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Electroweak $W^{\pm}W^{\pm}jj$ Production in ATLAS

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Vector boson scattering is one of the recent remarkable observations at the Large Hadron Collider. The longitudinal polarization modes of the massive vector bosons are strongly tied to the electroweak symmetry breaking mechanism. With the Standard Model predicted Higgs boson playing a crucial role in regularizing the scattering amplitude of these longitudinally polarized bosons, vector boson scattering is a pivotal process in experimentally probing the symmetry breaking mechanism. A golden channel for measuring vector boson scattering at the collider is the electroweak production of two W bosons with the same electric charges. This report presents the measurement of $W^{\pm}W^{\pm}jj$ production cross-sections using Run 2 proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS experiment.

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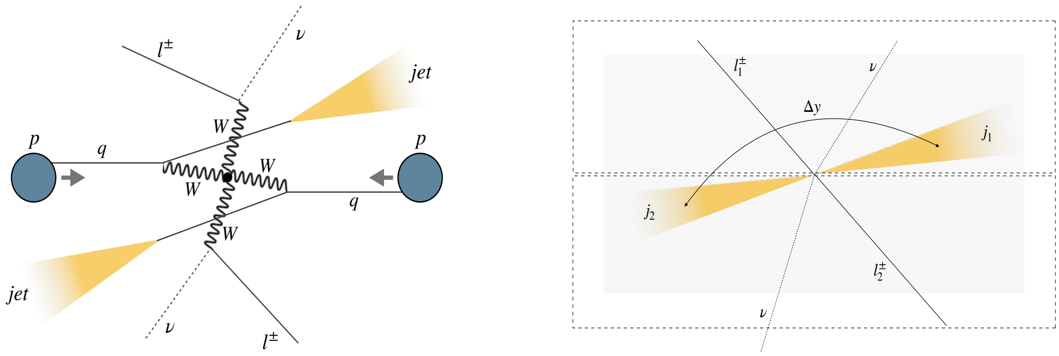

(a) **(b)**

Figure 1: A simplified picture of a proton-proton collision event resulting in the scattering of two W bosons with the same electric charge (left) and a schematic view of the event as seen in the ATLAS detector (right) are given.

1. Introduction

In the Standard Model (SM) of particle physics, the form and strength of the interaction of the electroweak gauge bosons, photon (γ), W and Z bosons, are determined by the $SU(2)_L \otimes U(1)_Y$ gauge symmetry characterizing the electroweak theory. The non-Abelian nature of the gauge symmetry allows self-interactions among the gauge bosons providing valuable insights into the fundamental interactions and symmetries of elementary particles. When longitudinally polarized gauge bosons scatter at energies much larger than the mass of the particle, the cross-section grows indefinitely with energy and violates the unitarity principle. For increasing centre of mass energies, the cross-section diverges and the divergence is canceled exactly by the contributions from Higgs mediated interactions. Due to the unique role played by the Higgs boson in regularizing the scattering amplitude, Vector Boson Scattering (VBS) is of historic interest to validate the predictions of the Standard Model. The process probes the couplings between the Higgs and gauge bosons at large energy scales and the self-couplings of gauge bosons, and is one of the few processes providing tree-level sensitivity to quartic gauge couplings.

At the Large Hadron Collider [1], VBS occurs when the incoming quarks from the protons radiate electroweak gauge bosons which then undergo subsequent scattering. The trajectory of the incoming quarks is altered only slightly when the gauge bosons are radiated. Consequently, the two associated outgoing jets, known as tagging jets, are typically seen in the forward regions close to the beam direction, at the opposite sides of the detector. Two tagging jets with a large dijet invariant mass (m_{jj}) separated by large rapidities (Δy_{jj}) serve as the experimental signature of a VBS event identified as $VVjj$ production. Figure 1 presents a simplified picture of the scattering of two W bosons and their subsequent decay into leptons.

In addition to the VBS production mode, $VVjj$ production can occur without the scattering of gauge bosons and is studied together with the VBS component as electroweak $VVjj$. A dominant background to the electroweak mode is the gluon-induced production. On account of the color connection between the gluons that pulls them closer together, gluons and quarks in strong production scatter at large angles with respect to the colliding beams, unlike the small scattering angles in electroweak production.

2. $W^{\pm}W^{\pm}jj$ Production

A golden channel characterizing VBS is the scattering of two W bosons with the same electric charge. Due to the same-sign nature of the W bosons, there are no gluon initiating diagrams, as a result of which the process has the largest electroweak to strong induced production ratio compared to any other diboson combinations. The process is studied in the leptonic channels, and the final state consists of two leptons (electrons or muons) with the same electric charge, neutrinos identified as missing transverse energy, and two forward tagging jets with $m_{jj} > 500\,\text{GeV}$ and $\Delta y_{jj} > 2$. Despite the smaller cross-section of this process, the presence of two leptons in the final state with the same electric charge significantly reduces the many backgrounds from other Standard Model processes.

The dominant background stems from WZ events, when one of the charged leptons falls outside of the acceptance range, and from mis-identified leptons, when leptons from secondary decays or jets are falsely identified as leptons originating from the W bosons. The WZ background is estimated from Monte Carlo predictions and is controlled in a dedicated three lepton $WZjj$ control region, whereas mis-identified leptons are evaluated using data-driven techniques. In electron final states, charge mis-identification and photon conversions are additional sources of background.

2.1 Cross-Section Measurement

A profile likelihood fit is performed to constrain and derive background yields and uncertainties that maximize the likelihood with the observed data. Cross-sections are obtained in a fiducial region after applying corrections to particle level and the results are compared with predictions from MadGraph+Herwig, MadGraph+Pythia, Sherpa and Powheg Box+Pythia. The integrated cross-sections are shown in Figure 2 and differential cross-sections obtained as a function of the dilepton invariant mass, m_{ll}, are shown in Figure 3 [3]. The results agree with SM expectations within the uncertainties. The leading uncertainty in the measurement is the limited statistics in data. The uncertainty in theoretical modeling is dominated by variations of the renormalization and factorization scales to account for the missing higher order corrections of the perturbative expansion of the partonic cross-section.

Description	$\sigma_{\text{fid}}^{\text{EW}}$, fb	$\sigma_{\text{fid}}^{\text{EW+Int+QCD}}$, fb
Measured cross section	$2.88 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{syst.})$	$3.35 \pm 0.22\,(\text{stat.}) \pm 0.20\,(\text{syst.})$
MG_aMC@NLO+Herwig	$2.53 \pm 0.04\,(\text{PDF}) \pm^{0.22}_{0.19}$ (scale)	$2.93 \pm 0.05\,(\text{PDF}) \pm^{0.34}_{0.27}$ (scale)
MG_aMC@NLO+Pythia	$2.55 \pm 0.04\,(\text{PDF}) \pm^{0.22}_{0.19}$ (scale)	$2.94 \pm 0.05\,(\text{PDF}) \pm^{0.33}_{0.27}$ (scale)
Sherpa	$2.44 \pm 0.03\,(\text{PDF}) \pm^{0.40}_{0.27}$ (scale)	$2.80 \pm 0.03\,(\text{PDF}) \pm^{0.53}_{0.36}$ (scale)
Powheg Box +Pythia	2.67	–

Figure 2: The integrated fiducial cross-section is shown for the electroweak production and the inclusive production [3]. The results are compared with Standard Model predictions modeled by various MC generators.

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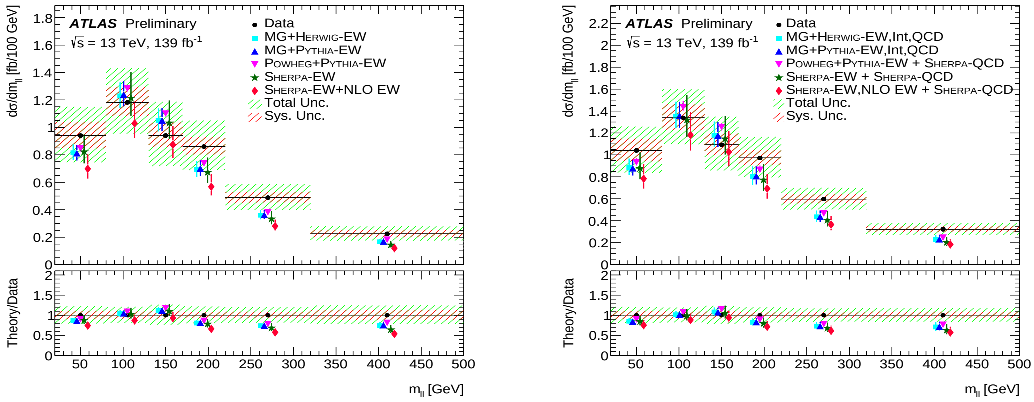

(a) (b)

Figure 3: The measured differential cross-section as a function of the dilepton invariant mass is shown for the electroweak production in (a) and the inclusive production in (b) [3]. The results are compared with Standard Model predictions modeled by various MC generators.

2.2 Search for Anomalous Quartic Gauge Couplings

Even if all the measurements reported agree with SM expectations within uncertainties, the results can still be used to search for hints of physics beyond the SM. New physics can induce anomalous gauge boson couplings thus enhancing the production cross-sections and modifying the kinematic distributions of the gauge bosons involved. The effect of new physics introduced by anomalous couplings can be realized using an effective field theory (EFT), where the SM Lagrangian $\mathcal{L}_{\text{SM}}$ is extended with new interactions encoded in operators of dimensions $d > 4$, which are suppressed by the energy scale Λ of the new process. The effective Lagrangian encoding anomalous quartic gauge couplings (aQGCs) can be written as $\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i^{(8)}}{\Lambda^4} O_i^{(8)}$, where O_i is the dimension-8 operator while $\frac{f_i^{(8)}}{\Lambda^4}$ is the corresponding Wilson coefficient that specify the strength of the anomalous interaction.

Events are simulated for each operator and the limits on the Wilson coefficients are set at 95% confidence level by scanning a profile likelihood ratio. In the EFT framework, the presence of non-zero aQGCs violates tree-level unitarity at sufficiently large energies. More physical limits are obtained by removing EFT contributions above a certain energy scale E_c based on the parton level boson kinematics (before parton showering). In $W^\pm W^\pm jj$ events, this is done by requiring $m_{WW} < E_c$, and a comparison of the upper and the lower limits obtained before and after unitarization is given in Figure 4.

2.3 Search for a Doubly Charged Higgs

The results are additionally interpreted to search for a doubly charged Higgs boson produced in vector boson fusion (VBF) that decay into two same-sign W bosons with a branching fraction of 100% in the context of H5plane benchmark of the Georgi-Machacek (GM) model. Model independent upper limits at 95% CL on $\sigma_{\text{VBF}}(H_5^{\pm\pm}) \times \text{BR}(H_5^{\pm\pm} \to W^\pm W^\pm)$ are extracted for $m_{H_5^{\pm\pm}}$ ranging from 200 GeV to 3000 GeV. The results, shown in Figure 5, show a local excess of data

Coefficient	Type	No unitarisation cut-off [TeV^{-4}]	Lower and upper limit at the respective unitarity bound [TeV^{-4}]
f_{M0}/Λ^4	exp.	[-3.9, 3.8]	-64 at 0.9 TeV, 40 at 1.0 TeV
	obs.	[-4.1, 4.1]	-140 at 0.7 TeV, 117 at 0.8 TeV
f_{M1}/Λ^4	exp.	[-6.3, 6.6]	-25.5 at 1.6 TeV, 31 at 1.5 TeV
	obs.	[-6.8, 7.0]	-45 at 1.4 TeV, 54 at 1.3 TeV
f_{M7}/Λ^4	exp.	[-9.3, 8.8]	-33 at 1.8 TeV, 29.1 at 1.8 TeV
	obs.	[-9.8, 9.5]	-39 at 1.7 TeV, 42 at 1.7 TeV
f_{S02}/Λ^4	exp.	[-5.5, 5.7]	-94 at 0.8 TeV, 122 at 0.7 TeV
	obs.	[-5.9, 5.9]	–
f_{S1}/Λ^4	exp.	[-22.0, 22.5]	–
	obs.	[-23.5, 23.6]	–
f_{T0}/Λ^4	exp.	[-0.34, 0.34]	-3.2 at 1.2 TeV, 4.9 at 1.1 TeV
	obs.	[-0.36, 0.36]	-7.4 at 1.0 TeV, 12.4 at 0.9 TeV
f_{T1}/Λ^4	exp.	[-0.158, 0.174]	-0.32 at 2.6 TeV, 0.44 at 2.4 TeV
	obs.	[-0.174, 0.186]	-0.38 at 2.5 TeV, 0.49 at 2.4 TeV
f_{T2}/Λ^4	exp.	[-0.56, 0.70]	-2.60 at 1.7 TeV, 10.3 at 1.2 TeV
	obs.	[-0.63, 0.74]	–

Figure 4: Expected and observed exclusion limits on the Wilson coefficients on dimension-8 operators at 95% CL are given before and after applying unitarization [3].

at a resonance mass of around 450 GeV. The global significance of the excess is only 2.5 standard deviations indicating no deviations from SM predictions.

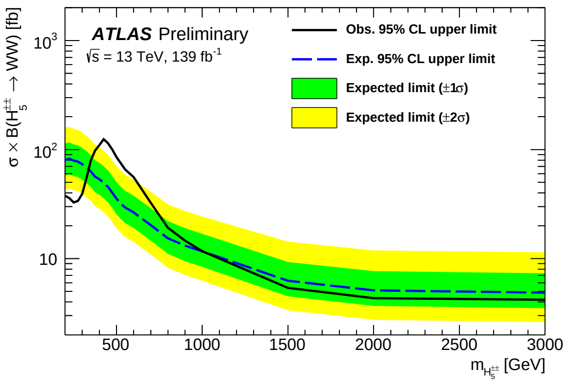

Figure 5: Expected and observed exclusion limits at 95% CL are given for $\sigma \times \mathrm{BR}(H_5^{\pm\pm} \rightarrow W^\pm W^\pm$ as a function of $m_{H_5^{\pm\pm}}$ in the GM model [3].

3. Conclusion

Vector boson scattering offer tree level sensitivities to quartic gauge couplings and serve as a powerful tool to stringently test SM predictions. A golden channel characterizing VBS is the $W^\pm W^\pm jj$ production and this report presents the cross-section measurements from the ATLAS experiment during the second experimental phase of the LHC. The results are found to be consistent with SM predictions within uncertainties and are additionally interpreted to explore sensitivities to new physics.

References

[1] Lyndon Evans and Philip Bryant (editors), JINST 3 (2008), S08001.

[2] ATLAS Collaboration, JINST 3 (2008), S08003.

[3] ATLAS Collaboration, ATLAS-CONF-2023-023, URL: https://cds.cern.ch/record/2859330.