MMHT Updates and Single Top

Robert Thorne

November 29th 2018

University College London

With contributions from Lucian Harland-Lang, Alan Martin and Ricky Nathvani

PDFs and Single Top production

At LO the production mechanisms are

$$b + u\,(c) \to t + X, \qquad \bar{b} + d(s,b) \to \bar{t} + X.$$

Where the final state invariant mass $\sim 200\ \mathrm{GeV}$ or greater, so the x of the PDFs (at 7,8 TeV) is $x \gtrsim 0.04$.

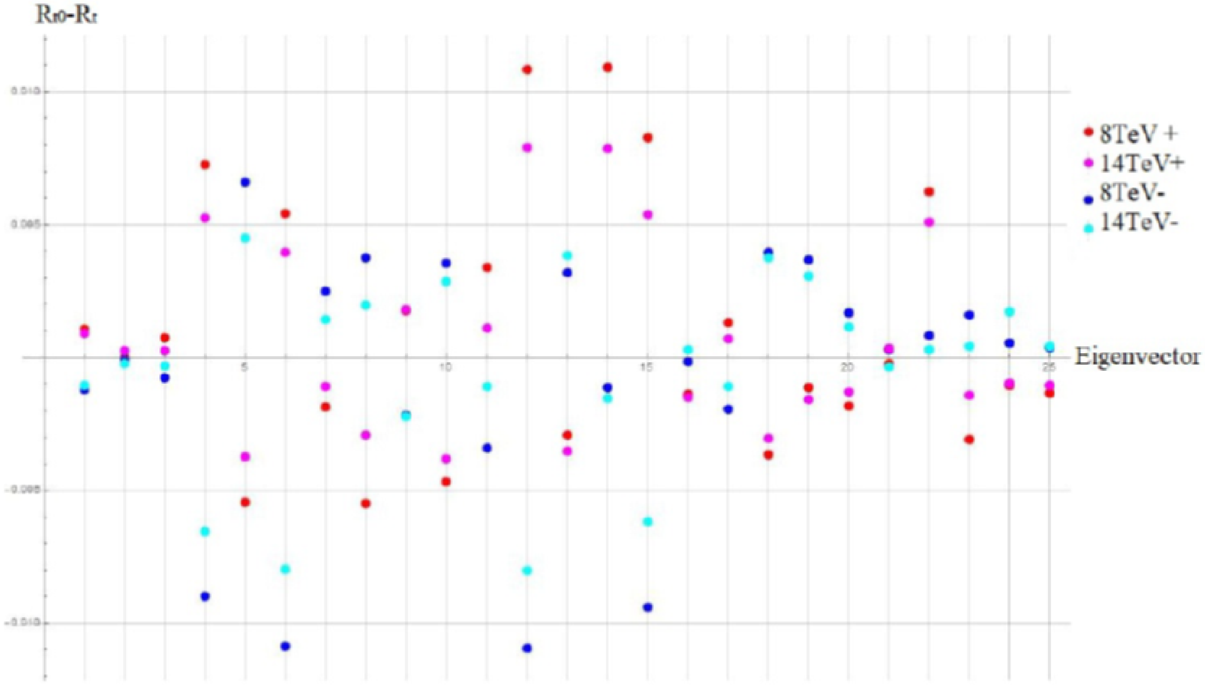
The dominant u, d quarks very well-known in this x region, and $b, \bar{b}$ generated from gluon splitting, and are also known very precisely (ignoring possible large intrinsic components) - main uncertainty coming from m_b.

Hence, individual cross sections and distributions likely to be a test of consistency of PDFs until very high precision reached, though distributions can potentially probe shape of $b, \bar{b}$ quark to some extent, and hence variations inthe gluon.

However, much greater precison in ratio $\sigma_t/\sigma_{\bar{t}}$.

Ratio will test $u(x)/d(x)$ for $x \gtrsim 0.04$ (or slightly lower at 13(14) TeV), and to some extent (less well known) strange distribution.

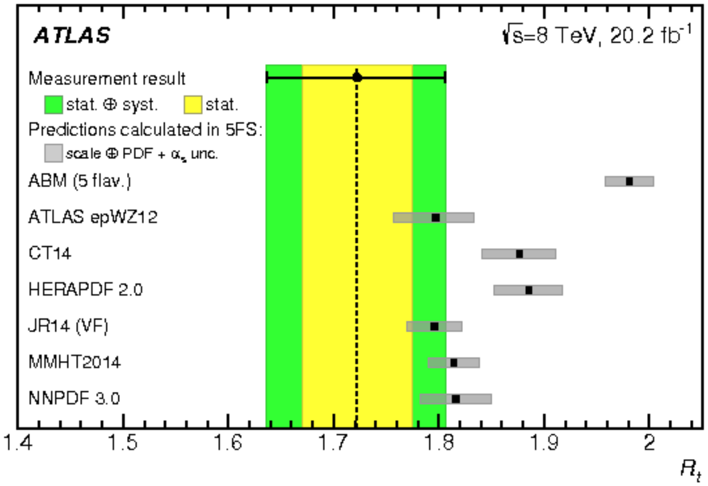
Study by MSc student (Tomoki Goda) on fractional variation in $\sigma_t/\sigma_{\bar{t}}$. prediction with MMHT eigenvectors.



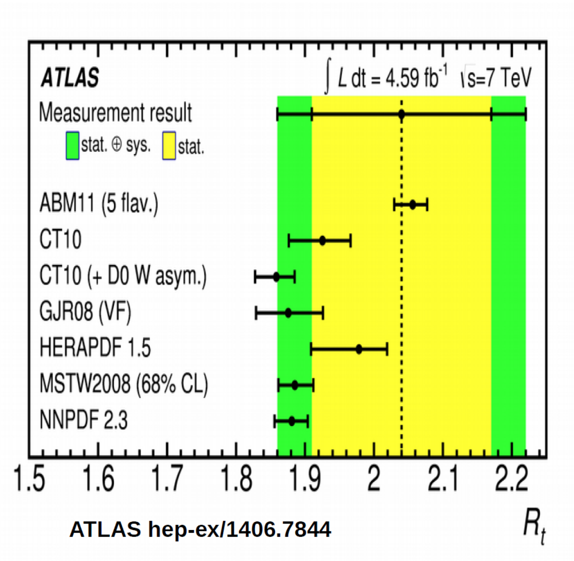
Main sensitivity from eigenvectors 12, 14, 4, which involve relatively high or medium x, $u(x), d(x)$ uncertainty. However, eigenvector 6 also important – depends on $s(x) - \bar{s}(x)$.

Data Implications

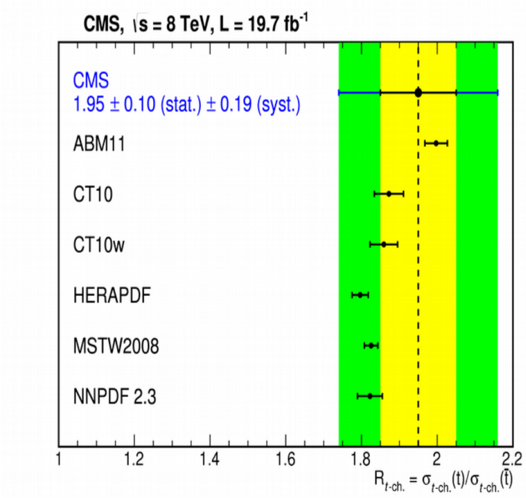
High $u(x)/d(x), x \gtrsim 0.04$ PDF sets in tension with recent most accurate ATLAS measurement of single top ratio.



Larger ratio preferred by older, but less precise measurements.

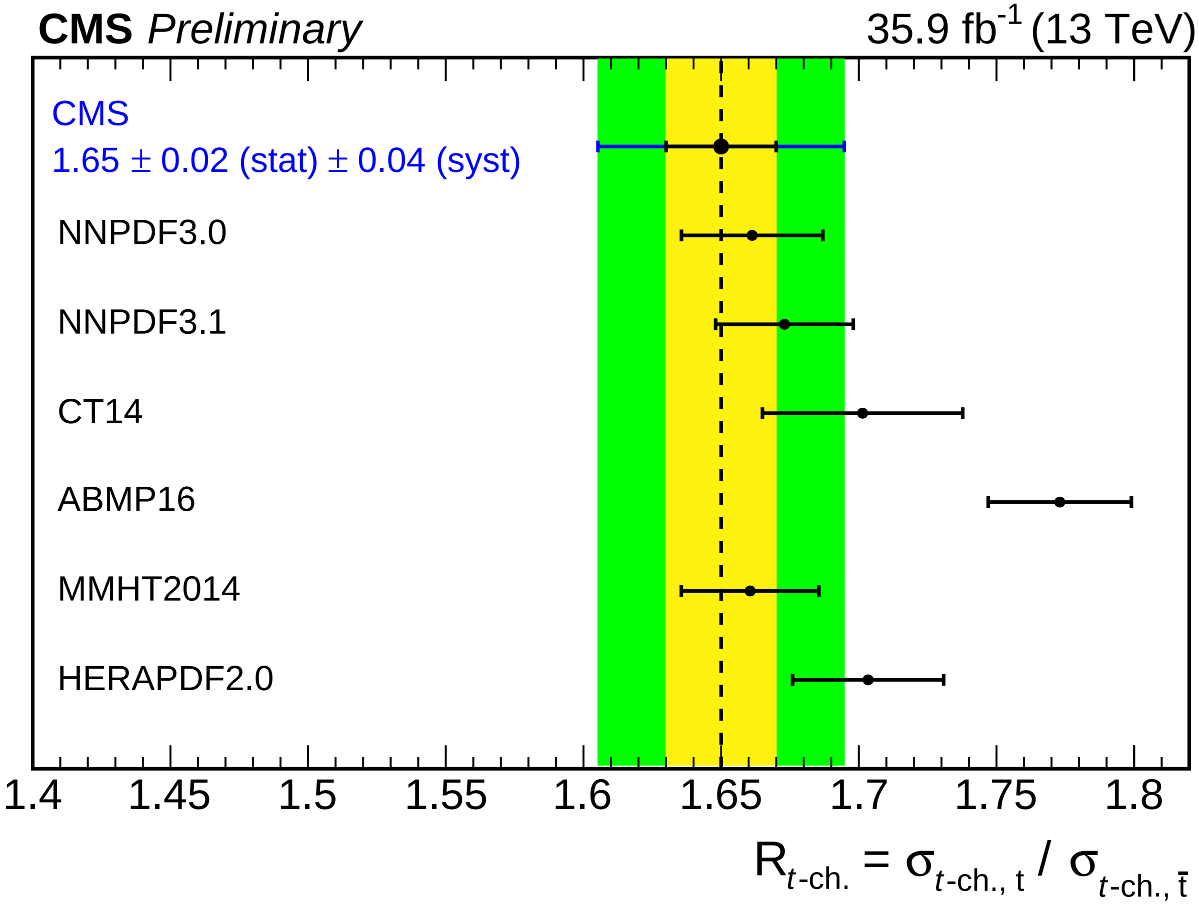


ATLAS hep-ex/1406.7844



CMS hep-ex/1403.7366

Also the most recent precise measurement from CMS prefers smaller $u(x)/d(x)$.



MMHT preliminary set - fit to new hadron collider (mainly LHC) data

We now also fit to high rapidity W, Z data from LHCb at 7 and $8\ \mathrm{TeV}$, $W + c$ 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.

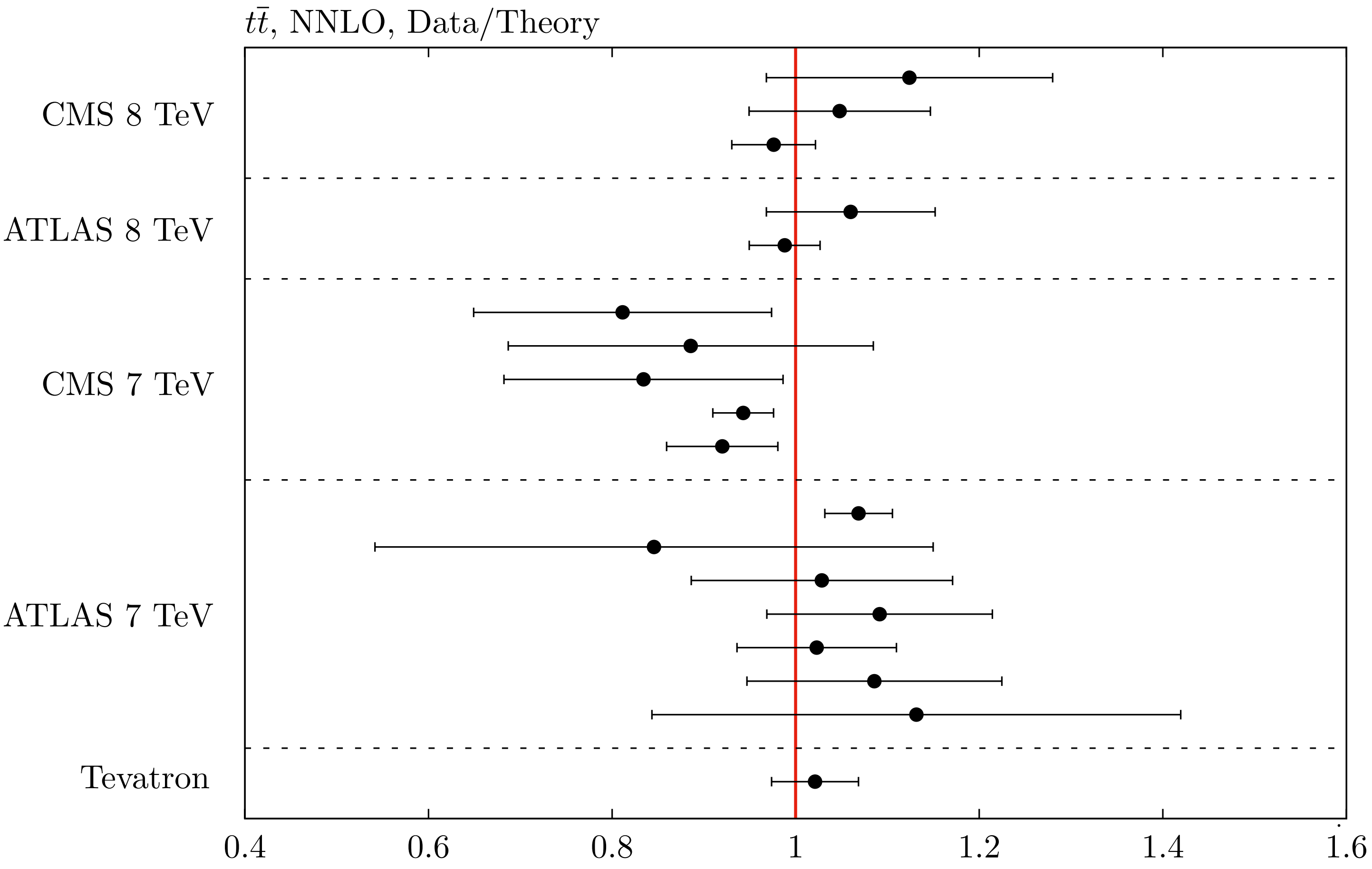
	no. points	NLO χ^2_{pred}	NLO χ^2_{new}	NNLO χ^2_{pred}	NNLO χ^2_{new}
$\sigma_{t\bar{t}}$ Tevatron +CMS+ATLAS	18	19.6	20.5	14.7	15.5
LHCb 7 TeV $W + Z$	33	50.1	45.4	46.5	42.9
LHCb 8 TeV $W + Z$	34	77.0	58.9	62.6	59.0
LHCb 8TeV e	17	37.4	33.4	30.3	28.9
CMS 8 TeV W	22	32.6	18.6	34.9	20.5
CMS 7 TeV $W + c$	10	8.5	10.0	8.7	8.0
D0 e asymmetry	13	22.2	21.5	27.3	25.8
total	3738/3405	4375.9	4336.1	3741.5	3723.7

Predictions good, and no real 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 $\Delta\chi^2 = 8$.

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.

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 $m_t^{pole} = 173.4$ GeV. At NLO $m_t^{pole} = 170.2$ GeV. MMHT values $m_t^{pole} = 174.2$ GeV and $m_t^{pole} = 171.7$ GeV

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

MMHT – updated fits also with high precision ATLAS W, Z data.

Prefers larger strange quark to fit Z/W ratio.

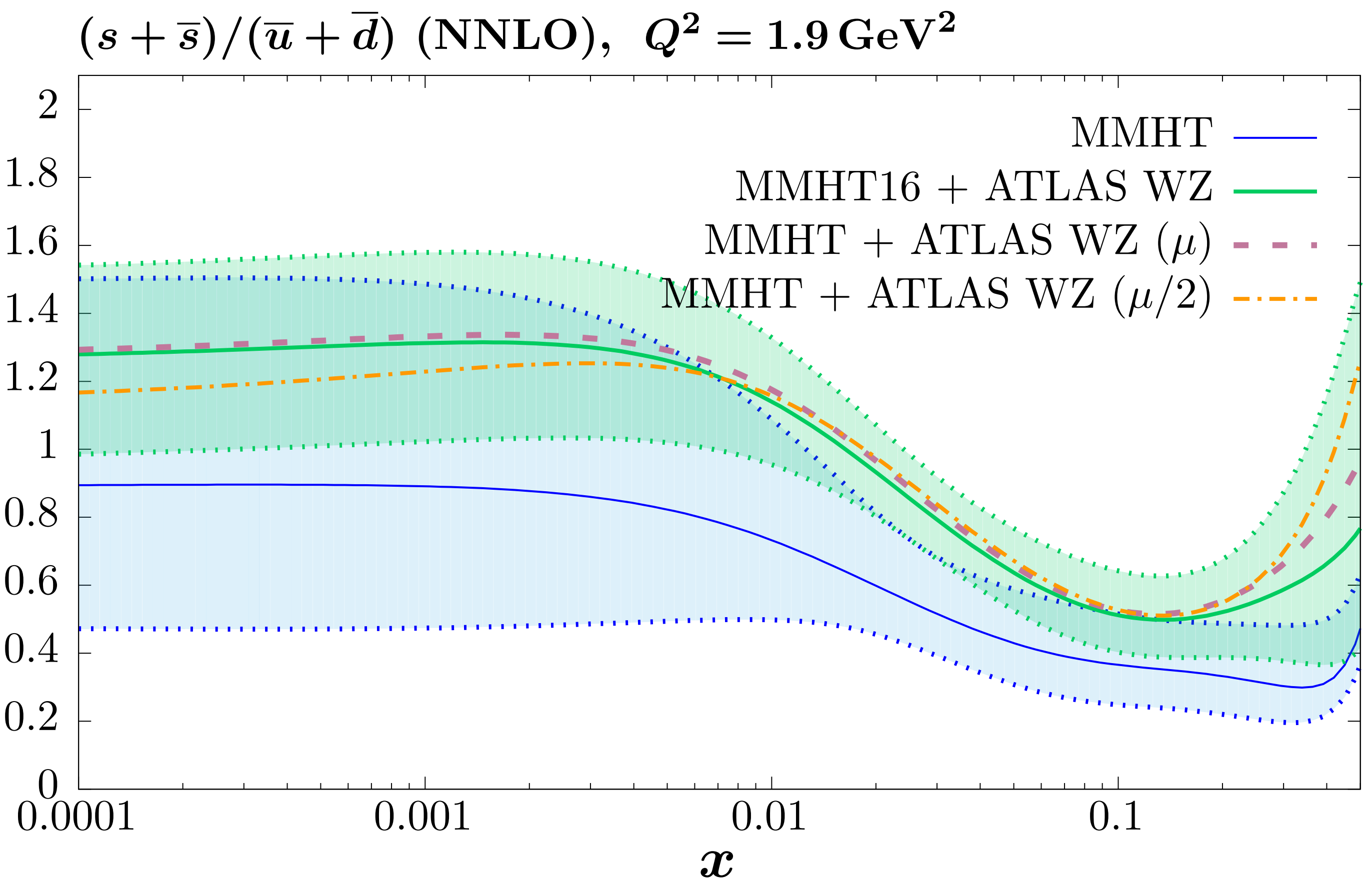
Including ATLAS W, Z data in fit goes from $\chi^2/N_{pts} \sim 387/61 \rightarrow \chi^2/N_{pts} \sim 130/61$, similar to ATLAS profiling.

Deterioration in fit to other data $\Delta\chi^2 = 54$. CMS double differential Z/γ data ($\Delta\chi^2 = 17$) and CCFR/NuTeV dimuon data ($\Delta\chi^2 = 16$).

Also fixed target DIS , E866 Drell-Yan asymmetry and CDF W-asymmetry.

Also try fit with scales set to $\mu_{R,F} = M_{W,Z}/2$ rather than $\mu_{R,F} = M_{W,Z}$ (thanks to V. Radescu, A. Cooper-Sarkar)

As in ATLAS study find reduction in χ^2 of about 20 units (almost no change in fit to other data or PDFs).

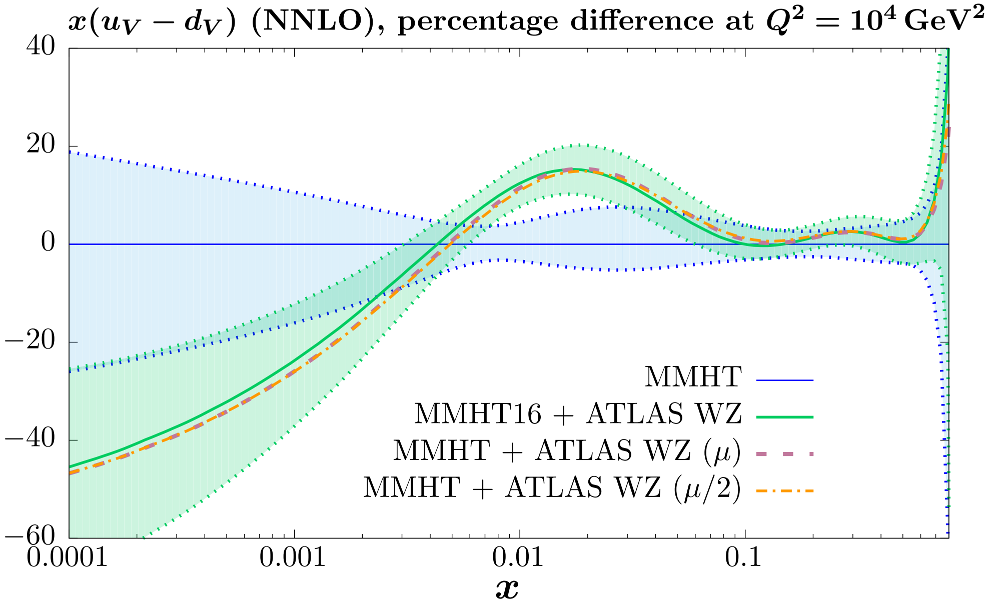


Ratio of $(s+\bar{s})$ to $\bar{u}+\bar{d}$, i.e. R_s at $Q^2 = 1.9\ \mathrm{GeV}^2$.

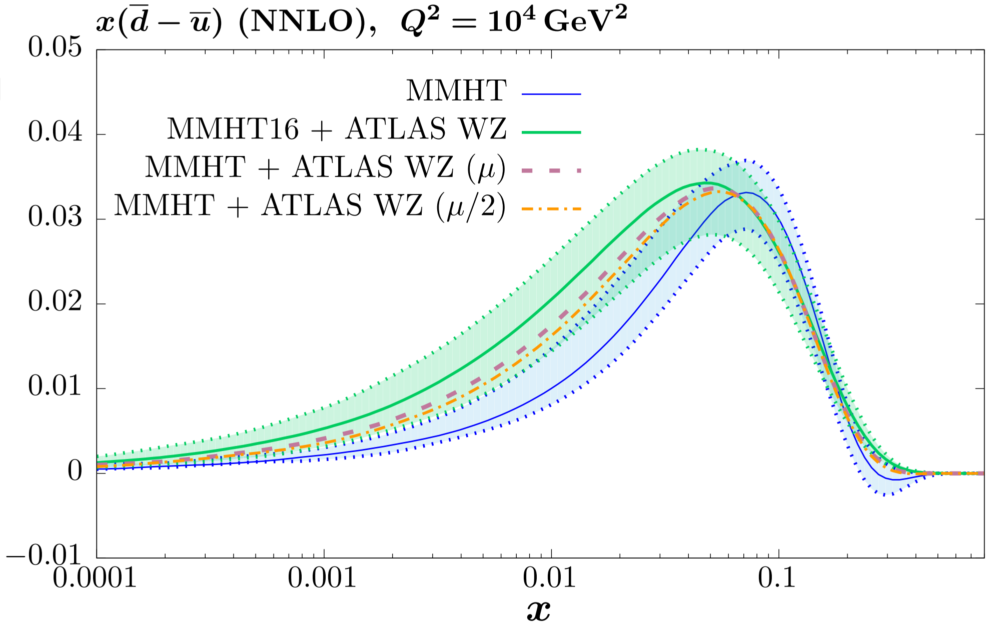
At $x = 0.023$ $R_s \sim 0.83 \pm 0.15$. Compare to ATLAS with $R_s = 1.13^{+0.08}_{-0.13}$

R_s exceeds unity at lower x, but essentially an extrapolation. Comfortably consistent with unity.

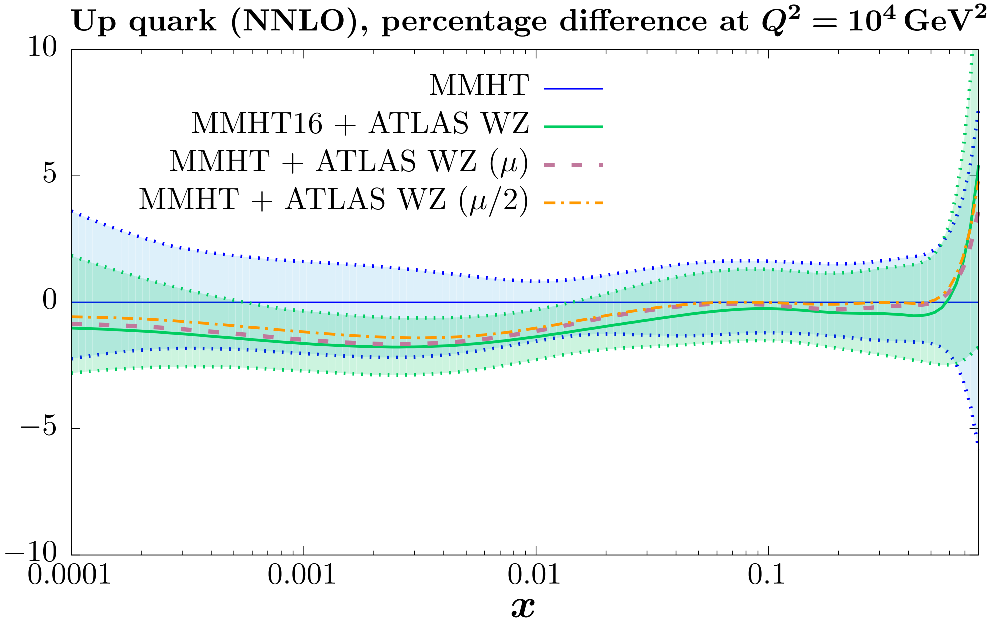
As implied by individual distributions, significant change in $u_V - d_V$.



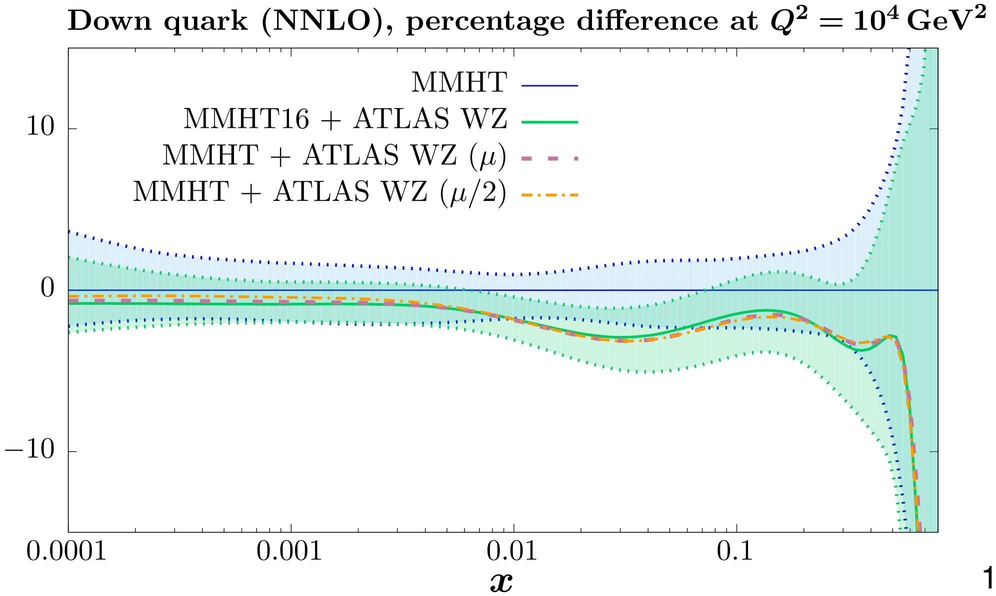
Shift in best fit $\bar{d} - \bar{u}$ accompanying deterioration in fit to E866 Drell-Yan asymmetry.



Little change in total $u(x, Q^2)$.

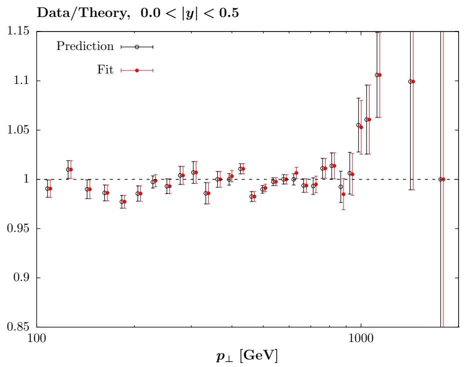


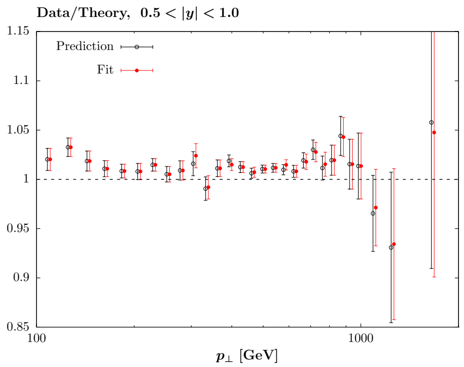
Shift down in best fit $d(x, Q^2)$ due to increase in the strange quark. Will compensate for $\bar{t}$ production.

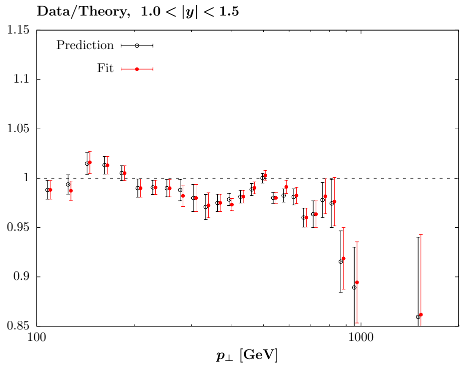


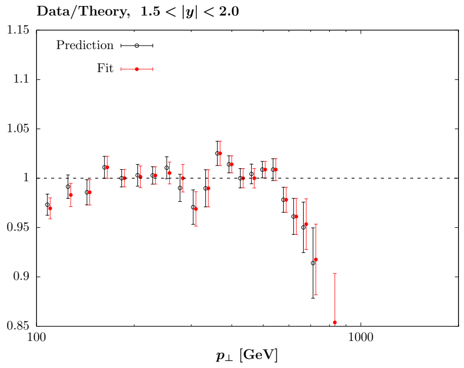
Fit to high luminosity ATLAS 7 TeV inclusive jet data – MMHT (JHEP 02 (2015) 153)

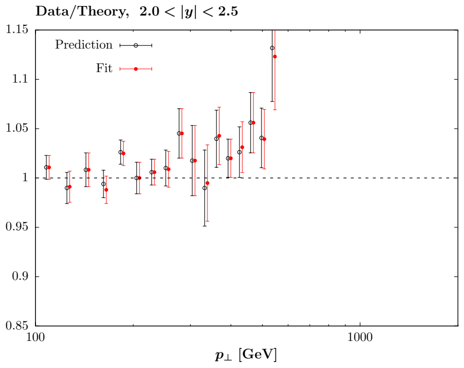
Cannot simultaneously fit data in all bins. Mismatch in one rapidity bin different to others probing PDFs of similar flavour, x and Q^2.











Exercise on decorrelating uncertainties and including NNLO

We consider the effect on the χ^2 of the simultaneous fit to all data of decorrelating two uncertainty sources, i.e. making them independent between the 6 rapidity bins.

Compared to the original $\chi^2/N_{pts} = 2.85$ we get instead

	Full	21	62	21,62
$\chi^2/N_{\rm pts.}$	2.85	1.56	2.36	1.27

Very significant improvement, particularly from decorrelating jes21.

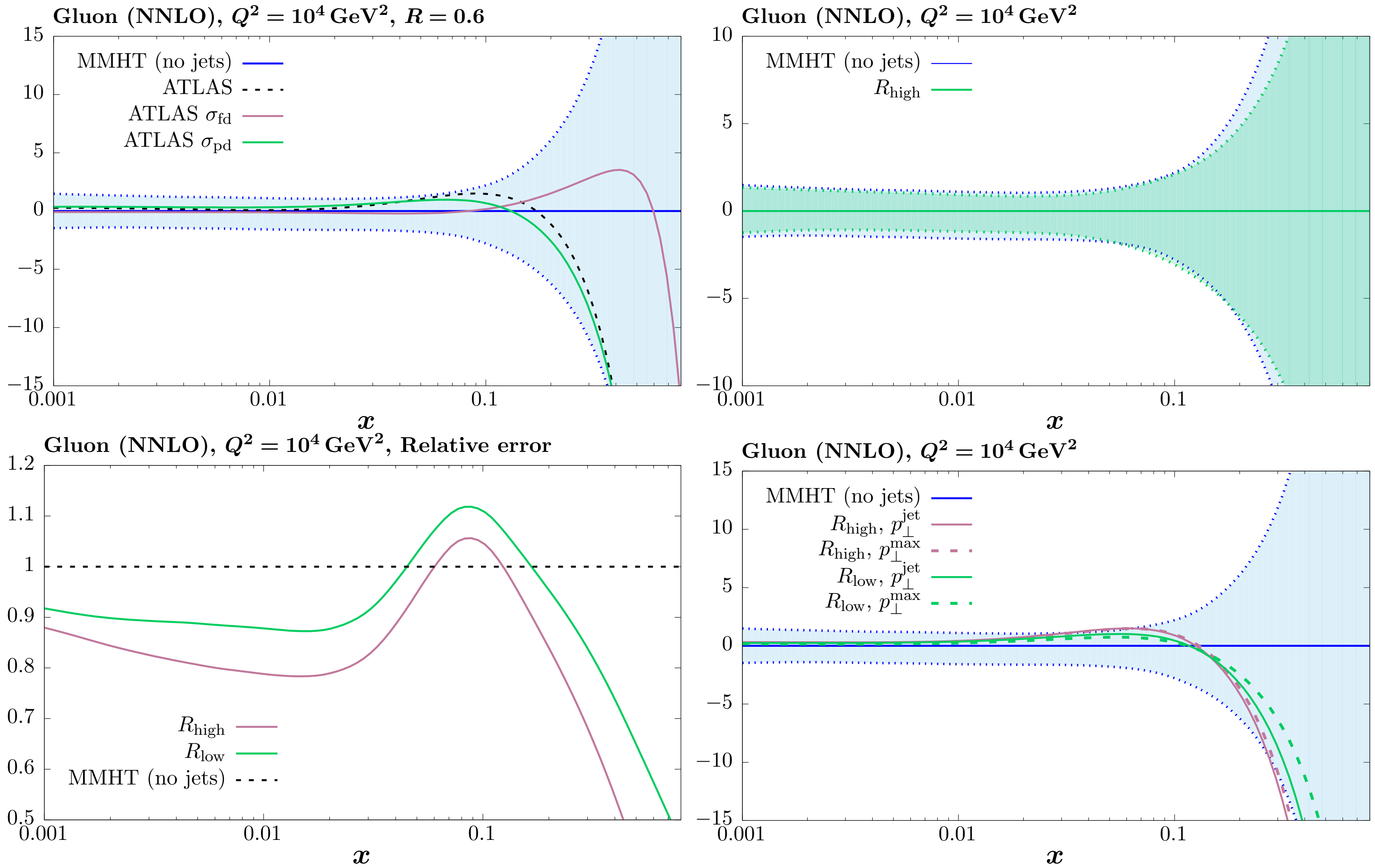
With correlations between rapidity bins relaxed for just two sources of systematics $\chi^2/N_{pts} = 178/140 = 1.27$.

More extensive decorrelation study in ATLAS – JHEP 09 020 (2017).

Similar results using new NNLO results.

	$R_{\rm low},\, p_\perp^{\rm jet}$	$R_{\rm low},\, p_\perp^{\rm max}$	$R_{\rm high},\, p_\perp^{\rm jet}$	$R_{\rm high},\, p_\perp^{\rm max}$
NLO	210.0 (187.1)	189.1 (181.7)	175.1 (193.5)	164.9 (191.2)
NNLO	172.3 (177.8)	199.3 (187.0)	149.8 (182.3)	152.5 (185.4)

New data results of fits



Central values and uncertainties insensitive to decorrelation of two sources between rapidity bins. Find softer gluon, reduced uncertainty.

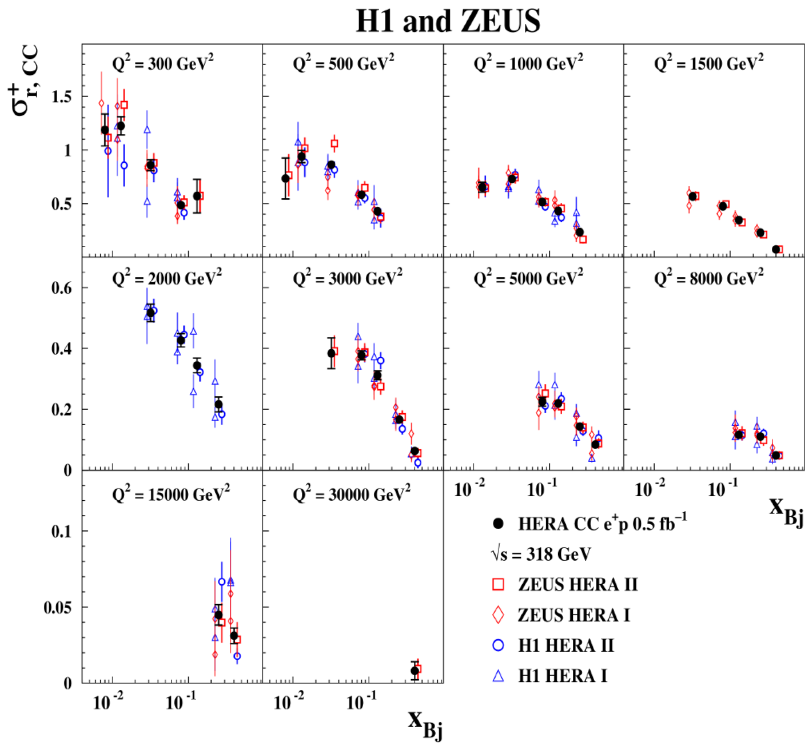
Also relatively little sensitivity to scales and jet radius.

Reasons for $u(x)/d(x)$ enhancement - Data Tensions.

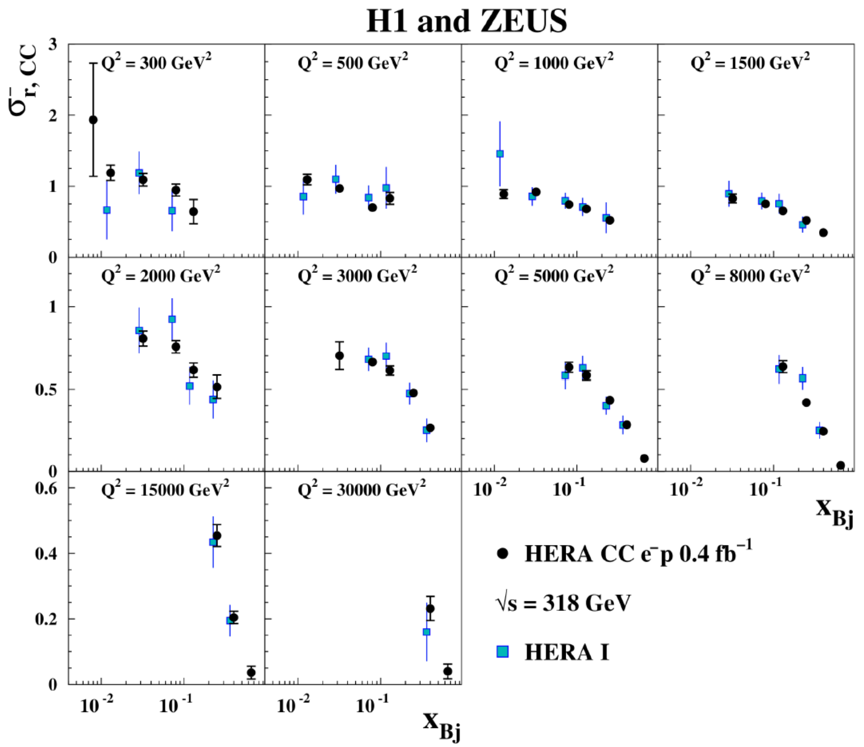
HERAI+II combination data.

Averaged cross sections: CC e$^{\pm}$p

CC e^{+}p

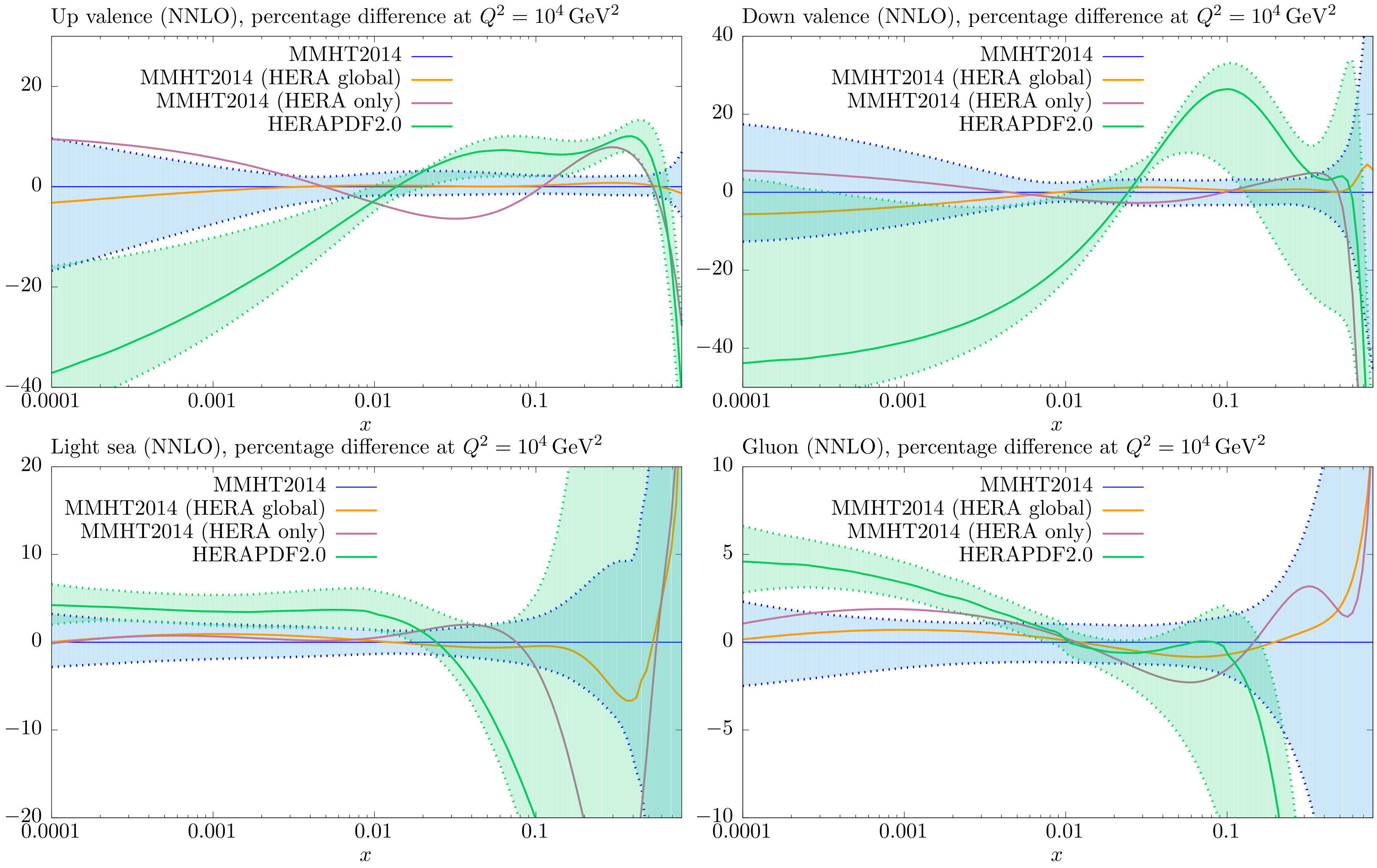


CC e^{-}p



Makes HERAPDF PDFs more precise, but in general a bit further from other PDFs in some places, e.g highish-x up quark.

HERA II Combined data in other PDFs



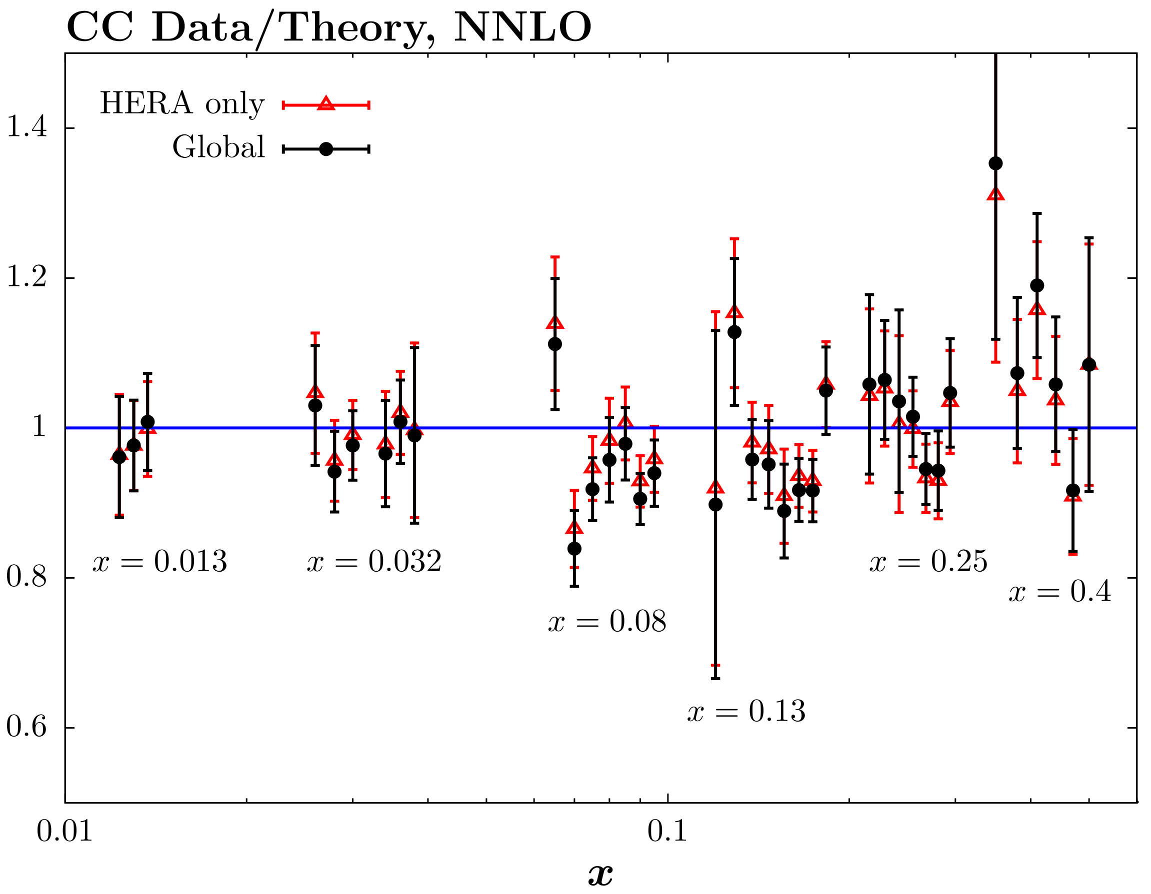
Updated PDFs very well within MMHT2014 uncertainties. PDFs from HERA II data only fit in some ways similar to HERAPDF2.0.

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 $Q^2_{\rm min} = 3.5~{\rm GeV}^2$.

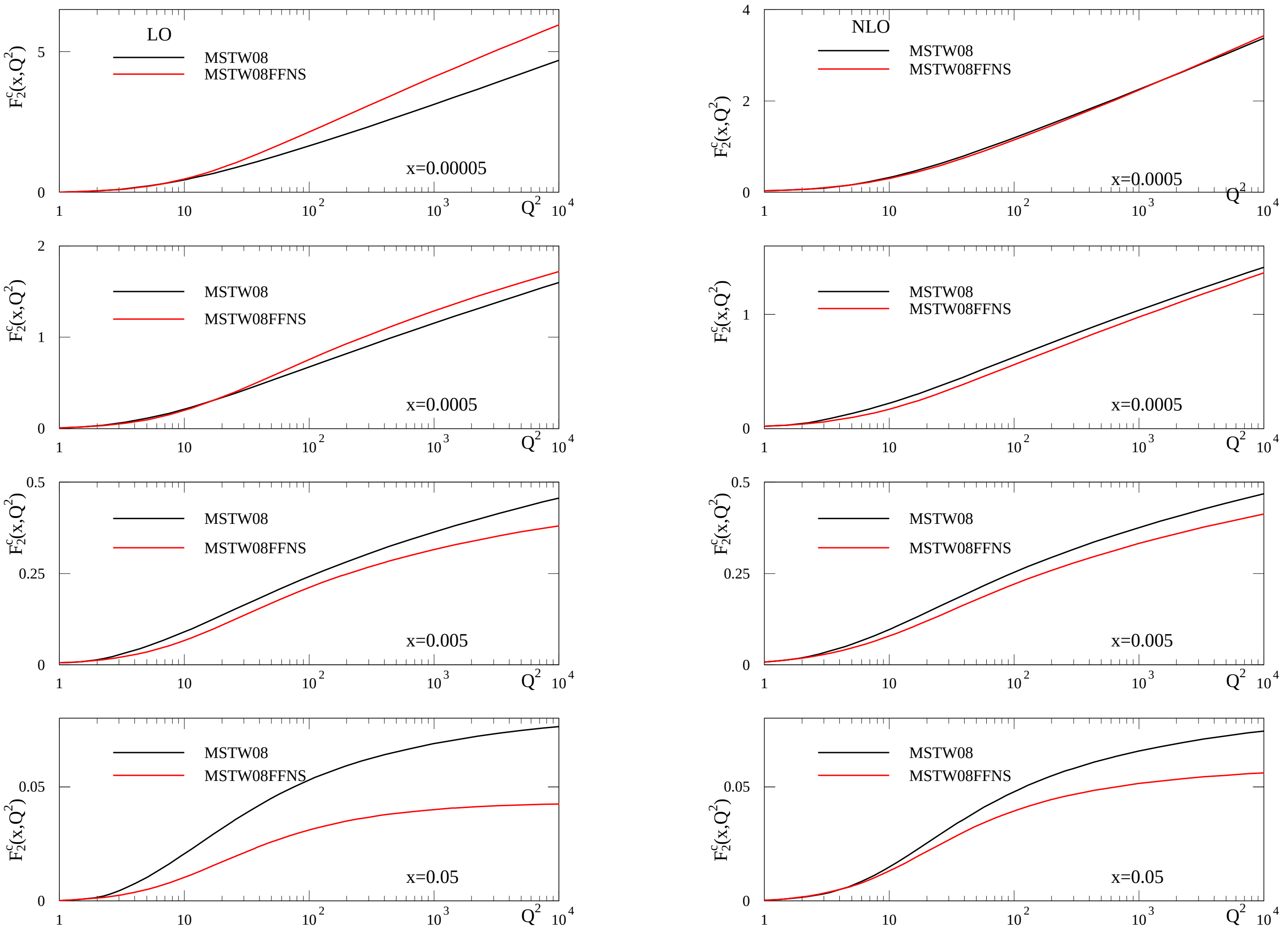
Large improvement in CC e^-p data when only HERA data fit. Probe of up (valence) quark at high x. Bigger effect at NLO.



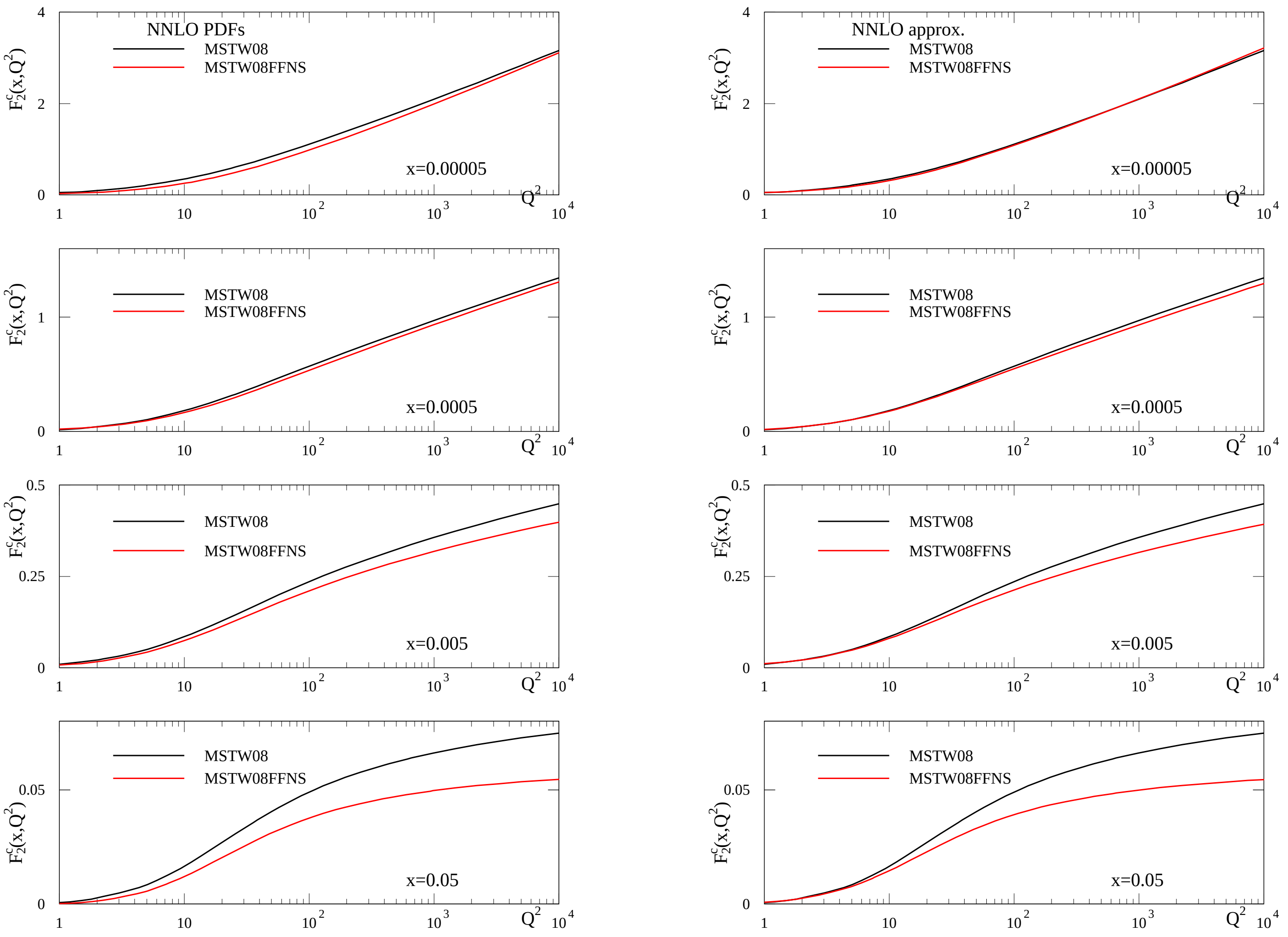
Clearly a different shape for the CC e^-p data against theory in global and HERA-only fits.

Affects up quark which is constrained by lots of other data. Slightly high x for main single top production, but affects $y \sim 1$ data.

Methodology – difference between FFNS and GM-VFNS



GM-VFNS resums $\ln Q^2/m_c^2$ terms. Big difference at LO. At higher Q^2 charm structure function for FFNS nearly always lower than any GM-VFNS at NLO, but mainly at higher x.



No dramatic change or improvement at NNLO.Left only NNLO PDFs, right uses $\mathcal{O}(\alpha_S^2)$ coefficient functions for $F_2^c(x,Q^2)$. Little difference at high Q^2.

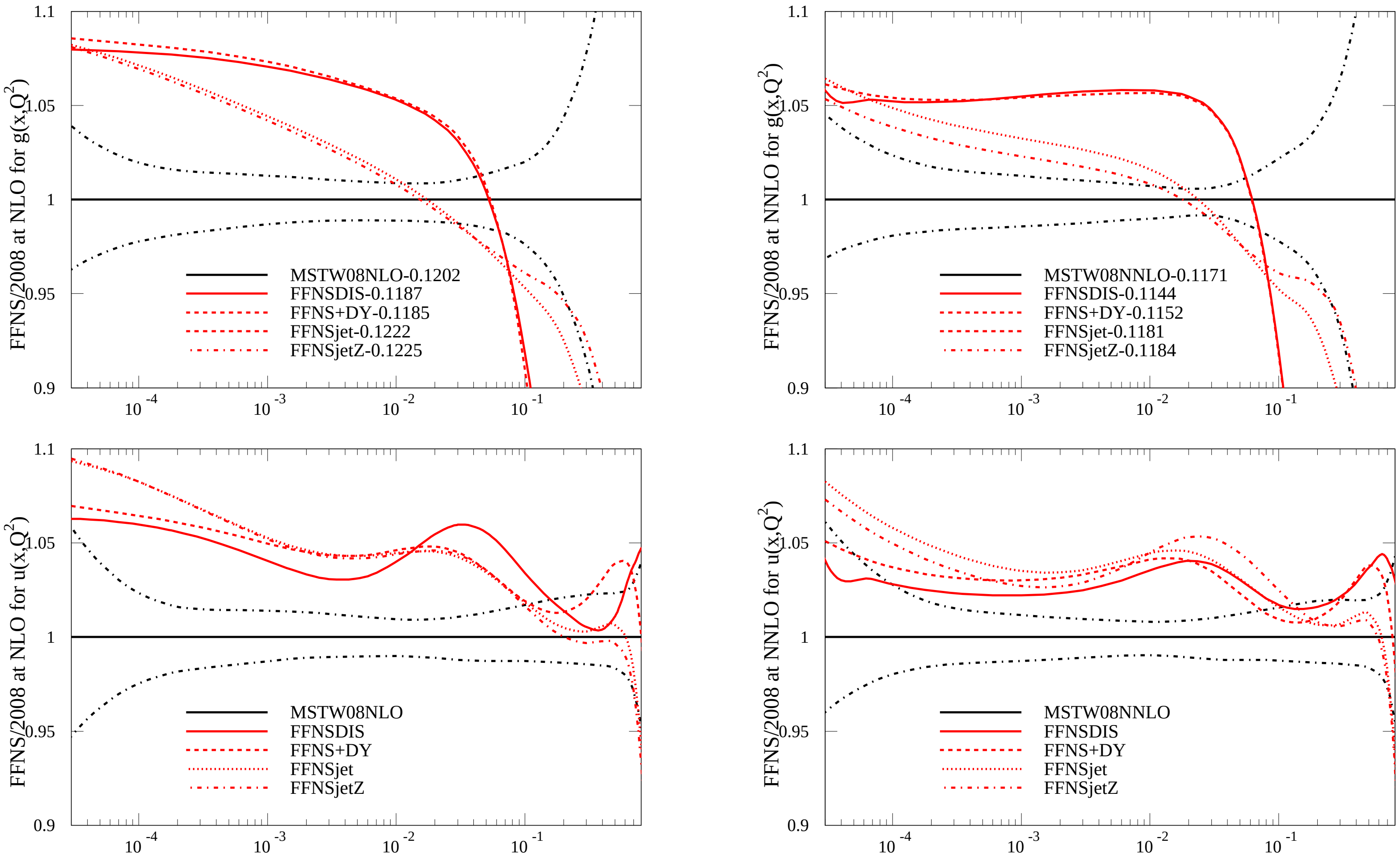
Total $F_2(x, Q^2)$ in region of $x \sim 0.05$ and high Q^2 extremely precise. Expect that lower charm contribution requires extra light quark contribution, particularly from up quark due to charge weighting.

In previous study performed a series of NLO fits using the FFNS scheme and NNLO with up to $\mathcal{O}(\alpha_S^2)$ heavy flavour coefficient functions. (Approximations to the $\mathcal{O}(\alpha_S^3)$ expressions change results very little).

Fits to DIS and Drell-Yan data usually at least a few tens of units worse than MSTW08 to same data. Often slightly better for $F_2^c(x, Q^2)$, but flatter in Q^2 for $x \sim 0.01$ for inclusive structure function.

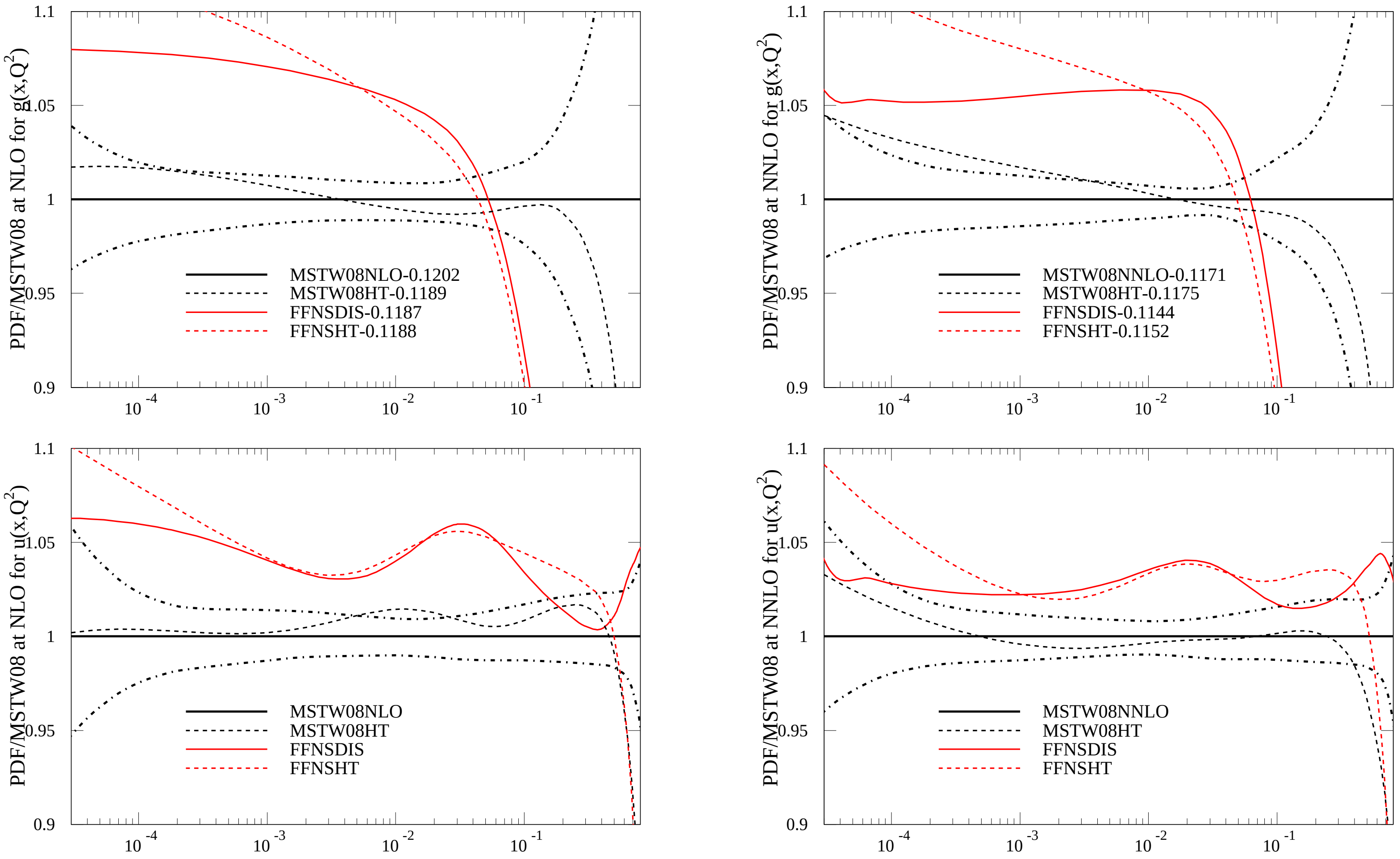
As well as a worse fit to DIS and Drell-Yan data only, in FFNS the fit quality for the DIS and low-energy Drell Yan data deteriorates by in general ~ 50 units when all jet data is included (in 5-flavour scheme) as opposed to < 10 units when using a GM-VFNS.

PDFs evolved up to $Q^2 = 10,000\mathrm{GeV}^2$ (using variable flavour evolution for consistent comparison) different in form to MSTW08. Similar differences found by NNPDF and older ZEUS fits.



See claer increase in up quark over range of x, as well as different gluon shape which will affect $b, \bar{b}$ quark shape.

Low Q^2 – Higher Twist.



Not a big effect. Largely washes out quickly with Q^2. Similar effect using FFNS as for GM-VFNS.

Conclusions

LHC data on single top quark production a good probe of certain aspects of PDFs.

Individual differential distributions may provide information on $b, \bar{b}$ distributions.

Very precise measurements on the ratio $\sigma_t/\sigma_{\bar{t}}$ constrains the $u(x)/d(x)$ ratio, and may even help a little with $s(x) - \bar{s}(x)$ (which is very uncertain).

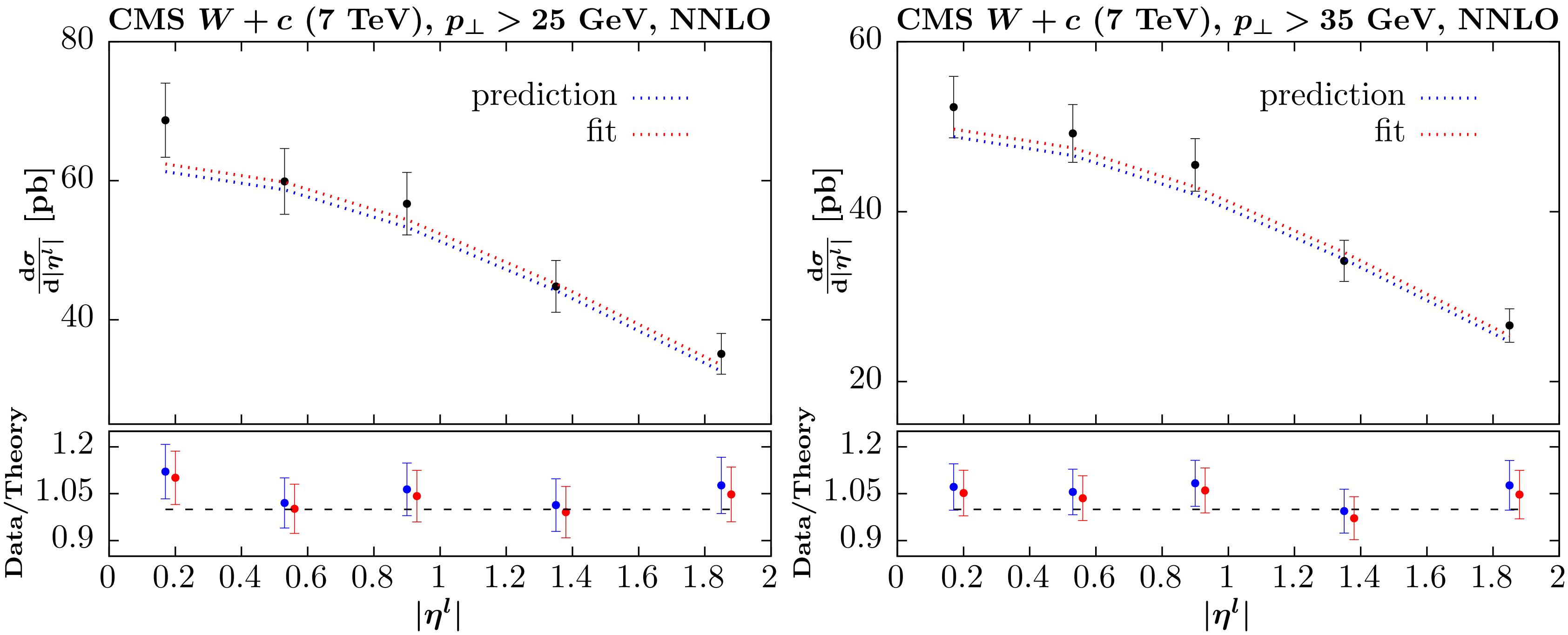
Some reasons for differences in $u(x)/d(x)$ in existing PDFs, which can be due to data tensions, or theoretical procedures.

Precision data so far sometimes favouring one set and sometimes another. Very interested to see developments and will study these data in MMHT approach.

Back-up

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

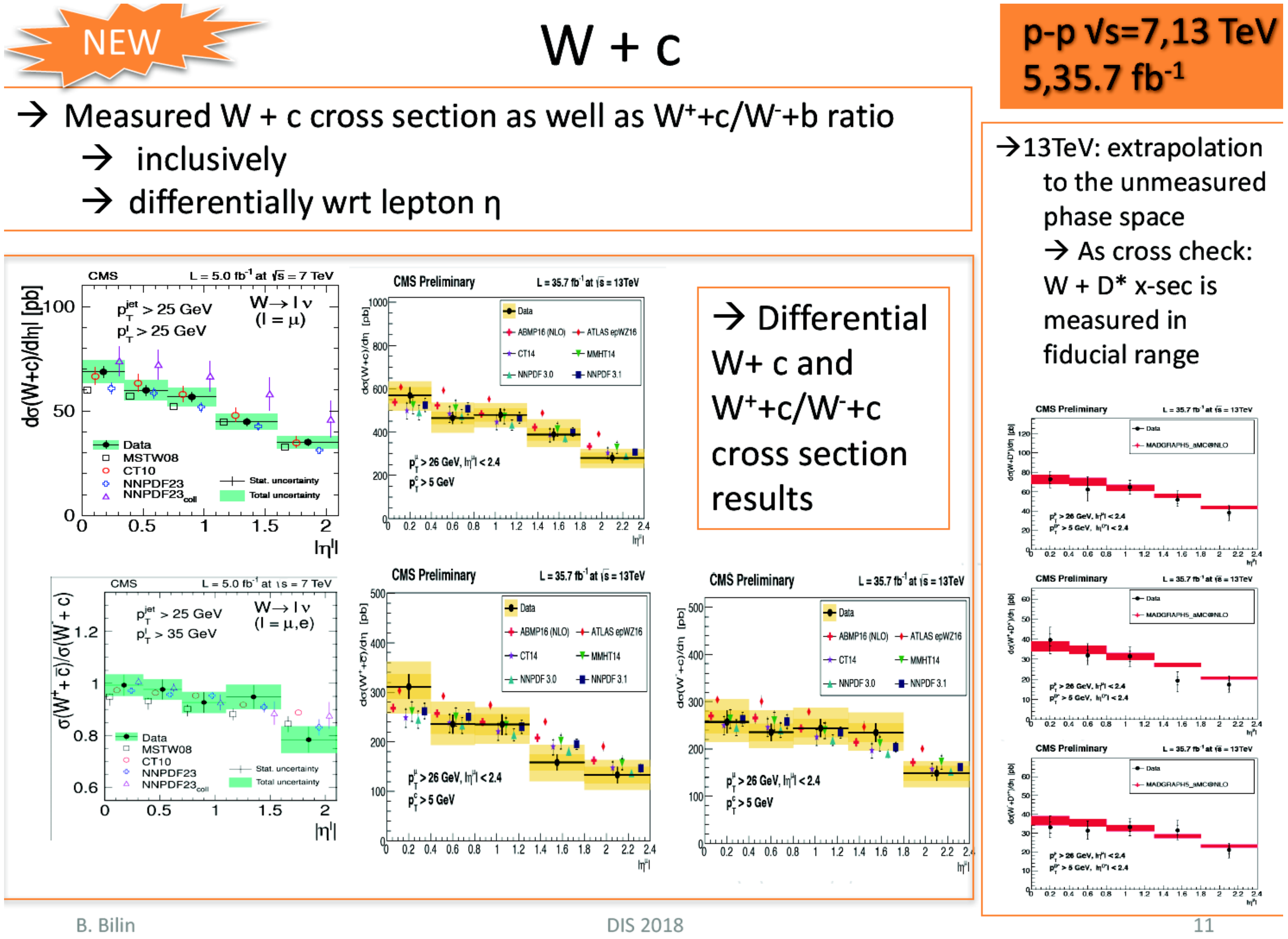
Direct constraint on strange quark - $s + g \to W + c$.



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).

Newer CMS data at 13 TeV – doesn't favour very large $s + \bar{s}$.



NEW

W + c

p-p √s=7,13 TeV
5,35.7 fb^{-1}

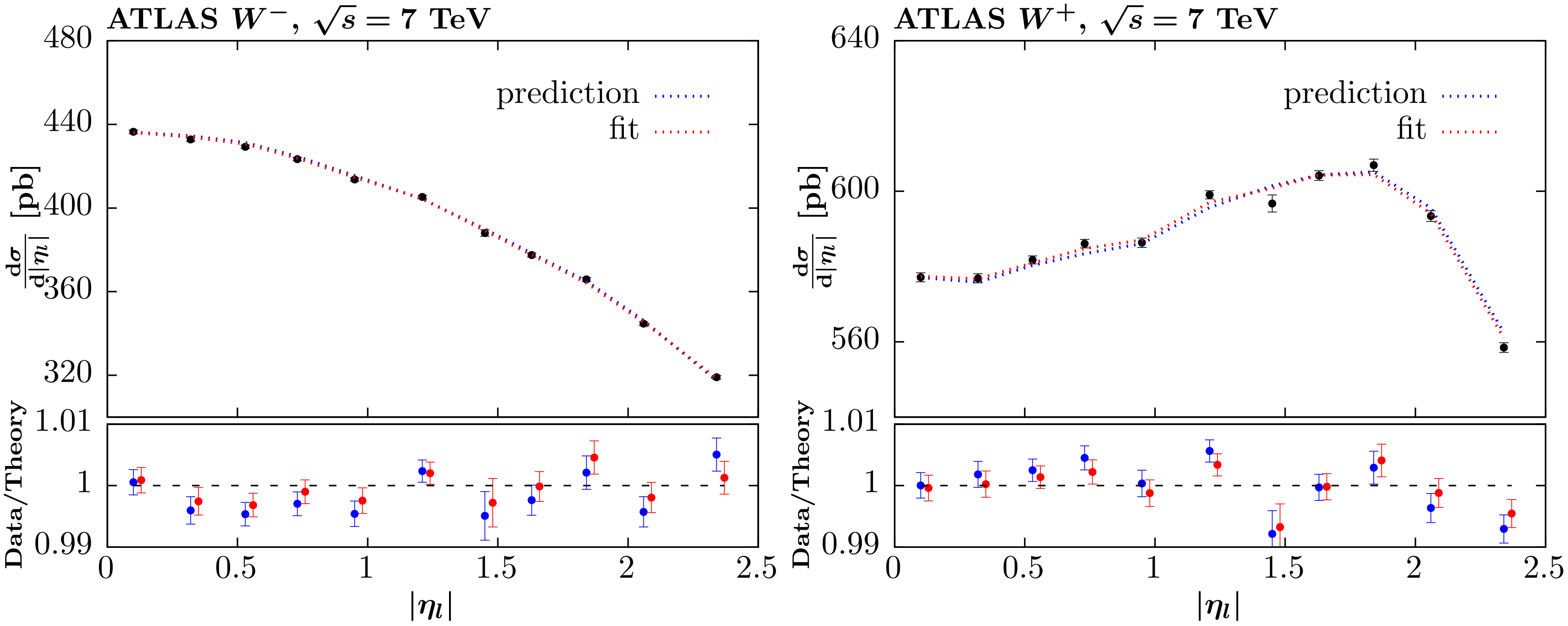
→ Measured W + c cross section as well as W$^+$+c/W$^-$+b ratio
  → inclusively
  → differentially wrt lepton η

→13TeV: extrapolation to the unmeasured phase space
  → As cross check: W + D* x-sec is measured in fiducial range

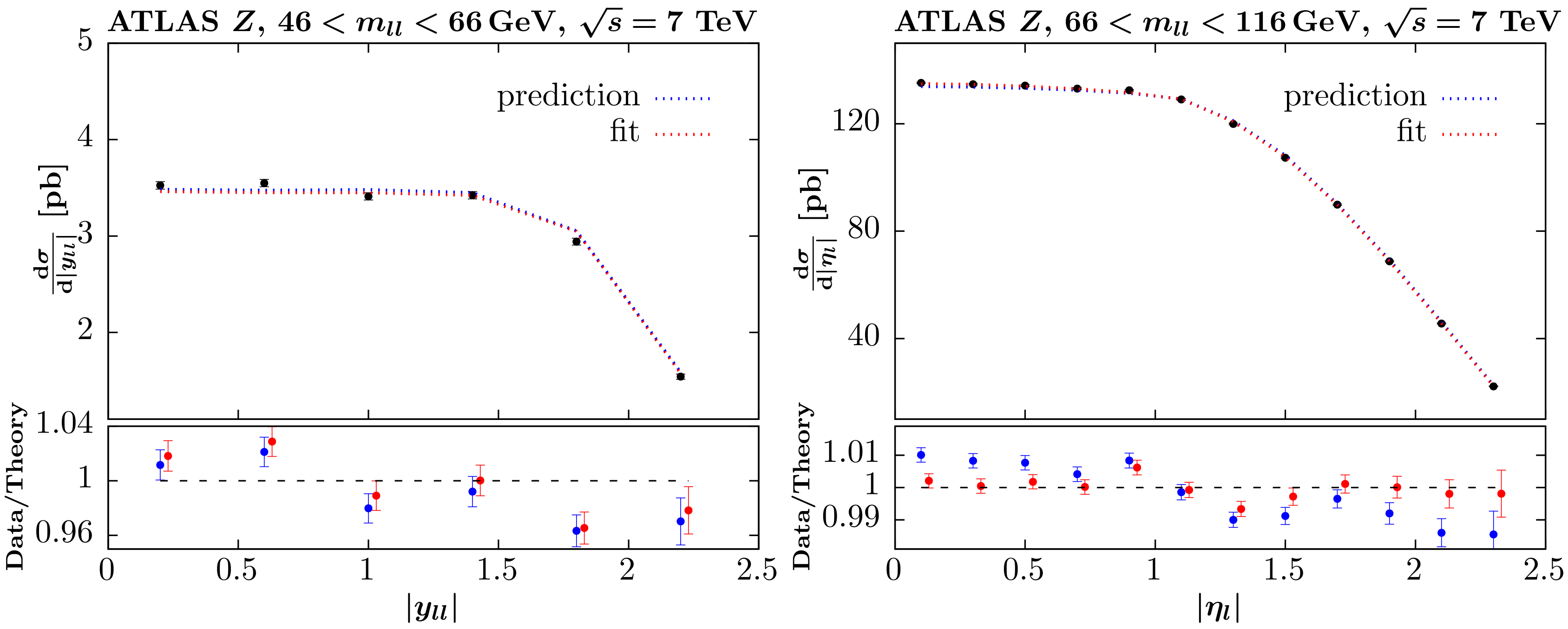
→ Differential W+ c and W$^+$+c/W$^-$+c cross section results

B. Bilin DIS 2018 11

Prediction and Fit to data



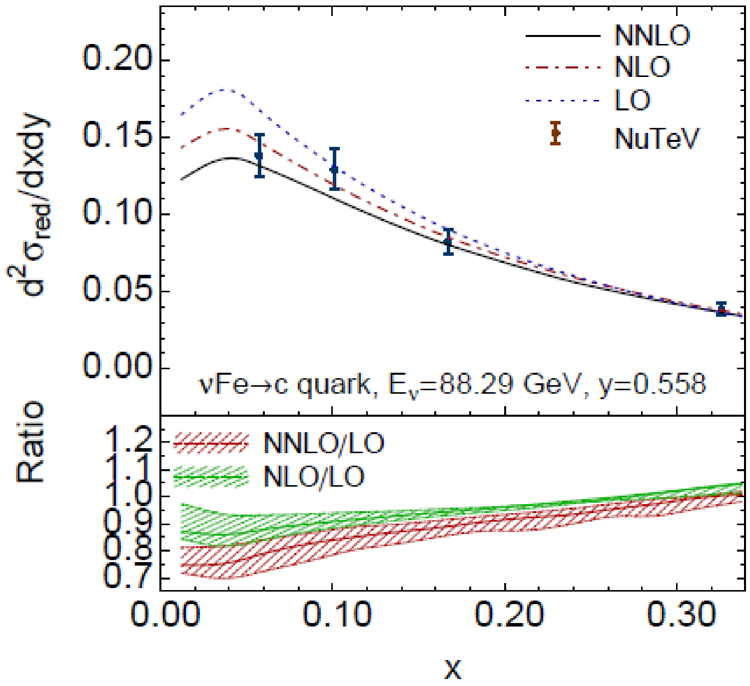
Slight reduction in lower $|\eta|$ W^- required and opposite for W^+.

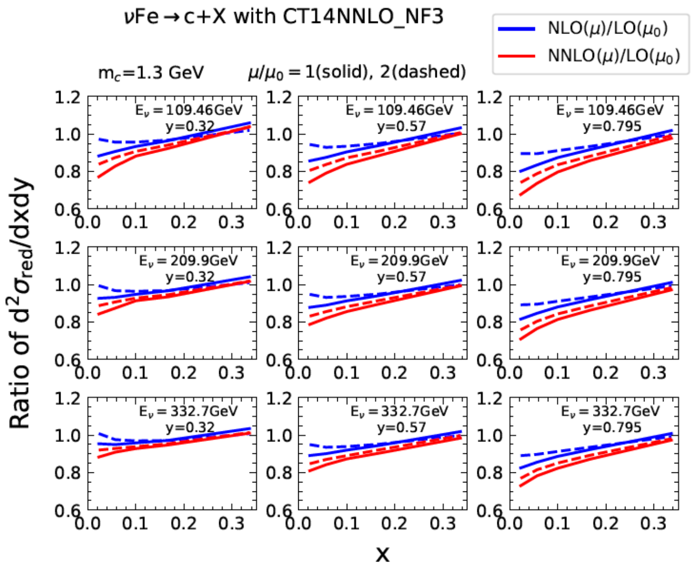


Significant change in shape required for Z production, Higher at low $|\eta|$ and lower at high $|\eta|$

Even with fit difficulty in shape for lower mass data.

Details of tension of W, Z data may be mitigated by NNLO corrections to dimuon production (Phys. Rev. Lett. 116 (2016), Berger *et al.*, J. Gao, `arXiv:1710.04258`).





NNLO correction negative, but larger in size at lower x

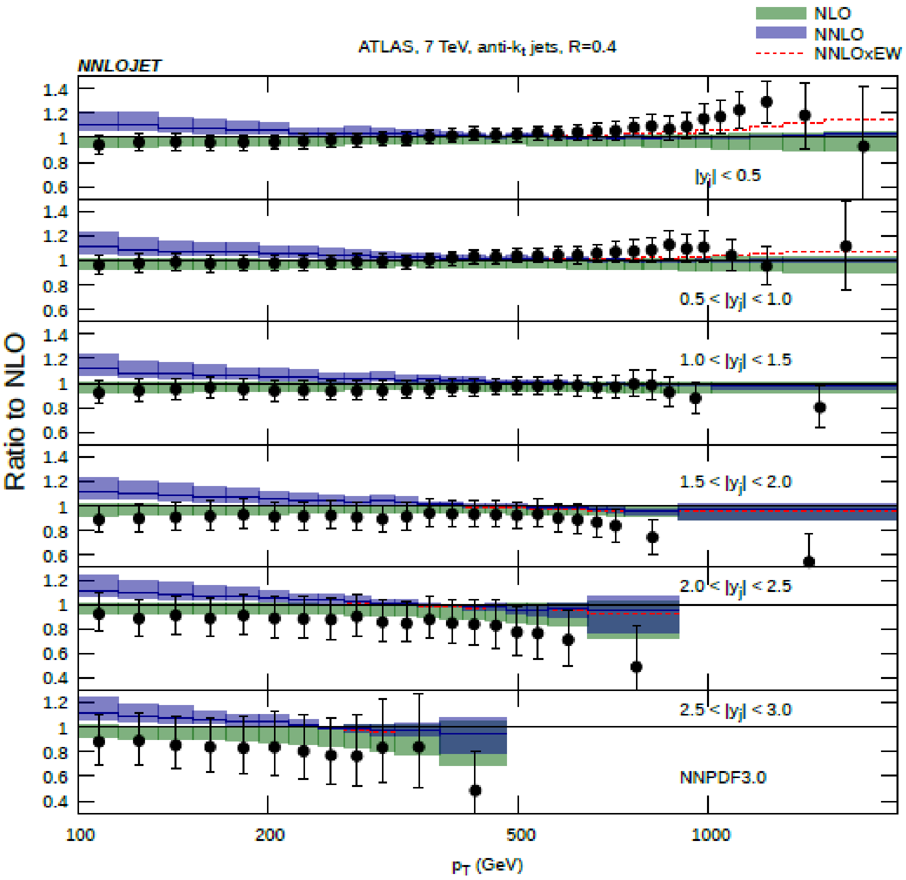
Preliminary results see some improvement in consistency.

NNLO corrections

Now calculated Currie *et al* Phys.Rev.Lett. 118 (2017) 072002.

Fit quality can slightly improve or decrease compared to NLO depending on choices.

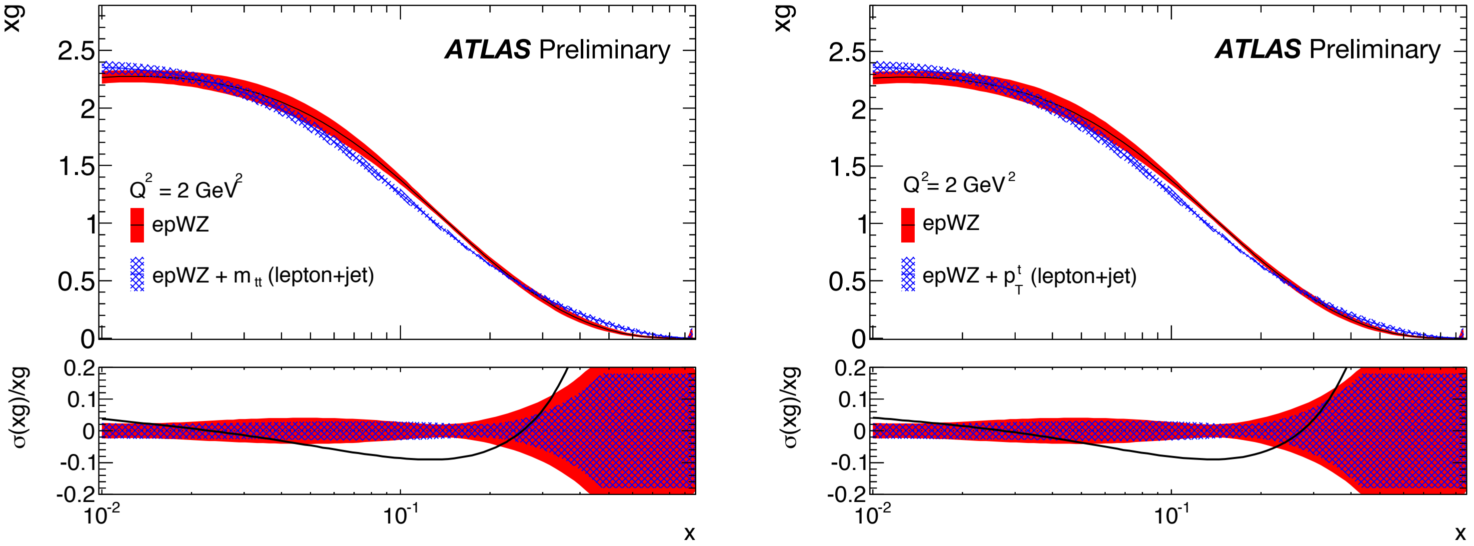
Electroweak corrections to jets different in different bins, but much smaller than systematic effect.



Exact form dependent on R and on scale choice, e.g. p_T or p_T. Up to 20% at low p_T. Authors now recommend using more physical scale, $\hat{p}_T$ – sum of parton p_T (`arXiv:1807.03692`), improved convergence criteria properties. Can also resum R dependence Liu, Moch and Ringer – Phys.Rev.Lett. 119 (2017) 212001.

Differential $t\bar{t}$ data.

A similar issue noticed in ATL-PHYS-PUB-2018-017 –(NNLO Differential top-antitop production now available Czakon *et al*).



Distributions in $m_{t\bar{t}}$ and p_T^t both fit well with similar pulls on gluon.

However, χ^2 in joint fit very poor.

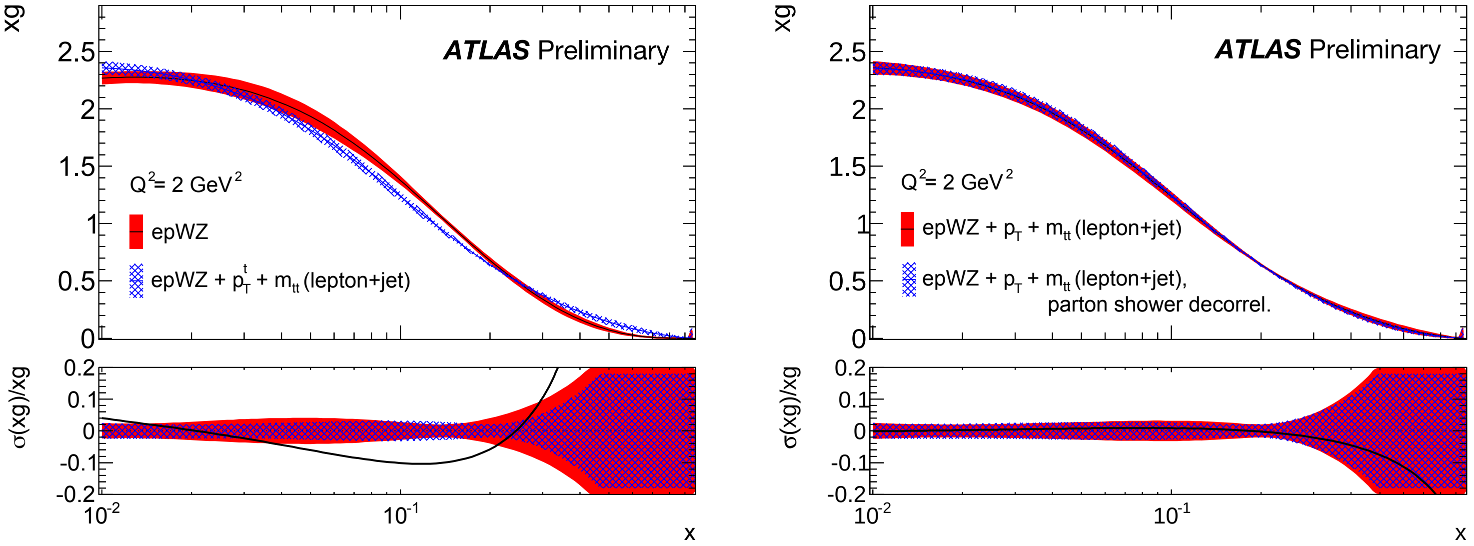
		lepton+jets spectra			
		p_T^t and y_t with statistical correlations	p_T^t and y_t without statistical correlations	p_T^t and m_{tt} with statistical correlations	p_T^t and m_{tt} without statistical correlations
Total χ^2/NDF		1264 / 1068	1260 / 1068	1290 / 1070	1287 / 1070
Partial χ^2/NDP	HERA	1148 / 1016	1147 / 1016	1162 / 1016	1162 / 1016
Partial χ^2/NDP	ATLAS $W, Z/\gamma^*$	82.7 / 55	83.5 / 55	83.2 / 55	83.1 / 55
Partial χ^2/NDP	ATLAS $t\bar{t}$	33 / 13	30 / 13	45 / 15	42 / 15

Again because some correlated systematic uncertainties require very different pulls. All related to 2-point model uncertainties.

Systematic uncertainty source	lepton+jets spectrum			
	p_T^t	y_t	y_{tt}	m_{tt}
Hard scattering model	+0.74± 0.31	+0.48± 0.22	+0.92± 0.37	-0.43± 0.20
Parton shower model	-1.32± 0.43	-0.79± 0.26	-0.51± 0.17	+0.39±0.13
ISR/FSR model	-0.47± 0.18	-0.87±0.30	-1.27± 0.38	+0.33± 0.10

Decorrelation between distributions give much better fit but very similar effect on the gluon distribution.

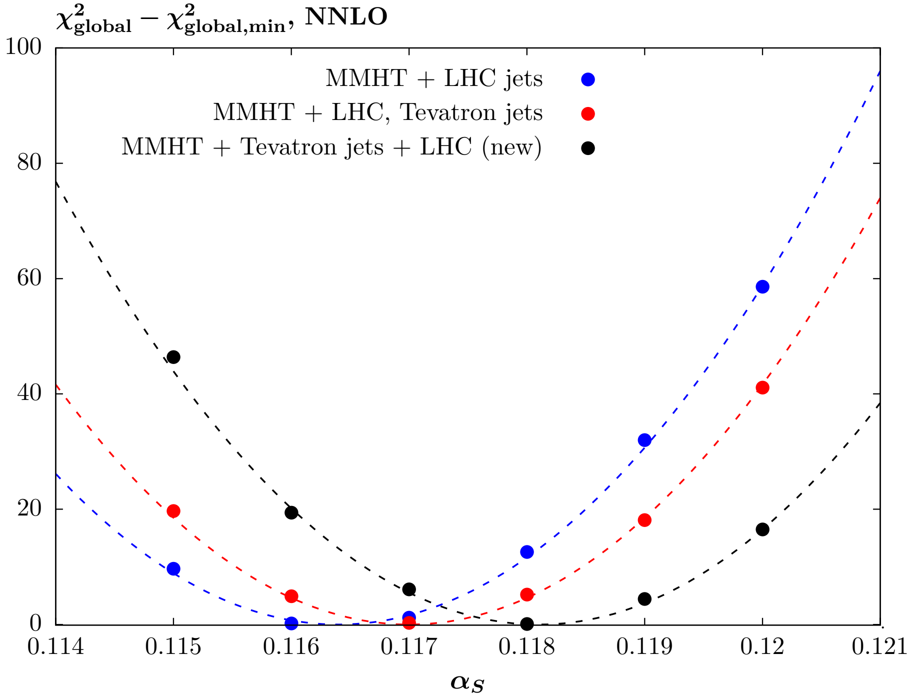
		lepton+jets spectra		
		p_T^t and y_t decorrelate 2-point uncertainties	p_T^t and m_{tt} decorrelate 2-point uncertainties	p_T^t and m_{tt} decorrelate parton-shower model uncertainty
Total χ^2/NDF		1259 / 1068	1247 / 1070	1248 / 1070
Partial χ^2/NDP	HERA	1147 / 1016	1154 / 1016	1153 / 1016
Partial χ^2/NDP	ATLAS $W, Z/\gamma^*$	83.9 / 55	81.9 / 55	81.6 / 55
Partial χ^2/NDP	ATLAS $t\bar{t}$	27.8 / 13	11.5 / 15	14.1 / 15



Studies on best-fit $\alpha_S(M_Z^2)$

For MMHT2014 $\alpha_S(M_Z^2) = 0.1172 \pm 0.0013$ ($\alpha_S(M_Z^2) = 0.1178$ when world average added as data point). With 8 TeV data on $\sigma_{\bar{t}t}$ and final HERA data went to $\alpha_S(M_Z^2) = 0.118$.

For further addition of LHC jets and removal of Tevatron jet data, $\alpha_S(M_Z^2) = 0.1164$. When Tevatron jets added back $\alpha_S(M_Z^2) = 0.1173$



Also include newer W, Z data of ATLAS, CMS, LHCb. Without newer LHC jet data $\alpha_S(M_Z^2) = 0.1179$ but with these data $\alpha_S(M_Z^2) = 0.1176$.

Choices for Heavy Flavours in DIS.

Near threshold $Q^2 \sim m_H^2$ massive quarks not partons. Created in final state. Described using **Fixed Flavour Number Scheme** FFNS (used in ABM(P) PDF determination).

$$F(x, Q^2) = C_k^{FF,n_f}(Q^2/m_H^2) \otimes f_k^{n_f}(Q^2)$$

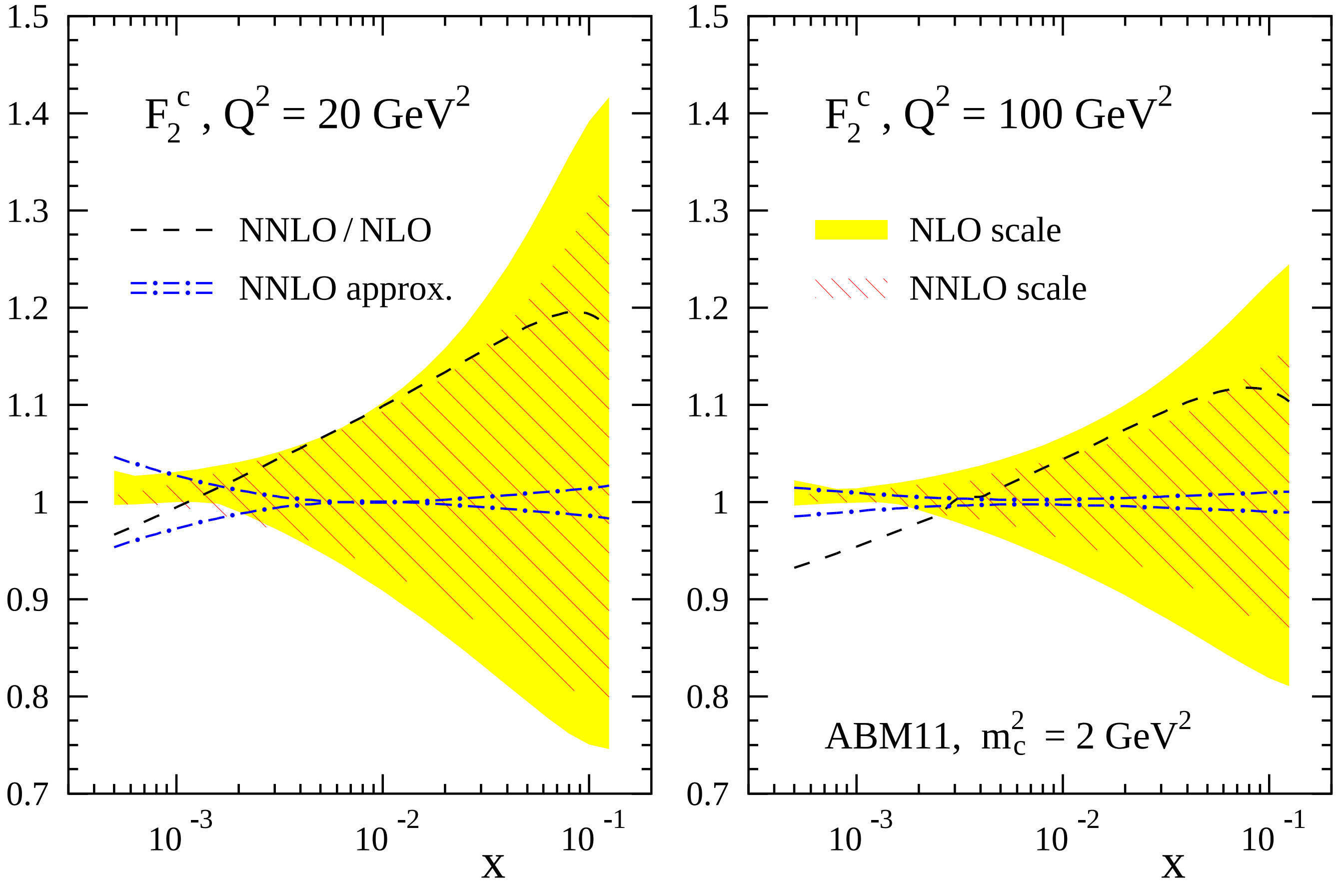
Does not sum $\alpha_S^n \ln^n Q^2/m_H^2$ terms in perturbative expansion.

Variable Flavour - at high scales $Q^2 \gg m_H^2$ heavy quarks behave like massless partons. Sum $\ln(Q^2/m_H^2)$ terms via evolution. Partons in different number regions related to each other perturbatively.

$$f_j^{n_f+1}(Q^2) = A_{jk}(Q^2/m_H^2) \otimes f_k^{n_f}(Q^2),$$

Can define a **General-Mass Variable Flavour Number Scheme** taking one from $Q^2 \leq m_H^2$ to $Q^2 \gg m_H^2$ in a well-defined manner.

Variants used in CT, HERA, MMHT, NNPDF fits. Different versions converge at higher orders.



Approximate $\mathcal{O}(\alpha_S^3)$ corrections to $F_2^c(x, Q^2)$ by Kawamura *et al.* in Nucl.Phys. B864 (2012) 399-468.

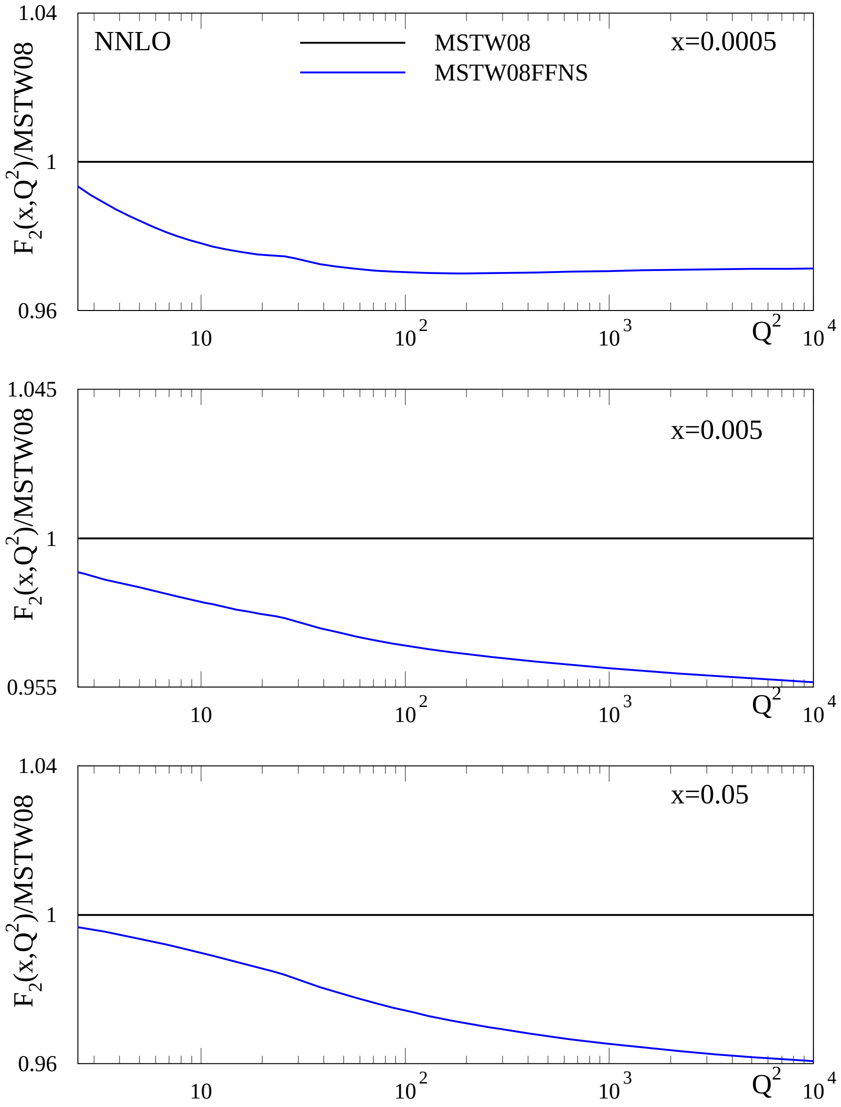
Similar results for $\mathcal{O}(\alpha_S^3)$ approximation used by MSTW at low Q^2 extended to higher Q^2.

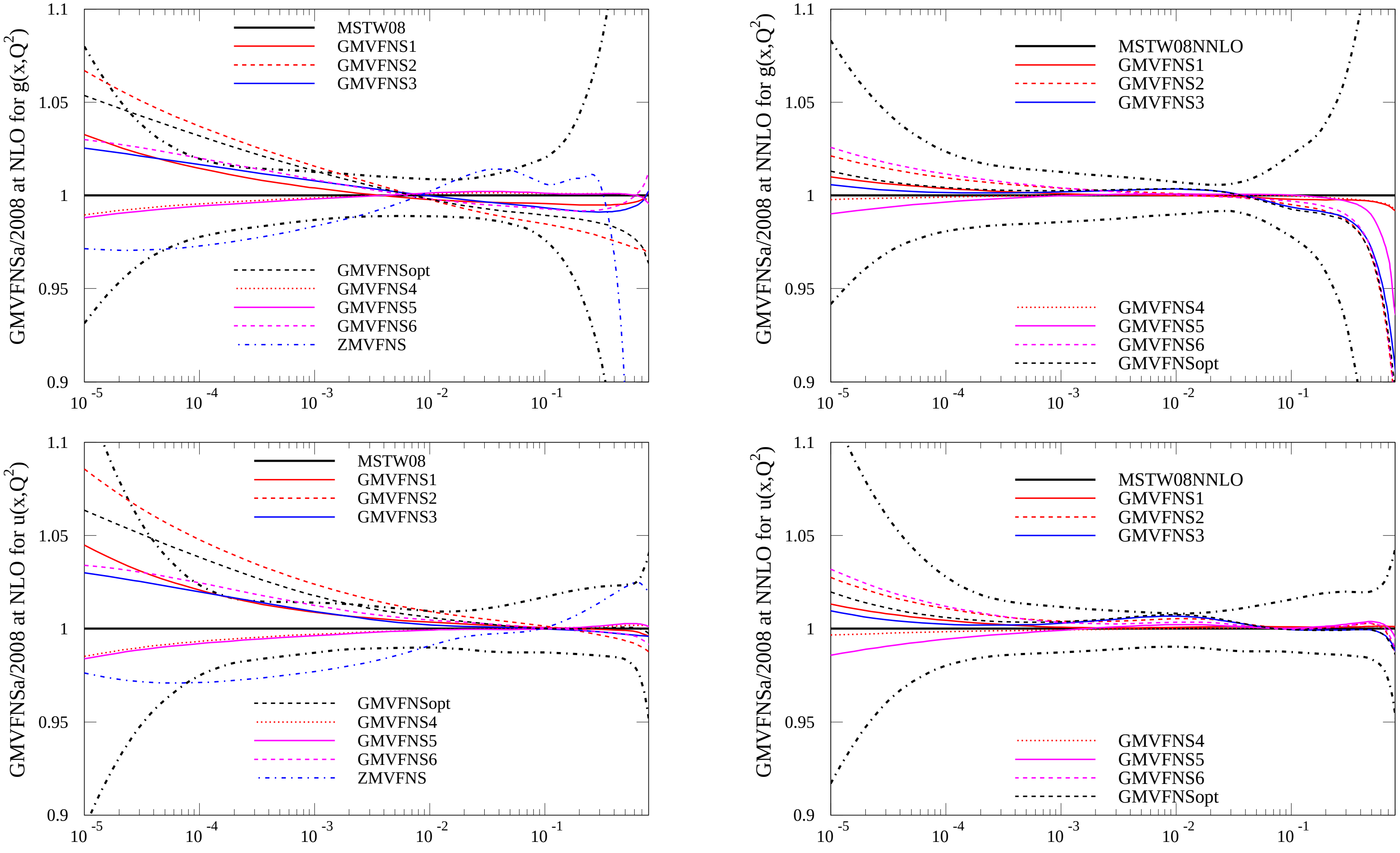
Can lead to over 4% changes in the total $F_2(x,Q^2)$ if the same input PDFs are used in two schemes.

At higher x mainly due to $F_2^c(x,Q^2)$.

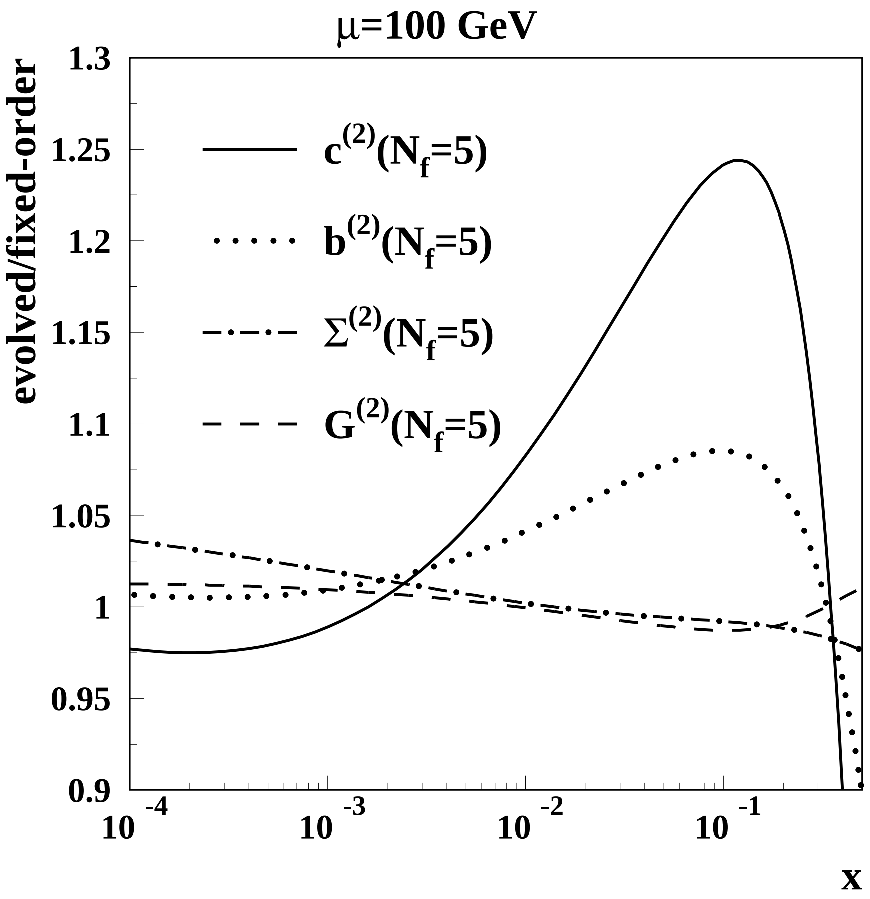
At lower x there is a large contribution from light quarks evolving slightly more slowly in FFNS.

At much higher x difference dies away. Charm component becomes very small and light quark evolution not much different. (Light quarks slightly bigger at the highest x.)





Using FFNS leads to much larger changes than any choice of GM-VFNS mainly due to fitting high-Q^2 DIS data.



Results for $F_2^c(x,Q^2)$ in GM-VFNS compared to those for FFNS similar to results for PDFs by Alekhin *et al.* in Phys.Rev. D81 (2010) 014032 comparing NNLO evolution to the fixed order result up to $\mathcal{O}(\alpha_S^2)$.

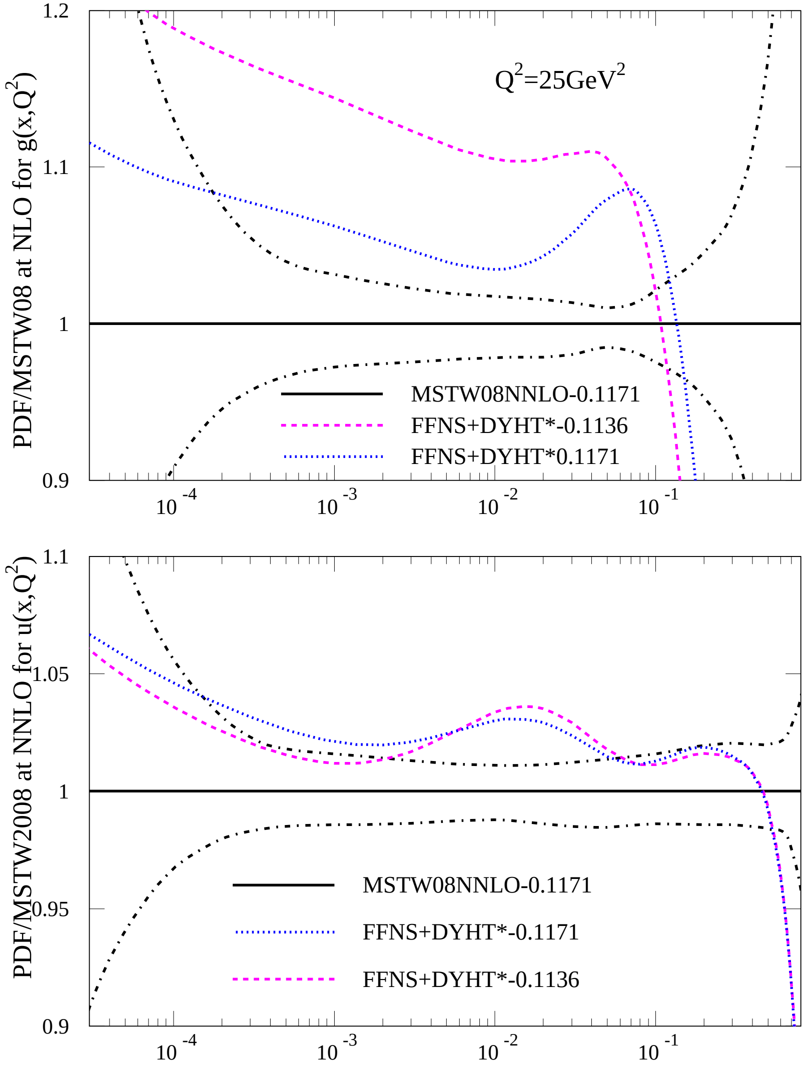
Use of FFNS rather than GM-VFNS leads to smaller high-x gluon and smaller α_S (RT, Eur.Phys.J. C74 (2014) 2958).

Why is α_S lower in FFNS?

Look at parton ratios at lower Q^2 where evolution must match data, and respective $\alpha_S(M_Z^2)$ values are 0.1171 and 0.1136.

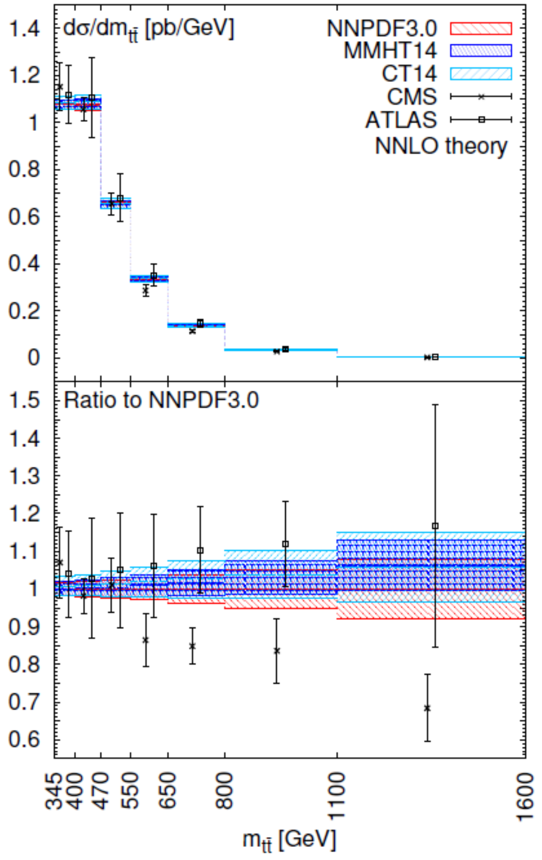
Gluon needs to be bigger at $x \sim 0.001$-0.1 – smaller at high x – to fit data. Feeds to lower x at higher Q^2.

Inverse correlation between high-x gluon and α_S. Without high-x gluon quark evolution too quick.



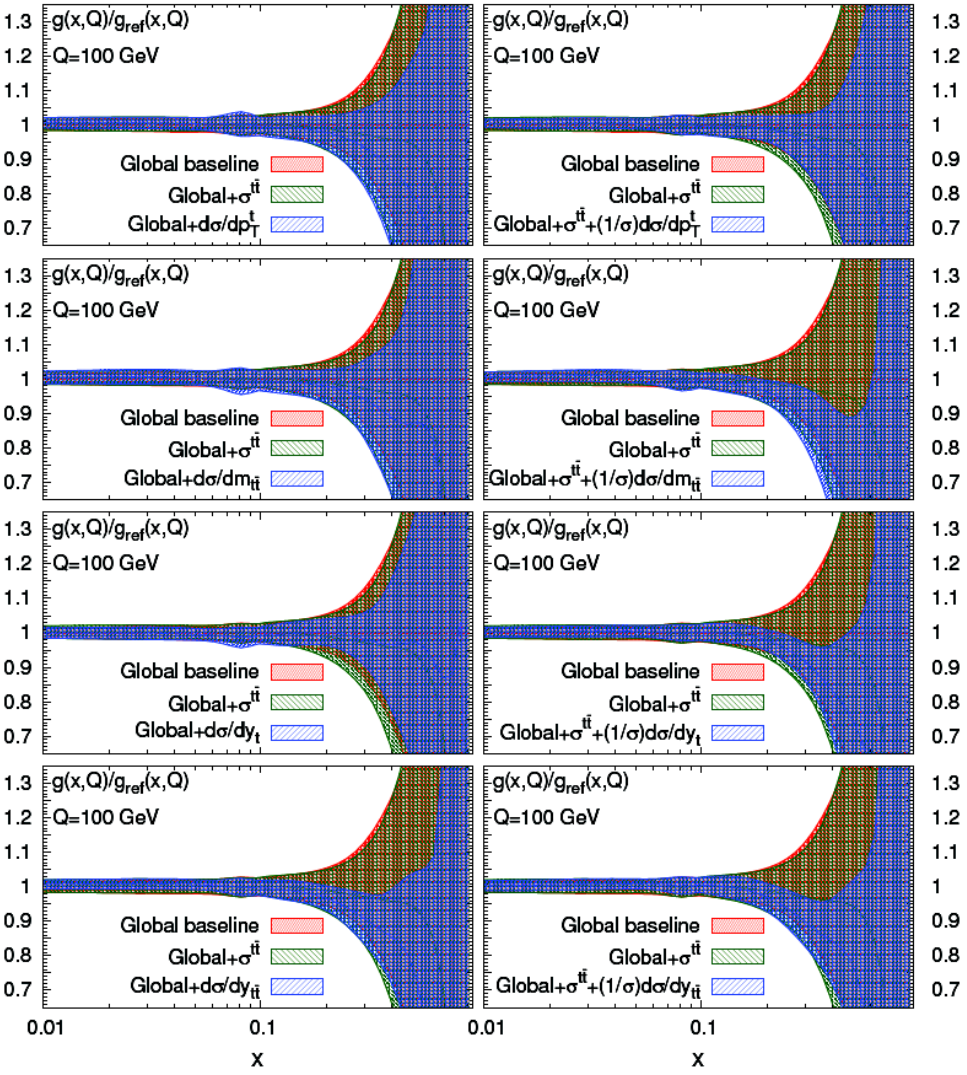
NNLO Differential top-antitop production now available and studied in Czakon *et al*. JHEP 1704 (2017) 044.

Data/Theory comparison: $m_{t\bar{t}}$



Incompatibility between distributions and some very difficult to fit. Overall imply softer gluon and slightly reduced high-x uncertainty.

Impact of $t\bar{t}$ distributions on the gluon PDF at large x



Significant reduction in the gluon uncertainty at large x

Affected kinematic region as expected from the correlation coefficients $(0.1 \lesssim x \lesssim 0.7)$

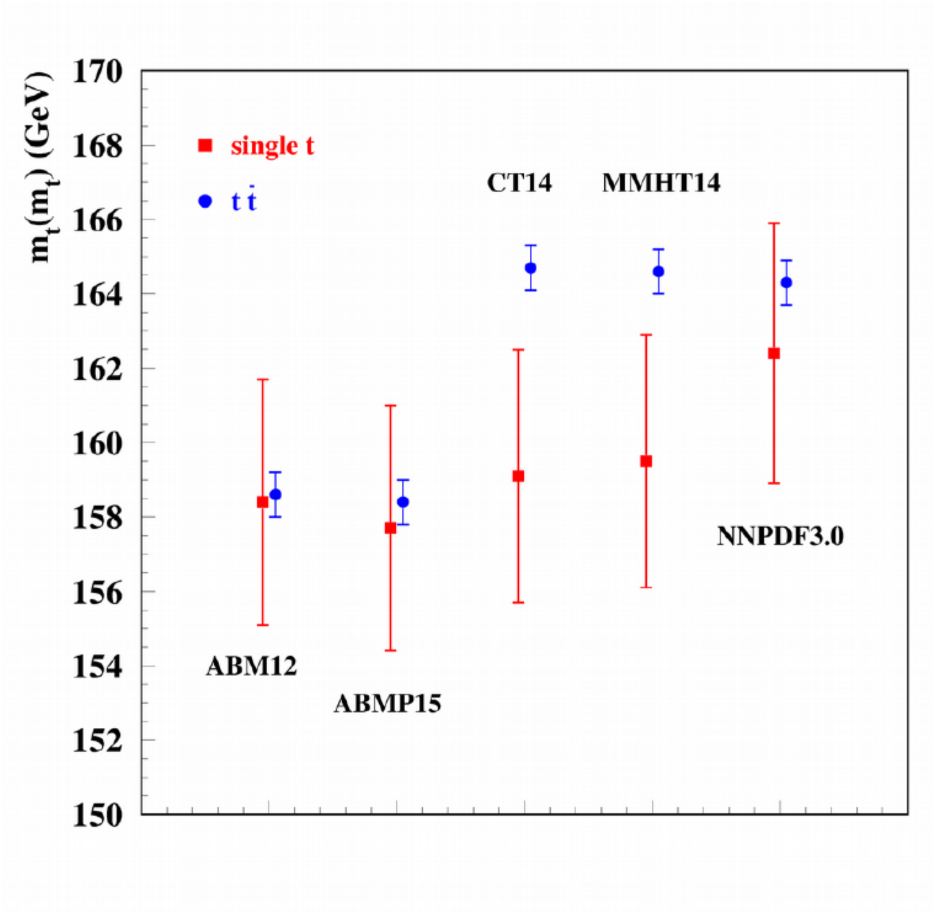
Gluon remarkably consistent in the fit across the choice of distributions

Normalised distributions appear to lead to a greater reduction of uncertainties

Almost negligible impact of total inclusive cross sections (in green)

Settle on using ATLAS y_t distribution and CMS $y_{t\bar{t}}$ distribution, both normalised.

t-quark mass from the single-top data



- Electroweak production → reduced impact of α_s and the PDF umcertainties

- HATHOR framework

  t-channel: NNLO

  Brucherseifer, Caola, Melnikov PLB 736, 58 (2014)

  s-channel: NNLO threshold. resum.

  sa, Moch, Thier hep-ph/1608.05212

- Different PDFs prefer value of

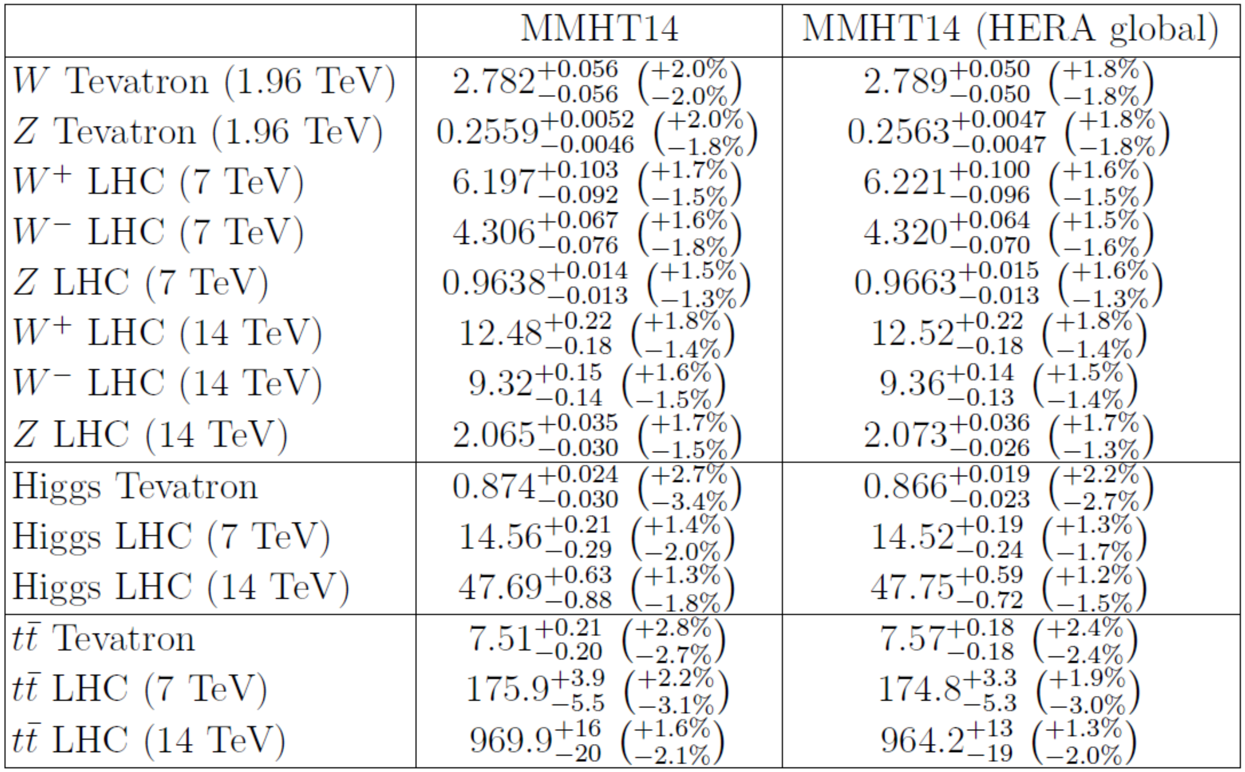
  $m_t(m_t)$ ~160± 3.5 GeV

NNPDF goes higher by 3 GeV.

- The CT14 and MMHT14 go higher by 3 GeV with the ttbar channel

Still lower $\alpha_S(M_Z^2)$ (0.1147) and different gluon shape.

Easier to see impact in predictions for benchmark cross sections.

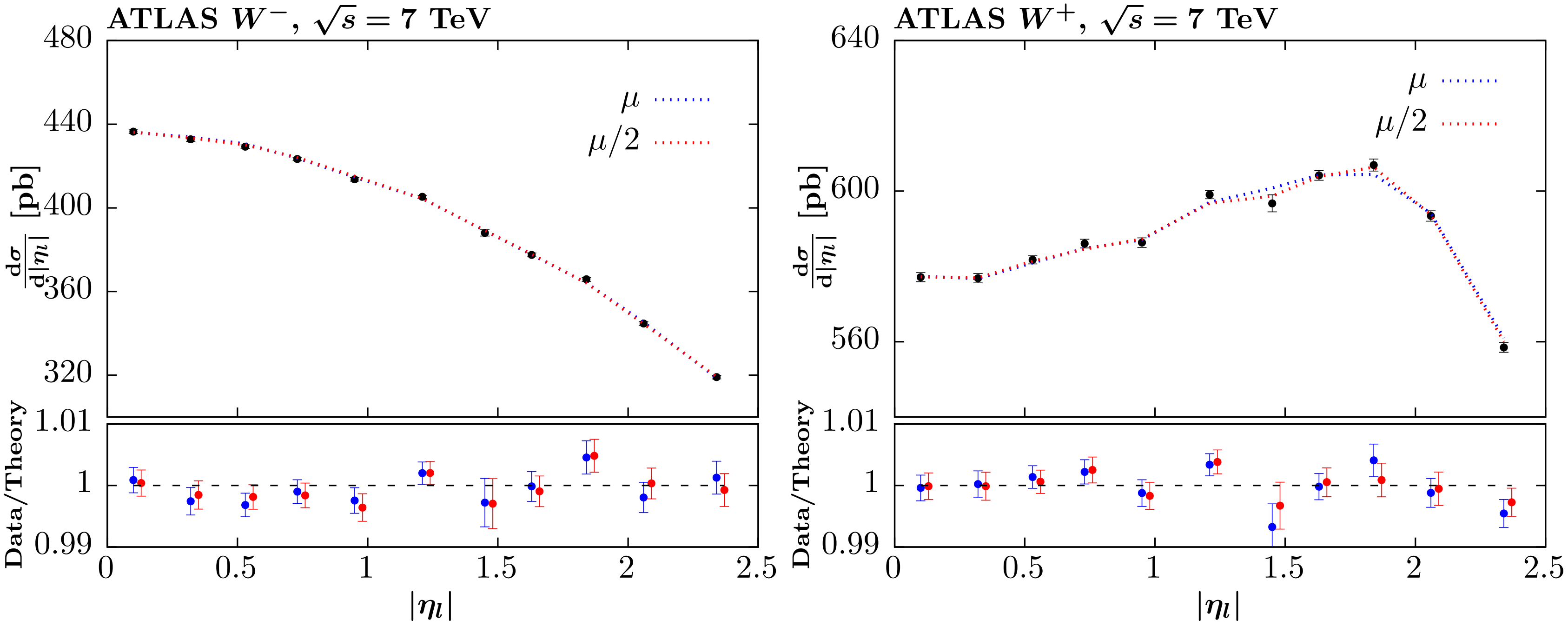


	MMHT14	MMHT14 (HERA global)
W Tevatron (1.96 TeV)	$2.782^{+0.056}_{-0.056}$ $\left(^{+2.0\%}_{-2.0\%}\right)$	$2.789^{+0.050}_{-0.050}$ $\left(^{+1.8\%}_{-1.8\%}\right)$
Z Tevatron (1.96 TeV)	$0.2559^{+0.0052}_{-0.0046}$ $\left(^{+2.0\%}_{-1.8\%}\right)$	$0.2563^{+0.0047}_{-0.0047}$ $\left(^{+1.8\%}_{-1.8\%}\right)$
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)	$0.9638^{+0.014}_{-0.013}$ $\left(^{+1.5\%}_{-1.3\%}\right)$	$0.9663^{+0.015}_{-0.013}$ $\left(^{+1.6\%}_{-1.3\%}\right)$
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)	969.9^{+16}_{-20} $\left(^{+1.6\%}_{-2.1\%}\right)$	964.2^{+13}_{-19} $\left(^{+1.3\%}_{-2.0\%}\right)$

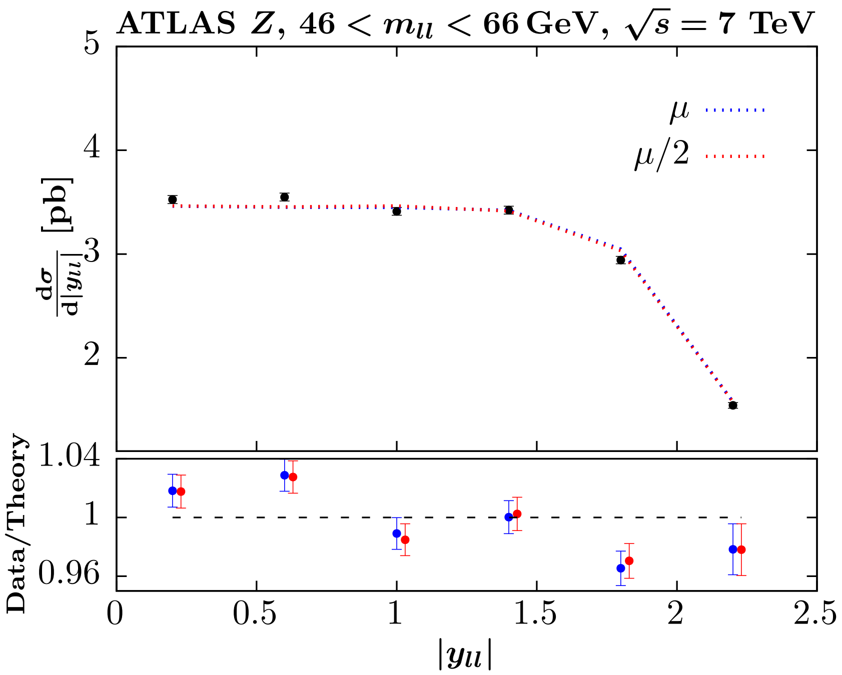
Table 2: The values of various cross sections (in nb) obtained with the NNLO MMHT 2014 sets, with and without the final HERA combination data set included. PDF uncertainties only are shown.

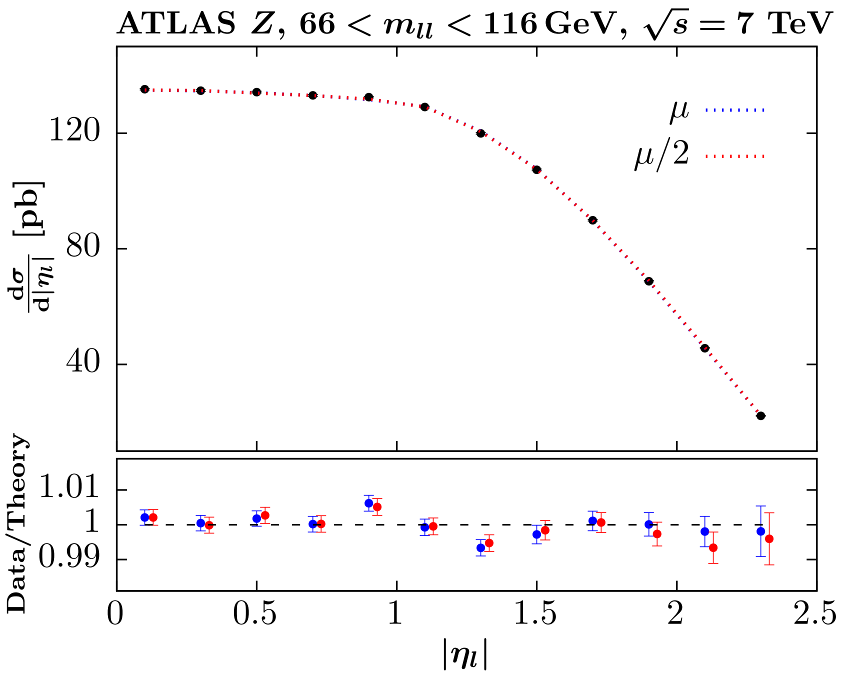
For MMHT very little change in central values. Up to about 10% improvement in uncertainty for $\sigma_{\bar{t}t}$ and $\sigma(gg \rightarrow h)$, i.e. in gluon dominated processes. Less in (anti)quark initiated final states.

Change scales to $\mu_{R,F} = M_{W,Z}/2$



More noticeable improvement for W^+.





Marginal improvement in shape problem at lower mass.

Less fluctuation for Z peak rapidity distribution.