PDF the path to discovery

PDF experimental overview

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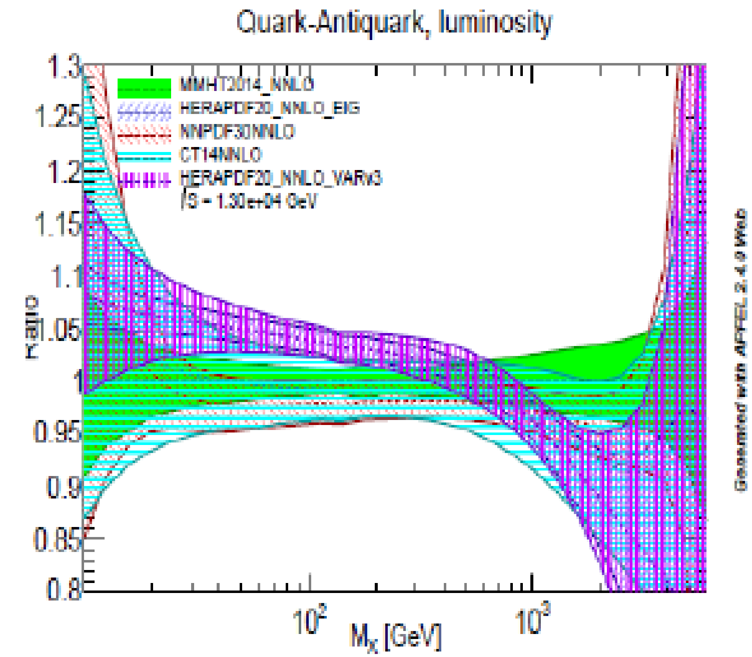
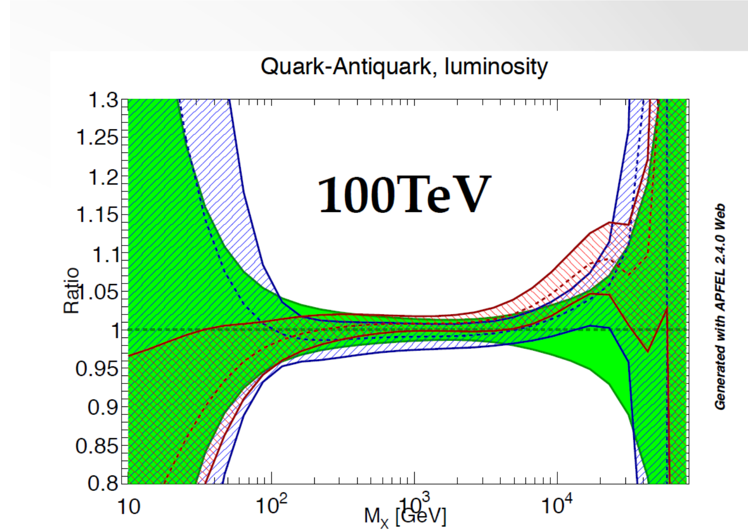
July 2018– pushing the boundaries meeting

A personal view

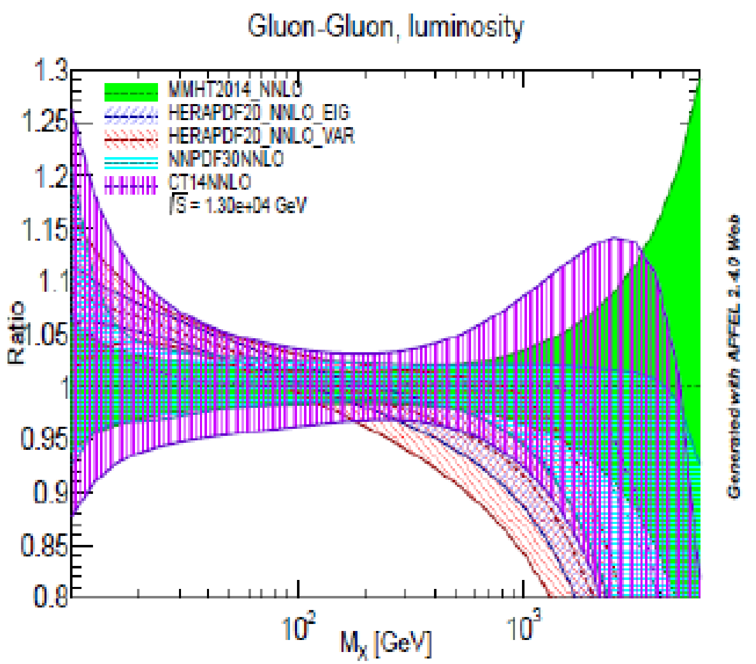
- High scale BSM searches limited by high-x PDF uncertainty, where we know PDFs less well
- Precision measurements like M_W, $\sin^2\theta_W$, where small discrepancies may indicate BSM physics are also limited by PDF uncertainty and this time the relevant kinematic region at which we need to know the PDFs is x ~0.01 where we already know them best! So it looks like we need to know them even better

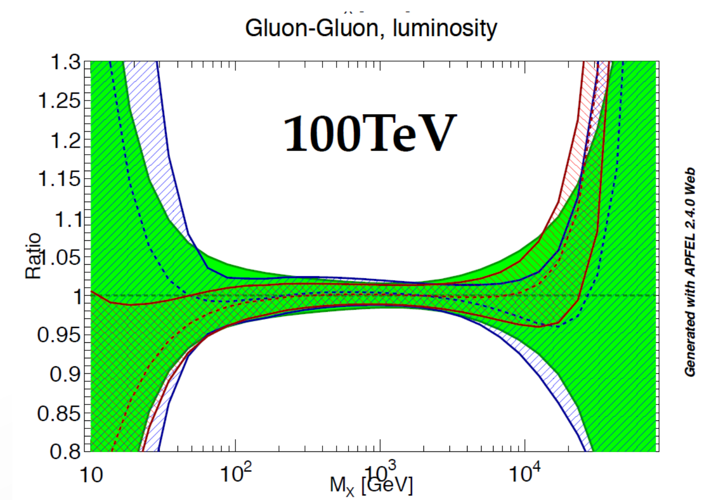
Also reviewing experimental results from ATLAS and CMS





What do we know about PDFs at 13 and 100 TeV
They are well known at medium scale Mx=100, x~0.01, badly known at high x and low x





… many thanks to Joey Huston

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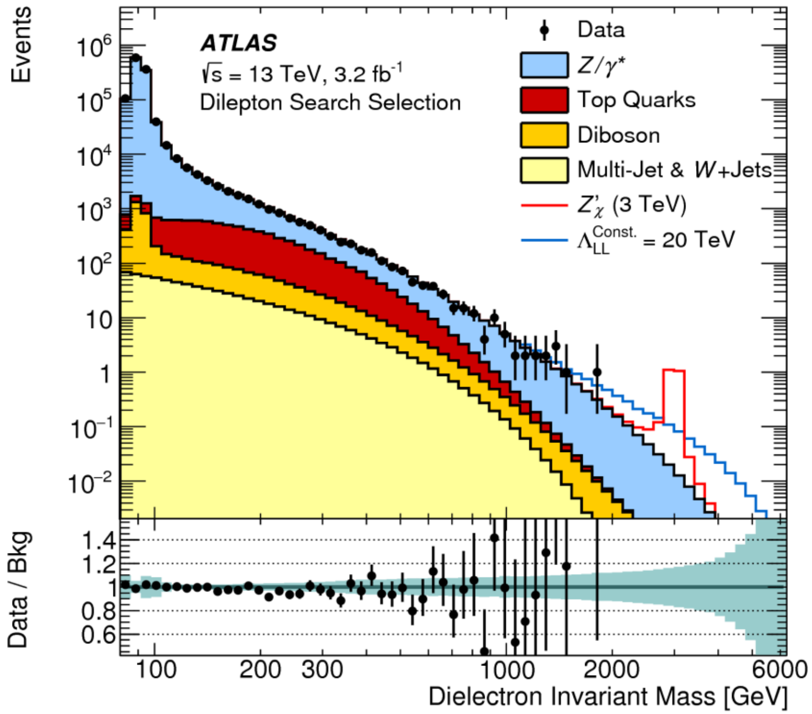
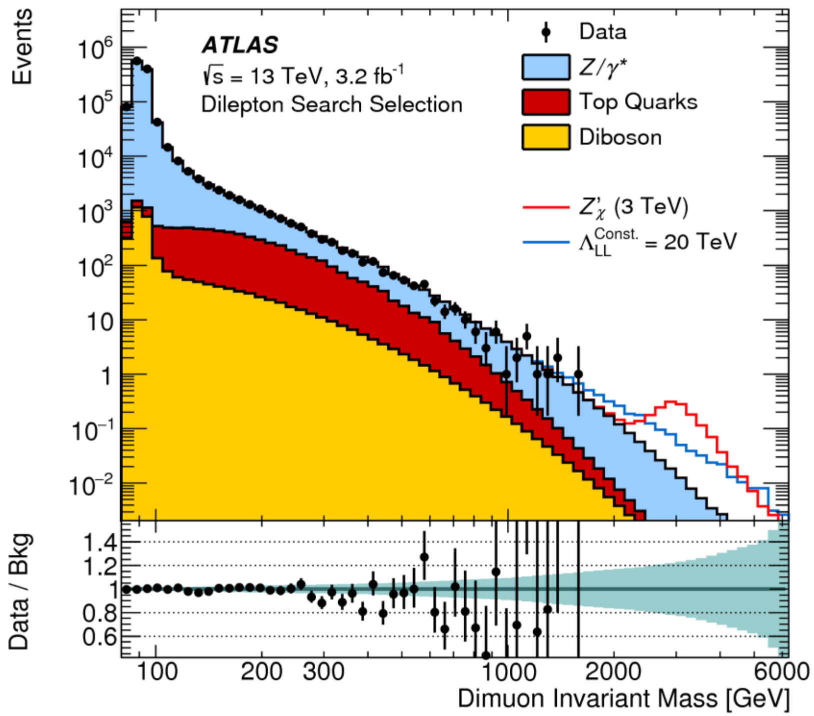
Why are PDFs the key?

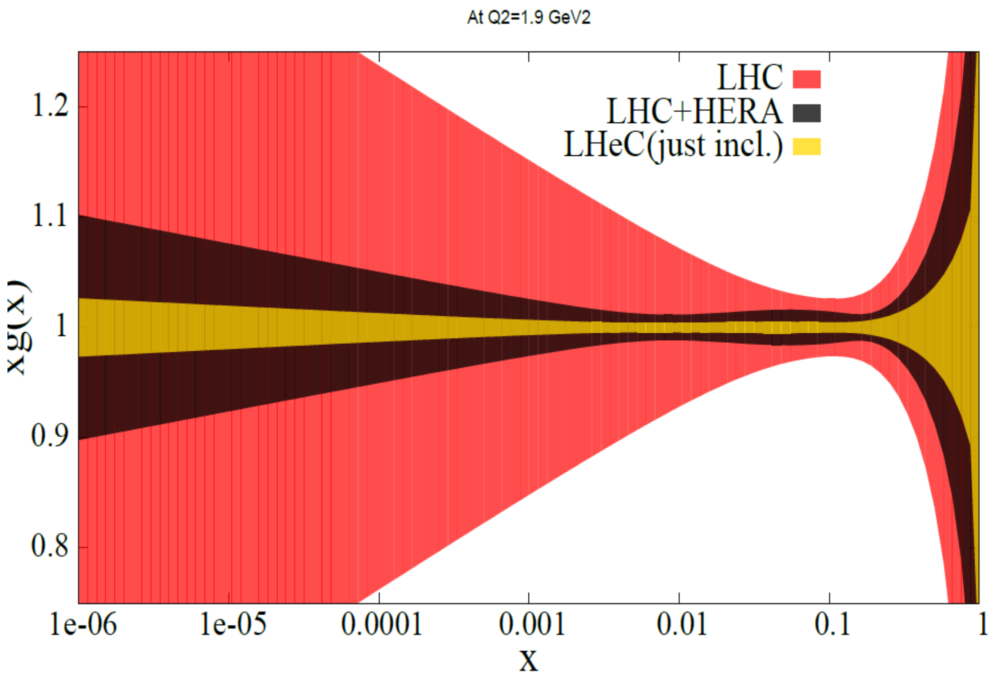
Current BSM searches are limited by high-x PDF uncertainties
One example from High-Mass Drell-Yan





arXiv:1607.03669

The dominant contribution to the grey shaded experimental uncertainty is the PDF uncertainty



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

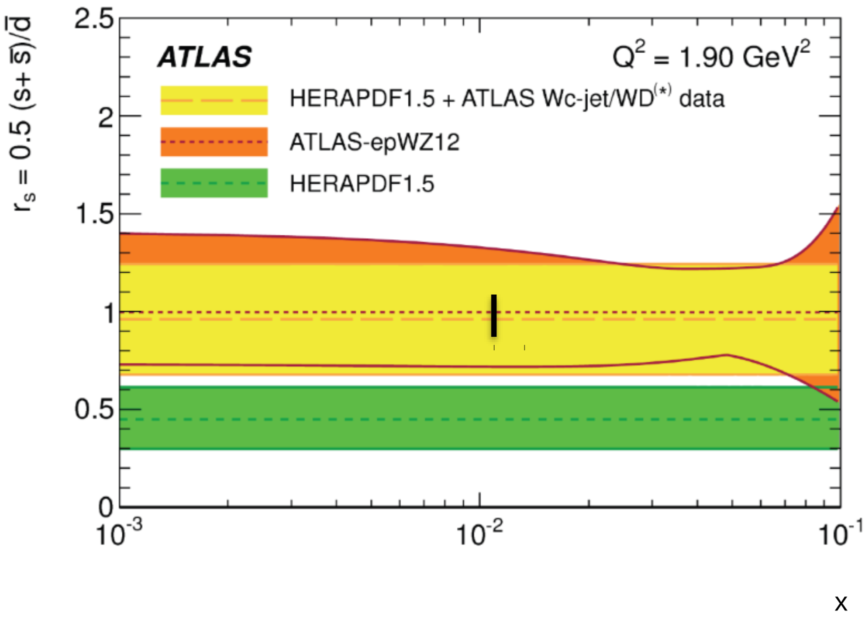
NOT with any precision NO !

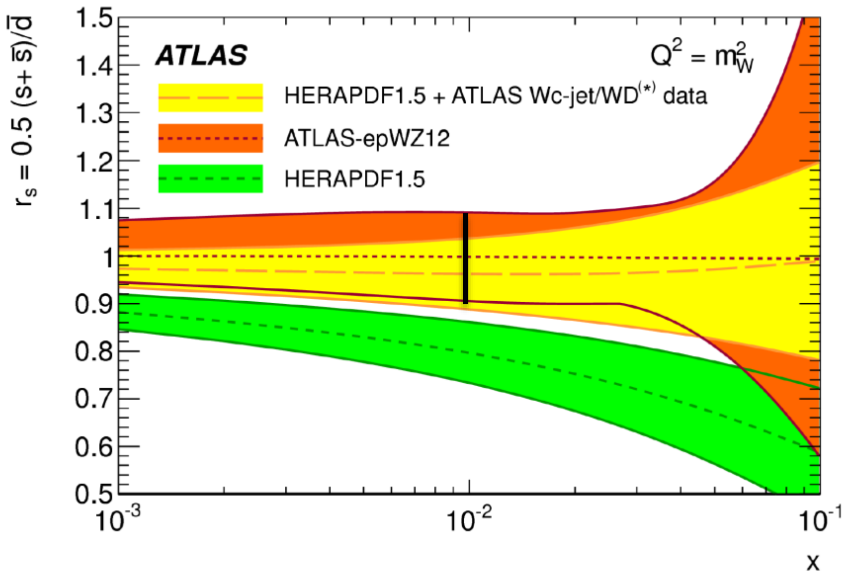
Present LHC W,Z data and jet data are included and LHC ultimate precision is extrapolated according to our current experience– we are systematics limited already

PDFs come from DIS

But this plot is a little old (2014) let us examine:

- Why the DIS data do better
- IF this is still true with our experience of PDF fitting today (2018)





Let us first examine WHY?

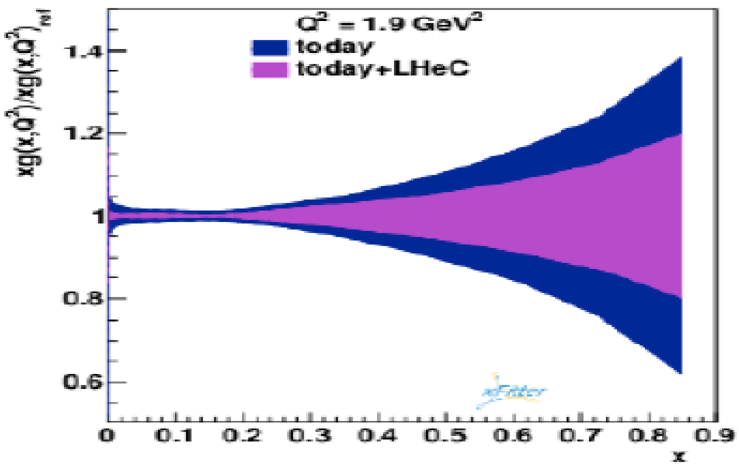
For illustration, these are plots of the strangeness fraction in the proton r_s from ATLAS analyses in which it is equal to the light quarks and in the HERAPDF1.5 in which it is ~0.5 of the light quarks.

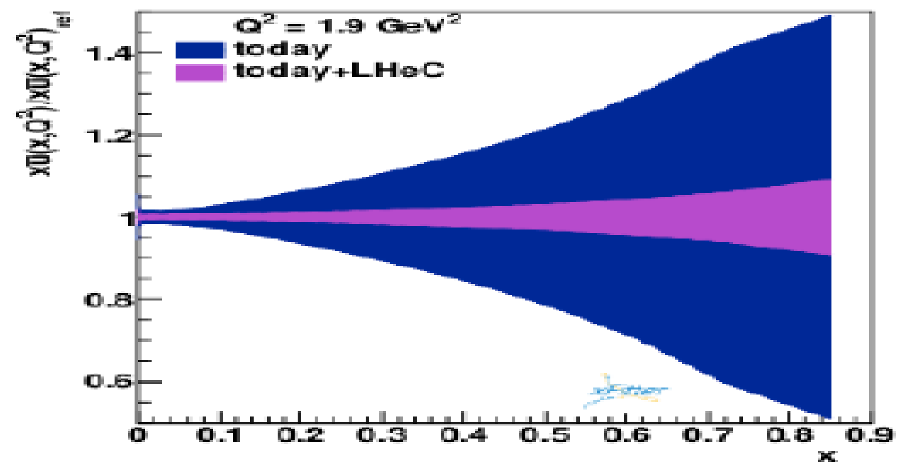
This fraction is shown at the starting scale Q^2_0 ~2 GeV^2 and at $Q^2=M_W{}^2$
NOTE the difference in scale.
PDF uncertainties decrease as Q^2 increases because the PDFs depend LESS on the parametrisation at the starting scale and MORE on the known QCD evolution.

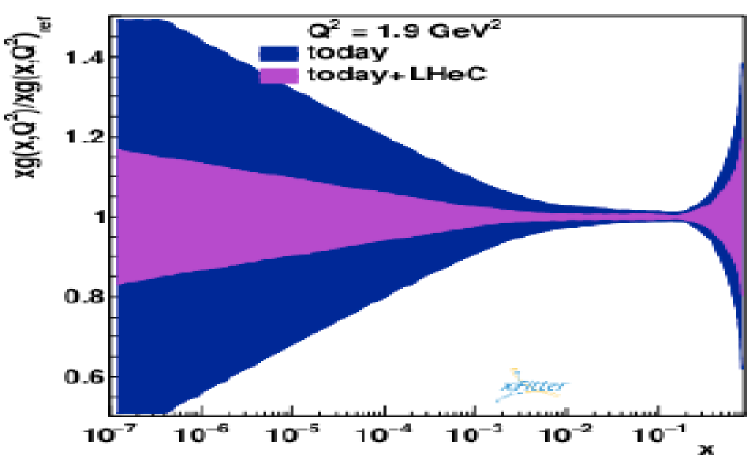
On each plot is shown a hypothetical measurement with ±10% accuracy.
Clearly this could distinguish the rs predictions if performed at Q^2_0, but not if performed at high scale.
At high scale we have to have much more accurate measurements.

The potential for precision parton distributions at the LHeC is assessed using

- LHeC simulated data
- HERA final combined data plus HERA jet data, BCDMS F2p data
- ATLAS 2010 jet data, CMS jet data 2011, CDF, D0 jet data
- CDF, D0 Z rapidity, CDF,D0 W-asymmetry, CMS Z rapidity, CMS W-lepton asymmetries
- ATLAS total and differential t-tbar 2011, CMS total and differential t-tbar 2011
- ATLAS 2011 W and Z precision data







An LHeC could improve PDFs dramatically
BUT we cannot bank on this SO..
What data do we have from the LHC itself which gives us substantial improvement?
AND will it get better?

Data which affect the high-x gluon

NOW and in future:

- JETS
- TOP
- Zpt, Z+jets, W+jets?
- Direct photon

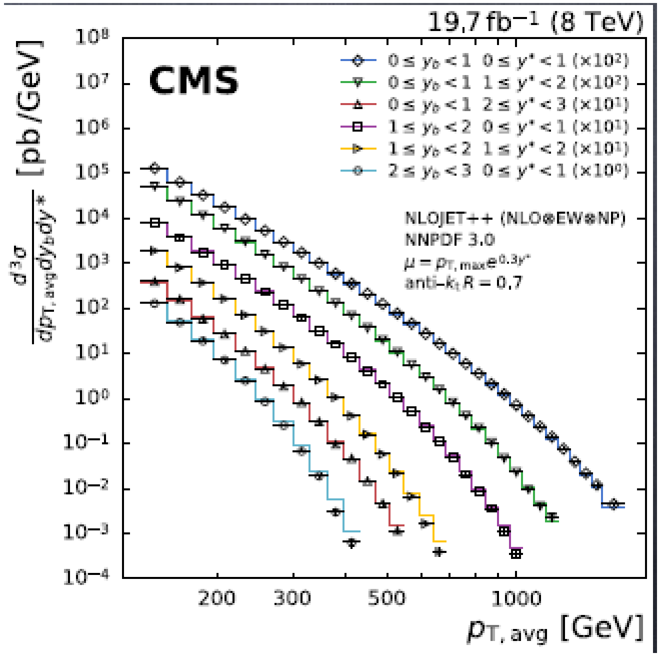
Data which affect high-x quarks

- High-Mass Drell-Yan

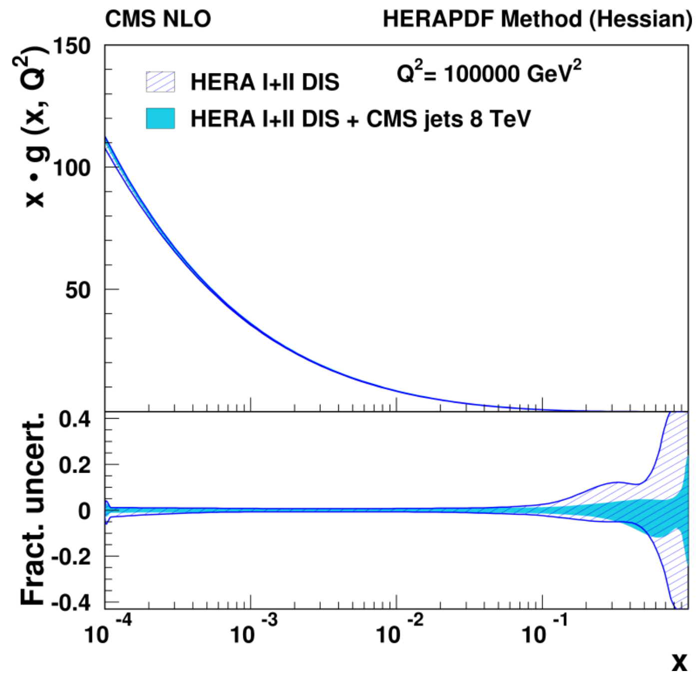
Data which affect medium and lower- x quarks

- W,Z production
- Low-mass Drell-Yan
- W, Z+c data

Jet distributions

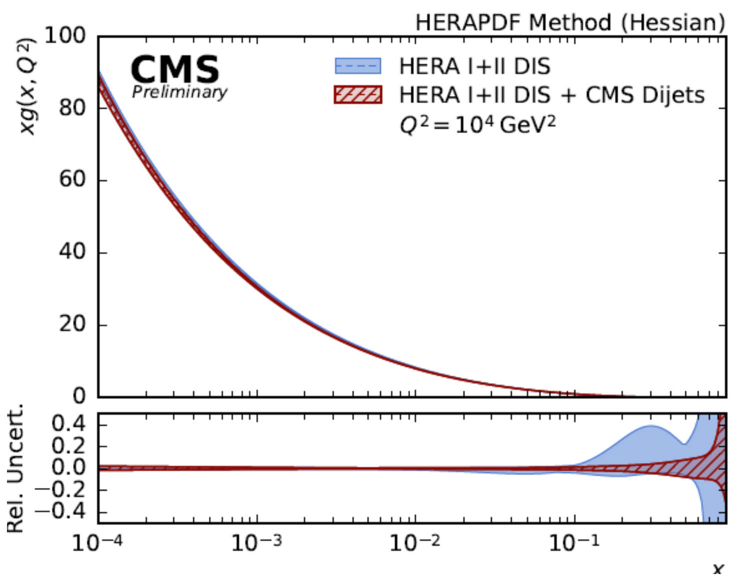


CMS 8 TeV inclusive jet data: arXIV:1609.05331
CMS Triple Differential Dijets 8TeV:EPJC77(2017)11



- Ratios $2.76/8$, $7/8$ available: partial reduction of uncertainties

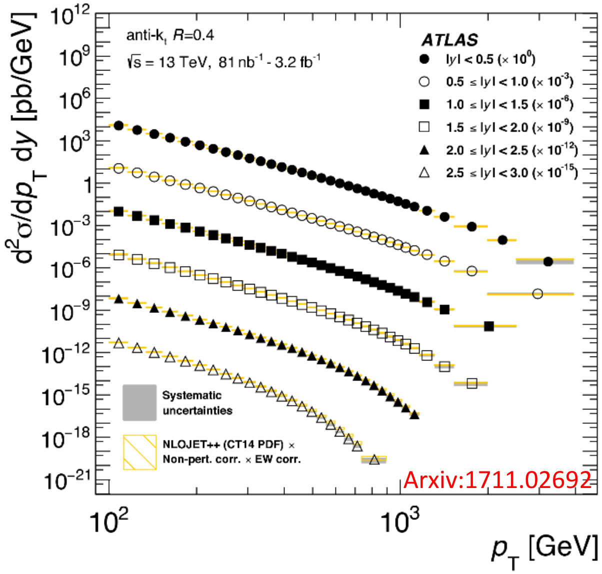
Ratios of 2.76 and 7 TeV data were already used by ATLAS: arXiv:1304.4739

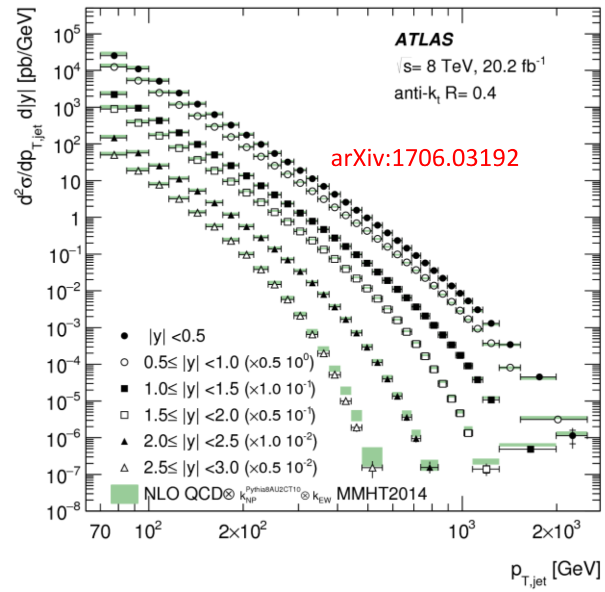


$$\alpha_S(M_Z) = 0.1199 \pm 0.0015\,(\text{exp}) \pm 0.0002\,(\text{mod})\,^{+0.0002}_{-0.0004}\,(\text{par})\,^{+0.0031}_{-0.0019}\,(\text{scale})$$

New ATLAS jet production data at 8 and 13 TeV

(Older at 7 TeV, inclusive dijet,trijet)





State of the art prediction only becomes NNLO- BUT many studies still at NLO

Large χ2 when fitting different rapidity bins simultaneously for all inclusive jet samples at NLO. This has been found both by ATLAS and by global fitters

Much work on considering realistic de-correlations for 2-point systematics and on alternative scale variations choices and one still obtains χ2/ndp ~ 260/159- (and decorrelating theory systematics is just as important as decorrelating experimental systematics) see arXIV:1706.03192

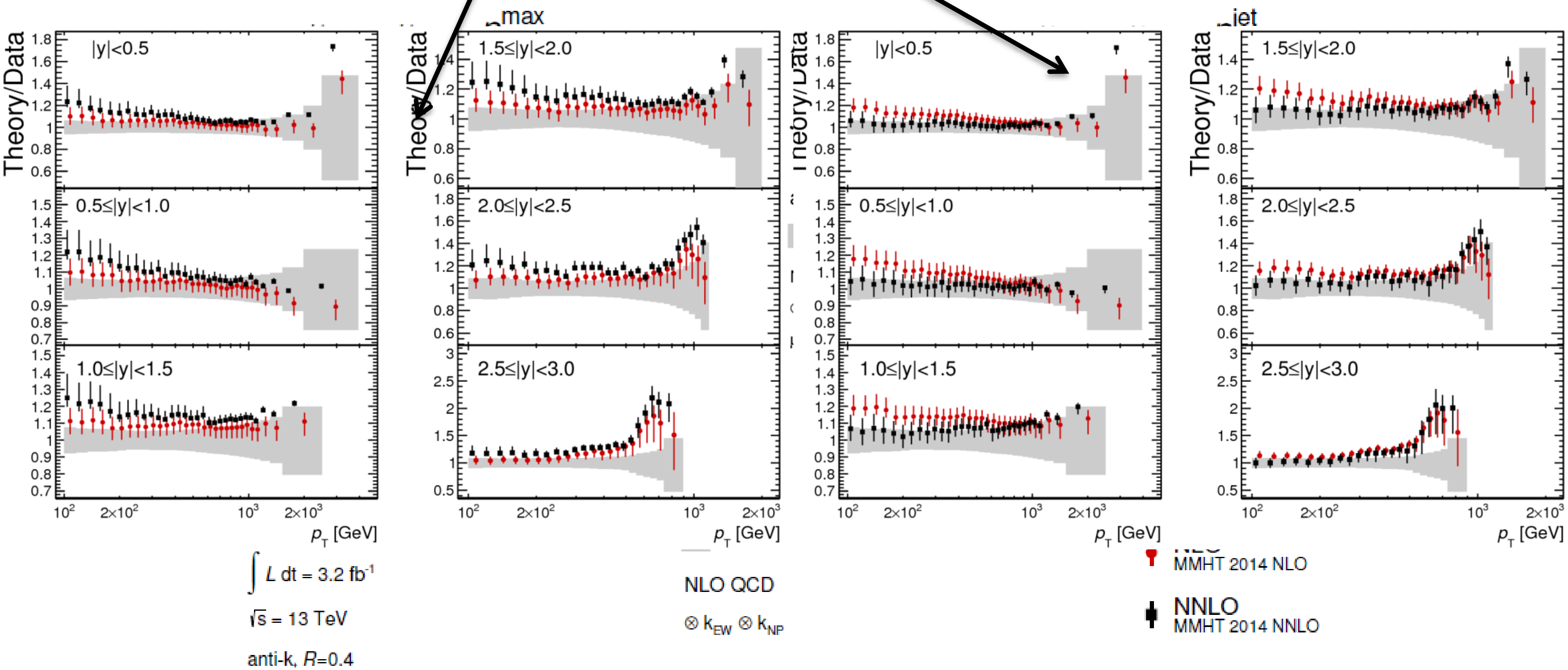
BUT NNLO can describe the data better?....

There is progress on the NNLO corrections- scale choice matters.

P_T^{jet} as the scale choice and larger cone size R=0.6, gives the most compatible results

NLO/Data vs NNLO/Data

- NNLO ($\mu = p_T^{jet}$) describes the data within uncertainties
  - except at $|y| > 2$ and high-p_T
- NNLO ($\mu = p_T^{max}$) overestimates the measured cross-section

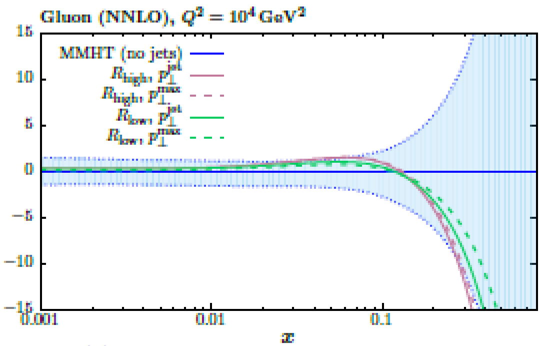


However……

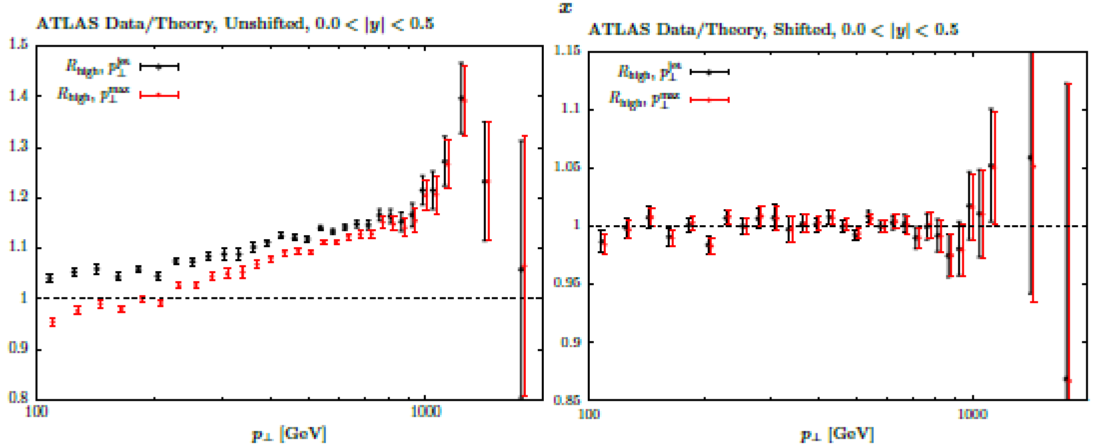
It seems that fits do not care so much about scale– the jet radius matters more

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

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



All fits result in a somewhat softer high-x gluon



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

Different shifts of data relative to theory required.

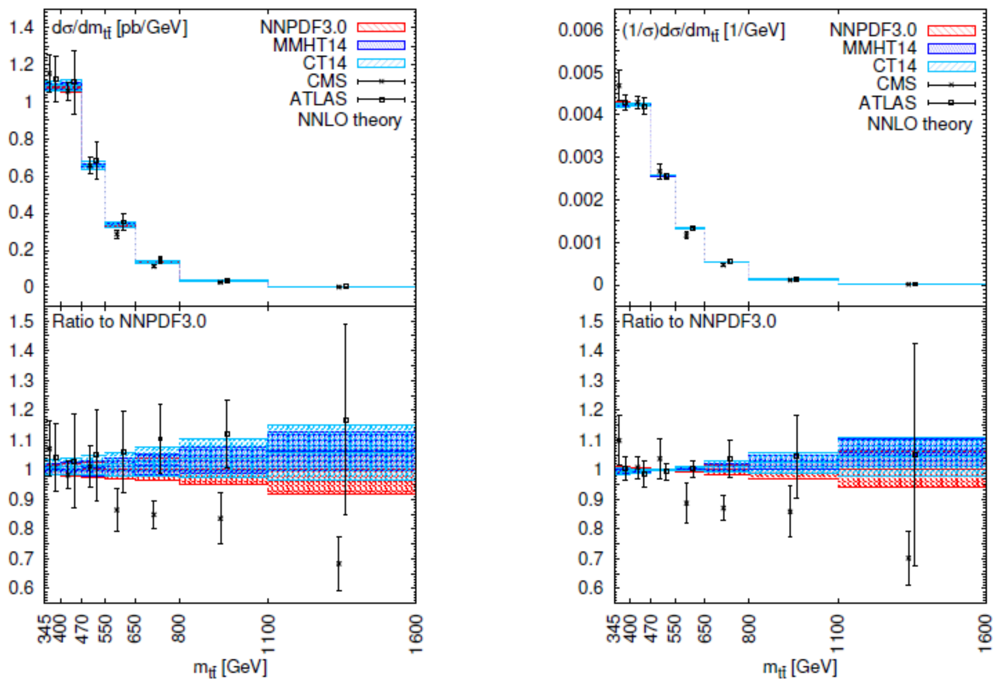
Can one improve in future ?

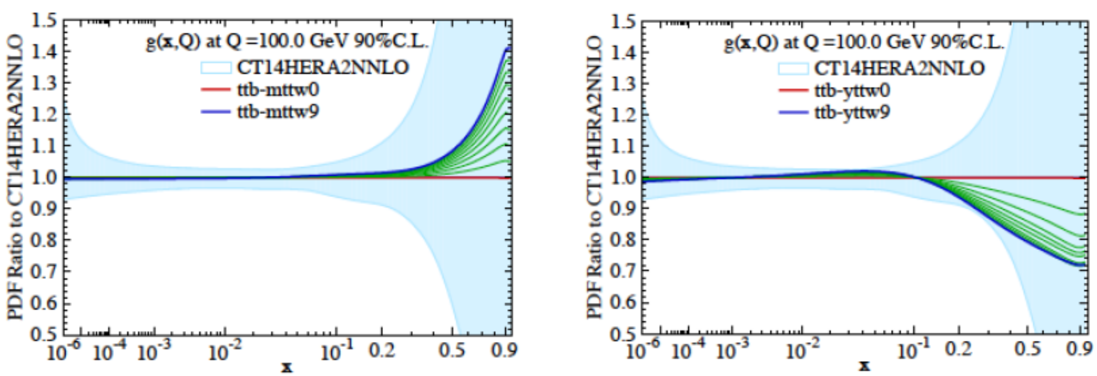
Since jet data do not suffer from lack of statistics this points up the fact that it is data systematic uncertainties which really matter. More data always helps us to improve our understanding of systematics but it is not easy to quantify this.

Top distributions

NNLO predictions are now available for ATLAS (1511.04716) and CMS (1505.04480) 8 TeV lepton +jets single differential distributions (arXiv: 1611.08609 and 1704.08551). EW corrections arXiv:1705.04105.

Data/Theory comparison: $m_{t\bar{t}}$





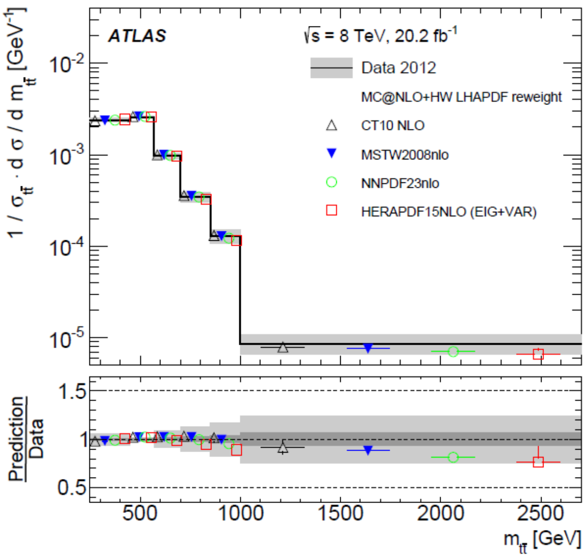
There are several distributions that constrain the high-x gluon: mass t-tbar, rapidity t-tbar, rapidity-top and pt-top

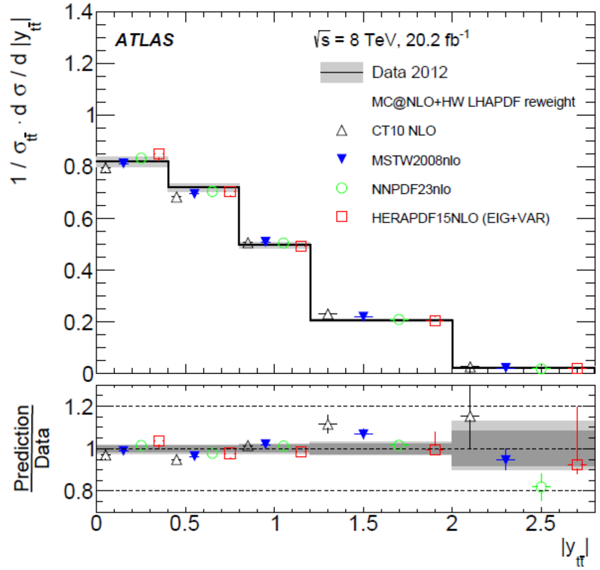
Both normalised and absolute spectra have been compared to various PDFs

There are some issues:

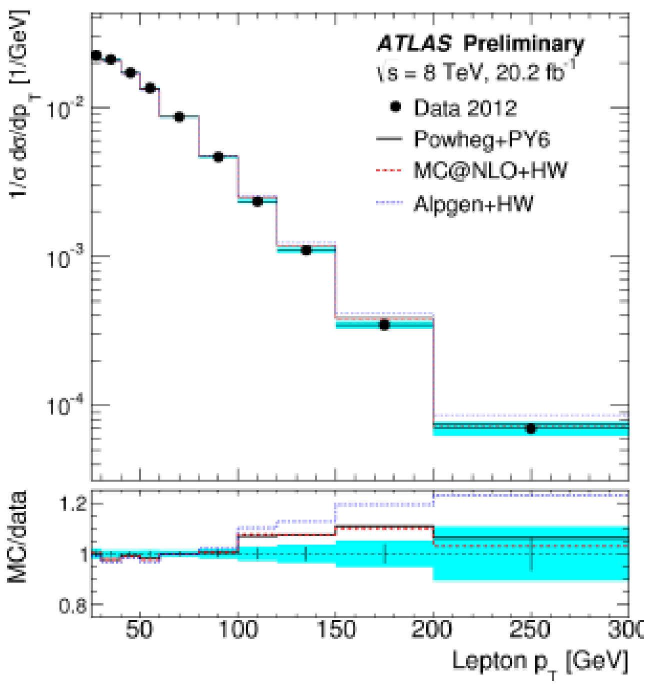
1. The CMS and ATLAS data are not always consistent with each other for the same spectra- and nor are their uncertainty estimates
2. Within the experiments the different spectra are not consistent with each other E.g--- for ATLAS M-tt wants a harder gluon, Y-tt wants a softer gluon CMS data gives similar inconsistencies
3. **To fit more than one spectrum at a time one needs statistical correlation matrices– COMING!!**

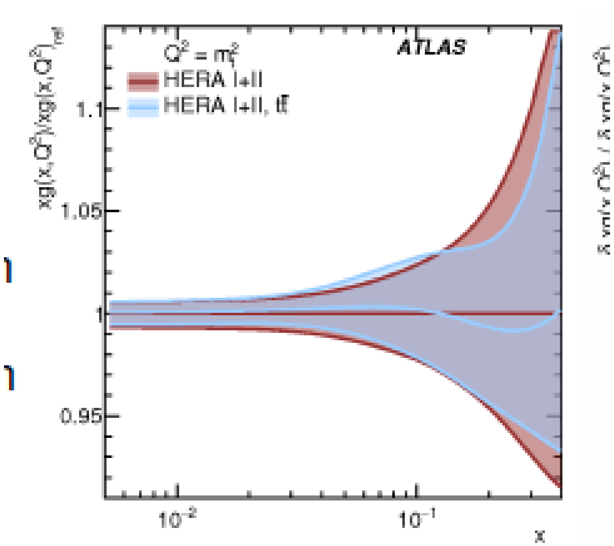
Top distributions





ATLAS has also presented data for the normalised M-tt and Y-tt spectra for the dilepton mode ArXiv:1607.07281 --these can be analysed at NNLO



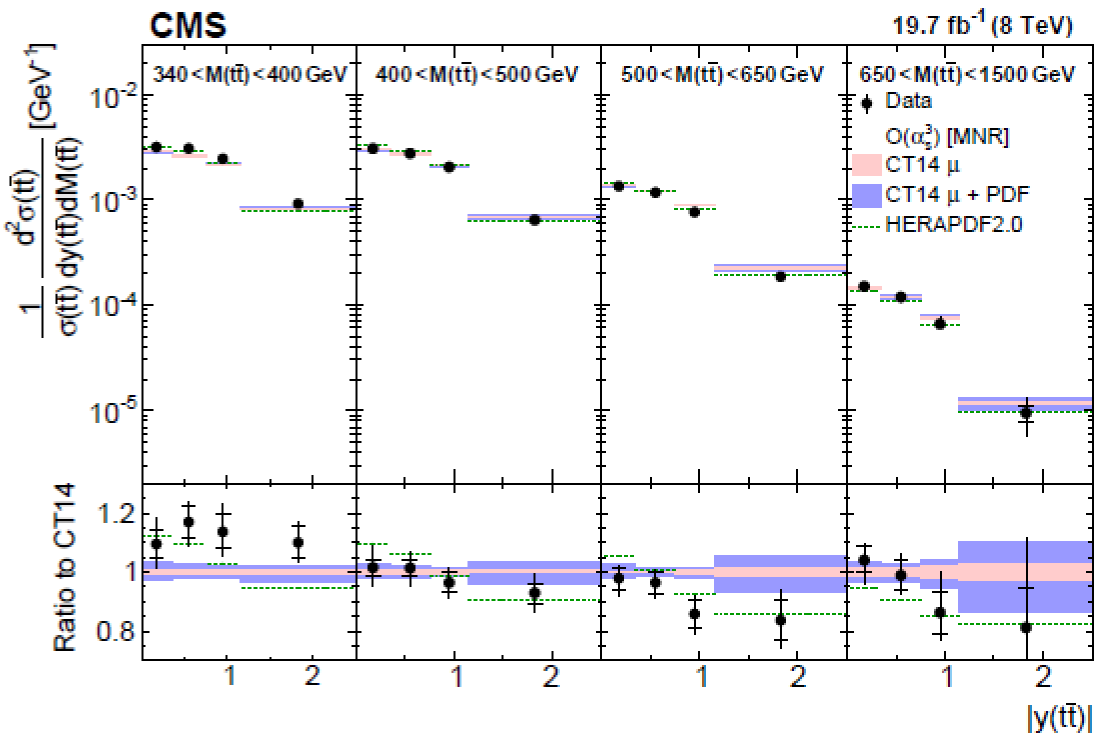


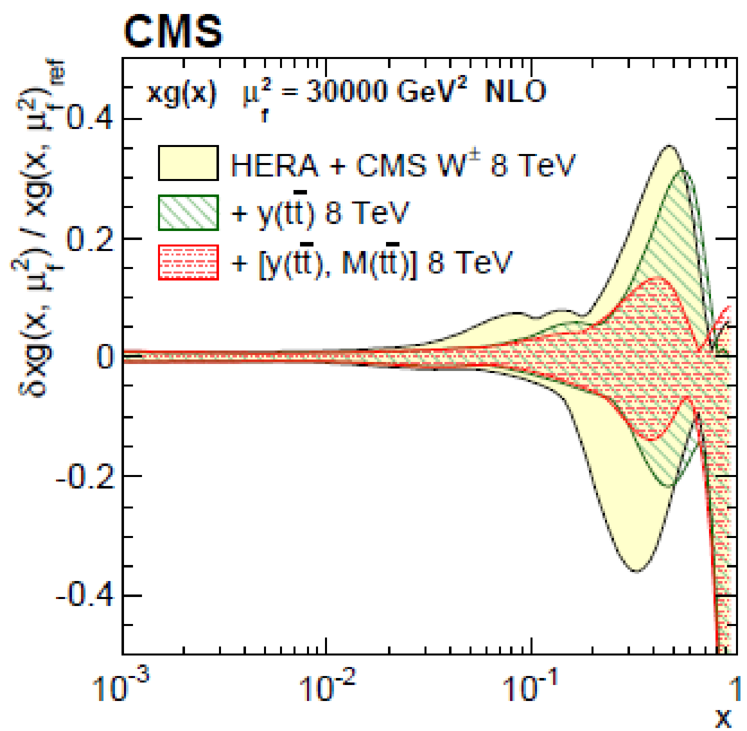
The data in the dilepton channel can also be analysed in terms on the lepton decay variables Arxiv:1709.09407 But so far this can only be analysed at NLO

Datasets fitted	HERA I+II	HERA I+II + $t\bar{t}$
Partial χ^2 / N_{point}		
- HERA I+II	1219 / 1056	1219 / 1056
- $t\bar{t}$ ($\lvert\eta^{\ell}\rvert$, $\lvert y^{e\mu}\rvert$, $E^e + E^{\mu}$)	-	27 / 25
Total χ^2 / N_{dof}	1219 / 1042	1247 / 1067

Top distributions

CMS have recently (arXiv:1703.01630) presented double differential top distributions in mass and rapidity of the t-tbar pair



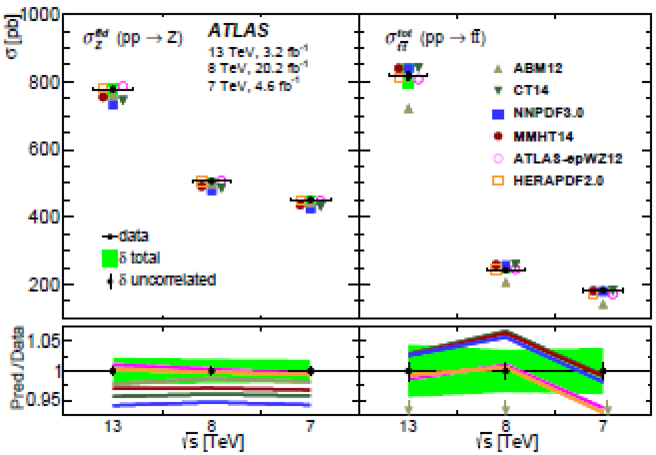


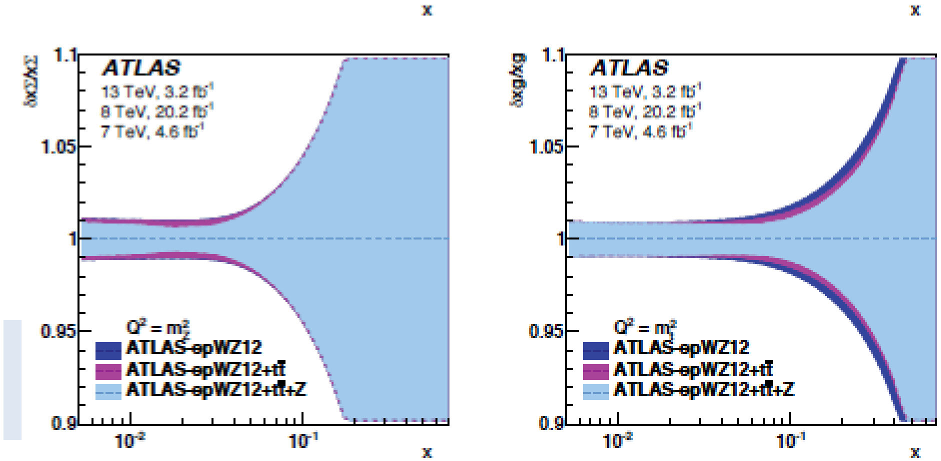
When input to a PDF fit these double differential is much more constraining than the single BUT analysis can only be done at NLO presently since there are no predictions at NNLo for the double differential distributions

CMS top data at 5 TeV (27pb-1) are also available JHEP03(2018)115

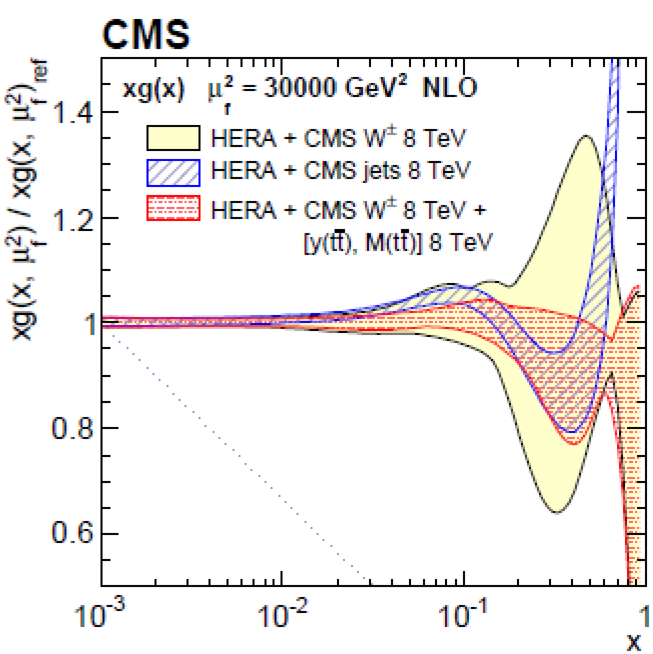
Simultaneous analyses of different data sets:

ATLAS measurement **of inclusive t-tbar to Z cross-sections** at 7, 8 and 13 TeV (arXiv:1612.03636) With accounting for correlations between them





T-tbar data mostly affects the gluon
Z data mostly affects the quarks



CMS analysis of **W, jets and top** arXiv:1703.01630

Can one improve in future?

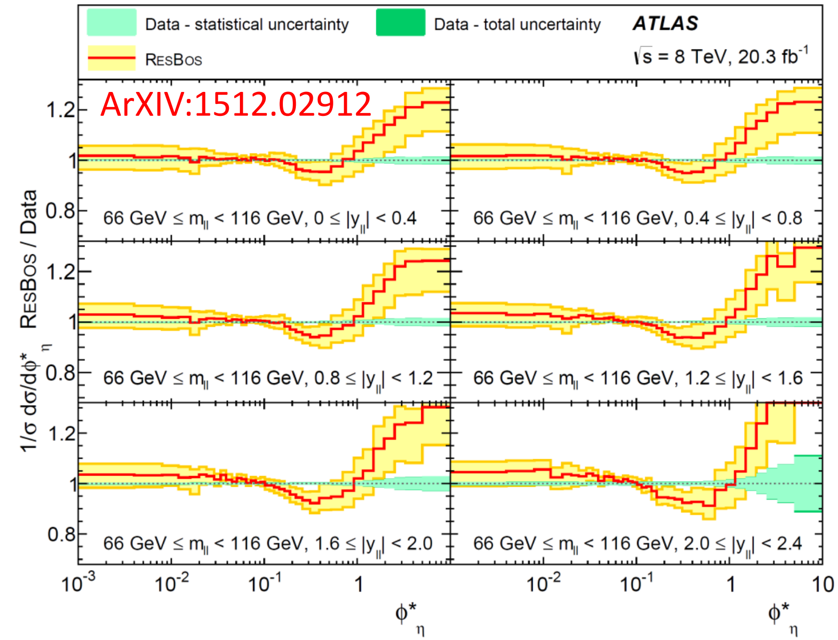
Top distributions have not yet hit their potential systematic uncertainty limit.
We can have more clever ideas like taking ratios of different quantities
And ratios of different CM energies

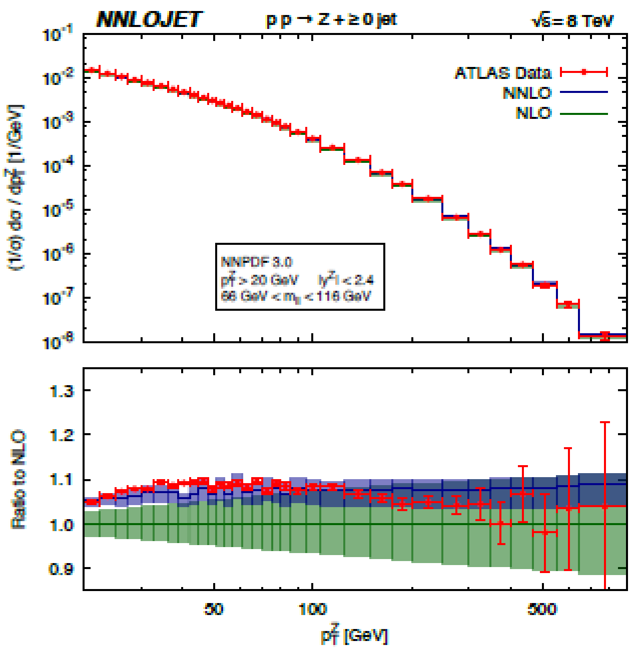
Boson (W,Z) pt and Boson+jets distributions

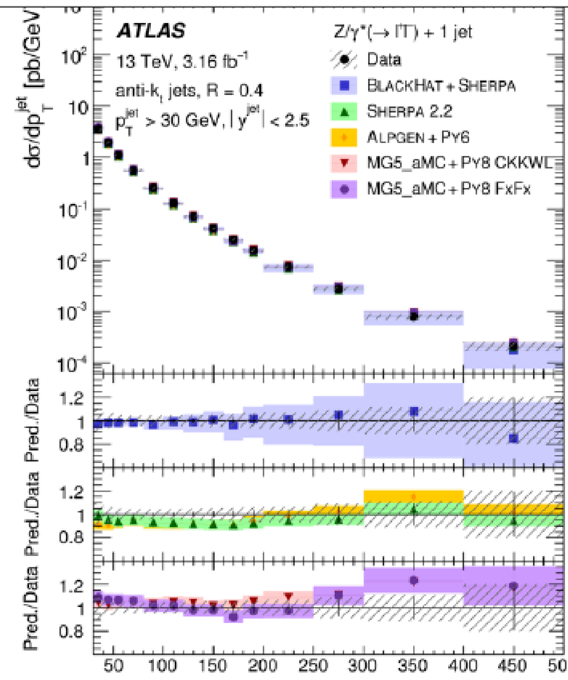
There are now NNLO predictions for Z +jets, Zpt and W+jets arXIV: 1607.01749, 1605.04295

There is new data– and more in the pipeline.

The data on Zpt or ZΦ* is very accurate –and have stimulated these developments, which even aim to cover quite low pt – impact on fits is not large so far







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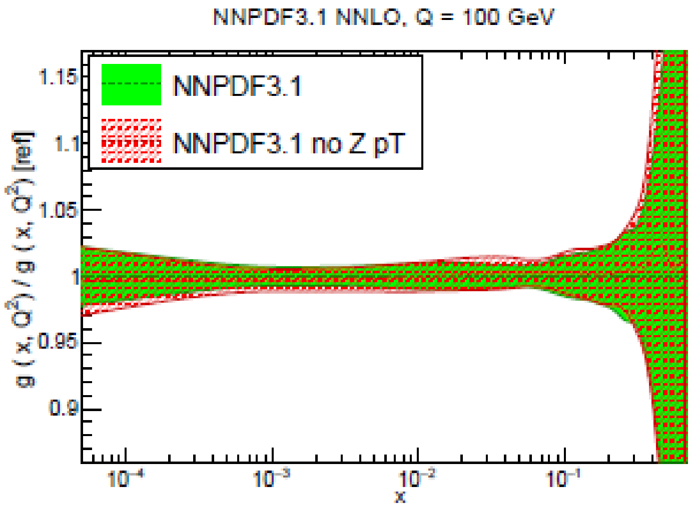
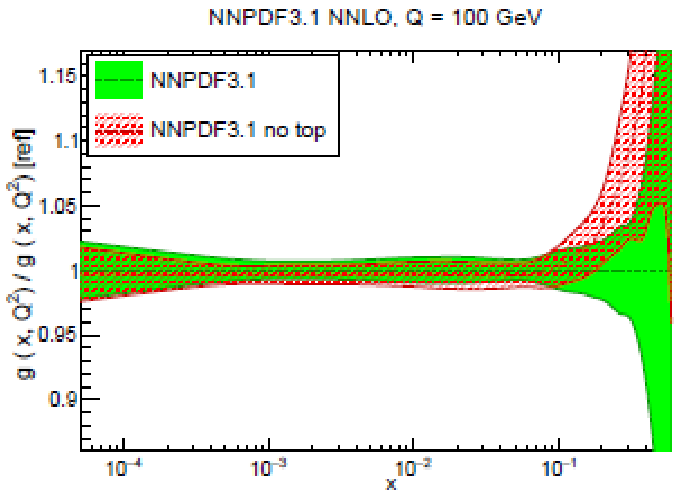
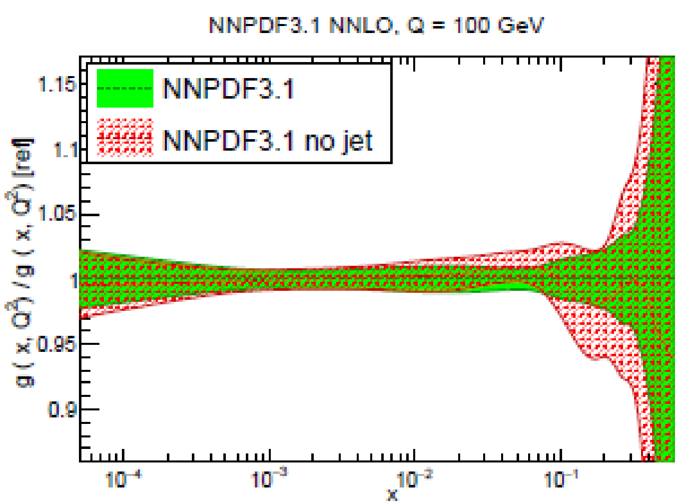
The data on Z+jets and W+jets is much less accurate and can improve in future

Let's see how much the gluon PDF is improving due to these data
Look at some separate LHC data sets from NNPDF3.1 analysis

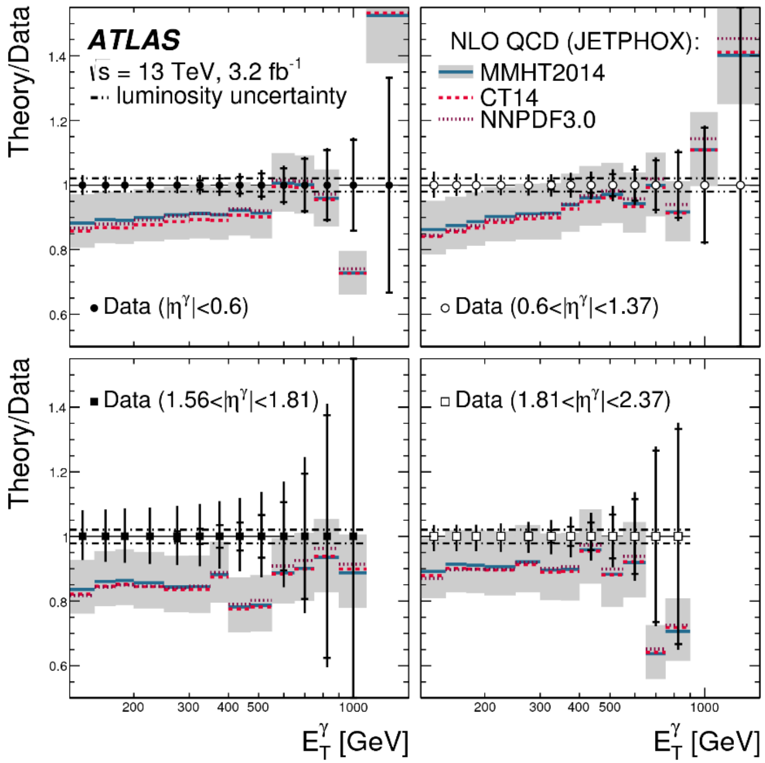






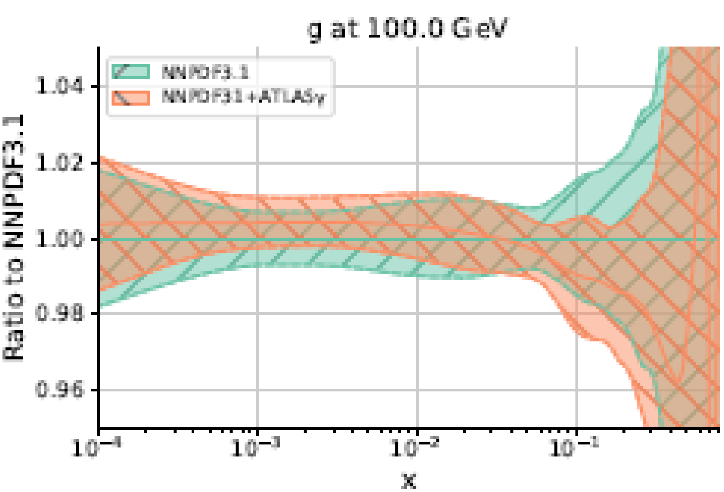
Data sets which affect the gluon:
Zpt
T-tbar differential distributions
Jet production

There is also: Direct photon production

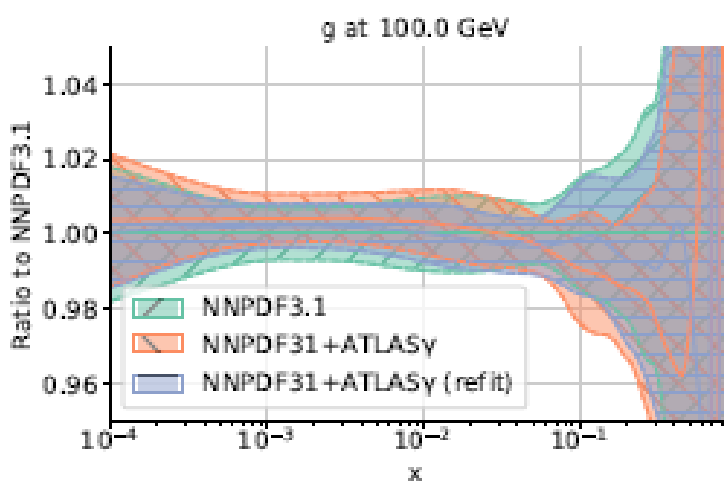


There is new data at 8 TeV arXiV:1704.03839
And 13 TeV arXiv: 1701.06882
Direct photon data were abandoned in PDf fits more than 15 years ago due to lack of theoretical understanding. It has now been established that at collider energies these data can give useful information on the gluon
Studies at NLO have been done, but there are now NNLO predictions arXIV: 1701.06882
Now applied in 1802.03021

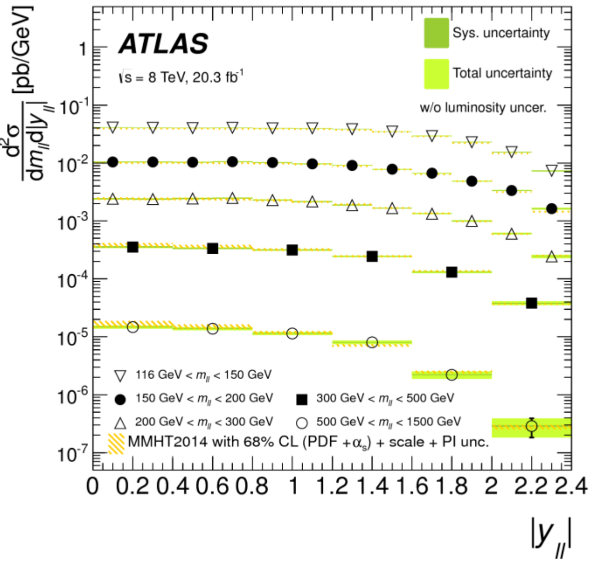
This can improve with 13/8 TeV ratios



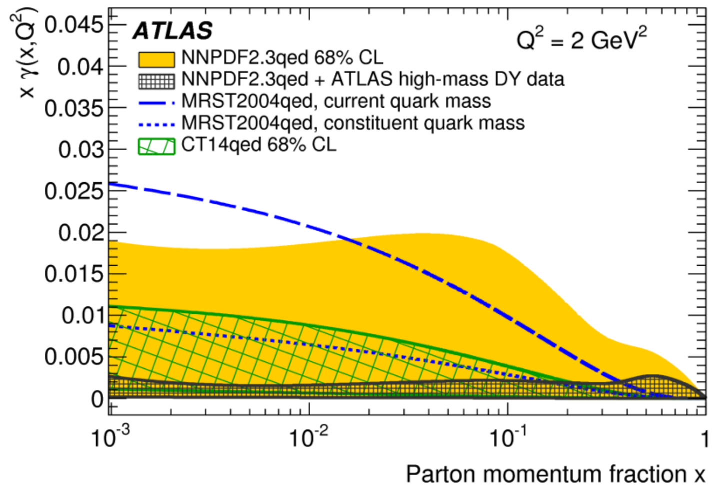
More information on systematic correlations led to this→



High-mass Drell-Yan: arXiv:1606.01736

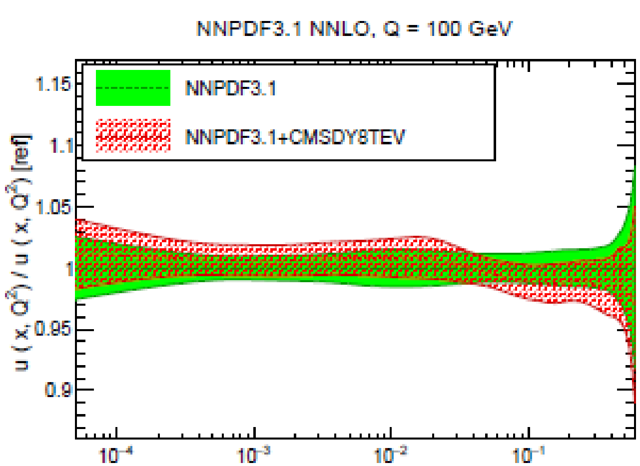


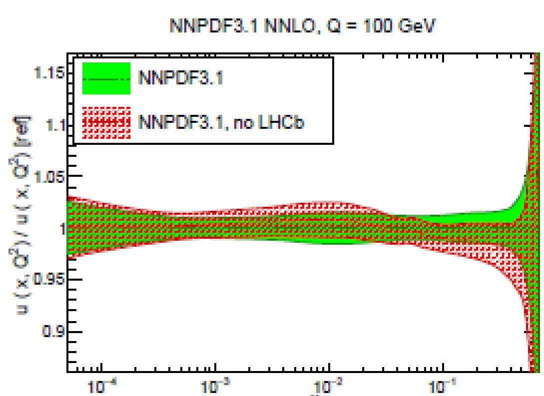
At high-mass di-lepton pairs may be photon induced rather than true Drell-Yan processes. These data have been used to **constrain the photon-PDF**

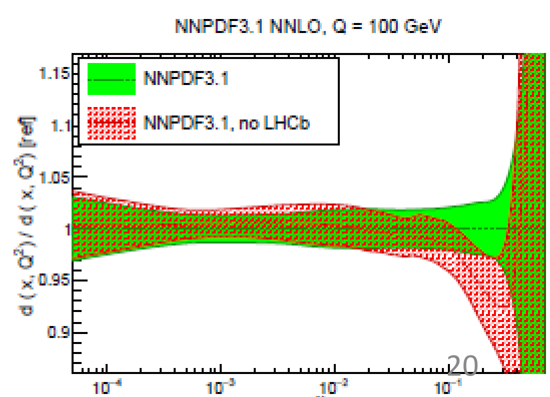


There is also CMS 8 TeV Z/γ* double differential Drell-Yan data (arXiv:1412.1115). However these data have very poor χ2/ndp~3.3
These data do not have a big pull on PDF fits

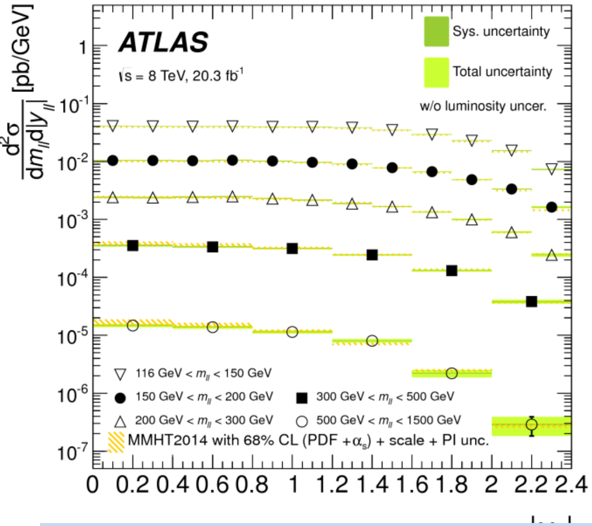
LHCb W,Z data probe a different kinematic region to both lower and higher-x values Their impact is mostly seen on high-x quarks. Low-x can present theoretical challenges







ATLAS 8 TeV high-mass Drell-Yan and the photon PDF arXiv:1606.01736



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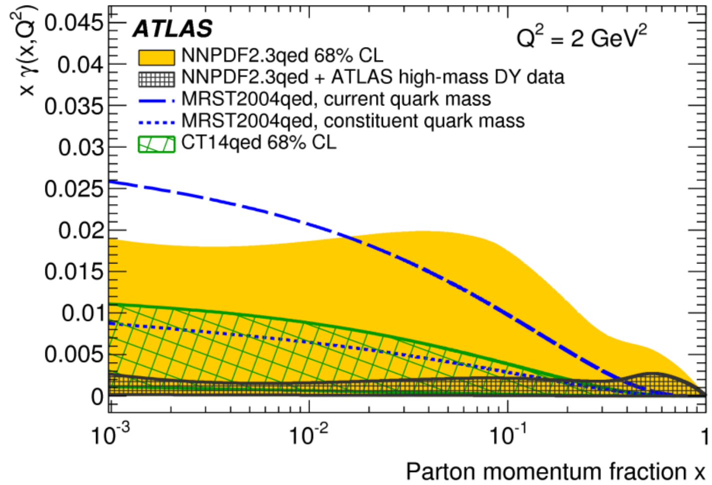

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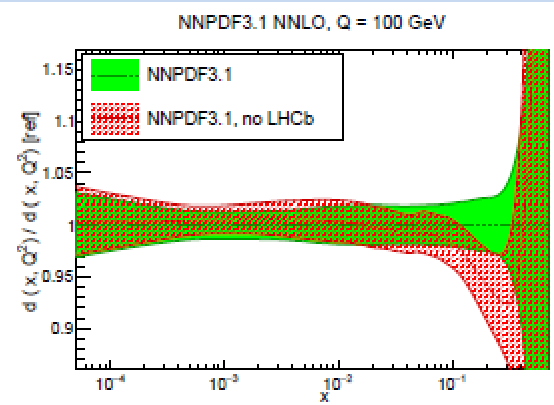


Off-peak Drell-Yan can still improve both statistically and systematically- and there is greater reach to low and high-x from HE running

BUT low-mass brings the **low-x theory challenges-ln(1/x)** resummation etc

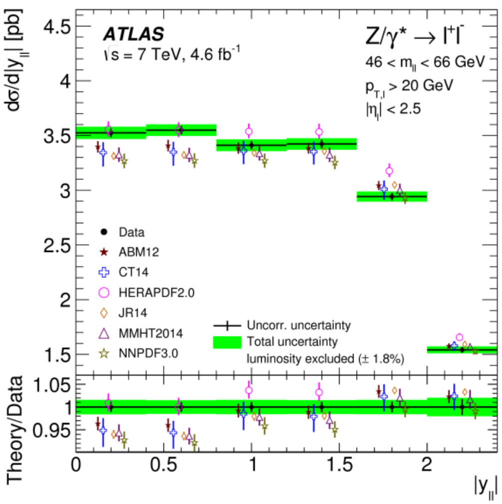
This also affects the LHCb data, NOTE the low- and high-x regions are of course coupled- both come from high rapidity

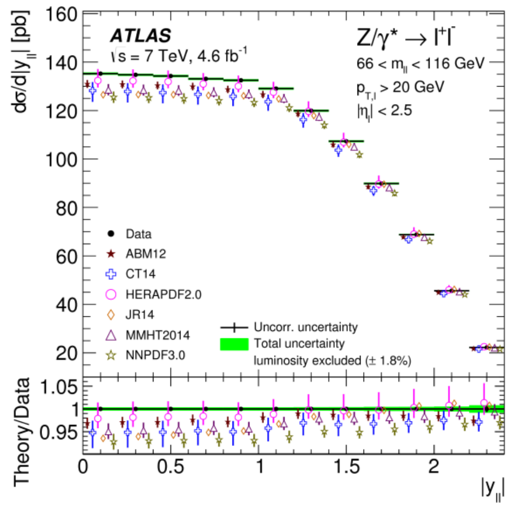
High-mass requires good understanding of the **NLO-EW corrections and photon PDF** (considerable recent progress)

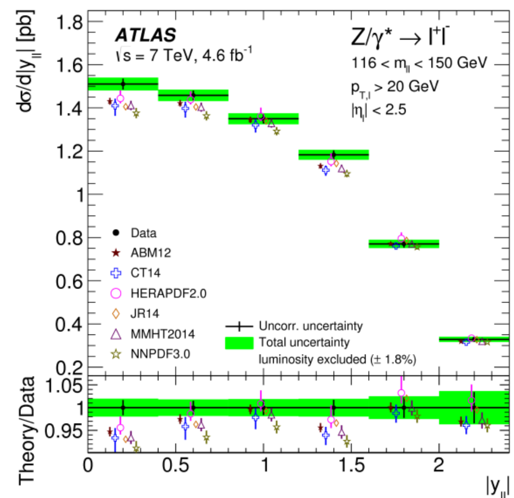
W,Z and Drell-Yan distributions

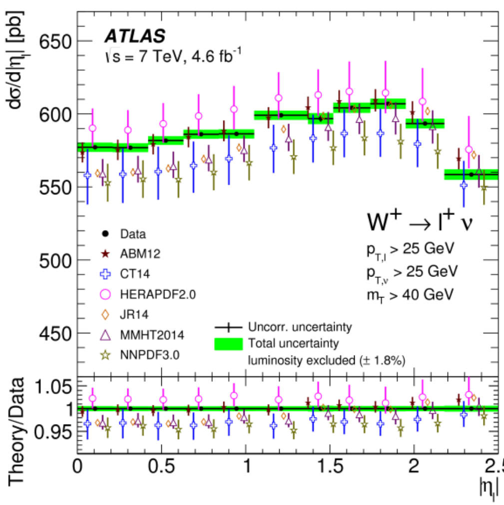
ATLAS inclusive W and Z differential distributions
arXiv:1612.03016
Very high precision

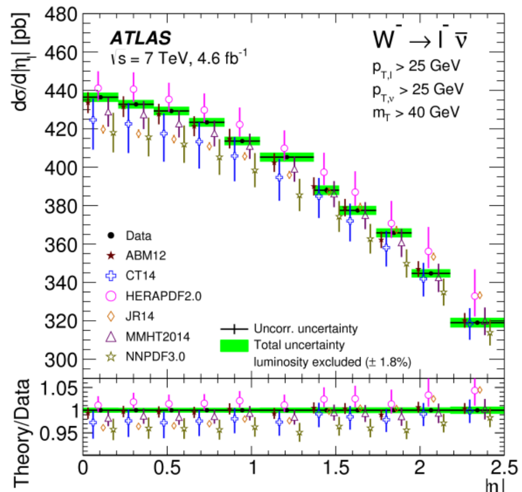
- W: Total (0.6–1.0%), multijet background (0.3–0.7%)
- Z Central: Total (0.4%), reconstruction efficiency (0.2–0.3%)
- Z Forward: Total (2.3%), identification efficiency (1.5%)
- 1.8% luminosity uncertainty



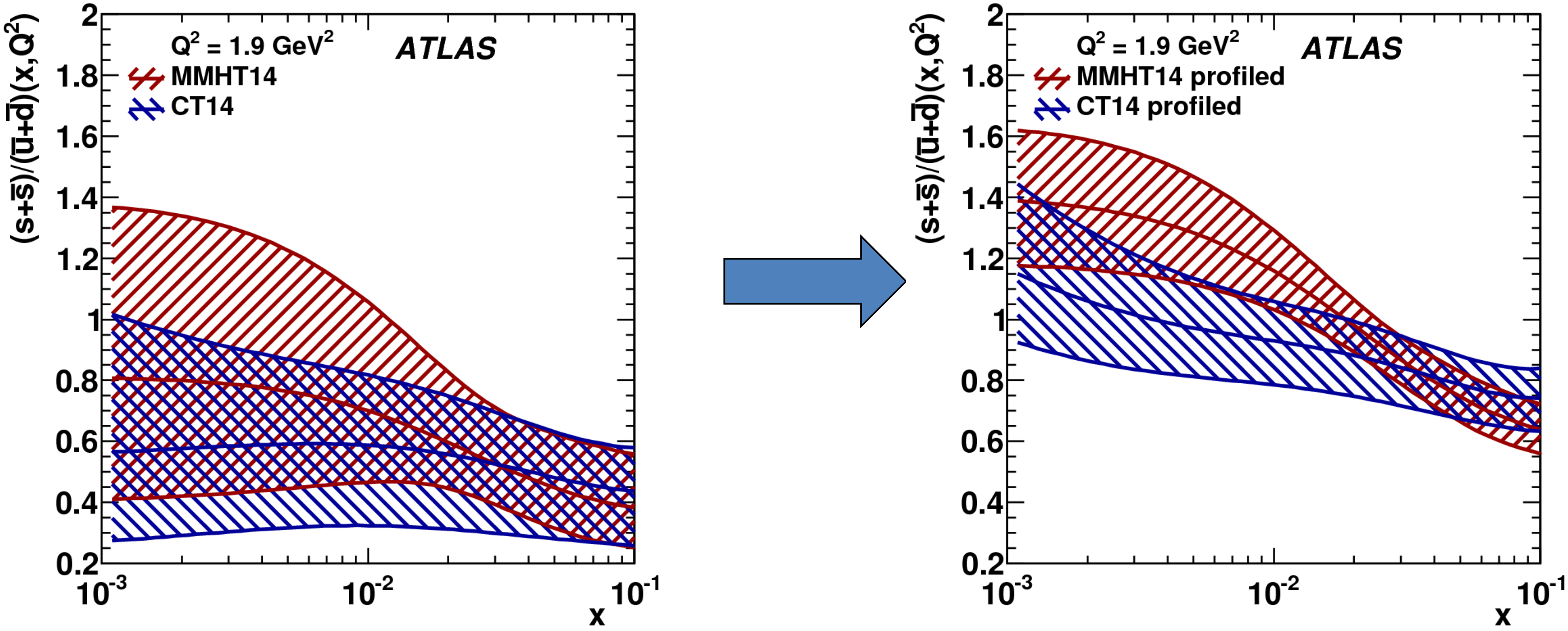


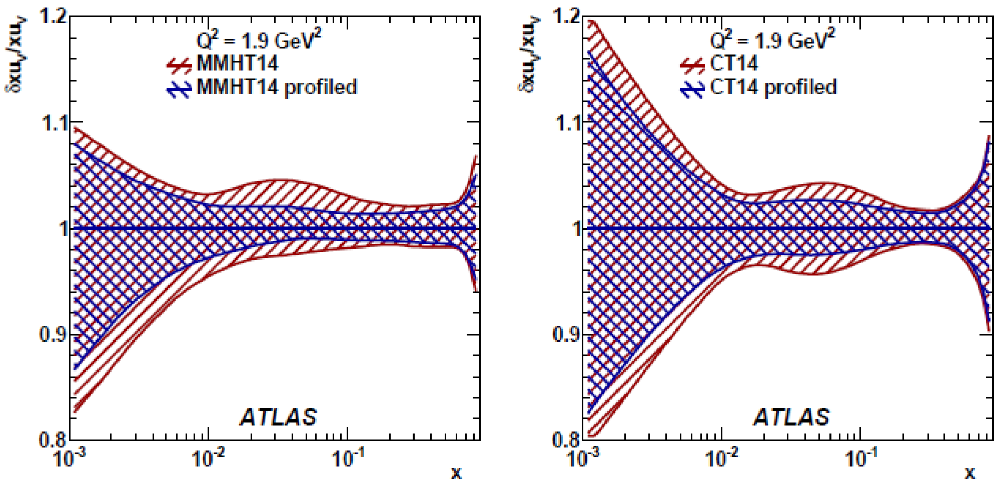






State of the art predictions at NNLO

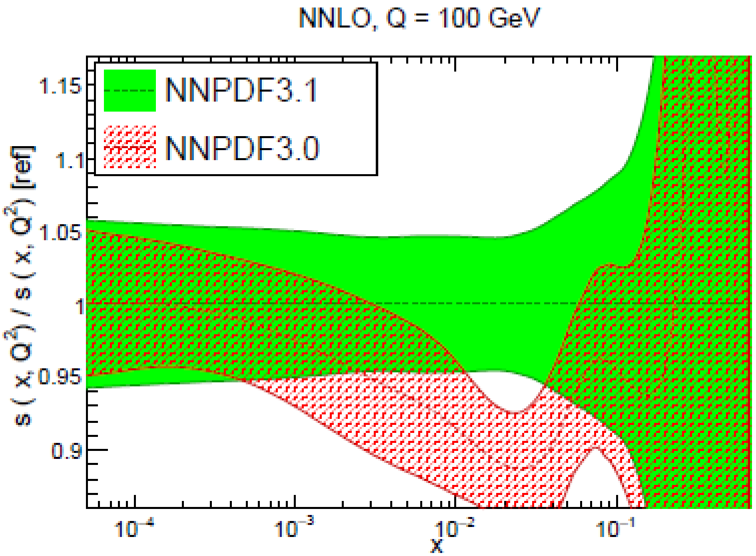


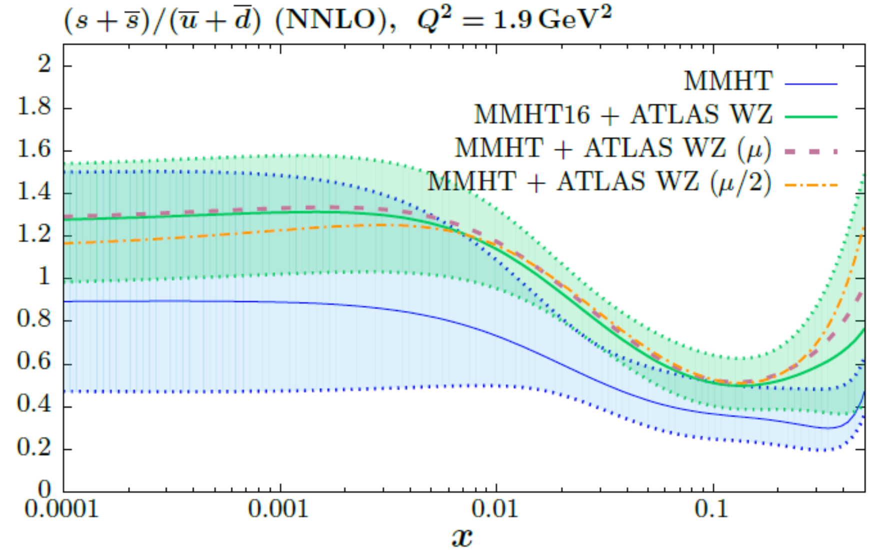


Input of the ATLAS W,Z data to PDF fits can be assessed by profiling.

This indicates reduction of the uncertainties on the strange sea- as well as pulling up its absolute value at low-x.

This also indicates a reduction in uncertainties of the valence PDFs

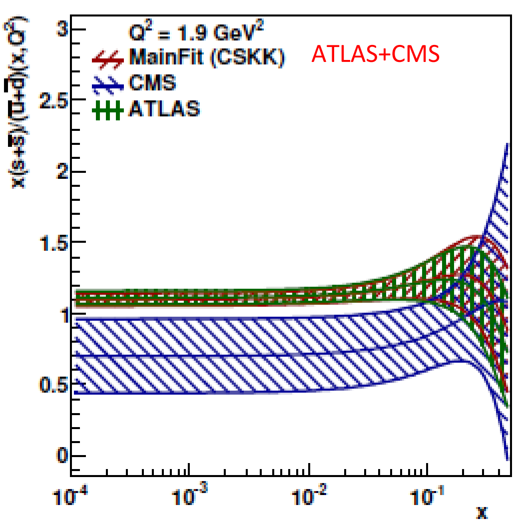




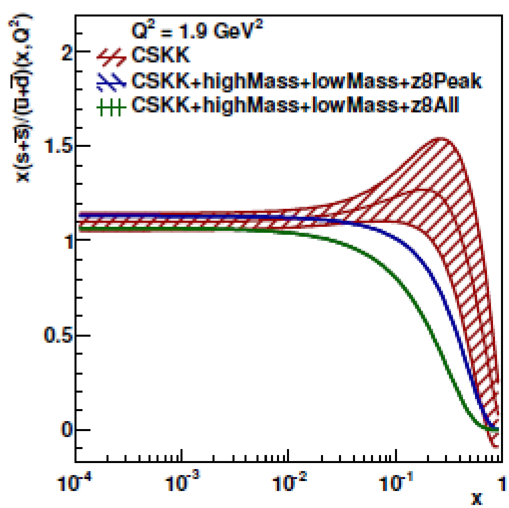
NNPDF and MMHT both see larger strangeness when using ATLAS W,Z data

ATLAS precision W,Z data are compatible with CMS 7 , 8 TeV double differential Drell-Yan Z/γ* (arXiV:1310.7291, arXiv:1412.1115) and 8 TeV W data 1603.01803

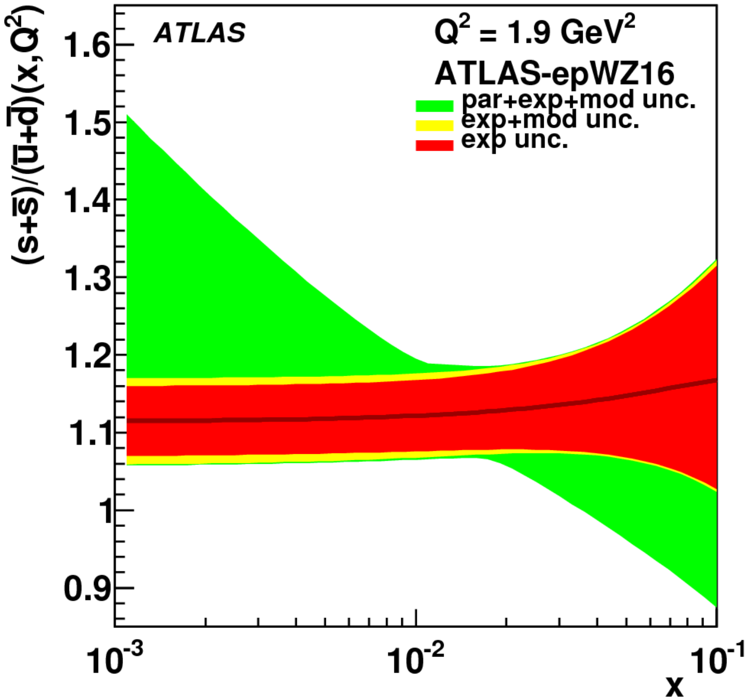
ATLAS and CMS W, Z Drell-Yan data are compatible with a higher than conventional strangeness fraction at low-x < 0.1 -see arXIV:1803.00968 joint ATLAS/CMS analysis

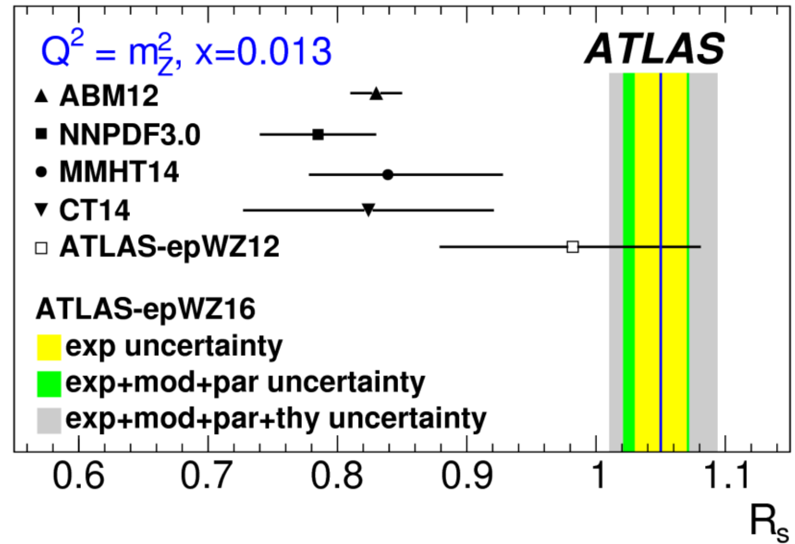


ATLAS +CMS Z peak data, using only 7 TeV CMS Z data



ATLAS +CMS Z peak + off peak data and 7 and 8 TeV CMS Z data





ATLAS new W,Z data are compatible with earlier CMS 7 and 8 TeV W data
NNPDF 3.1 collider PDFs use HERA+ CMS, ATLAS LHCb and Tevatron data to obtain
Rs=0.82±0.18 at x=0.023, Q^2=2 GeV^2 , where conventional values have been Rs~0.5

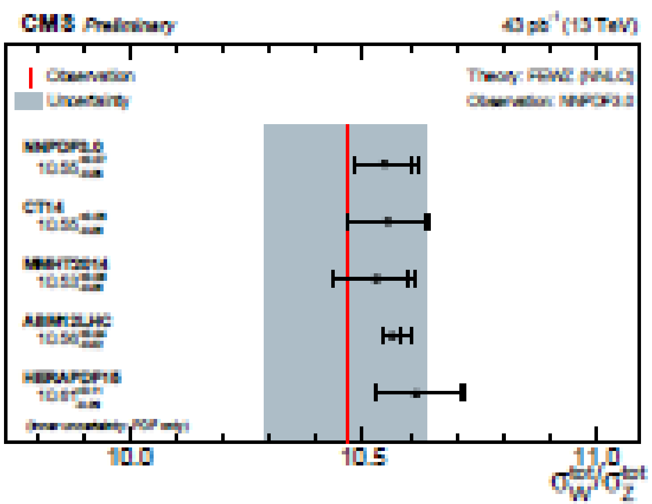
PDF set	$R_s(0.023, 2\ \mathrm{GeV}^2)$	$R_s(0.013, M_Z^2)$
NNPDF3.0	0.47 ± 0.09	0.79 ± 0.04
NNPDF3.1	0.61 ± 0.14	0.83 ± 0.06
NNPDF3.1 collider-only	0.85 ± 0.16	0.93 ± 0.06
NNPDF3.1 HERA + ATLAS W, Z	0.96 ± 0.20	0.98 ± 0.09
ATLAS W, Z 2010 HERAfitter (Ref. [100])	$1.00\,^{+0.25}_{-0.28}$ (*)	$1.00\,^{+0.09}_{-0.10}$ (*)
ATLAS W, Z 2011 xFitter (Ref. [72])	$1.13\,^{+0.11}_{-0.11}$	1.05 ± 0.04

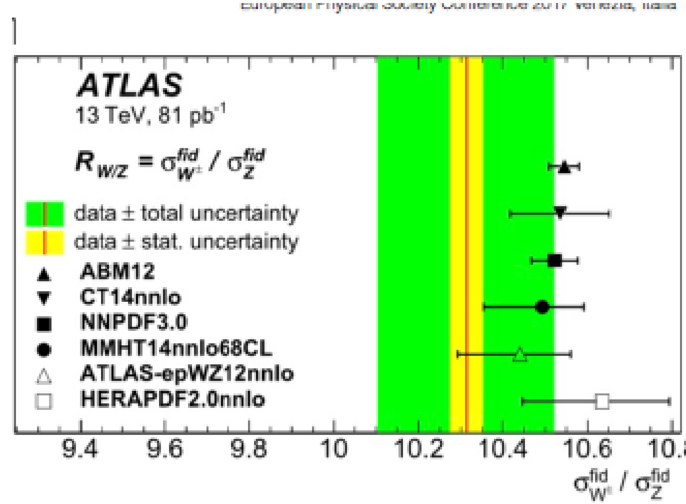
CAN one improve in future?

ATLAS peak W,Z data has already reached systematic uncertainties of ~0.5%, experimental improvement unlikely and this is already challenging NNLO calculations---see later

The reach to lower x at 13,14 TeV brings more theoretical challenges- need for ln(1/x) resummation- see arXIV:1710.05935

There is also 13 TeV data from 2015/2016
W/Z ratios are lower than most predictions – as you would expect if more strangeness is needed

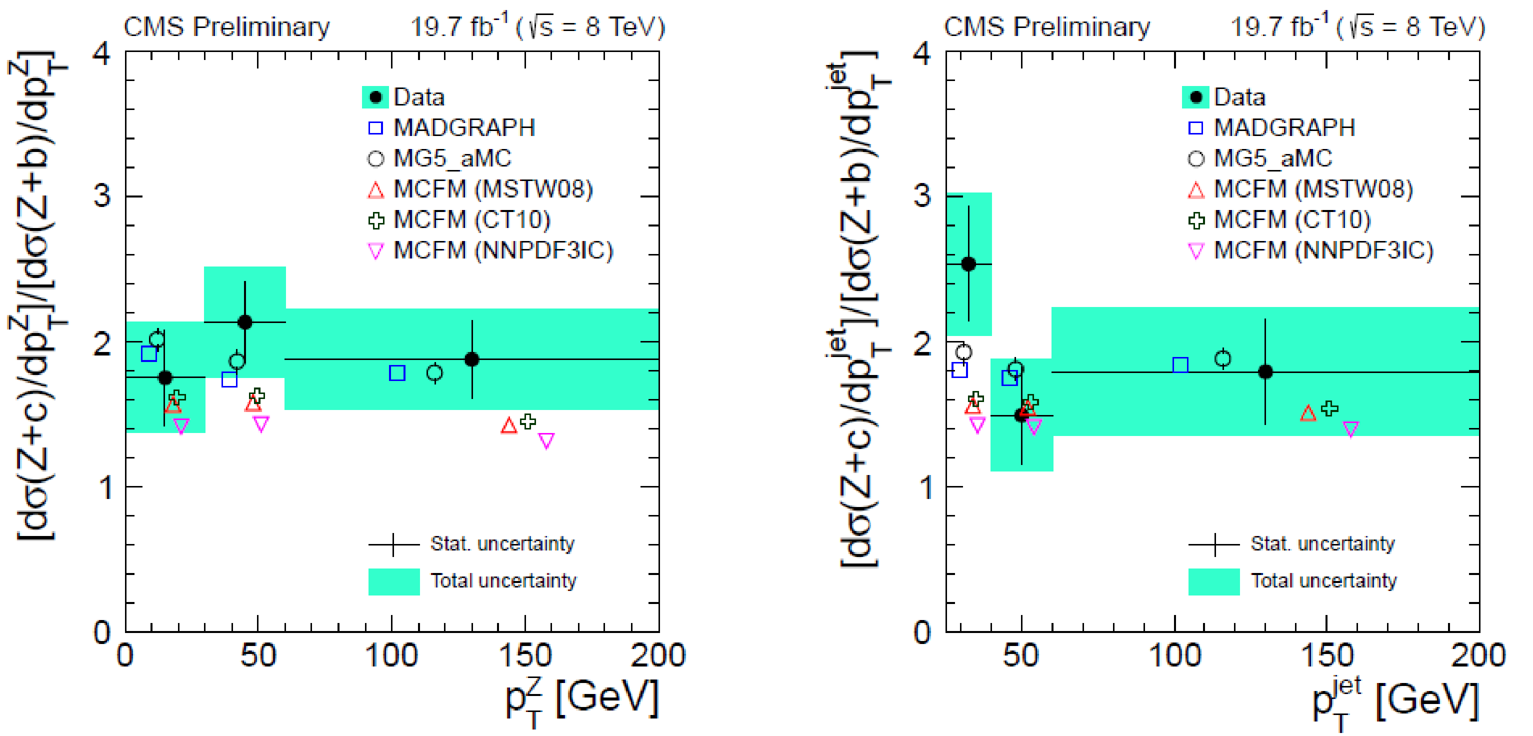




Boson (W,Z or γ) +heavy flavour distributions

Measurement of associated Z + charm production [CMS-PAS-SMP-15-009]

- Measurement at 8 TeV, $L = 19.7$ fb^{-1}
- Cross section of $Z + c$ and ratio $Z + c/Z + b$ as function of p_T
- **Important for searches beyond SM, sensitive to possible intrinsic charm**

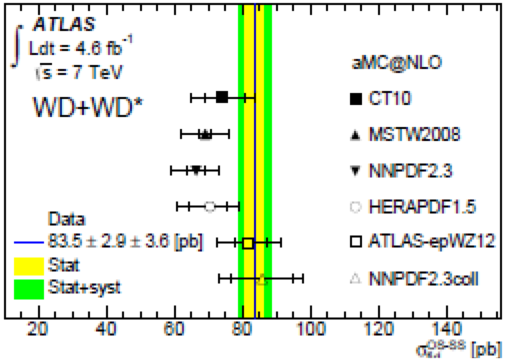


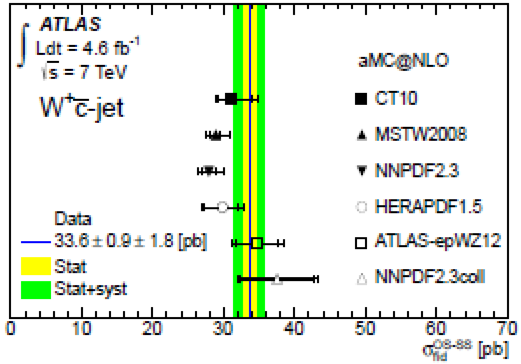
Z +c data is not yet very discriminating

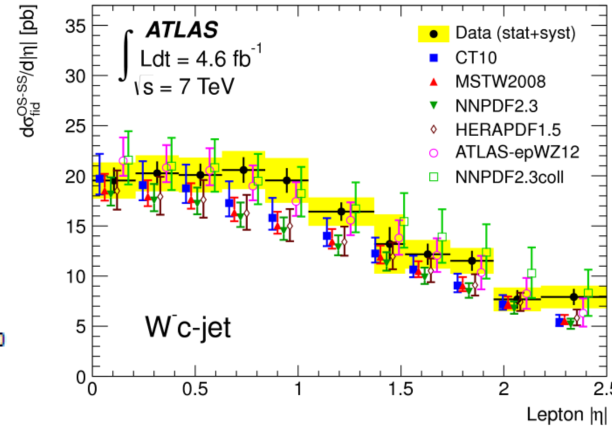
There is also VERY RECENTLY γ+c/b – ATLAS arXIV:1710.0 0560 which favours a 5-flavour scheme vas 4-flavour. However it is not discriminating against different intrinsic charm models

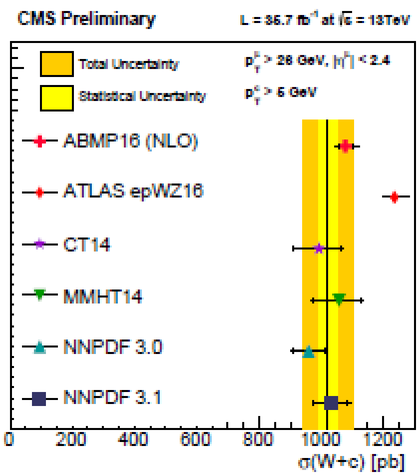
Measurements of $W+c$ from ATLAS and CMS

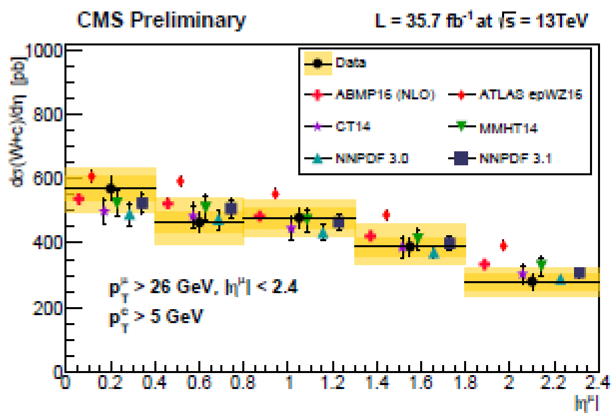
arXiv:1402.6263







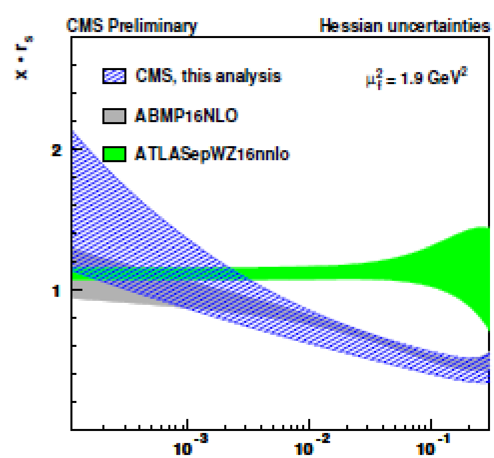


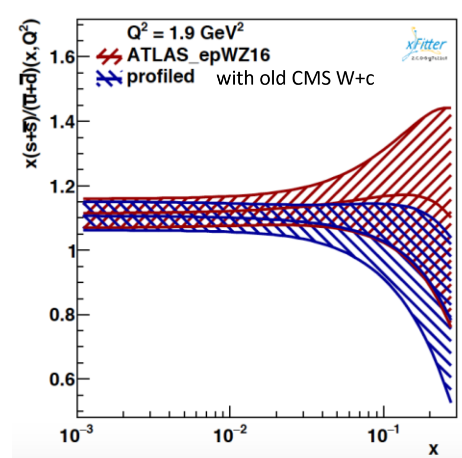


ATLAS data agrees with PDFs which have unsuppressed strangeness

CMS – now at 13 TeV--data has a smaller cross section and less strangeness CMS-PAS-SMP-17-014

BUT CMS data still implies larger strangeness than the conventional suppression at low –x, x< 0.01





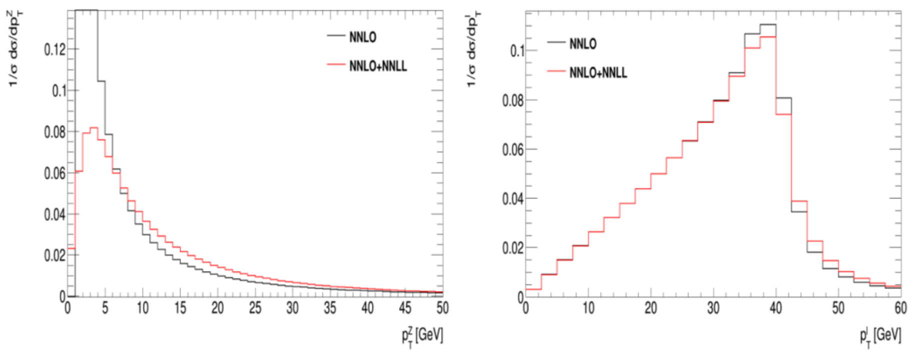
Can one improve? *YES new data is coming* BUT W/Z +c cross-section is a long way from raw data

Precision measurements like M_W, $\sin^2\theta_W$, where small discrepancies may indicate BSM physics are also limited by PDF uncertainty and this time the relevant kinematic region at which we need to know the PDFs is x ~0.01 where we already know them best.

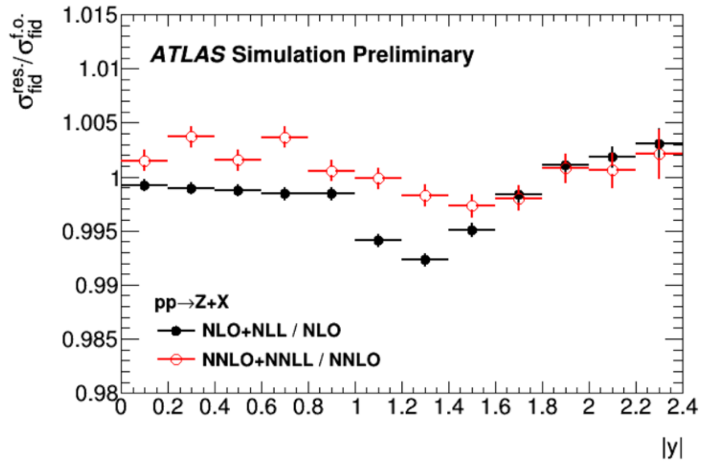
Can we do better than our current best?

When we are talking about VERY high precision data there is another aspect that comes in: ARE fixed order calculations good enough?

They have an unrealistic boson p_T distribution, and although we integrate over it, we do have to make p_T cuts on the leptons – is there an impact on acceptance?



- Compared fiducial cross sections at various orders (NLO vs. NLO+NLL; NNLO vs. NNLO+NNLL), imposing that the total cross sections be identical in fixed-order and resummed calculations.
- Ratio between resummed and foxed-order fiducial cross sections; for Z :

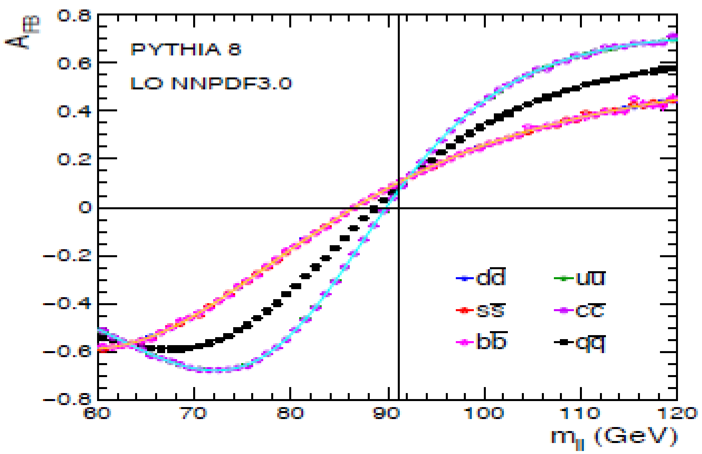


This was noticed in context of the M_W measurement but was also visible in the ATLAS high precision Z analysis— Predictions from FEWZ and DYNNLO differ at this level according to how pt cuts are handled

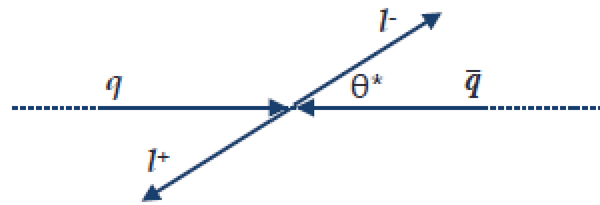
  - Effects are O(1—1.5%) at NLO, and still O(0.5%) at NNLO

Now look specifically at PDF uncertainties in $\sin^2\theta_W$

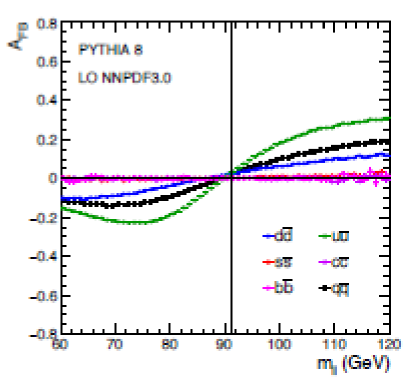
The weak mixing angle can be measured from the forward backward asymmetry in Drell-Yan production BUT we don't know the direction of the incoming quark. In pp it is most likely to be along the direction of the Z boson because valence quarks are harder than sea quarks. This difference will be larger at larger rapidity as we access high-x

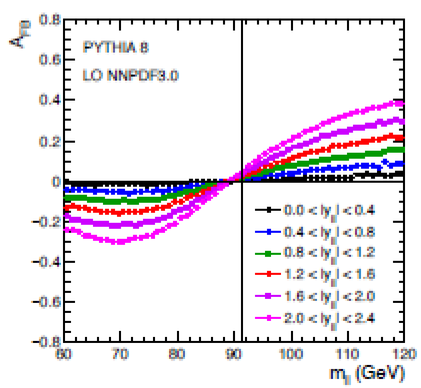


- A_{FB} in $\cos\theta^*$ near Z peak sensitive to leptonic $\sin^2\theta_{eff}$
- Mass dependence from Z/γ^* interference



$$\cos\theta^* = \frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{\sqrt{M^2(M^2 + p_T^2)}} \times \frac{P_z}{|P_z|}$$





- Obs. A_{FB} in pp based on boost
- A_{FB} dependence on PDFs:
  1. fraction of valence u and d in total production
  2. size of (y-dependent) dilution effect (qbar/q)

CMS :Arxiv:1806.00863

If we know $\mathbf{sin^2\theta_W}$ then we can get information on PDFs (1805.09239) and conversely PDF uncertainties will affect measurement of $\mathbf{sin^2\theta_W}$

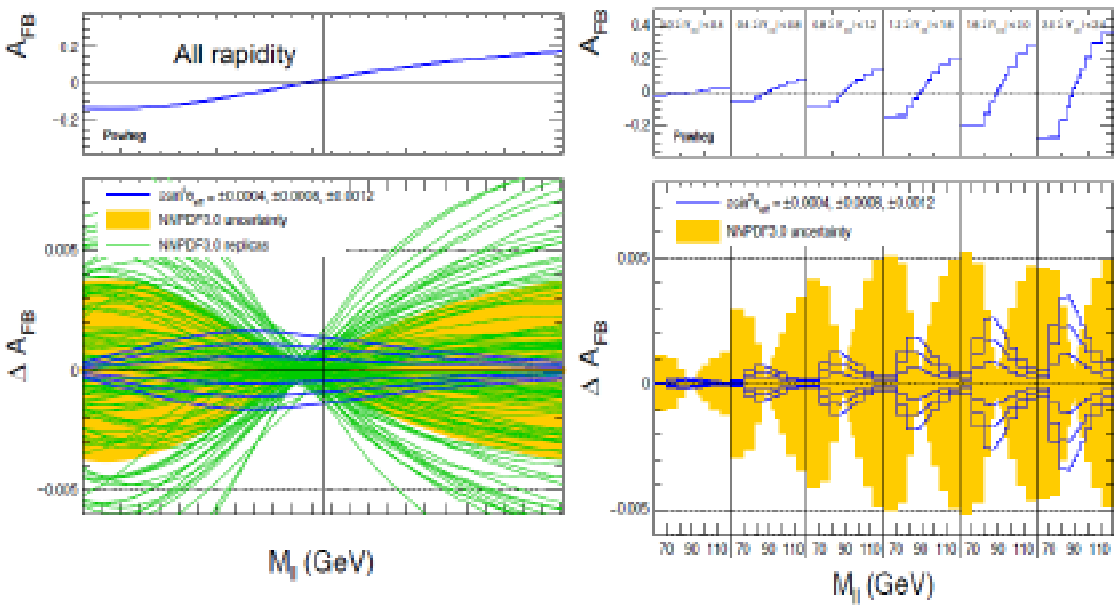
Can we do both?

CMS :Arxiv:1806.00863

Effect of $\mathbf{sin^2\theta_W}$ **and PDFs is different so maybe YES**

BLUE :Vary $\sin^2\theta_{eff}$ for fixed PDF

ORANGE: Vary 100 NNPDF3.0 replicas for fixed $\sin^2\theta_{eff}$ i



To get a better $\mathbf{sin^2\theta_W}$ measurement one needs better (less uncertain) PDF hence weight the NNPDF3.0 PDFs which are used by the data to improve the PDFs.

Giele/Keller weights are used and this can be disputed but the general idea is sound

Reduction in uncertainty in $\mathbf{sin^2\theta_W}$ from 0.00054 to 0.00031

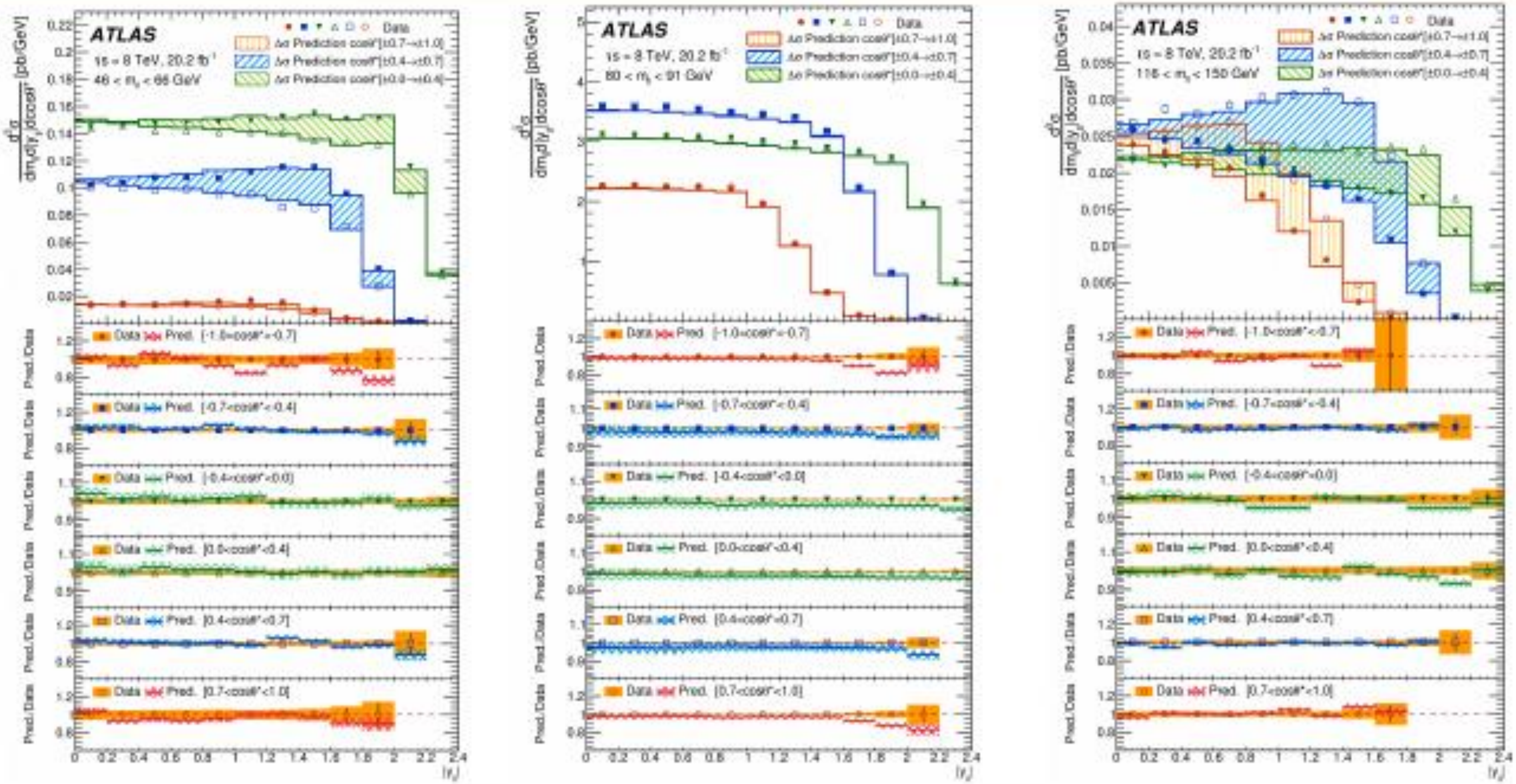
Result:

$$\sin^2\theta^{\ell}_{\rm eff} = 0.23101 \pm 0.00036\,({\rm stat}) \pm 0.00018\,({\rm syst}) \pm 0.00016\,({\rm theo}) \pm 0.00031\,({\rm PDF}),$$

NOTE PDF uncertainty is still very substantial

ATLAS Arxiv: 1710.05167

- Triple differential measurement in $m_{\ell\ell}$, $y_{\ell\ell}$, $\cos\theta^*$



Aim to fit PDFs and $\mathbf{sin^2\theta_W}$ simultaneously and hence reduced PDF uncertainty from use of fixed PDFs

The result from this is not yet public (may become so today)but measurements of Drell –Yan at both 7 and 8 TeV reach 0.5% accuracy– it will be HARD to improve on this.

Summary: where can we improve in future?

- **W,Z and Drell-Yan distributions** – sensitivity to valence quarks, strangeness, photon PDF AND to M_W and $\sin^2\theta_W$

ATLAS peak W,Z data has already reached systematic uncertainties of ~0.5%, experimental improvement unlikely and this is already challenging fixed order NNLO calculations

The reach to lower x at 13,14 TeV brings more theoretical challenges- need for ln(1/x) resummation- see arXIV:1710.05935

Off-peak Drell-Yan can still improve BUT low-mass brings the same low-x challenges.

This also affects the LHCb data

And high-mass requires good understanding of the NLO-EW corrections and photon PDF

- **Inclusive, di-jet and tri-jet distributions-**-----sensitivity to gluon

Already challenging theoretical understanding -NNLO is needed, careful consideration of experimental systematics is needed

- **Top-antitop distributions** –sensitivity to gluon

NNLO calculations already required, data can also improve (data consistency?)

Combinations of types of data and different beam energies –accounting for their correlations- can help

For all of these below: precision of the data can improve

- **W,Z +jets** --------sensitivity to gluon- so far limited, can improve
- **W,Z/γ +heavy flavour** -sensitivity to strangeness and intrinsic charm- can improve
- **Direct photon-**------sensitivity to gluon— can improve

Back up

Exp.	Obs.	Ref.	$N_{\rm dat}$	Kin$_1$	Kin$_2$ (GeV)	Theory
ATLAS	W, Z 2010	[49]	30 (30/30)	$0 \le \|\eta_l\| \le 3.2$	$Q = M_W, M_Z$	MCFM+FEWZ
	W, Z 2011 (*)	[72]	34 (34/34)	$0 \le \|\eta_l\| \le 2.3$	$Q = M_W, M_Z$	MCFM+FEWZ
	high-mass DY 2011	[50]	11 (5/5)	$0 \le \|\eta_l\| \le 2.1$	$116 \le M_{ll} \le 1500$	MCFM+FEWZ
	low-mass DY 2011 (*)	[77]	6 (4/6)	$0 \le \|\eta_l\| \le 2.1$	$14 \le M_{ll} \le 56$	MCFM+FEWZ
	[Z p_T 7 TeV (p_T^Z, y_Z)] (*)	[78]	64 (39/39)	$0 \le \|y_Z\| \le 2.5$	$30 \le p_T^Z \le 300$	MCFM+NNLO
	Z p_T 8 TeV (p_T^Z, M_{ll}) (*)	[71]	64 (44/44)	$12 \le M_{ll} \le 150$ GeV	$30 \le p_T^Z \le 900$	MCFM+NNLO
	Z p_T 8 TeV (p_T^Z, y_Z) (*)	[71]	120 (48/48)	$0.0 \le \|y_Z\| \le 2.4$	$30 \le p_T^Z \le 150$	MCFM+NNLO
	7 TeV jets 2010	[57]	90 (90/90)	$0 \le \|y^{\rm jet}\| \le 4.4$	$25 \le p_T^{\rm jet} \le 1350$	NLOjet++
	2.76 TeV jets	[58]	59 (59/59)	$0 \le \|y^{\rm jet}\| \le 4.4$	$20 \le p_T^{\rm jet} \le 200$	NLOjet++
	7 TeV jets 2011 (*)	[76]	140 (31/31)	$0 \le \|y^{\rm jet}\| \le 0.5$	$108 \le p_T^{\rm jet} \le 1760$	NLOjet++
	$\sigma_{\rm tot}(t\bar{t})$	[74,75]	3 (3/3)	-	$Q = m_t$	top++
	$(1/\sigma_{t\bar{t}})d\sigma(t\bar{t})/y_t$ (*)	[73]	10 (10/10)	$0 < \|y_t\| < 2.5$	$Q = m_t$	Sherpa+NNLO
CMS	W electron asy	[52]	11 (11/11)	$0 \le \|\eta_e\| \le 2.4$	$Q = M_W$	MCFM+FEWZ
	W muon asy	[53]	11 (11/11)	$0 \le \|\eta_\mu\| \le 2.4$	$Q = M_W$	MCFM+FEWZ
	$W + c$ total	[60]	5 (5/0)	$0 \le \|\eta_l\| \le 2.1$	$Q = M_W$	MCFM
	$W + c$ ratio	[60]	5 (5/0)	$0 \le \|\eta_l\| \le 2.1$	$Q = M_W$	MCFM
	2D DY 2011 7 TeV	[54]	124 (88/110)	$0 \le \|\eta_{ll}\| \le 2.2$	$20 \le M_{ll} \le 200$	MCFM+FEWZ
	[2D DY 2012 8 TeV]	[84]	124 (108/108)	$0 \le \|\eta_{ll}\| \le 2.4$	$20 \le M_{ll} \le 1200$	MCFM+FEWZ
	$W^\pm$ rap 8 TeV (*)	[79]	22 (22/22)	$0 \le \|\eta_l\| \le 2.3$	$Q = M_W$	MCFM+FEWZ
	Z p_T 8 TeV (*)	[83]	50 (28/28)	$0.0 \le \|y_Z\| \le 1.6$	$30 \le p_T^Z \le 170$	MCFM+NNLO
	7 TeV jets 2011	[59]	133 (133/133)	$0 \le \|y^{\rm jet}\| \le 2.5$	$114 \le p_T^{\rm jet} \le 2116$	NLOjet++
	2.76 TeV jets (*)	[80]	81 (81/81)	$0 \le \|y_{\rm jet}\| \le 2.8$	$80 \le p_T^{\rm jet} \le 570$	NLOjet++
	$\sigma_{\rm tot}(t\bar{t})$	[82,88]	3 (3/3)	-	$Q = m_t$	top++
	$(1/\sigma_{t\bar{t}})d\sigma(t\bar{t})/y_{t\bar{t}}$ (*)	[81]	10 (10/10)	$-2.1 < y_{t\bar{t}} < 2.1$	$Q = m_t$	Sherpa+NNLO
LHCb	Z rapidity 940 pb	[55]	9 (9/9)	$2.0 \le \eta_l \le 4.5$	$Q = M_Z$	MCFM+FEWZ
	$Z \to ee$ rapidity 2 fb	[56]	17 (17/17)	$2.0 \le \eta_l \le 4.5$	$Q = M_Z$	MCFM+FEWZ
	$W, Z \to \mu$ 7 TeV (*)	[85]	33 (33/29)	$2.0 \le \eta_l \le 4.5$	$Q = M_W, M_Z$	MCFM+FEWZ
	$W, Z \to \mu$ 8 TeV (*)	[86]	34 (34/30)	$2.0 \le \eta_l \le 4.5$	$Q = M_W, M_Z$	MCFM+FEWZ

These spectra cannot be fitted at the same time because a statistical covariance matrix does not exist– although the systematic shift information IS provided

NNPDF have made fits and concluded that not only do CMs and ATLAS not agree so well but that also WITHIN an experiment the different spectra do not agree so well.

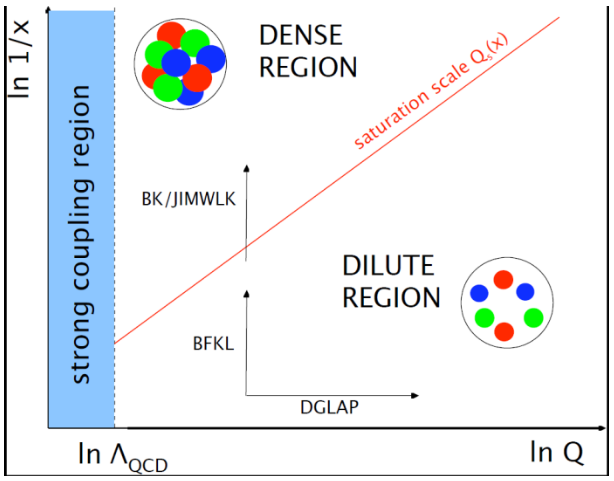
The chose to fit y_t from ATLAS and y_tt from CMS
When they do this they do NOT describe the other spectra very well

	ATLAS $d\sigma/dp_T^t$	ATLAS $d\sigma/dy_t$	ATLAS $d\sigma/dy_{t\bar{t}}$	ATLAS $d\sigma/dm_{t\bar{t}}$	ATLAS $(1/\sigma)d\sigma/dp_T^t$	ATLAS $(1/\sigma)d\sigma/dy_t$	ATLAS $(1/\sigma)d\sigma/dy_{t\bar{t}}$	ATLAS $(1/\sigma)d\sigma/dm_{t\bar{t}}$	ATLAS $\sigma_{t\bar{t}}$	CMS $d\sigma/dp_T^t$	CMS $d\sigma/dy_t$	CMS $d\sigma/dy_{t\bar{t}}$	CMS $d\sigma/dm_{t\bar{t}}$	CMS $(1/\sigma)d\sigma/dp_T^t$	CMS $(1/\sigma)d\sigma/dy_t$	CMS $(1/\sigma)d\sigma/dy_{t\bar{t}}$	CMS $(1/\sigma)d\sigma/dm_{t\bar{t}}$	CMS $\sigma_{t\bar{t}}$
Fit opt	2.19	0.64	1.84	5.01	2.49	**1.16**	3.81	4.55	**0.78**	2.91	4.98	1.07	4.77	3.33	5.78	**1.05**	8.05	**0.50**

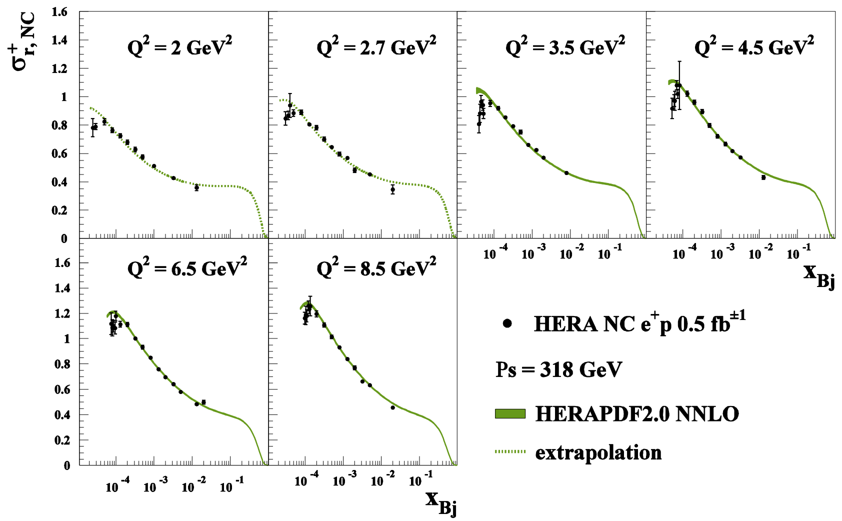
Why are we interested in low-x?

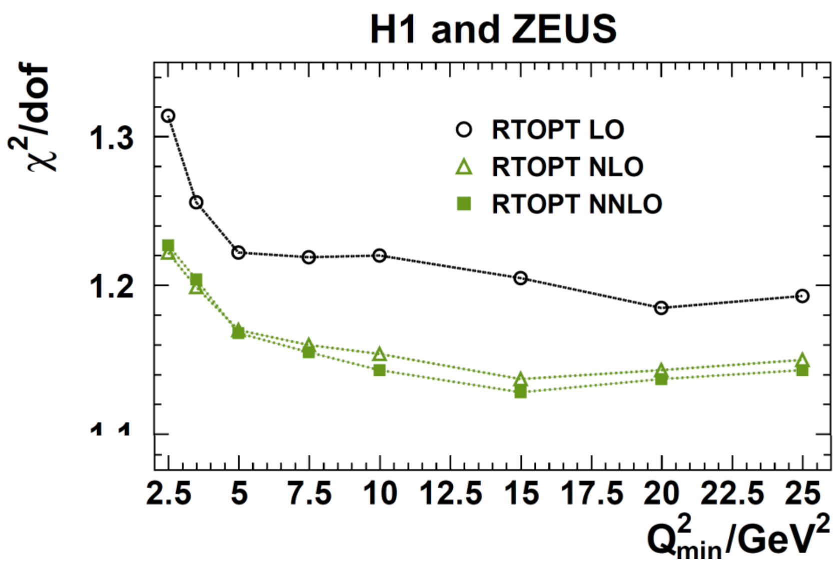
Because the HERA data indicated that there may be something new going on at low x

- New in the sense of a new regime of QCD
- Something that DGLAP evolution at NLO or NNLO cannot describe
- Needing ln(1/x) rather than lnQ^2 resummation (BFKL)
- Or even non-linear evolution (BK, JIMWLK, CGC) and gluon saturation



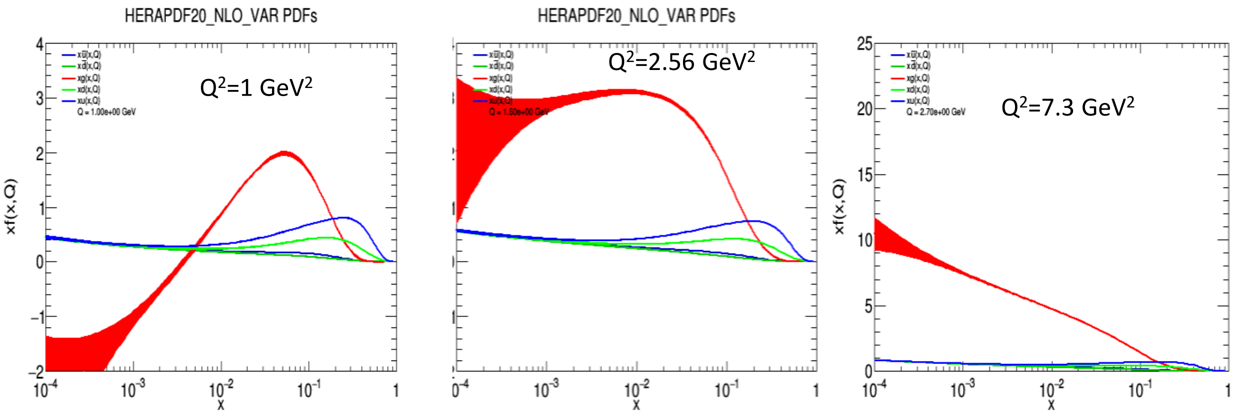
DGLAP describes DIS data down to surprisingly low Q^2





But not quite perfectly, the turn over in $\sigma_{red} = F_2 - y^2/Y_+ F_L$ is not so well described

The χ2 of fits decreases as the Q^2 cut increases



The shape of the gluon compared to the shape of the sea quarks flattens out and then turns over as one goes lower in NLO and NNLO PDF fits

IN DGLAP based fits to inclusive data at low-x, we have

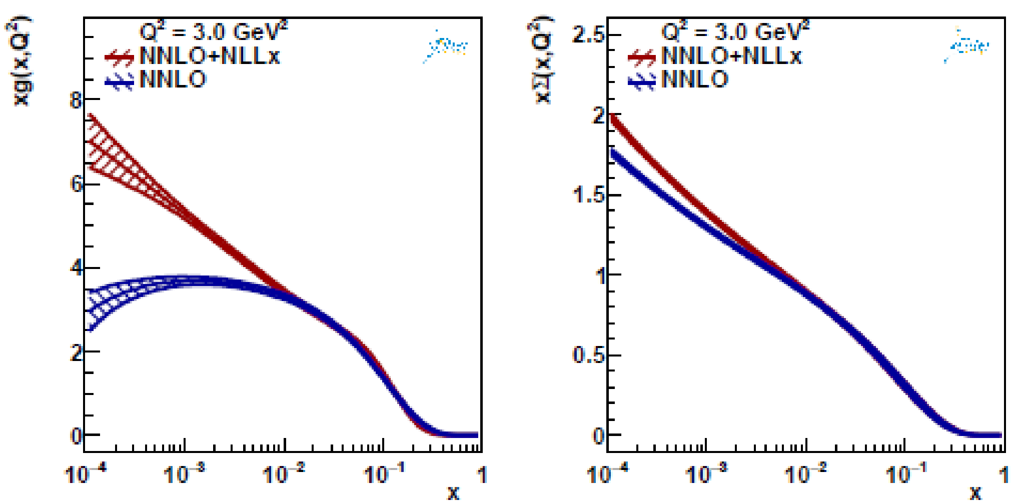
$F_2 \sim xq$ for the sea

$dF_2/d\ln Q^2 \sim Pqg\ xg$ for the gluon

Our deductions about gluon behaviour at low-x come via the DGLAP splitting function Pqg

If DGLAP is inadequate then so will our deductions about the shape of the gluon be inadequate.

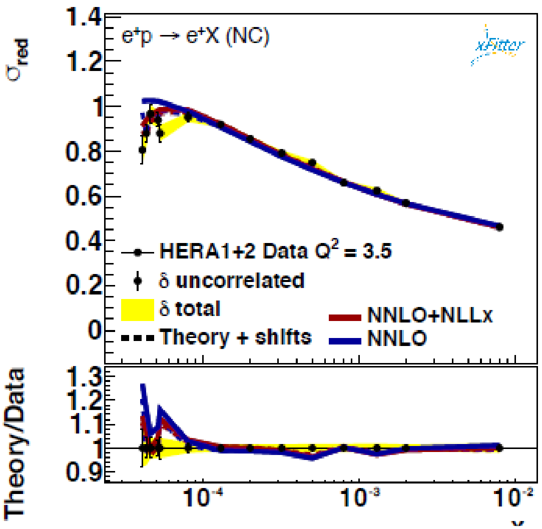
Recently ln(1/x) BFKL resummation has been worked out using the HELL code arXIV:1710.05935

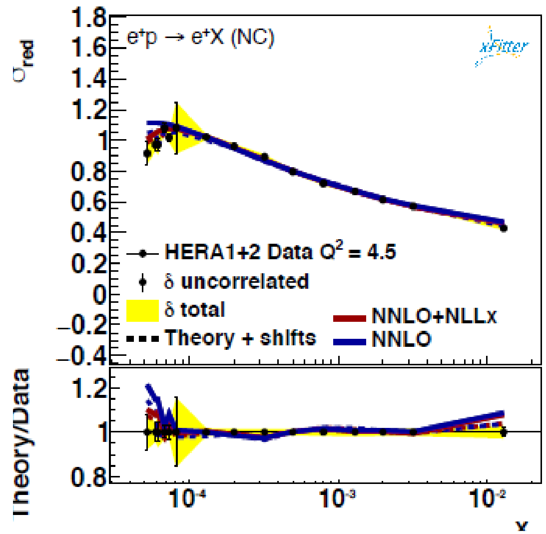


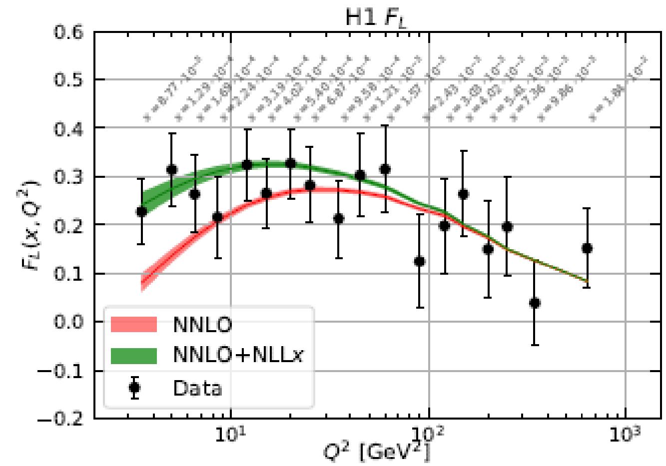
The shape of the gluon becomes singular at low-x and larger than the total sea when next-to-leading log low-x NLLX resummation is applied

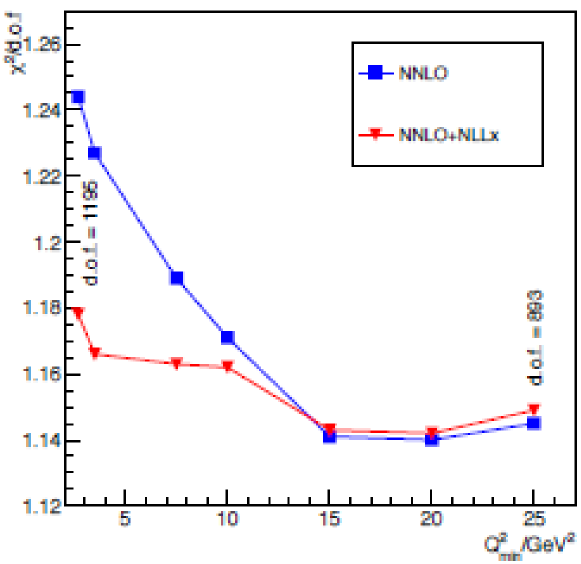
The χ2 is greatly improved
The improvement comes at low-x and low Q2 and the turn over of the data is well described because the gluon is larger and so FL is larger

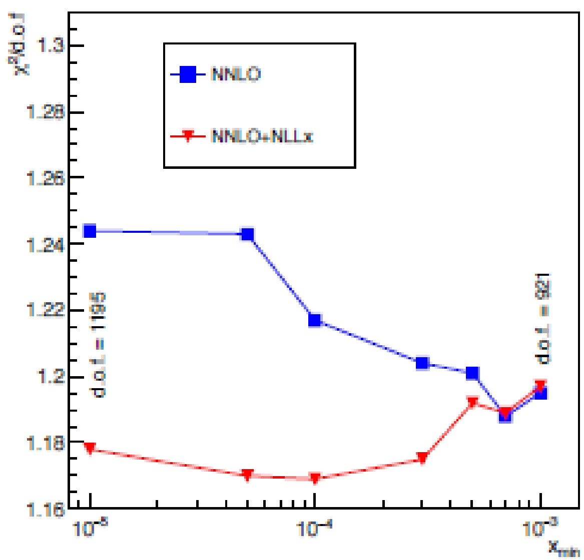
	NNLO fit with new settings	NNLO+NLLx fit with new settings
Total χ^2/d.o.f	1446/1178	1373/1178
subset NC 920 χ^2/n.d.p	446/377	413/377











Can one improve in future ?

Since jet data do not suffer from lack of statistics this points up the fact that it is data systematic uncertainties which really matter. More data always helps us to improve our understanding of systematics but it is not easy to quantify this.

The study below shows that jet data inconsistencies are not really so severe.

NNLO calculations have already improved the description of data, experimentalists would like clarity on scale choice

Adding jet data to HERAPDF2.0 shows reasonable consistency between the jets (apart from CMS 7 TeV) ATLAS jets in this figure is 7 TeV inclusive