

# Updates of MSTW PDFs

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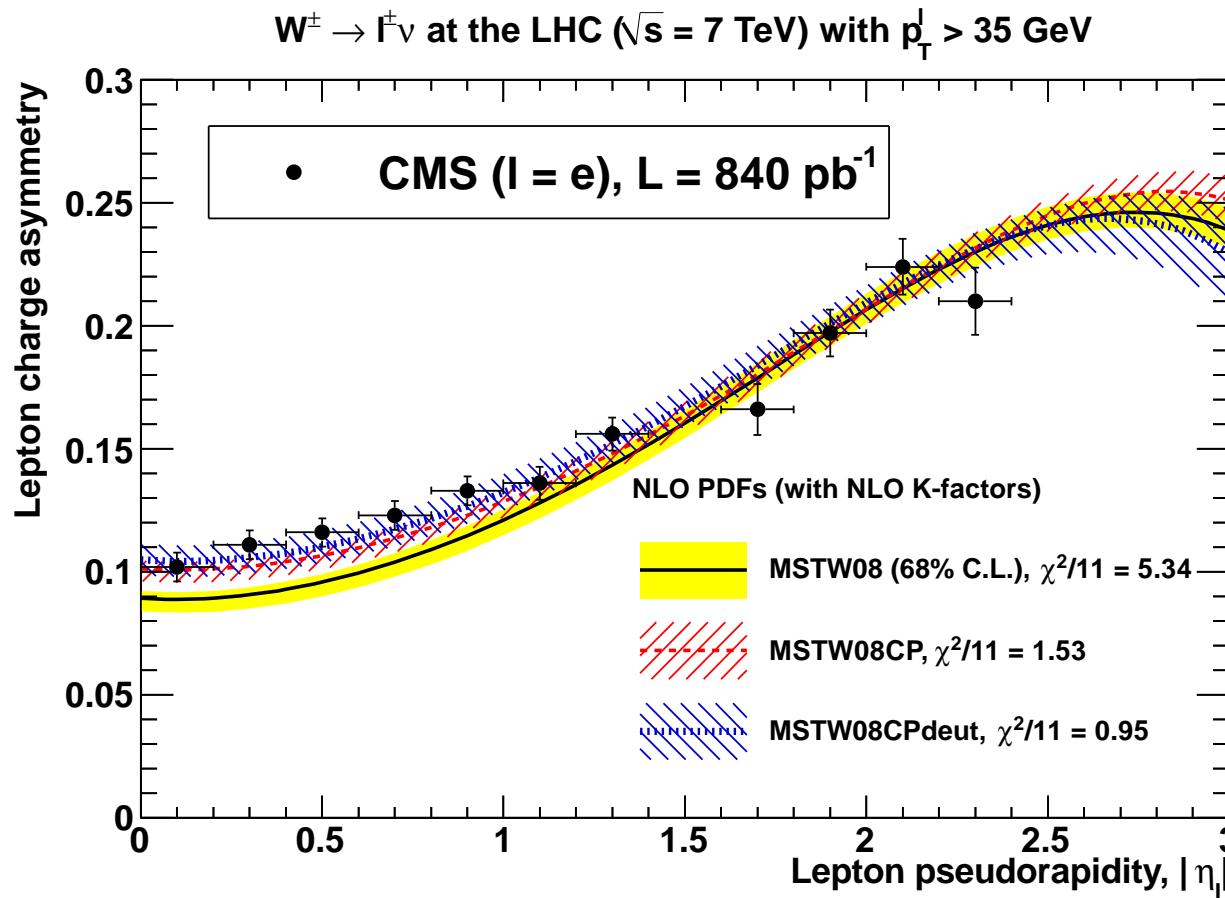
With contributions from Alan **Martin**, Patrick Motylinski, James **Stirling**,

Ben Watt and Graeme **Watt**

I will present results on continuing updates in PDFs within the **MSTW** framework due to some theory improvements and a variety of new data sets. Very much in progress. Partly a combination of individual modifications already presented.

## MSTWCPdeut PDFs now available on LHAPDF.

Note no change to data fit compared to MSTW2008, just parameterisation extension and change in deuterium corrections.



Prediction for  $p_T > 35\text{GeV}$  CMS asymmetry data.

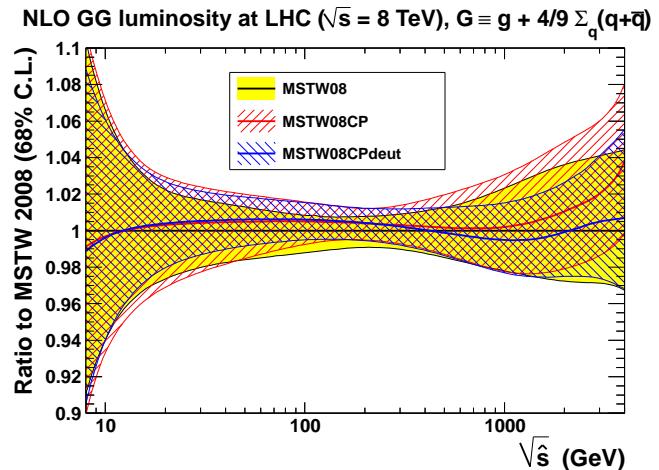
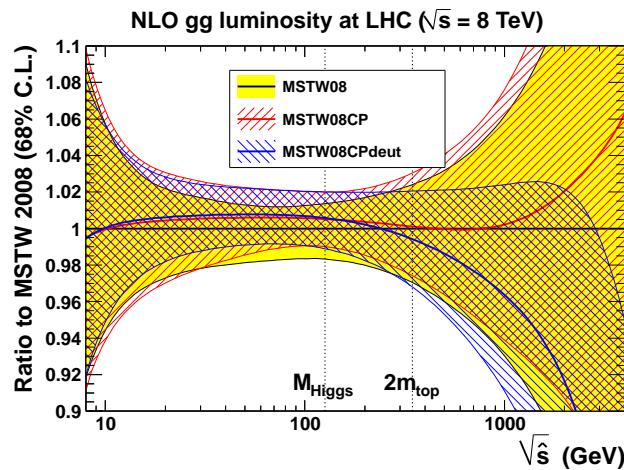
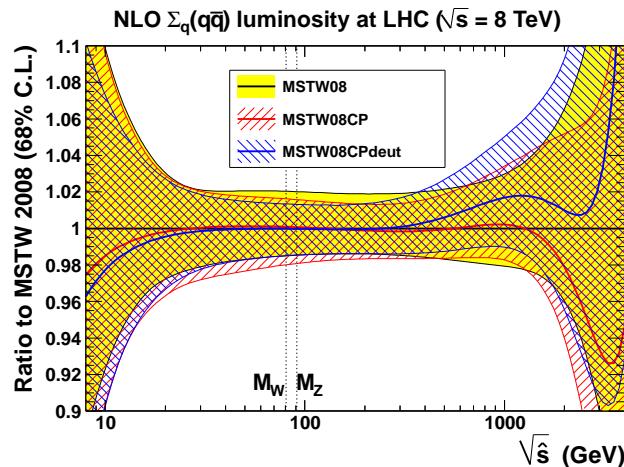
Big change in high- $p_T$  cut asymmetry,  
but this is very specifically sensitive to  
 $u_V(x, Q^2) - d_V(x, Q^2)$ .

Little effect on other quantities.

Other PDFs changed little.  $\alpha_S$  free but tiny change. Expect little variation.

Seen clearly on luminosity plots (**G. Watt**).

A not totally insignificant change in the high- $x$  gluon luminosity for the **MSTWCPdeut** set . Due to softer  $d_V$

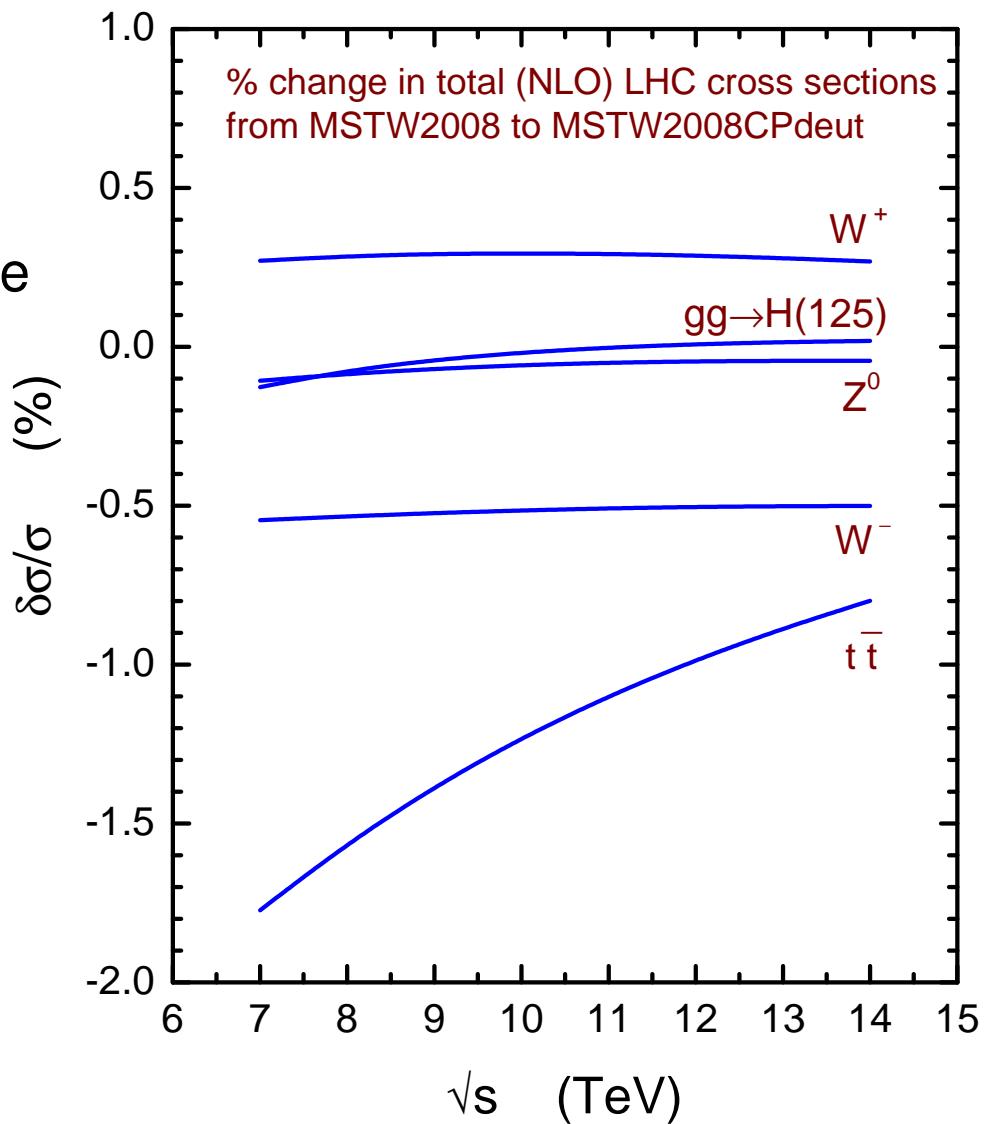


The percentage change of various cross sections due to the modifications of the **MSTW2008** PDFs. In order to demonstrate the small changes in the cross sections, we also show, in the final column, the symmetrized PDF  $+\alpha_S(M_Z^2)$  percentage uncertainties for **MSTW2008** PDFs.

	CP	CPdeut	unc.
$W$ Tevatron (1.96 TeV)	+0.6	+0.1	1.8
$Z$ Tevatron (1.96 TeV)	+0.8	+0.7	1.9
$W^+$ LHC (7 TeV)	+0.7	+0.3	2.2
$W^-$ LHC (7 TeV)	-0.7	-0.4	2.2
$Z$ LHC (7 TeV)	+0.0	-0.1	2.2
$W^+$ LHC (14 TeV)	+0.6	+0.3	2.4
$W^-$ LHC (14 TeV)	-0.6	-0.5	2.4
$Z$ LHC (14 TeV)	+0.1	-0.1	2.4
Higgs Tevatron	-0.5	-1.8	5.1
Higgs LHC (7 TeV)	+0.2	-0.1	3.3
Higgs LHC (14 TeV)	+0.1	+0.1	3.1
$t\bar{t}$ Tevatron	+0.5	-0.6	3.2
$t\bar{t}$ LHC (7 TeV)	-0.4	-1.8	3.9
$t\bar{t}$ LHC (14 TeV)	-0.2	-0.8	3.1

Can see variation of cross sections with energy.

No real point in using instead of **MSTW2008** unless sensitive to details of small- $x$  valence quarks.



## Updates in Fits with the **MSTW** Framework.

### Changes in theoretical treatment.

Continue to use extended parameterisation with Chebyshev polynomials, and freedom in deuteron nuclear corrections (and heavy nuclear corrections), as in recent **MSTWCPdeut** study ([Eur.Phys.J. C73 \(2013\) 2318](#)) – change in  $u_V - d_V$  distribution.

Now use “optimal” **GM-VFNS** choice ([Phys.Rev. D86 \(2012\) 074017](#)) which is smoother near to heavy flavour transition points (more so at **NLO**).

Correct dimuon cross-sections for missing small contribution, i.e. where charm is produced away from the interaction point. Previously assumed this was accounted for by acceptance corrections. Previous checks showed correction is a small effect on strange distribution.

Use **NMC** structure function data with  $F_L(x, Q^2)$  correction very close to theoretical  $F_L(x, Q^2)$  value. Very little effect.

## Changes in data sets.

Replacement of HERA run I neutral current data from HERA and ZEUS with combined data set. Already considered effect of this. Fit to data very good. Slightly better fit at NNLO – 33 units for 553 points.

Inclusion of HERA combined data on  $F_2^c(x, Q^2)$ . Fit quality  $\sim 60\text{-}65$  for 52 points.

Inclusion of run II ZEUS data EPJ C 62 (2009) 625, until recently only run II neutral current set published. Fit quality very similar to HERAPDF fits. Run II combination soon. Omit this (and not include other ZEUS,H1 sets) until this is complete?

Inclusion of all direct HERA  $F_L(x, Q^2)$  measurements. Undershoot data a little at lower  $Q^2$ , but  $\chi^2$  not much more than one per point.

Inclusion of the D0 electron asymmetry data for  $p_T > 25\text{GeV}$  based on  $1 \text{ fb}^{-1}$  and CDF  $W$ -asymmetry data. Keep lower luminosity D0 muon asymmetry data.

Fit quality for two new sets about 2 per point. Due mainly to fluctuations – similar for other groups. However, slight tension between these two sets.

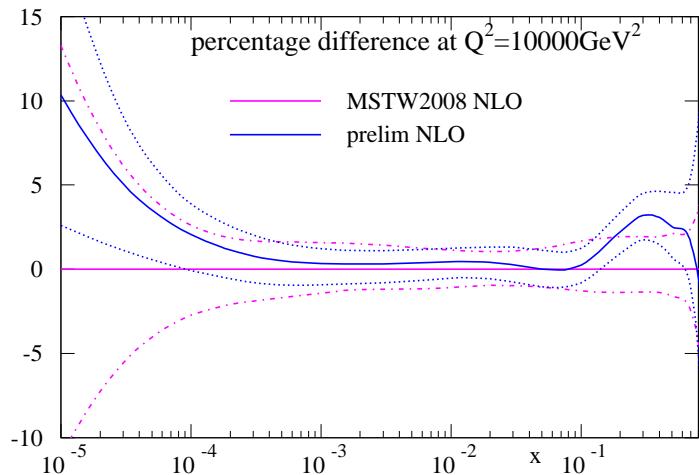
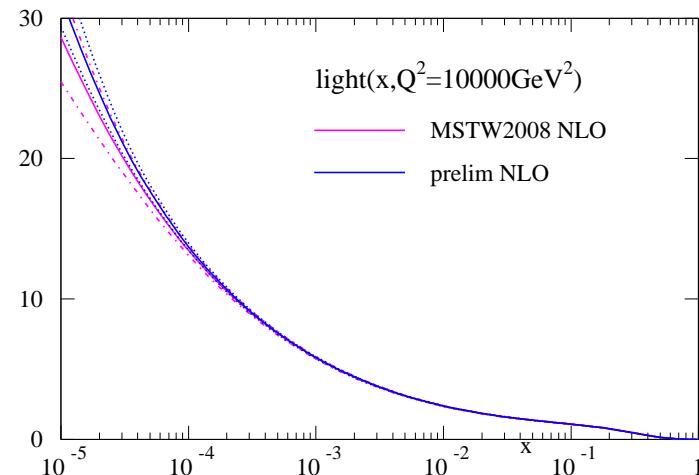
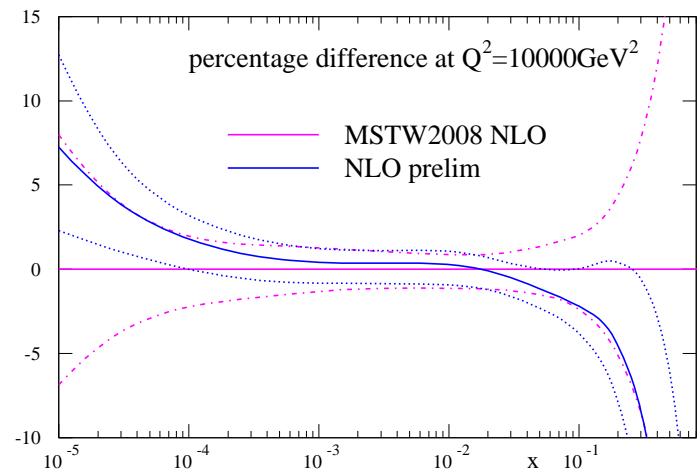
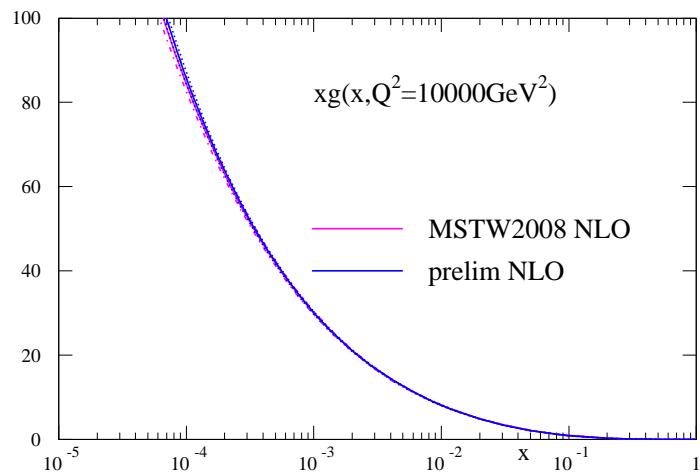
For D0 muon asymmetry data  $\chi^2 = 6/10$  as compared to  $\chi^2 = 25/10$  for MSTW2008. Due to  $u_V - d_V$  change mainly already in MSTWCPdeut.

Include final numbers for CDF  $Z$ -rapidity data – final numbers changed after MSTW2008 fit. (Also include very small photon contribution in theory.)

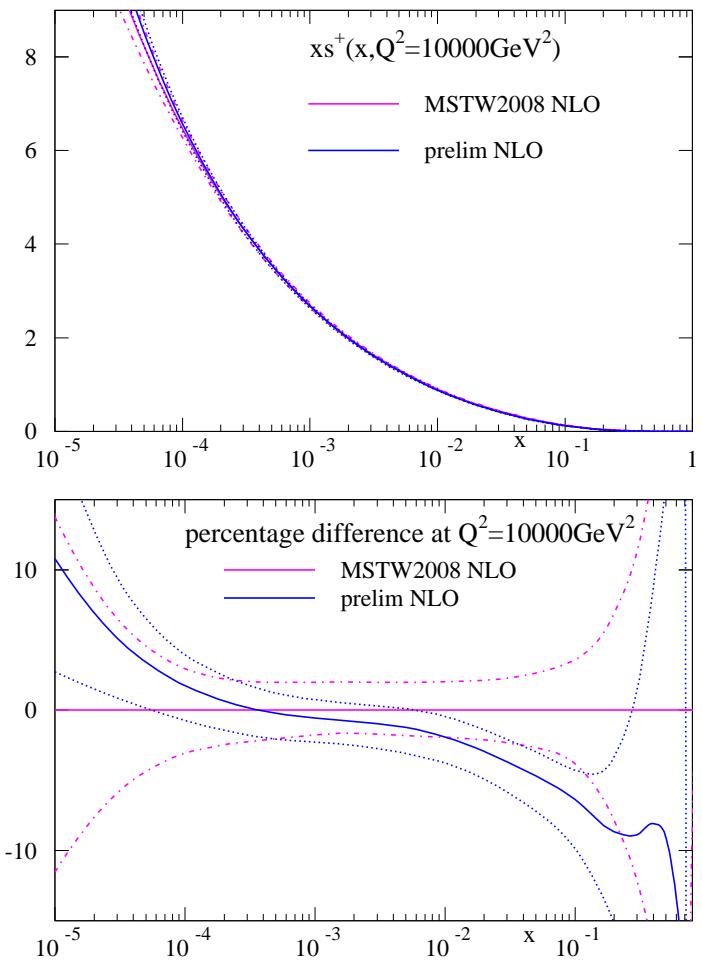
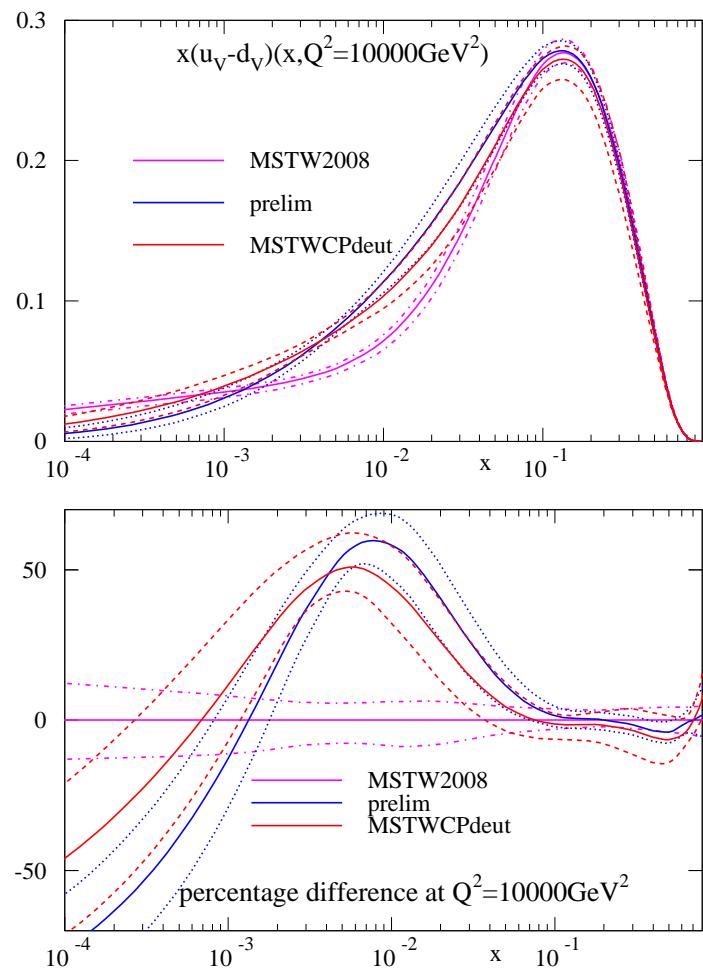
Little change in PDFs. Final data is more consistent with the theory –  $\chi^2 \sim 38/28$ .

Not much change in PDFs (other than already seen in  $u_V - d_V$ ).

At NLO  $\alpha_S(M_Z^2) = 0.1197$  from 0.1202 and at NNLO  $\alpha_S(M_Z^2) = 0.1168$  from 0.1171.



Change in **NLO PDFs** from all updates. Increase in *d* at high *x*.

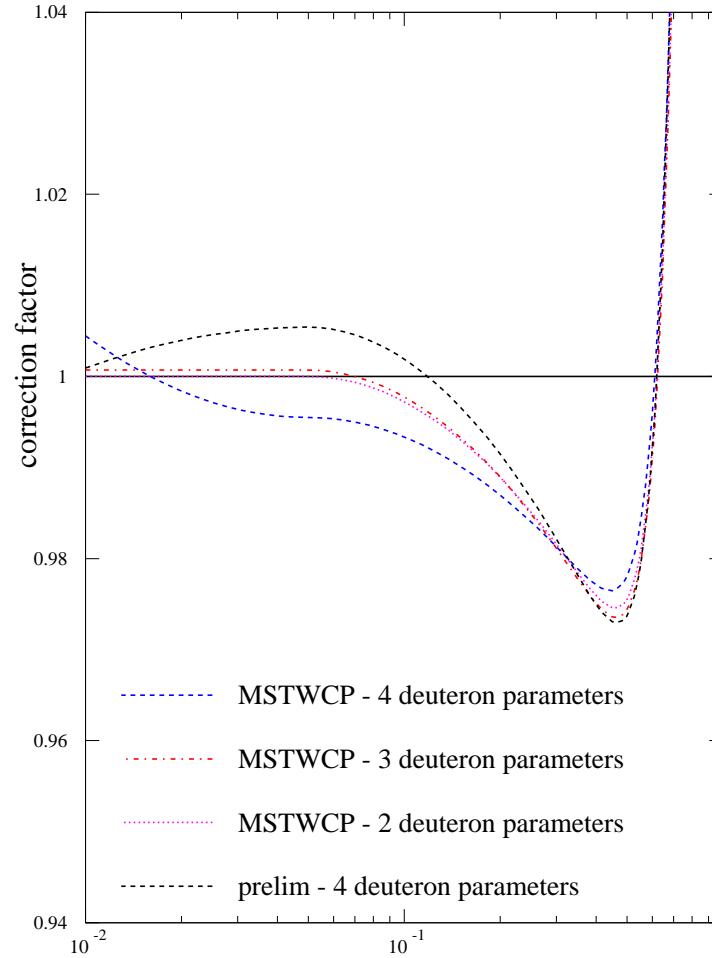


Change in **NLO** PDFs from all updates.

## Result for fitted deuteron correction.

Previously big improvement in fit for **MSTWCPdeut**, but not exactly as expected at lower  $x$ .

Now more like expected for and 4 parameters left free (at **NLO**). Uncertainty of about 0.5 – 1%. Feeds into PDF uncertainty.



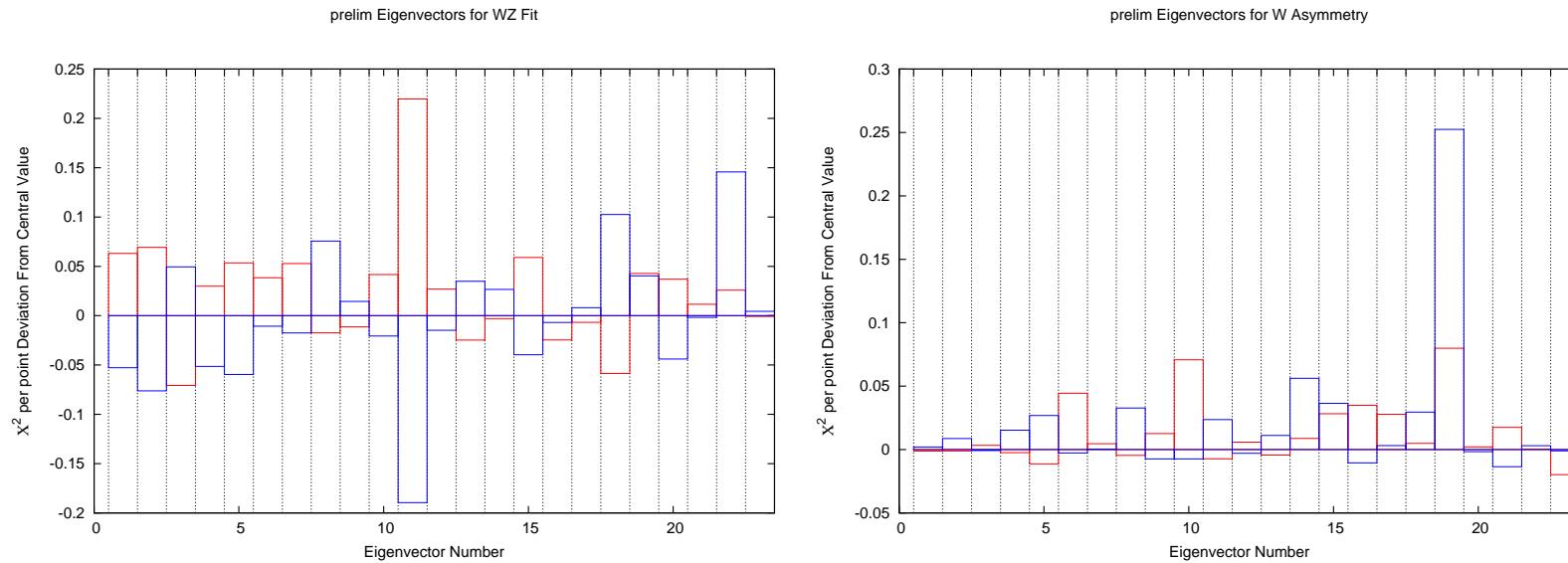
## Change in various cross section predictions compared to uncertainty for **MSTW2008**.

	NLO	NNLO	unc.
$W$ Tevatron (1.96 TeV)	+2.2	+3.3	1.8
$Z$ Tevatron (1.96 TeV)	+3.3	+2.6	1.9
$W^+$ LHC (7 TeV)	+2.6	+0.9	2.2
$W^-$ LHC (7 TeV)	+0.5	+0.6	2.2
$Z$ LHC (7 TeV)	+1.3	+0.6	2.2
$W^+$ LHC (14 TeV)	+2.7	+0.2	2.4
$W^-$ LHC (14 TeV)	+0.8	-0.3	2.4
$Z$ LHC (14 TeV)	+1.1	-0.2	2.4
Higgs Tevatron	-5.0	-3.9	5.1
Higgs LHC (7 TeV)	-2.2	-1.3	3.3
Higgs LHC (14 TeV)	-1.6	-1.3	3.1
$t\bar{t}$ Tevatron	+1.1	+1.6	3.2
$t\bar{t}$ LHC (7 TeV)	-4.1	-2.3	3.9
$t\bar{t}$ LHC (14 TeV)	-3.0	-1.6	3.1

Some changes of order size of uncertainty - smaller at **NNLO**. Change in **Tevatron  $W, Z$**  mainly due to combined **HERA** data.

## Comparison to LHC data.

At NLO  $\chi^2 = 1.64$  per point for ATLAS  $W, Z$  rapidity data, slightly higher at NNLO. Comparable with many other sets and similar to MSTWCPdeut. Asymmetry data alone gives  $\chi^2 = 0.4$  per point.



No plausible improvement for asymmetry data. Full rapidity data sensitive to eigenvector 11 (gluon dominated). Inconsistency with ZEUS run II data – seen explicitly. (Plots by B. Watt).

# PDF reweighting

Can generate random PDFs or predictions from eigenvectors directly (see LHCb study and De Lorenzi thesis).

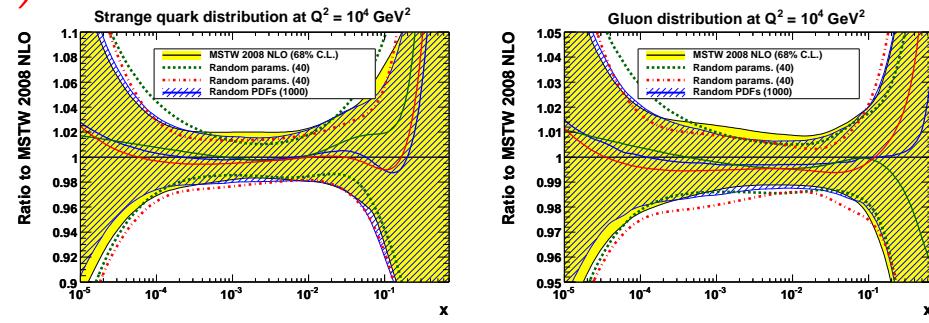
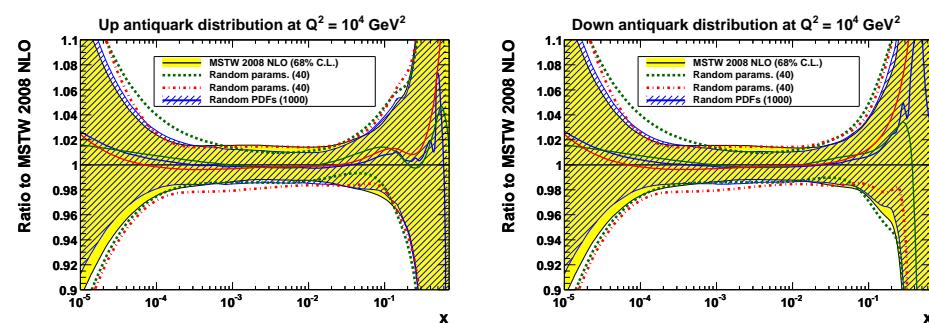
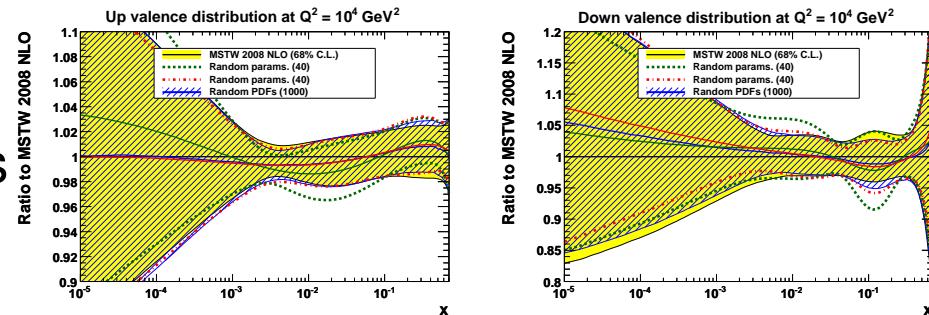
$$F(\mathcal{S}_k) = F(S_0) + \sum_j [F(S_j^\pm) - F(S_0)] |R_{jk}|$$

Use in reweighting studies as NNPDF

$$w_i(\chi^2) = \frac{W_i(\chi^2)}{\frac{1}{N_{pdf}} \sum_{j=1}^{N_{pdf}} W_j(\chi^2)}$$

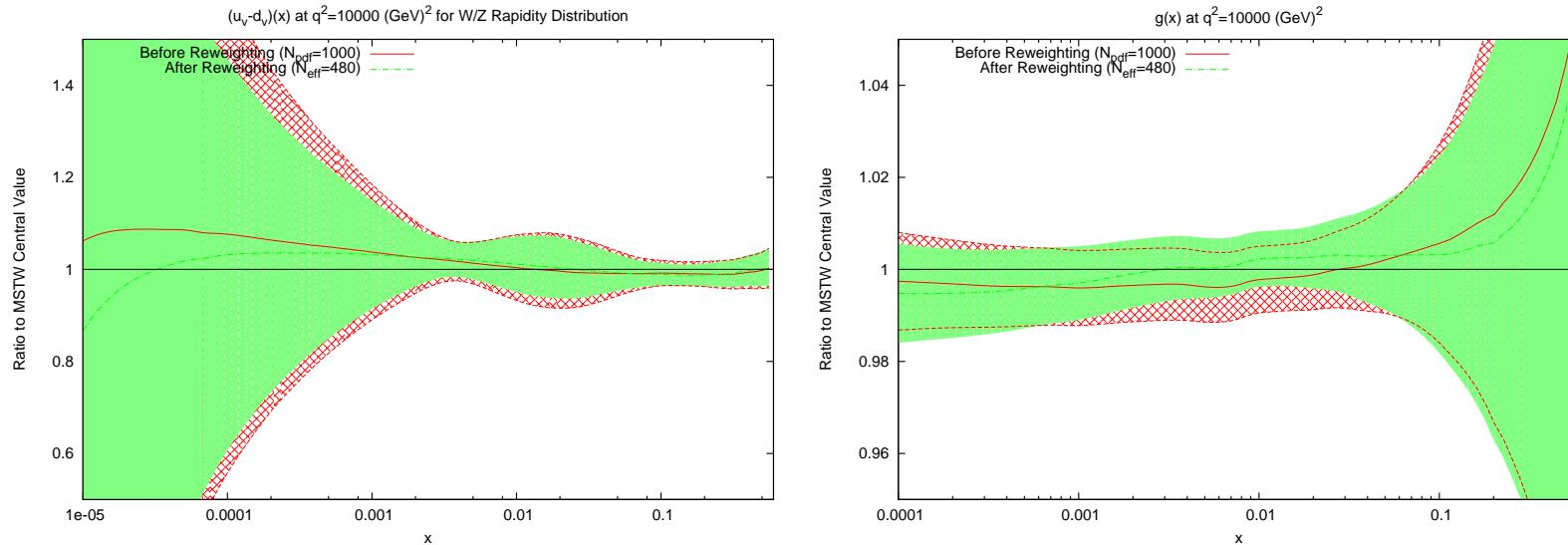
$$W_i(\chi^2) = [\chi^2_i]^{\frac{m*(N_{pts}-1)}{2}} \exp\left(-\frac{\chi^2_i}{2}\right).$$

$m$  can account for a fit with quality different (better) than one per point.



Example, use for ATLAS  $W, Z$  data.

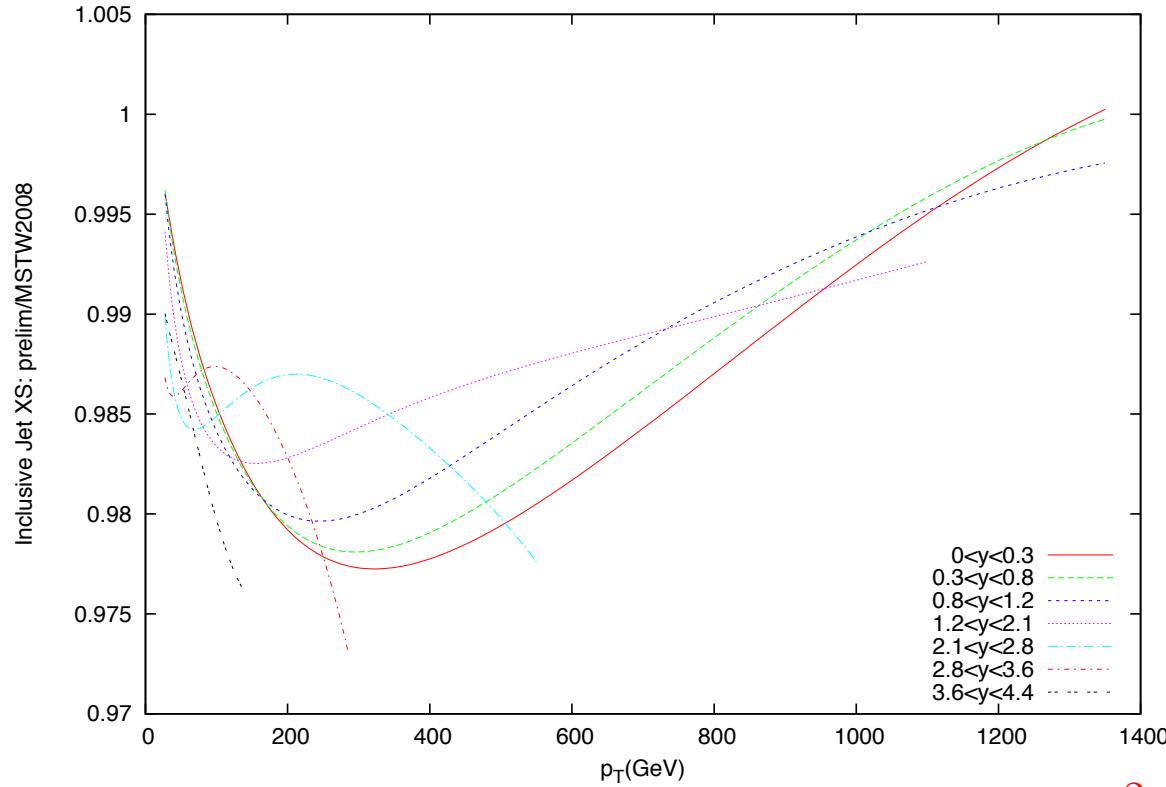
Under PDF reweighting  $\chi^2 = 1.44$  per point, a reasonable improvement.



No real change in  $u_V - d_V$  – slight improvement on **MSTWCPdeut**

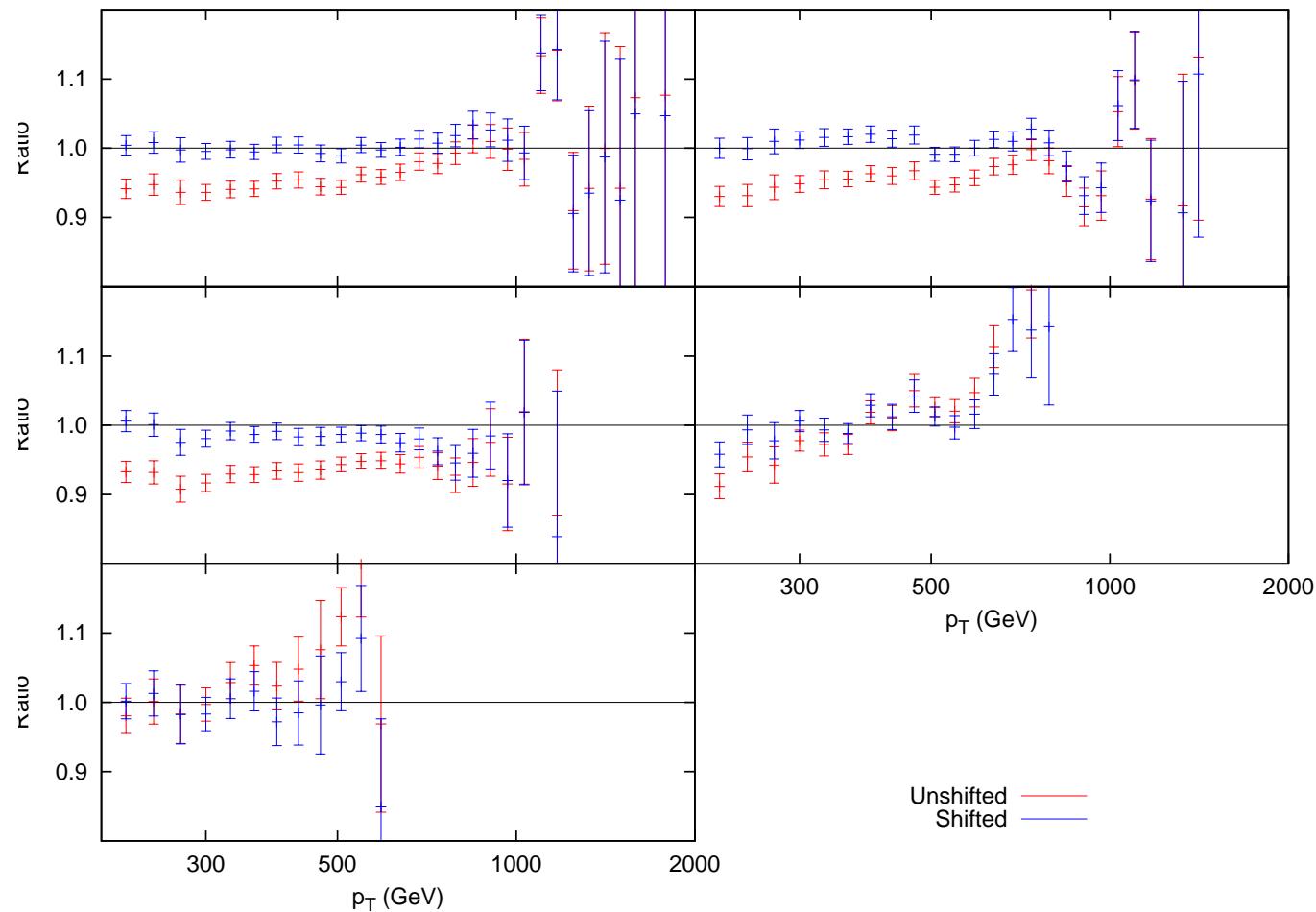
Main change in details of shape of gluon distribution.

For ATLAS 7 TeV jet data  $\chi^2 = 0.78 \rightarrow 0.74$  for  $R = 0.4$  and practically unchanged at  $\chi^2 = 0.79$  for  $R = 0.6$  (Ben Watt). Very little change in PDF shape or uncertainty. Same as for MSTW2008



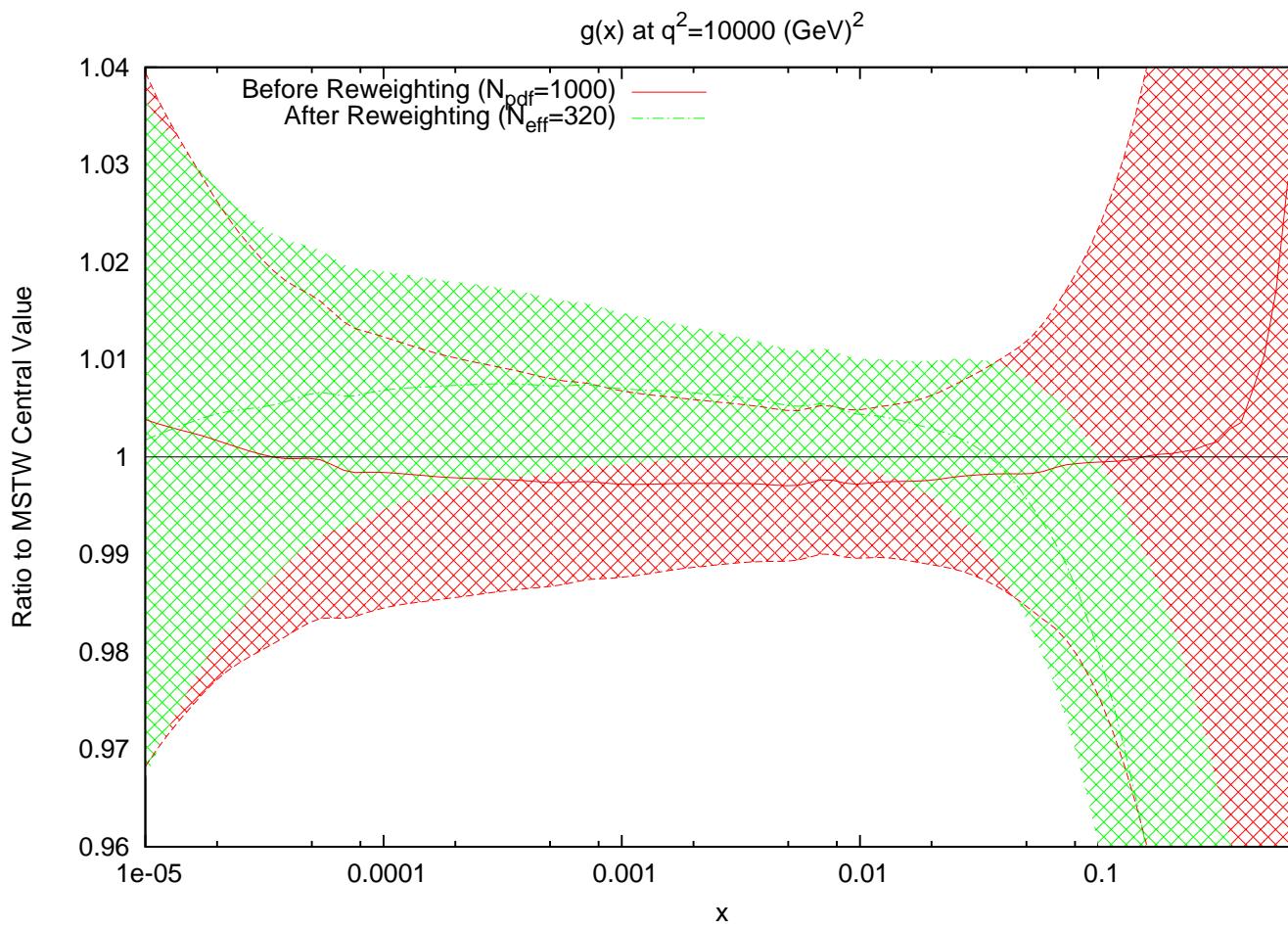
Using  $\chi^2$  definition  $\chi^2 = \sum_{i=1}^{N_{pts}} \left( \frac{D_i - \sum_{k=1}^{N_{corr}} r_k \sigma_{k,i}^{corr} - T_i}{\sigma_i^{uncorr}} \right)^2 + \sum_{k=1}^{N_{corr}} r_k^2$ ,  
 where  $\sigma_{k,i}^{corr}$  are percentage error multiplied by data, i.e. additive.  
 Usually higher  $\chi^2$  value.

# CMS data with $5 \text{ fb}^{-1}$



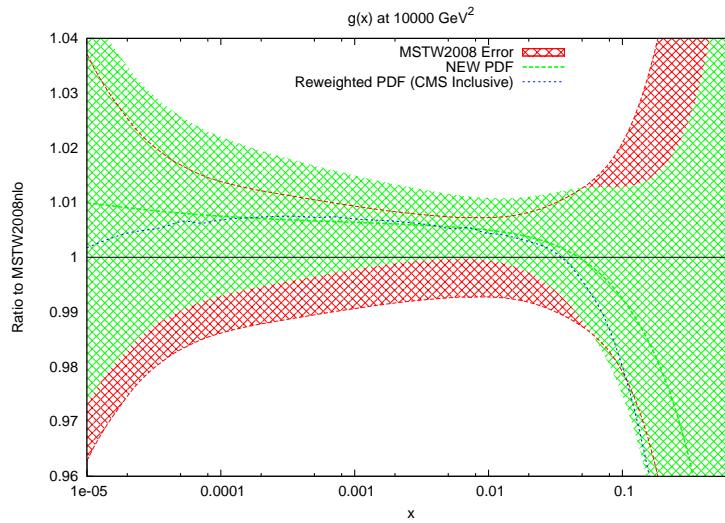
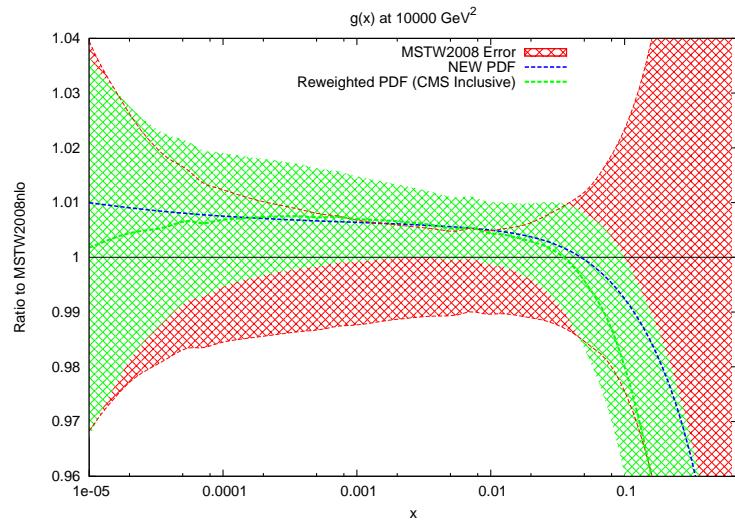
MSTW2008 gives very good fit,  $\chi^2 \sim 1.4$  per point for  $\mu = p_T$ . Among the lowest for PDF sets.

Raw data nearer theory than ATLAS 7 TeV data.



Using reweighting implies significant effect on gluon.  $\chi^2$  improves by about 0.15 per point. Very similar shape, but slightly smaller effect from ATLAS 7 TeV + 2.76TeV data.

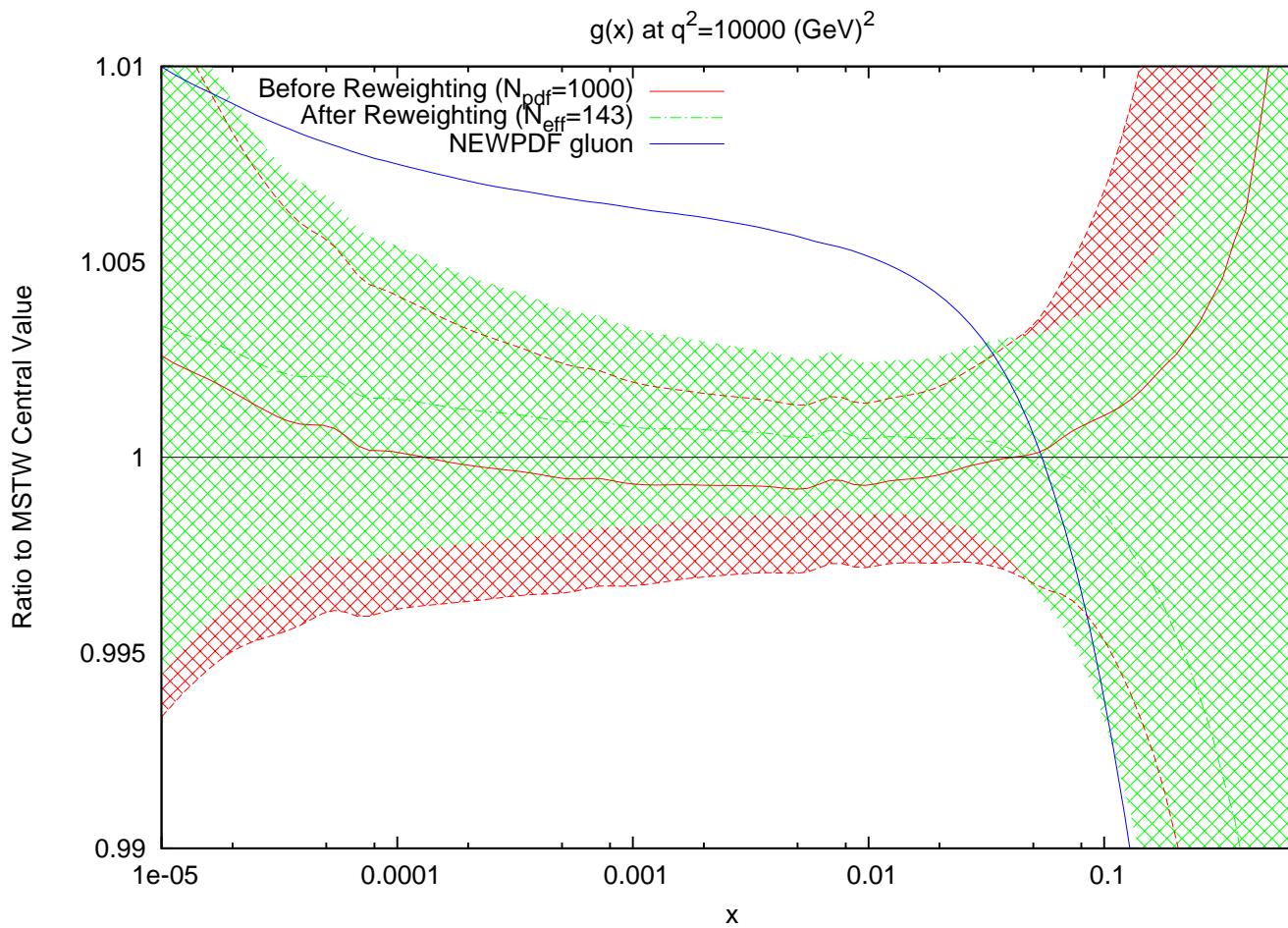
Working with [Motylinski, B. Watt](#), including jet data directly in fit using [FastNLO – NLOjet++](#). Include [CMS](#) and [ATLAS 7TeV](#) (former very dominant).



$\chi^2$  for CMS data from  $180/133 \rightarrow 169/133$ .

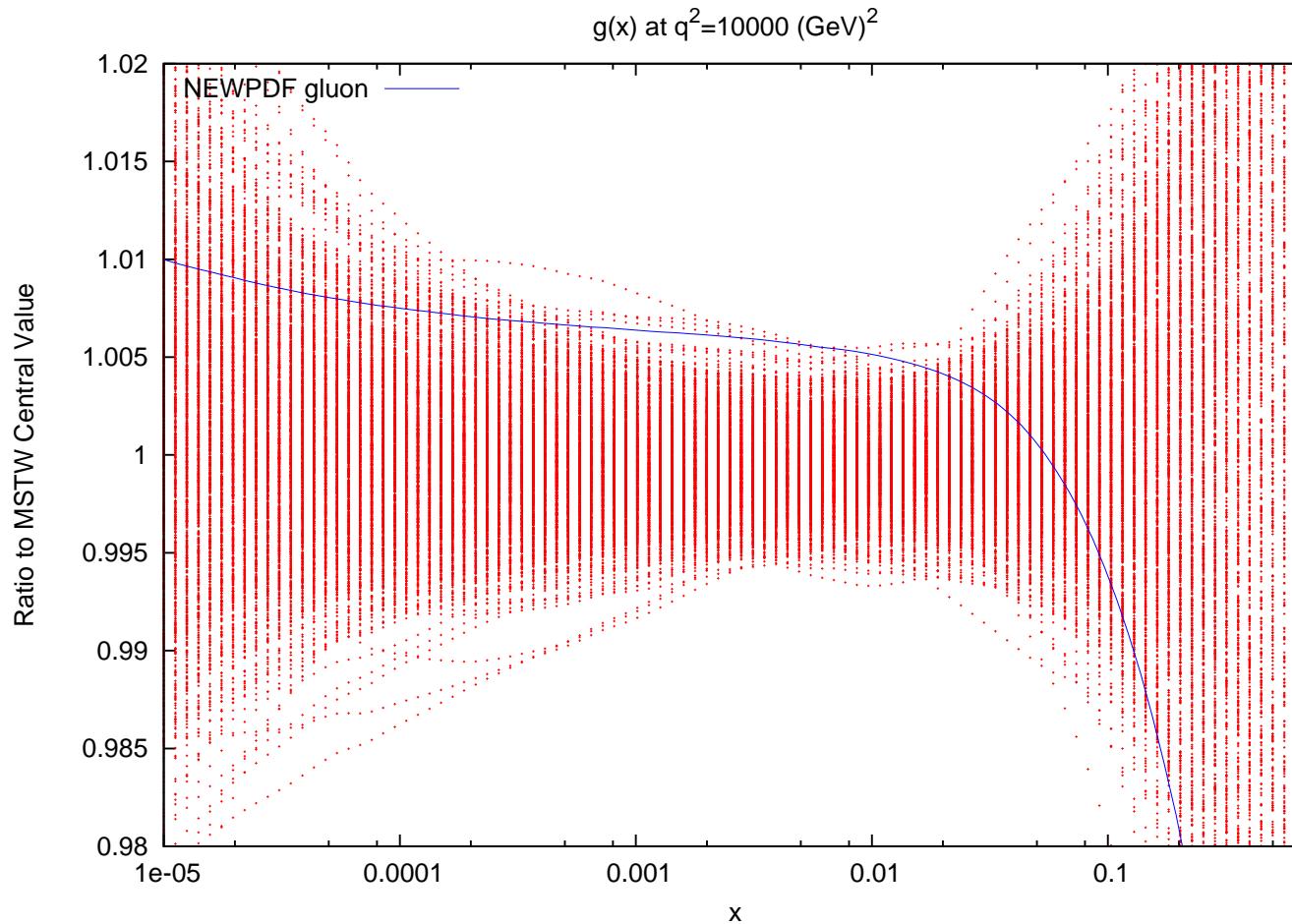
Reweighting similar to real fit, but slightly bigger effect. Data consistent with [MSTW](#), but fairly significant effect.

Interesting exercise. Try reweighting with eigenvectors defined by  $\Delta\chi^2 = 1$  rather than tolerance ( $\Delta\chi^2 \sim 10$ ).



Reweighting does not nearly reproduce shift in central value, which is now **2 – 3 sigma** outside error band. (Plots by (B. Watt))

Not surprising as with  $\Delta\chi^2 = 1$  eigenvectors almost none of the 1000 random sets gets the required shift as deterioration in the rest of the data is a few units.



Also include CMS data together with ATLAS 7TeV + 2.76 TeV data.

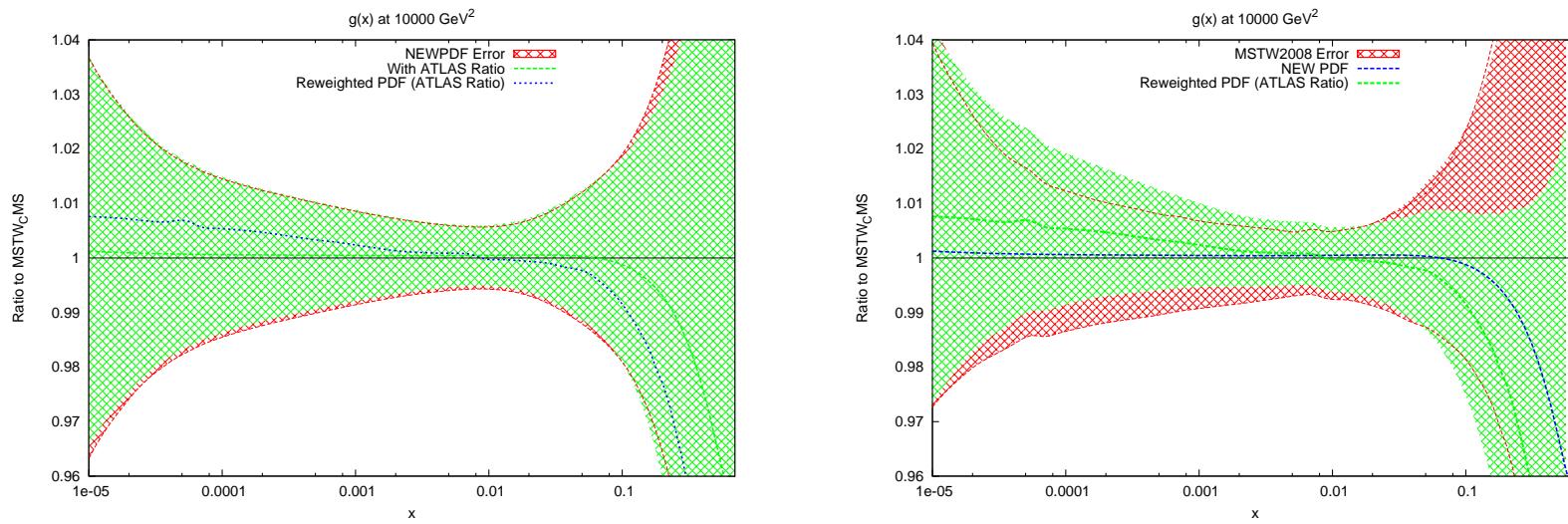
Use ATLAS/HERAPDF study cuts, which eliminate lowest two  $p_T$  points in each bin and some highest  $p_T$  points.

Using additive errors and  $R = 0.4$  data find one of the lowest remaining  $p_T$  points in 2.76 data and highest- $p_T, y$  for 7 TeV data give enormous  $\chi^2$  (no as much of a problem using multiplicative errors or  $R = 0.6$  data). Cut these - almost no effect on PDFs.

$\chi^2 = 155/114$  before included directly – as good as any PDF. Simultaneous fit of CMS data together with ATLAS 7Tev + 2.76 TeV leads to slightly bigger improvement for CMS than before including 2.76 TeV data and a few units for ATLAS.

Both improve a little more if  $\alpha_S(M_Z^2)$  is left free and falls to about  $\alpha_S(M_Z^2) = 0.1187$  at NLO. The two experiments seem extremely compatible.

Try reweighting of ATLAS 7TeV + 2.76 TeV data on top of fit with CMS data.

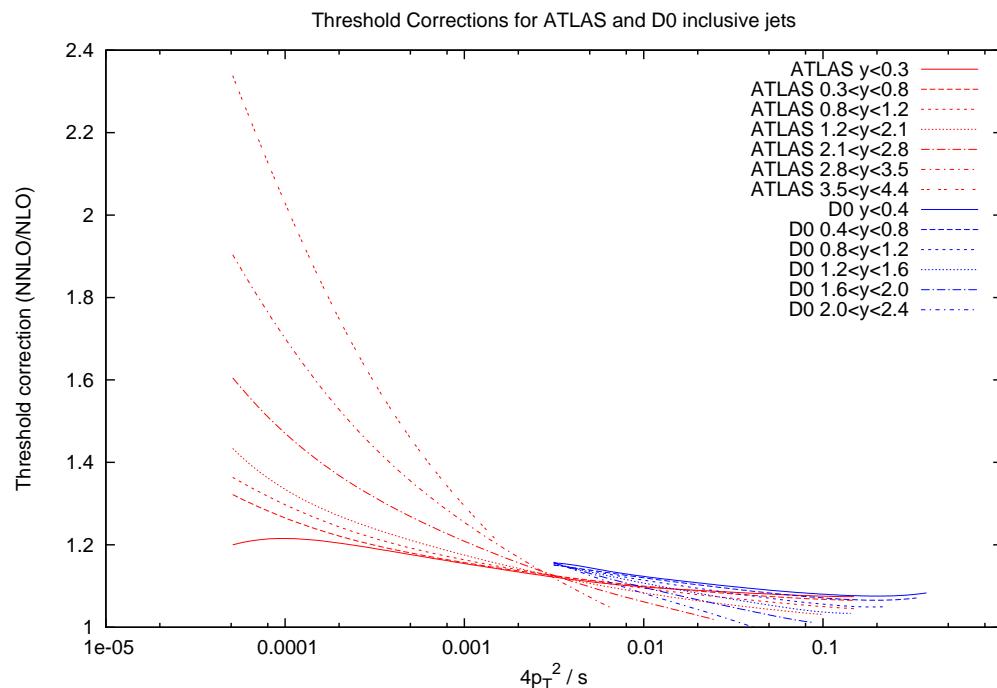


ATLAS data extremely compatible with CMS data, but bigger effect on central value and uncertainties implied by reweighting than real fit.

## LHC jet data at NNLO?

For Tevatron data use approximate “threshold” corrections ([Kidonakis and Owens](#)),  $\sim 10\%$  positive correction.

LHC corrections very similar for highish  $x$  probed at the Tevatron, but blow up when low  $x$  probed at the LHC, i.e. far from threshold.

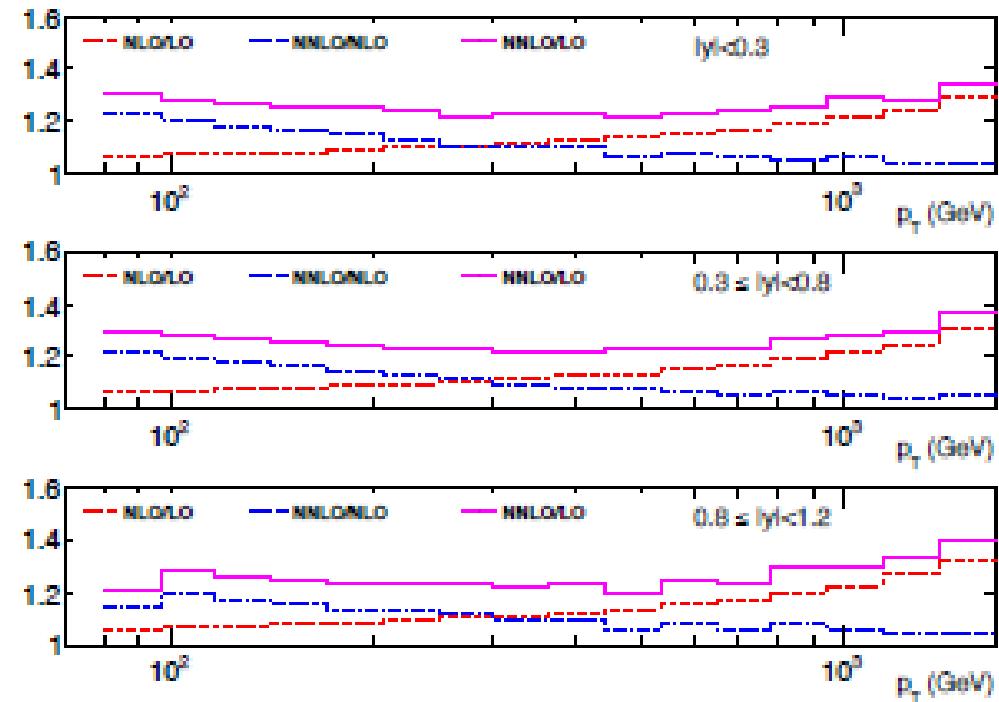


Enormous project of full NNLO calculation ([Gehrmann-de-Ridder, Gehrmann, Glover and Pires](#)) nearing completion. Some indications of full form of the correction.

Appears to be fairly similar to “threshold” correction near threshold. Overall  $\sim 5 - 20\%$  positive correction growing at lower  $p_T$ .

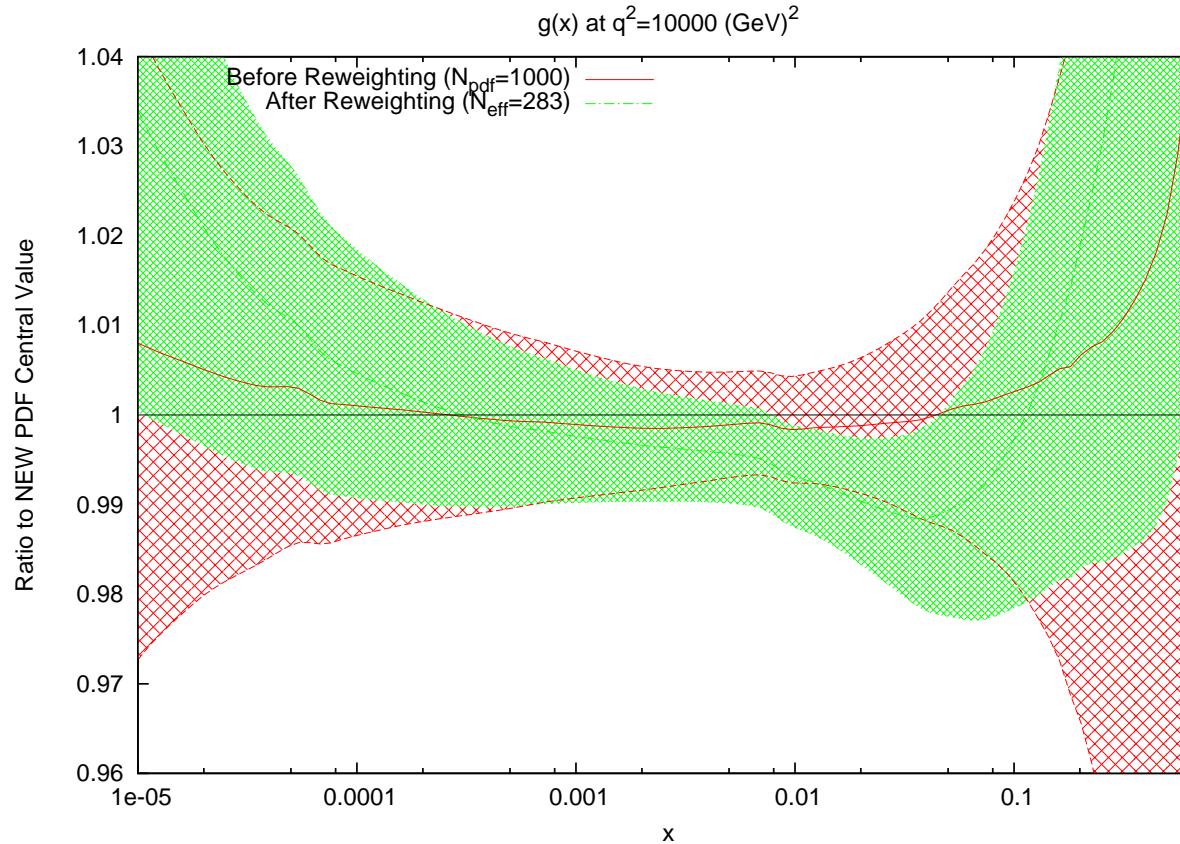
Try NNLO PDFs without the data in fit using NLO calculations –  $\chi^2$  lower than at NLO.

## Inclusive jet production: double differential distributions $R = 0.4$



Put in very approx NNLO correction of  $\sim 5 - 20\%$  positive correction growing at lower  $p_T$  and fit. Quality a bit worse than at NNLO with again  $\alpha_S(M_Z^2)$  a bit lower, e.g.  $\alpha_S(M_Z^2) = 0.116$ . Not clear on best approach. Hopefully full NNLO ready soon.

## Dijets – (B. Watt)



Using reweighting exercise for CMS dijets results in a rather modified shape of gluon.

Not as high rapidity as other sets – dependence on renormalisation/factorisation scales not so severe.

Reflection of different shape of higher order corrections?

## LHC data on $W,Z$

Now using APPLGrid – MCFM include the ATLAS  $W,Z$  rapidity data directly in the fit.

Before inclusion  $\chi^2 \sim 1.6$  per point. though improves by about 0.1 per point if ZEUS run II data omitted.

Inclusion leads to very little extra improvement, or change in PDFs.

$W^+ - W^-$  asymmetry no longer an issue at all (CMS asymmetry data not currently fit, but comparison very good), but relative shape/size of  $W, Z$  not perfect. Recognised as being related to strange quark fraction.

However,  $W,Z$  data provides little pull on strange quark distribution which is constrained by dimuon data.

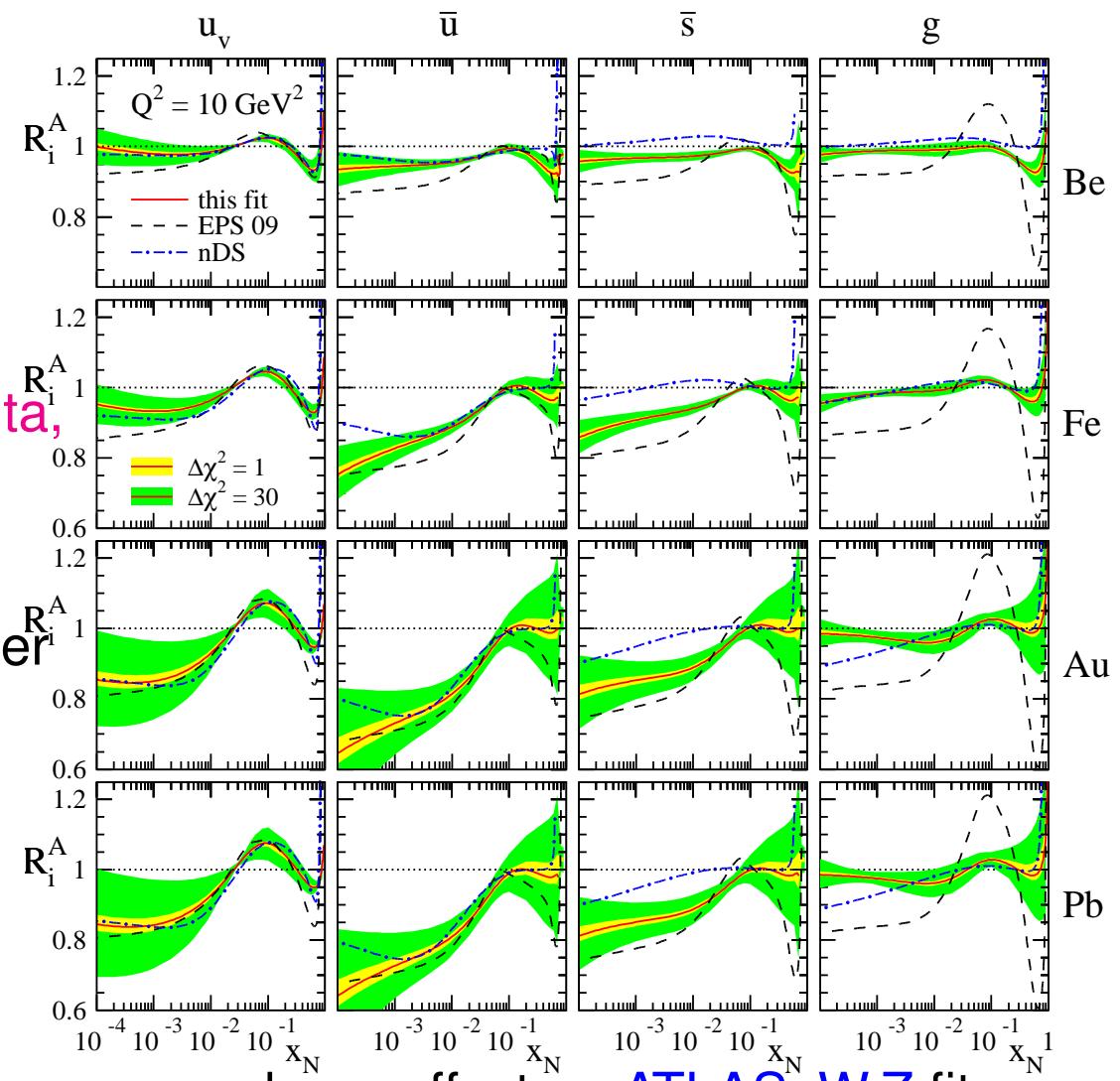
No perceptible result when making strange quark parameterisation (much) more flexible.

Have been using de Florian, Sassot nuclear corrections.

Update to more recent version, de Florian, Sassot, Stratmann, Zurita, Phys.Rev. D85 (2012) 074028.

Mainly similar, but smaller for small- $x$  strange.

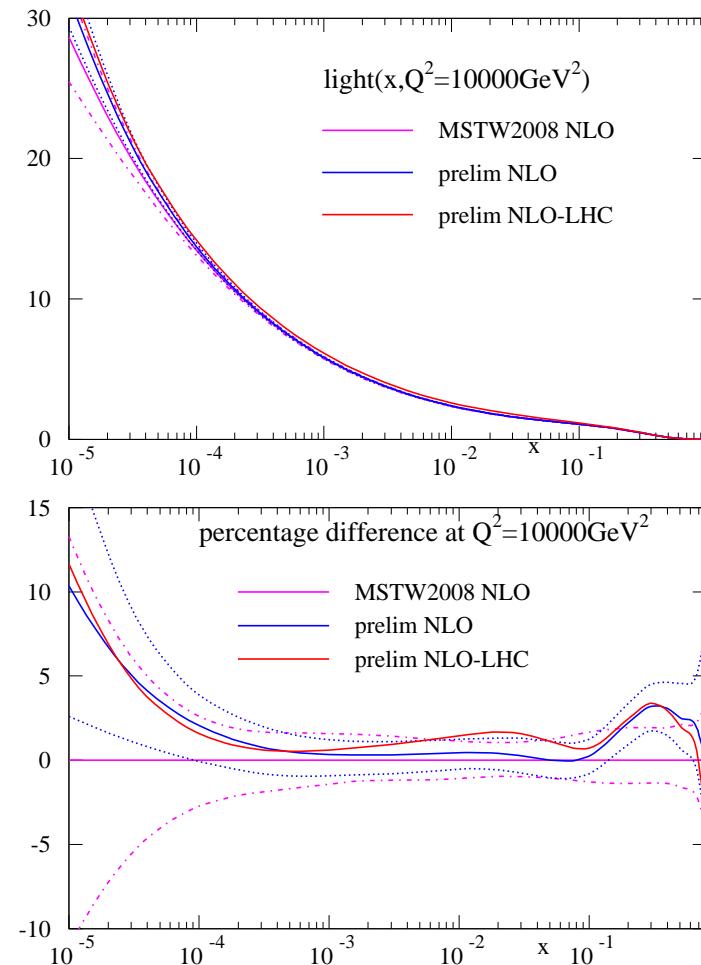
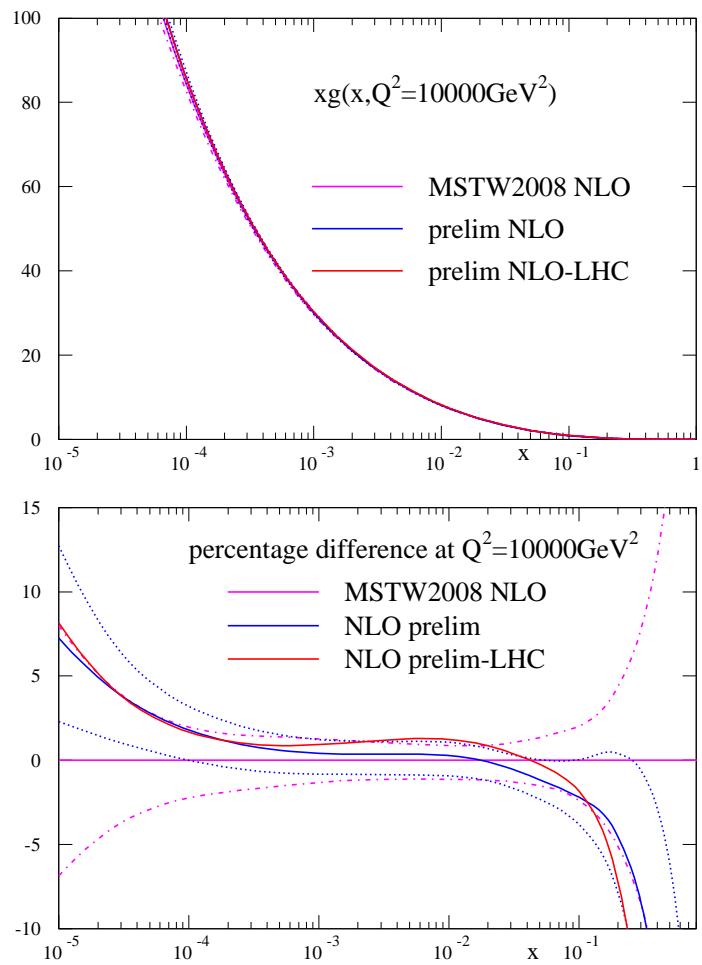
Improves global fit by  $\sim 25$  units - NuTeV  $F_2$ , HERA  $F_2$ , CMS jet.



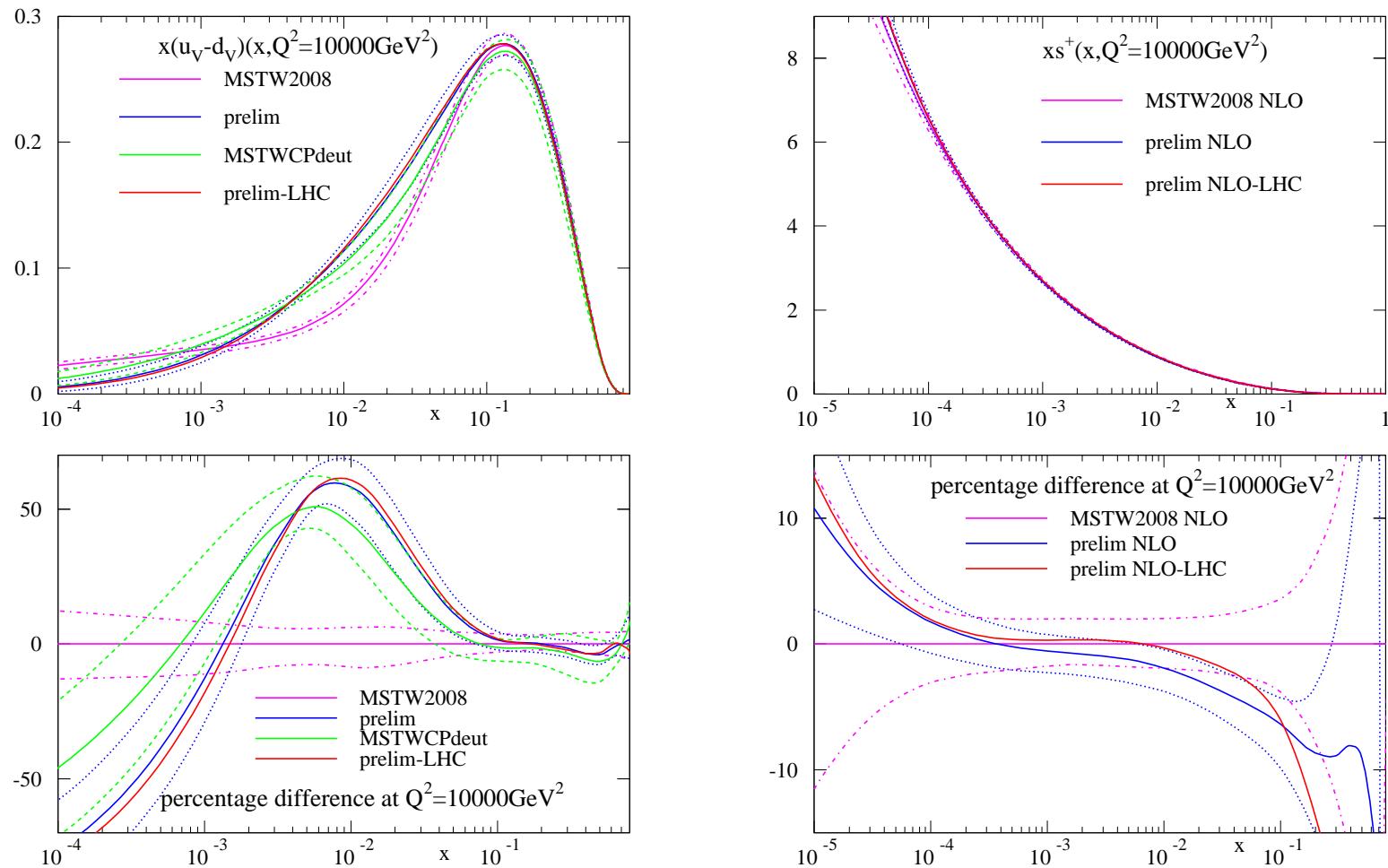
Only small change in strange quark, no effect on ATLAS, W,Z fit.

Treat as most up-to-date set (at the moment).

No significant change in cross sections compared to fit without LHC data.



Change in **NLO** PDFs from all previous updates (minus **ZEUS** run II) plus **LHC** data.  $\alpha_S(M_Z^2) = 0.1192$ .



Change in **NLO** PDFs from all previous updates (minus **ZEUS run II**) plus **LHC** data.  $\alpha_S(M_Z^2) = 0.1192$ .

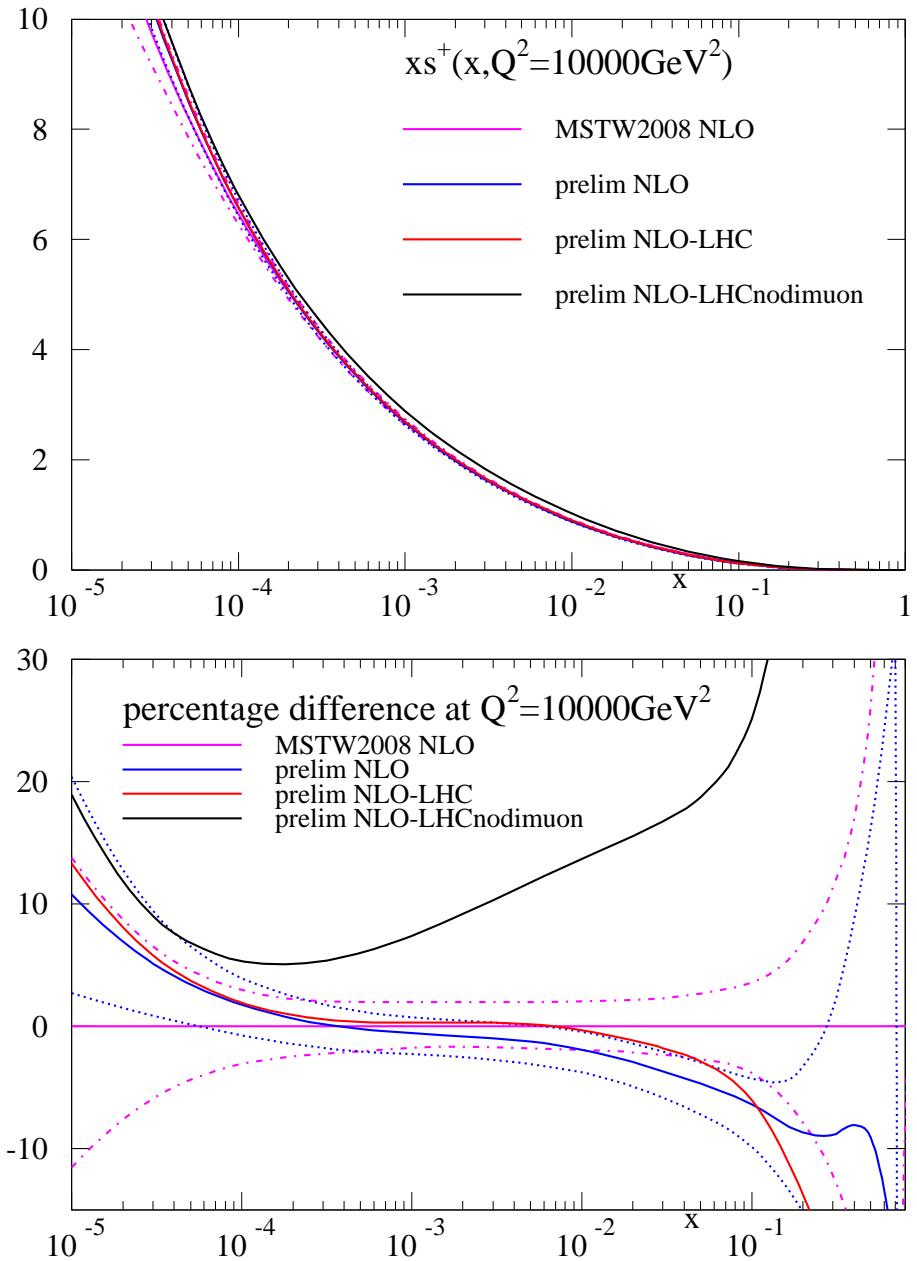
Extreme study - try cutting the direct strange constraint from dimuon data from fit.

Rest of data improves by  $\sim$  25 units.

ATLAS W,Z now  $\chi^2 = 38/30$ . Nuclear  $F_2, F_3$  and Drell-Yan data improve slightly. HERA data slightly worse.

Dimuon data  $\chi^2 \sim 9$  per point (with updated nuclear correction). Factor 1.25–2.0 too high, depending on  $Q^2$ .

Constraint strong enough that improvement to other (ATLAS W,Z) data doesn't register in normal fit.



However, branching ratio for charm mesons to muons **0.099**, probably a bit high.

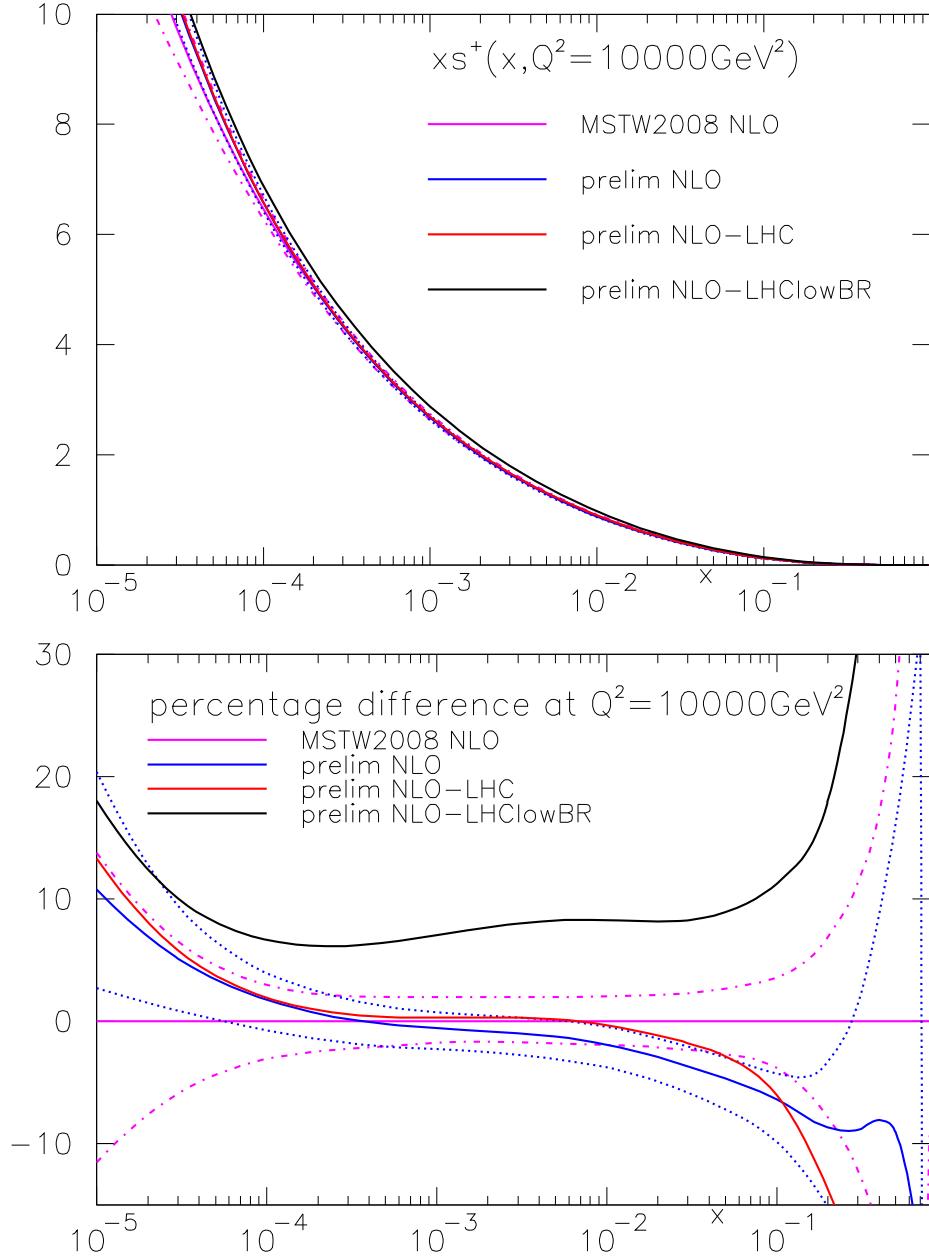
Try **0.080** – low but plausible (maybe) looking number.

Fit improves by  $\sim 12$  units, mainly in **ATLAS W,Z**, now  $\chi^2 = 40/30$ .

Strange distribution increases by  $\sim 8 - 10\%$  in region of **LHC** data. Now likes extra parameterisation freedom.

Little change in the other PDFs, except a compensating lowering of up and down sea.  $\alpha_S(M_Z^2) = 0.1194$

Looks promising.



## Conclusions

Ongoing updates on PDFs in **MSTW** framework. Combination of many previous individual investigations.

Improvement in parameterisation and heavy flavour treatments, and ultimately of nuclear corrections.

Inclusion of more up-to-date **HERA** and **Tevatron** data.

No particularly major changes beyond those in **MSTWCPdeut**.

Slight improvement in agreement with predictions for **LHC** data.

Also directly included most significant available **LHC** data, i.e. **ATLAS**  $W, Z$  rapidity data and all published **ATLAS** and **CMS** inclusive jet data. Fit good, particularly for jets.

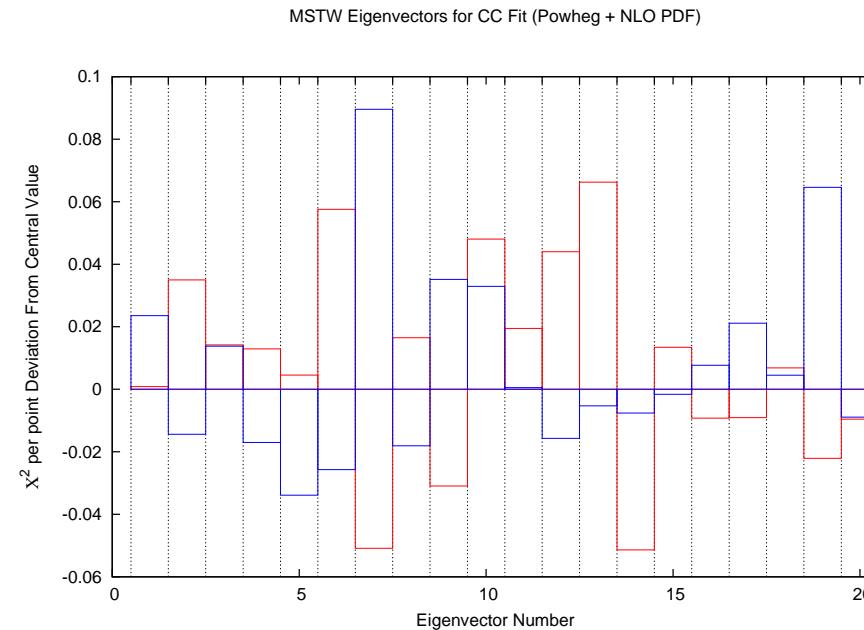
So far have little further effect on PDFs, though some effect on gluon uncertainty. Starting to understand role of strange in  $W, Z$  distributions?

At **NLO** at present  $\alpha_S(M_Z^2) = 0.1192$ , i.e 0.001 smaller than **MSTW2008**. At **NNLO** similar indication though also  $\sim 0.001$  uncertainty in manner **NNLO** may affect jets, i.e.  $\alpha_S(M_Z^2) = 0.1155 - 0.1175$ .

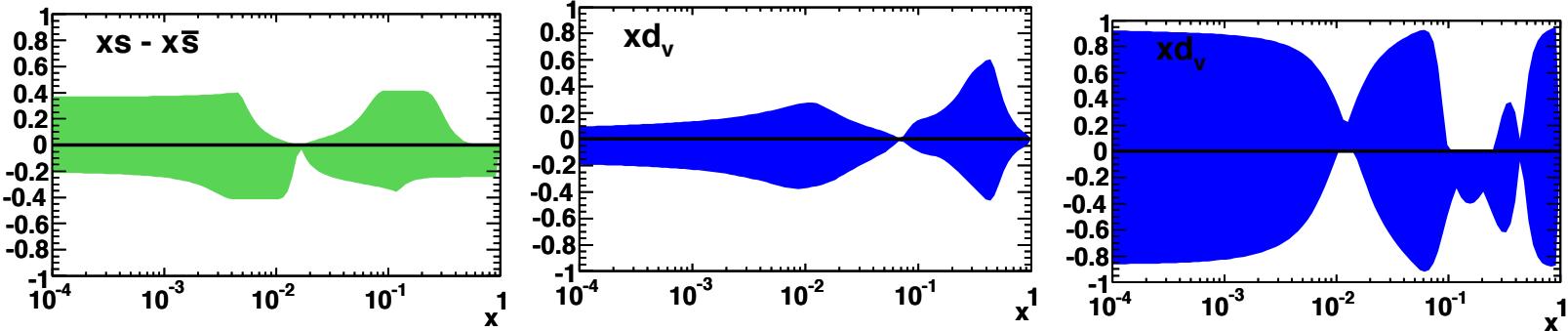
# **Back-up**

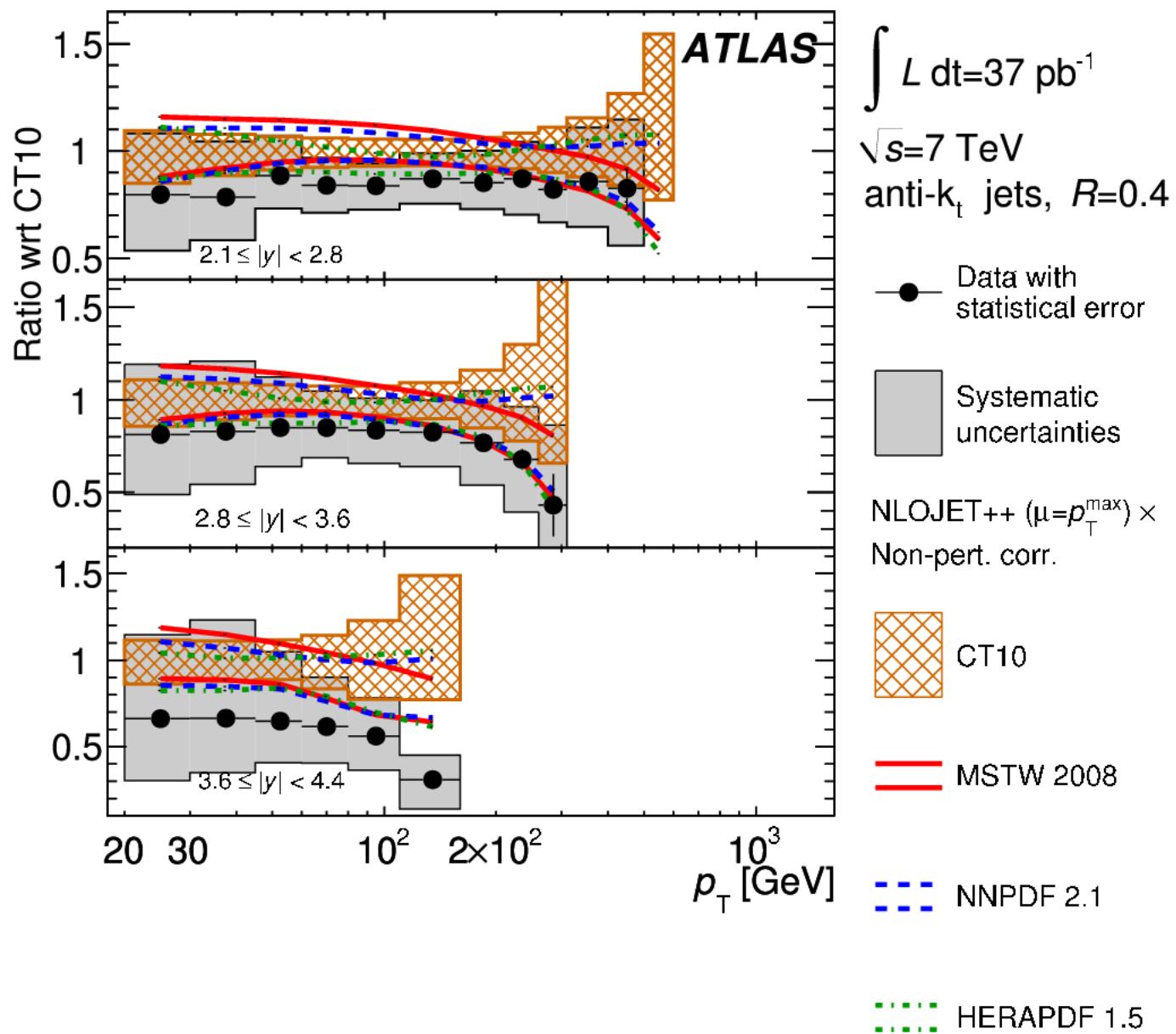
## DIS jets - B. Watt

Interesting observation in eigenvector sensitivity to charged current ZEUS jet data using [POWHEG](#).



Some sensitivity to  $s - \bar{s}$ .





**ATLAS**

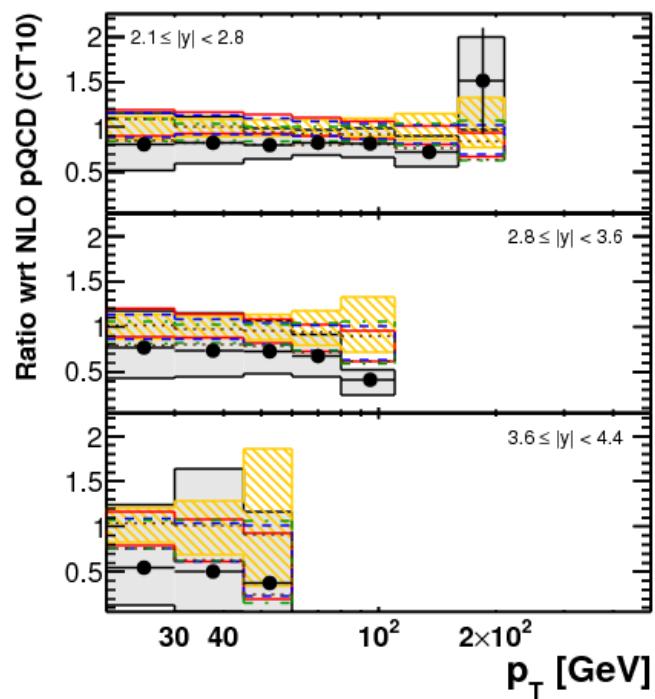
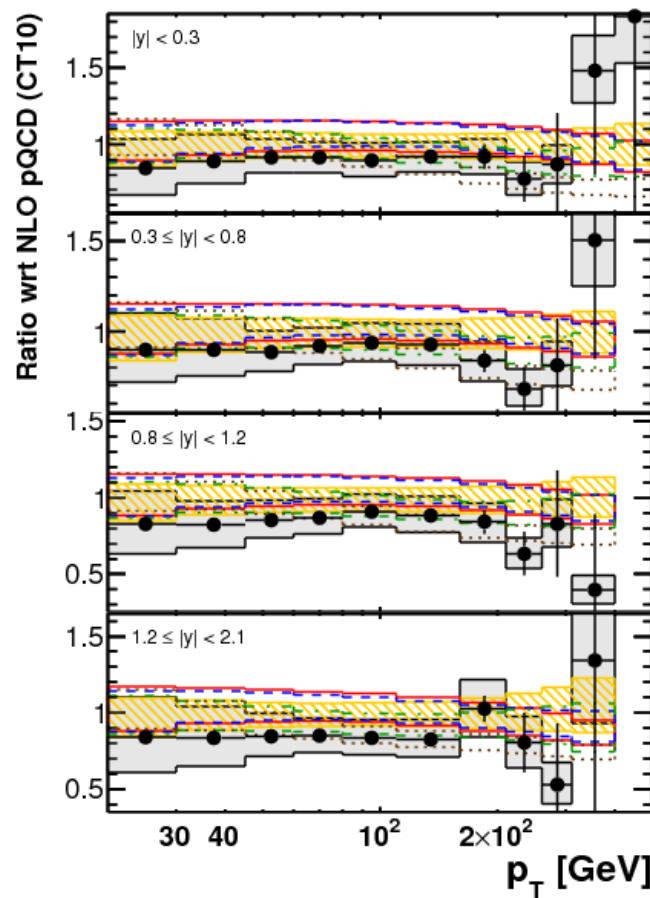
$$\int L dt = 0.20 \text{ pb}^{-1}$$

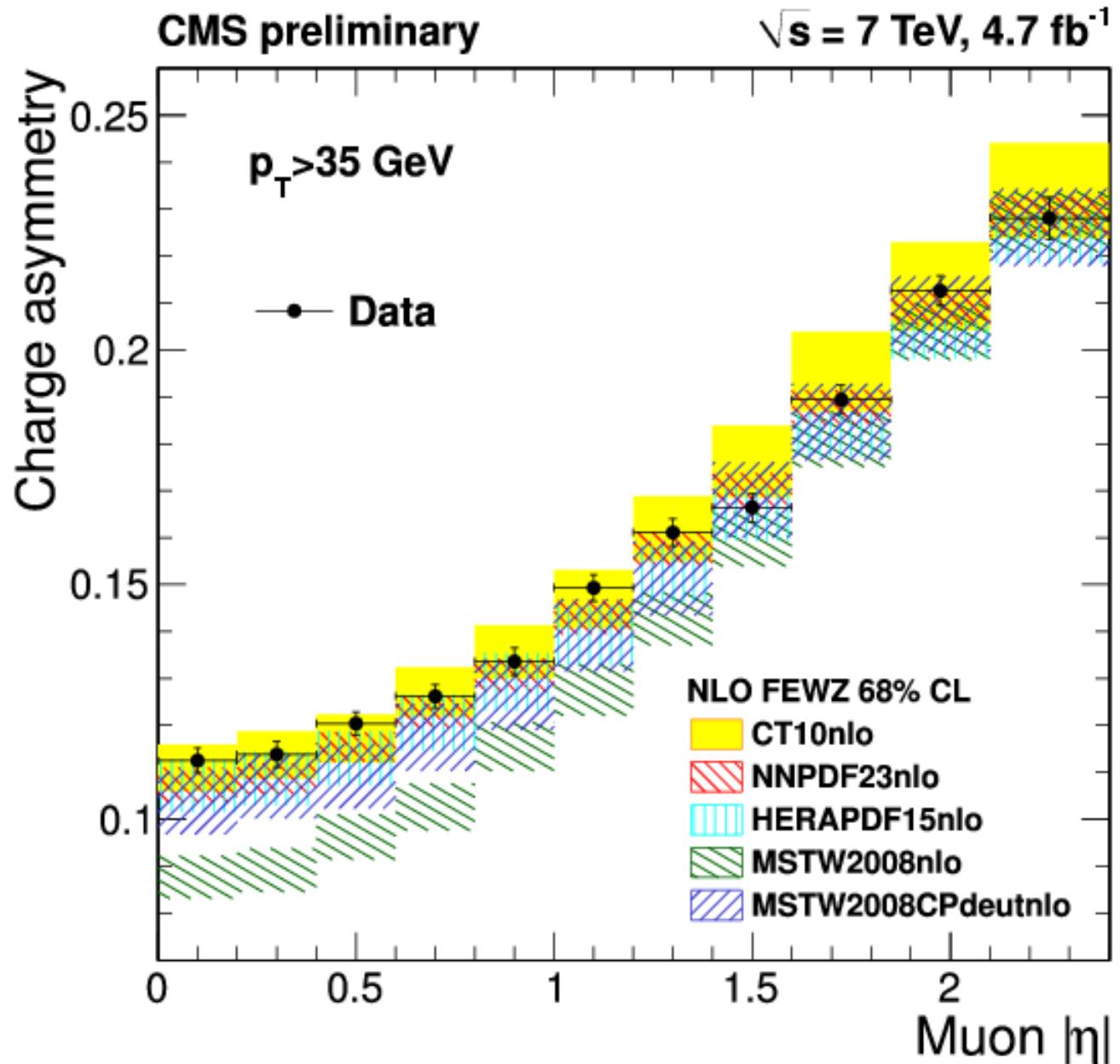
 $\sqrt{s} = 2.76 \text{ TeV}$   
 $\text{anti-}k_t, R = 0.4$ 

Data with  
statistical  
uncertainty  
Systematic  
uncertainties

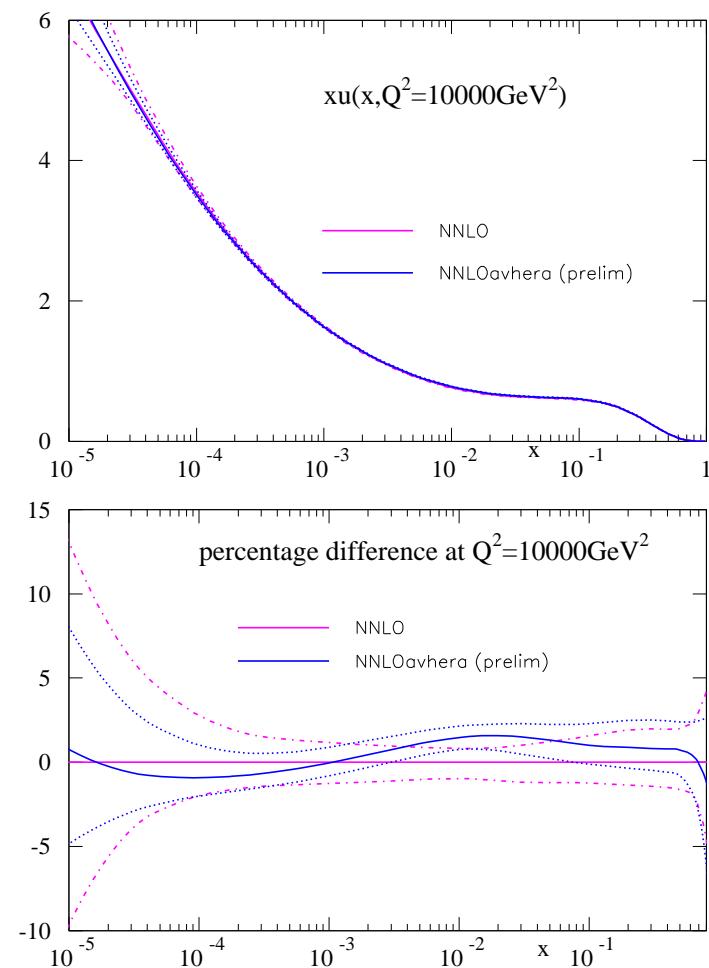
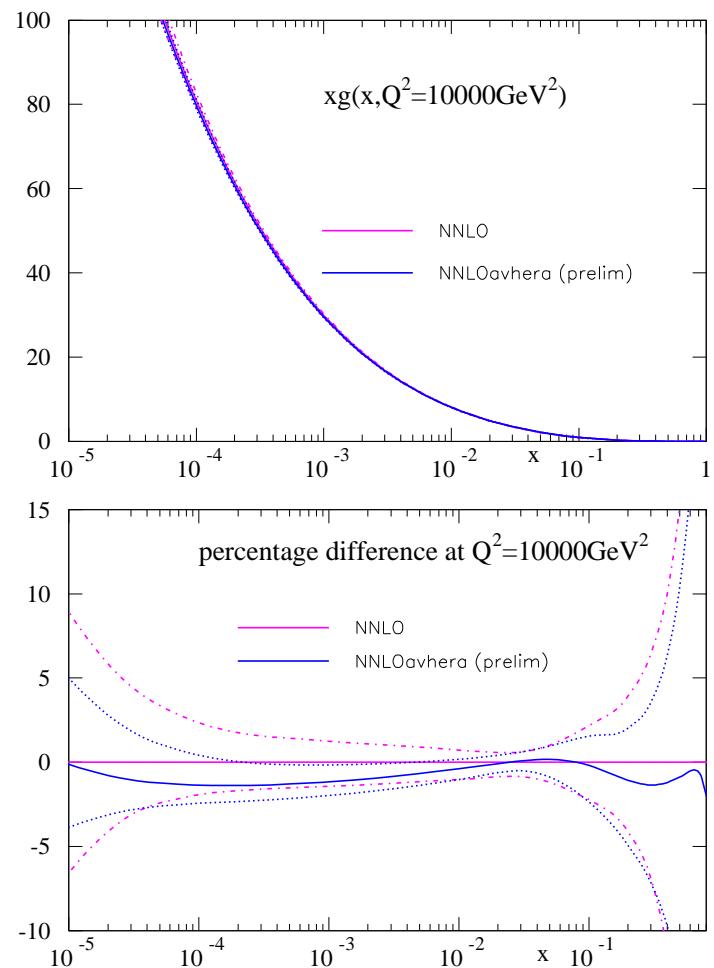
NLO pQCD  $\otimes$   
non-pert. corrections

- \diagup CT10
- MSTW 2008
- NNPDF 2.1
- HERAPDF 1.5
- .... ABM 11 NLO

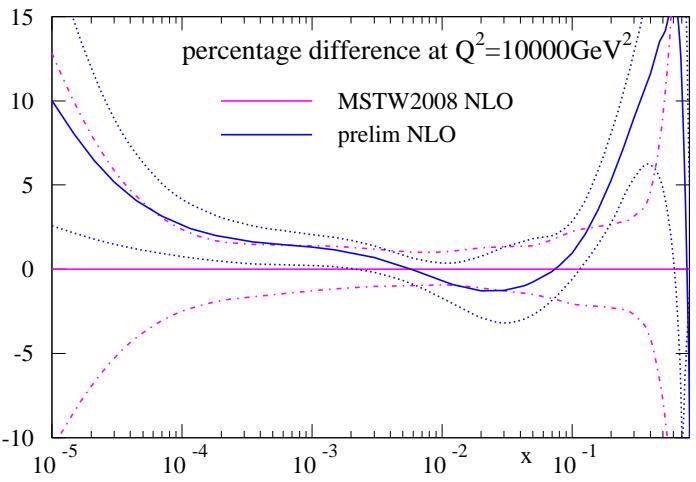
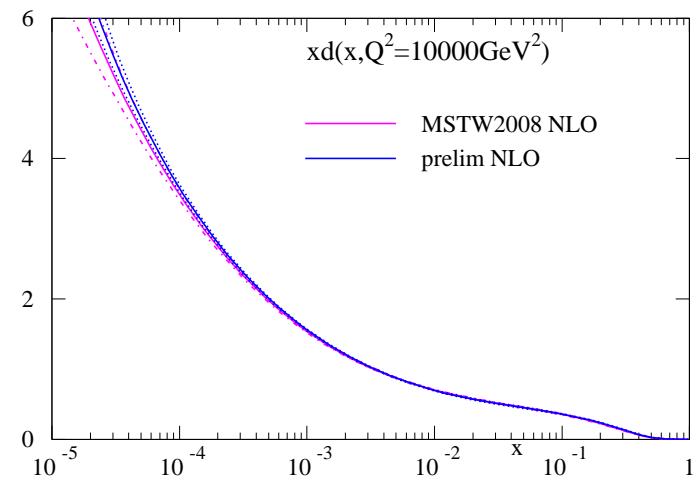
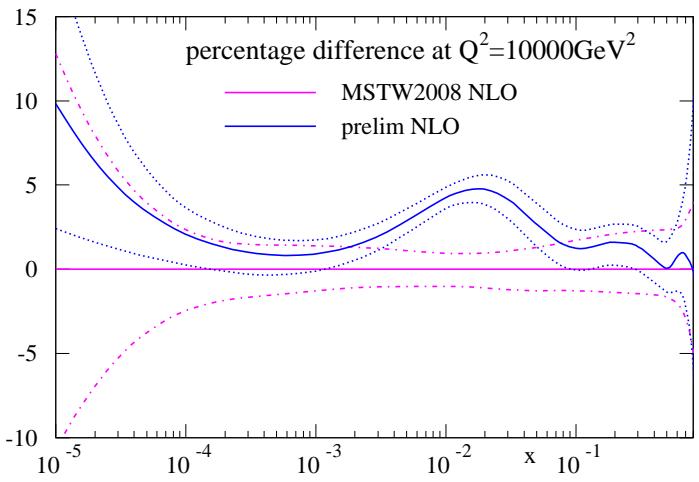
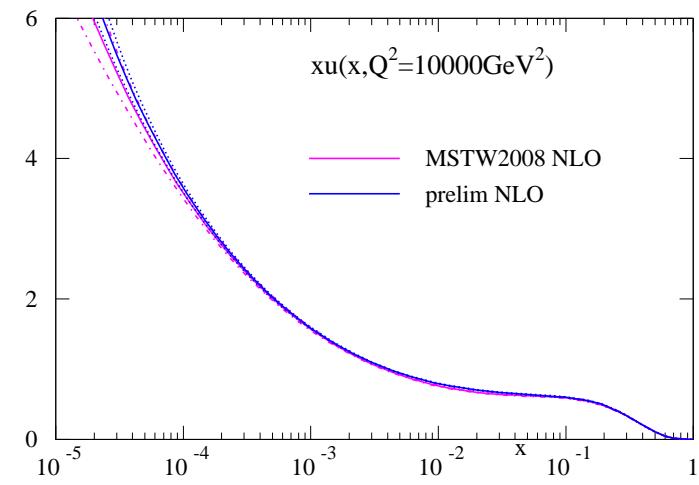




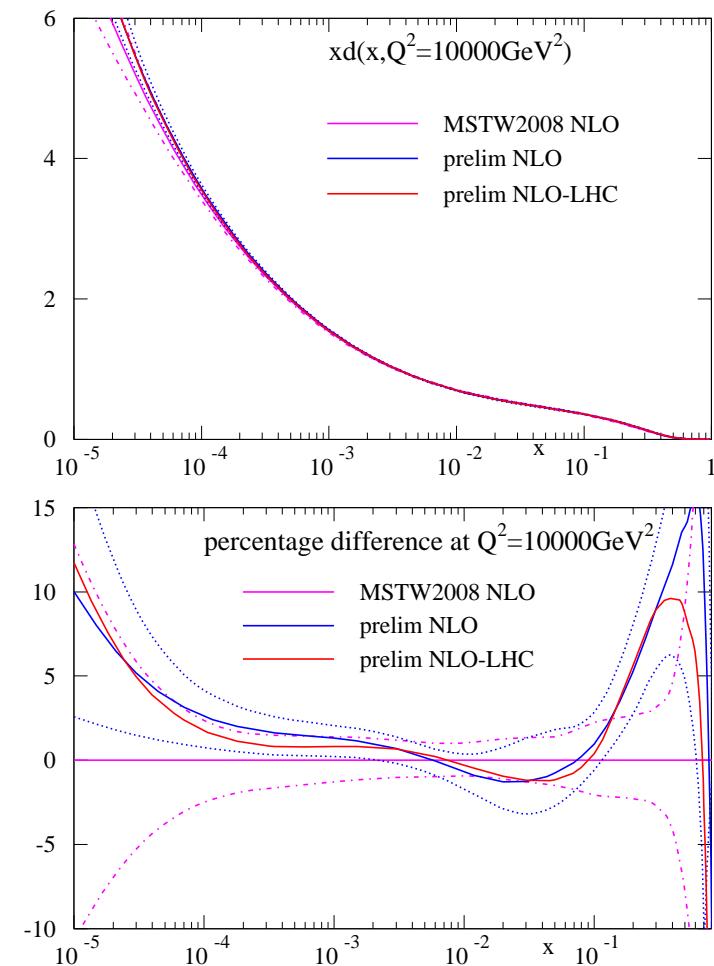
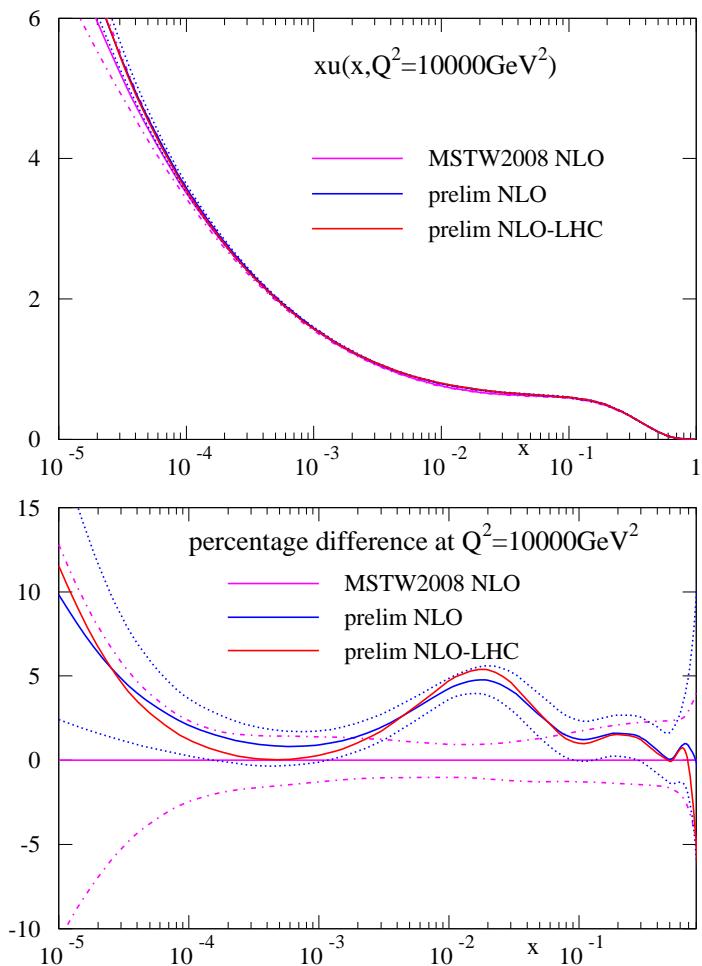
Comparison of various PDFs to CMS lepton asymmetry.



Change in **MSTW2008 NNLO PDFs** when fitting **HERA** combined data.

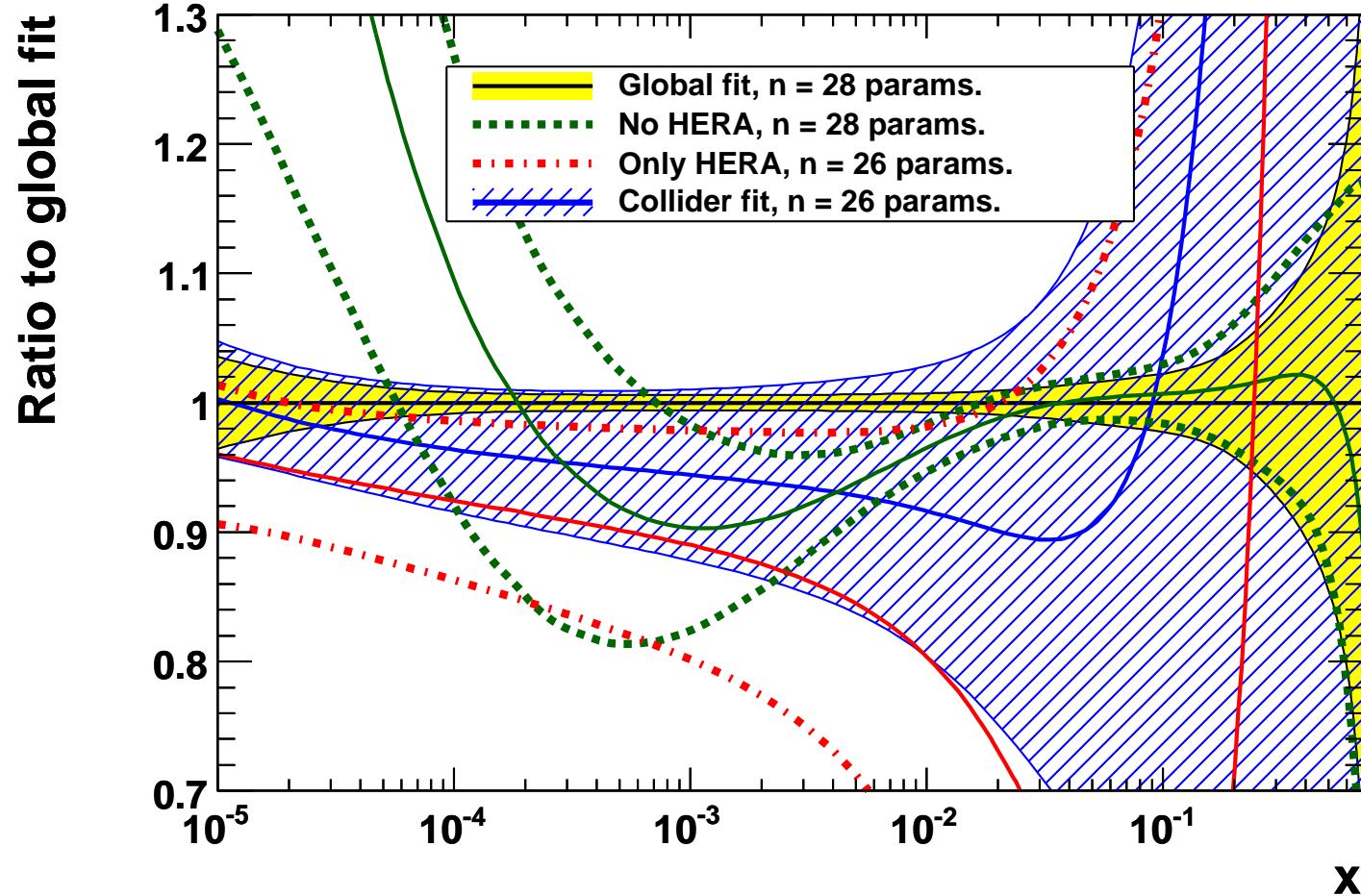


Change in **NLO PDFs** from all updates.



Change in **NLO** PDFs from all previous updates (minus **ZEUS run II**) plus **LHC** data.  $\alpha_S(M_Z^2) = 0.1192$ .

## Strange quark distribution at $Q^2 = 10^4 \text{ GeV}^2$



Change in strange distribution when fitting to different selections of data.