Vector boson production in association with jets and heavy flavor quarks at the LHC

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The associated production of jets and vector bosons allows for stringent tests of perturbative QCD calculations and is sensitive to the possible presence of new physics beyond the Standard Model. The mechanism of production of heavy quarks in association with a W or a Z, in particular, is only partially understood. A measurement of jet production rates in association with W and Z bosons in proton-proton collisions at a 7 TeV center-of-mass energy is presented, using LHC data recorded by the CMS and ATLAS experiments.

Vector bosons (V = W or Z) produced in association with jets (V + jets) provide a precise way to test pertubative QCD predictions. The small theoretical uncertainty on the V + jets production together with the small experimental uncertainty on the selection of the V + jets signal, makes it possible to study higher order pertubative effects and parton distribution functions (PDFs). The V + jets signal itself is a background process in searches for new physics phenomena, therefore a good understanding of it is vital for searches at the LHC. Measurements from CMS [1]and ATLAS [2] using 5/fb data at $\sqrt{s} = 7$ TeV collected during 2011 are reported.

The experimental results are corrected for detector effects and are compared with predictions from Blackhat [3], Powheg [5], aMC@NLO [4], MCFM [6], Madgraph [7], Alpgen [8] and Sherpa [9]. The leading order (LO) matrix element (ME) Monte Carlo (MC) event generators are interfaced with Pythia [11] and HERWIG [12] for parton showering (PS) with the exception of Sherpa which uses its own built-in PS. The NLO ME calculations from Powheg and aMC@NLO are interfaced with Pythia and HERWIG and their predictions are provided at particle level (NLO+PS). The MC samples from Madgraph, Alpgen and Sherpa have been normalized, for the inclusive V production, to the next-to-next-to-leading-order (NNLO) cross section calculated with FEWZ [10]. Details on the exact MC configurations including the used PDFs and the choice of scales can be found in the cited articles.

The jet multiplicity in Z + jets data (Fig. 1 left) is well predicted by BlackHat+Sherpa parton level NLO calculation (up to four hard partons). The NLO+PS prediction from aMC@NLO is NLO for the inclusive Drell–Yan production and is only LO for the Z + 1-jet (Fig. 1 left). The complexity of an exact ME calculation increases dramatically as a function of N_{jets}. While an exact ME calculation is available here, to LO for up to five partons, jet multiplicity in data extends to $N_{\text{jets}} \geq 6$. The PS seems (within uncertainties) capable of filling the phase space in terms of event rate as a function of N_{jets}. Azimuthal correlations $\Delta\phi(Z, j_{\text{i}})$ and $\Delta\phi(j_{\text{i}}, j_{\text{j}})$ for $N_{\text{jets}} \geq 3$ are measured in an attempt to complement the picture in terms of angular properties (Fig. 2). Predictions from NLO+PS for the Z + 1−jet final state are of particular interest here, and show agreement with $N_{\text{jets}} \geq 3$ data despite the fact that, beyond the subleading jet, additional radiation comes exclusively from PS. High jet multiplicity implies a large scale and an increased phase space available for parton emission. An inclusive observable of high interest, in LHC searches, is the Z transverse momentum (Fig. 1 right) which shows a systematic trend as a function of p_{T}^{Z} for the ME+PS comparisons. ME+PS predicts a higher event yield than what is observed in data,

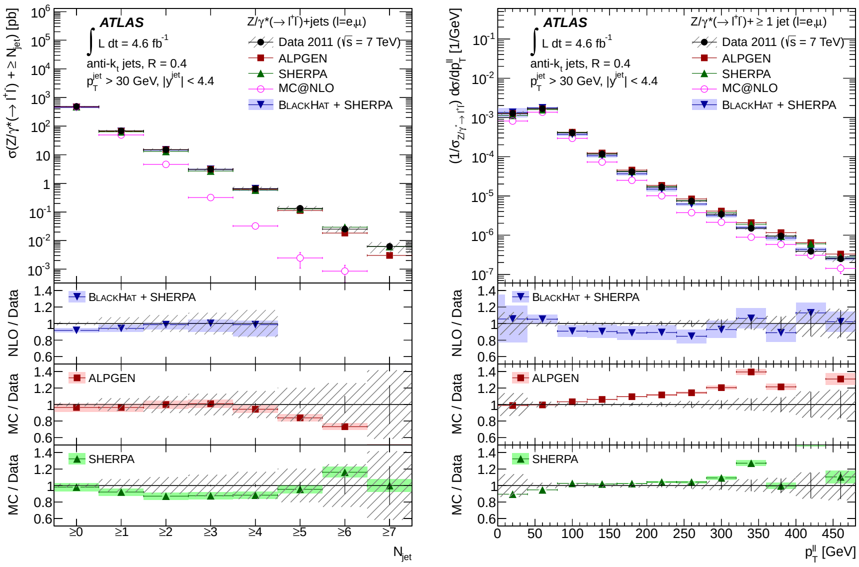

Figure 1: Cross section measured as a function of the jet multiplicity (left) and the transverse momentum of the Z boson (right).

the size of this effect is consistent with the reduction of the Z + jets cross section due to higher-order electroweak corrections [19]. In searches for new physics with jets and invisible energy that have Z $\rightarrow \nu\nu$ as irreducible background, a systematic effect of this order will decrease the discovery potential of the smallest signals of interest. The Z + jets picture is completed with the measurement of the rapidity distributions of the Z and the leading jet which are found to be in good agreement ($< 5\%$) with theory [15]. However, an interesting behavior is observed in the rapidity variables $Y_{\rm sum} = 0.5(Y_{\rm Z} + Y_{\rm jet})$ and $Y_{\rm diff} = 0.5(Y_{\rm Z} - Y_{\rm jet})$, which rely on a proper theoretical description of the correlations between $Y_{\rm Z}$ and $Y_{\rm jet}$ (Fig. 3). The $Y_{\rm sum}$ and $Y_{\rm diff}$ distributions show different level of agreement between the different implementations of ME+PS, while they agree with the NLO prediction.

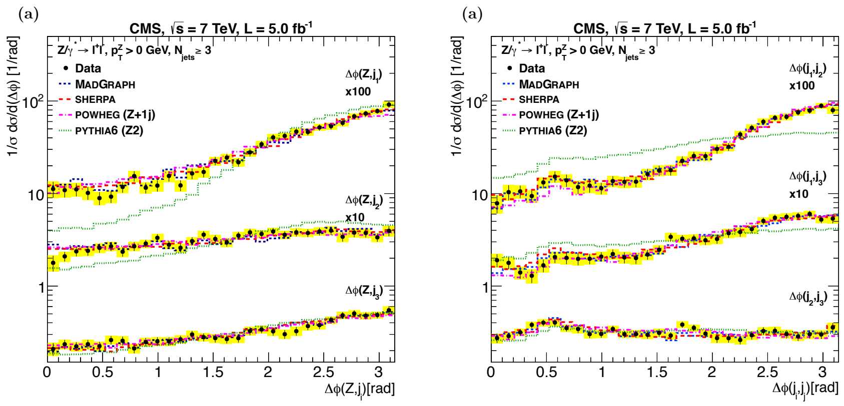

Figure 2: Cross section measured as a function of the azimuthal correlations $\Delta\phi(Z, j_{\rm i})$ (left) and $\Delta\phi(j_{\rm i}, j_{\rm j})$ (right) for $N_{\rm jets} \geq 3$.

The question of whether the strange content of the proton is suppressed with respect to the light quarks, is directly assessed here with the measurement of the W plus charm cross section and the ratio of $\sigma(\mathrm{W}^+ + \bar{c})/\sigma(\mathrm{W}^- + c)$. The measurements are consistent with the strange suppression $s/d \leq 0.5$ which is predicted by MSTW08, CT10 and NNPDF23 [16]. The production of a W in association with two b-jets is important for the studies of WH $\rightarrow$ W$b\bar{b}$. This motivates the measurement of the W$b\bar{b}$ cross section which is found to be 0.53 ± 0.05 (stat) ± 0.1 (sys) pb, in very good agreement with the NLO prediction 0.52 ± 0.03 pb [17]. On the other hand, a systematic

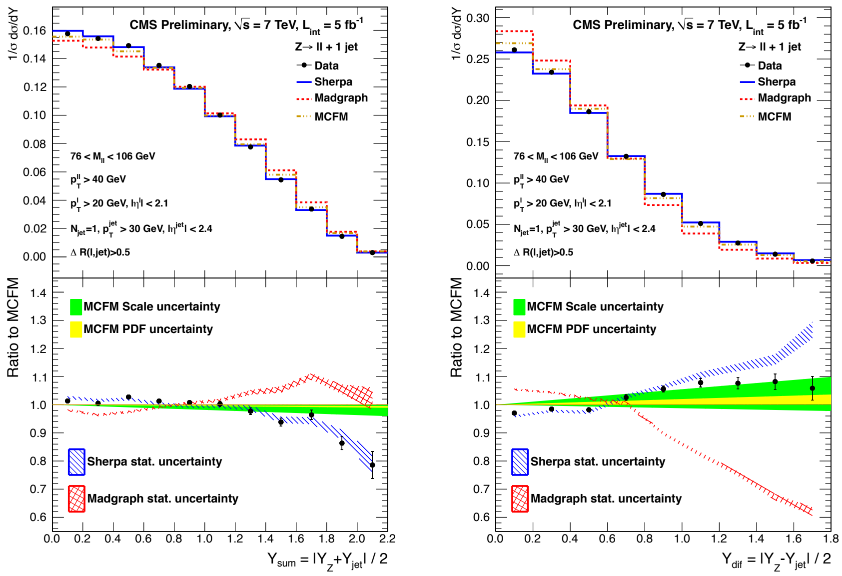

Figure 3: Cross section measured as a function of the rapidity sum $Y_{\rm sum} = 0.5(Y_{\rm Z} + Y_{\rm jet})$ (left) and the rapidity difference $Y_{\rm diff} = 0.5(Y_{\rm Z} - Y_{\rm jet})$ (right) between the Z boson and the leading jet.

bias is observed in the W plus one b-jet final state (Fig. 5 left). The disagreement becomes more significant if the single top contribution is not subtracted from the cross section measurement [18] (Fig. 5 right).

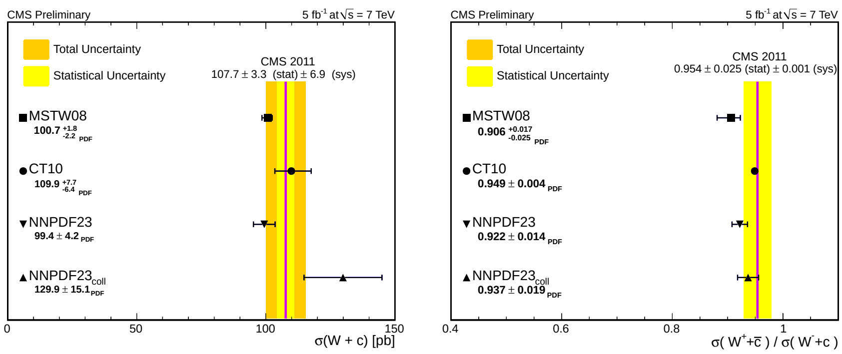

Figure 4: Cross section measured for the W + c process (left) and the $\sigma(\mathrm{W}^+ + \bar{c})/\sigma(\mathrm{W}^- + c)$ cross section ratio (right).

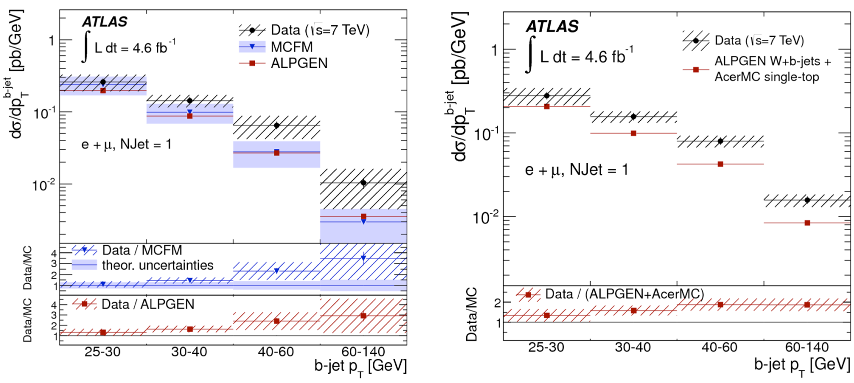

Figure 5: Cross sections measured as a function of the b-jet $p_{\rm T}$ for the W + b process (left) and for the combined W + b plus single top processes (right).

In summary, the LHC's substantial amount of delivered data at 7 TeV to the experiments has made it possible to probe extreme kinematics of the V + jets signal that were not previously accessible. Different levels of agreement has been observed among the various predictions and data, reflecting to some extent the current understanding of the LHC data.

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