Vector boson plus jet physics at CMS

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Abstract. We present recent results on the jet production rates in association with weak vector bosons and their properties using proton-proton collision data collected with the CMS detector. Azimuthal correlations and events shapes in $Z + \text{jets}$ events are also shown. A first measurement of the electroweak production cross section of a $Z$ boson with 2 jets is presented, including measurements of the hadronic activity between the two associated jets.

1. Jet production in association with vector bosons
The study of jet production in association with a $W$ or $Z$ boson allows for tests of perturbative QCD calculations. On the other hand the productions of vector bosons with jets is an important background in searches for new physics and for studies of the top quark. We report here results [1] on jet production rates in association with $W$ and $Z$ bosons, using 36 pb$^{-1}$ of proton-proton collision data at $\sqrt{s} = 7$ TeV recorded with the CMS detector [2].

Events are selected if they have at least one lepton (electron or muon) with transverse momentum $p_T > 20$ GeV, and satisfying quality and isolation requirements. Electron candidates are required to be in the fiducial region of the electromagnetic calorimeter with pseudorapidity $|\eta| < 2.5$, with the exclusion of $1.44 < |\eta| < 1.57$. Muon candidates are required to have $|\eta| < 2.1$. $Z$ bosons are reconstructed if a second lepton of the same flavour is found, which fulfills looser quality requirements and $p_T > 10$ GeV, and the dilepton invariant mass falls between 60 GeV and 120 GeV. Events which are not assigned to the $Z$+jets sample, could qualify for the $W$+jets sample. Due to the undetected neutrino, these events are characterized by a large missing transverse energy $E_T$. Therefore, the events are assigned to the $W$+jets sample if they have a transverse mass $M_T = \sqrt{2p_T E_T (1 - \cos \Delta \phi)}$ of at least 20 GeV, where $\Delta \phi$ is the angle in the transverse plane between $p_T$ and $E_T$. Jets constituents are reconstructed with the particle flow (PF) algorithm and are clustered using the anti-$k_T$ algorithm with size parameter of 0.5. These jets are accepted if they have $p_T > 30$ GeV, $|\eta| < 2.4$ and fulfill standard quality identification criteria.

Figures 1 and 2 show the ratio of $\sigma(V + \geq n \text{jets})/\sigma(V)$ for $W$ and $Z$ bosons respectively, where $\sigma(V)$ is the inclusive cross section. The data agrees with MADGRAPH [3] predictions, both fusing either the Z2 or D6T PYTHIA [4] tunes, while the pure parton model from PYTHIA fails to describe the data in the presence of a large number of jets.

A fit is performed in order to test Berends-Giele scaling:

$$ C_n \equiv \frac{\sigma_n}{\sigma_{n+1}} = \alpha + \beta n $$
Figure 1. The ratios $\sigma(W + \geq n\text{ jets})/\sigma(W)$ and $\sigma(W + \geq n\text{ jets})/\sigma(W + \geq (n - 1)\text{ jets})$. The error bars show the total uncertainty.

Figure 2. The ratios $\sigma(Z + \geq n\text{ jets})/\sigma(Z)$ and $\sigma(Z + \geq n\text{ jets})/\sigma(Z + \geq (n - 1)\text{ jets})$. The error bars show the total uncertainty.

where $\sigma_n = \sigma(V + \geq n\text{ jets})$, and $\alpha$ and $\beta$ are constants. Leading order calculations predict $C_n = \alpha$, where the constant $\alpha$ is inversely proportional to the strong coupling constant. The $\beta$ parameter is introduced to allow for possible deviations which could appear due to next-to-leading order effects and phase space effects. Figures 3 and 4 show the fit of $\alpha$ and $\beta$ for both $Z + \text{ jets}$ and $W + \text{ jets}$. The data is in agreement with the MADGRAPH predictions within one or two standard deviations depending on the channel. The $\beta$ parameter lies within one standard deviation from zero.

A measurement on the ratio of $W + \text{ jets}$ and $Z + \text{ jets}$ cross sections, in which many systematic uncertainties such as the luminosity and jet energy scale cancel, are shown in figure 5. We see again a good agreement between data and simulation.
2. Azimuthal correlations and event shapes in $Z$ plus jet events
A detailed study [5] of azimuthal correlations in $Z$ plus at least one jet events in $pp$ collisions at $\sqrt{s} = 7$ TeV was done using CMS data, corresponding to an integrated luminosity of 5 fb$^{-1}$. Events with $Z$ bosons were selected by requiring an oppositely charged electron or muon pair with an invariant mass within a mass window of 20 GeV around the $Z$ boson mass. Both leptons satisfy $p_T > 20$ GeV and $|\eta| < 2.4$ and fullfill quality and isolation criteria. PF jets with $p_T > 50$ GeV and $|\eta| < 2.5$ were used, clustered using the anti-$k_T$ algorithm with size parameter of 0.5.
2.1. Azimuthal angles

Figure 6 shows the azimuthal angle between the $Z$ boson and the leading jet, either for all $Z$ bosons or in a subset of events with $p_T > 150 \text{ GeV}$. The boosted region is of interest because it is critical in searches for new phenomena. The results agree within uncertainties with the MADGRAPH prediction. In $Z^+ \geq 1$ jet events, the SHERPA [6] prediction is about 10% too low whereas POWHEG [7, 8, 9, 10] overestimates the distribution by about 10%. The $Z$ boson and leading jet are completely correlated for $N_{\text{jets}} = 1$, as $\Delta\phi(Z, j_1)$ tends to $\pi$. If $\Delta\phi(Z, j_1) < \frac{\pi}{2}$, the leading jet is in the same hemisphere as the $Z$ boson and the $Z$ boson is balanced by subleading jets in the opposite hemisphere. Therefore the $\Delta\phi(Z, j_1)$ becomes more isotropic at larger inclusive jet multiplicities.

![Figure 6](image)

**Figure 6.** Normalized $\Delta\phi(Z, j_1)$ distributions categorized as a function of jet multiplicity. The yellow band shows the sum of statistical and systematic errors on the data.

Figure 7 shows the azimuthal angles among the three leading jets, which show good agreement between MADGRAPH, SHERPA and PYTHIA predictions, and the data. In the boosted regime, the angles between the jets decorrelate.

2.2. Transverse thrust

The properties of $Z$ plus jet events have also been studied using the transverse thrust $\tau_T$, defined as:

$$
\tau_T \equiv 1 - \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{T,i} \cdot \vec{n}_T|}{\sum_i p_{T,i}}
$$

where the sum over $i$ runs over the $Z$ and each accepted jet in the event. The sum is maximized by the unit vector $\vec{n}_T$, called the thrust axis. In the limit of a perfectly balanced $Z$ plus one jet event, $\tau_T$ tends to zero ($\ln \tau_T \rightarrow -\infty$). In the limit of a homogeneously distributed event, the transverse thrust reaches $1 - \frac{\pi}{2}$ ($\ln \tau_T \rightarrow -1$), its maximum possible value. The $\ln \tau_T$ distribution is shown in figure 8. The data is best described by POWHEG and MADGRAPH, except at large negative values for the transverse thrust where an overestimation by MADGRAPH is seen. PYTHIA and SHERPA have larger discrepancies and predict also too small values for $\ln \tau_T$. The peak at $\ln \tau_T \approx -2$ in the boosted region corresponds with events where the $Z$ is balanced by two or more jets.
3. Electroweak production of $Z+jets$

We have measured [11] the pure electroweak cross section of a $Z$ boson in association with two jets in $pp$ collisions at $\sqrt{s} = 7$ TeV, using 5 fb$^{-1}$ of data recorded by the CMS detector. In addition, the hadronic activity in the rapidity interval between the two jets has also been studied. There are three classes of diagrams, shown in figure 9, contributing to the electroweak

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Z + 2 jets production: bremsstrahlung, vector boson fusion (VBF) processes and multiperipheral. The standard model predicts large negative interference effects between the VBF process and the other two categories.

![Representative diagrams for the EW ℓℓ jj production processes.](image)

**Figure 9.** Representative diagrams for the EW ℓℓ jj production processes.

### 3.1. Event selection

Events are selected by requiring a muon or electron pair with opposite charge, in which both leptons satisfy a series of quality and isolation criteria, a transverse momentum of at least 20 GeV and $|\eta| < 2.4$. The Z bosons are reconstructed by taking events with a dimuon (dielectron) mass within the 15 GeV (20 GeV) mass interval around the nominal Z boson mass. The two leading PF jets within $|\eta| < 4.7$ are selected as the tagging jets. Further selections were optimized by maximizing the signal significance defined as $N_S/\sqrt{N_B}$ and lead to a requirement of $p_T^{j1,j2} > 65, 40$ GeV and $|\eta_j| < 3.6$ for the two tagging jets.

### 3.2. Cross section measurement

The signal cross section has been extracted from a fit of the signal and background contributions to the output of a boosted decision tree (BDT) applied to the selected events. The BDT was trained with EW ℓℓ jj simulated events as signal model and DY ℓℓ jj as background model using the following variables:

- the transverse momenta of the tagging jets
- the invariant dijet mass and the pseudorapidity separation between the two tagging jets
- the $y^*$ variable, defined as $y^* = y_{ll} - 0.5(y_{j1} + y_{j2})$ using the rapidities of the two tagging jets and the dilepton system
- the transverse momentum and rapidity of the dilepton system
- the sum of the pseudorapidities of the two tagging jets
- the difference between the azimuthal angles: $(\phi_{ll} - \phi_{j1})$, $(\phi_{ll} - \phi_{j2})$ and $(\phi_{j1} - \phi_{j2})$

In the dielectron channel, a quark-gluon likelihood for both tagging jets is also used as input. The jets in the EW signal process originate only from quarks while in the DY background half of the jets are initiated by gluons. Using this likelihood discriminator, built out of 5 internal jet properties, a decrease of the statistical uncertainty of the measured signal by 5% was achieved.

Figure 10 shows the BDT output for the data, simulated signal and backgrounds. The signal and background contributions in the data, relative to the expected contributions in the simulation are denoted as $s$ and $b$, and are evaluated from a maximum likelihood fit of the data BDT output distribution to the expected signal and background output shapes from the simulation. The signal cross section measured in the data is then given by
\[ \sigma_{\text{meas}} = s \times \sigma_{\text{MADGRAPH}}(\text{EW } \ell\ell jj), \] where \( \sigma_{\text{MADGRAPH}}(\text{EW } \ell\ell jj) \) is obtained from MADGRAPH simulation using PDFs CTEQ6L1 with the following parton-level selections: \( m_{\ell\ell} > 50 \text{ GeV}, \) \( p_T^j > 25 \text{ GeV}, \) \( |\eta| < 4.0 \) and \( m_{jj} > 120 \text{ GeV}. \)

The combined cross section from the \( \mu^+\mu^- \) and \( e^+e^- \) channels is:

\[ \sigma^{\text{EW}}_{\text{meas,}\mu\mu + ee} = 154 \pm 24 \text{ (stat)} \pm 46 \text{ (syst)} \pm 27 \text{ (theory)} \pm 3 \text{ (lumi)} \text{ fb} \]

This is in good agreement with a theoretical cross section of 166 fb, calculated with next-to-leading order QCD corrections.

3.3. Central hadronic activity

The hadronic activity between the tagging jets is expected to be small in the case of a purely electroweak production. Although we do not use the hadronic activity to separate the EW \( \ell\ell jj \) from the backgrounds, studies have been done to test the agreement between data and simulation. For this study, tracks associated with the primary vertex and not associated with either the two leptons or the two tagging jets are selected if they satisfy a high purity requirement and have a transverse momentum exceeding 300 MeV. These tracks are clustered into soft track jets with the anti-\( k_T \) algorithm with distance parameter of 0.5. This method gives us a collection of jets with energy as low as a few GeV which are not affected by the pileup.

In order to monitor the hadronic activity in the rapidity gap between the two tagging jets, only track jets with pseudorapidity \( \eta_{\text{min}}^{\text{tag,jet}} + 0.5 < \eta < \eta_{\text{max}}^{\text{tag,jet}} - 0.5 \) are considered. Figure 11 shows the scalar sum of the three leading soft track jets (\( H_T \)). The evolution of the average \( H_T \) as a function of the dijet invariant mass and the pseudorapidity separation between the two tagging jets is shown in figure 12 and demonstrates a good agreement between data and simulation up to the most highest regions of dijet invariant mass and pseudorapidity separation.

These results establish an important benchmark in the more general study of VBF processes, of great interest for studies of the Higgs boson, electroweak gauge couplings, and vector boson scattering.
Figure 11. The $H_T$ distribution of the three leading soft track jets in the rapidity gap between the two leading jets with $p_T^{j_1,j_2} > 65, 40$ GeV in $Z + 2$ jets events

(a) dimuon channel
(b) dielectron channel

Figure 12. Average $H_T$ of the three leading soft track jets in the rapidity gap between the two leading jets with $p_T^{j_1,j_2} > 65, 40$ GeV in $Z + 2$ jets events versus (a) the dijet invariant mass (b) the pseudorapidity separation between the two tagging jets

References
[1] CMS Collaboration 2012 JHEP 01 010 (arXiv: 1110.3226)
[2] CMS Collaboration 2008 JINST 3 S08004
[3] J. Alwall et al. 2011 JHEP 06 128 (arXiv: 1106.0522)
[4] T. Sjostrand, S. Mrenna, and P.Z. Skands 2006 JHEP 05 026 (arXiv: hep-ph/0603175)
[5] CMS Collaboration 2012 Submitted to Phys. Lett. B (arXiv: 1301.1646)
[6] T. Gleisberg et al. 2009 JHEP 02 007 (arXiv: 0811.4622)
[7] P. Nason 2004 JHEP 11 040
[8] S. Frixione, P. Nason and C. Oleari 2007 JHEP 11 070 (arXiv: 0709.2092)
[9] S. Alioli et al. 2010 JHEP 06 043 (arXiv: 1002.2581)
[10] S. Alioli et al. 2011 JHEP 01 095 (arXiv: 1009.5594)
[11] CMS Collaboration 2012 CMS Physics Analysis Summary CMS-PAS-FSQ-12-019