

# **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](mailto:andrea.sciandra@cern.ch)

A search for the production of three massive vector bosons in proton–proton collisions is per-Formed using data at  $\sqrt{s} = 13$  TeV recorded with the ATLAS detector at the Large Hadron Col-<br>formed 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<sup>-1</sup>. Events with two same-sign leptons  $\ell$  (electrons or muons) and at least two reconstructed jets are selected to search for  $W^{\pm}W^{\pm}W^{\mp} \to \ell\nu\ell\nu qq$ . Events with three leptons without any same-flavour oppositesign lepton pairs are used to search for  $W^{\pm}W^{\pm}W^{\mp} \to \ell\nu\ell\nu\ell\nu$ , 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  $W^{\pm}W^{\mp}Z \rightarrow \ell \nu q q \ell \ell$ . Finally, events with four leptons are analysed to search for  $W^{\pm}W^{\mp}Z \rightarrow \ell\nu\ell\nu\ell\ell$  and  $W^{\pm}ZZ \rightarrow qq\ell\ell\ell\ell$ . 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.

*XXVII International Workshop on Deep-Inelastic Scattering and Related Subjects - DIS2019 8-12 April, 2019 Torino, Italy*

\*Speaker.

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0). https://pos.sissa.it/

<sup>†</sup>On behalf of the ATLAS Collaboration.

# 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 *Zγγ*) with several channels still unexplored.

#### 2. Search for the production of three massive vector bosons with the ATLAS detector 22 Model (SM) theory and any organisation would prediction would provide the SM prediction provided the SM provide himself at  $\alpha$  $230 \text{ m/s}$

ATLAS has presented evidence for the joint production of three massive vector bosons in *pp* 26 This paper 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<sup>-1</sup>. Feynman diagrams representing the production of VVV at leading order in the quantum chromodynamics (QCD) coupling  $\alpha_s$  are shown in Figure 1. ne le Asie<br>Asie<br>Vro using the dataset collected with the ATLAS detector [2] between 2015 and 2018 furm of *VVV* at leading order in the quantum chromodynamics (QCD) coup  $31$  two vector bosons, or from a quartic gauge coupling vertex. Representative  $\frac{1}{2}$ 



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

 $W \times U = \frac{1}{2}$  (denoted as  $\frac{1}{2}$  and  $\frac{1}{2}$   $\frac{1}{2}$  processes. To search for the *WWW.* 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  $\ell$  (electrons  $\frac{3}{2}$  and  $\frac{3}{2}$  channels, respectively. To search for the  $\frac{3}{2}$  processes, events as  $\frac{3}{2}$  processes, events as  $\frac{3}{2}$  processes. or muons) and at least two reconstructed jets are selected to search for  $W^{\pm}W^{\pm}W^{\mp} \to \ell\nu\ell\nu qq$ . Events with three leptons without any same-flavour opposite-sign lepton pairs are used to search for  $\frac{1}{2}$  discriminant that maximizes the sensitivity of  $\frac{1}{2}$  signal is defined in each channel. *W*<sup>±</sup>*W*<sup>±</sup>*W*<sup>∓</sup> →  $\ell$ *v* $\ell$ *v* $\ell$ *v*, while events with three leptons and at least one same-flavour opposite-sign  $\mu$  and one or more reconstructed is to one used to example for  $W^{\pm}W^{\mp}Z \rightarrow \ell\nu\sigma$ lepton pair and one or more reconstructed jets are used to search for  $W^{\pm}W^{\mp}Z \to \ell\nu q q \ell\ell$ . Finally, events with four leptons are analysed to search for  $W^{\pm}W^{\mp}Z \to \ell\nu\ell\nu\ell\ell$  and  $W^{\pm}ZZ \to qq\ell\ell\ell\ell$ .

The on-shell *VVV* samples are generated with SHERPA and with 0 additional partons at NLO  $\frac{14}{9}$  two searches. Event selection criteria, signal and background modelling are described for the  $\frac{1}{9}$ in QCD and 1 or 2 additional partons at LO in QCD. Events with off-mass-shell bosons through *WH* → *WVV*<sup>∗</sup> and *ZH* → *ZVV*<sup>∗</sup> were generated using POWHEG-BOX interfaced to PYTHIA for diboson (*WW*,*WZ*,*ZZ*) and single boson ( $W/Z + \text{jets}$ ) production, as well as electroweak producthe  $W^{\pm}W^{\pm}W^{\mp}$  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 ∼ 10%. Background contributions from tion of  $VV + 2$  jets, are modelled using SHERPA. In order to improve the agreement between the simulated and observed jet multiplicity distributions for the  $WZ \to \ell \ell \ell \ell$  and  $ZZ \to \ell \ell \ell \ell$  events, a <span id="page-2-0"></span>jet-multiplicity based reweighting was applied to the simulated *W Z* and *ZZ* samples. Top-quark pair events  $(t\bar{t})$  were generated using POWHEG-BOX interfaced to PYTHIA. Other background processes containing top quarks ( $t\bar{t}Z$ ,  $tZ$ ,  $tW$ ,  $\bar{t}W$ ,  $tWZ$ ,  $\bar{t}H$ ,  $\bar{t}\bar{t}\gamma$ ,  $\bar{t}t\bar{t}$ ,  $\bar{t}WW$ , 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  $p_T > 15$  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  $W^{\pm}W^{\mp}W^{\mp}$  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<sup>t</sup>* algorithm with a radius parameter of 0.4. Jet candidates are required to have  $p_T > 20$  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  $W^{\pm}W^{\mp}W^{\mp}$ (*WV Z*) 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,  $W^{\pm}W^{\pm}W^{\mp} \to \ell^{\pm}\nu\ell^{\pm}\nu qq$  and  $W^{\pm}W^{\pm}W^{\mp} \to \ell^{\pm}\nu\ell^{\pm}\nu\ell^{\mp}\nu$ , are hereafter referred to as  $\ell v \ell v q q$  and  $\ell v \ell v \ell v$ . In  $W^{\pm} W^{\pm} W^{\mp}$  channels electrons and muons are required to have  $p_T > 20$  GeV. The experimental signature of the  $\ell v \ell v q q$  channel is the presence of two same-sign leptons, missing transverse momentum  $(E_{\text{T}}^{\text{miss}})$  and two jets with an invariant mass close to the *W*-boson mass. Selected  $\ell v \ell v q q$  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*,  $e\mu$ ,  $\mu e$ , and  $\mu\mu$ .  $e\mu$  ( $\mu e$ ) indicates events where the leading lepton is an electron (a muon). The invariant mass of the dilepton system is required to fulfill  $40 < m_{\ell\ell} < 400$  GeV and, in the *ee* channel, also  $|m_{ee} - 90$  GeV | > 10 GeV. The dijet system is required to have  $m_{ij}$  < 300 GeV and  $|\Delta \eta_{ij}|$  < 1.5 in order to suppress the contamination from  $VV + 2$  jets through vector-boson scattering. A  $E_{\text{T}}^{\text{miss}}$  lower threshold is set to 55 GeV only in the *ee* final state, since a smaller contamination from the  $Z +$  jets background is expected in the other three regions. The signature of the  $\ell v \ell v \ell v$  channel is the presence of three leptons and significant  $E_T^{\text{miss}}$ , so three tight leptons and  $E_{\text{T}}^{\text{miss}} > 55 \,\text{GeV}$  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 *W Z*-dominated control region is defined by selecting events with exactly three tight leptons and at

<span id="page-3-0"></span>least one same-flavour  $\ell^+\ell^-$  (SFOS) lepton pair. Events in this region are also required to have zero *b*-jets,  $E_{\rm T}^{\rm miss} > 55$  GeV and  $m_{3\ell} > 110$  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  $\ell v \ell v q q$  and  $\ell v \ell v \ell v$  channels, where no  $Z \to \ell^+ \ell^-$  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  $\eta$  in a two-lepton same-sign region enriched with  $Z \to e^+e^-$  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  $\ell v \ell v \ell v$  channel, this background is estimated by using these rates to reweight the simulation prediciton of the *W Z* 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  $\ell v \ell v q q$  ( $\ell v \ell v \ell v$ ) channel. Fake factors are derived in a *tt*¯-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 back-ground description is accurate, as shown in Figure [2a](#page-4-0) and [2b](#page-4-0) for the leading lepton  $p<sub>T</sub>$  in the *WZ*  $\mu\mu\mu$  control region and the leading jet  $p_T$  in the  $\ell\nu\ell\nu q q e\mu$  sideband ( $|m_{jj} - 85 \text{ GeV}| > 20 \text{ GeV}$ ) region, respectively.

#### 4. The *WV Z* search

The experimental signature of the  $WVZ \rightarrow \ell \nu qq\ell\ell$ ,  $W^{\pm}W^{\mp}Z \rightarrow \ell \nu \ell \nu \ell\ell$ , and  $W^{\pm}ZZ \rightarrow qq\ell\ell\ell\ell$ 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  $|m_{\ell\ell} - m_Z|$  < 10GeV, 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 thirdand 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  $(4\ell$ -DF), or same-flavour, and whether their mass lies within 10 GeV of the *Z* boson mass (4 $\ell$ -SF-*Z*) or not (4 $\ell$ -SF-noZ). In each of the six regions the distribution of a dedicated BDT, separating the *WV Z* signal from the dominating diboson back<span id="page-4-0"></span>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'  $p_T$ ;  $E_T^{\text{miss}}$ ;  $H_T$ ; the invariant mass of all leptons, jets and  $E_T^{\text{miss}}$ .

Backgrounds are dominated by processes with prompt leptons and thus the estimation of all backgrounds relies on simulation. The  $WZ + \text{jets}$  and  $Z + \text{jets}$  backgrounds are validated in a region defined in the same way as the  $3\ell$ -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 (10GeV  $\lt p_T \lt 15$ GeV), and the invariant mass of the three leptons has to be smaller than 150 GeV. Data and expectation agree in the  $3\ell$ -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  $3\ell$ -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  $p<sub>T</sub>$  distribution in the *WZ*  $\mu\mu\mu$  control region, (b) the leading jet  $p_T$  distribution in the  $W^{\pm}W^{\mp}W^{\mp}$  sideband region, (c) the transverse momentum of the third-highest- $p_T$  lepton in the 3 $\ell$ -1j region, with the additional requirement  $m_{\ell\ell\ell} < 150$  GeV, no requirement on  $H_T$ , and including the 10GeV  $< p_T < 15$  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\)](#page-3-0) region are considered. The distributions used in the fit are the  $m_{ij}$  distributions for the  $\ell v \ell v q q$  channel and the BDT distributions for the *WV Z* three-lepton and four-lepton channels. The numbers of selected events in the  $\ell v \ell v \ell v$  channel and the *t*<sub>*t*</sub> $\ell$ <sup>*z*</sup> 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](#page-2-0) is also used in the fit. The *W Z* 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  $\mu$  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  $4.0\sigma$  level, with an expectation of  $3.1\sigma$  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 log10(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  $\sigma_{WWZ} = 0.49 \pm 0.14 \text{(stat.)} ^{+0.14}_{-0.13} \text{(syst.) pb.}$ 

### References

- [1] M. Baak et al., *Working Group Report: Precision Study of Electroweak Interactions*, Proceedings, 2013 Community Summer Study on the Future of U.S. Particle Physics, arXiv:1310.6708
- [2] ATLAS Collaboration, JINST 3 136 (2008) S08003
- [3] ATLAS Collaboration, Phys. Rev. D 97 (2018) 072003
- [4] ATLAS Collaboration, arXiv:1902.04655
- [5] ATLAS Collaboration, arXiv:1903.10415
- [6] ATLAS Collaboration, ATL-PHYS-PUB-2016-012, 2016, url: https://cds.cern.ch/record/2160731