NEW HEAVY GAUGE BOSONS DECAYING TO PAIR OF ELECTROWEAK BOSONS: PROSPECT STUDIES AT RUN 3 AND HL-LHC WITH ATLAS

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The expected ATLAS Run 3 data set with time-integrated luminosity of $300 \ fb^{-1}$ and HL-LHC option of the LHC with $L = 3000 \ fb^{-1}$ in the diboson channels in semileptonic final states are used to probe a simple benchmark model with an extended gauge sector, proposed by Altarelli et al. This model accommodates new charged W' and neutral Z' vector bosons with modified trilinear Standard Model gauge couplings, decaying into electroweak gauge boson pairs WZ or WW, where W/Z decay semileptonically. We present upper limits on the mixing parameters, $W - W'$ and $Z - Z'$, by using the expected Run 3 data and HL-LHC options of the LHC.

Keywords: new gauge Z' and W' bosons, ATLAS experiment, Large Hadron Collider (LHC).

1. Introduction

The High Luminosity LHC (HL-LHC) upgrade will eventually collect an integrated luminosity of 3 ab^{-1} of data in pp collisions at a centre-of-mass energy of 14 TeV, which should maximise the LHC potential to uncover new phenomena [1]. One of the main aims of the physics programme at the Large Hadron Collider (LHC) is to search for new phenomena that become visible in high-energy proton-proton collisions. A possible signature of such new phenomena would be the production of a heavy resonance with its subsequent decay into a final state consisting of a pair of fermions or vector bosons. Many new physics scenarios beyond the Standard Model (SM) predict such a signal. Possible candidates are charged and neutral heavy gauge bosons. In the simplest models these particles are considered copies of the SM W and Z bosons and are commonly referred to as W' and Z' bosons [2]. In the Sequential Standard Model (SSM) [3] the W'_{SSM} and Z'_{SSM} bosons have couplings to fermions that are identical to those of the SM W and Z bosons, but for which the trilinear couplings $W'WZ$ and $Z'WW$ are absent. The SSM has been used as a reference for experimental W' and Z' boson searches for decades, the results can be reinterpreted in the context of other models of new physics, and it is useful for comparing the sensitivity of different experiments.

At the LHC, such heavy W' and Z' bosons could be observed through their single production as s-channel resonances with subsequent leptonic decays

$$pp \to W'X \to l\nu X \qquad (1)$$

and

$$pp \to Z'X \to l^+l^-X \qquad (2)$$

respectively, where in what follows, $l = e, \mu$ unless otherwise stated. The production of W' and Z' bosons at hadron colliders is expected to be dominated by the process $q\bar{q}'/q\bar{q} \to W'/Z'$. Leptonic final states provide a low-background and efficient experimental signature that results in excellent sensitivity to new phenomena at the LHC.

Heavy resonances that can decay to gauge boson pairs are predicted in many scenarios

15

of new physics, including extended gauge models (EGM) [3], models of warped extra dimensions [4], technicolour models [5] associated with the existence of technirho and other technimesons, more generic composite Higgs models [6], and the heavy vector-triplet (HVT) model [7], which generalises a large number of models that predict spin-1 charged (W') and neutral (Z') resonances etc. Searches for exotic heavy particles that decay into WZ or WW pairs are complementary to searches in the leptonic channels $l\nu$ and l^+l^- of the processes (1) and (2). Moreover, there are models in which new gauge boson couplings to SM fermions are suppressed, giving rise to a fermiophobic W' and Z' with an enhanced coupling to electroweak gauge bosons. It is therefore important to search for W' and Z' bosons also in the WZ and WW final states.

The analysis is based on pp collision data at a center-of-mass energy $\sqrt{s} = 14$ for the expected data from Run 3 and HL-LHC options at the LHC, at $300\ fb^{-1}$ and $3000\ fb^{-1}$, respectively [8]. In ATLAS W^+W^- and WZ events are reconstructed via semileptonic channels. We present results as constraints on the relevant $Z-Z'$ $(W-W')$ mixing factor $\xi_{Z-Z'}$ ($\xi_{W-W'}$) and on the $M_{Z'}$ ($M_{W'}$) mass.

2. $Z' \rightarrow WW$

Here, we will consider a new physics (NP) model where Z' interacts with light quarks and charged gauge bosons via their mixing with the SM Z assuming that the Z' couplings exhibit the same Lorentz structure as those of the SM. In particular, in the present analysis we will focus on a gauge boson of the SSM and EGM. Here, we will consider a new physics (NP) model where Z' interacts with light quarks and charged gauge bosons via their mixing with the SM Z assuming that the Z' couplings exhibit the same Lorentz structure as those of the SM. In particular, in the present analysis we will focus on a gauge boson of the EGM. In the simple reference model described in [3], the couplings of the Z' boson to fermions (quarks, leptons) and W bosons are a direct transcription of the corresponding standard-model couplings. Note that such a Z' boson is not expected in the context of gauge theories unless it has additional couplings to exotic fermions. However, it serves as a useful reference case when comparing constraints from various sources.

In many extended gauge models, while the couplings to fermions are not much different from those of the SM, the $Z'WW$ coupling is substantially suppressed with respect to that of the SM. In fact, in an extended gauge model the standard-model trilinear gauge boson coupling strength, $g_{WWZ}(= \cot\theta_W)$, is replaced by $g_{WWZ} \rightarrow \xi_{Z-Z'} \cdot g_{WWZ}$, where $\xi_{Z-Z'} = C \cdot (M_W/M_Z')^2$ is the mixing factor and C the coupling strength scaling factor. One should note that most Z' search results report mass limits along the $\xi_{Z-Z'} = (M_W/M_Z')^2$ line ($C = 1$ is referred to as "reference model") EGM and we have also done so for comparison.

The number of signal events for a narrow Z' resonance state can be written as follows

$$N^{Z'} = L \cdot \varepsilon \cdot A_{ww} \cdot \sigma(pp \rightarrow Z') \cdot BR(Z' \rightarrow W^+W^-) \qquad (3)$$

Here, L denotes the integrated luminosity, and the overall kinematic and geometric acceptance times trigger, reconstruction and selection efficiencies, $A_{WW} \times \varepsilon$, is defined as the number of signal events passing the full event selection divided by the number of

16

generated events [10]. Finally, $\sigma(pp \rightarrow Z') \cdot BR(Z' \rightarrow W^+W^-)$ is the (theoretical) total production cross section in narrow width approximation (NWA) times branching ratio extrapolated to the total phase space.

In the calculation of the total width $\Gamma_{Z'}$ we included the following channels: $Z' \rightarrow f\bar{f}, W^+W^-$, and ZH [10], where H is the SM Higgs boson and f are the SM fermions $f = l, \nu, q$. The total width $\Gamma_{Z'}$ of the Z' boson can be written as follows:

$$\Gamma_{Z'} = \sum_f \Gamma_{Z'}^{f\,f} + \Gamma_{Z'}^{WW} + \Gamma_{Z'}^{ZH} \,. \qquad (4)$$

The presence of the two last decay channels, which are often neglected, is due to $Z - Z'$ mixing. However for large Z' masses there is an enhancement that cancels the suppression due to the tiny $Z - Z'$' mixing parameter $\xi_{Z-Z'}$ [9 -11]. Notice that for all $M_{Z'}$ values of interest for LHC the width of the Z'_{SSM} boson is considerably smaller than the mass resolution ΔM.

The expression for the partial width of the $Z' \rightarrow W^+W^-$ decay channel can be written as [3]:

$$\Gamma_{Z'}^{WW} = \frac{\alpha}{48} \cot^2 \theta_W M_{Z'} \left(\frac{M_{Z'}}{M_W} \right)^4 \left(1 - 4\frac{M_W^2}{M_{Z'}^2} \right)^{3/2} \times \left[1 + 20 \left(\frac{M_W}{M_{Z'}} \right)^2 + 12 \left(\frac{M_W}{M_{Z'}} \right)^4 \right] \xi_{Z-Z'}^2 . \qquad (5)$$

The dominant term for $M^2 \,\square\, M_W^2$ is proportional to $(M/M_W)^4$ and corresponds to the production of longitudinally polarized $W's, Z' \rightarrow W_L^+ W_L^-$. This strong dependence on the invariant mass results in a very steep growth of the cross section with energy and therefore a substantial increase of the cross section sensitivity to mixing at high $M_{Z'}$. In its turn, for a fixed mixing factor $\xi_{Z-Z'}$ and at large $M_{Z'}$ where $\Gamma_{Z'}^{WW}$ dominates over $\sum_f \Gamma_{Z'}^{f\,f}$ and $\Gamma_{Z'}^{ZH}$ the total width increases very rapidly with the mass $M_{Z'}$ because of the quintic dependence on the Z' mass of the W^+W^- mode as shown in Eq. (5) [3]. In this case, the W^+W^- mode becomes dominant and $BR(Z' \rightarrow W^+W^-) \rightarrow 1$, while the fermionic decay channels are increasingly suppressed.

ATLAS [8] analyzed the W^+W^- production in process $pp \rightarrow Z'X \rightarrow WWX$ through the semileptonic final states. Our strategy in the present analysis is to use the SM backgrounds that have been simulated by the experimental collaboration and we simulate only the Z' signal. Fig. 1 shows the expected 95% C.L. upper limits on the production cross section times the branching fraction for a s a function of Z' mass [8], $M_{Z'}$. The expected data analyzed comprises pp collisions at $\sqrt{s} = 14$ TeV with 300 fb^{-1} and 3000 fb^{-1}. Also shown are theoretical production cross sections $\sigma \cdot BR(Z' \rightarrow W^+W^-)$ for Z'_{EGM}, calculated from PYTHIA 8.2 [12] adapted for such kind of analysis. Higher-order QCD corrections for the SM and Z' boson cases were estimated using a K-factor presented in [13]. These theoretical curves for the cross sections, in descending order, correspond to values of the $Z - Z'$ mixing factor $\xi_{Z-Z'}$ from 0.0001 to 0.002. The

intersection points of the expected upper limits on the production cross section with these theoretical cross sections for various $\xi_{Z-Z'}$ give the corresponding lower bounds on it. We found that the minimum expected exclusion limit on $\xi_{Z-Z'}$ as small as $\square\, 2 \cdot 10^{-4} (\square\, 1.1 \cdot 10^{-4})$ for 300 fb^{-1} (3000 fb^{-1}).
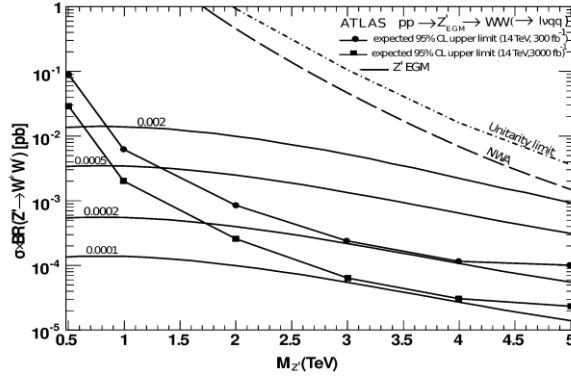
Fig. 1. Expected 95% C.L. upper limits on the production cross section times the branching fraction for $Z' \to W^+W^-$ **as a function of** Z' **mass,** $M_{Z'}$, **for 300** fb^{-1} **and 3000** fb^{-1} [8]. **Theoretical production cross sections** $\sigma \cdot BR(Z'_{EGM} \to W^+W^-)$ **are calculated with PYHTHIA 8.2 and given by thin solid curves. Labels attached to the curves for the** Z'_{EGM} **cross section correspond to the considered mixing factor** $\xi_{Z-Z'}$ **.**

3. $W' \to WZ$

At lowest order in the EGM, W' production and decay into WZ in proton-proton collisions occurs through quark-antiquark interactions in the s-channel. The cross section of process

$$pp \to W'Z \to WZX \,, \qquad (6)$$

can at the LHC be observed through resonant pair production of gauge bosons WZ. Using the NWA, one can factorize the process (6) into the W' production and the W' decay,

$$\sigma(pp \to W'X \to WZX) = \sigma(pp \to W'X) \cdot BR(W' \to WZ) \,. \qquad (7)$$

Here, $\sigma(pp \to W'X)$ is the total (theoretical) W' production cross section and $BR(W' \to WZ) = \Gamma_{W'}^{WZ} / \Gamma_{W'}$ with $\Gamma_{W'}$ the total width of W'. "Narrow" refers to the assumption that the natural width of a resonance is smaller than the typical experimental resolution of 5% of its mass, which is true for a large fraction of the parameter space of the reference EGM model.

In the EGM the W' bosons can decay into SM fermions, gauge bosons (WZ), or a pair of the charged SM W boson and the Higgs boson H. In the calculation of the total width $\Gamma_{W'}$ we consider the following channels: $W' \to f \bar{f}', WZ$ and WH, here f are SM fermions ($f = l, \nu, q$). Only left-handed neutrinos are considered, while possible right-handed neutrinos are assumed to be kinematically unavailable as final states. Also, throughout the paper we shall ignore the couplings of the W' to other beyond-SM particles such as SUSY partners and exotic fermions in the theory. The presence of such

18

channels would increase the width of the W' and hence lower the branching ratio into a WZ pair. As a result, the total decay width of the W' boson is taken to be

$$\Gamma_{W'} = \sum_f \Gamma_{W'}^{f\bar{f}'} + \Gamma_{W'}^{WZ} + \Gamma_{W'}^{WH} \tag{8}$$

The fermion contribution $\sum_{ff'} \Gamma_{W'}^{f\bar{f}'}$, would depend on the number n_g of generations of heavy exotic fermions which can contribute to the W' decay without phase suppression. This number is model dependent too, and introduce a phenomenological uncertainty. The presence of the last two decays channels, which are often neglected at low and moderate values of $M_{W'}$, is due to $W - W'$ mixing which is constrained to be tiny. In particular, for the range of $M_{W'}$ values below 1.0-1.5 TeV, the dependence of $\Gamma_{W'}$ on the values $\xi_{W-W'}$ (within its allowed range) induced by $\Gamma_{W'}^{WZ}$ and $\Gamma_{W'}^{WH}$ is unimportant because $\sum_f \Gamma_W^{f\bar{f}'}$ dominates over diboson partial widths. Therefore, in this mass range, one can approximate the total width as $\Gamma_{W'} \approx \sum_f \Gamma_{W'}^{f\bar{f}'} = 3.5\% \times M_{W'}$ [14], where the sum runs over SM fermions only.

Here, we utilize the expected measurement of diboson processes provided by ATLAS [8] for time-integrated luminosity of 300 fb^{-1} (Run 3) and 3000 fb^{-1} (HL-LHC). As mentioned above, ATLAS analyzed the WZ production (6) through the seileptonic final states. In Fig. 2, the theoretical production cross section $\sigma(pp \to W'_{EGM}) \cdot BR(W'_{EGM} \to WZ)$ for W'_{EGM} boson is calculated from PYTHIA 8.2 [12]. We found that the minimum observed exclusion limit on $\xi_{W-W'}$ as small $1.7 * 10^{-4} (9.3 * 10^{-5})$ for 300 (3000) fb^{-1}.
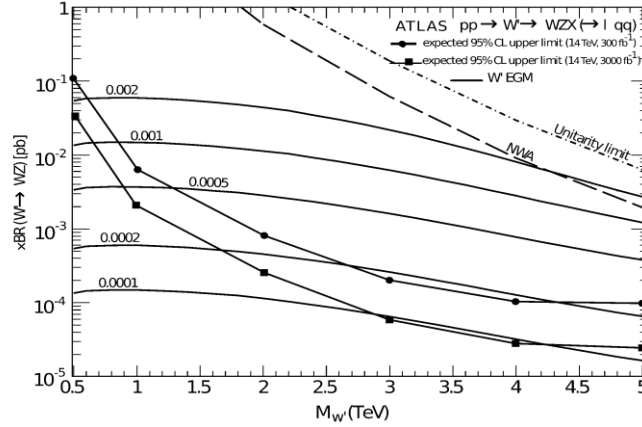
Fig. 2. **Expected 95% C.L. upper limits on the production cross section times the branching fraction for** $W' \to WZ$ **as a function of** W' **mass,** $M_{W'}$, **taken from Ref. [8]. Theoretical production cross sections** $\sigma \cdot BR(W'_{EGM} \to W'X)$ **for** W'_{EGM} **are calculated from PYHTHIA 8.2, and given by thin solid curves. Labels attached to the curves for the** W'_{EGM} **cross section correspond to the considered mixing factor** $\xi_{W-W'}$ **.**

4. Conclusions

If a new $W'(Z')$ bosons exist in the mass range $3\Box5$ TeV, its discovery is possible at the LHC in the Drell – Yan channels, (1) and (2). Moreover, the detection of the $Z' \rightarrow WW (W' \rightarrow WZ)$ mode is eminently possible and would presents an analysis of $Z - Z' (W - W')$ mixing in the process of $WW(WZ)$ pair production. The present analysis is based on the expected pp collision data at a center-of-mass energy at the LHC with integrated luminosities of 300 fb^{-1} and 3000 fb^{-1}.

We show that the expected constraints on the mixing parameters, $\xi_{Z-Z'}$ and $\xi_{W-W'}$, achieved from the analysis of data to be collected in Run 3 as well as at the next option of hadron collider HL-LHC, can be substantially improved with respect to those obtained from the LHC Run 1 and Run 2 at 13 TeV [9, 10, 14–16].

Acknowledgements

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