ATLAS determination of the strange quark content of the proton

A M Cooper-Sarkar
Oxford
On behalf of the ATLAS Collaboration

Kaon 2016, Birmingham

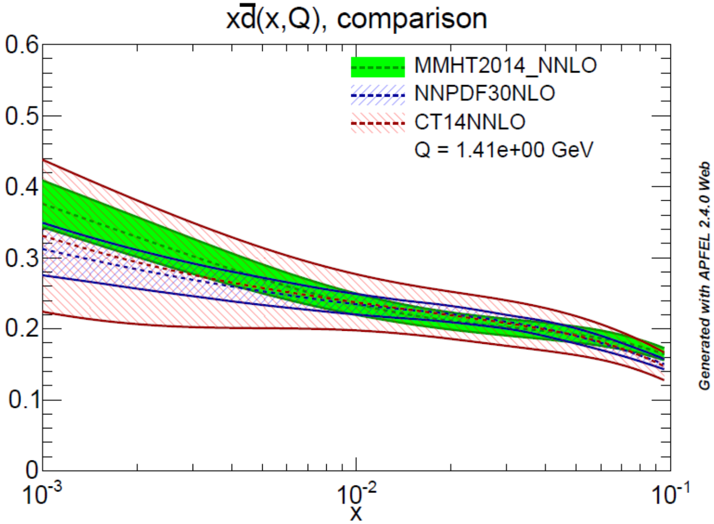
- W,Z inclusive measurement Phys Rev Lett 109(2012)012001
- W+charm JHEP05(2014)068

How much strangeness is there in the proton?

We don't know this very well.

There is a traditional view that it is suppressed, but what is the evidence for this?

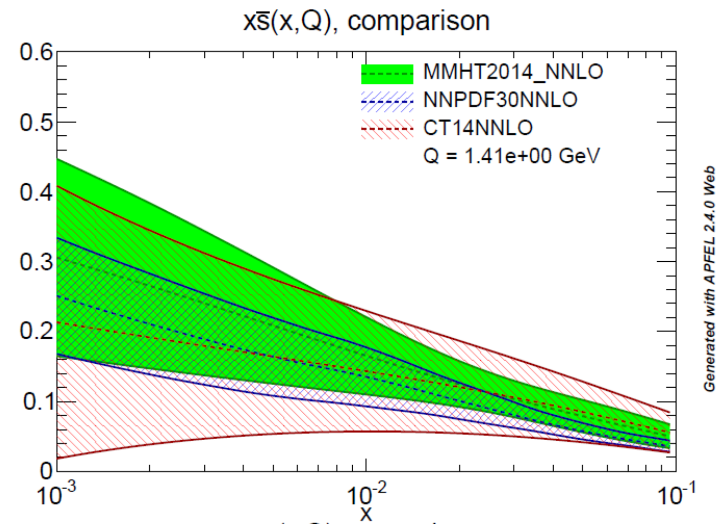
Compare the anti-down and anti-strange parton distribution functions (PDFs) in the sea

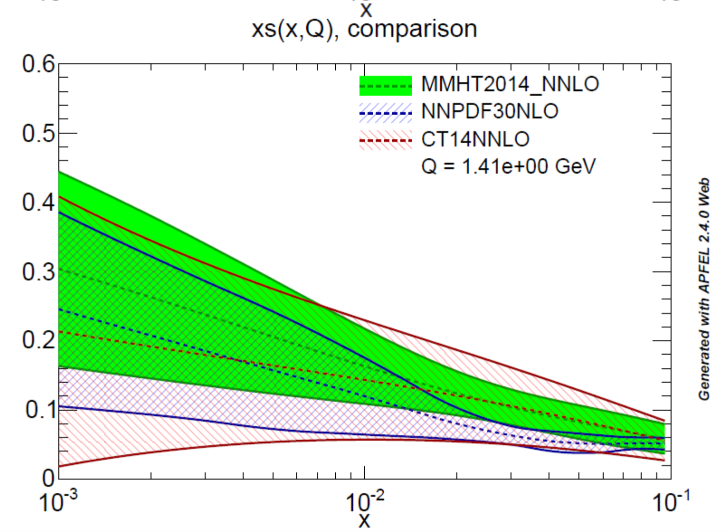


Clear suppression for x ~0.1

Not so clear for lower x

where ATLAS data contribute



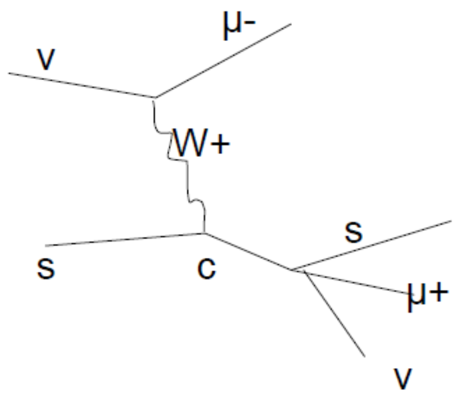


And the difference between strange and anti-strange is small- in fact zero for CT14 PDFs

So we will mostly assume s = sbar in this talk

Where does the suppression come from?

It comes from di-muon production in NuTeV neutrino induced deep inelastic scattering data (NuTeV, Chorus, Nomad)
Opposite sign dimuon events from neutrino scattering give information on the strange quark
And anti-strange comes from the equivalent antineutrino scattering



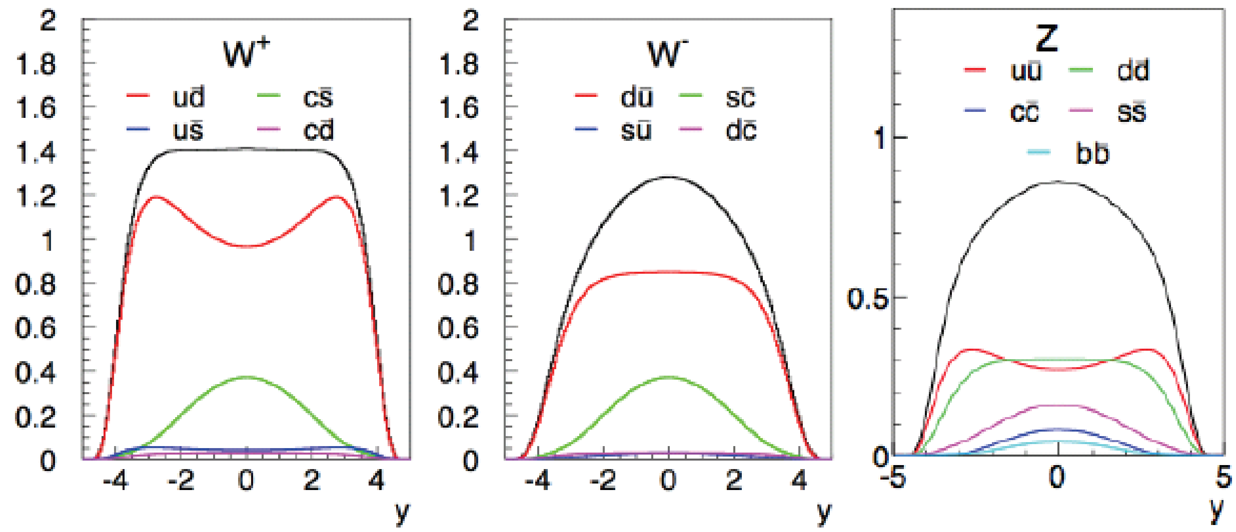
The neutrino data are most sensitive at x~0.1----where we see the suppression in the PDFs

But these (anti-)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 parton/particle in the nuclear medium

It would be useful to have more sources of information

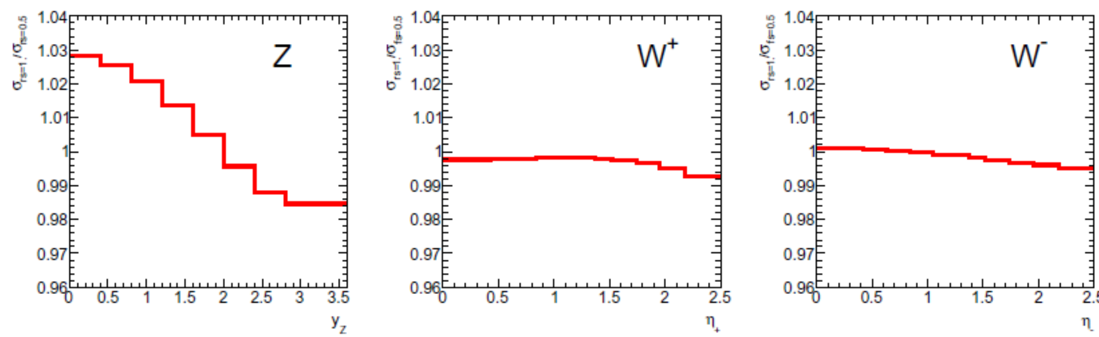
Flavour contributions to W and Z show that s-sbar is prominent in Z production at central rapidity.

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



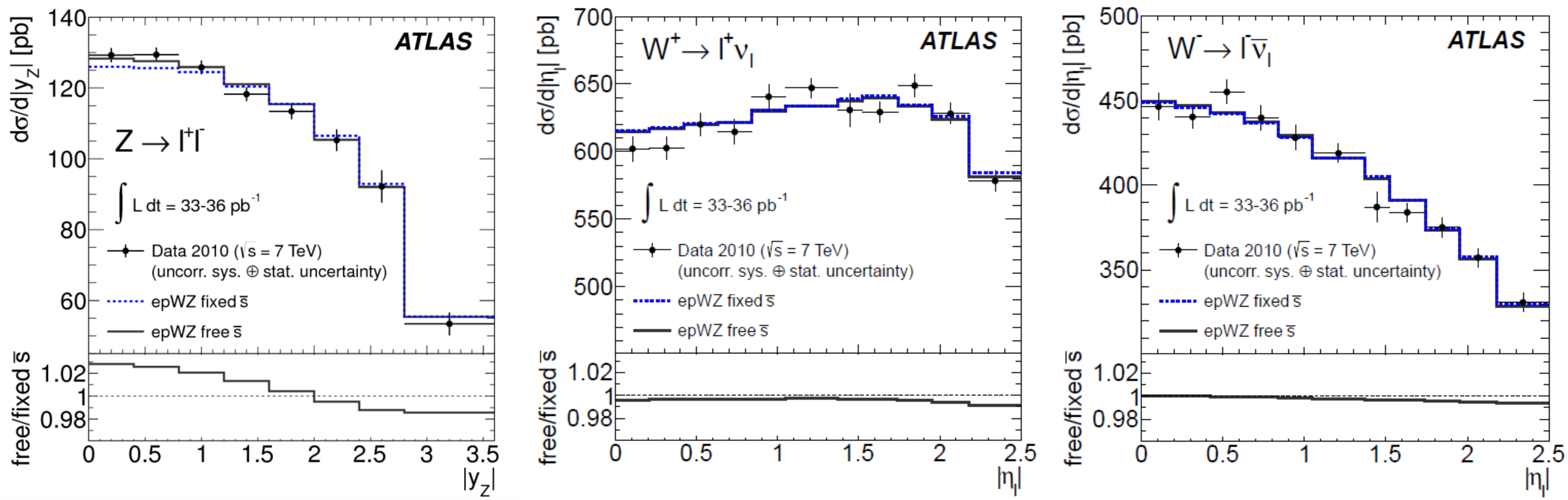
How would Z and W rapidity spectra at the LHC change if strangeness were enhanced?

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



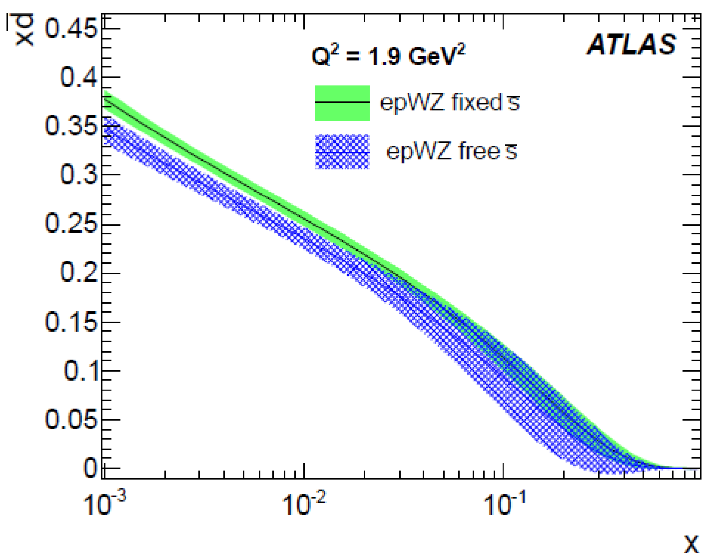
The shape of the Z rapidity distribution is affected – the W distributions are not- thus they give an absolute normalisation for the change in Z

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

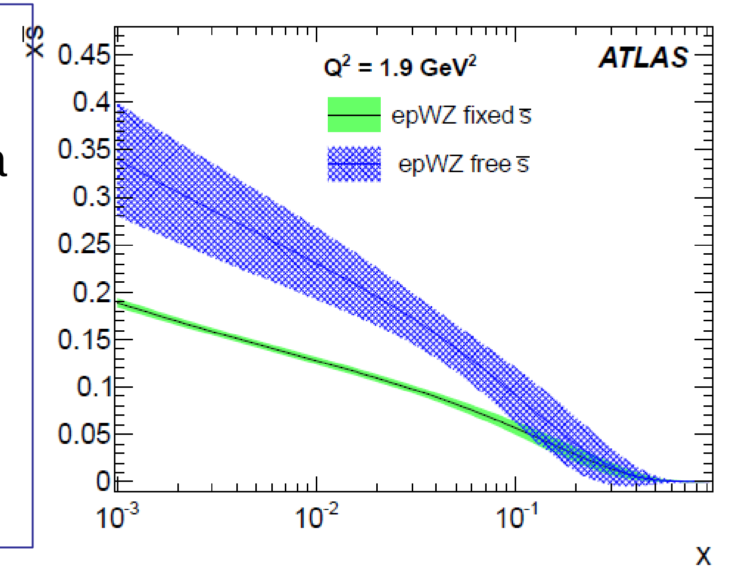


YES WE CAN: ATLAS Phys Rev Lett 109(2012)012001

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



The free strangeness fit describes the data better– χ2/ndp = 33/30 rather than 45/30 and has unsuppressed strange at low-x



How do we get this result? 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. We assume PDF shapes at a low starting scale.

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

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.

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

Obviously there are assumptions in that this number of parameters is adequate. It is chosen by 'saturation of $\chi 2$' such that addition of extra parameters does not improve the fit.
However, some extra parameters do change the shapes somewhat. These are included as part of parametrisation uncertainty.

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

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
- NLO-EW corrections also applied
- HERA data from HERA-I combination 593 data points, 114 sources of correlated systematic uncertainty
- ATLAS W,Z data 30 data points, 31 sources of correlated systematic uncertainty
- MINUIT for χ2 minimisation using a form of χ2 which accounts for correlated systematics using nuisance parameters b_j for each source of systematic j

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

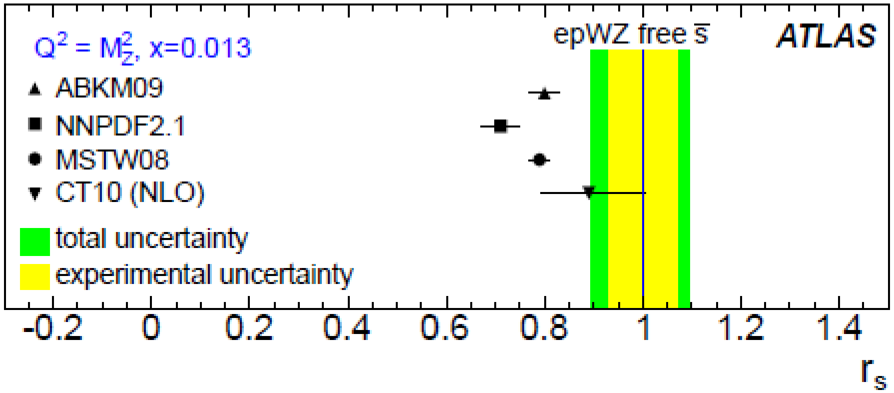
Where μ^i is the measurement for point i , m^i is the prediction, γ^i_j is the fractional systematic errors on point I from source j and δ's are uncorrelated errors.

We produce a new PDF set ATLAS-epWZ12

we chose to summarise the result on strangeness in terms of the ratio of strange to down sea at two x, Q2 points:

$x=0.013$ and $Q^2= M_Z^2$ where the ATLAS data are most sensitive

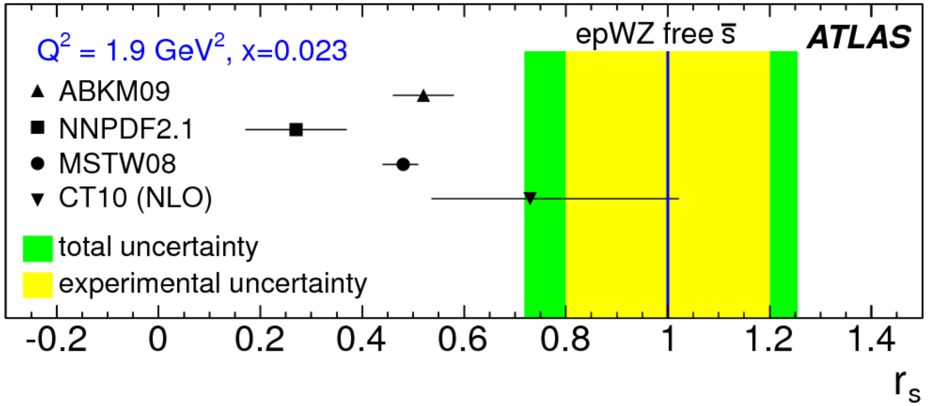
$s/d = r_s = 1.00\ ^{+0.09}/_{-0.10}$



$$r_s = 1.00 \pm 0.07_{exp} \pm 0.03_{mod}\ ^{+0.04}/_{-0.06\ par} \pm 0.02_{\alpha s} \pm 0.03_{th}$$

And $x= 0.023$ and $Q^2=1.9$ GeV^2 the equivalent point at low scale,
the starting point of QCD evolution and closer to the scale at which the original neutrino dimuon data suggested strangeness suppression

$s/d = r_s = 1.00 \pm 0.25$



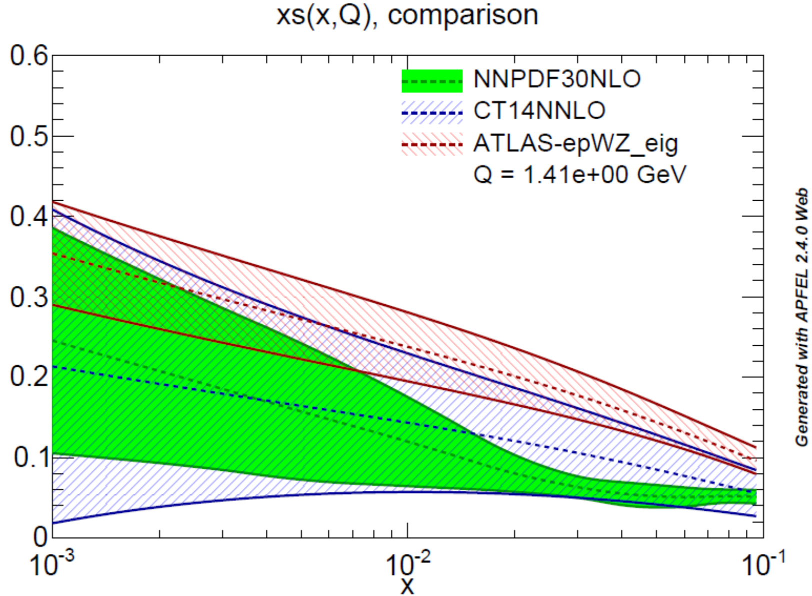
$$r_s = 1.00 \pm 0.20_{exp} \pm 0.07_{mod}\ ^{+0.10}/_{-0.15\ par}\ ^{+0.06}/_{-0.07\ \alpha s} \pm 0.08_{th}$$

There are many cross –checks:

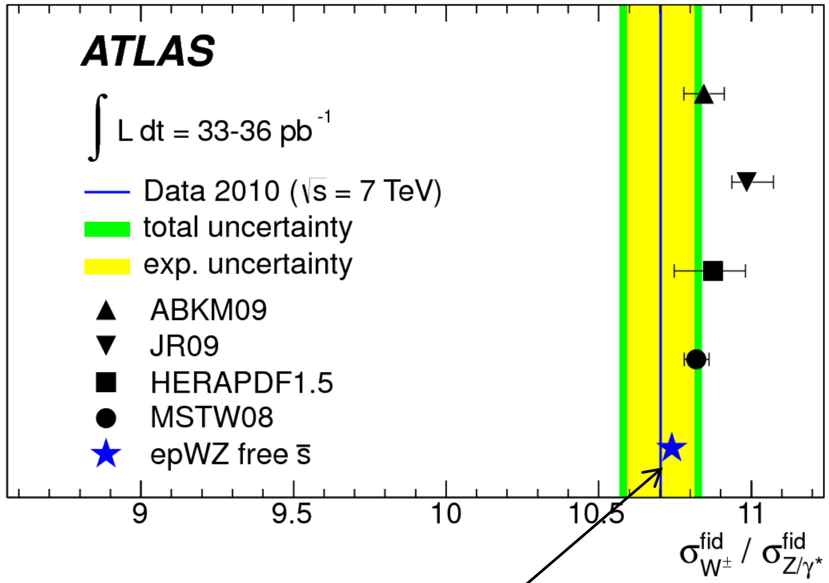
- Do not use the correlated systematic uncertainties $r_s = 0.97 \pm 0.25$
- Do the QCD analysis at NLO the same $r_s = 1.03 \pm 0.19$
- Use a different heavy favour scheme ZMVFN $r_s = 1.05 \pm 0.19$
- Do not assume dbar = ubar at low-x $r_s = 0.96 \pm 0.25$
- Let s ≠sbar, s/sbar= 0.93±0.15 $r_s = 1.00 \pm 0.25$
- Fit Tevatron data $r_s = 0.66 \pm 0.29$, fit ATLAS+Tevatron $r_s = 0.95 \pm 0.17$
- Fit ATLAS W-asymmetry and Z shape only $r_s = 0.92 \pm 0.31$
  this is similar to CMS analysis but it lacks information on the relative normalisation of W and Z

It is essentially the SHAPE of the Z rapidity distribution plus the W/Z normalisation which constrain the strange quark for $10^{-3} < x < 10^{-1}$
Having just W-asymmetry and the shape of the Z does not give as strong an effect

Compare the ATLAS PDF to NNPDF3.0 and CT14 for strange

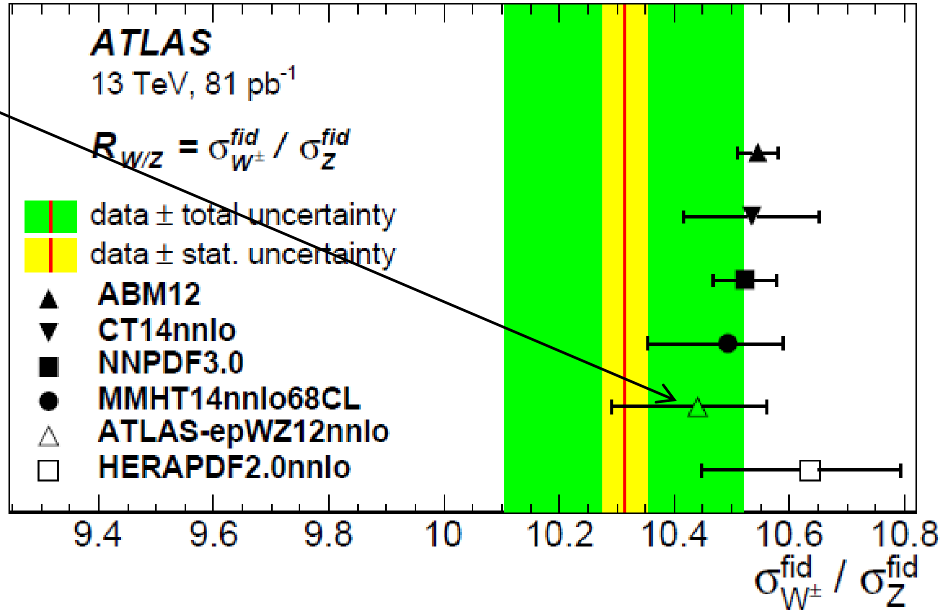


Unsuppressed strangeness results in more Z and a low W/Z ratio and we see this.

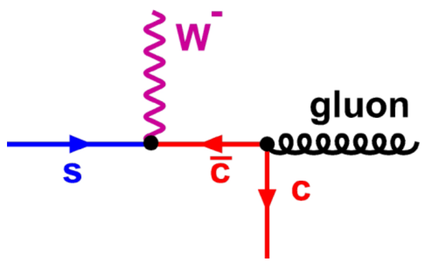


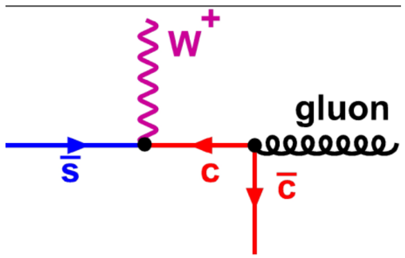
This is our own ATLAS-epWZ12 fit

We ALSO see it in the new 13 TeV data



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





A gluon from one proton and a (anti-)strange quark from the other dominantly produce $W^{-(+)}$ + charm(anti-charm)

How to detect this?

ATLAS analysed W+c-jet W+D, W+D* channels

JHEP05(2014)068

Using $W \to e\,\nu$, $\mu\,\nu$ channels of both charges- then combining e and μ.

$p_T^{lepton} > 20$ GeV, $|\eta^{lepton}| < 2.5$, $p_T^{\nu} > 25$ GeV, $m_T^{W} > 40$ GeV

Identifying c-jet via a further decay to a soft muon within the jet, with opposite sign to the lepton from the W

Identifying D or D* of opposite sign to the lepton from the W, from the decay modes $D^+ \to K^- \pi^+\pi^+$ and $D^{*+} \to D^0 \pi^+$ with $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^0$, $D^0 \to K^-\pi^+\pi^-\pi^+$ and their charge conjugates.

The opposite sign (SS) criterion reduces backgrounds substantially. The cross section is presented as the difference between OS –SS which also Helps to disentangle contributions from the parton shower in MC modelling

Compare these data to theoretical predictions

Theoretical predictions come from aMC@NLO with Herwig++ to model the parton shower, hadronisation and the underlying event.
The predictions for the charmed hadron production fractions are corrected to the average of measurements of obtained in e^+e^- and ep events

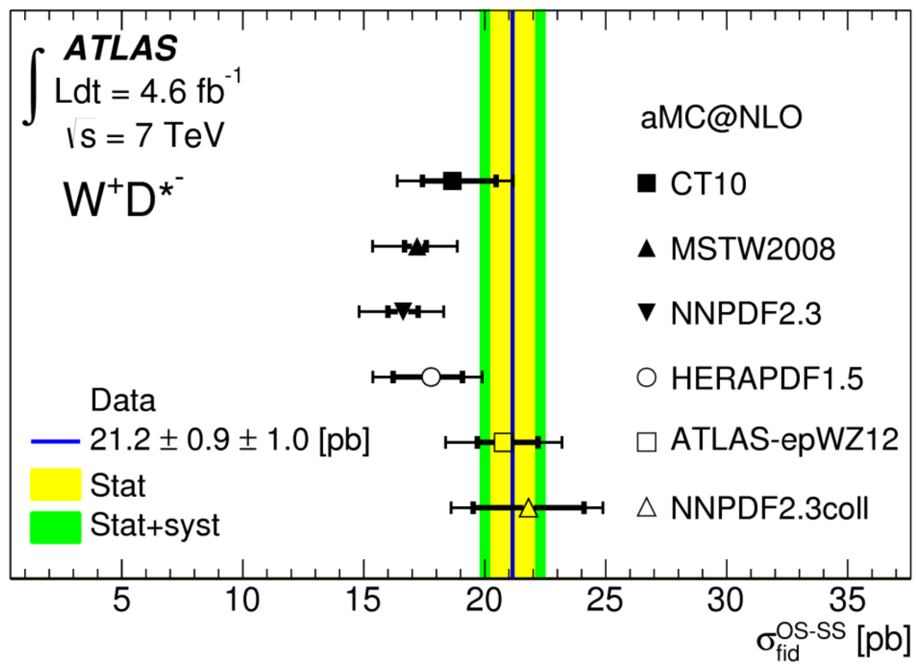
MSTW2008, NNPDF2.3, HERAPDF1.5 have suppressed strangeness wrt light quarks for all x

CT10 has suppressed strangeness at large x, but far less so at x~0.01 where ATLAS is sensitive

ATLAS –epWZ12 comes from the previous ATLAS inclusive analysis and has strange equal to light quarks at x~0.01

NNPDF2.3coll is a fit to only collider data and has enhanced strangeness at x~0.01

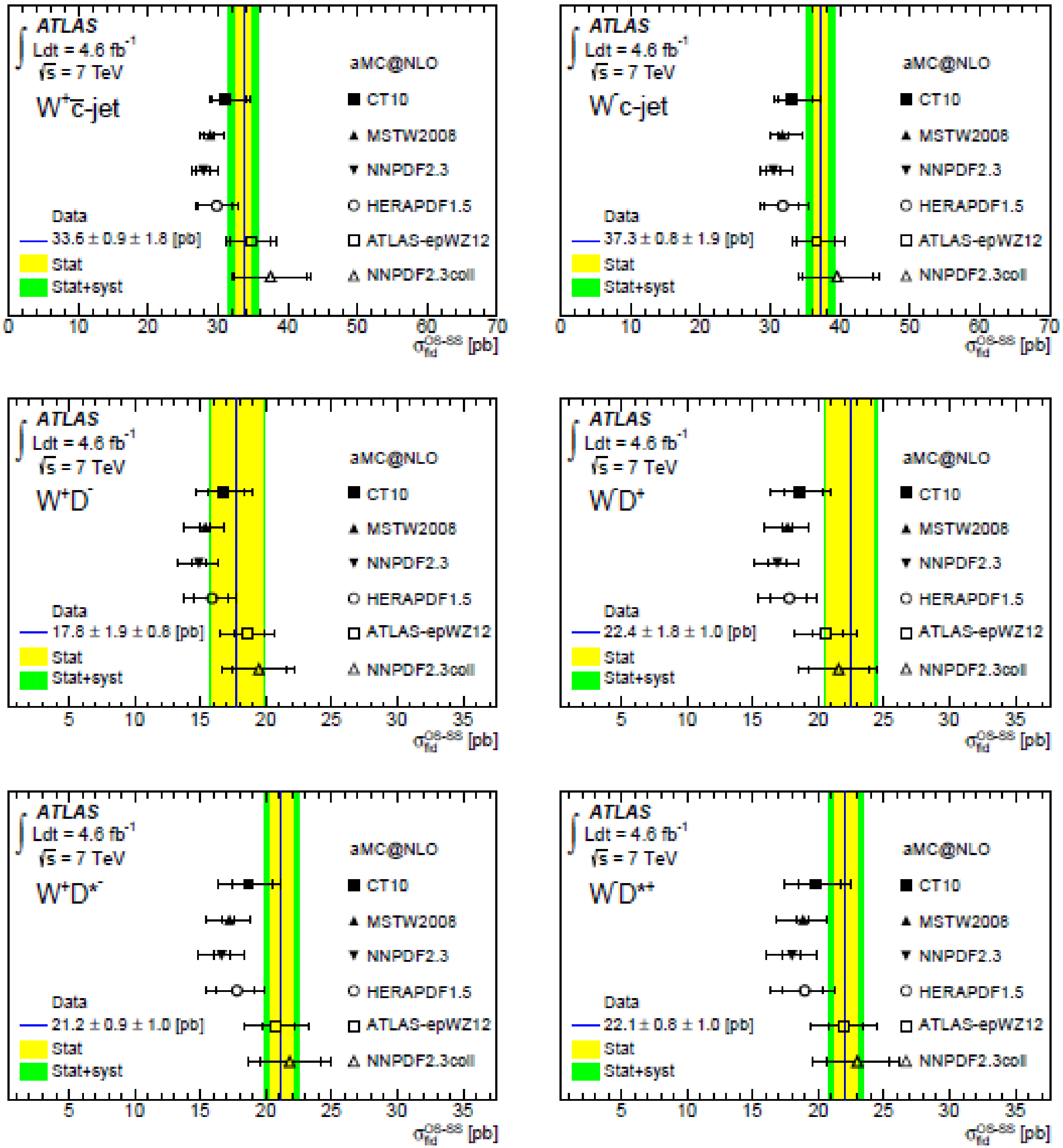
The difference between the cross-sections for opposite-sign and same sign events in the fiducial volume



In addition to uncertainties from the PDFs
Scale uncertainties
Uncertainties from charm fragmentation
Uncertainties from the parton shower

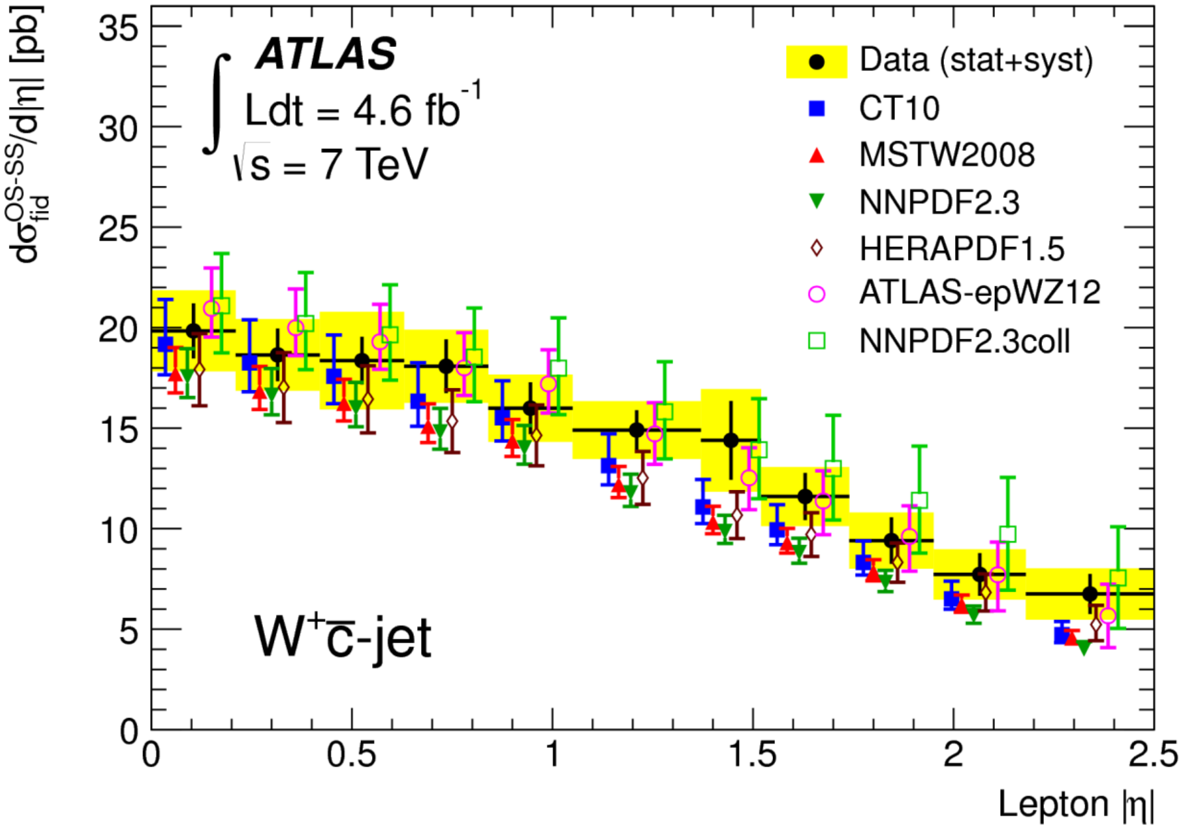
The data for W^+D^{*-} prefer the equal/enhanced strangeness

We get the same result in all channels W^+D^{*-} , W^-D^{*+} , W^+D^- , W^-D^+ , $\overline{W}^+$ c-jets, W^+ c-jet



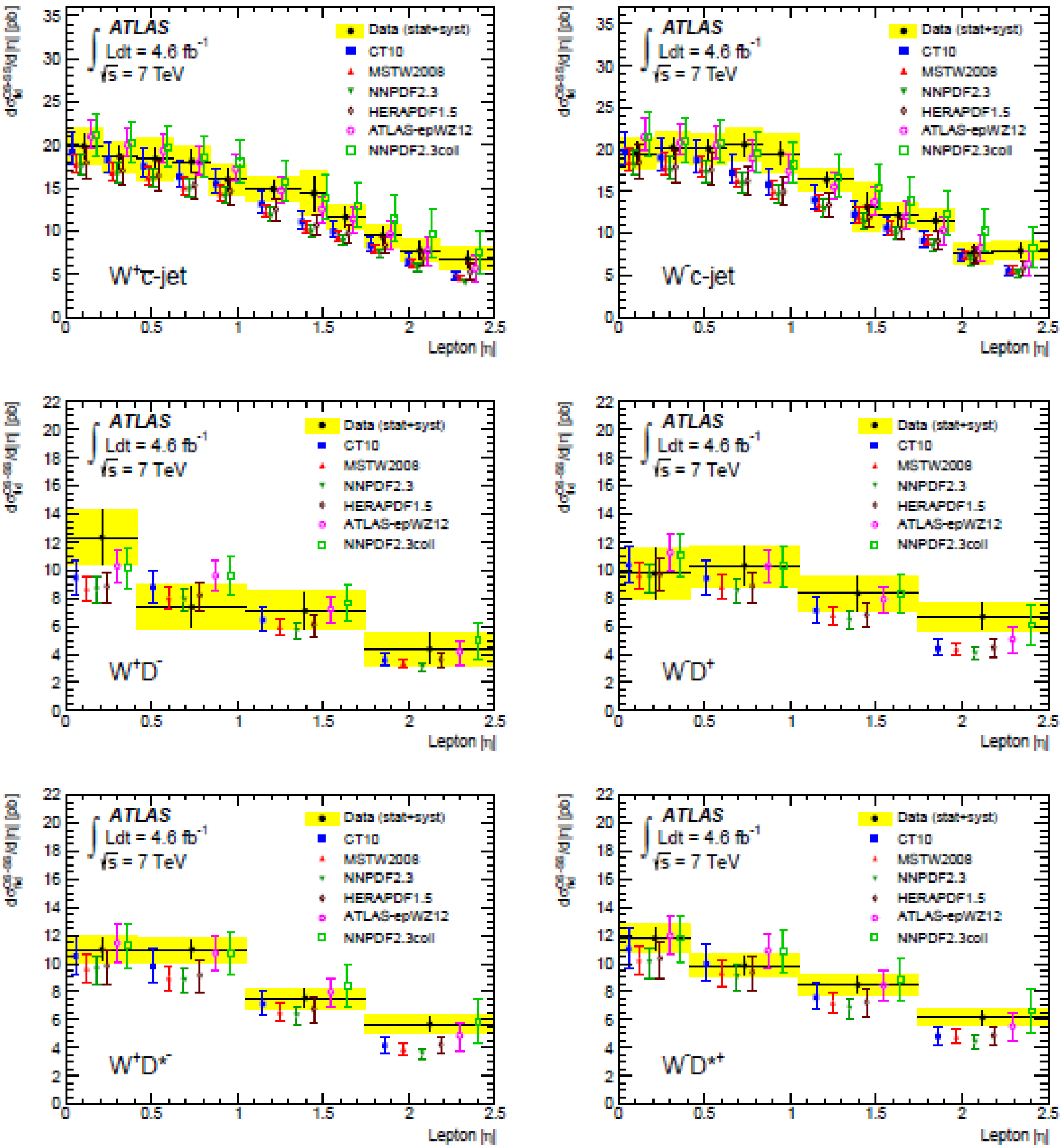
The data for W + c in all channels prefer the equal/enhanced strangeness

There is much more information in the differential distributions of these data as a function of the lepton pseudo-rapidity



There is much more information in the differential distributions of these data

Here all 6 channels are shown as a function of the lepton pseudo-rapidity



In all cases the data favour the predictions based on unsuppressed strangeness

We can quantify this..

$$\chi^2 = \sum_{k,i} w_k^i \frac{\left[\mu_k^i - m^i\left(1 + \sum_j \gamma_{j,k}^i b_j + \sum_j (\gamma^{\rm theo})_{j,k}^i b_j^{\rm theo}\right)\right]^2}{(\delta_{{\rm sta},k}^i)^2 \Delta_i^k + (\delta_{{\rm unc},k}^i m^i)^2} + \sum_j b_j^2 + \sum_j (b_j^{\rm theo})^2$$

where

$$\Delta_i^k = \mu_k^i m^i \left(1 - \sum_j \gamma_{j,k}^i b_j - \sum_j (\gamma^{\rm theo})_{j,k}^i b_j^{\rm theo}\right).$$

Define a χ2 which takes into account correlated experimental uncertainties and theoretical uncertainties, via nuisance parameters b_j for each source of systematics j, for percentage systematic uncertainties γ^i_{jk} for each data point i, data set k

	CT10	MSTW2008	HERAPDF1.5	ATLAS-epWZ12	NNPDF2.3	NNPDF2.3coll
$W^+\bar{c}$-jet (χ^2/ndof)	3.8/11	6.1/11	3.5/11	3.1/11	8.5/11	2.9/11
W^-c-jet (χ^2/ndof)	9.0/11	10.3/11	8.3/11	6.3/11	10.5/11	6.1/11
W^+D^- (χ^2/ndof)	3.6/4	3.7/4	3.7/4	3.4/4	3.8/4	3.4/4
W^-D^+ (χ^2/ndof)	3.7/4	4.6/4	3.3/4	2.0/4	4.7/4	1.6/4
W^+D^{*-} (χ^2/ndof)	2.9/4	6.0/4	2.2/4	1.7/4	8.1/4	1.6/4
W^-D^{*+} (χ^2/ndof)	3.0/4	4.4/4	2.4/4	1.6/4	4.2/4	1.4/4
$N_{\rm exp}$	114	114	114	114	114	114
$N_{\rm theo}$	28	22	16	20	40	40
Correlated χ^2 (exp)	0.8	1.8	0.9	1.1	2.2	1.0
Correlated χ^2 (theo)	6.2	1.9	2.6	0.1	7.4	0.2
Correlated χ^2 (scale)	0.6	2.5	1.1	0.0	2.7	0.0
Total χ^2/ndof	33.6/38	41.3/38	28.0/38	19.2/38	52.1/38	18.2/38

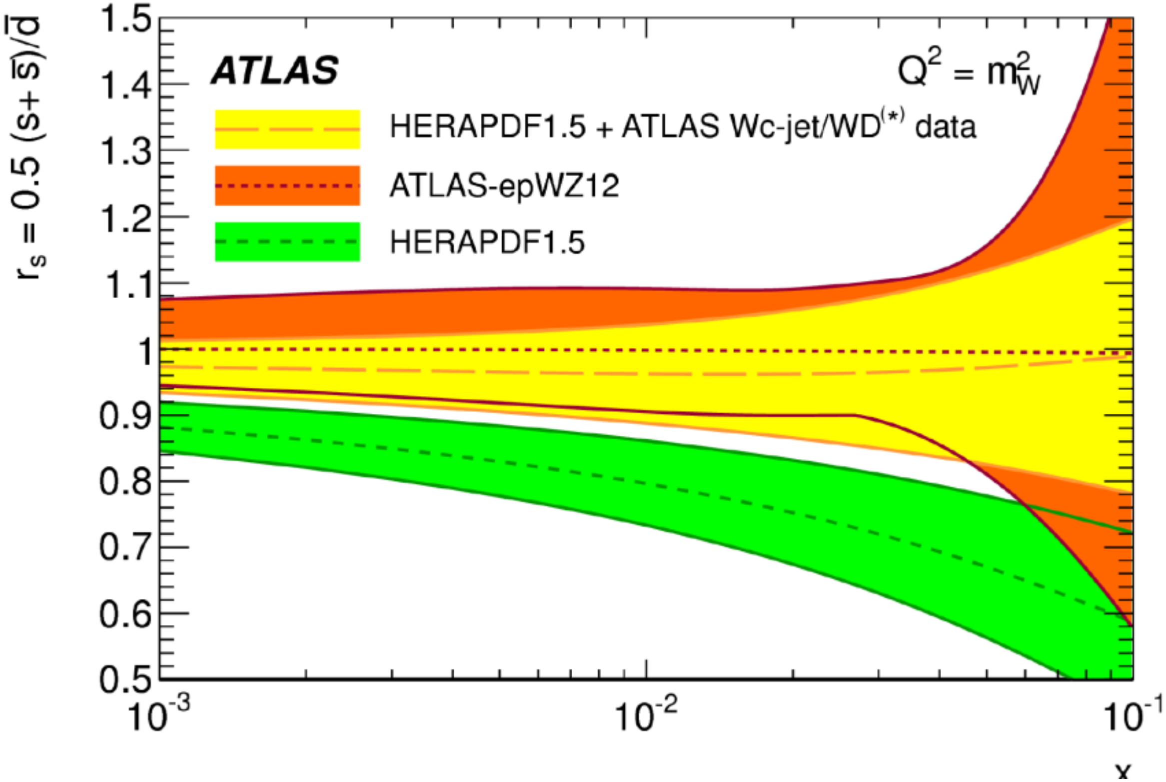
114 sources of correlated experimental uncertainties
Differing numbers of theory uncertainties depending on number of PDF parameters. Theory uncertainties include scale uncertainty and the modelling of the charm fragmentation function

To go further consider one of the uncertainties of the HERAPDF

This PDF is constructed to have a single uncertainty source representing the fraction of strangeness in the proton.
This fraction can be varied and the fit using the HERAPDF repeated to obtain the best χ2.
A value of

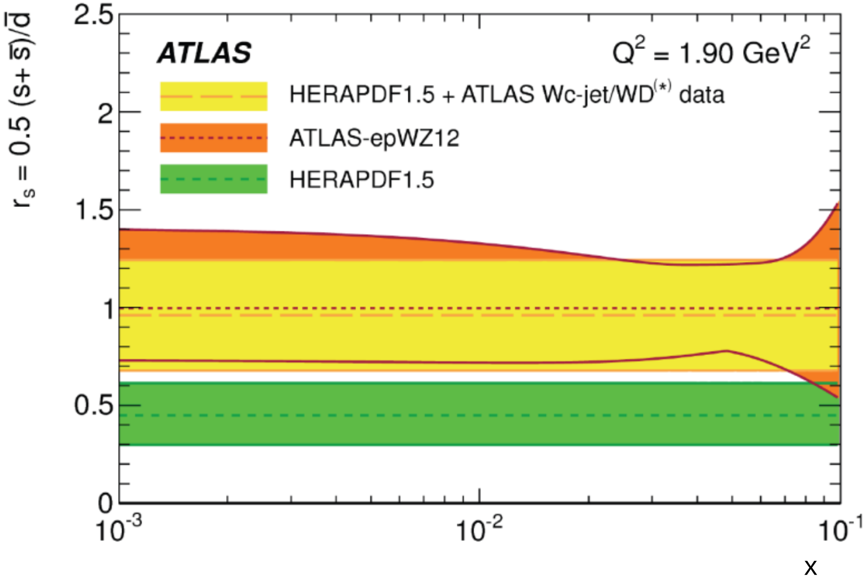
$$r_s \equiv 0.5(s+\bar{s})/\bar{d} \quad = 0.96\,^{+0.16}_{-0.18}\,^{+0.21}_{-0.24}$$

Is obtained, where the first uncertainty comes from the experimental AND other PDF uncertainties and the second is from the scale uncertainty.



The result is shown here compared to the result ATLAS-epWZ12 from the previous inclusive W, Z analysis and compared to the HERAPDF

The result is independent of x
In the x region in which ATLAS is sensitive and applies at scale $Q^2 \sim m_W^2$

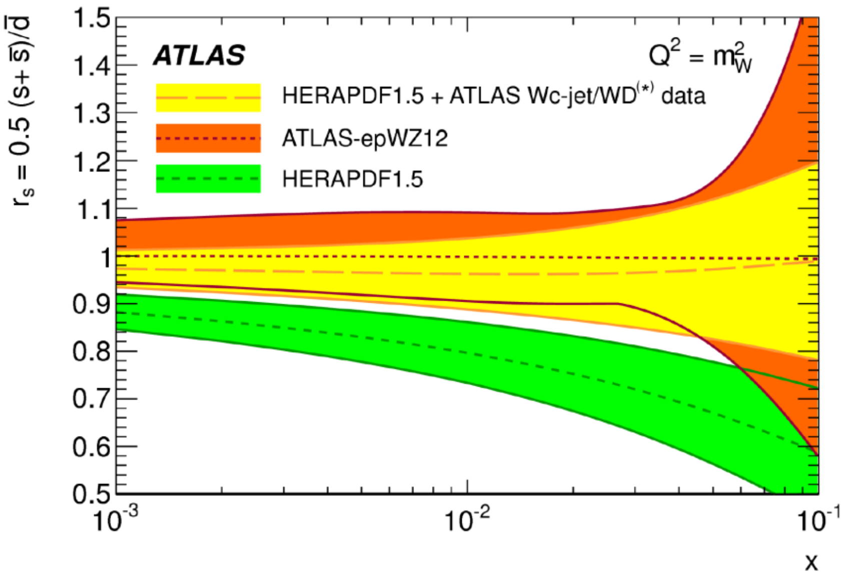


Since PDF fitting starts with assumptions as to the PDF parameters- and the fraction of strangeness- at low scale

And since the neutrino data which originally suggested suppressed strangeness was also taken at low scale

We also show the comparison of strangeness fraction at Q^2 =1.9 GeV^2 where HERAPDF has an assumption that the strangess fraction is x indepedent

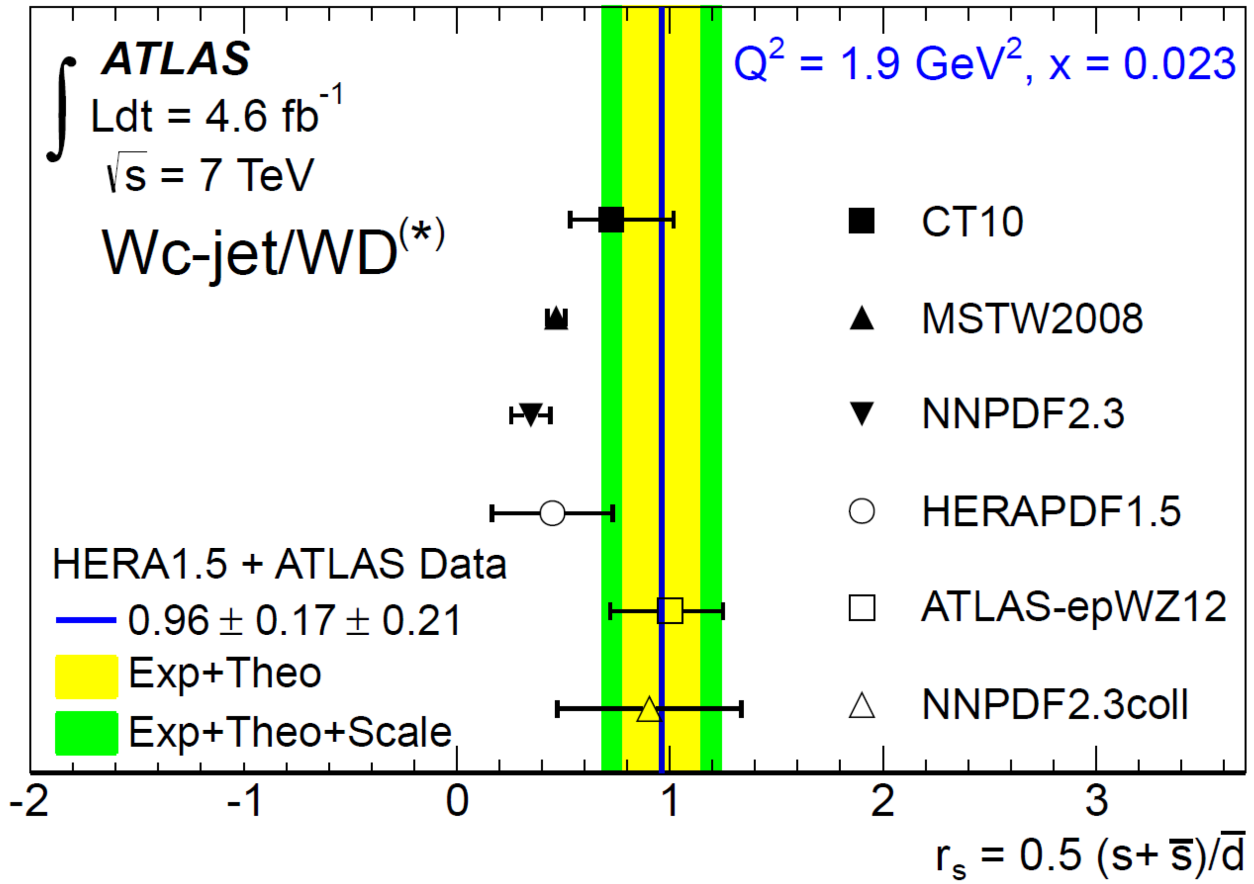
$0.44^{+0.17}_{-0.14}$



After QCD evolution to $Q^2 \sim M_W^2$

This is no longer x independent since quarks with higher x split to quark-gluon of lower-x and then the gluon splits to q-qbar flavour independent at even lower x such that flavour symmetry is recovered at low x and high scale even starting from a very suppressed value.

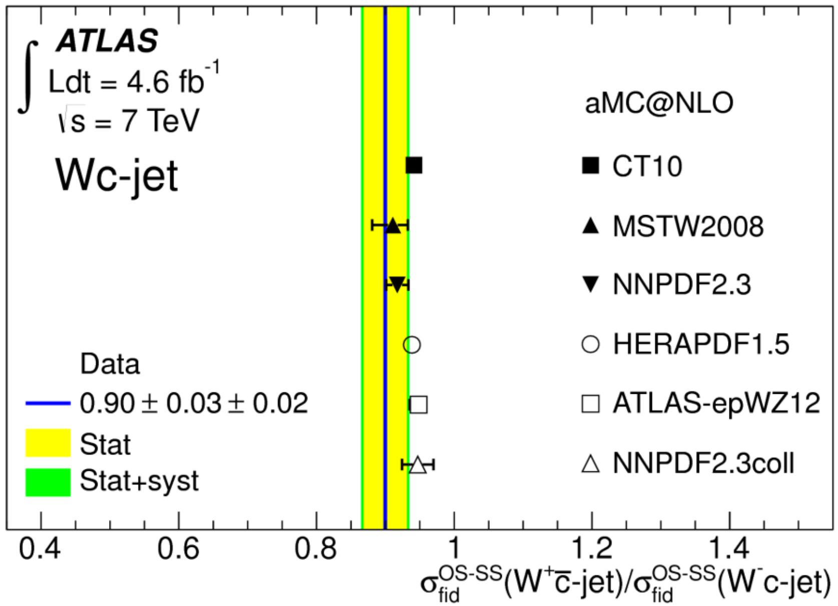
To summarise: the level of strangeness suppression for various PDFs plus the ATLAS analyses is shown here, where the present result for W+c is shown in yellow and green and the previous ATLAS inclusive W,Z result is shown as ATLAS-epWZ12

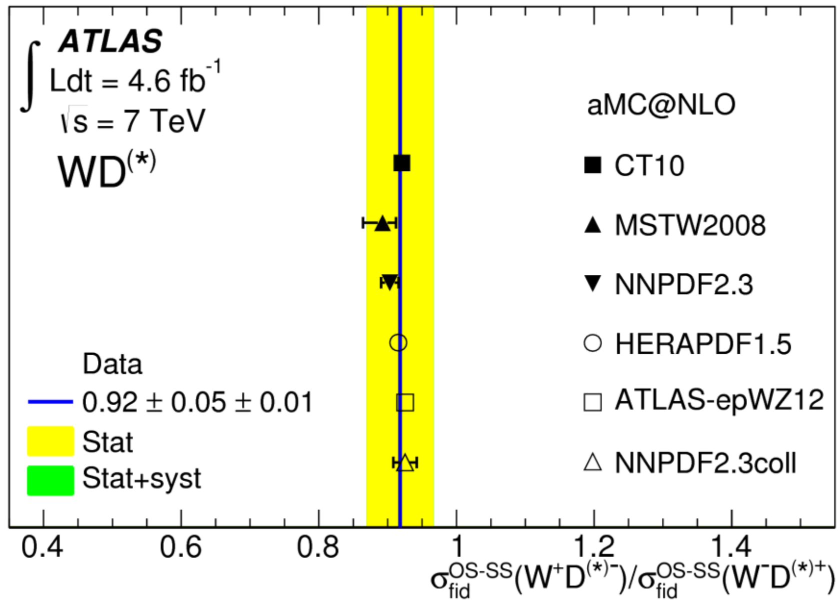


Looking at any difference between W^+ and W^- channels can give information on the difference between anti-strange and strange

But note: the Cabbibo suppressed d → c and dbar → cbar is not equal since d also includes valence quarks so the expected ratio of W^+/W^- channels is not unity even if s=sbar

The CT10 PDF and the HERAPDF have s=sbar and thus can be used to judge the level of any strangeness asymmetry in the data





The level of asymmetry in the data is

$A_{s\text{-}sbar}$ = (s - sbar)/s = 2 ± 3%

And is thus ignored

Summary

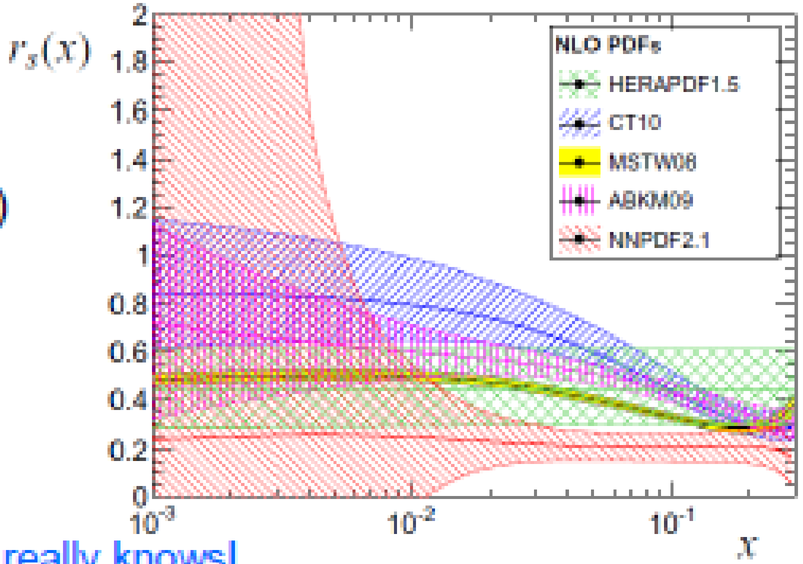
ATLAS sees unsuppressed strangeness in the parton sea for x~0.01
From two independent observations

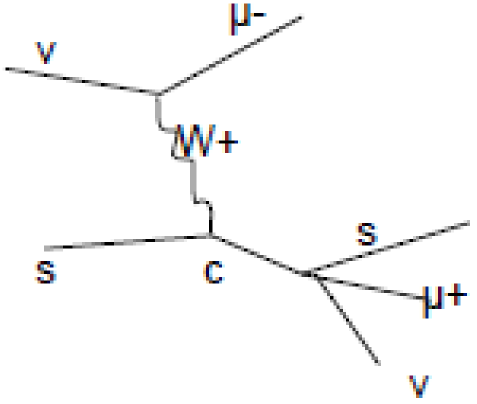
- W,Z inclusive measurement Phys Rev Lett 109(2012)012001
- W+charm JHEP05(2014)068

New high precision W,Z data with > 100 times more luminosity are coming soon extras

What is the ratio of the strange parton distribution to the light quark PDFs?

Ratio xs(x)/xd(x)





Nobody really knows!

We had a traditional view that $r_s(x)$ ~0.5. Why?

Because of neutrino opposite-sign dimuon data (NuTeV CCFR)

But this has been fed into fits CT10, NNPDF, MSTW, ABKM and look at the large discrepancies!

The NuTeV data only provides any information for x~0.1, plus it needs nuclear target corrections, plus it needs understanding of the s →c threshold transition- note that charm treatment differs between the groups.

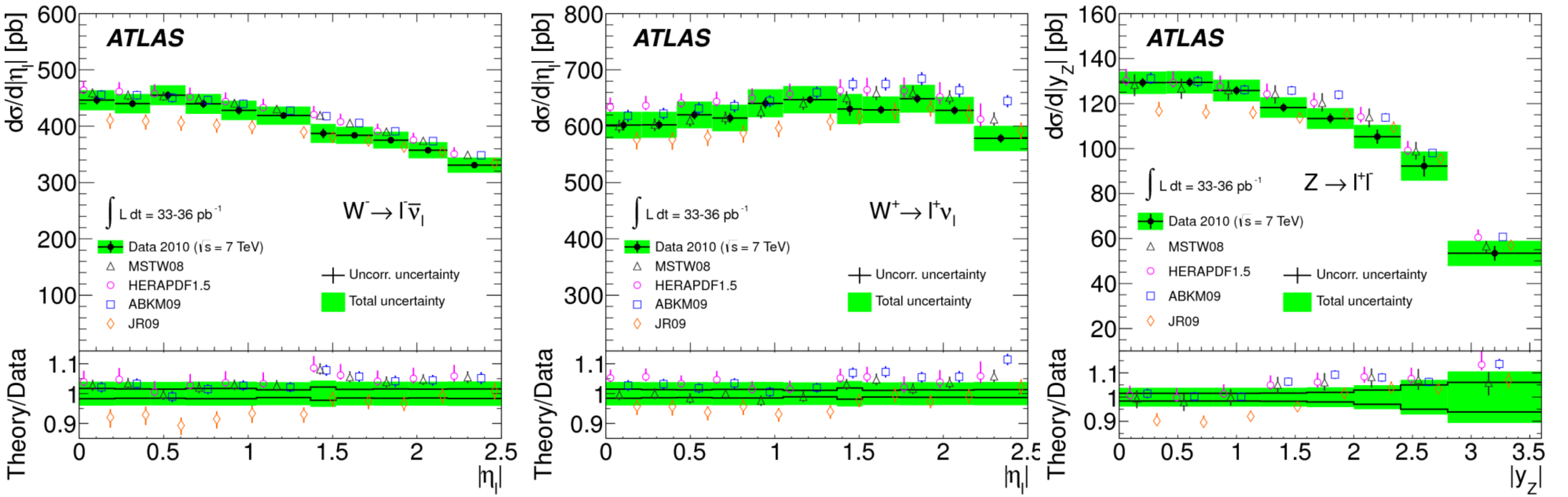
20

W and Z differential cross sections

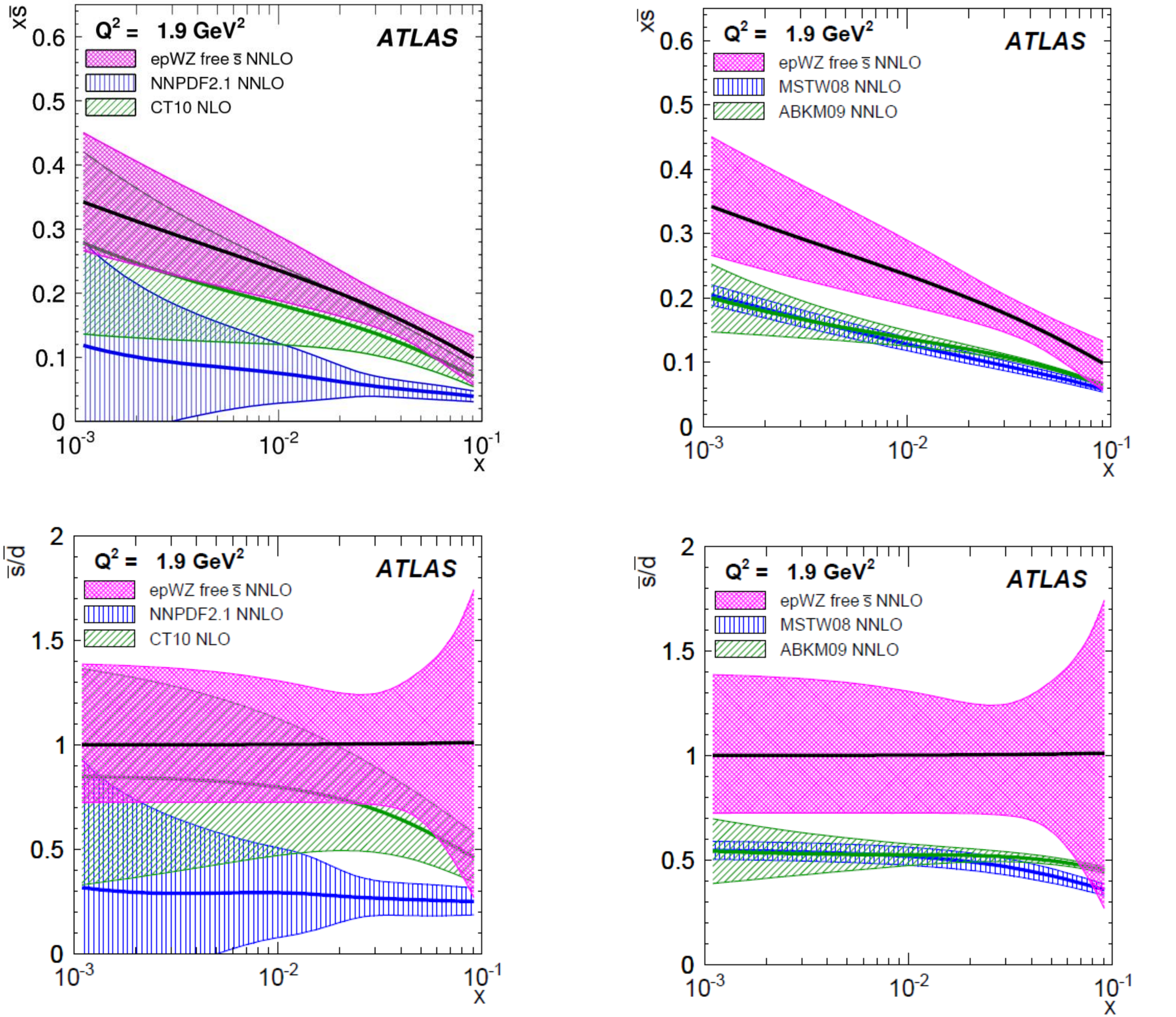
ATLAS Measurement of W and Z cross sections in electron and muon channels

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

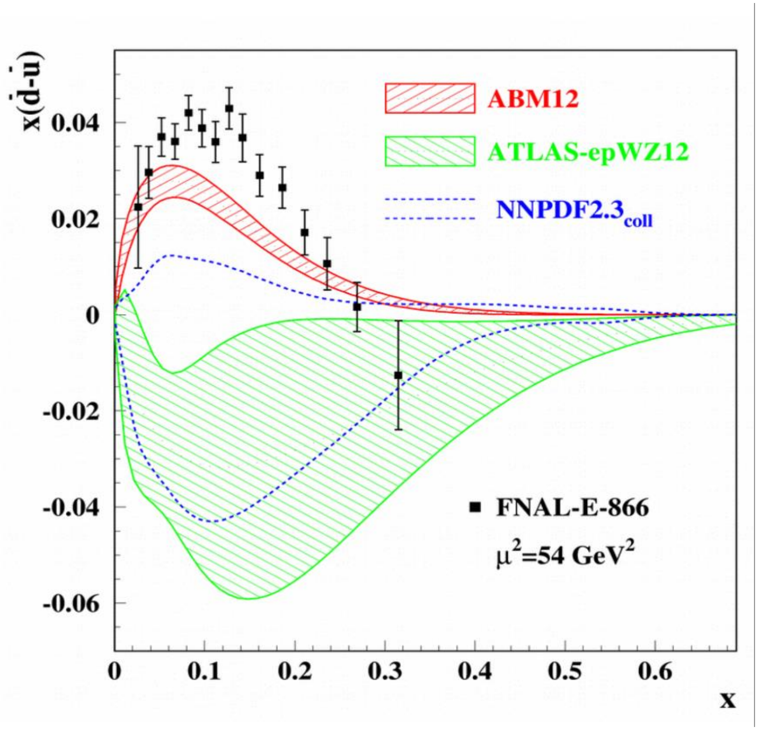

xs̄
Q² = 1.9 GeV²
ATLAS
epWZ free s̄ NNLO
NNPDF2.1 NNLO
CT10 NLO
x
xs̄
Q² = 1.9 GeV²
ATLAS
epWZ free s̄ NNLO
MSTW08 NNLO
ABKM09 NNLO
x
s̄/d̄
Q² = 1.9 GeV²
ATLAS
epWZ free s̄ NNLO
NNPDF2.1 NNLO
CT10 NLO
x
s̄/d̄
Q² = 1.9 GeV²
ATLAS
epWZ free s̄ NNLO
MSTW08 NNLO
ABKM09 NNLO
x

Now let's discuss a criticism of our previous analysis namely:

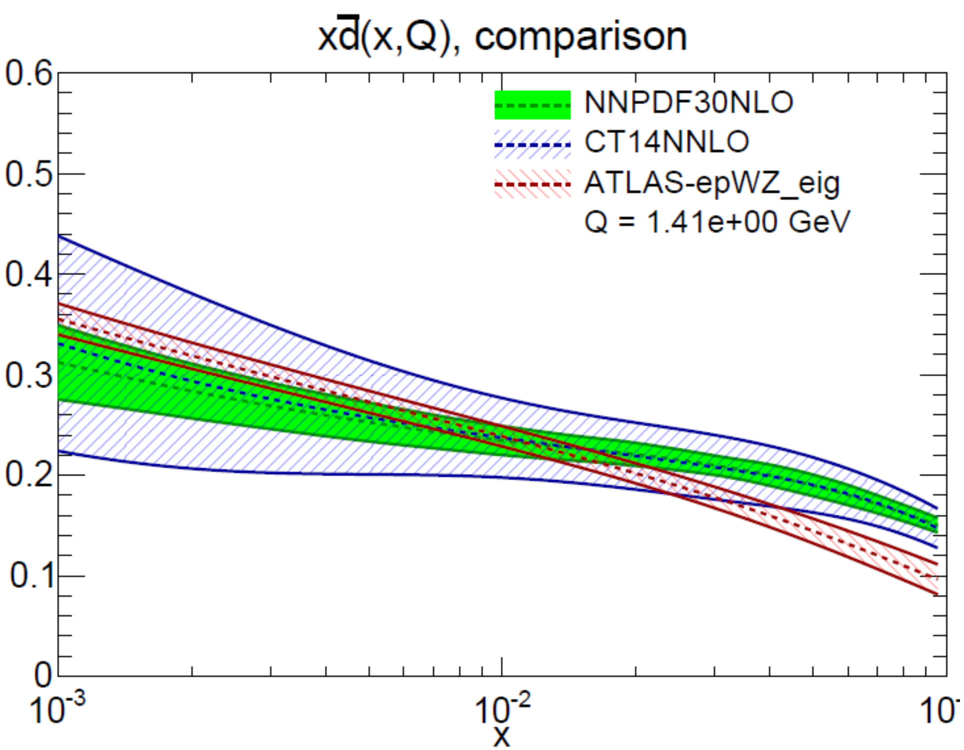
That our large strangeness only comes because we have a dbar-ubar which is negative
He reasons that because we parametrise strange as a fraction of d-type sea our large strange gives a corresponding dbar which is too small.
llustrate this with this plot of dbar-ubar predictions versus E866 pseudo-data

What is E866 pseudodata?
It is an LO extraction of dbar-ubar from E866 Drell-Yan data for pp and pD.

If our dbar were increased
To cover these data then would our strange go down?
At x ~0.1 YES, but not where ATLAS is sensitive at x ~0.01

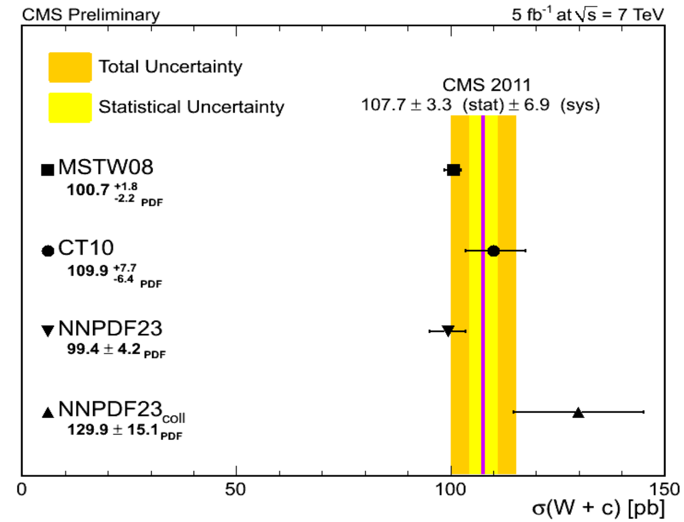


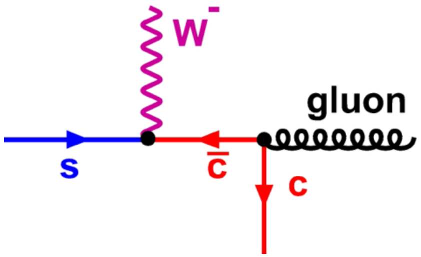
Compare the ATLAS PDF to NNPDF3.0 and CT14 for dbar

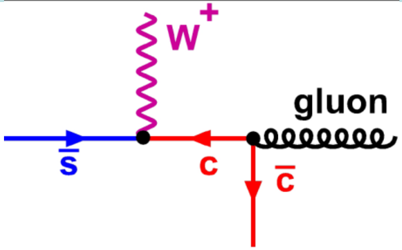


Another process which can yield information on strangeness is W+c production

CMS SMP-12002

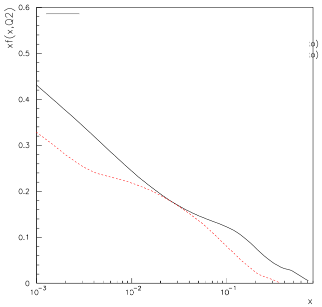




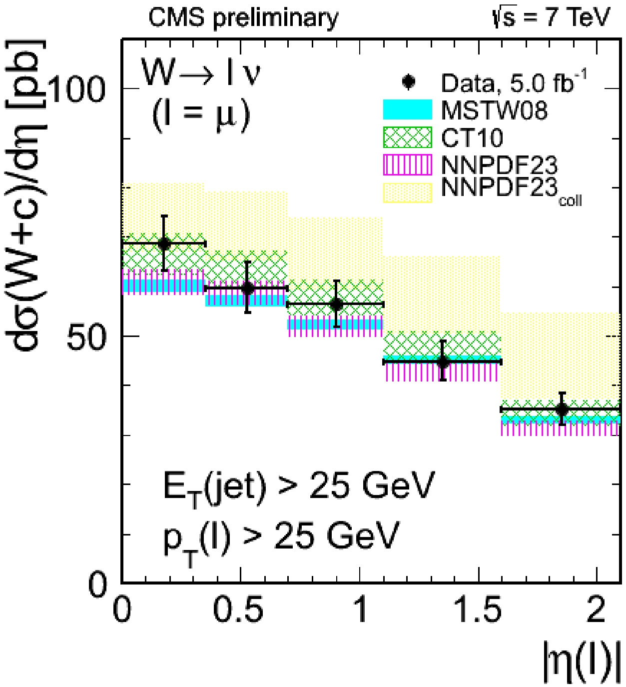


First compare W +c cross section for W's of both charges to predictions.

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



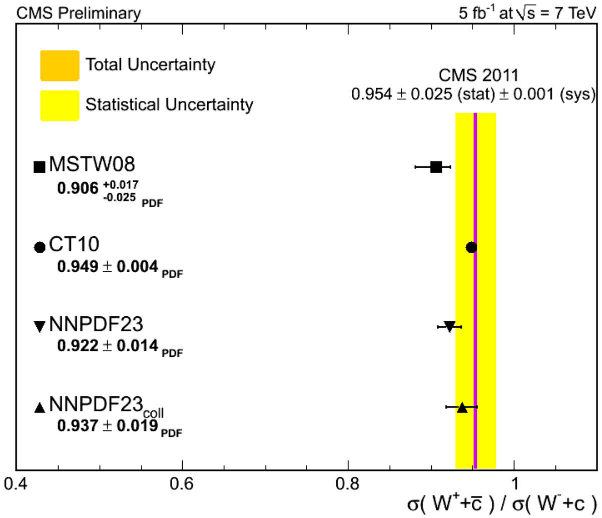
Q^2=2 GeV^2
NNPDF23(Coll)
Strange
Downsea



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.

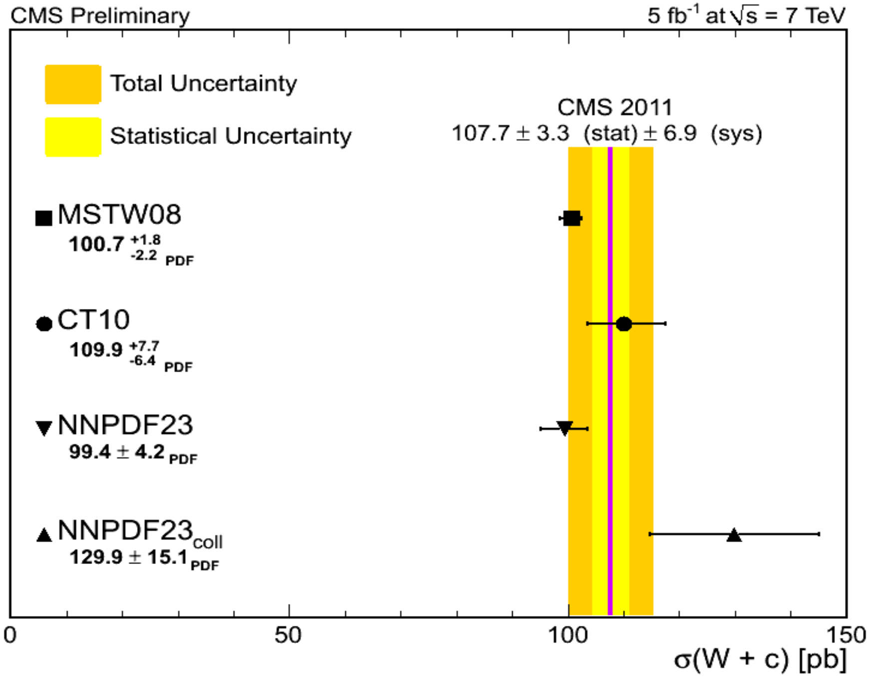
Strangeness asymmetry s ≠ sbar is small for all PDFs, for CT it is zero

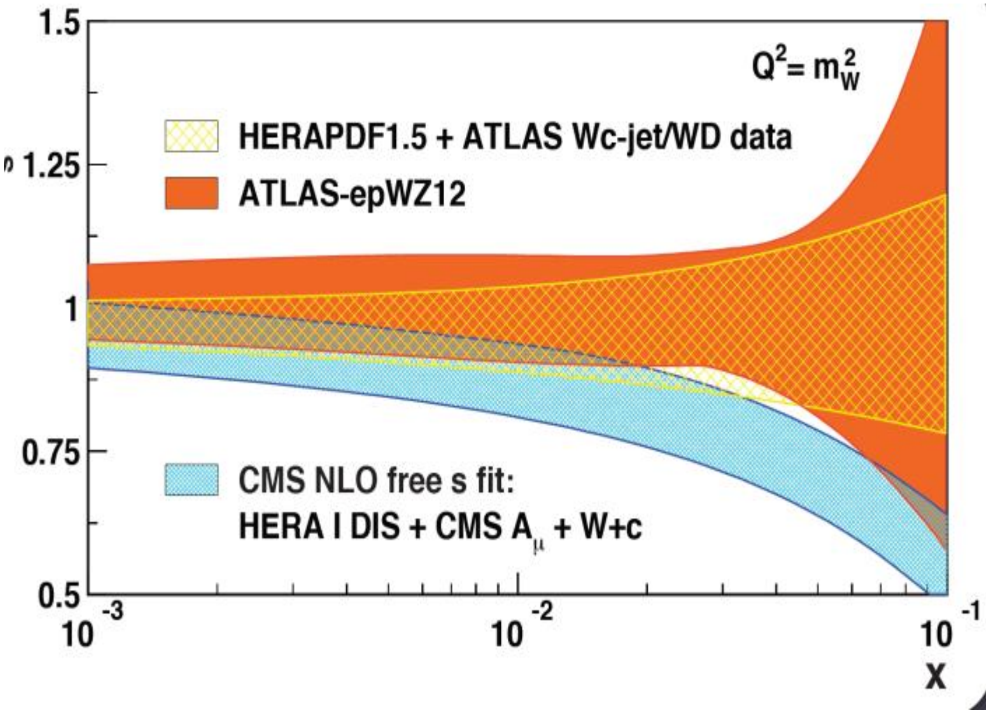


Is there a disagreement with CMS W+c? - marginally

Note the CMS analysis is done with only the W+c-jet channels

And only to $|\eta| < 2.0$





CMS favours the CT10 level of strangeness suppression

r_s ~0.7 rather than either rs ~0.5 or equal rs =1.0