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## VBS/VBF from CMS

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### ABSTRACT

Vector Boson Scattering (VBS) and Vector Boson Fusion (VBF) studies in pp collisions at 7 and 8 TeV center of mass energy based on data recorded by the CMS detector at the LHC in 2011 and 2012 are reported.

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# 1 Introduction

Although the Standard Model of Particle Physics has been extensively tested at the colliders, proving to be accurate over many order of magnitude in the prediction of processes cross-sections, still some fundamental pieces need to be measured. The question about the existence of the Higgs boson, has now been split into two queries: is this the only Higgs boson present in Nature, and is it really doing the Higgs boson job. To answer these questions, there are three main roads: keep searching for scalars outside of  $m = 125$  GeV [1]; measure with high precision the properties of the 125 GeV boson [2]; measure the electroweak vector boson interactions, establishing whether this Higgs boson really can make unitarity-preserving the Vector Boson Scattering (VBS) amplitudes at all energies. The test electroweak production of single Z boson, that is one of the first Vector Boson Fusion (VBF) processes measured at LHC [3, 4], and the projections for VBS searches at 13 TeV [5] performed by CMS experiment are the topics of this report.

## 2 Electroweak production of Z boson in association with two forward/backward jets

In proton proton collisions the dominant source of production of a Z boson followed by a leptonic decay  $Z \rightarrow \ell\ell$  in association with two jets is through mixed electroweak (EW) and strong (QCD) processes of order  $O(\alpha_{EWK}^2 \alpha_{QCD}^2)$ , commonly known as Drell-Yan (DY) plus two jets processes. Pure electroweak productions of the  $\ell\ell jj$  final state, of order  $O(\alpha_{EWK}^4)$ , are more rare at the LHC [6], but are expected to carry a distinctive signature which can be explored experimentally: two jets of very high energy, well separated in pseudorapidity and with a large invariant mass, are expected to be produced in association with the dilepton pair. In the following, these jets that originate from the fragmentation of the outgoing quarks in EW processes will be referred as “tag jets” and to the the process which originated them as EW-Z+2jets. Figure 1 shows representative Feynman diagrams for the EW production of dilepton pairs in association with two jets including Vector Boson Fusion (VBF) processes, Z-bremstrahlung processes, and multiperipheral processes; which have a large negative interference between each other. However the

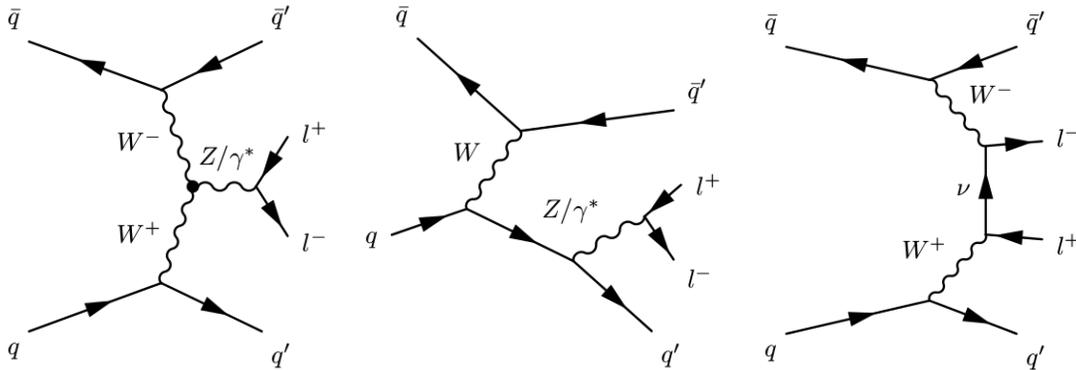


Figure 1: Representative diagrams for dilepton production in association with two jets from pure electroweak processes. Vector boson fusion (left), Bremsstrahlung-like (center), and multiperipheral (right) productions.

VBF electroweak production can be isolated from other processes, by means of selections based on the VBF topology, that reduce also important backgrounds to the search. One important background of this search is the QCD production of Z+2 jets. As shown in Figure 2 (left), the pseudorapidity separation between the tag jets ( $\Delta\eta_{jj}$ ) is greater for electroweak production of Z+2 jets with respect to the QCD production mechanism. Another important variable to distinguish between VBF Z production and other backgrounds is the invariant mass of the two tag jets,  $m_{jj}$ , as shown in Figure 2 (right).

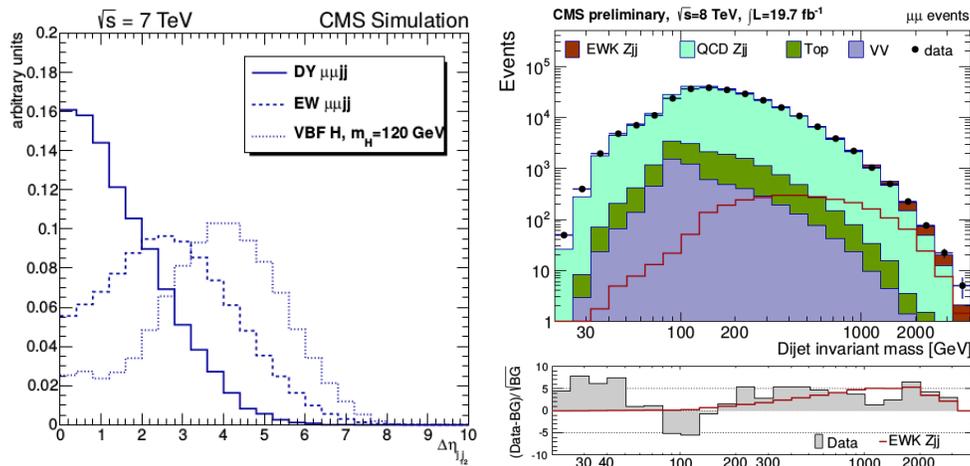


Figure 2: Pseudorapidity separation between tag jets,  $\Delta\eta_{jj}$  (left). The invariant mass of the two tag jets,  $m_{jj}$  (right).

### 3 Analysis strategy and results

Events with at least two charged leptons (electrons or muons) are selected in data using dilepton triggers. Each lepton is required to have a transverse momentum  $p_T > 20$  GeV and to be reconstructed within  $|\eta| < 2.4$ , where  $\eta$  is its pseudo-rapidity. Isolation criteria is furthermore imposed by using the tracks which are reconstructed close to the leptons. The sum of the transverse momenta of the tracks is required not to exceed more than 10% of the  $p_T$  of each lepton candidate. In each event the leptons are required to have opposite charge and the invariant mass of the system must be compatible with a Z boson, i.e.  $|M_{ll} - M_Z| < 15$  GeV. The two tag jets are selected within  $|\eta| < 4.7$  and required to have  $p_T > 30$  GeV.

Since the main background is QCD production of Z+2 jets, two different approaches to have an estimation of its contribution are performed. The first one is based on the use of MC expectation, propagating all theoretical and experimental uncertainties. In this method a multivariate discriminator based on jets  $p_T$ , azimuthal and pseudorapidity distance between jets, invariant mass of the two tag jets, the azimuthal distance between jets and the Z boson, and the rapidity of the Z boson in the lab and in the di-jet frame, is used. Figure 3 (left) shows the multivariate discriminator distribution, where the electroweak Z+2 jets contribution is clearly visible in the high score region.

The second method is based on the use of  $\gamma$ +jets sample from data to emulate Z+jets after re-weighting the  $p_T$  distribution between the photon and the Z boson. The analysis is then performed, in several  $m_{jj}$  bins, by means of a linear discriminator based on  $\Delta\eta_{jj}$ ,  $m_{jj}$  and the ratio between the transverse momentum of the di-jet system and the scalar sum of the transverse momentum of the two jets. Figure 3 (right) shows the distribution of the linear discriminator: a  $5.9\sigma$  ( $5.0\sigma$ ) observed (expected) discovery significance has been established.

### 4 Characterization of VBF topology

After establishing the signal, the properties of the hadronic activity in the selected events are studied: radiation patterns in Z+multijet events, the charged hadronic activity as function of several kinematics variables, and the production of extra jets in a high purity region ( $m_{jj} > 1250$  GeV) have been measured. Overall, a significant suppression of the hadronic activity for the signal is expected, due to the fact that the final state objects have their origin in pure electroweak interactions in contrast with the production of Z+2 jets via QCD. In Figure 4, the distribution of the number of jets and jet veto efficiency are reported. A good agreement between MC expectations and data is found. Such variables and a deep understanding of

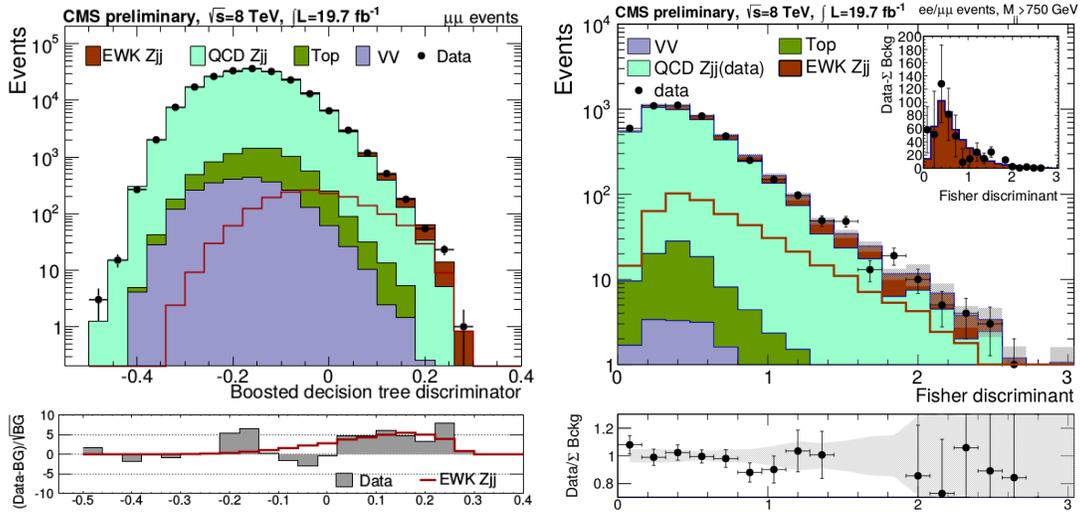


Figure 3: The BDT output (left) after selecting the Z candidate and the tag jets. The expected contributions from the signal and background processes are evaluated from simulation. The right figure shows the linear discriminator shape in the most sensitive region ( $m_{jj} > 750$  GeV) and the inset displays the result of a bin-by-bin background subtraction. The total uncertainty from the data-driven background prediction obtained from the photon control sample is shown as a shaded band in both the distribution and the bottom panel.

the VBF topology are crucial also as input for VBF Higgs searches, where the correct prediction of signal and background distributions is very important.

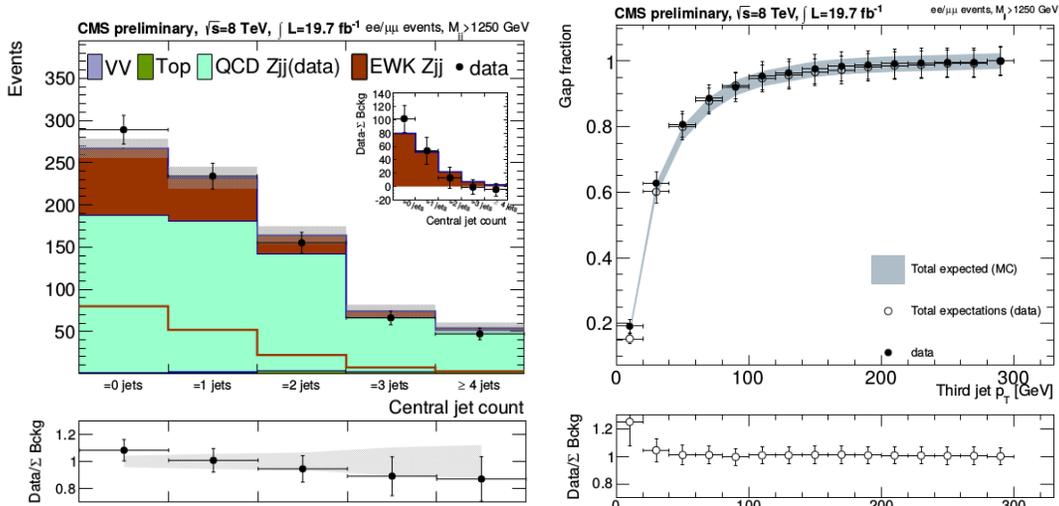


Figure 4: Distribution of the number of reconstructed jets (left) and the jet veto efficiency as a function of the jet transverse momentum (right). The reconstructed quantities are compared directly to the prediction obtained with a full simulation of the CMS detector.

## 5 Future studies

The LHC performances during run I are very successful, and fruitful results have been accomplished. In the preparation for LHC run II, not being limited any more by statistics thanks to higher cross section of rare processes and higher instantaneous luminosity, new vector boson scattering processes, such as WZ electroweak production [5], have been looked for. An integrated luminosity of about  $75 \text{ fb}^{-1}$  is sufficient for  $3\sigma$  evidence of the WZ electroweak production, while  $185 \text{ fb}^{-1}$  is sufficient for  $5\sigma$  observation at 14 TeV center of mass energy. With 13 TeV center of mass energy, approximately 15% more data is needed for the discovery of the electroweak scattering process.

To search for new physics processes that result in anomalous couplings, the WZ transverse mass has been used for final discrimination as the center of mass of the scattering system is highly sensitive to new physics involving massive particles. For  $300 \text{ fb}^{-1}$  the expected sensitivity to anomalous couplings is  $f_{T1} / \Lambda^4 = 0.8 \text{ TeV}^{-4}$ . Figure 5 shows the transverse mass of the WZ system for the SM case and in case of anomalous couplings.

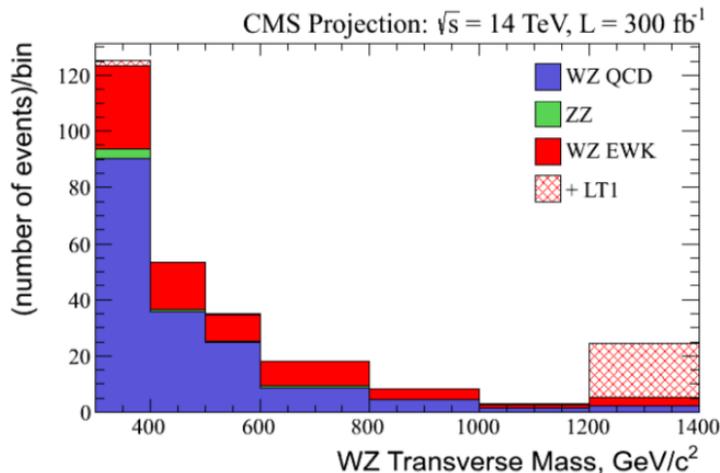


Figure 5: The WZ transverse mass at 14 TeV with  $300 \text{ fb}^{-1}$ . The additional contribution of an anomalous couplings signal for the  $L_{T1}$  operator (LT1) with  $f_{T1} / \Lambda^4 = 1.0 \text{ TeV}^{-4}$  is illustrated by the red hatched histogram.

## 6 Conclusions

The LHC run I has been very successful. The first vector boson fusions processes have been observed: the electroweak  $Z + 2$  jets production has been established with more than  $5\sigma$  significance. So far, consistency between theory and data has been found. A measurement of the properties of the hadronic activity in  $Z + 2$  jets events is performed. It is clear that although we discovered a Higgs boson, the comprehension of the Electroweak Symmetry Breaking is not completed, as several EW boson self-couplings still need to be observed. To exhaustively complete the picture, 100 to  $300 \text{ fb}^{-1}$  of integrated luminosity of data collected at  $\sqrt{s} = 13\text{-}14 \text{ TeV}$  are needed. First projections on the discovery potential of anomalous gauge couplings have been performed. The vector boson scattering and vector boson fusion processes are going to be two of the hot topics at Run II of LHC.

## References

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