Bounds on Z' from 3-3-1 model at the LHC energies

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The Large Hadron Collider will restart with higher energy and luminosity in 2015. This achievement opens the possibility of discovering new phenomena hardly described by the Standard Model, which is based on the following two neutral gauge bosons: the photon and the Z. This perspective imposes a deep and systematic study of models that predicts the existence of new neutral gauge bosons. One such model is based on the gauge group $SU(3)_C \times SU(3)_L \times U(1)_N$, called the 3-3-1 model for short. In this paper we perform a study with Z' predicted in two versions of the 3-3-1 model and compare the signature of this resonance in each model version. By considering the present and future LHC energy regimes, we obtain some distributions and the total cross section for the process $p + p \rightarrow \ell^+ + \ell^- + X$. Additionally, we derive lower bounds on Z' mass from the latest LHC results. Finally we analyze the LHC potential for discovering this neutral gauge boson at 14 TeV center-of-mass energy.

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I. INTRODUCTION

The search for new physics is one of the top priorities after a particle consistent with the Higgs boson has been found at the Large Hadron Collider (LHC) [1,2]. Although this discovery can elucidate the mass-generation mechanism, it is still believed that the standard model (SM) is not the ultimate truth, and that physics beyond it must exist at the TeV scale. New phenomena are predicted in various alternative models and theoretical extensions of SM. The existence of a new neutral current, called Z', is a common feature of most of these models.

Among the models that have new physics, the 3-3-1 model is the one that provides an elegant answer to one of the most intriguing modern questions, the problem of fermion families in nature. The model is built so that anomalies cancel out when all families are summed over, so the family number must be a multiple of the color number.

The phenomenological consequences of the 3-3-1 model depend on its version. The different versions of this model are a consequence of the characteristics of the $SU(3)$ matrices. It is well known that two representations of the group generators can be simultaneously diagonalized. This makes the charge operator dependent on the ratio of λ_3 to λ_8 matrix representations leading to a different model version. There is a version with an extra neutral Z' and charged $V^{\pm}$ and $U^{\pm\pm}$ gauge bosons carrying double leptonic charge, which are called bileptons. Moreover, in this version the Z' width can be large, and it is usually called the minimal version of the model [3,4]. There are two versions of the model where there are no exotic charged quarks: one is called the right-handed neutrino version [5–9] and the other is called the Özer version [10,11]. For both, the Z' is a narrow resonance. As we will discuss in the next section, the properties of the new neutral boson depend on the model version, which is determined by the charge operator. Consequently, one needs to establish phenomenological criteria to disentangle these versions by analyzing the production cross section and some angular distributions that follow from each of them.

Several studies have been performed in order to derive bounds on the mass of the new gauge bosons. These bounds come from either direct experimental searches or from phenomenological analysis using the available experimental data. In the universe of the 3-3-1 model, bounds on $M_{Z'}$ were obtained from different analyses such as the contribution from exotics to the oblique electroweak correction parameters (S, T and U) [12–14], corrections to the Z-pole observables for arbitrary values of β [15–17], the study of the energy region where perturbative treatment is still valid [18], Z' and exotic boson masses contribution to the muon decay parameters [19,20], the decay $\mu \rightarrow 3e$ [21], and the contribution from neutral bosons to the flavor changing neutral current [22–32].

In the original work from Pisano and Pleitez [3], a very restrictive bound on the Z' mass was obtained ($M_{Z'} >$ 40 TeV) by considering the contribution from Z' to the $K_S^0 - K_L^0$ mass difference. More recently, a work from Pleitez *et al.* [33], based on additional contribution from a light scalar boson to flavor changing neutral current, lowered the strong previous limit on the new neutral gauge boson for the minimal version of the 3-3-1 model. This new

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result allows the minimal 3-3-1 model predictions to be probed at LHC.

Direct experimental searches performed by DØ [34] and CDF [35,36] Collaborations derived bounds on Z' mass based on analyses with dielectron and dimuon final states at $\sqrt{s} = 1.96$ TeV. They established lower bounds for different models and had excluded a Z' with mass in the range of 963 to 1030 GeV.

Recently, the ATLAS and CMS Collaborations presented results on narrow resonances with dilepton final states (e^+e^- and $\mu^+\mu^-$) [37–40] and excluded a sequential Standard Model Z' with mass smaller than 2.49 TeV (ATLAS) and 2.59 TeV (CMS). Although their data have been interpreted in terms of different scenarios for physics beyond the SM, no limits on the Z' from 3-3-1 model were derived from the latest LHC results. The purpose of this paper is to derived these unknown limits.

In this work we consider the production and decay of the 3-3-1 Z' in the process $p + p \to \ell^+ + \ell^- + X$ ($\ell = e, \mu$) for different LHC energy regimes, when Z' is a narrow resonance as predicted in two versions of the model, namely, the right-handed neutrino model (RHN) [5–9] and the Özer model [10,11].

Studies using CDF results have excluded a Z' from the RHN model with mass below 920 GeV [41]. For the Özer model, no limit on Z' mass has been derived so far. A previous study on Z' at the ILC energies was made by one of the authors, where it was possible to disentangle versions from the 3-3-1 model, considering the process $e^+ + e^- \to \mu^+ + \mu^-$ and establishing from hadronic final states lower bounds on $M_{Z'}$ with 95% C.L. [42]. The possibility to see signs from these models will considerably increase at the LHC running at 14 TeV, a scenario that we also explore in this work.

This paper is organized as follows: in Sec. II we describe the right-handed neutrinos and Özer versions, highlighting the differences between them. In Sec. III we present the Z' width and the total cross section for the process investigated and for different Z' masses. In Secs. IV and V, we derive lower bonds on Z' mass at $\sqrt{s} = 8$ and $\sqrt{s} = 14$ TeV and explore the LHC potential to find this new state at 14 TeV. The conclusions are presented in Sec. VI.

II. TWO VERSIONS OF THE 3-3-1 MODEL

The 3-3-1 model has many attractive features, including that it is free from anomalies considering the number of fermion families equal to the quantum number of color. The beginning is the electric charge operator that defines the version of the model,

$$Q = T_3 - \beta T_8 + XI, \tag{1}$$

where the two generators T_3 and T_8 satisfy the $SU(3)$ algebra, I is the unit matrix, and finally X is the $U(1)$ charge.

Depending upon the β value, the charge operator determines the arrangement of the fields, for the minimal version $\beta = \sqrt{3}$; $\beta = 1/\sqrt{3}$ leads to a model with right-handed neutrinos (RHN) and quarks with ordinary charges. Also, another choice, $\beta = -1/\sqrt{3}$, leads to a model without exotic charges.

We are interested in the following two versions: one known as the right-handed neutrino version with $\beta = 1/\sqrt{3}$, called here version I [5–8], and the other version with $\beta = -1/\sqrt{3}$ [10,11], called version II.

Besides the ordinary gauge bosons ($\gamma, Z, W^\pm$), both versions present neutral extra gauge bosons Z' and single charged bileptons $V^\pm$ and the neutral one X^0, which carry the double lepton number. The heavy exotic quarks carry ordinary charges, $2/3$ for the u type and $-1/3$ for the d type.

Each lepton family is arranged in triplets. The first two elements are the charged and the neutral lepton, the third element is a conjugate of the charged lepton or neutral lepton, depending on the β factor. In order to cancel anomalies, the quarks are arranged in triplets and antitriplets (one family must be different from the other two).

The Higgs structure to give mass to all particles is composed of three triplets (χ, ρ, η), whose neutral fields develop nonzero vacuum expectation values, respectively, v_χ, v_ρ, and v_η. To reproduce the SM phenomenology, a large scale is associated with the vacuum expectation value v_χ, which gives mass to the exotic quarks and extra gauge bosons. Thus, we have the conditions $v_\chi \gg v_\rho, v_\eta$, with $v_\rho^2 + v_\eta^2 = v_W^2 = (246)^2$ GeV^2.

The general Lagrangian for the neutral current involving only the Z' contribution is

$$\mathcal{L}^{\rm NC} = -\frac{g}{2\cos\theta_W}\sum_f [\bar{f}\gamma^\mu(g'_V + g'_A\gamma^5)fZ'_\mu], \tag{2}$$

where f are leptons and quarks, and the couplings g'_V and g'_A are shown in Tables I and II for RHN and Özer versions. Here g is the $SU_L(3)$ coupling and θ_W is the Weinberg angle.

TABLE I. The vector and axial couplings of Z' with leptons (e, μ, and τ) and quarks (u and d) in the RHN (version I). θ_W is the Weinberg angle.

	RHN-version I g'_V	g'_A
$Z'\bar{\ell}\ell$	$\frac{-1+4\sin^2\theta_W}{2\sqrt{3-4\sin^2\theta_W}}$	$\frac{1}{2\sqrt{3-4\sin^2\theta_W}}$
$Z'\bar{u}u$	$\frac{3-8\sin^2\theta_W}{6\sqrt{3-4\sin^2\theta_W}}$	$-\frac{1}{2\sqrt{3-4\sin^2\theta_W}}$
$Z'\bar{d}d$	$\frac{3-2\sin^2\theta_W}{6\sqrt{3-4\sin^2\theta_W}}$	$-\frac{3-6\sin^2\theta_W}{6\sqrt{3-4\sin^2\theta_W}}$

TABLE II. The vector and axial couplings of Z' with leptons (e, μ and τ) and quarks (u and d) in the Özer (version II). θ_W is the Weinberg angle.

Özer-version II	g'_V	g'_A
$Z'\bar{\ell}\ell$	$-\frac{1+2\sin^2\theta_W}{2\sqrt{3-4\sin^2\theta_W}}$	$\frac{1-2\sin^2\theta_W}{2\sqrt{3-4\sin^2\theta_W}}$
$Z'\bar{u}u$	$-\frac{3+2\sin^2\theta_W}{6\sqrt{3-4\sin^2\theta_W}}$	$\frac{1-2\sin^2\theta_W}{2\sqrt{3-4\sin^2\theta_W}}$
$Z'\bar{d}d$	$\frac{-3+4\sin^2\theta_W}{6\sqrt{3-4\sin^2\theta_W}}$	$\frac{1}{2\sqrt{3-4\sin^2\theta_W}}$

III. NUMERICAL IMPLEMENTATION

The two versions of 3-3-1 models discussed above were implemented in the COMPHEP package [43], which was used for cross-section calculation and event generation. The parton distribution function CTEQ6L was used, and the QCD factorization scale was set as the dilepton invariant mass of the event. Concerning the particle parameters, we considered heavy quarks, heavy leptons, and bilepton masses to be 1 TeV, and we took the Z' mass in the range of 500 to 4000 GeV.

In Fig. 1 we present the total Z' width as a function of its mass for the two versions studied here. As we can see, the resonance is narrow in both versions, varying from 2% to 4% of $M_{Z'}$ in the mass range considered. At $M_{Z'} = 2$ TeV, the slope of the curve increases because, from this point, the decay of Z' into exotic quarks becomes kinematically allowed. In both versions, the new neutral gauge boson can also decay into exotic fermions with branching ratios at the order of 2%.

Figure 2 shows the total cross section calculated at tree level for the process $p + p \to \ell^+ + \ell^- + X$ at $\sqrt{s} = 8$ TeV, where ℓ is either an electron or a muon. Figure 3 shows the same cross section calculation for 14 TeV. Both versions foresee cross sections that can be probed at LHC. Version II is the most optimistic, since the Z' coupling to leptons is stronger than in version I. Note that depending on $M_{Z'}$, the cross sections increase by a factor of 10 to 10^2 at 14 TeV in comparison with their value at 8 TeV.

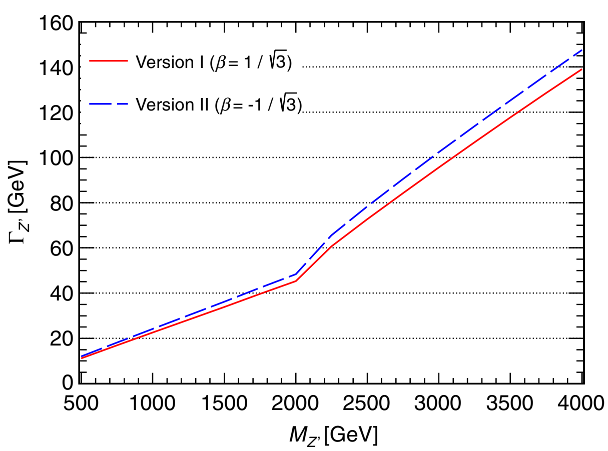

FIG. 1 (color online). Z' width as a function of $M_{Z'}$ for versions I and II of the 3-3-1 model.

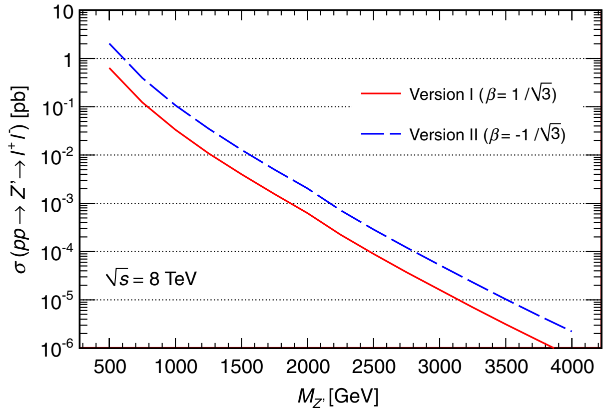

FIG. 2 (color online). Total cross section as a function of $M_{Z'}$ for the process $p + p \to Z' \to \ell^+ + \ell^-$ in versions I and II of the 3-3-1 model at $\sqrt{s} = 8$ TeV. A cut on the dilepton invariant mass of $M_{Z'}/2$ was applied for this calculation.

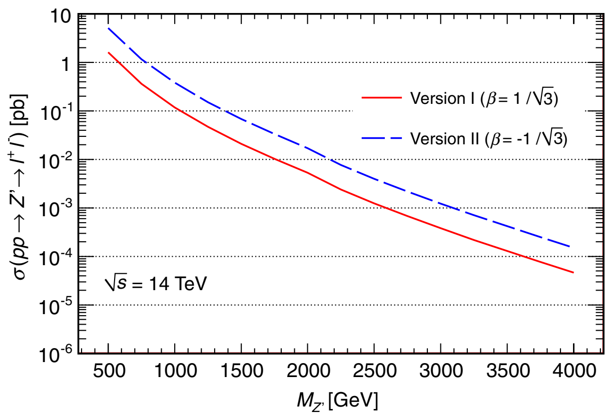

FIG. 3 (color online). Total cross section as a function of $M_{Z'}$ for the process $p + p \to Z' \to \ell^+ + \ell^-$ in versions I and II of the 3-3-1 model at $\sqrt{s} = 14$ TeV with the same cut as Fig. 2.

IV. EXCLUSION LIMITS AT $\sqrt{s} = 8$ TEV

The LHC experiments have performed many analyses, searching for signals of new spin 1 gauge bosons in different final states, but so far no deviation of SM has been found. These analyses are usually model dependent, where a set of benchmark model predictions is compared to data.

In the absence of any signal, ATLAS and CMS Collaborations have extended the E_6 superstring-inspired Z' exclusion mass to above 2 TeV with 6 and 4 fb^{-1} of collision data, respectively, at $\sqrt{s} = 8$ TeV [38,40]. In particular, the CMS Collaboration has combined the results from 7 and 8 TeV to set 95% C.L. limits on the ratio R_σ of the cross section times branching fraction for Z' to that of the SM,

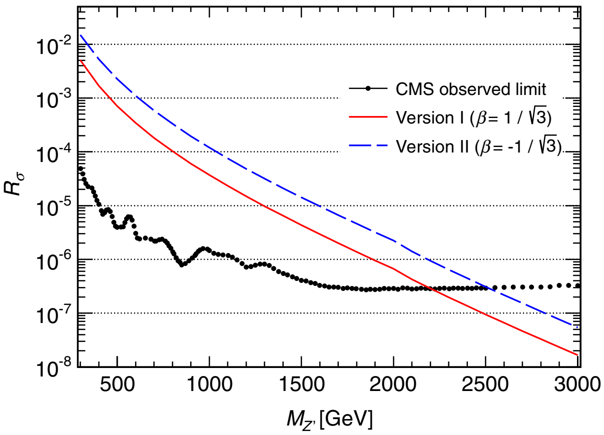

FIG. 4 (color online). R_σ curves for both versions. The CMS observed limits on R_σ (black dots) are for the combination of electron and muon channels at 7 and 8 TeV.

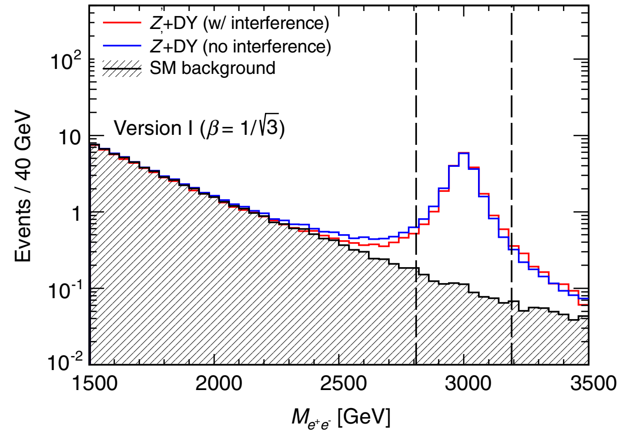

FIG. 5 (color online). Invariant mass distribution in the electron channel for $M_{Z'} = 3000$ GeV for version I. The vertical lines represent the mass window used for selecting signal events.

$$R_\sigma = \frac{\sigma(p + p \to Z' \to \ell^+ + \ell^-)}{\sigma(p + p \to Z \to \ell^+ + \ell^-)}. \quad (3)$$

We use the CMS results to set lower limits on the Z' mass from 3-3-1 models. Following what was done by CMS, the Z' cross sections for both versions are calculated in a range of 40% about the Z' pole mass, and the Z cross section is calculated in the interval 60 GeV $< m_{\ell\ell} <$ 120 GeV. The ratio R_σ is evaluated for Z' masses in the range between 500 and 3000 GeV.

Figure 4 shows the CMS observed limits and the theoretical ratio R_σ curve for both versions. The Z' lower mass limit is obtained from the point where the theoretical ratio curve crosses the observed limit. From the plot, we can conclude that the current data exclude with 95% C.L. the version I new neutral gauge boson with mass below 2200 GeV and the version II new resonance lighter than 2519 GeV. This result does not change significantly if the value of the exotic quarks' mass is changed.

V. DISCOVERY POTENTIAL AND LIMITS AT $\sqrt{s} = 14$ TEV

After a shutdown that is expected to take two years from 2013, the LHC will restart its operation at the design center-of-mass energy of 14 TeV. Here we assume this scenario to investigate the LHC potential to find a Z' from the 3-3-1 model and to determine the lower bounds on the Z' mass that can be set with this energy regime.

In order to determine the minimal integrated luminosity needed to claim a Z' discovery or to exclude it, the number of background and signal events expected in the processes $p + p \to e^+ + e^- + X$ and $p + p \to \mu^+ + \mu^- + X$ is calculated. To make our results more realistic, we consider an overall efficiency of 66% for the electron channel and 43% for the muon channel, as determined by the ATLAS experiment [37]. These efficiencies take into account the geometrical acceptance of the detector ($|\eta| < 2.5$), cuts on lepton transverse momentum, and lepton reconstruction and identification efficiencies.

The dominant and irreducible background taken into account in this paper is the Drell-Yan (DY) process. Although the Z' interfere with the $Z/\gamma*$ process, the interference is minimal, and therefore we treat signal and background as independent. Others backgrounds include QCD jets and ttbar events, but at high masses these backgrounds can be heavily suppressed by isolation cuts and are not considered here.

Figures 5 and 6 show the invariant mass distributions for the DY and for a signal mass hypothesis of 3000 GeV for versions I and II, considering 100 fb^{-1} of data and the efficiencies mentioned above. Only the distribution for the electron channel is shown, but at the generator level the muon channel distributions looks the same. To determine the significance of a signal like those shown in the plots, we estimate the number of signal and background events by calculating the cross sections within a window

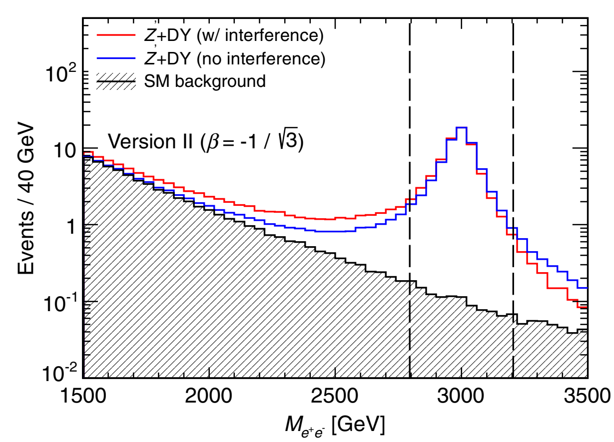

FIG. 6 (color online). Invariant mass distribution in the electron channel for $M_{Z'} = 3000$ GeV for version II. The vertical lines represent the mass window used for selecting signal events.

$[M_{Z'} - 2\Gamma_{Z'}, M_{Z'} + 2\Gamma_{Z'}]$ for both channels. This selection, represented by the two vertical lines in Figs. 5 and 6, suppress considerably the background while maintaining high signal efficiency. We can also see in these plots the effect of Z'-DY interference on the invariant mass, which is small in both models, and under the selected mass window around the Z' mass, it is highly suppressed.

The potential of the search to find a Z' of a given mass is determined by the integrated luminosity needed to observe a signal with statistical significance of 5σ. The significance is obtained via the estimator [44],

$$S = \sqrt{2\left((N_s + N_b)\ln\left(1 + \frac{N_s}{N_b}\right) - N_s\right)}, \qquad (4)$$

where N_s and N_b are, respectively, the number of signal and backgrounds events expected in the mass window mentioned above.

Figures 7 and 8 show the amount of integrated luminosity required to have a 5σ Z' discovery in the electron and muon channels for both versions. As we can see, a 3-3-1 Z' with mass just above the exclusion limit (2519 GeV) can be reached with an amount of data at the order of 1 to 10 fb^{-1}, depending on the channel and model. This scenario can be achieved in the first year of LHC operation at 14 TeV. For $M_{Z'} \sim 4$ TeV in version II, we would require less than 100 fb^{-1} to discover this new heavy state, while for version I, at least 250 fb^{-1} of data would be needed to observe a boson with that mass.

If no resonance is found in the data, the current Z' limits can be considerably extended in the next years. Assuming the presence of only background in the data, we can calculate the expected limits on various Z' mass hypotheses considering different integrated luminosities. This is done by performing a single-bin likelihood analysis, using the estimated number of signal and background events and the algorithm described in [45]. It adopts a frequentist approach to compute the confidence level for exclusion of small signals by combining different searches. The electron and muon channels are combined to set 95% C.L. exclusion on $\sigma \times \text{Br}(Z' \to \ell^+ + \ell^-)$, and these limits are translated to limits on $M_{Z'}$.

Figure 9 shows the minimal integrated luminosity needed to exclude the new gauge boson as a function of $M_{Z'}$. With ~ 23 fb^{-1} of data, the version II Z' can be excluded up to masses of 4000 GeV, but for version I, we would need at least 3 times more luminosity to exclude a Z' with mass of 4000 GeV. Note that for $M_{Z'} \sim 3000$ GeV, less than 10 fb^{-1} of data is enough for exclusion. This is important to point out because, although we have not considered in this work the 3-3-1 version that has theoretical upper bounds on Z', our results suggest that such a version can be completely excluded in the very early stages of LHC running at 14 TeV, since these upper bounds are usually below 3500 GeV.

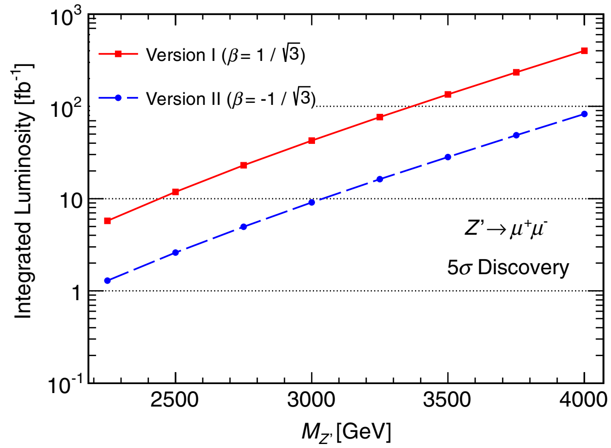

FIG. 8 (color online). Discovery potential for versions I and II as a function of $M_{Z'}$ at 14 TeV in the muon channel.

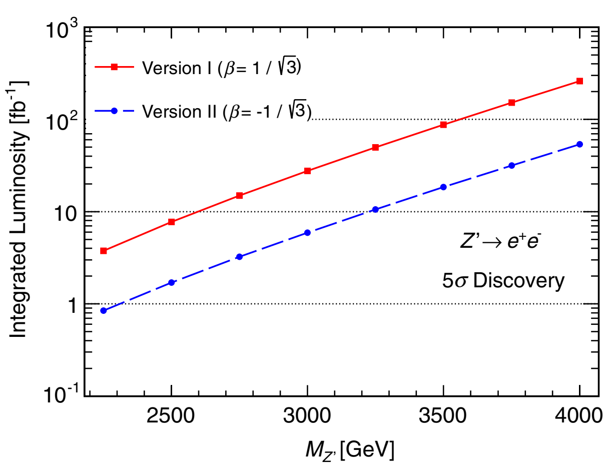

FIG. 7 (color online). Discovery potential for versions I and II as a function of $M_{Z'}$ at 14 TeV in the electron channel.

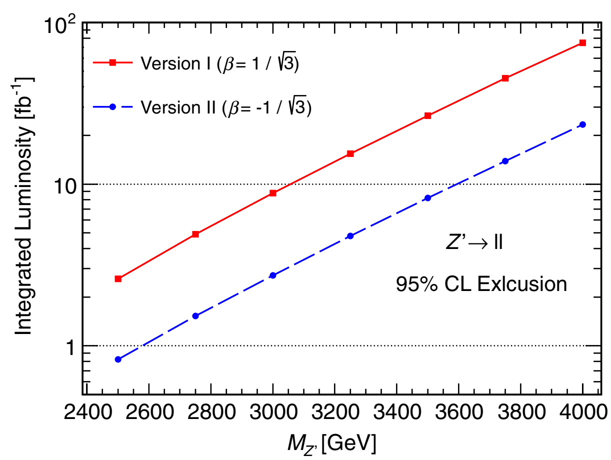

FIG. 9 (color online). Minimal integrated luminosity needed to exclude a Z' from version I and version II as a function of $M_{Z'}$ at 14 TeV.

VI. CONCLUSIONS

New resonances are expected to manifest at the LHC in the next years, and among them, the neutral heavy gauge boson Z' has a special role, since it appears in different beyond-SM scenarios. In this paper we have presented a study involving the 3-3-1 model predictions considering the process $p + p \to \ell^+ + \ell^- + X$. Lower limits on Z' mass from two versions of the 3-3-1 model were derived using the latest CMS published results. For the RHN model, a Z' with mass below 2200 GeV is excluded. This limit is a considerable improvement on the bounds obtained with CDF results. On the other hand, we derived a first limit for the Özer version: a Z' lighter than 2519 GeV is excluded.

Considering the LHC running at the design center-of-mass energy of 14 TeV, we have shown that a new resonance with mass of 4000 GeV can be reached at the LHC with integrated luminosities at the order of 100 fb^{-1}. On the other hand, if no signal is found, the LHC can already exclude $M_{Z'} = 4000$ GeV in the first year of operation at the high energy regime. This is the first investigation of this kind performed for the 3-3-1 models considering the LHC upgraded energy. As the 3-3-1 model predicts a number of new particles, the observation of a Z' in combination with other exotic searches like bileptons and leptoquarks would provide a powerful way of discriminating between 3-3-1 versions and other BSM scenarios with new neutral heavy states.

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