PROCEEDINGS OF SCIENCE

Status of Vector Boson Scattering measurements at the LHC

Shu Li, on behalf of ATLAS and CMS Collaborations[a,b,c,*]

[a] *Tsung-Dao Lee Institute, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai, P.R.China*

[b] *Institute of Nuclear and Particle Physics, School of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Key Laboratory for Particle Physics, Astrophysics and Cosmology (Ministry of Education), 800 Dongchuan Road, Shanghai, P.R.China*

[c] *Center for High Energy Physics, Peking University, 5 Yiheyuan Road, Beijing, P.R.China*

E-mail: shuli@sjtu.edu.cn, Shu.Li@cern.ch

We present the latest results of Vector Boson Scattering measurements with the ATLAS and CMS detectors at the LHC experiment, using proton-proton collision data from LHC Run 2 operating at center-of-mass energies of 13 TeV. The results of the latest measured total, fiducial and differential cross sections are shown depending on the exact channels, in comparison with the theory predictions. Limits are set on anomalous quartic gauge couplings with Effective Field Theory high dimension operators utilizing some of the measurements.

**** Particles and Nuclei International Conference - PANIC2021 ****
**** 5 - 10 September, 2021 ****
**** Online ****

[*] Speaker

PoS(PANIC2021)406

1. Introduction to Vector Boson Scattering

Multi-Boson productions are among those most important Standard Model (SM) processes to be measured at the Large Hadron Collider (LHC), which generally include Di-Boson productions (VV), Tri-Boson productions (VVV), Vector Boson Fusion productions (VBF Vjj) and Vector Boson Scattering productions (VBS $VVjj$). Precisely measuring the Multi-Boson processes will provide not only a better understanding of SM, especially in the electroweak sector, but also a solid estimation of SM backgrounds for many Beyond SM (BSM) new physics searches, as the Multi-Boson productions are usually the irreducible backgrounds of many BSM signatures in similar decay final states.

Vector Boson Scattering (VBS), being the rare process in the SM Multi-Boson productions at LHC, is one of the key processes to probe the mechanism of electroweak symmetry breaking. Moreover, without the presence of Higgs boson, the longitudinal components of VBS amplitudes will increase as a function of center-of-mass energy, and violate the unitarity eventually. Therefore, VBS is also a key process to probe the Higgs mechanism in unitarization of such $VV \rightarrow VV$ scattering processes. Besides, many resonant BSM models and Effective Field Theory (EFT) parameterized anomalous quartic gauge couplings can be realized via VBS processes.

ATLAS [1] and CMS [2] at LHC are the two general-purpose experiments aiming for SM precise measurements and BSM searches. VBS are thoroughly searched for in both experiments utilizing LHC Run 1 to Run 2 proton-proton collision data. Many processes are eventually measured with sufficiently high statistical significance and reached the observation threshold of 5 σ. Figure 1 shows a clean signature of VBS like-sign WW pair production with typical VBS topology: two forward-backward jets and two centrally produced vector boson decayed like-sign leptons.

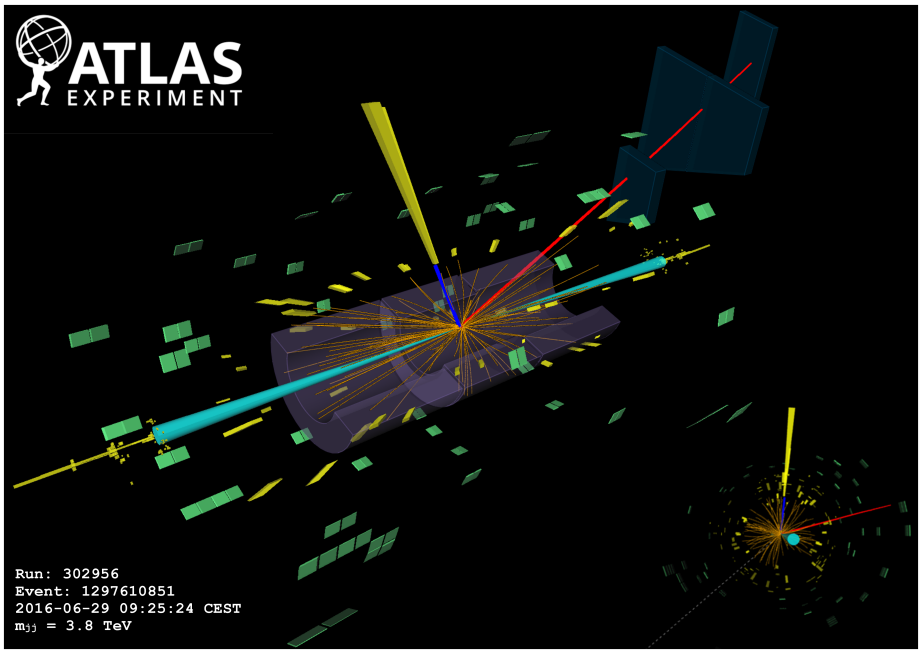

Figure 1: Event display of VBS like-sign $WWjj$ production with like-sign e and μ leptons and two jets. [3]

It is worth emphasizing that, in the current measurements, VBS $VVjj$ processes are usually

measured together with other non-VBS $VVjj$ processes induced via electroweak interactions, which do not come along with the scattering topologies but with the same electroweak coupling orders, because of the preservation of gauge invariance. Therefore, the process dependent VBS results are presented below by showing the latest measured electroweak $VVjj$ cross sections (total, fiducial and/or differential) at ATLAS or CMS. So far overall results are consistent with theory predictions.

2. Review of latest VBS measurements in massive VV processes

The milestone 1^{st} observations of VBS has been accomplished in like-sign $WWjj$ electroweak process measurements by CMS [4] and ATLAS [3] experiments in 2018 and 2019. These measurements greatly benefit from the presence of two like-sign charged leptons, which helped to greatly suppress the QCD-induced backgrounds and Drell-Yan backgrounds. The VBS WZ process has been observed by ATLAS [5] and CMS [6] in 2019 and 2020, taking the advantage of the relatively simple background composition and the presence of Z boson decaying into same-flavor opposite-sign charged lepton pairs. Differential cross section measurements are also performed in both experiments for the 1^{st} time in VBS processes.

A set of more recent analyses targetting rarer VBS processes in the electroweak $ZZjj$ productions, and more complex final states with semi-leptonically decayed $WV \to \ell\nu jj$, are performed in ATLAS and CMS. ATLAS combined the measurements of electroweak $ZZjj$ productions in both four charged leptons and two charged leptons plus two neutrinos final states with Boosted Decision Tree (BDT) techniques to enhance the measured electroweak $ZZjj$ signal sensitivities against backgrounds 2. As a result, background-only hypothesis is rejected with a statistical significance of 5.5 σ which lead to the 1^{st} observation of the electroweak $ZZjj$ process at LHC. [7] The measured cross section is consistent with SM predictions within the uncertainties. CMS performed the electroweak $ZZjj$ production measurements with evidence in four charged lepton final states, and the final measured observed (expected) significance reaching 4.0 (3.5) standard deviations. [8] This measurement also provides experimental constraints on the anomalous quartic gauge couplings, parameterized with EFT operators T0, T1, T2, T8, and T9. Both experiments also report the total cross sections of jj production in association with two Z bosons inclusively incorporating both QCD and electroweak components, in consistency with SM theory predictions.

A more complex final state of $WV(\to \ell\nu jj)$+jj has been explored by CMS by categorizing both the signal regions (SR) and control regions (W+jets and Top CR) into boosted and resolved categories, using large-Radius and small-Radius jet reconstructions. A deep neural network trained discriminants are developed in SR for signal and background separations. The finally measured cross section is found to be consistent with SM predictions, with a background-only hypothesis rejected at a statistical significance of 4.4 σ.

3. Review of latest VBS measurements in $V\gamma$ processes and as a probe to BSM

VBS processes are also probed by measuring the electroweak $V\gamma jj$ productions, which in general have higher signal yields than massive $VVjj$ processes given the presence of one photon with no further boson decay branching ratio sacrifice. ATLAS and CMS both explored the high purity channels of electroweak $Z\gamma jj$ charged lepton decays, and the measured cross sections are

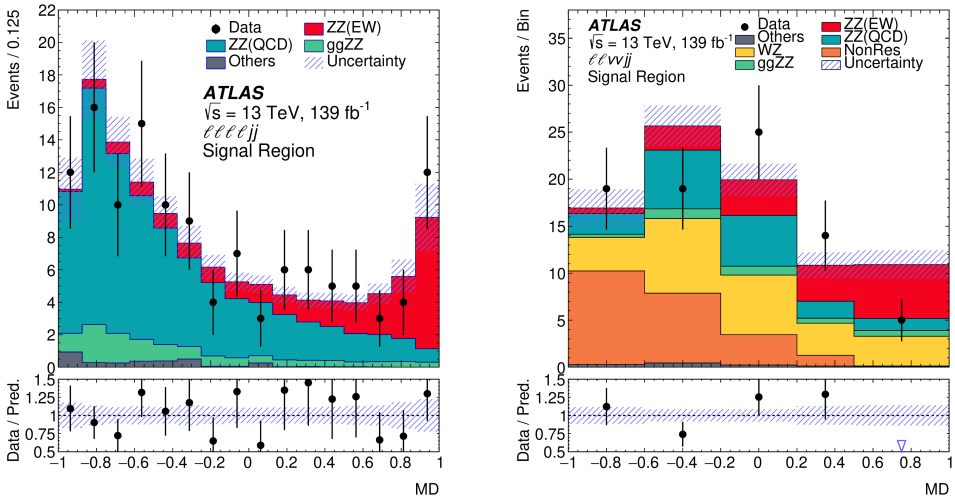

Figure 2: The observed and expected multivariate discriminant distributions after the statistical fit in the $\ell\ell\ell\ell$ and $\ell\ell\nu\nu$ signal regions. [7]

in good agreement with SM predictions and measured significance around 10 σ. [9, 10] In more complex final states of $W(\rightarrow \ell\nu)\gamma jj$, CMS combined the measurements with 13 TeV and 8 TeV data which gave the final measured significance exceeding 5 σ observation threshold. [11] In both electroweak $W\gamma jj$ and $Z\gamma jj$ measurements, CMS provides constraints on anomalous quartic gauge couplings with EFT dimension-8 operator parameterization. ATLAS for the 1^{st} time challenged the complex decay channels of $Z(\rightarrow \nu\bar{\nu})\gamma jj$ with high background contaminations with background-only hypothesis rejected at a statistical significance of 5.3 σ. [12] The results also help to provide constraints on invisible Higgs decays in VBF mode with additional photon as well as VBF Higgs to dark photons.

4. Review of latest VBS measurements in exclusive WW productions

The photon-induced $\gamma\gamma \rightarrow W^{\pm}W^{\mp}$ process is a unique VBS channel at LHC, as all the Feynman diagrams at Born level involve uniquely pure gauge boson interactions. With full Run 2 data, ATLAS manages to obtain the 1^{st} observation of such process at LHC with the focus on analyzing its unique experimental signatures: charged leptonic decays of the W pair and no additional charged-particle activity. "Different Flavor and Opposite Sign" requirement helps to further enhance the signal sensitivities against enormous backgrounds. The measured fiducial cross section is consistent with SM prediction and the background-only hypothesis is rejected with a statistical significance of 8.4 σ, leading to the 1^{st} observation of such signal process. [13]

5. Summary

ATLAS and CMS devoted huge efforts into VBS measurements in electroweak $VVjj$ processes which intensively consolidated the understanding of the electroweak sector of SM. Most of such measurements reached the observation thresholds and provided also constraints on BSM phenomena

via anomalous gauge couplings and other BSM hypothesis. Such work defines the milestones in marching for LHC electroweak physics and will bridge future studies of VBS longuitudinal polarization extractions and more intensive tests of Higgs mechanism in VV scatterings.

References

[1] ATLAS Experiment at the CERN Large Hadron Collider, 2008 JINST 3 S08003

[2] CMS experiment at the CERN LHC, 2008 JINST 3 S08004

[3] ATLAS Collaboration, Observation of electroweak production of a same-sign W boson pair in association with two jets in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector, Phys. Rev. Lett. 123, 161801 (2019)

[4] CMS Collaboration, Observation of electroweak production of same-sign W boson pairs in the two jet and two same-sign lepton final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV, Phys. Rev. Lett. 120, 081801 (2018)

[5] ATLAS Collaboration, Observation of electroweak $W^{\pm}Z$ boson pair production in association with two jets in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector, Phys. Lett. B 793 (2019) 469

[6] CMS Collaboration, Measurements of production cross sections of WZ and same-sign WW boson pairs in association with two jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV, Phys. Lett. B 809 (2020) 135710

[7] ATLAS Collaboration, Observation of electroweak production of two jets and a Z-boson pair with the ATLAS detector at the LHC, arXiv:2004.10612 [hep-ex]

[8] CMS Collaboration, Evidence for electroweak production of four charged leptons and two jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV, Phys. Lett. B 812 (2020) 135992

[9] ATLAS Collaboration, Measurement of the cross-section of the electroweak production of a $Z\gamma$ pair in association with two jets in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector, ATLAS-CONF-2021-038, https://cds.cern.ch/record/2779171

[10] CMS Collaboration, Measurement of the electroweak production of $Z\gamma$ and two jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV and constraints on anomalous quartic gauge couplings, arXiv:2106.11082 [hep-ex]

[11] CMS Collaboration, Observation of electroweak production of $W\gamma$ with two jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV, Phys. Lett. B 811 (2020) 135988

[12] ATLAS Collaboration, Observation of electroweak production of two jets in association with an isolated photon and missing transverse momentum, and search for a Higgs boson decaying into invisible particles at 13 TeV with the ATLAS detector, arXiv:2109.00925 [hep-ex]

[13] ATLAS Collaboration, Observation of photon-induced W^+W^- production in pp collisions at $\sqrt{s}$ = 13 TeV using the ATLAS detector, Phys. Lett. B 816 (2021) 136190