Search for anomalous electroweak gauge boson self-interactions with ATLAS at the LHC

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Abstract
The ATLAS collaboration has set limits on anomalous contributions to electroweak triple gauge boson couplings based on data produced at the LHC with both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. Sensitivity to measurements of anomalous electroweak quartic gauge boson couplings with an upgraded ATLAS detector at $\sqrt{s} = 14$ TeV has been estimated for vector boson scattering and triple boson production in the context of effective field theories and searches for additional resonances.

Keywords: LHC, ATLAS, Standard Model, electroweak, triple gauge coupling, TGC, aTGC, quartic gauge coupling, QGC, aQGC

1. Introduction

In the Standard Model of particle physics the electromagnetic and weak interactions are described by the electroweak theory, which is based on the spontaneously broken SU(2)$_L \otimes$ U(1)$_Y$ gauge group. All aspects of this theory are in good agreement with the current experimental data.

Interactions between fermions are mediated by bosonic fields describing massless (photon $\gamma$) and massive ($W$- and $Z$-bosons) particles, the electroweak gauge bosons. The Standard Model also predicts self-interactions between these bosons. Allowed self-interactions are charged triple and quartic gauge boson vertices: $WWZ$, $WW\gamma$, $WWW$, $WWZZ$, $WZ\gamma$ and $WW\gamma\gamma$.

The study of these vertices aim to test the Standard Model at the TeV scale. Such studies are possible with ATLAS at the LHC in channels involving the production of two or three gauge bosons in the final state. An important special case is vector boson scattering (VBS) accessible in the (inclusive) two jet bin of electroweak diboson production. VBS has never been observed before but plays an important role in understanding the electroweak symmetry breaking. In addition, the search for signals of new physics at the high energy frontier is possible. A direct search for physics beyond the Standard Model would involve the test of hypothetical models like Technicolor, Little Higgs or Extended Gauge Models. Here, the results of a more general ansatz are collected and indirect searches for anomalous triple and quartic gauge couplings are presented.

The reported results are based on data collected by the ATLAS detector [1] during the data-taking periods 2011 and 2012. Two different center-of-mass energies of the colliding protons were used by the LHC during these years, $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. Analyses performed at both energies are presented based on different amounts of collected data: 35 pb$^{-1}$ to 4.6 fb$^{-1}$ integrated luminosity for $\sqrt{s} = 7$ TeV and 5.8 fb$^{-1}$ to 20 fb$^{-1}$ for $\sqrt{s} = 8$ TeV. With a fraction of operational detector channels above 95% and data taking efficiencies higher than 93% the ATLAS detector performed very well during these periods.

2. Standard Model diboson production

As a first step towards measuring anomalous contributions to electroweak gauge boson vertices, the measurement of the Standard Model production of two gauge boson in the final state as performed by ATLAS is presented. Triple gauge boson production has not been studied up to now, mainly due to the small production cross-section.

An overview of the measured production cross-sections corrected for leptonic branching fractions and comparison to theoretical expectations can be seen in Figure 1. No significant deviation from the Standard Model has been observed.

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Figure 1: Standard Model production cross section measurements, corrected for leptonic branching fractions, compared to the corresponding theoretical expectations [2].
3. Anomalous triple gauge couplings

Since triple gauge couplings are completely determined by the Standard Model, any deviation in terms of anomalous triple gauge couplings (aTGC) would indicate the existence of new physics. At the LHC, the sensitivity to aTGC is driven by s-channel diboson production. The corresponding tree level diagram can be seen in Figure 2. In the Standard Model, final states with $Z\gamma$, $\gamma\gamma$ and $ZZ$ final states cannot be produced through the process represented in Figure 2 since just charged triple gauge couplings ($WW$, $WW\gamma$) are allowed.

![Figure 2: A schematic Feynman diagram of TGC in diboson production. The circle indicates possible existence of anomalous contributions. $V$ indicates electroweak gauge bosons $W$, $Z$ or $\gamma$. The final states $Z\gamma$, $\gamma\gamma$ and $ZZ$ are not allowed for this diagram in the Standard Model.](image)

3.1. Unitarity

When adding aTGCs, unitarity can be violated at high $\sqrt{s}$. This fact implies undefined probabilities leading to infinite cross-sections and therefore to unphysical results. In order to obtain physical results, an unitarization procedure is needed.

Nevertheless, two scenarios have been used in ATLAS for publishing results:

1. no unitarization
2. form-factor unitarization.

No unitarization introduces no model dependence and no assumptions, while the introduction of a form factor makes the result less general. The form factor is chosen to be energy dependent in order to restore unitarity. A general form varies each aTGC parameter $\alpha$:

$$\alpha \rightarrow \alpha(\hat{s}) = \frac{\alpha}{(1 + \frac{\hat{s}}{\Lambda_{FF}^2})^n}. \quad (1)$$

Here, $\Lambda_{FF}$ is the energy scale of the form factor and $n$ is a free parameter that is chosen differently for different final states: $n = 2$ for $WW$ and $WZ$ analyses, $n = 3$ for $ZZ$ analysis and $n = 3$ or $4$ for $Z\gamma$ final states. $\hat{s}$ is the center-of-mass energy of the outgoing bosons.

3.2. WW$Z$ and $WW\gamma$ vertices

There are just two triple gauge vertices in the Standard Model: $WWZ$ and $WW\gamma$. Both are fixed by the gauge theory. They are accessible in $WW$, $WZ$ and $WW\gamma$ production.

Model independent aTGC can be introduced within an effective Lagrangian:

$$\mathcal{L}_{WWV} \propto g_1^V(W_{\mu\nu}^B W^\mu V^\nu - W_{\mu\nu}^B W^\mu W^\nu) + \kappa_V W_{\mu\nu}^B W^\mu V_{\rho\sigma} + \frac{\lambda_V}{m_W} W_{\rho\nu}^B W_{\sigma\mu} V^{\rho\sigma}, \quad (2)$$

where $V$ denotes either $Z$ or $\gamma$. All parameters are fixed in the Standard Model: $g_1^Z = \kappa_V = 1, \lambda_V = 0$. When searching for physics beyond the Standard Model, the parameters are allowed to change. Therefore, five free parameters are introduced: $\Delta g_1^Z = g_1^Z - 1$, $\Delta \kappa_V = \kappa_V - 1$ and $\lambda_V$.

Diboson WZ production was used to set limits on the three parameters $\lambda_Z$, $\Delta \kappa_Z$ and $\Delta g_1^Z$. The influence of each of these parameters on the transverse momentum of the $Z$ candidate is shown in Figure 3 for three different choices of parameters. Data are shown together with expected background and signal events, assuming Standard Model. The colored lines indicate the possible aTGC scenarios without unitarization. All parameters change the high energy region while keeping the low energy regime. No evidence for any of the anomalous scenarios is found. Therefore limits on all parameters can be set.

![Figure 3: Transverse momentum of the reconstructed $Z$ candidate in data compared to the sum of all backgrounds and Standard Model WZ production. Possible un-unitarized aTGC contributions are stacked in addition for three different sets of parameters.](image)
Δκγ using Wγ final states. The observed results of these analyses are shown in Figure 10. D0 confidence regions are shown as comparison. For Wγ, also results of CDF, LEP and CMS are added to the plot.

3.3. ZZZ, ZZγ and Zγγ vertices

Neutral vertices are not allowed in the Standard Model. Possible anomalous vertices are tested by ATLAS in ZZ and Zγ production.

In the ZZ final state analysis [6], the following effective Lagrangian was used:

\[ \mathcal{L}_{ZZV} \propto g_3 (\partial_\gamma V_{\mu\nu}) Z_\gamma (\partial_\nu V_{\alpha\beta}) \mathcal{Z}_{\alpha\beta}. \]

All four parameters \( g_3 \) are zero in the Standard Model and limits on nonzero values are set. The results of the measurements can be seen in Figure 5. ATLAS could improve the current 95% C.L. limits of LEP and D0 by approximately one order of magnitude.

The Zγ final state was used to set limits on the ZZγ and Zγγ vertices [5] that is also not allowed in the Standard Model. A different parametrization with four free parameters \( h_1^Y \) and \( h_5^Y \) was used [7]. 95% C.L. limits on these parameters are shown in Figure 11 using a form factor unitarization with \( n = 3 \) \( (h_3^Y) \) and \( n = 4 \) \( (h_5^Y) \).

No deviation from the Standard Model has been observed for the neutral triple gauge vertices.

4. Anomalous quartic gauge couplings

Possible deviations from the Standard Model quartic boson vertices are accessible at the LHC in electroweak gauge boson scattering and triple vector boson production. A schematic view of both processes is shown in Figure 6.

Changing Standard Model quartic gauge boson interactions can lead to violation of unitarity. When testing for anomalous couplings, a unitarization similar to triple gauge boson studies (see 3.1) has to be applied.

4.1. Direct searches

Additional resonances can be introduced in the context of vector boson scattering. Following [8], they can be grouped in terms of spin and isospin. Prospects for the sensitivity of ATLAS at \( \sqrt{s} = 14 \text{ TeV} \) for additional resonances was investigated in [9].

The sensitivity of vector boson scattering ZZjj → ℓℓℓℓjj production when adding a \( f_0 \) resonance with spin \( S = 0 \), isospin \( I = 2 \), mass \( m = 1 \text{ TeV} \), coupling to electroweak bosons \( g = 1.75 \) and width \( \Gamma = 50 \text{ GeV} \) has been estimated using a cut on \( m(t,j) > 1 \text{ TeV} \). The invariant mass of the four lepton system after this cut is shown in Figure 7. With an expected integrated luminosity of 300 fb\(^{-1}\), the discovery sensitivity has been estimated to 1.7σ. With 3 ab\(^{-1}\), 5.5σ can be reached.

4.2. Indirect searches

Instead of searching for additional direct contributions of new physics to the quartic gauge boson vertices in terms of additional resonances, a search for the traces in the low energy region can be performed. The Standard Model Lagrangian is...
replaced by an effective Lagrangian extended by additional operators \[10\]. Depending on the dimension of these operators, they contribute to triple or quartic gauge boson vertices, or both. The lowest order affecting just the quartic vertices is eight. 18 independent parameters can be added according to \[10\].

Sensitivity of ATLAS at 14 TeV for additional operators of dimension eight is estimated in \[11\]. Unitarity has been restored using a cutoff unitarization discarding all events in the unitarity violating region of \(M(V, V)\).

As an example, Figure 8 shows the result for VBS in the \(WZjj \rightarrow t\ell\ell jj\) final state. The QCD induced SM process is shown in yellow, EW induced processes including VBS are shown in blue. The contribution of an additional dimension eight operator with parameter \(f_{11} = 1\) TeV\(^{-4}\) is shown in red. The largest deviation from the SM appears in the high mass region.

<table>
<thead>
<tr>
<th>analysis</th>
<th>parameter (\text{[TeV}^{-4})</th>
<th>int. lumi. (\text{[300 fb}^{-1})</th>
<th>int. lumi. (\text{[3 ab}^{-1})</th>
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<tr>
<td>(WZjj \rightarrow t\ell\ell jj)</td>
<td>(f_{11}/\Lambda^4)</td>
<td>1.3</td>
<td>0.6</td>
</tr>
<tr>
<td>(W^\pm W^\mp jj \rightarrow t^\mp \ell^\pm \ell^\pm jj)</td>
<td>(f_{00}/\Lambda^4)</td>
<td>10</td>
<td>4.5</td>
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<td>(ZZ)</td>
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<td>(Z\gamma)</td>
<td>(f_{99}/\Lambda^4)</td>
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<td>0.7</td>
</tr>
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Table 1: 5\(\sigma\) discovery significance regions for different dimension eight parameter contributing to aQGC in various final states for two scenarios of total integrated luminosity collected by ATLAS.

A summary in terms of 5\(\sigma\) discovery values can be seen in Table 1.

5. Summary

Thanks to the successful running of the LHC and smooth operation of the ATLAS detector, Standard Model diboson production has been measured and limits on anomalous triple gauge couplings have been set in many channels. No significant deviations from the Standard Model have been observed. In addition, studies of anomalous quartic gauge couplings in VBS and triple gauge boson production are presented. MC studies have shown that ATLAS is sensitive to direct and indirect searches for physics beyond the Standard Model at 14 TeV.

References

[10] O.J.P. Eboli, M.C. Gonzalez-Garcia, and J.K. Mizukoshi. pp \(\rightarrow jjet\ell^\nu\ell^\nu\) and jjet\ell^\nu\ell^\nu at \(O(\alpha em^2)\) and \(O(\alpha em)^2\alpha'^2\) for the study of the quartic electroweak gauge boson vertex at LHC. Phys. Rev., D73:S03005, 2006.
Figure 9: Two dimensional 95% confidence regions for all combinations of parameters accessible in WZ production [3]. No unitarization has been applied.

Figure 10: 95% confidence regions in all possible aTGC parameters as obtained by the WW final state analysis (left, [4]) and the Wγ final state analysis (right, [5]).

Figure 11: 95% confidence regions in aTGC parameters for the ZVγ (V = Z, γ) vertices as obtained by the Zγ final state analysis [5]. Unitarized and un-unitarized ATLAS results are compared to unitarized results from LEP.