

Evidence for the production of three massive vector bosons in pp collisions with the ATLAS detector

Andrea Sciandra^{*†}

*Physics Department and Santa Cruz Institute for Particle Physics, University of California,
Santa Cruz 95064 U.S.A.*

E-mail: andrea.sciandra@cern.ch

A search for the production of three massive vector bosons in proton–proton collisions is performed using data at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector at the Large Hadron Collider in the years 2015–2017, corresponding to an integrated luminosity of 79.8 fb^{-1} . Events with two same-sign leptons ℓ (electrons or muons) and at least two reconstructed jets are selected to search for $W^{\pm}W^{\pm}W^{\mp} \rightarrow \ell\nu\ell\nu q\bar{q}$. Events with three leptons without any same-flavour opposite-sign lepton pairs are used to search for $W^{\pm}W^{\pm}W^{\mp} \rightarrow \ell\nu\ell\nu\ell\nu$, while events with three leptons and at least one same-flavour opposite-sign lepton pair and one or more reconstructed jets are used to search for $W^{\pm}W^{\mp}Z \rightarrow \ell\nu q\bar{q}\ell\ell$. Finally, events with four leptons are analysed to search for $W^{\pm}W^{\mp}Z \rightarrow \ell\nu\ell\nu\ell\ell$ and $W^{\pm}ZZ \rightarrow q\bar{q}\ell\ell\ell\ell$. Evidence for the joint production of three massive vector bosons is observed with a significance of 4.0 standard deviations, where the Standard Model expectation is 3.1 standard deviations.

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^{*}Speaker.

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1. Introduction

The production of three massive vector bosons (VVV , where $V = W, Z$) in pp collisions at the LHC is sensitive to Standard Model triple (TGC) and quartic (QGC) gauge couplings. It also constitutes a preferential portal connecting the pure electroweak gauge theory to the Higgs-boson sector, as the Higgs-mediated production $VH(\rightarrow VV)$ is one of the mechanisms involved in the production of VVV . Deviations from the Standard Model predictions may point to physics beyond the Standard Model, effects described by anomalous TGC and QGC [1]. Triboson production is currently among the processes which are the least precisely measured (apart from very few high purity neutral triboson processes such as $Z\gamma\gamma$) with several channels still unexplored.

2. Search for the production of three massive vector bosons with the ATLAS detector

ATLAS has presented evidence for the joint production of three massive vector bosons in pp collisions using the dataset collected with the ATLAS detector [2] between 2015 and 2017 at $\sqrt{s} = 13$ TeV, corresponding to a total integrated luminosity of 79.8 fb^{-1} . Feynman diagrams representing the production of VVV at leading order in the quantum chromodynamics (QCD) coupling α_s are shown in Figure 1.

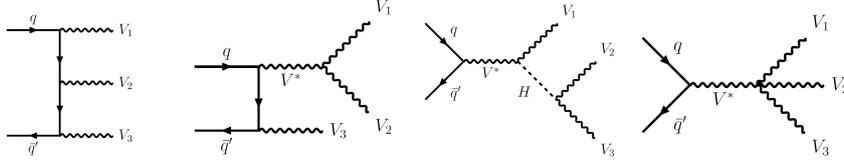


Figure 1: Representative Feynman diagrams at LO for the production of VVV .

Two dedicated searches are performed, one for the $W^\pm W^\pm W^\mp$ process and one for the $W^\pm W^\mp Z$ and $W^\pm ZZ$ processes, hereafter labelled as WVZ . Events with two same-sign leptons ℓ (electrons or muons) and at least two reconstructed jets are selected to search for $W^\pm W^\pm W^\mp \rightarrow \ell\nu\ell\nu qq$. Events with three leptons without any same-flavour opposite-sign lepton pairs are used to search for $W^\pm W^\pm W^\mp \rightarrow \ell\nu\ell\nu\ell\nu$, while events with three leptons and at least one same-flavour opposite-sign lepton pair and one or more reconstructed jets are used to search for $W^\pm W^\mp Z \rightarrow \ell\nu qq\ell\ell$. Finally, events with four leptons are analysed to search for $W^\pm W^\mp Z \rightarrow \ell\nu\ell\nu\ell\ell$ and $W^\pm ZZ \rightarrow qq\ell\ell\ell\ell$.

The on-shell VVV samples are generated with SHERPA and with 0 additional partons at NLO in QCD and 1 or 2 additional partons at LO in QCD. Events with off-mass-shell bosons through $WH \rightarrow WV V^*$ and $ZH \rightarrow ZV V^*$ were generated using POWHEG-BOX interfaced to PYTHIA for the $W^\pm W^\pm W^\mp$ analysis, while for the WVZ analysis PYTHIA+EVTGEN was used. Both on-shell and off-shell VVV event samples are generated at NLO in QCD and are included in the definition of signal events. The expected cross sections for $W^\pm W^\pm W^\mp$ and $W^\pm W^\mp Z$ production are 0.50 pb and 0.29 pb, respectively, with a theoretical uncertainty of $\sim 10\%$. Background contributions from diboson (WW, WZ, ZZ) and single boson (W/Z +jets) production, as well as electroweak production of $VV + 2$ jets, are modelled using SHERPA. In order to improve the agreement between the simulated and observed jet multiplicity distributions for the $WZ \rightarrow \ell\nu\ell\ell$ and $ZZ \rightarrow \ell\ell\ell\ell$ events, a

jet-multiplicity based reweighting was applied to the simulated WZ and ZZ samples. Top-quark pair events ($t\bar{t}$) were generated using POWHEG-BOX interfaced to PYTHIA. Other background processes containing top quarks ($t\bar{t}Z$, tZ , tW , $t\bar{t}W$, tWZ , $t\bar{t}H$, $t\bar{t}\gamma$, $t\bar{t}\bar{t}$, $t\bar{t}WW$, and tWH) were generated with MADGRAPH5_AMC@NLO interfaced to PYTHIA for showering and hadronisation.

Electrons are reconstructed as energy clusters in the EM calorimeter that are matched to tracks found in the Inner Detector (ID). Muons are reconstructed by combining tracks reconstructed in the ID with tracks or track segments found in the Muon Spectrometer. *Loose leptons* need to satisfy $p_T > 15\text{ GeV}$ and have $|\eta| < 2.47$ for electrons (electrons between the barrel and endcap calorimeters, $1.37 < |\eta| < 1.52$, are excluded) and $|\eta| < 2.5$ for muons. Leptons are required to be consistent with originating from the primary vertex, to pass certain identification quality requirements and to be isolated from other particles in both the calorimeters and the ID. Quality and isolation requirements are more restrictive in the $W^\pm W^\pm W^\mp$ analysis because a larger contamination from jets misidentified as leptons or leptons from hadron decays, *non-prompt leptons* in the following, is expected. In order to reject leptons likely to be originating from heavy-flavour decays, *tight leptons* also have to pass a requirement on a dedicated boosted decision tree (BDT), called “non-prompt lepton BDT” [3]. In addition, *tight electrons* have to pass the “charge misidentification suppression BDT” [4] to reject electrons likely to have the electric charge wrongly measured (“charge flip”). Jets are reconstructed from calibrated topological clusters built from energy deposits in the calorimeter using the anti- k_r algorithm with a radius parameter of 0.4. Jet candidates are required to have $p_T > 20\text{ GeV}$ and $|\eta| < 2.5$. Jets containing b -hadrons (b -jets) are identified by a multivariate discriminant [6], with an expected efficiency of 85% (70%) for the $W^\pm W^\pm W^\mp$ (WVZ) analysis requirement. A detailed description of lepton definitions and the overlap removal algorithm, employed to resolve ambiguous identifications, can be found in Ref. [5].

3. The $W^\pm W^\pm W^\mp$ search

The two $W^\pm W^\pm W^\mp$ channels, $W^\pm W^\pm W^\mp \rightarrow \ell^\pm \nu \ell^\pm \nu q q$ and $W^\pm W^\pm W^\mp \rightarrow \ell^\pm \nu \ell^\pm \nu \ell^\mp \nu$, are hereafter referred to as $\ell\nu\ell\nu q q$ and $\ell\nu\ell\nu\ell\nu$. In $W^\pm W^\pm W^\mp$ channels electrons and muons are required to have $p_T > 20\text{ GeV}$. The experimental signature of the $\ell\nu\ell\nu q q$ channel is the presence of two same-sign leptons, missing transverse momentum (E_T^{miss}) and two jets with an invariant mass close to the W -boson mass. Selected $\ell\nu\ell\nu q q$ candidate events are required to have exactly two tight leptons with the same electric charge and at least two jets. This channel is split into four signal regions, based on the lepton flavour: ee , $e\mu$, μe , and $\mu\mu$. $e\mu$ (μe) indicates events where the leading lepton is an electron (a muon). The invariant mass of the dilepton system is required to fulfill $40 < m_{\ell\ell} < 400\text{ GeV}$ and, in the ee channel, also $|m_{ee} - 90\text{ GeV}| > 10\text{ GeV}$. The dijet system is required to have $m_{jj} < 300\text{ GeV}$ and $|\Delta\eta_{jj}| < 1.5$ in order to suppress the contamination from $VV + 2$ jets through vector-boson scattering. A E_T^{miss} lower threshold is set to 55 GeV only in the ee final state, since a smaller contamination from the $Z + \text{jets}$ background is expected in the other three regions. The signature of the $\ell\nu\ell\nu\ell\nu$ channel is the presence of three leptons and significant E_T^{miss} , so three tight leptons and $E_T^{\text{miss}} > 55\text{ GeV}$ are required. To reduce the contribution from WZ , events are required to have zero same-flavour $\ell^+\ell^-$ lepton pairs. This requirement results in two possible final states: $\mu^\pm e^\mp e^\mp$ and $e^\pm \mu^\mp \mu^\mp$. The WVZ and $W^\pm W^\pm W^\mp$ signal regions are not overlapping. A WZ -dominated control region is defined by selecting events with exactly three tight leptons and at

least one same-flavour $\ell^+\ell^-$ (SFOS) lepton pair. Events in this region are also required to have zero b -jets, $E_{\text{T}}^{\text{miss}} > 55 \text{ GeV}$ and $m_{3\ell} > 110 \text{ GeV}$. The WZ control region is divided into four channels (eee , $ee\mu$, $e\mu\mu$, $\mu\mu\mu$) and binned in the $m_{3\ell}$ distribution. This control region is used for the standalone $W^\pm W^\pm W^\mp$ measurement, but is fully overlapping with the WVZ three-lepton channel and is, therefore, not included in the VVV combination discussed below. Jets identified as coming from the hadronisation of a b -quark are vetoed in both channels using a more efficient requirement, as compared to WVZ , since this allows a better rejection of $t\bar{t}$ events, important process in both, the $\ell\nu\ell\nu qq$ and $\ell\nu\ell\nu\ell\nu$ channels, where no $Z \rightarrow \ell^+\ell^-$ is present.

The $W^\pm W^\pm W^\mp$ analysis is affected by both charge-flip and non-prompt leptons. The estimation of the charge-flip background relies on the measurement of the charge-flip rate as a function of the electron p_{T} and η in a two-lepton same-sign region enriched with $Z \rightarrow e^+e^-$ events. In the $\ell\nu\ell\nu qq$ channel, the charge-flip background is estimated by applying the electron charge-flip rate to data events, selected using all signal criteria, except requiring the two leptons to be opposite-sign. In the $\ell\nu\ell\nu\ell\nu$ channel, this background is estimated by using these rates to reweight the simulation prediction of the WZ and ZZ processes, based on the probability for opposite-sign events of this kind to migrate into the signal region, i.e. with zero same-flavour $\ell^+\ell^-$ lepton pairs. Events containing one (two) tight lepton and one non-tight lepton are scaled by a *fake factor* to predict the non-prompt lepton contribution in the $\ell\nu\ell\nu qq$ ($\ell\nu\ell\nu\ell\nu$) channel. Fake factors are derived in a $t\bar{t}$ -enriched three-lepton region. Uncertainties in data-driven background estimations mainly come from statistical and systematic uncertainties on the charge-flip rate and the fake factor. The background description is accurate, as shown in Figure 2a and 2b for the leading lepton p_{T} in the WZ $\mu\mu\mu$ control region and the leading jet p_{T} in the $\ell\nu\ell\nu qq$ $e\mu$ sideband ($|m_{jj} - 85 \text{ GeV}| > 20 \text{ GeV}$) region, respectively.

4. The WVZ search

The experimental signature of the $WVZ \rightarrow \ell\nu q\ell\ell$, $W^\pm W^\mp Z \rightarrow \ell\nu\ell\nu\ell\ell$, and $W^\pm ZZ \rightarrow q\ell\ell\ell\ell$ processes is the presence of three or four charged leptons. Six regions are defined with either three or four loose leptons (in order to increase the signal acceptance), sensitive to triboson final states containing Z bosons. Among all possible SFOS lepton pairs, the one with $m_{\ell\ell}$ closest to m_Z is defined as the Z candidate. In all regions, the presence of such a Z candidate with $|m_{\ell\ell} - m_Z| < 10 \text{ GeV}$, is required. Furthermore, any SFOS lepton pair combination is required to have a minimum invariant mass of $m_{\ell\ell} > 12 \text{ GeV}$. Events with b -tagged jets are vetoed. For the three-lepton channel, the lepton which is not part of the Z candidate is required to be tight and the scalar sum of the transverse momenta of all leptons and jets (H_{T}) is required to be larger than 200 GeV . This significantly reduces the contribution of the $Z \rightarrow \ell\ell$ processes with one additional non-prompt lepton. Three regions are defined according to the number of jets in the event: one jet ($3\ell-1j$), two jets ($3\ell-2j$), and at least three jets ($3\ell-3j$). For the four-lepton channel, the third- and fourth-leading leptons are required to be tight. The two leptons which are not part of the Z candidate definition are required to have opposite charges. They are used to define three regions, depending on whether they are different-flavour (4ℓ -DF), or same-flavour, and whether their mass lies within 10 GeV of the Z boson mass (4ℓ -SF-Z) or not (4ℓ -SF-noZ). In each of the six regions the distribution of a dedicated BDT, separating the WVZ signal from the dominating diboson back-

ground, is fed as input to the binned maximum-likelihood fit to extract the signal. The variables are chosen from a list of discriminating variables, like: the trilepton and four-lepton invariant mass; the invariant mass of different lepton or jet pairs; the number of reconstructed jets; the scalar sum of all leptons' or jets' p_T ; E_T^{miss} ; H_T ; the invariant mass of all leptons, jets and E_T^{miss} .

Backgrounds are dominated by processes with prompt leptons and thus the estimation of all backgrounds relies on simulation. The WZ +jets and Z +jets backgrounds are validated in a region defined in the same way as the 3ℓ -1j region, with the exception that no requirement on H_T is applied, the third-highest- p_T lepton is required to have a small transverse momentum ($10\text{GeV} < p_T < 15\text{GeV}$), and the invariant mass of the three leptons has to be smaller than 150 GeV. Data and expectation agree in the 3ℓ -1j validation region, as shown in Figure 2c for the transverse momentum distribution of the third-highest- p_T lepton. The $t\bar{t}Z$ background is determined in a region defined like the 3ℓ -3j region with the exception that no requirement on H_T is applied, and at least four jets are required, of which at least two are b -tagged. Data and expectation agree, as shown in Figure 2d for the number of reconstructed jets in the $t\bar{t}Z$ control region.

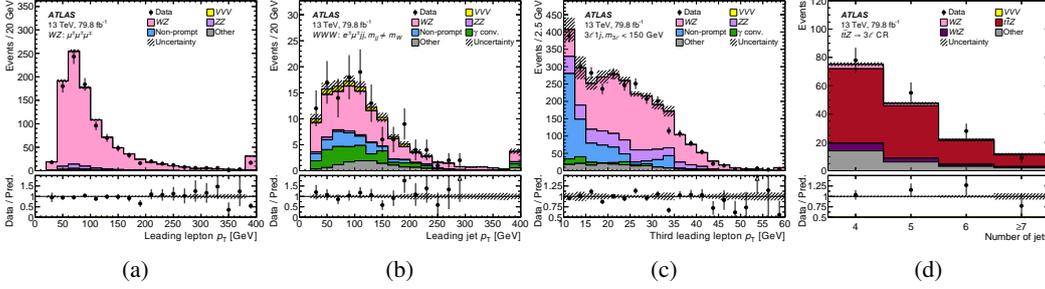


Figure 2: Comparison between data and prediction of (a) the leading lepton p_T distribution in the $WZ \mu\mu\mu$ control region, (b) the leading jet p_T distribution in the $W^\pm W^\pm W^\mp$ sideband region, (c) the transverse momentum of the third-highest- p_T lepton in the 3ℓ -1j region, with the additional requirement $m_{\ell\ell\ell} < 150\text{GeV}$, no requirement on H_T , and including the $10\text{GeV} < p_T < 15\text{GeV}$ validation region and (d) the number of jets in the $t\bar{t}Z$ control region.

5. The VVV combination: evidence for the production of three massive vector bosons

The $W^\pm W^\pm W^\mp$, $W^\pm W^\mp Z$ and $W^\pm ZZ$ regions are combined using the profile likelihood method based on a simultaneous fit to distributions in the signal and background control regions. A total of eleven signal regions and one control (the $t\bar{t}Z$ described in Section 4) region are considered. The distributions used in the fit are the m_{jj} distributions for the $\ell\nu\ell\nu qq$ channel and the BDT distributions for the WVZ three-lepton and four-lepton channels. The numbers of selected events in the $\ell\nu\ell\nu\ell\nu$ channel and the $t\bar{t}Z$ control region are included as a single bin in the fit. A grand total of 186 bins is used in the combined fit. Nuisance parameters related to experimental uncertainties and theory uncertainties are treated as correlated among all channels. Uncertainties in data-driven background evaluations affect the $W^\pm W^\pm W^\mp$ channels only and are treated as correlated for backgrounds evaluated using the same method and from the same systematic sources.

Figure 3a shows the observed best-fit value of the signal strength. Results are shown for the $W^\pm W^\pm W^\mp$ and WVZ channels separately, fixing the other signal to its SM expectation, and combined. For the fits of the $W^\pm W^\pm W^\mp$ channels, the WZ control region defined in Section 3 is also used in the fit. The WZ control region is not included in the VVV combined fit, as, when combined with the WVZ channels, the three WVZ three-lepton signal regions provide a similar constraint on the WZ +jets background normalisation.

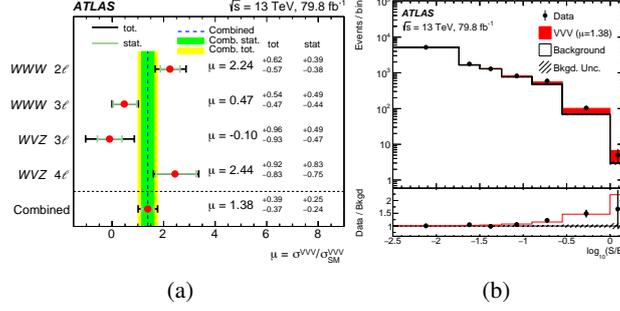


Figure 3: (a) Extracted signal strengths μ for the four analysis regions and for the combination. (b) Event yields in all eleven regions as a function of $\log_{10}(S/B)$ for data, background B and the signal S .

The observed best-fit signal strength, scaling both, the WVZ and $W^\pm W^\pm W^\mp$ processes, yields $\mu_{VVV} = 1.38^{+0.39}_{-0.37} = 1.38^{+0.25}_{-0.24}$ (stat.) $^{+0.30}_{-0.27}$ (syst.). The largest systematic uncertainties come from data-driven background uncertainties, affecting the $W^\pm W^\pm W^\mp$ channels, and theoretical uncertainties related to scale variations. The no- VVV hypothesis is excluded at the 4.0σ level, with an expectation of 3.1σ in the case of SM signal processes. This constitutes *evidence* for the production of three massive vector bosons. Figure 3b shows the data, background and signal yields, where the final-discriminant bins in all signal regions are combined into bins of $\log_{10}(S/B)$, S being the expected signal yield and B the background yield. The measured signal strengths, and their uncertainties, from the fits reported in Figure 3a are converted to inclusive cross-section measurements. The results, fixing $W^\pm ZZ$ to the SM expectation, are: $\sigma_{WWW} = 0.68^{+0.16}_{-0.15}$ (stat.) $^{+0.16}_{-0.15}$ (syst.) pb and $\sigma_{WVZ} = 0.49 \pm 0.14$ (stat.) $^{+0.14}_{-0.13}$ (syst.) pb.

References

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