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ATLAS measurements of jets and heavy flavor produced in association with W and Z bosons

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The production of light and heavy flavors jets in association with a W or Z boson at the LHC represent important processes with which to study QCD in a multi-scale environment. Unprecedented precision is achieved in measurements of differential cross sections and multiplicities with the ATLAS detector, and comparisons are made to state-of-the-art high NLO QCD calculations of high-multiplicity final states. W/Z+jets events involving jets containing b-hadrons are also identified, and small tensions with theoretical predictions discussed.

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Events with jets in the final states are copiously produced via the strong interaction at the LHC. Precise measurements of Standard Model cross sections and parameters as well as most of the searches for new physics benefit from a thorough understanding of QCD in both soft and perturbative regimes. Studying QCD therefore has an important impact on the overall LHC physics program.

From the factorization theorem, the production rate of any processes at the LHC is given by the convolution of short distance physics with non-perturbative effects. Perturbative QCD (pQCD) predictions can be used to describe the hard processes constituting the short distance physics when the final states involve at least a quark or a gluon. It can also be used to model QCD bremsstrahlung effects, directly from fixed order QCD predictions at next-to-leading order (NLO) or more, or via leading-log (LL) parton shower models. The description of the parton distribution functions (PDF), of the fragmentation and hadronization processes and of the multiple parton interactions within a given collision are in the realm of soft-QCD non-perturbative effects. They must be described by phenomenological or empirical models.

The present studies concentrate on pQCD effects in W/Z+jets events at the LHC with the ATLAS detector [1]. The measurements have been performed with about $\int Ldt = 35 pb^{-1}$ of $\sqrt{s} = 7$ TeV data taken in 2010. Similar studies have been performed at the Tevatron collider at $\sqrt{s} = 1.96$ TeV. At the LHC, jets are however produced at higher transverse momentum (p_{T}) and multiplicity (N_{jets}) than at the Tevatron. In addition, the flavor composition is very different: the ratio of the number of quark jets over gluon jets in W/Z+jets events is more than two times higher at the LHC than at the Tevatron.

In order to test pQCD, differential cross sections for various observables such as the number of jets in an event, the p_{T} of the leading and sub-leading jets, their rapidity, the angular distance between two jets and the invariant mass of the two leading jets have been measured in W+jets [2] and Z+jets [3] events and compared with the various theoretical predictions available for these observables and processes. The detector effects on jet and lepton reconstruction are unfolded from the observed differential distributions, after background subtraction. Lepton acceptance selections reflecting the limited pseudo-rapidity coverage of the ATLAS tracking system ($\eta < 2.5$) and the limited bandwidth of lepton triggers ($p_{\mathrm{T}} > 20$ GeV) are not corrected for, in order to minimize the dependence of the measurements on theoretical inputs.

Even if predictions on short distance physics quantities can be analytically computed with pQCD, different level of approximations are typically adopted in the various predictions made for the observables of physics processes involving jets. For example, leading order calculations complemented by a parton shower description of QCD bremsstrahlung emissions and a model of hadronization (LO+PS) provided by generators such as PYTHIA [4] give a good description of QCD inclusive observables such as the transverse momentum (p_{T}) of vector bosons, but does not provide the best description of large angle jet emissions. The reason is the soft and collinear approximations made in the description of QCD radiation effects in parton shower calculations. This is clearly visible on the left panel of Figure 1, where the PYTHIA predictions largely underestimate the angular distance $\Delta R^{jj} = \sqrt{\Delta y(j-j)^2 + \Delta\phi(j-j)^2}$ between the two leading jets in Z+jets events. This is responsible for an underestimate of the jets momentum and jet multiplicity in highly energetic kinematic regions, as can be seen on the right panel of Figure 1, as well as in the left panel of Figure 2. This can lead to underestimate of SM predictions in many searches for new physics.

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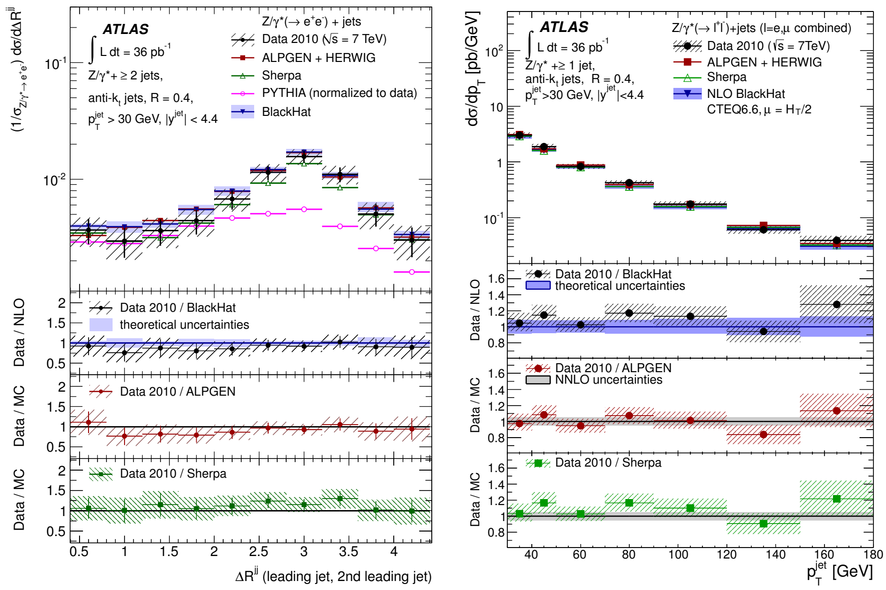

Figure 1: Left: Measured normalized Z/γ* (-> ee)+jets cross section (black dots) as a function of the angular separation (y-phi space) of the two leading jets. Right: Measured Z/γ* (->ll)+jets cross section (black dots) as a function of inclusive jet p_{T}. In both cases, the error bars indicate the statistical uncertainty and the dashed areas the total uncertainty [3]. The measurements are compared to NLO pQCD predictions from BLACKHAT-SHERPA, as well as the predictions from ALPGEN and SHERPA.

Higher jet multiplicity leading order predictions provide a better description of processes involving hard jets in the final states. The ALPGEN [5] and SHERPA [6] generators utilize such high multiplicity matrix elements to provide reliable predictions of hard jet spectra, and complement these predictions with parton shower and hadronization models, to get a good description of more inclusive observables. We can see on Figure 1 the generally good agreement between data and ALPGEN or SHERPA predictions. However, in order to have hard emissions from matrix element calculations and parton shower, an ad hoc matching or merging procedure is needed to avoid the double counting of same partonic multiplicity final states, therefore adding an extra source of uncertainty in the calculation. While the differences are not expected to be large, we can see that the leading jet p_{T} distribution in W+jets events (middle panel of Figure 2), and H_{T}, the scalar sum of the p_{T} of all the reconstructed objects in these events (right panel of Figure 1), present some small tensions between data and SHERPA predictions, while the agreement with ALPGEN is good.

Full fixed order calculations avoid the need of such procedures to describe the hard and soft emission of QCD radiations. Generators such as MCFM [7] and BLACKHAT-SHERPA [8] are however limited to one extra parton radiation in addition to the tree-level hard process generated. Such calculations can thus suffer from a logarithmic dependence on some arbitrary renormalization and factorization scales because parton emissions from hard jets with large p_{T} are ignored after the first emission. This could explain the shape of the H_{T} distribution, which tends to disagree with experimental results, as can be seen in Figure 2. To remedy such situation, parton shower can be merged with NLO fixed order calculations. Such calculations are presently limited to low jet

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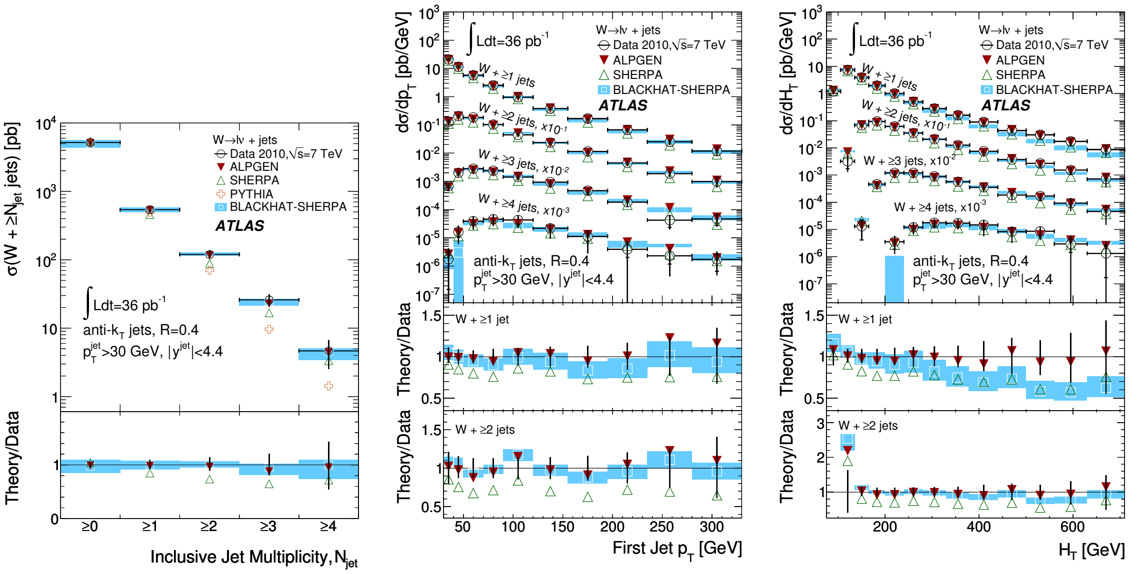

Figure 2: Left: W+jets cross section as a function of corrected jet multiplicity. Middle: W+jets cross section as a function of the p_T of the leading jet in the event. This p_T is shown separately for events with >=1 jets to >=4 jets. Right: W+jets cross section as a function of H_T, shown separately for >=1 jets to >=4 jets. In all cases, the statistical uncertainties are shown with a tick on the vertical bars, and the total uncertainty are shown with the full error bar [2]. Also shown are predictions from ALPGEN, SHERPA, PYTHIA and BLACKHAT-SHERPA, and the ratio of theoretical predictions to data.

multiplicity final states and have not been tested in the present W/Z+jets measurements.

Systematic uncertainties limit the QCD information that can be extracted from these experimental measurements. In the W+jets and Z+jets differential cross sections reported above, the total systematic uncertainty varies from 10% to 20% depending on the observable measured and the kinematic region probed with the measurements. These uncertainties are dominated by the uncertainty on jets energy scale and resolution of jets. One way to significantly reduce experimental uncertainties related to jet or lepton reconstruction (calibration, resolution, efficiencies, etc) is to measure ratio of observables. For example, by measuring the ratio of W+jets to Z+jets cross sections in function of the p_T of the leading jet [9], most of the jet corrections typically applied to W+jets and Z+jets observables to unfold their detector effects cancel in the ratio. This indicates that the residual systematic uncertainties on the ratio measurement will be largely reduced as can be seen in the left panel of Figure 3. In addition, theoretical uncertainties on the factorization and renormalization scales, as well as on PDF, largely cancel in the ratio. Such measurement confirms that NLO predictions can describe W/Z+jets data at a very high level of accuracy, as can be seen in the right panel of Figure 3.

W/Z+jets events with specific heavy flavor selections offer the possibility to directly study the heavy flavor content of the PDF as about 30% of the W+b-jets events involve a b-quark in the initial state. Moreover, these predictions are poorly constrained. The latest CDF measurement of the W+b-jets cross section is about three standard deviations away from NLO predictions [10]. This tension between theory and observation could be due to the impact of various flavor and mass

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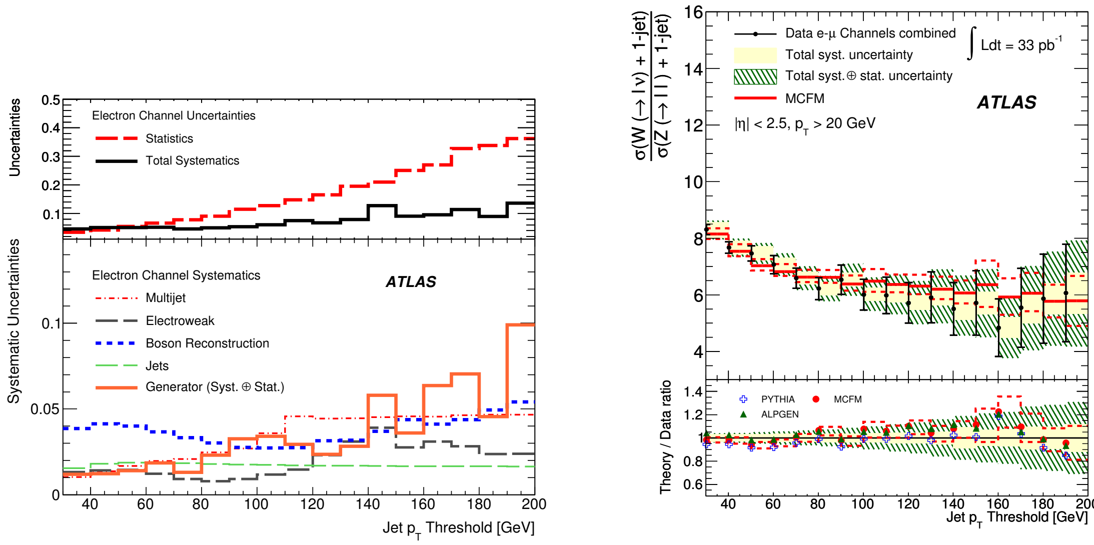

Figure 3: Left: Relative systematic uncertainties on the W+jets to Z+jets ratio in the electron channel. The top plot displays the total systematic and statistics uncertainties. Right: W+1-jets to Z+1-jets ratio in a fiducial region versus the jet p_T thresholds. The results are compared to predictions from MCFM. Data are shown with black error bars indicating the statistical uncertainty. The yellow band shows the systematic uncertainty while the green band shows the total uncertainty [9].

schemes used in the different W+b-jets calculation approaches. The fact that W/Z+b-jets events constitute an important background to Higgs, top and various beyond the Standard Model searches enhances the importance of these measurements.

The W+b-jets [11] and Z+b-jets [12] cross section measurements are challenging with only 35 pb^{-1} of data because they suffer from more than one order of magnitude reduction in the statistics compared to inclusive flavor analyses, and have to cope with larger backgrounds. The systematic uncertainties range from 25% to 35% on the total cross sections depending on the vector boson selections and the jet multiplicity. The production of one or more b-jets in association with a Z boson has been measured. The total cross sections for a W boson with exactly one b-jet or exactly two jets, one of which contains a B-meson, have also been measured. In both cases, the signal has been obtained from a fit to data of the mass of the secondary vertex distributions obtained from Monte Carlo for the different signal and background contributions, as shown in the left panel of Figure 4.

The Z+b-jets inclusive cross section of $3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi})$ pb is found to be consistent with the NLO prediction of 3.88 ± 0.58 pb obtained with the MCFM generator. The measurement result is also in agreement with the SHERPA prediction of $3.29 \pm 0.04(\text{stat only})$, while it features a small 1.2σ deviation with the prediction of $2.23 \pm 0.01(\text{stat only})$ pb obtained from ALPGEN. Although more data are needed to draw stronger conclusions from this measurement, these results tend to favor schemes where the b-quark is taken initially from the PDF. As can be seen on Figure 4, small tensions (over 1.5σ) is observed between W+b-jets measurements and theory predictions. Such discrepancies are significantly smaller than previous measurements at the

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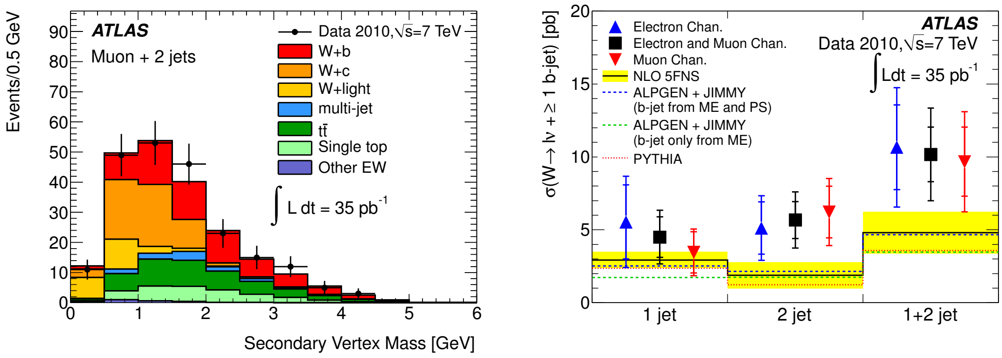

Figure 4: Left: Secondary vertex mass distributions for the b-tagged jet in data and MC, after fit of the W+jets templates to the data. Right: Measured fiducial cross sections with the statistical (inner error bar) and total (outer error bar) uncertainties in the electron, muon, and combined electron plus muon channels. The cross section is given in the 1, 2, and 1+2 jet exclusive bins. The measurements are compared with NLO predictions obtained in the 5 flavor number scheme. The yellow (shaded) band represents the total uncertainty on the prediction [11].

Tevatron [10]. The deviations seem to be larger in the 2-jets final states. Once again, the size of the uncertainties limit the conclusions that can be drawn from this measurement, but nevertheless indicates that W+b-jets events are not yet very well understood.

In conclusion, with an integrated luminosity of $L = 35$ pb^{-1}, ATLAS provided serious tests of pQCD from an extensive set of measurements, such as differential cross sections for various observables in W/Z+jets events, ratios in function of the same jet observables and W/Z+b-jet total cross section measurements. These measurements often achieved sufficient precision for already challenging NLO calculations. These studies set references for futures analyses with more data and set the stage for discovery.

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