Parton Distribution Functions and LHC physics

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LHeC, Chavannes, Jan 20th 2014

- PDF discrimination – using data to rule out some PDF sets
- PDF improvement – using data to make PDF sets more accurate

Measurements:

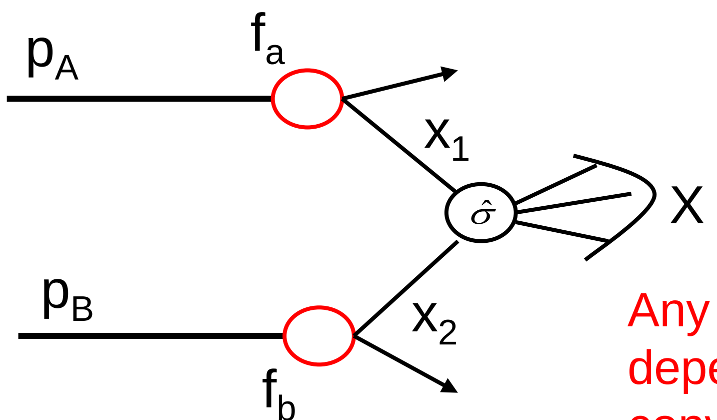
1. W and Z production, Valence PDFs, strange and maybe more on sea quarks
2. W+c production, strange
3. Inclusive Jet and Di-Jet production, gluon and $\alpha_S(M_Z)$
4. Drell-Yan: low and high invariant mass, sea quarks at high-x, DGLAP at low-x
5. Top-antitop, gluon and $\alpha_S(M_Z)$
6. Single top u and d
7. Direct Photon, gluon

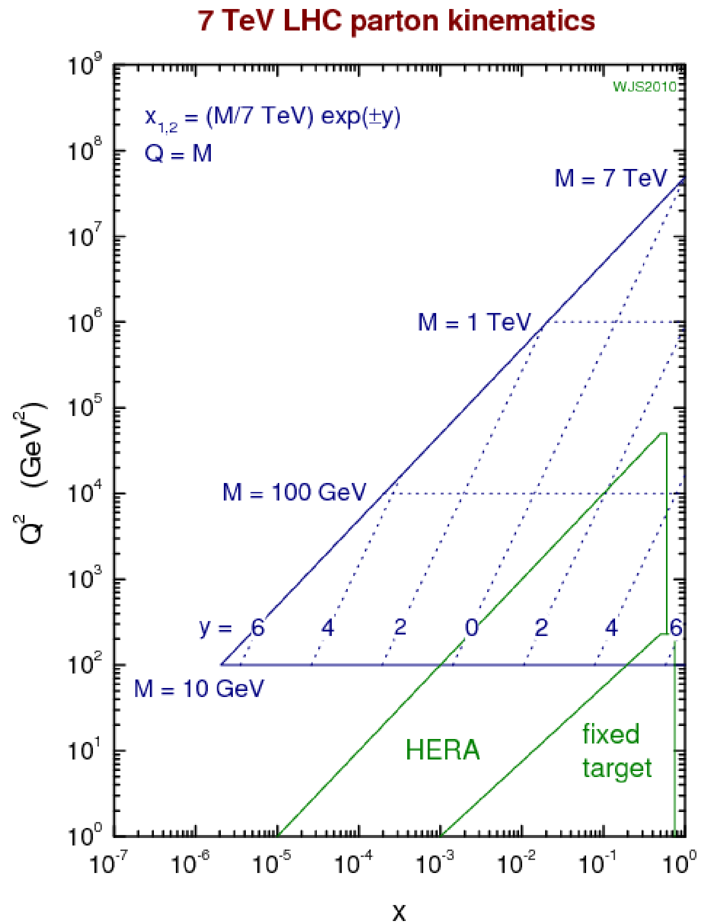
Some have been used in PDF fits already, some have potential.

Uncertainties on Parton Distribution Functions (PDFs) limit our knowledge of cross sections whether SM or BSM.

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2)\, f_b(x_2, \mu_F^2)$$
$$\times\ \hat{\sigma}_{ab\to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

where X=W, Z, D-Y, H, high-E_T jets, prompt-γ and σ is known to some fixed order in pQCD and EW or in some leading logarithm approximation (LL, NLL, …) to all orders via re-summation





Any claim for new physics at the highest masses is dependent on the PDF chosen to describe conventional physics.

The extent to which the Higgs that we are seeing agrees with the SM Higgs cross section predictions depends on the PDF.

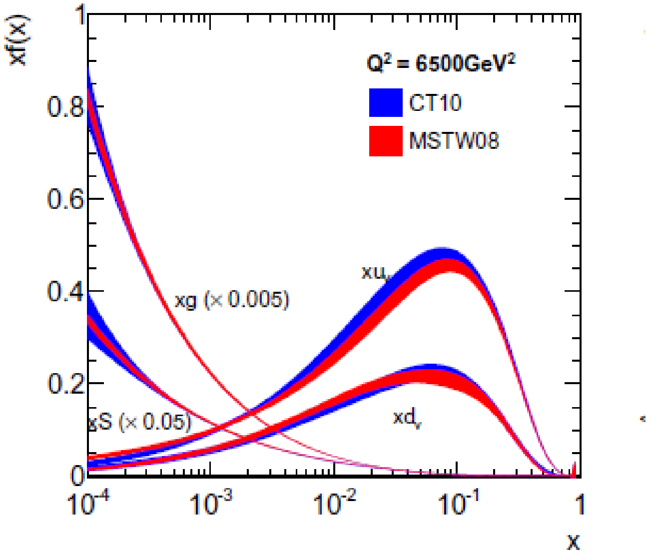
We can use SM measurements to discriminate and improve current PDFs

W and Z production are the best known sub-process cross-sections: known to NNLO, so how did current PDFs do in predicting what we have actually measured?

And at central rapidity $x_1 = x_2$ and assuming ubar = dbar (at small x)

So $A_W \sim \frac{(u - d)}{(u + d)} = \frac{(u_v - d_v)}{(u_v + d_v + 2\,\text{qbar})}$

And the PDF predictions for valence differ at small-x

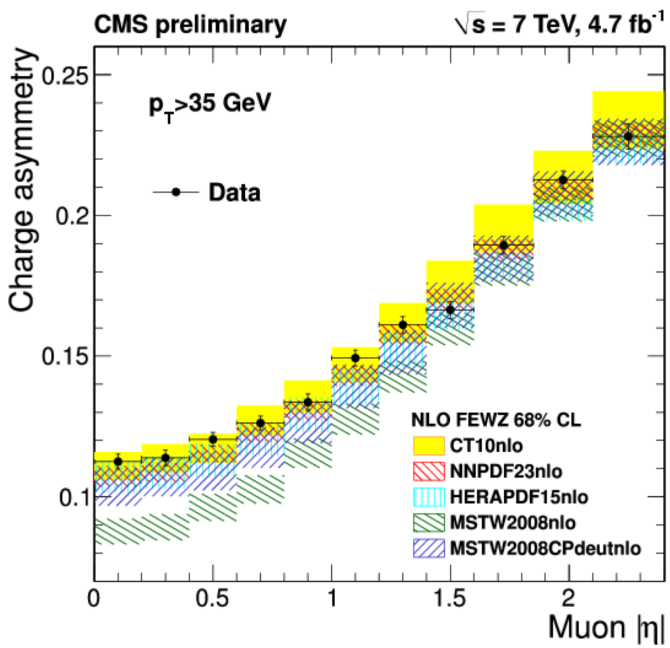


LHC data probe precisely the x range $10^{-3} < x < 10^{-1}$ where the difference is maximal

W-asymmetry

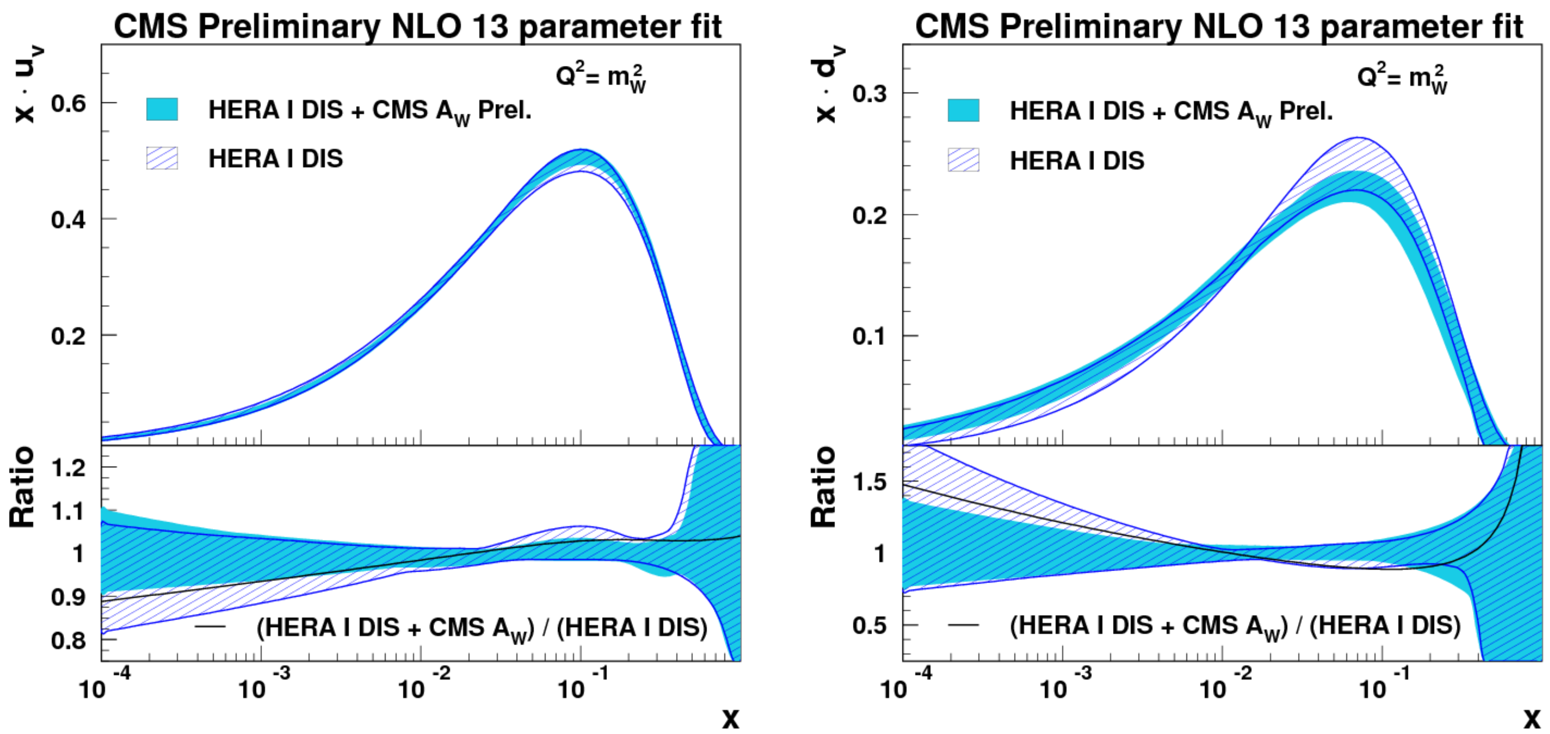
$$A_W = [\sigma(W^+) - \sigma(W^-)] / [\sigma(W^+) + \sigma(W^-)]$$

This translates into a difference in predictions for the W-lepton asymmetry pseudo-rapidity spectrum:



The CMS muon asymmetry data from 2011 (arXiv:1312.6283) clearly disfavour MSTW2008 (MSTW have addressed this in MSTWCPdeut)

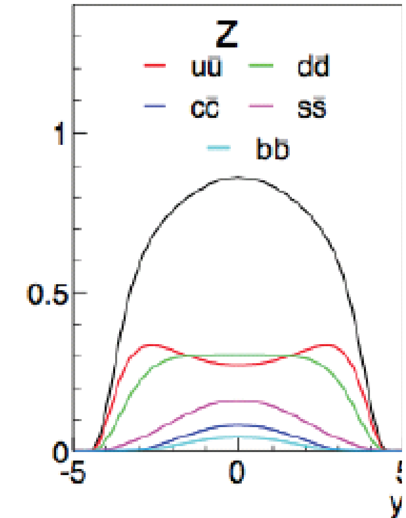
A PDF fit of these CMS muon asymmetry data together with the combined HERA-I inclusive deep inelastic scattering (DIS) data **(JHEP 1001 -109)**
shows the potential of the CMS data to constrain valence quarks

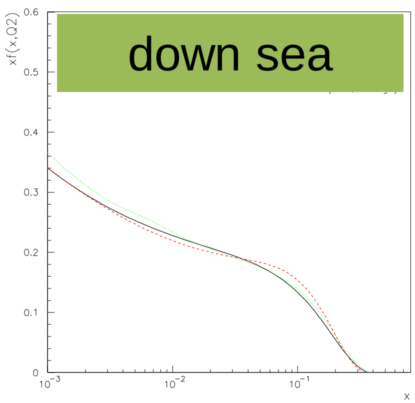


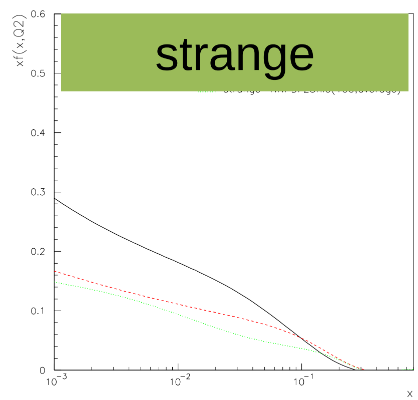
W and Z differential cross sections

Flavour contributions to W and Z show that s-sbar is prominent in Z production at central rapdidty.
This plots were made for the usual assumption that strange sea is suppressed ~0.5 of down sea.

This comes from di-muon production in neutrino induced deep inelastic scattering data. But not all PDFs which use these data have strange so suppressed at low-x



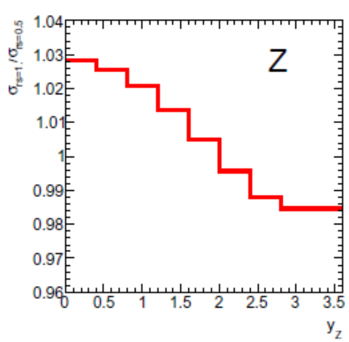


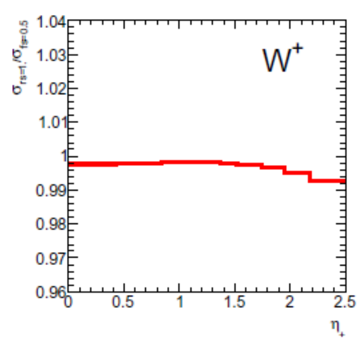


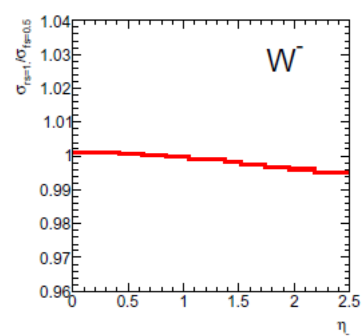
Q^2=2 GeV^2
CT10
MSTW08
NNPDF23

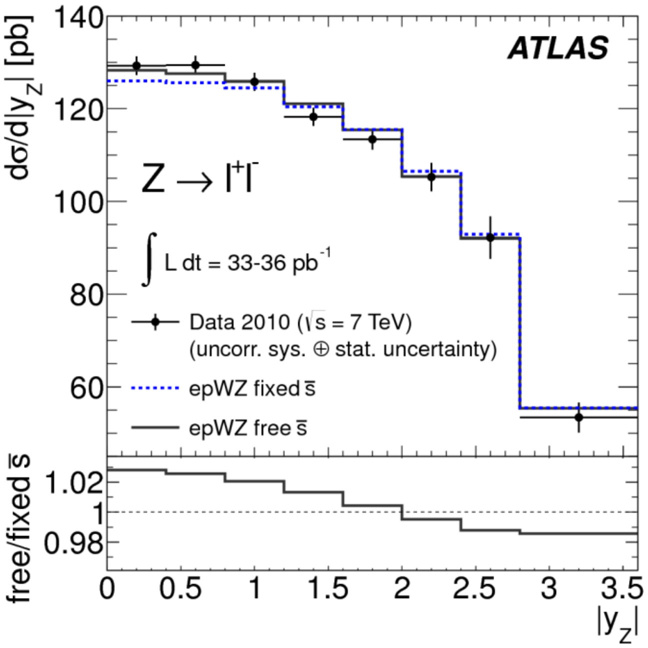
CT10 has enhanced strangeness ~0.75 of down sea, at x~0.01, as compared to ~0.5 for MSTW08 or NNPDF2.3

How would Z and W rapidity spectra at the LHC change if strangeness were enhanced?This is the ratio of Z and W cross-sections for strange = down sea in ratio to strange = 0.5 down sea
It affects the Z not the W's
This is a small effect ~ 4%- can we see it?









YES WE CAN: ATLAS Phys Rev Lett 109(2012)012001

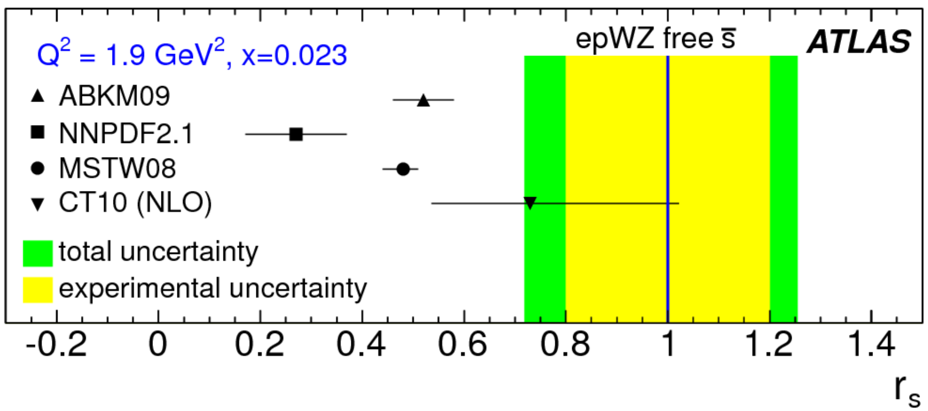
NNLO PDF fits to the ATLAS W,Z data plus HERA data (using HERAfitter) are shown for two assumptions about strangeness: s/d = 0.5 fixed and s/d = r_s (1-x) $^{(Cs\text{-}Cd)}$ – fitted.

The fit gives s/d = r_s = 1.0 ± 0.25

$r_s = 1.00 \pm 0.20_{exp} \pm 0.07_{mod}\ {}^{+0.10}/_{-0.15\ par}\ {}^{+0.06}/_{-0.07\ \alpha s} \pm 0.08_{th}$

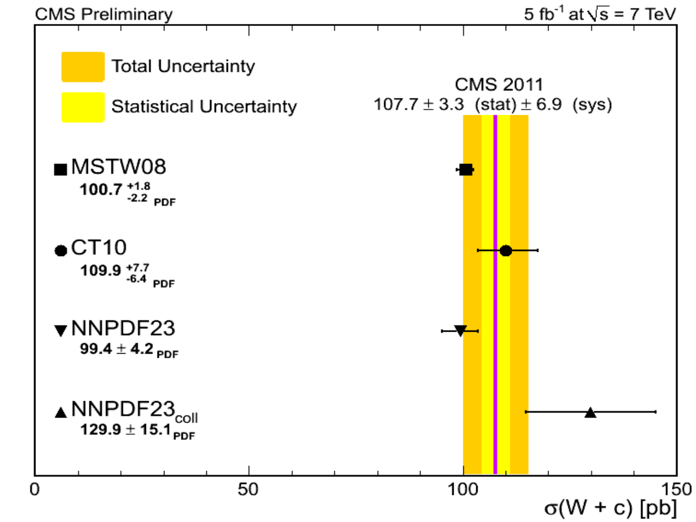
The experimental accuracy of the result depends on the shape of the Z spectrum and on its correlation to the W spectra, which fix the normalisation.

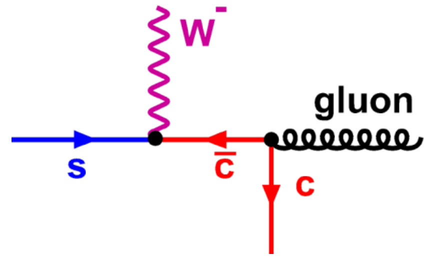
This result indicates enhanced strangeness in agreement with the CT10 predictions at x~0.01 - which is the kinematic region probed by LHC data.
In fact the ATLAS 'epWZ' fit has even more strangeness than CT10

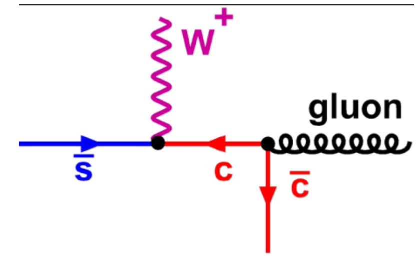


Another process which can yield information on strangeness is W+c production

CMS SMP-12002

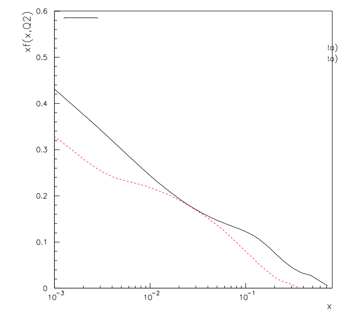




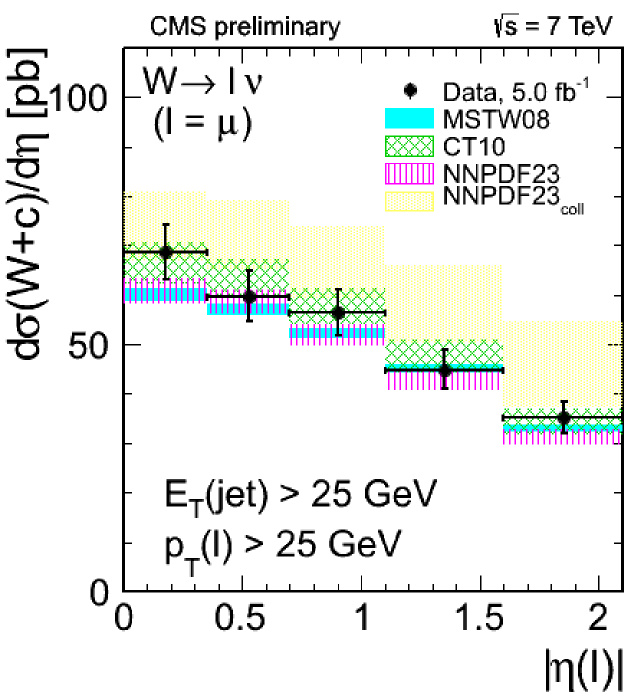


First compare W +c cross section for W's of both charges to predictions.

Very good agreement with CT10 and not in such good agreement with NNPDF2.3 (Coll) but the latter has VERY large strangeness



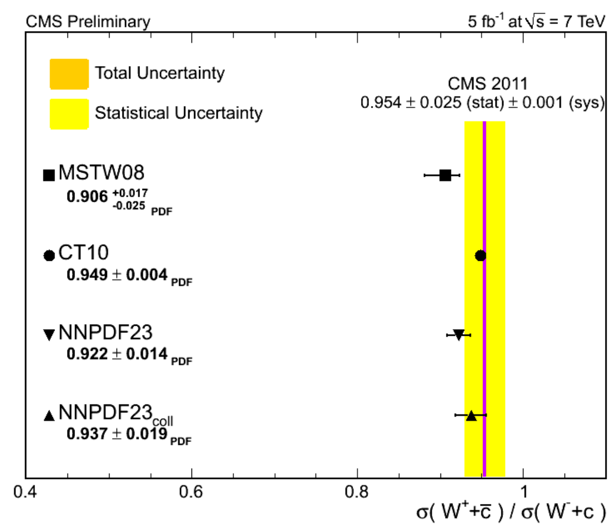
Q^2=2 GeV^2
NNPDF23(Coll)
Strange
Downsea



CT10 also describes the pseudo-rapidity spectrum of the lepton from the W

Finally CT10 does a good job on the ratio of the W^+ +c / W^- +c cross sections.

Strangeness asymmetry s ≠ sbar is small for all PDFs, for CT it is zero

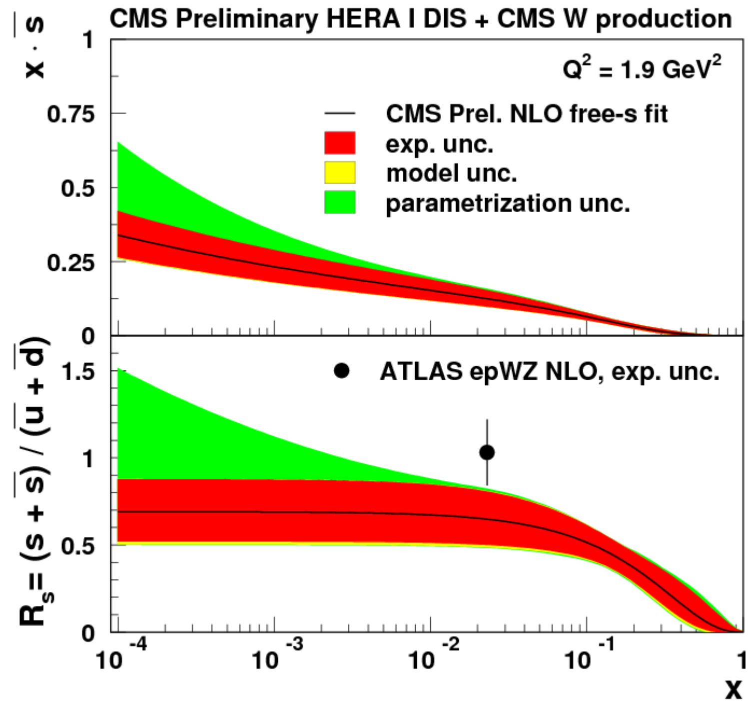


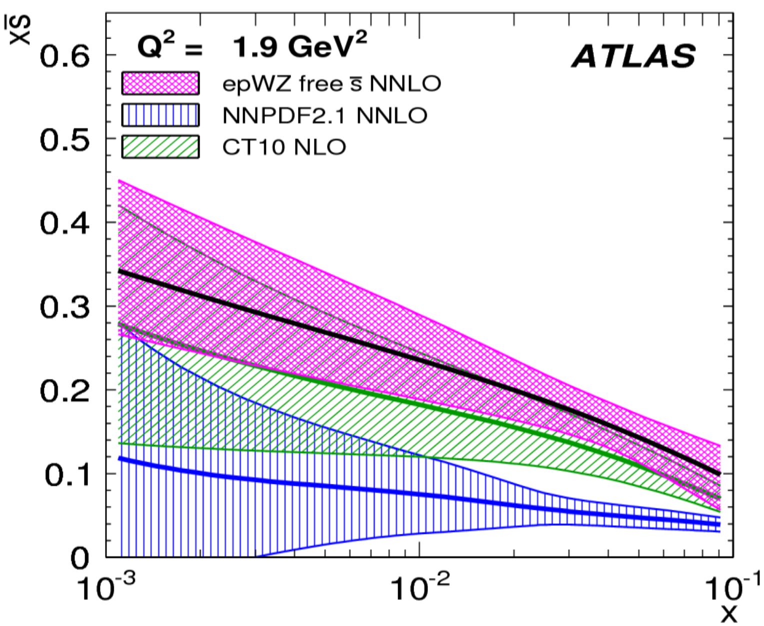
CMS have input these W+c result to a PDF fit together with the CMS W-asymmetry data and the combined HERA DIS data

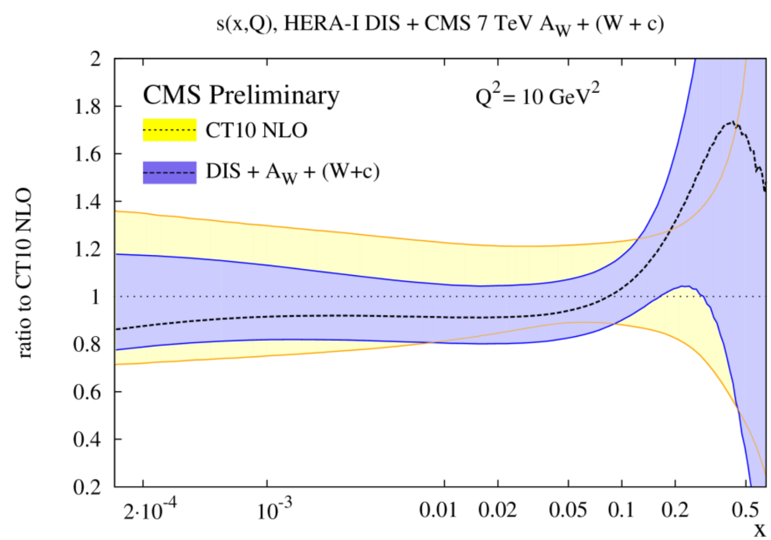
They obtain a strange quark distribution compatible with CT10.

Their analysis is at LO so can only be compared to a single point from the ATLAS analysis

However the ATLAS NNLO analysis also gave distributions

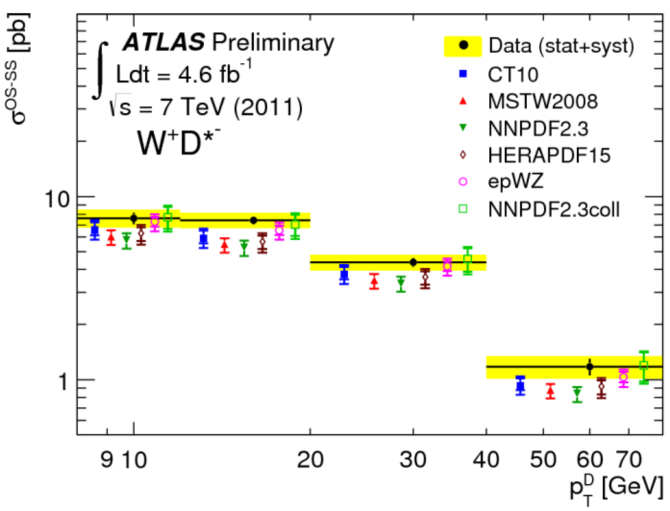


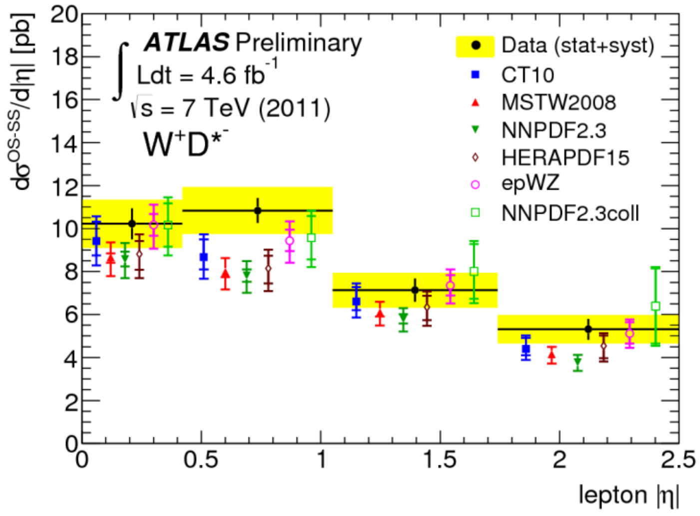


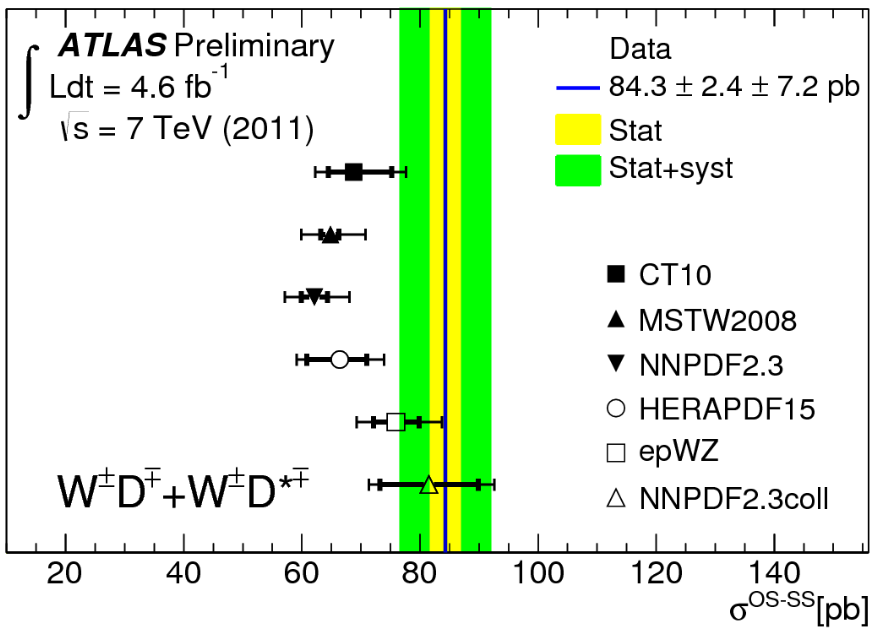


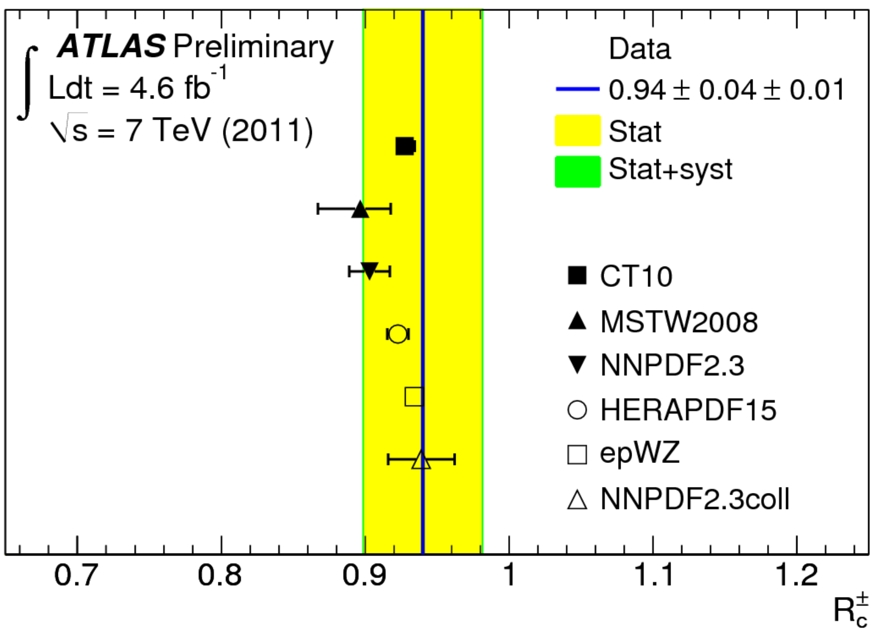
ATLAS does seem to yield somewhat larger strangeness than CMS…..?

Recently released ATLAS data on W+c favour even more strangeness than CT10,
iin agreement with ATLAS epWZ and NNPDF2.3(Coll).







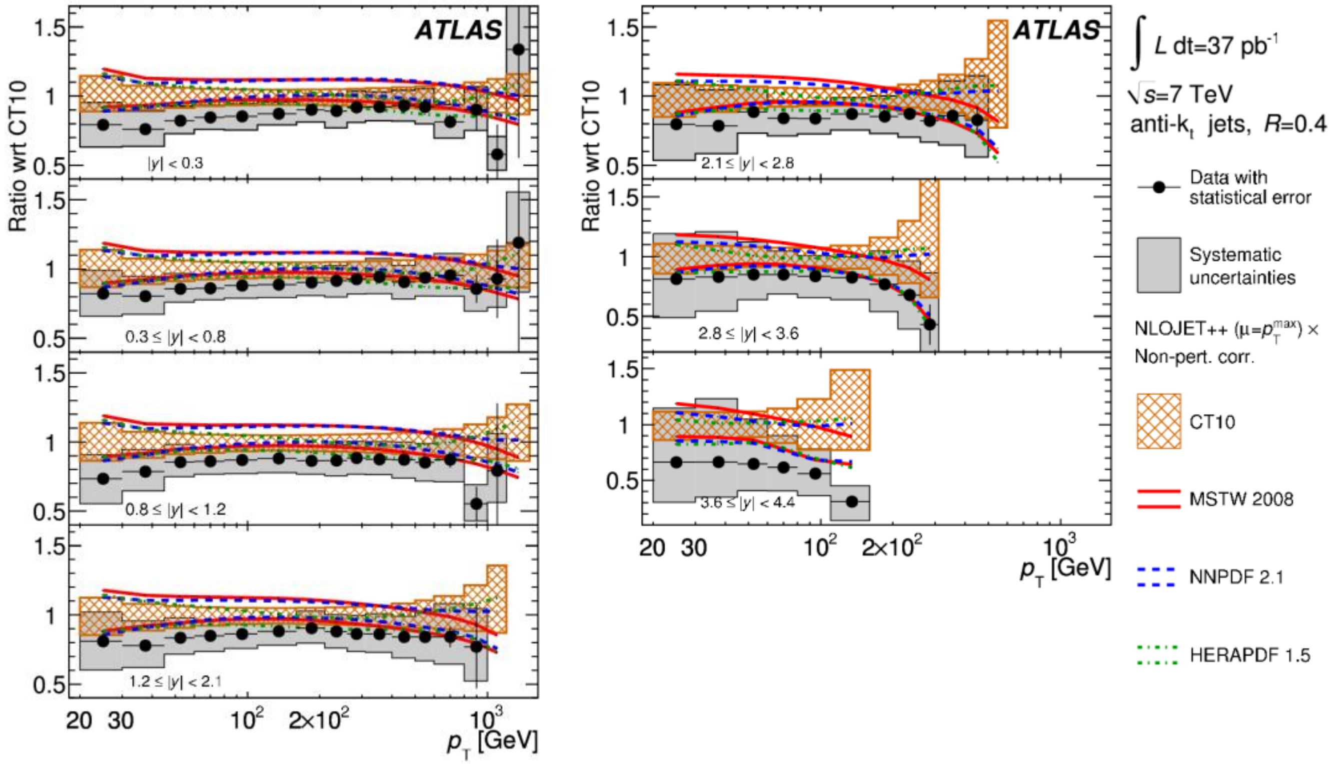


Now let's consider jet production, this gives information on the high-x gluon

ATLAS inclusive jet cross-sections for anti-kt algorithm,R=0.4 and R=0.6

ATLAS :Phys ReV D86(2012)014022

are provided with 90 sources of correlated error

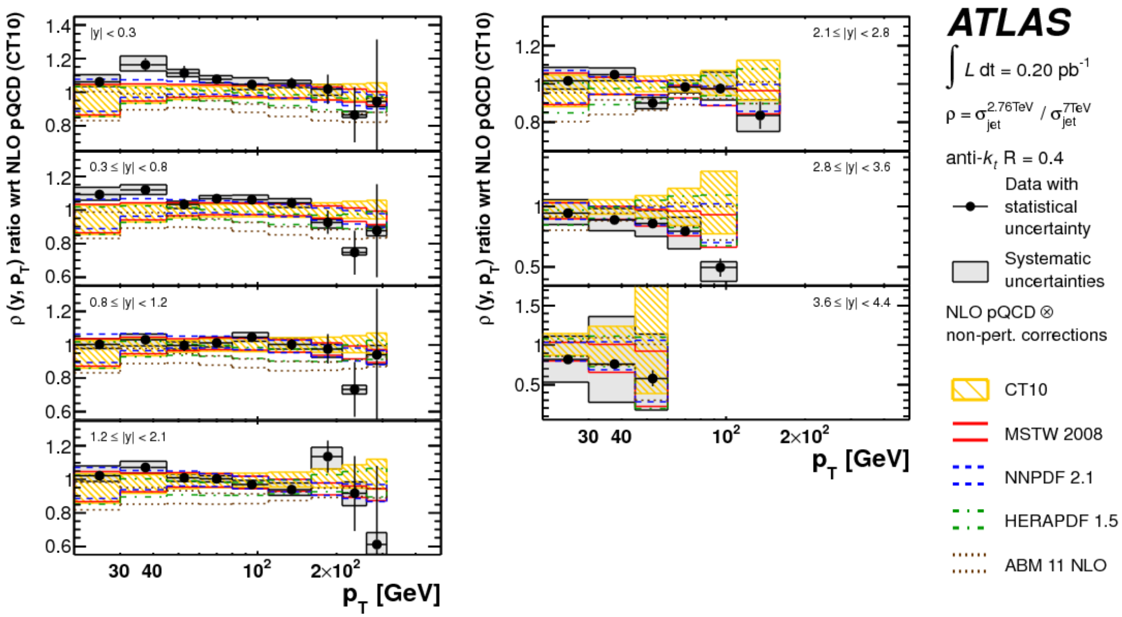


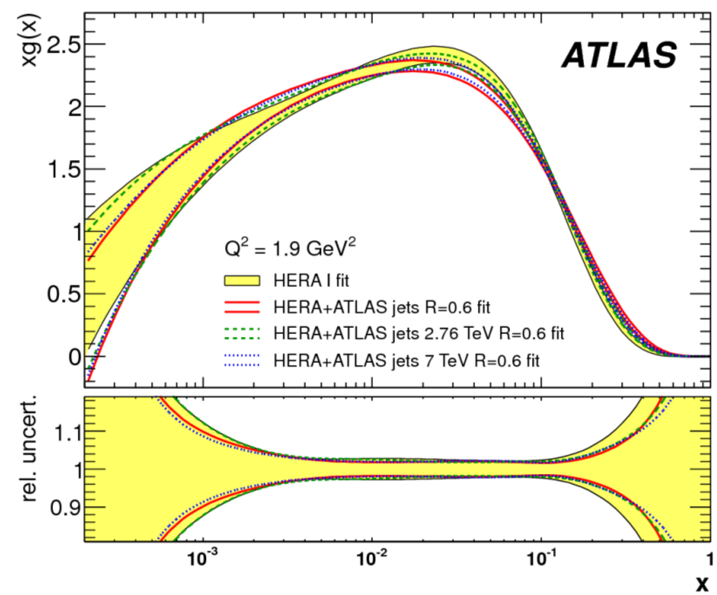
Here the inclusive jet cross sections are shown in ratio to the predictions of CT10, with the predictions of other PDFs also illustrated.

However these data have already been included in PDF fits– e.g. NNPDF2.3 and found not to have much impact

For the jet data to have more impact it is smart to consider ratios- the major experimental systematic - the Jet Energy Scale- largely cancels out

Consider the ratio of the 2.76 TeV jet cross-sections (0.2 pb^{-1} 2011 data arXiv:1304.4739) to the 7 TeV jet cross sections in ratio to the CT10 predictions for this ratio and compared to the predictions of MSTW2008, NNPDF2.1, HERAPDF1.5 and ABM





The two different beam energies probe different x and Q^2 values for the same pt and y ranges so that theoretical uncertainties due to PDFs do not cancel in the ratio.

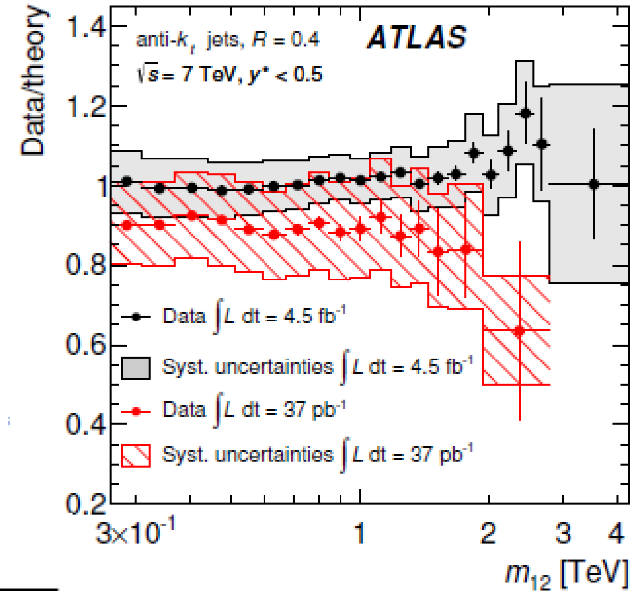
Compare the gluon PDFs for PDF fit using just HERA data and a fit using HERA+ ATLAS 2.76 and 7 TeV jet data.

The gluon becomes harder and the uncertainties on the gluon are reduced.

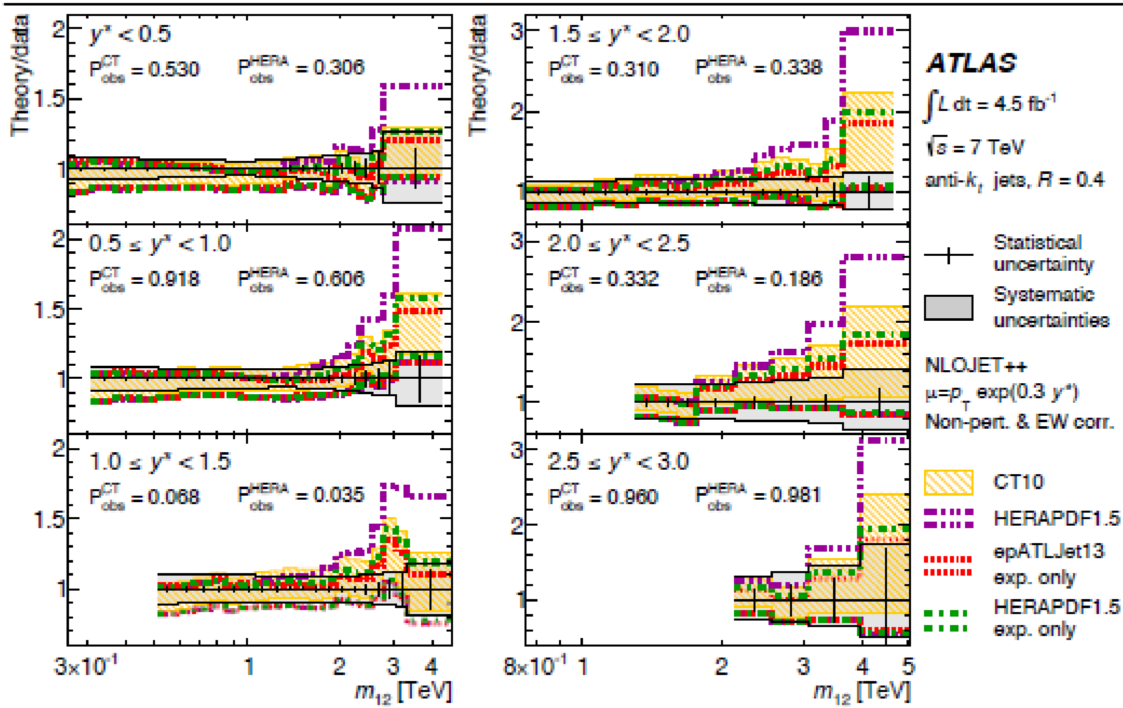
There is new dijet data from ATLAS arXiv:1312.3524

Comparison with 2010 data

- Reduced systematic and statistical uncertainty
- Extended range



Dijet production from 2011 data



Comparison with PDFs

Looks OK for HERAPDF and CT10 despite the fact that HERAPDF1.5 does not use tevatron Tevatron jet data and thus has a softer gluon.

Comparison with PDFs

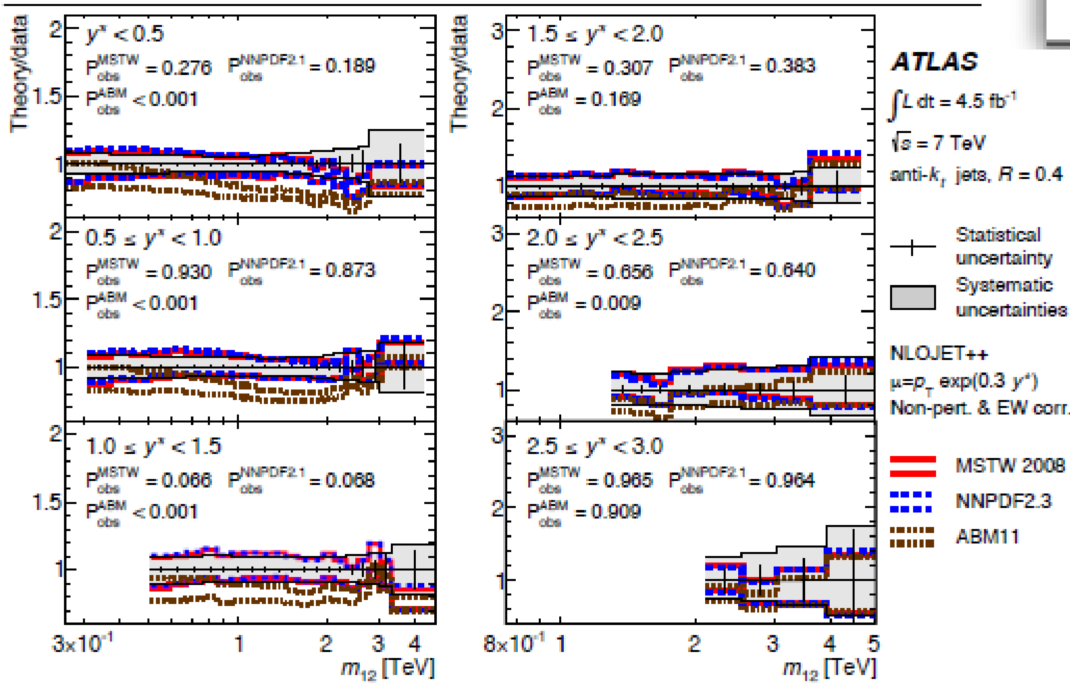
Looks OK for MSTW and NNPDF

But let's get quantitative

A frequentist method is employed to asses the probability that the measured cross sections are described by the SM predictions for each PDF considered. Different rapidity and mass ranges are considered.

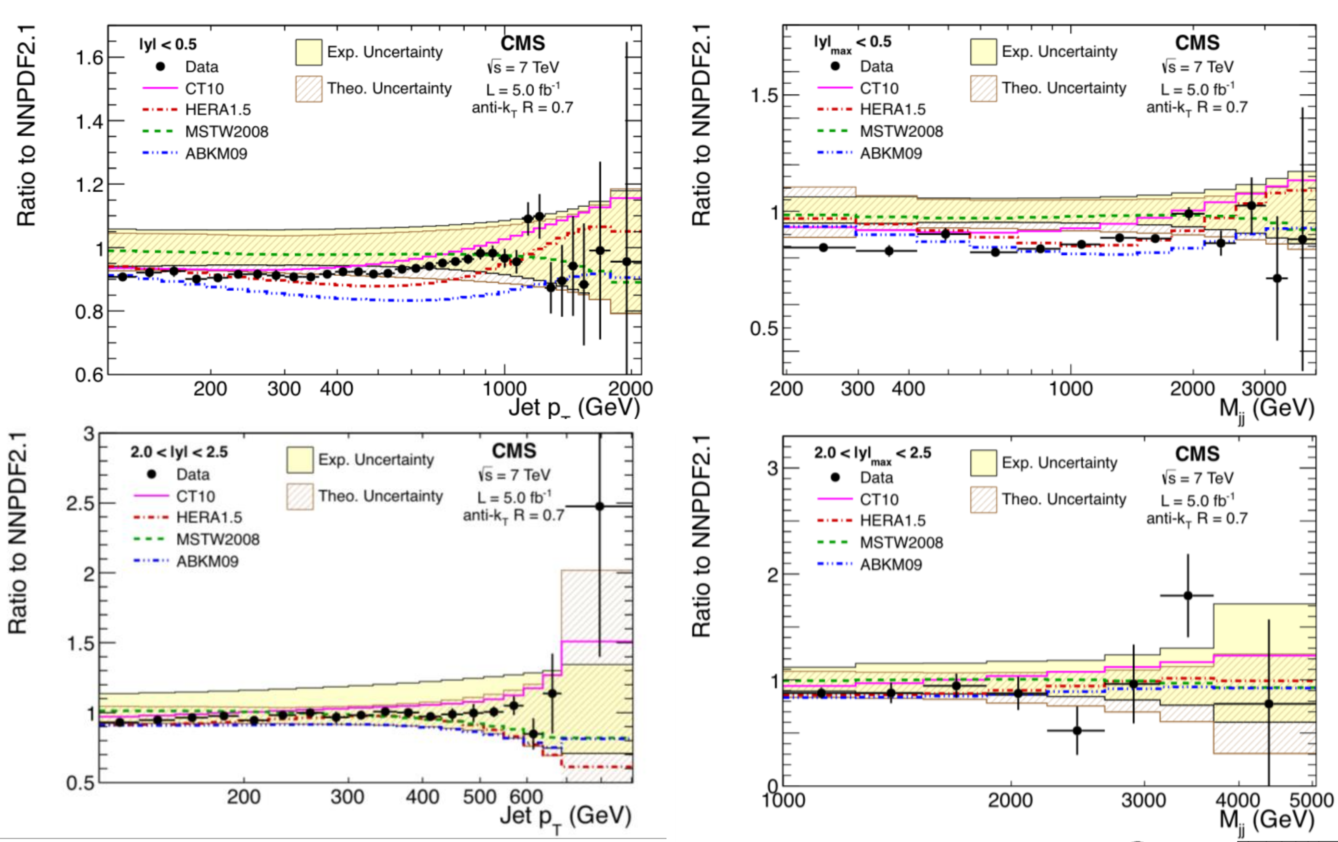
PDF set	y^* ranges	mass range (full/high)	P_{obs} $R = 0.4$	P_{obs} $R = 0.6$
CT10	$y^* < 0.5$	high	0.742	0.785
	$y^* < 1.5$	high	0.080	0.066
	$y^* < 1.5$	full	0.324	0.168
HERAPDF1.5	$y^* < 0.5$	high	0.688	0.504
	$y^* < 1.5$	high	0.025	0.007
	$y^* < 1.5$	full	0.137	0.025
MSTW 2008	$y^* < 0.5$	high	0.328	0.533
	$y^* < 1.5$	high	0.167	0.183
	$y^* < 1.5$	full	0.470	0.352
NNPDF2.1	$y^* < 0.5$	high	0.405	0.568
	$y^* < 1.5$	high	0.151	0.125
	$y^* < 1.5$	full	0.431	0.242
ABM11	$y^* < 0.5$	high	0.024	$< 10^{-3}$
	$y^* < 1.5$	high	$< 10^{-3}$	$< 10^{-3}$
	$y^* < 1.5$	full	$< 10^{-3}$	$< 10^{-3}$

Dijet production from 2011 data



- Lower prediction from ABM, possibly due to the softer gluon

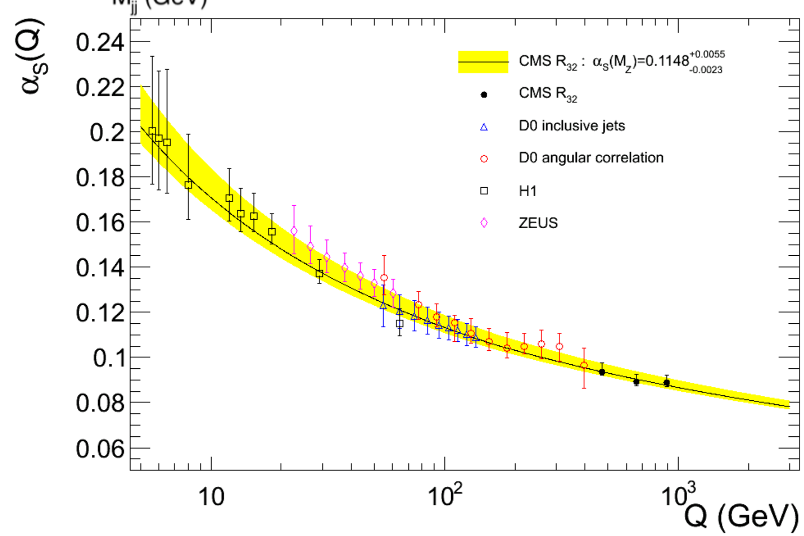
There are CMS inclusive jet and di-jet data from 5fb^{-1} of 2011 data



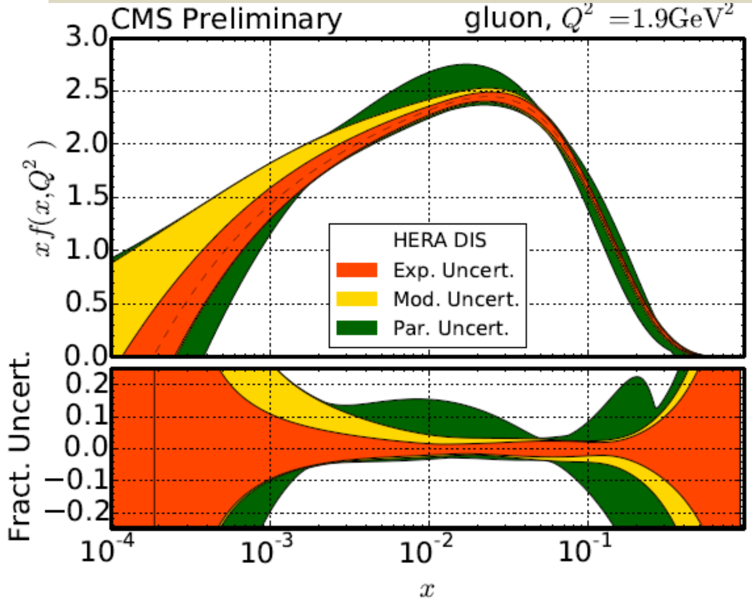
CMS QCD-12028
Arxiv:1212.6660

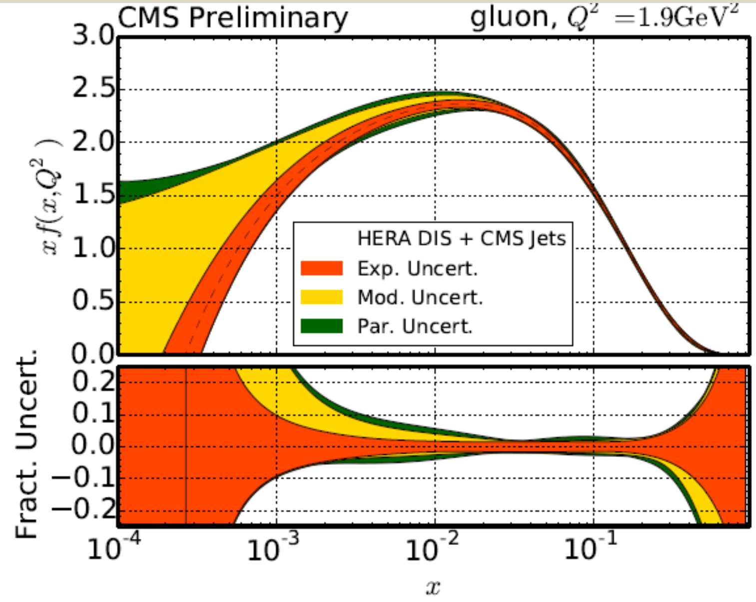
These are yet to be input to a PDF fit, they should provide more information on the high-x gluon.

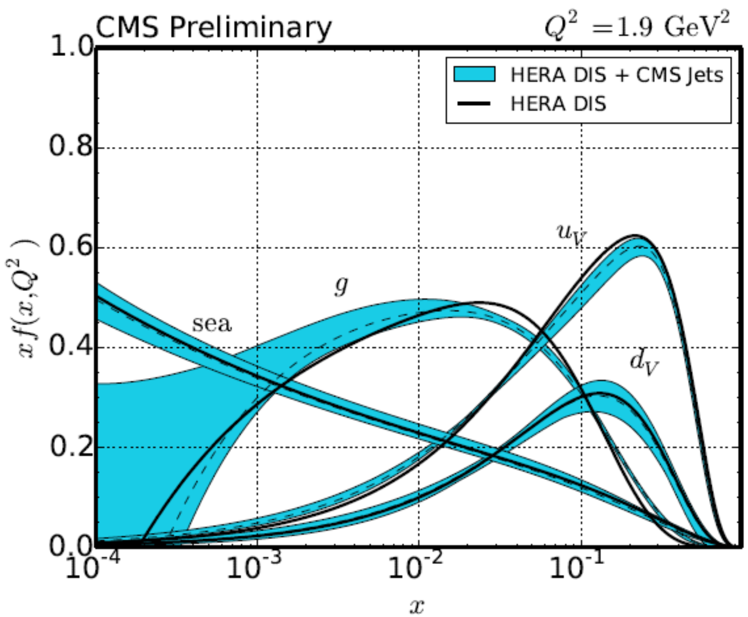
The strong coupling constant from the inclusive data (using fixed PDFs) is
$\alpha_S(M_Z) = 0.1185 \pm 0.0019(\mathrm{exp}) \pm 0.0028(\mathrm{PDF})\ ^{+0.0055}_{-0.0022}\,(\mathrm{scale})$



A PDF fit of these CMS inclusive jet data together with the combined HERA-I inclusive deep inelastic scattering (DIS) data **(JHEP 1001 -109)** shows the potential of the CMS data to constrain PDFs, in particular the gluon





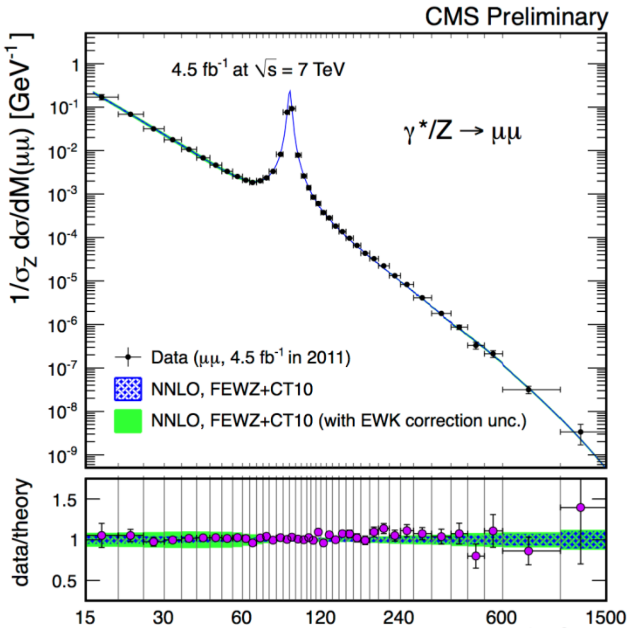


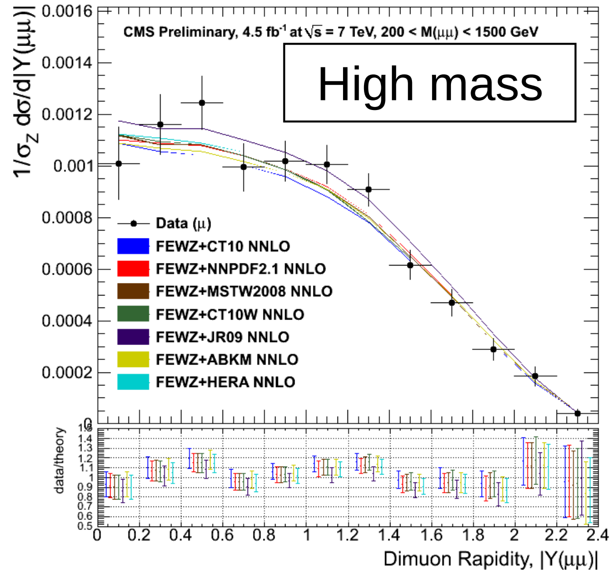
Note reduced uncertainty and change of shape of both gluon and u-valence

The strong coupling constant from a simultaneous fit of PDfs and $\alpha_S(M_Z)$ is

$\alpha_S(M_Z) = 0.1192 \pm 0.0016(\text{exp/NP})$

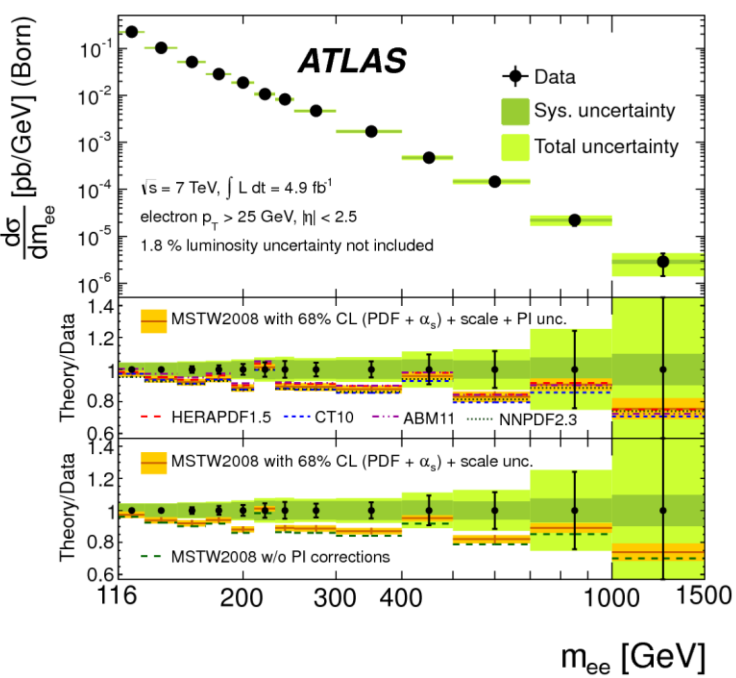
Drell Yan data can give information on sea quark PDFs





CMS-SMP-13003

CMS updated their Drell-Yan analysis of 7 TeV 2011 data from CMS-EWK-11007 to CMS-SMP-13003.



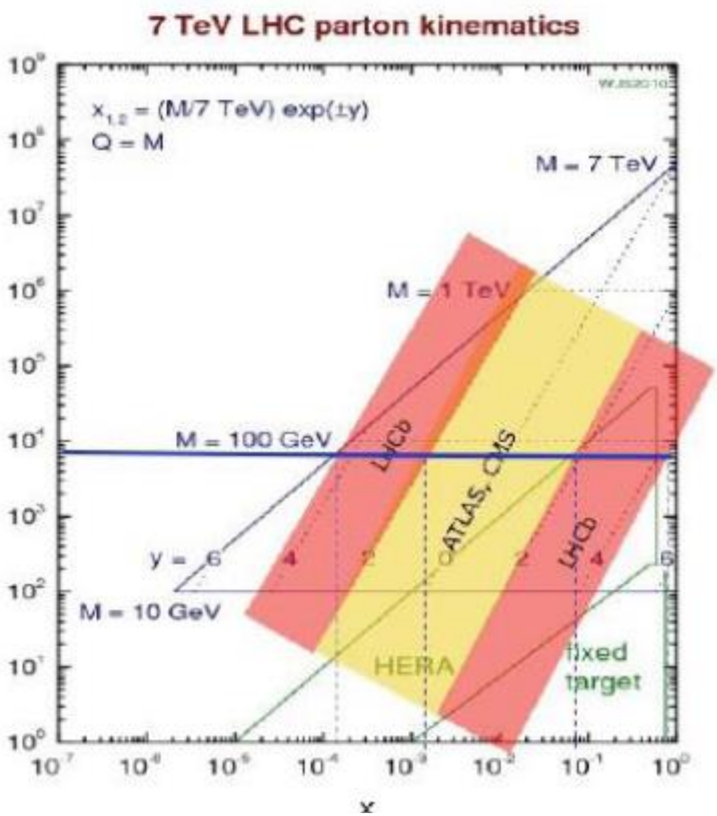
ATLAS High Mass Drell-Yan data arXiv:1305.4192

Currently all PDFs shown give a good description

X2 for 13dp	NNLO PDF
13.9	MSTW2008
18.9	CT10
13.5	HERAPDF1.5
14.7	ABM11
14.8	NNPDF2.3

Theoretical calculation needs care:
NNLO QCD (FEWZ) + NLO EW+ the photon induced (PI) contribution.

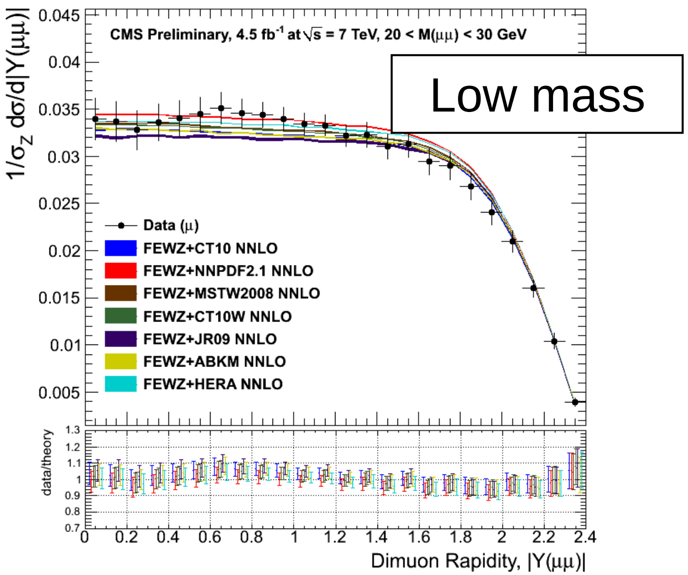
Low-mass Drell-Yan could probe a low-x region where DGLAP no longer works



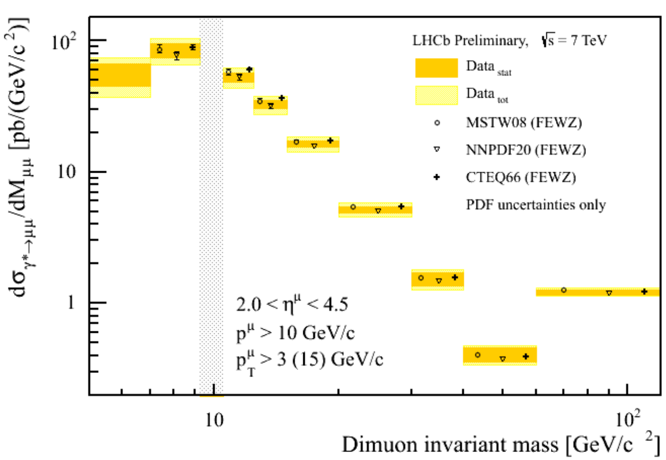
The PDFs are not so well known at low-x

but do we even have the right theory?

Do we need ln(1/x) resummation or non-linear evolution?



To do better we need re-summed evolution equations and re-summed coefficients functions
Some calculations exist for DIS at low-x
Altarelli Ball Forte, Thorne and White
What can we use for Drell-Yan?
Ball and Marzani 0812.3602 for invariant mass or Caola, Forte and Marzani 1012.2743 for rapidity distribution

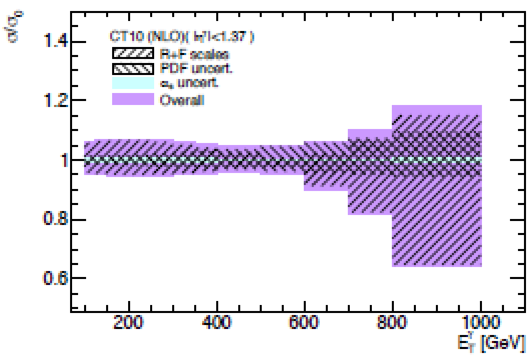


LHCb also have low-mass Drell-Yan data LHCb-CONF-2012-013. **This shows no sign of non-DGLAP effects, but errors are large**

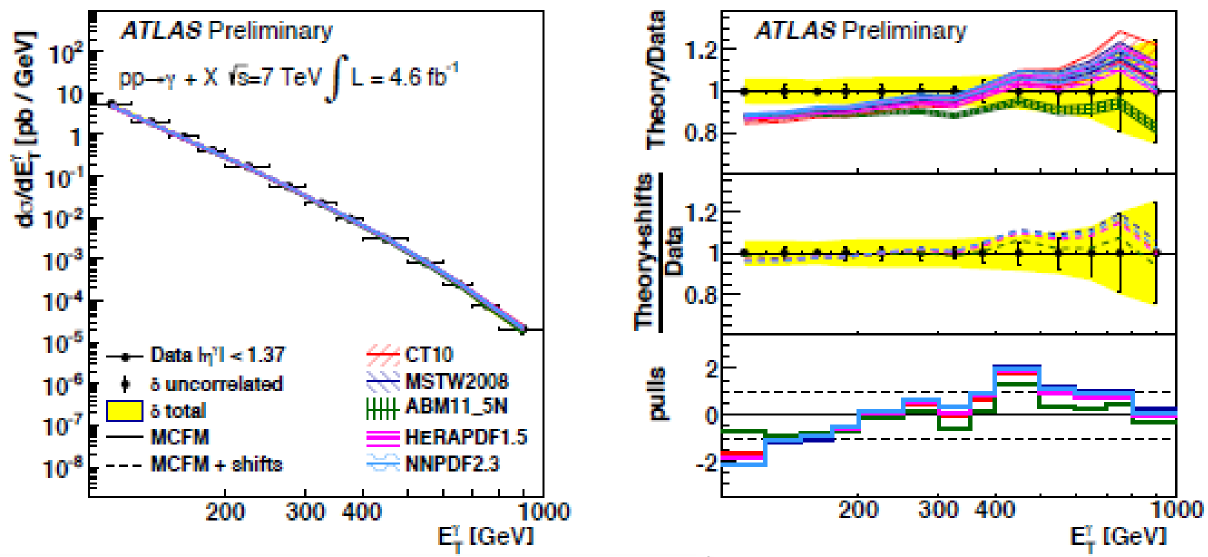
Prompt photon data has been resurrected as a possible input to determine the high-x gluon see arXiv:1202.1762

ATLAS has made a study
ATL-PHYS-PUB-2013-018 based on data arXiv:1311.1440
PDFs are compared with the data using a χ2 comparison which can account for PDF uncertainty as well as experimental uncertainties

Different scales (2ET, ET/2) are used since scale uncertainty is significant



Central photon production



	Excluding PDF uncertainties				Including PDF uncertainties			
	$\mu_r = \mu_f = E_T^\gamma$	Envelope			$\mu_r = \mu_f = E_T^\gamma$	Envelope		
CT10	49.1	34.7	-	63.1	29.8	20.0	-	38.4
MSTW2008	39.9	27.2	-	52.7	32.0	21.3	-	42.3
ABM11_5N	16.2	9.2	-	25.5	15.7	8.9	-	24.9
HERAPDF1.5	28.7	19.0	-	38.9	23.6	15.7	-	32.0
NNPDF2.3	33.5	22.6	-	44.7	27.6	18.7	-	36.9

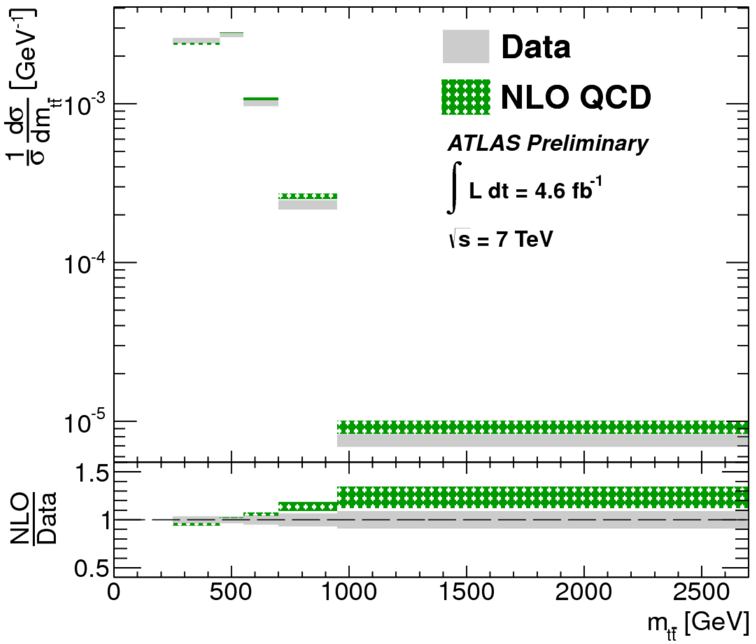
χ^2 for 23 degrees of freedom

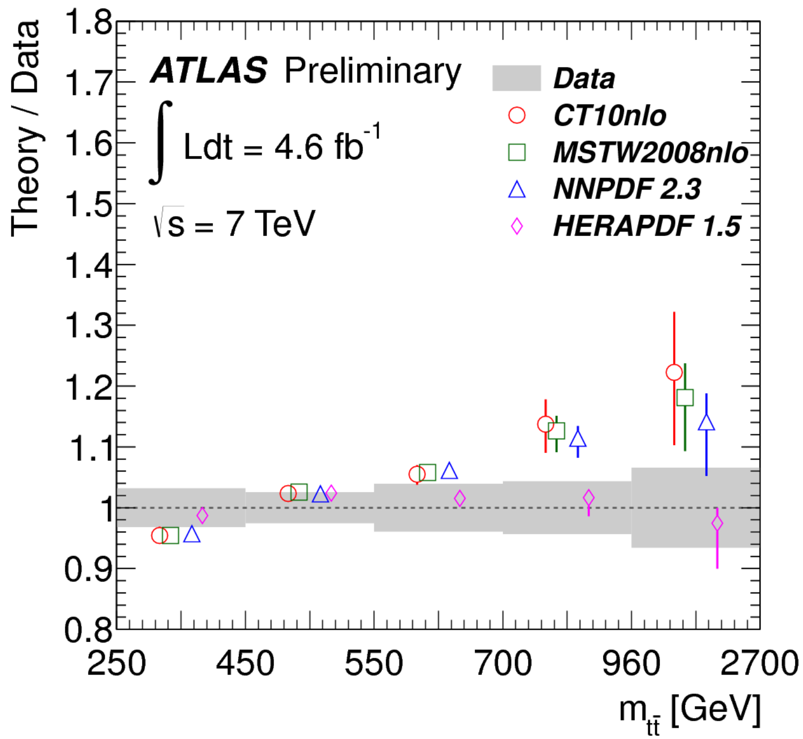
- Large variation of the predictions from MCFM with each PDF
  - Again, ABM11 softer at high E_T

Top production also has PDF sensitivity

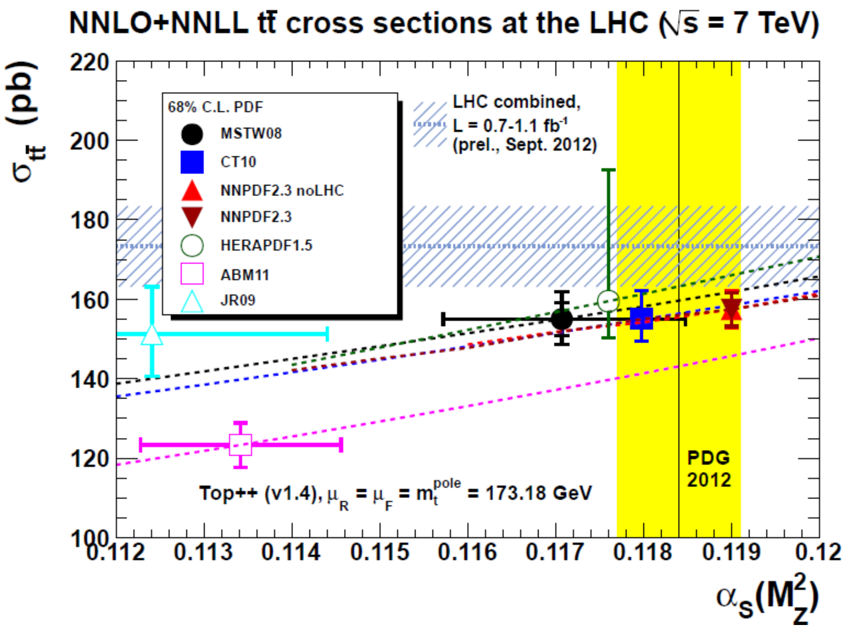
ATLAS-CONF-2013-099
Calculations for differential distributions at NLO
NNLO is coming
Comparison to CT10

And ratios to various PDFs
HERAPDF describes the data best for
Mass t-tbar
y t-tbar and pt-top spectra are also measured
(see back-up)





Top total cross sections already yield PDF discrimination



The ATLAS and CMS combined t-tbar cross section is 173 ± 2.3 ± 9.8pb at 7 TeV
ATLAS-CONF-2012-134/ CMS-TOP-12003

BUT the calculation of the t-tbar cross section depends on the top quark mass.

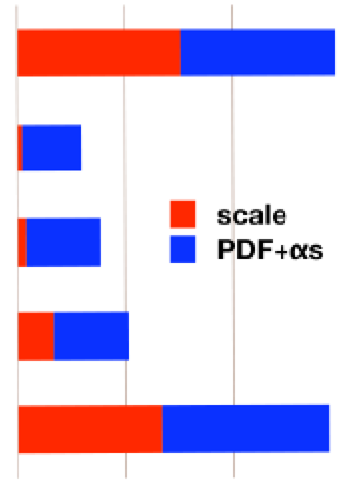
.

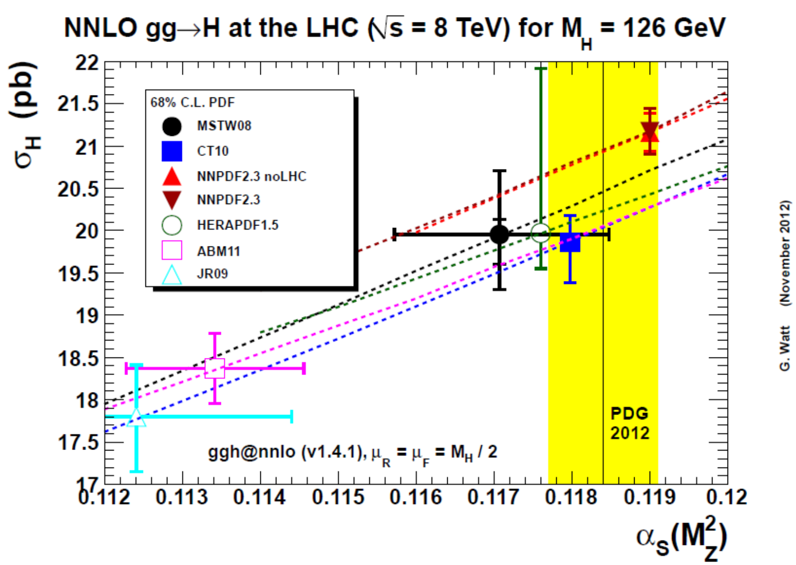
The calculation also depends on whether running mass or pole-mass is used

The predictions for this cross section also have a strong $\alpha_S(M_Z)$ dependence-.....

PDFs and the Higgs

	Process	σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%





The gg →Higgs cross section is strongly $\alpha_S(M_Z)$ and gluon PDF dependent, rather like the t-tbar cross section

The extent to which the Higgs that we are seeing agrees with the SM Higgs cross section predictions depends on the PDF and $\alpha_S(M_Z)$ value used for these predictions.

Summary

•Uncertainties on Parton Distribution Functions (PDFs) limit our knowledge of cross sections whether SM or BSM.
•Any claim for new physics at the highest masses is dependent on the PDF chosen to describe conventional physics
•Standard Model LHC measurements can themselves contribute to PDF discrimination and PDF improvement

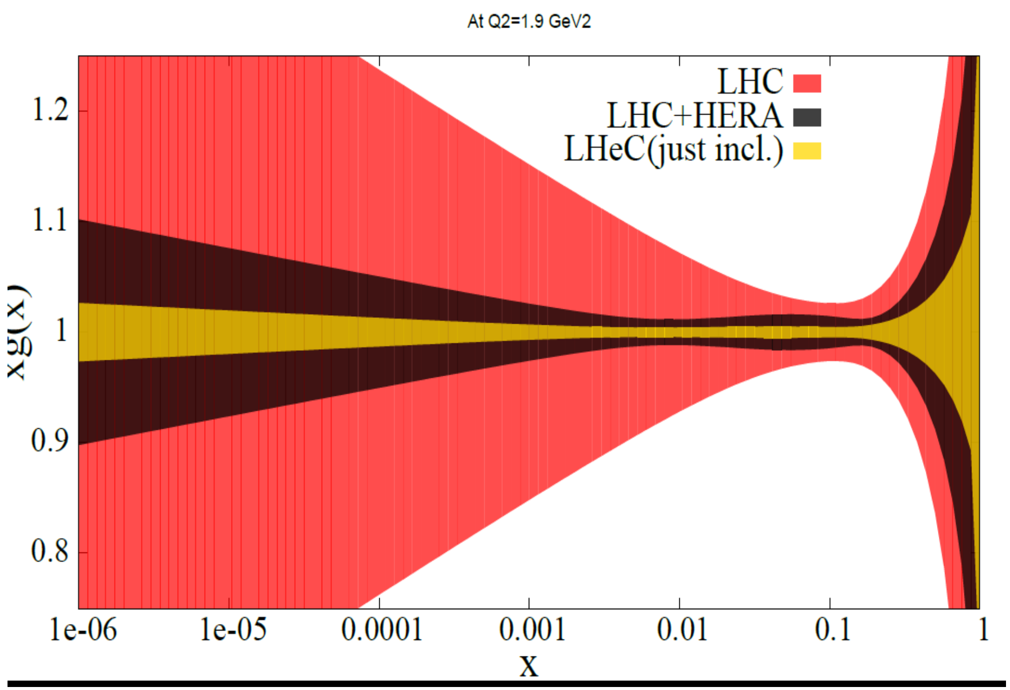
LHC measurements on:

1. W and Z production
2. W+c production
3. Inclusive Jet and Di-Jet production
4. Drell-Yan: low and high invariant mass
5. Vector boson pt spectra
6. Direct photon and photon +jet
7. Top, single and t-tbar

All have impact

In future we may also hope to use:

- W,Z+ c,b (intrinsic charm, beauty PDF?)
- W,Z+jets, Z pt (gluon, u/d from W+/W- ratio?)
- Charmonium- (low-x gluon)



FINALLY

We are used to seeing plots of how much the LHC data improve over HERA data alone, or even over global fits (NNPDF2.3)

So let's ask the question-
Can we determine PDFs just from the LHC?

NOT with any precision NO !

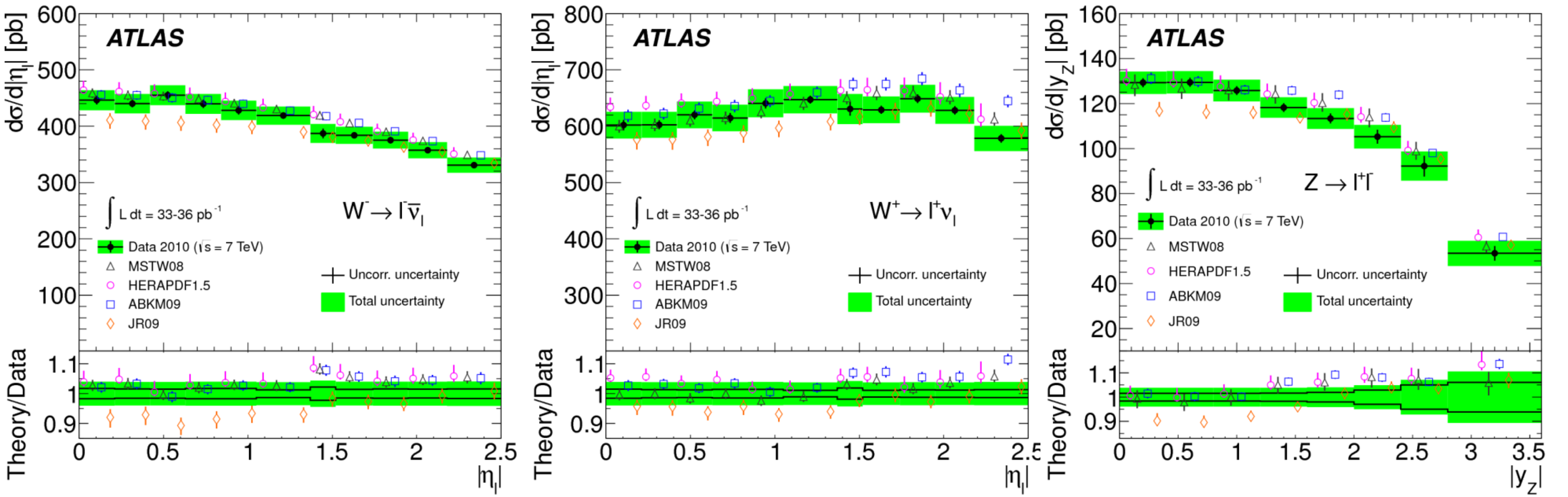
Present LHC W,Z data and jet data are included and LHC ultimate precision is extrapolated according to our current experience– we are systematics limited already

PDFs come from DIS

Extras

ATLAS Measurement of W and Z cross sections in electron and muon channels
Phys Rev D85(2012)072004

The electron and muon data have been combined accounting for the correlated systematic errors using the HERAaverager programme, the results are given with 30 sources of correlated error

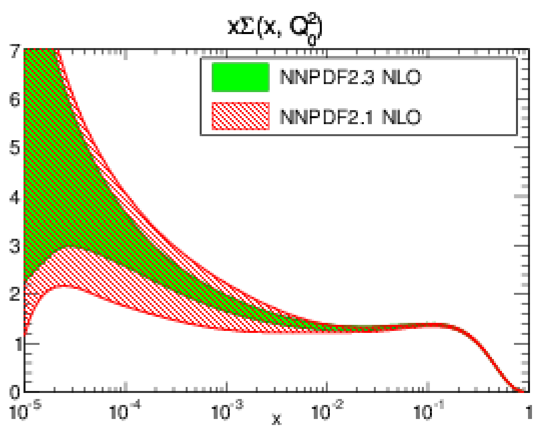


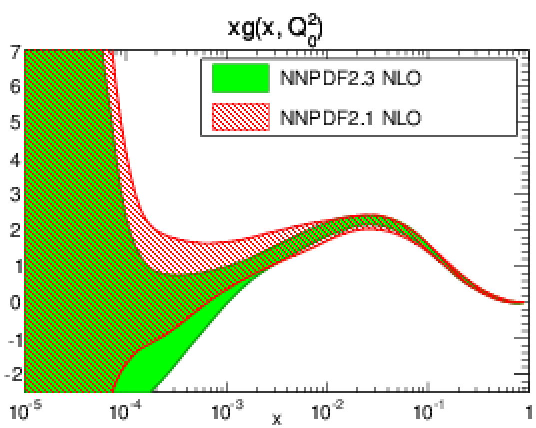
These distributions disfavour both JR09 and ABKM09– but let us look more carefully at the flavour information in these distributions

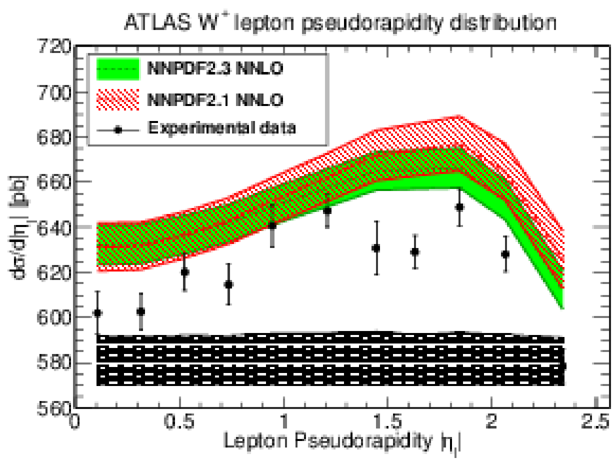
Using LHC data to improve PDFs– NNPDF2.3 arXiv:1207.1303

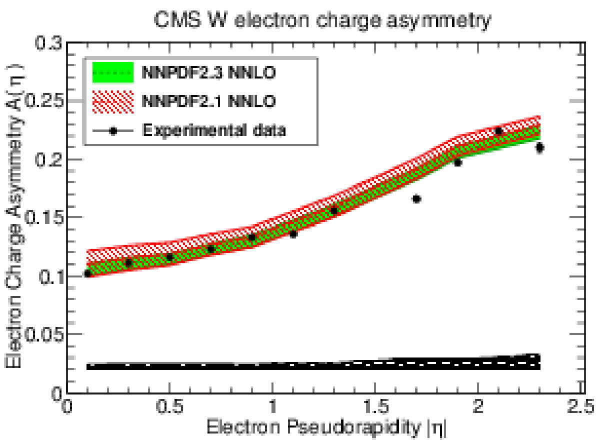
NNPDF2.3 is the only PDF set to include some LHC data. They made a decision only to include data for which information on correlated systematics exists.

- W lepton and Z rapidity distributions from ATLAS 2010 data Phys Rev D85(2012)072004
- Electron asymmetry data from 840pb^{-1} CMS 2011 data Phys.Rev.Lett.109.11806
- Inclusive jet measurements from ATLAS 2010 data Phys ReV D86(2012)014022
- Z rapidity and W asymmetry at high rapidity from LHCb 2010 data JHEP6(2012)58





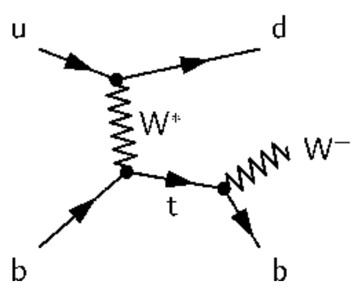


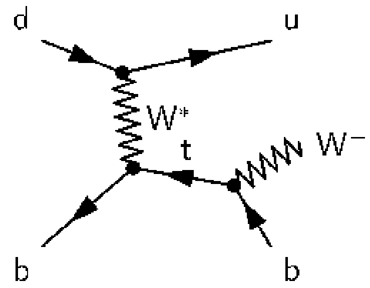


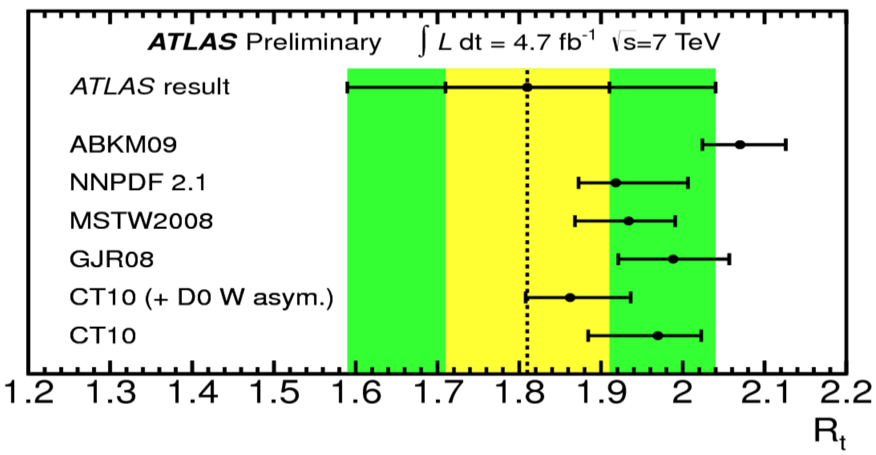
ATLAS W,Z data give the largest changes / improvements

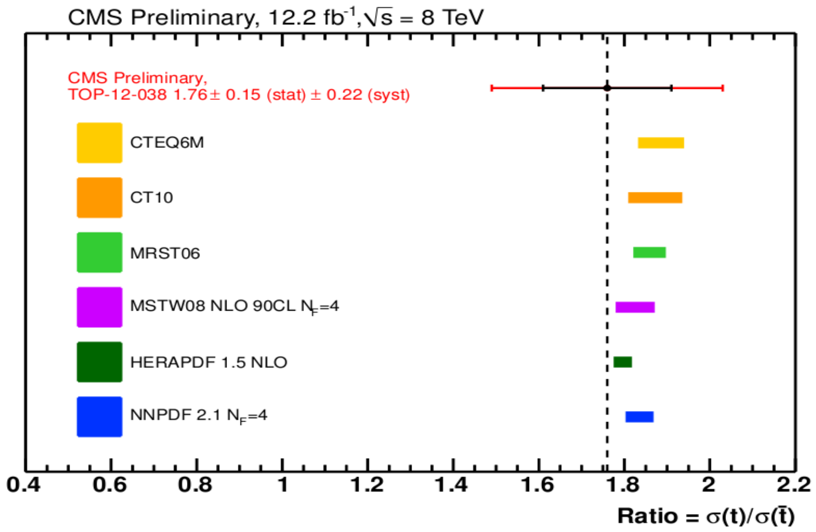
Top production also has PDF sensitivity

- Single top t/tbar ratio can give u/d PDF



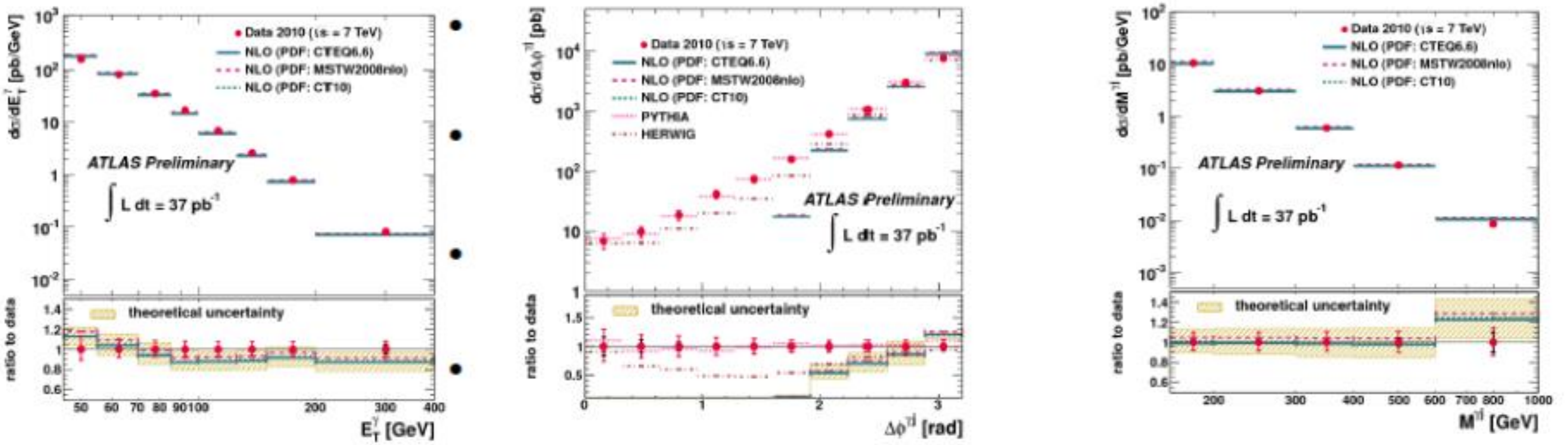






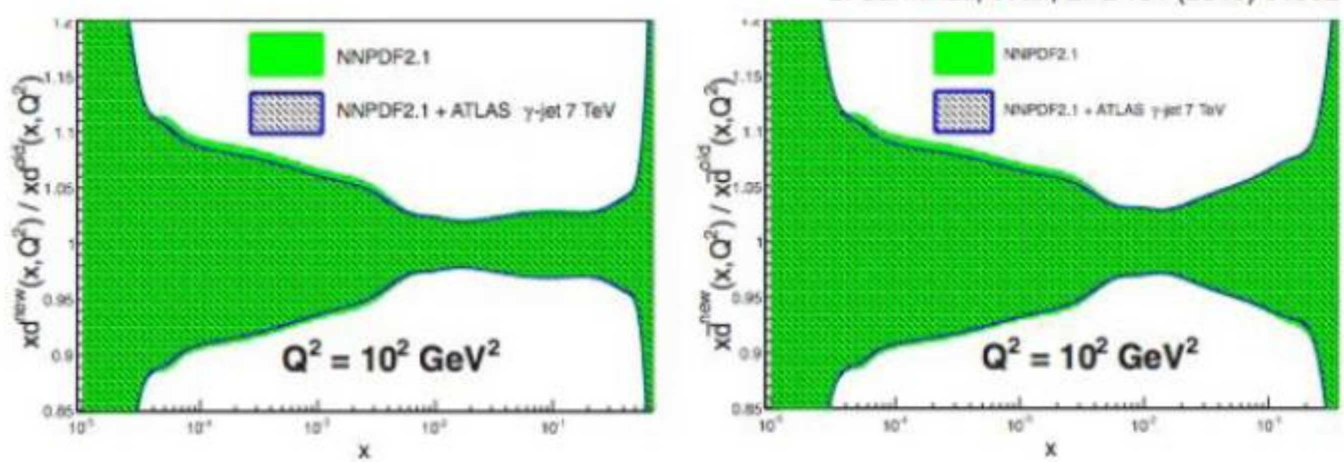
ATLAS-CONF-2012-056
CMS-TOP-12038

Similarly photon + jet data may be used as a possible input to determine the high-x gluon see arXiv:1212.5511



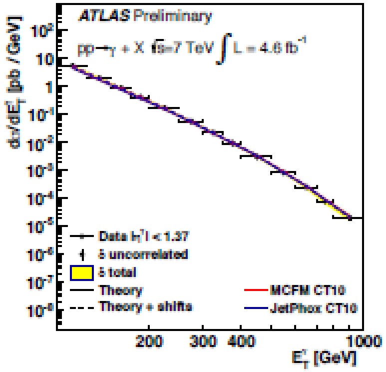
ATLAS-CONF-2013-023

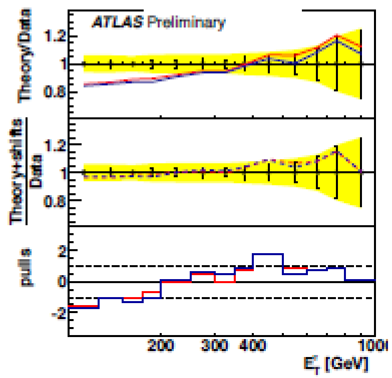
L. Carminati, et al., EPL 101 (2013) 61002

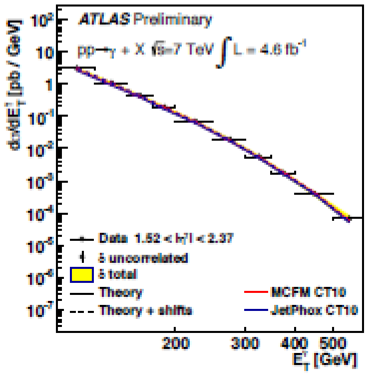


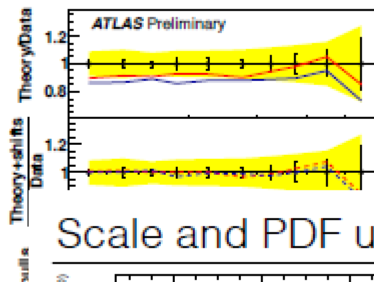
Direct photon production

- **ATL-PHYS-PUB-2013-018**
- Data from **arXiv:1311.1440**
- Comparison of JetPhox and MCFM calculations with the data
  - NLO fragmentation calculated using JetPhox
  - Consistent shape between the calculations
- EW corrections not included
- Both calculations differ in shape with data for central photons
- Include effect of experimental systematic as nuisance parameter shifts

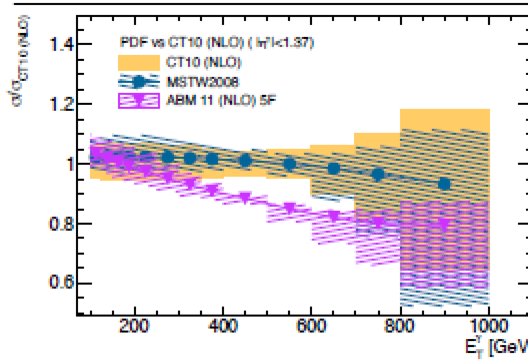


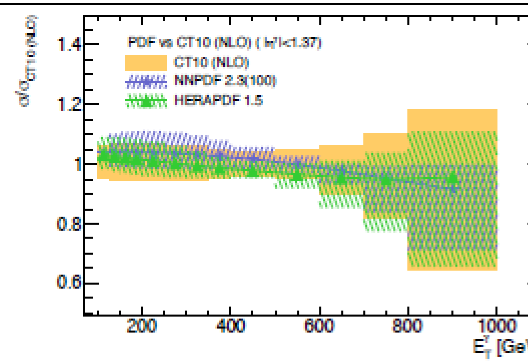




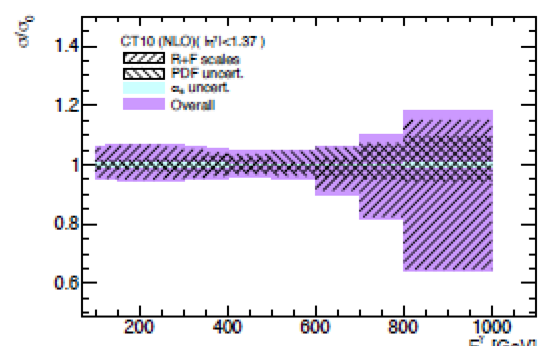


Scale and PDF uncertainties



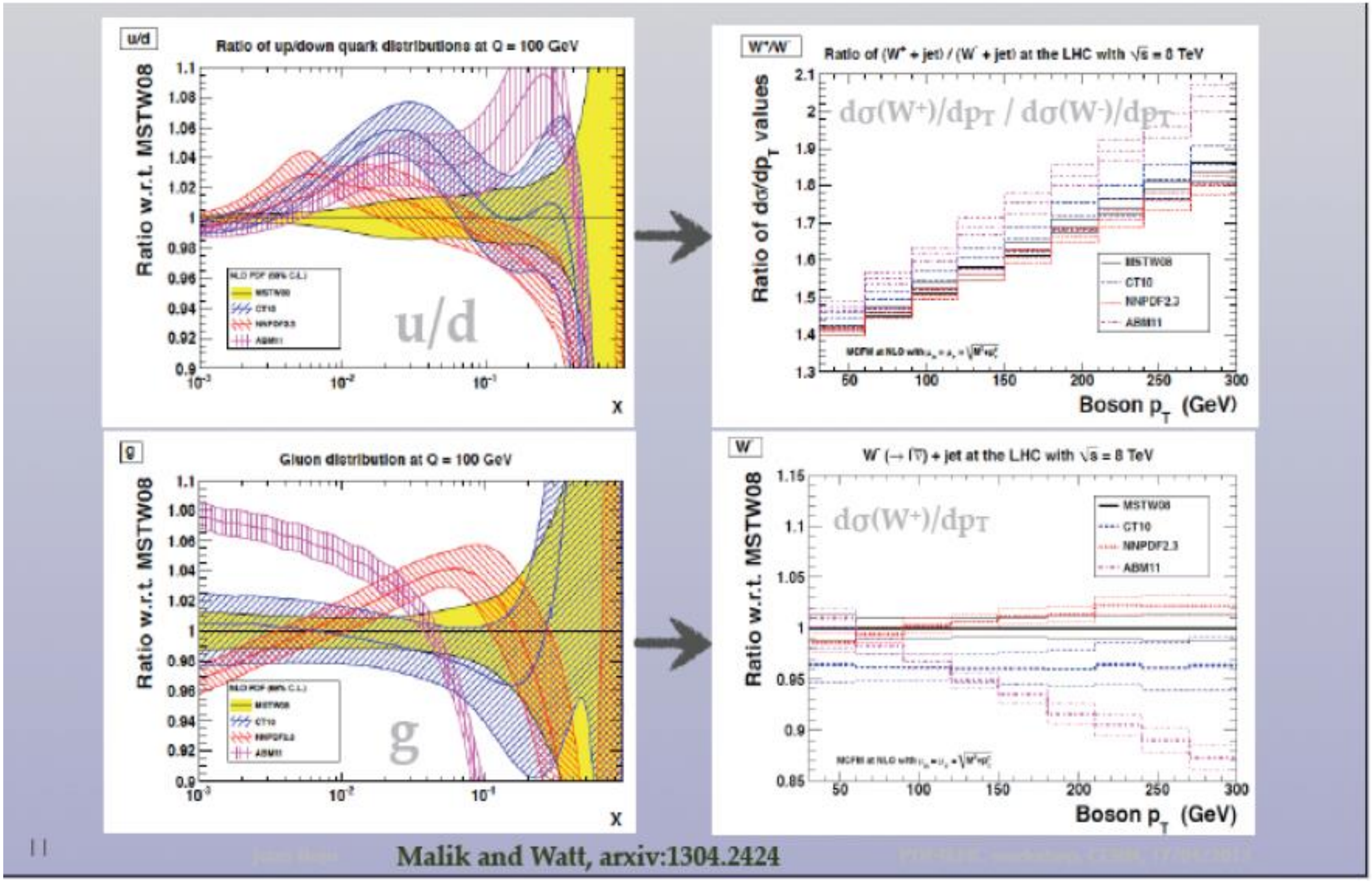


- Large scale uncertainties, comparable to individual PDF uncertainties
- Potentially large differences between PDFs, larger than quoted uncertainties on individual PDF sets for intermediate ET
  - Data should still have the potential to constrain the shape of the gluon distribution

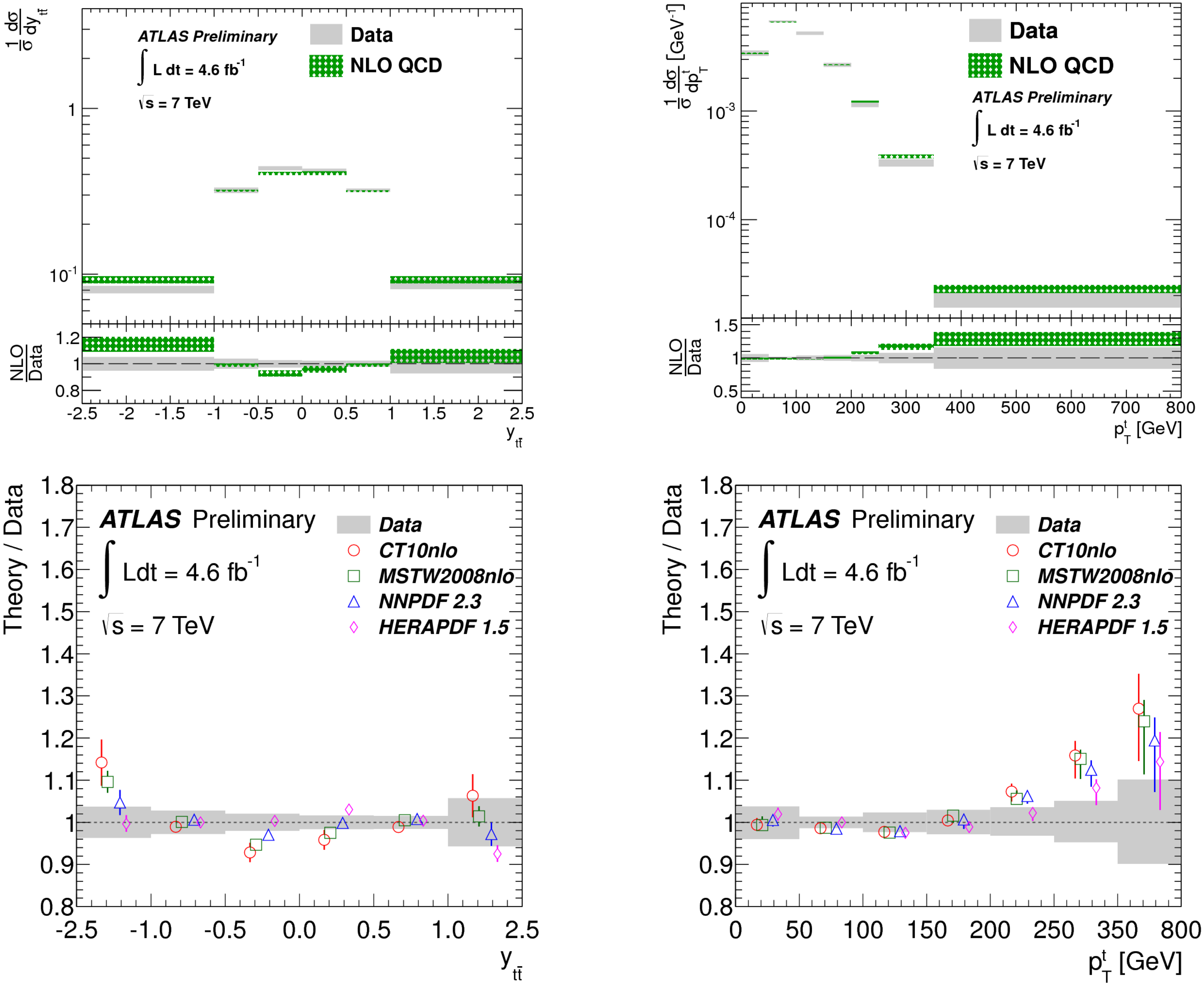


Vector boson at high pt

ArXiv:1304.2424



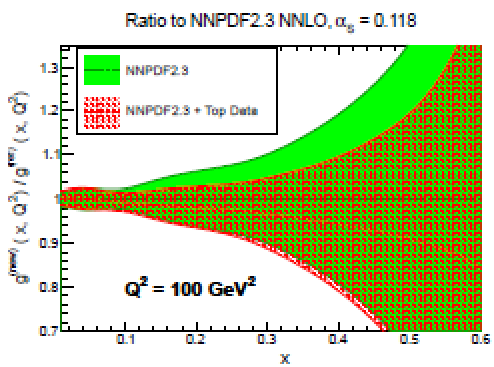
High pt W,Z spectra may discriminate gluon, but needs NNLO and electroweak corrections. Ratios of vector-boson high pt spectra may have an advantage

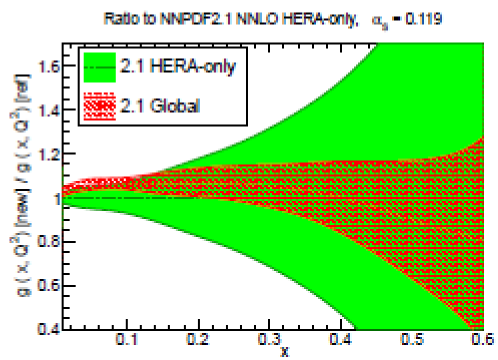

ATLAS Preliminary
∫ L dt = 4.6 fb^{-1}
$\sqrt{s}$ = 7 TeV
Data
NLO QCD
$\frac{1}{\sigma}\frac{d\sigma}{dy_{t\bar{t}}}$
$\frac{\text{NLO}}{\text{Data}}$
$y_{t\bar{t}}$
$\frac{1}{\sigma}\frac{d\sigma}{dp_T^t}$ [GeV^{-1}]
p_T^t [GeV]
Theory / Data
CT10nlo
MSTW2008nlo
NNPDF 2.3
HERAPDF 1.5

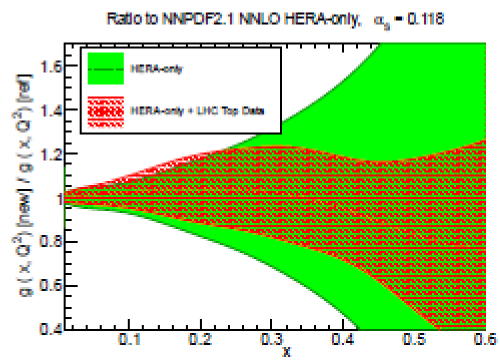
Top total cross sections are calculated to NNLO

Measurement	$\sigma_{t\bar{t}}$ (pb)	stat. (pb)	sys. (pb)	lumi. (pb)	total (pb)
Tevatron CDF+D0 (Ref. [47])	7.65	± 0.20	± 0.29	± 0.22	7.65 ± 0.42 (5.5%)
Atlas 7 TeV (Ref. [48])	177	± 3	$^{+8}_{-7}$	± 7	177^{+10}_{-11} $\binom{+5.6\%}{-6.2\%}$
CMS 7 TeV (Ref. [49])	160.9	± 2.5	$^{+5.1}_{-5.0}$	± 3.6	160.9 ± 6.6 (4.0%)
Atlas 8 TeV (Ref. [50])	241	± 2	± 31	± 9	241 ± 32 (13.0%)
CMS 8 TeV (Refs. [51, 52])	227	± 3	± 11	± 10	227 ± 15 (6.7%)

Czakon, Mangano, Mitov, Rojo arXiV:1303.7215
Uses just this cross section information to improve PDFs

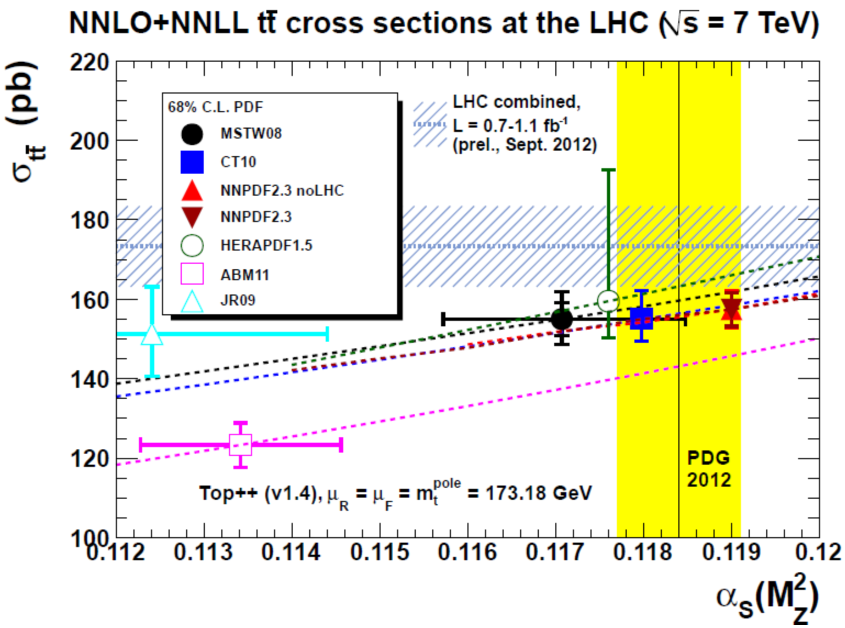






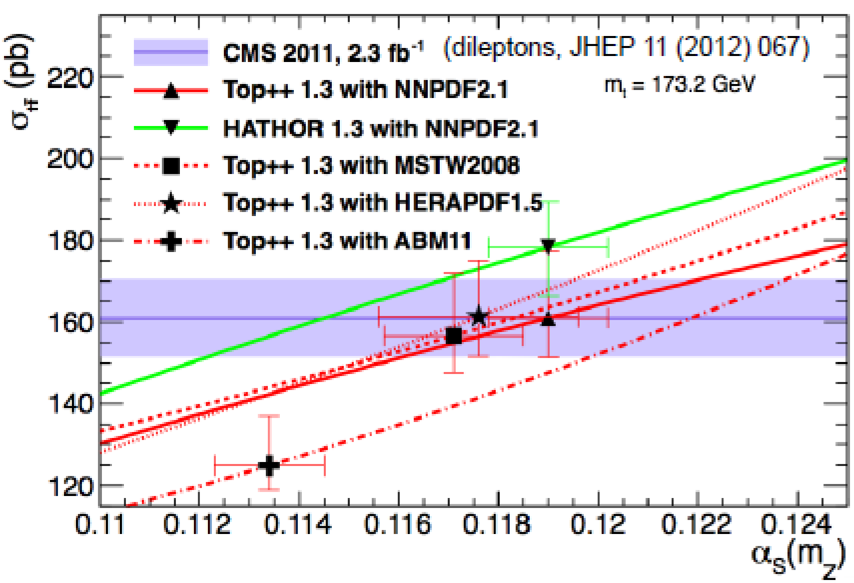
But not all PDF groups agree that such an improvement can be achieved
It depends on whether the reweighting is done accounting for enhanced χ2 tolernaces (Jun Gao- Les Houches)

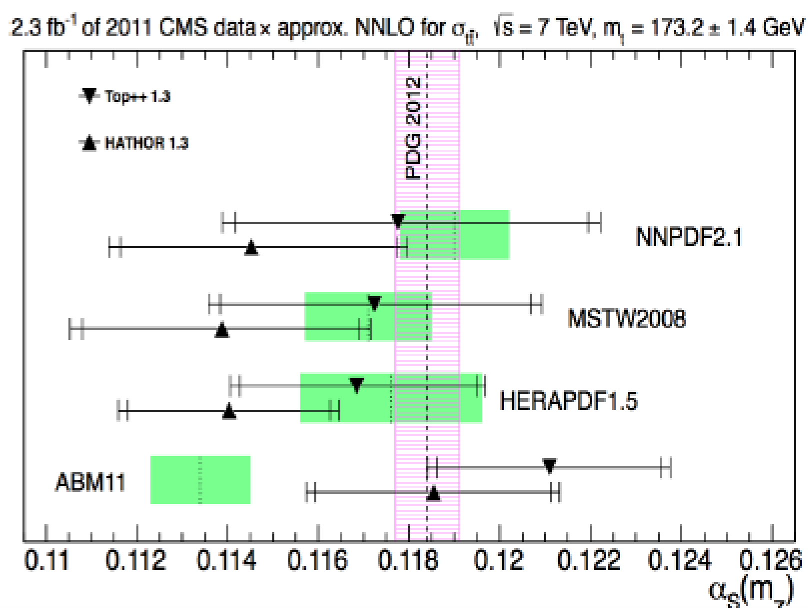
Top total cross sections already yield PDF discrimination



The ATLAS and CMS combined t-tbar cross section is 173 ± 2.3 ± 9.8pb at 7 TeV
ATLAS-CONF-2012-134/ CMS-TOP-12003

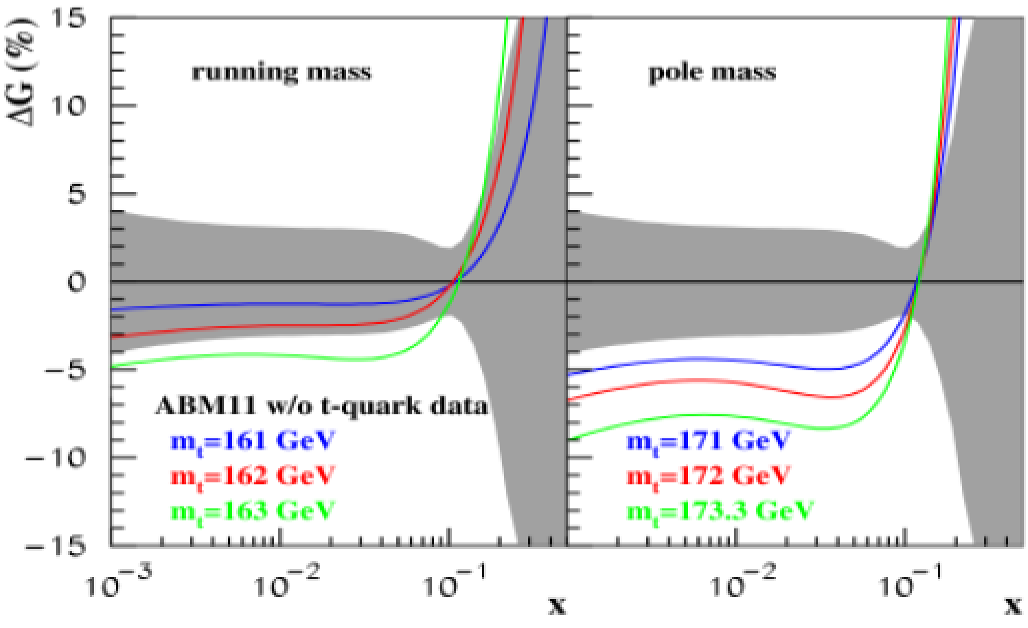
The predictions for this cross section have a strong $\alpha_S(M_Z)$ dependence- which has been used by CMS for a preliminary extraction of $\alpha_S(M_Z)$ at NNLO, using various PDFs and top prediction programmes





BUT the calculation of the t-tbar cross section depends on the top quark mass.
On the previous page the value 173.2 was used.
The calculation also depends on whether running mass or pole-mass is used

ABM have used the cross section data in their own fit and they find that a running mass calculation with mt =161 GeV (and $\alpha_S(M_Z)$=0.1138) is compatible.
However it has a dramatic effect on the shape of the gluon, which is becoming MUCH harder



$\alpha_s(M_z)$ 0.1138 – 0.1149 0.1155 – 0.1162