MMHT updates, QED PDFs LHC data and α_S

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

Update results on PDFs with QED corrections, with input photon based on the LUXqed photon. (Manohar *et. al PRL 117, 242002 (2016), JHEP 1712 (2017) 046*.)

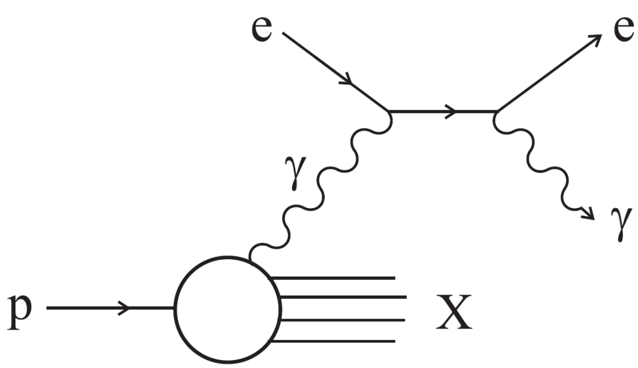
I will briefly summarise final results on studies for new LHC jet collider data at NLO and NNLO.

I will also discuss recent preliminary results on the best-fit $\alpha_S(M_Z^2)$ values.

PDFs with QED corrections

At the level of accuracy we are now approaching it is important to account for electroweak corrections. At the LHC this can be important for many processes ($W, Z, WH, ZH, WW, jets\ldots$).

For a consistent treatment need PDFS which incorporate QED into the evolution, i.e. the inclusion of the photon PDF $\gamma(x, Q^2)$. (A. De Rujula *et. al.* NPB154 (1979) 394, J. Kripfganz and H. Perlt, ZPC41 (1988) 319, J. Blümlein, ZPC47 (1990) 89.)



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

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

Breakdown into well-known elastic (coherent) contribution and moderately model dependent inelastic part Harland-Lang *et al.* PRD94 (2016) 074008. Much better constraint on input.

Put on truly quantitative footing in LUXqed photon PDF (A. Manohar et al., PRL 117, 242002 (2016), arXiv:1708.01256).

LUXqed

- Recent study of arXiv:1607.04266:

CERN-TH/2016-155

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

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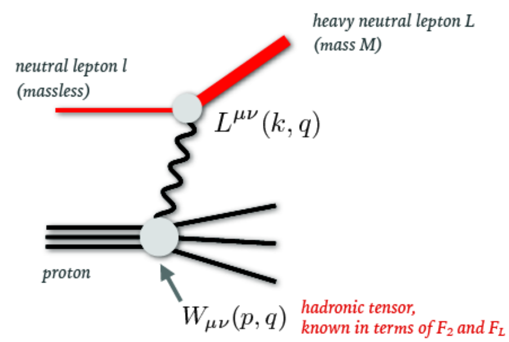
- Show how photon PDF can be expressed in terms of F_2 and F_L. Use measurements of these to provide well constrained `LUXqed` photon PDF.

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



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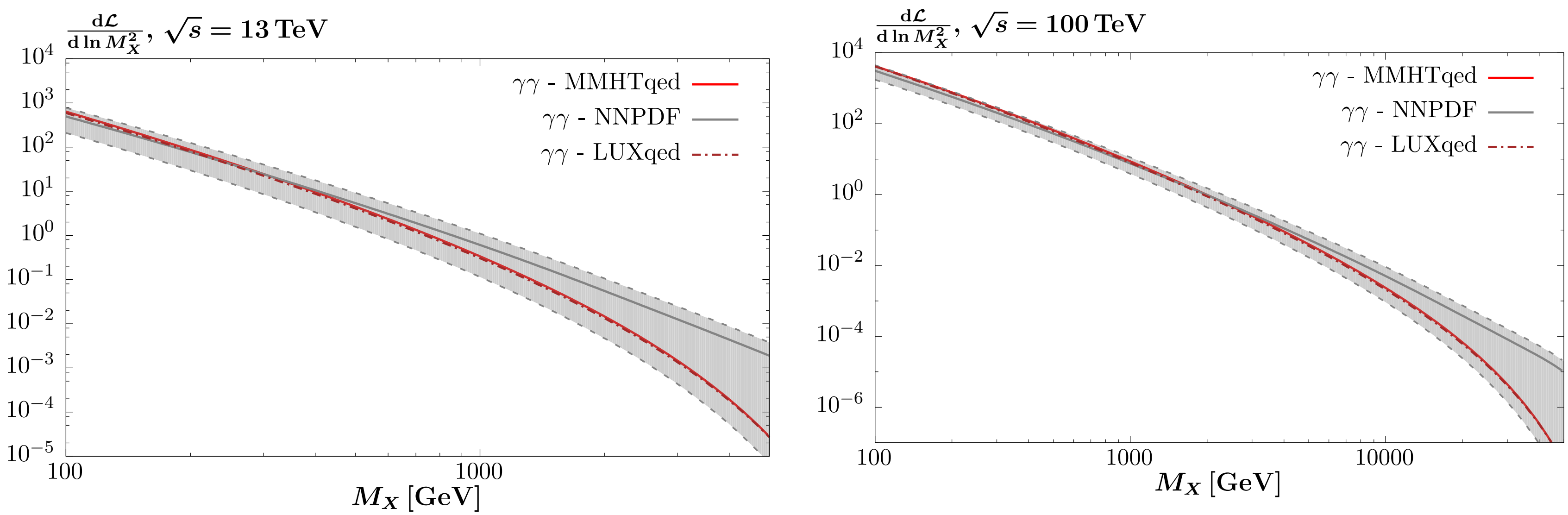
Relates photon to structure functions, and hence precision of at worst a few percent.

MMHT PDFs with QED corrections – Nathvani

We now base photon input for PDFs at low Q^2 on the LUXqed prescription, MMHT photon (Nathvani) very similar to LUXqed.



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

Evolution now included at $\mathcal{O}(\alpha + \alpha_S\alpha + \alpha^2)$.

Details of Photon distribution

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 $\mu^2 = Q_0^2$. Hence contribution up to this scale should be identical. (Minor difference from using μ^2 rather than $\mu^2/(1-z)$ as integral limit, with correction in last term $\propto \alpha \ln(1-z) P_{\gamma q}$.)

Above this all PDFs evolve according to DGLAP evolution up to given order in α_s with all order $\alpha, \alpha\alpha_S$ and α^2 correction to splitting functions included.

In addition the photon receives contributions/corrections from:

– coherent scattering

– terms $\propto x^2 m_p^2/Q^2$ in quark-photon splitting function.

– corrections for higher twist contributions to $F_2(x,Q^2)$ at high x.

– imposition of correct kinematic constraint on photon production

All of these important (only) for (very) high x.

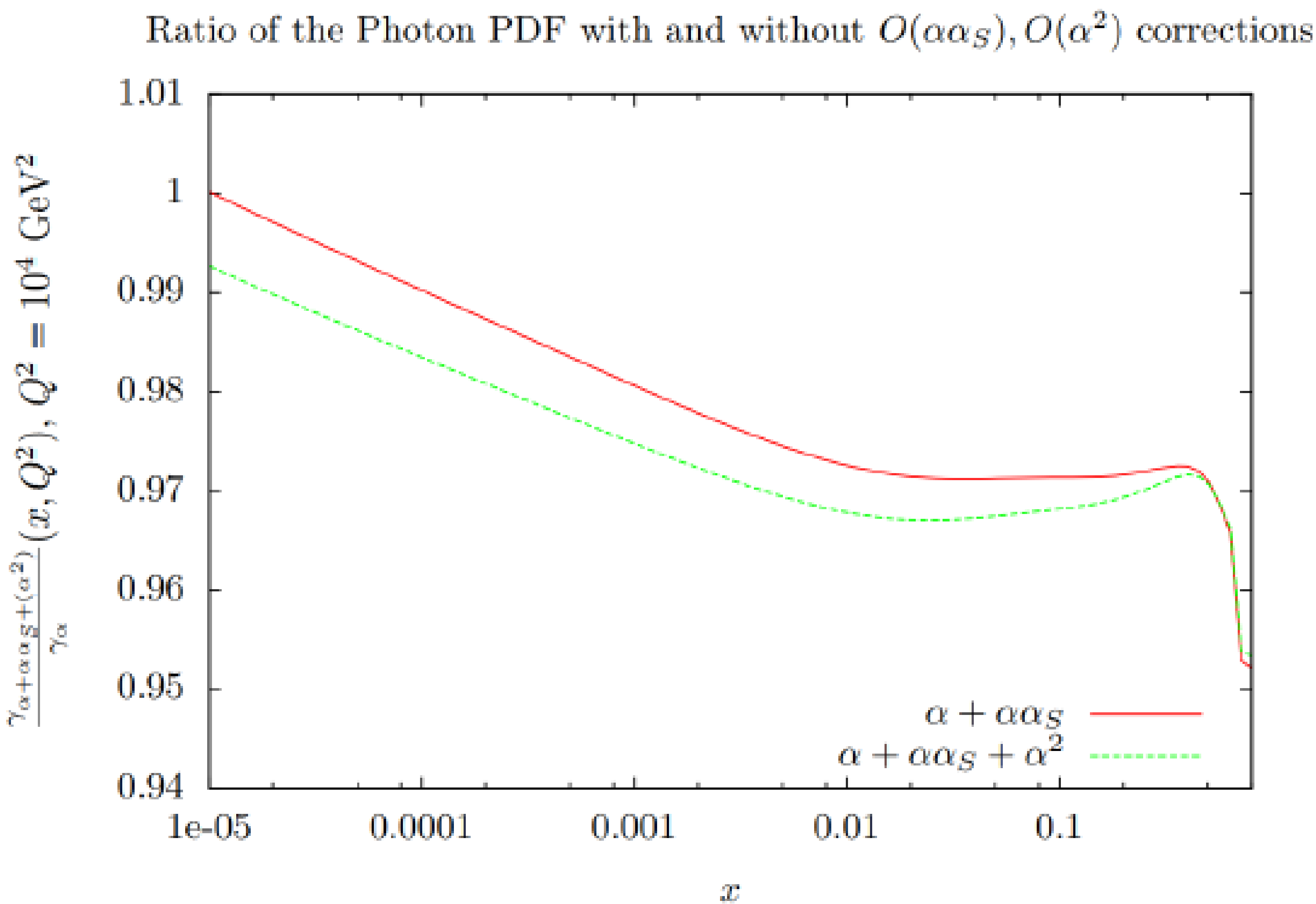
Uncertainties considered on first three.

In principle all contributions beyond standard perturbative evolution and violate momentum conservation in evolution. In practice each generates momentum $< 5 \times 10^{-5}$, kinematic constraint acts in opposite direction.

Total $< 1 \times 10^{-4}$, and therefore negligible in practice.

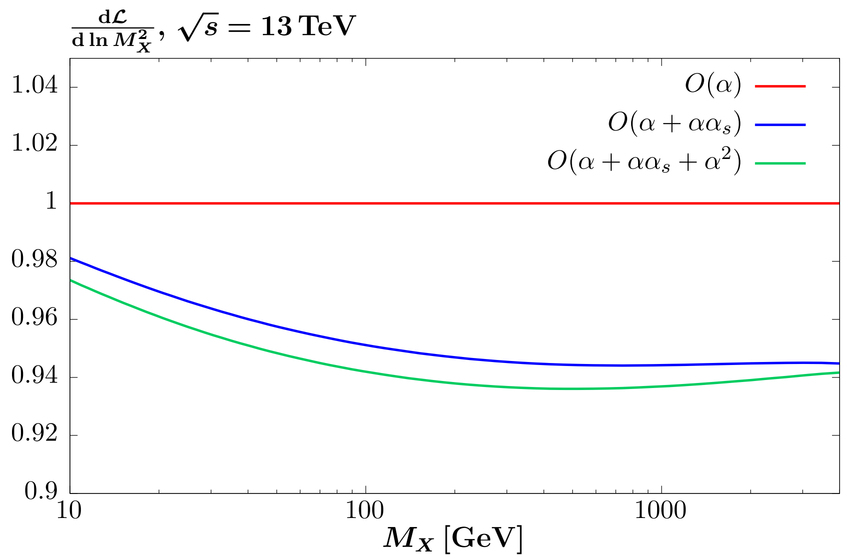
Significant relative effect to high-x photon, but absolute magnitude tiny.

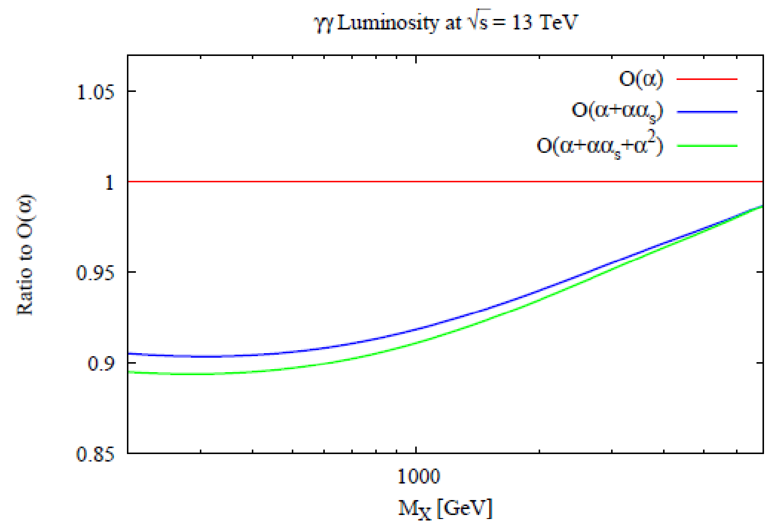
Corrections beyond $\mathcal{O}(\alpha)$.



Corrections negative and larger at high x.

Photon-Photon Luminosity

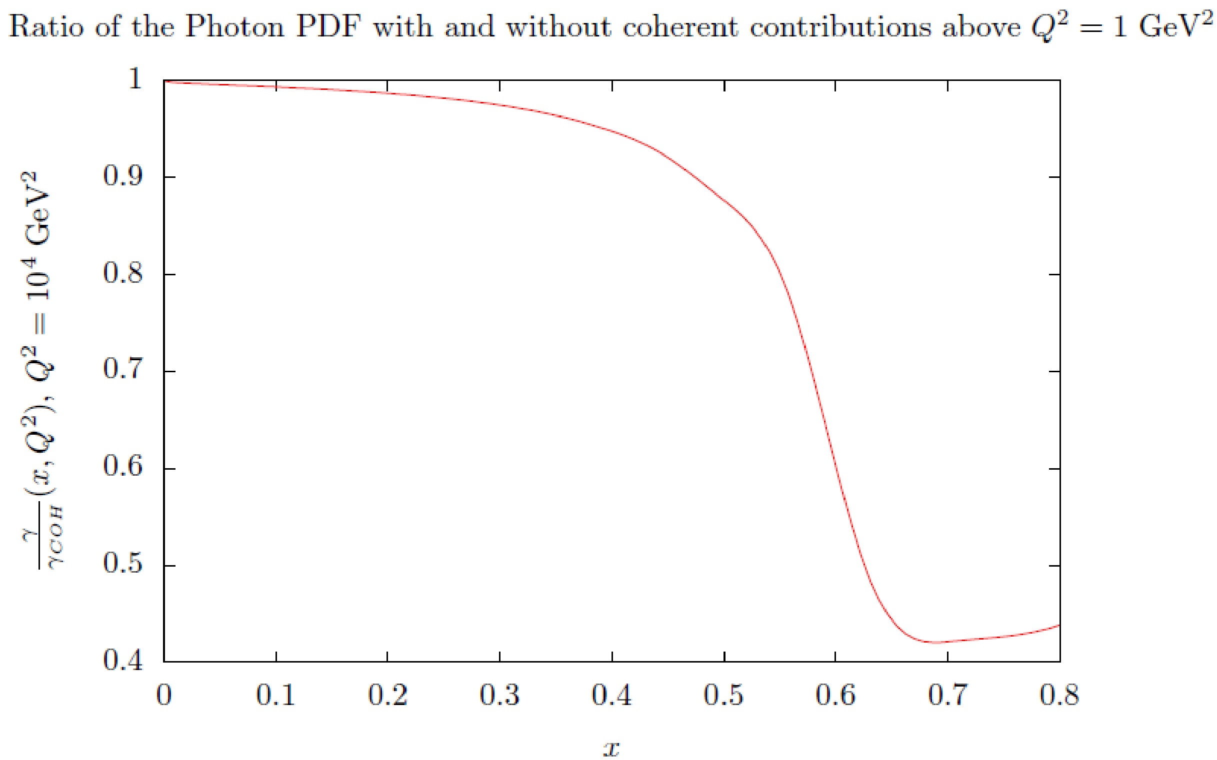




Smaller effect than for NNPDF3.0 photon (right), F. Giuli, *et al*, EPJC77 (2017) 400.

(Note different scale on horizontal axes.)

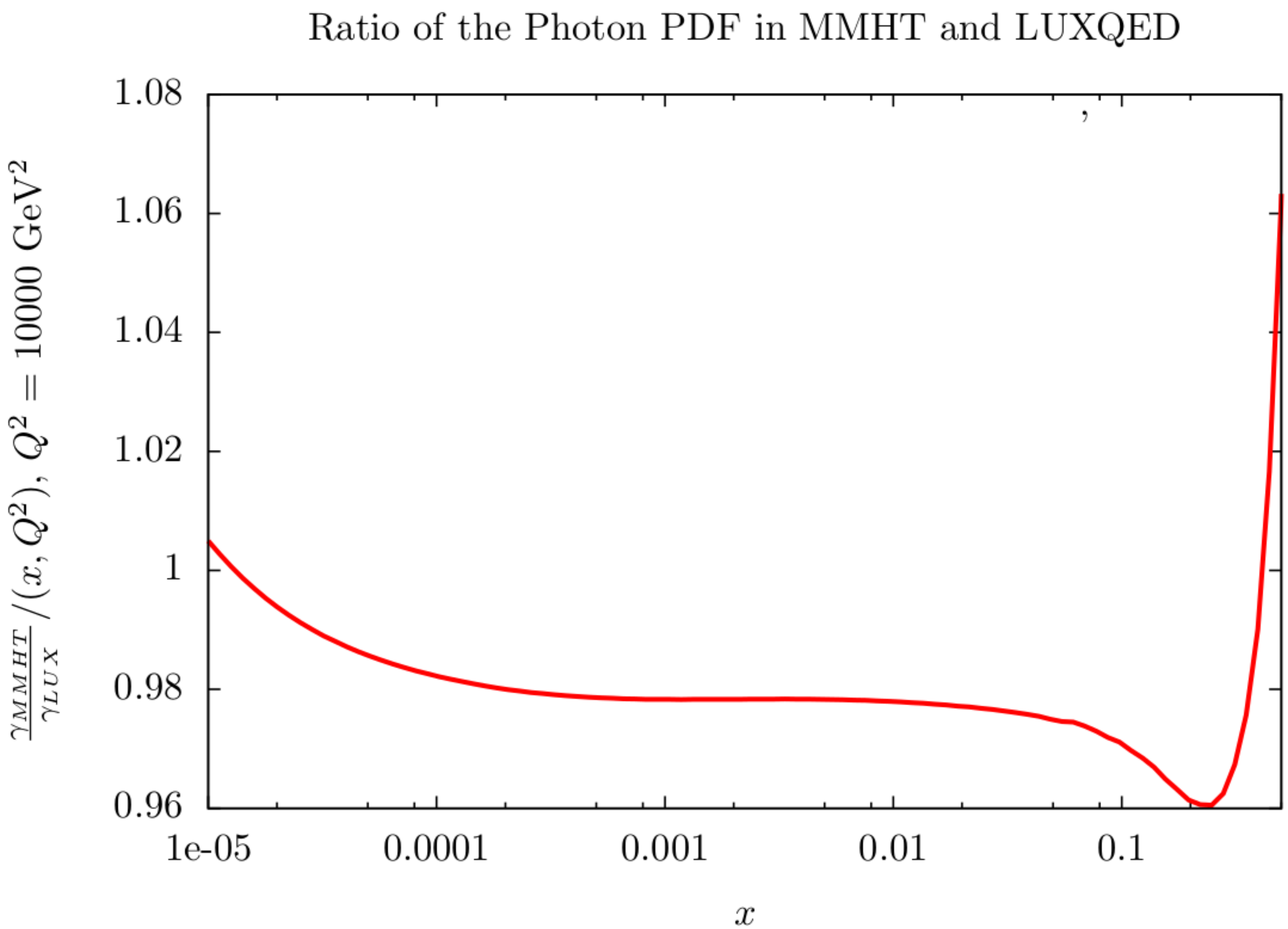
Corrections from coherent contribution and other contributions above input



Coherent contributions above input very significant at very high x.

$m_p x^2/Q^2$ correction significant but at most a few percent. Higher twist and kinematic constraint cancel quite significantly – max few percent effect.

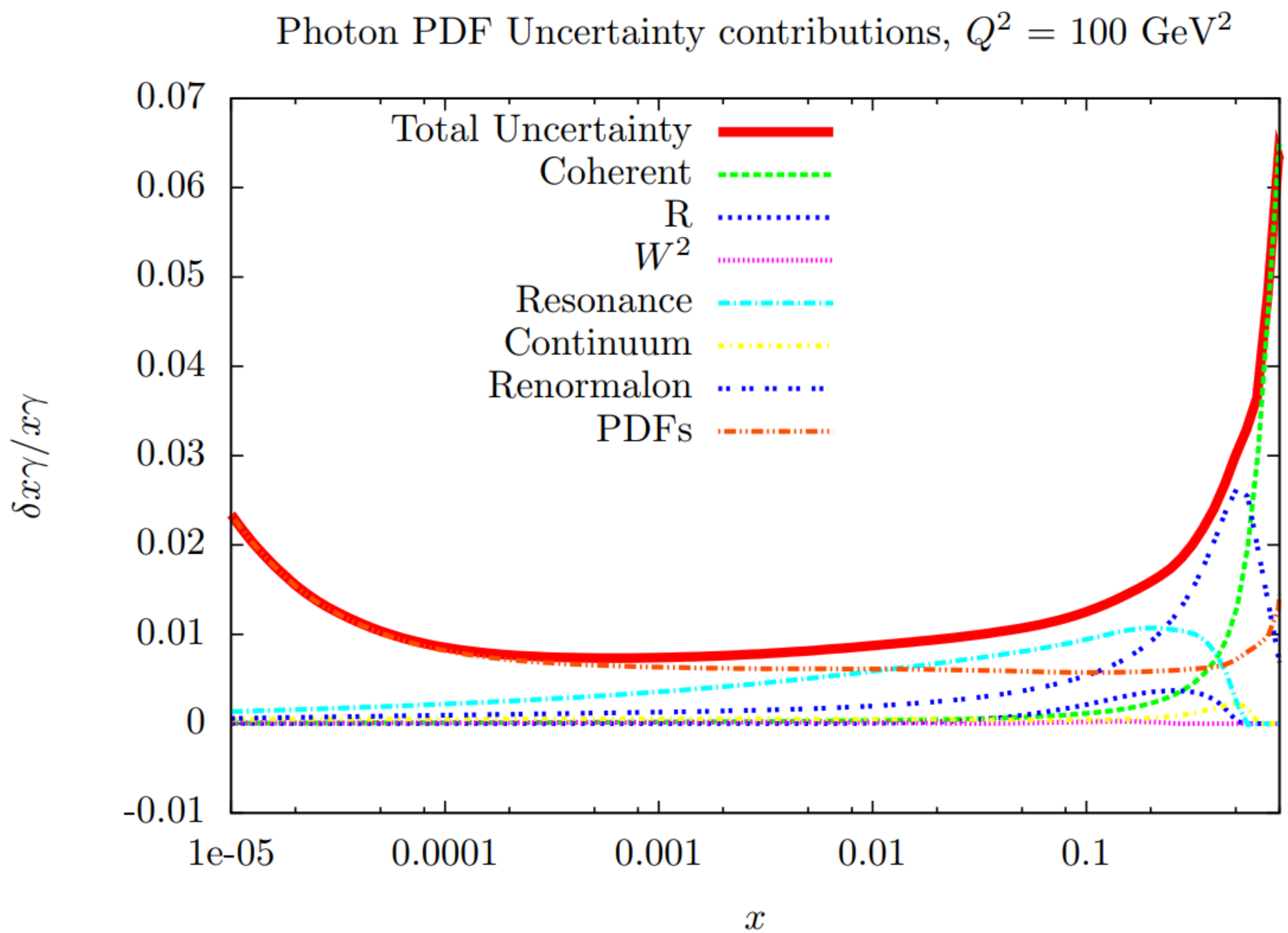
Comparison to LUXqed photon.



Only significant difference at very high x where uncertainties getting large .

At general x main reason for differences just due to different overall PDFs at $1-2\%$ level.

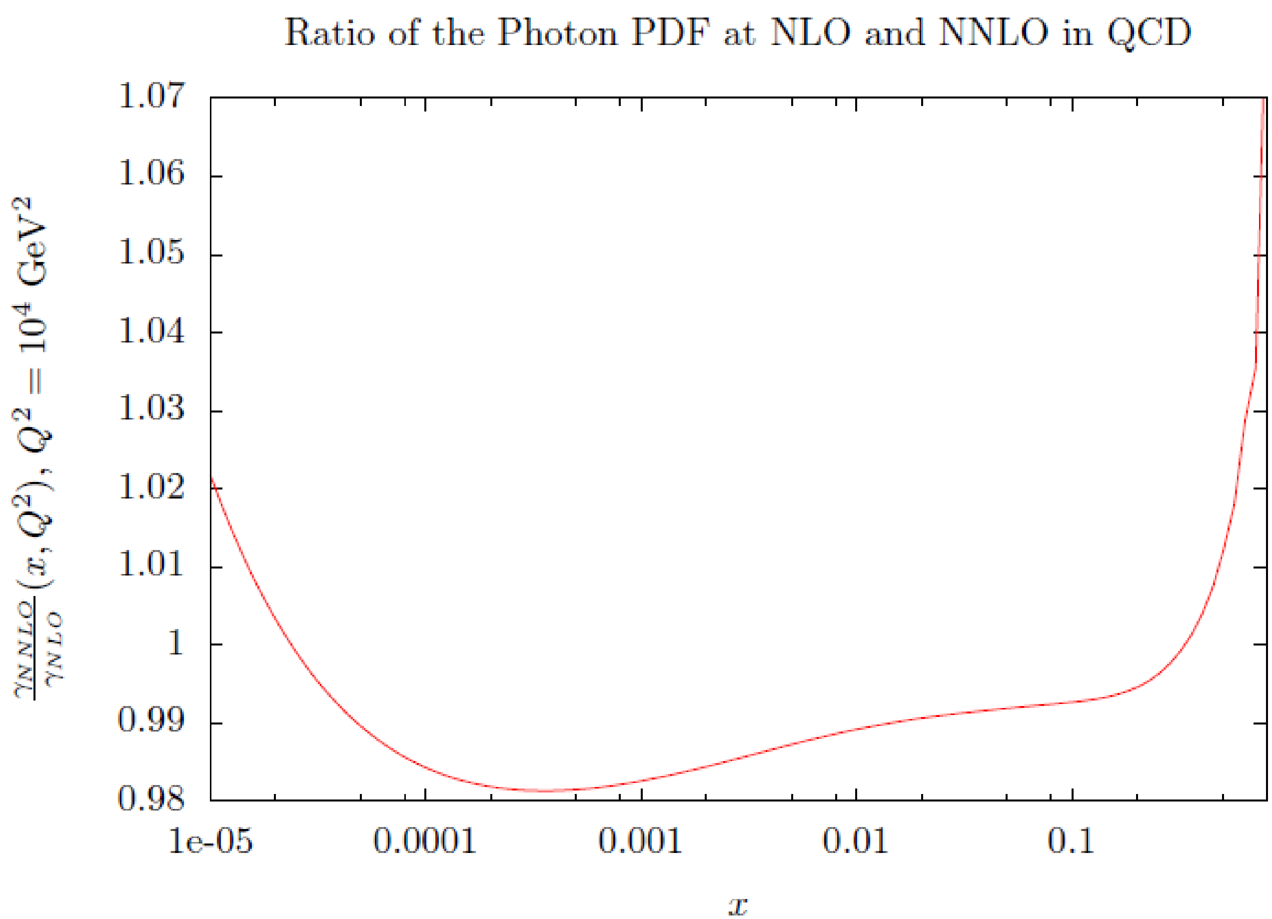
Uncertainties



Uncertainties from a variety of sources, not quite the same as LUX.

Overall uncertainty broadly compatible.

Change from QCD order



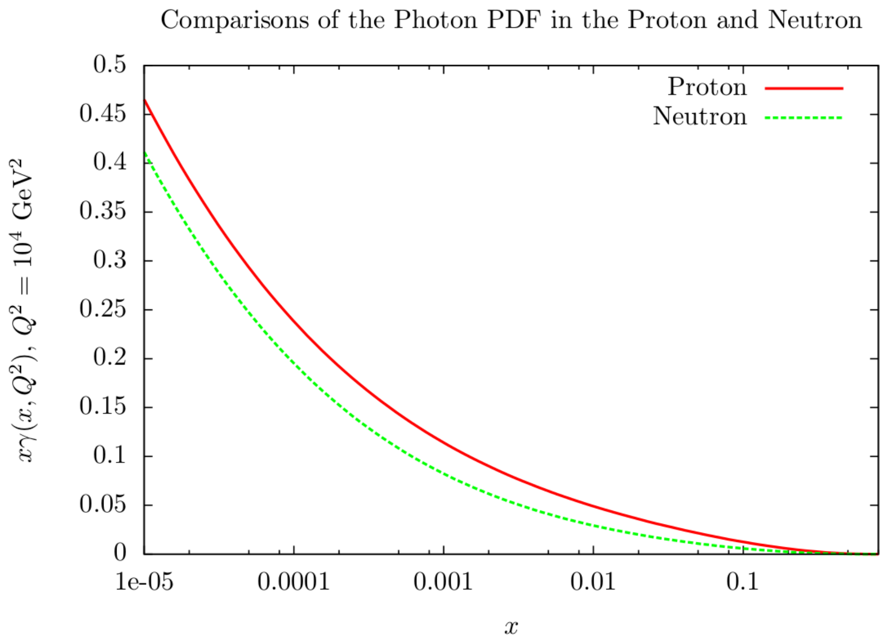
Reflects differences in quarks between orders.

Inputs for the Neutron

For the coherent part the form factors for the neutron are used. The data is not very precise and gives a very small contribution.

For the incoherent part the neutron approximation is achieved by assuming that the ratio of the structure functions is well approximated by the ratio of partons at input between the neutron and protons

Consequently the neutron input photon carries less momentum than for the proton. $\int_0^1 dx\, x(\gamma^p - \gamma^n) \approx 0.0015$



Differences at small x wash out at higher Q^2.

QED corrected PDF fit

As well as correcting evolution, corrections to DIS coefficient functions at $\mathcal{O}(\alpha)$ added.

At NLO $\Delta\chi^2 = 28$ before refit $\rightarrow$ $\Delta\chi^2 = 17$ after refit.

At NNLO $\Delta\chi^2 = 29$ before refit $\rightarrow$ $\Delta\chi^2 = 13$ after refit.

Increased evolution speed of quarks at high x leads to $\Delta\chi^2 = 5$ for BCDMS data.

At NLO some effect in NMC and HERA CC data as well.

At NNLO no significant change in any other data set.

Change in PDFs due to refit

Without refit at input the inclusion of the photon is all taken account of in the gluon since a gluon parameter is fixed from the momentum sum rule. Affects small x.

Quarks decrease with evolution at high x due to photon radiation.

After refit -

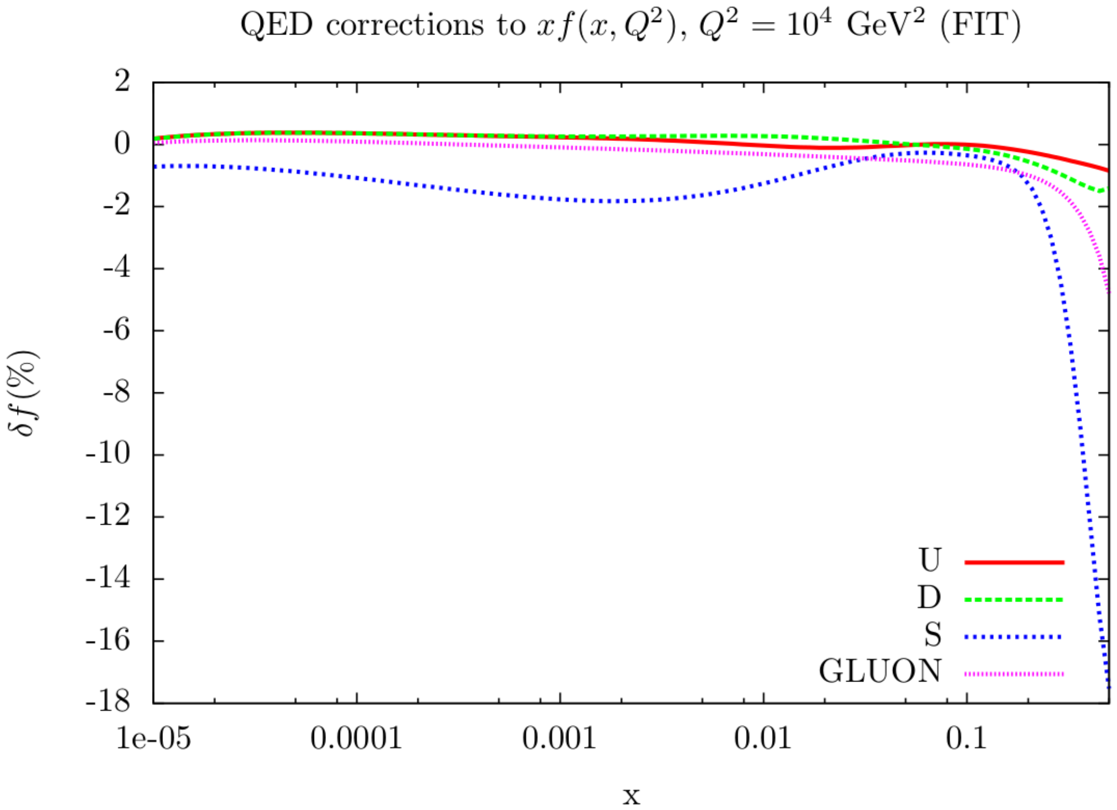
Large x u_V increased at input since loss greater due to extra photon radiation. $\rightarrow$ larger d_V in neutron.

d_V hardly changes at input (less photon radiation). In fact marginally less momentum.

Sea quarks carry slightly more momentum.

Loss of gluon momentum in QED corrected PDFs after refit > 1.5 times more than input momentum carried by photon.

Photon changed by generally $<< 1\%$.



Differences induced by QED altered significantly in refit.

Gluon affected more widely over x, less at small x.

Small x flavour rearrangement in quarks – less strange.

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

Inclusion of full $7\ \mathrm{TeV}$ ATLAS, CMS jet data.

Initial fit to high luminosity ATLAS $7\ \mathrm{TeV}$ inclusive jet data (JHEP 02 (2015) 153) taking as default $R = 0.4$ and $\mu = p_{T,1}$ and work at NLO.

Prediction at NLO gives $\chi^2/N_{pts} = 413.1/140$.

Refit gives improvement only to $\chi^2/N_{pts} = 400.4/140$.

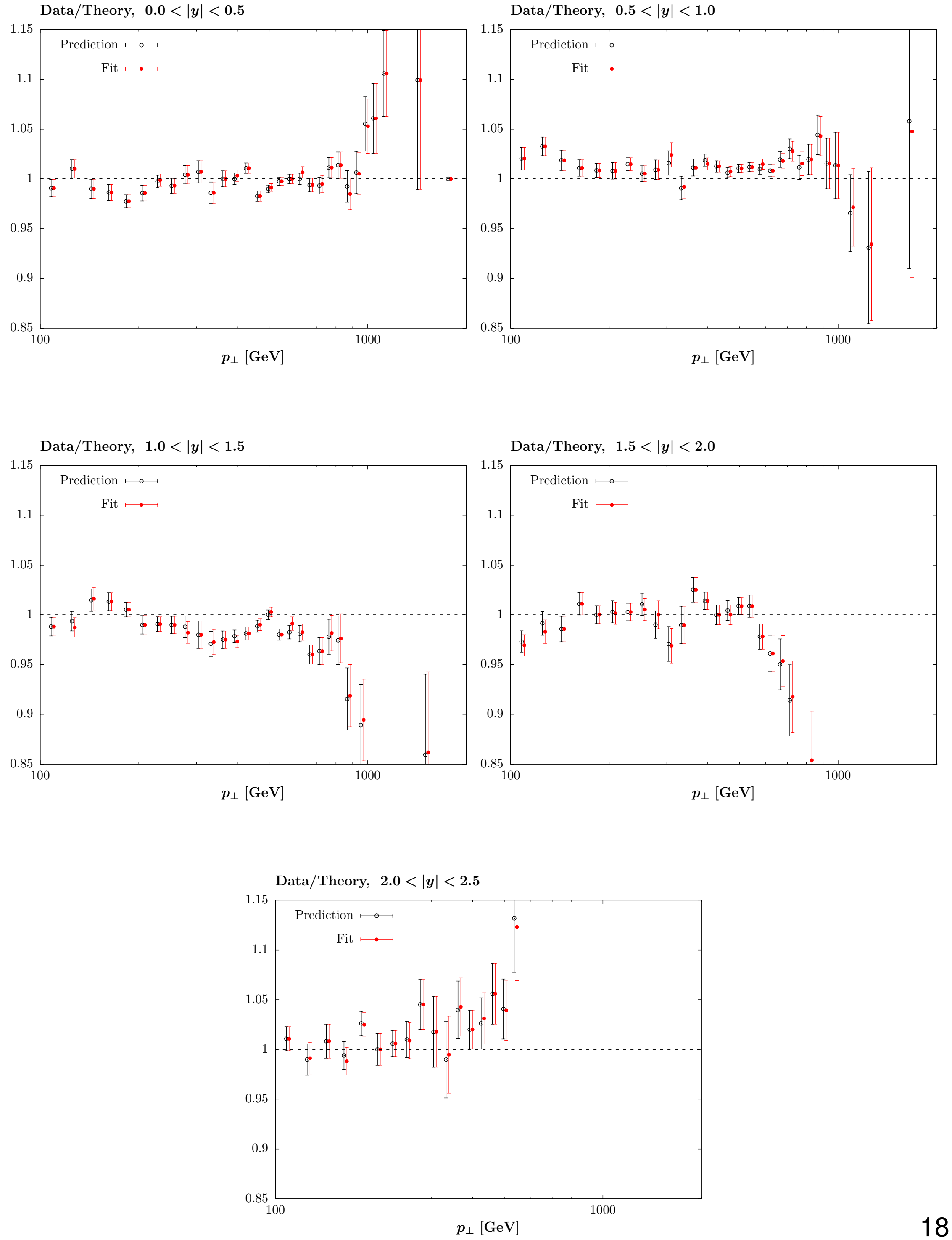
Deterioration in other data $\Delta\chi^2 \sim 3$, so no strong tensions.

Cannot simultaneously fit 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, though χ^2 often a bit better.

Cannot simultaneously fit well 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

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	1.58	2.36	1.27

Table 1: χ^2 per number of data points ($N_{\rm pts} = 140$) for fit to ATLAS jets data [23], with the default systematic error treatment ('full') and with certain errors, defined in the text, decorrelated between jet rapidity bins.

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).

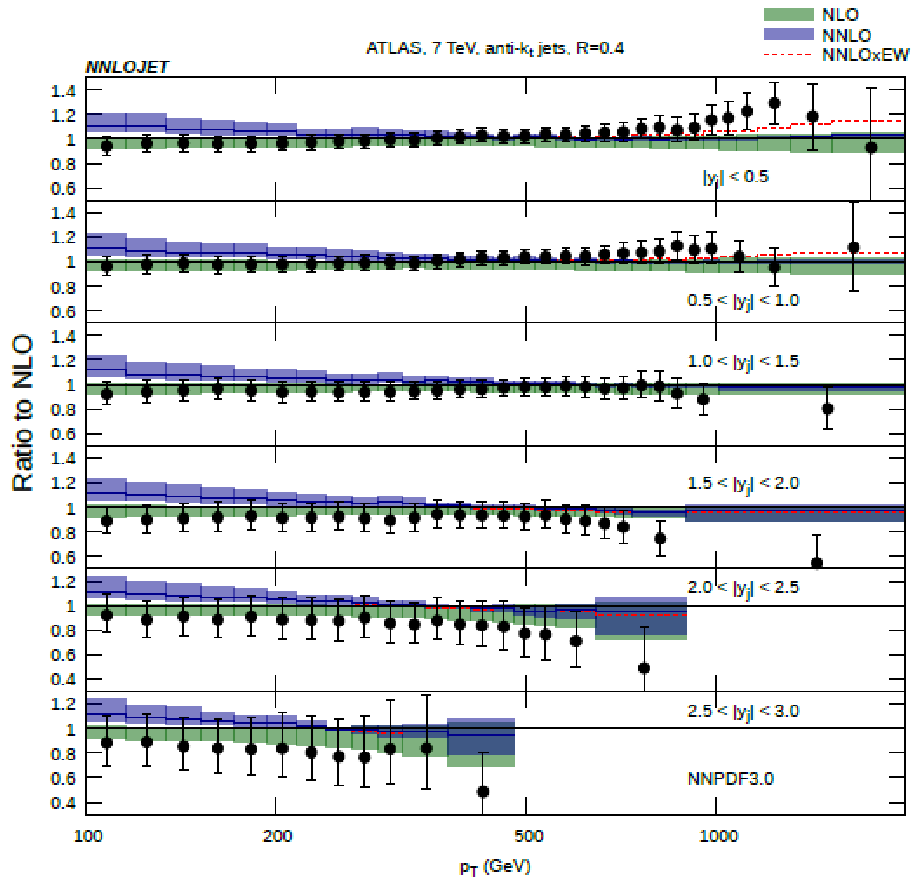
NNLO corrections

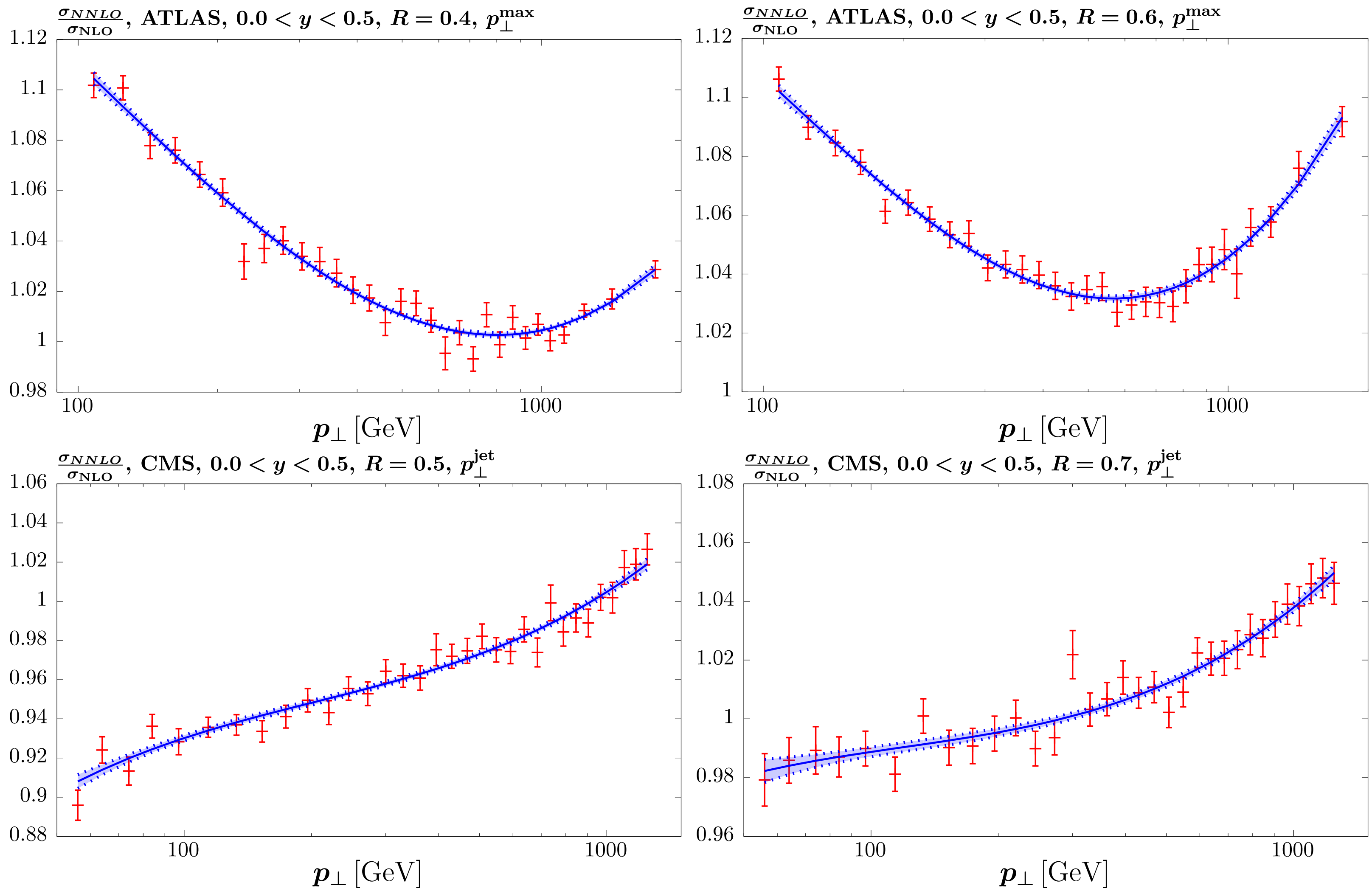
Currie *et al* Phys.Rev.Lett. 118 (2017) 072002.

Exact form dependent on R (smaller for $R \sim 0.6$) and on scale choice, e.g $\mu = p_{T,1}$ or p_T. Up to 20% at low p_T.

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.





We fit K-factors (with uncertainties) to calculated corrections.

Depend significantly on scale, less on R.

Similar results on improvement with decorrelation using new NNLO results.

	ATLAS	ATLAS, σ_{pd}	ATLAS, σ_{fd}		CMS
$R = 0.4$	350.8 (333.7)	183.1 (170.7)	128.4 (122.2)	$R = 0.5$	191.7 (163.4)
$R = 0.6$	304.0 (264.0)	178.8 (148.9)	128.9 (115.7)	$R = 0.7$	200.1 (175.2)

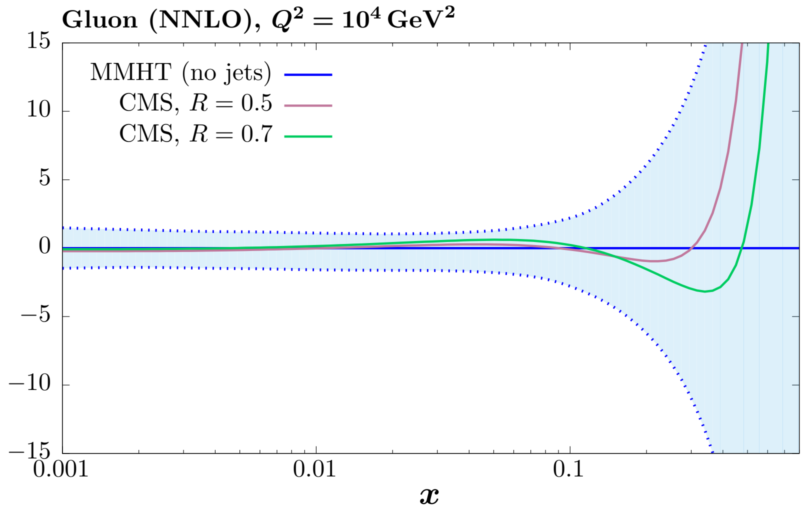
Table 2: The χ^2 for the ATLAS ($N_{\rm pts} = 140$) and CMS 7 TeV jet data ($N_{\rm pts} = 158$) at NNLO. The quality of the description using the baseline set is shown, while the result of re–fitting to the single jet data set is given in brackets. Results with the different treatments of the ATLAS systematic uncertainties, described in the text, are also shown.

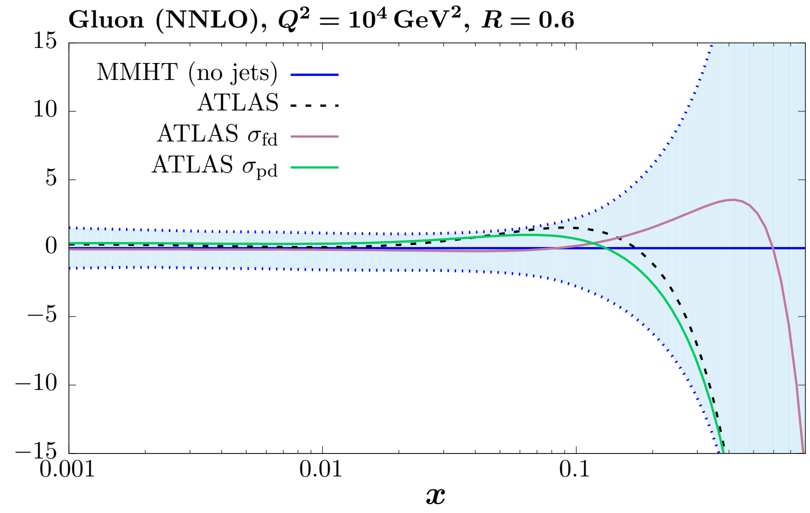
Clear that generally fit better at NNLO.

Also very dependent on scale and jet radius.

Fit to final CMS jet data (Phys.Rev. D90 (2014) 072006) generally quite good quality.

New data – results of fits





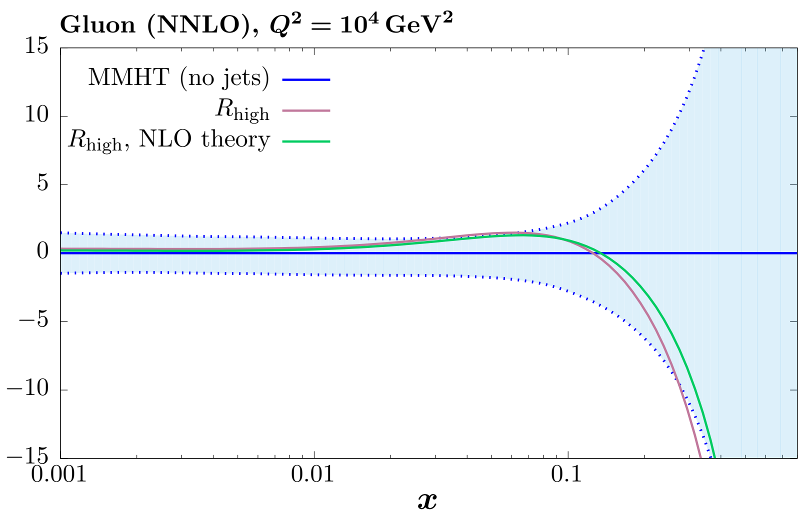
ATLAS and CMS pull in opposite direction for gluon – both within or comparable to uncertainties.

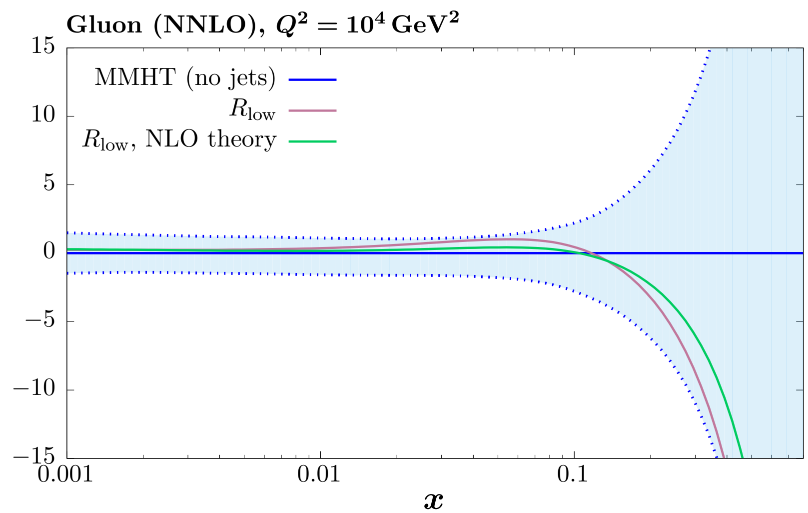
No or partial decorrelation have almost identical results for ATLAS (full decorrelation does not).

Inclusion of both data sets.

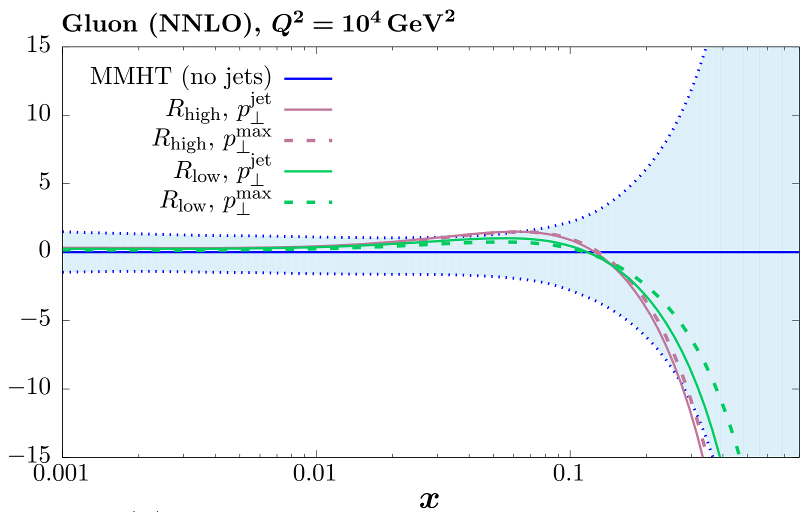
	$R_{\text{low}},\, p_\perp^{\text{jet}}$	$R_{\text{low}},\, p_\perp^{\text{max}}$	$R_{\text{high}},\, p_\perp^{\text{jet}}$	$R_{\text{high}},\, p_\perp^{\text{max}}$
ATLAS (NLO)	213.8	190.5	171.5	161.2
ATLAS (NNLO)	172.3	199.3	149.8	152.5
CMS (NLO)	190.3	185.3	195.6	193.3
CMS (NNLO)	177.8	187.0	182.3	185.4

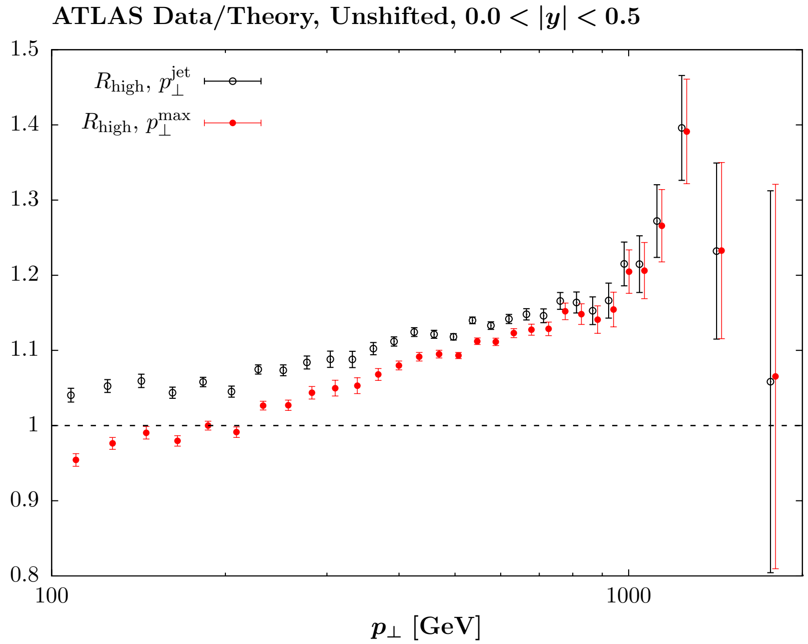
Table 3: The χ^2 for the combined fit to the ATLAS ($N_{\text{pts}} = 140$) and CMS ($N_{\text{pts}} = 158$) 7 TeV jet data. The values for the ATLAS and CMS contributions are given, for different choices of jet radius and scale, at NLO and NNLO.

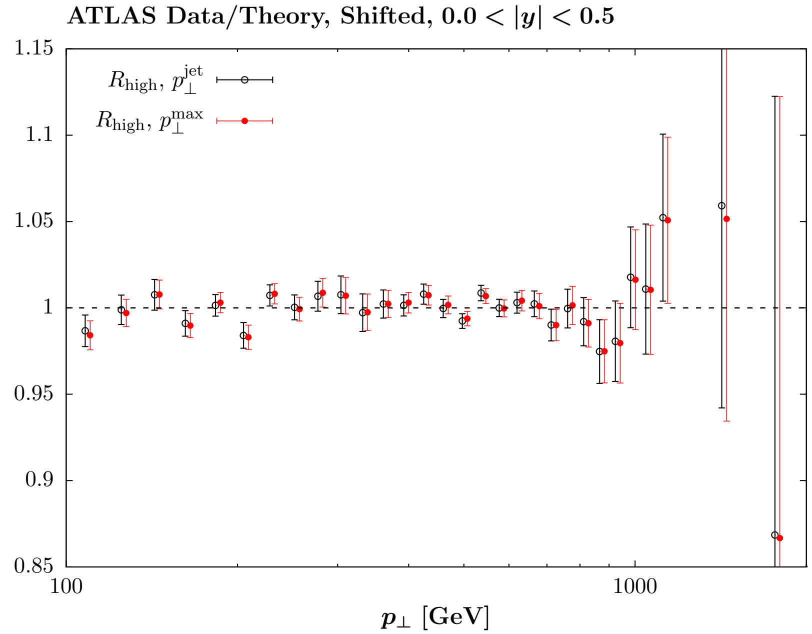




ATLAS data seems to present bigger pull.



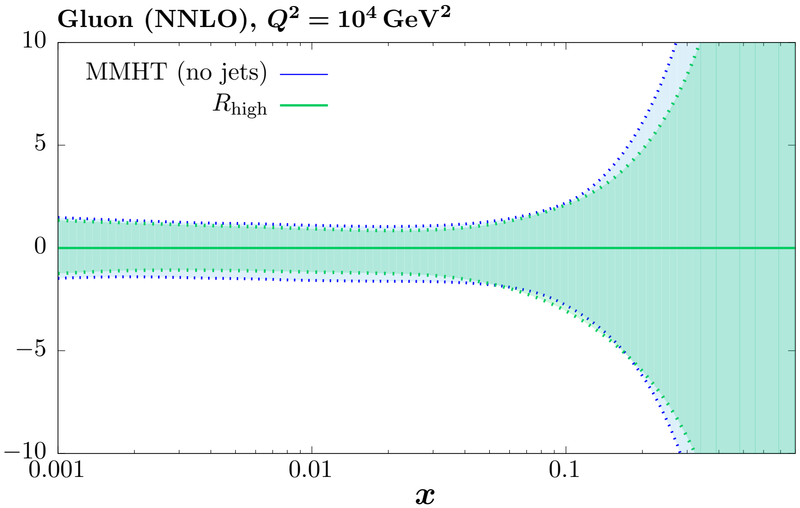


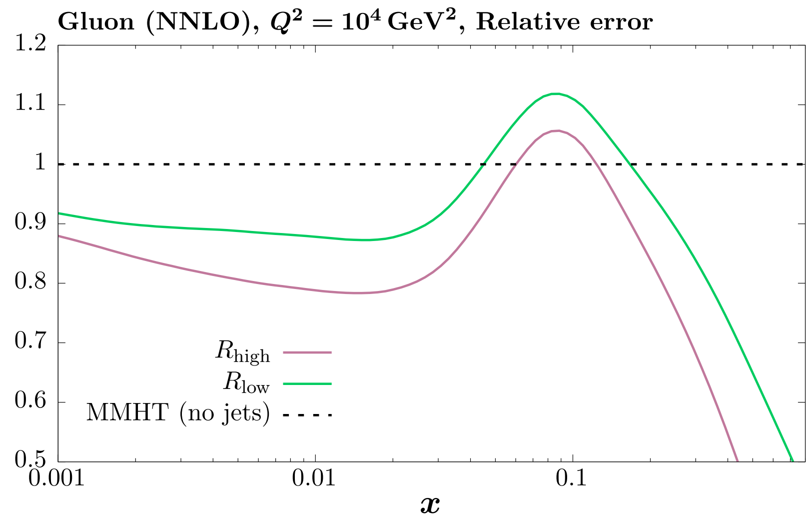


PDFs currently insensitive to choice of scale and jet radius at NNLO.

Different shifts of data relative to theory required.

Uncertainties





LHC jet data reduces uncertainties at level of up to 20% (more at very high x.

Fit Quality

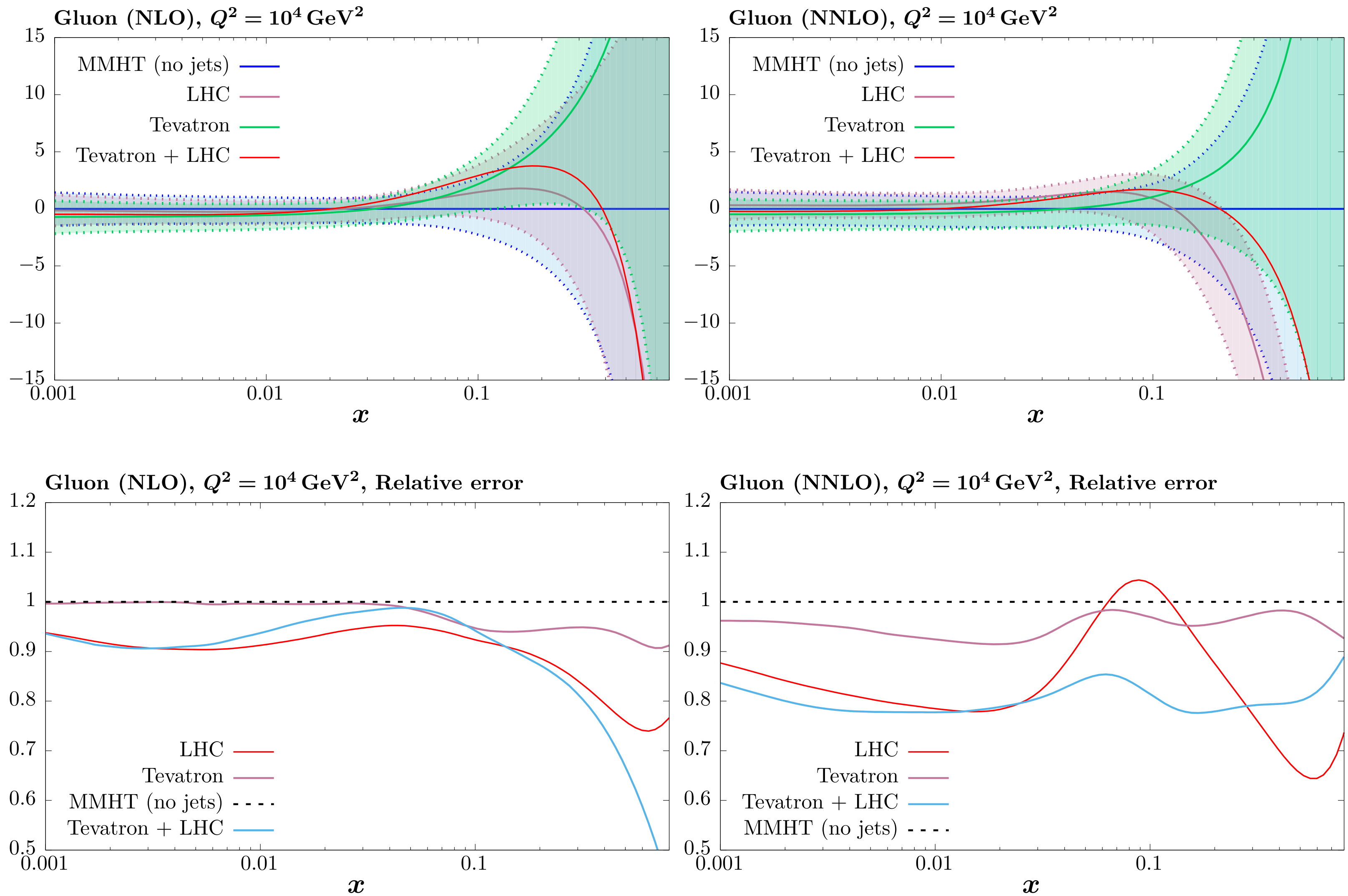
	NLO theory	NNLO	NNLO (no errors)
ATLAS, $R_{\rm low}$	215.3	172.3	179.1
ATLAS, $R_{\rm high}$	159.2	149.8	153.5
CMS, $R_{\rm low}$	194.2	177.8	182.8
CMS, $R_{\rm high}$	198.5	182.3	188.8

Table 4: The χ^2 for the combined NNLO fit to the ATLAS and CMS 7 TeV jet data, excluding and including the calculated NNLO K–factors, and excluding the errors associated with the polynomial fit to the K–factors. The $p_\perp^{\rm jet}$ factorization/renormalization scale is taken.

Much of the improvement in χ^2 at NNLO due to cross section, rather than PDFs.

However, change in PDFs currently relatively insensitive to this.

Addition of Tevatron jet data with NNLO threshold corrections.



Makes high-x gluon harder at NNLO and makes uncertainty reduction over wider x.

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

$\alpha_s(M_Z^2)$	LHC jets 3388 pts	LHC+Tev jets 3574 pts
0.115	3885.7	3894.7
0.116	3676.2	3879.9
0.117	3677.2	3875.3
0.118	3688.6	3880.2
0.119	3708.0	3893.1
0.120	3734.6	3916.1

Reminder that 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), and with addition of 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 best-fit and removal of Tevatron jet data, $\alpha_S(M_Z^2) = 0.1164$. Smaller high-x gluon leads to larger coupling. When Tevatron jets added back $\alpha_S(M_Z^2) = 0.1173$

Also look at inclusion of newer W, Z data from ATLAS, CMS, LHCb included previously in preliminary MMHT fits.

Without newer LHC jet data find $\alpha_S(M_Z^2) = 0.1179$

Including newer LHC jet data find $\alpha_S(M_Z^2) = 0.1176$

Therefore, recent Drell-Yan type data stabilises $\alpha_S(M_Z^2)$ value slightly.

Conclusions

Slightly updated (near final) results on new QED corrected partons with the photon input at $Q_0^2 = 1\ \mathrm{GeV}^2$ given by LUXqed.

“Non-DGLAP” contributions above Q_0^2 significant, but not for sum rule.

Some small differences in photon compared to LUXqed.

Refit PDFs different in detail to those where photon and QED evolution just added to fixed input PDFs.

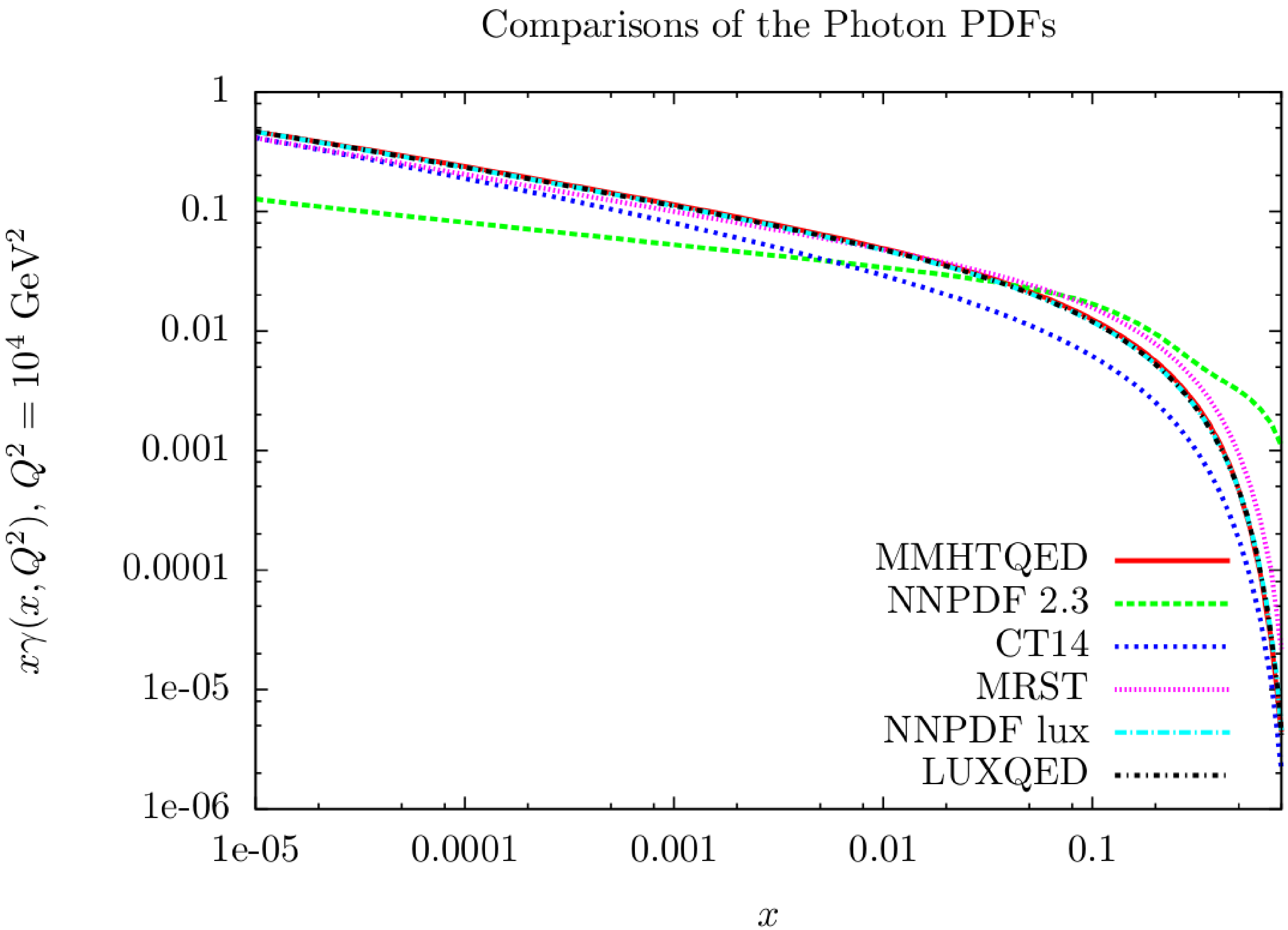
Neutron PDFs obtained with some assumptions/approximations for inputs of photon.

Fit ATLAS and CMS jet data. Pull of each relatively small, but in opposite direction. Overall slightly softer high-x gluon.

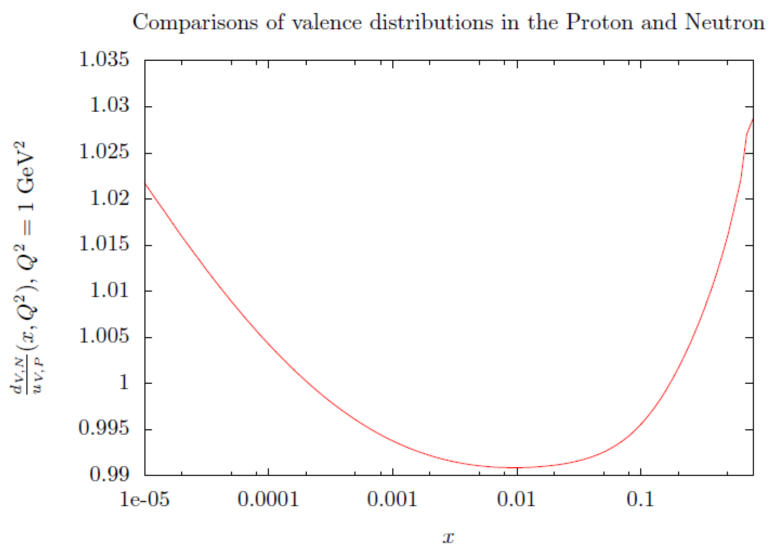
For ATLAS data partial decorrelation of systematics improved χ^2 but does not affect results. Largely the same for NNLO cross section corrections.

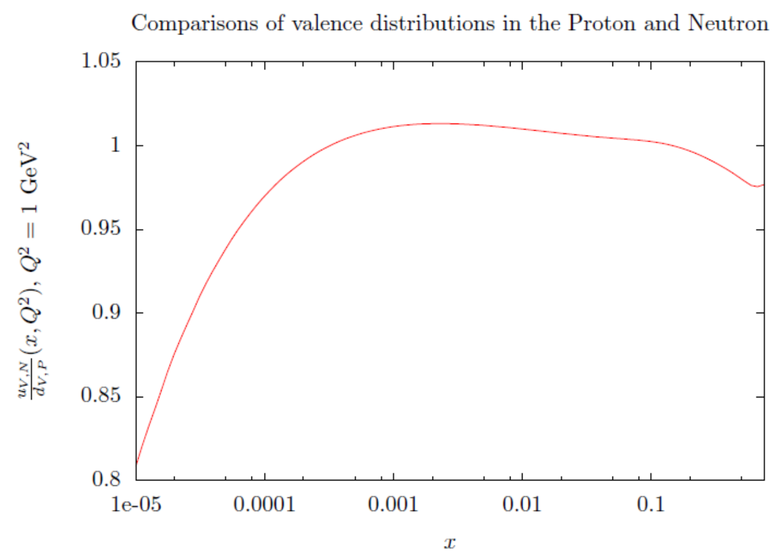
LHC jet data reduces $\alpha_S(M_Z^2)$ by less than 0.001 due to softer high-x gluon. Best current value $\alpha_S(M_Z^2) = 0.1176$.

Back-Up


Comparisons of the Photon PDFs
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-05
0.0001
0.001
0.01
0.1
$x\gamma(x, Q^2)$, $Q^2 = 10^4$ GeV^2
x
MMHTQED
NNPDF 2.3
CT14
MRST
NNPDF lux
LUXQED

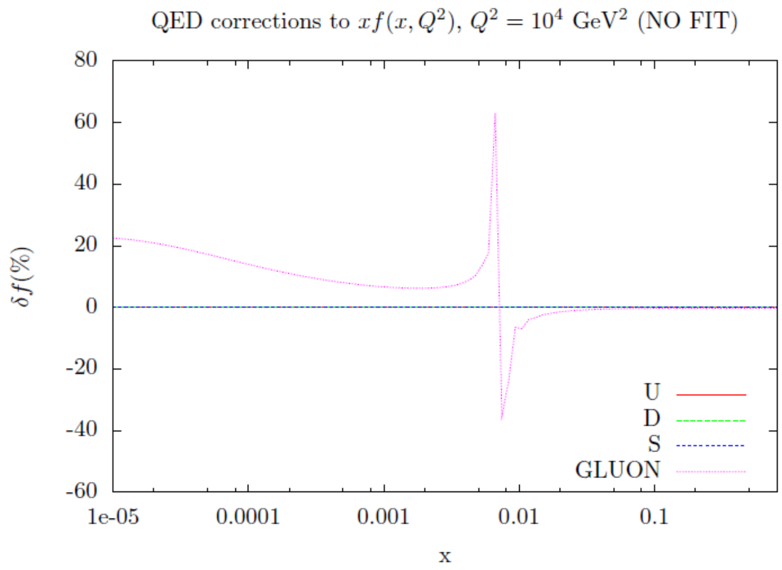
Isospin violating changes in valence quarks in Neutron

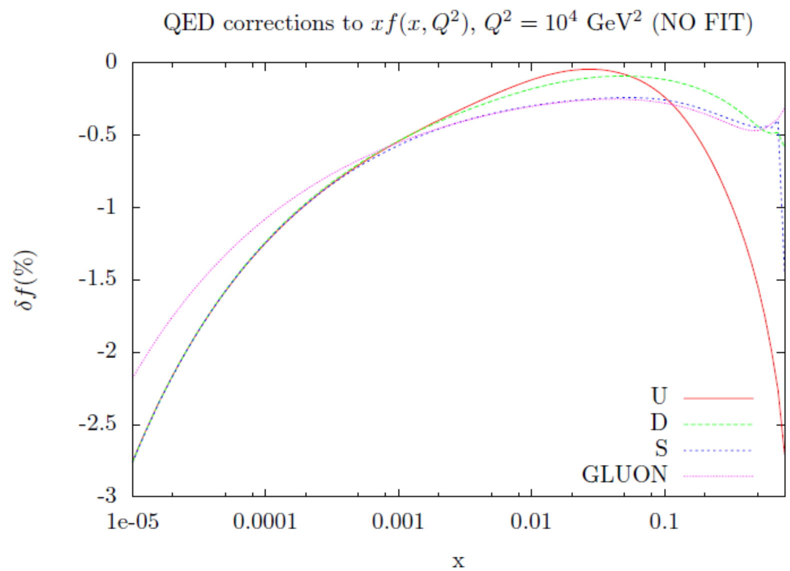




Differences reflect respective QED evolution.

QED effect on other partons



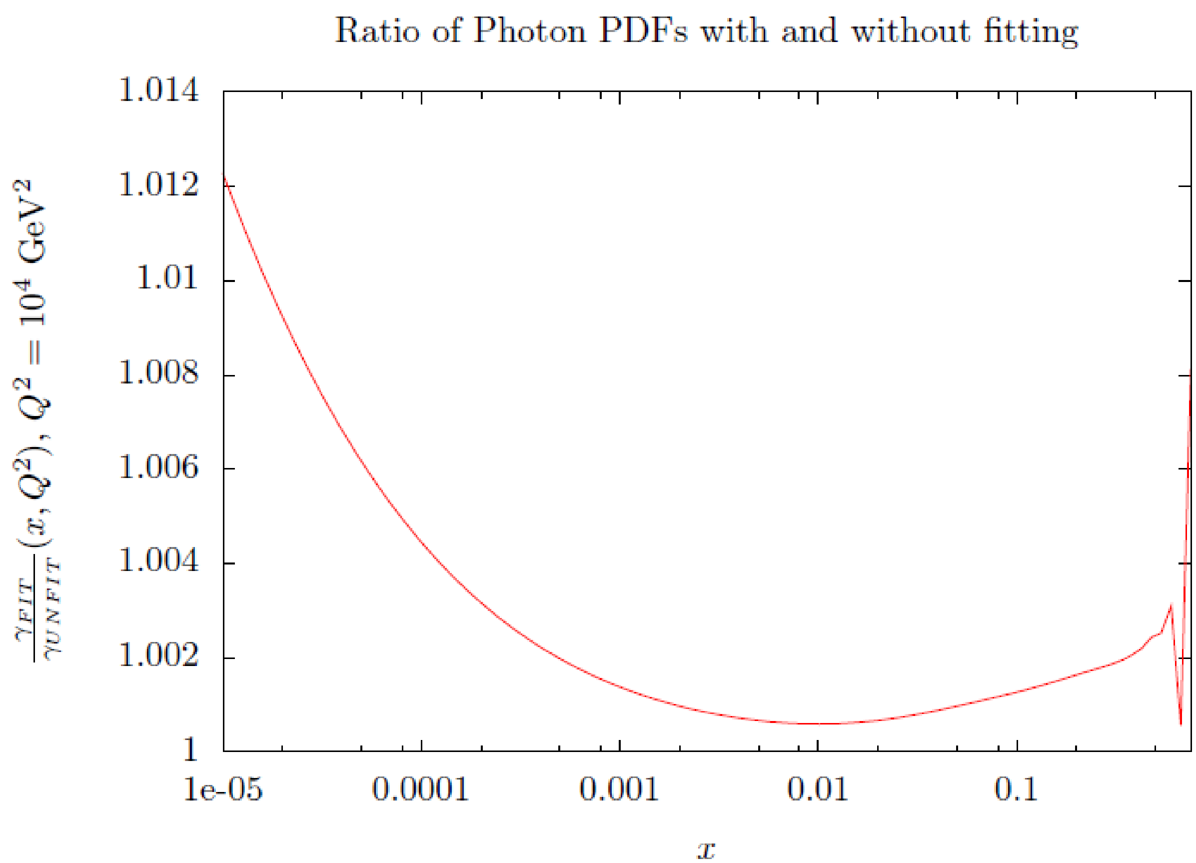


At input the inclusion of the photon is all taken account of in the gluon since a gluon parameter is fixed from the momentum sum rule. Affects small x.

Quarks decrease with evolution at high x due to photon radiation.

All PDFs decrease at small x due to smaller input gluon.

Effect of refit on photon



Tiny increase mainly due to larger up quark contribution.

An isospin violating component of the neutron $\Delta d_V^n = d_V^n - u_V^p$ comes in during evolution.

MRST introduced an isospin-violating component at input (whose zeroth moment vanishes to obey sum rules) was determined by the difference between u_V^p and d_V^p, with the constant of proportionality being determined by conservation of momentum.

We now assume that the difference introduced is proportional to the contribution to valence distributions from QED evolution.

$$\Delta d_V^n = \epsilon(1 - \frac{e_d^2}{e_u^2})\Delta u_V^{QED}; \qquad \Delta u_V^n = \epsilon(1 - \frac{e_u^2}{e_d^2})\Delta d_V^{QED}$$

taken from the integration step immediately after input.

The constant of proportionality is then set by conservation of momentum, similar to MRST.

$$\epsilon = \frac{\int_0^1 dx\, x(\gamma^p - \gamma^n)}{\int_0^1 dx\, x(3/4\Delta u_V^{QED} - 3\Delta d_V^{QED})}$$