PROCEEDINGS OF SCIENCE

Electroweak production of vector bosons and jets at the CMS experiment

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The production of massive vector boson pairs is a key process for the understanding of the non-abelian gauge structure of the standard model and for the comprehension of the electroweak symmetry breaking mechanism. The study of the production of vector boson pairs with the presence of two jets in the event allows measuring the electroweak production of vector bosons in association with jets, in particular made up through vector boson scattering processes. In this contribution, we presented the recent results from the study of the production of dibosons in association with two jets at $\sqrt{s} = 13$ TeV.

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1. Introduction

The CMS Collaboration put in place a large effort to cover all channels sensitive to the vector boson scattering (VBS). Arriving to the observation of the VBS is a long journey, but it has finally started and the first milestones of the path have been posed: the first measurement and observation of the electroweak production of vector bosons and jets. However, we just scratched the surface that covers the processes which are sensitive to the most intimate part of the electroweak symmetry breaking (EWSB), the acquisition of the longitudinal degree of polarization of the massive electroweak bosons.

I presented three analyses that targeted the observation of the electroweak production of di-bosons in association with jets, $pp \to ZZjj \to 4\ell jj$ [1], $pp \to W^{\pm}W^{\pm}jj \to \ell^{\pm}\ell^{\pm}\nu\nu jj$ [2], and $pp \to WZjj \to 3\ell\nu jj$ [3], and an analysis searching the evidence of anomalous quartic gauge couplings, using the channels $pp \to ZVjj \to 2\ell jjj$ and $pp \to WVjj \to \ell\nu jjj$ [4]. In all cases, $\ell = e, \mu$ and the data set corresponds to an integrated luminosity of 35.9 fb^{-1} (LHC Run II, 2016 data only). The measured cross sections are among the smallest measured so far in a collider experiment (Fig. 1). The description of the CMS detector can be found in Ref. [5].

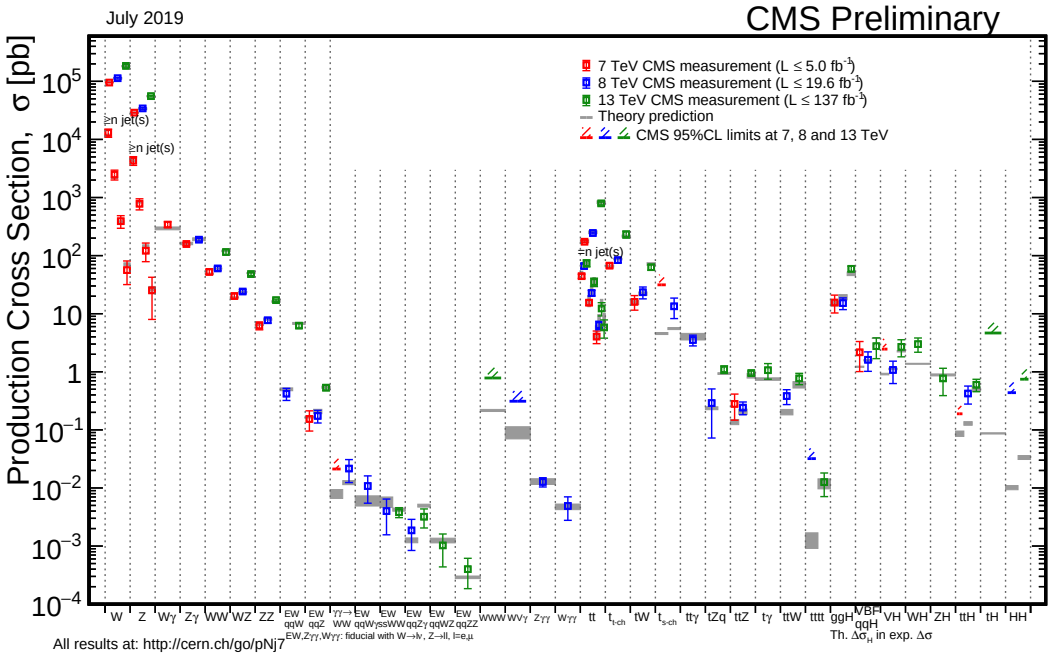

Figure 1: CMS cross section measurements summary [6].

2. Search for VBS in the fully leptonic ZZ+jets final state

In this analysis [1] we search for two pairs of same-flavor opposite-sign leptons that have an invariant mass between 60 and 120 GeV. The leptons must be isolated, prompt and satisfy minimal kinematic cuts: $p_T > 7$ GeV and $|\eta| < 2.5$, or $p_T > 5$ GeV and $|\eta| < 2.4$, for electrons and muons, respectively. Events are considered only if there are at least two jets (reconstructed with the anti-k_T algorithm [7], with a distance parameter of 0.4) with a transverse momentum

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larger than 30 GeV. This is the analysis with the cleanest experimental signature of the set: the instrumental background, where jets are misidentified as leptons, is very low, and all kinematic variables can be directly measured. However, the total cross section is very low compared both to the other VBS channels and, most importantly, to the processes that produce two Z bosons and two jets via diagrams of order α_s^2. Understanding this background is therefore paramount. CMS developed a dedicated analysis [8] to measure differential cross sections in the observables related to the hadronic properties of the process. To enhance the sensitivity of the analysis, the signal is extracted using a boosted decision trees technique, training it with seven variables. This results in an observed significance of 2.7 standard deviations (σ), with an expectation of 1.6 σ. Figure 2 shows the output of the BDT in a QCD-induced jets control region (left) and in the full search region (right).

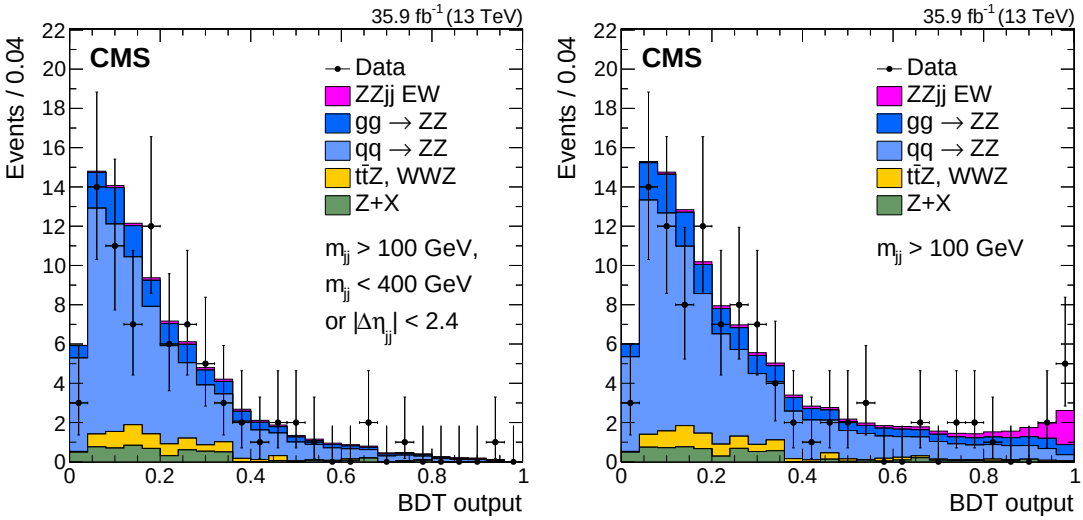

Figure 2: Distribution of the BDT output in the control region obtained by selecting ZZjj events with m_{jj} < 400 GeV or $|\Delta\eta_{jj}| < 2.4$ (left) and for the full search region (right) [1]. Points represent the data, filled histograms the expected signal and background contributions.

3. Search for VBS in the fully leptonic $W^{\pm}W^{\pm}$+jets final state

This is the first analysis that observed the electroweak production of two electroweak vector bosons in association with two jets [2]. The analysis strategy is based on the search for two charged leptons with a transverse momentum of at least 25 GeV (leading) and 20 GeV (sub-leading). Events are considered if there are at least two jets with 30 GeV of p_T, the two highest-p_T jets form an invariant mass larger than 500 GeV, $|\Delta\eta_{jj}| > 2.5$, and for each lepton $Z_l^* = |\eta_l - (\eta_{jet,1} + \eta_{jet,2})/2|/|\Delta\eta_{jj}| < 0.75$. Events with additional leptons are vetoed, as well as events with less than 40 GeV of missing transverse energy. Despite the presence of neutrinos escaping detection, the channel is very clean, because the final state with two same-sign charged leptons is rare in the standard model. The signal is extracted via a 2D-template fit of the invariant masses of the dijet and the dilepton systems. The final result brought to the observation of the process, with an observed significance of 5.5 σ (5.7 σ expected). Figure 3 shows the shape of m_{jj} and m_{ll} observables.

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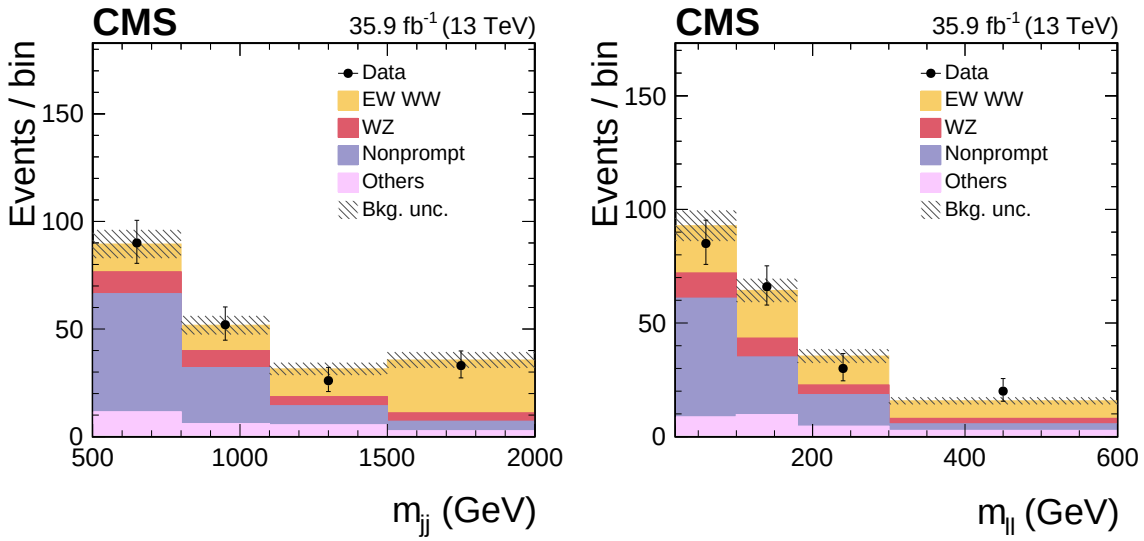

Figure 3: Distributions of m_{jj} (left) and m_{ll} (right) in the signal region of the $W^{\pm}W^{\pm}$ [2]. The normalization of the EW $W^{\pm}W^{\pm}$jj and background distributions corresponds to the result of the fit. The hatched bands include statistical and systematic uncertainties from the predicted yields.

4. Search for VBS in the fully leptonic WZ+jets final state

In this analysis [3] we search for exactly three charged leptons with a p_T larger than 25 and 15 GeV, if the leptons have been associated to the decay of the Z boson, or larger than 20 GeV if the lepton has been judged to come from the W decay. Events are accepted if there are at least two jets with 50 GeV of p_T, the two highest-p_T jets form an invariant mass larger than 500 GeV, $|\Delta\eta_{jj}| > 2.5$, and $\eta^*_{3l} = |\eta_{3l} - (\eta_{jet,1} + \eta_{jet,2})/2| < 2.5$. In the analysis we both measure the QCD+EW contribution to the WZ+jets cross section and the EW only component, which is approximately 38% of the previous. The extraction of the EW cross section only is done via a 2D-template fit of m_{jj} and $\Delta\eta_{jj}$. The observed significance is 2.2 σ, with an expected significance of 2.5 σ. Figure 4 shows the post-fit yields in the signal region in bins of m_{jj} and $|\Delta\eta_{jj}|$.

5. Search for aQGC in the semileptonic ZV and WV + jets final state

The CMS Collaboration designed a dedicated analysis [4] to be highly sensitive to anomalous quartic gauge couplings. In the analysis we make use of aggressive cuts to highly suppress the background. The hadronically decaying vector boson is reconstructed only in a boosted topology, where the product of the decay are reconstructed as a unique jet, using the anti-k_T algorithm with a distance parameter R=0.8 [4]. The tag jets, taken as the two which form the dijet system with the highest invariant mass, are required to have m_{jj} larger than 800 GeV, $|\Delta\eta_{jj}| > 4$. A detailed description of the cuts is in Ref. [4]. The results of the analysis does not show any excess with respect to the standard model prediction, thus the most stringent limits, so far, on dimension-8 operators in an effective field theory framework [9, 10] have been placed. Figure 5 shows the summary plots for the anomalous quartic gauge couplings search.

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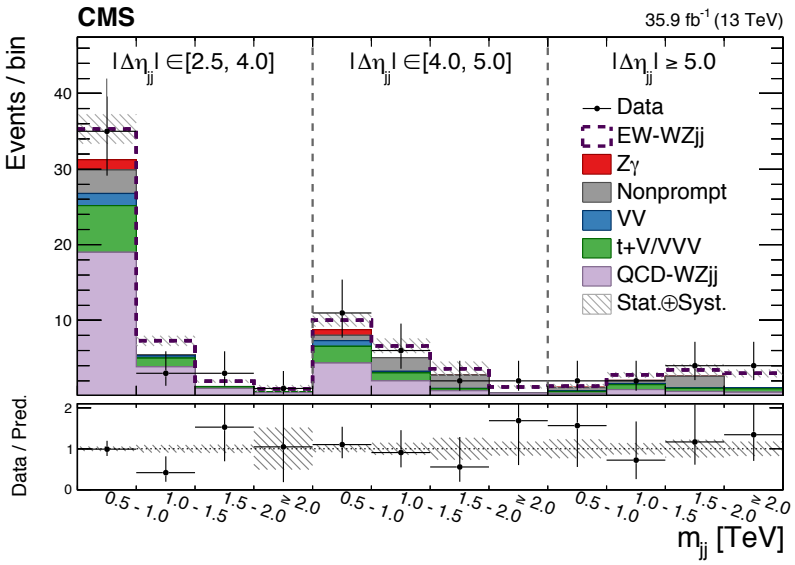

Figure 4: The one-dimensional representation of the 2D distribution of m_{jj} and $|\Delta\eta_{jj}|$, used for the EW signal extraction [3]. The x axis shows the m_{jj} distribution in the indicated bins, split into three bins of $|\Delta\eta_{jj}|$: [2.5, 4], [4, 5], ≥ 5. The dashed line represents the EW WZ+jets contribution stacked on top of the backgrounds that are shown as filled histograms. The hatched bands represent the total and relative systematic uncertainties on the predicted yields. The bottom panel shows the ratio of the number of events measured in data to the total number of expected events. The predicted yields are shown with their best-fit normalizations.

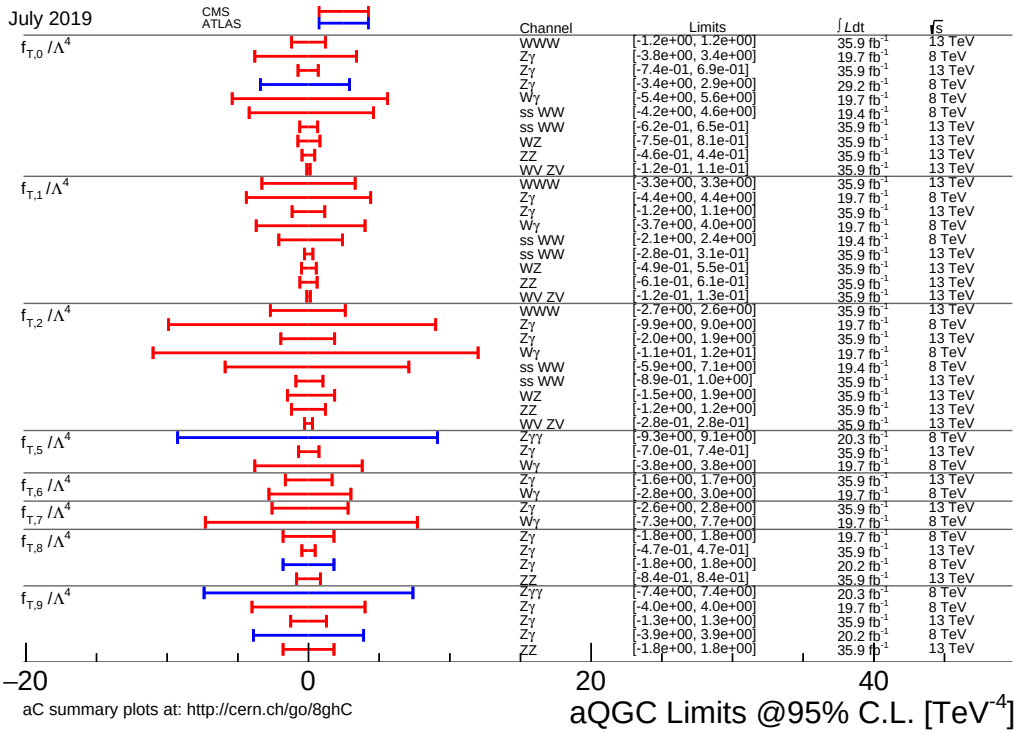

Figure 5: 95% confidence level limits on dimension-8 transverse parameters from the ATLAS and CMS Collaborations [6].

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6. Conclusions

The CMS Collaboration explored several VBS-like final states using 2016 LHC data. So far, we have observed the electroweak production of two same-sign W and two jets, a hint of the production of the ZZ+jets, and WZ+jets through electroweak processes. Detailed results on VBS with the CMS detector can be found in Ref. [6].

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