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Production of W/Z in Association with Jets

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Abstract. This article summarizes recent Tevatron and LHC measurements of W/Z production in association with inclusive jets. The differential cross sections are measured as a function of jet multiplicity and various kinematic variables of jets or W/Z boson. Third-jet emission probability, angular correlations among reconstructed objects, and an event shape variable are studied. A first measurement of electroweak production cross section of the Z boson with two forward-backward jets is also presented. All results are compared to next-to-leading order perturbative QCD calculations and predictions of simulations that interface matrix-element calculations with parton showers. These studies constrain the backgrounds to searches for physics beyond the standard model.

1 Introduction

The studies of W/Z production in association with inclusive jets (V + jets) in hadron colliders provide a test of perturbative quantum chromodynamics (pQCD). The V + jets production also constitutes an important background to searches for rare standard model (SM) processes, such as single top and the SM Higgs boson, and to searches for particles predicted by new physics. In these searches, the kinematic distributions of V + jets backgrounds are usually estimated with hybrid MCs, i.e. the simulations that include leading order (LO) or next-to-leading order (NLO) multiparton matrix-element (ME) calculations, supplemented by parton showers. The performance of these hybrid MCs must be tuned and validated using V + jets measurements.

This article presents recent measurements of V + jets productions performed by the Tevatron and LHC experiments. The W and Z bosons are reconstructed via the electron and muon decay channels, providing clean experimental signatures in the complex environment of hadron colliders.

2 ATLAS W + jets

A study of W + jets production in pp collisions at $\sqrt{s}$ = 7 TeV, using the full 36 pb^{-1} of data collected in 2010, is reported by the ATLAS Collaboration [1, 2]. Jets are reconstructed using the anti-k_t algorithm [3] with a radius parameter $R = 0.4$, and are required to have transverse momentum $p_T > 30$ GeV, rapidity $|y| < 4.4$, and be separated from the charged lepton $\Delta R(\ell, \text{jet}) > 0.5$. The cross sections are measured as a function of the inclusive jet multiplicity ($N_{\text{jet}} \geq 0$ to $N_{\text{jet}} \geq 4$), the p_T of the n^{th} p_T-ordered jet (n^{th} = 1–4), scalar sum of the missing transverse momentum and the p_T's of the charged lepton and all jets in the event (H_T), invariant mass of jets, and the rapidity distributions and angular correlations of the charged lepton and jets. The data are compared to the NLO pQCD calculation of BLACKHAT-SHERPA [4] and predictions from two hybrid MCs: ALPGEN v2.13 [5] interfaced to HERWIG v6.5 for parton shower, and SHERPA v1.3.1 [6]. Both ALPGEN and SHERPA perform LO calculations and are generated with up to five final-state partons at the ME. The distributions from ALPGEN and SHERPA are normalized to the next-to-next-to-leading order (NNLO) inclusive W cross section.

SHERPA v1.3.1 is found to underpredict high-jet-multiplicity events due to an excessive α_s scale factor for initial state shower, resulting in a lower value of α_s and thus smaller emission probabilities [7]; this problem has been fixed in SHERPA v1.4.0. BLACKHAT-SHERPA is found to predict a softer H_T distribution with respect to data for $N_{\text{jet}} \geq 1$ events (Fig. 1). When predicting an inclusive variable like H_T for $W+ \geq 1$ jet events, BLACKHAT-SHERPA calculation does not include three or more real emissions of final-state partons. Once the contributions of three and four real emissions are added to the $N_{\text{jet}} \geq 1$ distribution, an improved agreement of modified BLACKHAT-SHERPA with data and ALPGEN is observed. The shapes of the rapidity distributions predicted by ALPGEN are different from those predicted by BLACKHAT-SHERPA and SHERPA. Since the variables y(first jet) and $y(\ell) \pm y$(first jet) are sensitive to the Parton Distribution Functions (PDFs) used in the ME calculations, the difference may be caused by the fact that BLACKHAT-SHERPA and SHERPA use an NLO PDF CTEQ6.6M [8] while ALPGEN uses an LO PDF CTEQ6L1 [9]. Except the distributions discussed above, ALPGEN and BLACKHAT-SHERPA are in good agreement with data and give consistent predictions.

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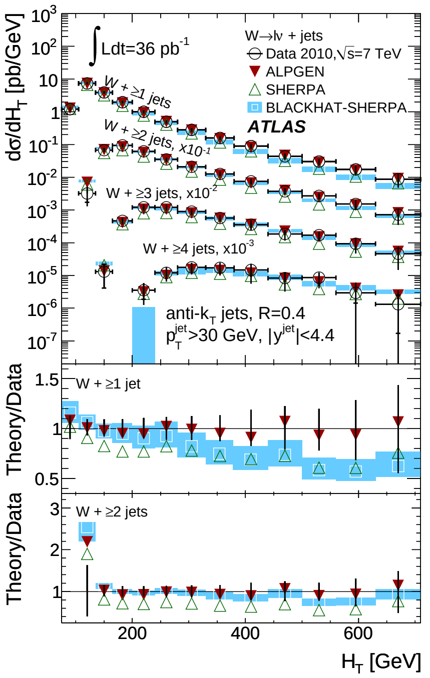

Figure 1. The cross section as a function of H_T for $W+\geq 1$ jet to $W+\geq 4$ jets events. Shown are ATLAS data and predictions of ALPGEN, SHERPA, and NLO BLACKHAT-SHERPA, and the ratios of these predictions to data.

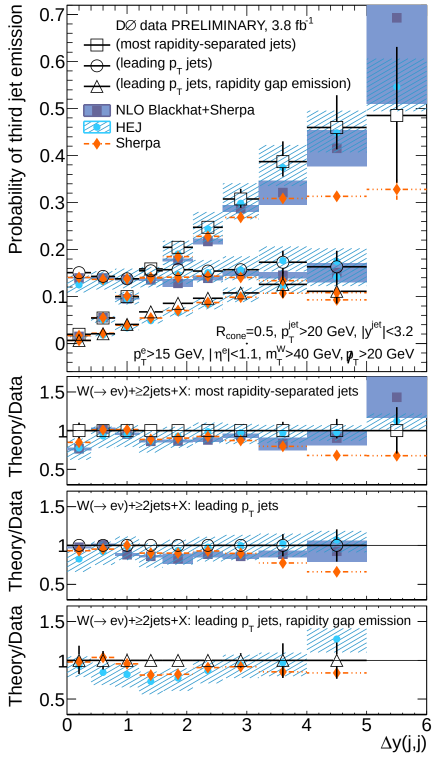

Figure 2. Third-jet emission probability as a function of dijet rapidity separation in $W+\geq 2$ jets events. Shown are DØ data and predictions of NLO BLACKHAT-SHERPA, HEJ, and SHERPA, and the ratios of these predictions to data.

3 DØ W + jets

A study of W + jets production using 3.8 fb^{-1} of p$\bar{\text{p}}$ collisions at $\sqrt{s}$ = 1.96 TeV is reported by the DØ Collaboration [10, 11]. Jets are reconstructed using the mid-point cone algorithm [12] with $R_{\text{cone}} = 0.5$ and must have $p_T > 20$ GeV, $|y| < 3.2$, and $\Delta R(\ell,\text{jet}) > 0.5$. The data are compared to predictions of NLO BLACKHAT-SHERPA, SHERPA v1.4.0, and High Energy Jets (HEJ) [13]. HEJ is a parton-level generator that performs all-order re-summation of the perturbative contributions to production of wide-angle emissions; it is capable only of describing $N_{\text{jet}} \geq 2$ events. The measurements and theoretical predictions of differential production cross sections are normalized to the inclusive W cross section.

The predicted p_T distributions of the W boson are in good agreement with data, for $W+\geq 1$ jet to $W+\geq 4$ jets events, respectively. The invariant mass of the two hardest jets is sensitive to the kinematic correlations among jets and is important for searches for new physics; the data are well described by all three predictions. HEJ predicts well the rapidity distributions of the n^{th} p_T-ordered jet while BLACKHAT-SHERPA and SHERPA tend to overestimate at the high-jet-rapidity region.

Figure 2 shows the third-jet-emission probability in $W+\geq 2$ jet events, as a function of the dijet rapidity separation [$\Delta y(j,j)$] of: (a) the two most rapidity-separated jets, (b) the two leading-p_T jets, and (c) the two leading-p_T jets with a requirement that the third jet is emitted in the rapidity gap defined by these two leading-p_T jets. In case (a), the three predictions behave differently: HEJ shows a good agreement with data for the full range while SHERPA gives significantly lower probability for $\Delta y(j,j) > 3$. The central values of BLACKHAT-SHERPA start to deviate from data at high $\Delta y(j,j)$, nevertheless, its predictions are still consistent with data with the scale uncertainties increasing with $\Delta y(j,j)$. In cases (b) and (c), BLACKHAT-SHERPA and HEJ describe data well while SHERPA tends to underestimate at large $\Delta y(j,j)$. Case (c) is sensitive to wide-angle soft-gluon emission and rises with $\Delta y(j,j)$ as the available phase space for third-jet emission increases. In order to reduce multi-jet and V + jets backgrounds, very often central jets are vetoed in the searches for Higgs produced via vector boson fusion (VBF). This measurement of jet-emission-probability is crucial for the understanding of jet-veto efficiency: one should pay attention that the emission probability could vary by a large factor depending on the value of $\Delta y(j,j)$ and how VBF jets are tagged.

4 CDF Z/γ^* + jets

A study of Z/γ^* + jets production in p$\bar{\text{p}}$ collisions at $\sqrt{s}$ = 1.96 TeV, using the full 9.64 fb^{-1} of Run II data, is reported by the CDF Collaboration [14, 15]. Jets are reconstructed using the midpoint cone algorithm with $R_{\text{cone}} = 0.7$ and must have $p_T > 30$ GeV, $|y| < 2.1$, and $\Delta R(\ell,\text{jet}) > 0.7$. The cross sections are measured as a function of the inclusive jet multiplicity ($N_{\text{jet}} \geq 1$ to $N_{\text{jet}} \geq 4$), the p_T of the

n^{th} p_{T}-ordered jet ($n^{\text{th}} = 1$–3), scalar sum p_{T} of jets ($H_{\text{T}}^{\text{jet}}$), invariant mass of jets, $p_{\text{T}}(Z)$, lepton p_{T}'s, and the rapidity distributions and angular correlations of Z and jets. The data are compared to various predictions: pQCD calculations of NLO BLACKHAT-SHERPA and NLO/LO MCFM v6.0, and predictions of two hybrid MCs: POWHEG 1.0 [16] in which $Z/\gamma^* + \geq 1$ jet events are generated and calculated at NLO, and ALPGEN v2.14 in which up to six final-state partons are generated at the ME; both are interfaced to PYTHIA v6.4 for parton shower. For $Z/\gamma^* + \geq 1$ jet events only, data are also compared to $\bar{\text{n}}$NLO LOOPSIM+MCFM, an approximation of next-next-to-leading order (NNLO) pQCD calculation where the double-loop terms are estimated through LOOPSIM, and to NLO QCD $\otimes$ NLO EW, an NLO pQCD calculation with NLO electroweak correction factors evaluated based on the LO pQCD calculation.

As discussed in Section 2, the NLO pQCD predictions fail to describe the shape of the $H_{\text{T}}^{\text{jet}}$ distribution in $N_{\text{jet}} \geq 1$ events. In the high-$H_{\text{T}}^{\text{jet}}$ tail, the NLO to LO K-factor is greater than two and a large scale uncertainty is observed. The $\bar{\text{n}}$NLO LOOPSIM+MCFM prediction, on the other hand, properly models the distribution in data and has a significantly reduced scale uncertainty (Fig 3). The measured $\Delta\phi(Z, j_1)$ between Z and the leading jet in $Z+ \geq 1$ jet events has a good agreement with POWHEG and ALPGEN, but large discrepancy from $\bar{\text{n}}$NLO LOOPSIM+MCFM and NLO MCFM in the region of $\Delta\phi(Z, j_1) < \pi/2$. This region has 20-40% non-perturbative QCD corrections and is dominated by $Z/\gamma^* + 3$ jet events where the p_{T} of the Z and the leading jet is balanced against the p_{T} of the two (or more) subleading jets. For the other variables, theoretical predictions are consistent with data within uncertainties. For the leading jet p_{T} in $Z/\gamma^* + \geq 1$ jet events, the NLO electroweak correction in NLO QCD $\otimes$ NLO EW is -5% in the highest p_{T} bin due to the large Sudakov logarithms which appears in the virtual part of the calculation; the correction is expected to be important at the LHC energy.

5 CMS Z/γ^* + jets

Two analyses studying the Z/γ^* + jets production in pp collisions at $\sqrt{s} = 7$ TeV, with the full 5 fb^{-1} of data collected in 2011, are reported by the CMS Collaboration [17–19].

In the first analysis [18], jets are reconstructed using the anti-k_t algorithm with $R = 0.5$ and must have $p_{\text{T}} >$ 50 GeV, pseudorapidity $|\eta| < 2.5$, and $\Delta R(\ell, \text{jet}) > 0.4$. The azimuthal correlations $\Delta\phi(Z, j_1)$ in $N_{\text{jet}} \geq 1$–3 events and the $\Delta\phi(Z, j_i)$ and $\Delta\phi(j_i, j_k)$ in $N_{\text{jet}} \geq 3$ events are studied; here, the indices refer to the i^{th} and k^{th} p_{T}-ordered jet, respectively ($i, k = 1$–3). The logarithm of an event shape variable τ_{T}, $\ln \tau_{\text{T}}$, is also measured. This variable τ_{T} is most sensitive to the modeling of two-jet and three-jet topologies and is defined as in [20]:

$$\tau_{\text{T}} \equiv 1 - \max_{\vec{n}_\tau} \frac{\sum_i \left|\vec{p}_{\text{T},i} \cdot \vec{n}_\tau\right|}{\sum_i p_{\text{T},i}},$$

where $\vec{p}_{\text{T,i}}$ is the transverse-momentum vector of object i, with the sum running over the Z boson and each selected jet in the event. The unit vector $\vec{n}_\tau$ that maximizes the sum is called the thrust axis. For back-to-back $Z/\gamma^* + 1$ jet events, τ_{T} tends to zero. With additional jet emission, the values of τ_{T} increase. In the limit of a spherical, isotropically distributed event, the maximum value is reached: $\tau_{\text{T}} \to 1 - 2/\pi$ and $\ln \tau_{\text{T}} \to \ln(1 - 2/\pi) \approx -1$.

The distributions in both data and MC are normalized to unity and are presented for two regions of phase space: (i) all events, without the $p_{\text{T}}(Z)$ requirement, and (ii) events containing a highly-boosted Z boson with $p_{\text{T}}(Z) >$ 150 GeV. The measurements with such a high $p_{\text{T}}(Z)$ threshold are of particular interest: in the searches for new physics that predicts large missing momentum, one major background is the SM production of events containing a boosted Z boson with invisible decays $Z \to \nu\bar{\nu}$. Measurements using the charged-leptonic decays of Z help to improve the accuracy of available MCs. The data are compared to the predictions of three hybrid MCs: MadGraph v5.1.1.0 and POWHEG 1.0 interfaced to PYTHIA v6.4, SHERPA v1.3.1, and the standalone PYTHIA v6.4. Both MadGraph and SHERPA perform LO calculations and are generated with up to four final-state partons at the ME.

MadGraph has the best agreement with data for all $\Delta\phi$ variables. SHERPA underestimates and POWHEG overestimates the distributions of $\Delta\phi(Z, j_1)$ in $N_{\text{jet}} \geq 1$ events and the discrepancy is reduced at larger inclusive jet multiplicities. All three hybrid MCs are consistent with data within uncertainties for the distributions of $\Delta\phi(Z, j_i)$ and $\Delta\phi(j_i, j_k)$ in $N_{\text{jet}} \geq 3$ events. Although POWHEG represents an NLO prediction only for the leading jet, the agreement with data is enhanced due to its interface to PYTHIA: additional radiation is modeled using parton shower. A large disagreement is observed between data and standalone PYTHIA, which demonstrates the importance of hybrid MCs. For events with highly-boosted Z, the disagreement of PYTHIA is reduced due to the increase of available phase space for parton missions.

Figure 4 shows the distributions of $\ln \tau_{\text{T}}$. For $p_{\text{T}}(Z) >$ 150 GeV, the peak at values of $\ln \tau_{\text{T}} \approx -2$ is contributed by the $N_{\text{jet}} \geq 2$ events with a large spherical component. MadGraph and POWHEG are consistent with the data within 10%, except a $\approx$20% deviation at large negative values of $\ln \tau_{\text{T}}$. SHERPA and PYTHIA have larger disagreement with data and predict too small values of $\ln \tau_{\text{T}}$, indicating a bigger proportion of back-to-back $Z/\gamma^* + 1$-jet events and an under-prediction of high-jet-multiplicity events.

The second analysis reports a measurement of the electroweak (EWK) production cross section of the Z boson with two forward-backward jets [19]. There are three classes of diagrams (Fig. 5): bremsstrahlung, VBF processes and multiperipheral diagrams with a large negative interference between them. The signal is extracted by fitting independently the distributions of two variables. The first variable is the invariant mass of two highest-p_{T} jets that satisfy the requirements: (i) $p_{\text{T}}^{\text{j1}} > 65$ GeV, $p_{\text{T}}^{\text{j2}} > 40$ GeV, $|\eta| < 3.6$, and (ii) $|\text{y}^*| < 1.2$ where $\text{y}^* \equiv \text{y}_Z - 0.5(\text{y}_{\text{j1}} + \text{y}_{\text{j2}})$. The second variable is the output of a boosted decision tree (BDTD option) with the two highest-p_{T} jets satisfying the requirement (i) [Fig. 6]. Mul-

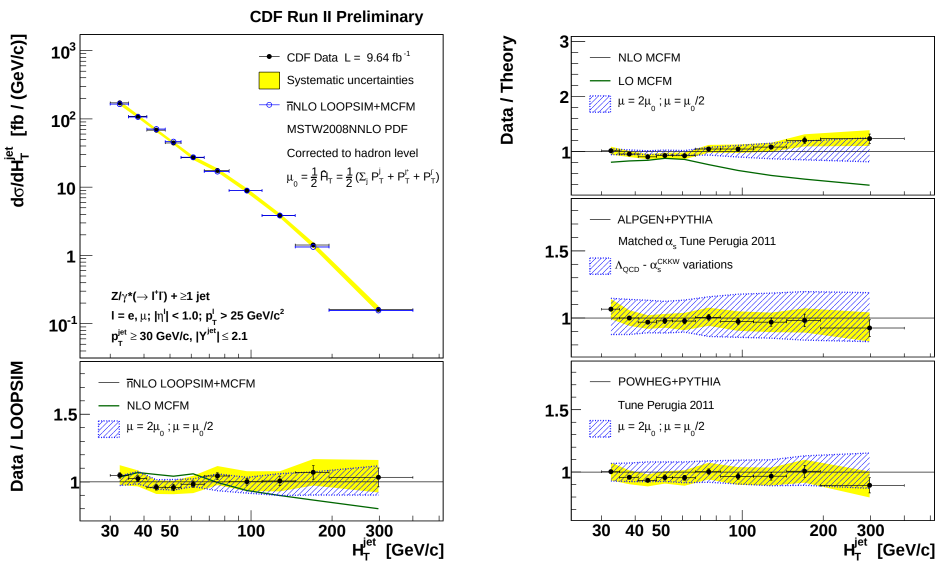

Figure 3. The cross section as a function of $H_T^{\rm jet}$ for $Z/\gamma^* + \geq 1$ jet events. Shown are CDF data and predictions of n̄NLO LOOPSIM+MCFM, NLO and LO MCFM, ALPGEN +PYTHIA, and POWHEG +PYTHIA, and the ratios of data to these predictions.

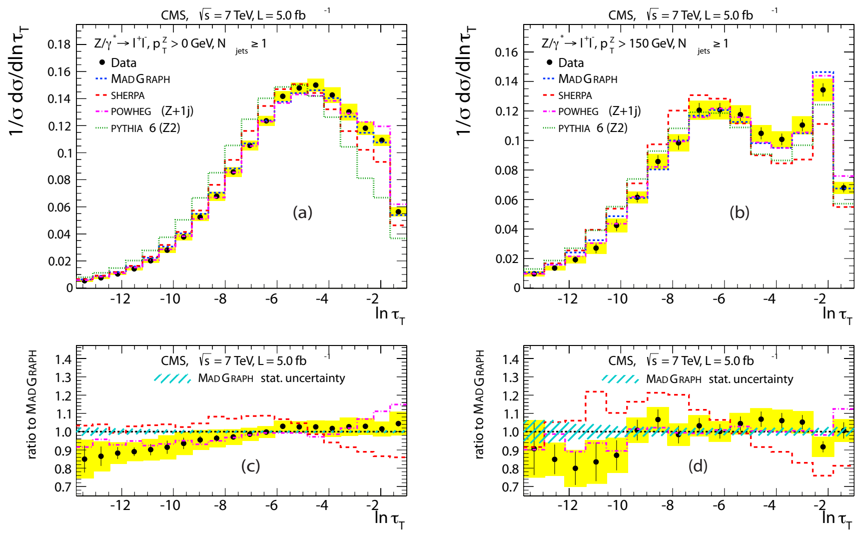

Figure 4. Normalized distributions of $\ln\tau_T$ for (a) all the $N_{\rm jet} \geq 1$ events, and (b) the $p_T(Z) > 150$ GeV and $N_{\rm jet} \geq 1$ events, from CMS data and predictions of MadGraph, SHERPA, POWHEG, and standalone PYTHIA. Plots in (c) and (d) show the ratios of data and these predictions relative to MadGraph.

tiple variables are used in BDTD, including: jet p_T, dijet mass, y*, p_T and rapidity of the dilepton, and the ϕ and η correlations between the two highest-p_T jets.

The result based the second variable has smaller error and is used to determine the ratio of measured to expected contribution of EWK production, s, in the kinematic region as defined by requirement (i). The measured EWK production cross section is then obtained via: $\sigma_{\rm meas} = s \times \sigma_{\rm MadGraph}$, where $\sigma_{\rm MadGraph} = 162$ fb and is the cross section of the EWK $\ell\ell$jj production process calculated by MadGraph with the parton-level selections: $m_{\ell\ell} > 50$ GeV, $p_T^{\rm j} > 25$ GeV, $\eta^{\rm j} < 4.0$, $m_{\rm jj} > 120$ GeV. The measurement gives $\sigma_{\rm meas} = 154 \pm 24$ (stat) $\pm$ 46 (exp syst) $\pm$ 27 (th yst) $\pm$ 3 (lumi) fb. The LO and NLO pQCD cross-sections calculated by VBFNLO [21] are $\sigma_{\rm LO}$(EWK $\ell\ell$jj) = 157 fb and $\sigma_{\rm NLO}$(EWK $\ell\ell$jj) = 166 fb.

A measurement of the hadronic activity in the η gap between the two highest-p_T jets with $p_T^{\rm j1,j2} > 65$, 40 GeV is also performed. A collection of "soft-track-jets" is built by clustering with the anti-k_t algorithm the high-purity tracks that have $p_T > 300$ MeV and are associated with primary vertex. The hadronic activity is quantified by an H_T variable, defined as the sum p_T's of the three leading-p_T soft-track-jets; a good agreement between the data and the predictions of MadGraph simulations is observed (Fig. 7).

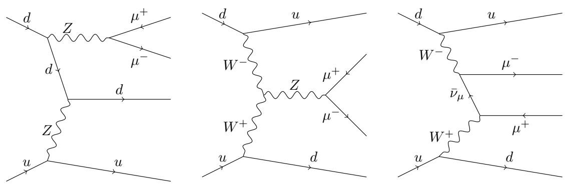

Figure 5. Representative diagrams for EWK $\ell\ell$ jj production processes: bremsstrahlung (left), VBF process (middle), and multiperipheral (right).

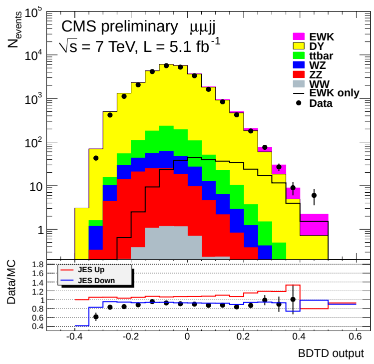

Figure 6. The BDTD output distributions for the $\mu^+\mu^-$ mode and the ratio of CMS data over the expected contribution of the signal plus backgrounds (estimated from simulation).

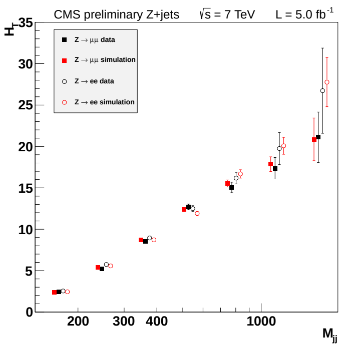

Figure 7. Average H_T of the three leading-p_T soft-track-jets in the pseudorapidity gap as defined by the two leading-p_T jets, as a function of the dijet invariant mass.

6 Conclusion

Recent Tevatron and LHC measurements of V + jets production have been presented. Thanks to the high performance of LHC, the kinematic region with highly-boosted Z has been explored for the first time. The NLO pQCD calculations and predictions of hybrid MCs agree with data for most of the kinematic distributions. Discrepancy is seen in the tails of the distributions, such as the high-H_T region, which encourages the development of NNLO pQCD predictions or simulations that interface NLO ME calculations to parton showers. A measurement of EWK production cross section of Z boson with two forward-backward jets has been performed, and the result is in an agreement with NLO pQCD calculation. The hadronic activities in the rapidity gap of two highest-p_T jets or two most rapidity-separated jets have been studied in detail and are important to searches of the Higgs boson produced via vector boson fusion. Updates of Tevatron measurements using other kinematic variables and LHC measurements with the 8 TeV data are expected in the near future.

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