Parton Distribution Functions and LHC physics

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•Any claim for new physics at the highest masses is dependent on the Parton Distribution Function (PDF) chosen to describe conventional physics.

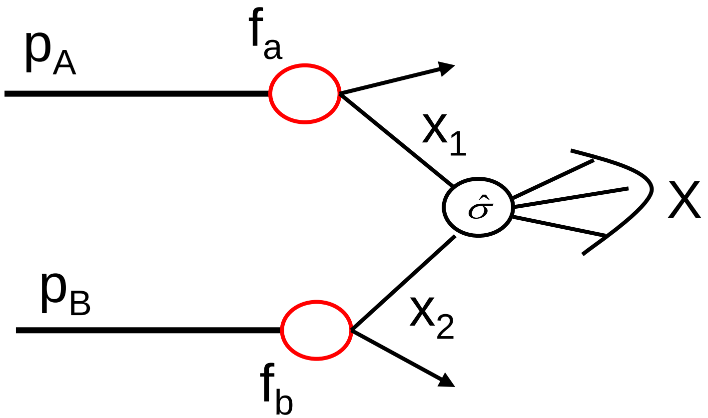
•The extent to which the Higgs that we are seeing agrees with the SM Higgs cross section predictions depends on the PDF.

•We can use SM measurements at the LHC to discriminate and improve current PDFs

The Standard Model is not as well known as you might think.
In particular in the QCD sector

LHC cross sections are constructed as

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

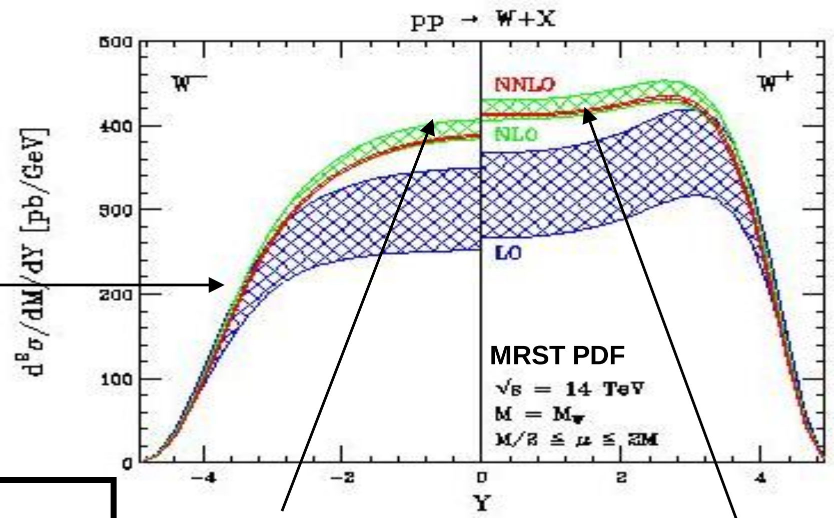


where X=W, Z, D-Y, H, high-E_T jets, prompt-γ
and σ is known to some fixed order in pQCD and EW or in some leading logarithm approximation (LL, NLL, …) to all orders via re-summation

- The reliability of the calculation of the sub-process cross section depends on the order of the calculation– and only a few processes are known beyond next-to-leading order NLO.
- The reliability of the process cross-section depends on the accuracy of our knowledge of the Parton distribution Functions (PDFs)– and these are not well known in all kinematic regions thus uncertainties on Parton Distribution Functions (PDFs) limit our knowledge of cross sections whether SM or BSM

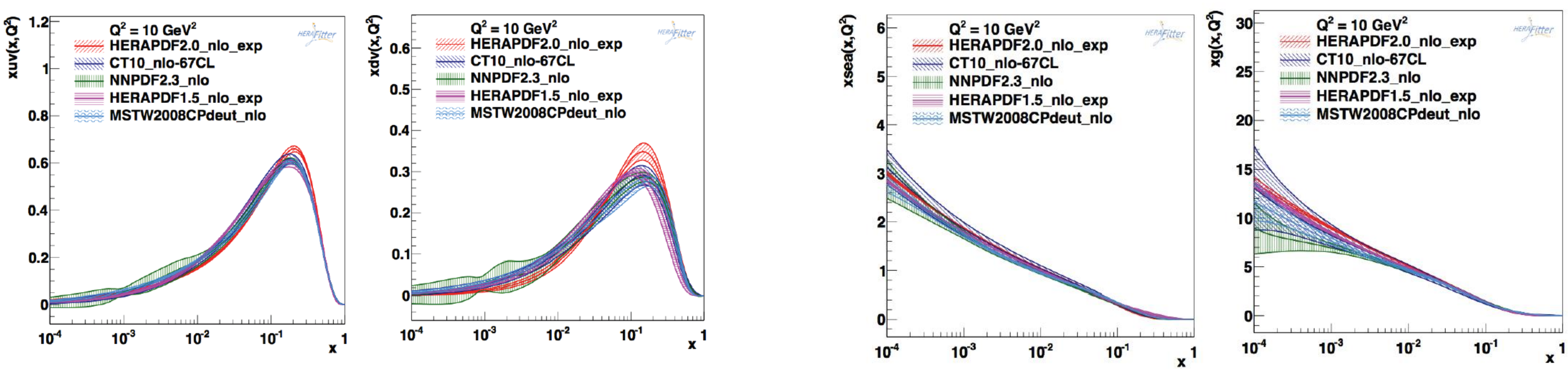
W/Z production have been considered as good standard candle processes with small theoretical uncertainty.

Since the sub-process cross section is well known the dominant uncertainty becomes the PDF uncertainty



NNLO corrections small ~ few%
NNLO residual scale dependence < 1%

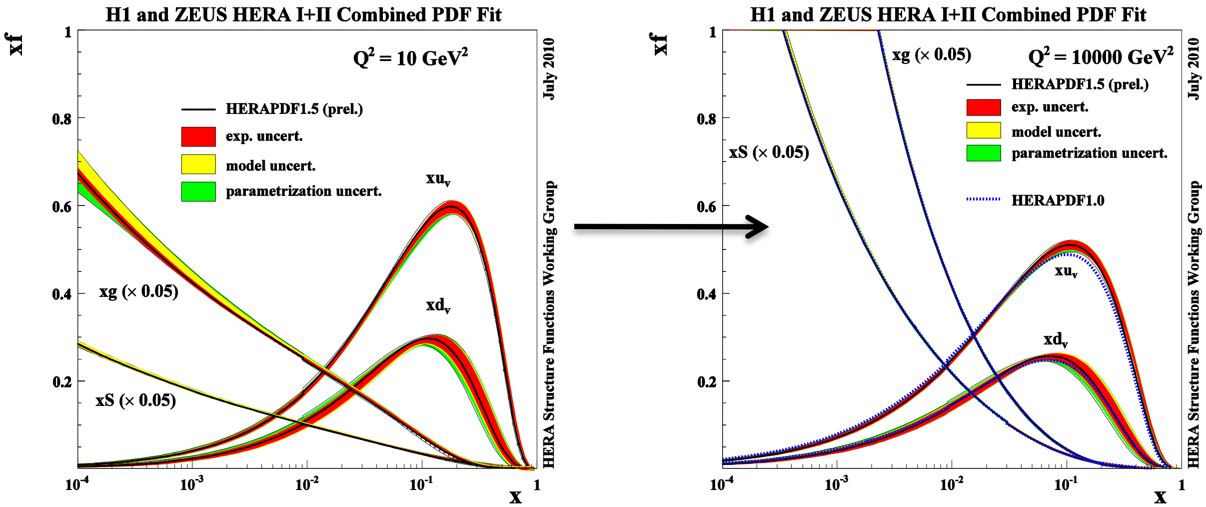
But how well known are PDFs?
There are many choices available on the LHAPDF parton library
There are uncertainties quoted within each PDF set and there are also differences between different PDF sets

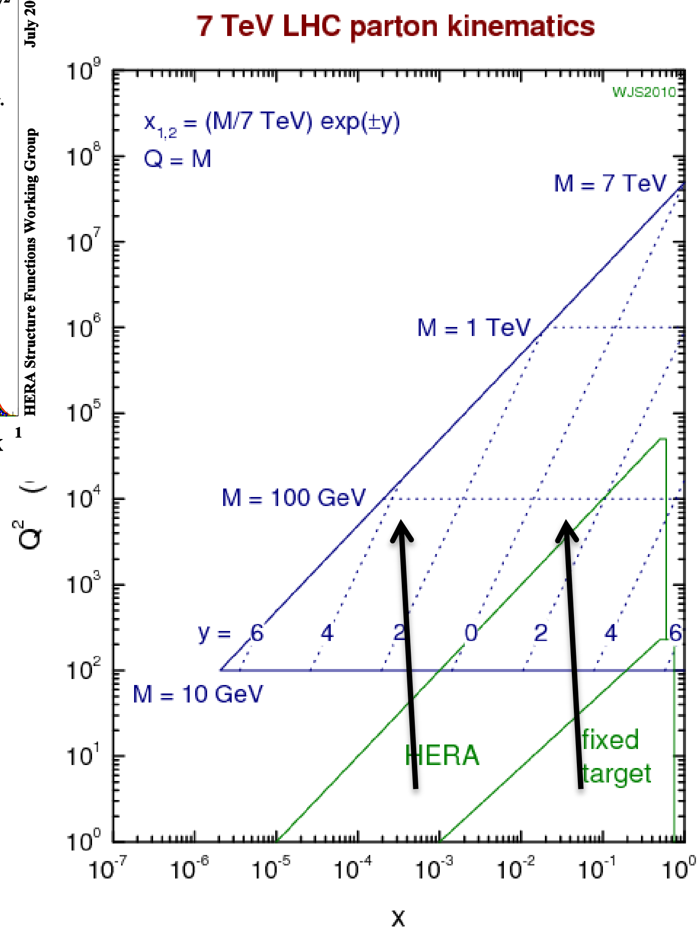


Here are the u and d-valence and total Sea and gluon PDFs for several modern PDF sets shown at scale Q^2=10GeV^2. . How much does this matter at the LHC?

At the LHC the ATLAS and CMS detectors are probing Bjorken-x values $5.10^{-4} < x < 0.5$ at scale Q^2=10000 and above. How do we know the PDF in these regions?

We use QCD DGLAP evolution from the measured regions





Note Sea and Gluon are multiplied by 0.05 in these figures--- valence do not matter until x> 0.3– ie very high scales. For most LHC data-- including searches-- it is the high-x sea and gluon which matters most.

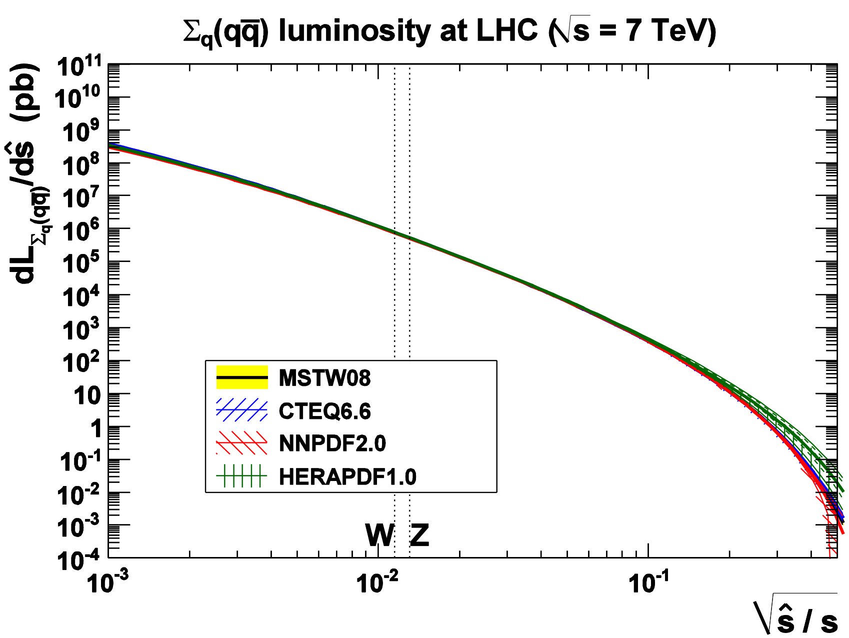
It is most useful for LHC physics if we compare PDFs in terms of parton-parton luminosities

q-qbar for W,Z production

$$\frac{\partial \mathcal{L}_{\Sigma_q(q\bar{q})}}{\partial \hat{s}} = \frac{1}{s}\int_\tau^1 \frac{dx}{x} \sum_{q=d,u,s,c,b} \left[f_q(x,\hat{s}) f_{\bar{q}}(\tau/x,\hat{s}) + f_{\bar{q}}(x,\hat{s}) f_q(\tau/x,\hat{s})\right],$$

And g-g for Top, Higgs

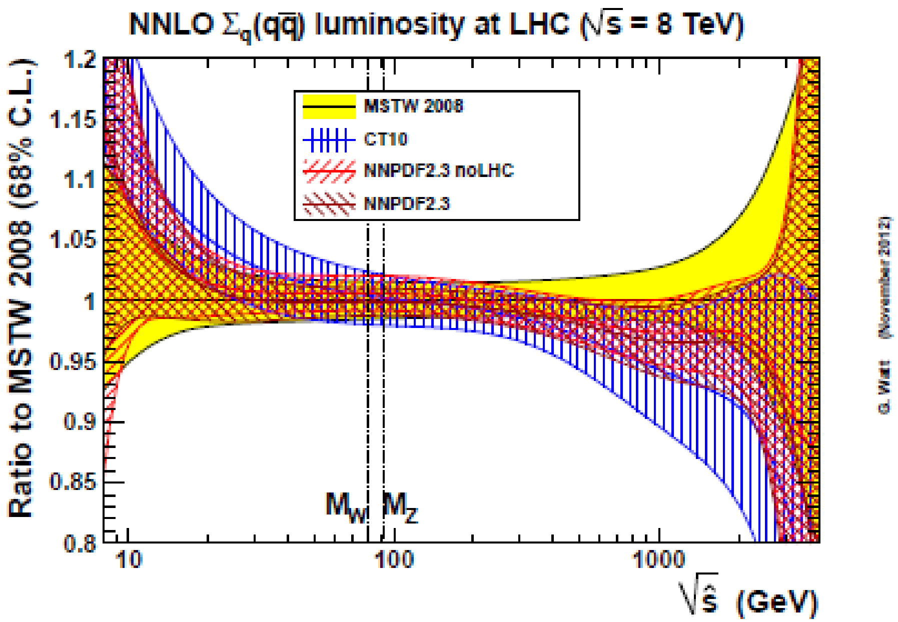
$$\frac{\partial \mathcal{L}_{gg}}{\partial \hat{s}} = \frac{1}{s}\int_\tau^1 \frac{dx}{x} f_g(x,\hat{s}) f_g(\tau/x,\hat{s}),$$

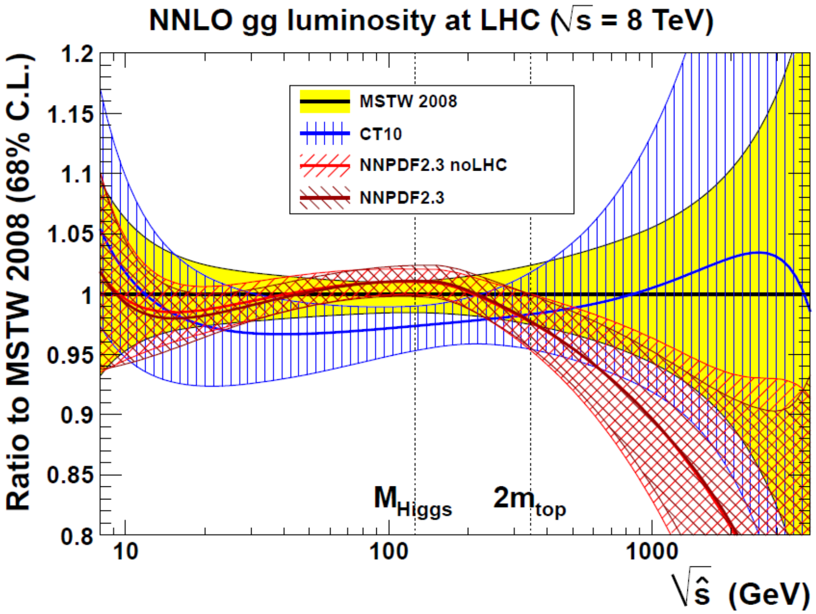


But since luminosities are very steeply falling functions of the invariant mass of the hard sub process

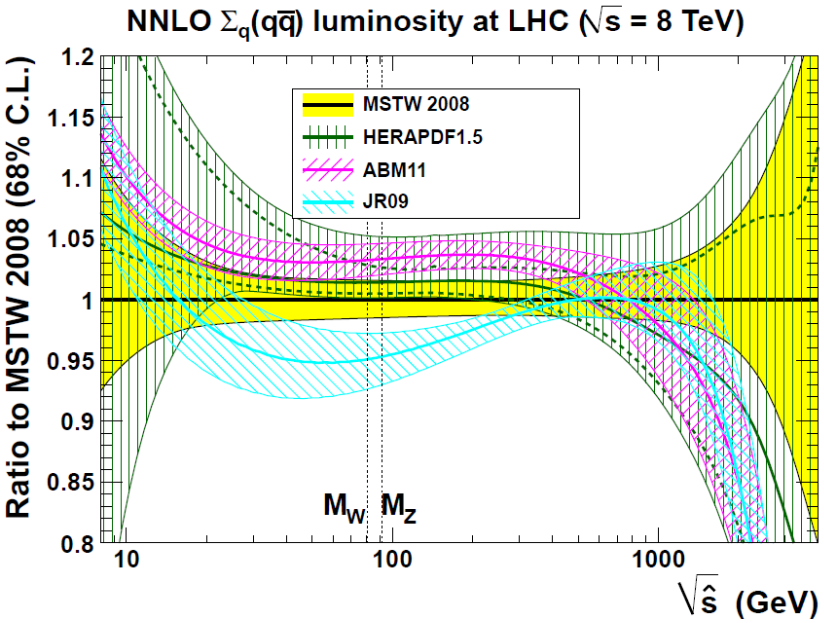
$$M^2 = x_1 x_2 s$$

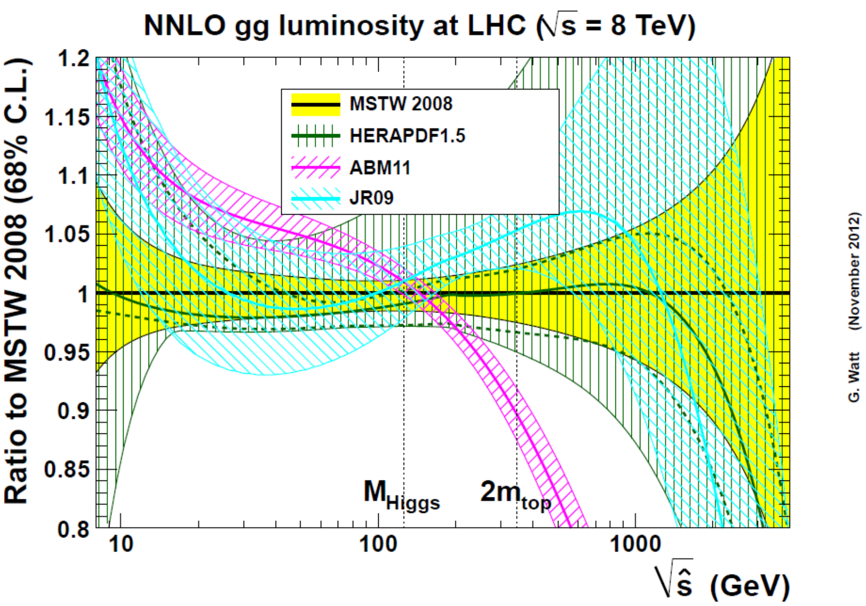
It is most instructive to compare them as ratios to a fixed PDF





So here q-qbar and g-g luminosities are compared for modern PDFs at NNLO. Why are there differences? How are PDFs detrmined?

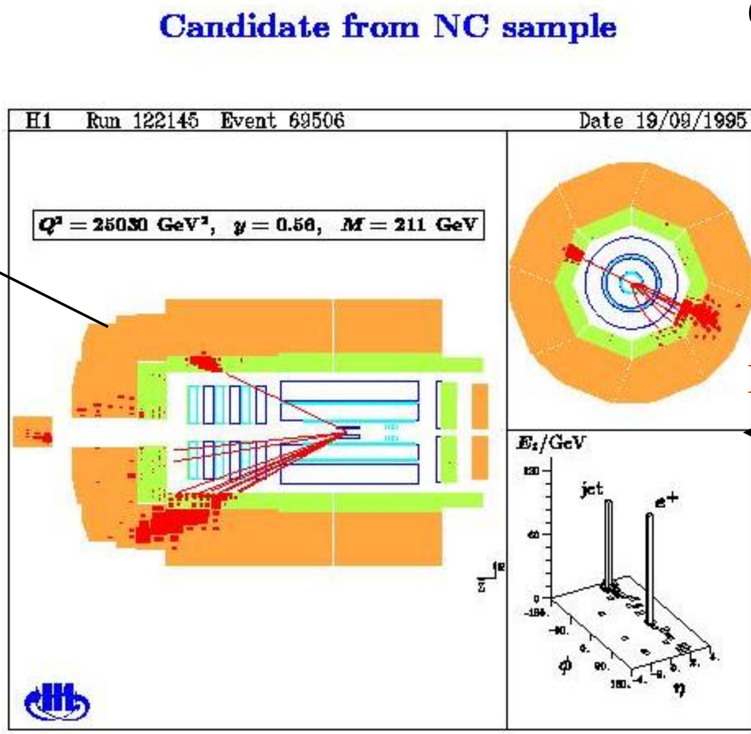




PDFs were first investigated in deep inelastic lepton-hadron scatterning -DIS

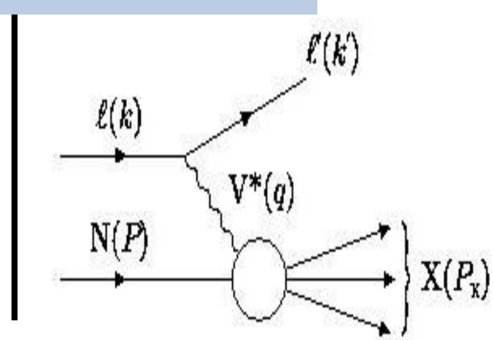
E

E_e



E_p

$d\sigma \sim$



$|\ldots|^2 \; L^{\mu\nu} W_{\mu\nu}$

Leptonic tensor - calculable

Hadronic tensor- constrained by Lorentz invariance

$q = k - k'$, $Q^2 = -q^2$ momentum transfer

$s = (p + k)^2$ c.of m. energy 2

$P_x = p + q$, $W^2 = (p + q)^2$

$x = Q^2 / (2p.q)$

$y = (p.q)/(p.k)$ inelasticity

$W^2 = Q^2 (1/x - 1)$ hadronic c.of m energy2

$Q^2 = s\ x\ y$ scale of the process

$s = 4 E_e E_p$

$Q^2 = 4 E_e E' \sin^2\theta_e/2$

$y = (1 - E'/E_e \cos^2\theta_e/2)$

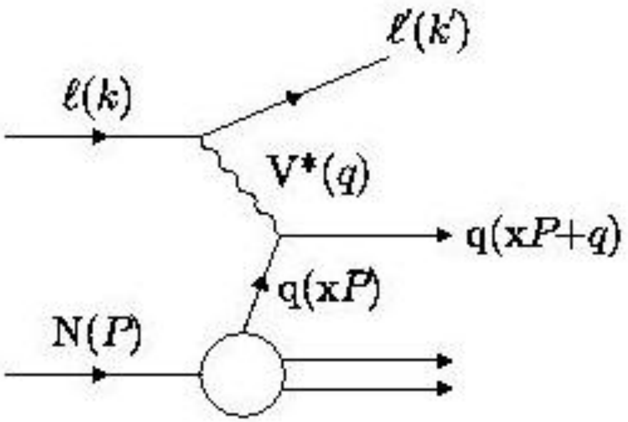
$x = Q^2/sy$

The kinematic variables are measurable

Completely generally the double differential cross-section for e-N scattering

$$\frac{d^2\sigma(e\pm N)}{dxdy} = \frac{2\pi\alpha^2 s}{Q^4}\left[Y_+ F_2(x,Q^2) - y^2 F_L(x,Q^2) \pm Y_- xF_3(x,Q^2)\right], \quad Y\pm = 1 \pm (1-y)^2$$

Leptonic part — hadronic part



F_2, F_L and xF_3 are structure functions

which express the dependence of the cross-section

on the structure of the nucleon–

The Quark-Parton model interprets these structure functions as related to the momentum distributions of quarks or partons within the nucleon – the PDFs- and the measurable kinematic variable $x = Q^2/(2p.q)$ is interpreted as the FRACTIONAL momentum of the incoming nucleon taken by the struck quark

$$F_2(lp) = x\left(\frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}) + \frac{1}{9}(s+\bar{s}) + \frac{4}{9}(c+\bar{c})\right)$$

We can extract all three structure functions experimentally by looking at the x, y, Q^2 dependence of the double differential cross-section

$(xP+q)^2=x^2p^2+q^2+2xp.q \sim 0$

for massless quarks and $p^2 \sim 0$

$x = Q^2/(2p.q)$

The FRACTIONAL momentum of the incoming nucleon taken by the struck quark is the MEASURABLE quantity x

HERA measured 4-cross sections across a broad kinematic range

Neutral current:

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2}=\frac{2\alpha\pi^2}{xQ^4}\left(Y_+ F_2 \mp Y_- xF_3 - y^2 F_L\right)$$

$F_2 \propto \sum_i e_i^2 (xq_i + x\bar{q}_i)$ — quark distributions, gluon from scaling violation

$xF_3 \propto \sum_i (xq_i - x\bar{q}_i)$ — valence quarks

$F_L \propto \alpha_s \times g$ — gluon at NLO

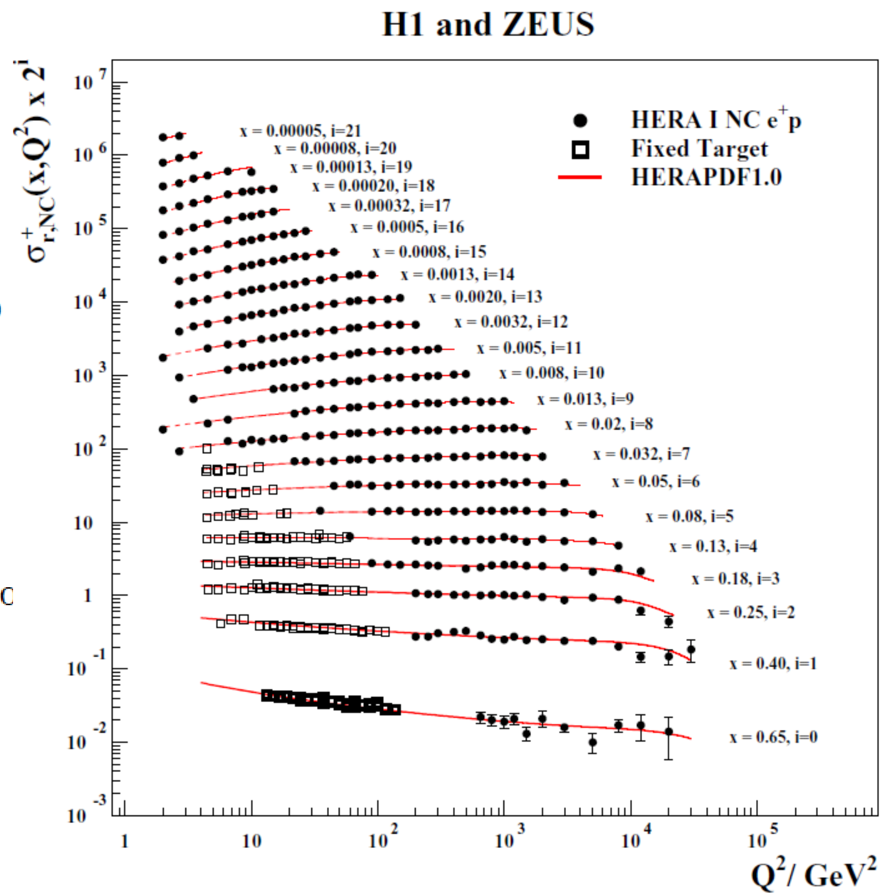
LO expressions

Charged current:

$$\frac{d^2\sigma^{-}_{CC}}{dxdQ^2}=\frac{G_F^2}{2\pi}\frac{M_W^2}{M_W^2+Q^2}\left(u+c+(1-y^2)(\bar{d}+\bar{s})\right)$$

$$\frac{d^2\sigma^{+}_{CC}}{dxdQ^2}=\frac{G_F^2}{2\pi}\frac{M_W^2}{M_W^2+Q^2}\left(\bar{u}+\bar{c}+(1-y^2)(d+s)\right)$$

flavour decompositic



QCD improves the QPM by telling us how the PDFs depend on the scale of the process Q^2 as well as on the momentum fraction x.

If parton distributions are known at some starting scale Q^2_0, then QCD tell us how they evolve to $Q^2 > Q^2_0$.

So in general we parametrise $q(x,Q^2_0)$ for all types of parton, evolve to Q^2 values of the measurements and confront with data via χ2 fit to determine parameters

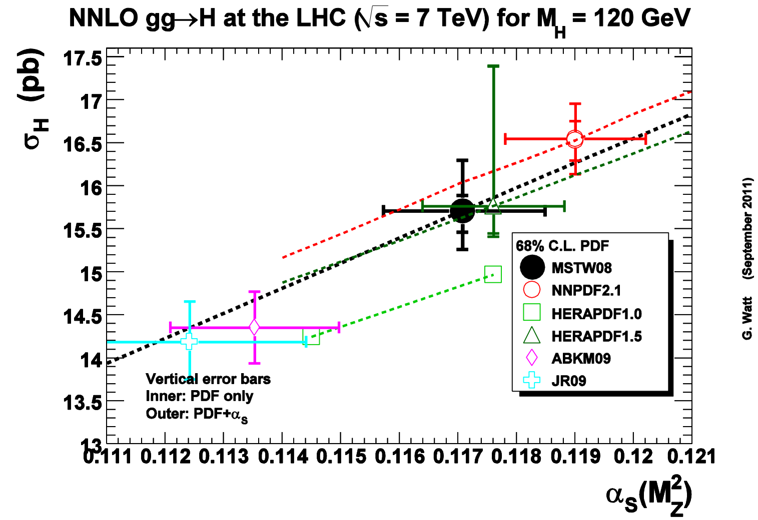
Gluon PDFs also control the scaling violations: DGLAP equations tell us how the partons evolve

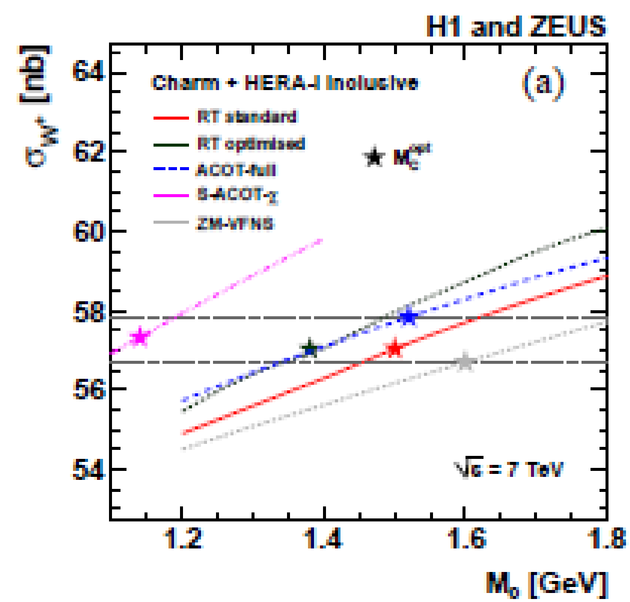
$$\frac{dq(x,Q^2)}{d\ln Q^2}=\frac{\alpha_s(Q^2)}{2\pi}\int_x^1\frac{dy}{y}\left[P_{qq}(z)q(y,Q^2)+P_{qg}(z)g(y,Q^2)\right]$$

$$\frac{dg(x,Q^2)}{d\ln Q^2}=\frac{\alpha_s(Q^2)}{2\pi}\int_x^1\frac{dy}{y}\left[\Sigma_q P_{gq}(z)q(y,Q^2)+P_{gg}(z)g(y,Q^2)\right]$$

So why are there differences between PDF sets?

1. Use of different values of $\alpha_S(M_Z)$ and there is a correlation between the value of alphas chosen/fitted and the gluon shape such that a larger value of $\alpha_S(M_Z)$ goes with a harder high-x gluon. A common value would bring some of the predictions into better agreement
2. Different ways of accounting for heavy quark production through Fixed Flavour Number or Variable Flavour Number Schemes and different choices of the values of the heavy quark masses
3. Different input data sets- (like older fixed-target DIS and newer Tevatron data)- with different levels of consistency , different methods of error estimation and different hidden systematics- like the evaluation of nuclear target corrections for data taken on heavy targets
4. Differences in choices of PDF parametrisation and starting scale, further model choices.





Let's confront the predictions with LHC data

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

Measurements:	Calculations:
1. W and Z production, Valence PDFs	NNLO though NLO 'will do'
2. W+c production, strange	NLO
3. Inclusive Jet and Di-Jet production, gluon and $\alpha_S(M_Z)$	NLO and this is a problem
4. Drell-Yan: high invariant mass, sea quarks at high-x	NNLO
5. Drell-Yan: low invariant mass DGLAP at low-x ?	only NNLO 'will do'
6. Top-antitop, gluon and $\alpha_S(M_Z)$	NLO with NNLO nearly there
7. Direct Photon, gluon	NLO but is fixed order enough
8. W,Z +jets or Zpt gluon	NLO but is fixed order enough?

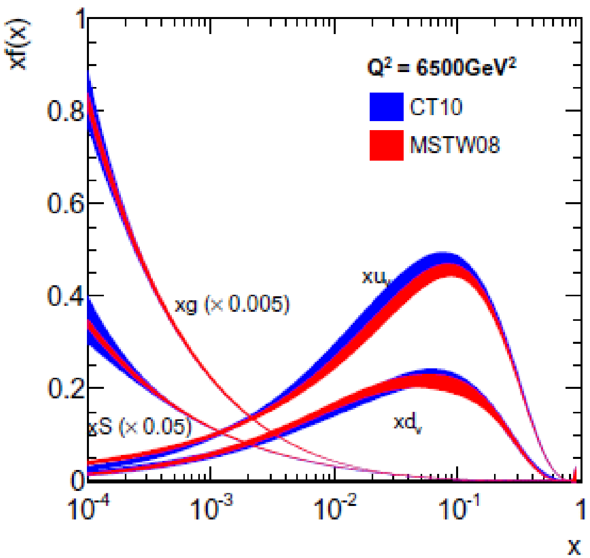
Some have been used in PDF fits already, some have potential.

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

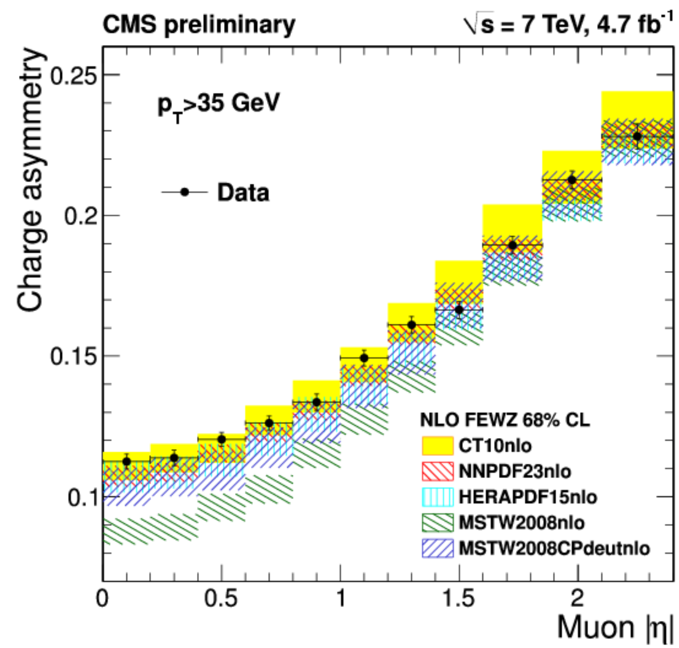


LHC data probe precisely the x range $10^{-3} < x < 10^{-1}$ where the difference is maximal

W-asymmetry

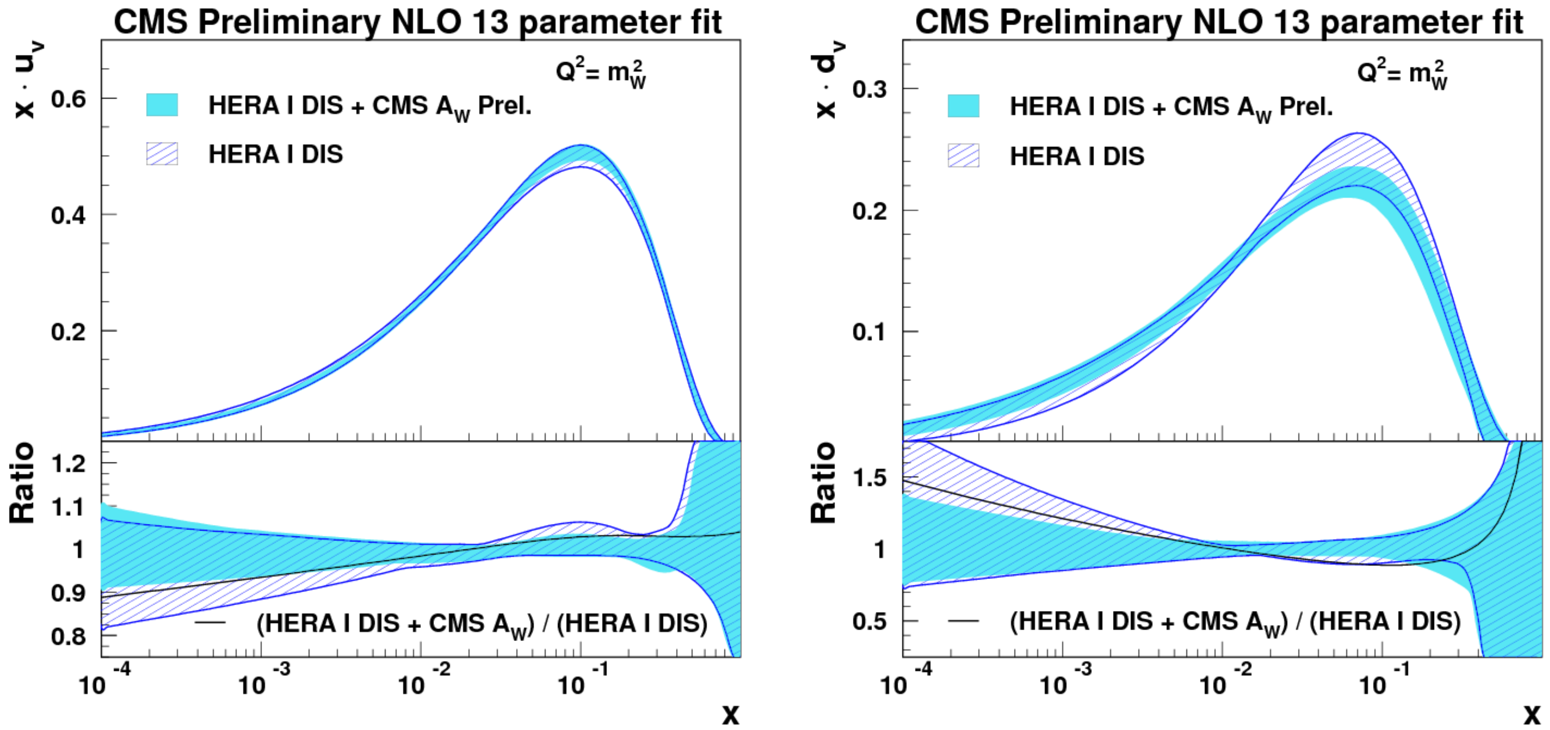
$$A_W = [\sigma(W^+) - \sigma(W^-)] / [\sigma(W^+) + \sigma(W^-)]$$

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)

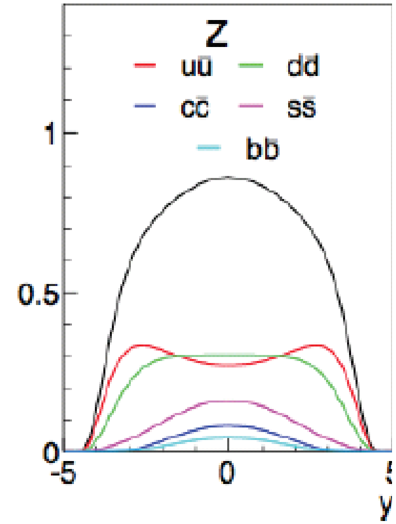
A PDF fit of these CMS muon asymmetry data together with the combined HERA-I inclusive deep inelastic scattering (DIS) data **(JHEP 1001 -109)** shows the potential of the LHC data to constrain valence quarks

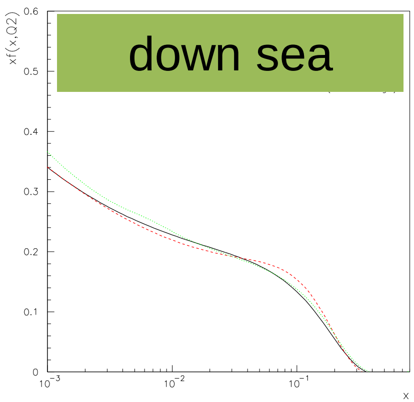


W and Z differential cross sections

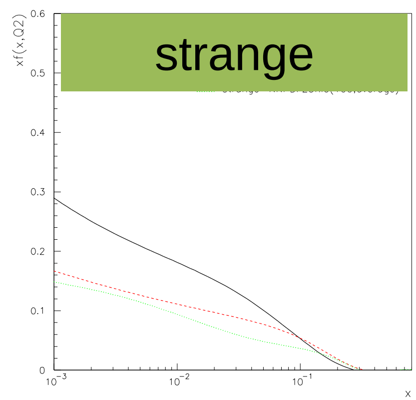
Flavour contributions to W and Z show that s-sbar is prominent in Z production at central rapdidty.
This plots were made for the usual assumption that strange sea is suppressed ~0.5 of down sea.

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



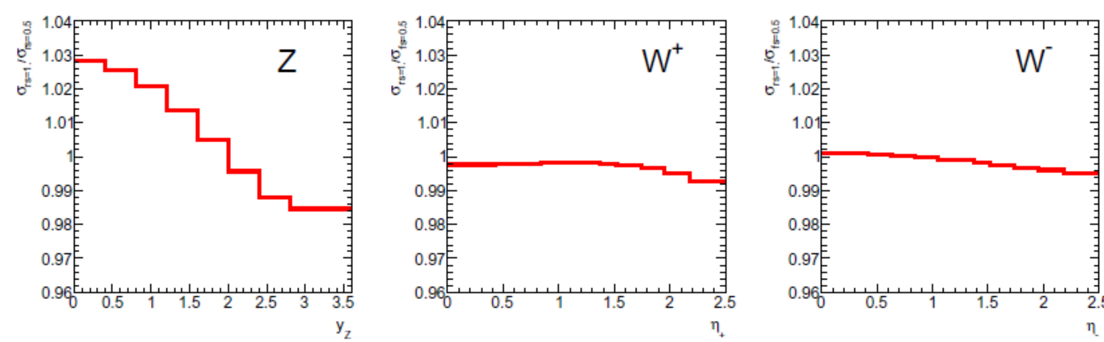


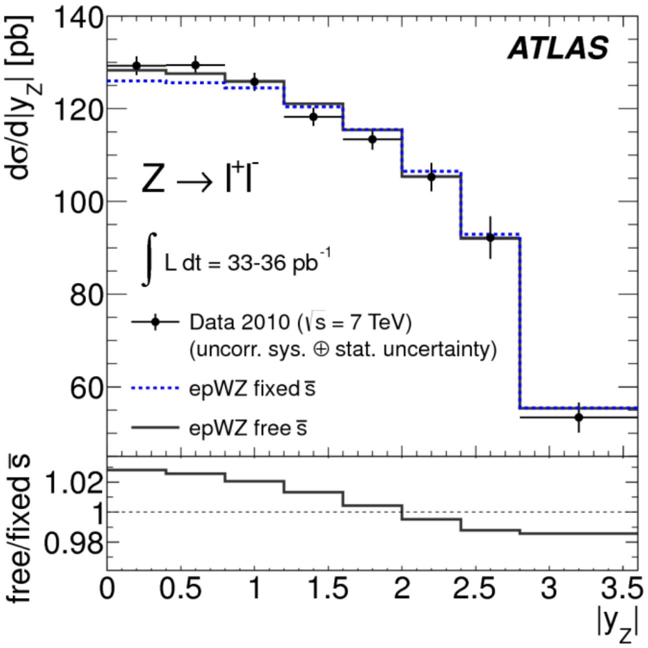
Q^2=2 GeV^2
CT10
MSTW08
NNPDF23



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

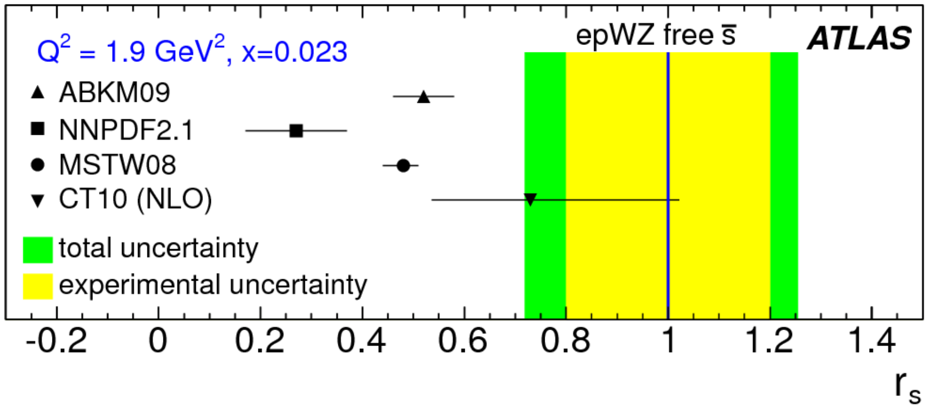
NNLO PDF fits to the ATLAS W,Z data plus HERA data (using HERAfitter) are shown for two assumptions about strangeness: s/d = 0.5 fixed and s/d = r_s (1-x) $^{(Cs-Cd)}$ – fitted.

The fit gives s/d = r_s = 1.0 ± 0.25

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

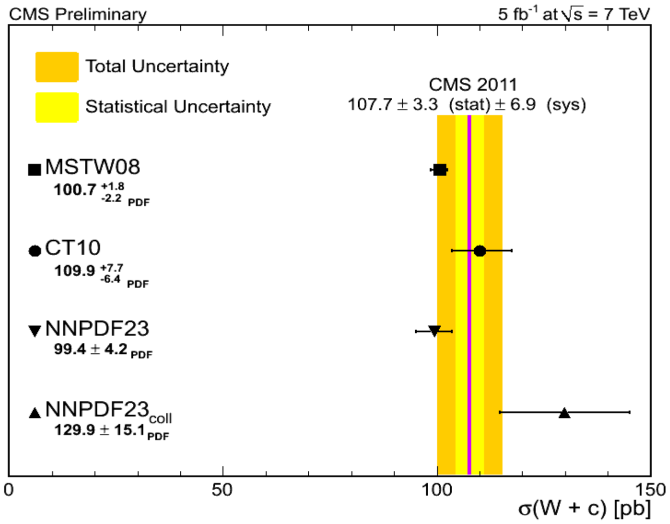
The experimental accuracy of the result depends on the shape of the Z spectrum and on its correlation to the W spectra, which fix the normalisation.

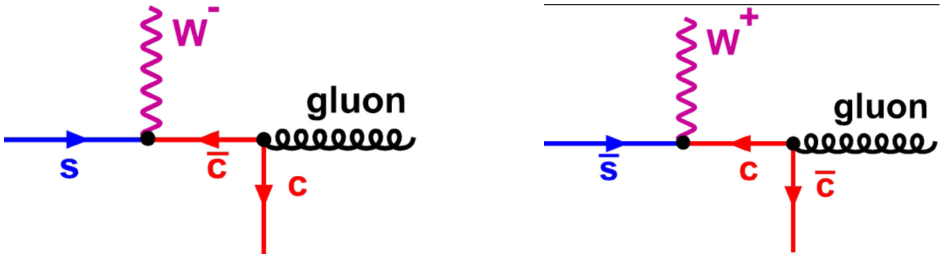
This result indicates enhanced strangeness in agreement with the CT10 predictions at x~0.01 - which is the kinematic region probed by LHC data.
In fact the ATLAS 'epWZ' fit has even more strangeness than CT10



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

CMS SMP-12002





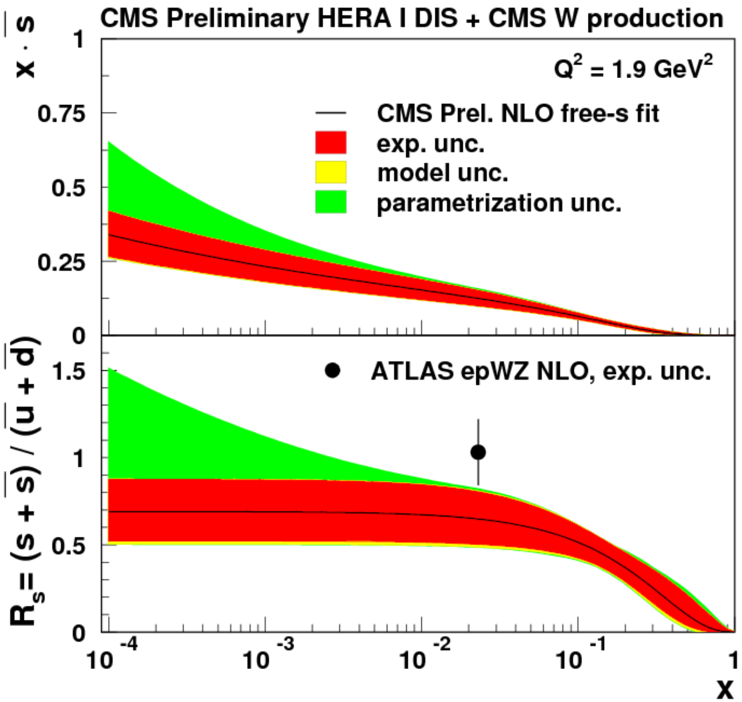
Compare W +c cross section for W's of both charges to predictions.

Very good agreement with CT10

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

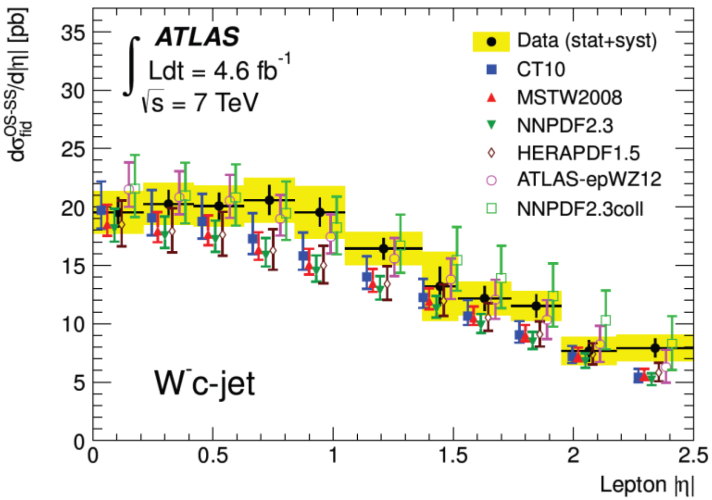
They obtain a strange quark distribution compatible with CT10.

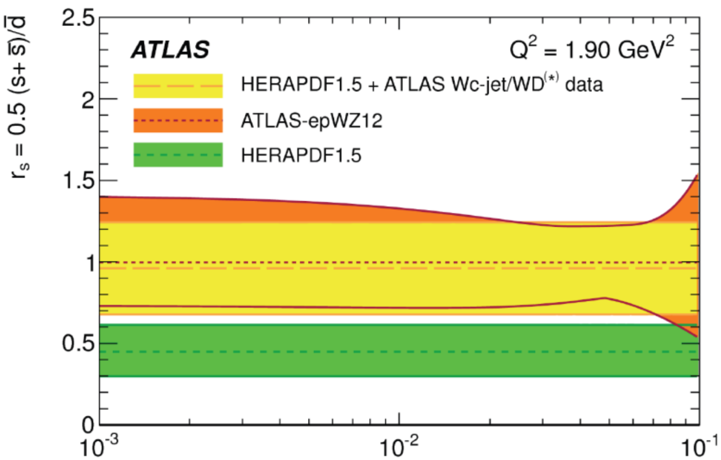
Their analysis is at NLO so can only be compared to a single point from the ATLAS analysis



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

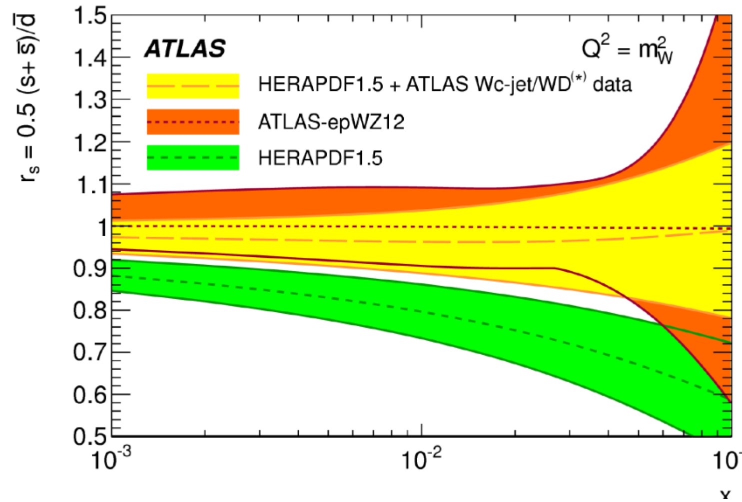
BUT recently released ATLAS data on W+c favour more strangeness than CT10, iin agreement with ATLAS epWZ and NNPDF2.3(Coll). JHEP05(2014)068



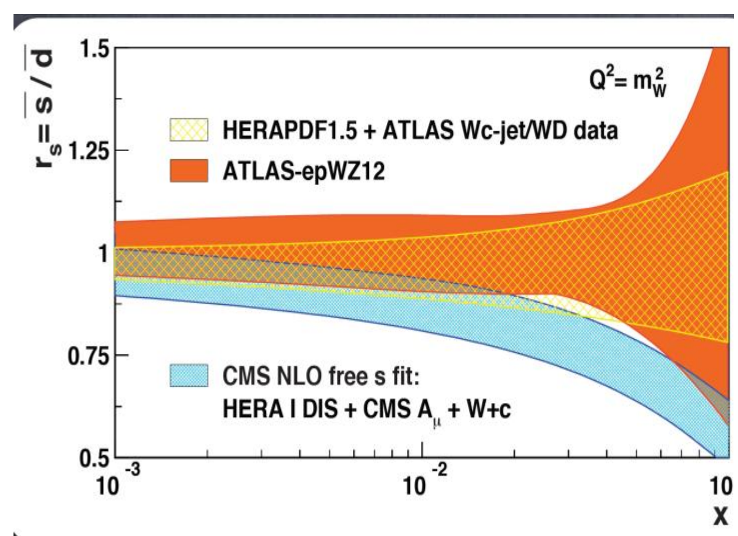


$\rightarrow r_s \equiv 0.5(s+\bar{s})/\bar{d} = 0.96\,^{+0.16}_{-0.18}\,^{+0.21}_{-0.24}$

And once you evolve to $Q^2 \sim M_W^2$



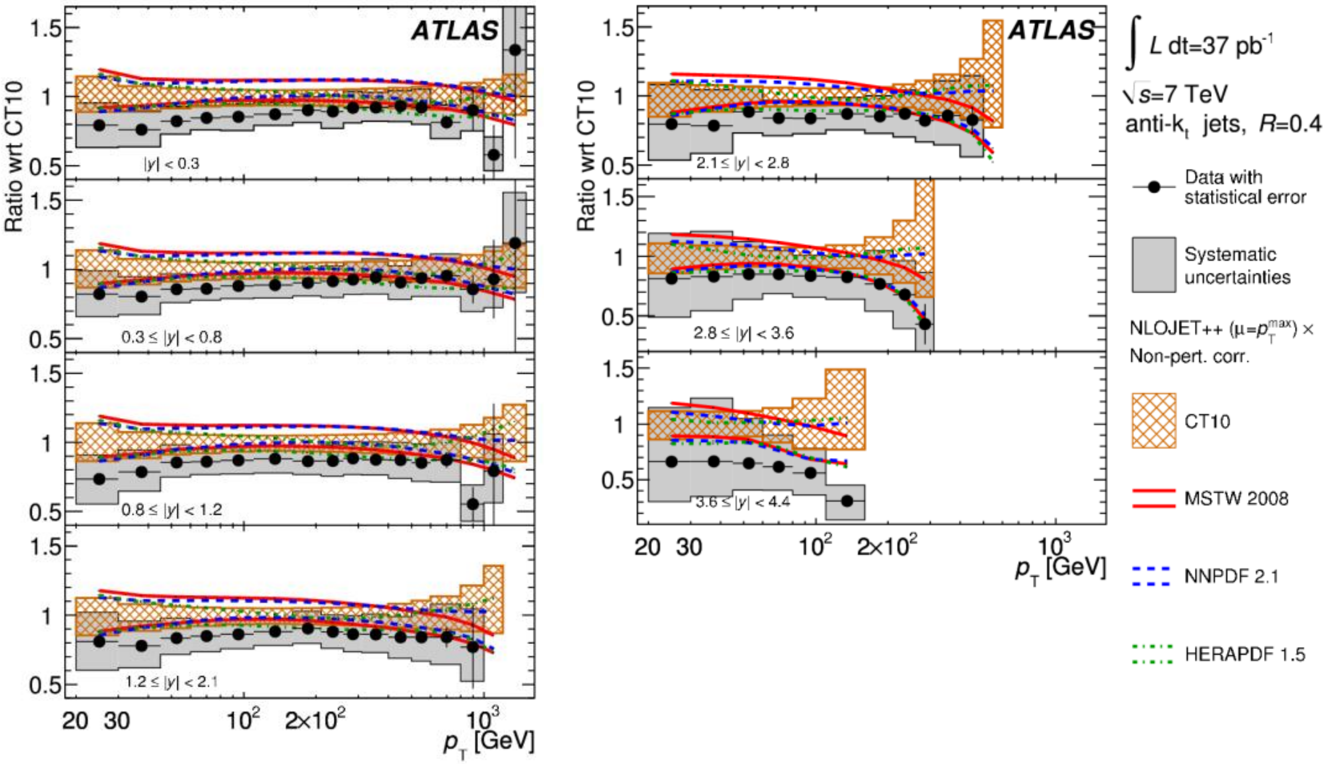
Disagreement with CMS?



Now let's consider jet production, at the highest scales this may reveal new physics. The reliability of the predictions depends on how well we know the high-x gluon PDF

ATLAS :Phys ReV D86(2012)014022 –ATLAS 2010 7 TeV jet data

are provided with 90 sources of correlated error

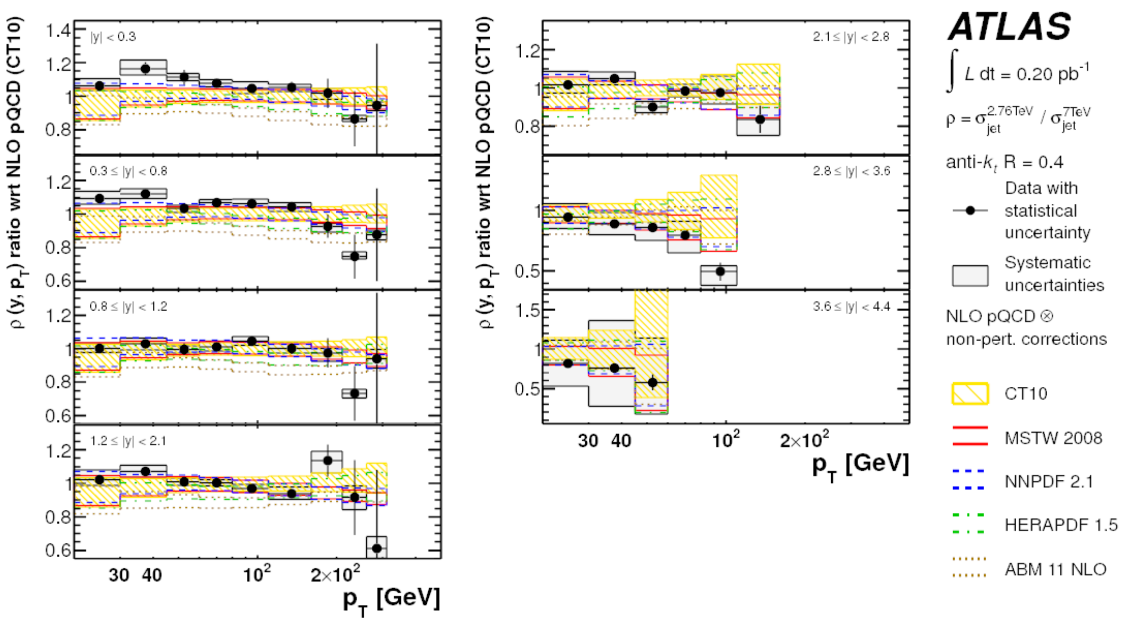


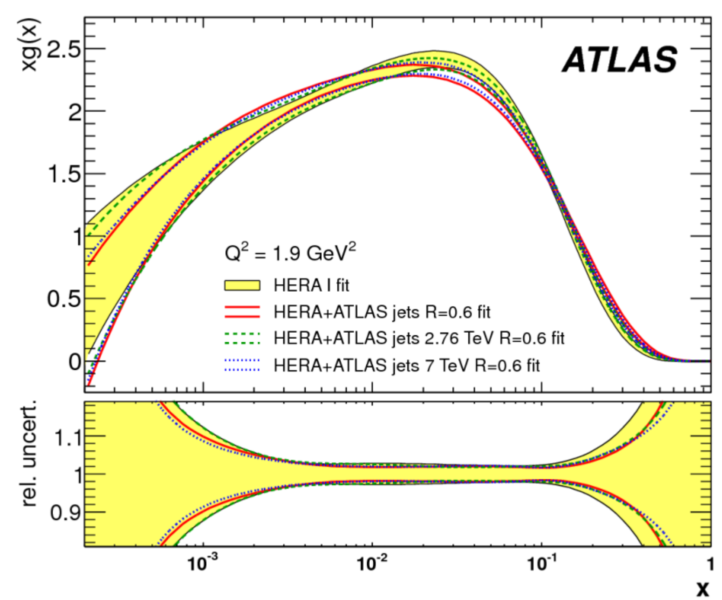
Here the inclusive jet cross sections are shown in ratio to the predictions of CT10, with the predictions of other PDFs also illustrated.

These jet data show no sign of new physics and are well fit by modern PDFs. They can be used to try to improve our knowledge of the high-x gluon. 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.

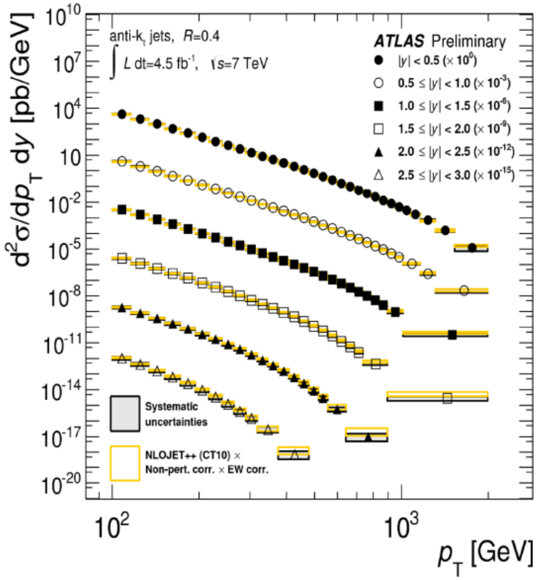
There is now much more data on jets from 2011 7 TeV running , 4.5fb^{-1} of data
Both CMS and ATLAS have made inclusive, di-jet and tri-jet measurements

ATLAS inclusive, di-jet, tri-jet

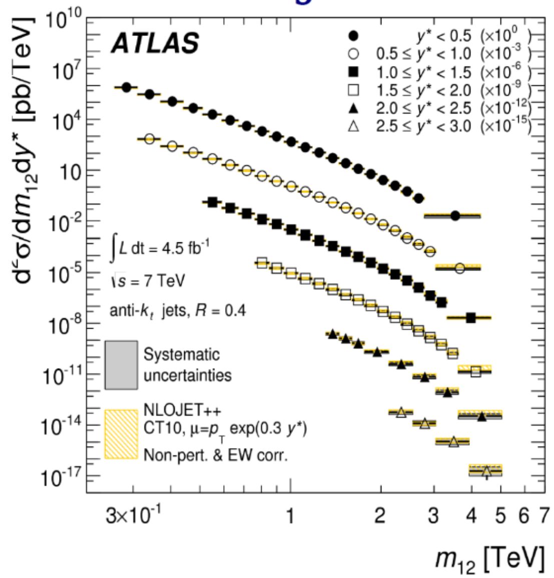
- Experimental double-differential cross-section compared to NLO pQCD + non-pert. (+ EW) corrections

R=0.4, L=4.5fb^{-1}, $\sqrt{s}$=7 TeV

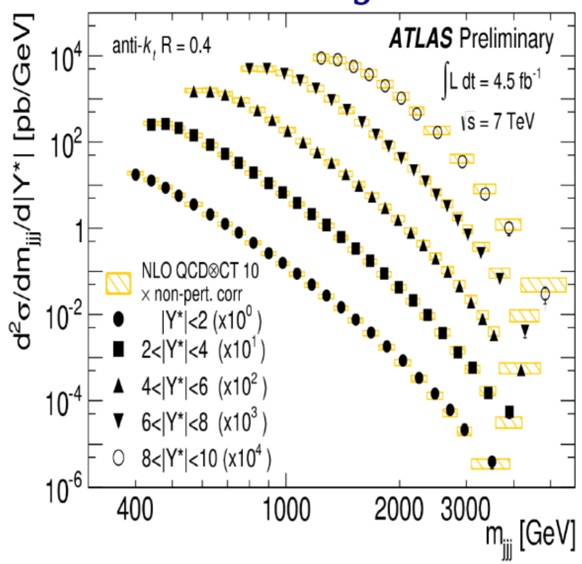
Inclusive jets



Dijets



Three jets



$y^* = |y_1 - y_2|/2$

$Y^* = |y_1 - y_2| + |y_1 - y_3| + |y_2 - y_3|$

$p_{T1;2} > 100; 50$ GeV

$p_{T1;2;3} > 150; 100; 50$ GeV

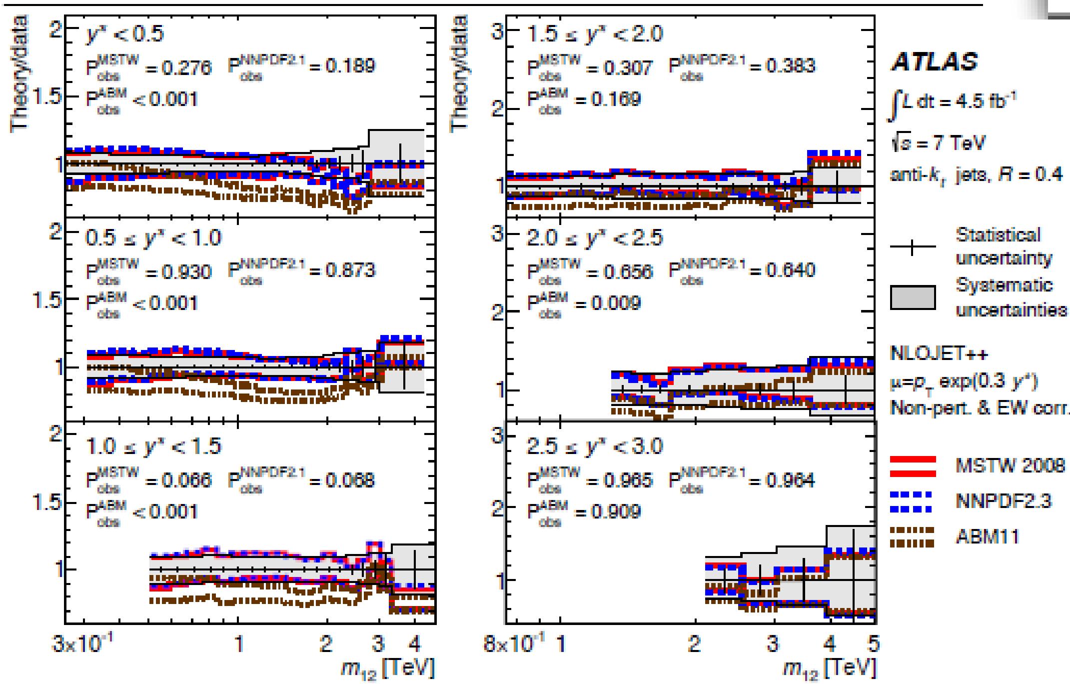
ATLAS di-jets JHEP05(2014)059

Comparison with PDFs

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

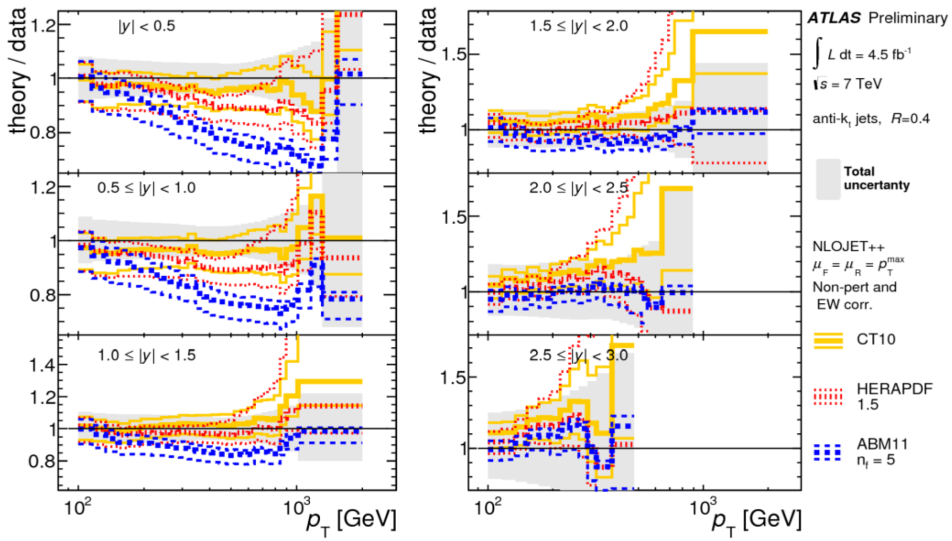


- Lower prediction from ABM, possibly due to the softer gluon

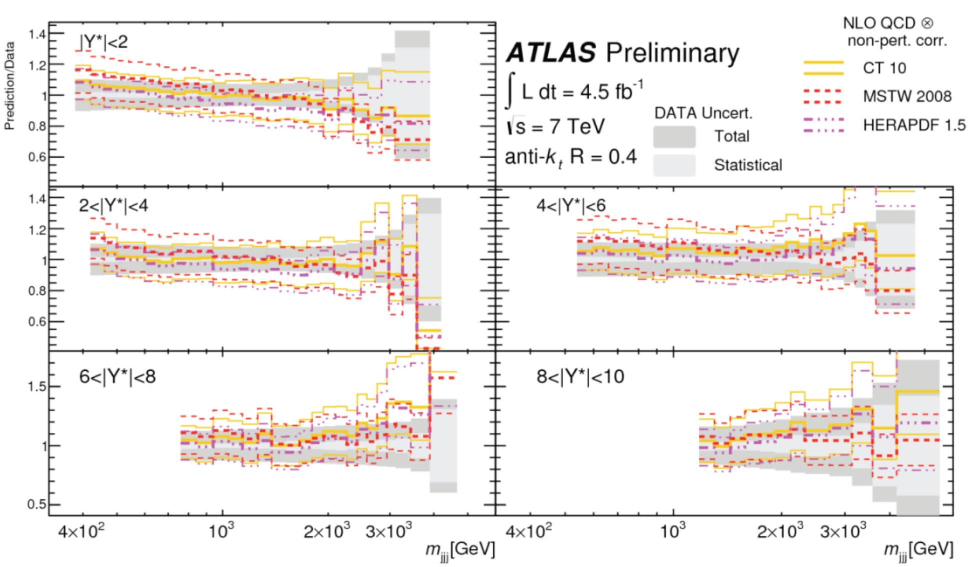
What if there is new physics at the highest scales? E.g contact interactions wth compositeness scale Λ. Then we can set limits on this- but they depend on the PDF used

PDF set	Λ [TeV] $R = 0.4$ Exp	$R = 0.4$ Obs	$R = 0.6$ Exp	$R = 0.6$ Obs
CT10	7.3	7.2	7.1	7.1
HERAPDF1.5	7.5	7.7	7.3	7.7
MSTW 2008	7.3	7.0	7.1	6.9
NNPDF2.1	7.3	7.2	7.2	7.0

ATLAS inclusive jets/tri-jets comparison to PDFs



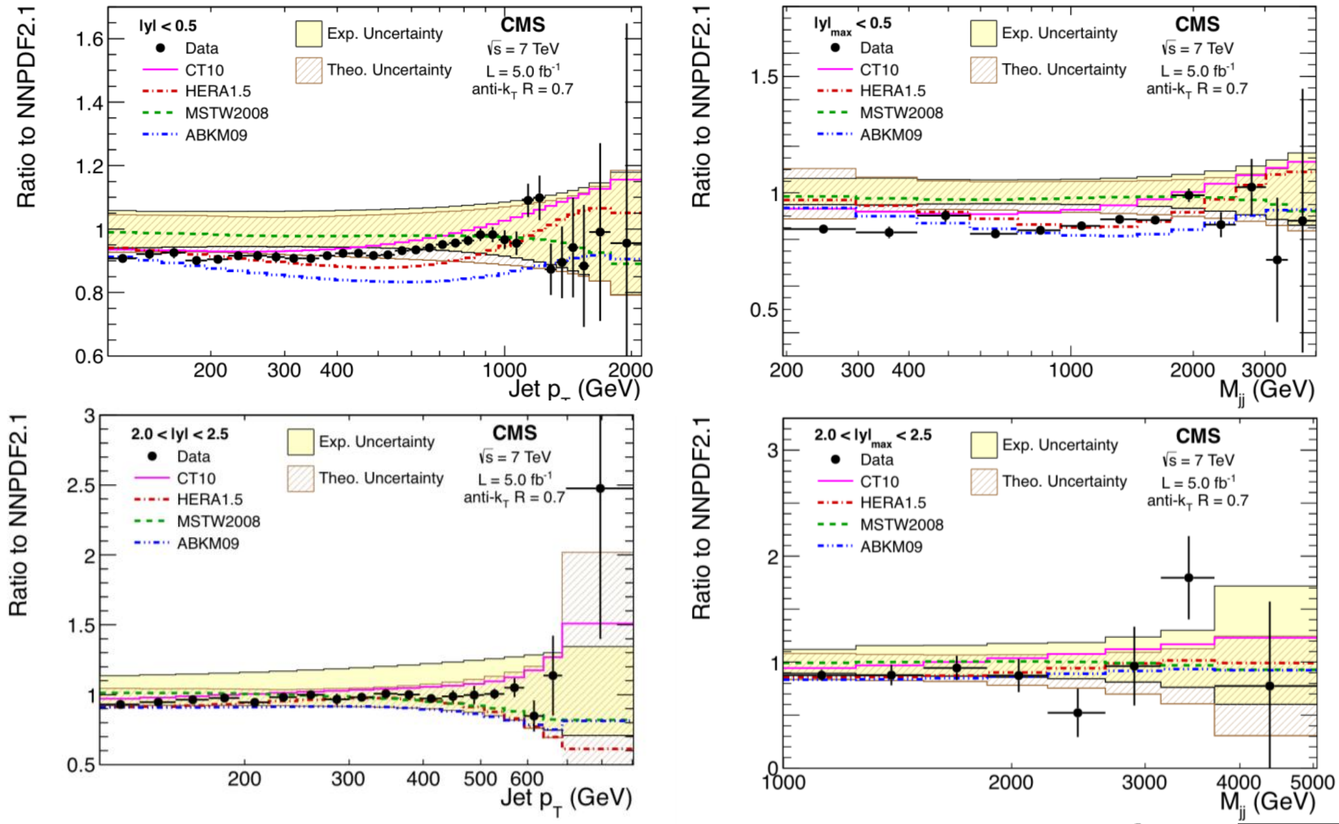
y ranges	P_{obs} (ATLAS Preliminary)					
	NLO PDF set:	CT10	MSTW2008	NNPDF2.1	HERAPDF1.5	ABM11
$\lvert y\rvert < 0.5$		84%	61%	72%	56%	< 0.1%
$0.5 \le \lvert y\rvert < 1.0$		91%	93%	89%	49%	< 0.1%
$1.0 \le \lvert y\rvert < 1.5$		89%	88%	85%	93%	2.7%
$1.5 \le \lvert y\rvert < 2.0$		93%	88%	91%	75%	55%
$2.0 \le \lvert y\rvert < 2.5$		86%	82%	85%	26%	57%
$2.5 \le \lvert y\rvert < 3.0$		95%	94%	97%	82%	85%

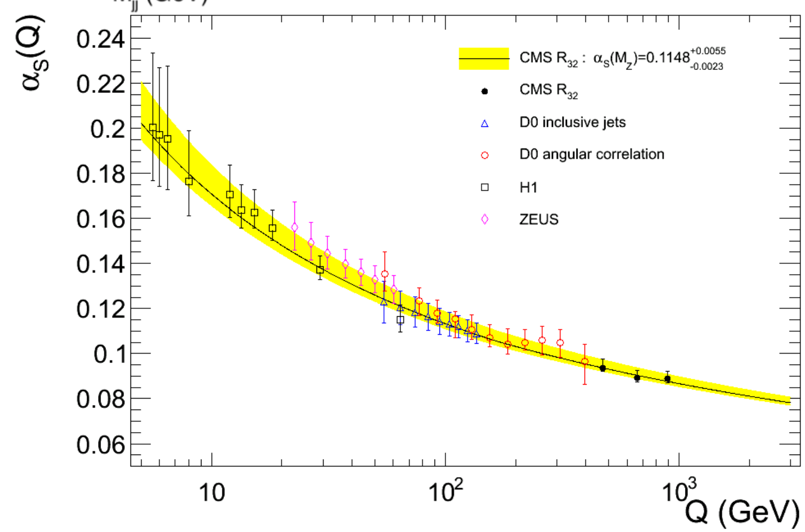


- Good agreement for NNPDF2.3, GJR09, CT10, MSTW and HERADPDF1.5 (not all of them shown here)
- Some tension with ABM11

CMS inclusive jet and di-jet data at 7 TeV

CMS QCD-12028
Arxiv:1212.6660



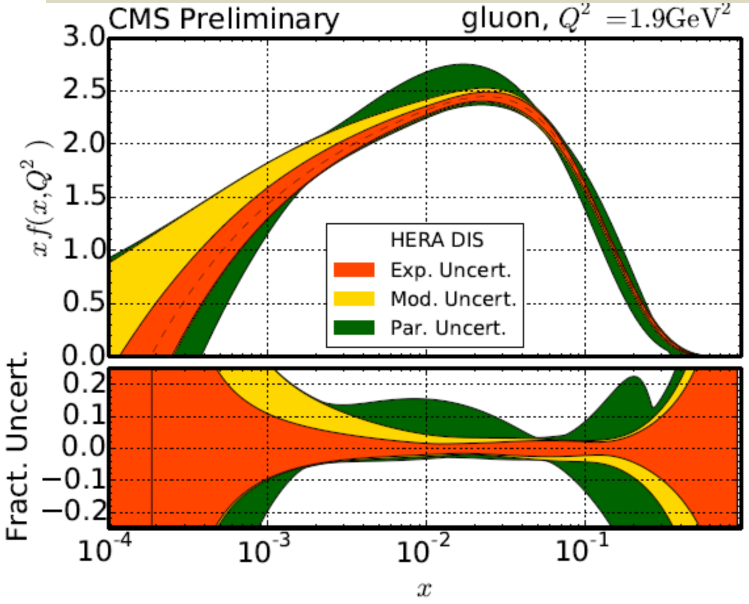


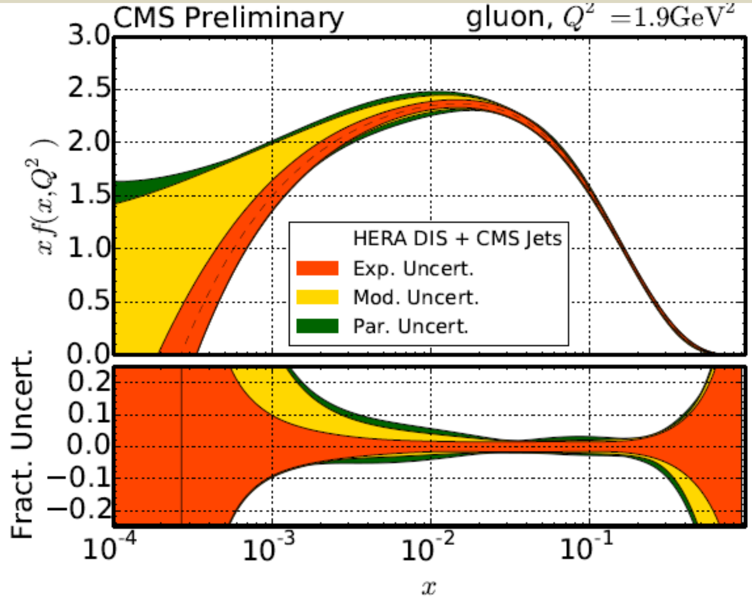
The strong coupling constant from the inclusive data (using fixed PDFs) is

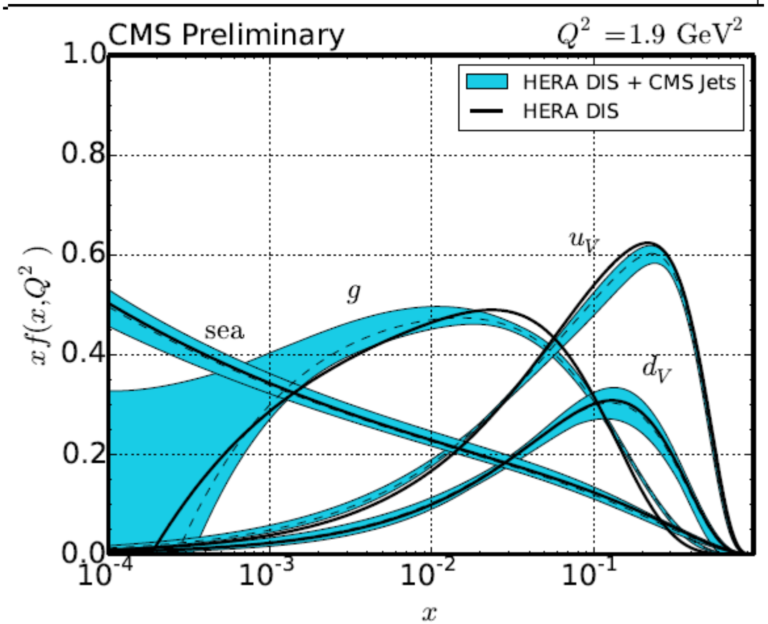
$$\alpha_S(M_Z) = 0.1185 \pm 0.0019(\text{exp}) \pm 0.0028(\text{PDF})\,^{+0.0055}_{-0.0022}(\text{scale})$$

One limitation is that jet calculations are still only available to NLO and there is thus still a substantial scale dependence on predictions

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







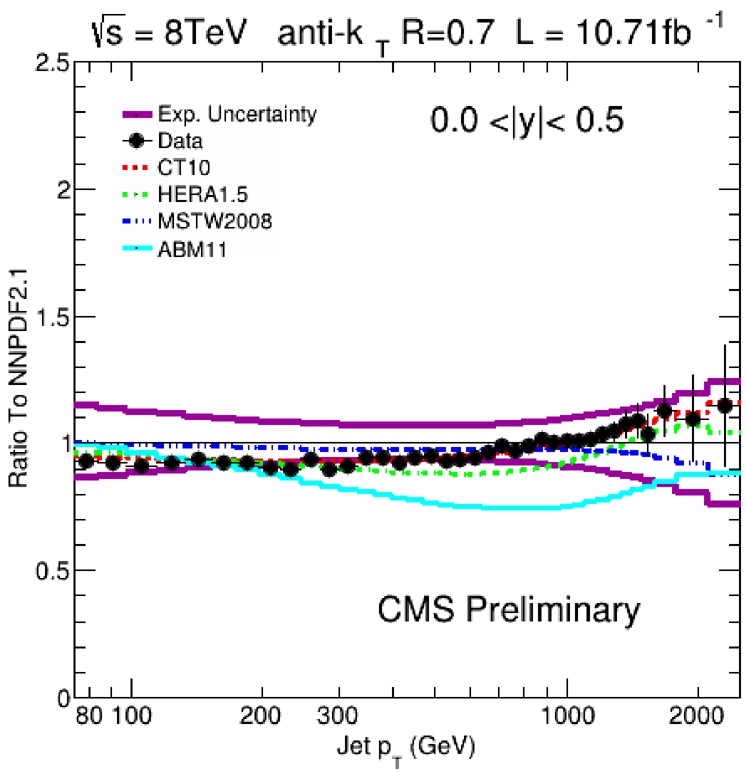
Note reduced uncertainty and change of shape of both gluon and u-valence

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

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

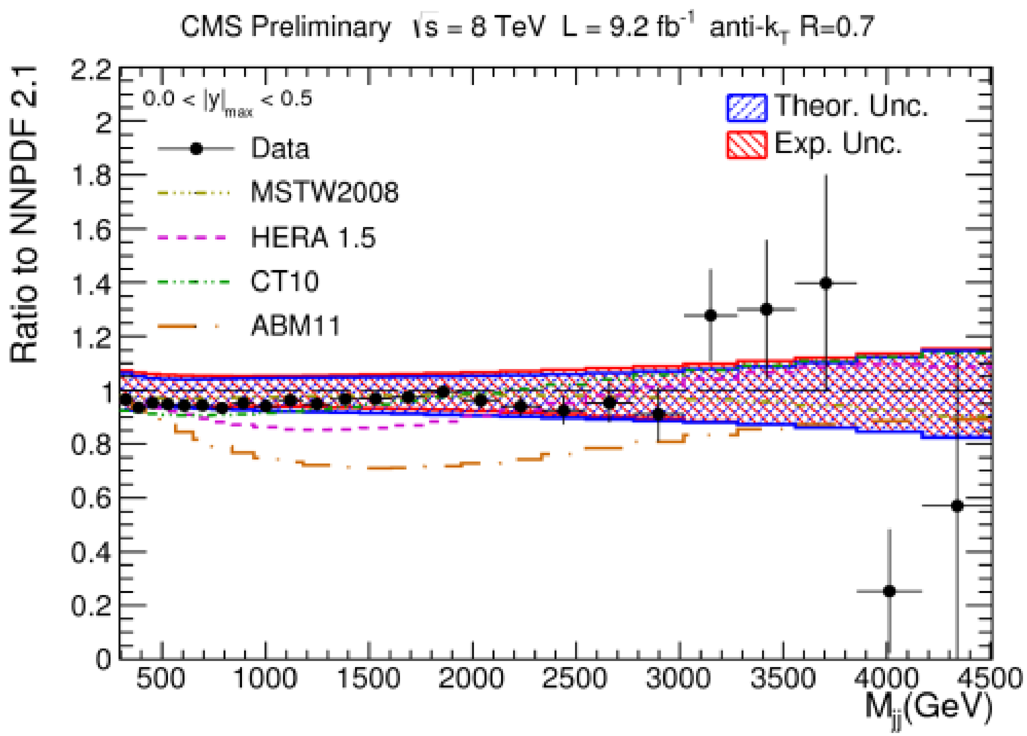
CMS also have results at 8 TeV from ~10fb^{-1}

Inclusive jets



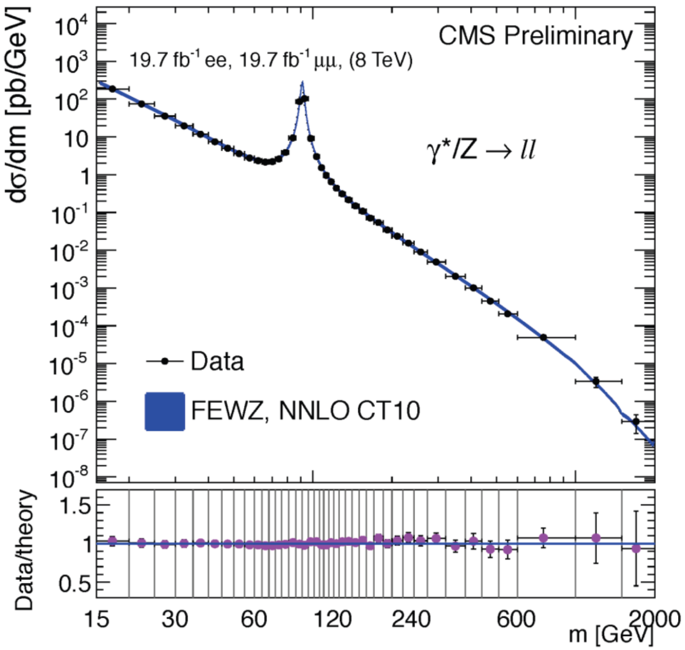
CMS PAS SMP-12-012

Di- jets



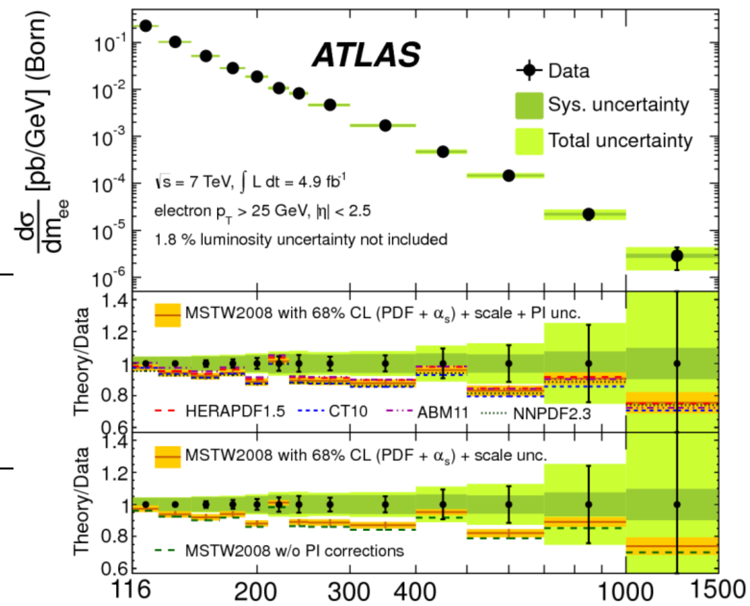
CMS-PAS-SMP-14-002

Drell Yan data is sensitive to new physics at high-scale and can give information on sea quark PDFs



CMS 8 TeV mass spectrum

ATLAS High mass Drell-Yan at 7 TeV and 8 TeV



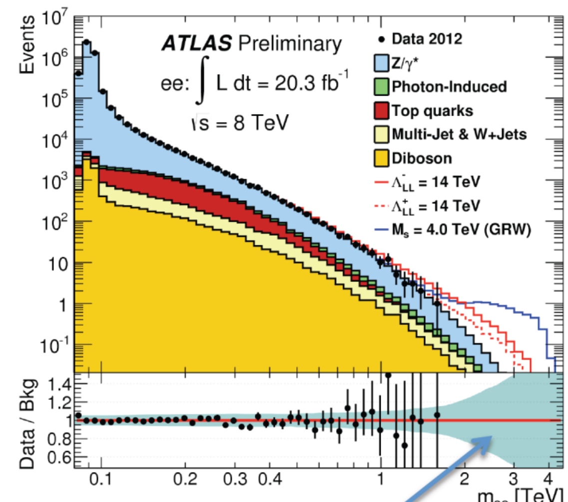
ATLAS High Mass 7 TeV Drell-Yan data arXiv:1305.4192

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.



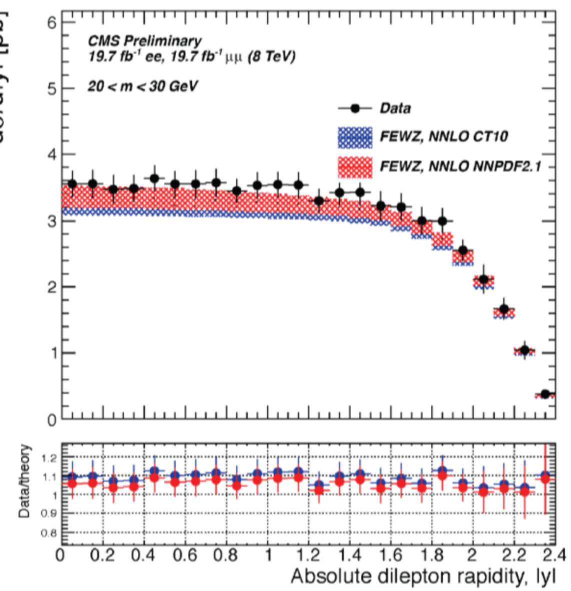
ATLAS-CONF-2014-030

Dominated by PDF uncertainty

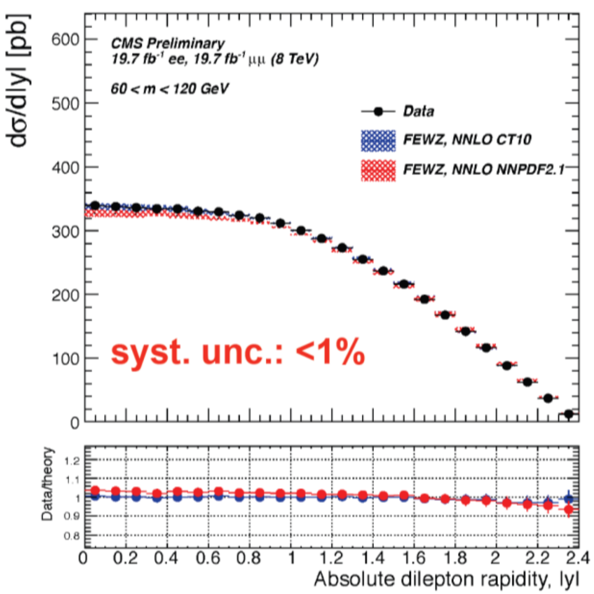
CMS have also issued rapidity distributions from low to high-mass for 8 TeV

- ✦ **Good agreement with NNLO predictions based on CT10/NNPDF2.1 PDFs.**

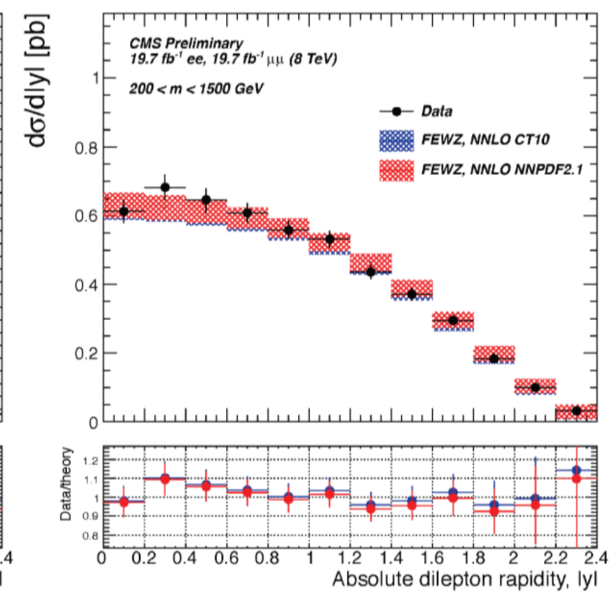
20-30 GeV



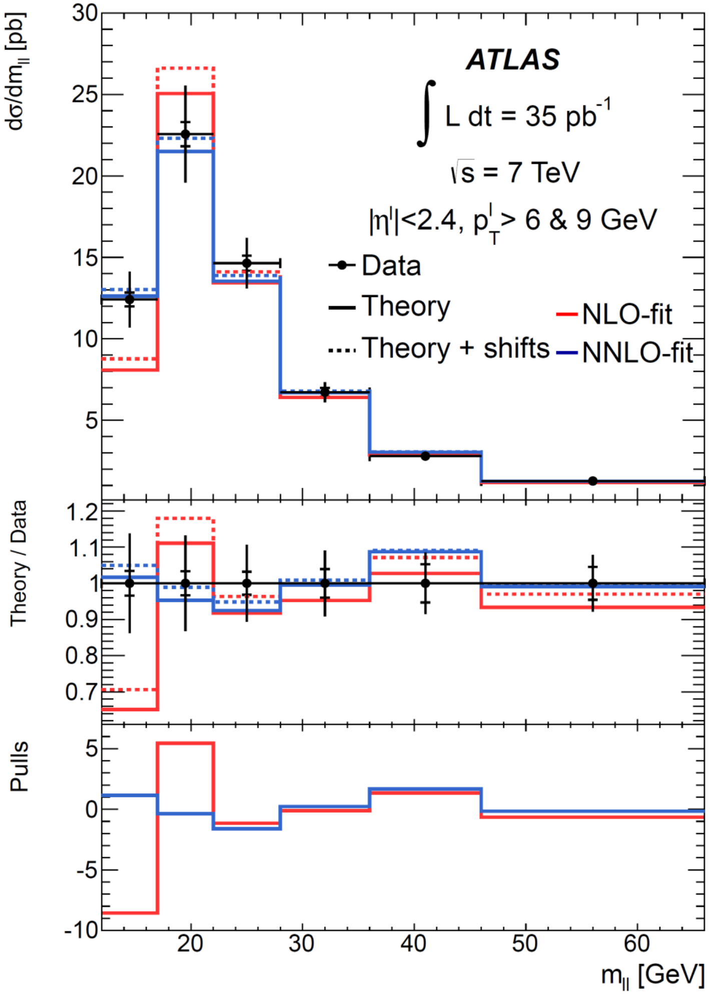
60-120 GeV

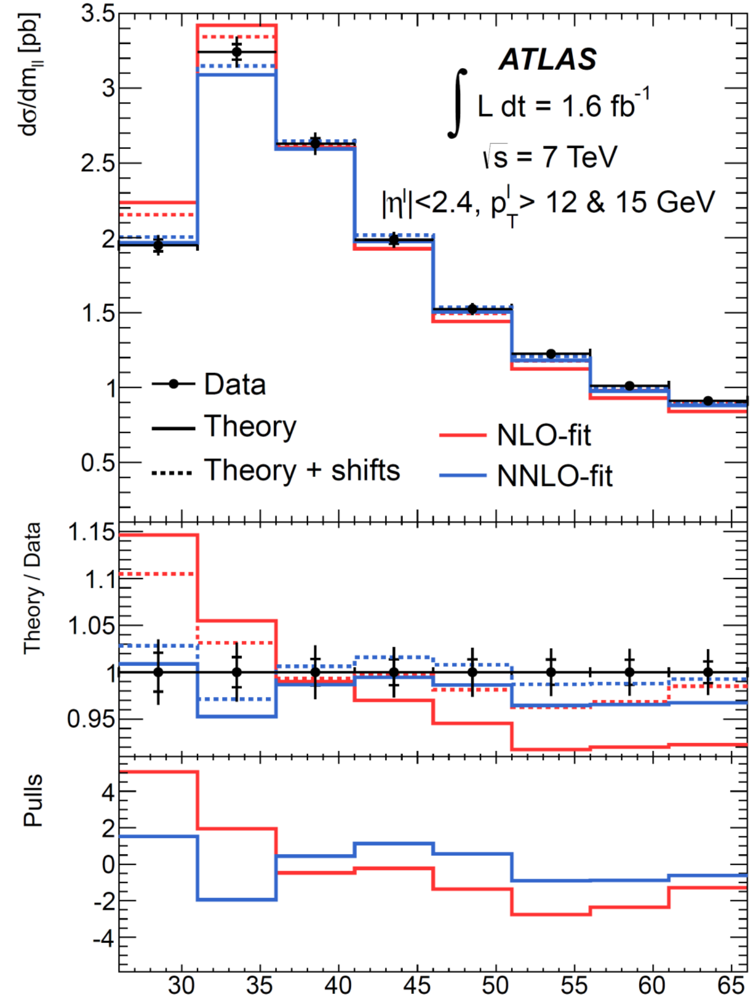


200-1500 GeV



Also 7 TeV CMS-SMP-13003





ATLAS 7 TeV low-mass Drell-Yan data   Arxiv:1404:1212

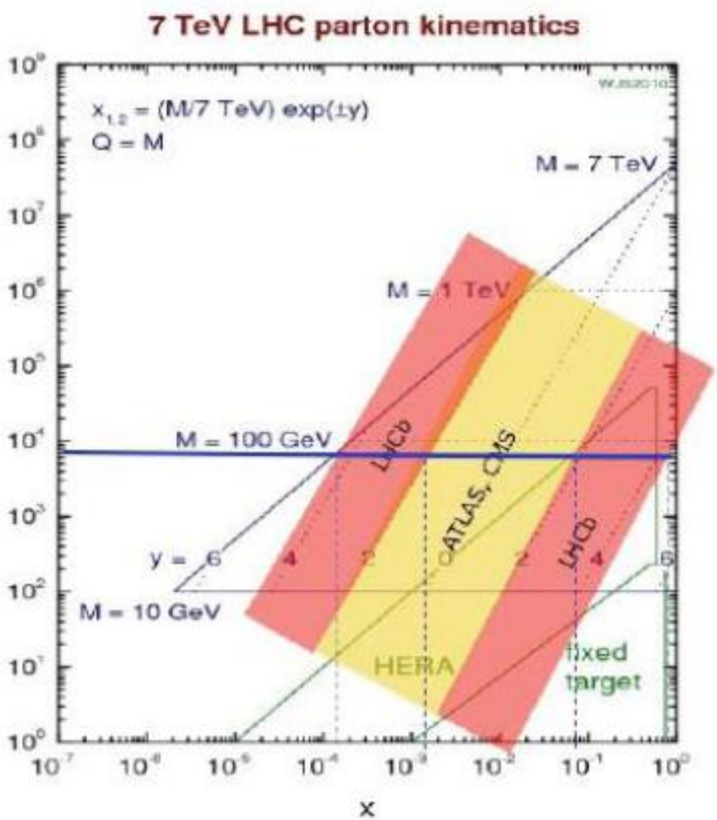
Has been extended down to low mass ~10GeV

PDF fits have been done to HERA-I data plus these ATLAS low –mass data

Only NNLO fits do well

Prediction	χ^2 (8 points) Nominal	χ^2 (6 points) Extended
NLO Fit	40.7	117.1
NNLO Fit	8.5	7.8

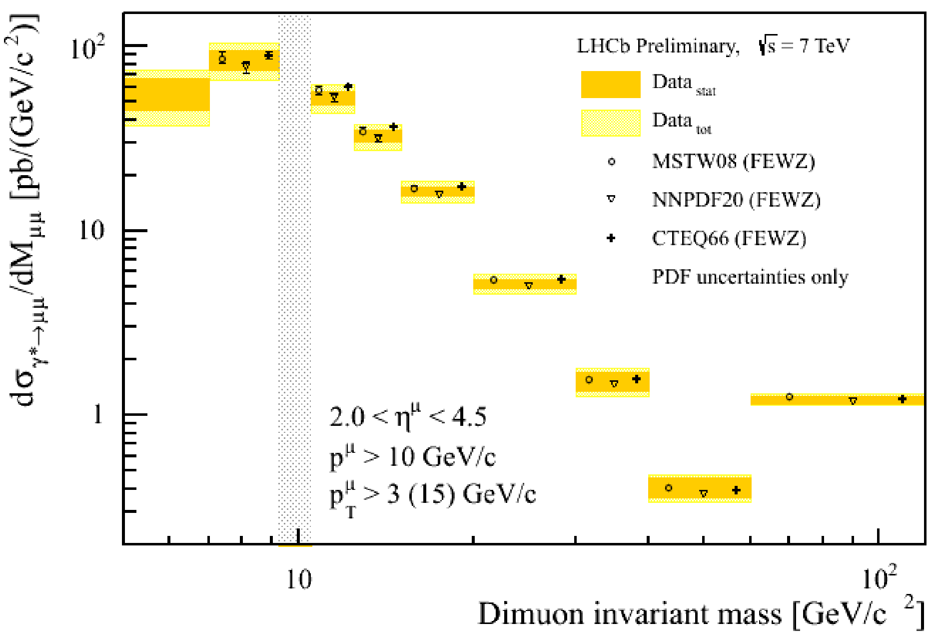
Low-mass Drell-Yan could probe a low-x region where DGLAP no longer works



The PDFs are not so well known at low-x

but do we even have the right theory?

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

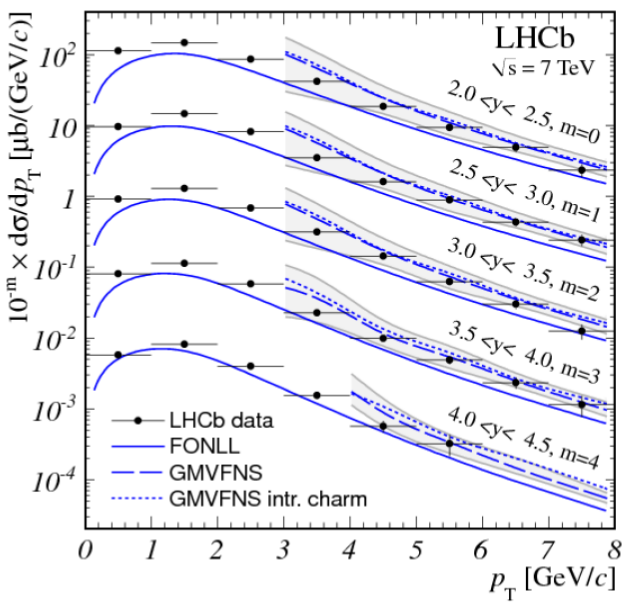


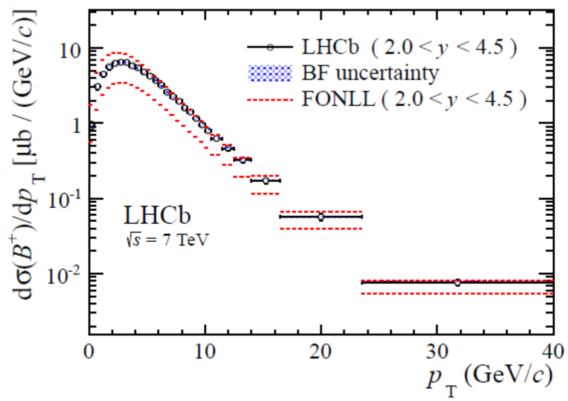
LHCb also have low-mass Drell-Yan data
LHCb-CONF-2012-013. **This shows no sign of non-DGLAP effects, but errors are large**

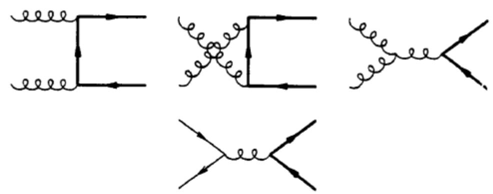
Impact of LHCb heavy flavour data on PDFs. LHCb data

LHCb has recently measured charm and beauty production in the forward region $2.0 < y < 4.5$:

- charm, $0 < p_T < 8\ GeV$ [NPB871 (2013) 1]
- beauty, $0 < p_T < 40\ GeV$ [JHEP08 (2013) 117]



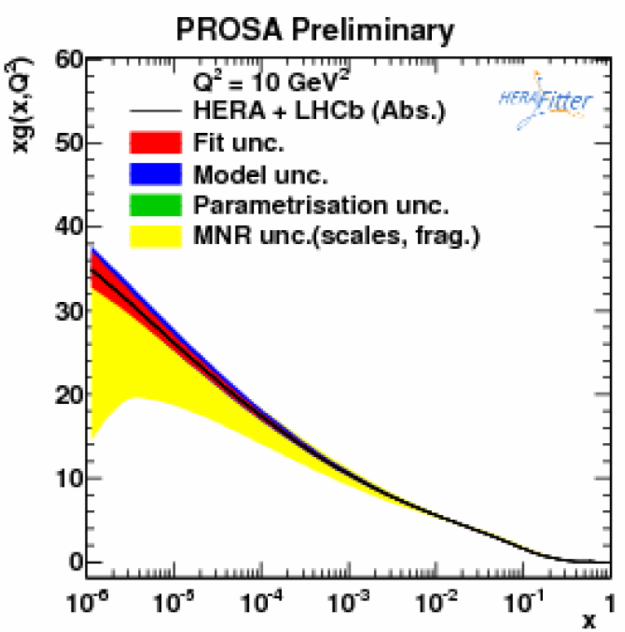


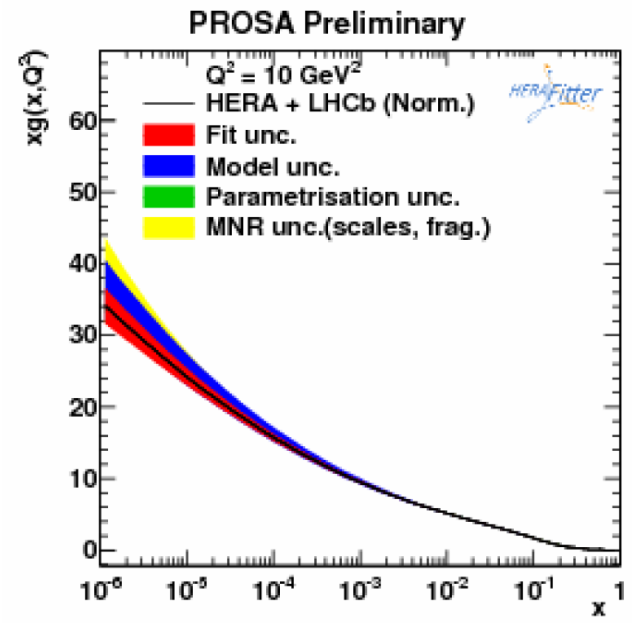


- Theory describes data well within large theoretical uncertainties
- Dominant theoretical uncertainties (~ 2) from scales μ_f, μ_r variations

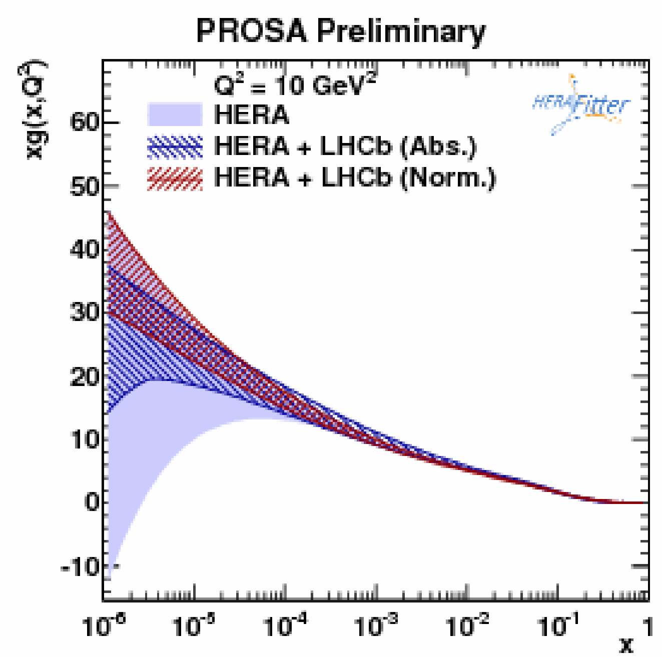
Theory at NLO using FFN by Magano Nason Ridolfi (MNR)

Fits have been done to Absolute and Normalised LHCb Heavy flavour data together with HERA data



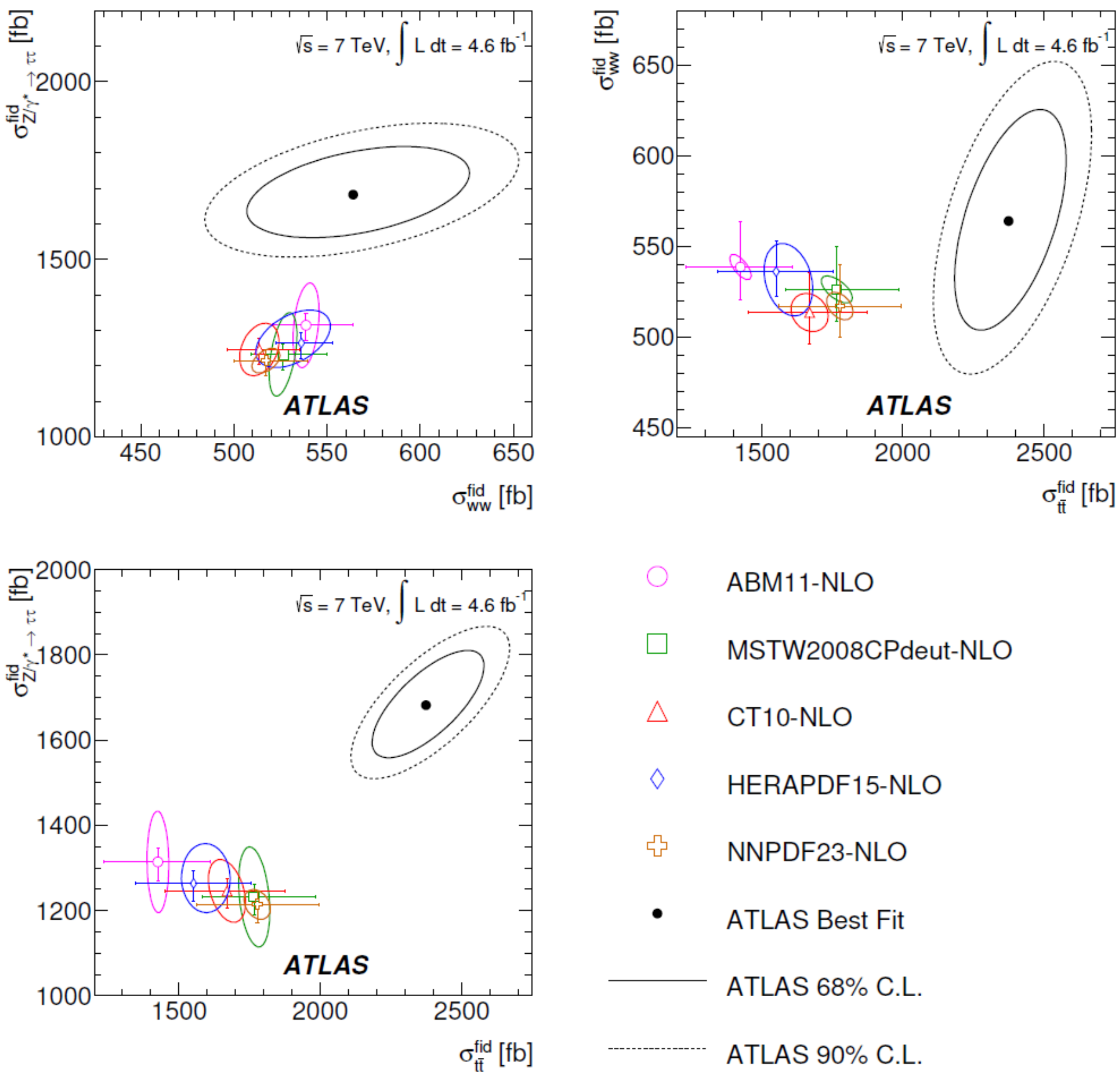


Despite scale uncertainties in the MNR predictions there is still a significant improvement in low-x uncertainty of the gluon PDF compared to the use of HERA data alone (and these HERA data include HERA heavy flavour data)



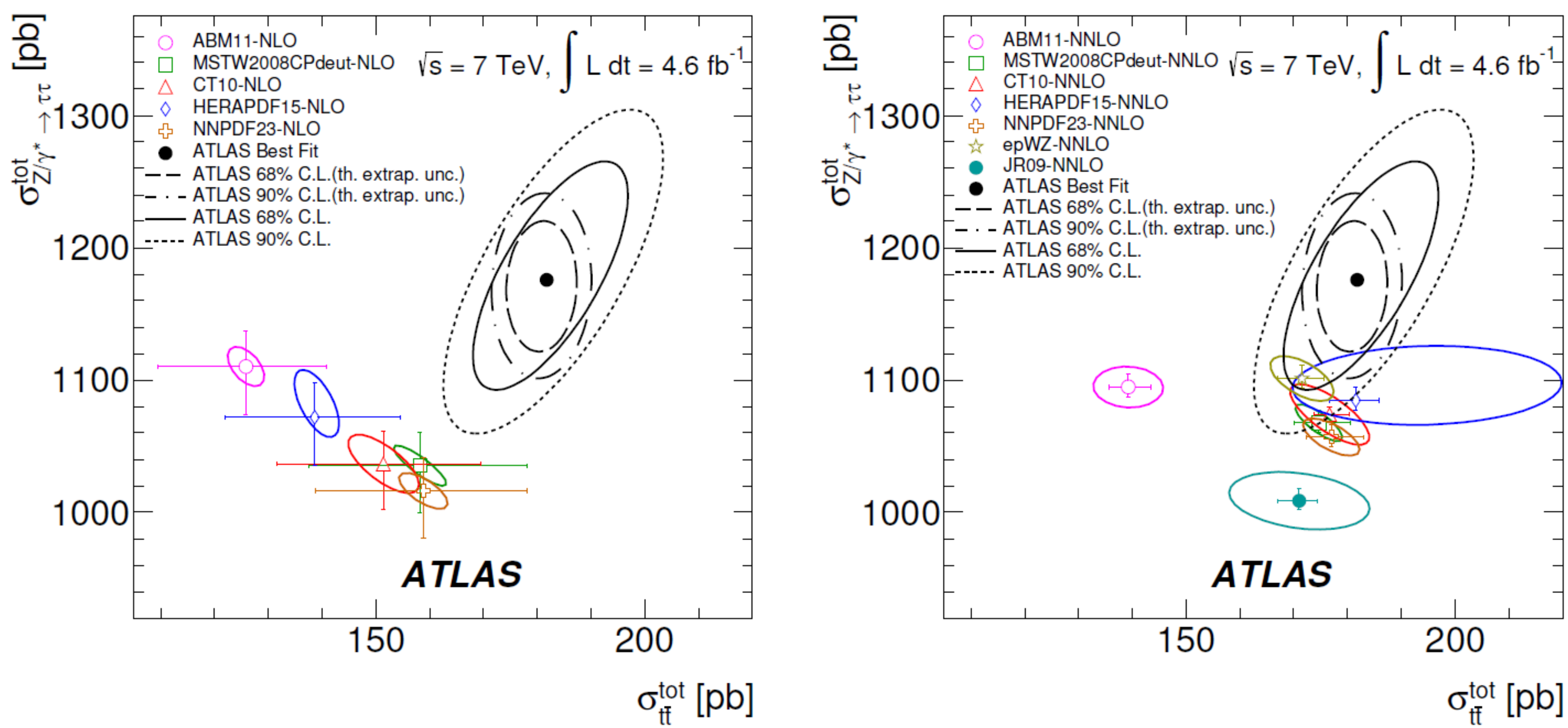
An analysis of di-lepton e-mu pairs from 3 different channels WW, t-tbar, Z→ττ

arXiv:1407.0573



- Cross-sections calculated using a specific PDF with error bars depicting the uncertainty due to the choice of renormalization and factorization scales, and contour represents intra-PDF uncertainty
- NLO predictions underestimate $Z/\gamma^* \to \tau\tau$ versus $t\bar{t}$, irrespective of the PDF model.
- *WW* fiducial measurement is consistent with predictions from each PDF model considered.

This also shows that NNLO caluclations are needed– and shows some PDF discrimination

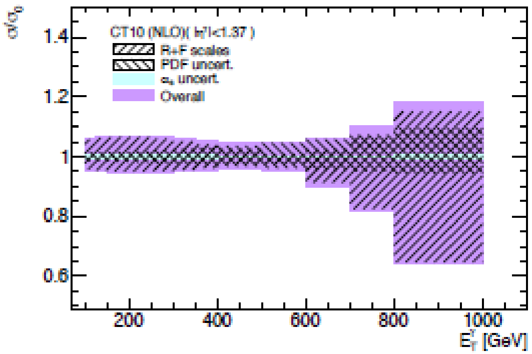


- Good overlap with most of the NNLO theoretical predictions and corresponding PDF sets.
- Difference in the uncertainties in theoretical predictions: in the NLO case scale uncertainties are dominant, while in the NNLO case the PDF model provides the dominant uncertainty.
- ABM11 employes lower value of α_s employed. At NNLO $\alpha_s = 0.113$, c.f. $\alpha_s = 0.117 - 0.118$ other PDF models.
- For JR09, the 5% difference in the $Z/\gamma^* \to \tau\tau$ cross-section is consistent with what is reported elsewhere (PhysRevD.80.114011).

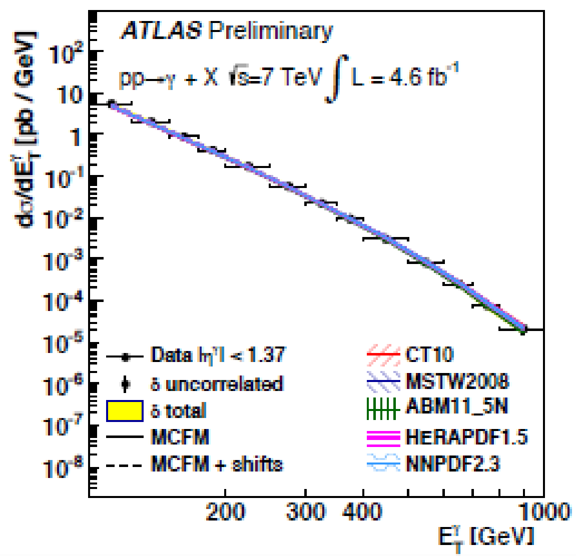
Prompt photon data has been reintroduced as a possible input to determine the high-x gluon see arXiv:1202.1762

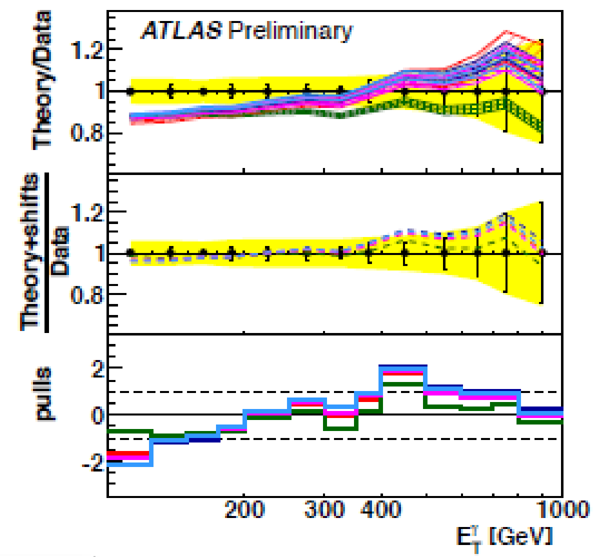
ATLAS has made a study (ATL-PHYS-PUB-2013-018) based on data arXiv:1311.1440
PDFs are compared with the data using a χ2 comparison which can account for PDF uncertainty as well as experimental uncertainties

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



Central photon production





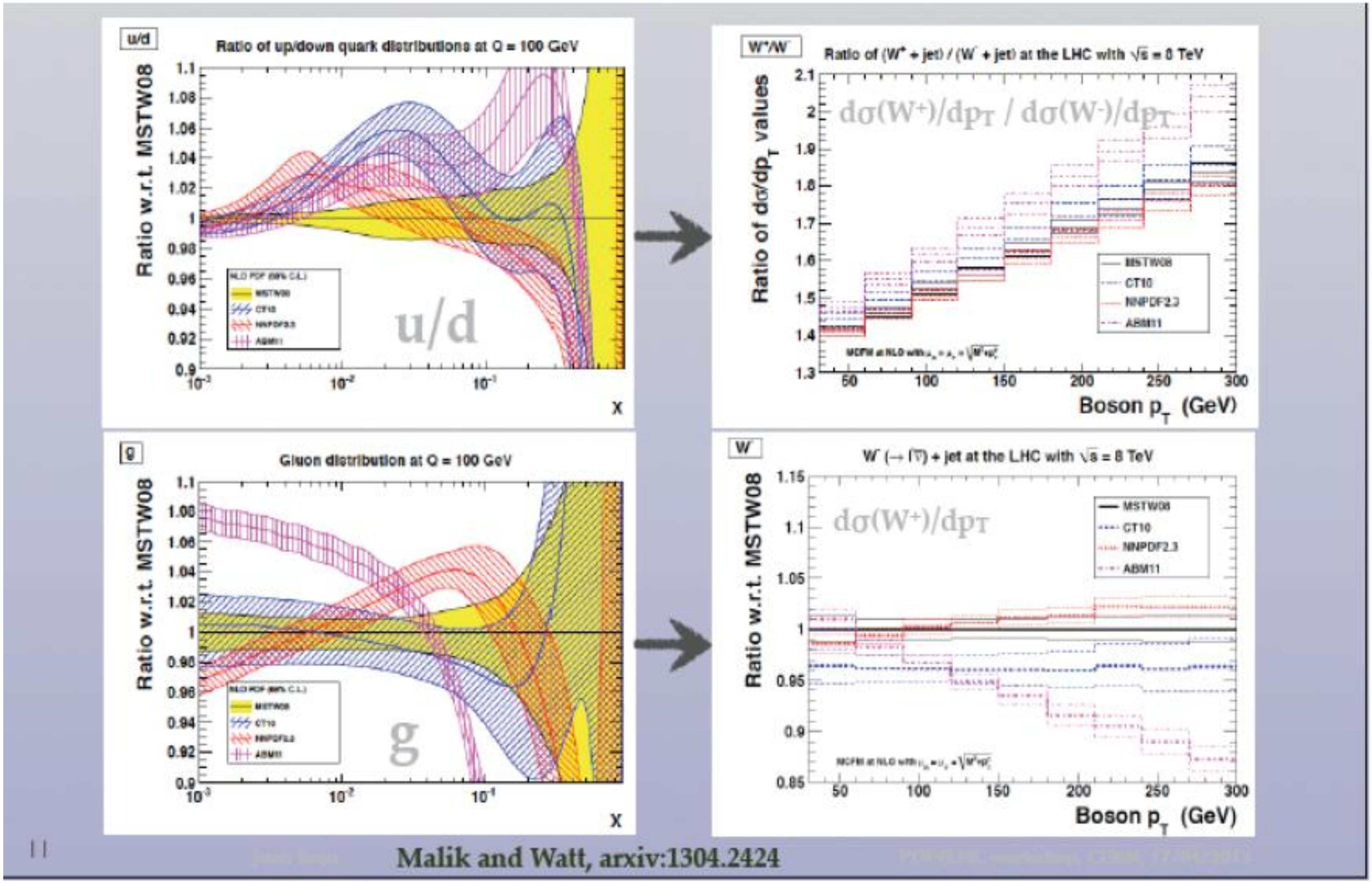
	Excluding PDF uncertainties		Including PDF uncertainties	
	$\mu_r = \mu_f = E_T^\gamma$	Envelope	$\mu_r = \mu_f = E_T^\gamma$	Envelope
CT10	49.1	34.7 - 63.1	29.8	20.0 - 38.4
MSTW2008	39.9	27.2 - 52.7	32.0	21.3 - 42.3
ABM11_5N	16.2	9.2 - 25.5	15.7	8.9 - 24.9
HERAPDF1.5	28.7	19.0 - 38.9	23.6	15.7 - 32.0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

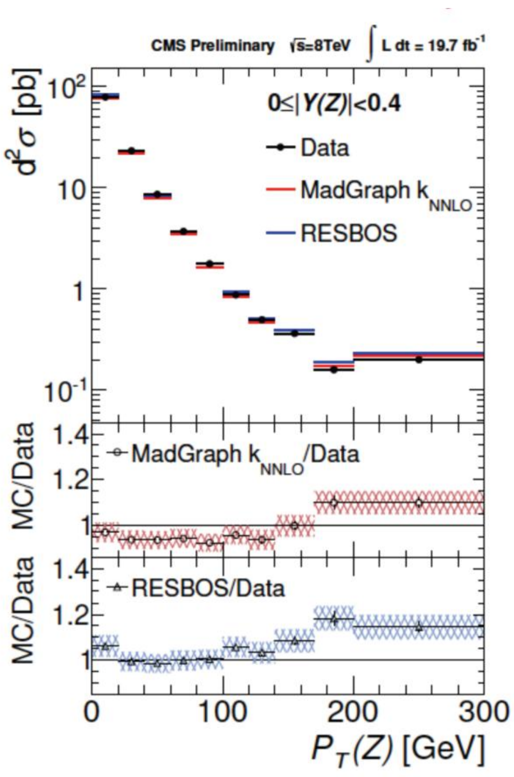
Vector boson at high pt

ArXiv:1304.2424

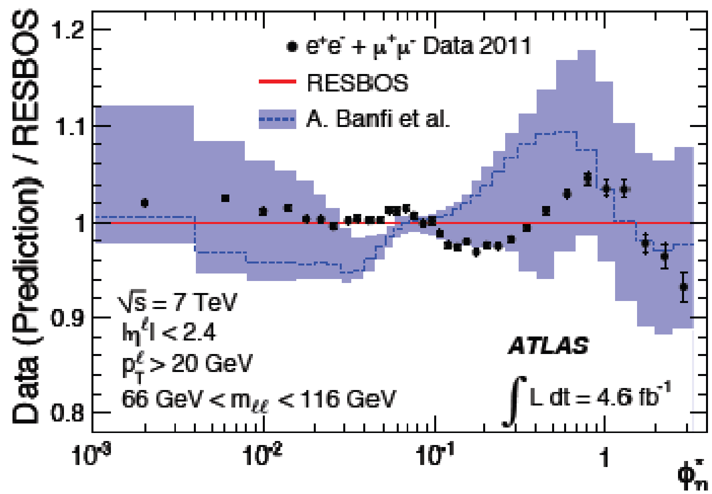


High pt W,Z spectra may discriminate gluon, but needs NNLO and electroweak corrections. Ratios of vector-boson high pt spectra may have an advantage

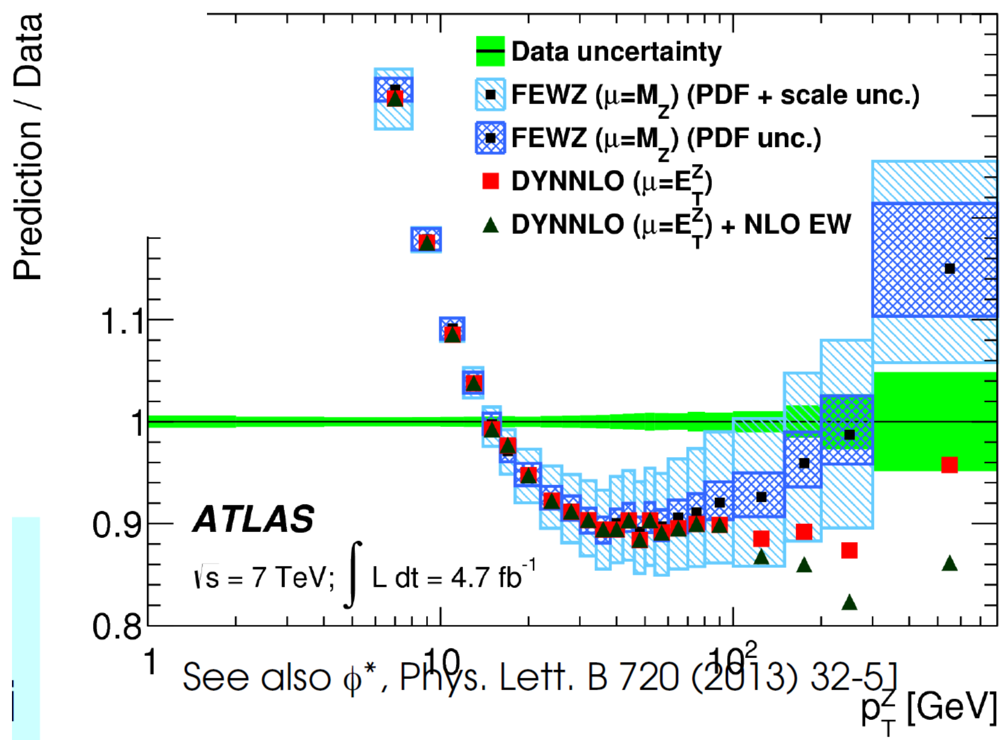
ATLAS and CMS have also both studied the pt spectrum in rapidity bins



CMS 8 TeV low rapidity bin

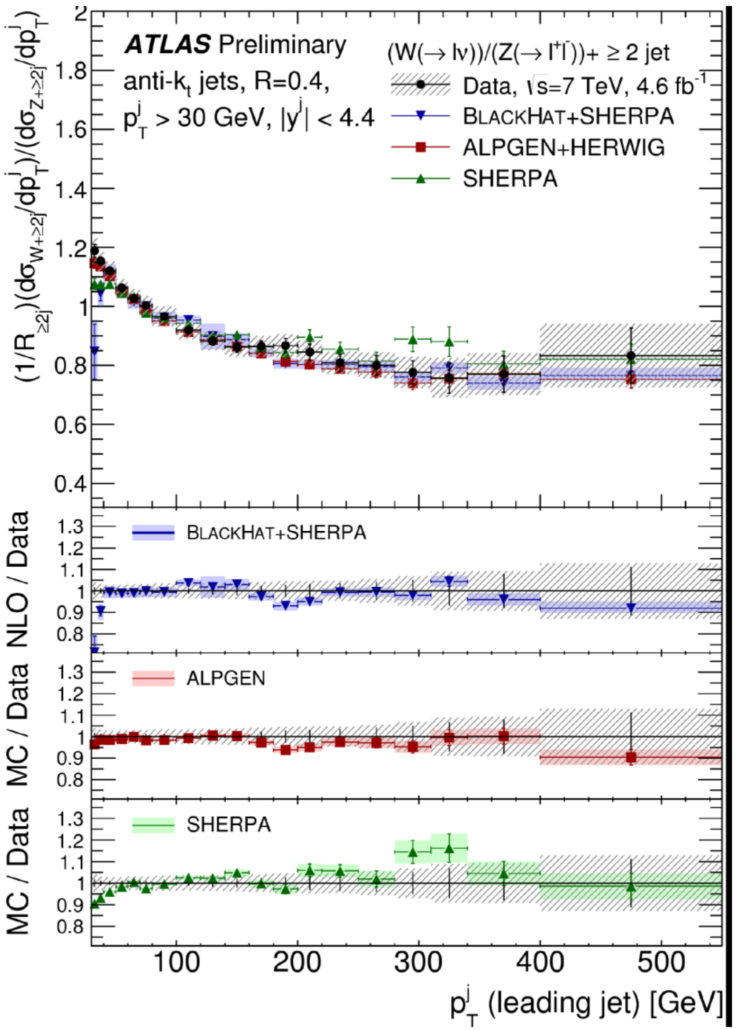


ATLAS 7 TeV all rapidity bins –
home in on high-pt,
clear scale dependence
Predictions are not yet good enough

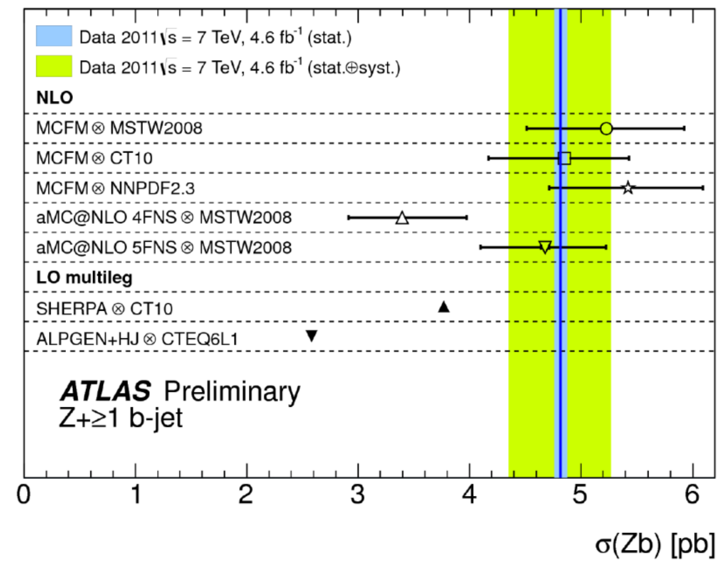


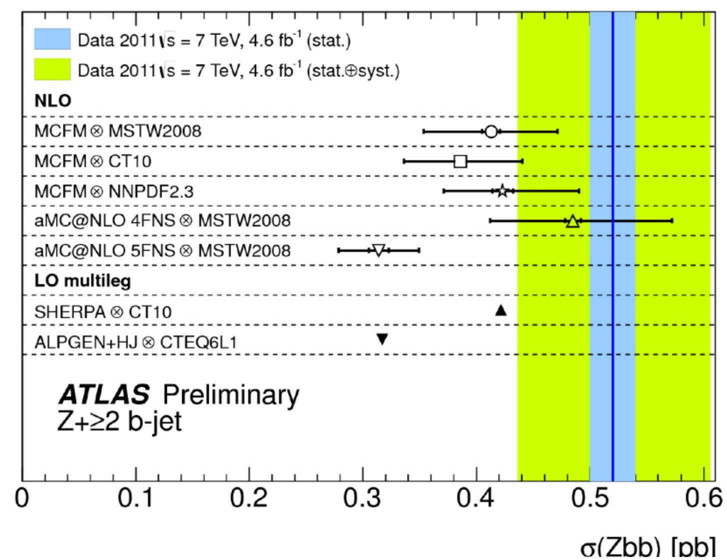
See also φ*, Phys. Lett. B 720 (2013) 32-5]

Similar considerations apply to Z+jets, W+jets and their ratio: shown here for >2jets



And to W,Z+flavour, here Z+b and Z+bb is shown

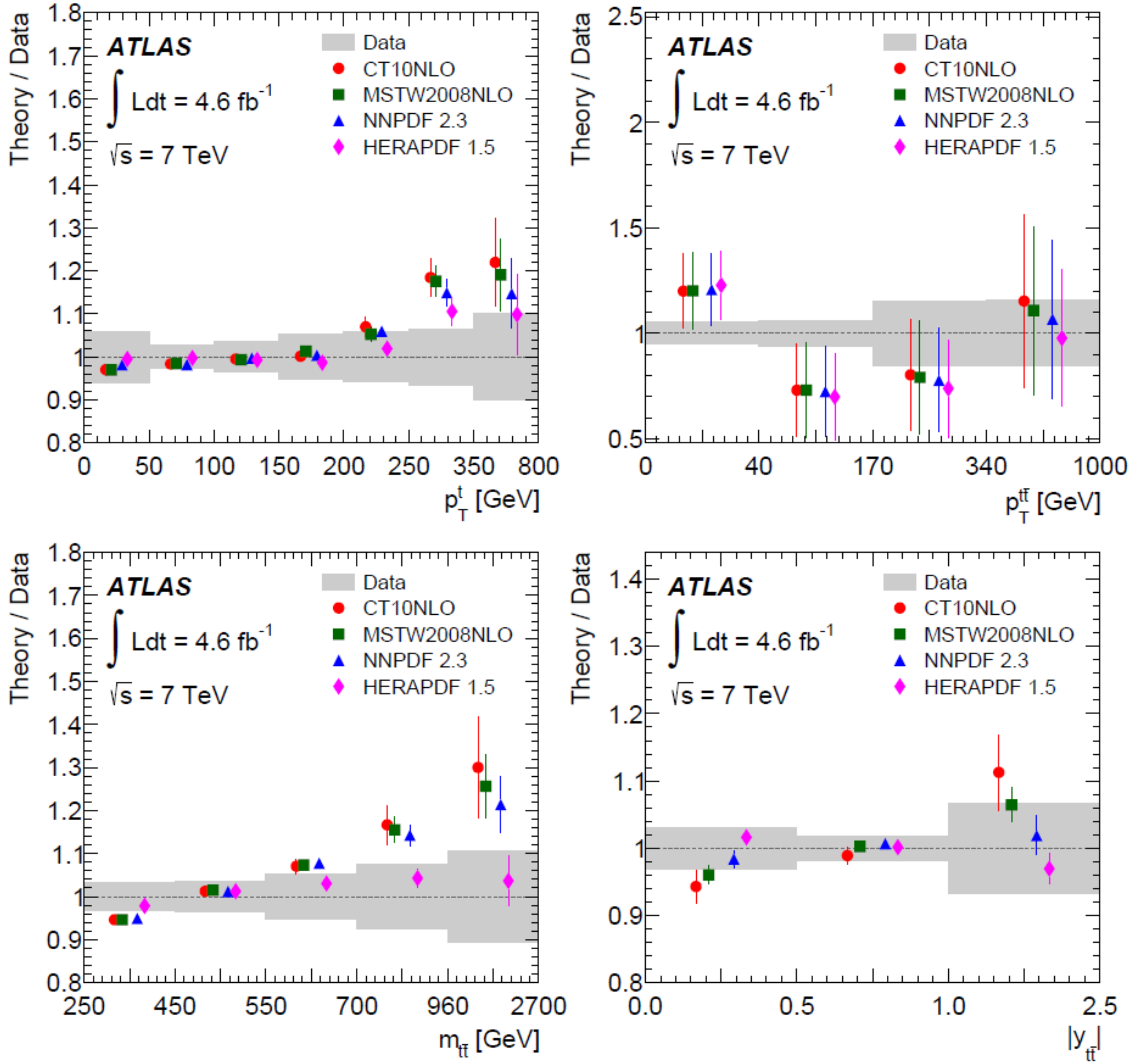




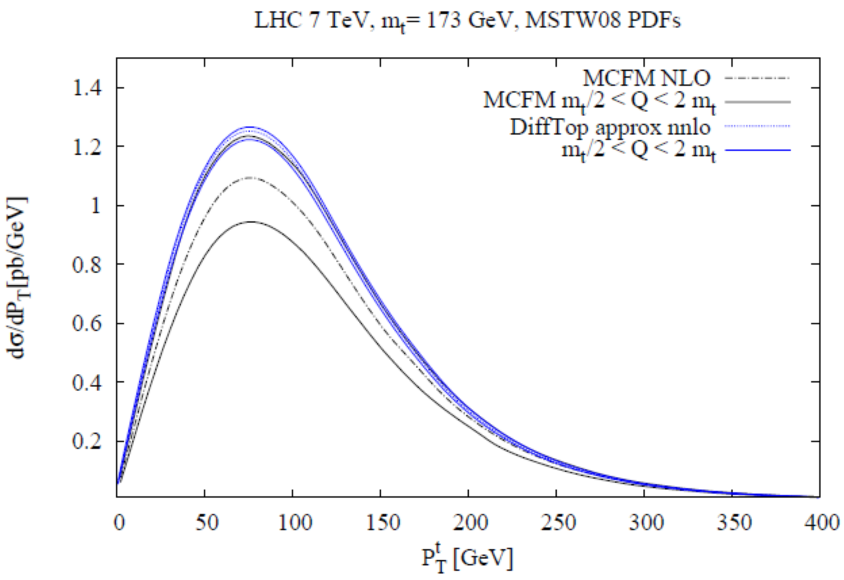
Top production also has PDF sensitivity

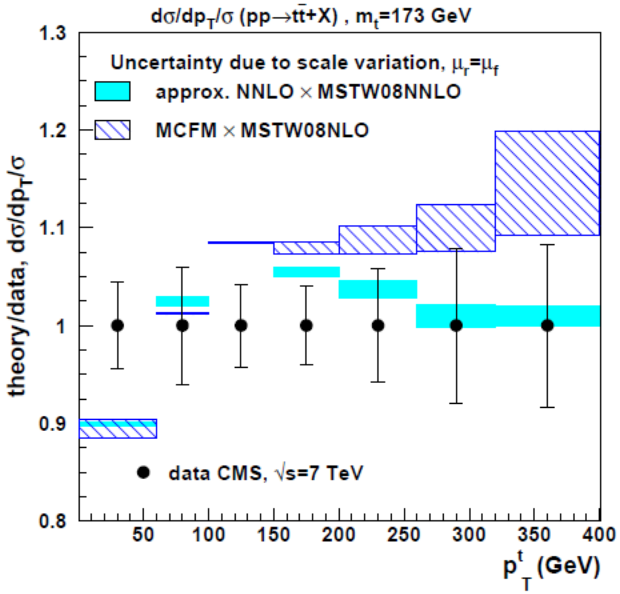
ATLAS-arXiv:1407. 0371
Calculations for differential distributions at NLO
NNLO is coming

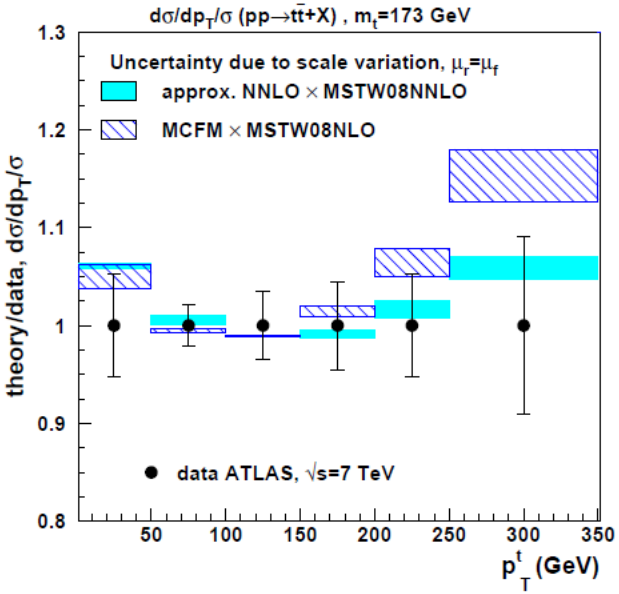
Ratios to various PDFs



NNLO Guzzi et al., DiffTop arXiv:1406.0386







PDF constraints measurements of top-quark pair production

Full PDF fit at NNLO using HERAFitter, DGLAP parton evolution

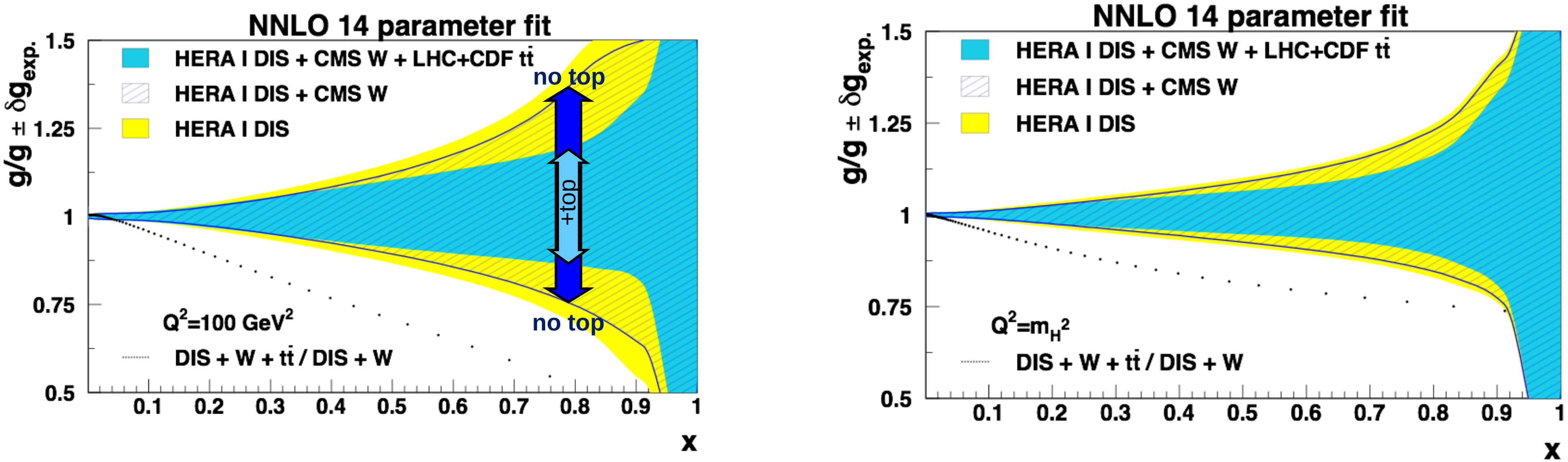
Data in PDF fit:

- Deep Inelastic Scattering in ep collisions (combined HERA I *[JHEP 1001:109 (2010)]*)
- CMS muon charge asymmetry in *W* production at √s=7 TeV (L=4.7 fb^{-1}) *[CMS* Phys. Rew. D 90 (2014) 032004*]*
- Top-quark pair production:

total cross sections: CMS Collaboration, JHEP11 (2012) 067; CMS-PAS-TOP-12-007; ATLAS Collaboration, ATLAS-CONF-2012-024, ATLAS-CONF-2012-149; CDF Collaboration, CDF Conference Note 9913 (2009).

differential cross sections √s=7 TeV: CMS Eur. Phys. J. C73 (2013) 2339; ATLAS [arXiv:1407.0371]

aNNLO prediction for p^t_T implemented via DiffTop in HERAFitter (arXiv:1406.0386), http://difftop.hepforge.org/

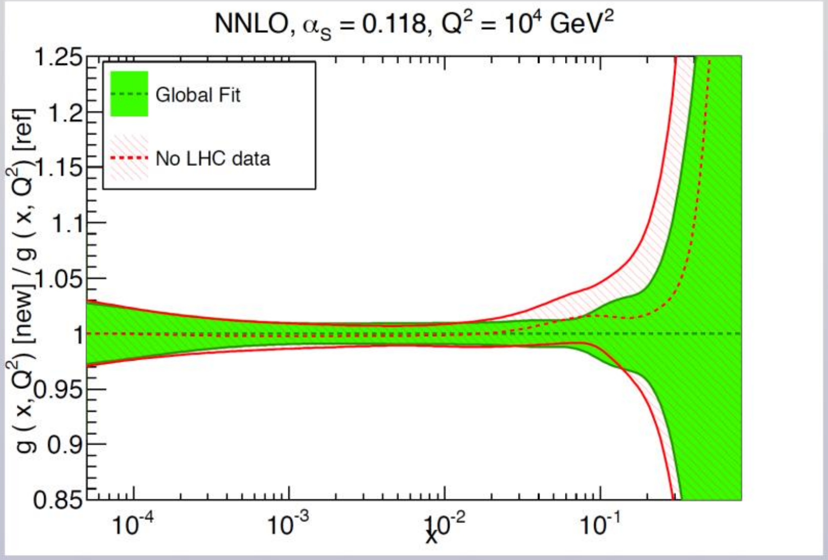


Moderate improvement of the uncertainty on the gluon distribution for x > 0.1, as expected
significant change of the shape of the gluon distribution

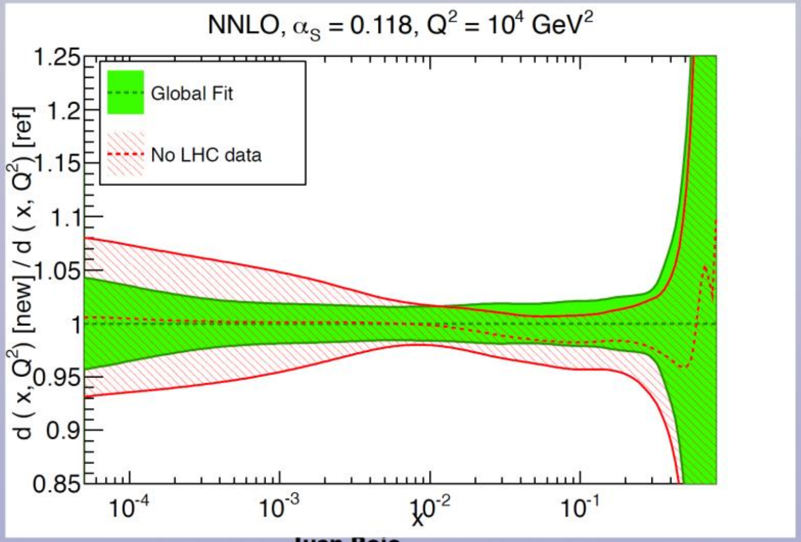
Details of the analysis can be found in M. Guzzi, K. Lipka, S. Moch, arXiv:1406.0386

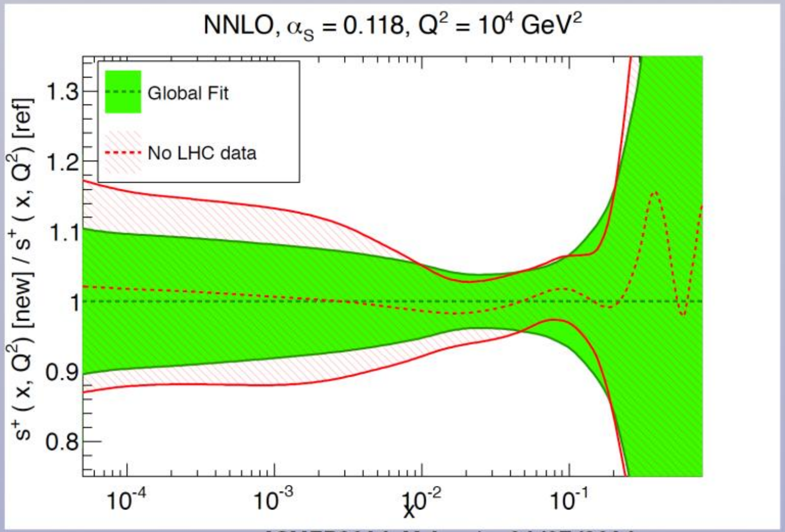
Using LHC data to improve PDFs– NNPDF3.0

Impact of LHC data

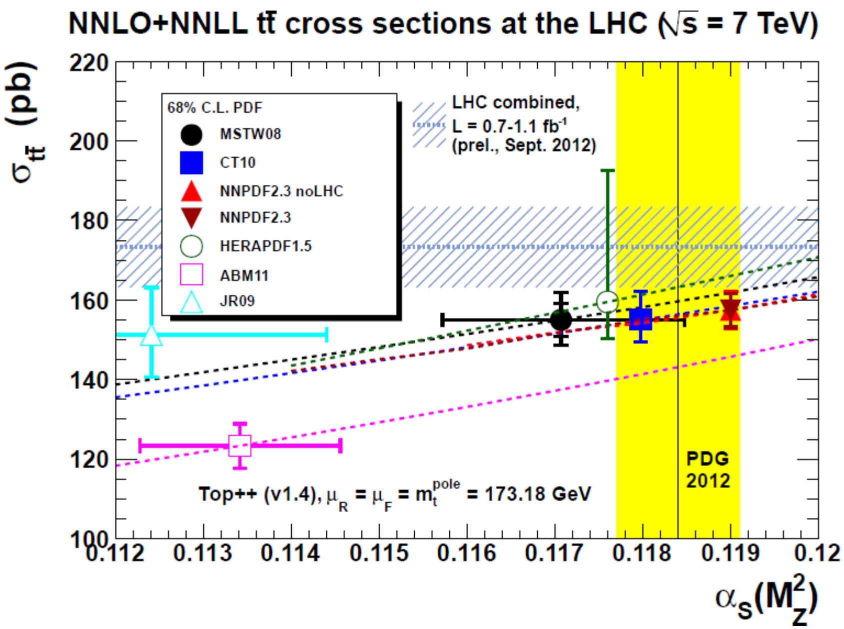


- Compare global NNPDF3.0 fit with a fit **without LHC data**
- PDF uncertainties on **large-x gluon** reduced due to **top quark and jet data**
- PDF uncertainties on **light quarks** reduced from the **Drell-Yan** and **W+charm data**
- The **description of all new LHC data**, already good in NNPDF2.3, is further improved in NNPDF3.0



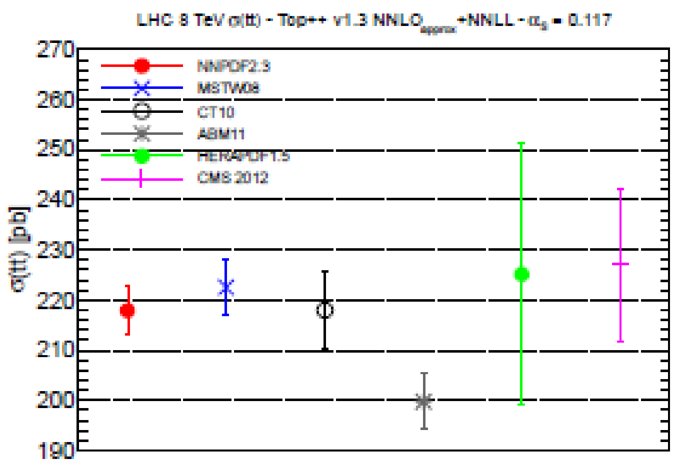


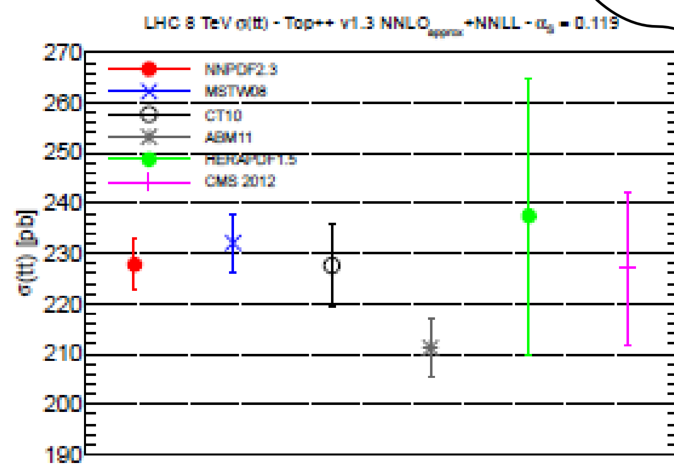
Do the top cross sections already provide PDF discrimination?



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. But even if we use the same alphas values predictions differ

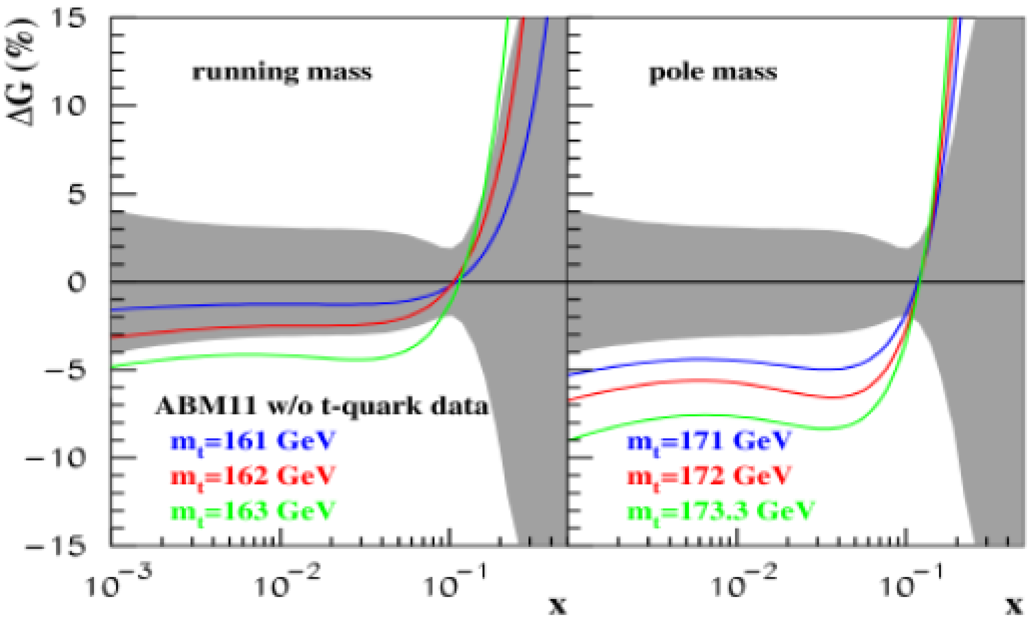
How about at 8 TeV? The range of the ATLAS and CMS top cross-sections presented at ICHEP14 241.4 ± 8.5 pb is to the high side of the predictions





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

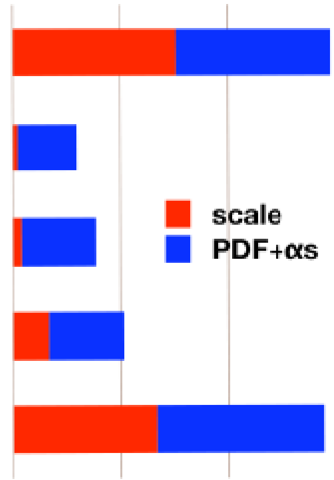
ABM have used the cross section data in their own fit and they find that a running mass calculation with Mt =161 GeV (and $\alpha_S(M_Z)$=0.1138) is compatible.
However it has a dramatic effect on the shape of the gluon, which is becoming MUCH harder at high-x.

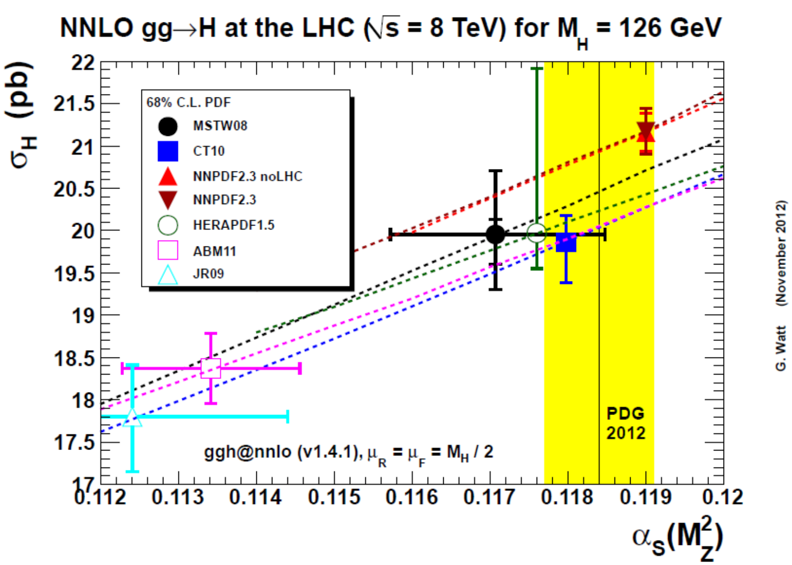


$\alpha_s(M_z)$ 0.1138 – 0.1149 0.1155 – 0.1162

PDFs and the Higgs

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
NNLO QCD +NLO EW	VBF	1.56 pb	2.9%
	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

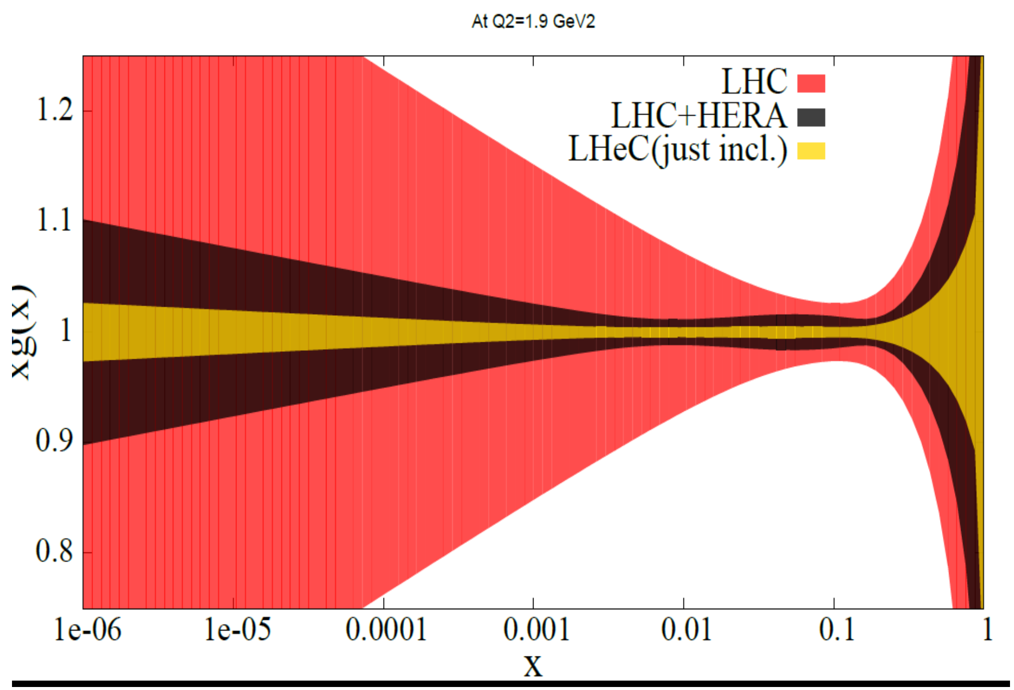
- Uncertainties on Parton Distribution Functions (PDFs) limit our knowledge of cross sections whether SM or BSM.
- Any claim for new physics at the highest masses is dependent on the PDF chosen to describe conventional physics
- Standard Model LHC measurements can themselves contribute to PDF discrimination 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. W,Z+jets
7. W,Z+ c,b (intrinsic charm, beauty PDF?)
8. Direct photon and photon +jet
9. Top, single and t-tbar

Can all have impact

Extras



FINALLY

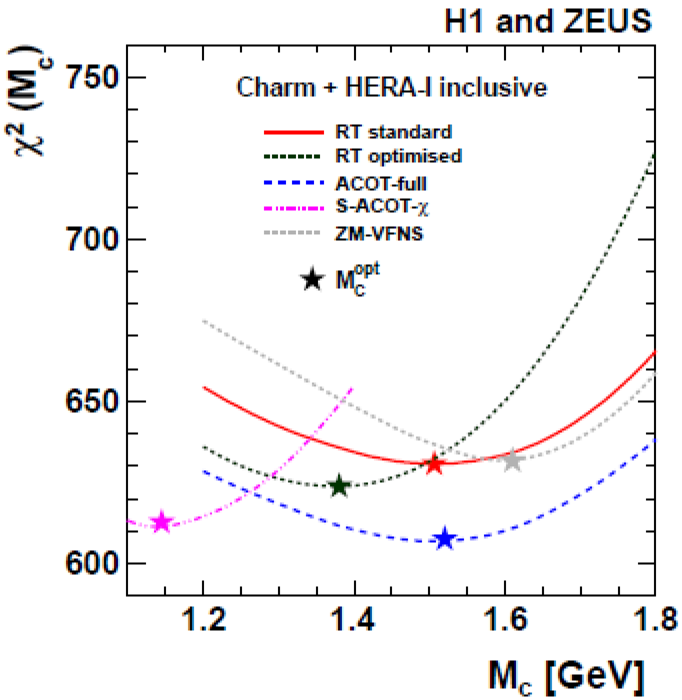
We are used to seeing plots of how much the LHC data improve over HERA data alone, or even over global fits (NNPDF2.3)

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



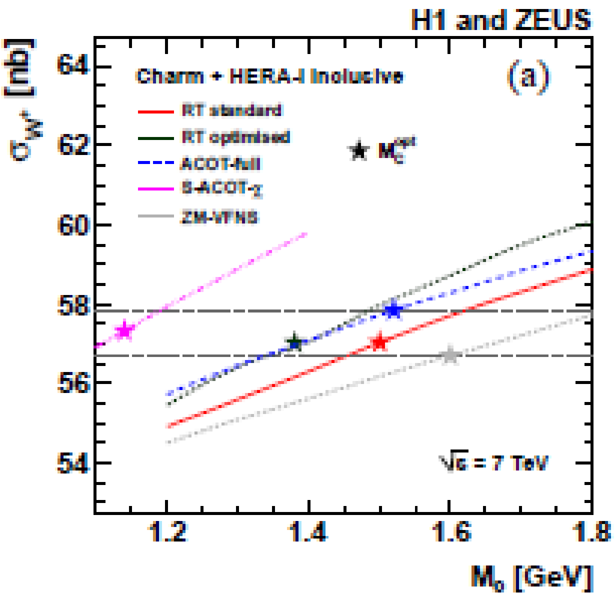
But that was for the Thorne Massive Variable Flavour Number Scheme for heavy quarks (as used by MSTW08)

This is not the only VFN

CTEQ use ACOT- χ

NNPDF2.0 use ZMVFN, 2.1 uses FONLL

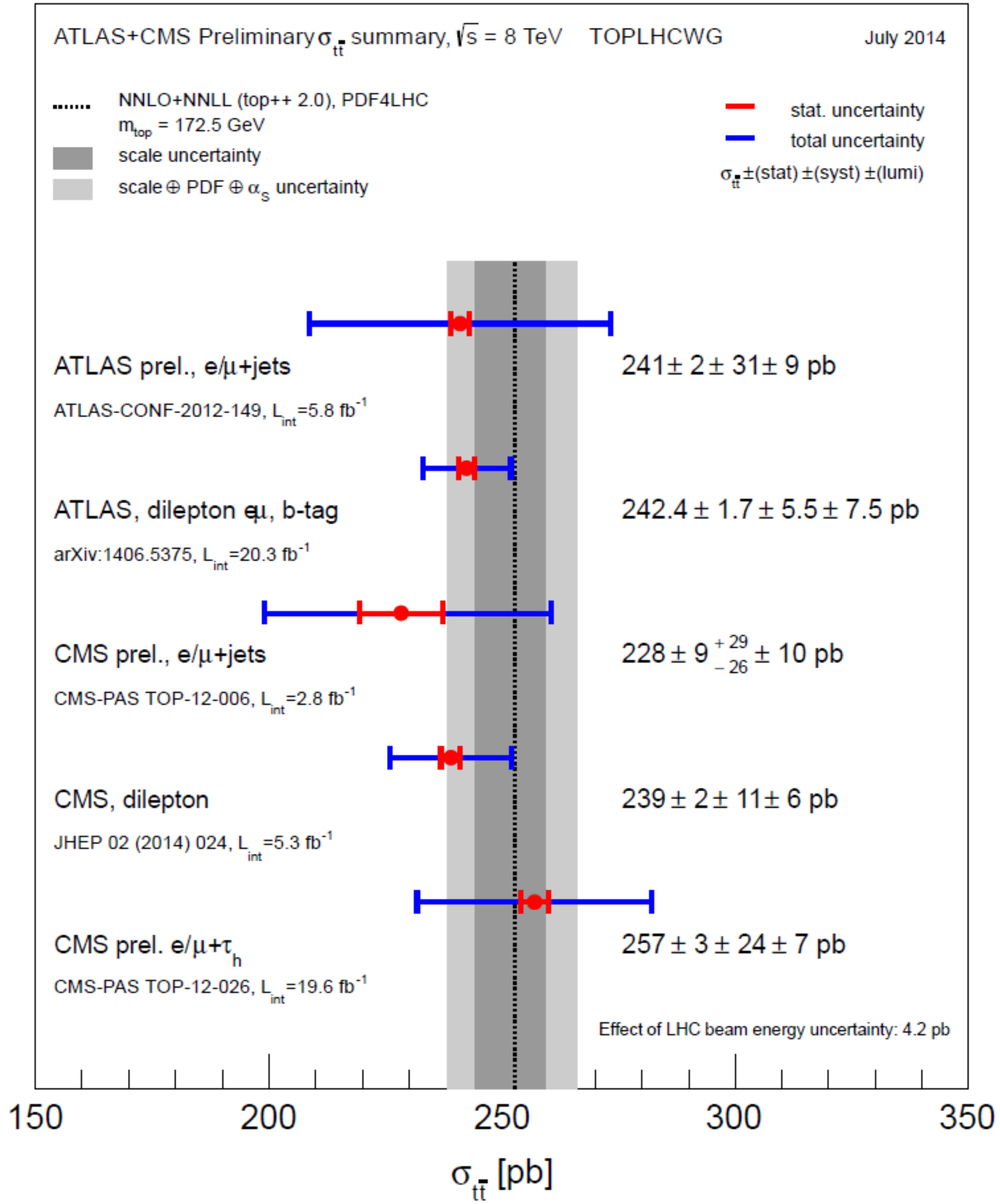
These all have different preferred charm mass values, and all fit the data well when used with their own best fit charm mass



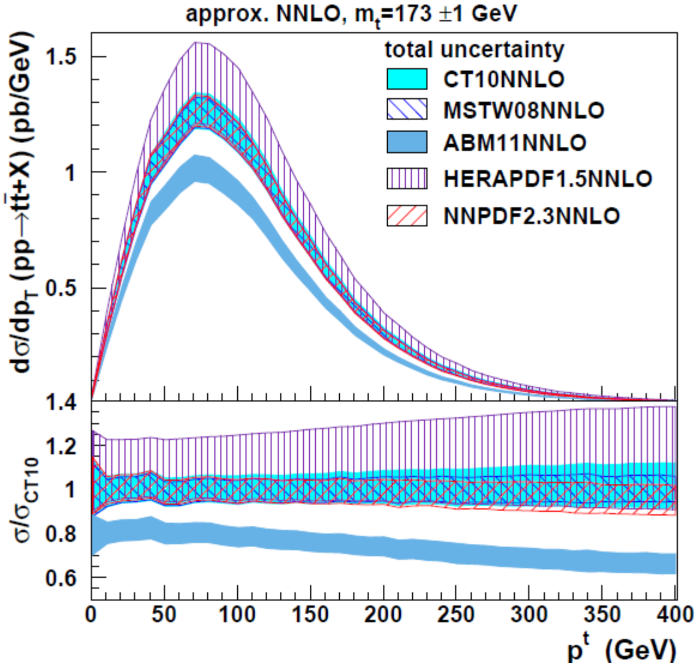
We can use each of these schemes to predict W and Z cross-sections at the LHC (at 7 TeV) as a function of charm mass parameter

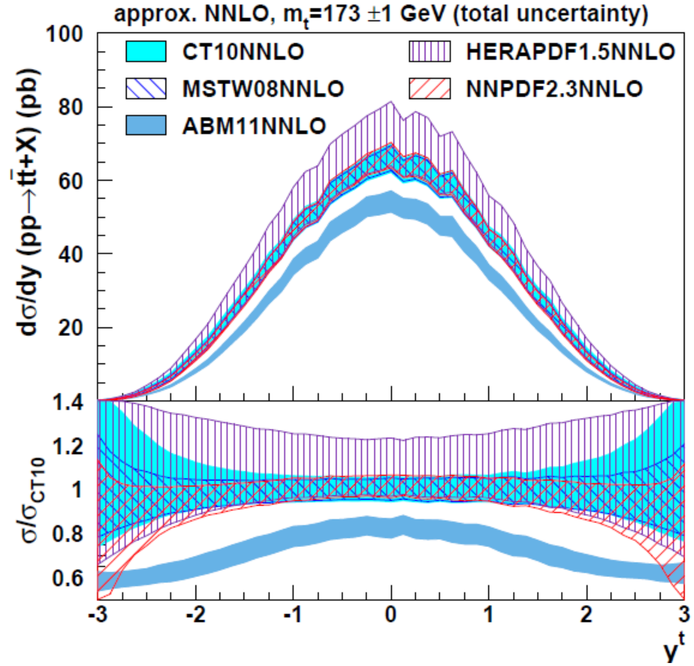
If a fixed value of Mc is used then the spread is considerable (~6%)- but if each prediction is taken at its own optimal mass value the spread is dramatically reduced (~2%) even when a Zero-Mass (ZMVFN) approximation has been used

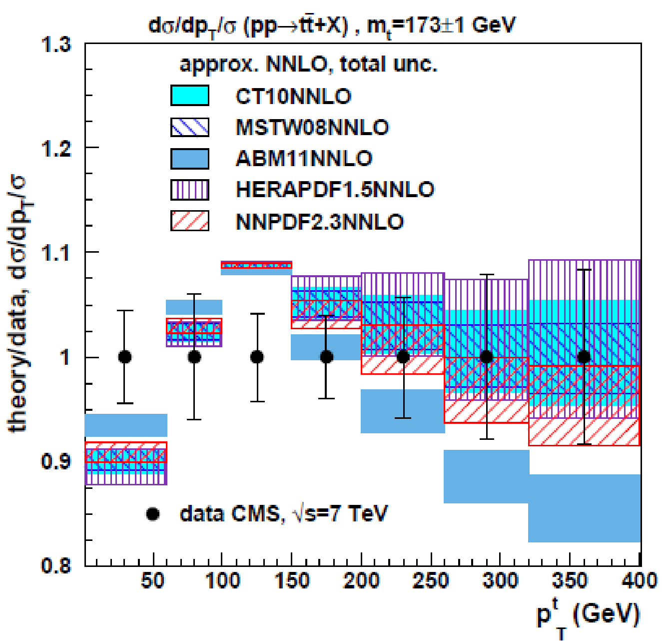
So consistent choice of Mc could help reduce differences- groups now provide PDFs with different Mc and Mb

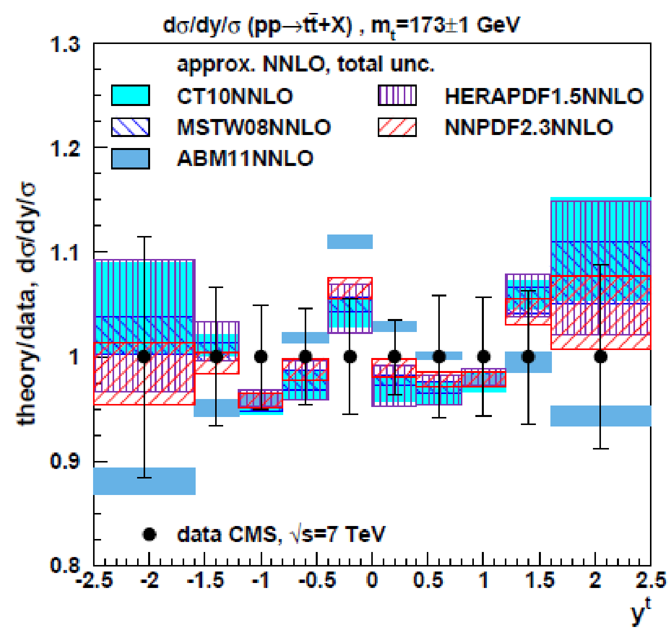


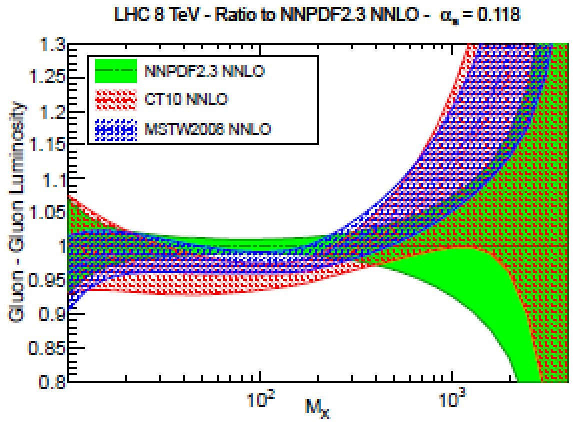
ATLAS+CMS Preliminary σ_tt summary, √s = 8 TeV TOPLHCWG
July 2014
NNLO+NNLL (top++ 2.0), PDF4LHC
m_top = 172.5 GeV
scale uncertainty
scale ⊕ PDF ⊕ α_S uncertainty
stat. uncertainty
total uncertainty
σ_tt ±(stat) ±(syst) ±(lumi)
ATLAS prel., e/μ+jets
ATLAS-CONF-2012-149, L_int=5.8 fb^-1
241 ± 2 ± 31 ± 9 pb
ATLAS, dilepton eμ, b-tag
arXiv:1406.5375, L_int=20.3 fb^-1
242.4 ± 1.7 ± 5.5 ± 7.5 pb
CMS prel., e/μ+jets
CMS-PAS TOP-12-006, L_int=2.8 fb^-1
228 ± 9 +29 −26 ± 10 pb
CMS, dilepton
JHEP 02 (2014) 024, L_int=5.3 fb^-1
239 ± 2 ± 11 ± 6 pb
CMS prel. e/μ+τ_h
CMS-PAS TOP-12-026, L_int=19.6 fb^-1
257 ± 3 ± 24 ± 7 pb
Effect of LHC beam energy uncertainty: 4.2 pb
150
200
250
300
350
σ_tt [pb]

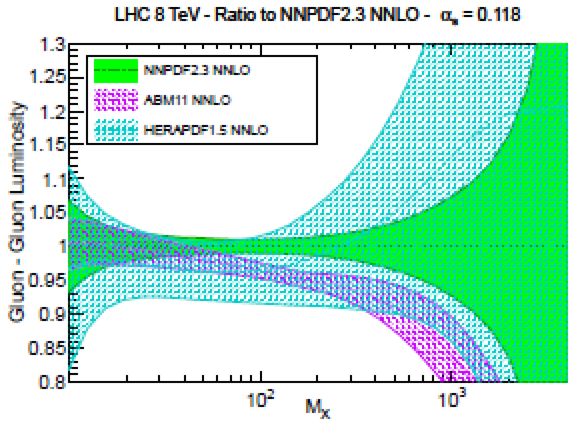

approx. NNLO, m_t=173 ±1 GeV
total uncertainty
CT10NNLO
MSTW08NNLO
ABM11NNLO
HERAPDF1.5NNLO
NNPDF2.3NNLO
dσ/dp_T (pp→tt̄+X) (pb/GeV)
σ/σ_CT10
p^t (GeV)


approx. NNLO, m_t=173 ±1 GeV (total uncertainty)
CT10NNLO
MSTW08NNLO
ABM11NNLO
HERAPDF1.5NNLO
NNPDF2.3NNLO
dσ/dy (pp→tt̄+X) (pb)
σ/σ_CT10
y^t

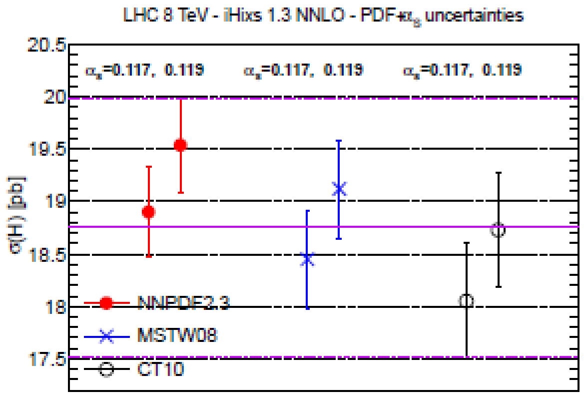

dσ/dp_T/σ (pp→tt̄+X) , m_t=173±1 GeV
approx. NNLO, total unc.
CT10NNLO
MSTW08NNLO
ABM11NNLO
HERAPDF1.5NNLO
NNPDF2.3NNLO
data CMS, √s=7 TeV
theory/data, dσ/dp_T/σ
p^t_T (GeV)


dσ/dy/σ (pp→tt̄+X) , m_t=173±1 GeV
approx. NNLO, total unc.
CT10NNLO
MSTW08NNLO
ABM11NNLO
HERAPDF1.5NNLO
NNPDF2.3NNLO
data CMS, √s=7 TeV
theory/data, dσ/dy/σ
y^t





This shows the gluon-gluon luminosities at 8 TeV for PDFs evaluated at $\alpha_S(M_Z)$ =0.118



And this shows the envelope of MSTW2008, NNPDF2.3 and CT10 PDFs plus $\alpha_S(M_Z)$ uncertainty. This is suggested for estimation of the total PDF uncertainty

BUT

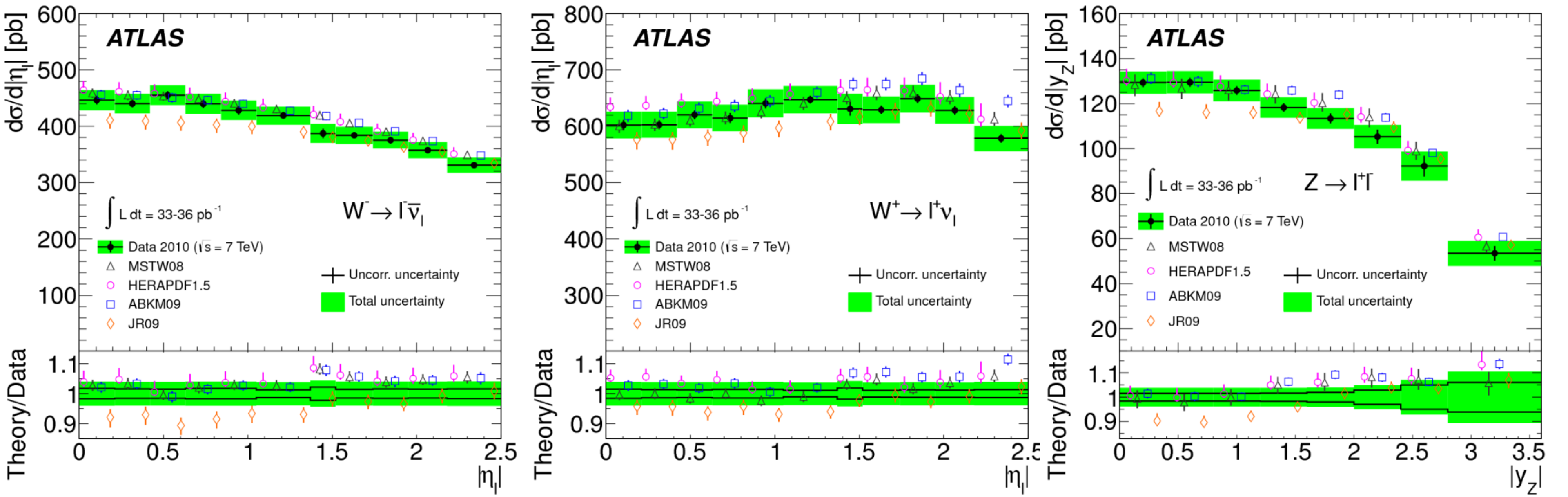
The ABM PDF group would certainly not agree. Their value of $\alpha_S(M_Z)$ =0.1135 and their Higgs cross-section is below these bounds = 14.4 ± 0.04 pb

W and Z differential cross sections

ATLAS Measurement of W and Z cross sections in electron and muon channels

Phys Rev D85(2012)072004

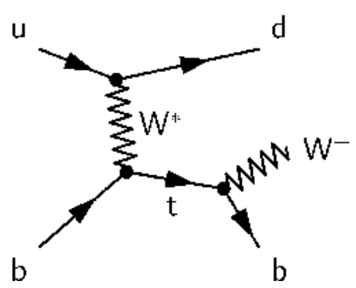
The electron and muon data have been combined accounting for the correlated systematic errors using the HERAaverager programme, the results are given with 30 sources of correlated error

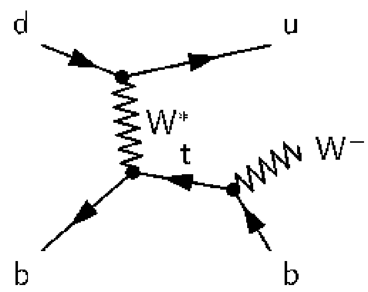


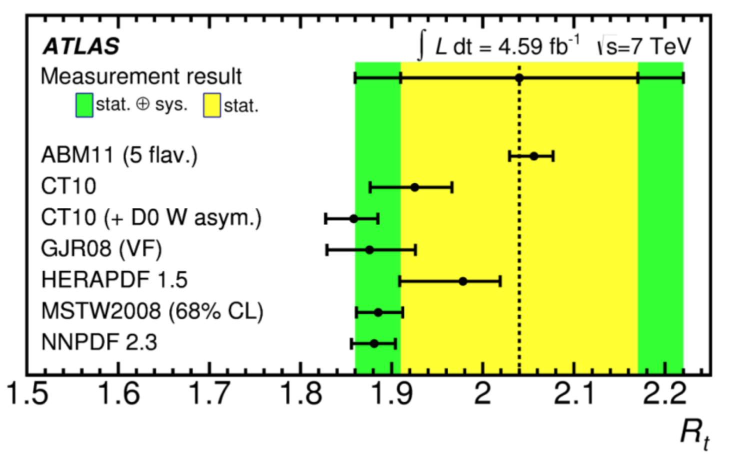
These distributions disfavour both JR09 and ABKM09– but let us look more carefully at the flavour information in these distributions

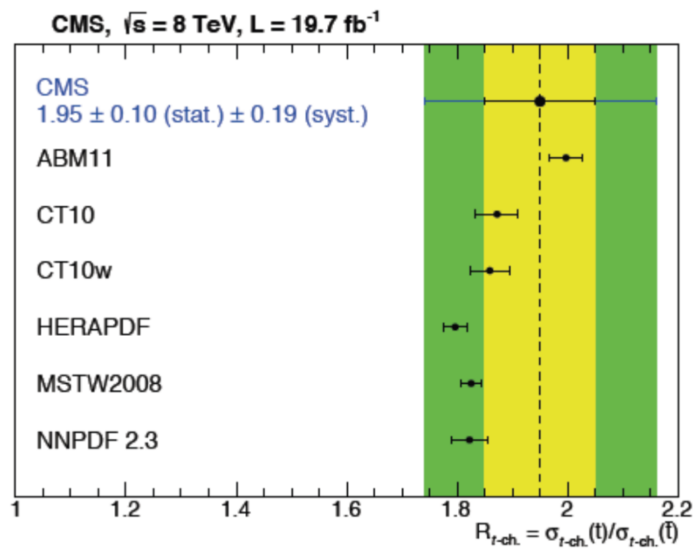
Top production also has PDF sensitivity

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



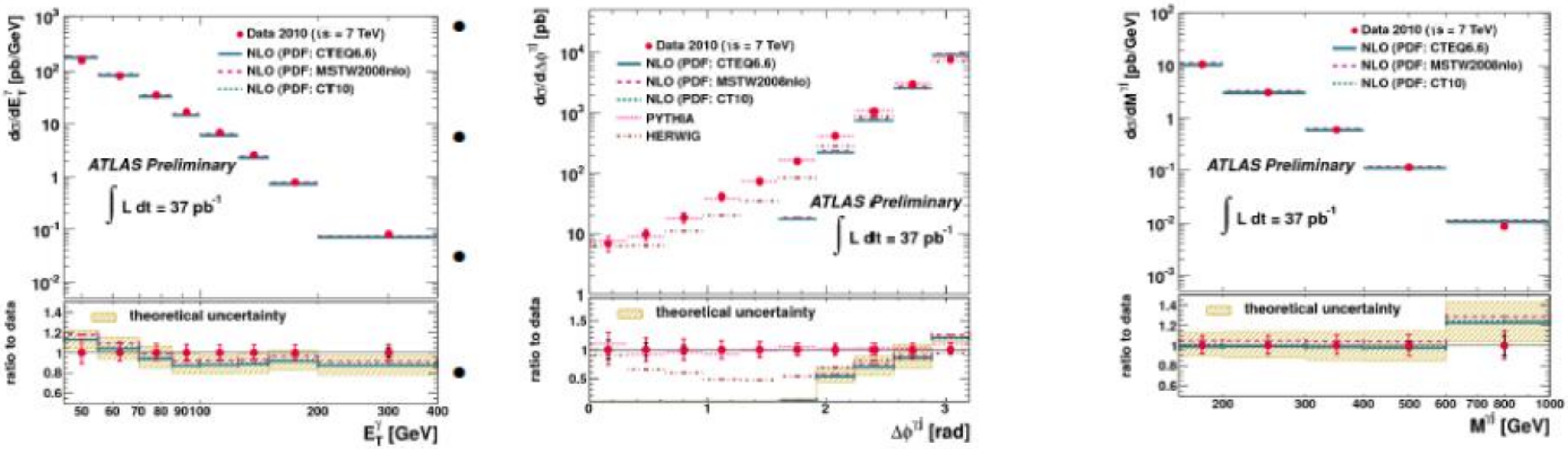






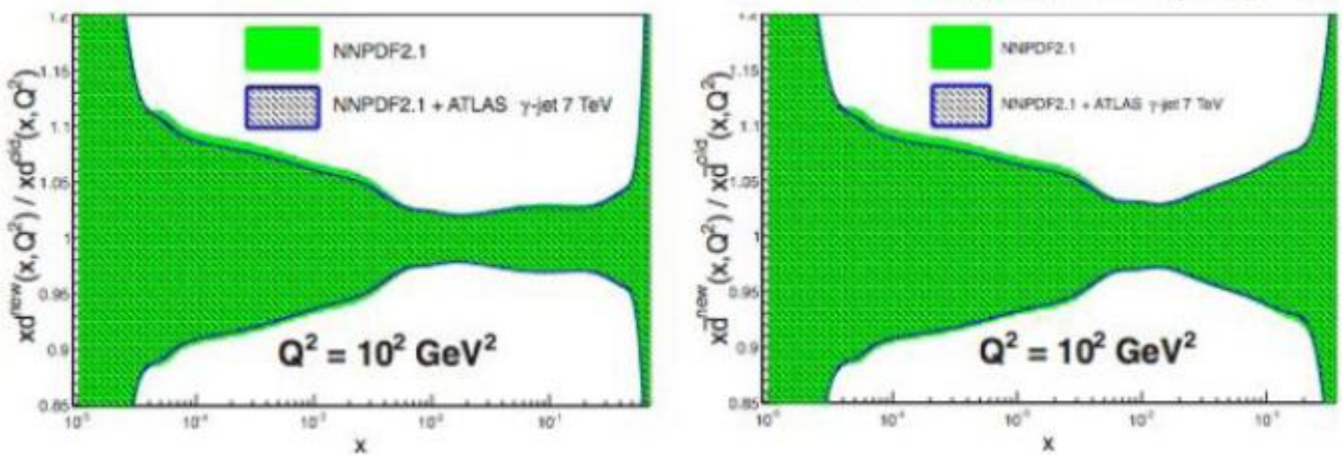
ATLAS-arXiv:1406.7844
CMS-JHEP06(2014)090

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

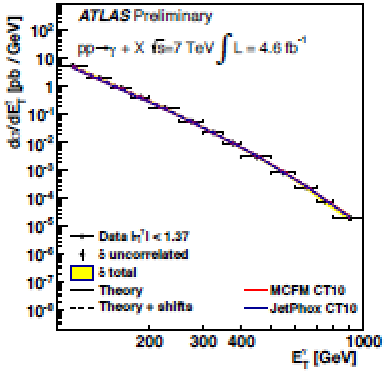


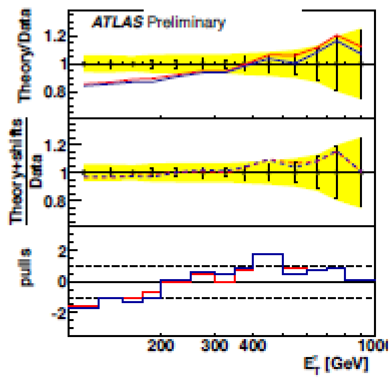
Direct photon production

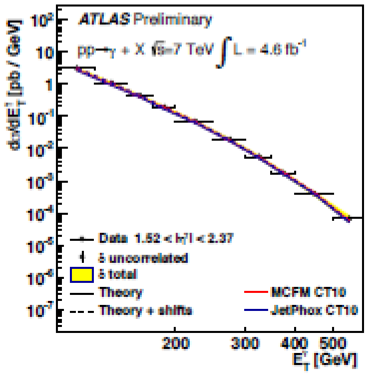
- **ATL-PHYS-PUB-2013-018**
- Data from **arXiv:1311.1440**

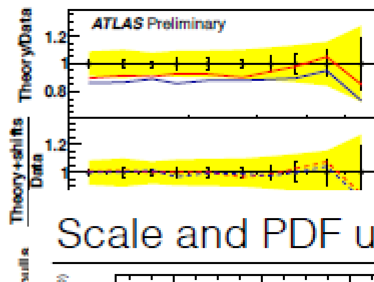
- Comparison of JetPhox and MCFM calculations with the data
  - NLO fragmentation calculated using JetPhox
  - Consistent shape between the calculations
- EW corrections not included

- Both calculations differ in shape with data for central photons
- Include effect of experimental systematic as nuisance parameter shifts

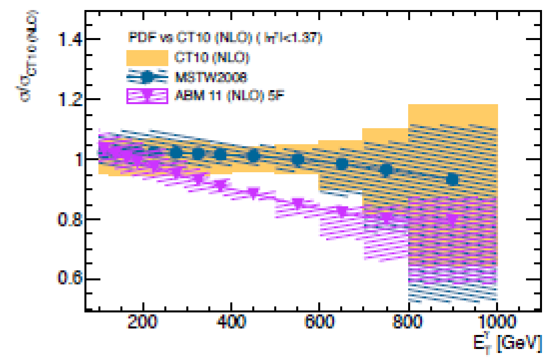


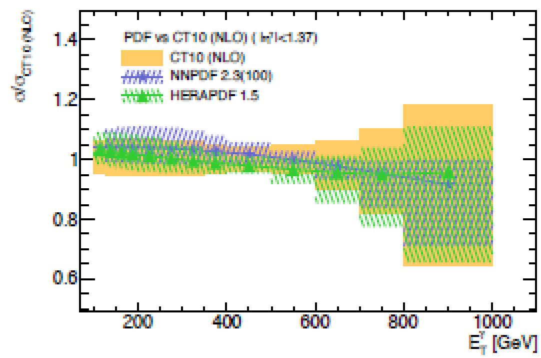




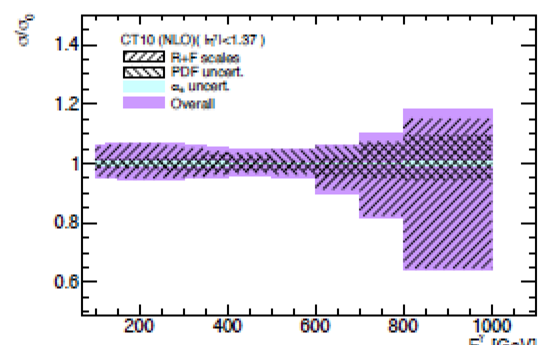


Scale and PDF uncertainties





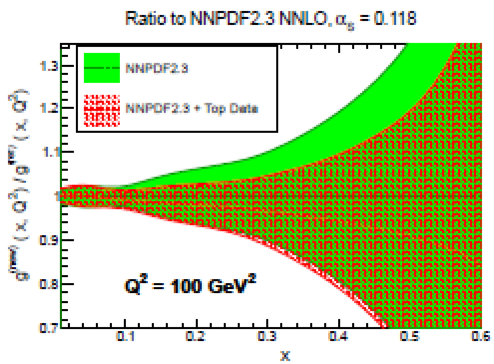
- Large scale uncertainties, comparable to individual PDF uncertainties
- Potentially large differences between PDFs, larger than quoted uncertainties on individual PDF sets for intermediate ET
  - Data should still have the potential to constrain the shape of the gluon distribution

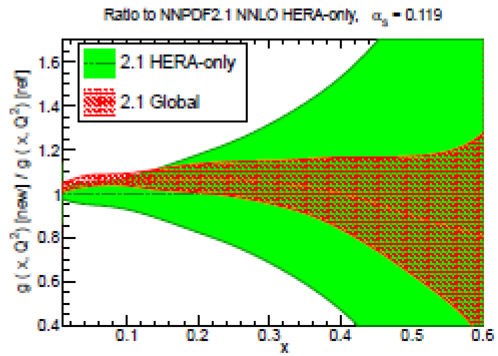


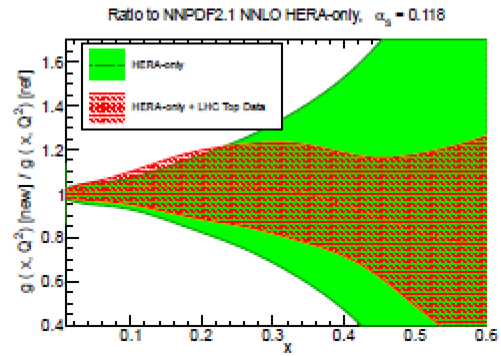
Top total cross sections are calculated to NNLO

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} $^{(+5.6\%)}_{(-6.2\%)}$
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



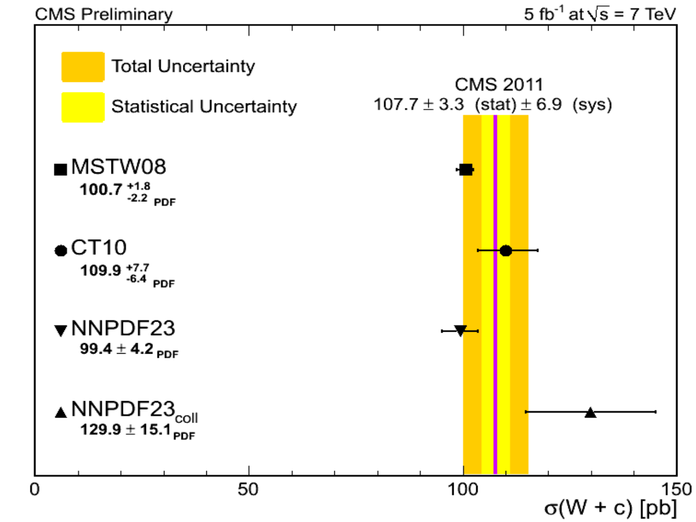


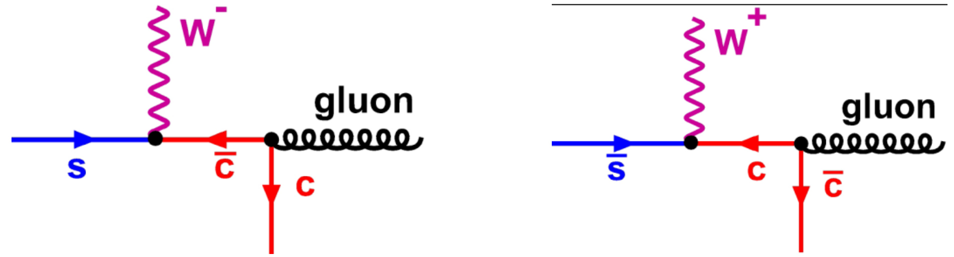


But not all PDF groups agree that such an improvement can be achieved
It depends on whether the reweighting is done accounting for enhanced χ2 tolernaces (Jun Gao- Les Houches)

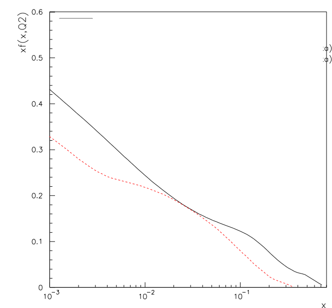
Another process which can yield information on strangeness is W+c production

CMS SMP-12002

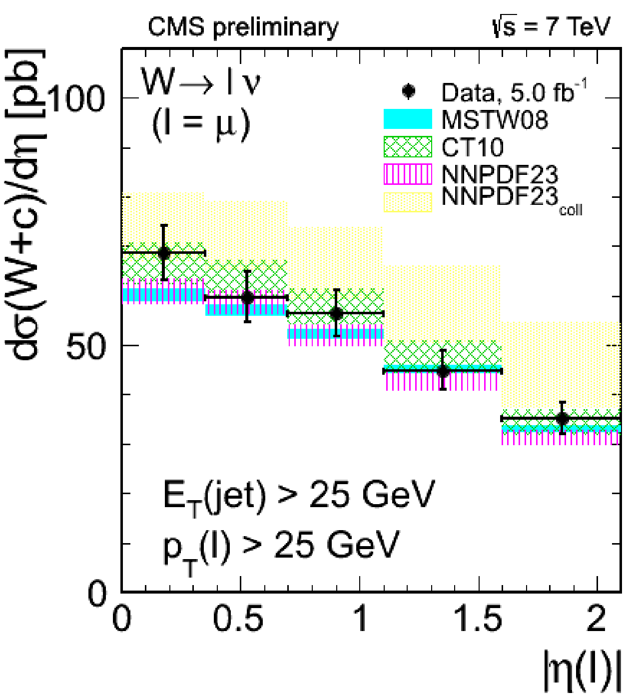




First compare W +c cross section for W's of both charges to predictions.
Very good agreement with CT10 and not in such good agreement with NNPDF2.3 (Coll) but the latter has VERY large strangeness

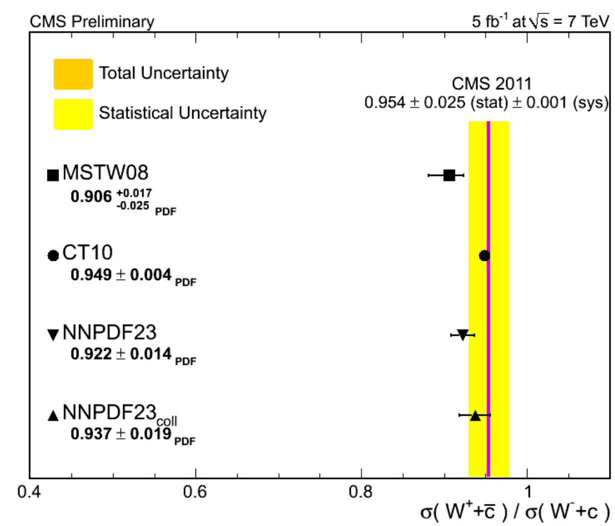


Q^2=2 GeV^2
NNPDF23(Coll)
Strange
Downsea



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

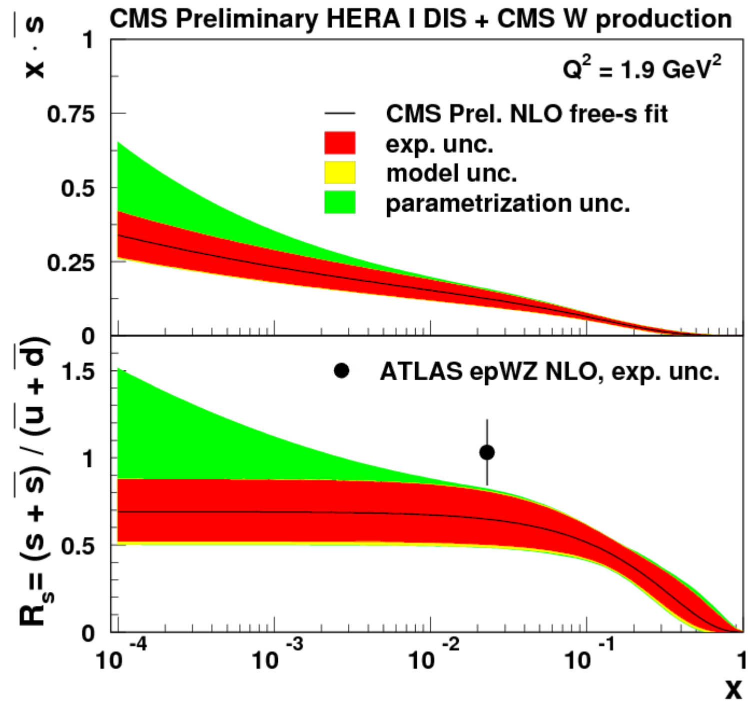


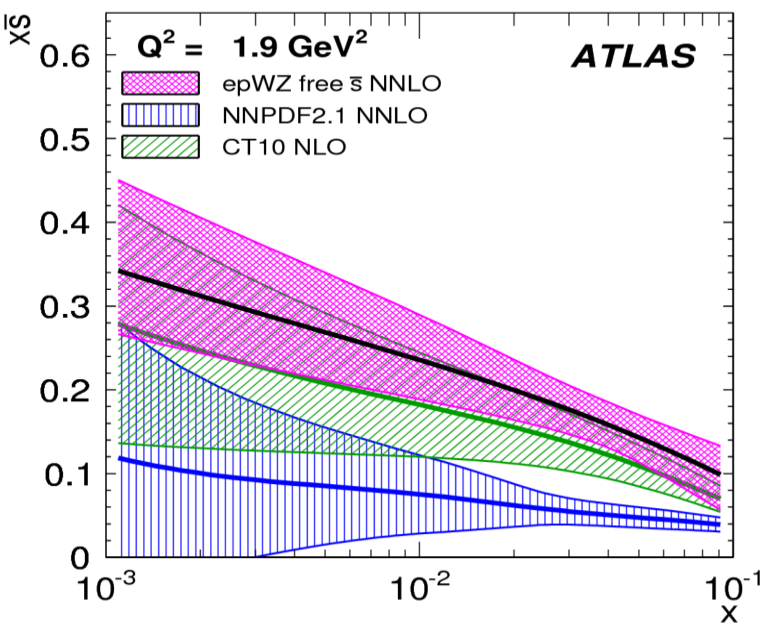
CMS have input these W+c result to a PDF fit together with the CMS W-asymmetry data and the combined HERA DIS data

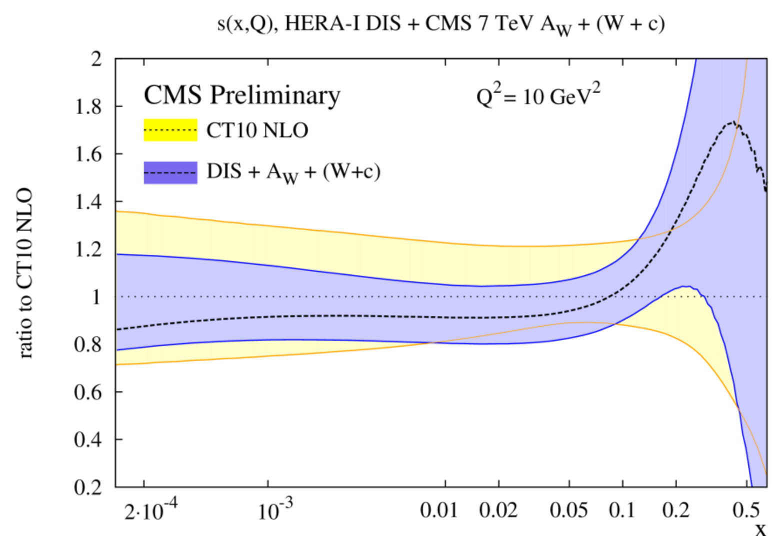
They obtain a strange quark distribution compatible with CT10.

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

However the ATLAS NNLO analysis also gave distributions

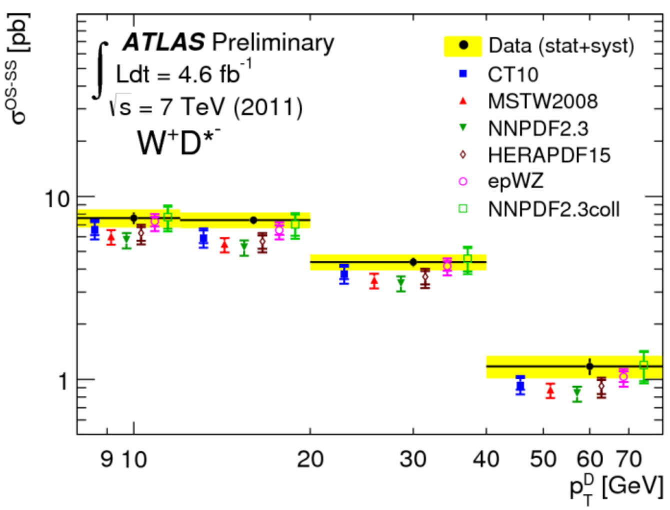


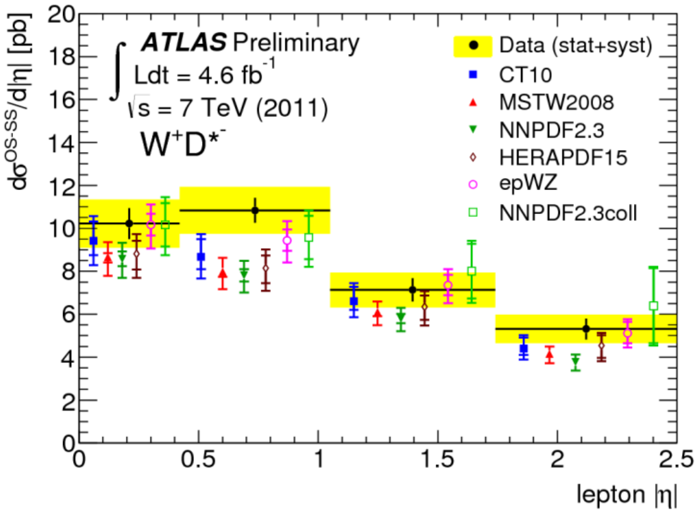


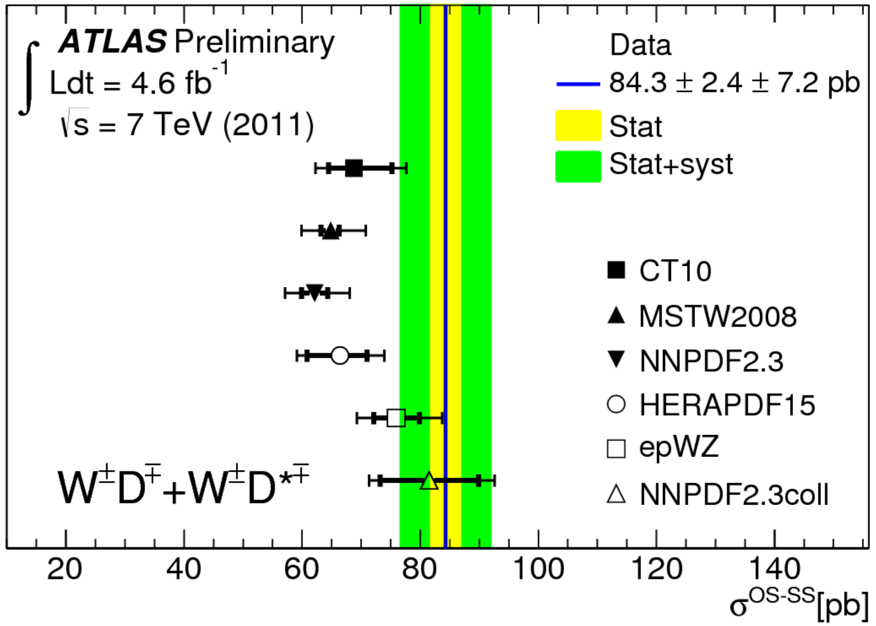


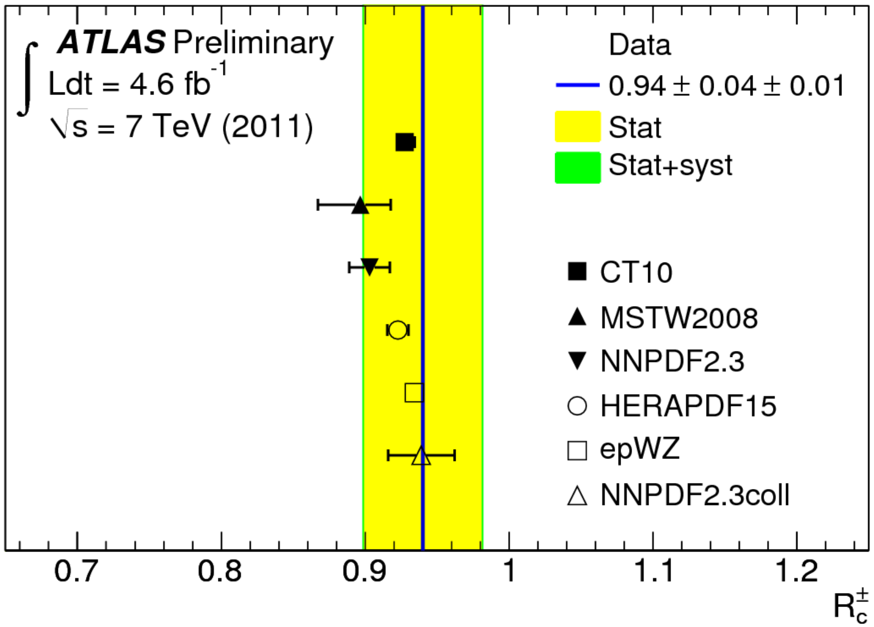
ATLAS does seem to yield somewhat larger strangeness than CMS…..?

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





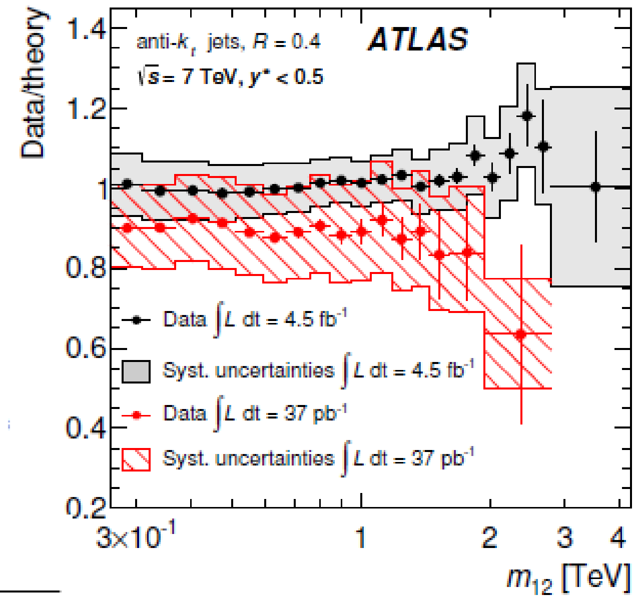




There is new dijet data from ATLAS arXiv:1312.3524

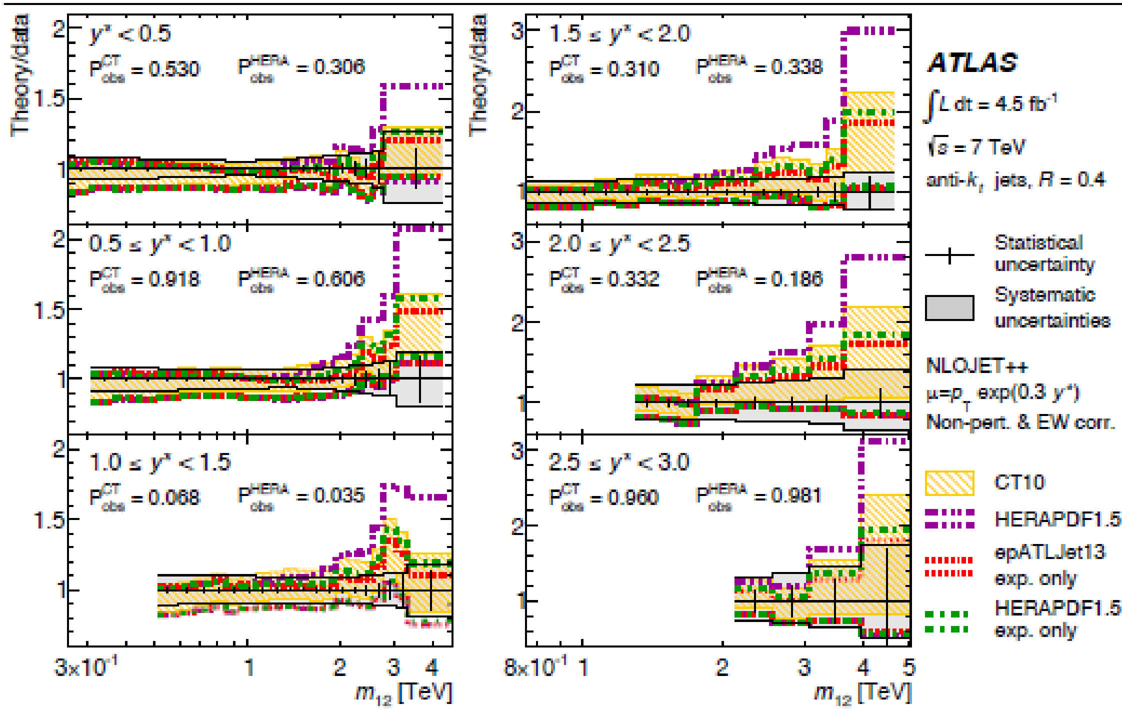
Comparison with 2010 data

- Reduced systematic and statistical uncertainty
- Extended range



JHEP 05 (2014) 059

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.

CMS 2 to 3 jet ratio has been used for an $\alpha_S(M_Z)$ extraction

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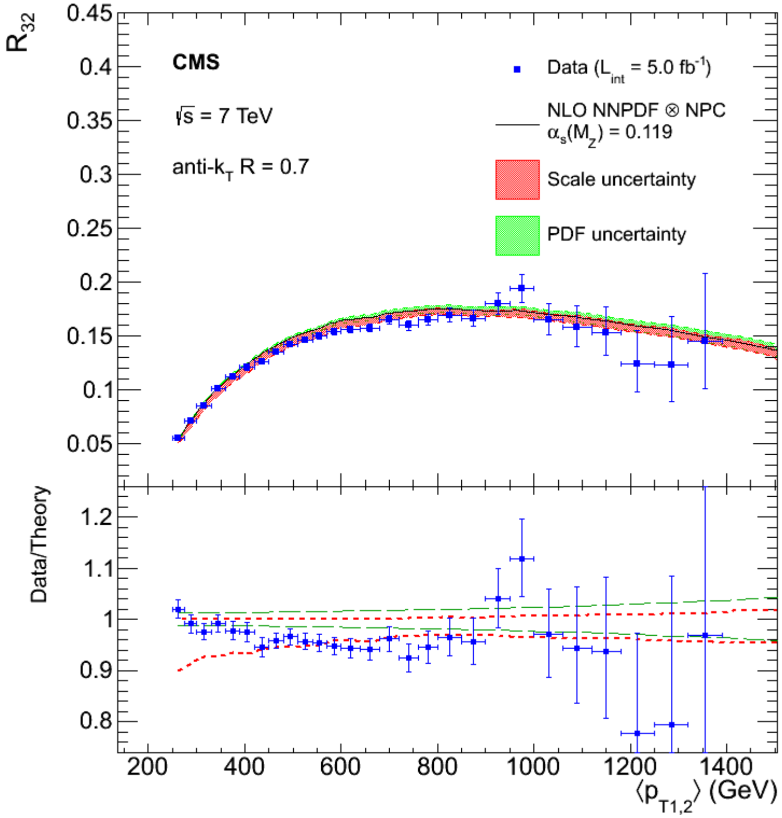

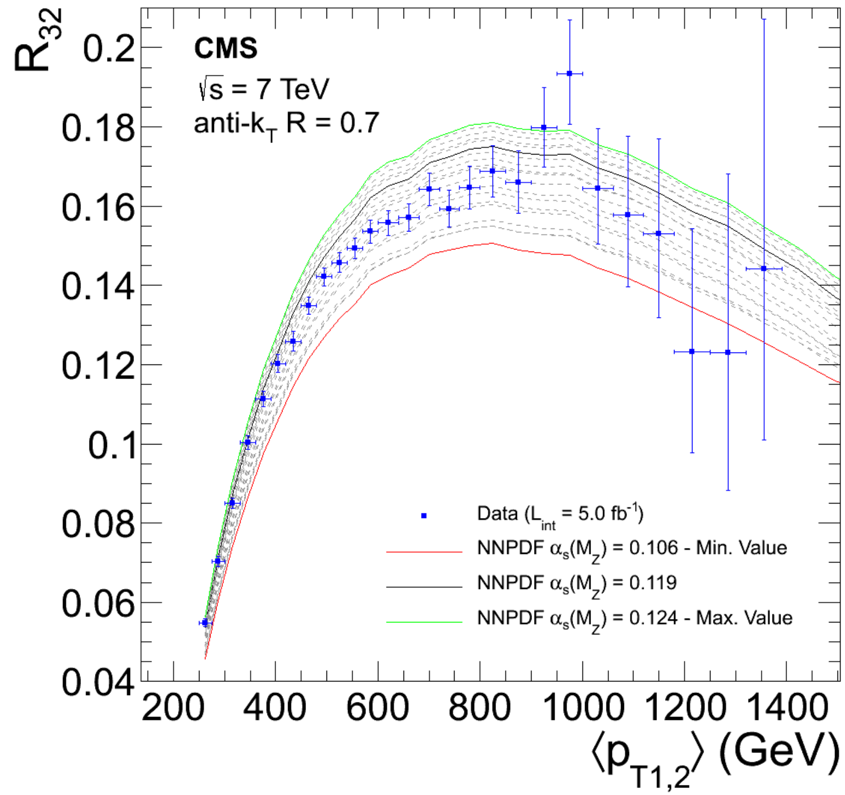

$$\alpha_S(M_Z) = 0.1148 \pm 0.0014\,(\text{exp.}) \pm 0.0018\,(\text{PDF}) \pm 0.0050\,(\text{theory})$$

The 3-jet mass has also been used for an $\alpha_S(M_Z)$ extraction

$$\alpha_S(M_Z) = 0.1160 \pm^{0.0025}_{0.0023} (\text{Exp.}, \text{PDF}, \text{NP}) \pm^{0.0068}_{0.0021} (\text{scale})$$