W/Z + jet Production at the LHC

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This paper summarises results on W and Z plus jet production in pp collisions at $\sqrt{s} = 7$ TeV at the CERN Large Hadron Collider, from both the ATLAS and CMS experiments. Based on the 2010 and 2011 datasets, measurements have been made of numerous cross sections providing excellent tests of the latest predictions from QCD calculations and event generators.

1 Introduction

The leptonic (specifically electron and muon) decay modes of the W and Z (V) boson provide very clean experimental signatures in the complex environment of a hadron collider. At the CERN LHC, the collision energy allows enough phase space to produce several high energy QCD jets in association with the W or Z boson, and studies of these complex final states provide an excellent testing ground for theoretical predictions. The variety of possible scale choices (including the boson mass and jet momenta) necessitate the use of explicit matrix elements for each additional jet, rather than producing jets simply through a parton shower model. While such multi-leg matrix elements have been calculated at leading order (LO) in perturbation theory for some time, recent theoretical developments have increased the reach of next-to-leading order (NLO) calculations out to V + 5 jets, as available at parton level in BLACKHAT. In terms of full event generators, ALPGEN, MADGRAPH and SHERPA match multi-leg LO matrix elements to parton showers. Complementary efforts to interface NLO matrix elements to parton shower models, such as MC@NLO and POWHEG which utilise PYTHIA and HERWIG make this a very active area of theoretical development, with several possible tools to test against the data. As well as being clean calibration sources, V + jets also constitute the main source of background in many searches for new physics. A detailed understanding of these final states is therefore essential. The ATLAS and CMS experiments have performed a variety of cross section measurements at a centre of mass energy of 7 TeV, from inclusive quantities such as the rate of V+ ≥ 1 jet, through to more exclusive quantities like differential distributions for jets of specific flavours. This paper summarises the results obtained to date with the 2010 (approximately 36 pb$^{-1}$) and 2011 (approximately 5 fb$^{-1}$) datasets, as presented at the Rencontres du Blois, May 2012.

2 V + inclusive jet production

At both ATLAS and CMS, the basic W or Z event selection is based on triggering on and reconstructing a high transverse momentum ($p_T$) lepton (typically $p_T > 20$ GeV), and in the case of the W, missing transverse energy ($E_T^{miss}$) corresponding to the undetected neutrino
jets) \[ pb \]

$N \geq (W + \sigma)^10^2 - 10^3 - 10^4 \, \text{jets}$

$\nu_l \rightarrow W = 7 \, \text{TeV}$

Data 2010, ALPGEN SHERPA PYTHIA BLACKHAT-SHERPA

$Ldt = 36 \, \text{pb}$

$\int_{\text{jets, } R=0.4} \text{anti-}k_t |<4.4 \, \text{jet } y>30 \, \text{GeV, } |T_{\text{jet}}| > 36 \, \text{pb}$

$W + \nu_l \rightarrow W = 7 \, \text{TeV}$

Charge asymmetry

Figure 1: Left: The $W + n$-jets cross section, in inclusive jet multiplicity bins, measured by ATLAS. Right: the lepton charge asymmetry in jet multiplicity bins for $W$ events, as measured by CMS.

(typically $E^\text{miss}_T > 25 \, \text{GeV}$). Both experiments use the anti-$k_t$ algorithm to reconstruct jets, albeit with different radius parameter settings ($R = 0.4$ at ATLAS, 0.5 at CMS). Cross sections are generally presented within a fiducial volume, and corrected to the level of particles entering the detector, to minimise dependence on theoretical corrections.

The first benchmark is to measure the inclusive jet rates produced in association with the $W$ or $Z$ (see Fig. 1). Both experiments find the predictions of ALPGEN and SHERPA, and the latest NLO predictions from BLACKHAT, provide a good description of the data, within uncertainties. The data uncertainties are dominated by the uncertainty on the jet energy scale. This, along with some other uncertainties, can be partially cancelled by taking ratios, such as $W + n$-jets/$W + (n-1)$-jets, as measured at CMS. ATLAS measure also the ratio of $W + \text{jet}/Z + \text{jet}$ as a function of the jet $p_T$ threshold (see Fig. 2), which benefits from this cancellation while also testing the evolution of the predictions with increasing scale, and being sensitive to any new physics appearing preferentially in one of the $W$ or $Z$ channels. CMS also measure the $W$ charge asymmetry ($A_W = \frac{\sigma(W^+)}{\sigma(W^+)} - \frac{\sigma(W^-)}{\sigma(W^-)}$) in bins of inclusive jet multiplicity (see Fig. 1). The data show a trend for reduced charge asymmetry at higher jet multiplicity, possibly due to the increased importance of gluon instead of valence quark initial states. This trend is reproduced in event generators which include explicit matrix elements for multiple jet production, but not in PYTHIA which relies on the parton shower to produce multiple jets. ATLAS also measure a number of differential distributions in $V+$jet production, from individual jet momenta and rapidity ($y$) distributions, to correlations between jets and the boson, such as $\Delta y(\text{lepton, jet})$, $\Delta y(\text{jet, jet})$, dijet mass distributions in different jet bins. These distributions pick out many different aspects of the underlying physics. For example, the azimuthal angular separation, $\Delta \phi(\text{jet, jet})$, (see Fig. 2) highlighting the failure of the parton shower only approach in PYTHIA to produce well separated jets, and is also sensitive to multiple hard parton interactions producing a separate balanced (back-to-back) jet system in association with the $Z$.

3 V + Heavy Flavour Jets

Further information on the underlying physics can be obtained by identifying the flavour of hadrons produced within jets. Measuring the production of $W$+charm, for example, gives a
Figure 2: Left: the $W+$jet/$Z+$jet ratio as a function of the jet $p_T$ threshold. Right: $\Delta \phi$ (jet,jet) in $Z+\geq 2$ jet events. Both measured by ATLAS.

Figure 3: Left: constraints on the strange PDF from the CMS $W+$charm analysis. Right: ATLAS measurements of $W + b$-jet production.

unique constraint on the strange quark content of the proton. Looking for semi-leptonic charm decays producing a muon inside a jet, and using the fact that in $W+$charm this muon will be of the opposite sign to the $W$ (compared to a random sign in most sources of background), CMS made a preliminary analysis of the 2010 dataset to place constraints on the strange content of recent PDF sets (see Fig. 3).

The production of $b$ hadrons can be calculated in a 5-flavour PDF scheme (with a massless $b$-quark) or a 4-flavour scheme (including the $b$-mass); both suffer large theoretical uncertainties. As $V+b$-jets forms the main background to low mass associated VH production, it is of particular interest to constrain this signal. Jets containing $b$ hadrons can be identified based on the relatively long lifetime of these hadrons, and both experiments “tag” jets by looking for matching secondary decay vertices or tracks displaced from the primary vertex. This information, along with other sensitive quantities, are combined into multi-variate discriminants to maximise the tagging efficiency. The actual $b$-jet yield is separated from light flavour and charm jet mis-tags by fitting simulated templates to the data in discriminating variable such as the mass of the reconstructed secondary vertex in the event. The production of $W + b$ suffers particularly
large backgrounds from $W+charm$ and top pair production. However, ATLAS extract the $b$-jet yield in $W + 1$- and 2-jet events, and see a 1.5$\sigma$ excess over NLO predictions\textsuperscript{19} (see Fig. 3). The $Z + b$ case has much lower backgrounds, and ATLAS and CMS extract cross sections using different kinematic selections: ATLAS $3.55^{+0.82}_{-0.74}\text{(stat)}^{+0.73}_{-0.55}\text{(syst)} \pm 0.12\text{(lumi)}$ pb (using 36 pb$^{-1}$)\textsuperscript{20} and CMS $5.84 \pm 0.08\text{(stat.)} \pm 0.72\text{(syst.)}^{+0.25}_{-0.55}\text{(theory)}$ pb (using 2.2 fb$^{-1}$)\textsuperscript{21}. Both are compatible with NLO predictions within uncertainties. Using the full 2011 dataset, CMS have also made a first preliminary study of the angular correlation between $b$-hadrons in $Z$ events\textsuperscript{22}. V+heavy flavour studies will clearly benefit significantly from the statistics available in the large datasets now collected by both ATLAS and CMS, and this will continue to be a strong area for development.

4 Conclusions

Thanks to the energy reach of the LHC, it is already possible to make an impressive range of measurements in the V+jets final state. So far, the latest theoretical predictions have generally been successful in describing the data, but as the precision increases with future results this remains an interesting area in which to test our understanding of such complex final states. As the understanding of these final states is essential also to describe these backgrounds to searches for new physics like the Higgs boson, it also remains an essential area for development on both the experimental and theoretical side.

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$\sigma(W + \geq n\text{-jets}) \geq \text{data, energy scale, unfolding}$

$36 \text{ pb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$

$W \rightarrow e\nu$

$E_T^{\text{jet}} > 30 \text{ GeV}$

inclusive jet multiplicity, $n$