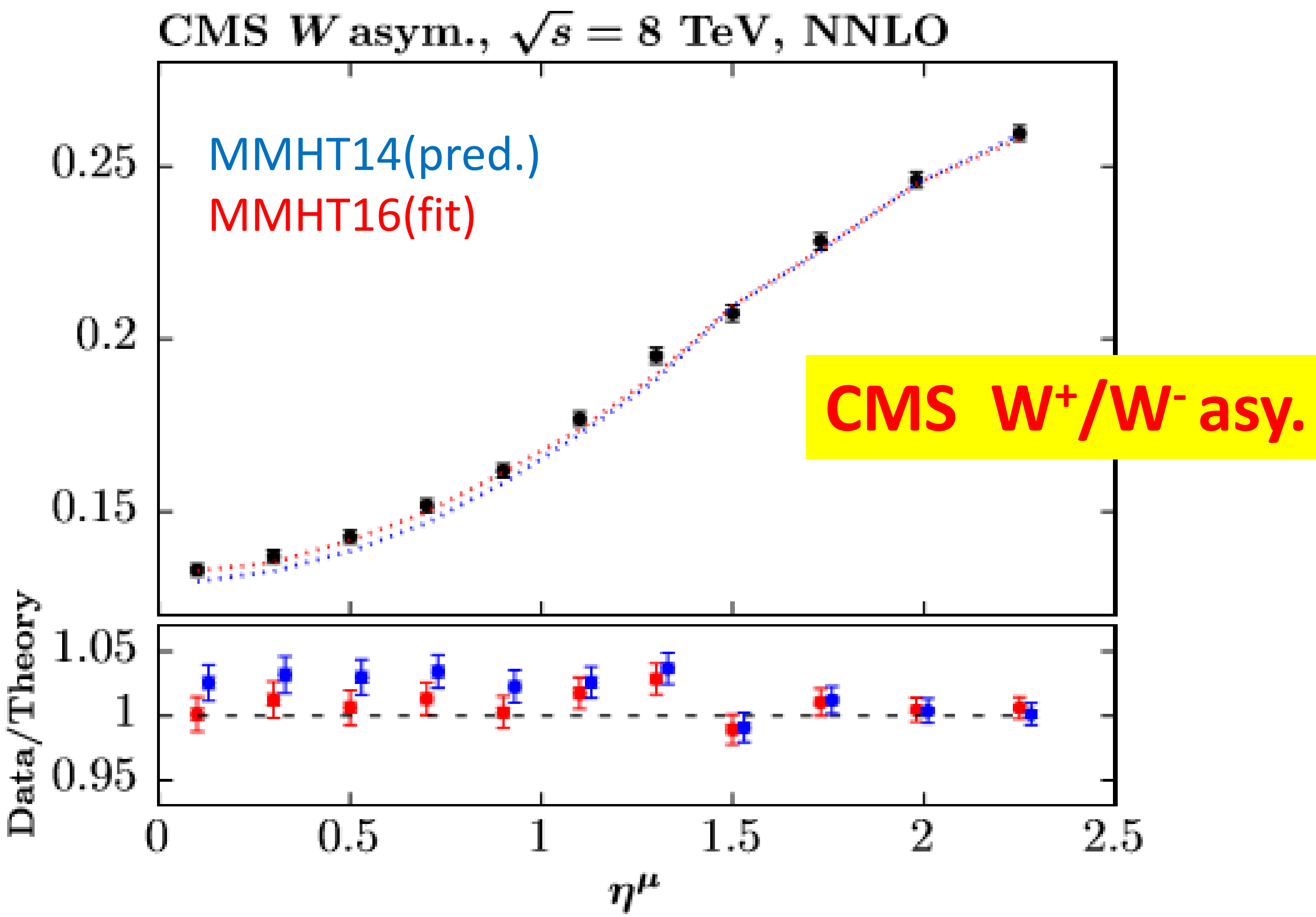
New data on high rapidity *W* production at LHCb at 8 TeV





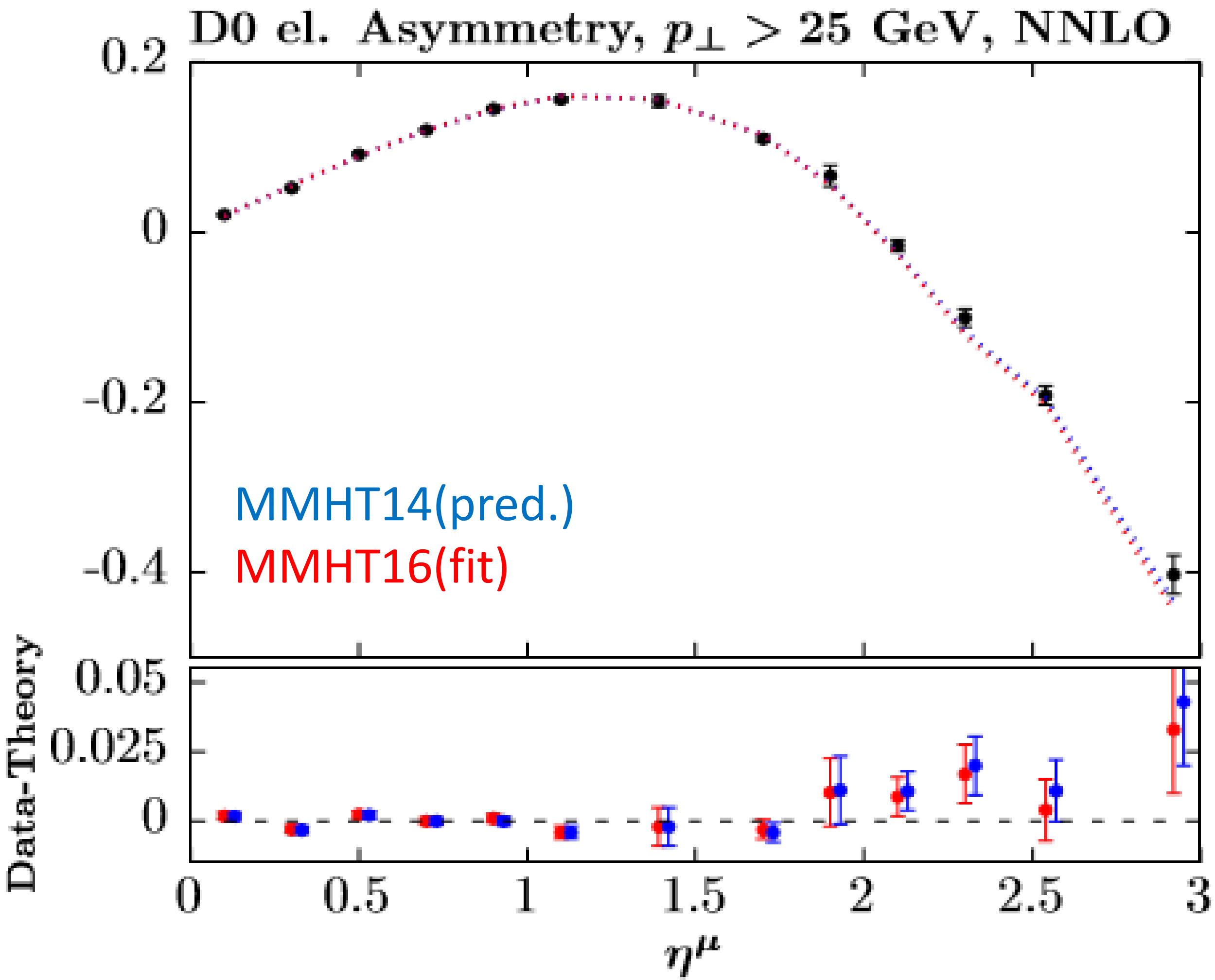
Good fit except at lowest η_μ point in each case.

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.

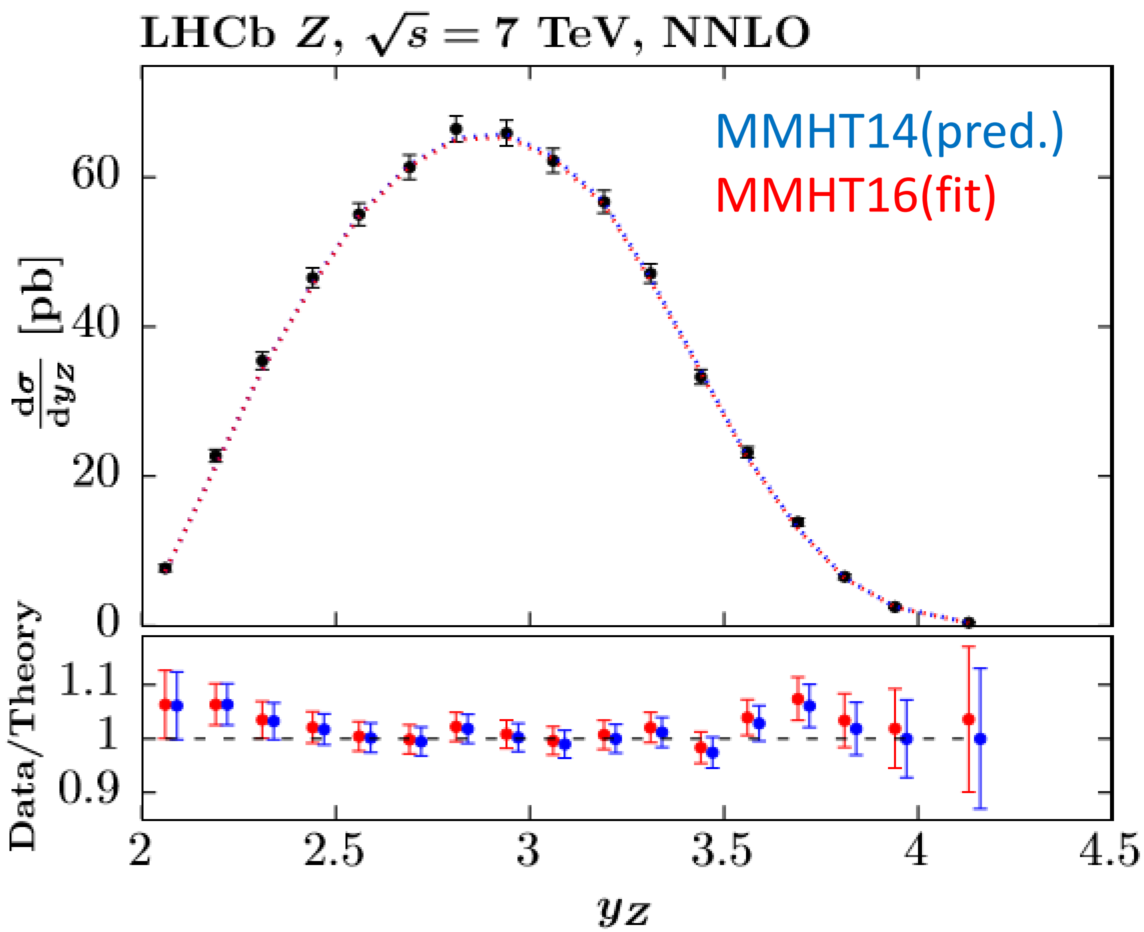
Good agreement with new D0 e asymmetry data



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

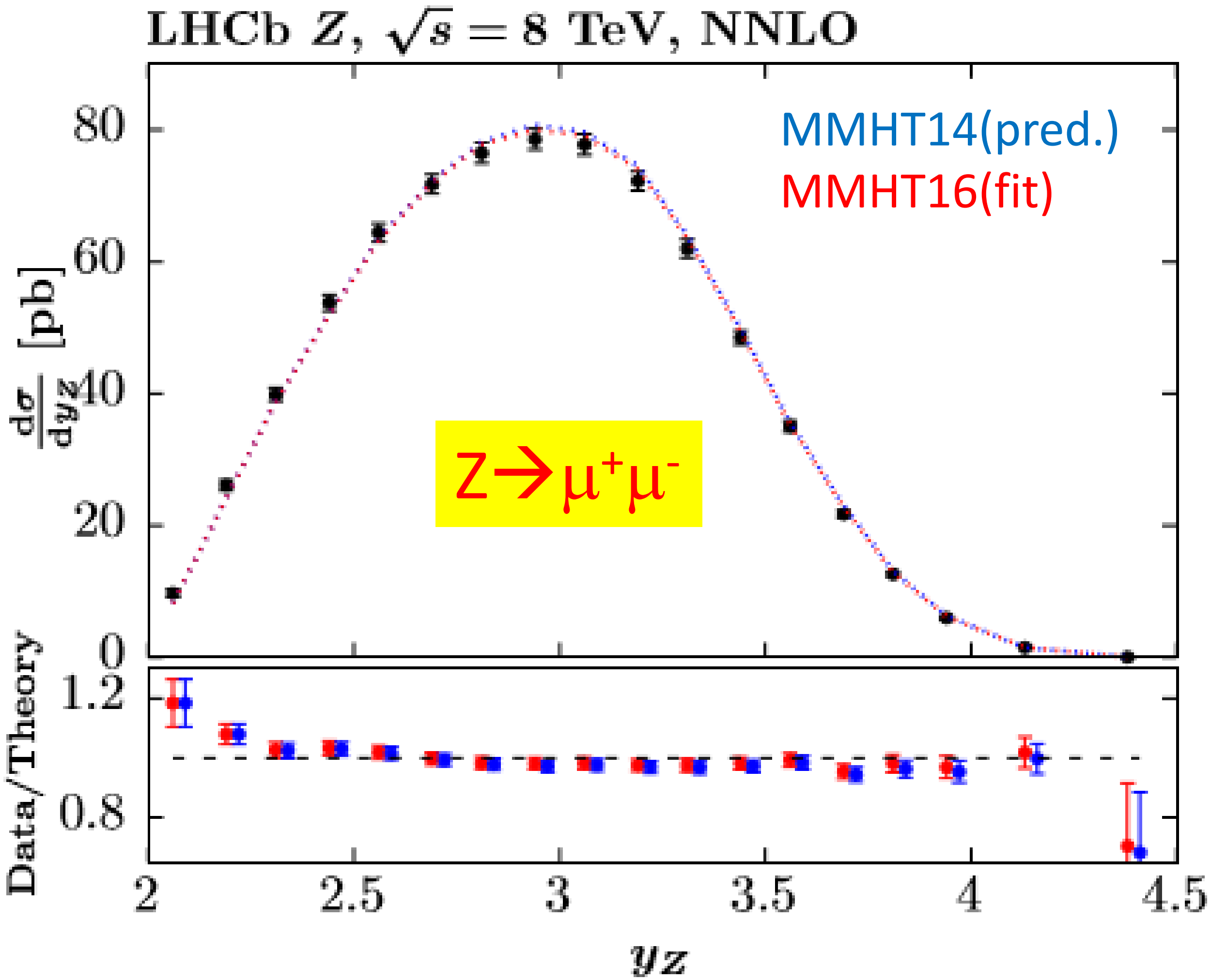
Z production

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



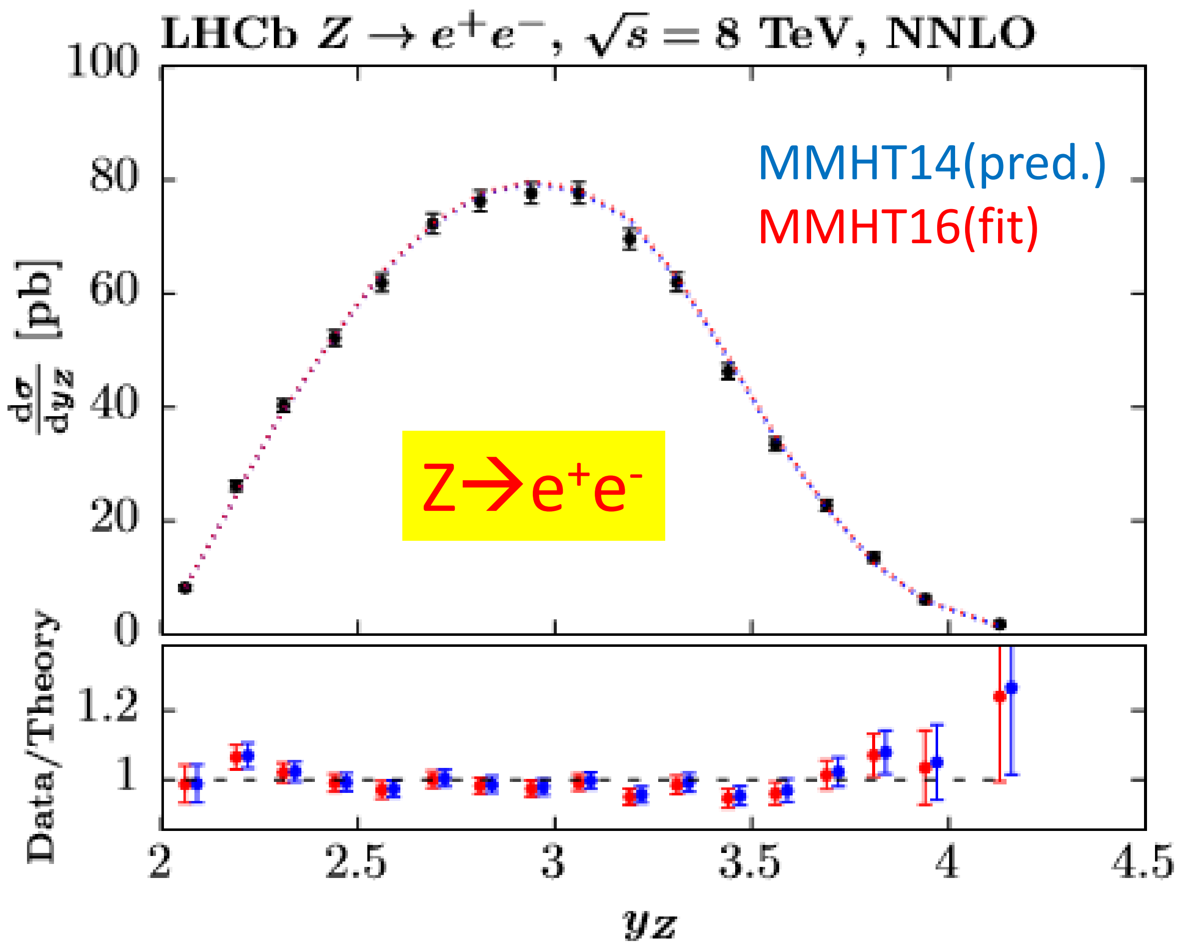
Generally perfectly good agreement using NNLO. A little low at low y_Z.

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



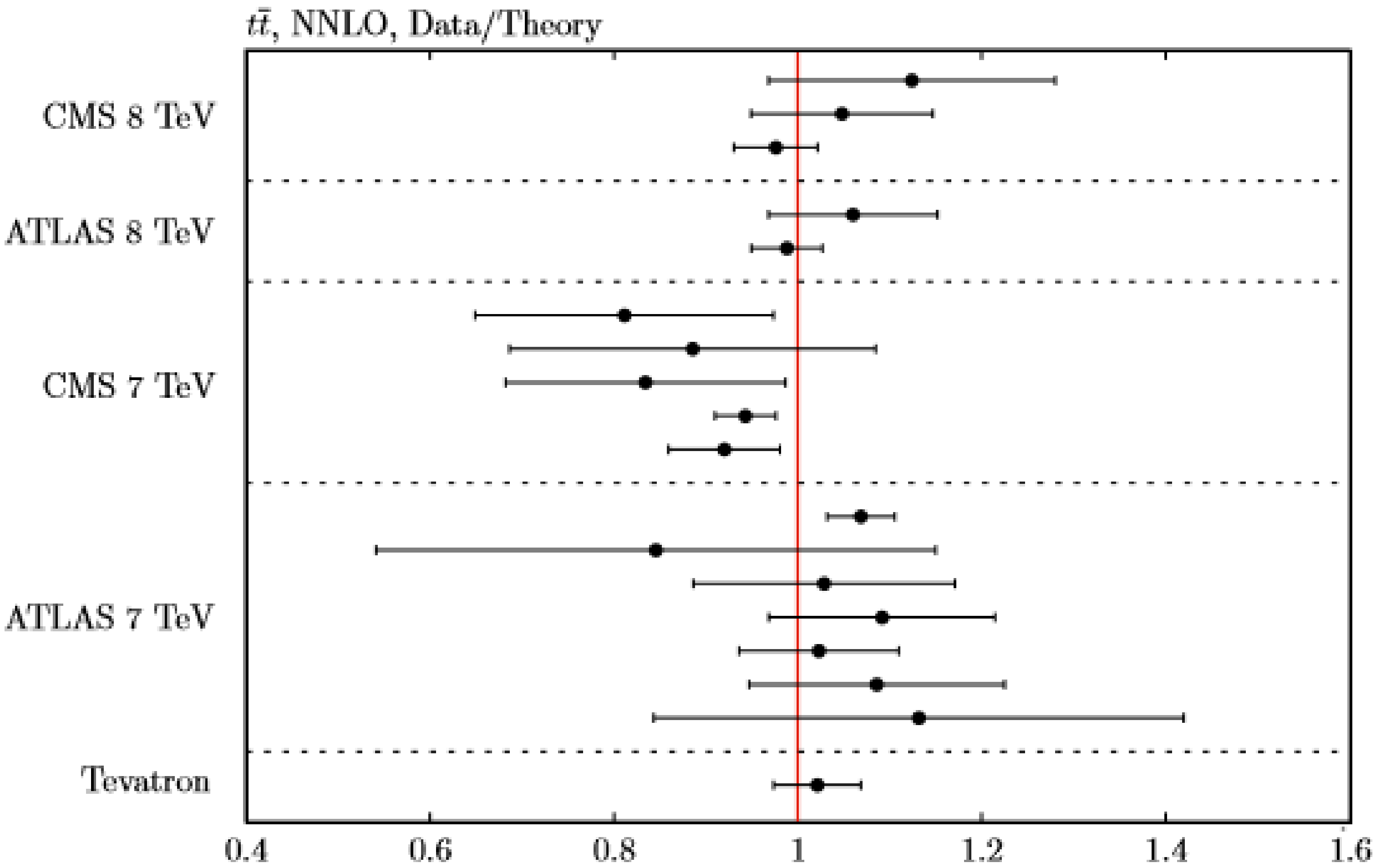
Same issue with lowest y_z point. PDFs at moderate x for these points and well constrained by DIS data.

New data on high rapidity Z production at **LHCb** at 8 TeV with electrons.



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

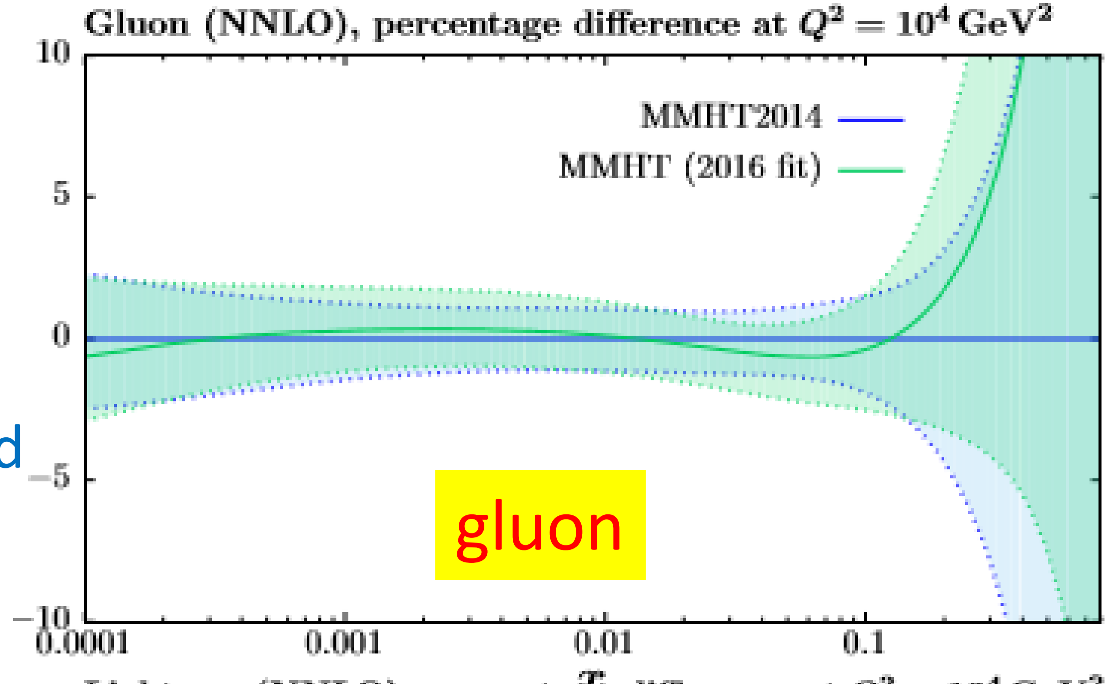
Included some more up-to-date results on $\sigma_{\bar{t}t}$.



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

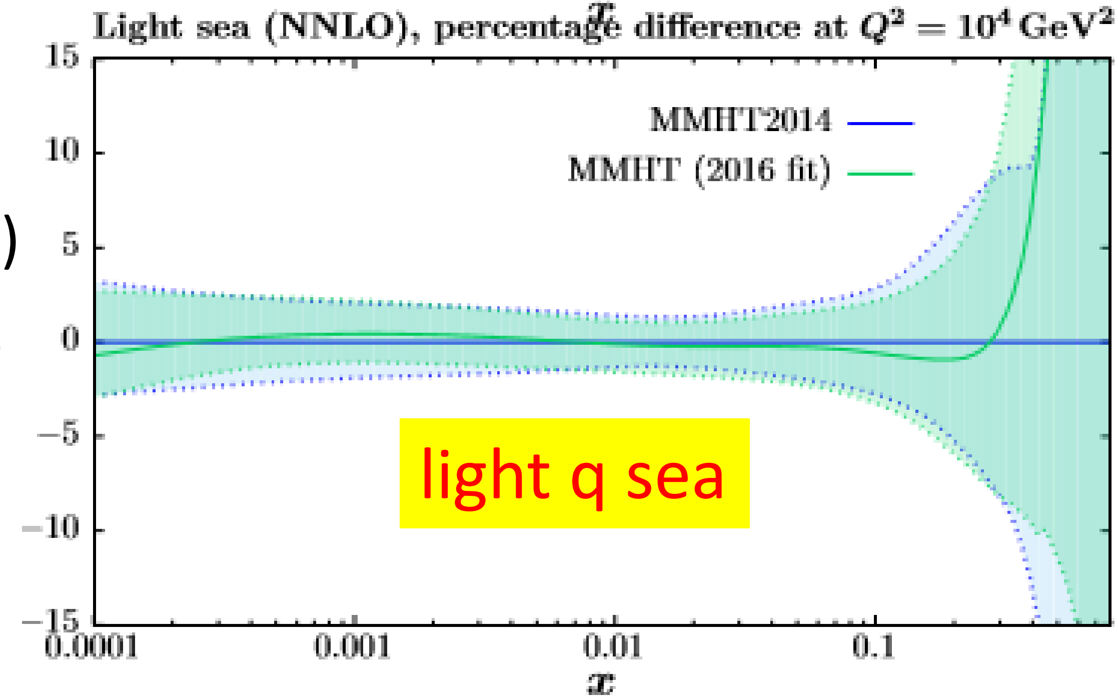
Effect on PDFs

MMHT16 set (not for distrib^n) at NNLO with PDF evectors for unc. 25 PDF parameters with 50 evector dir^{ns}---9 constrained by one of new LHC data sets

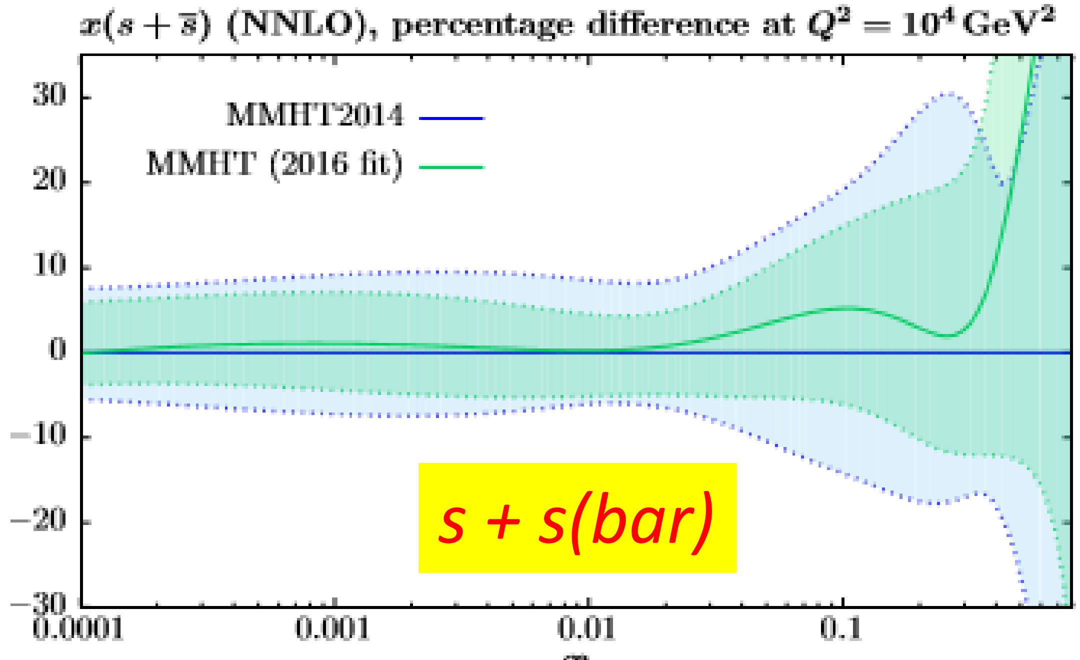


No significant change in gluon or light sea. (but large x)

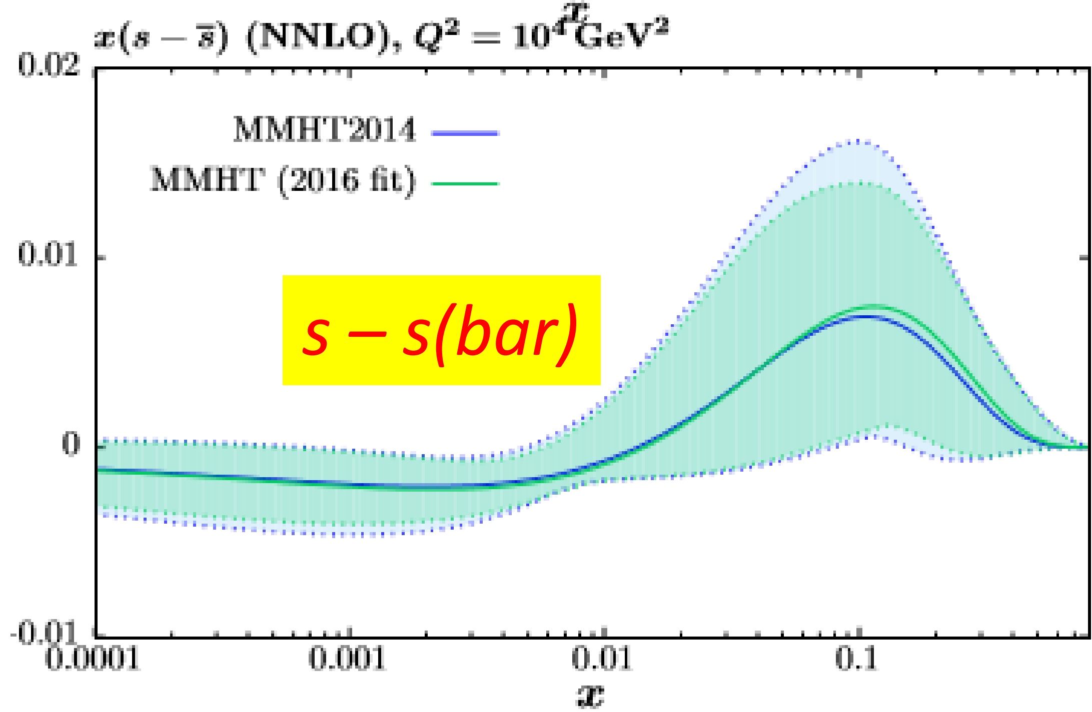
Small decrease in uncertainty in some small-x regions due to new HERA data.



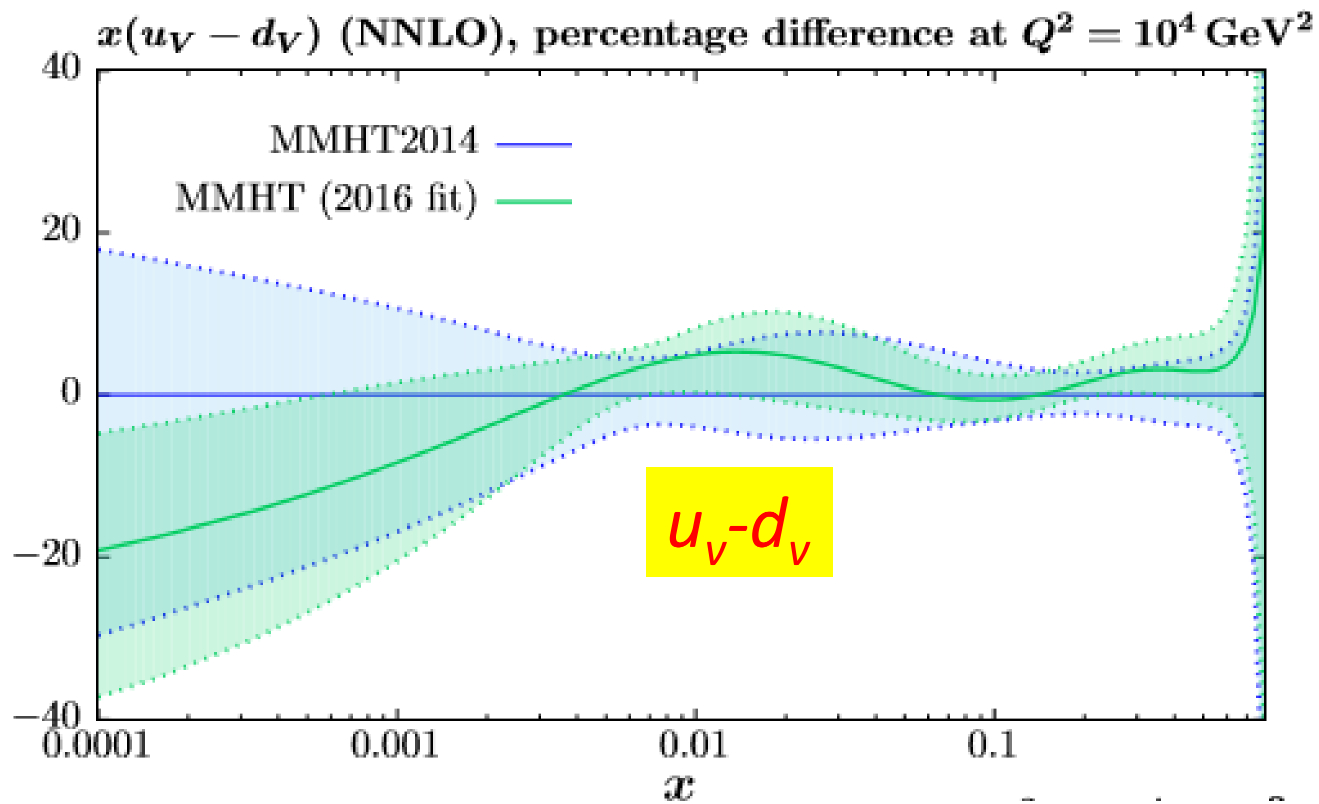
Large reduction in the $s+\bar{s}$ uncertainty, but little change in central value. Due to $W+c$ jets data.

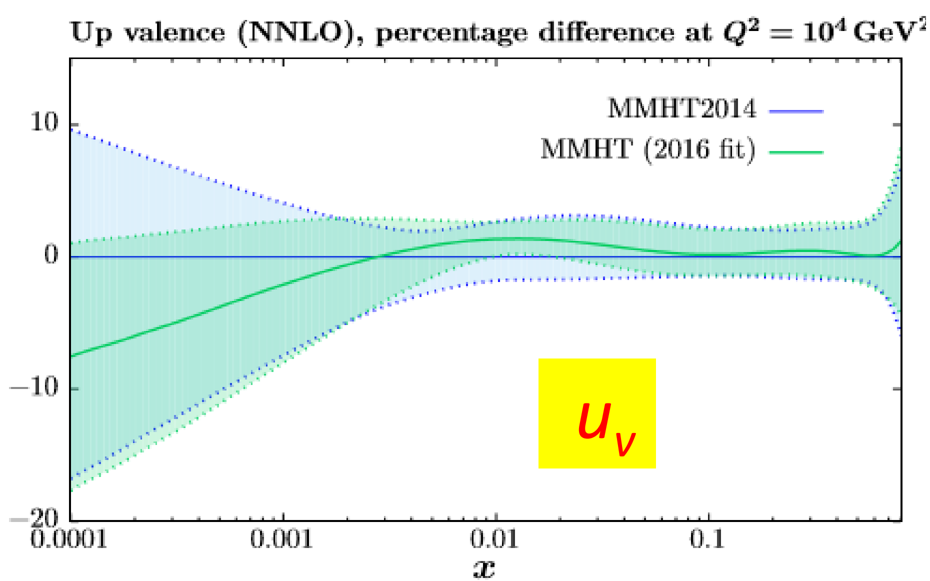


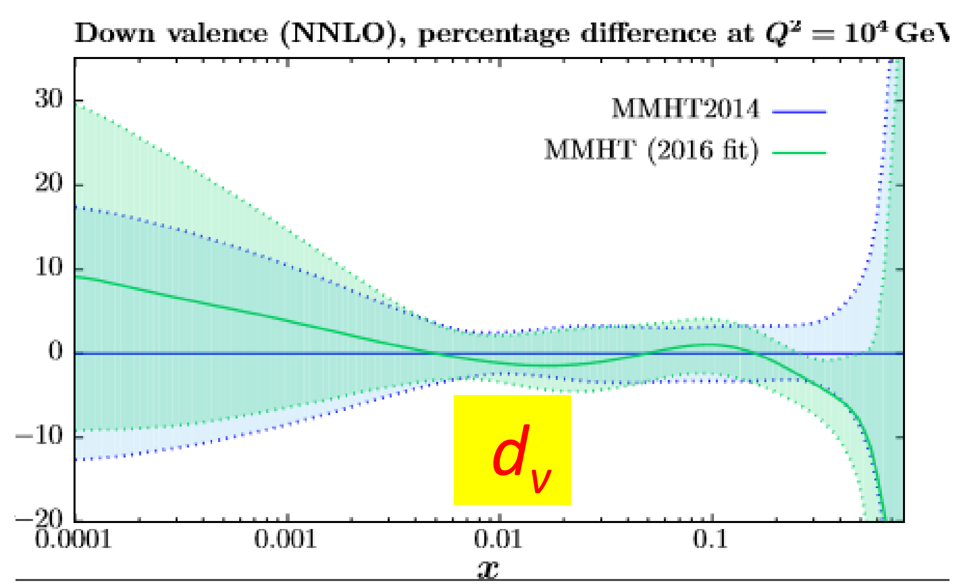
Some impact on $s-\bar{s}$ uncertainty, from (effective) asymmetry data.

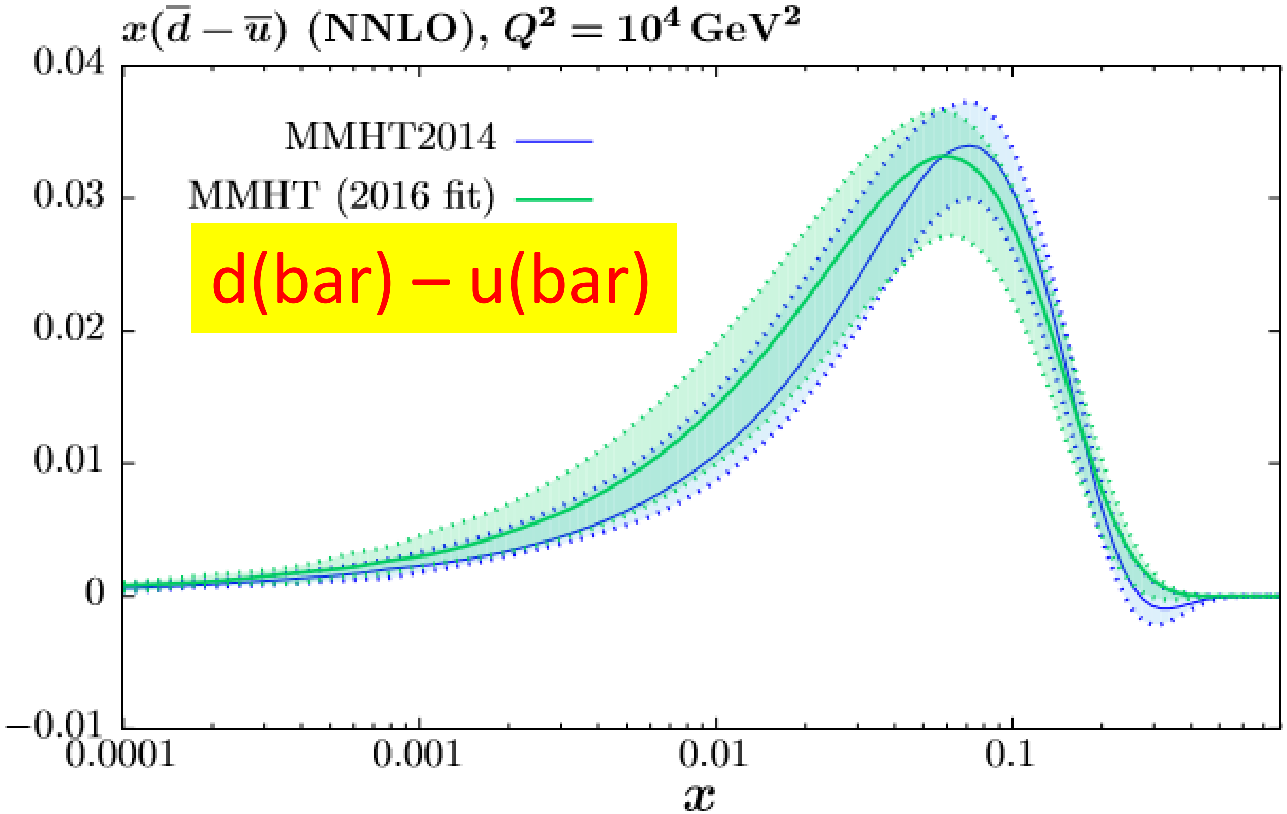


Significant change in u_v-d_v and reduction in uncertainty, from W^+/W^- asymmetry data, including the very accurate CMS asymmetry data









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.

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

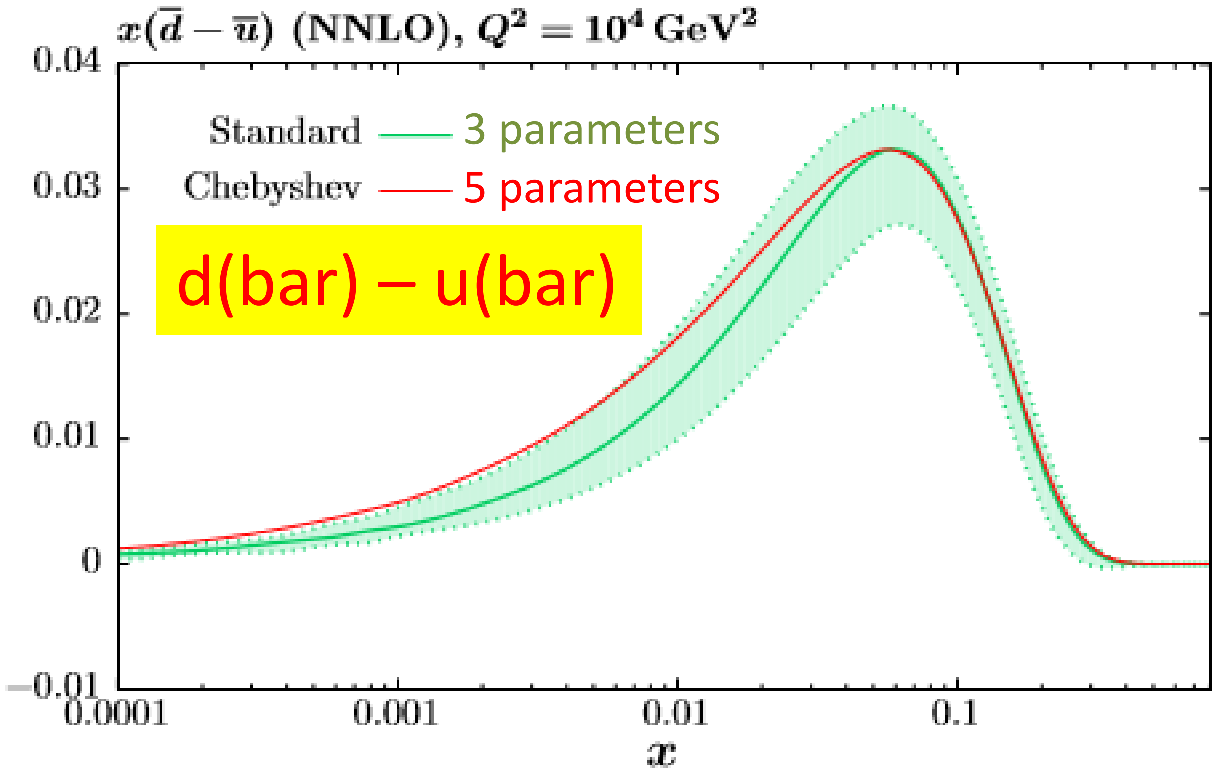
Extend to

$$(\bar{d}-\bar{u})(x,Q_0^2) = A(1-x)^{\eta_{sea}+2}x^{\delta}(1+\textstyle\sum_{i=1}^{4} a_i T_i(1-2x^{0.5})),$$

where $T_i(1-2x^{0.5}))$ 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.

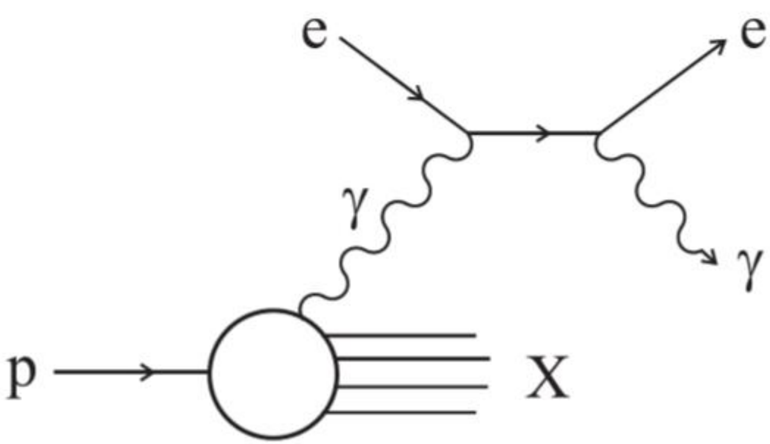
Now a slightly smaller decrease towards zero at low x at edge of previous uncertainty band.

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

PDFs with QED corrections

At the level of accuracy we are now approaching it is important to account for electroweak corrections.

We need PDFs which incorporate QED into the evolution --- that is we need to include the photon PDF $\gamma(x,Q^2)$



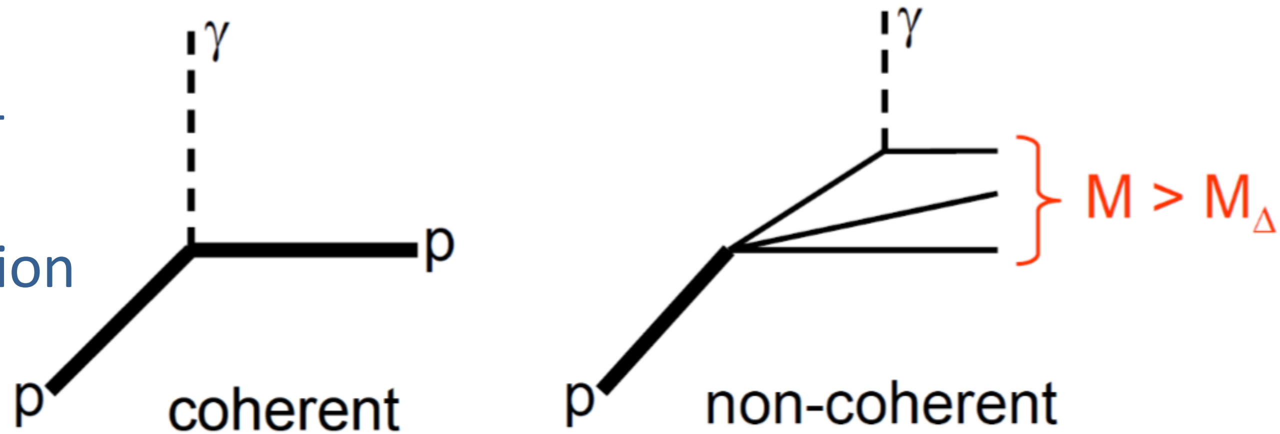
$$\frac{\partial\gamma(x,Q^2)}{\partial \log Q^2} = \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\left(P_{\gamma\gamma}\otimes\gamma + \sum_1 e_i^2 P_{\gamma q}\otimes q_i\right)$$

etc.

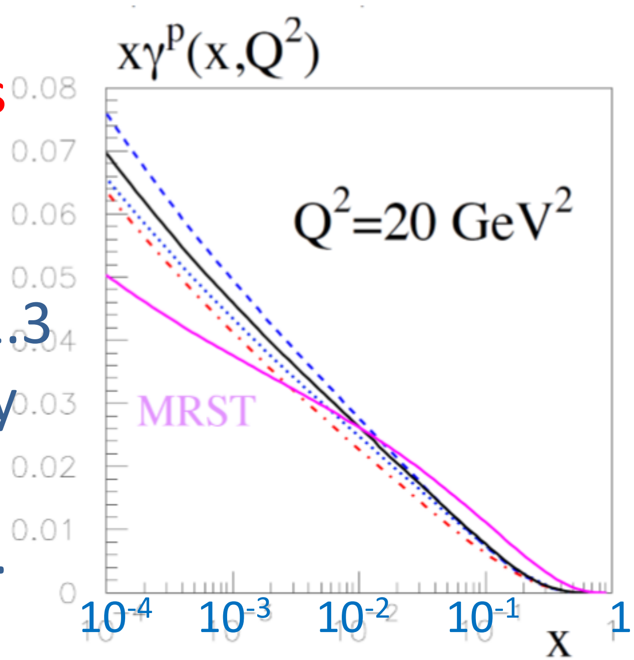
Sets published recently by NNPDF & CT. ---- large uncertainties

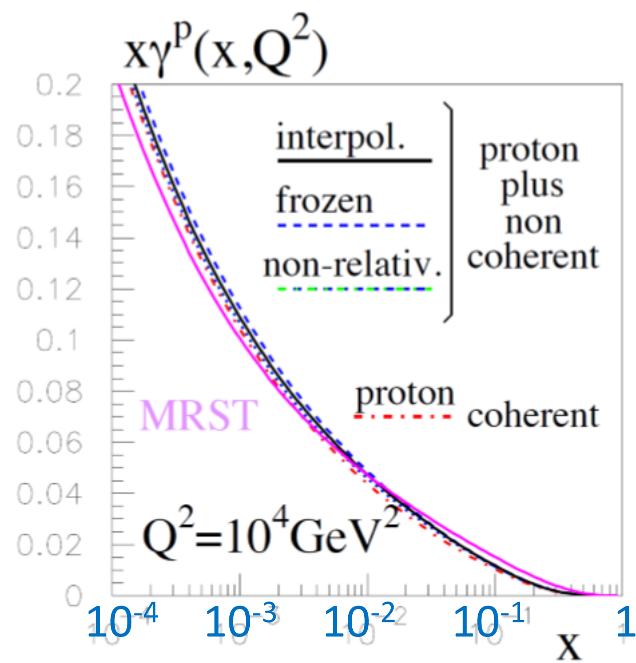
Previous MRST2004 sets assumed $\gamma(x,Q^2)$ generated by photon emission off a model for valence quarks with QED evolution from $m_q \rightarrow Q_0$

“New” development -- (1406.2118) consider coh. & non-coh. emission $\gamma(x,Q^2) = \gamma_{coh} + \gamma_{incoh}$.



Major part of input, especially at low x, comes from coherent which is known to good accuracy. Uncertainty is due to non-coh. part which is calculated from emission from quarks





MRST2004 > NNPDF2.3 for x<0.01, but mainly due to evolution differences not input.

Conclusions

New HERA II combined data well described by MMHT14 PDFs. No significant changes in PDFs in new re-fit. Slight reduction in uncertainties. Low x, low Q^2 data accommodated by power corr^n in F_L (none needed in F_2).

MMHT14 predictions turn out to be very good for (most) LHC data not included in the fit. In re-fit ("MMHT16") find few changes of significance in central values, but some data reduce uncertainties, mainly in strange and low x valence quarks.
Some new σ(tt(bar)) data--fit compatible with world average $m_t^{(pole)}$ and there is a small increase in fitted $\alpha_S(M_Z^2)$ to 0.118 at NNLO.
Much extended d(bar) – u(bar) parametrization only leads to very minor changes. No deviation preferred at small x.

Work in progress on updated PDFs with QED corrections

PDFs and Heavy Quarks

arXiv: 1510.02332

Choice of range of heavy quark masses:

Other determinations generally quoted in $\overline{\mathrm{MS}}$ scheme

$$m_c(m_c) = (1.275 \pm 0.025)\ \mathrm{GeV}$$
$$m_b(m_b) = (4.18 \pm 0.03)\ \mathrm{GeV}$$

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

MMHT2014 chose m_c=1.40 GeV, m_b=4.75 (in pole scheme)
Restrict to pQCD production g→ H$\overline{\text{H}}$ with threshold Q=m_H (H=c,b)

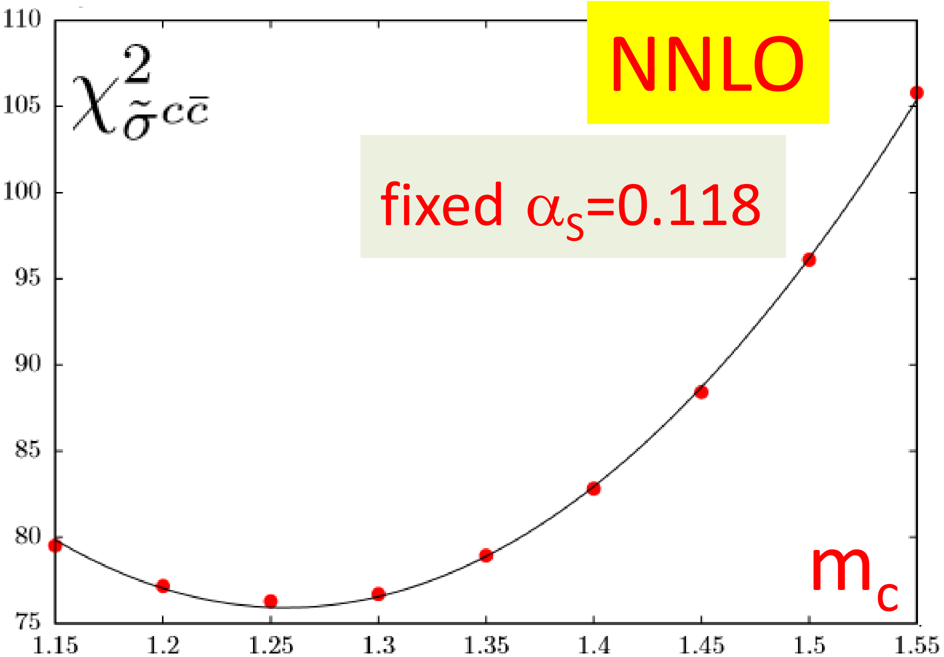
Below we vary m_c (1.15, 1.55) and m_b (4.25, 5.25) GeV

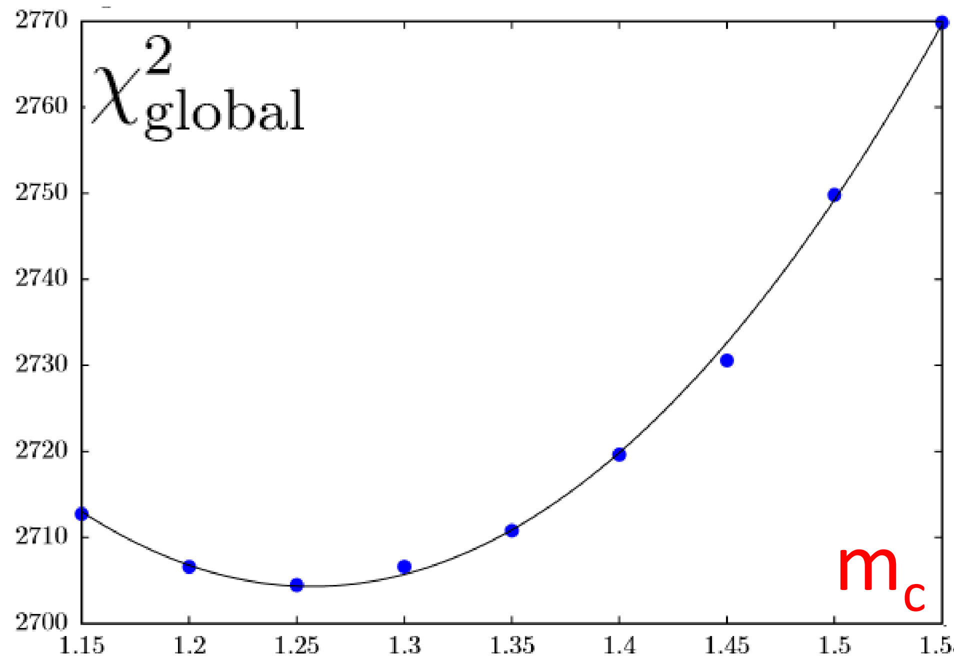
Procedure

Use GM-VFNS: start at input scale (Q_0^2=1 GeV^2) with 3 flav.
At $Q=m_c$ charm enters evolution, at $Q=m_b$ bottom enters.
Use massless evolution & `optimal' matching at thresholds.

FFNS: Heavy quarks kept only in coefficient functions –
H quarks generated only in final state – not partons
e.g. 3-flavour FFNS neither c or b treated as partons.
Fit is **not optimal** -- much data where $m_{c,b}$ relatively small.
However, we make available `FFNS' PDFs using GM-VFNS
input but with H quark evolution turned off.

Note $\alpha_S(M_Z^2)$ and large *x* gluon PDF are significantly smaller in FFNS as compared to GM-VFNS





m_c (GeV) m_c	χ^2_{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

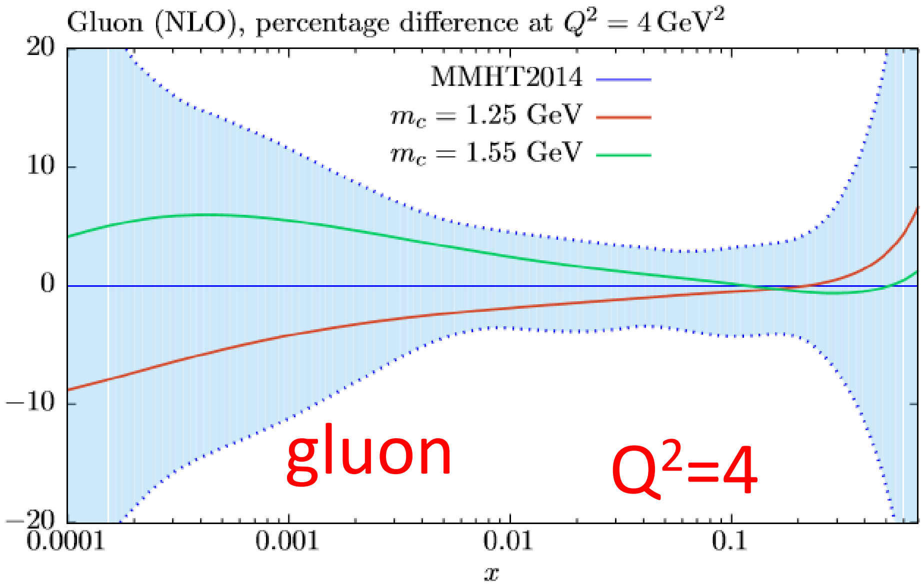
←now allow α_S to be parameter-- weak dependence on α_S

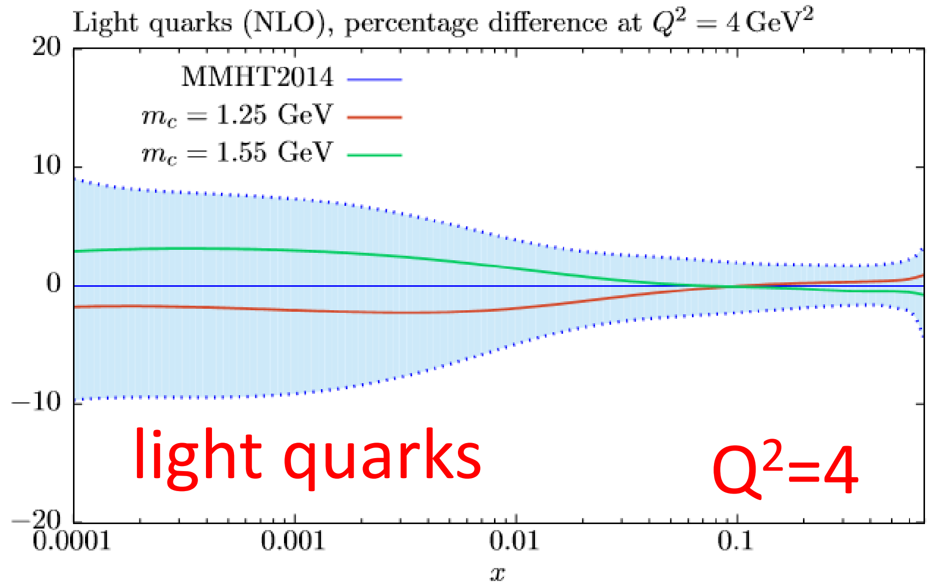
←best global & cc fit - **m_c=1.25GeV**

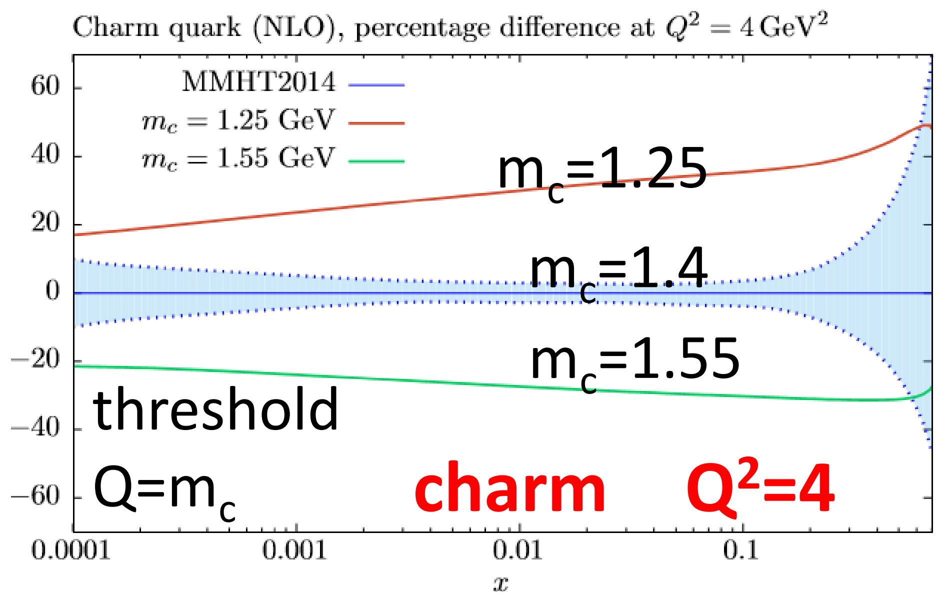
←MMHT14 ---- fixed m_c=1.4 GeV

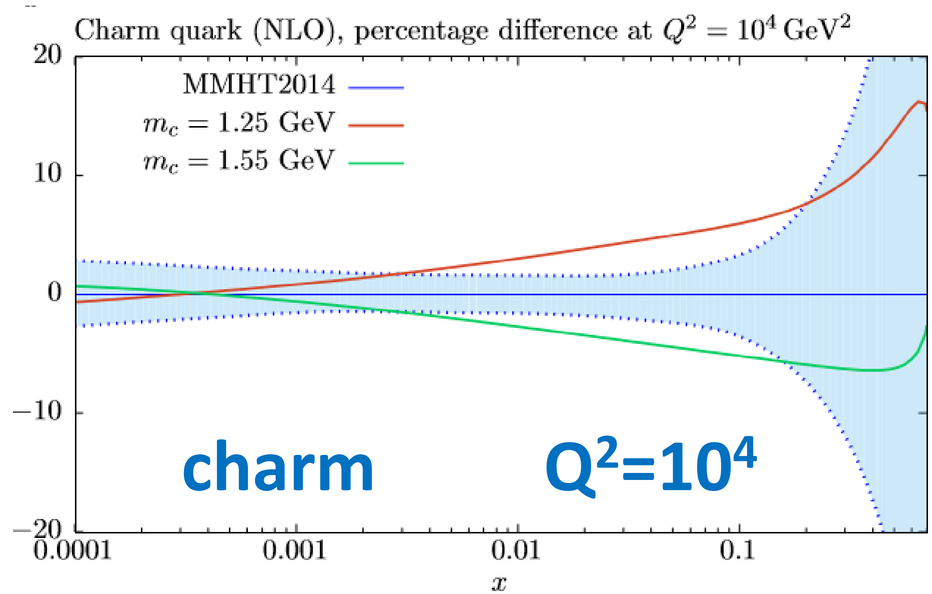
default m_c=1.4

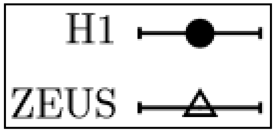
% change of PDFs $m_c = 1.25 \rightarrow 1.4 \rightarrow 1.55$ GeV



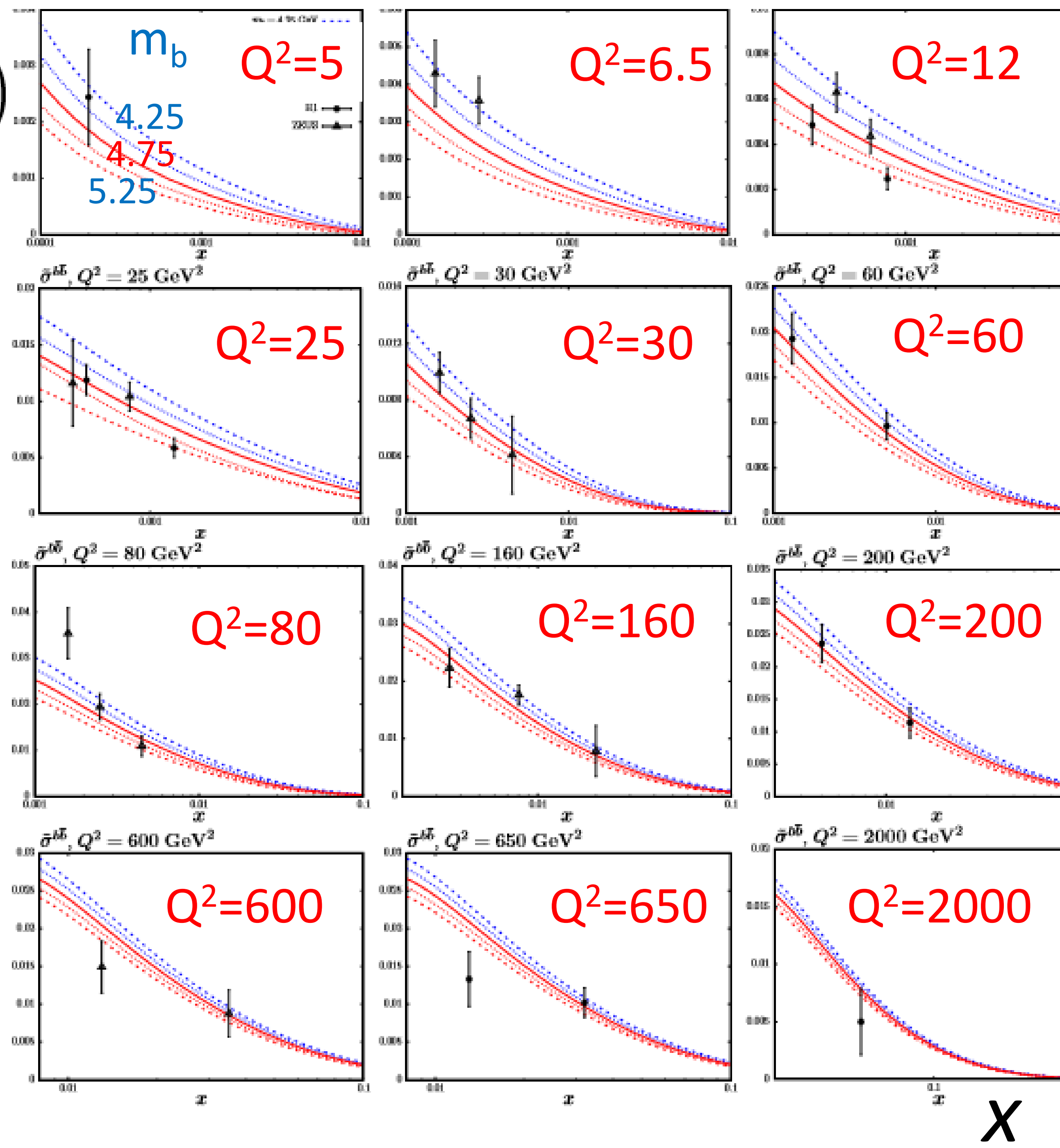








$\tilde{\sigma}(b\bar{b})$



NNLO predictions

Large fluctuations. Data show some preference for lower m_b, $m_b \lesssim 4.5\,\mathrm{GeV}$

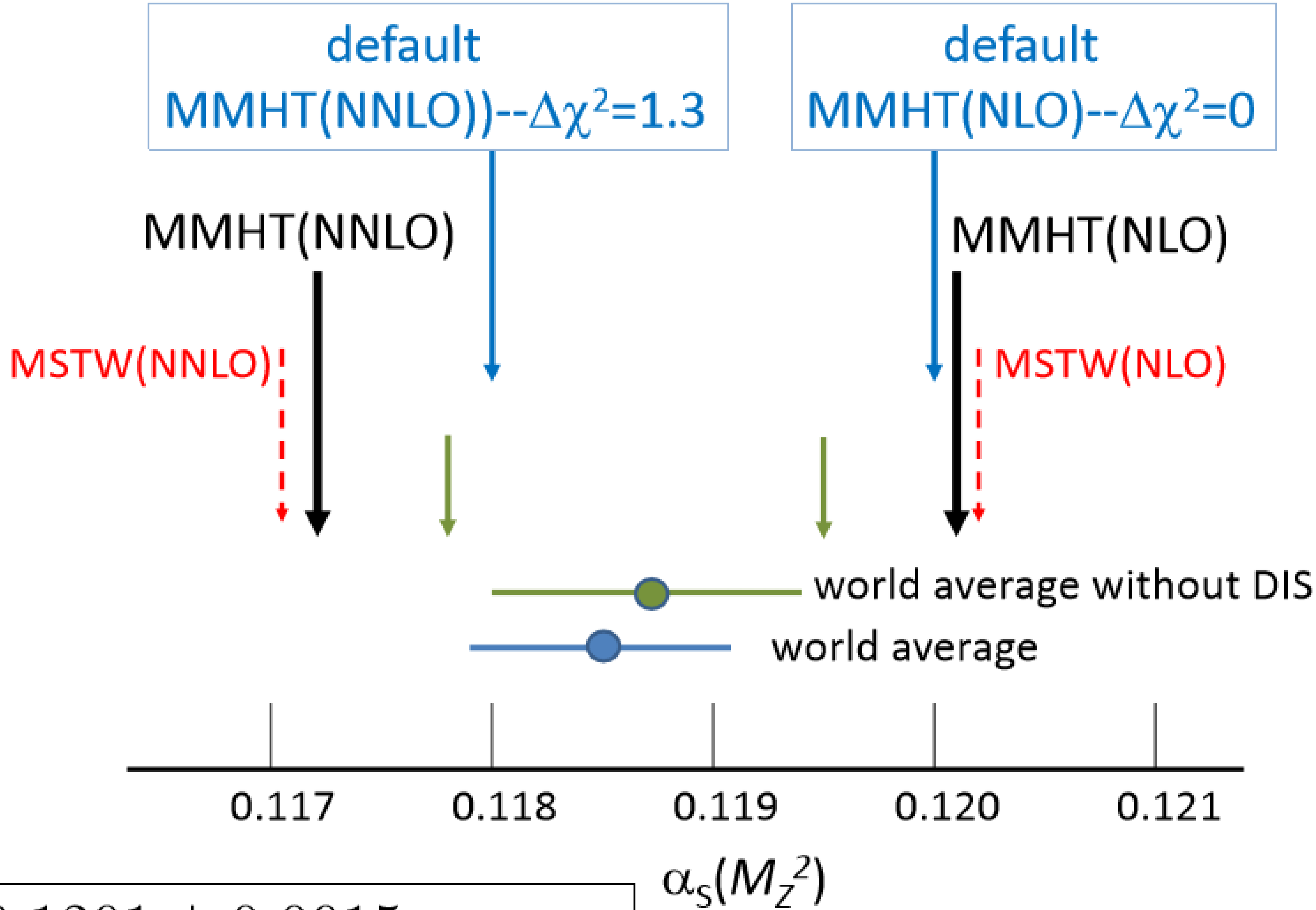
Benchmark cross sections

	σ	PDF unc.	m_c var.	m_b var.
W^+ LHC (14 TeV)	12.5	$^{+0.22}_{-0.18}$ $\left(^{+1.8\%}_{-1.4\%}\right)$	$^{-0.11}_{+0.093}$ $\left(^{-0.92\%}_{+0.75\%}\right)$	$^{-0.035}_{+0.011}$ $\left(^{-0.28\%}_{+0.084\%}\right)$
W^- LHC (14 TeV)	9.3	$^{+0.15}_{-0.14}$ $\left(^{+1.6\%}_{-1.5\%}\right)$	$^{-0.077}_{+0.063}$ $\left(^{-0.82\%}_{+0.68\%}\right)$	$^{-0.030}_{+0.011}$ $\left(^{-0.32\%}_{+0.11\%}\right)$
Z LHC (14 TeV)	2.06	$^{+0.035}_{-0.030}$ $\left(^{+1.7\%}_{-1.5\%}\right)$	$^{-0.025}_{+0.021}$ $\left(^{-1.2\%}_{+1.03\%}\right)$	$^{-0.0017}_{-0.0035}$ $\left(^{-0.08\%}_{-0.17\%}\right)$
$t\bar{t}$ LHC (14 TeV)	970	$^{+16}_{-20}$ $\left(^{+1.6\%}_{-2.1\%}\right)$	$^{-3.0}_{+3.1}$ $\left(^{-0.31\%}_{+0.32\%}\right)$	$^{+3.1}_{-1.7}$ $\left(^{-0.32\%}_{+0.17\%}\right)$
Higgs LHC (14 TeV)	47.7	$^{+0.63}_{-0.88}$ $\left(^{+1.3\%}_{-1.8\%}\right)$	$^{-0.22}_{+0.27}$ $\left(^{-0.48\%}_{+0.57\%}\right)$	$^{-0.16}_{+0.16}$ $\left(^{-0.33\%}_{+0.34\%}\right)$

Uncertainties on some NNLO benchmark LHC cross sections (in nb) due to +/- 10% variation in heavy quark masses

Generally uncertainty due to m_c is less than the PDF uncertainty, but is not insignificant; while uncertainty due to m_b is smaller

α_S



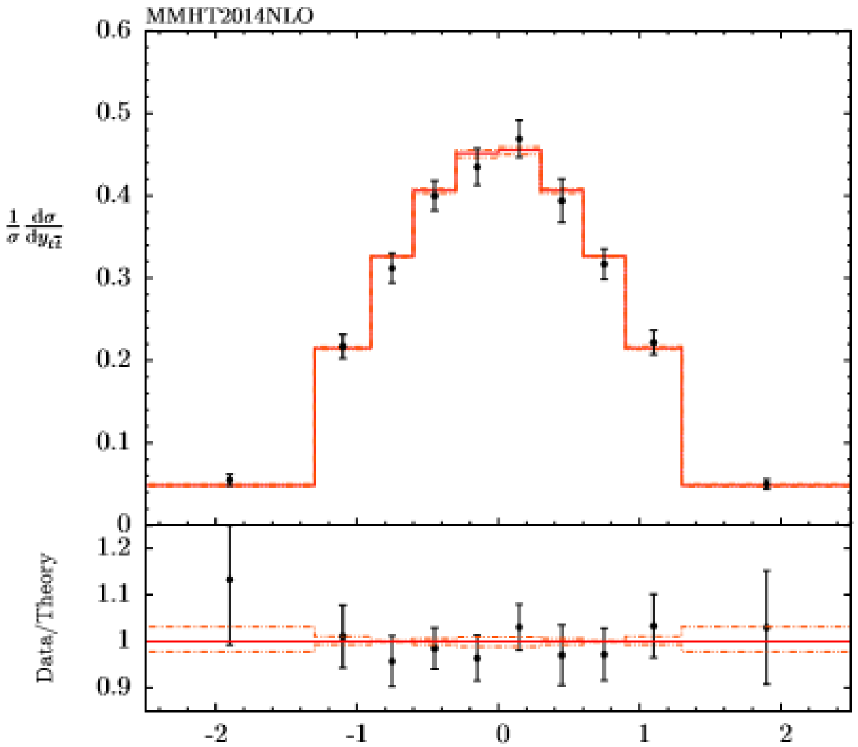
$$\alpha_S(M_Z^2) = 0.1201 \pm 0.0015 \quad \text{NLO}$$
$$\alpha_S(M_Z^2) = 0.1172 \pm 0.0013 \quad \text{NNLO}$$

default MMHT14 **NNLO** PDFs take α_S=**0.118**,

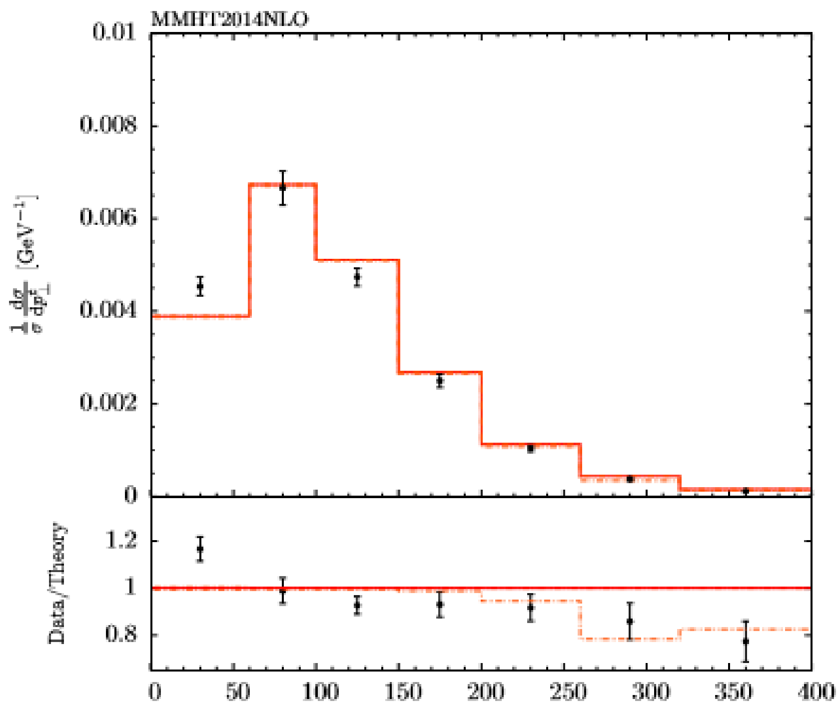
NLO PDFs have α_S=**0.120** (also give a PDF set with 0.118)

tt(bar) differential distributions

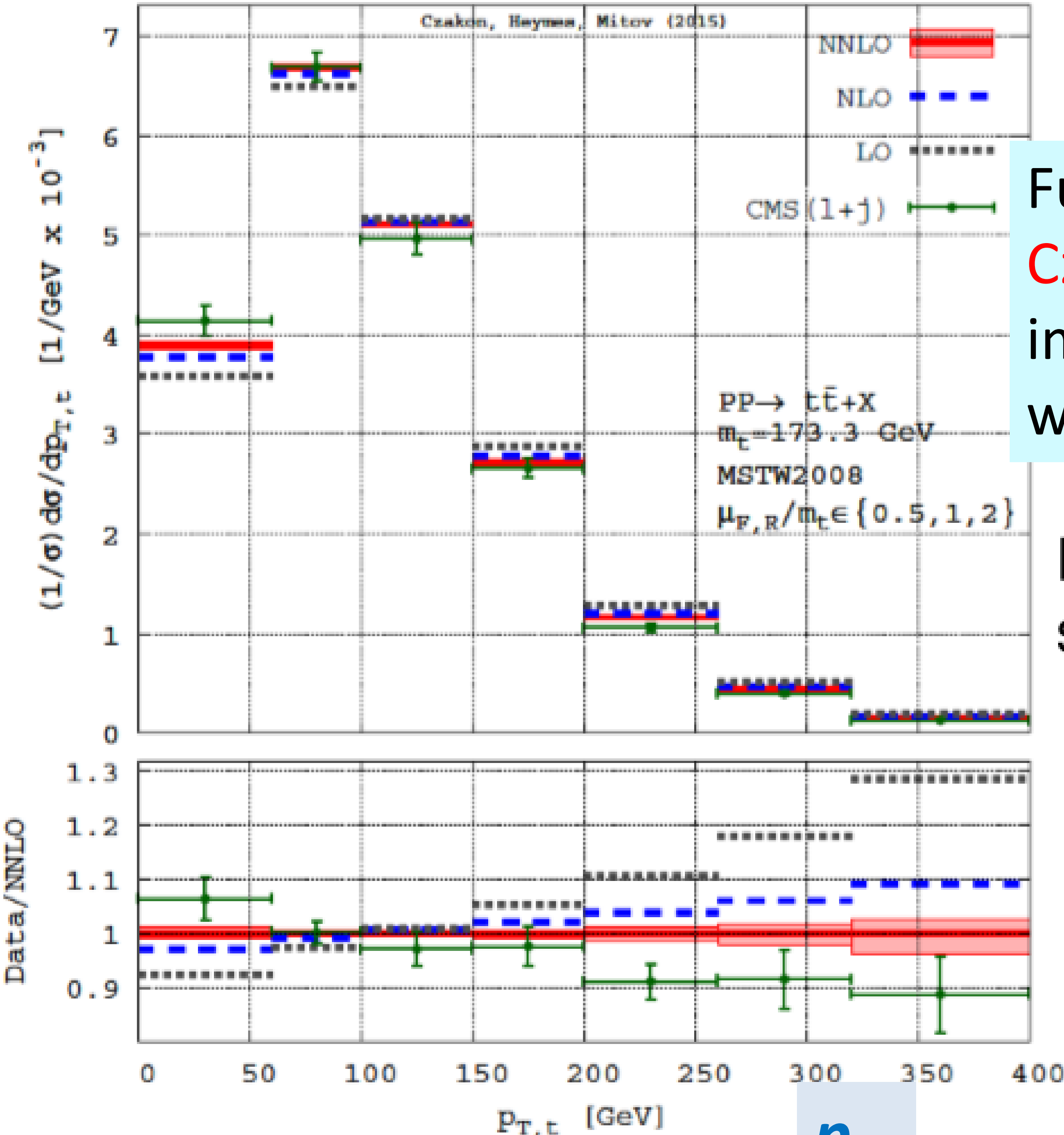
For example, differential $\bar{t}t$ production (show CMS below). $y_{\bar{t}t}$ distribution at NLO very good, p_t distribution off in shape ($m_{\bar{t}t}$ somewhere in between).



$y_{\bar{t}t}$



p_t



Full NNLO correction
Czakon,Heymes,Mitov
improves comparison
with $p_{T,t}$ data

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

$p_{T,t}$

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.