

Vector boson associated with jets in CMS

Qun Wang* for the CMS collaboration

Deutsches Elektronen-Synchrotron, D-22607 Hamburg, Germany

E-mail: qun.wang@desy.de

The study of the associated production of vector bosons and jets constitutes an excellent environment to check numerous QCD predictions. Total and differential cross sections of vector bosons produced in association with jets have been studied in pp collisions using CMS data. Differential distributions as function of a broad range of kinematical observables are measured and compared with theoretical predictions.

*** *The European Physical Society Conference on High Energy Physics (EPS-HEP2021)*, ***

*** *26-30 July 2021* ***

*** *Online conference, jointly organized by Universität Hamburg and the research center DESY* ***

*Speaker

The production of Z-bosons in Drell-Yan (DY) [1] in pp collisions is one of the most precisely measured processes at the LHC [2–6]. The measurement of vector boson production in association with jets provides a sensitive evaluation of the accuracy of QCD modeling, which is important for modeling the production mechanism involved in the Higgs boson and new physics searches. The production of a vector boson together with jets is a dominant background in many Standard Model (SM) processes, such as Higgs production, $t\bar{t}$ production for searches for dark matter and supersymmetric particles. Comparisons of measurements with the predictions from Monte Carlo (MC) based event generators and higher order theoretical calculations improves our understanding of the prediction uncertainties and motivates the development of generators.

1. Z boson invisible width at 13 TeV

A direct measurement of the invisible width of the Z boson [7] in proton-proton collisions at a center-of-mass energy of 13 TeV is presented, based on data recorded by the CMS experiment [8] corresponding to an integrated luminosity of 36.3 fb^{-1} . The Z boson invisible width is extracted from the ratio of measured cross sections of the Z boson to neutrinos and to the charged dileptons.

In the analysis, the events can be categorized into three main regions: the p_T^{miss} plus jets (where p_T^{miss} is the missing transverse momentum vector) signal region that is composed predominantly of $Z \rightarrow \nu\bar{\nu}$ events, a dilepton plus jets region for $Z/\gamma^* \rightarrow \mu\mu$ and $Z/\gamma^* \rightarrow ee$ determination, and a single lepton plus jets region, l +jets, where $l = e, \mu, \tau_h$ (hadronically decaying τ) for W+jets measurement.

A set of baseline selection criteria is applied to all regions, requiring $p_T^{\text{miss}} > 200 \text{ GeV}$ and the leading jet to have $p_T > 200 \text{ GeV}$. The value of $|p_{T,\text{Calo}}^{\text{miss}} - p_T^{\text{miss}}|/p_T^{\text{miss}}$ is required to be less than 0.5, where $p_{T,\text{Calo}}^{\text{miss}}$ is the p_T^{miss} measured only by the calorimeter systems and corrected for the presence of leptons. Events are vetoed if they contain jets with $p_T > 40 \text{ GeV}$ and $|\eta| > 2.4$; there is an isolated photon passing a loose identification criteria with $p_T > 25 \text{ GeV}$ and $|\eta| < 2.5$; they contain a b-tagged jet with $p_T > 40 \text{ GeV}$ and $|\eta| < 2.4$.

Many background processes have been considered in the analysis, such as W+jets, γ +jets, $t\bar{t}$ +jets, diboson, QCD multijet and single top. Background is suppressed by vetoing events containing an isolated muon or electron with $p_T > 10 \text{ GeV}$ and $|\eta| < 2.4$, or a τ_h with $p_T > 20 \text{ GeV}$ and $|\eta| < 2.3$. The largest background, W+jets, is estimated from data using the control region of l +jets. A transfer factor has been determined as a function of p_T^{miss} and used to correct the event yields in data to obtain the expected number of W+jets events in the signal region. The contribution from QCD multijet events is estimated from a control region. Other backgrounds are taken from simulation.

The invisible width of the Z boson, Γ_{inv} , is extracted from a simultaneous likelihood fit to data in the p_T^{miss} plus jets, Z/γ^* ($\mu\mu$ and ee) plus jets, μ + jets, and e + jets regions. The observed Z boson invisible width is measured to be $\Gamma_{\text{inv}} = 523 \pm 3(\text{stat}) \pm 16(\text{syst}) \text{ MeV}$. Figure 1 shows a comparison with the direct measurements from the LEP experiments L3, OPAL and ALEPH and the LEP combined measurement. The CMS measurement of the Z boson invisible width with an uncertainty of 16 MeV is comparable to the LEP combined result. and is the single most precise direct measurement of Γ_{inv} .

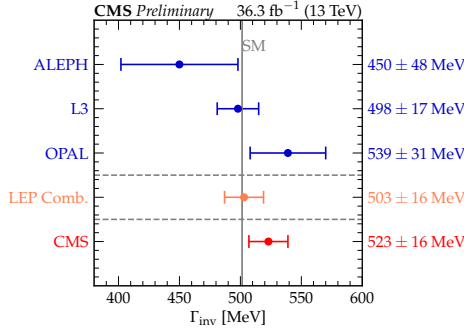


Figure 1: Measurements of the Z boson invisible width with the CMS experiment and the results by the LEP experiments [7].

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

The cross sections for the production of Z bosons in association with jets, in proton-proton collision at a center-of-mass of 13 TeV [9] is performed with data recorded in 2016 by CMS, corresponding to 35.9 fb^{-1} of integrated luminosity. The cross section has been measured as a function of jet multiplicity (N_{jets}) and the individual jet kinematic variables, and the scalar sum of the jet transverse momenta (H_T) for events up to 5 energetic jets.

The measured Z+jets differential cross sections is compared to three predictions. The first one is MADGRAPH5_AMC@NLO (denoted MG5_AMC) including NLO Matrix Elements (MEs) calculations for $pp \rightarrow Z + N_{jets}$ with N up to 2. PYTHIA 8 is used to model the parton showers and hadronization, the merging of PYTHIA 8 and MEs is performed with the FxFx scheme. The second one is MG5_AMC interfaced with PYTHIA 8, with MEs computed at Leading Order (LO) for five processes $pp \rightarrow Z + N_{jets}$, $N = 0..4$ and matched to the parton shower using $k_T - \text{MLM}$ scheme. The CUETP8M1 PYTHIA 8 tune is used for both MG5_AMC samples. The third calculation uses the GENEVA 1.0-RC3 MC program, where an NNLO calculation for Drell-Yan (DY) production is combined with higher-order resummation. Logarithms of the 0-jettiness resolution variable, τ , also known as beam thrust, are resummed at NNLL'. It is interfaced with PYTHIA 8 using the CUETP8M1 tune.

The measured cross section are unfolded to the particle level. The phase space is restricted to events with two leptons with $|\eta| < 2.4$, $p_T^{\text{leading lep}} > 25 \text{ GeV}$, $p_T^{\text{sub-leading}} > 20 \text{ GeV}$, and a Z boson mass between 71 and 111 GeV. Jets are required to have $p_T > 30 \text{ GeV}$, $|\eta| < 2.4$ and a spatial separation from the dressed leptons of $\Delta R > 0.4$.

The measured cross sections as a function of the inclusive jet multiplicity are shown in fig 2. The agreement is very satisfactory for the distributions for all the theoretical estimations up to the maximum number of final state partons included in the ME in the MC generators. The GENEVA generator predicts a much steeper spectrum than observed due to the lack of hard jets at ME level beyond two. The double differential cross sections as a function of leading jet p_T is shown in fig 2. In general, all the predictions are in the agreement with data and the NLO prediction provides a better description than LO MG5_AMC and GENEVA for double differential cross sections.

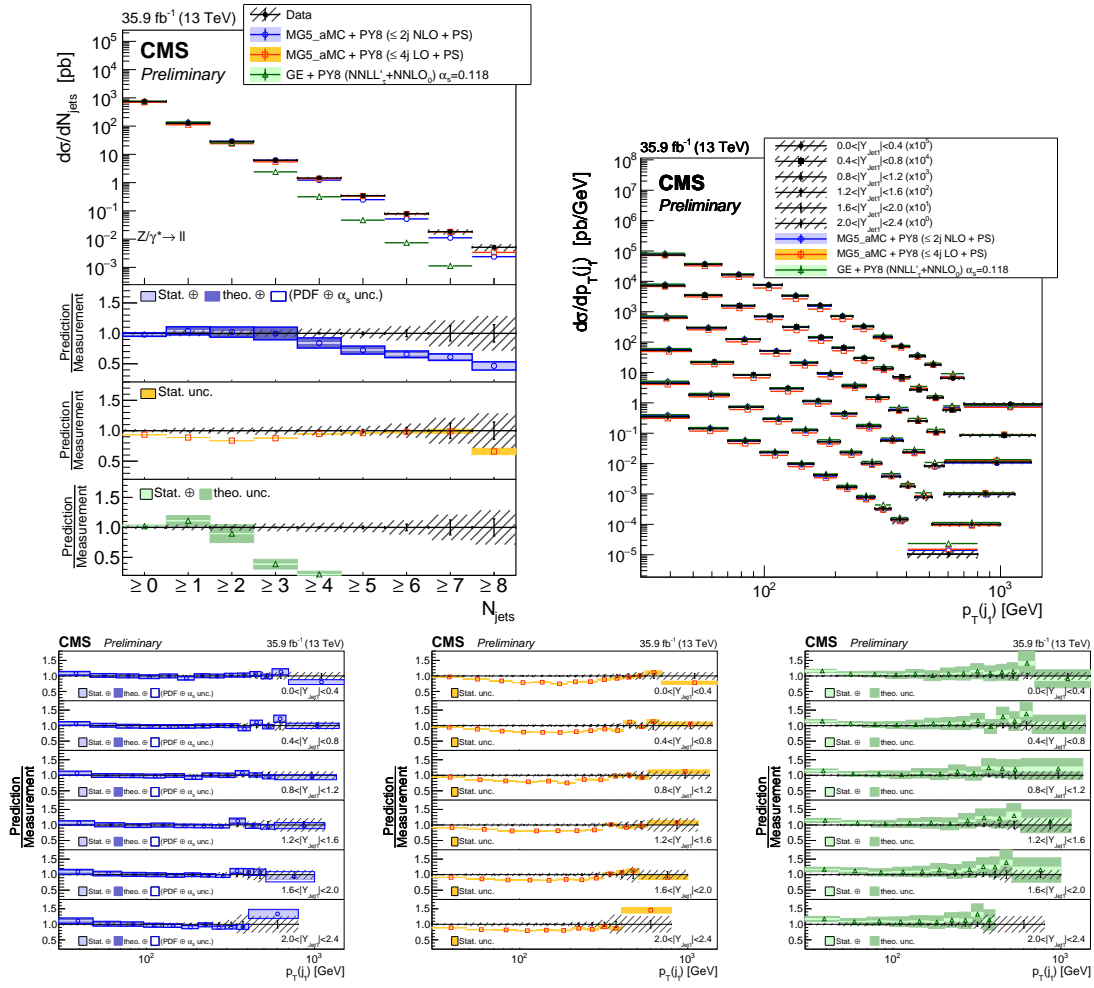


Figure 2: Measured Z +jets differential cross section as a function of the inclusive jet multiplicity (top left), and the double differential cross section as a function of the leading jet p_T (top right) [9]. The measurement is compared to NLO MG5_AMC (bottom left), LO MG5_AMC (bottom middle), and GENEVA (bottom right).

3. Azimuthal correlations in Z +jets at 13 TeV

We study in detail the production of a Z boson with associated jets at a center-of-mass energy of 13 TeV with data recorded at the LHC corresponding to a luminosity of 36.3 fb⁻¹ [10]. We measure the jet multiplicity, the azimuthal correlation between the Z boson and the leading jet $\Delta\phi_{Z,Jet1}$, as well as the correlation between the two leading jets $\Delta\phi(j_1, j_2)$ in different regions of $p_T(Z)$.

The measured differential cross sections are compared to four predictions. The prediction MG5_AMC interfaced PYTHIA 8 at NLO and the NNLO calculation GENEVA have been described 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 phase space for the particle level is restricted to events with a Z boson mass between 76

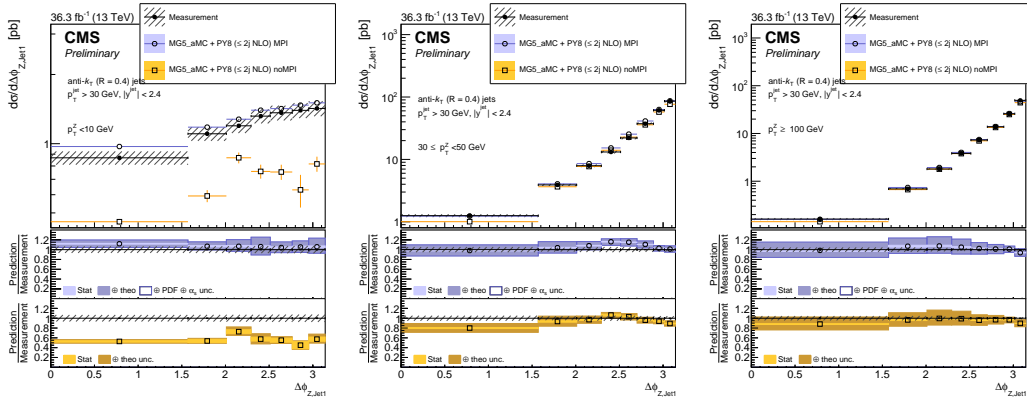


Figure 3: Measured Z+jets differential cross section as a function of $\Delta\phi_{Z,Jet1}$ in different $p_T(Z)$ region: $p_T(Z) < 10$ GeV, $30 \leq p_T(Z) < 50$ GeV and $p_T(Z) \geq 100$ GeV [10].

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 $R > 0.4$.

Fig 3 shows 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, $30 \leq p_T(Z) < 50$ GeV and $p_T(Z) \geq 100$ GeV. In the low $p_T(Z)$ region ($p_T(Z) < 10$ GeV) the Z boson is only very weakly correlated with the leading jet, the distribution is almost flat. In the large $p_T(Z)$ region ($p_T(Z) \geq 100$ GeV) the Z boson is highly correlated with the leading jet, the distribution falls over more than two orders of magnitude from the back-to-back region to the small $\Delta\phi_{Z,Jet1}$ region. The systematic uncertainty in the low $p_T(Z)$ region is $O(10\%)$. the prediction from NLO MG5_AMC with and without multiparton interactions (MPI) are compared with the measurement. In the low $p_T(Z)$ region, the contribution from MPI weighs for about 40 % of the total. The MPI contributes significantly in the low $p_T(Z)$ regions, for $p_T(Z) > 100$ GeV MPI becomes negligible.

The predictions from MG5AMC+CA3 (Z+1) NLO, MG5AMC+CA3 (Z+2) NLO and GENEVA have been compared with the measurement, as shown in fig 4. The prediction of GENEVA for Z +jet observables is similar to the ones from MG5AMC+CA3 (Z+1) NLO. One can see the missing MPI contribution in MG5AMC+CA3 (Z+1) NLO when compared to GENEVA which includes MPI. 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.

4. Conclusion

We have presented the single most precise direct measurement of the Z boson invisible width by the CMS experiment. The differential cross section for the production of a Z boson in association with jets have been measured in details 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.

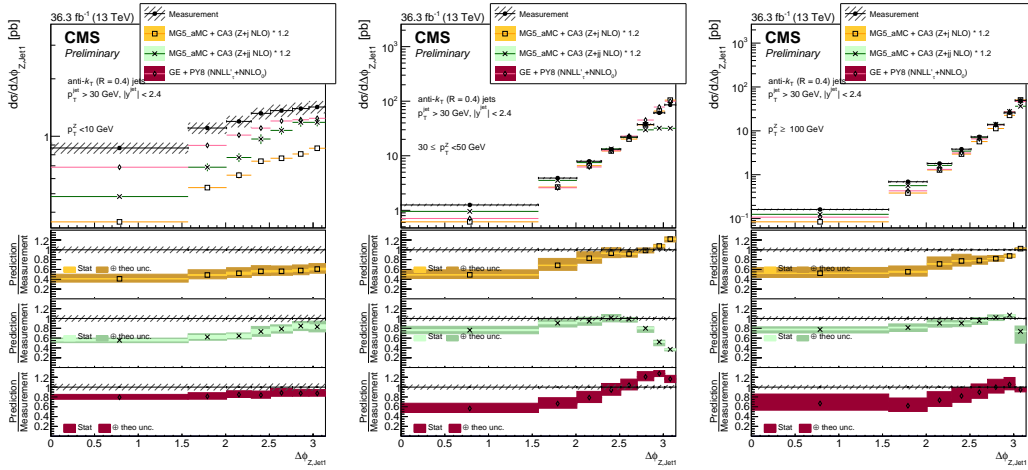


Figure 4: Measured Z+jets differential cross section as a function of $\Delta\phi_{Z,Jet1}$ in different $p_T(Z)$ region: $p_T(Z) < 10$ GeV, $30 \leq p_T(Z) < 50$ GeV and $p_T(Z) \geq 100$ GeV [10].

References

- [1] S. Drell and T.-M. Yan, “Massive Lepton Pair Production in Hadron-Hadron Collisions at High-Energies”, *Phys.Rev.Lett.* **25** (1970) 316–320.
- [2] CMS Collaboration, “Measurement of the transverse momentum spectra of weak vector bosons produced in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JHEP* **02** (2017) 096, [arXiv:1606.05864](#).
- [3] ATLAS Collaboration, “Measurement of the transverse momentum and ϕ_{η}^* distributions of Drell–Yan lepton pairs in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *Eur. Phys. J.* **C76** (2016), no. 5, 291, [arXiv:1512.02192](#).
- [4] CMS Collaboration, “Measurement of the rapidity and transverse momentum distributions of Z Bosons in pp collisions at $\sqrt{s} = 7$ TeV”, *Phys.Rev.* **D85** (2012) 032002, [arXiv:1110.4973](#).
- [5] ATLAS collaboration, *Measurement of the transverse momentum distribution of Drell-Yan lepton pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, [1912.02844](#).
- [6] CMS collaboration, *Measurements of differential Z boson production cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **12** (2019) 061 [[1909.04133](#)].
- [7] CMS collaboration, *Precision measurement of the Z invisible width with the CMS experiment in pp collisions at $\sqrt{s} = 13$ TeV*, [[cds/2775364](#)]
- [8] CMS Collaboration, “The CMS experiment at the CERN LHC. The Compact Muon Solenoid experiment”, *JINST* **3** S08004 (2008)
- [9] CMS collaboration, *Measurement of multi-differential cross sections for the production of a Z boson in association with jets in proton-proton collisions at $\sqrt{s} = 13$ TeV*, [[cds/2767703](#)]
- [10] CMS collaboration, *Azimuthal correlations in Z+jets events at 13 TeV*, [[cds/2777194](#)]