The strange quark content of the proton From studying inclusive W,Z data from ATLAS and CMS

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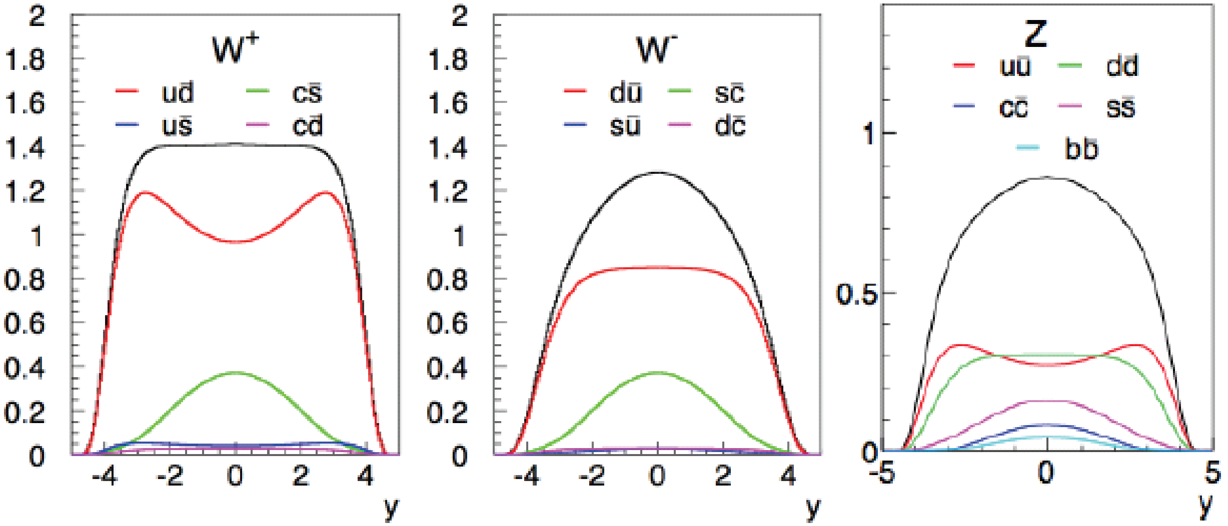
- arXiV: 1803.00968

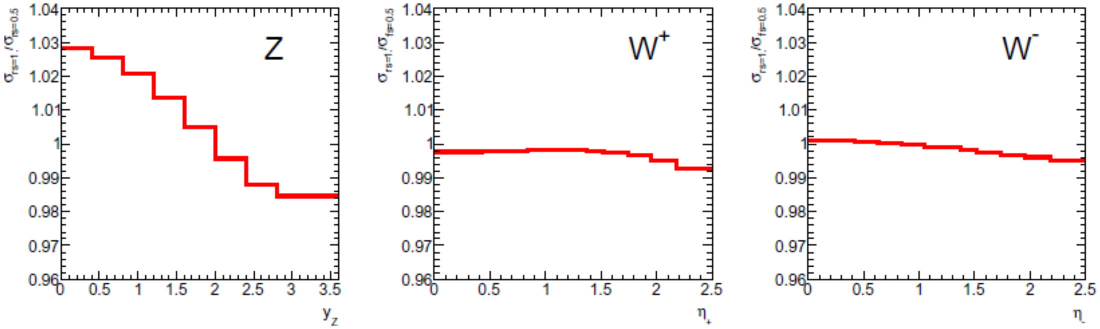
Flavour contributions to W and Z show that s-sbar is prominent in Z production at central rapidity.

These plots were made for the usual assumption that strange sea is suppressed ~0.5 of down-type sea



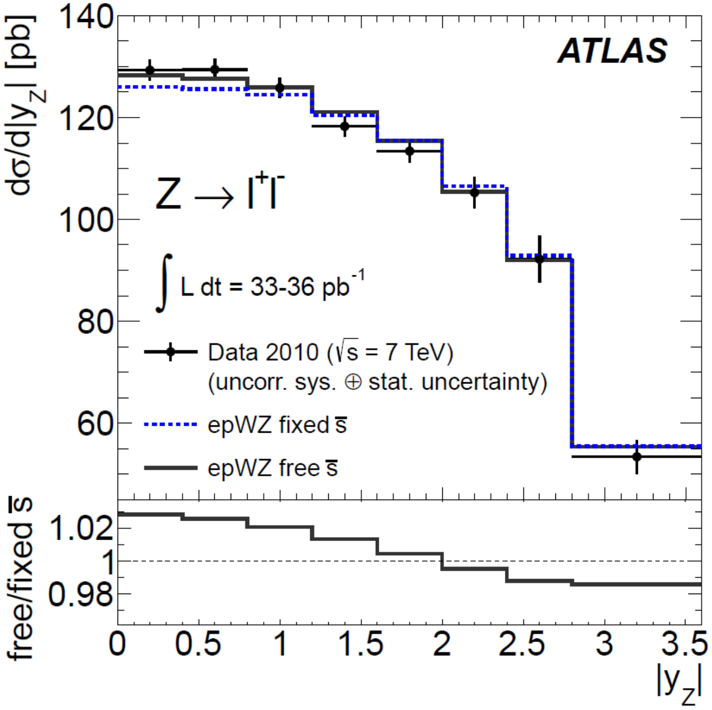
How would Z and W rapidity spectra at the LHC change if strangeness were enhanced?

Consider the ratio of Z and W cross-sections for (strange = down sea) in ratio to (strange = 0.5 down sea)



The shape of the Z rapidity distribution is affected – the W distributions are not- thus they give an absolute normalisation for the change in Z

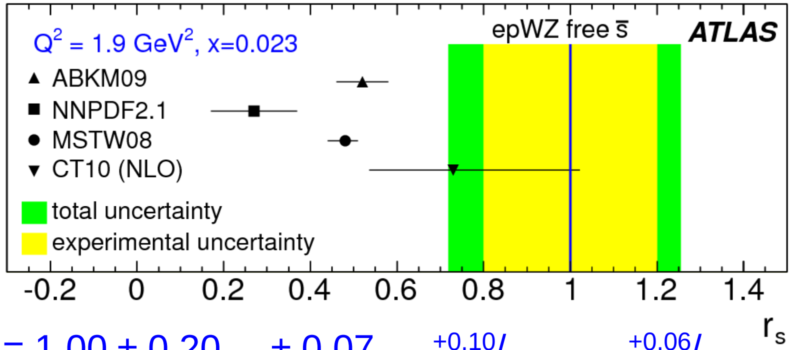
This is a small effect ~ 4%- can we see it?- it seems that we can



We expect to see a modified shape of the Z rapidity spectrum according to the amount of strangeness.

Let us remind ourselves what we saw before in the 2010 data PRL109(2012)012001

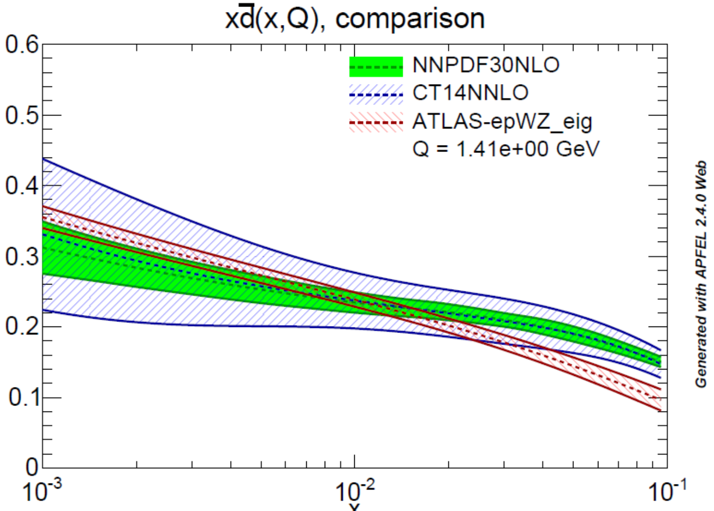
Fixed sbar =0.5dbar, free sbar = dbar

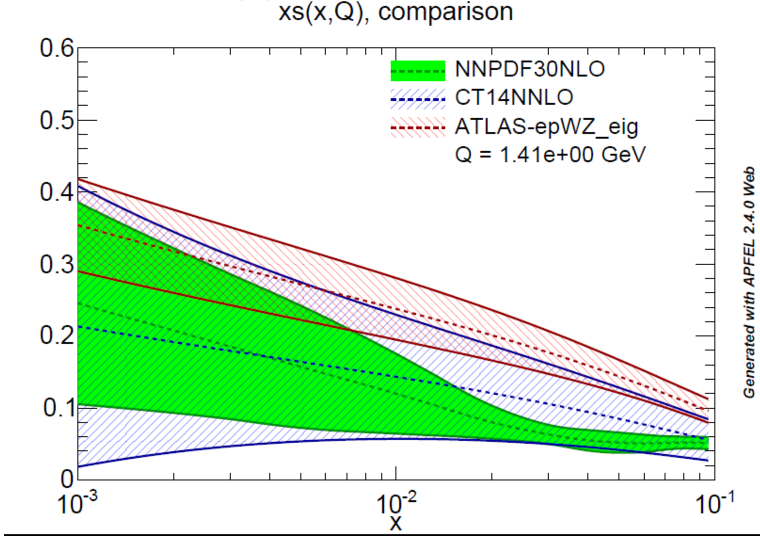


$r_s = s/d = 1.00 \pm 0.20_{exp} \pm 0.07_{mod}\ ^{+0.10}/_{-0.15\ par}\ ^{+0.06}/_{-0.07\ \alpha s} \pm 0.08_{th}$

Essentially the SHAPE of the Z rapidity distribution plus the W/Z normalisation constrain the strange quark for $10^{-3} < x < 10^{-1}$

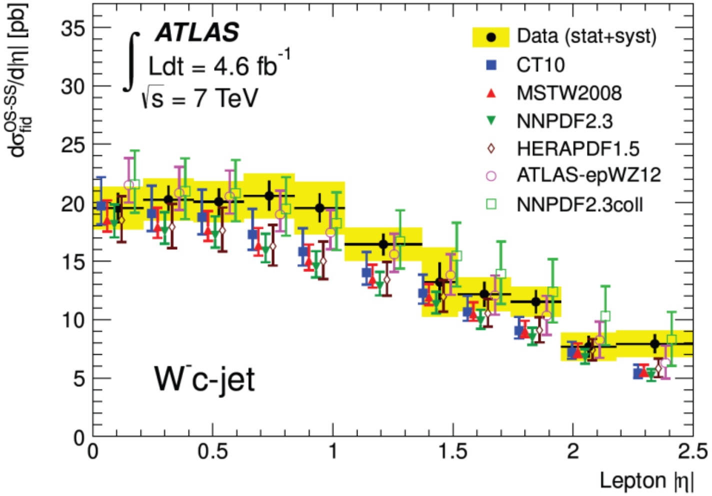
A fit together with HERA data produced the ATLASepWZ12 PDF set

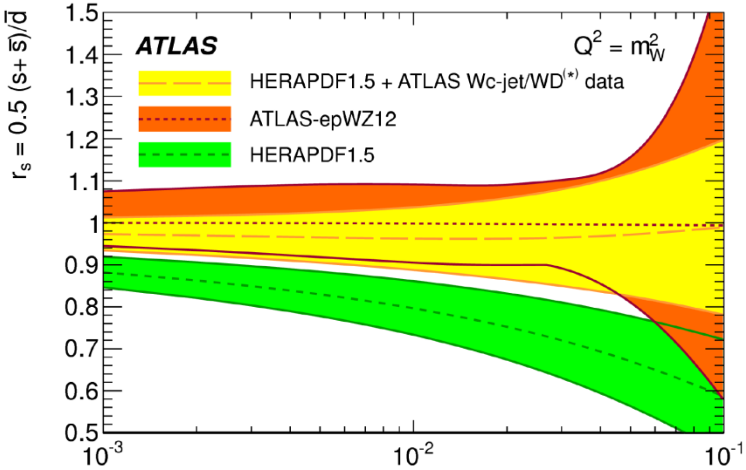




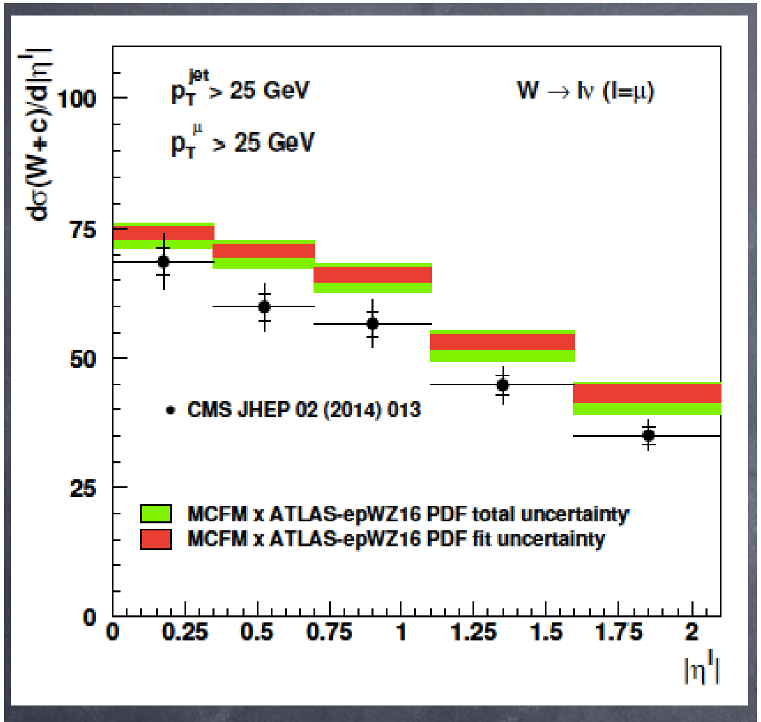
Another process which can yield information on strangeness is W+charm

ATLAS data on W+D/D* and W+c-jet (JHEP05(2014)068**) agree with the ATLAS W,Z 2010 analysis**

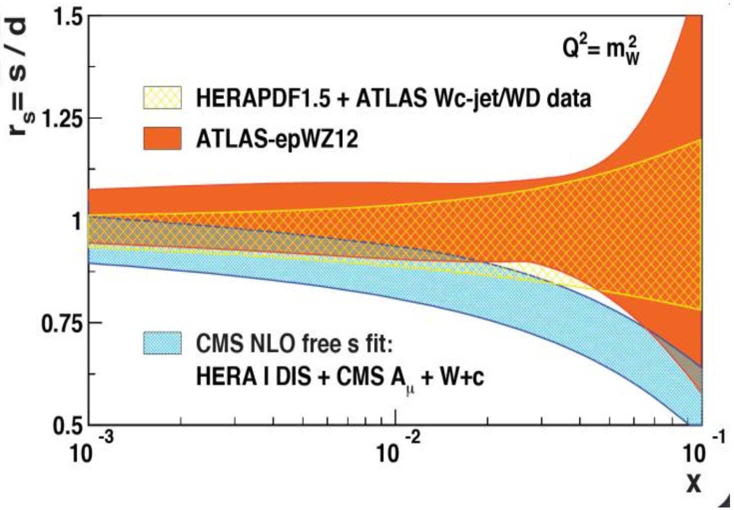




$$\rightarrow r_s \equiv 0.5(s+\bar{s})/\bar{d} = 0.96\,{}^{+0.16}_{-0.18}\,{}^{+0.21}_{-0.24}$$

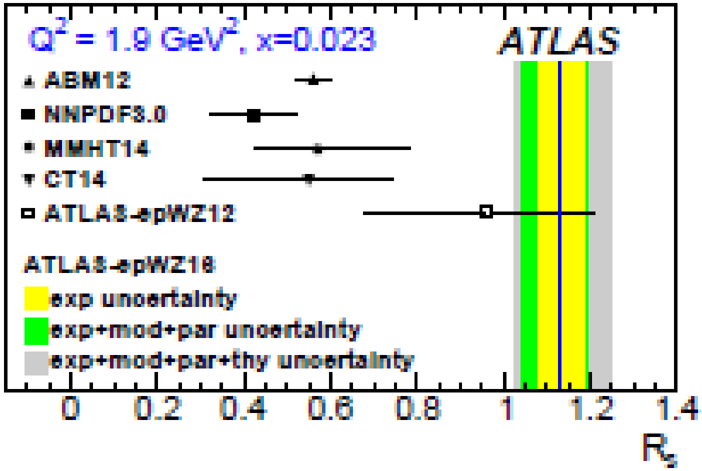


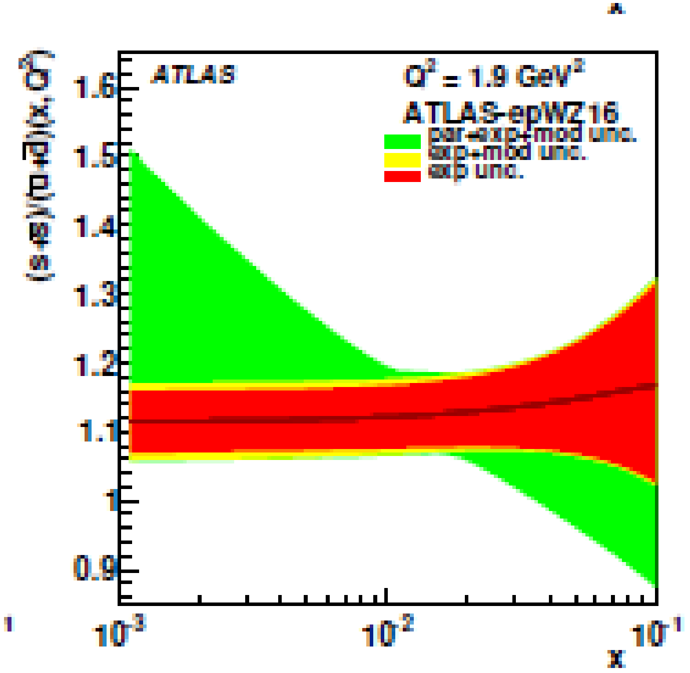
Is there a disagreement with CMS W+c?



So what do we see now with the W,Z 2011 precision data? arXIV:1612.03016

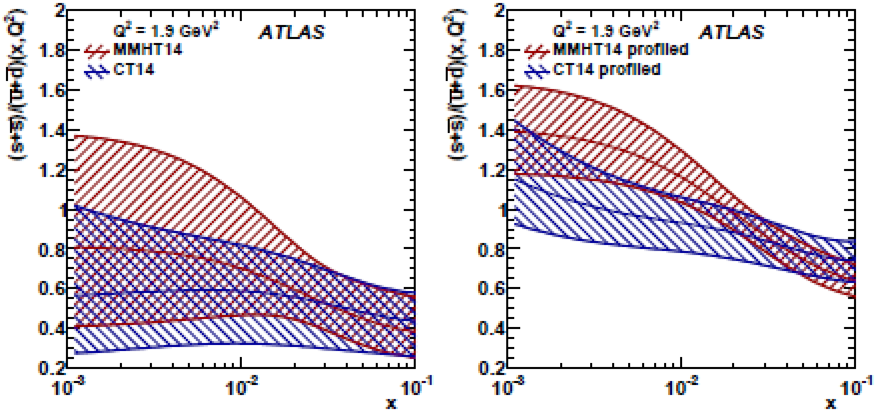
We see that strangeness is unsuppressed just as it was for the 2010 data AND the experimental uncertainty is considerably reduced





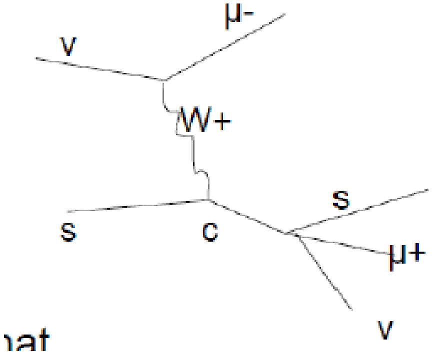
We consider strangeness in ratio to the light quark PDFs as a function of x Not just at a single x,Q2 point

Profiling other PDFsets tells the same story- more strangeness at low-x



Where does the original evidence for strangeness suppression come from?
From neutrino dimuon data: at low scale ~a few GeV^2 and highish x~ 0.1

But these neutrino data are shot on heavy targets. This not only involves uncertain nuclear corrections for the struck parton, but also the possibility of absorption of the outgoing charmed particle in the nuclear medium



W+charm production at the LHC does not suffer from nuclear effects but there is still a need for assumptions on charm jet framgmentation and hadronisation.
It is quite a long way from the raw data to the W+c cross section

So we ask the question what do inclusive W and Z data from both CMS and ATLAS tell us?
The Drell-Yan process is the theoretically best understood process in p-p collisions.
We know that we can take the PDFs from Deep Inelastic Scattering and use them in this process, the factorisation theorem is proven.

The questions we are now addressing are:

1. Is there tension between CMS and ATLAS inclusive data sets
2. What is the strangeness ratio using BOTH CMS and ATLAS inclusive W,Z data?

How do we do this? We have to make a full PDF fit.
This cannot be done with just ATLAS W,Z data BUT we can add it to the HERA deep-inelastic scattering data.

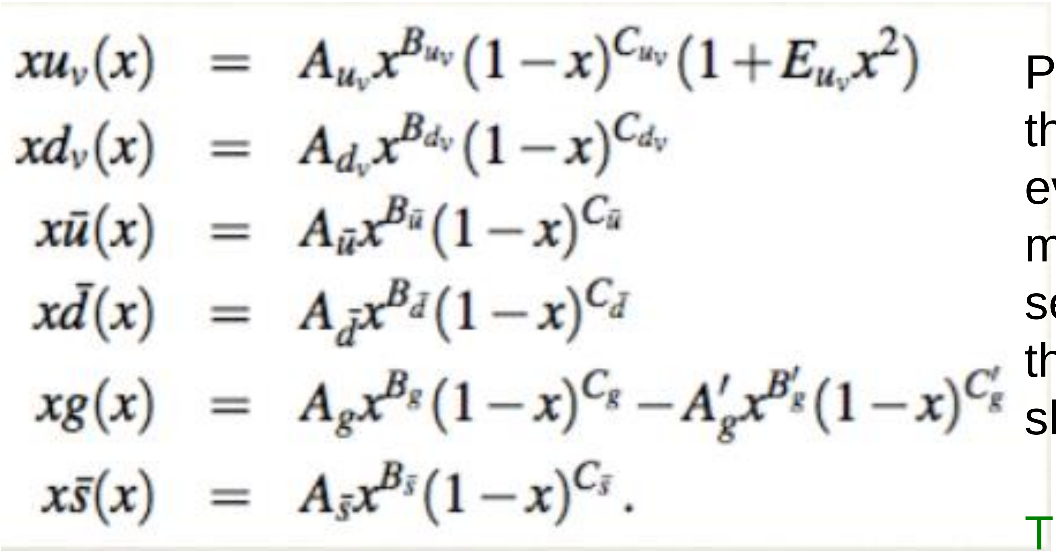
- HERA data from HERA combination 1056 data points, 169 sources of correlated systematic uncertainty
- ATLAS W,Z data at 7 TeV: 61 data points, 43 in peak-mass region, 131 sources of correlated systematic uncertainty
- CMS W,Z data at 7 TeV: 119 data points, 35 in peak-mass region, normalised Z data and 11 data points W-asymmetry
- CMS W at 8 TeV: 22 or 11 data points (used as W+,W- checked using W-asymmetry)
- CMS Z data at 8 TeV: 108 data points, 24 in peak-mass region – not used in main fit

Details

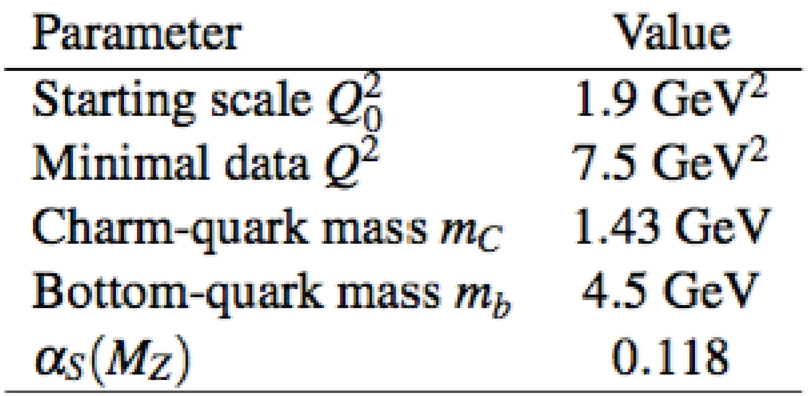
- QCDNUM for DGLAP evolution at NNLO
- DIS matrix-elements also from QCDNUM with RTVFN heavy quark scheme
- W,Z matrix elements at NLO from MCFM using Applgrid for input to PDF fit
- Augmented with NNLO/NLO k-factors from DYNNLO cross-checked with FEWZ for ATLAS, just FEWZ for CMS.
- NLO-EW and photon induced corrections also applied for ATLAS

- **The Main Fit uses W+, W- data and data from the Z peak-mass region** (66-116 GeV for ATLAS , 60-120GeV for CMS) since corrections for EW and PI effects are larger off-peak. However, checks are made for the Z-off peak data.
- The lowest off-peak bin 20-30GeV is not used at all since NNLO/NLO k-factors cannot be reliably estimated (process is ~zero at LO)
- The 8 TeV CMS Z data are not used in the main fit since the covariance matrix leads to unreasonably large χ2, as found by other PDF groups. However a check is made with these data. Work is currently going on within CMS to address this problem

As usual, we assume PDF shapes at a low starting scale.



$$
\begin{aligned}
xu_v(x) &= A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1+E_{u_v} x^2)\\
xd_v(x) &= A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}}\\
x\bar{u}(x) &= A_{\bar{u}} x^{B_{\bar{u}}} (1-x)^{C_{\bar{u}}}\\
x\bar{d}(x) &= A_{\bar{d}} x^{B_{\bar{d}}} (1-x)^{C_{\bar{d}}}\\
xg(x) &= A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g}\\
x\bar{s}(x) &= A_{\bar{s}} x^{B_{\bar{s}}} (1-x)^{C_{\bar{s}}}\,.
\end{aligned}
$$



Parameter	Value
Starting scale Q_0^2	1.9 GeV^2
Minimal data Q^2	7.5 GeV^2
Charm-quark mass m_C	1.43 GeV
Bottom-quark mass m_b	4.5 GeV
$\alpha_S(M_Z)$	0.118

There are other assumed values in constructing the predictions and these are included as part of model uncertainties and $\alpha_S(M_Z)$ uncertainty

Perform DGLAP evolution to the scale of the measurements –and convolute the evolved PDFs with the hard process matrix-elements to calculate the cross-sections. We then fit the data by varying the parameters A,B,C,E in the starting shapes.

The parameters are chosen by 'saturation of χ2' such that addition of extra parameters does not improve the fit.

In the main fit we have B_{ubar} =B_{dbar} = B_{sbar} and A_{ubar}= A_{dbar} ie low-x dbar=ubar plus the slope of sbar (but not necessarily its magnitude)= slope dbar= slope ubar

However, some extra parameters can change the shape of the PDFs, even if they don't improve the χ2.These are included as part of parametrisation uncertainty.

Use a form of χ2 which accounts for correlated systematics using nuisance parameters b_j for each source of systematic j for ATLAS

$$\chi^2_{\mathrm{exp}}(m,b) = \sum_i \frac{\left[m^i - \sum_j \gamma^i_j m^i b_j - \mu^i\right]^2}{\delta^2_{i,\mathrm{stat}}\,\mu^i m^i + \left(\delta_{i,\mathrm{uncor}}\, m^i\right)^2} + \sum_j b_j^2 .$$

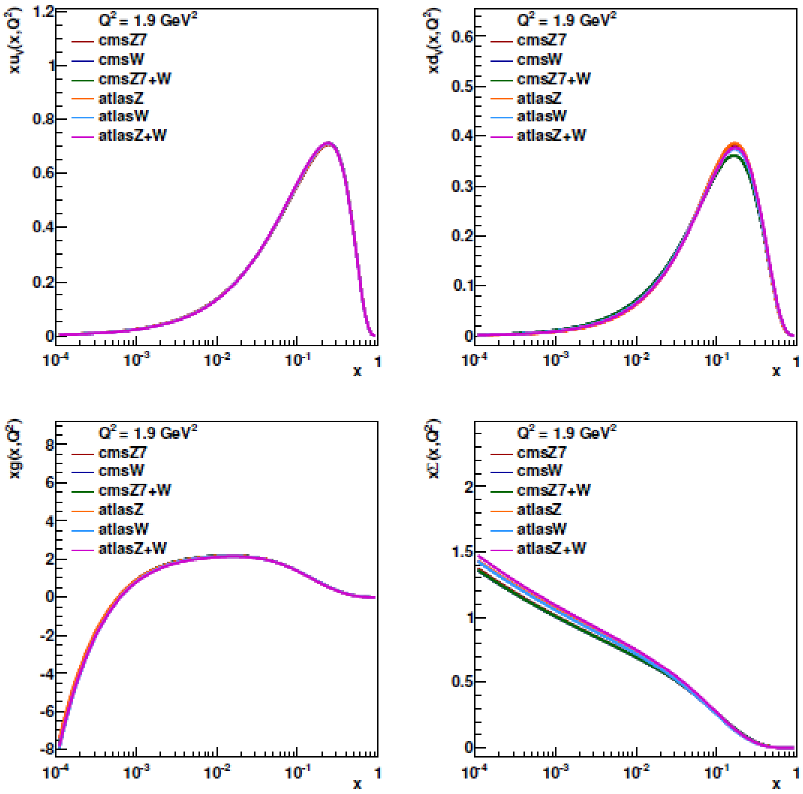
Where μ^i is the measurement for point i , m^i is the prediction, γ^i_j is the fractional systematic errors on point I from source j and δ’s are uncorrelated errors.

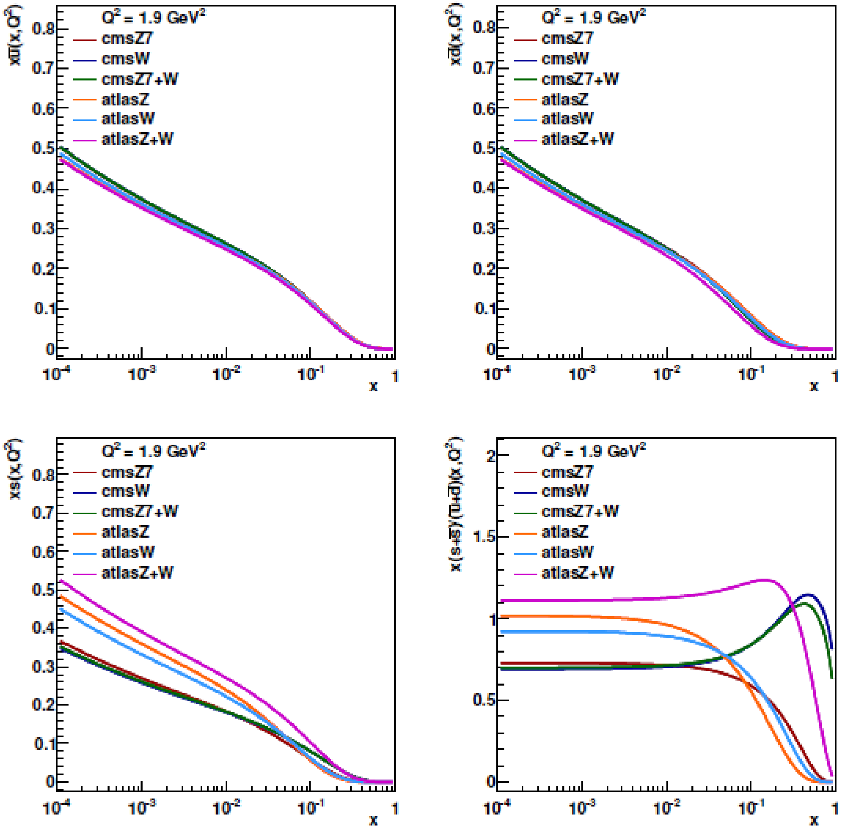
For CMS use covariance matrices which contain systematic and statistical components

$$\chi^2(m) = \sum_{i,k} (m_i - \mu_i) C^{-1}_{ik} (m_k - \mu_k),$$

$$C_{ik} = C^{\mathrm{stat}}_{ik} + C^{\mathrm{uncor}}_{ik} + C^{\mathrm{sys}}_{ik} .$$

There is just one systematic shift for the 8 TeV CMS Z data which are not normalised—namely the normalisation systematic parameter



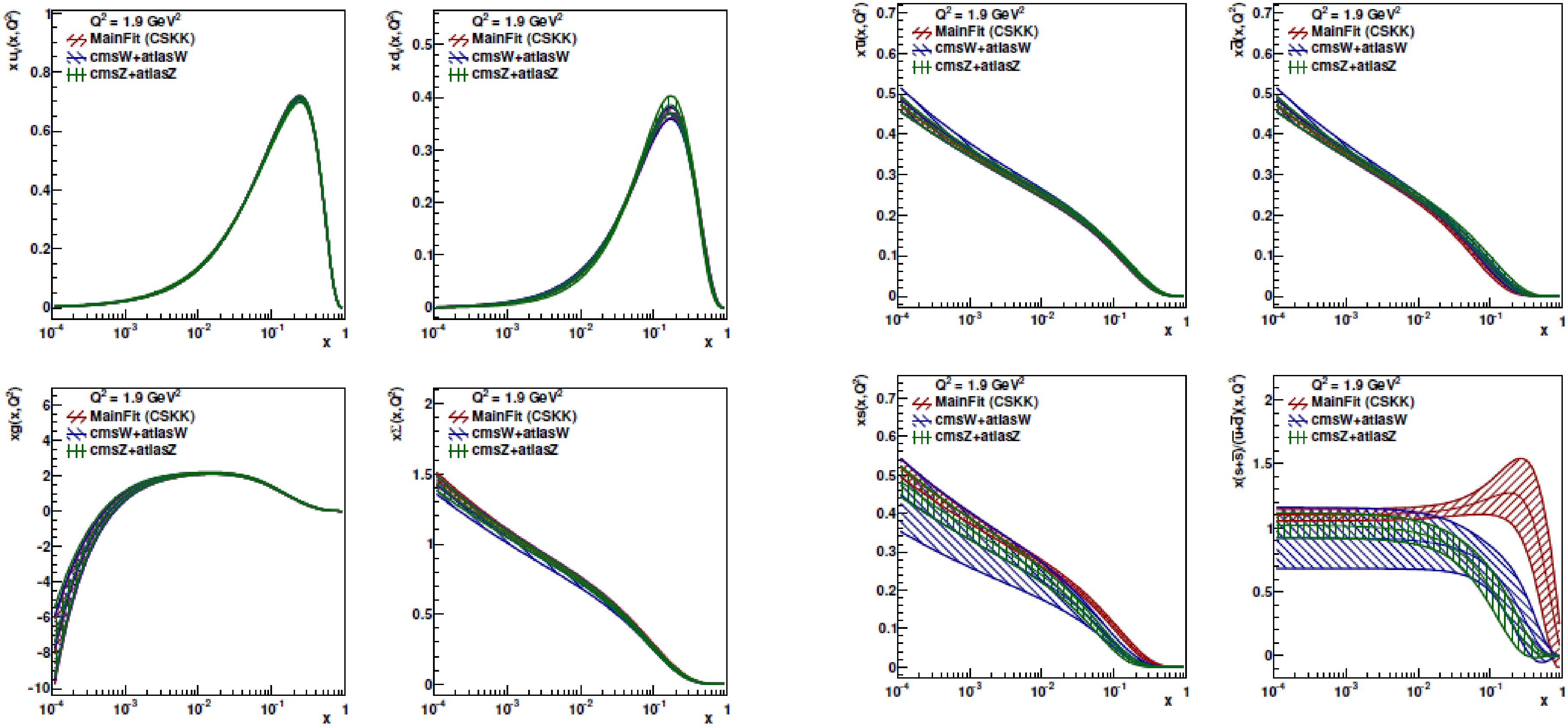


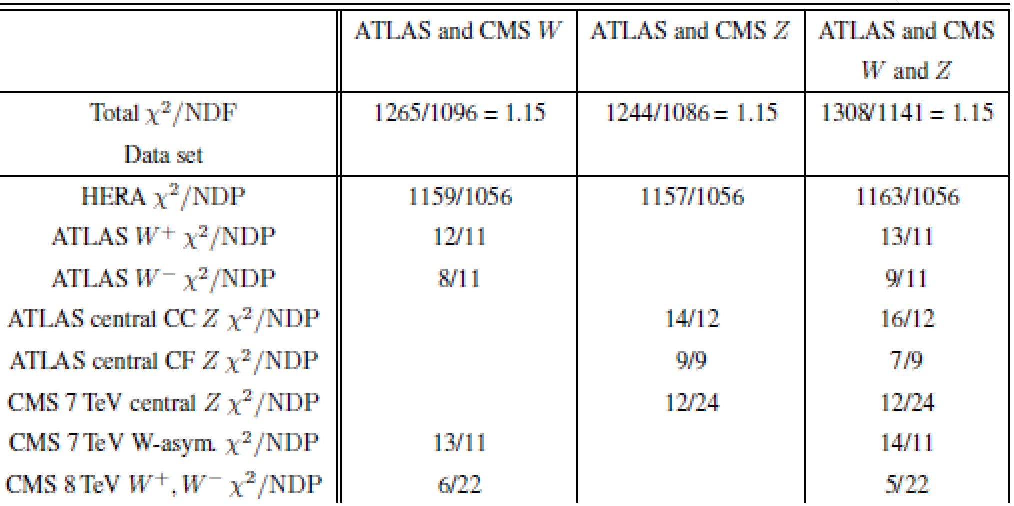
Consider W and Z data sets from each experiment separately

Very similar valence, gluon and total sea PDFs Different flavour break up to strangeness **BUT none are as suppressed as Rs = 0.5**

	CMS Z7	CMS W7,8	CMS Z7 + W7,8
Total χ^2/NDF Data set	1218/1965	1225/1074	1236/1098
HERA χ^2/NDP	1156/1056	1157/1056	1157/1056
CMS 7 TeV central Z χ^2/NDP	11/24		11/24
CMS 7 TeV W-asym. χ^2/NDP		13/11	13/11
CMS 8 TeV W^+, W^- χ^2/NDP		4/22	4/22

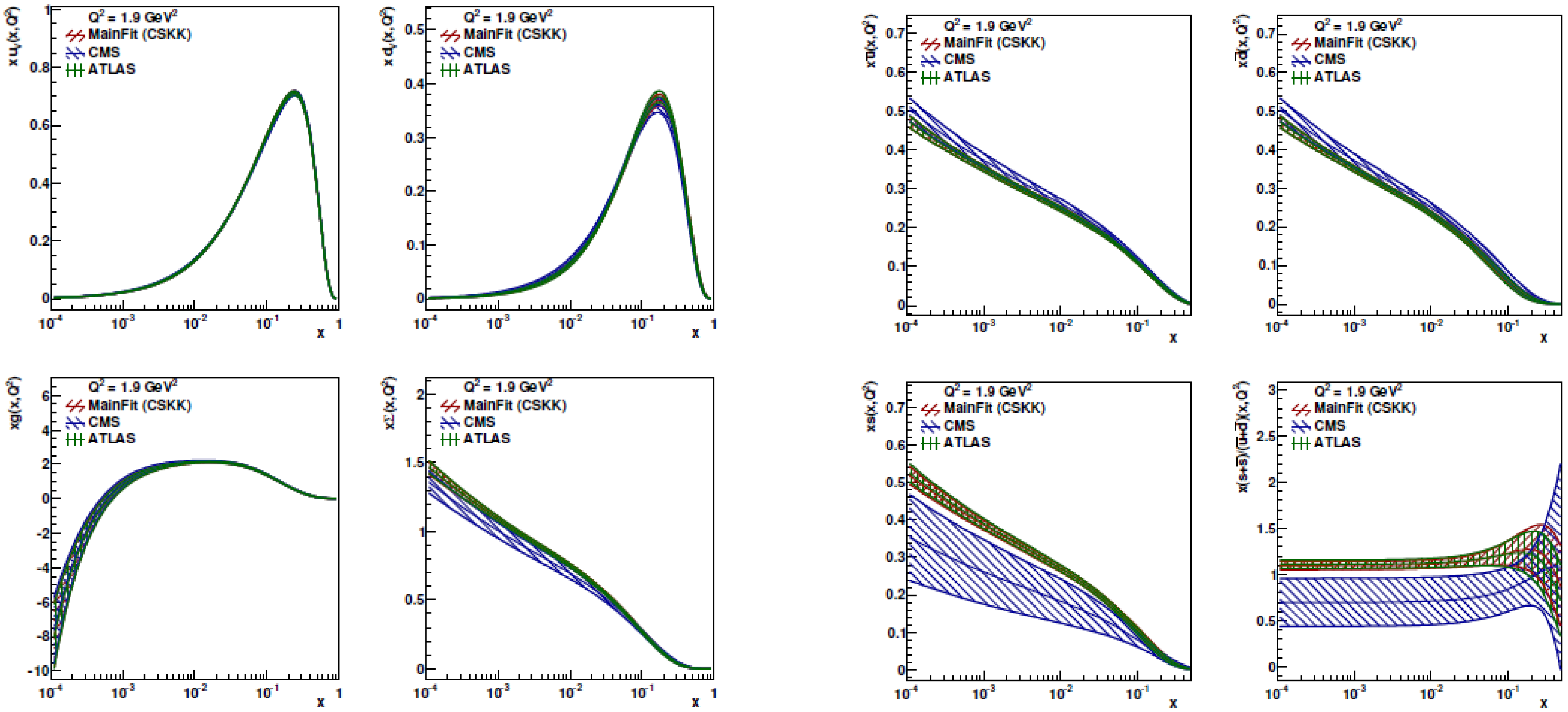
	ATLAS Z	ATLAS W	ATLAS W,Z
Total χ^2/NDF Data set	1233/1062	1245/1063	1276/1084
HERA χ^2/NDP	1155/1056	1160/1056	1164/1056
ATLAS W^+ χ^2/NDP		12/11	12/11
ATLAS W^- χ^2/NDP		8/11	9/11
ATLAS Z central CC χ^2/NDP	14/12		15/12
ATLAS Z central CF χ^2/NDP	9/9		8/9





	ATLAS and CMS W	ATLAS and CMS Z	ATLAS and CMS W and Z
Total χ^2/NDF Data set	1265/1096 = 1.15	1244/1086 = 1.15	1308/1141 = 1.15
HERA χ^2/NDP	1159/1056	1157/1056	1163/1056
ATLAS W^+ χ^2/NDP	12/11		13/11
ATLAS W^- χ^2/NDP	8/11		9/11
ATLAS central CC Z χ^2/NDP		14/12	16/12
ATLAS central CF Z χ^2/NDP		9/9	7/9
CMS 7 TeV central Z χ^2/NDP		12/24	12/24
CMS 7 TeV W-asym. χ^2/NDP	13/11		14/11
CMS 8 TeV W^+, W^- χ^2/NDP	6/22		5/22

Then consider ATLAS +CMS for W
And ATLAS+CMS for Z central
Z is much more strangeness sensitive than W
Z and W together has a different shape because of the ATLAS correlations.
Note the chisq for ATLAS and CMS together shows no tension between the data sets



	CMS Z7 + W7,8
Total χ^2/NDF	1236/1098
Data set	
HERA χ^2/NDP	1157/1056
CMS 7 TeV central Z χ^2/NDP	11/24
CMS 7 TeV W-asym. χ^2/NDP	13/11
CMS 8 TeV W^+, W^- χ^2/NDP	4/22

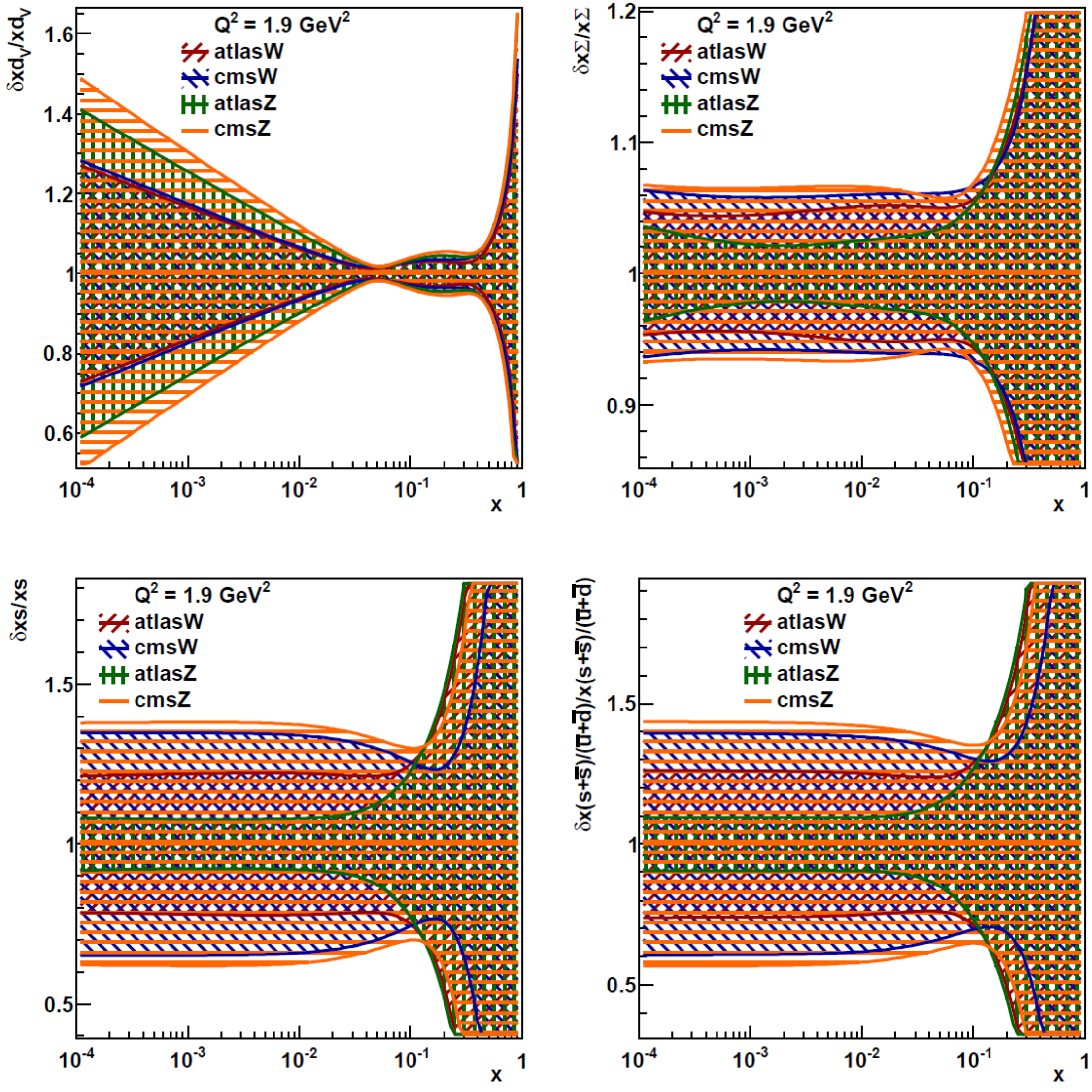
	ATLAS W,Z
Total χ^2/NDF	1276/1084
Data set	
HERA χ^2/NDP	1164/1056
ATLAS W^+ χ^2/NDP	12/11
ATLAS W^- χ^2/NDP	9/11
ATLAS Z central CC χ^2/NDP	15/12
ATLAS Z central CF χ^2/NDP	8/9

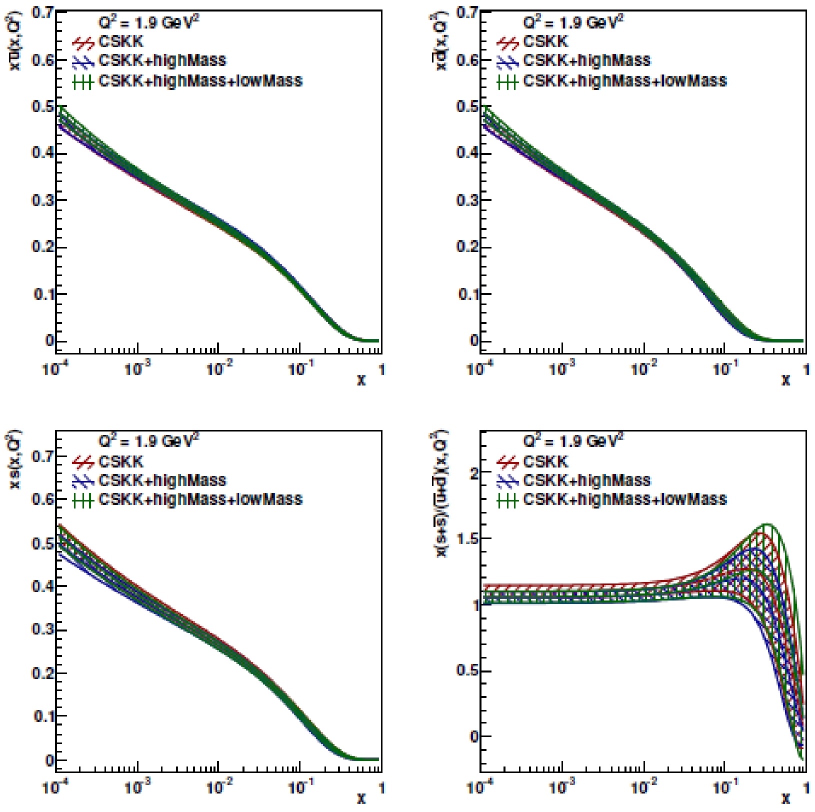
	ATLAS and CMS W and Z
Total χ^2/NDF	1308/1141 = 1.15
Data set	
HERA χ^2/NDP	1163/1056
ATLAS W^+ χ^2/NDP	13/11
ATLAS W^- χ^2/NDP	9/11
ATLAS central CC Z χ^2/NDP	16/12
ATLAS central CF Z χ^2/NDP	7/9
CMS 7 TeV central Z χ^2/NDP	12/24
CMS 7 TeV W-asym. χ^2/NDP	14/11
CMS 8 TeV W^+, W^- χ^2/NDP	5/22

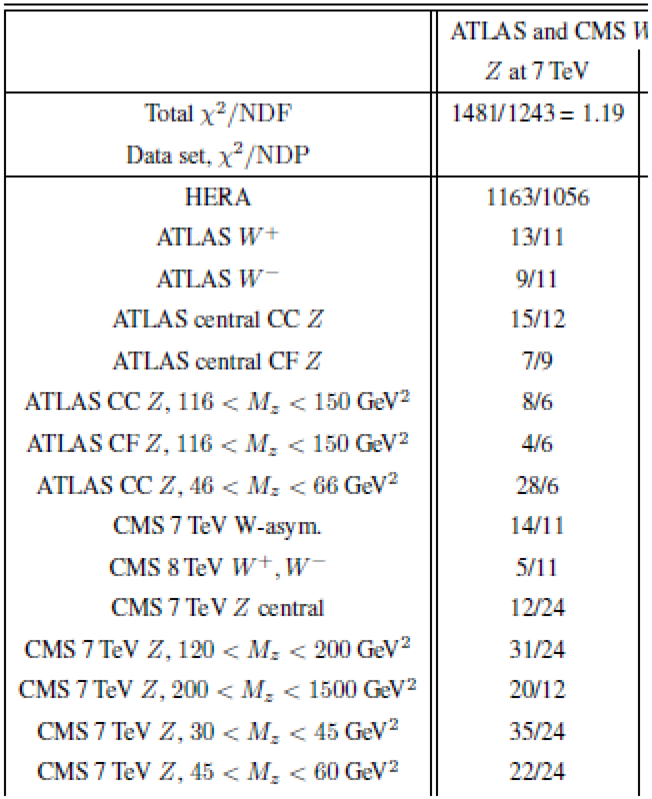
Then consider CMS W+Z and ATLAS W+Z and compare to ALL: **no tension, disagreement in strangeness is only at 1.5σ level.** ATLAS is more accurate and thus dominates the fit to both together

Let’s take a brief pause to look at the effect of the ATLAS and CMS W and Z data on PDF uncertainties

The ATLAS and CMS W data are equally constraining wrt valence distributions- as seen here with dv, whereas the Z data are not so constraining.
However if we look at sea-quarks then the ATLAS Z are always the most constraining, followed by ATLAS W, CMS W and CMS Z- as seen here on the total sea, strange sea and strangeness ratio



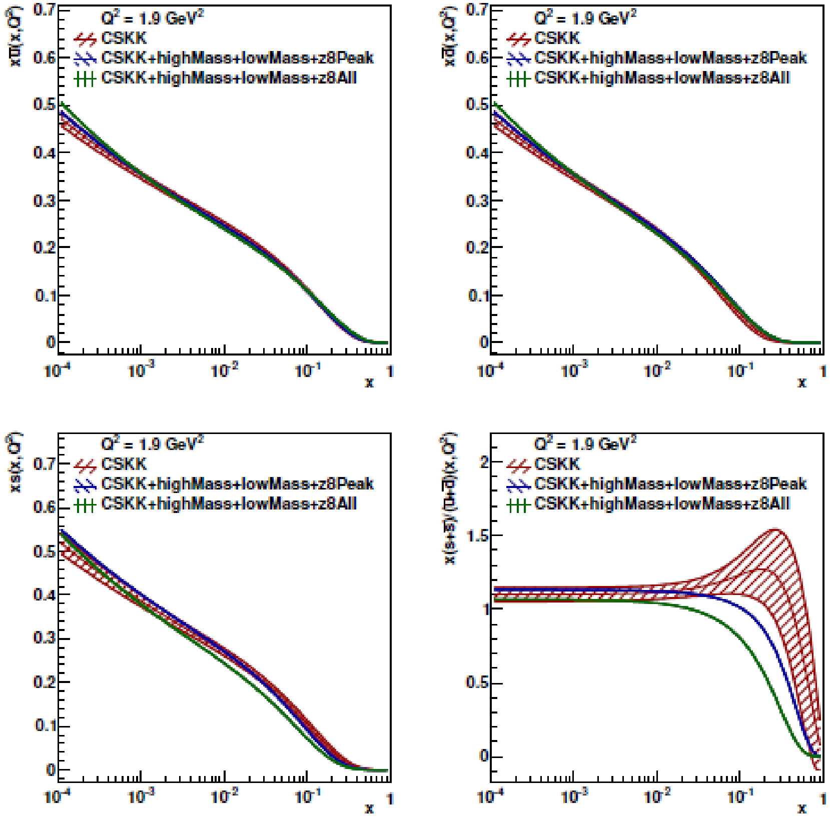


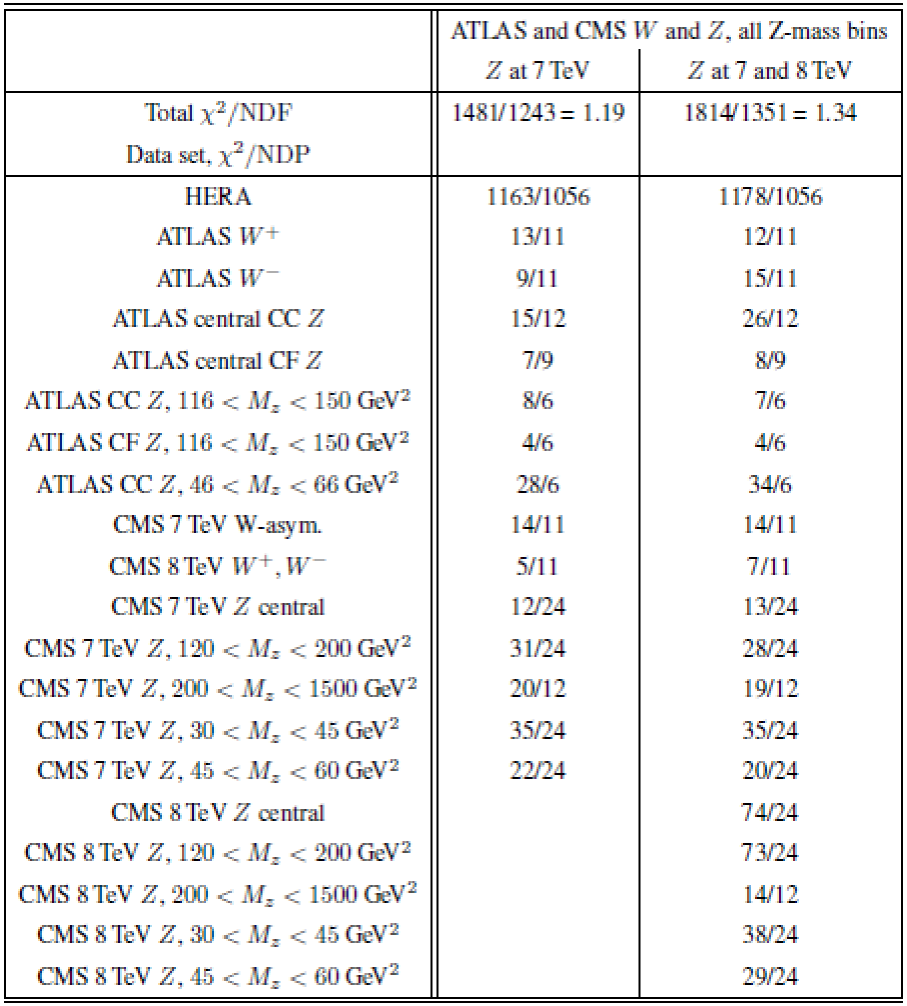


	ATLAS and CMS W Z at 7 TeV
Total χ^2/NDF Data set, χ^2/NDP	1481/1243 = 1.19
HERA	1163/1056
ATLAS W^+	13/11
ATLAS W^-	9/11
ATLAS central CC Z	15/12
ATLAS central CF Z	7/9
ATLAS CC Z, $116 < M_z < 150$ GeV^2	8/6
ATLAS CF Z, $116 < M_z < 150$ GeV^2	4/6
ATLAS CC Z, $46 < M_z < 66$ GeV^2	28/6
CMS 7 TeV W-asym.	14/11
CMS 8 TeV W^+, W^-	5/11
CMS 7 TeV Z central	12/24
CMS 7 TeV Z, $120 < M_z < 200$ GeV^2	31/24
CMS 7 TeV Z, $200 < M_z < 1500$ GeV^2	20/12
CMS 7 TeV Z, $30 < M_z < 45$ GeV^2	35/24
CMS 7 TeV Z, $45 < M_z < 60$ GeV^2	22/24

Now add off-peak Z bins as a check
High mass : 116-136 GeV ATLAS
(central and forward rapidity)
120-200 GeV CMS
200-1500 GeV CMS
Low Mass: 46-66 GeV ATLAS
30-45 GeV CMS
45-60 GeV CMS

- The result for strangeness is barely affected
- Even uncertainties are not much improved
- The off peak bins are well described (apart from ATLAS lowest mass bin, as also found by ATLAS)
- Not worth the added uncertainty from EW and PI effects





	ATLAS and CMS W and Z, all Z-mass bins	
	Z at 7 TeV	Z at 7 and 8 TeV
Total χ^2/NDF	1481/1243 = 1.19	1814/1351 = 1.34
Data set, χ^2/NDP		
HERA	1163/1056	1178/1056
ATLAS W^+	13/11	12/11
ATLAS W^-	9/11	15/11
ATLAS central CC Z	15/12	26/12
ATLAS central CF Z	7/9	8/9
ATLAS CC Z, $116 < M_z < 150$ GeV^2	8/6	7/6
ATLAS CF Z, $116 < M_z < 150$ GeV^2	4/6	4/6
ATLAS CC Z, $46 < M_z < 66$ GeV^2	28/6	34/6
CMS 7 TeV W-asym.	14/11	14/11
CMS 8 TeV W^+, W^-	5/11	7/11
CMS 7 TeV Z central	12/24	13/24
CMS 7 TeV Z, $120 < M_z < 200$ GeV^2	31/24	28/24
CMS 7 TeV Z, $200 < M_z < 1500$ GeV^2	20/12	19/12
CMS 7 TeV Z, $30 < M_z < 45$ GeV^2	35/24	35/24
CMS 7 TeV Z, $45 < M_z < 60$ GeV^2	22/24	20/24
CMS 8 TeV Z central		74/24
CMS 8 TeV Z, $120 < M_z < 200$ GeV^2		73/24
CMS 8 TeV Z, $200 < M_z < 1500$ GeV^2		14/12
CMS 8 TeV Z, $30 < M_z < 45$ GeV^2		38/24
CMS 8 TeV Z, $45 < M_z < 60$ GeV^2		29/24

Now add CMS 8 TeV Z data both central and offpeak
The 8 TeV data are not well fitted- as also found by NNPDF
The result for strangeness at low-x is not affected significantly

For the Main fit to the ATLAS and CMS W and Z-peak data (excluding CMS 8 TeV) we consider model variations, parametrisation variations and alphas variations. We characterise them in the value of Rs at

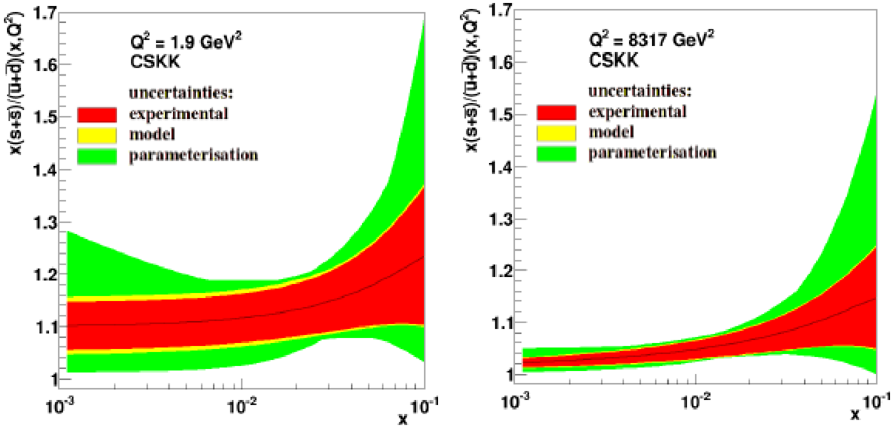
$x = 0.023$ and $Q_0^2 = 1.9\ \mathrm{GeV}^2$

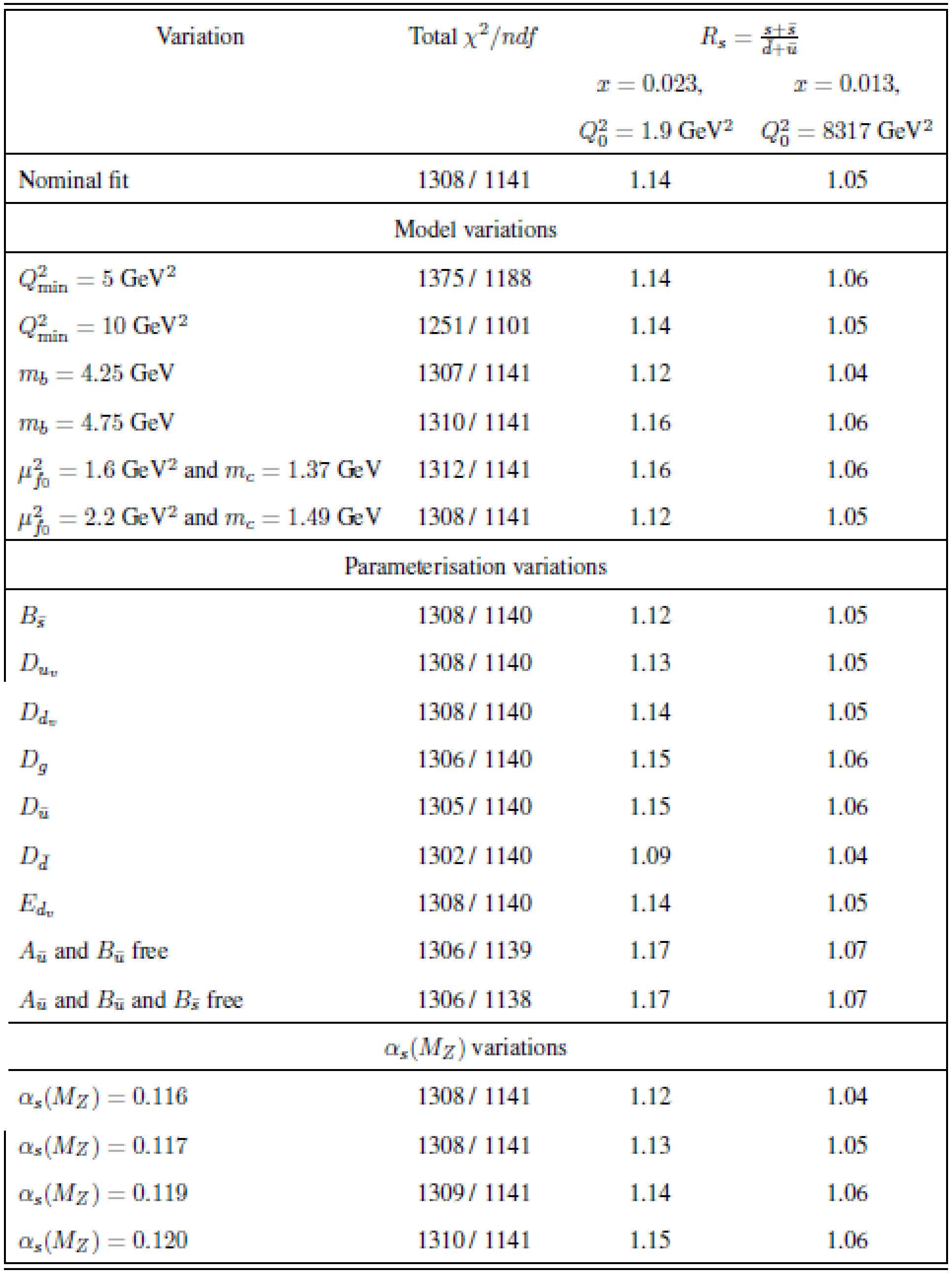
$$R_s = 1.14 \pm 0.05 \pm 0.03\ (\mathrm{model})^{+0.03}_{-0.05}\ (\mathrm{parameterisation})\ ^{+0.01}_{-0.02}\ (\alpha_s)$$

and at $x = 0.013$ and $Q^2 = M_Z^2$

$$R_s = 1.05 \pm 0.02 \pm^{+0.02}_{-0.01}\ (\mathrm{model})^{+0.02}_{-0.01}\ (\mathrm{parameterisation}) \pm 0.01\ (\alpha_s).$$

The strangeness ratio is shown as a function of x including the model and parametrisation variations here

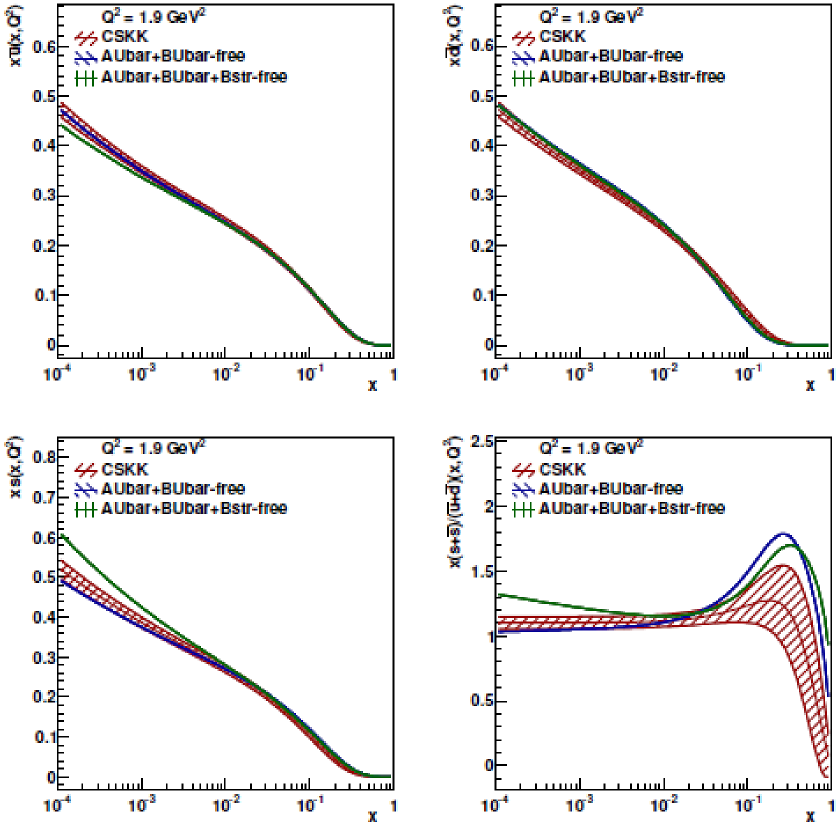




Variation	Total χ^2/ndf	$R_s = \frac{s+\bar{s}}{\bar{d}+\bar{u}}$	
		$x = 0.023$,	$x = 0.013$,
		$Q_0^2 = 1.9\ \mathrm{GeV}^2$	$Q_0^2 = 8317\ \mathrm{GeV}^2$
Nominal fit	1308 / 1141	1.14	1.05
Model variations			
$Q^2_{\mathrm{min}} = 5\ \mathrm{GeV}^2$	1375 / 1188	1.14	1.06
$Q^2_{\mathrm{min}} = 10\ \mathrm{GeV}^2$	1251 / 1101	1.14	1.05
$m_b = 4.25$ GeV	1307 / 1141	1.12	1.04
$m_b = 4.75$ GeV	1310 / 1141	1.16	1.06
$\mu^2_{f0} = 1.6\ \mathrm{GeV}^2$ and $m_c = 1.37$ GeV	1312 / 1141	1.16	1.06
$\mu^2_{f0} = 2.2\ \mathrm{GeV}^2$ and $m_c = 1.49$ GeV	1308 / 1141	1.12	1.05
Parameterisation variations			
$B_{\bar{s}}$	1308 / 1140	1.12	1.05
D_{u_v}	1308 / 1140	1.13	1.05
D_{d_v}	1308 / 1140	1.14	1.05
D_g	1306 / 1140	1.15	1.06
$D_{\bar{u}}$	1305 / 1140	1.15	1.06
$D_{\bar{d}}$	1302 / 1140	1.09	1.04
E_{d_v}	1308 / 1140	1.14	1.05
$A_{\bar{u}}$ and $B_{\bar{u}}$ free	1306 / 1139	1.17	1.07
$A_{\bar{u}}$ and $B_{\bar{u}}$ and $B_{\bar{s}}$ free	1306 / 1138	1.17	1.07
$\alpha_s(M_Z)$ variations			
$\alpha_s(M_Z) = 0.116$	1308 / 1141	1.12	1.04
$\alpha_s(M_Z) = 0.117$	1308 / 1141	1.13	1.05
$\alpha_s(M_Z) = 0.119$	1309 / 1141	1.14	1.06
$\alpha_s(M_Z) = 0.120$	1310 / 1141	1.15	1.06

Note worthy parametrisation variations are:

- Allowing the low-x sea parameter B_{sbar} to be free
- Allowing ubar to be free from dbar at low-x, so Aubar and Bubar are additional free parameters.
- Combining these two to allow freedom in low-x, ubar,dbar sbar simultaneously



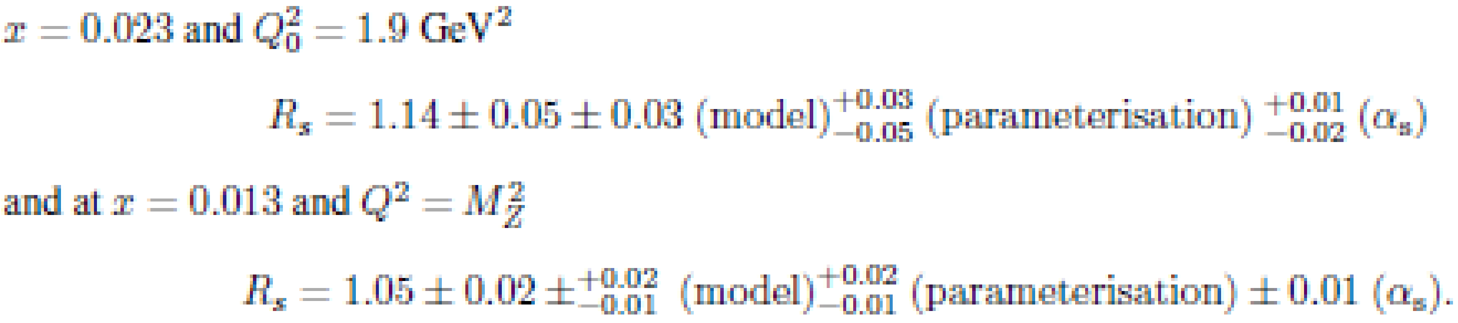
The data are consistent with the ubar and dbar distributions being very similar at low-x even when freedom is allowed.
The extra freedom for low-x sbar leads to even more strangeness at low-x!!

These parameters are now part of the standard parametrisation uncertainty
(unlike for the ATLAS study where they were additional cross-checks.)

A further variation forces the fit to describe E866 data -which gives dbar-ubar positive at high x ~0.1- by using the ZEUS-S parametrisation, (which fits dbar+ubar and fixes dbar-ubar).
This gives Rs=0.95 \pm 0.07, still enhanced but 2σ away from our central result. However, this is a poor fit to the HERA+ATLAS/CMS data χ2/ndf=1363/1142 rather than ~1308/1141 for the standard fits

Conclusions

- No tension ATLAS vs CMS, in either W or Z
- Enhanced strangeness is supported by both CMS and ATLAS



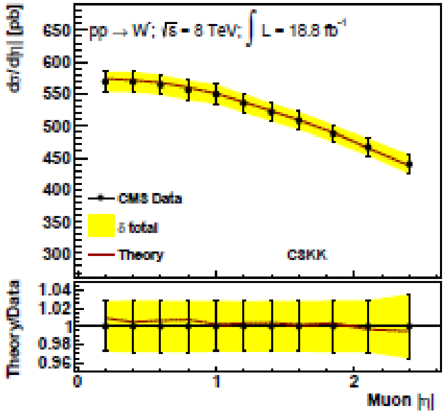
$x = 0.023$ and $Q_0^2 = 1.9\ \mathrm{GeV}^2$

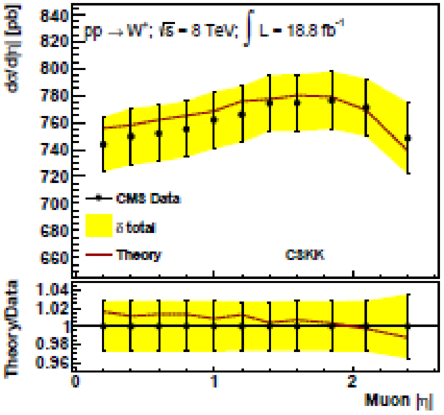
$$R_s = 1.14 \pm 0.05 \pm 0.03\ (\text{model})^{+0.03}_{-0.05}\ (\text{parameterisation})\ ^{+0.01}_{-0.02}\ (\alpha_s)$$

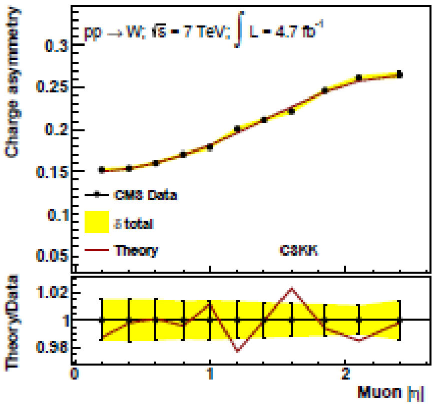
and at $x = 0.013$ and $Q^2 = M_Z^2$

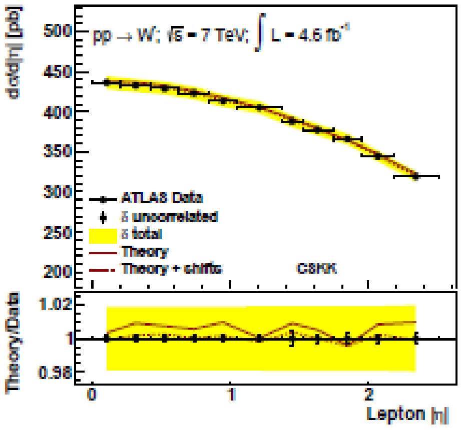
$$R_s = 1.05 \pm 0.02 \pm^{+0.02}_{-0.01}\ (\text{model})^{+0.02}_{-0.01}\ (\text{parameterisation}) \pm 0.01\ (\alpha_s).$$

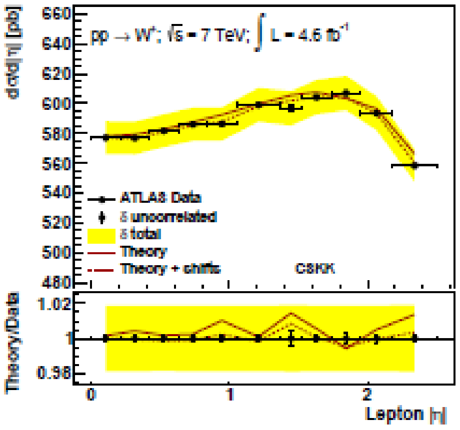
Extra freedom in the low-x ubar, dbar and sbar still supports this conclusion

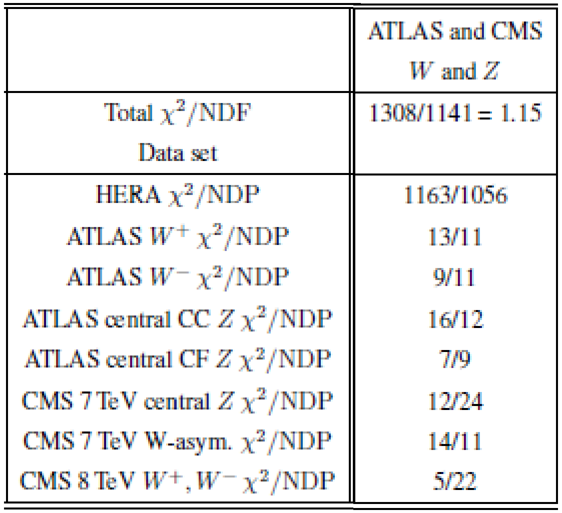






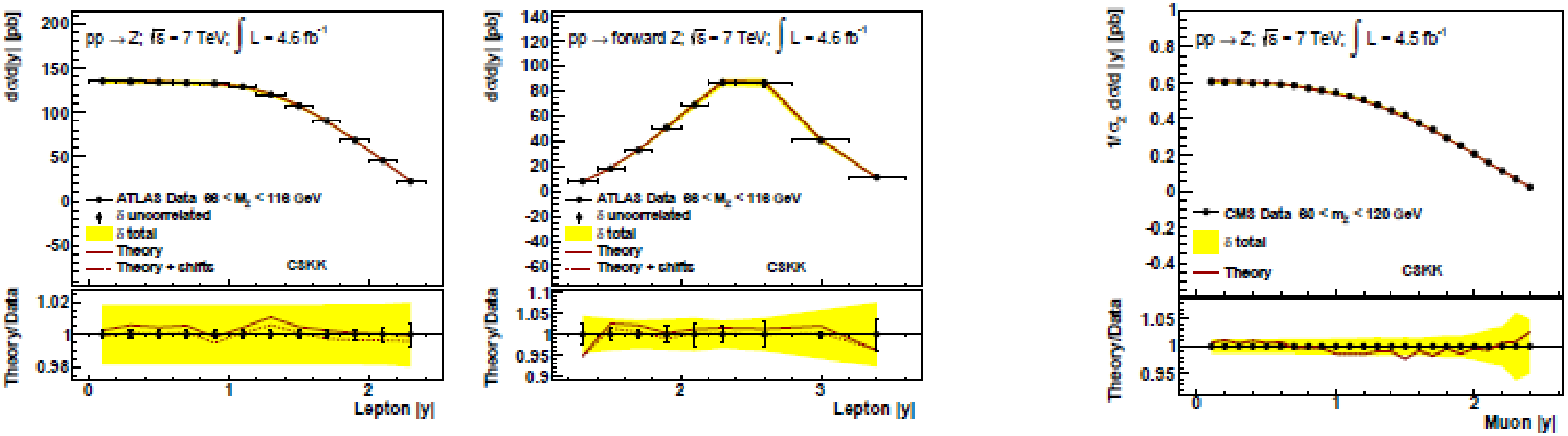




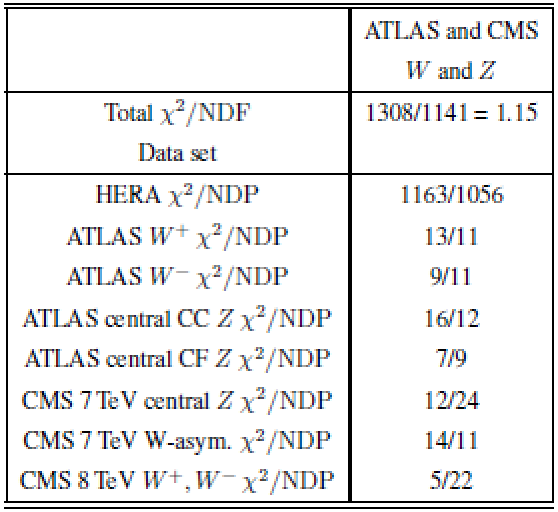


	ATLAS and CMS W and Z
Total χ^2/NDF Data set	1308/1141 = 1.15
HERA χ^2/NDP	1163/1056
ATLAS W^+ χ^2/NDP	13/11
ATLAS W^- χ^2/NDP	9/11
ATLAS central CC Z χ^2/NDP	16/12
ATLAS central CF Z χ^2/NDP	7/9
CMS 7 TeV central Z χ^2/NDP	12/24
CMS 7 TeV W-asym. χ^2/NDP	14/11
CMS 8 TeV W^+, W^- χ^2/NDP	5/22

Compare the Main CSKK fit to ATLAS and CMS W data



Compare the Main CSKK Fit to ATLAS (central and forward rapidity) and CMS Z-peak data



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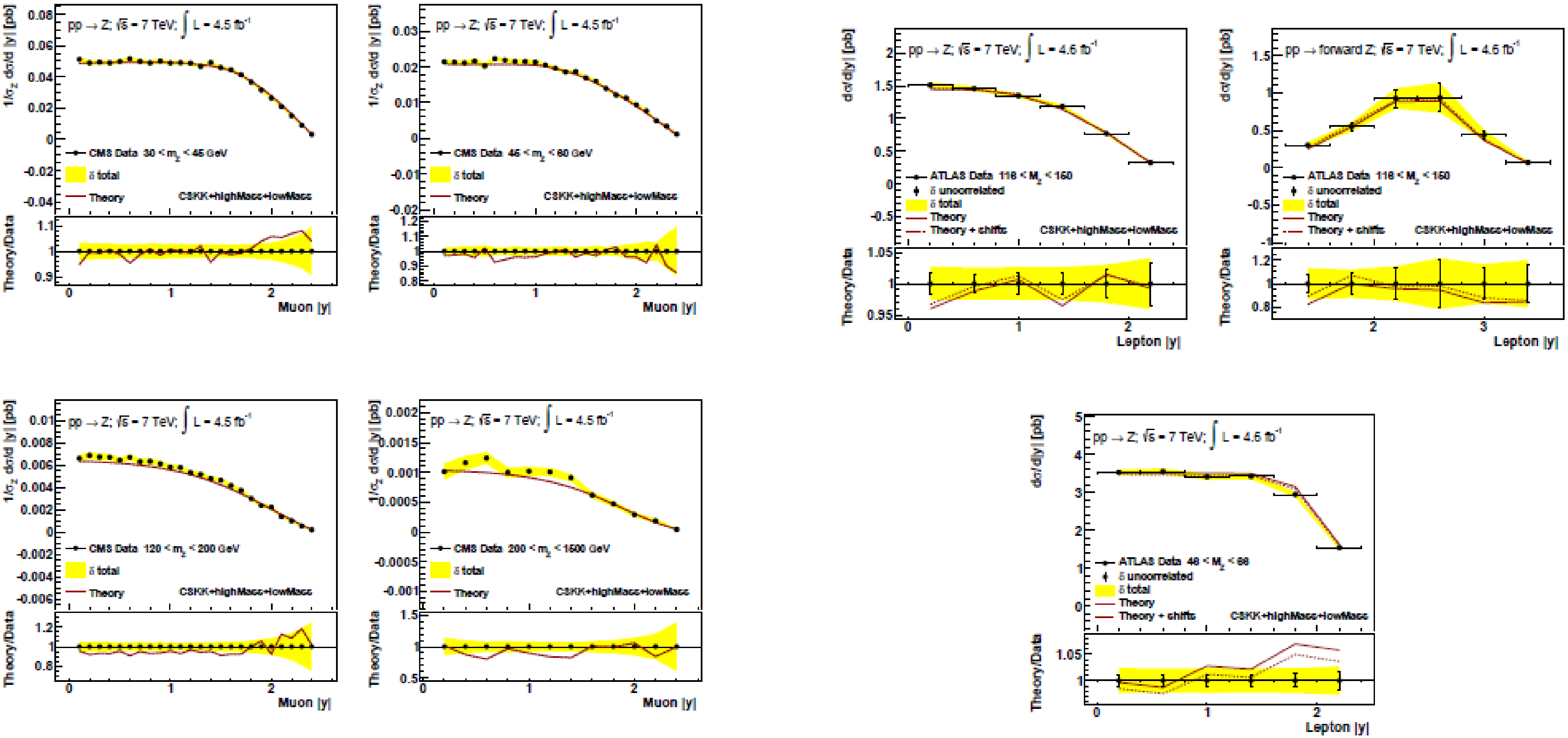
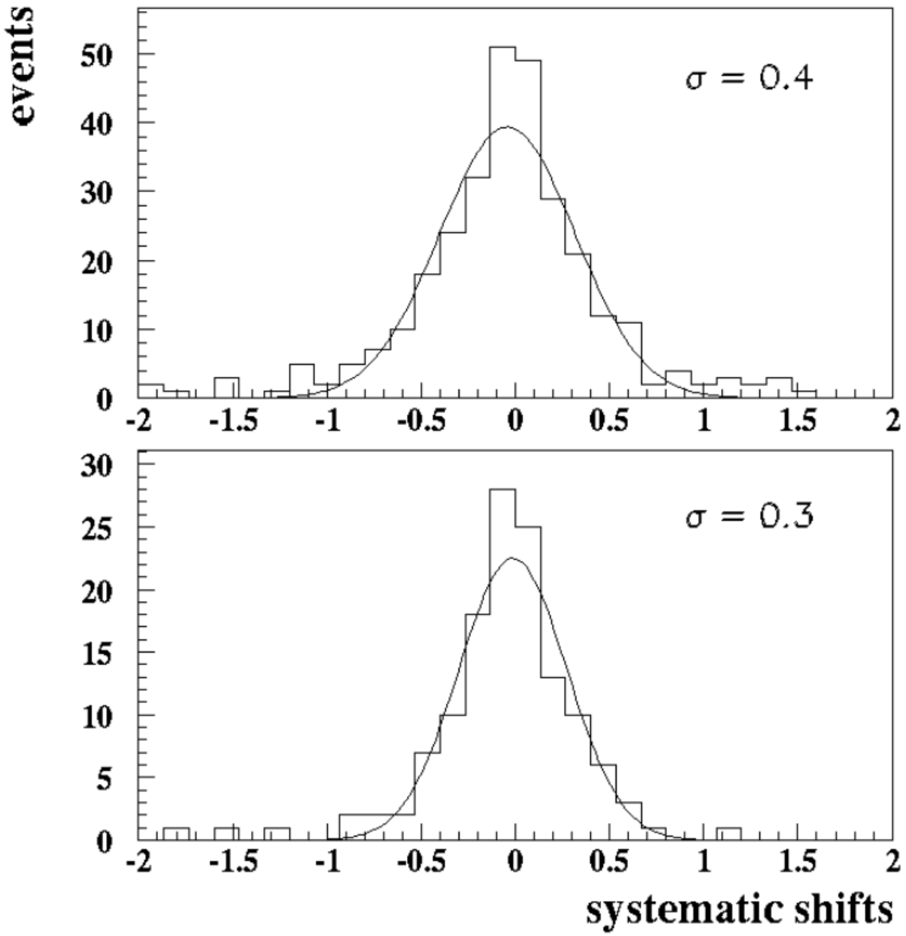
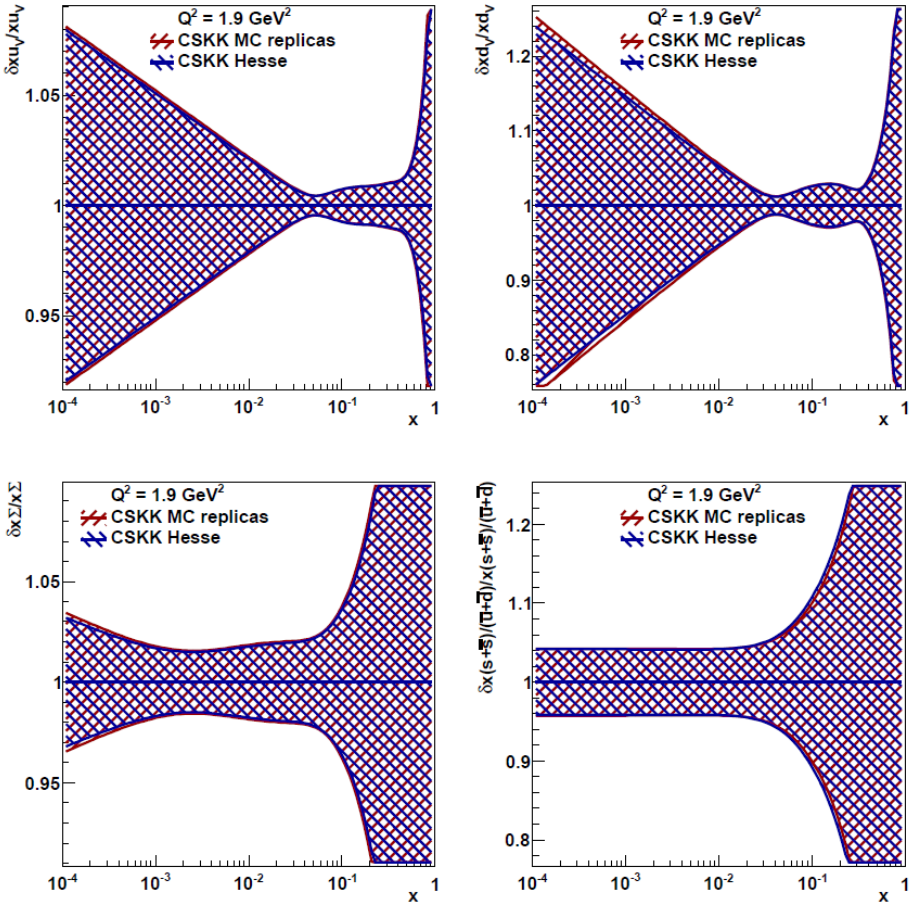


Compare the CSKK+highMass+lowMass fit to the CMS and ATLAS (central and forward rapidity) off-mass-peak data

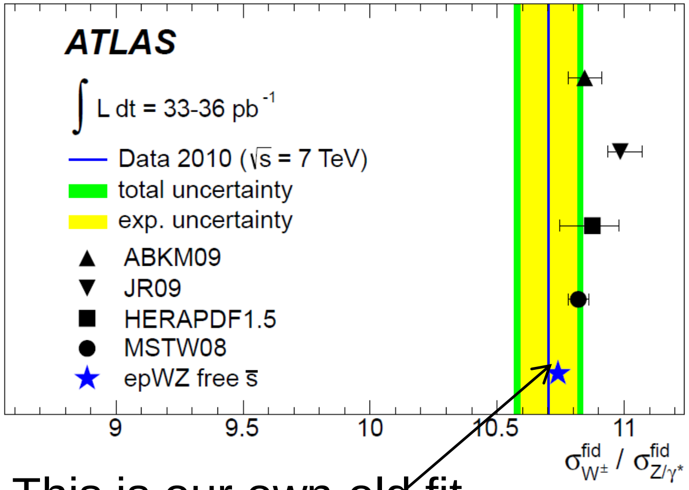
The shifts of the nuisance parameters for systematic correlations are nearly all within one sigma

The uncertainties were determined by the Hessian method but have been checke

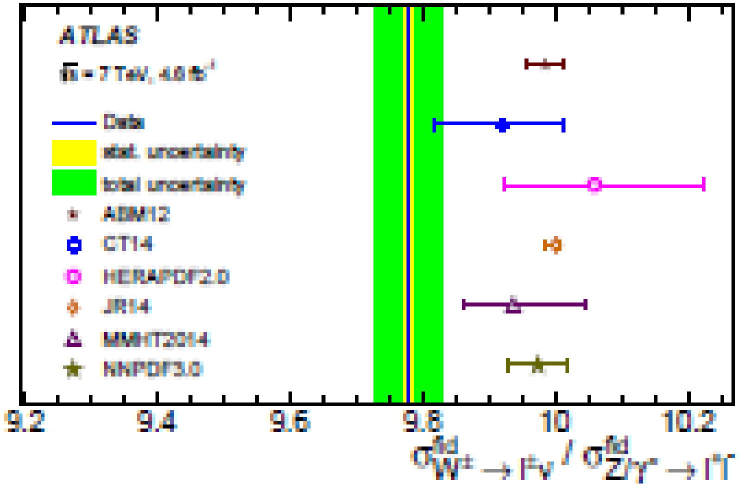




Unsuppressed strangeness results in more Z and a low W/Z ratio. We see this in the ATLAS 2010 data and in the new analysis of 2011 data

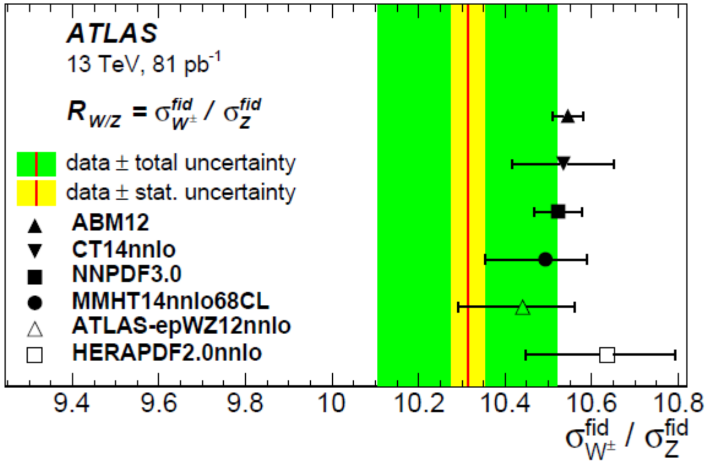


This is our own old fit ATLASepWZ12

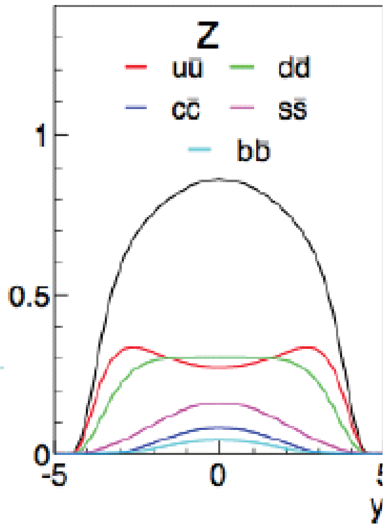


This figure is from arXIV:1612.03016

We ALSO see it in the 13 TeV data

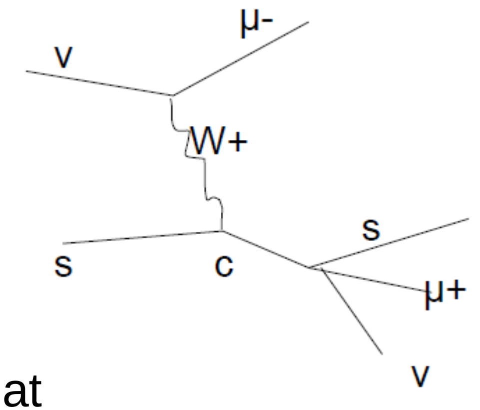


Flavour contributions to W and Z show that s-sbar is prominent in Z production at central rapidity.
This plots were made for the usual assumption that strange sea is suppressed ~0.5 of down-type sea



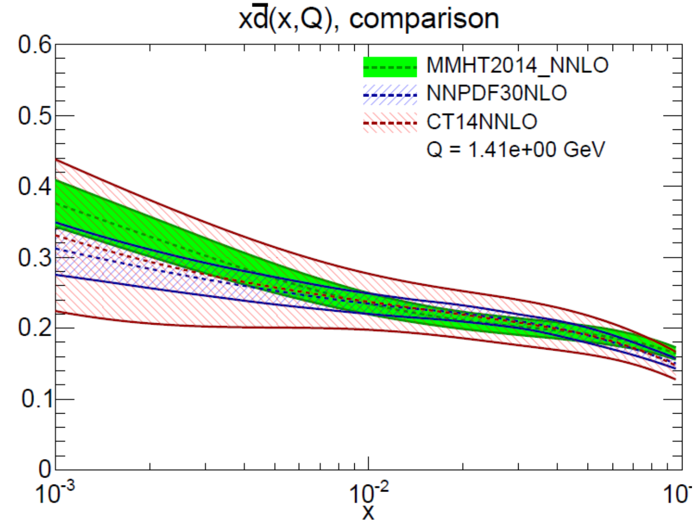
This comes from di-muon production in neutrino induced deep inelastic scattering data.

But these neutrino data are shot on heavy targets. This not only involves uncertain nuclear corrections for the struck parton, but also the possibility of absorption of the outgoing charmed particle in the nuclear medium

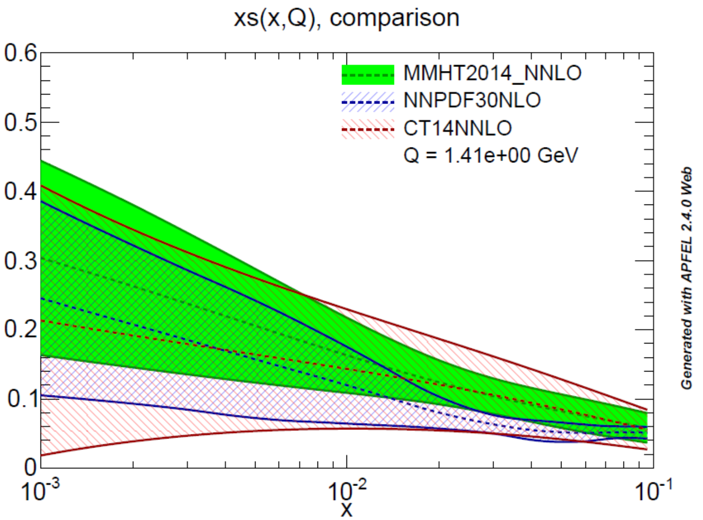


But without worrying too much about this what does it give for strange compared to dbar?

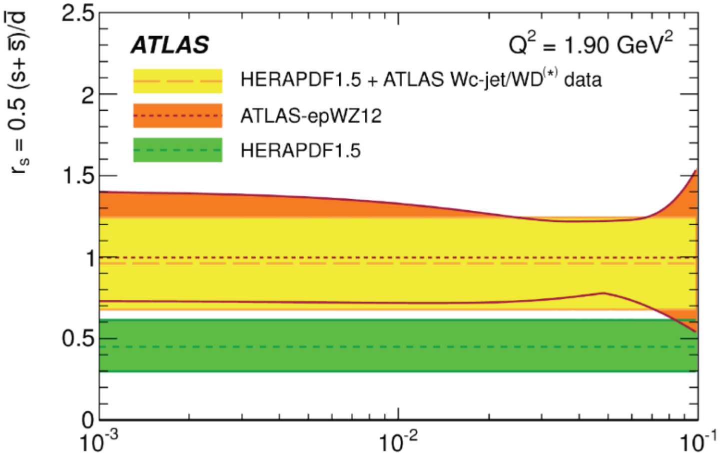
Assume s=sbar, violations are very small



Clear suppression for x ~0.1
Not so clear for lower x



Strangeness suppression is measured at low scale



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