Studies of the $b$-tagged control region for same sign $W^\pm W^\pm$ production in proton-proton collision data recorded by the ATLAS detector

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Abstract. Vector Boson Scattering has been identified as a promising process in order to study the nature of electroweak symmetry breaking. One of its production mechanisms, same electric charge $W$ boson scattering is a rare Standard Model process. At the LHC, $W$ boson scattering can occur when $W$ bosons are radiated off incoming proton beams and scatter. The proton’s remnants would be detected in the forward calorimeters of the detector as jets, while events are selected where both $W$ bosons decay leptonically. This process therefore has a distinct experimental signature of two same electric charge leptons and two jets, however various Standard Model processes can mimic this signature. These background processes are modelled by making use of Monte Carlo simulations and then tested in several same electric charge dilepton control regions. Non-prompt leptons originating from $t \bar{t} \rightarrow W^+W^-b \rightarrow l^+l^-\nu\bar{\nu}jjb\bar{b}$ are tested in the $b$-tagged control region, which requires that at least one of the two jets is identified as a $b$ jet. In this presentation results from the $b$-tagged control region, using proton-proton collision data at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector in 2015, will be discussed.

1. Introduction
An interesting feature arises with the calculation of the scattering amplitude for $WW$ scattering. In the absence of a Standard Model (SM) Higgs boson, the longitudinally polarised scattering amplitude grows as a function of center-of-mass energy squared and violates unitarity at $\sqrt{s} \approx 1$ TeV [1]. With the addition of a Higgs scalar the scattering amplitude of these processes can be regulated at high energies, restoring unitarity, only if the recently discovered Higgs boson [2] [3] behaves as the predicted SM Higgs boson [4]. Representative Feynman diagrams of the processes are shown in Figures 1 and 2. One type of Vector Boson Scattering, $W$ boson scattering, is therefore a process of great interest, since the process is linked to the mechanism of electroweak symmetry breaking. Two possible processes may be used in order to study $WW$ scattering: same electric charge $WW$ scattering, $W^\pm W^\pm$, and opposite electric charge $WW$ scattering, $W^+W^-$. Even though the predicted electroweak cross section for the opposite sign $W^\mp W^\pm$ process is far greater than the electroweak cross section for the same sign $W^\pm W^\pm$ process, the strong scattering cross section completely dominates the former process. On the other hand, the QCD processes (mediated by a gluon) for the $W^\pm W^\pm$ process are very small. This is due to the fact that LO gluon-gluon initial states are not present in the $W^\pm W^\pm$ process [5], which makes the electroweak and strong cross sections for this process roughly of the same order [6]. The
Figure 1. Feynman diagram of WW scattering, which violates unitarity at $\sqrt{s} \approx 1\text{ TeV}$.

Figure 2. The addition of a Higgs scalar to the Feynman diagram of WW scattering restores unitarity.

excellent signal-to-background ratio together with the unique experimental signature of same sign $W^\pm W^\pm$ scattering, which greatly reduces the Standard Model background processes, makes this process ideal for studying Vector Boson Scattering and probing the nature of electroweak symmetry breaking.

2. Same sign $W^\pm$ production

An incredibly rare process, same electric charge $W$ boson scattering can occur at hadron colliders like the LHC, as an interaction of $W$ bosons that are radiated off incoming proton beams. These $W$ bosons scatter and subsequently decay, however events selected are where the $W$ bosons decay leptonically, i.e $W^\pm \rightarrow l^\pm \nu$, $l = e, \mu$. The process therefore has a very distinctive experimental signature of a lepton pair with the same electric charge and two high energy forward jets. Two analysis regions for the study of $W^\pm W^\pm jj$ production can be defined: an inclusive analysis region and a VBS analysis region [7]. The inclusive analysis region includes a combination of both strong and weak production mechanisms, which is used to measure the fiducial cross section of $W^\pm W^\pm$ production. In the VBS analysis region, events from strong $W^\pm W^\pm jj$ production are considered as background in order to study the purely electroweak $W^\pm W^\pm jj$ production process. The Standard Model cross section predictions for the inclusive analysis region and VBS analysis region are $1.52 \pm 0.11\text{ fb}$ and $0.95 \pm 0.06\text{ fb}$, respectively [7].

This rare Standard Model process has recently been observed by ATLAS and CMS, by making use of $pp$ collision data at $\sqrt{s} = 8\text{ TeV}$ collected by both detectors. Cross sections for both the inclusive analysis and VBS analysis regions were measured by ATLAS. The cross section for strong and electroweak $W^\pm W^\pm jj$ production in the inclusive analysis region was measured to be $\sigma^{fid} = 2.1 \pm 0.5\text{ fb}$, while the cross section for electroweak $W^\pm W^\pm jj$ production, which includes interference of strong production, was measured to be $\sigma = 1.3 \pm 0.4\text{ fb}$ for the VBS analysis region [7]. Furthermore, the observed combined significance over the background-only hypothesis was 4.5 and 3.6 standard deviations in the inclusive region and the VBS region, respectively. CMS measured the cross section for electroweak $W^\pm W^\pm jj$ production to be $\sigma = 4.0^{+2.4}_{-2.0}\text{ fb}$ at an observed significance level of 2 standard deviations [8]. Results from both ATLAS and CMS can be seen in Figures 3 and 4, respectively, showing an excess of data events over the predicted background processes.

3. The $b$-tagged control region

Many SM processes can mimic the signal region for $W^\pm W^\pm jj$ production and must be excluded or reduced as background processes by defining specific event selections. In order to effectively reduce contributions from background processes, Monte Carlo (MC) simulations are used to estimate these background processes. The MC predictions must then be tested in several same charge di-lepton control regions. Control regions are regions used to test MC predictions of
background processes by specifically selecting a region where a certain background process of interest is dominant. Non-prompt leptons originating from $t\bar{t} \rightarrow l\nu jj b\bar{b}$ are tested in the $b$-tagged control region, which requires that at least one of the two jets is identified as a $b$-jet [7]. By requiring a $b$-tagged jet in the event selection for this control region, events from non-prompt backgrounds originating from $t\bar{t}$ processes are specifically selected. This control region is also used to test the description of event kinematics for the charge misidentification background as well as the fake background, where jets are mis-reconstructed as charged leptons. Figure 5 shows the $p_T$ distribution for the leading and sub-leading leptons in the $b$-tagged control region, from proton-proton collision data at $\sqrt{s} = 8$ TeV recorded by the ATLAS detector in 2012. In these plots it can be seen that this region is clearly dominated by fakes from $t\bar{t}$ and other non-prompt leptons that originated from hadronic decays. However $t\bar{t} + W/Z$ processes as well as the charge misidentification background also play important roles in this control region. It is important to understand the backgrounds in this control region in order to ensure that the lepton $p_T$ defined in the event selection excludes contributions from non-prompt leptons originating from hadronic decays.

4. Conclusion and outlook
Vector Boson Scattering have been identified as a promising process in order to study and understand the mechanism of electroweak symmetry breaking. One of the production mechanisms of VBS is a rare Standard Model process known as same sign $W$ boson scattering. First evidence of this process have recently been observed by both ATLAS and CMS, where both analyses made use of $pp$ collision data at $\sqrt{s} = 8$ TeV. Further studies implementing $pp$ collision data collected by the ATLAS and CMS detectors during 2015 and 2016, at a higher center-of-mass energy than the previous analyses, will aim to provide conclusive evidence for the existence of electroweak $W^+W^±jj$ production, as well as increase our current understanding of VBS processes.
Figure 5. Transverse momentum distributions for leading (left) and sub-leading (right) leptons in the $b$-tagged control region. The black, hatched bars in the upper plots shows the systematic uncertainty on the total prediction, while the yellow band in the lower plots shows the uncertainty as a fraction of the total prediction [9].

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