Measurement of V+jet production and MPI with ATLAS*

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Abstract

The production of jets in association with a W or Z boson in proton-proton collisions at 7 TeV allows the study of multileg QCD diagrams. Differential cross sections have been measured with the ATLAS detector as a function of several kinematic variables up to high jet multiplicities and compared to new higher-order QCD calculations. The ratio of (W + a single jet)/(Z + a single jet) can provide a very precise test of QCD and has also been measured. Topologies with a vector boson and jets in the final state are also sensitive to double parton scattering which has been measured using W+2 jet events. More exclusive processes of $W + b$ production and $W + D$ production have also been measured.

1 Introduction

The study and measurement of vector boson (V) production in association with jets provides an important test of perturbative quantum chromodynamics (pQCD). Such measurements can also be used to constrain parton distribution functions (PDFs). Furthermore such processes constitute a non-negligible background to many searches for new phenomena.

In the past ATLAS [1] has reported measurements of such processes at moderate energies and jet multiplicities. With larger LHC datasets now becoming available such measurements are being carried out at higher jet multiplicities and in higher energy regimes. More exclusive V+jets studies are also carried out which, along with providing further constraints on pQCD, are also sensitive to Multiple Parton Interactions (MPI).

These proceedings summarise recent studies of these processes using the ATLAS detector at the Large Hadron Collider (LHC). Section 2 presents studies

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of Z and W production in association with light jets. Section 3 presents studies of W production in association with D mesons and section 4 looks at W production in association with b mesons. Finally section 5 presents a measurement of double parton interactions (DPI) using W production in association with exactly two jets.

2 V+jet Production

ATLAS has performed measurements of W and Z production in association with jets along with the ratio of W to Z production with exactly one jet as a function of jet p_T threshold. These measurements are complementary to one another and provide stringent tests of pQCD calculations.

2.1 Z+jet Production

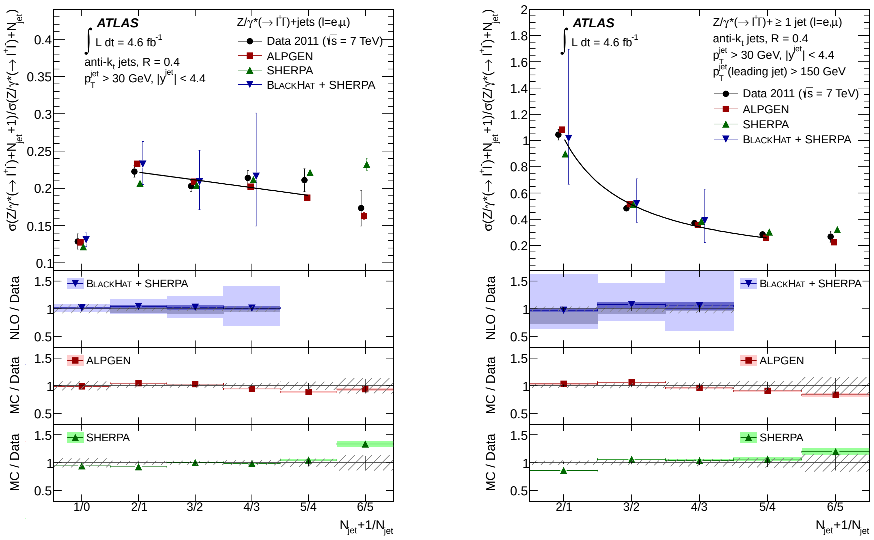
Z+jet production has been measured using 4.6 fb^{-1} of pp collisions taken in 2011 at $\sqrt{s}$ = 7 TeV [2]. This large dataset is sufficient for studies of Z production with up to 7 jets. The measurement is compared to NLO predictions from the Blackhat + Sherpa program [3, 4, 5] and LO predictions from Alpgen [6] and Sherpa [7].

Figure 1 shows the scaling patterns investigated in Z+jet events by investigating $R_{(n+1)/n}$, the ratio of Z production with exactly $(n + 1)$ jets to that with exactly n jets. Exclusive jet multiplicities are expected to be described by a combination of:

- 'Staircase scaling' in which $R_{(n+1)/n}$ is constant
- 'Poisson scaling' in which $R_{(n+1)/n}$ is inversely proportional to n

The standard selection is used to investigate staircase scaling in Figure 1(a) whilst Poisson scaling is enhanced in Figure 1(b) by introducing a large scale difference between the core Z+1-jet process and the second leading jet. This is achieved by requiring a leading jet p_T of at least 150 GeV. It is seen that staircase scaling is well modelled in the standard selection and a flat staircase pattern provides an acceptable description of the scaling relation. Similarly Poisson scaling is well modelled and also well described by fitting a function of the form $R_{(n+1)/n} = \frac{\bar{n}}{n}$, where $\bar{n}$ is the expectation value of the jet multiplicity distribution.

The Z+jet measurement observes large discrepancies between fixed order pQCD calculations and data in inclusive distributions such as the scalar sum p_T of all objects in an event, H_T, as shown in Figure 2(a) in which significant deviations are observed above 350 GeV. Such a deviation is consistent with the point where the mean jet multiplicity of events increases above 2 as is shown in Figure 2(b) which shows the mean jet multiplicity versus H_T in Z+jet events. This leads to the conclusion that H_T may be better modelled using an exclusive sum of fixed order pQCD calculations of the form Z(+1 jet)+$Z(+ \geq 2$ jets) as demonstrated in Figure 2(c).



(a) Staircase Scaling

(b) Poisson Scaling

Figure 1: Ratio of jet multiplicities for Z+jet events. Staircase scaling is exhibited using the standard selection whilst Poisson scaling is enhanced in (b) by requiring a leading jet p_T of at least 150 GeV. From ref. [2].

2.2 W+jet Production

The measurement of W boson production with jets provides a complementary result to the Z+jet measurement providing increased statistics but also increased backgrounds. Shown here is a measurement of W+jets carried out using 36 pb^{-1} of 2010 pp collisions at $\sqrt{s}$ = 7 TeV [8]. The measurement is compared to NLO predictions from the BLACKHAT + SHERPA program and LO predictions from ALPGEN and SHERPA.

This measurement shows similar results to Z+jets as seen in Figure 3(a) which shows the leading jet p_T for W+jet events.

2.3 R_{jets}

R_{jets} is a measurement of the ratio of W+jet production to Z+jet production. The similarity of the Z and W production enables a cancellation of both experimental and theoretical systematics to reduce systematic uncertainties associated to V+jet measurements. This measurement is performed using 33 pb^{-1} of 2010 pp collisions at $\sqrt{s} = 7$ TeV [9]. The measurement is presented in the exclusive 1-jet bin as a function of the jet p_T threshold and compared to predictions from LO PYTHIA [10] and ALPGEN and NLO MCFM [11]. All the predictions show consistency with the measurement as shown in Figure 3(b).

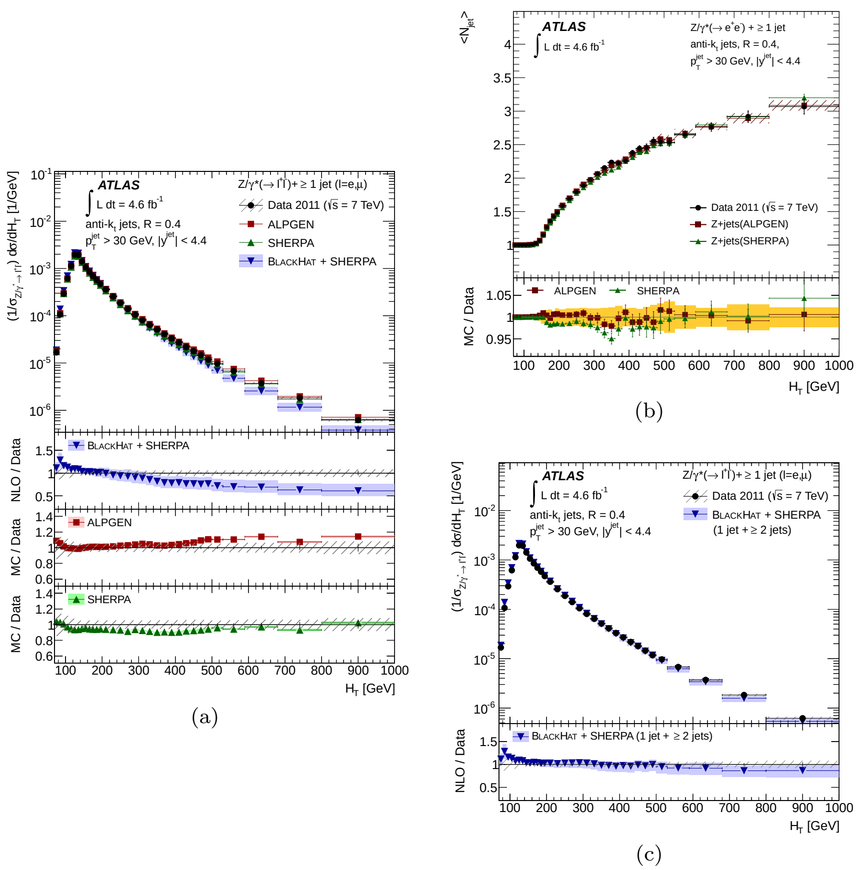
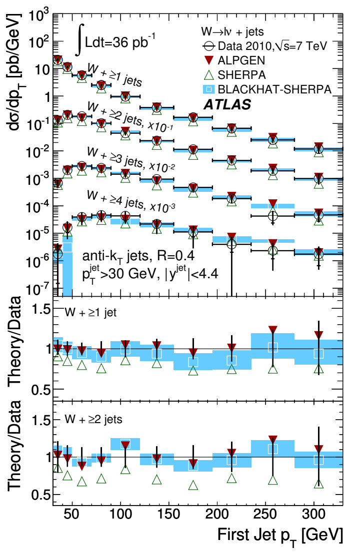
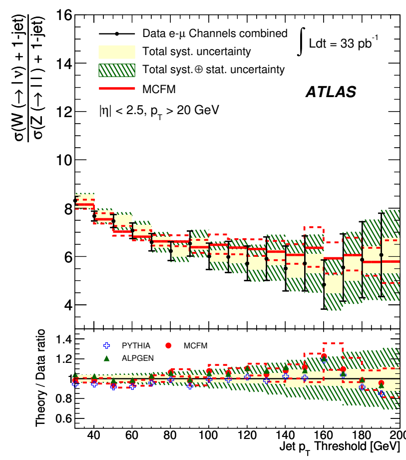


Figure 2: (a) shows the cross section for production of Z bosons in association with jets versus H_T, the distributions are normalised to the total measured or calculated cross section. (b) shows the mean jet multiplicity versus H_T while (c) shows the H_T distribution replacing the NLO calculation with an exclusive sum of NLO calculations as described in the text. From ref. [2].



(a) Leading jet p_T in W+jets



(b) R-jets Measurement

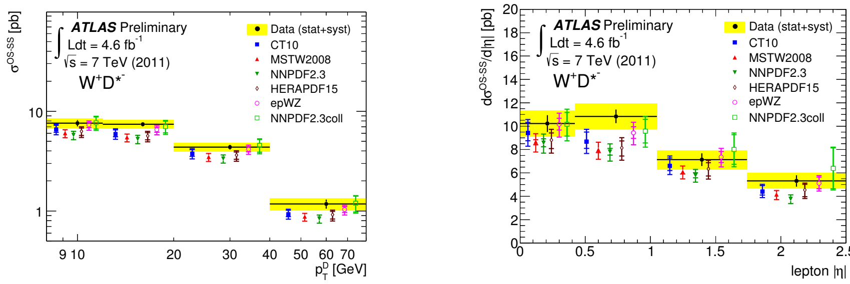
Figure 3: Leading jet p_T W+jet events and the R_{jets} measurement for exactly one jet versus jet p_T threshold. From ref. [8] and [9].

3 $W + D$ Production

Previous analysis using ATLAS inclusive W and Z measurements along with HERA data has bolstered the case for there being an SU(3) symmetric sea at $x \sim 0.01$ [12]. Large production rates of W bosons in association with D mesons now provide the possibility of performing a measurement which can directly constrain the s-quark PDF. Such an analysis is particularly sensitive in the region of interest, $x \sim M_W/\sqrt{s} \sim 0.01$. This analysis is carried out using 4.6 fb^{-1} of 2011 pp collisions at $\sqrt{s} = 7$ TeV [13].

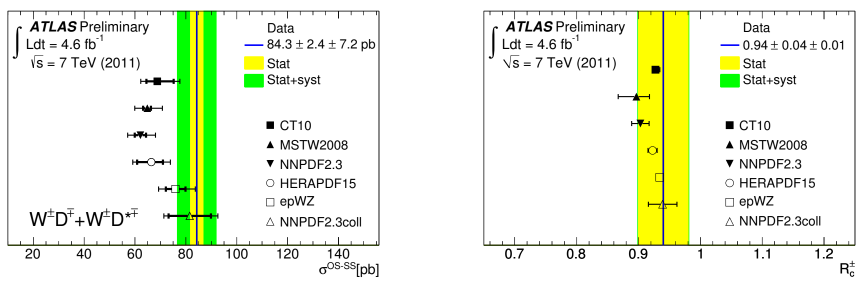
The cross sections are extracted using the charge correlation between the lepton from the W and the $D^{(*)}$ to extract the single-charm component. Distributions are formed for both opposite charge (OS) and same charge (SS) distributions and the OS-SS combination used for the extraction of the final cross section. The yield is then found by fitting the $D^{\pm}$ mass (for $D^{\pm}$) or the $D^{*} - D^{0}$ mass difference (for $D^{*\pm}$).

The results of this analysis are presented as a function of lepton $|\eta|$ and p_T^D as shown in Figure 4. The results are compared to predictions from aMC@NLO [14] using 6 different PDF sets. 'Standard' PDF sets of CT10, MSTW2008, NNPDF2.3 and HERAPDF15 which all have suppressed strangeness (although CT10 is not as suppressed as the others), epWZ which is the resultant PDFs from simultaneous inclusive W and Z results from ATLAS and HERA results with strangeness equal to $\bar{u}$ and $\bar{d}$, and NNPDF2.3coll which includes only collider data and has



(a) p_T^D (b) Lepton $|\eta|$

Figure 4: Cross section of production of W^+D^{*-} versus p_T^D and lepton $|\eta|$. Results are compared to aMC@NLO calculated using a range of different PDF sets. From ref. [13].



(a) $\sigma\left(W + D^{(*)}\right)$ (b) $R_C^{\pm}$

Figure 5: Total cross section for the production of $W + D^{(*)}$ and the charge asymmetery measurement. From ref. [13].

even more enhanced strange than epWZ. It is observed that the shapes are well modelled and the measurement is most consistent with predictions using epWZ and NNPDF2.3coll, both of which have enhanced strangeness as compared to standard PDFs.

All channels are combined into a total cross section for $W+D/D^*$ production as shown in Figure 5. A further measurement is presented showing the ratio

$$R_C^{\pm} = \frac{\sigma\left(W^+D^{(*)-}\right)}{\sigma\left(W^-D^{(*)+}\right)} \tag{1}$$

which is sensitive to the asymmetery between the s and $\bar{s}$ PDFs. Again it is observed that the total cross section results favour PDFs with enhanced strangeness whilst the $R_C^{\pm}$ results show that all PDFs are consistent with the measurement.

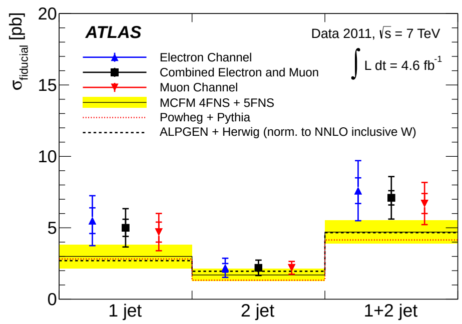


Figure 6: Measured cross sections for $W + b$ production in the fiducial phase space for exactly 1-jet, exactly 2-jets and 1- or 2-jets. Results are shown for muon, electron and the combined channels. From ref. [15].

	1 jet	2 jets
σ_{fid} [pb]	5.0 $\pm$ 0.5 (stat) $\pm$ 1.2 (syst)	2.2 $\pm$ 0.2 (stat) $\pm$ 0.5 (syst)
Non-perturbative	0.92 $\pm$ 0.02 (had.) $\pm$ 0.03 (UE)	0.96 $\pm$ 0.05 (had.) $\pm$ 0.03 (UE)
DPI [pb]	1.02 $\pm$ 0.05 (stat) $\pm^{0.4}_{0.29}$ (syst)	0.32 $\pm$ 0.02 (stat) $\pm^{0.12}_{0.09}$ (syst)

Table 1: Additive DPI and multiplicative non-perturbative corrections in $W + b$ predictions. It can be seen that the DPI correction represents up to a 25% contribution to the total cross section. From ref. [15].

4 $W + b$ Production

The measurement of W boson production in association with b-quark jets provides a test of pQCD in the presence of heavy quarks using 4.6 fb^{-1} of 2011 pp collisions at $\sqrt{s} = 7$ TeV [15].

Results are compared to NLO predictions from MCFM and Powheg [16, 17] and LO Alpgen predictions scaled to NNLO. The measured results are observed to be above both LO (scaled to NNLO) and NLO predictions as shown in Figure 6. Results are also presented differential in jet p_T and with and without subtraction of the single t contribution.

Neither MCFM nor Powheg includes the contribution from double parton interactions (DPI). An additive correction is derived using Alpgen. This represents a 25% contribution to the total cross section and is concentrated in the low momentum 1-jet region. Table 1 shows the additive DPI correction and compares it to the multiplicative non-perturbative correction. This DPI contribution has been shown to be consistent with a direct DPI measurement (see Section 5).

5 $W + 2$ jet Production and DPI

Double parton interactions (DPI), when two partons in the same proton interact in the same collision, are characterised by the effective area parameter, $\sigma_{\text{eff}}(s)$. This is assumed to be independent of phase space or process. Previous measurements in pp and $p\bar{p}$ collisions at $\sqrt{s} = 63$ GeV, 630 GeV, 1.8 TeV and 1.96 TeV have ranges from 5 mb at low energies to 15 mb at Tevatron energies. The LHC is a rich environment to investigate DPI as the higher centre-of-mass enhances PDFs so we expect a larger impact of DPI. Furthermore, higher energy and luminosity mean that multiple interactions occur at higher transverse momentum.

ATLAS measures $\sigma_{\text{eff}}(s)$ using 36 pb^{-1} of 2010 pp collisions at $\sqrt{s} = 7$ TeV using W production in association with exactly two jets [18]. This is done by extracting the fraction of W+2 jet events arising from DPI

$$f_{\text{DP}}^{(\text{D})} = \frac{N_{W_{2\text{j}}+2\text{j}_{\text{DPI}}}}{N_{W_{2\text{j}}+2\text{j}}} = \frac{N_{W_{2\text{j}}+2\text{j}_{\text{DPI}}}}{N_{W_{2\text{j}}} + N_{W_{2\text{j}}+2\text{j}_{\text{DPI}}}}. \tag{2}$$

This is then used to extract a value of $\sigma_{\text{eff}}(s)$.

Three samples are constructed:

- W+0-jet: events passing W selection but with no additional jets
- W+2-jet: events passing W selection with exactly two additional jets
- dijet: events with exactly two jets using a minimum bias trigger in data

The variable

$$\Delta_{\text{jets}}^{\text{n}} = \frac{\left|\vec{p}_T^{J_1} + \vec{p}_T^{J_2}\right|}{\left|\vec{p}_T^{J_1}\right| + \left|\vec{p}_T^{J_2}\right|} \tag{3}$$

is used to extract $f_{\text{DP}}^{(\text{D})}$ by fitting the W+2-jet distribution with a template without DPI taken from MC and a template with DPI only taken from the dijet sample. $f_{\text{DP}}^{(\text{D})}$ is also evaluated at parton level in MC and after hadron level unfolding, both of which are seen to be within 10% of $f_{\text{DP}}^{(\text{D})}$. The measured value of σ_{eff} is found to be

$$\sigma_{\text{eff}} = 15 \pm 3(\text{stat})\ ^{+5}_{-3}\ (\text{syst})\ \text{mb}.$$

Figure 7 shows the ATLAS measurement of σ_{eff} compared to previous measurements at various centre of mass energies. It is seen that the ATLAS measurement is consistent with previous measurements at the Tevatron and UA2.

6 Summary and conclusion

ATLAS has carried out measurements of V+jet production which can directly be used to test and constrain perturbative QCD calculations. In many regions

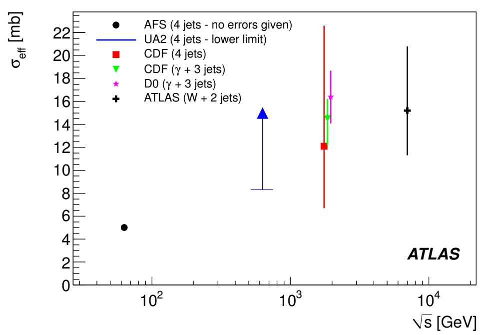


Figure 7: $\sigma_{\rm eff}$ as a function of centre of mass energy showing the ATLAS measurement and previous measurements. The ATLAS measurement is seen to be consistent with previous Tevatron and UA2 measurements. From ref. [18].

of phase space such measurements have experimental uncertainties which are competitive with if not below theoretical uncertainties.

More exclusive measurements of $W + D$ have been carried out and can be used to extract information on the s-quark PDF. Such measurements have been shown to prefer PDFs with an SU(3) symmetric sea with strangeness enhanced above what 'standard' PDFs currently assume.

ATLAS has also made a direct measurement of the cross section of double parton interactions. This measurement has been seen to be consistent with previous measurements carried out at lower centre of mass energies.

Some of these measurements, such as the inclusive V+jet measurements, will benefit from increased datasets or increased energy as available from 2012 running. Such an extended set will allow reduced errors on measurements and extensions to more extreme phase spaces both of which will further contrain theoretical calculations and PDFs.

7 Acknowledgements

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