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Vector Boson Fusion and Vector Boson Scattering Measurements at the Large Hadron Collider

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Vector boson fusion and vector boson scattering at high energies are direct probes of boson interactions in the Standard Model and beyond. The non-Abelian nature of the electroweak Standard Model admits triple and quartic couplings of the electroweak vector bosons and the photon. Measurements of the boson production cross sections give insight into the couplings themselves. Recent measurements have been made using proton–proton collisions at a center-of-mass energy of 13 TeV with the ATLAS and CMS experiments on the Large Hadron Collider at CERN. These results and others provide stringent tests of the techniques for electroweak cross section calculations and kinematic modeling. They are designed to capture all aspects of the couplings, including differential cross sections, polarized weak boson scattering, and anomalous electroweak gauge boson couplings. For maximum sensitivity, the results are unfolded in electroweak fiducial regions where vector boson fusion and vector boson scattering are enhanced relative to other production mechanisms. They are also interpreted in the context of effective field theories, where additional operators and coefficients in the Lagrangian parameterize the anomalous couplings.

The Tenth Annual Conference on Large Hadron Collider Physics - LHCP2022
16-20 May 2022
online

[*] Speaker

https://pos.sissa.it/

PoS(LHCP2022)024

1. Introduction to VBF and VBS at the LHC

As the ATLAS [1] and CMS [2] experiments at the Large Hadron Collider [3] collect larger high-energy datasets for analysis, electroweak measurements of rare processes are becoming more precise and more sensitive to triple and quartic gauge boson couplings. These couplings are a direct consequence of the non-Abelian nature of the Standard Model (SM). The suite of weak vector boson fusion (VBF) and vector boson scattering (VBS) measurements presented here are designed to capture information about these couplings through inclusive cross sections, differential distributions, and probes of polarized weak boson scattering. In broad terms, VBF refers to production of a single boson in the final state, while VBS refers to production of a pair of bosons in the final state. The measurements can ultimately be interpreted in effective field theories as constraints on anomalous electroweak gauge boson couplings, as may be present in theories beyond the Standard Model [4].

In general, the VBF and VBS processes, examples of which are shown in Figure 1, include a mix of electroweak (EWK) and strong interaction (QCD) diagrams that cannot be disentangled due to gauge invariance requirements. It is possible to define electroweak-enriched regions of phase space in Vjj and $VVjj$ signatures where the EWK production dominates. Even then, the interference between EWK and QCD production must be considered and treated correctly in the calculations.

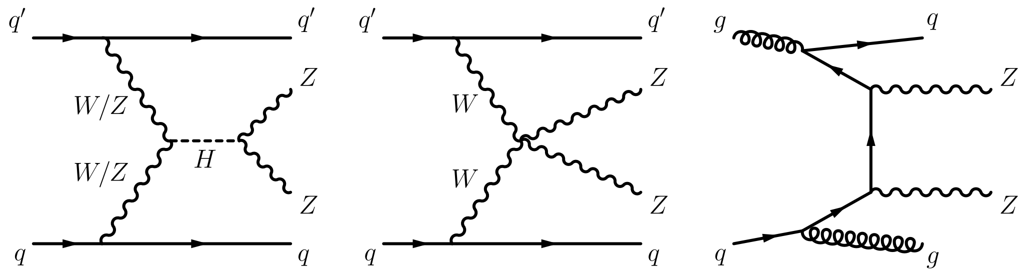

Figure 1: Representative Feynman diagrams for $pp \to ZZjj$ production, including electroweak contributions (left, middle) and strong quantum chromodynamics contributions (right).

The typical VBF/VBS signature is two jets from the inital scattering quarks, widely separated in η and having a large dijet invariant mass, with one or two weak bosons in the central region. Such events have little or no central hadronic jet activity because the VBF and VBS diagrams lack color flow between the initial state quarks. Therefore, requirements on the dijet invariant mass and centrality metrics are most effective in highlighting the electroweak contributions, and nearly all measurements focus on unfolding results in those fiducial regions.

The electroweak production cross sections are among the smallest measured by ATLAS and CMS, with significant backgrounds from QCD weak boson production. Some of the measured VBS cross sections are on the order of 1 fb, about seven orders of magnitude smaller than the inclusive W cross section. The list of measurements presented here is not comprehensive; it focuses instead on new measurements or measurements that hold special promise in testing the SM gauge boson couplings.

2. VBF measurements

The ATLAS collaboration has measured the differential Zjj cross section as a function of several kinematic variables, in order to separate the QCD and EWK production contributions [5]. The measurements are precise enough that they can be used to distinguish between the EWK Zjj predictions from different generators, as shown in Figure 2. As a result, the generators can be tuned to match the VBF Zjj measurements and then applied to other VBS/VBF measurements with smaller cross sections. The Zjj cross section is extracted from data distributions after unfolding the effects of detector efficiency and resolution. In a reduced fiducial region selection that highlights the EWK contribution, the measured EWK cross section is 37.4 ± 6.5 fb.

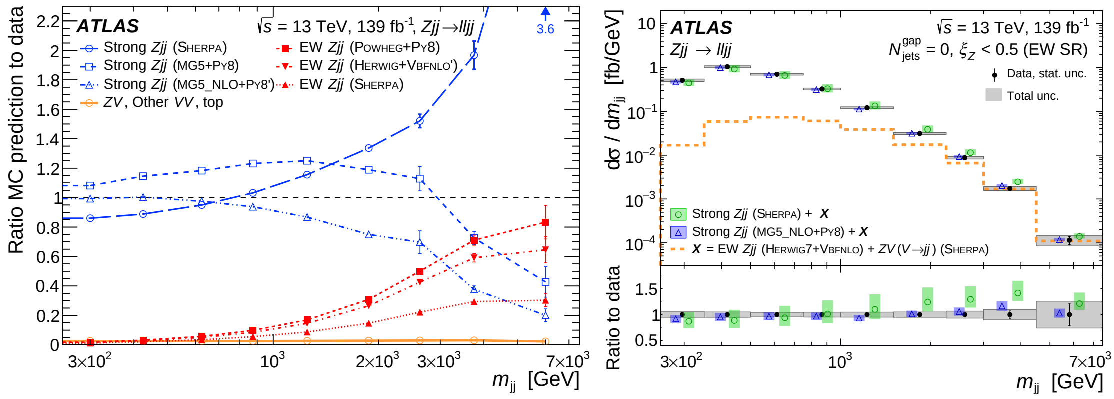

Figure 2: Ratio of Monte Carlo prediction to data for strong and electroweak Zjj physics processes and generators (left) and differential cross sections measured in the signal region for inclusive Zjj production as a function of m_{jj} (right) [5]. The mismodeling of m_{jj} in the inclusive regime motivates data-driven background estimates for the VBF/VBS signatures.

3. VBS $Z\gamma$ and $W\gamma$ measurements

The ATLAS measurement of $Z\gamma jj$ at $\sqrt{s} = 13$ TeV probes a neutral quartic gauge coupling with a larger cross section than $ZZjj$ production [6]. The centrality of the $\ell\ell\gamma$ system $\zeta_{\ell\ell\gamma}$, shown in Figure 3, is calculated as a means of enhancing the electroweak contributions. It has essentially the same definition as the so-called Rainwater-Zeppenfeld variable, $Z = \left[y - \frac{1}{2}(y_{j1} + y_{j2})\right] / |\Delta y_{jj}|$, with values near 0 in events with a central electroweak system [7]. The total fiducial cross section in the electroweak-dominated phase space, including both EWK and QCD production, is 20.3±1.3 fb, in agreement with SM predictions.

The CMS measurement of $Z\gamma jj$ production yields results reported in a more restricted phase space, with $m_{jj} > 500$ GeV instead of 150 GeV [8]. In Figure 3, the comparison is shown in two dimensions of m_{jj} and $|\Delta\eta_{jj}|$. A combined EWK+QCD $Z\gamma jj$ cross section is measured in this region with a best fit value of 14.7 ± 1.53 fb, while the EWK contribution alone is 5.21 ± 0.76 fb. These results are also consistent with the SM predictions at the 10–15% level.

Similar measurements, but of $H\gamma jj$ production instead of $Z\gamma jj$, are being pursued with $H \to b\bar{b}$ and $H \to$ invisible decays [9, 10].

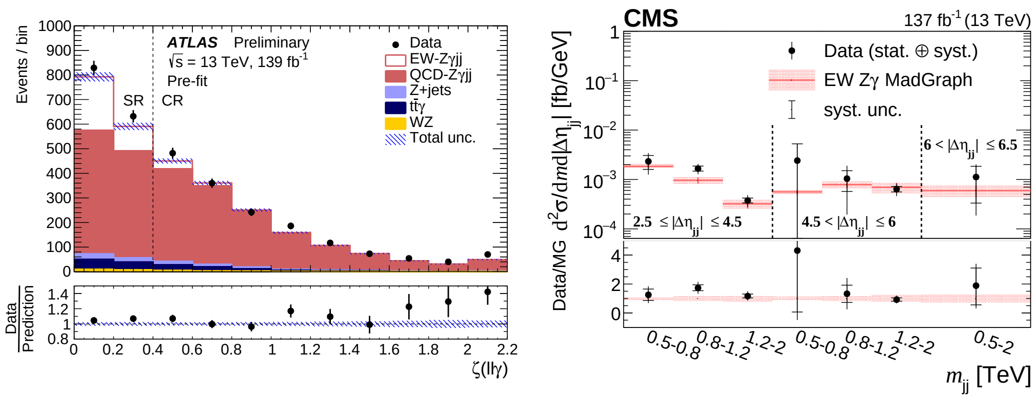

Figure 3: Pre-fit centrality distributions of the $\ell\ell\gamma$ system in ATLAS $Z\gamma$ events (left) [6] and the unfolded differential cross section for EW $Z\gamma jj$ as a function of the VBF jet invariant mass m_{jj} in CMS (right) [8]. The centrality value is used to separate the data sample into a signal region (SR) and control region (CR), so that the CR can be used in data-driven background estimates.

CMS recently released a new measurement of electroweak $W\gamma jj$ production that probes the $WW\gamma\gamma$ quartic coupling using the $m_{W\gamma}$ mass distribution [11]. This measurement uses the entire Run 2 dataset at $\sqrt{s} = 13$ TeV. The event signature is a leptonic W decay with a high-momentum photon, with dominant backgrounds from misidentified leptons and photons, in addition to strong production of $W\gamma jj$. A control region in data is defined to perform a background estimate with reduced dependence on detector simulation. The $m_{W\gamma}$ distribution, shown in Figure 4, is used to highlight the region sensitive to anomalous quartic gauge couplings, and a two-dimensional binning in m_{jj} and $m_{\ell\gamma}$ is used to extract the cross sections. The total inclusive cross section is measured to be 90 ± 11 fb, and the cross section in the restricted fiducial region is 19.2 ± 4.0 fb.

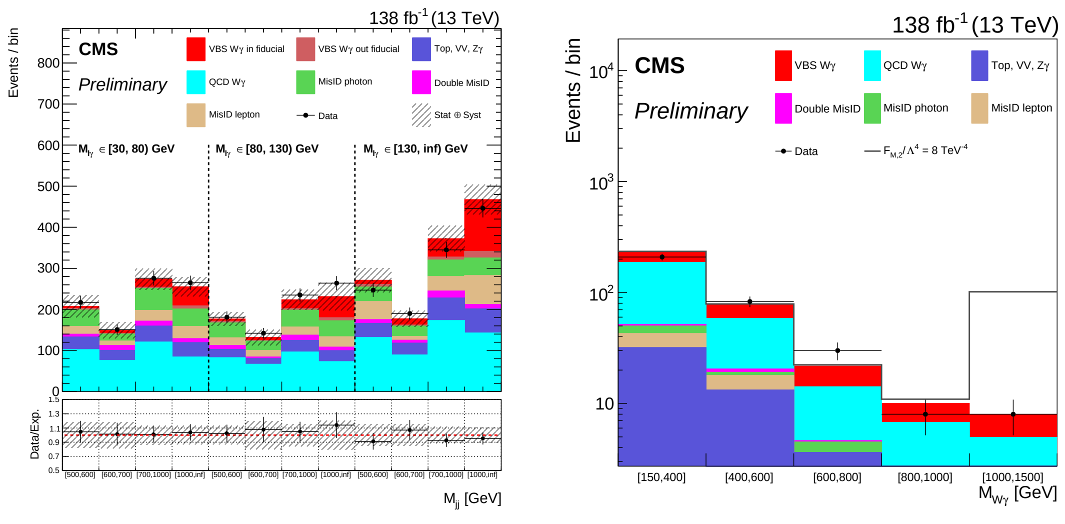

Figure 4: Kinematic distributions used to fit for the inclusive EWK $W\gamma$ cross section in the CMS barrel region (left) and combined mass distribution for events satisfying the region selection used to constrain anomalous quartic gauge boson couplings (right) [11].

4. VBS ZZ and WW measurements

The ATLAS measurement of $ZZjj$ production in the multi-lepton signatures ($\ell\ell\ell\ell$ and $\ell\ell\nu\nu$) has now reached a significance of 5.7σ. Even though the signature is clean with little background, except for Drell-Yan and WZ in the $\ell\ell\nu\nu$ channel, the signal cross section is small. The VBS kinematics are modeled well with a combination of simulation and data-driven methods, as shown in Figure 5, even for very high values of m_{jj}. This is a good test of the VBS differential cross section calculations in comparison with data.

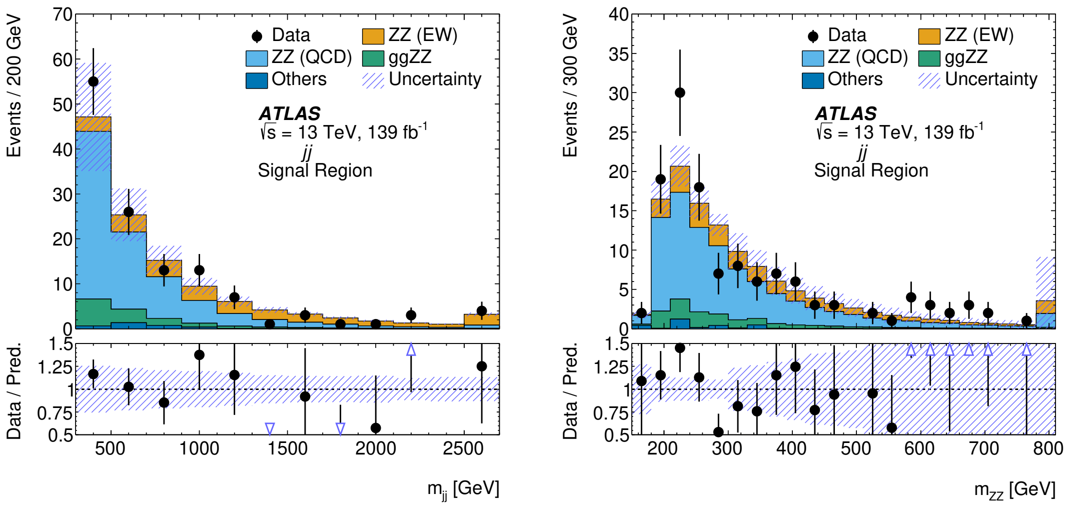

Figure 5: Kinematic distributions of the jet-jet invariant mass (left) and ZZ invariant mass (right) used to fit for the electroweak component of $ZZjj$ production in the multi-lepton signature in ATLAS [12].

One of the most compelling opportunities for ATLAS and CMS is the measurement of polarized vector boson scattering at large values of momentum transfer. Without the light Higgs boson providing key cancellation effects, the differential cross section for longitudinally-polarized W^+W^- scattering would increase monotonically, thereby violating unitary in the scattering. Now that the Higgs boson has been observed experimentally with a mass of 125 GeV, it is important to begin to develop polarized VBS measurements to test this prediction. The analysis is challenging because of the contributions from transversely-polarized VBS that are an order of magnitude larger than the longitudinally-polarized VBS.

A preliminary step toward achieving the goal is the CMS measurement of the electroweak production of $W^{\pm}_L W^{\pm}_L jj$ using the full 13 TeV dataset [13]. The advantage of this channel is that the same-sign W boson pair signature has smaller backgrounds than the opposite-sign signature. While the electroweak production is targeted by restricting the phase space to large m_{jj} values, the boson polarizations can be disentangled by considering the difference in lepton azimuthal angles. As shown in Figure 6, the angular distributions for longitudinally-polarized scattering are uniquely different from the distributions from transversely-polarized scattering and mixed-polarization scattering. A boosted decision tree using kinematic input patterns (Figure 6) is used to further discriminate between the three scattering cases. The measurement of the cross section times branching ratio for the completely longitudinally-polarized same-sign $W^{\pm}_L W^{\pm}_L$ scattering is

$0.32^{+0.42}_{-0.40}$ fb, and the measurement of the mixed-polarization $W^{\pm}_L W^{\pm}_X$ scattering is $1.20^{+0.56}_{-0.53}$ fb, both in line with the theoretical predictions.

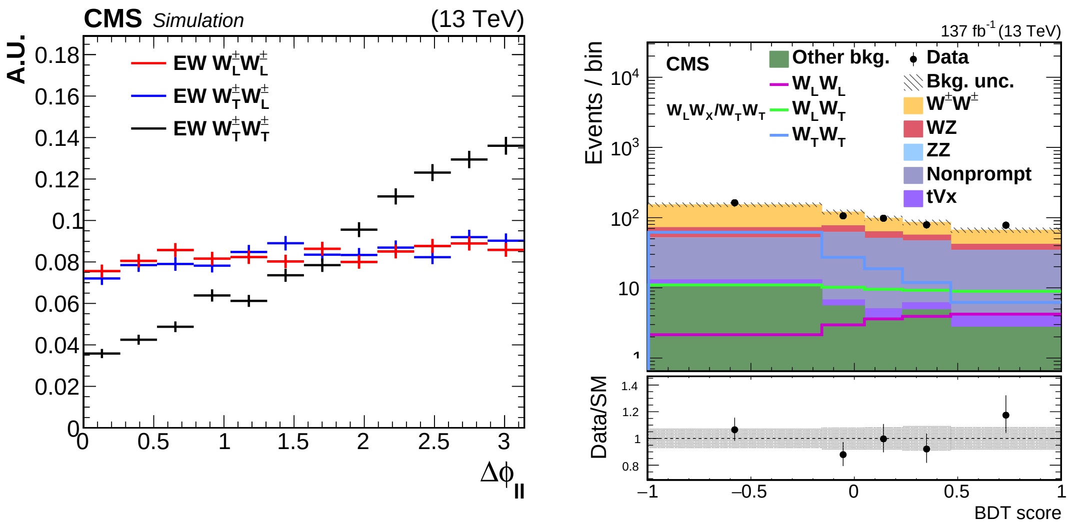

Figure 6: Generator-level distributions of the jet-jet azimuthal angle for $W^{\pm}W^{\pm}$ processes with different helicity eigenstates (left) and reconstructed distributions of the CMS BDT output score used to measure the cross sections (right) [13].

In another advance toward the ultimate goal of measured longitudinally-polarized W^+W^- scattering, CMS reported an observation of W^+W^-jj scattering, integrated over all possible polarizations, at the 5.6σ significance level [14]. Events with a same-flavor lepton pair (e^+e- or $\mu^+\mu^-$) are selected with simple requirements designed to minimize the dominant Drell-Yan background; events with a mixed-flavor pair ($e\mu$) are selected with a feed-forward deep neural network (DNN) trained to separate the VBS signal from the $t\bar{t}$ background and QCD production of W^+W^- pairs. The same-flavor events are binned in m_{jj} to highlight the EWK production process, and the opposite-flavor events are further separated by using the Zeppenfeld variable for the dilepton system: $Z_{\ell\ell} < 1$ or $Z_{\ell\ell} > 1$. The large backgrounds from $t\bar{t}W$ and $t\bar{t}$ events are estimated from a dedicated control region in the data. The results with the full Run 2 dataset are shown in Figure 7.

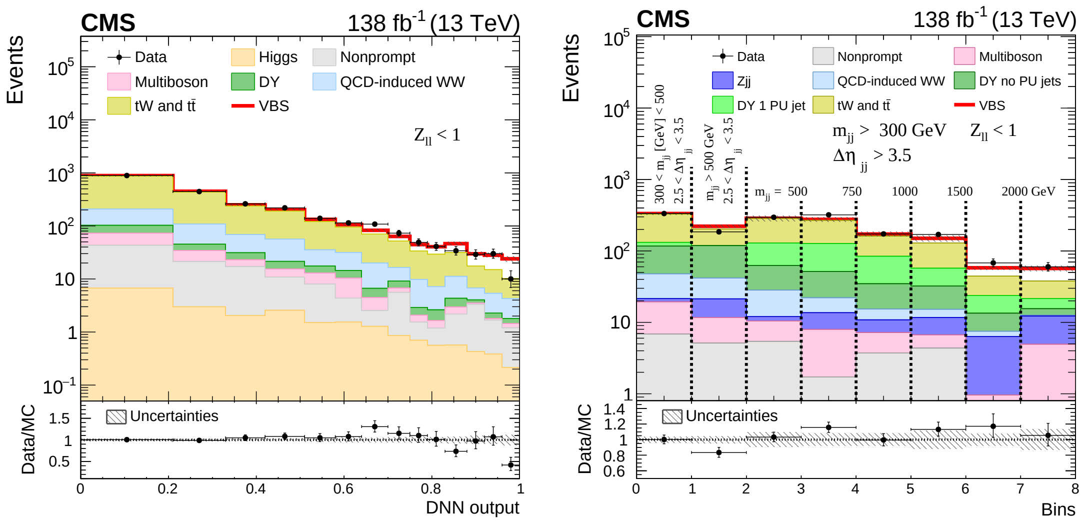

Figure 7: Post-fit DNN output distribution (left) and post-fit m_{jj} distribution (right) in same-flavor W^+W^-jj events for low Zeppenfeld variable values [14].

5. Conclusion

A large number of experimental signatures sensitive to weak boson fusion and weak boson scattering continue to be pursued with 13 TeV data. The results presented here and other VBF/VBS measurements provide stringent challenges to electroweak cross section calculations and kinematic modeling. In spite of those challenges, none of the measurements have presented serious discrepancies with the Standard Model predictions.

With the ATLAS and CMS detector upgrades, new trigger algorithms focused on VBF and VBS have been implemented for Run 3 of the LHC at $\sqrt{s}$ = 13.6 TeV. The increased dataset and enhanced trigger efficiencies will be key to improving the measurements of very small cross sections inherent to VBF and VBS. Sensitivity to anomalous gauge boson couplings will improve in turn, giving new insight into the Higgs and electroweak sectors.

Acknowledgements

We thank the Large Hadron Collider Physics 2022 conference organizers for arranging the interesting program and encouraging stimulating discussions. This work was supported in part by the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

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PoS(LHCP2022)024