Determination of proton parton distribution functions using ATLAS data

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On behalf of the ATLAS Collaboration

Deep Inelastic Scattering 2021, April 2021

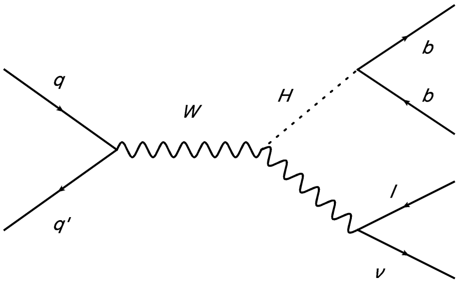
Overview

In this talk I will present the most recent determination of Parton Distribution Functions (PDFs) performed by the ATLAS Collaboration:

- arXiv:2101.05095

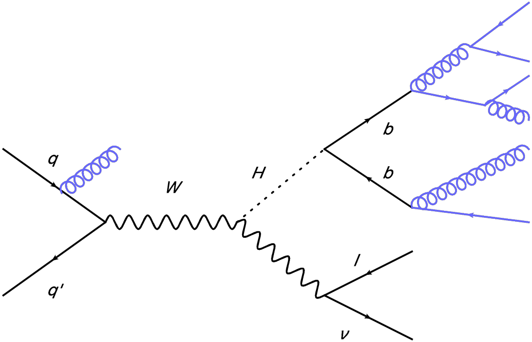
This extraction uses inclusive W/Z and W/Z+jets data sets from LHC Run 1 data. Together with HERA combined data.

Reminder: modelling *pp* processes



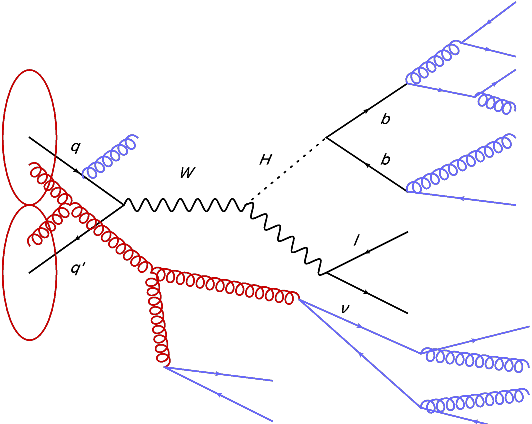
- **Parton Distribution Functions (PDFs):** affect rapidity, mass, charge asymmetry of final state system, and cross-section
- **Matrix Element (ME):**
- **Parton Shower (PS):**
- **Underlying Event (UE):**

Reminder: modelling *pp* processes



- **Parton Distribution Functions (PDFs):**
- **Matrix Element (ME):** Typically calculated at NLO in QCD for MC generation of SM processes, describes main energy flow, FS object kinematics. Higher-order for some fixed-order (+ resummed) predictions
- **Parton Shower (PS):**
- **Underlying Event (UE):**

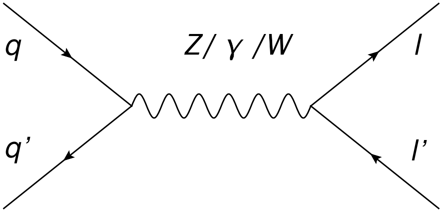
Reminder: modelling *pp* processes



- **Parton Distribution Functions (PDFs):**
- **Matrix Element (ME):**
- **Parton Shower (PS):** Extra radiation down to hadronisation scale
- **Underlying Event (UE):** Extra soft activity

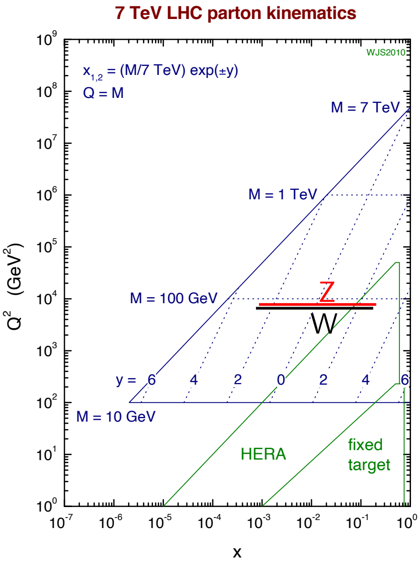
W/Z (Jet+) production and Parton Distribution Functions

Drell-Yan process



- Simplest hard scattering process to calculate at the LHC
- Cross section has form of integral over: $q(x_1)q(x_2,)\mathcal{M}(x, Q^2)\times$ LIPS.
  LIPS=Lorentz Invariant Phase Space
- Here $q(x, Q)$ are PDFs, if the boson is on shell then $Q^2 = M_V^2$
- At rest $(y = 0)$ $x_1 = x_2 = M_V/\sqrt{s}$
- if $x_1 > x_2$ then $|y| > 0$, sample higher and lower x at same Q^2
- Going very forward simultaneously samples higher and lower x
- Flavour sensitivity:
  - Z boson sum pairs of all flavours $u\bar{u}, d\bar{d}$,....
  - W^+ sums pairings of +ve charged (anti)quarks $(u\bar{d}), (u\bar{s})$, ...
  - W^- sums pairings of -ve charged (anti)quarks $(d\bar{u}), (d\bar{c})$,...

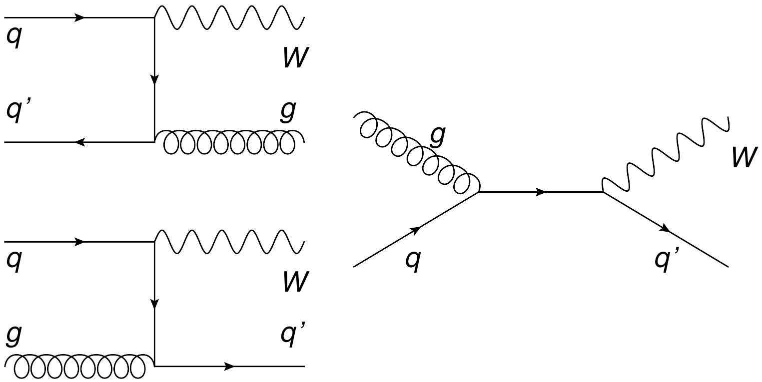
W/Z Production , @ LHC



W/Z Production at the LHC

- Exploring a new range of parton kinematics
- Run I data: not only lower x than TeVatron, also lower x than HERA at central rapidity
- LHCb further extends measurement in x
- Inclusive W/Z essentially probes a horizontal band in x, Q^2 space
- 13 TeV Run II data will probe lower x for the same Q^2

Why V+jets?



Aim of including V+jets:

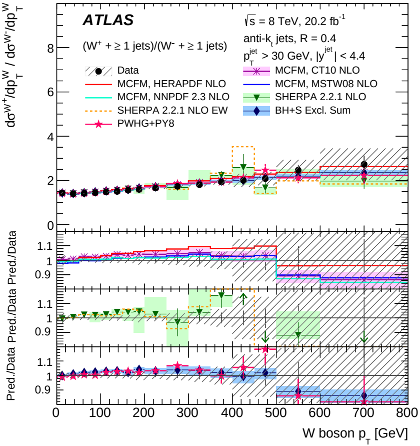
- probe higher Q^2,x
- more sensitivity to gluon

Available V+jets data

Run 1 (8 TeV) measurements of V+jets are available:

- W+jets: JHEP 1805 (2018) 077
- Z+jets : Eur. Phys. J. C 79 (2019) 847

  Also NNLO calculations for V+1 jet now available (Phys. Rev. Lett. 115, 062002 (2015)) thus an NNLO PDF QCD fit to extract PDFs is possible



Extracting Parton Distribution Functions

Our PDF fit

ATLAS V+jets PDF fit: input data

- Combined HERA NC/CC DIS data ($Q^2 > 10$ GeV^2) Eur.Phys.J.C 75 (2015) 12, 580
- ATLAS inclusive 7 TeV W and Z production measurements Eur. Phys. J. C 77 (2017) 367
- 8 TeV W+jets (p_T^W) and Z+jets ($p_T^{\text{jet}}, |y_{\text{jet}}|$) production data
- Performed using xFitter (xFitter)

Expecting to see V+jets help to constrain high-x (anti)quark distributions and possibly also the gluon

New ATLAS fits:

- **ATLASepWZVjet20**: all this data
- **ATLASepWZ20**: without the W/Z+jets

Old ATLAS Fit:

- **ATLASepWZ16**: without the W/Z+jets, pre-combined W/Z inclusive data, looser Q^2 cut on DIS data (> 7.5 GeV^2) ,and different parametrisation

Fit Assumptions and procedure

- Parametrise PDFs at $Q_0^2 = 1.9\ \mathrm{GeV}^2$
  - $xq(x) = A_i x^{B_i}(1-x)^{C_i}(1 + D_i x + E_i x^2)e^{F_i x}$
  - $xg(x) = A_g x^{B_g}(1-x)^{C_g}(1 + D_g x + E_g x^2)e^{F_g x} - A'_g x^{B'_g}(1-x)^{C'_g}$
  - Parametrised distributions $xu_V, xd_V, x\bar{d}, x\bar{u}, x\bar{s}, xg$
- Assume:
  - $A_{\bar{u}}=A_{\bar{d}},\ B_{\bar{u}}=B_{\bar{d}}$
  - $D_{\bar{s}} = E_{\bar{s}} = 0,\ B_{\bar{s}} = B_{\bar{d}}$
  - $xs = x\bar{s}$
  - $C'_g = 25$

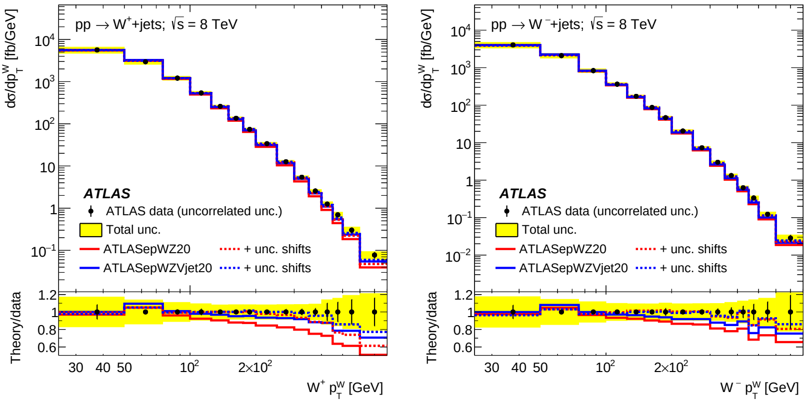
Fit these parameters: using xFitter to evolve PDFs to appropriate scales and calculate corresponding theory cross-section predictions which are compared to data

Difference compared to ATLASpeWZ16:

- D_g parameter shown in red is new

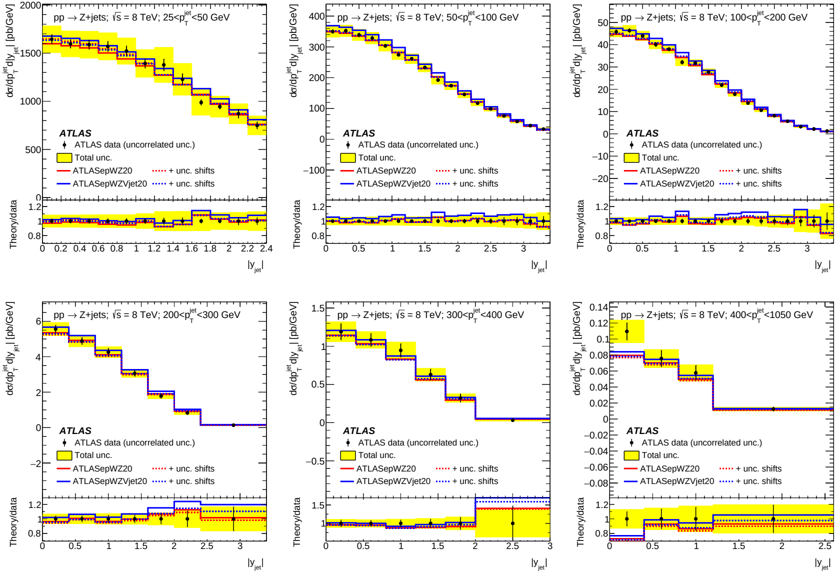
New parametrization is more flexible

Fit Quality



W+jets data described better than for the original ATLAS+HERA data fit

Fit Quality



Quality of fit to Z+jets data shows less difference than W case

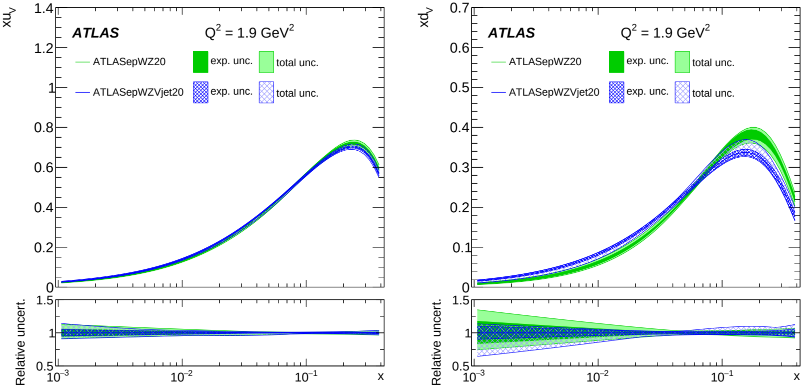
Fit Quality

Fit	ATLASepWZVjet20
Total χ^2/NDF	1460 / 1198
HERA partial χ^2/NDP	1132 / 1016
HERA correlated χ^2	50
HERA log penalty χ^2	-12
ATLAS W, Z partial χ^2/NDP	113 / 105
ATLAS W + jets partial χ^2/NDP	25 / 30
ATLAS Z + jets partial χ^2/NDP	82 / 63
ATLAS correlated χ^2	65
ATLAS log penalty χ^2	6

New data are well fitted.

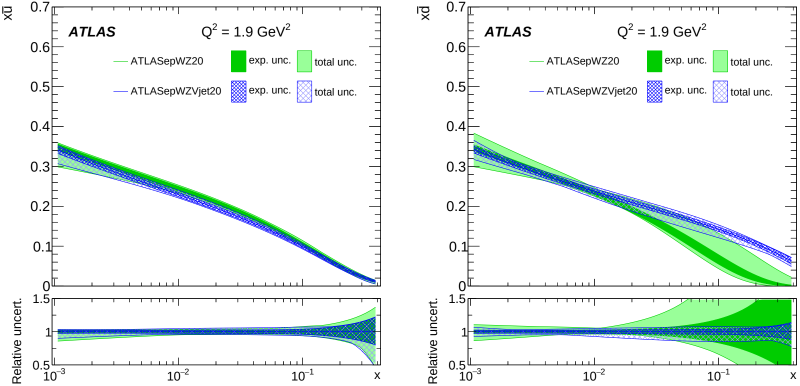
$$\chi^2 = \sum_{ik} \left(D_i - T_i (1 - \sum_j \gamma_{ij} b_j) \right) C^{-1}_{\mathrm{stat},ik}(D_i, D_k) \left(D_k - T_k (1 - \sum_j \gamma_{kj} b_j) \right)$$
$$+ \sum_j b_j^2$$
$$+ \sum_i \log \frac{\delta^2_{i,\mathrm{uncor}} T_i^2 + \delta^2_{i,\mathrm{stat}} D_i T_i}{\delta^2_{i,\mathrm{uncor}} D_i^2 + \delta^2_{i,\mathrm{stat}} D_i^2},$$

Valence Quarks



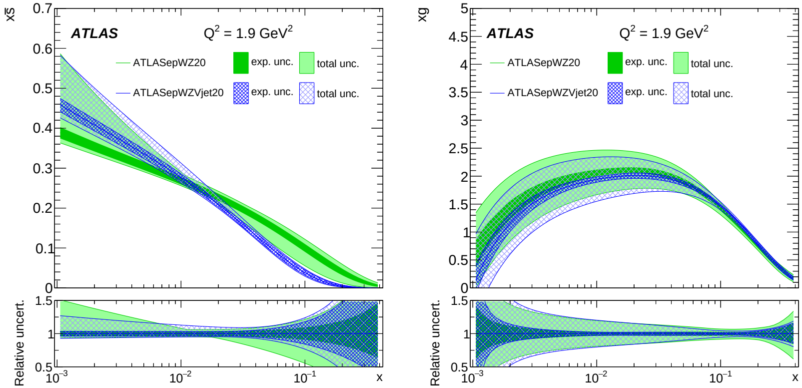
u_V better determined than d_V, V+jets data has a larger effect on d_v moving it towards results from global fitters

Sea and Gluon



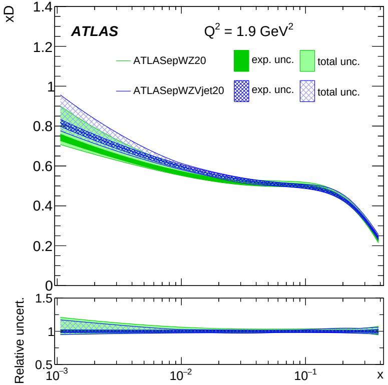
high-x $\bar{d}$ uncertainty reduced considerably, large pull

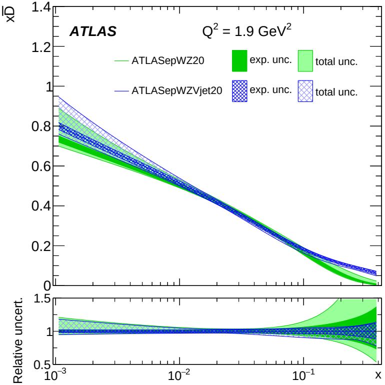
Sea and Gluon



high-x gluon uncertainty reduced considerably,

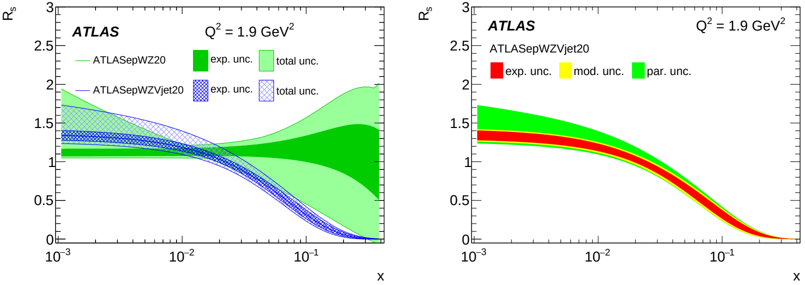
Sea and Gluon





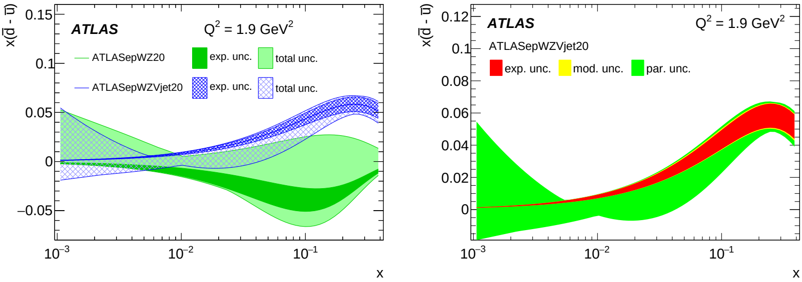
Sums of down type quarks ($xD = xd_v + x\bar{d} + x\bar{s}$, $x\bar{D} = x\bar{d} + x\bar{s}$) quite stable, rise in $\bar{d}$ compensated by fall in $\bar{s} + d_v$

Constraining PDFs with W+jets



- These data also show more strangeness suppression above $x > 0.03$ $\left(R_s = \frac{s+\bar{s}}{\bar{d}+\bar{u}}\right)$ than older fits (though consistent with them), consistent with CMS result.
- Data also favours a +ve $\bar{d} - \bar{u}$ above $x > 0.2$, global fits have this feature usually coming from fitting fixed target (E866) data.

Constraining PDFs with W+jets



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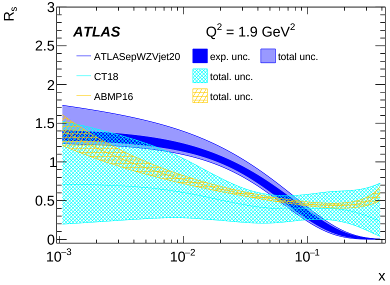
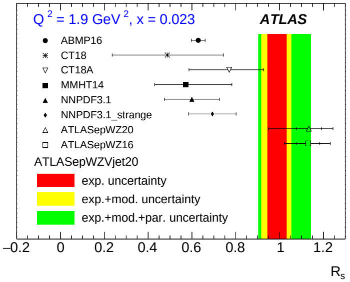
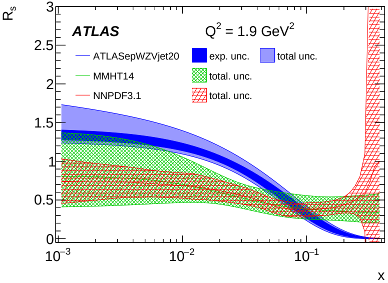
Comparing to Global Fits: R_s

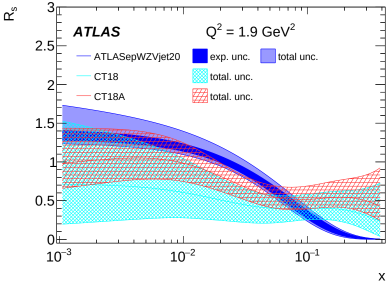


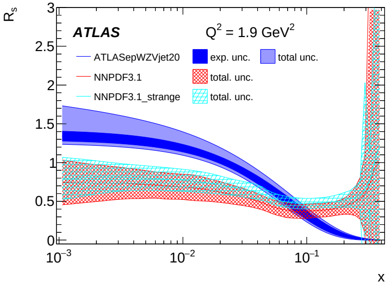


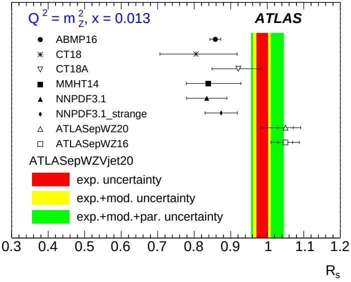


ATLAS fits still find a larger R_S than global fits, but V+jets data bring them closer to each other.

Comparing to Global Fits: R_s

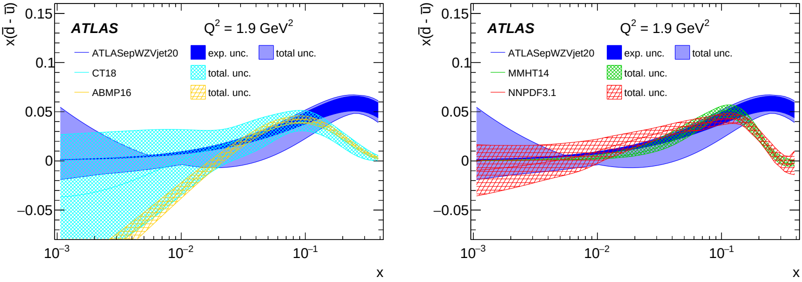






Including W/Z 7 TeV data in global fits (e.g. CT18A), increases R_s distribution

Comparing to Global Fits: $x(\bar{d} - \bar{u})$



Consistent with global fits up to $x \sim 0.1$, above this x the V+jets is most sensitive and shows different behaviour

Summary

- Progress in theory and recent measurements allow us to include V+jets data in PDF fits
- Data has power to constrain mid-high-x d and s quark distributions
- Results show that including this data improves consistency of fits to HERA data+ATLAS data with Global fits that also include fixed target data
- Falling R_s distribution and $x\bar{d} > x\bar{u}$ at high-x; still unsuppressed strange at low-x

Back-up Slides

Back up

Back-up slides from now on:

- Model and Parametrisation uncertainties
- Correlation Model
- Extra $x(\bar{d} - \bar{u})$
- Figures at $Q^2 = M_Z^2$

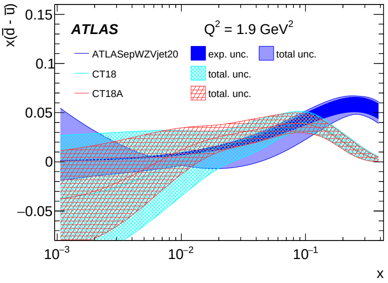
Model and Param Uncertainties

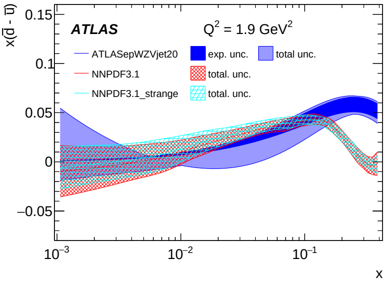
Nominal χ^2/NDF	1460 / 1198
Parameter variations	
$A_{\overline{u}} \neq A_{\overline{d}}$	1458 / 1197
$A_{\overline{u}} \neq A_{\overline{d}}$ & $B_{\overline{u}} \neq B_{\overline{d}}$	1454 / 1196
$B_{\overline{s}} \neq B_{\overline{d}}$	1459 / 1197
$B_{\overline{u}} \neq B_{\overline{d}}$	1459 / 1197
$D_{\overline{d}}$	1459 / 1197
D_{d_v}	1460 / 1197
$D_{\overline{s}}$	1460 / 1197
D_{u_v}	1457 / 1197
$E_{\overline{d}}$	1459 / 1197
$E_{\overline{s}}$	1460 / 1197
$E_{\overline{u}}$	1459 / 1197
F_{d_v}	1460 / 1197
$F_{\overline{s}}$	1460 / 1197
$F_{\overline{u}}$	1458 / 1197
F_{u_v}	1456 / 1197
Model variations	
$Q^2_{\min} = 12.5\ GeV^2$	1393 / 1149
$Q^2_{\min} = 7.5\ GeV^2$	1529 / 1238
$Q^2_0 = 2.2\ GeV^2$ and $m_c = 1.49\ GeV$	1465 / 1198
$Q^2_0 = 1.6\ GeV^2$ and $m_c = 1.37\ GeV$	1458 / 1198
$\alpha_S(m_Z) = 0.120$	1463 / 1198
$\alpha_S(m_Z) = 0.116$	1458 / 1198
$m_b = 4.75\ GeV$	1461 / 1198
$m_b = 4.25\ GeV$	1458 / 1198

Correlation Model

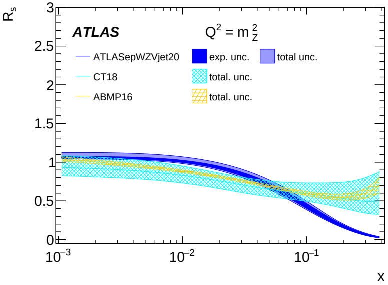
Systematic Uncertainty	7 TeV inclusive W, Z	8 TeV W + jets	8 TeV Z + jets
Jet energy scale [55]	*	JetScaleEff1	ATL_JESP1
		JetScaleEff2	ATL_JESP2
		JetScaleEff3	ATL_JESP3
		JetScaleEff4	ATL_JESP4
		JetScaleEff5	ATL_JESP5
		JetScaleEff6	ATL_JESP6
		JetScaleEta1	ATL_JESP7
		JetScaleEta2	ATL_JESP8
		JetScaleHighPt	ATL_JESP9
		JetScaleMC	ATL_JESP10
	JetScaleNPV	JetScalePileup1	ATL_PU_OffsetNPV
	JetScaleMu	JetScalePileup2	ATL_PU_OffsetMu
Jet punchthrough [55]	-	JetScalepunchT	ATL_PunchThrough
Jet resolution [55]	JetRes	JetResolution10	ATL_JER
Jet flavour composition [55]	-	JetScaleFlav1Known	ATL_Flavor_Comp
Jet flavour response [55]	-	JetScaleFlav2	ATL_Flavor_Response
Pile-up jet rejection (JVF) [56]	-	JetJVFcut	ATL_JVF
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale [57]	MetScaleWen	METScale	-
$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution [57]	MetRes	METResLong	-
		METResTrans	-
Electron energy scale [58]	*	ElScaleZee	ATL_ElecEnZee
Electron trigger efficiency [59]	*	ElSFTrigger	ATL_Trig
Electron reconstruction efficiency [60,61]	*	ElSFReco	ATL_RecEff
Electron identification efficiency [60,61]	*	ElSFId	ATL_IDEff
Luminosity [62,63]	*	LumiUncert	ATL_lumi_2012_8TeV
WW background cross section [64]	*	XsecDibos	ATL_WW_xs
Top background cross section [65]	*	XsecTop	ATL_ttbar_xs

Comparing to Global Fits: $x(\bar{d} - \bar{u})$, Extras

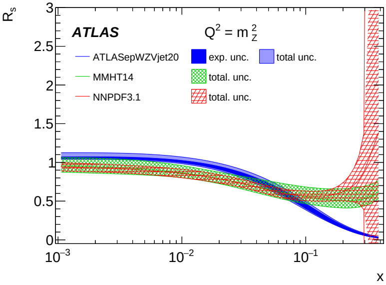




At $Q^2 = M_Z^2$: I

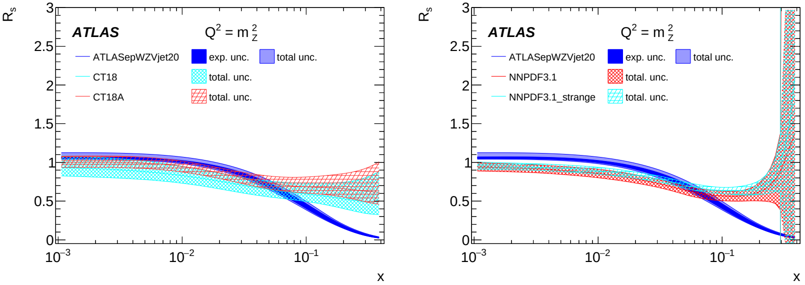


ATLAS
$Q^2 = m_Z^2$
ATLASepWZVjet20
exp. unc.
total unc.
CT18
total. unc.
ABMP16
total. unc.
R_s
x



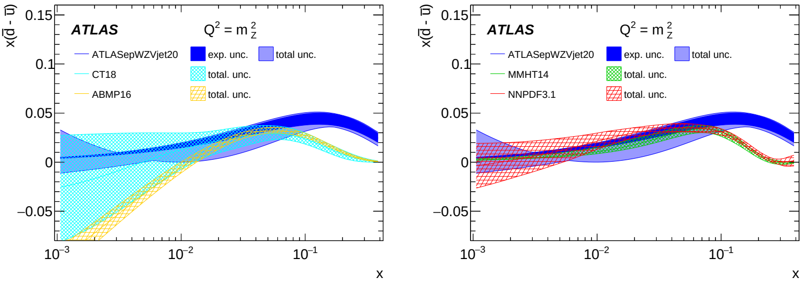
ATLAS
$Q^2 = m_Z^2$
ATLASepWZVjet20
exp. unc.
total unc.
MMHT14
total. unc.
NNPDF3.1
total. unc.
R_s
x

At $Q^2 = M_Z^2$: II



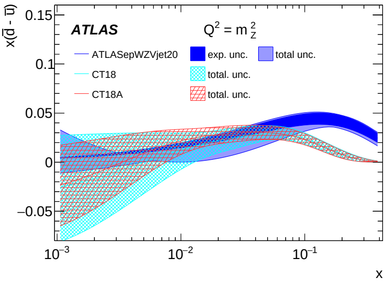
ATLAS
Q2 = m 2 Z
ATLASepWZVjet20
exp. unc.
total unc.
CT18
total. unc.
CT18A
total. unc.
R_s
x
ATLAS
Q2 = m 2 Z
ATLASepWZVjet20
exp. unc.
total unc.
NNPDF3.1
total. unc.
NNPDF3.1_strange
total. unc.
R_s
x

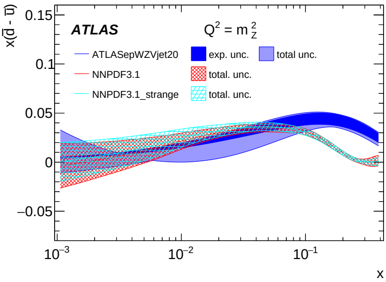
At $Q^2 = M_Z^2$: III



ATLAS
Q2 = m Z2
ATLASepWZVjet20
exp. unc.
total unc.
CT18
total. unc.
ABMP16
total. unc.
MMHT14
total. unc.
NNPDF3.1
total. unc.
x(d̄ - ū)
x

At $Q^2 = M_Z^2$: IV


ATLAS
$Q^2 = m_Z^2$
ATLASepWZVjet20
exp. unc.
total unc.
CT18
total. unc.
CT18A
total. unc.
$x(\bar{d} - \bar{u})$
x


ATLAS
$Q^2 = m_Z^2$
ATLASepWZVjet20
exp. unc.
total unc.
NNPDF3.1
total. unc.
NNPDF3.1_strange
total. unc.
$x(\bar{d} - \bar{u})$
x