Vector boson associated with jets in CMS

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Precision measurements of vector boson production in associated with jets provide stringent tests of perturbative quantum chromodynamics (pQCD). It allows a sensitive evaluation of the accuracy of pQCD predictions at the highest accessible energies and for a broad range of kinematic configurations and allows to measure the Z invisible width at a hadron collider. Total and differential cross sections of vector boson produced in association with jets have been measured using CMS data. The W boson hadronic decay branching fraction ratio $R_c^W = \mathcal{B}(W \to cq)/\mathcal{B}(W \to q\bar{q}')$ is measured with high precision at CMS thanks to the large cross section of top quark-antiquark production.

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At the LHC the production of Z or W boson [1–5] in pp collisions is one of the most precisely measured processes. The measurement of vector boson production in association with jets provides a stringent evaluation of the accuracy of QCD modeling. Comparisons of measurements with the predictions from Monte Carlo (MC) based event generators and higher order theoretical calculations help to improve these predictions to give an accurate description of the measurements.

The rate of charm (c) quark production in W boson decays relative to the rate of W hadronic decays to different quark flavours ($R_{\mathrm{c}}^{\mathrm{W}}$) can be measured precisely. The high-purity sample of W boson from the top quark-antiquark production is suitable for the high-precision study of their decays. A measurement of $R_{\mathrm{c}}^{\mathrm{W}}$ is important, because it is a direct test of the unitarity of the Cabibbo–Kobayashi–Maskawa (CKM) matrix.

1. Measurement of W boson hadronic decay branching fraction ratio

The most precise measurement of the W boson hadronic decay branching fraction ratio $R_{\mathrm{c}}^{\mathrm{W}} = \mathcal{B}(\mathrm{W} \to \mathrm{cq})/\mathcal{B}(\mathrm{W} \to \mathrm{q\bar{q}}^{'})$ [6] in proton-proton (pp) collisions at a center-of-mass energy ($\sqrt{s}$) of 13 TeV is presented using data recorded by the CMS experiment, corresponding to an integrated luminosity of 138 fb^{-1}. The large cross section of top quark-antiquark production offers an enormous high-purity sample of W bosons for measurement.

Within the Standard Model (SM), $R_{\mathrm{c}}^{\mathrm{W}}$ can be expressed as a function of CKM matrix elements. Assuming the unitarity of the CKM matrix, $R_{\mathrm{c}}^{\mathrm{W}}$ is expected to be equal to 0.5. A measurement of $R_{\mathrm{c}}^{\mathrm{W}}$ is a direct test of this assumption.

Events with one charged lepton (electron or muon) and at least four jets, two tagged as bottom quark jets are selected. Charm jets are tagged using the presence of a muon inside the jet. The observed and predicted global event yields split into four exclusive categories are used to make a fit with the CMS statistical analysis and combination tool to extract the $R_{\mathrm{c}}^{\mathrm{W}}$ branching fraction ratio. The fit yields a value $R_{\mathrm{c}}^{\mathrm{W}} = 1.489 \pm 0.005(stat) \pm 0.019(syst)$, with a total uncertainty of ± 0.020, in good agreement with the prediction of the SM. The precision of the measurement, limited by the systematic uncertainty in the charm tagging efficiency, is improved by more than a factor of two compared to the world average value. The sum of squared elements in the second row of the CKM matrix, 0.970 ± 0.041, and the CKM matrix element $|V_{cs}| = 0.959 \pm 0.021$ are derived. These results provide a consistency test of CKM unitarity and a measurement of V_{cs} from hadronic W boson decays.

2. Z boson invisible width at 13 TeV

A direct measurement of the invisible width of the Z boson [7] in pp collisions at $\sqrt{s} = 13$ TeV is presented using data recorded by the CMS experiment, corresponding to an integrated luminosity of 36.3 fb^{-1}.

In the analysis, the selected events can be categorized into three main regions: the $p_{\mathrm{T}}^{\mathrm{miss}}$ plus jets (where $p_{\mathrm{T}}^{\mathrm{miss}}$ is the missing transverse momentum vector) signal region with $\mathrm{Z} \to \nu\bar{\nu}$ events, a dilepton plus jets region for $\mathrm{Z}/\gamma^{*} \to \mu\mu$ and $\mathrm{Z}/\gamma^{*} \to ee$ events and a single lepton plus jets region, l+jets, where $l = e, \mu, \tau_{\mathrm{h}}$ (hadronically decaying τ) that is enriched with W+jets.

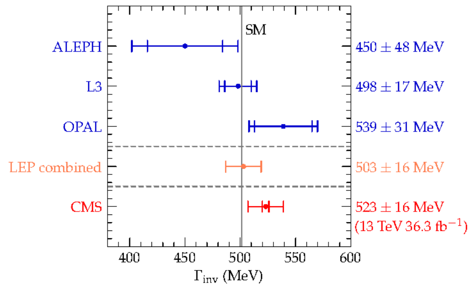

Figure 1: Direct measurements of the Z boson invisible width with the CMS experiment and the results by the LEPexperiments.

A basic selection criteria is applied to all regions: requiring $p_T^{miss} > 200$ GeV and the leading jet with $p_T > 200$ GeV. Events are vetoed if there are jets with $p_T > 40$ GeV and $|\eta| > 2.4$. In the signal region, backgrounds are suppressed by vetoing events containing an isolated muon or electron with $p_T > 10$ GeV and $|\eta| < 2.4$ or a τ_h with $p_T > 20$ GeV and $|\eta| < 2.3$ or an isolated photon with $p_T > 25$ GeV and $|\eta| < 2.5$.

The largest background in the signal region is from W+jets events where the lepton is out of acceptance, not reconstructed or misidentified. The W+jets is estimated from data using the l+jets control regions, and a transfer factor is used to correct the event yields in data. The QCD multijet events are also estimated from a control region. Other backgrounds from single top production, top quark pair production, diboson processes, and photon+jets are taken from the simulation.

The invisible width of the Z boson, Γ_{inv}, is extracted from a simultaneous likelihood fit to the p_T^{miss} or p_T of the charged leptons in the three regions. The measured Z boson invisible width is $\Gamma_{inv} = 523 \pm 3(\text{stat}) \pm 16(\text{syst})$ MeV. A comparison with the direct measurements from the LEP experiments ALEPH, L3, OPAL, and the LEP combined measurements is shown in Figure 1. This is the first precise measurement of the invisible width of the Z boson at a hadron collider and is the single most precise direct measurement of Γ_{inv}.

3. Multi-differential Z+jets cross sections at 13 TeV

Measurements of the cross sections for the production of Z bosons in association with jets in pp collision at a center-of-mass of 13 TeV [8] are presented, using data recorded by CMS and corresponding to an integrated luminosity of 36.3 fb^{-1}. The cross section has been measured as a function of the transverse momentum of the Z boson, jet transverse momentum, and rapidity of the five highest transverse momentum jets, and the jet multiplicity distribution (N_{jets}).

Events are selected with two isolated muons (electrons) with transverse momentum of at least 30 GeV for the first one and 20 GeV for the second one, and the invariant mass of the two leptons is between 71 and 111 GeV. Jets are required to have $p_T > 30$ GeV, $|\eta| < 2.4$ and to be separated from all selected lepton candidates.

The measured Z+jets differential cross sections are compared to three calculations: MG5_aMCat Next-to-Leading-Order (NLO), MG5_aMCat Leading Order (LO) and GenevaMC program. The MG5_aMCat NLO prediction includes NLO Matrix Elements (MEs) calculations for pp $\rightarrow$ Z + Njets

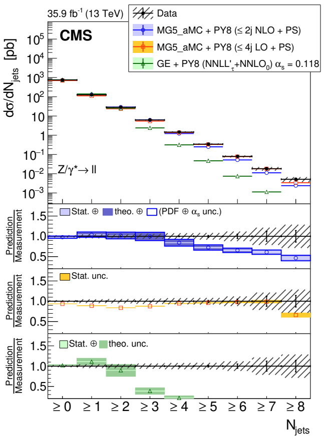

Figure 2: Measured Z+jets differential cross section as a function of the inclusive jet multiplicity.

with N up to 2. The MG5_aMCat LO includes MEs computed at LO for pp $\longrightarrow$ Z + Njets, N = 0...4. Genevais based on next-to-next-to-leading order calculations for the processes pp $\longrightarrow Z/\gamma \longrightarrow \mu^+\mu^-$ and e^+e^- combined with higher-order resummation.

The measured cross sections as a function of the inclusive jet multiplicity are shown in Figure 2. All the predictions are in agreement with the measurement for all the theoretical estimations up to the maximum number of final state partons included in the MEs. The Geneva generator predicts a much steeper spectrum than observed due to the lack of hard jets at the ME level beyond two.

4. Azimuthal correlations in Z+jets at 13 TeV

The production of Z boson associated with jets is measured in pp collisions at $\sqrt{s}$ = 13 TeV with data recorded at CMS corresponding to a luminosity of 36.3 fb^{-1} [9]. The jet multiplicity and the azimuthal correlation between the Z boson and the leading jet $\Delta\phi_{Z,j_1}$, and the correlation between the two leading jets in different region of the Z boson p_T(Z).

The phase space for the particle level is restricted to events with a Z boson mass between 76 and 106 GeV with two leptons with $|\eta| < 2.4$, $p_T^{leading\ lep} > 25$ GeV, $p_T^{sub-leading} > 20$ GeV. Jets are required to have $p_T > 30$ GeV, $|\eta| < 2.4$ and a spatial separation from the dressed leptons of $R > 0.4$.

The measured differential cross sections are compared with a variety of predictions. The predictions from NLO MG5_aMC at NLO and the NNLO calculation Geneva have been mentioned in the previous section. Two predictions are obtained from MG5_aMC with Parton Branching (PB) transverse momentum dependent parton densities (TMDs) and parton shower as implemented in Cascade3. The matrix elements are calculated at NLO for Z +1 and Z +2 partons (labelled as MG5aMC+CA3 (Z + 1) NLO and MG5aMC+CA3 (Z + 2) NLO separately.

The differential cross section as a function of the azimuthal correlation between the Z boson and the leading jet, $\Delta\phi_{Z,Jet1}$, in three different p_T(Z) bins: p_T(Z) < 10 GeV, 30 ≤ p_T(Z) < 50 GeV and p_T(Z) ≥ 100 GeV are shown in Figure 3. The predictions from NLO MG5_aMC with and without multiparton interactions (MPI) are compared with the measurement. The contribution

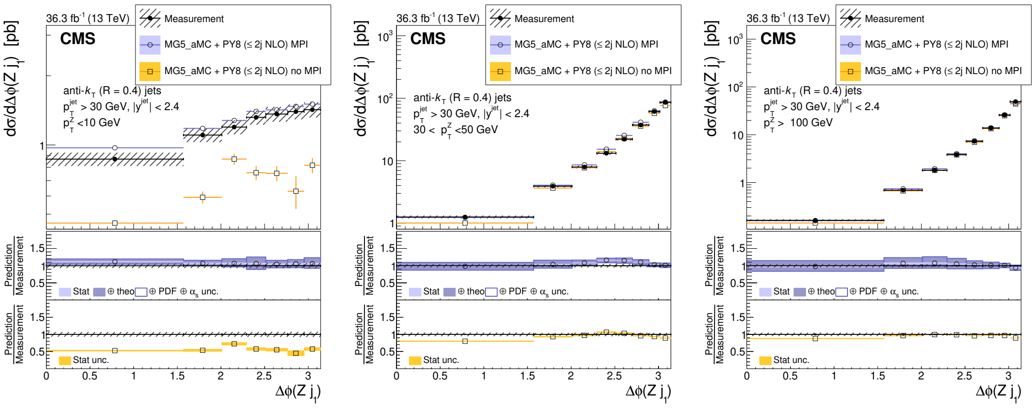

Figure 3: Measured Z+jets differential cross section as a function of $\Delta\phi_{Z,Jet1}$ in different $p_T(Z)$ region: $p_T(Z) < 10$ GeV, $30 \leq p_T(Z) < 50$ GeV and $p_T(Z) \geq 100$ GeV [9]. Predictions using NLO MG5_aMC with and without multiparton interactions are shown.

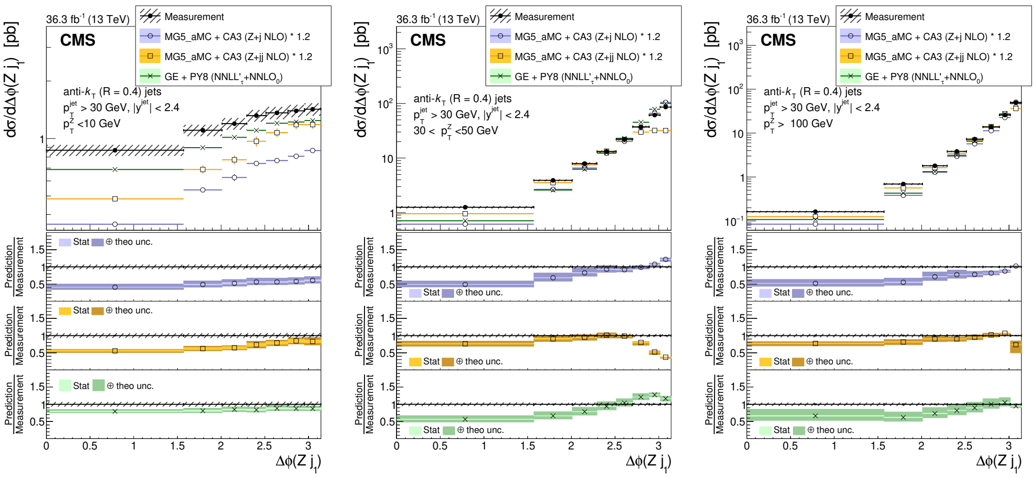

Figure 4: Measured Z+jets differential cross section as a function of $\Delta\phi_{Z,Jet1}$ in different $p_T(Z)$ region: $p_T(Z) < 10$ GeV, $30 \leq p_T(Z) < 50$ GeV and $p_T(Z) \geq 100$ GeV [9]. Predictions from GENEVA, MG5-AMC+CA3 (Z + 1) NLO and MG5AMC+CA3 (Z + 2) NLO are shown.

from MPI weighs about 40 % of the total in the low $p_T(Z)$ region. The MPI becomes negligible in the region $p_T(Z) > 100$ GeV.

The predictions from GENEVA, MG5AMC+CA3 (Z+1) NLO, and MG5AMC+CA3 (Z+2) NLO are also compared with the measurement, as shown in Figure 4. In the low $p_T(Z)$ range, the MG5-AMC+CA3 (Z+1) NLO and MG5AMC+CA3 (Z+2) NLO predictions differ from the measurements due to the missing contribution of MPI. In the other $p_T(Z)$ range, the predictions of GENEVA and MG5AMC+CA3 (Z + 1) NLO give similar descriptions of the measurement. The contribution from higher order matrix elements becomes important, especially in the low $\Delta\phi_{Z,Jet1}$ region as shown by the prediction MG5AMC+CA3 (Z + 2) NLO.

5. Conclusion

The most precise single direct measurement of the W boson hadronic decay branching fraction ratio has been presented. The first measurement of the Z boson invisible width at a hadron collider is presented, and it is also the single most precise measurement The differential cross section for the production of a Z boson in association with jets has been measured in detail by CMS. Good agreement can be achieved between data and predictions when including contributions of multiparton interactions, parton shower, parton densities as well as multijet matrix-element merging.

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