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Exclusion Limits on Neutral, Singly and Doubly Charged Vector Bosons at LHC

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In this paper, limits are set on Z', doubly-charged and singly-charged bileptons masses in the context of the the 331 model. The following measurable processes are studied: $pp \to \ell^+\ell^+\ell^-\ell^- X$, $pp \to \ell^+\ell^- \nu\nu X$ and $pp \to \ell^+\ell^- X$. Experimental limits on singly-charged bileptons within 331 models obtained for the first time. The mass lower bounds obtained are 3.7 TeV for Z'_{331}, 1.2 TeV for doubly-charged bileptons and 850 GeV for singly-charged bileptons. The computed limits are now the most stringent ones for these particles.

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1. Introduction

The extended elecroweak gauge symmetry group $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ is by now a nearly 30-year-old prediction [1, 2]. In the absence of any reports of deviations from the Standard Model (SM), in particular by the LHC experimental collaborations, it is important to understand just how strong tensions between predictions from 331 models and experimental results are. This is important on several grounds. 331 models are based on the gauge symmetry $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ and as a $SU(N)$ type of group they predict the existence of $N^2 - 1 = 8$ gauge bosons in its $SU(3)_L$ sector. Three of the gauge bosons are the familiar ones from the SM, namely the positively and negatively charged $W^{\pm}$ bosons and the neutral Z^0 boson. The other five non-SM gauge bosons are the positively and negatively double-charged bileptons $Y^{\pm\pm}$, the positively and negatively singly-charged bileptons $V^{\pm}$, and the heavy neutral Z' boson.

There are many interesting aspects of the 331 models worth noticing [3] but arguably, the most intriguing one is the explanation of three quark-lepton families, which is one of the main theoretical motivations for expecting bileptons in Nature. This is accomplished via a nontrivial anomaly cancellation in the model that takes place between families, unlike in the SM where the desired anomaly-free condition is accomplished for each family separately.

Doubly-charged bileptons are the most striking prediction of 331 models, but the expected LHC mass reach, considering the cleanest channel producing bileptons in proton-proton collisions, is $\sim$ 1 TeV and even if one considers the High-Luminosity LHC (HL-LHC) project, formerly known as Super-LHC (sLHC), the reach increases only by 20% [3]. Due to kinematics, however, these conclusions are heavily dependent on the leptoquarks masses that are predicted in the fermionic sector of the model. Should these particles be at least as heavy as 2 TeV the discovery reach for bileptons increases significantly [4]. Regarding experimental constraints, a mass bound of $M_Y > 740$ GeV for doubly-charged bilepton gauge bosons was derived from constraints on fermion pair production at LEP and lepton-flavour violating charged lepton decays [5]. It represented the most useful limit on doubly-charged vector bileptons for the past 20 years. Searches for muonium-antimuonium conversion [6] at PSI put the more stringent limit of $M_Y > 850$ GeV on $Y^{\pm\pm}$, however, this is a less general limit as it assumes flavor-diagonal coupling for bileptons. Both these limits are now surpassed by the results of this work.

2. Numerical implementation

Bileptons can be pair-produced at the LHC through a Drell-Yan-like process mediated by the photon, the SM Z^0 and the new neutral heavy boson Z'. They can also be produced via a t-channel with a leptoquark exchange. The additional t-channels are needed in order to guarantee that all relevant quark sub-processes respect unitarity. In doubly-charged bilepton pair production, each bilepton decay into a same-sign lepton pair, and therefore the natural processes to search for these type of bileptons are $pp \to Y^{++}Y^{--} \to \ell^+\ell^+\ell^-\ell^- X$, where $\ell = e, \mu$. For singly-charged bileptons, the characteristic decay is a signal with an opposite-charge lepton pair and two neutrinos, $pp \to V^+V^- \to \ell^+\ell^-\nu\nu X$. Leptonic decay is also the cleanest signal for Z' searches, hence in this work we investigate the processes $pp \to Z' \to \ell^+\ell^- X$.

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The production cross-sections for the 331 bosons were calculated using CALCHEP event generator [7], where the model was previously implemented [8]. Events were generated for all the processes mentioned above using the CTEQ6L1 parton distribution function and center-of-mass energy of 13 TeV. The generated events at parton level were processed by PYTHIA8 [9] to simulate parton shower, hadronization, and underlying event. A fast detector simulation was performed using DELPHES [10] with ATLAS detector configuration. Pile-up is taken into account by overlaying minimum-bias events simulated with PYTHIA with the main interaction. The average number of pp interaction per bunch crossing considered in this work is 24. The bilepton masses were taken in the range of 400 GeV to 1300 GeV, and the Z' mass ranged from 1 TeV to 5 TeV. The leptoquarks masses were fixed at $M_Q = 1.5$ TeV. When generating the bilepton events, the Z' mass was fixed at 5 TeV.

3. Limit Setting Procedure

The invariant mass distributions $m(\ell\ell)$ of lepton pairs coming from doubly-charged bileptons and from Z' are used to calculate upper limits on σB, where σ is the cross-section of the new physics and B is the branching ratio. For the singly-charged bilepton analysis, another distribution is used. A likelihood function defined as the product of Poisson probabilities over all distribution's bins of a given search is constructed. To calculate the limits, a Bayesian approach is applied with a flat prior probability distribution for σB, and the Bayes theorem is employed to evaluate the marginal posterior probability density function, $\mathscr{L}(\sigma B|N)$, where N is the number of observed events. Upper limits at 95% CL are set on σB by integrating the posterior probability density function as

$$0.95 = \frac{\int_0^{(\sigma B)_{up}} \mathscr{L}(\sigma B|N)d(\sigma B)}{\int_0^{\infty} \mathscr{L}(\sigma B|N)d(\sigma B)} \tag{3.1}$$

where $(\sigma B)_{up}$ is the calculated limit. The calculation is performed with the Bayesian Analysis Tool Kit [11]. The upper limits on σB are translated into lower limits on the mass of the new bosons by using the theoretical cross-section for the new boson production. The limits obtained with data are called observed limits. The expected limits are obtained by running a large number of pseudo-experiments where it is assumed that only background events are present. All the estimated backgrounds and efficiencies used in our analysis are extracted from the relevant ATLAS publications.

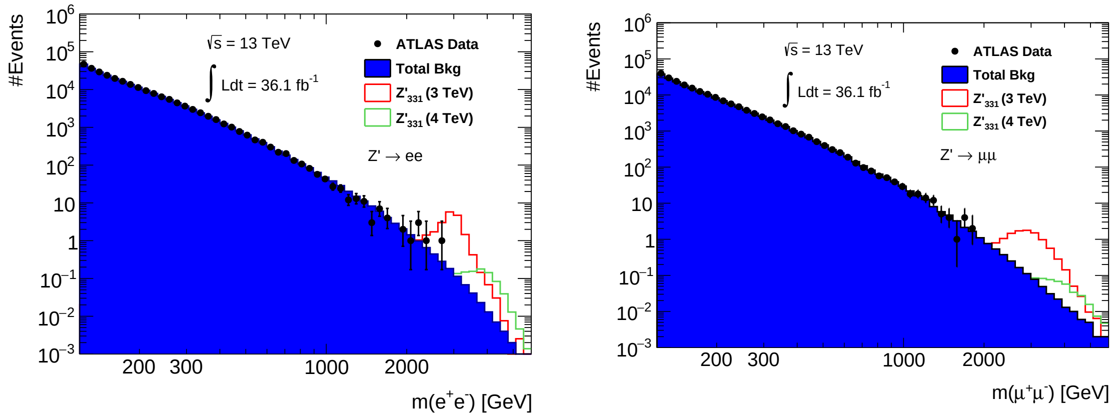
To set limits on bileptons and Z' masses, different ATLAS searches are considered. The data sample in all the analysis corresponds to an integrated luminosity of 36.1 fb^{-1}. These are discussed in the following sections.

4. Limits on Z'_{331}

Limits on Z'_{331} mass are set using the data from [12]. The signal candidates are selected by requiring at least one pair of same flavour leptons (electrons or muons). Electrons candidates are selected if they have transverse energy(E_T) greater than 30 GeV and pseudorapidity $|\eta| < 2.47$.

Events inside the region $1.37 \leq |\eta| \leq 1.52$ are excluded due to poor energy resolution. Muons candidates are required to have transverse momentum(p_T) greater than 30 GeV, $|\eta| < 2.5$ and opposite charges. This last requirement is not applied to the electron channel since it is not applied in data. If more than two leptons are found, the ones with highest transverse energy/momentum are kept.

The inputs to the statistical analysis are the reconstructed invariant mass distribution of the selected events shown in Figure 1a and Figure 1b for electron and muon channels, respectively. The ATLAS data points are shown with their statistical uncertainty. The dark histogram is the total estimated background. Two Z'_{331} signals with masses of 3 TeV and 4 TeV are also displayed as example.



(a) (b)

Figure 1: Dilepton invariant mass distribution for electron (a) and muon (b) channels.

The observed and expected upper limits $(\sigma B)_{up}$ are calculated for various Z'_{331} mass hypothesis and the results are shown in Figure 2. The lower limits on $M_{Z'_{331}}$ are extracted from the crossing point between the theoretical cross-section and $(\sigma B)_{up}$. The observed and expected mass limits found are 3.7 TeV and $3.6^{+0.1}_{-0.2}$ TeV, respectively. These limits represent significant improvement compared to previous bounds on Z' from 331 models [13, 14, 15].

5. Limits on Doubly Charged Bileptons

The ATLAS search for doubly charged Higgs bosons [16] are interpreted in terms of doubly charged bileptons. The analysis focus on $Y^{\pm\pm} \to e^{\pm}e^{\pm}$ and $Y^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$ decay channels. The bilepton decay in different lepton flavors, $Y^{\pm\pm} \to e^{\pm}\mu^{\pm}$, is not considered since there is no sensible data available for this particular channel.

As the doubly charged bileptons are produced in pairs, the selected final state must have at least three same flavour leptons, all within the inner detector coverage ($|\eta| < 2.5$). Events with three leptons are required to have one same-sign lepton pair and one lepton of opposite charge ($\ell^{\pm}\ \ell^{\pm}\ \ell^{\mp}$). If there are four leptons in the event, the net electric charge must be zero. Following the same selections applied to data, events with at least one b-tagged jet are rejected to suppress background from top quarks. An event is also rejected if the invariant mass of the opposite charge same flavor

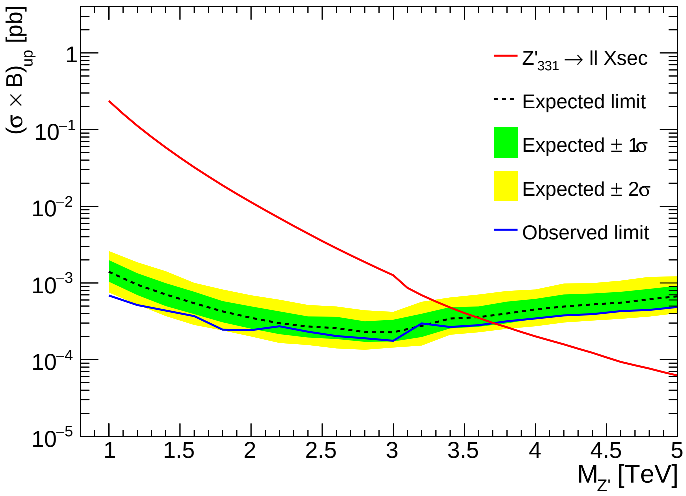


Figure 2: Observed and expected limits on σB as a function of the Z'_{331} mass assumption.

leptons pair is in the range 82.1 GeV $< m(\ell^+\ell^-) <$ 101.2 GeV. In the three leptons events, signal sensitivity is optimized by imposing the same charge lepton separation to be $\Delta R(\ell^\pm\ell^\pm) > 3.5$ and their combined transverse momentum to be $p_T(\ell^\pm\ell^\pm) > 100$ GeV. In addition, the scalar sum of the individual leptons transverse momenta is required to be greater than 300 GeV.

The invariant mass of the same sign leptons pair is used as discriminant variable. In the case of events with four leptons, the variable considered is the average invariant mass of the two same charge leptons. The analysis is performed in the region where $m(\ell^\pm\ell^\pm)$ is above 200 GeV.

The observed and expected limits on doubly-charged bileptons mass are 1.19 TeV and 1.19$\pm$0.01 TeV, respectively.

6. Limits on singly-charged Bileptons

The production of singly-charged bileptons are characterized by events with two leptons and missing transverse energy in the final state. It is the same measurable final state studied in charginos and sleptons searches from supersimetric models. Here we use the ATLAS data from supersimetric searches [17] to set bounds on singly-charged bileptons. This analysis considers all possible leptonic final states produced by the singly-charge bilepton pair production: $V^\pm \to e^+\nu e^-\nu$, $V^\pm \to \mu^+\nu\mu^-\nu$, $V^\pm \to e^+\nu\mu^-\nu$ and $V^\pm \to e^-\nu\mu^+\nu$.

The signal events candidates are required to have exactly two leptons and missing transverse energy. The leptons can be of the same or different flavors, but they must have opposite charges. Additionally, leptons are required to have $|\eta| < 2.5$ and $p_T > 10$ GeV, and a di-lepton invariant mass of $m_{\ell\ell} > 110$ GeV. An event is rejected if there is a b-tagged jet with $p_T > 20$ GeV or any other jet with $p_T > 60$ GeV. The selected events are separated in two categories: same-flavor (e^+e^- and $\mu^+\mu^-$ events) and different-flavor ($e^\pm\mu^\mp$ events).

The final selection applied is based on the the variable "stransverse mass", m_{T2}, defined as [18, 19]:

$$m_{T2} \equiv \min_{q_T}\left[\max\left(m_T(\mathbf{p}_T^{\ell 1},\mathbf{q}_T), m_T(\mathbf{p}_T^{\ell 2},\mathbf{p}^{\text{miss}}-\mathbf{q}_T)\right)\right], \tag{6.1}$$

where

$$m_T(\mathbf{p}_T,\mathbf{q}_T) = \sqrt{2(p_T q_T - \mathbf{p}_T \cdot \mathbf{q}_T)}, \tag{6.2}$$

$\mathbf{p}_T^{\ell 1}$ and $\mathbf{p}_T^{\ell 2}$ are the two leptons vectors transverse momentum, $\mathbf{p}^{\text{miss}}$ is the missing transverse momentum and $\mathbf{q}_T$ is a transverse momentum vector that minimizes the larger of $m_T(\mathbf{p}_T^{\ell 1},\mathbf{q}_T)$ and $m_T(\mathbf{p}_T^{\ell 2},\mathbf{p}^{\text{miss}}-\mathbf{q}_T)$.

The m_{T2} variable is used in the statistical analysis where the signal region is defined by requiring $m_{T2} > 100$ GeV. The calculated limits are 850 GeV (observed) and (950 ± 50) GeV (expected). These results are the first limits derived for singly-charged bileptons using LHC data.

7. Conclusions

Limits on the mass and couplings of vector bosons from 331 models are derived using different ATLAS searches at 13 TeV and 36.1 fb^{-1} of data. Three search channels are investigated: dilepton production, four lepton production and dilepton production plus missing transverse energy. These channels are used to derive exclusion limits on Z'_{331}, doubly-charged and singly-charged bileptons, respectively. A Z'_{331} with mass smaller than 3.7 TeV is excluded. For bileptons, it is found that doubly-charged bileptons with masses up to 1.2 TeV are excluded. For singly-charged bileptons, the maximum bound is 850 GeV, and it represents the very first direct limit on singly-charged bileptons obtained with hadron collision data. These results improves previous limits on 331 vector bosons and at the moment this paper is written, they are the most stringent limits on these particles.

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