The proton PDF from W+jet data at the ATLAS detector

Mark Sutton

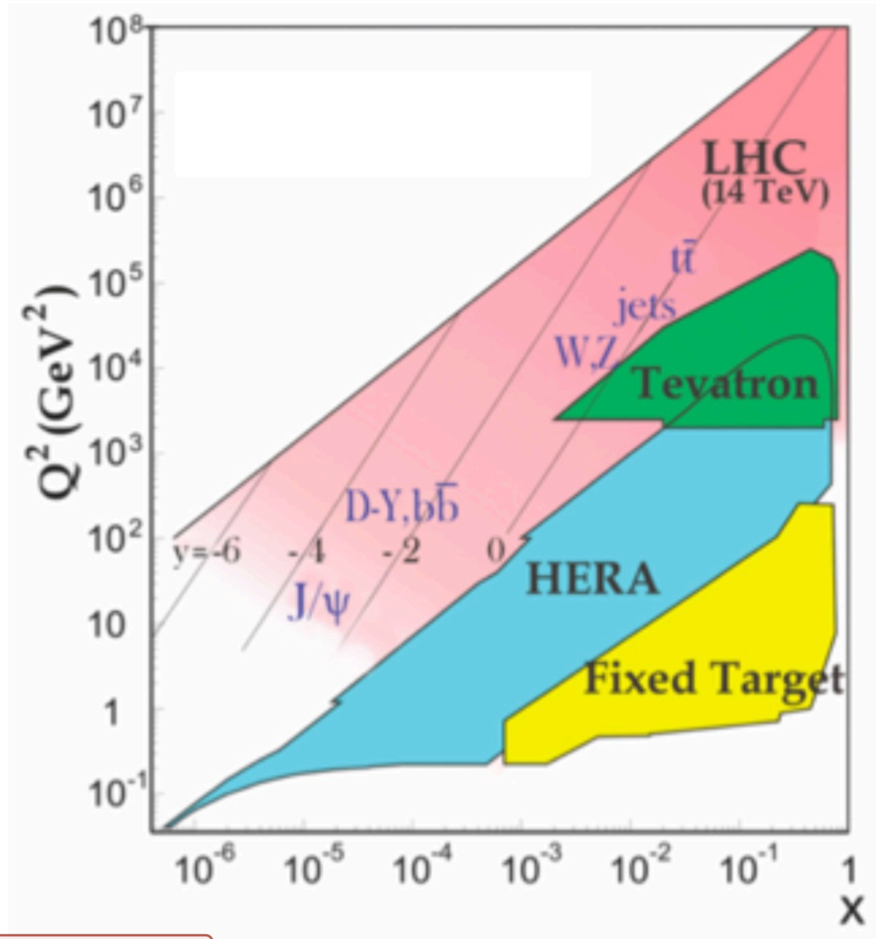
The University of Sussex

On behalf of the ATLAS Collaboration

Preface

- The LHC has performed extremely well during Run 1 and Run 2
- Information on the internal structure of the proton from the parton distribution functions (**PDFs**)
- The LHC has unprecedented coverage of the kinematic plane, extending by several orders of magnitude

- ATLAS has a large, and developing portfolio of precision measurements with the potential to constrain the PDFs in the proton
  - Will concentrate on what constraints we can obtain using data from inclusive ATLAS W and Z production, and recent W+jets data



- For LHC collisions with two momentum fractions, x_1 and x_2

$$d\sigma_X = \sum_{i,j} \int dx_1 \int dx_2 \, f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \times \hat{\sigma}_{ij \to X}(x_1, x_2, \mu_R^2)$$

PDFs

Hard subprocess

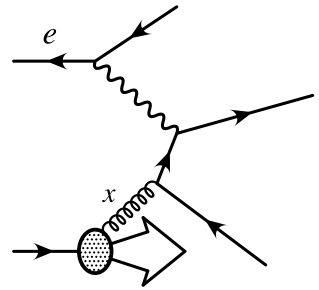
- The LHC provides unprecedented access to a previously unexplored region of phase space essential for the discovery and understanding of any new physics

Different final states inform different subprocesses

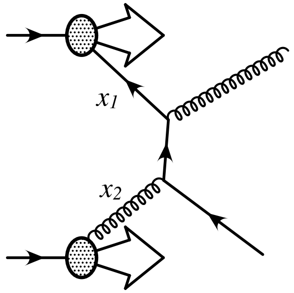
- DIS data constrains quarks at low-x
  - Born level scattering off of quarks, one momentum parton fraction x

$$d\sigma_{\mathrm{DIS}} \sim (1+(1-y_{\mathrm{Bj}})^2)F_2(x,Q^2) - y_{\mathrm{Bj}}^2 F_L(x,Q^2)$$

$$F_2 = x\sum_q e_q^2(q(x)+\bar{q}(x))$$



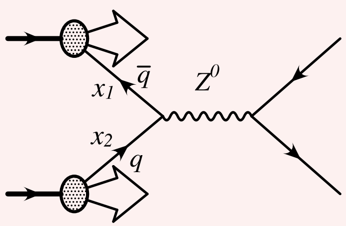
- Sensitive to the gluon distribution through $\mathcal{O}(\alpha_s)$ corrections
  - For LHC collisions with two momentum fractions, x_1 and x_2

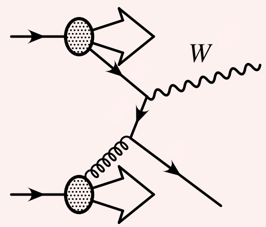


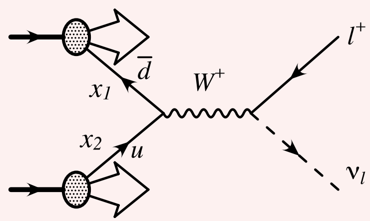
$$d\sigma = \sum_{i,j}\int dx_1 \int dx_2\ f_i(x_1,\mu_F^2) f_j(x_2,\mu_F^2)\ \hat{\sigma}_{ij}(x_1,x_2,\mu_R^2)$$

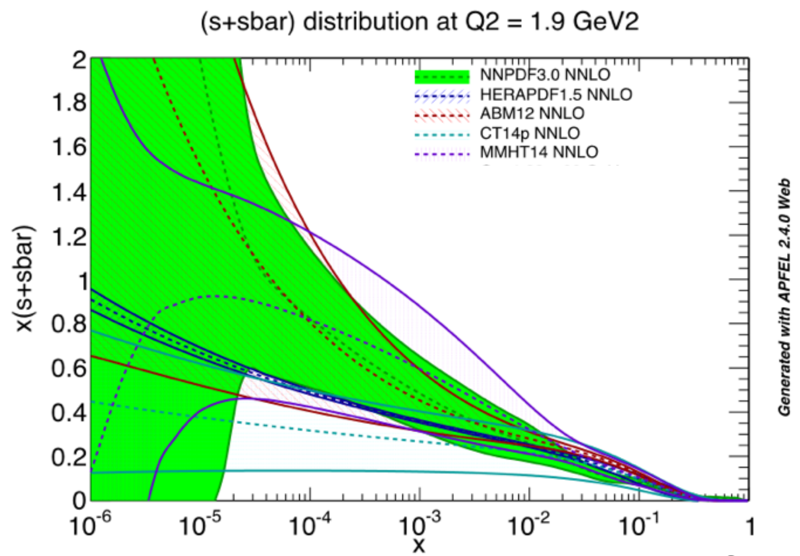
  - Inclusive jets, dijet + trijet production, ttbar, inclusive photon …
    all directly sensitive to the **gluon distribution**, the **strong coupling,** and the valence quarks at high E_T

- Electroweak boson production
  - Inclusive W, Z and asymmetries: **quark flavour separation**
  - Off peak Drell-Yan: u, d at high or low-x
  - W+charm: sensitivity to the **s-quark**
  - **W, Z + jets** (jet need not be unobserved)









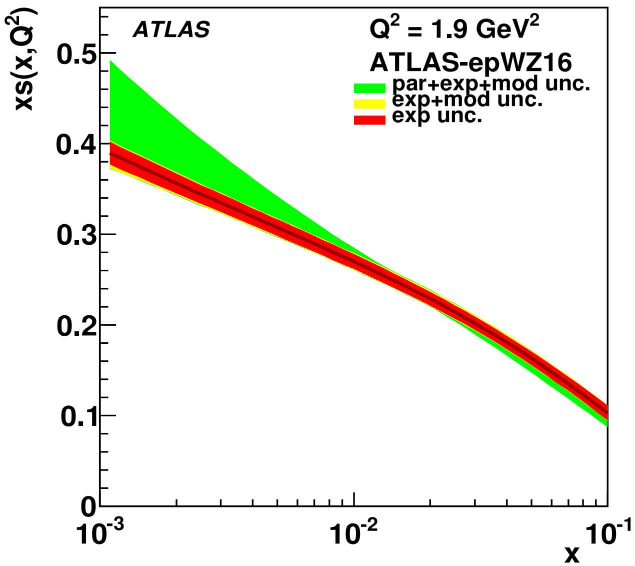
How strange is the proton ?

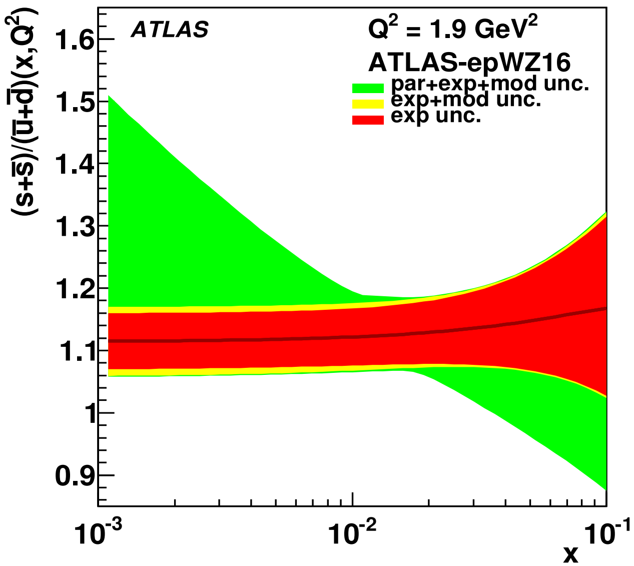
- Strange quark density poorly known
  - Usual assumption sbar ~ 0.5 dbar, from s⟶Wc in NuTeV, CCFR data
  - Large uncertainties from charm fragmentation and nuclear corrections
- The original ATLAS epWZ12 (Phys.Rev.Lett. 109 (2012) 012001) from fits at NNLO to the 2010 data, fitting inclusive Z and W± data found an enhanced strangeness contribution

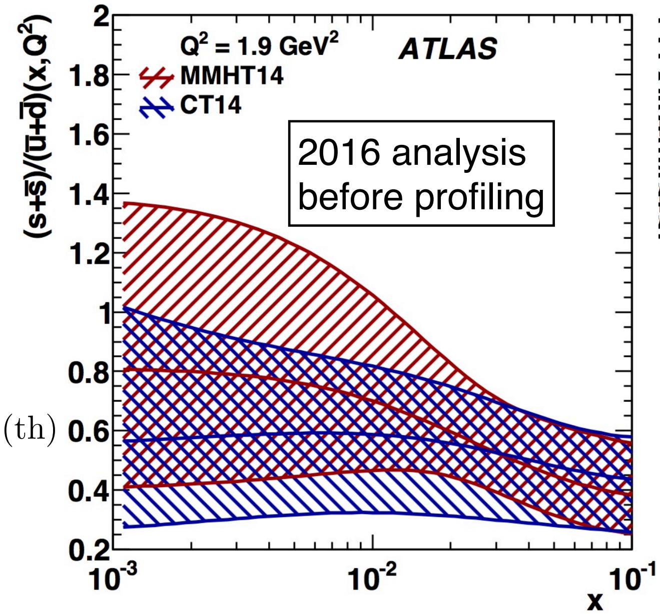
$$r_s = \frac{1}{2}(s+\bar{s})/\bar{d}$$

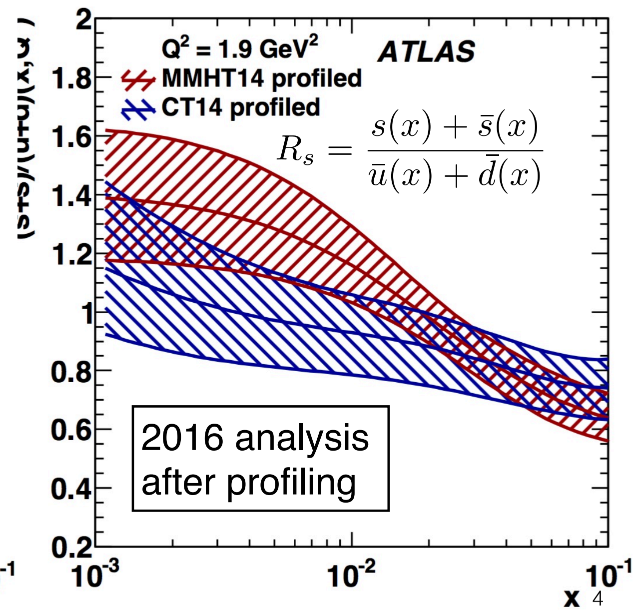
$$= 1.00 \pm 0.07(\mathrm{exp}) \pm 0.03(\mathrm{mod})^{+0.04}_{-0.06}(\mathrm{par}) \pm 0.02(\alpha_S) \pm 0.03(\mathrm{th})$$

- Profiling the CT14 and MMHT14 PDFs with the analysis of the 7 TeV 2011 data also yields an enhanced strangeness contribution at low-x









Including new data in a new fit …

- So far ATLAS has produced several fits using inclusive W and Z data†
  - ATLAS epWZ 12 (2010 data, 7 TeV 35 pb^{-1})
  - ATLAS epWZ 16 (2010 data, 7 TeV 4.6 fb^{-1})
  - ATLAS epWZ top 18 - with fully differential top data data to stabilise the gluon - **see Francesco's presentation tomorrow**

- Starting point for the new fit is the inclusive W, ATLAS data used in the the ATLAS epWZ16 fit plus the new W + jets data at 8 TeV from JHEP 05 (2018) 077
- Some differences and improvements with respect to the ew WZ16 fit to accommodate or exploit the new data …
  - More parameter variations as part of the model systematics, updated parameterisation with additional term in central fit for the ubar distribution with respect to 2016 fit …

$$x\bar{u} = A_{\bar{u}} x^{B_{\bar{u}}} (1-x)^{C_{\bar{u}}} (1 + \boldsymbol{D_{\bar{u}} x})$$

    consistent with recent ATLAS epWZ top18 fit
  - 131 sources of correlated systematic uncertainties in the inclusive data with electron and muon channels **combined**
    - For the new fit use the electron and muon data before the combination (**uncombined**) since more simply relates the original sources of the systematic uncertainty to aid the full correlation with the common sources from the new W + jets data - 50 sources from the new W + jets data
  - Variation of the minimum Q^2 selection of 10 GeV^2 (rather than 7.5 GeV^2) in the HERA DIS data to exclude the low Q2, low-x data which may be more adversely affected by higher twist and other effects

† NB: all fits use the HERA data to constrain the fit at lower Q^2

ATLAS epWZ+Wjets QCD fit technicalities

- Fits are performed using DIS data from HERA and the ATLAS Electroweak boson data
- The xFitter[†] package is used, with LHC cross sections reproduced using fastNLO and APPLgrid
  - NNLO corrections included as K-factors
- Parameterisation …

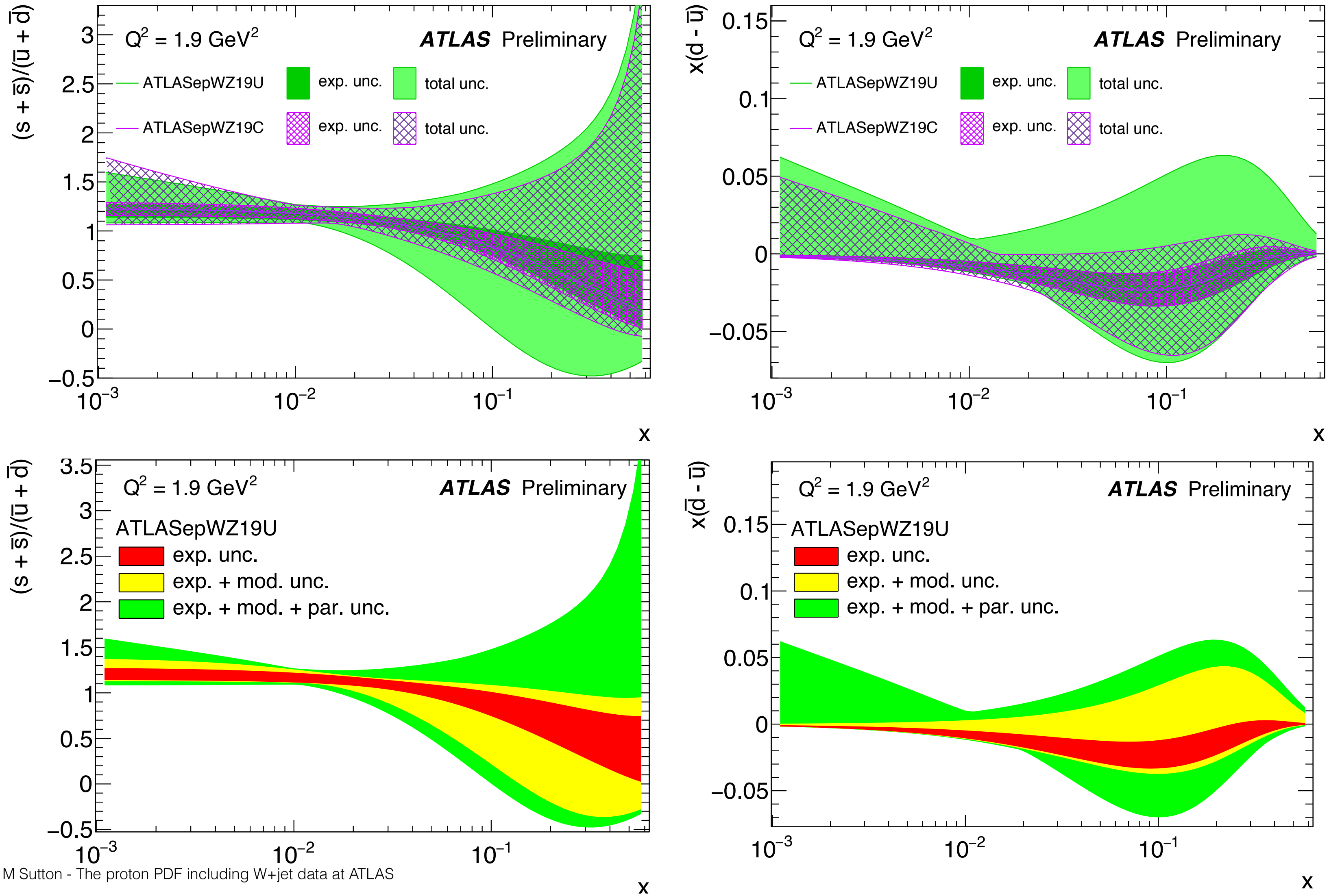
$$
\begin{aligned}
xd_v(x) &= A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + D_{d_v} x + E_{d_v} x^2) \exp F_{d_v} x \\
xu_v(x) &= A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}} (1 + D_{u_v} x + E_{u_v} x^2) \exp F_{d_v} x \\
x\bar{d}(x) &= A_{\bar{d}} x^{B_{\bar{d}}} (1-x)^{C_{\bar{d}}} (1 + D_{\bar{d}} x + E_{\bar{d}}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

- Additional constraints for the central fit from sum rules, and also $A_{\bar{u}} = A_{\bar{c}}$ and $B_{\bar{s}} = B_{\bar{u}} = B_{\bar{d}}$, with $C_{\bar{s}}$ and $A_{\bar{s}}$ free parameters, with and C'_g fixed >> C'_g (some constraints relaxed for the model uncertainty) $s(x) = \bar{s}(x)$
- This yields a 16 parameter central fit using a fixed strong coupling and a starting scale of Q^2 = 1.9 GeV^2
- NB: Greyed out parameters varied as part of the model dependency systematics, along with allowing some of the central fit contained parameters to vary independently

- First produce update to the epWZ16 fits using the **newer methodology** as a consistency check using both combined and uncombined data - new fits ATLAS epWZ19 C (combined) and ATLAS epWZ19 U (uncombined)

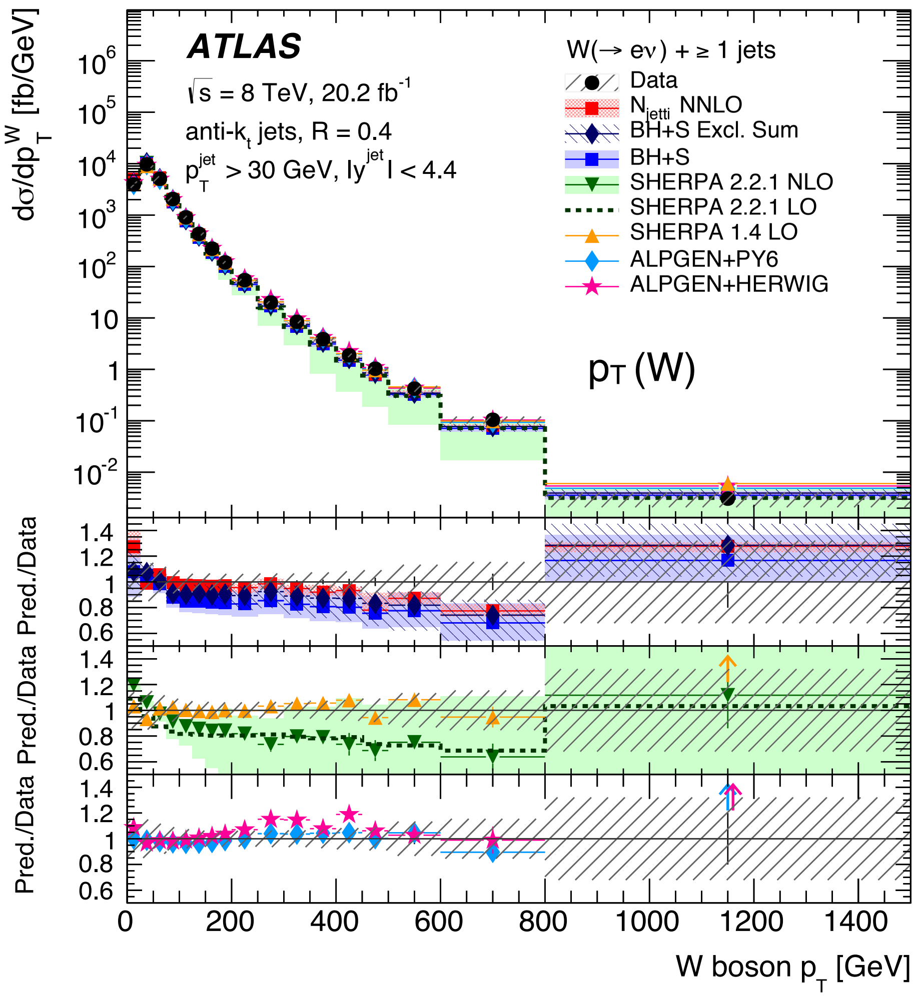
[†]xFitter program, www.xfitter.org; S. Alekhin et al. Eur. Phys. J. C 75 (2015) 304, arXiv: 1410.4412 [hep-ph]

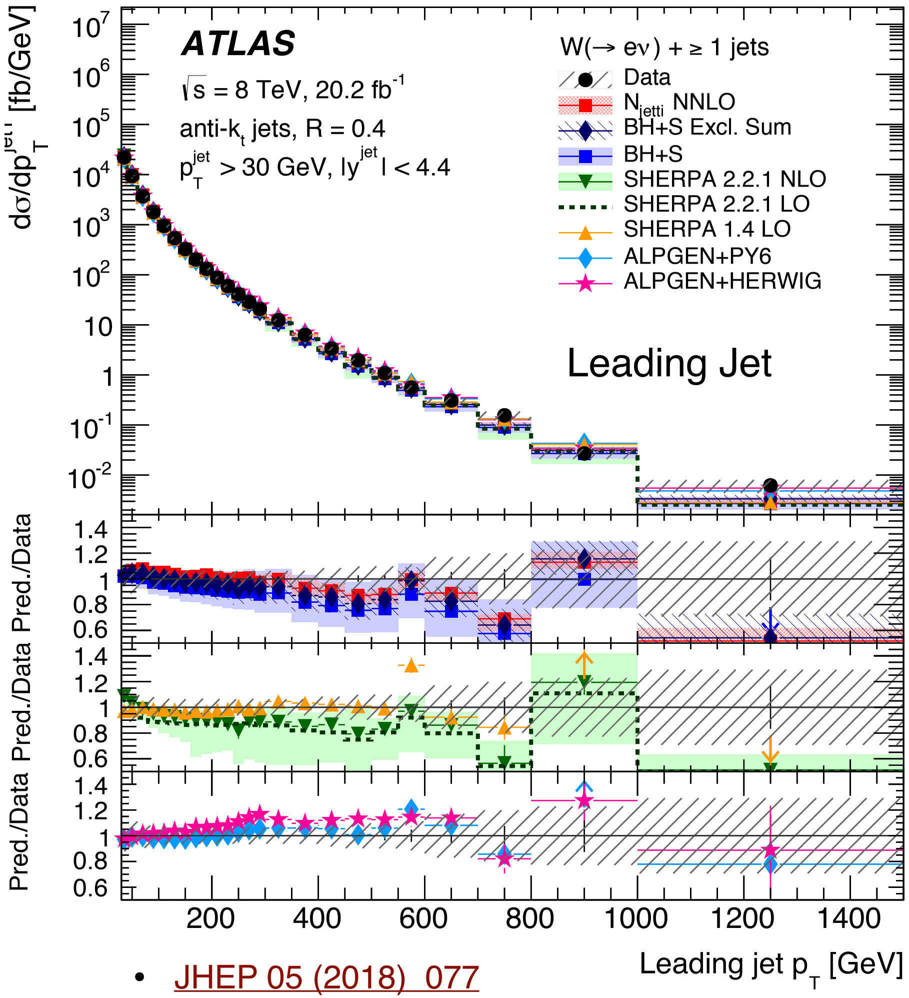
ATLAS epWZ 19 combined and uncombined fits



- Reproduce the negative dbar - ubar distribution
  - Larger uncertainty from model dependent systematics
    - More parameters considered - increase in the Q^2_{min} variation due to other theoretical uncertainties
  - Still see the enhanced strange at low-x even with the large dbar - ubar

W+jet production at 8 TeV data





- JHEP 05 (2018) 077

- Multiple distributions
  - $P_T(W)$, P_T(leading jet)
  - Unfortunately, correlations between different spectra not available, so unable to fit distributions simultaneously

Fit	ATLASepWZ19U	ATLASepWZ19U + p_T^W	ATLASepWZ19U + p_T^{leading}
Total χ^2/NDF	1310 / 1106	1354 / 1140	1365 / 1152
HERA partial χ^2/NDF	1123 / 1016	1132 / 1016	1141 / 1016
HERA correlated χ^2	48	49	50
HERA log penalty χ^2	-18.38	-22.4	-24.72
ATLAS W, Z partial χ^2/NDF	117 / 106	116 / 106	109 / 106
ATLAS W + jets partial χ^2/NDF	-	18 / 34	43 / 46
ATLAS correlated χ^2	40	62	47

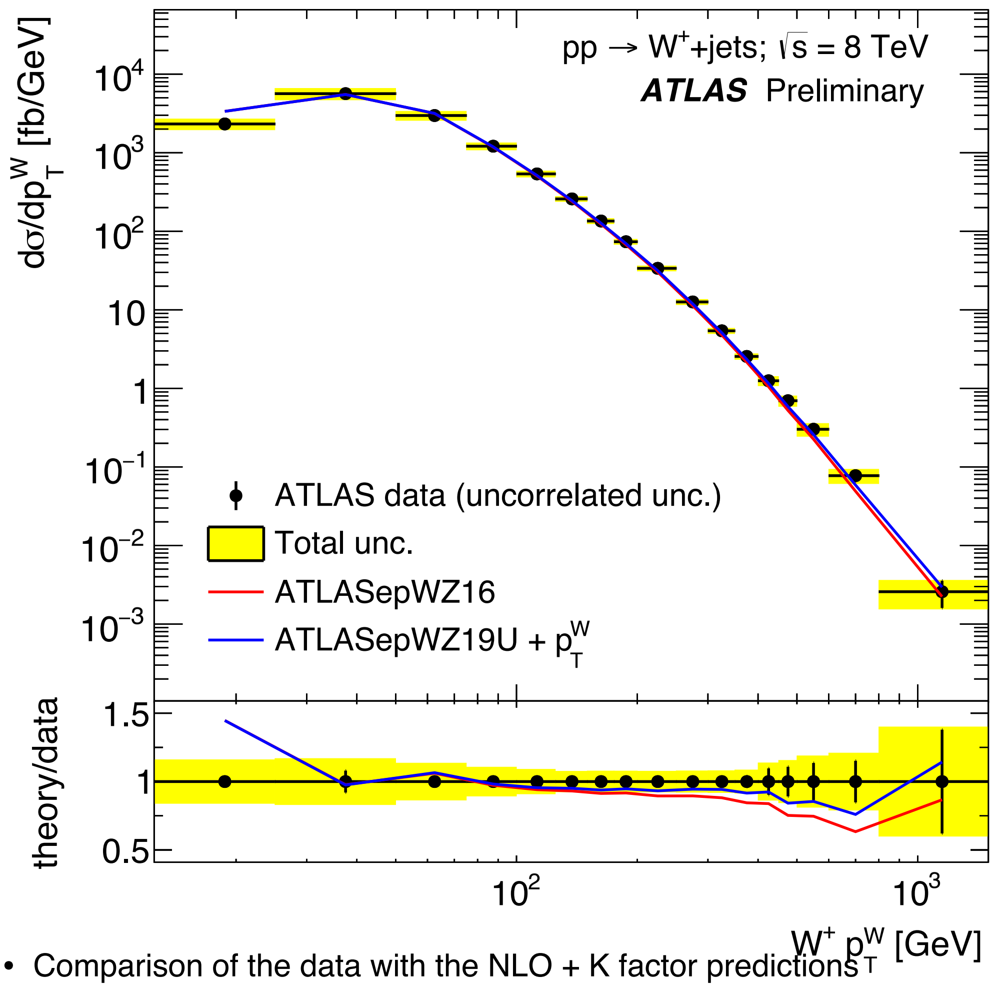
New fit quality …

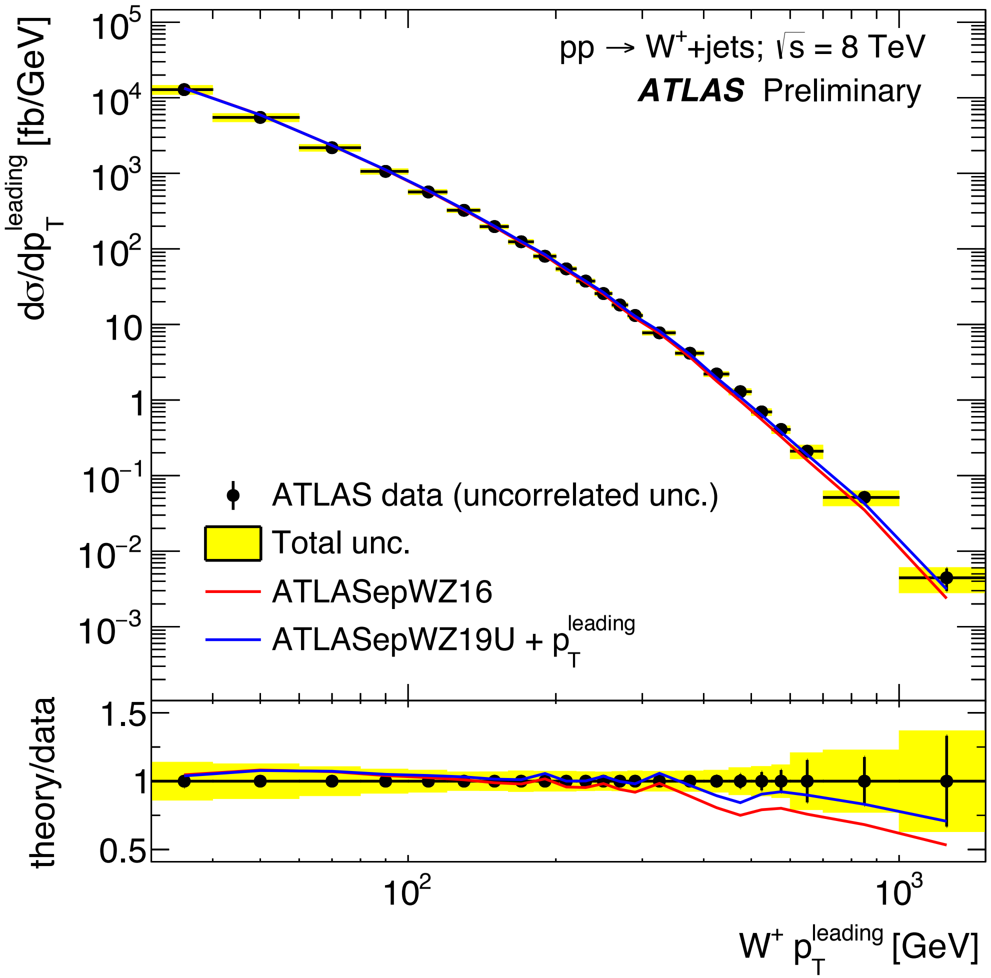
- Good fits including the W + jets data with no tension with the HERA or inclusive W, and Z data
- Slightly better χ^2 for the $P_T(W)$ data
  - More additional free parameters used in the contributions to the model dependencies
  - Relaxing some of the constraints …

- Use the $P_T(W)$ fit as the new central fit
  - new fit referred to as - ATLAS-epWZ-Wjet 19

Additional data	p_T^W	p_T^{leading}
Nominal χ^2/NDF	1354 / 1140	1365 / 1152
$A_g' = 0$	1409 / 1142	1428 / 1154
$A_{\bar{u}}$	1352 / 1139	1363 / 1151
$B_{\bar{u}}$	1352 / 1139	1362 / 1151
B_s	1353 / 1139	1363 / 1151
D_s	1353 / 1139	1359 / 1151
$D_{\bar{u}} = 0$	1357 / 1141	1373 / 1153
$D_{\bar{d}}$	1354 / 1139	1364 / 1151
D_{d_v}	1354 / 1139	1364 / 1151
D_{u_v}	1354 / 1139	1365 / 1151
D_g	1353 / 1139	- / 1151
E_s	1354 / 1139	1362 / 1151
$E_{\bar{d}}$	1354 / 1139	1365 / 1151
$E_{\bar{u}}$	1354 / 1139	1363 / 1151
E_g	1352 / 1139	1365 / 1151
F_{u_v}	1351 / 1139	1363 / 1151
F_{d_v}	1354 / 1139	1365 / 1151

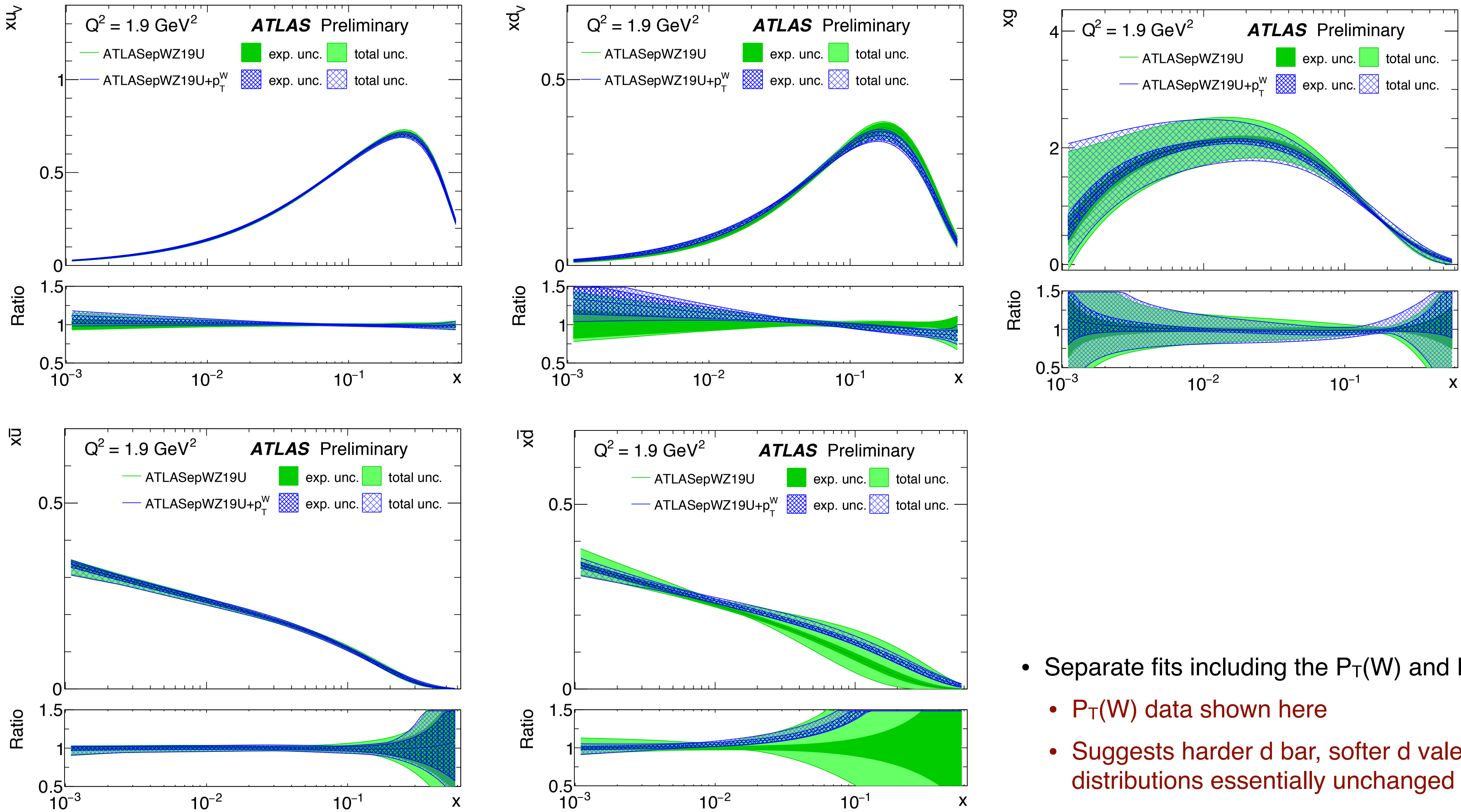
New fits



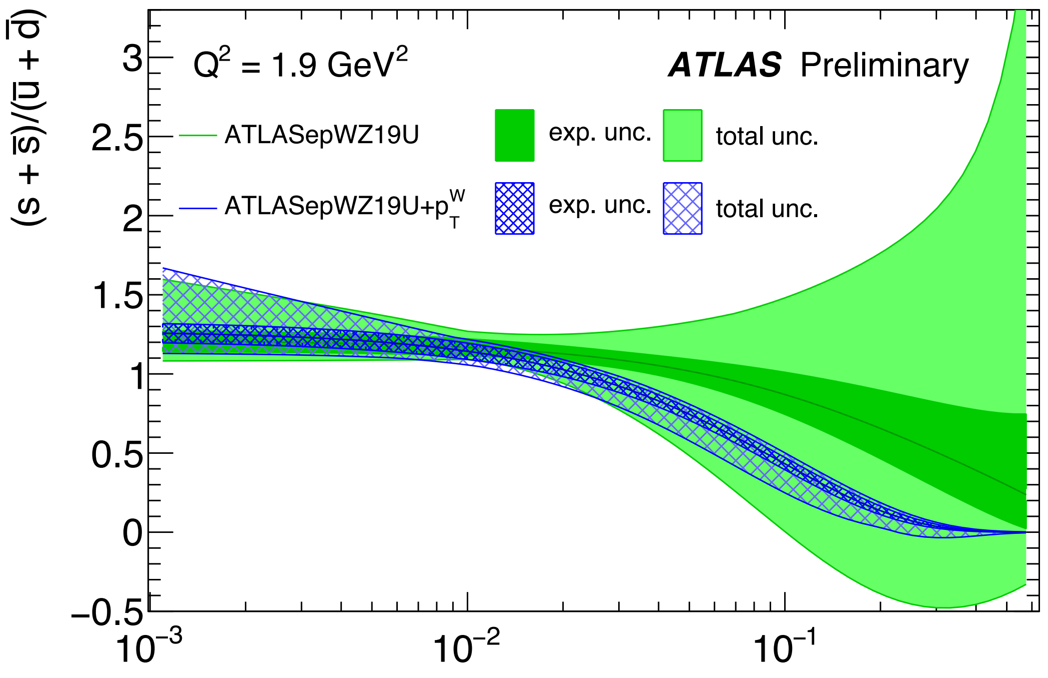


- Comparison of the data with the NLO + K factor predictions
- Not including the shifted systematics from the fit, see clear improvements at large P_T with the new fits

Fits including the W + Jets data



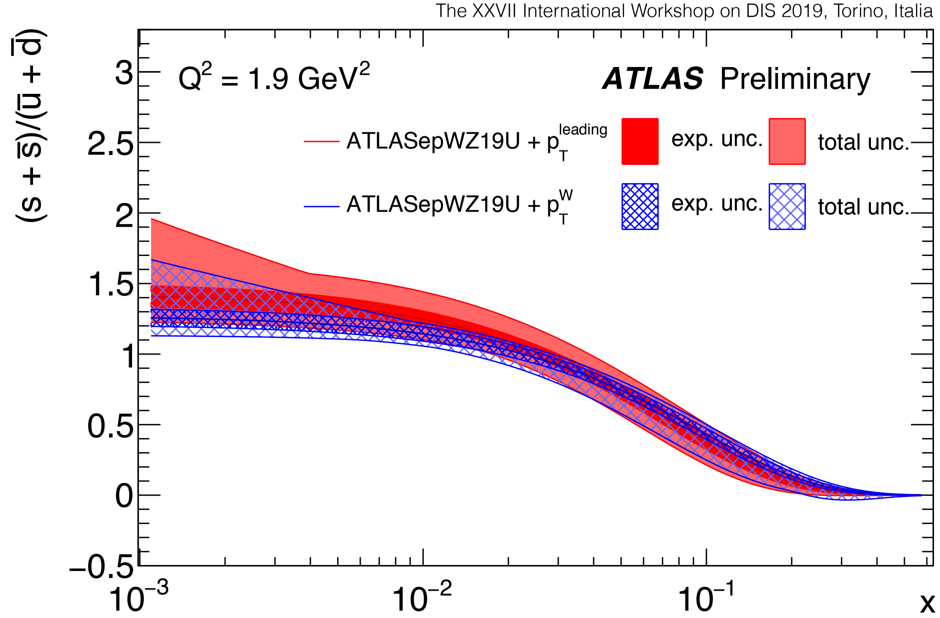
- Separate fits including the $P_T(W)$ and P_T(leading jet) data
  - $P_T(W)$ data shown here
  - Suggests harder d bar, softer d valence, u quark distributions essentially unchanged

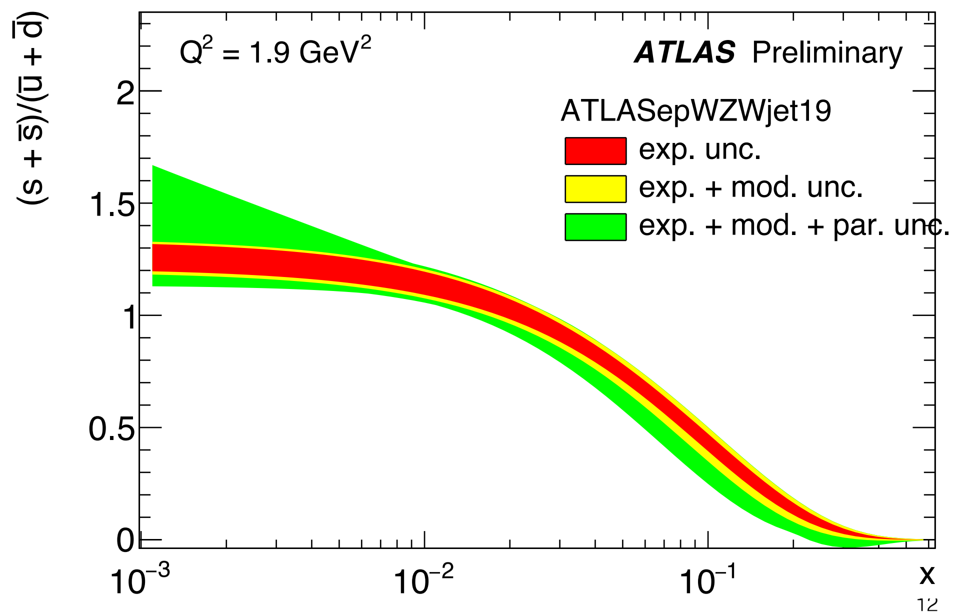


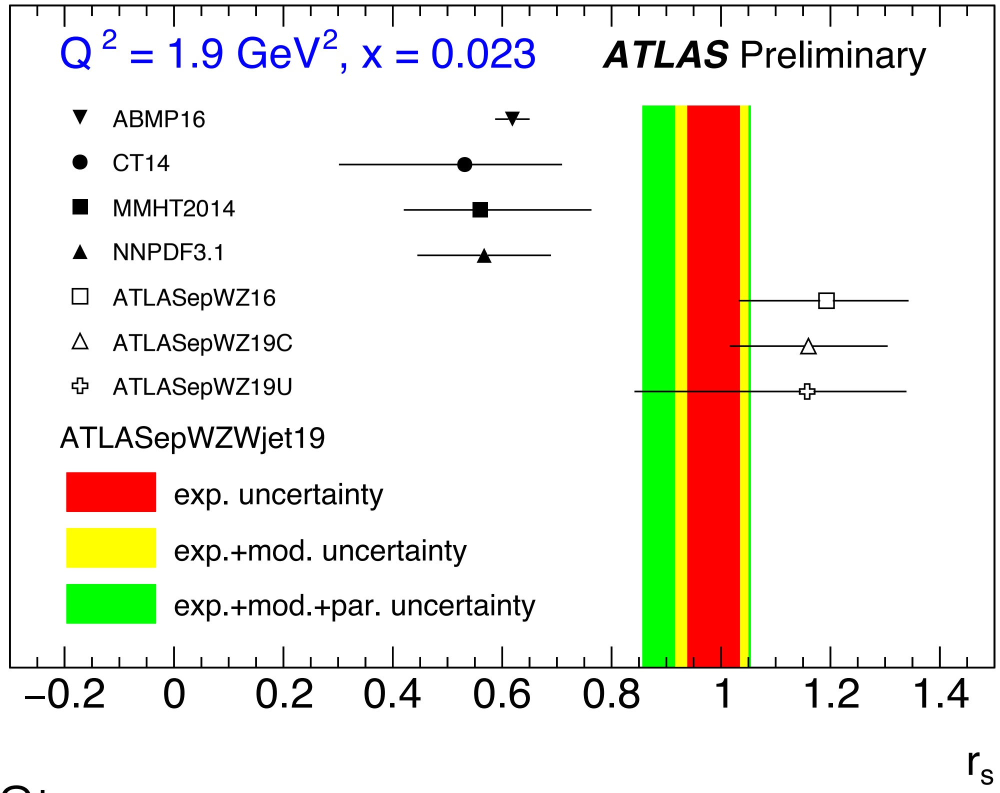
Strange density

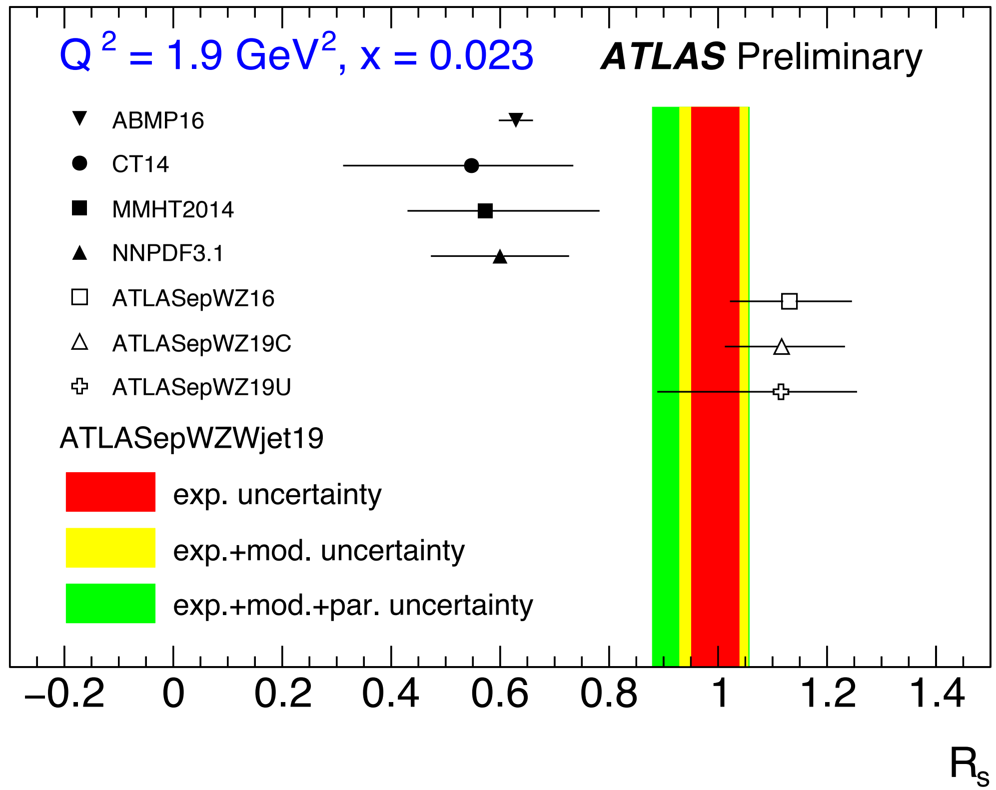
- Fit to epWZ uncombined data with larger error consistent with new epWZ fit with W P_T
- W+ jets fits with PT(W) and PT(leading jet) are themselves consistent
- Including the W + jet data reduces the strange density at higher-x

- Still consistent with enhanced strange at low-x







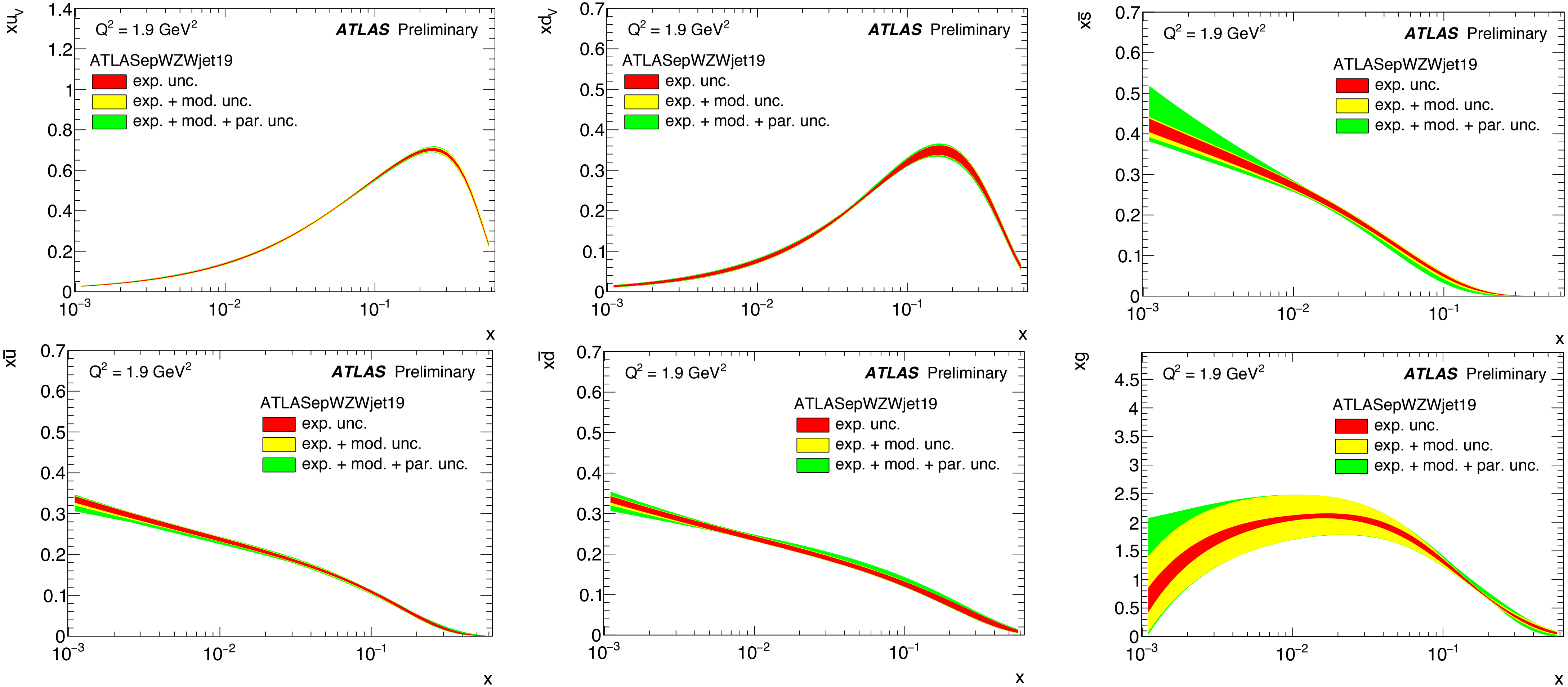


Strange summary

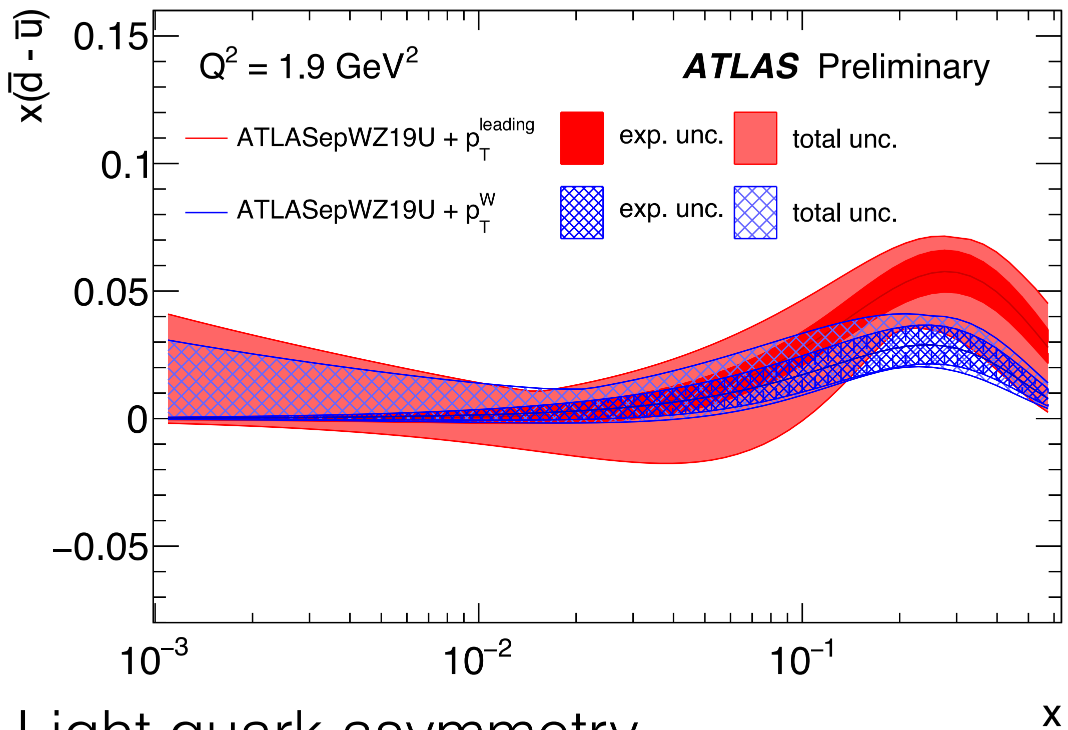
$$r_s = \frac{1}{2}(s+\bar{s})/\bar{d} \qquad R_s = \frac{s(x)+\bar{s}(x)}{\bar{u}(x)+\bar{d}(x)}$$

- Consistent with earlier ATLAS fits
- Slightly higher than PDF from the global fitters

New fit

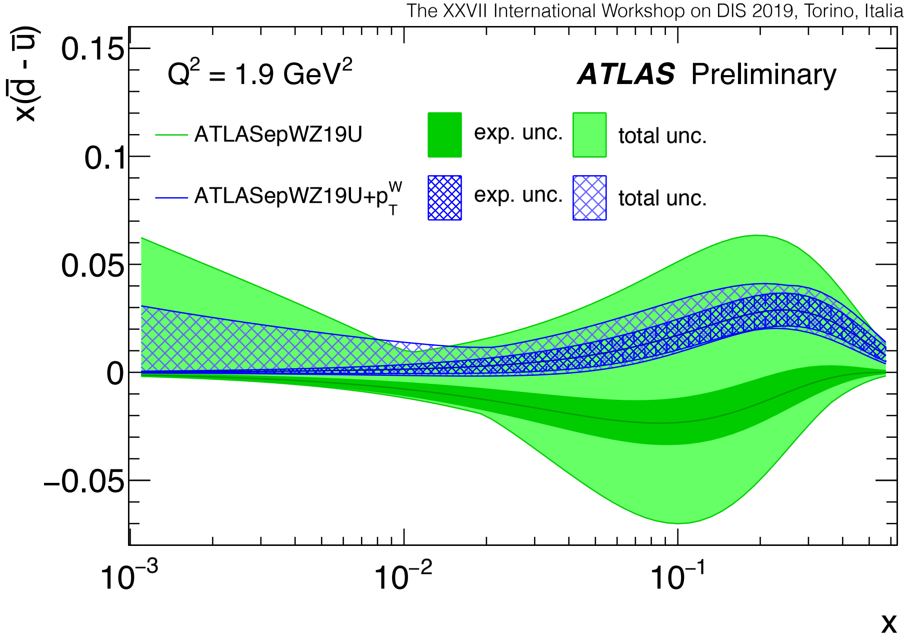


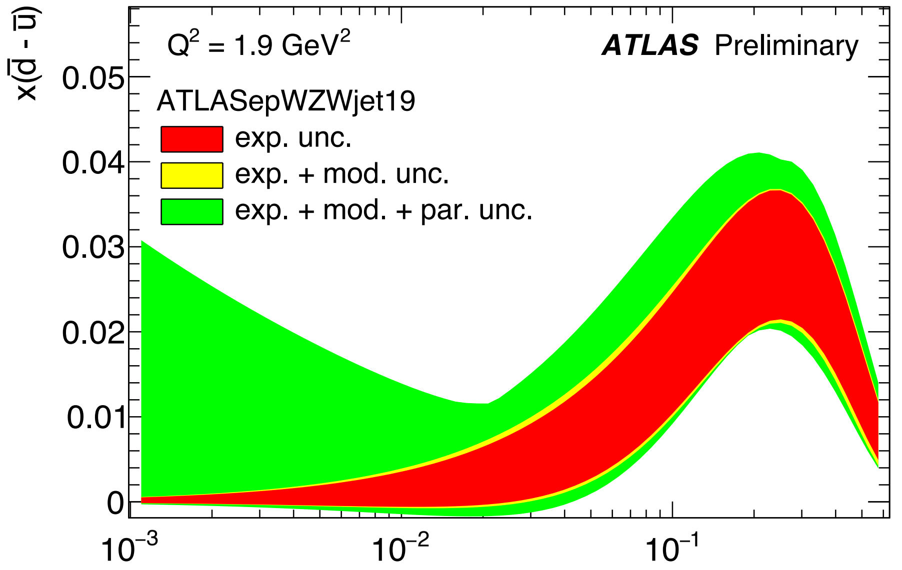
- Very small uncertainties
- Softer strange, and dvalence at high-x harder



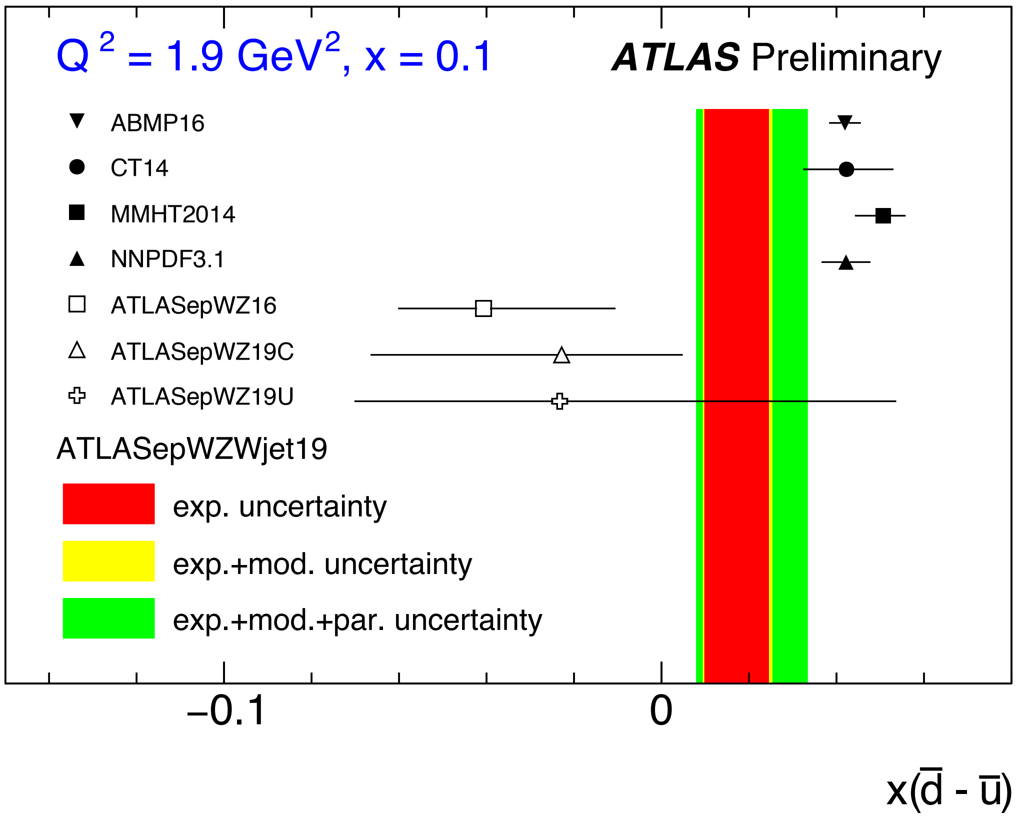
Light quark asymmetry

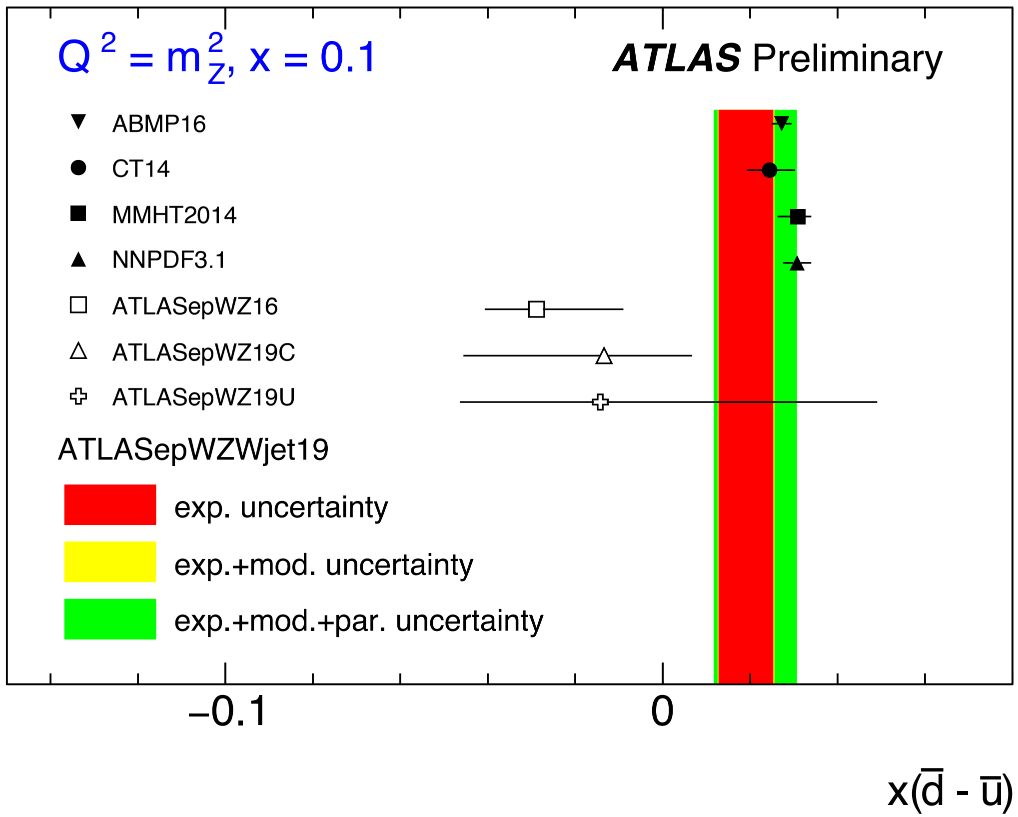
- ATLASepWZ16 fit showed a negative dbar - ubar
- New fit with the W + jet data results in the new dbar - ubar to be positive - much more consistent with the fits from the global fitters
- Recall the still present enhancement of strange at low-x





Light quark asymmetry





- Comparison with global fitters
- New fit consistent with previous ATLAS fits, but also more in line with the global fitters

Outlook

- ATLAS has an extensive, and growing portfolio of precision measurements, each having the potential to help constrain the parton distributions in the proton
  - Concentrated here on a **new fit** with the inclusive W and Z data, enhanced by the **inclusion of W+ jets data**
  - New fit confirms enhancement of the strange contribution at low-x, also with a positive dbar - ubar distribution

- To look forward to …
- … rich pickings to be had from the **full luminosity Run 1 data**, and with **higher energy 13 TeV collision data**
  - Including more published data is possible - top etc
  - New data samples are hoped to be available soon - Z + jets, new inclusive Boson data at higher beam energies etc
  - Further reductions in both the statistical and systematic uncertainties, better constraints on the gluon as well as these improvements on the valence and sea quarks
  - Data from different beam energies - data from similar Q^2 and similar E_T have similar systematic uncertainties, but sample different momentum fraction x - can lead to improved sensitivity
- For many measurements, theoretical uncertainties are often comparable to, or larger, than those from the data
- New NNLO calculations are available for important physics processes - developments in the grid technology (APPLfast, APPLgrid and fastNLO) mean these data - and HERA jet data - should be usable in a rigorous NNLO fits in the very near future
  - W+ jets, Z+jets, inclusive W, Z …

- We have come a long way, but are only now beginning on our journey towards realising the full potential of the data. It promises to be a very interesting time ahead ...