

The PDF interpretation of the measurement of a *W* **boson produced in association with jets at the ATLAS detector**

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A QCD analysis using heavy vector boson data from the ATLAS detector at the LHC collected during the 2012 running period at a centre-of-mass energy of 8 TeV, where the boson was produced in association with at least one hadronic jet, is presented. Included in the analysis are ATLAS data on inclusive *W* and *Z* boson production at 7 TeV. The results are presented together with a new fit to the ATLAS inclusive *W* and *Z* data alone, performed with an updated parameterisation. The consequences for the strangeness content of the proton are discussed. Systematic correlations between the input ATLAS data sets are fully accounted. The resulting PDF set is called ATLASepWZWjets19.

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1. Introduction

The LHC [\[1\]](#page-5-0) is an excellent machine for the study of perturbative QCD. Essentially all hard processes at the LHC result from the interaction between partons – quarks or gluons – in the proton and precise knowledge of the parton densities is therefore an essential prerequisite for the detailed understanding of the Standard Model or identification of any possible signature of physics beyond the Standard Model.

During Run 1, the LHC performed extremely well, allowing the ATLAS collaboration [\[2\]](#page-5-0) to collect a proton-proton data sample in excess of 20 fb⁻¹ at 8 TeV centre-of-mass energy and in excess of 4 fb⁻¹ at 7 TeV. When performing a QCD analysis for the proton parton distributions, different physics processes provide information on the different parton initial states. The very precise HERA inclusive DIS data typically only tightly constrain the parton distributions at lower *x*, and are sensitive to the gluon at next-to-leading order (NLO) only through scaling violations. The LHC cross section on the other hand, with two target hadrons, is sensitive to the gluon distribution and the strong coupling already at leading order (LO) for $t\bar{t}$ production or processes including hadronic jets. Electroweak boson production is sensitive both to the valence and sea quark distributions, and where such a boson is accompanied by a jet in the final state, then these interactions are also directly sensitive to the gluon distribution. In this case, the additional emission typically results in enhanced sensitivity to higher *x* than inclusive boson production.

For hadronic interaction processes, the cross section is typically only calculable after the numerical integration over the phase space to cancel the infrared divergences. As such, fast grid convolution techniques are required to reproduce the QCD calculation used in the fit. For this analysis such grids are generated using MCFM [\[3,](#page-5-0) [4](#page-5-0)] interfaced to APPLgrid [\[5,](#page-5-0) [6](#page-5-0)] with next-tonext-to-leading (NNLO) *K*-factors evaluated using DYNNLO [[7](#page-5-0), [8](#page-5-0)] and FEWZ [\[9,](#page-6-0) [10\]](#page-6-0).

Previous QCD analyses [[11,](#page-6-0) [12,](#page-6-0) [13](#page-6-0)] which include the ATLAS inclusive vector boson production data provide evidence for an enhanced strangeness contribution at lower *x*.

2. QCD analysis

At the time of writing, ATLAS has produced several QCD analyses including ATLAS data on inclusive vector boson production: the epWZ12[[11\]](#page-6-0), and epWZ16 [\[11](#page-6-0)] fits, using 35 pb^{-1} and 4.6 fb−¹ of inclusive *W* and *Z* boson production data at 7 TeV respectively, and the epWZtop18 fit [[13](#page-6-0)] which augments the epWZ16 fit by the inclusion of the leptonic [[14\]](#page-6-0) and semi-leptonic [\[15](#page-6-0)] ATLAS *tt*^d data.

The starting point for the current QCD analysis is the data used for the epWZ16 fit, with the addition of the ATLAS *W*+jet data at 8 TeV [\[16](#page-6-0)]. There are some differences with respect to the epWZ16 fit to accommodate or exploit the new data. A larger number of PDF parameter variations have been used as part of the model systematic uncertainties, together with an updated parameterisation with additional terms in the central fit for the \bar{u} density, consistent with that used for the epWZtop18 analysis. This results in a 16 parameter fit with a starting scale of Q^2 =1.9 GeV². Altogether there were 131 sources of correlated systematic uncertainty in the inclusive data with the electron and muon channels combined. For the new analysis the electron and muon data have been used uncombined to allow a more straightforward correlation of the systematic uncertainties

Figure 1: The strangeness ratio, $r_s = (s + \bar{s})/(\bar{u} + \bar{d})$ (left) and the light quark asymmetry $x(\bar{d} - \bar{u})$ (right) for the new fit to the inclusive *W* and *Z* data. The inner error band shows the experimental uncertainty, the outer error bands include the model and parameterisation uncerainties.

with those from the *W*+jet measurement. The new fits to the inclusive data are referred to as the ATLASepWZ19C, and ATLASepWZ19U fits for the fits using the combined, or uncombined data respectively, and the fit including the *W*+jet data is referred to as ATLASepWZWjets19. In addition, to the new parameterisation used for the fit, the minimum Q^2 of the HERA DIS data used has been increased from 7.5 GeV² to 10 GeV^2 to better exclude the low-*x*, low Q^2 data that may be more adversely affected by higher twist and other effects.

Figure 1 shows the strangeness ratio $r_s = (s + \bar{s})/(\bar{u} + \bar{d})$ and the light quark asymmetry, $x(\bar{d} - \bar{d})$ \bar{u}) for the new fits to the inclusive vector boson data only. As with the original ATLASepWZ16 fit, a negative value for the light quark asymmetry is observed with a negative peak around $x = 10^{-1}$. Although negative, within the large model uncertainty this is still consistent with zero, and the large contribution from the strange density at low *x* is reproduced.

The information on the full correlations between the different spectra – $p_T(W)$, and p_T of the leading jet – for the *W*+jet data is not available and as such it is not possible to include the data from both distributions simultaneously. Fits including each of the spectra individually, however, provide consistent results and give values for the χ^2 per degree of freedom of 1354/1140 and 1365/1152 respectively for fits including the data for $p_T(W)$, and p_T of the leading jet. The $p_T(W)$ distribution is chosen for the central fit, with the distribution for the p_T of the leading jet fitted as a cross check. For the model variation uncertainties, several additional parameters are allowed to be free in the fit, but in all cases the χ^2 per degree of freedom is consistent with the central fit.

Figure [2](#page-3-0) compares the parton distributions from the new inclusive fit to the uncombined inclusive *W* and *Z* data with the new fit including the *W*+jet data. The fits are consistent, but with the new fit including the *W*+jet data favouring harder \bar{d} , and softer *d* valence quark distributions, with the *u* quark distributions largely unchanged. The uncertainty on the gluon density is largely unchanged, however, the gluon distribution itself in the fit with the $p_T(W)$ is very slightly harder.

Looking in more details at the strangeness contributions in Figure [3](#page-3-0) for the fit including the *W*+jet data, the uncertainty at larger *x* is very greatly reduced largely due to the increased sensitivity to larger *x* from the additional radiation. The actual value of the r_s ratio at large *x* is reduced with respect to the fit to inclusive data only. However, the enhanced strangeness contribution at low *x*,

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Figure 2: A comparison of the *u* and *d* quark, and gluon distributions for the new fit to the uncombined as reduced as $\frac{d}{dx}$ or $\frac{d}{dx}$ and $\frac{d}{dx}$ and $\frac{d}{dx}$ and $\frac{d}{dx}$ and $\frac{d}{dx}$ and $\frac{d}{dx}$ and inclusive W and Z data with the new fit including also the data for the $p_T(W)$ distribution. \mathcal{C} gluon (f), when fitting *W* + jets, inclusive *W*, *Z* and HERA data, compared to a similar fit without *W* + jets data. **Figure 2:** A comparison of the u and d quark, and gluon distributions for the new fit to the uncombined
inclusive W and Z data with the new fit including also the data for the $p_T(W)$ distribution μ and d quark, and gluon distributions for the new fit to the uncombined Figure 2: A comparison of the u and d quark, and gluon distributions for the new fit to the uncombined $\overline{1}$ 10 $\overline{$ which uses the sum of *u*¯ and *d*¯ as reference for the strange-sea density. inclusive W and Z data with the new fit including also the data for the $p_T(W)$ distribution. **Figure 2:** A comparison of the u and d quark, and gluon distributions for the new fit to the uncombined parameterisation and model uncertainties. The fit using *W* + jets *p*

Figure 3: The strangeness ratio, $r_s = (s + \bar{s})/(\bar{u} + d)$ for the new ATL R and R is a function plotted as $P_1(x)$ due λ (*x* evaluation *x* and *x* and *x* and *x* approximately 1.3 to approximately 1.3 to approximately 1.3 to λ *x* λ *x* λ *x* λ *x* λ *x* λ *x* λ Eight 5. The stangeness ratio, $r_s = (s + s)/(u + u)$ for the new ATERSep w2150 in and the ATERSep-WZW jets19 fit including the $p_T(W)$ data (left), and showing the breakdown of the uncertainties into experimental model and parame the *W* + jets data is most significant in the kinematic region *x* > 0.02, where the uncertainty is significantly **Figure 3:** The strangeness ratio, $r_s = (s + \bar{s})/(\bar{u} + \bar{d})$ for the new ATLASepWZ19U fit and the ATLASepat *x* = 0.1. $WZWJetsI9$ in including the $p_T(w)$ data (left), and showing the breakdown of the uncertainties into experi-
mental, model and parameterisation uncertainties (right). WZWjets19 fit including the $p_T(W)$ data (left), and showing the breakdown of the uncertainties into experi-
mental, model and parameterisation uncertainties (right) $= (s + s) / (s)$ compatible with the ATLASepWZ16 fit. Fitted values of *^r*^s and *^R*s, evaluated at *^x* ⁼ ⁰.⁰²³ and *^Q*² **Figure 3:** The strangeness ratio, $r_s = (s + \bar{s})/(\bar{u} + \bar{d})$ for the new ATLASepWZ19U fit and the ATLASep-*ATLAS* Preliminary 2 = 1.9 GeV \sim WZWjets19 fit including the $p_T(W)$ data (left), and showing the breakdown of the uncertainties into experi-
mental model and parameterisation uncertainties (right) **Figure 3:** The strangeness ratio, $r = (s + \bar{s})/(\bar{s} + \bar{d})$ for the new ATLASepWZ19U fit and the ATLASep- σ (right). **Figure 3:** The strangeness ratio, $r_s = (s + s)/(u + d)$ for the new ATLASepWZ19U fit and the ATLASep-**Figure 3:** The strangeness ratio, $r_s = (s + \bar{s})/(\bar{u} + d)$ for the new ATLASepWZ19U fit and the ATLASep **Figure 3:** The strangeness ratio, $r_s = (s + \bar{s})/(\bar{u} + \bar{d})$ for the new ATLASepWZ19U fit and the ATLASepcompatible with the ATLASEPUZ fitted values of *rs* and *RS*, evaluated at *RS*, evaluated at $\frac{1}{2}$ and $\$ e WZWjets19 fit including the $p_T(W)$ data (left), and showing the breakdown of the uncertainties into experimental model and parameterisation uncertainties (right) WZW ets 19 fit including the $p_T(W)$ data (left), and showing the breakdown of the uncertainties into experimental, model and parameterisation uncertainties (right). ^T , (b) fitting the *W* + jets data as a function of *p* **the** *W* \mathbf{w} is most significant in the *W* \mathbf{w} \mathbf{w} is \mathbf{w} and the *W* \mathbf{w} and the *W* \mathbf{w} and the *W* \mathbf{w} and the *W* \mathbf{w} and \mathbf{w} and \mathbf{w} and \mathbf{w} and \mathbf{w} and $r(x) = \sqrt{(-1)^2}$ reduces \overline{P} and \overline{P} **Agricution falling from near-unity at** \overline{P} $=(s + s)/(s + s)$ compatible with the ATLASepWZ16 fit. Fitted values of *^r*^s and *^R*s, evaluated at *^x* ⁼ ⁰.⁰²³ and *^Q*² **Figure 3:** The strangeness ratio, $r_s = (s + \bar{s})/(\bar{u} + \bar{d})$ for the new ATLASepWZ19U fit and the ATLASepmental, model and parameterisation uncertainties (right). , determined from (a) fitting the *W* + jets data as a function WZWjets19 fit including the $p_T(W)$ data (left), and showing the breakdown of the uncertainties into experimental, model and parameterisation uncertainties (right). for the new AILASepWZ19U fit and the AILASepreduced and the fit results in the *R*^s distribution falling from near-unity at *x* 0.01 to approximately 0.3 At low *x* (*x* < 0.023), the fit with the *W* + jets data maintains an unsuppressed strange-quark density **Figure 3:** The strangeness ratio, $r_s = (s + \bar{s})/(\bar{u} + \bar{d})$ for the new ATLASepWZ19U fit and the ATLASep-WZWjets19 fit including the $p_T(W)$ data (left), and showing the breakdown of the uncertainties into experiimental, model and parameterisation uncertainties (right).

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 $\frac{1}{2}$ mostly positive, each with a low maxima around $\frac{1}{2}$ the uncombined inclusive data only. For both fits including the $W +$ jet data the asymmetry is now which also see a larger \bar{d} distribution fit including the $p_T(W)$, with the fit including the W+jet leading jet p_T . Also shown is the fit to Figure 4 compares the rest Figure 4 compares the result of the light quark asymmetry for the new ATLASepWZWjets19 mostly positive, each with a low maxima around $x = 0.2$. This is more in line with the global fits without ^Tets data, and (c) the obtained ATLASeptember of the fit with the fit with $\frac{1}{\sqrt{N}}$ larger d distribution is one of the factors resulting *ATLAS* Presentation 2 = 1.9 GeV = 1.9 G If including the $p_T(W)$, with the fit including the W+jet leading jet p_T . Also shown is the fit to which also see a larger \bar{d} distribution than \bar{u} . The larger \bar{d} distribution is one of the factors resulting compatible with the ATLASepWZ16 fit. Fitted values of *^r*^s and *^R*s, evaluated at *^x* ⁼ ⁰.⁰²³ and *^Q*² and total uncertainties, respectively. In (c), the uncertainty bands are displayed split in to the experimental, \mathbf{c} Figure 4 compares the result of the light quark asymmetry for the new ATLASepWZWjets19 which also see a larger \bar{d} distribution than \bar{u} . The larger \bar{d} distribution is one of the factors resulting compatible with the ATLASepWZ16 fit. Fitted values of *^r*^s and *^R*s, evaluated at *^x* ⁼ ⁰.⁰²³ and *^Q*² mostly positive, each with a low maxima around $x = 0.2$. This is more in line with the global fits , determined from (a) fitting the *W* + jets data as a function Figure 4 compares [t](#page-4-0)he result of the light quark asymmetry for the new ATLASepWZWjets19 the uncombined inclusive data only. For both fits including the $W + jet$ data the asymmetry is now which also see a larger d distribution than \bar{u} . The larger d distribution is one of the factors resulting mostly positive, each with a low maxima around $x = 0.2$. This is more in line with the global fits , determined from (a) fitting the *W* + jets data as a function with $\frac{1}{2}$ jets data, and (c) the obtained ATLASepWZWjetnika in jets data i which also see a larger \bar{d} distribution than \bar{u} . The larger \bar{d} distribution is one of the factors resulting *ATLAS* Preliminary 2 = 1.9 GeV 2 Q fit including the $p_T(W)$, with the fit including the W+jet leading jet p_T . Also shown is the fit to ϵ in the width the grobal fits Figure 5: The *^R*^s distribution, evaluated at *^Q*² = 1.9GeV2 mostly positive, each with a low maxima around $x = 0.2$. This is more in line with the global fits res
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distribution. The right figure compares the fits including the $p_T(W)$, and the leading jet p_T distributions. the fit including only the inclusive *W* and *Z* data, to that obtained when also including the data for the $p_{\rm T}(W)$ distribution. The right figure compares the fits including the *p*_T(*W*), and the leading jet *p*_T distributions. **Figure 4:** The light quark asymmetry, $x(\bar{d} - \bar{u})$, for the fits discussed in the text. The left figure compares

experience in the parameter of \mathbf{m} to quark asymmetry is achieved while still maintaining the enhanced strangeness at low x, but is exp. de la constatución de la cons
Constatución de la constatución de in the smaller value for the strangeness ratio at larger x . It should be noted that this positive light correlated with the reduction of the strangeness ratio at higher *x*.

x ATLASepWZ19U and ATLASepWZ19C fits to the inclusive *W* and *Z* data. The fits to the inclusive $\frac{3}{2}$ $\frac{3}{2}$ data are all in agreement, but predict a consistently higher value for the strangeness ratio than the is more in line with the global fits, but still predicts an enhanced strangeness ratio. Comparing the value of the light quark asymmetry with the global fits, also in Figure [5](#page-5-0), it is observed that the new future of the fight quark as fitthout *with the groom*? asymmetry when including the $w +$ Jet data is now in global fits - albeit still predicting a slightly smaller ratio. $\overline{10}$ 10 $\overline{10}$ 10 $\overline{10}$ 10 $\overline{10}$ can be seen in Figure [5.](#page-5-0) Also shown are values from the original ATLASepWZ16 fit and the new NNPDF3.1 [\[19](#page-6-0)] and ABMP16 [\[20](#page-6-0)] for the value of r_s evaluated at $x = 0.023$ and $Q^2 = 1.9 \text{ GeV}^2$ \mathbb{R}^n \mathbb{R}^n and \mathbb{R}^n fit corresponding to the fit with \mathbb{R}^n asymmetry when including the $W +$ jet data is now more consistent with the observations from the and the uncertainties, respectively. In \mathbb{R}^n in the experimental, modelling in the experime A comparison with the results of the additional global fits from CT14 [[17](#page-6-0)], MMHT2014 [[18\]](#page-6-0), new fit with the *W*+jet data, as expected from the strangeness ratio discussed earlier. The new fit

3. Outlook

ATLAS has an extensive, and growing portfolio of precision measurements, each having the potential to help constrain the parton distributions in the proton. For the analysis presented here a new fit including the inclusive *W* and *Z* data, enhanced by the inclusion of *W*+jet data has been performed. The new fit confirms the enhancement of the strange contribution at low *x*, but now also with a positive light quark $x(\bar{d}-\bar{u})$ asymmetry, more consistent with the global fits.

17 Together with the higher energy 13 TeV collision data from LHC Run II, the potential to even more There remain many analyses that could still benefit from the full luminosity of the Run I data. tightly constrain the proton PDF is great. Including more published data is possible – for example, data from top production or other vector boson data – and new precision vector boson data will be available soon, including new data on ATLAS $Z + i$ et production. New inclusive vector boson data at higher, and lower beam energies should lead to further reductions in both the statistical and systematic uncertainties, with better constraints on the gluon. For many measurements, the

Figure 5: A summary of the strangeness ratio, r_s evaluated at $Q^2 = 1.9 \text{ GeV}^2$ and $x = 0.023$ (left) and the light quark asymmetry evaluated at the Z mass and with $x = 0.1$ (right). Results are shown comparing the values from the new fits with those from the four major global PDE sets. ϵ and ϵ values from the new fits with those from the four major global PDF sets.

theoretical uncertainties are often comparable to, or larger, than those from the data. New NNLO \bigcap calculations for heavy boson production in association with a jet [[21\]](#page-6-0), are now available, and within the interface of the calculations with the fast interpolation grid technology mean these data – and data, as well as that accompanied by a hadronic jet. the same framework, many other significant physics processes are also available. Developments in HERA jet data – will be usable in rigorous NNLO fits, including the inclusive *W* and *Z* production

Atthough a great deal of progress has been achieved in the field of QCD fits including EHC
data, the journey towards realising the full potential of these data is only just beginning, and it Although a great deal of progress has been achieved in the field of QCD fits including LHC promises to be a very interesting time ahead.

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