“MMHT” PDF Update

Robert Thorne

April 9th 2019

University College London

With Shaun Bailey, Tom Cridge, Lucian Harland-Lang, Alan Martin and Ricky Nathvani

I will outline updates in the “MMHT” PDF approach.

Inclusion of new LHC data sets - largely electroweak processes, particularly precise ATLAS W, Z $7~\mathrm{TeV}$ results. Implications for strange with NNLO corrections to dimuon production.

Extended parameterisation and eigenvectors sets.

Problems with correlated uncertainties - jets and differential top data.

Completion and imminent release of MMHT PDFs with QED corrections.

Brief recap – MMHT preliminary set (2016) - fit to new hadron collider (mainly LHC) data

Fit new LHCb data at 7 and $8\ \mathrm{TeV}$, $W + c$ jets from CMS, CMS $W^{+,-}$ data, 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, mainly in $d_V(x, Q^2)$.

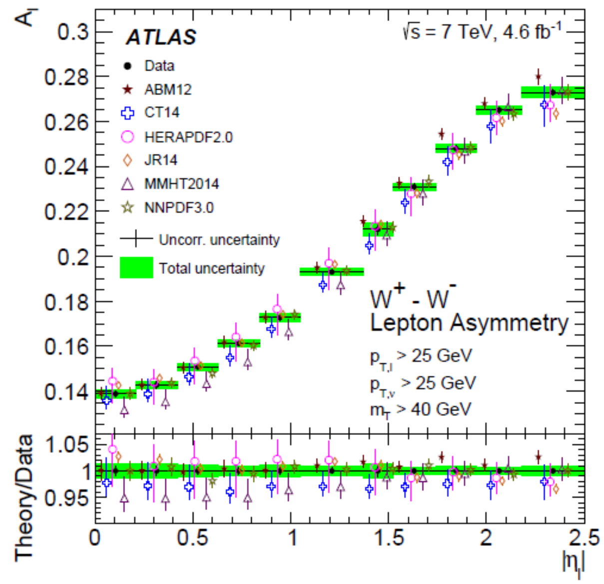
Little tension with previous data – at NLO $\Delta\chi^2 = 9$ for the remainder of the data and at NNLO $\Delta\chi^2 = 8$.

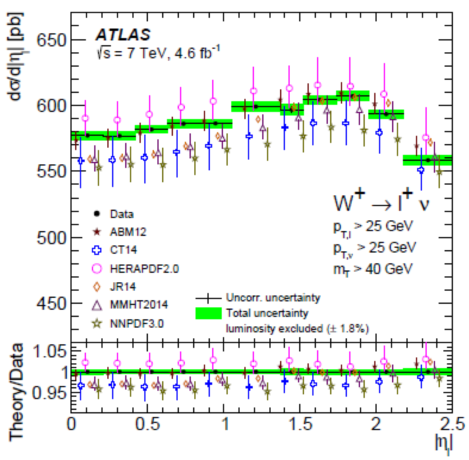
Some reduction in details of flavour decomposition uncertainties, e.g. low-x valence quarks.

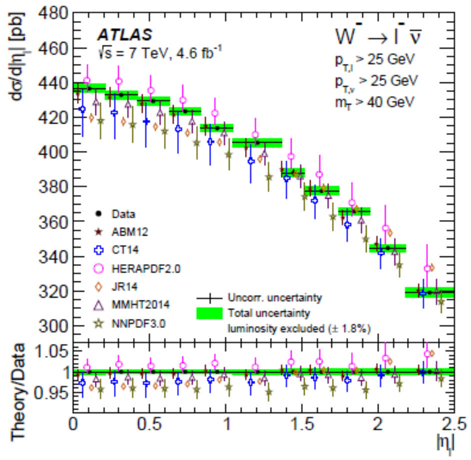
Recent extremely high precision data on W, Z from ATLAS

Differential $W \to \ell\nu$ Measurements

- shape of differential W cross sections generally well described
- particularly good description of the differential lepton charge asymmetry A_ℓ
- differences in PDF sets seen in the overall normalisation
- a precise measurement of the absolute cross section provides valuable information despite larger uncertainties







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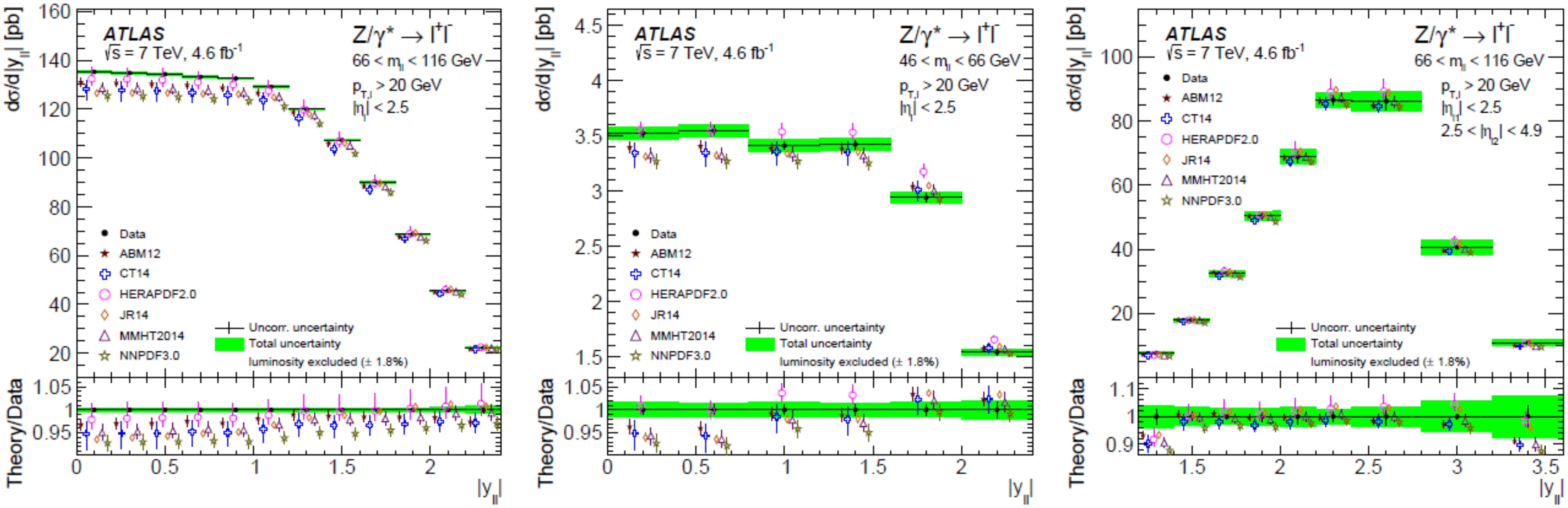
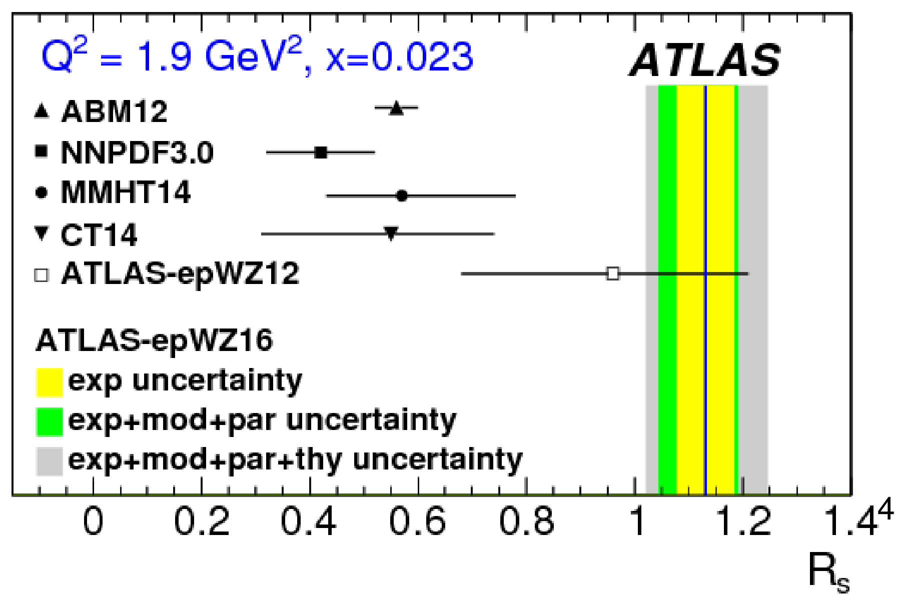
Differential $Z \to \ell\ell$ Measurements



- differences in the rapidity dependence between data and theoretical predictions

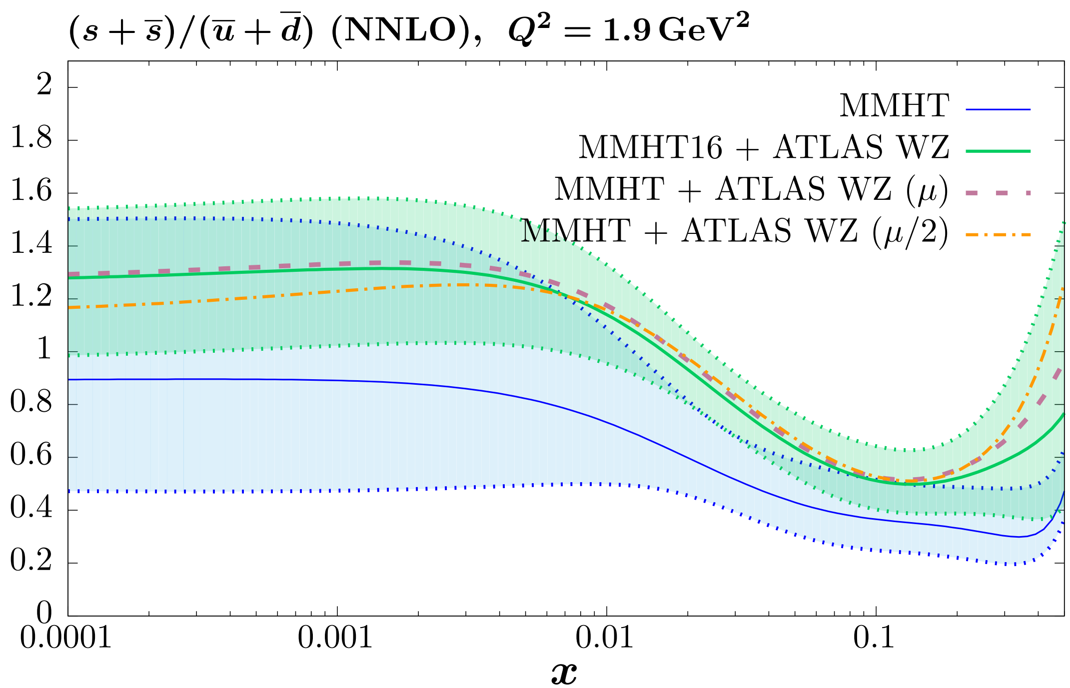
Fixed by increase in strange quark fraction in ATLAS study.



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

Including ATLAS W, Z data in fit goes from $\chi^2/N_{pts} \sim 387/61 \rightarrow \chi^2/N_{pts} \sim 108/61$ (with scales set to $\mu_{R,F} = M_{W,Z}/2$).

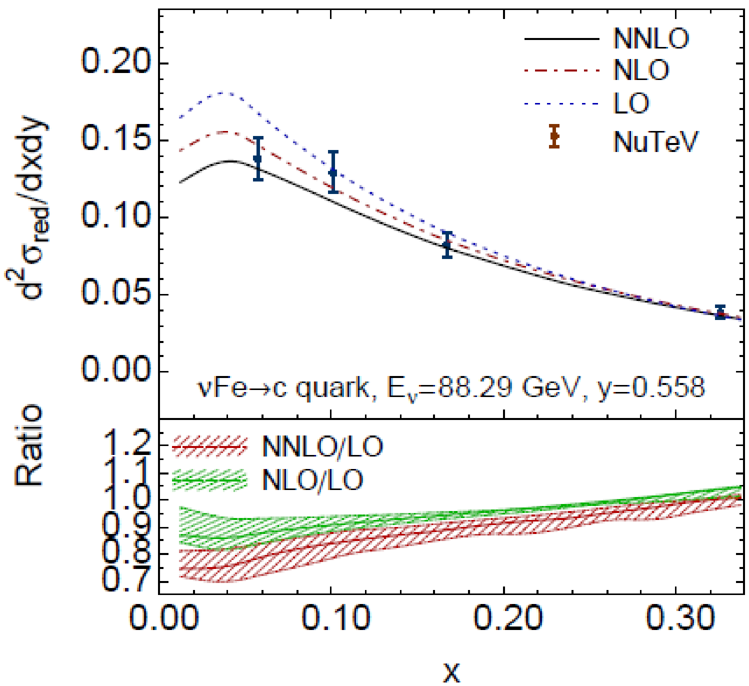
Deterioration in fit to other data $\Delta\chi^2 \sim 54$. CMS double differential Z/γ data CCFR/NuTeV dimuon data Drell-Yan asymmetry.

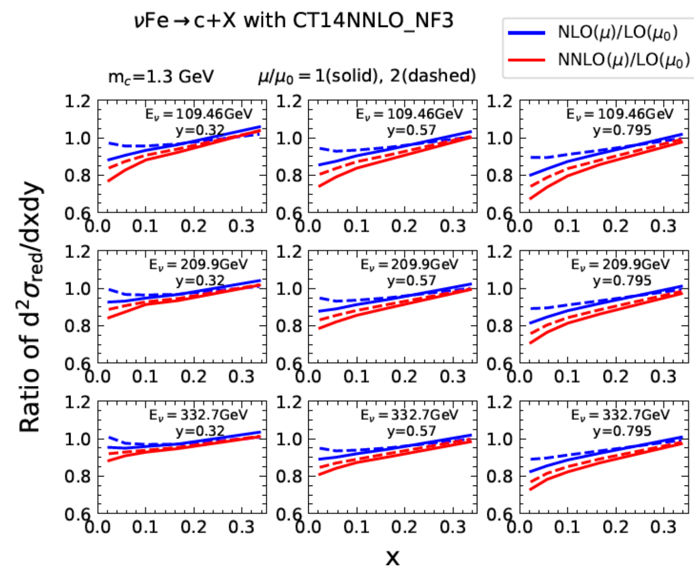


Ratio of $(s+\bar{s})$ to $\bar{u}+\bar{d}$, i.e. R_s at $Q^2 = 1.9\ \mathrm{GeV}^2$.

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

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`).





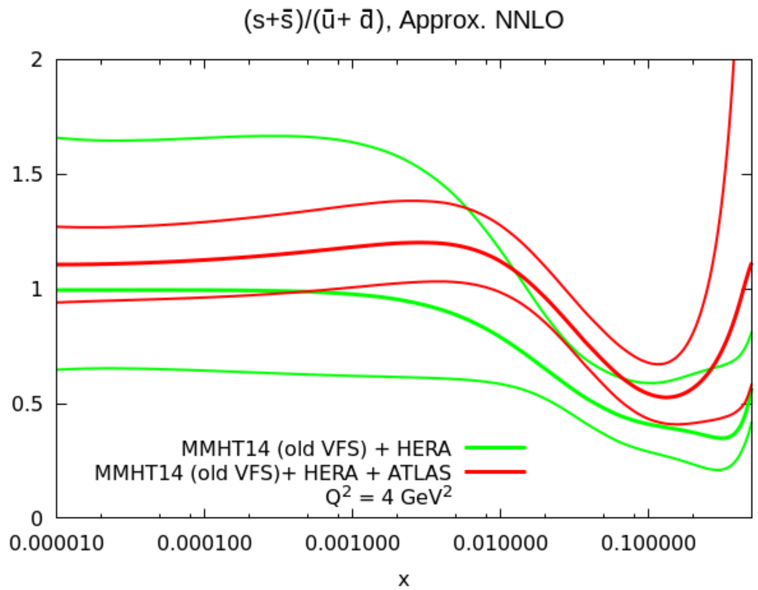
NNLO correction negative, but larger in size at lower x

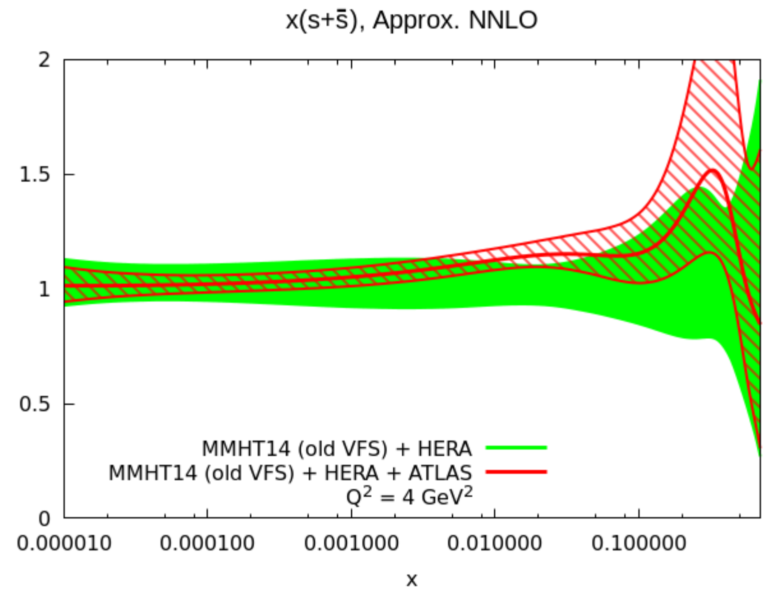
Now include these in fit (Bailey) (required some improvement in threshold treatment for charged-current VFNS scheme).

	BR$(c \to \mu)$	CCFR/NuTeV χ^2	ATLAS $W, Z\chi^2$	Total χ^2
MMHT+HERAII	0.090	120.5		3526.3
MMHT+HERAII (NNLO dimuon)	0.102	122.7		3527.3
MMHT+HERAII (NNLO VFNS dimuon)	0.101	123.9		3531.3
MMHT+HERAII+ATLAS(W, Z)	0.073	127.3	108.6	3684.7
MMHT+HERAII+ATLAS(W, Z) (NNLO dimuon)	0.084	137.8	106.8	3688.4
MMHT+HERAII+ATLAS(W, Z) (NNLO VFNS dimuon)	0.086	137.0	106.8	3688.5
N_{pts}		126.25	61	3337

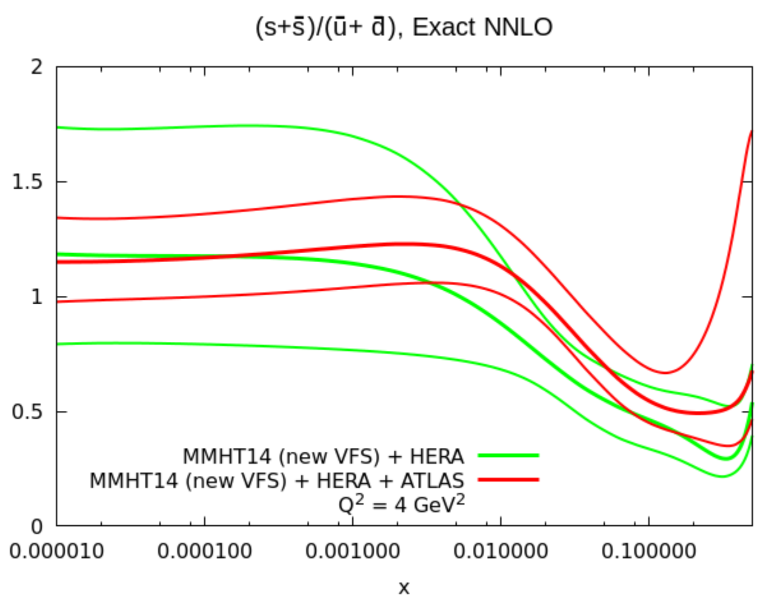
The default value of BR$(c \to \mu) = 0.092 \pm 10\%$.

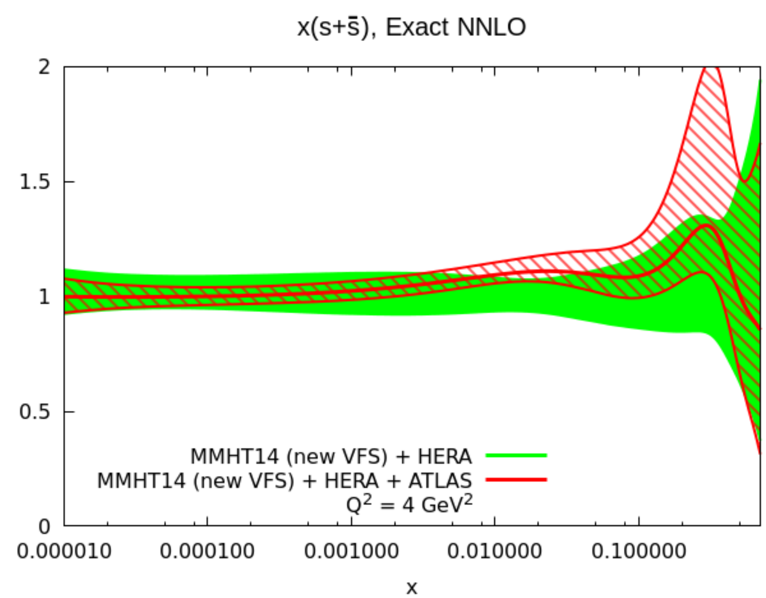
$s + \bar{s}$ illustration without full NNLO, i.e. as in MMHT2014.





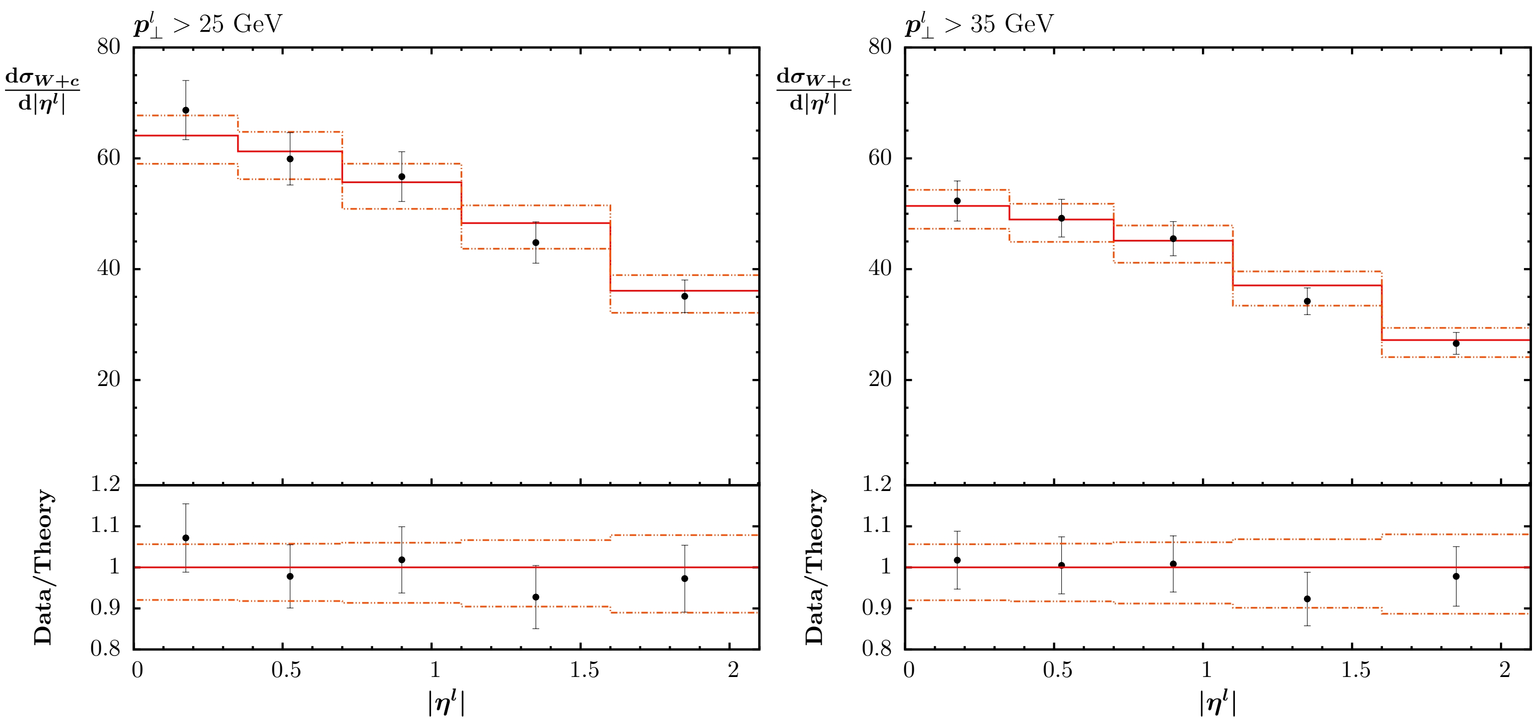
$s + \bar{s}$ illustration with full NNLO and updated VFNS.





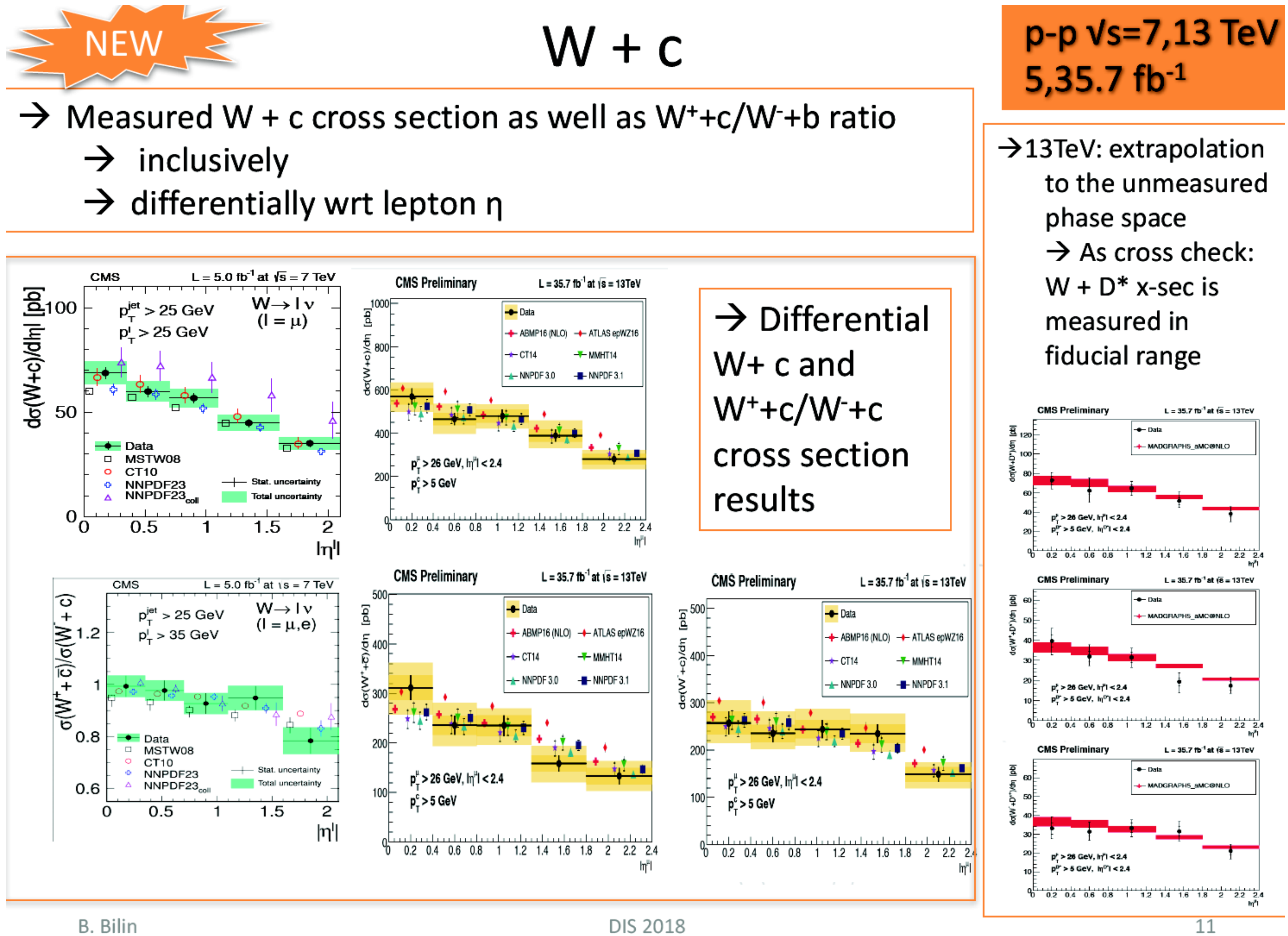
Direct constraint on Strange – $W + c$ differential distributions.

	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



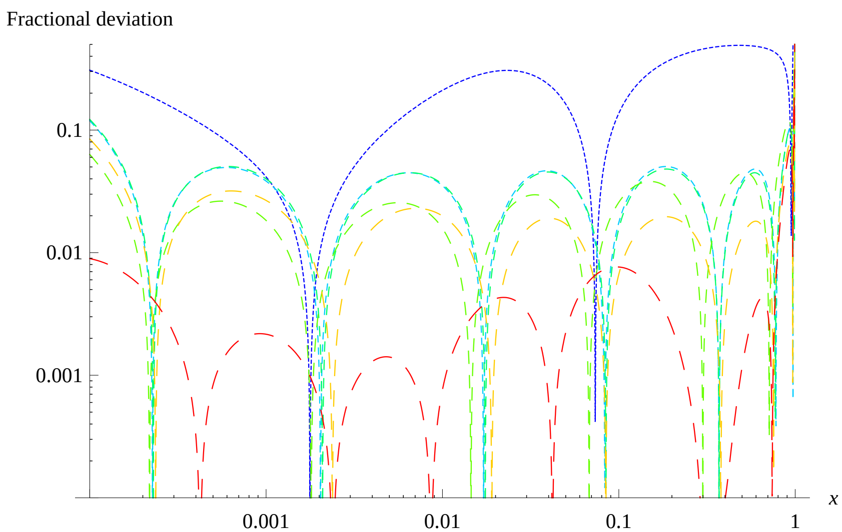
MSTW2008 a bit low (especially for ATLAS), but MMHT2014 seems fine particularly for CMS (shown). Data provides some constraint.

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



Extension of parameterisation. (Cridge)

General parameterisation used $A(1-x)^\eta x^\delta(1+\sum_{i=1}^n a_i T_i(1-2x^{\frac{1}{2}}))$,, where $T_i(1-2x^{\frac{1}{2}}))$ are Chebyshev polynomials.



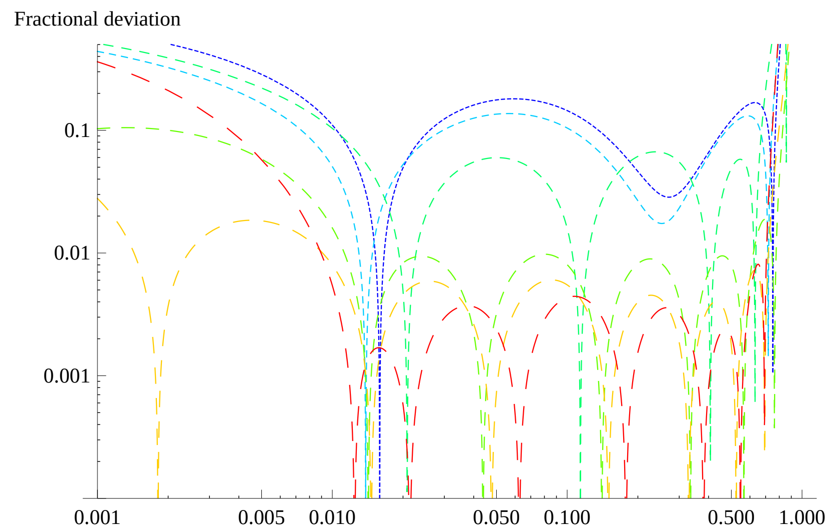


Illustration of precision possible with increasing n, sea-like (left) and valence-like (right) (where pseudo-data for $x > 0.01$).

For many inputs parameterisation using $n = 4$ is default for MMHT2014 - $g(x, Q_0^2)$ has a negative term, $s^+(x, Q_0^2)$ has two parameters tied to the sea and $(\bar{d} - \bar{u})(x, Q_0^2)$ and $s^-(x, Q_0^2)$ have fewer parameters.

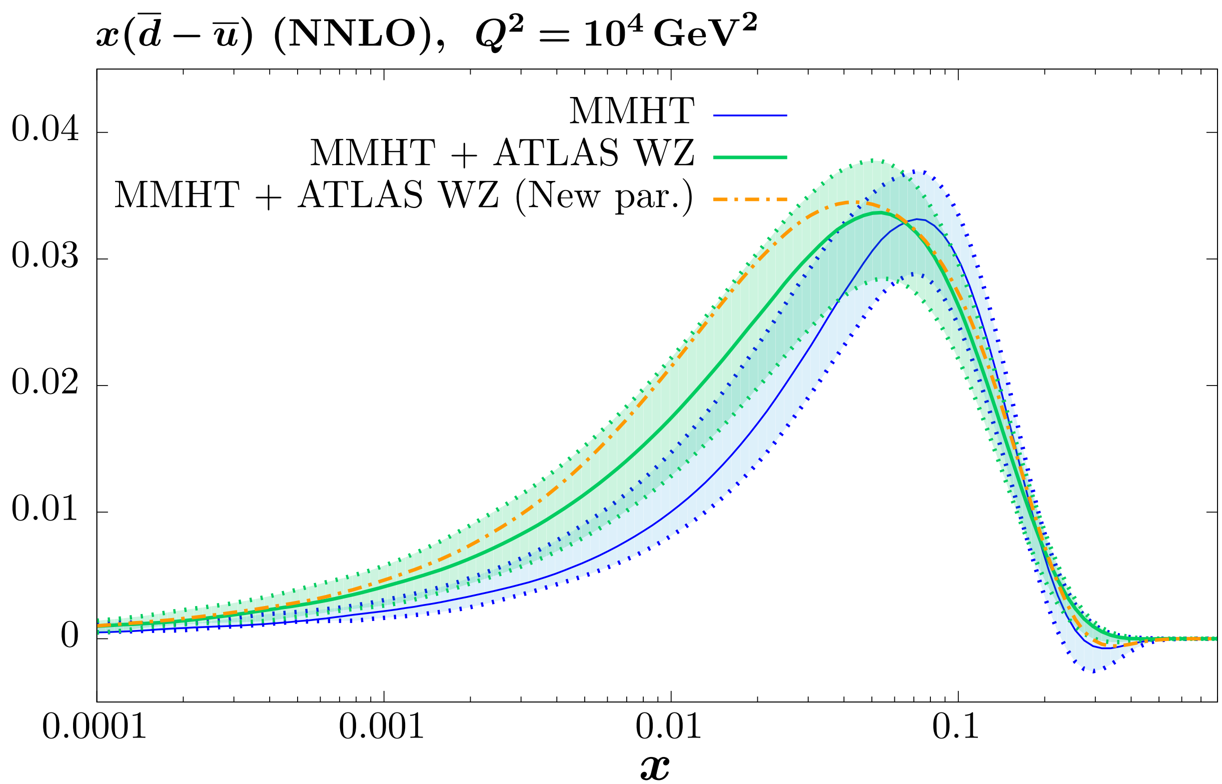
Using $n = 6$ would lead to much better than 1% precision.

For $(\bar{d}-\bar{u})(x,Q_0^2)$ by default use 4 parameters,

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

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

So 6 free parameters. Easily allows multiple turning points. Improves fit by > 10 points - eases ATLAS W, Z and DY ratio tension.



Try extending parameters of other PDFs sequentially, using $n = 6$ in Chebyshev polynomial for $u_v(x, Q_0^2), d_v(x, Q_0^2)$ and $sea(x, Q_0^2)$ ($s^+(x, Q_0^2)$, with two common parameters), and for gluon

$$g(x, Q_0^2) = A(1-x)^\eta x^\delta (1 + \sum_{i=1}^{4} a_i T_i(1 - 2x^{\frac{1}{2}})) - A_-(1-x)^{\eta_-} x^{\delta_-}.$$

($s^-(x, Q_0^2)$ not changed).

Change of 36 to a maximum of 48 parton parameters.

Main improvements after extension of $(\bar{d} - \bar{u})(x, Q_0^2)$ from additionally introducing $d_V(x, Q_0^2)$ – ($u_V(x, Q_0^2)$ not significant) and $g(x, Q_0^2)$ – ($sea(x, Q_0^2)$ and $s^+(x, Q_0^2)$ not significant).

When determining uncertainties go from 25 eigenvector pairs to 30 - one extra parameter for each PDF other than the light sea (and $s^-(x, Q_0^2)$). Extra eigenvectors highly non-quadratic $\rightarrow$ little extra uncertainty.

Improvements in Global Fit.

Data set	$-\Delta\chi^2 \quad (\bar{d}-\bar{u})$	$-\Delta\chi^2 \quad (\bar{d}-\bar{u}), d_V$	$-\Delta\chi^2$ All
Total	17.6	34.0	48.9
BCDMS F_2^p	-4.6	-3.3	-2.7
BCDMS F_2^d	-2.7	4.9	8.5
NMC F_2^n/F_2^p	6.5	6.1	6.0
NuTeV F_3^N	-0.3	1.7	3.2
E866 $\sigma(pd)/\sigma(pp)$	8.2	10.1	11.0
NuTeV dimuon	0.7	1.0	3.0
HERA I+II $\sigma(e^+p)$ 920 GeV	1.1	1.7	4.6
CMS $pp \to l^+l^-$	0.7	1.8	3.1
D0 $\sigma(e^+) - \sigma(e^-)$	-1.2	-3.4	-1.4
CMS 8 TeV $\sigma(l^+) - \sigma(l^-)$	4.4	5.0	4.6
ATLAS 7 TeV W, Z	-0.5	2.2	4.3
CMS 7 TeV jets	-0.5	0.2	3.2

Improved parameterisation reduces tension between DY ratio data and LHC data, not improves intrinsic fit quality to DY ratio (MMHT fit nearly optimal).

LHC lepton asymmetry improved, but D0 worse.

Gluon improvement only partially from HERA data.

Mean tolerance $T = 3.31$

27 eigenvector directions constrained primarily by LHC data sets – largely $7\,\mathrm{TeV}$ ATLAS W, Z data and CMS W (and $W + c$) data but some others including LHCb top and jets.

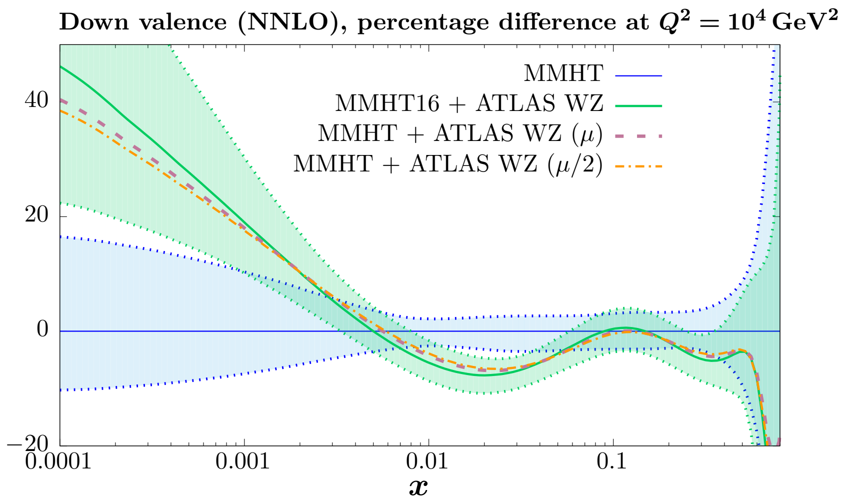
E866 Drell Yan asymmetry absolutely vital for constraining $\bar{d} - \bar{u}$.

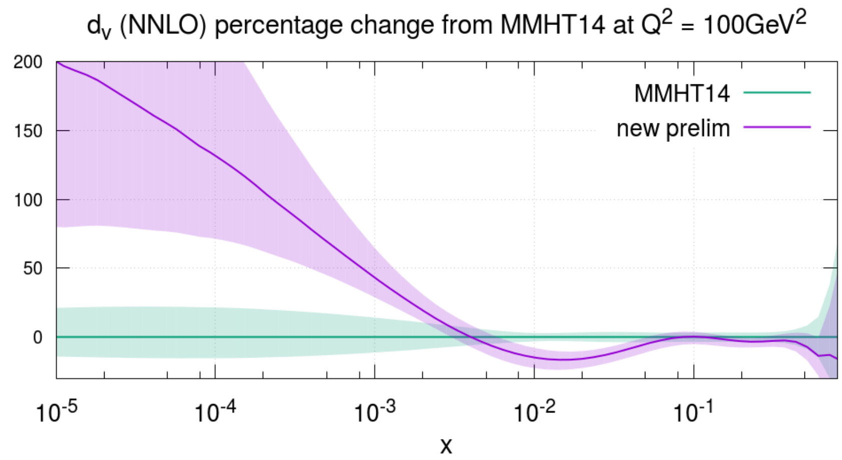
Tevatron data of various types primary constraint for 8 eigenvectors.

Fixed target DIS data (BCDMS, NMC, NuTeV, CCFR) still constrains 12 eigenvectors (mainly high-x).

Fully global fit necessary for full constraint with (almost) no assumptions/models.

The biggest change is in $d_V(x, Q^2)$ - largely due to $7\ \mathrm{TeV}$ ATLAS W, Z data, and extra parameterisation has a significant effect.

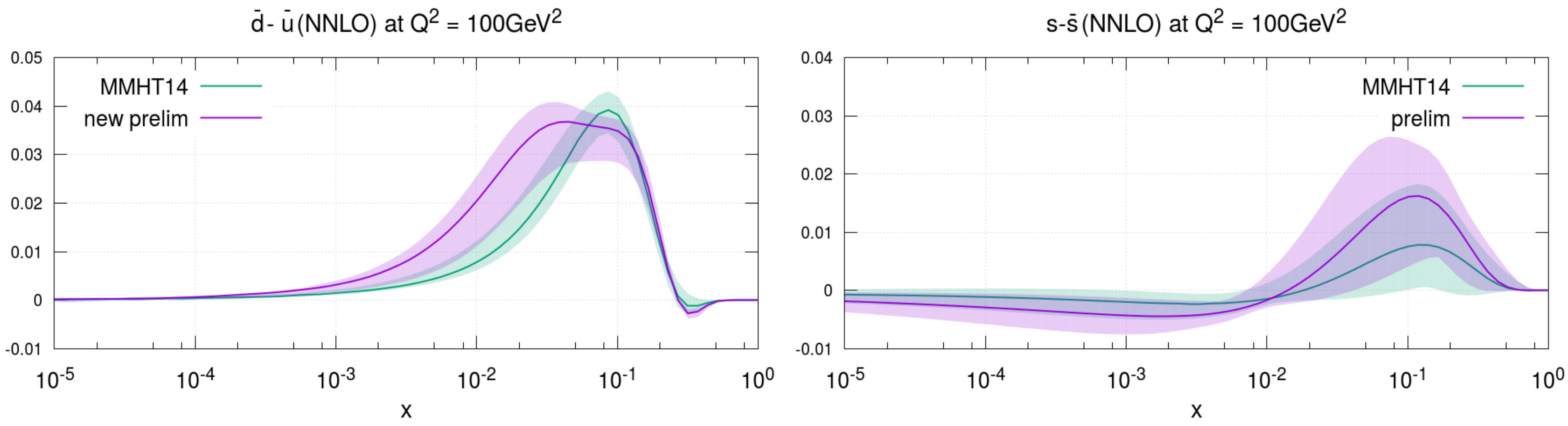




Left – new data. Right – newdata and extended parameterisation.

Note increased uncertainty at very large and small x due to extended parameterisation. Former a feature of many PDFs.

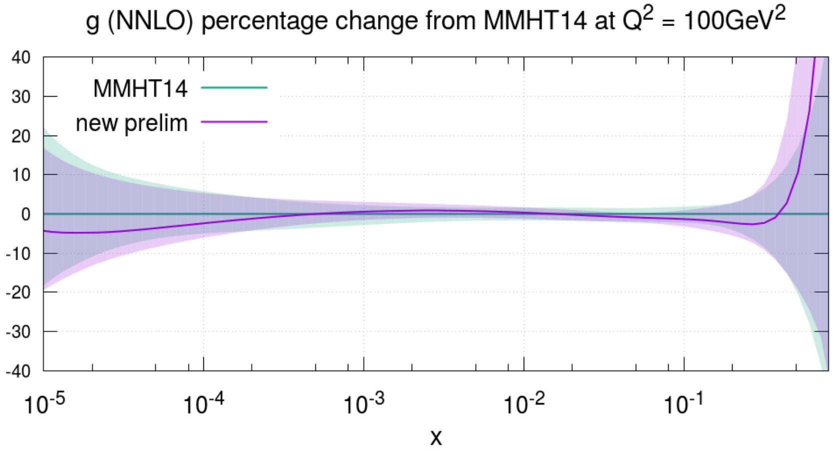
Plots of $(\bar{d}-\bar{u})(x,Q^2)$ and $(s-\bar{s})(x,Q^2)$

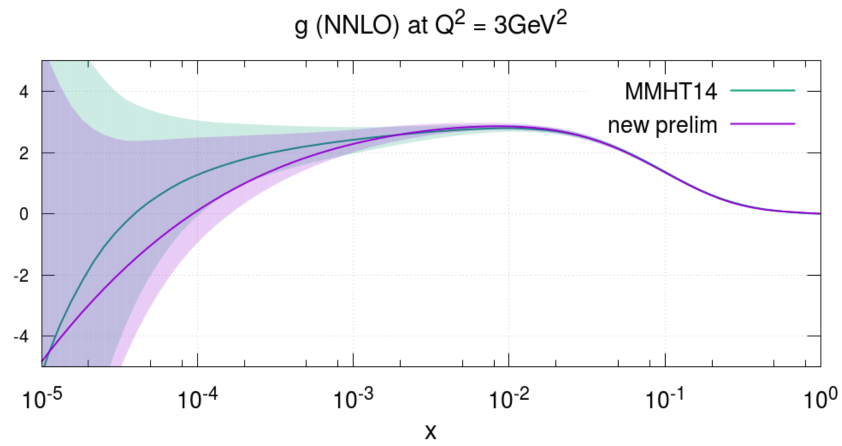


Data prefer a distinctly different shape in $(\bar{d}-\bar{u})(x,Q^2)$ and extra parameter gives extra uncertainty (just about goes negative in places).

Increase in size of $(s-\bar{s})(x,Q^2)$ driven by data – overwhelmingly $7\ \mathrm{TeV}$ ATLAS W, Z data. No change in parameterisation.

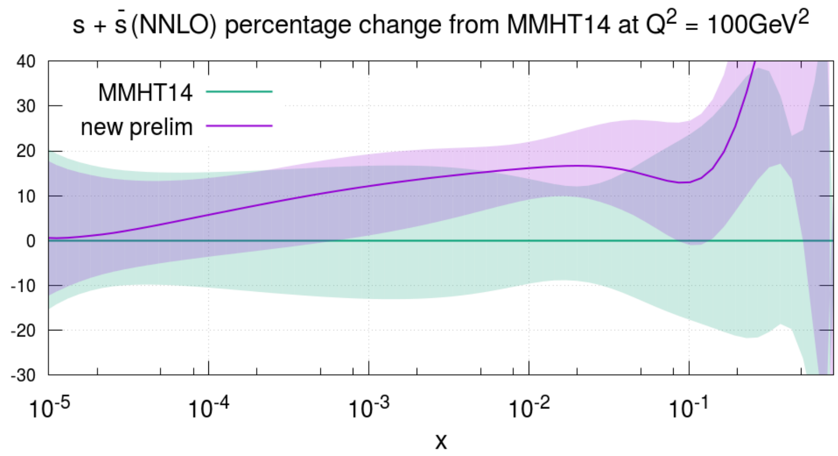
Plots of $g(x, Q^2)$ at high and lower Q^2.

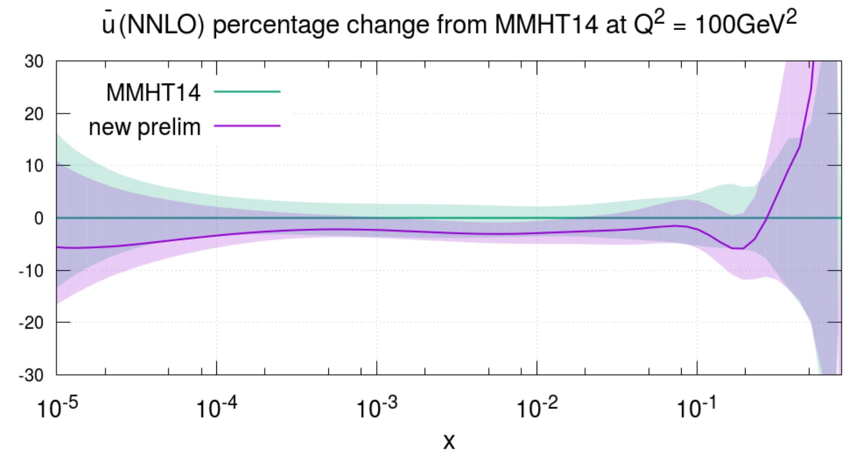




Some features in common with change in `arXiv:1902.11125`, but initial parameterisation much more free here.

Plots of $s^+(x, Q^2)$ and $\bar{u}(x, Q^2)$





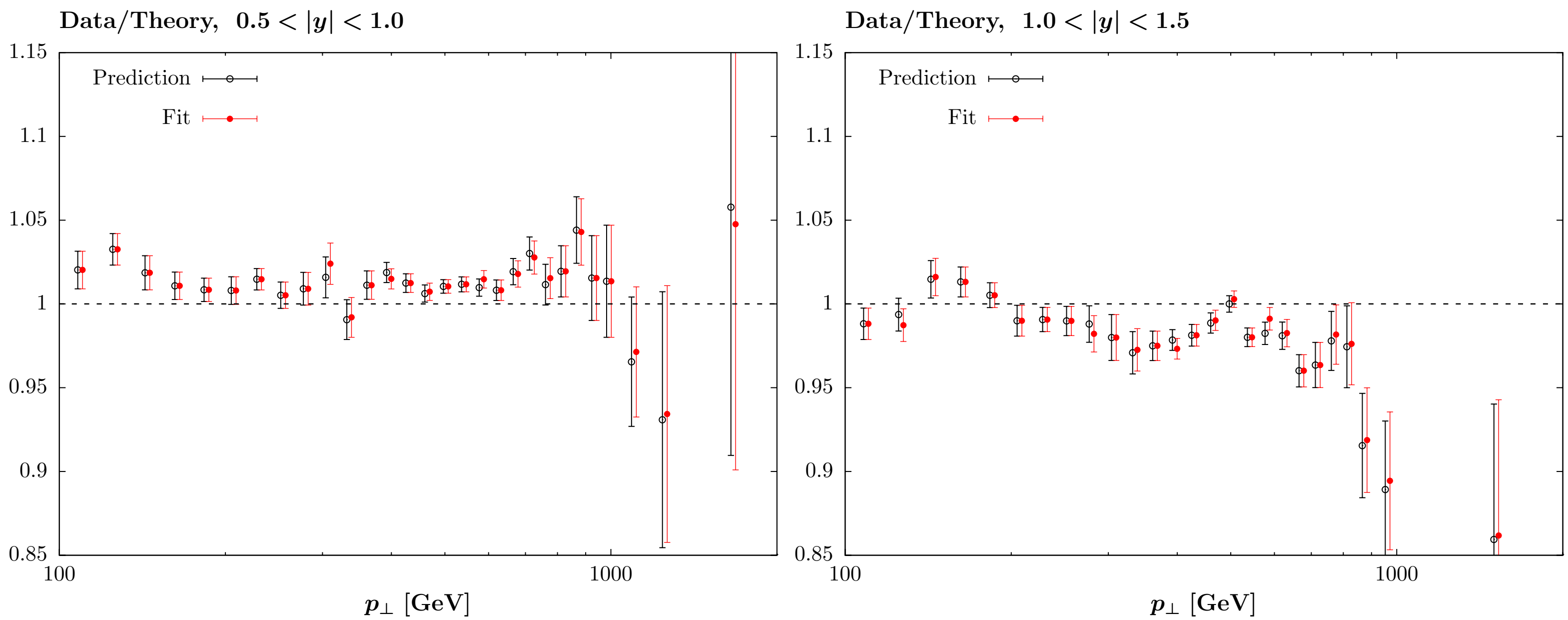
Significant change in shape of $s^+(x, Q^2)$ (note NNLO dimuon correction not included here).

Little change in $\bar{u}(x, Q^2)$. Slightly lower due to generally increased $s^+(x, Q^2)$.

Note – increased uncertainty for $x > 0.6$.

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

Difficulty simultaneously fitting data in all rapidity bins. Mismatch in one bin different in form to neighbouring bin constraining PDFs of similar x, Q^2.



Similar results also seen by other groups.

Qualitative conclusion shown to be independent of jet radius R, choice of scale or inclusion of NNLO corrections.

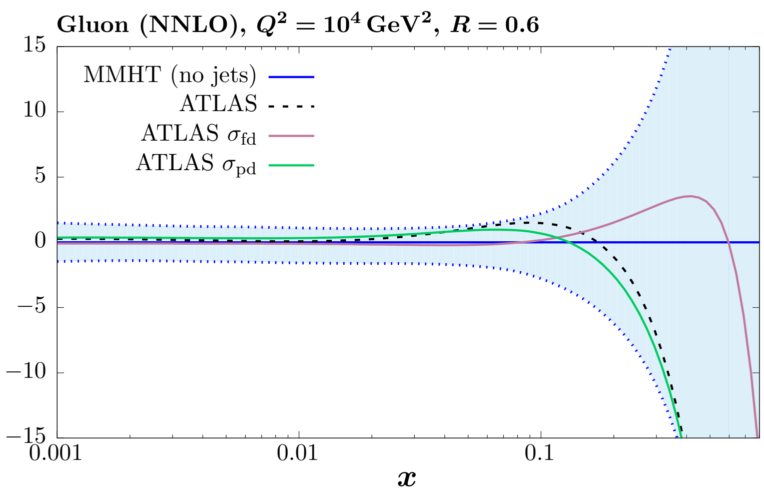
Exercise on decorrelating uncertainties

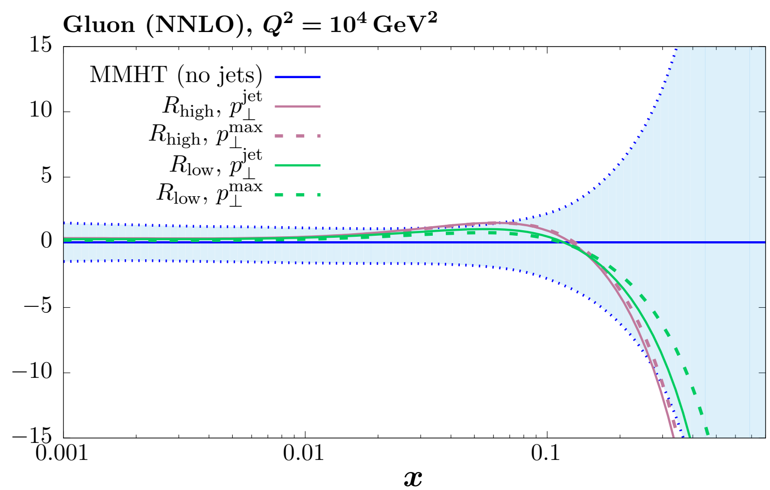
We consider the effect of decorrelating two uncertainty sources, i.e. making them independent between the 6 rapidity bins. More extensive decorrelation study in ATLAS – JHEP 09 020 (2017).

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

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)





Results insensitive to decorrelation. Find softer gluon, reduced uncertainty. Also relatively little sensitivity to scales and jet radius.

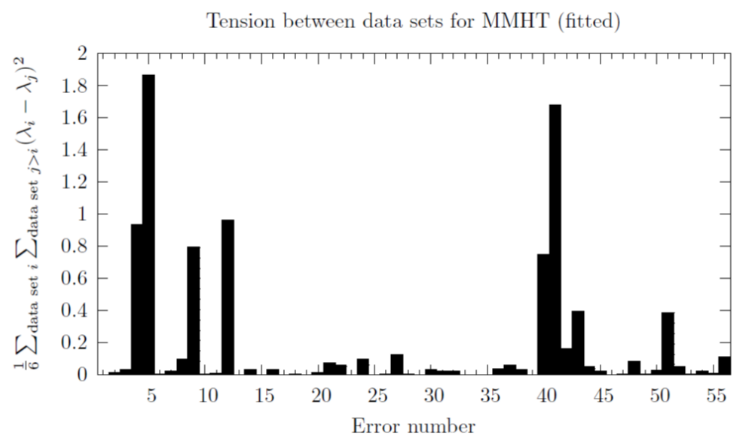
Differential $t\bar{t}$ data. Bailey

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

Distributions differential in $y_t, y_{\bar{t}t}, p_T^t, M_{\bar{t}t}$, and statistical correlations available (not fully implemented yet).

Find similar issues with correlated uncertainties when fitting all together, and fitting $y_t, y_{\bar{t}t}$ individually (seen by MMHT, CT, ATLAS not NNPDF.)

Contribution	Fitted data set(s): p_T	y_t	$y_{t\bar{t}}$	$M_{t\bar{t}}$	All
p_T	0.08				2.38
y_t		1.23			1.84
$y_{t\bar{t}}$			1.09		2.22
$M_{t\bar{t}}$				0.29	1.81
Penalty	0.24	1.83	2.35	0.17	0.88
Total	0.32	3.06	3.44	0.47	2.96



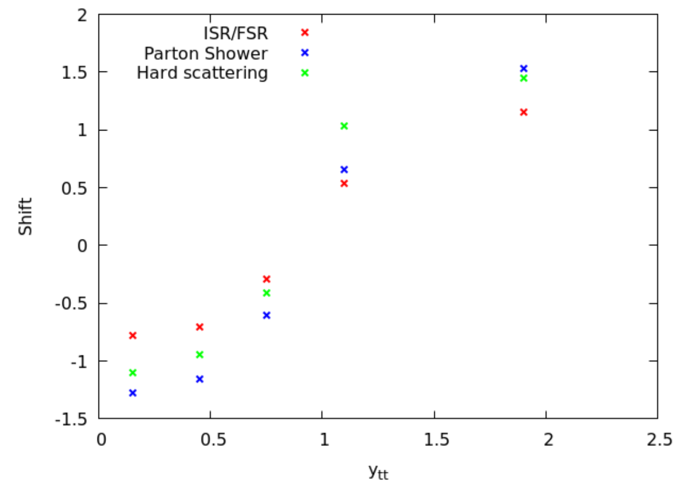
χ^2/N high in simultaneous fit and for rapidity distributions.

Highly sensitive to correlations in 3 large systematics – hard-scattering model, ISR/FSR and parton Shower. All Monte Carlo related.

$y_{\bar{t}t}, y_t$ fits still poor when decorrelating between types of distribution only.

For $y_{\bar{t}t}$ desired shift varies considerably between points.

Try decorrelating for individual distribution and between sets. (Between data sets only actually best χ^2.)



Two types of decorrelation for parton shower.

$$\beta_i^1 = \left(\frac{y_{tt,i} - y_{tt,min}}{y_{tt,max} - y_{tt,min}}\right)\beta_i^{\text{tot}}, \qquad \beta_i^2 = \left[1 - \left(\frac{y_{tt,i} - y_{tt,min}}{y_{tt,max} - y_{tt,min}}\right)\right]^{\frac{1}{2}}\beta_i^{\text{tot}}$$

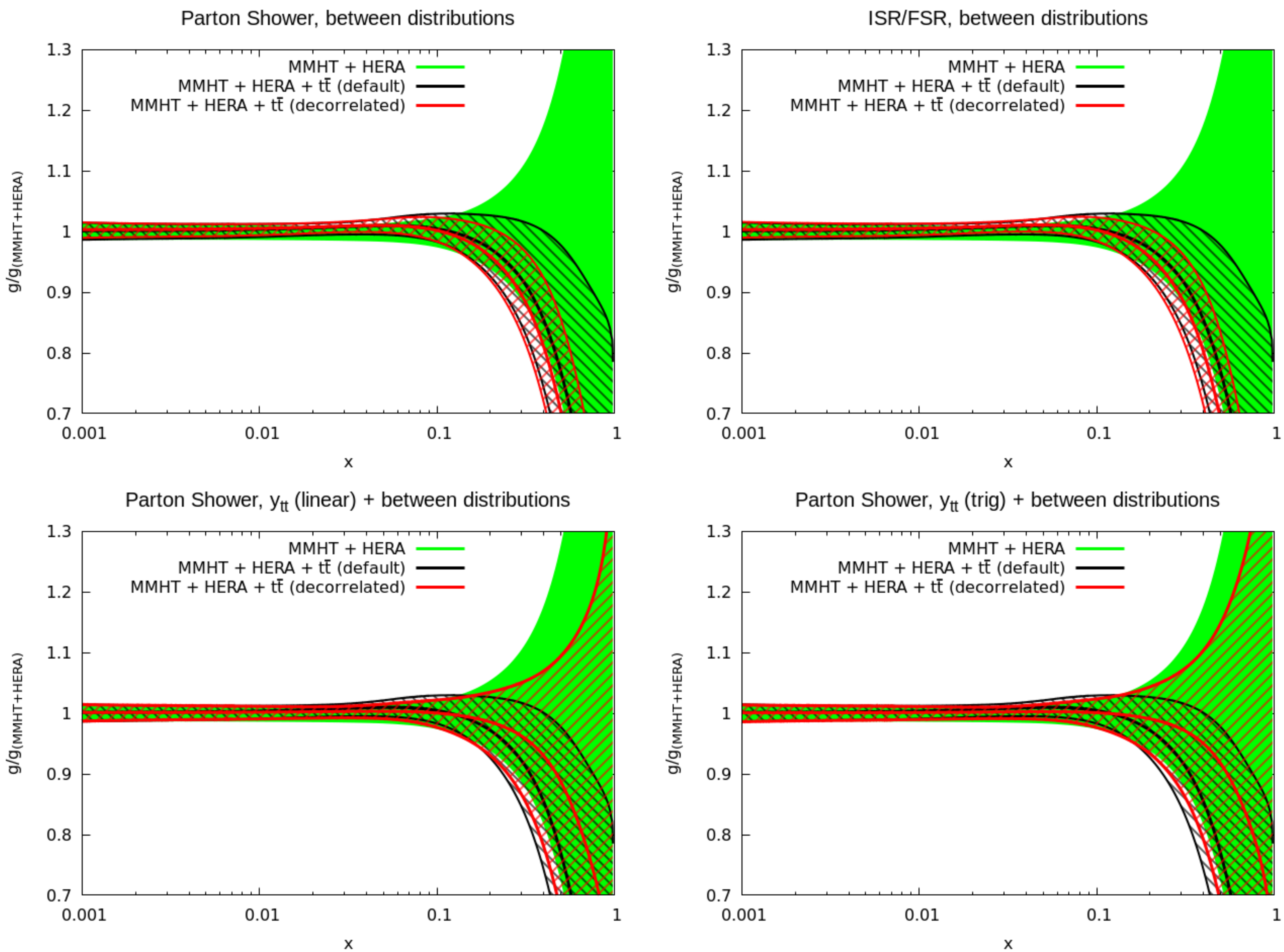
$$\beta_i^1 = \cos\left[\pi\left(\frac{y_{tt,i} - y_{tt,min}}{y_{tt,max} - y_{tt,min}}\right)\right]\beta_i^{\text{tot}}, \qquad \beta_i^2 = \sin\left[\pi\left(\frac{y_{tt,i} - y_{tt,min}}{y_{tt,max} - y_{tt,min}}\right)\right]\beta_i^{\text{tot}}$$

	Before decorrelating	After decorrelating
pT	2.38	0.57
yt	1.84	1.86
ytt	2.21	1.59
mtt	1.81	0.39
pen	0.88	0.83
tot	2.96	1.81

	Before decorrelating	After decorrelating
pT	2.38	0.52
yt	1.84	2.11
ytt	2.21	0.79
mtt	1.81	0.72
pen	0.88	0.72
tot	2.96	1.67

Sine-cosine decorrelation works better.

Results on the gluon moderately independent of decorrelation and method.



Perhaps better justification than jets.

MMHT PDFs with QED corrections – Nathvani

We now base photon input for PDFs at low Q^2 on LUX – much better constraint.

Effect of photon evolution fully incorporated to couple with that of quarks and gluon for both proton and neutron.

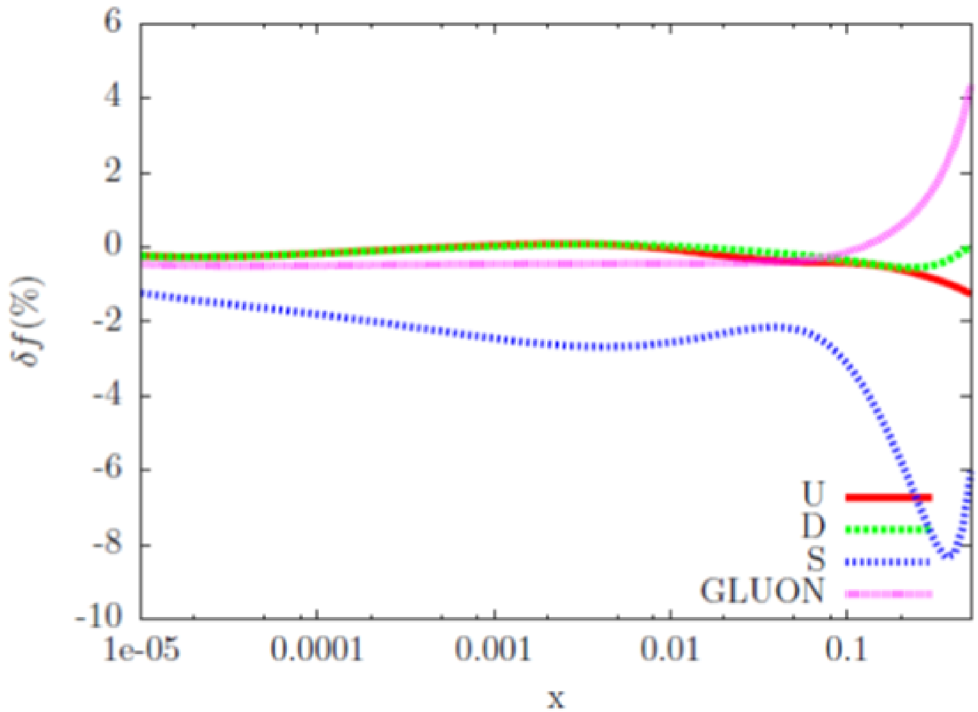
The photon input is defined at $Q_0^2 = 1\mathrm{GeV}^2$, the same as our other PDFs. Input momentum 0.00195.

Input defined by integrating LUX expression up to scale $\mu^2 = Q_0^2$.

PDFs evolve up using DGLAP splitting functions to given order in α_s with $\alpha, \alpha\alpha_S$ and α^2 corrections (De Florian *et al*) included.

In addition the photon receives contributions/corrections from “higher twist” sources above $Q_0^2 = 1\mathrm{GeV}^2$ – elastic, target mass, kinematic cuts, higher twist (renormalon) corrections to $F_2(x, Q^2)$.

Change in PDFs due to refit



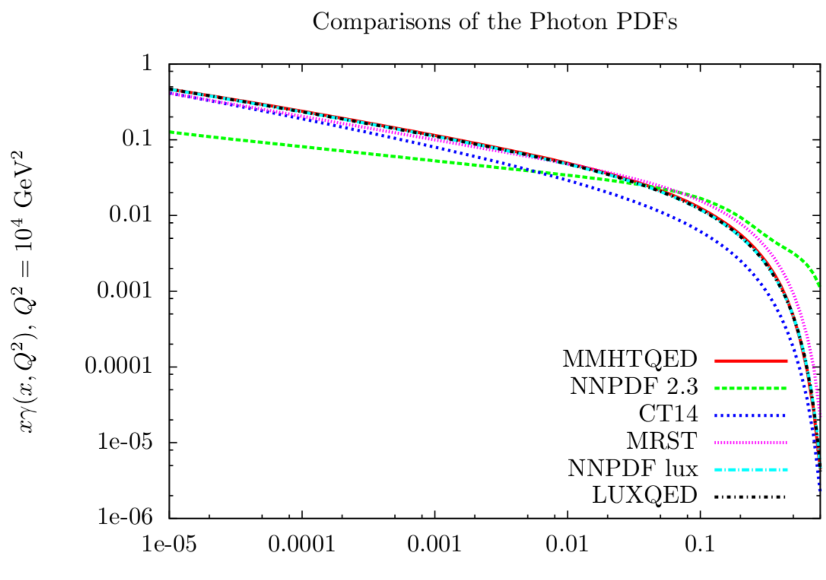
Gluon affected mainly at high x, loss of momentum.

Small x flavour rearrangement in quarks – less strange. Well within uncertainty.

Quarks lose momentum at high x from QED evolution, but reduction in high Q^2 up quark less as compensated for by input.

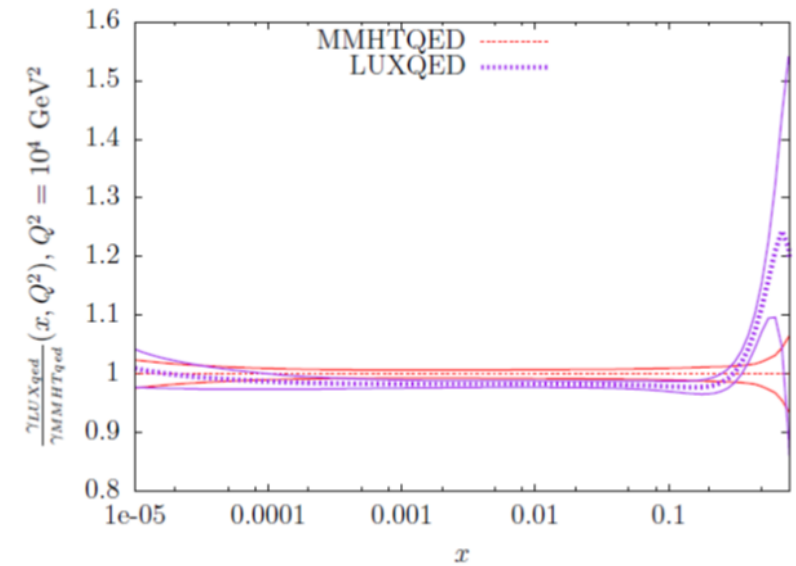
Modern LUX-based PDFs all in excellent agreement with very small uncertainty.

Historical photon PDFs have much more variation.

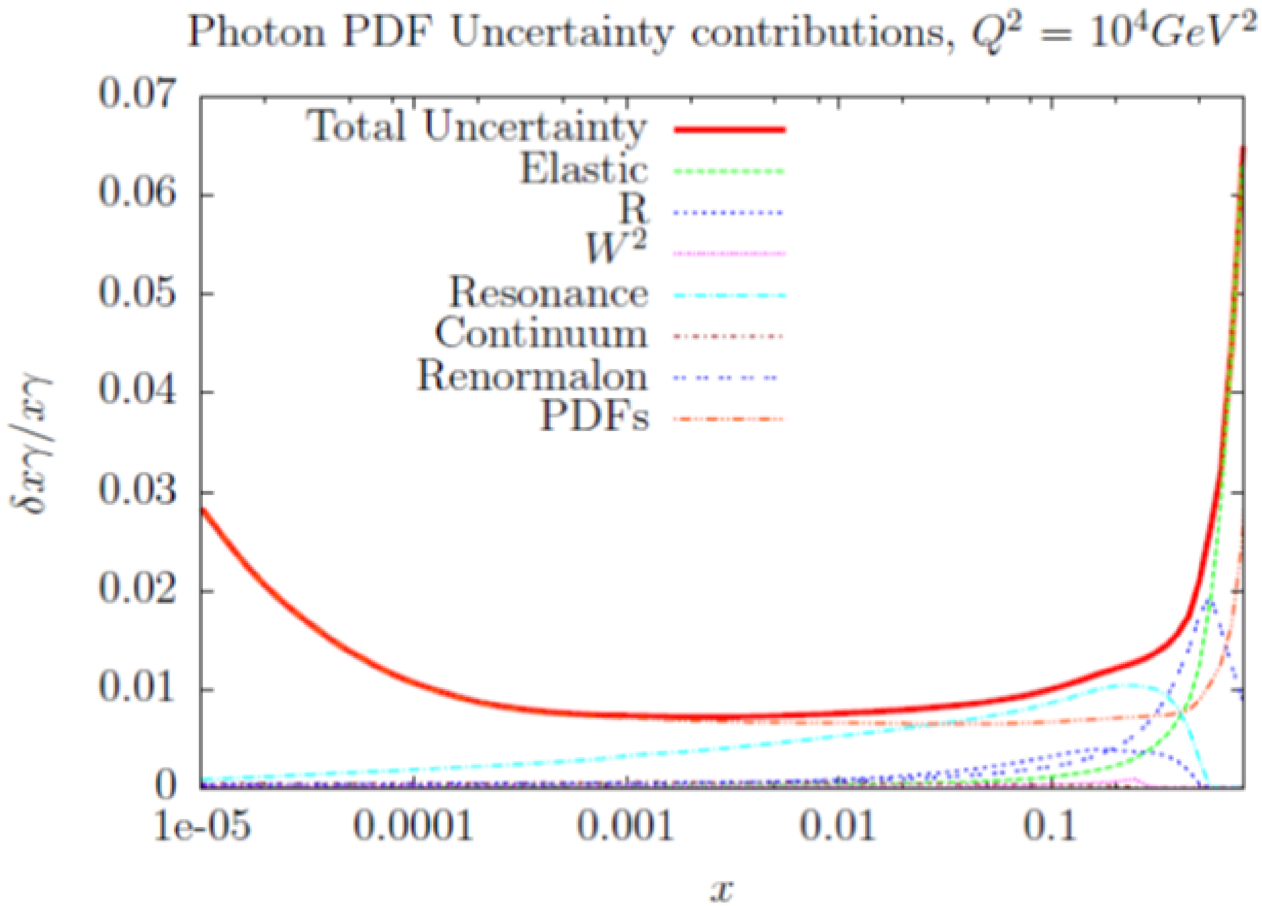


MMHTqed photon largely in good agreement with LUXqed.

Main differences (slightly larger at small x, smaller for $x \sim 0.5$) due to differences in quarks – PDFs not exactly the same as MMHT2014.



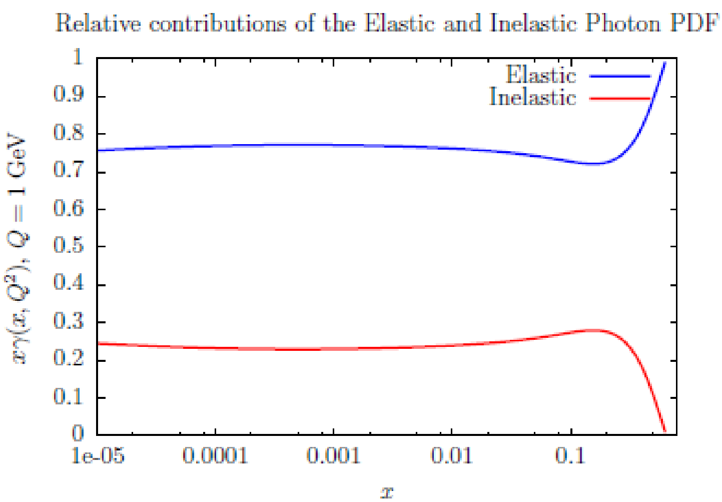
Uncertainties in Photon Distribution

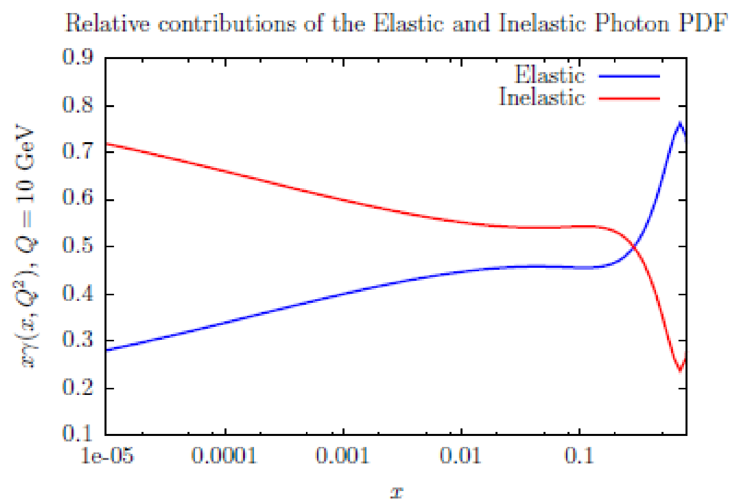


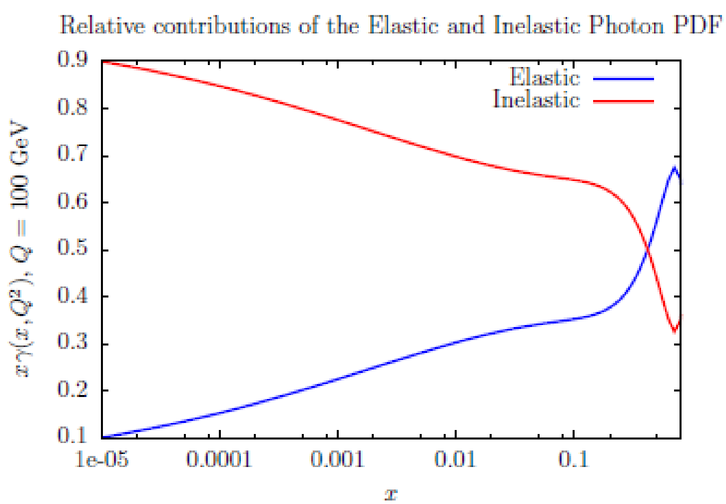
As with LUXqed mainly due to PDFs and elastic contribution and the resonance region.

But also a large contribution at high x from higher twist contributions for $Q^2 > Q_0^2$.

Inelastic and Elastic contributions provided separately.



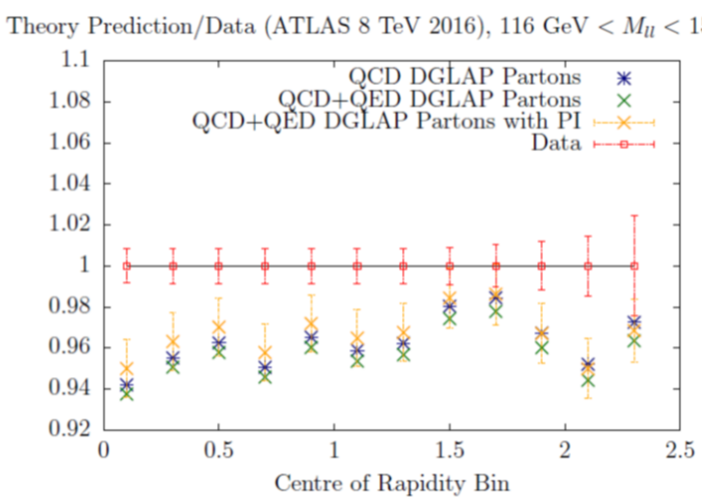


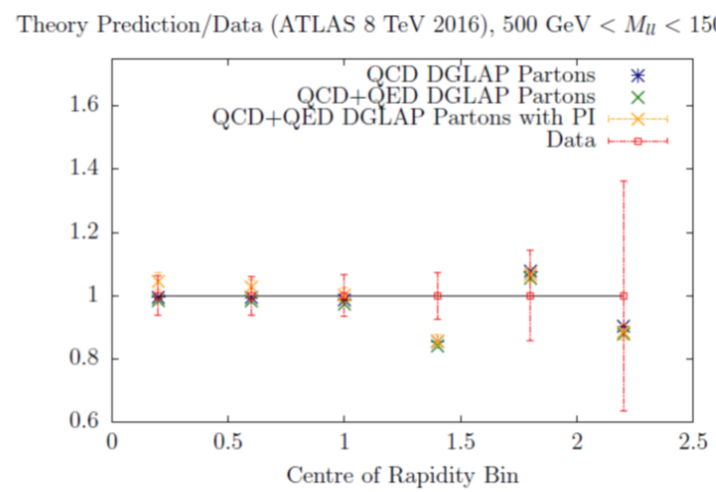


Impact on fit to ATLAS high-mass Drell-Yan data.

This data no longer constrains the photon in any meaningful way. Fit quality including photon contributions $\chi^2/\mathrm{Npts} = 65/48$.

In some bins QED-altered evolution of quarks more important than photon contribution.





Conclusions

LHC data starting to have a very significant impact on PDF extractions.

Theory catching up for precision data, e.g NNLO jets, differential top, ...

Significant changes in strange distribution most likely first major change (uncertainty and central value).

Improvements in parameterisation. Better fit to data - improves some (not all) data tensions and increases some uncertainties in extreme kinematic regions.

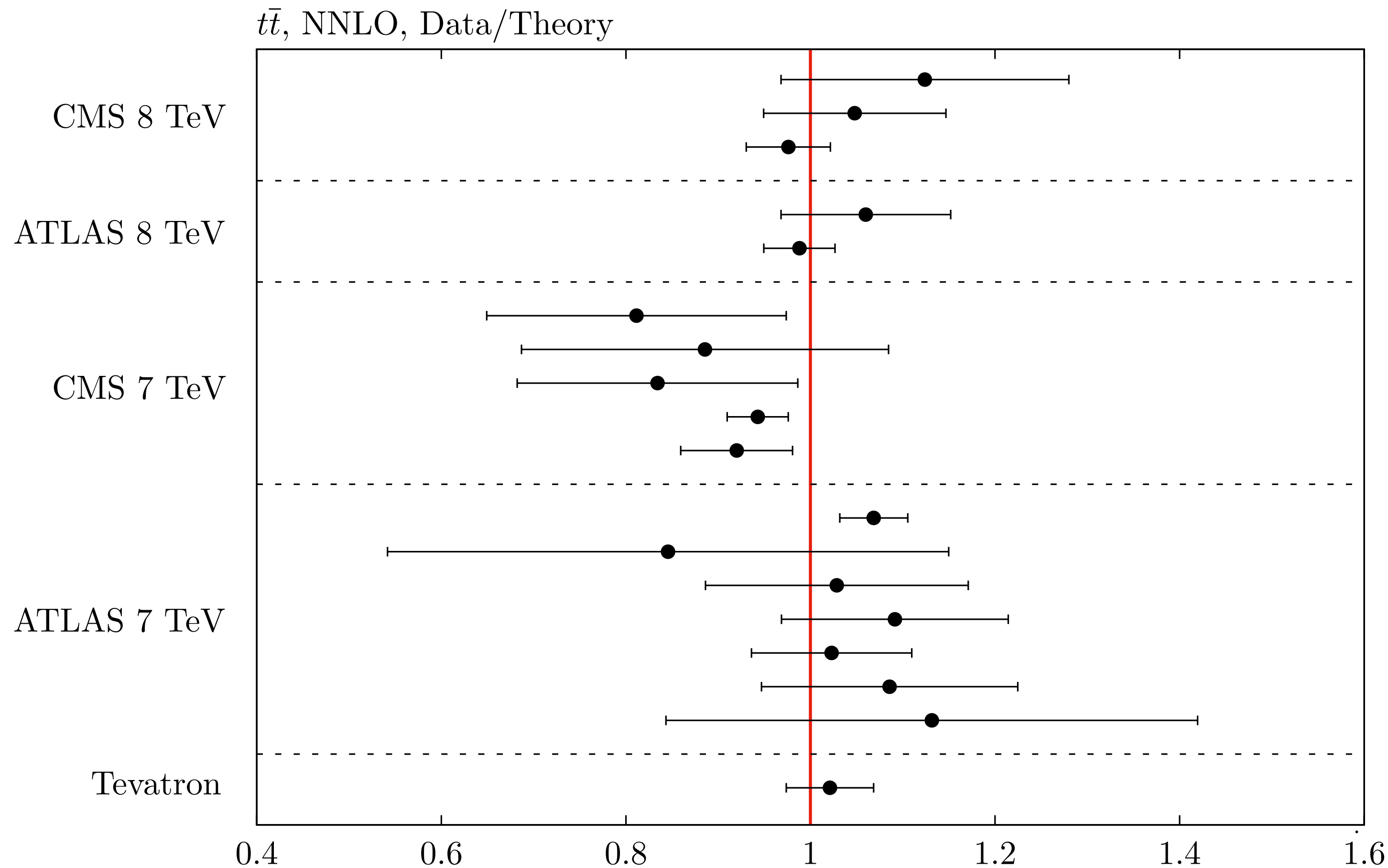
MMHT PDFs with full QED corrections complete and release imminent.

Put everything together (with a few more data sets) for full "MMHT" update.

Precision data and theory causing problems in cases where correlated systematics (which increasingly dominate) are important. Improved interplay between theory/experiment on these seems a priority.

Back-up

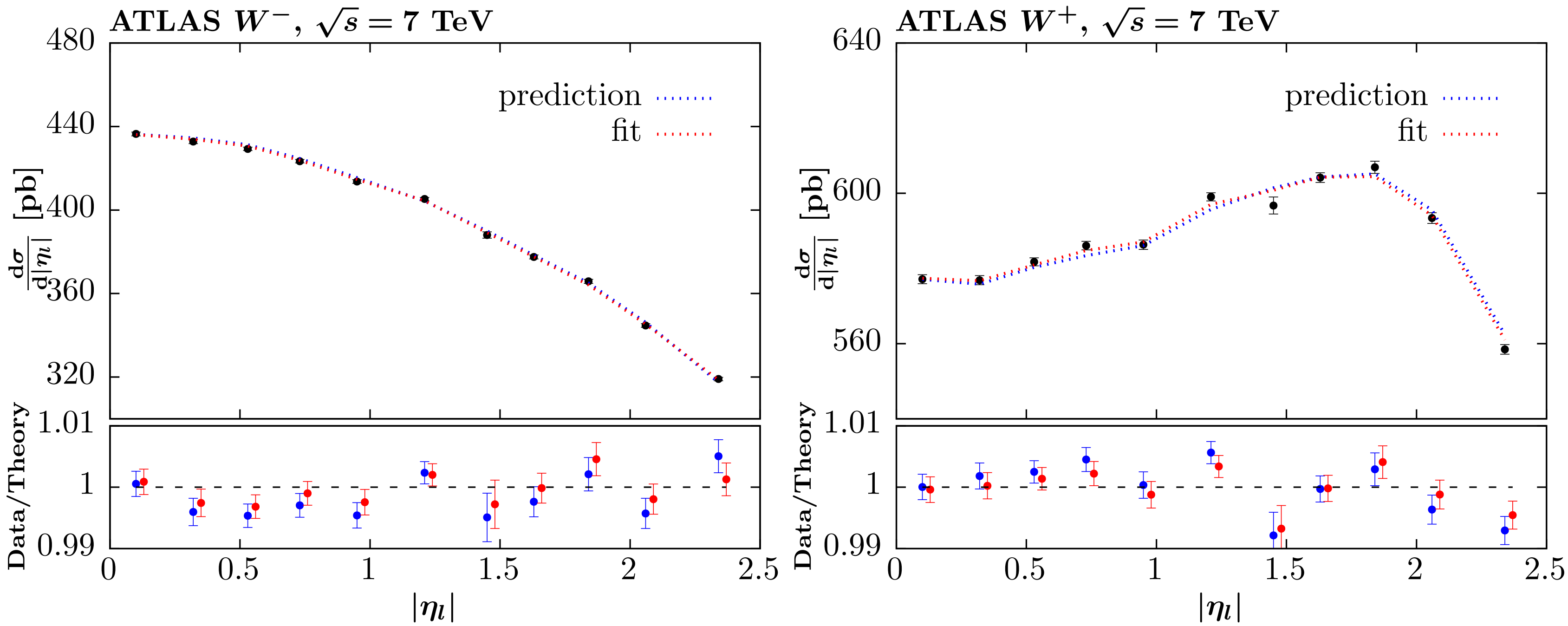
MMHT Included some more up-to-date results on $\sigma_{\bar{t}t}$.



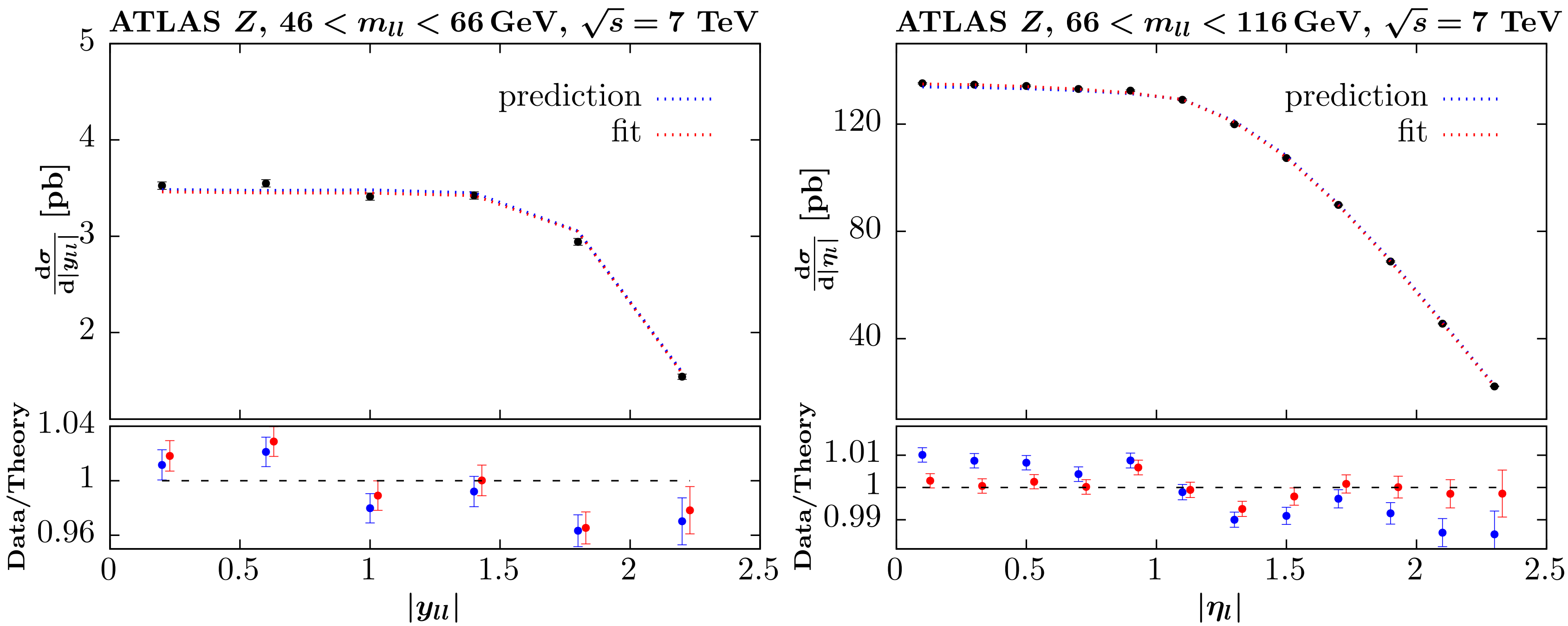
Fit very good and with $\alpha_S(M_Z^2) = 0.118$ the fitted $m_t^{pole} = 173.4$ GeV. At NLO $m_t^{pole} = 170.2$ GeV. MMHT values $m_t^{pole} = 174.2$ GeV and $m_t^{pole} = 171.7$ GeV

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

Prediction and Fit to data



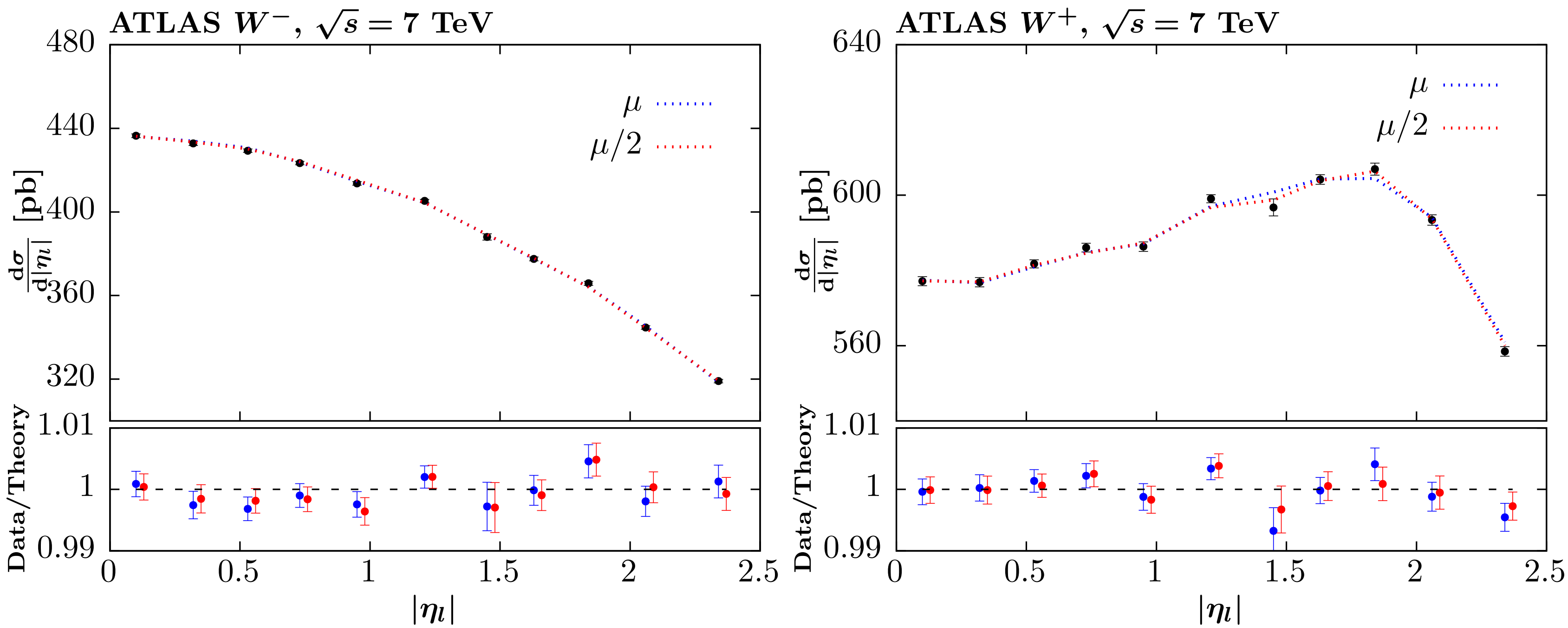
Slight reduction in lower $|\eta|$ W^- required and opposite for W^+.



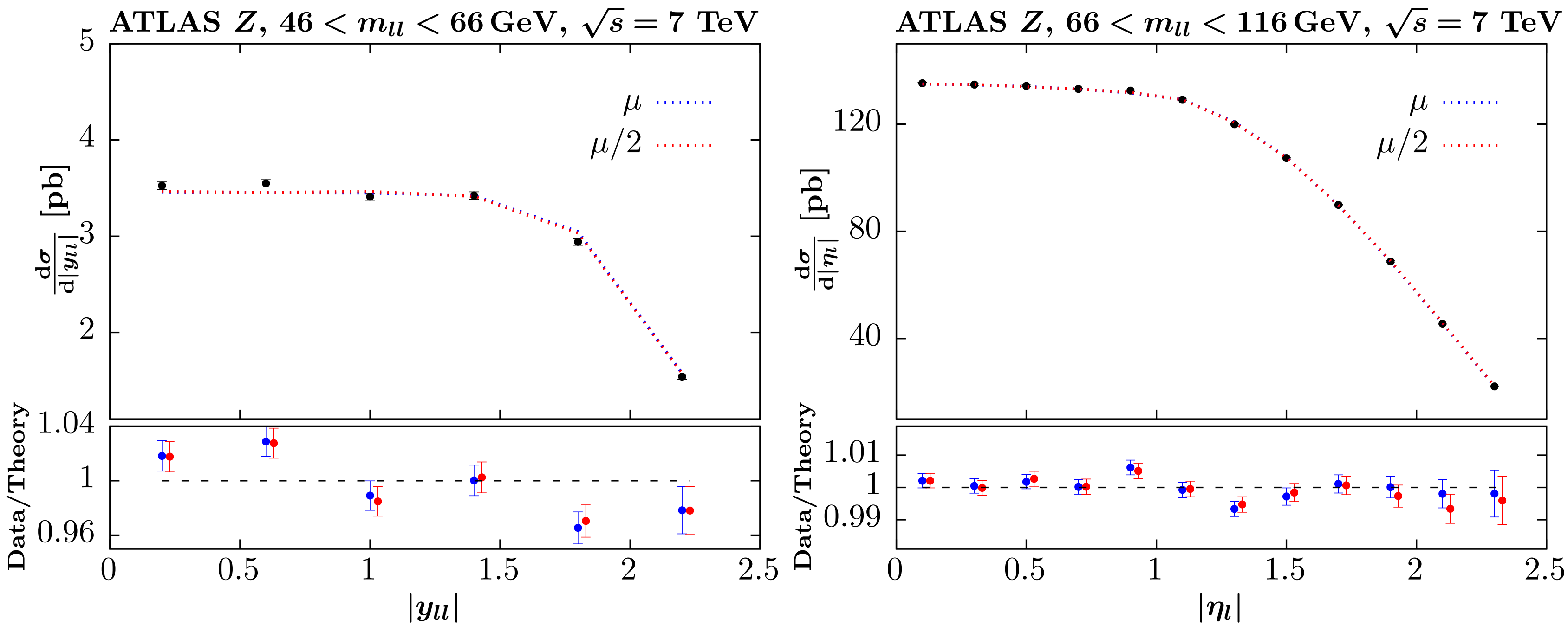
Significant change in shape required for Z production, Higher at low $|\eta|$ and lower at high $|\eta|$

Even with fit difficulty in shape for lower mass data.

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.

Studied by NNPDF - smaller strange enhancement.

PDF set	$R_s(x = 0.023, Q = 1.65$ GeV$)$	$R_s(x = 0.013, Q = M_Z)$
NNPDF3.0	0.47±0.09	0.79±0.04
NNPDF3.1	0.62±0.12	0.83±0.05
NNPDF3.1 collider-only	0.86±0.17	0.94±0.07
NNPDF3.1 HERA + ATLAS W, Z	0.96±0.20	0.98±0.09
ATLAS W, Z 2011 `xFitter` (Ref. [93])	$1.13^{+0.11}_{-0.11}$	-
ATLAS W, Z 2010 `HERAfitter` (Ref. [120])	$1.00^{+0.25}_{-0.28}$ (*)	$1.00^{+0.09}_{-0.10}$ (*)

- **Confirmed the strange symmetric fit** preferred by the ATLAS W,Z 2011 measurements, though we find PDF uncertainties larger by a factor 2
- The **global fit** accommodates both the neutrino data and the ATLAS W,Z 2011 (χ^2_{nutev}**=1.1,** χ^2_{AWZ11}**=2.1**) finding a compromise value for **R_S=0.62+-0.12**
- **Mild tension** in the global fit (1.5-sigma level at most) when simultaneously included neutrino data, CMS W+charm and ATLAS W,Z 2010+2011

$\sigma_W \propto c\bar{s}$, $\sigma_Z \propto g_S * s\bar{s} + g_d * c\bar{c}$, where $g_s > g_c$.

Smaller strange correlated with smaller charm, i.e. σ_Z/σ_W rises with smaller charm.

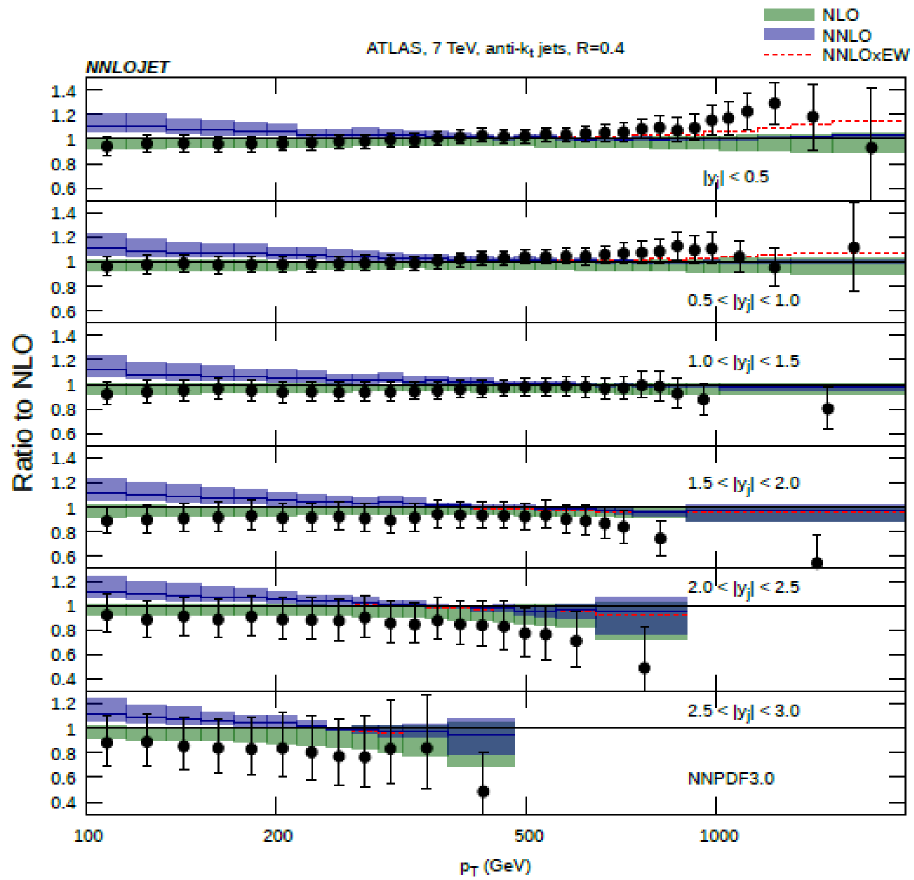
Improved fit to older ATLAS W, Z data with larger m_c evident in MMHT2014. Usually interplay with fitting HERA data.

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.

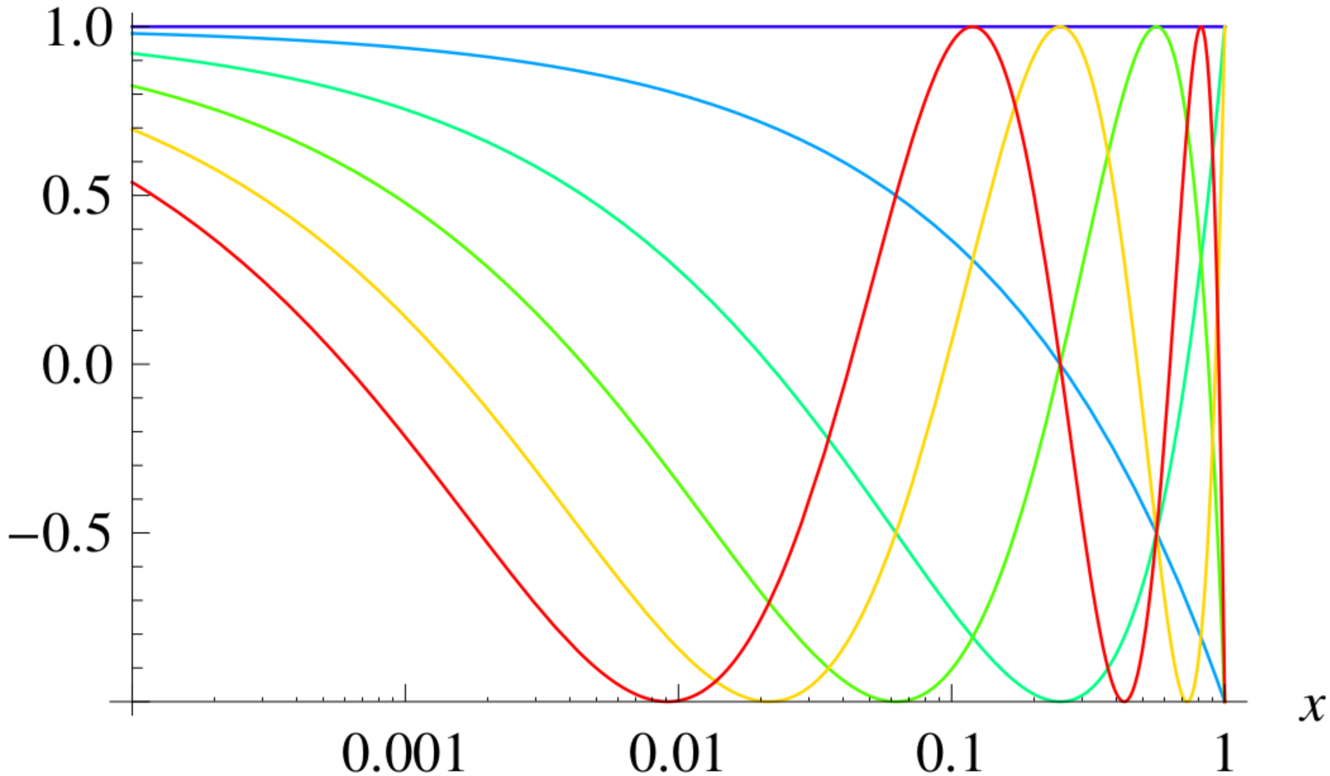
Electroweak corrections to jets different in different bins, but much smaller than systematic effect.



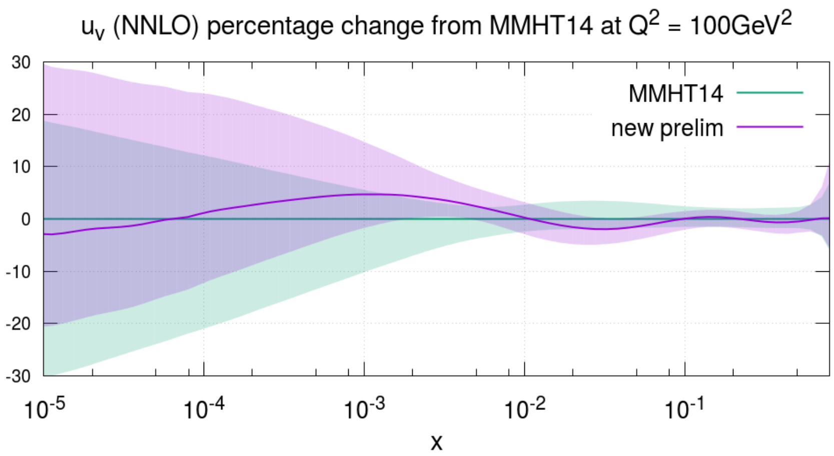
Exact form dependent on R and on scale choice, e.g $\mu = p_{T,1}$ or p_T. Up to 20% at low p_T. Authors now recommend using more physical scale, $\hat{p}_T$ – sum of parton p_T (arXiv:1807.03692), improved convergence criteria properties. Can also resum R dependence Liu, Moch and Ringer – Phys.Rev.Lett. 119 (2017) 212001.

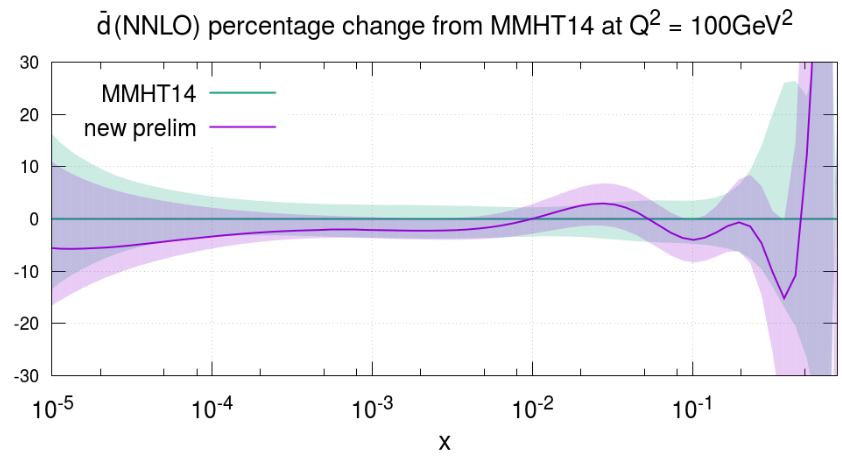
Form of Chebyshev Polynomials.

$$T_i\left(y(x) = 1 - 2\sqrt{x}\right)$$

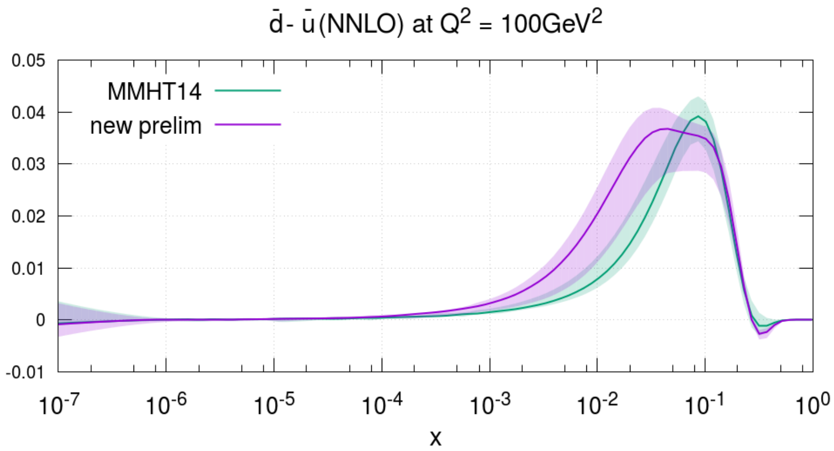


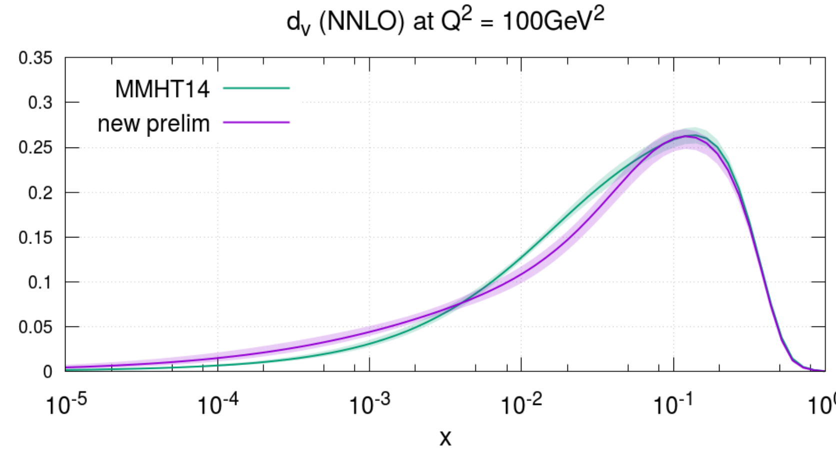
Plots of Plots of $u_v(x,Q^2)$ and $\bar{d}(x,Q^2)$



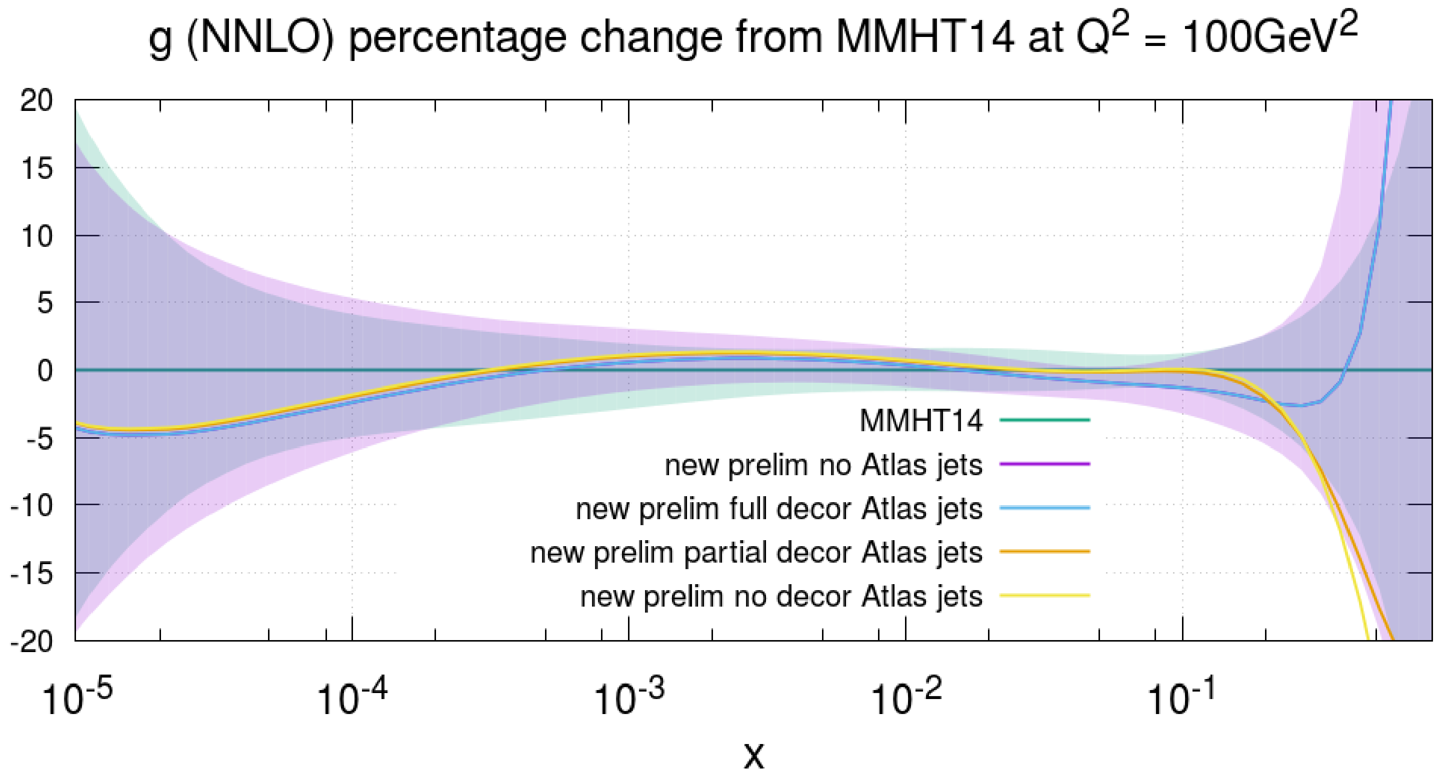


Plots of $d_V(x, Q^2)$ and $\bar{d}(x, Q^2) - \bar{u}(x, Q^2)$.





Impact of ATLAS jet data with extended parameterization



Photon PDF in proton

LUXqed photon PDF (A. Manohar et al., PRL 117, 242002 (2016), JHEP 1712, 046 (2017)) relates photon to structure functions.

LUXqed

- Recent study of arXiv:1607.04266:

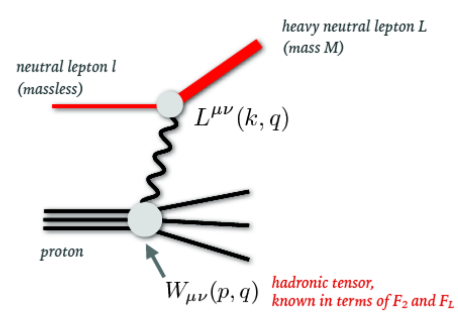
CERN-TH/2016-155

How bright is the proton?
A precise determination of the photon PDF

Aneesh Manohar,[1,2] Paolo Nason,[3] Gavin P. Salam,[2,*] and Giulia Zanderighi[2,4]
[1]Department of Physics, University of California at San Diego, La Jolla, CA 92093, USA
[2]CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland
[3]INFN, Sezione di Milano Bicocca, 20126 Milan, Italy
[4]Rudolf Peierls Centre for Theoretical Physics, 1 Keble Road, University of Oxford, UK

- Show how photon PDF can be expressed in terms of F_2 and F_L. Use measurements of these to provide well constrained LUXqed photon PDF.

$$xf_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{dz}{z}\left\{\int_{\frac{x^2m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2}\alpha^2(Q^2)\left[\left(zp_{\gamma q}(z)+\frac{2x^2m_p^2}{Q^2}\right)F_2(x/z,Q^2) - z^2F_L\left(\frac{x}{z},Q^2\right)\right] - \alpha^2(\mu^2)z^2F_2\left(\frac{x}{z},\mu^2\right)\right\}, \quad (6)$$



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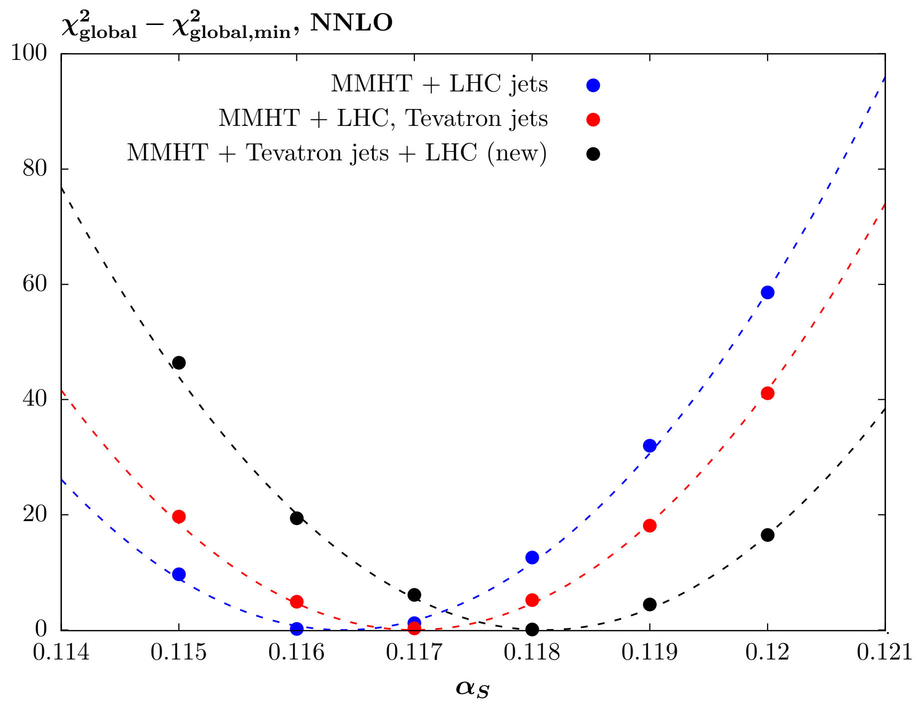
Breakdown into well-known elastic (coherent) contribution and moderately model dependent inelastic part Harland-Lang *et al.* PRD94 (2016) 074008 and earlier studies.

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 also added back $\alpha_S(M_Z^2) = 0.1173$



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