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Searching for doubly charged vector bileptons in the golden channel at the LHC

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In this paper we investigate the LHC potential for discovering doubly charged vector bileptons considering the measurable process $p, p \rightarrow e^{\mp}e^{\mp}\mu^{\pm}\mu^{\pm}X$. We perform the study using four different bilepton masses and three different exotics quark masses. Minimal LHC integrated luminosities needed for discovering and for setting limits on bilepton masses are obtained for both 7 and 14 TeV center-of-mass energies. We find that these spectacular signatures can be observed at the LHC in the next years up to a bilepton mass of order of 1 TeV.

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I. INTRODUCTION

Although bileptons [1] can be considered exotic particles relative to their standard model (SM) cousins due to their unfamiliar quantum numbers, they are, in a sense, a conservative prediction. Even though they are suggested only by special extensions of the SM, their existence is, in our view, no more special than other proposals such as weak-scale extra dimensions or supersymmetry (SUSY). Indeed bileptons are a prediction employing only the model building rules for renormalizable gauge theories so successful in the standard model. The main motivation for expecting bileptons is that they explain three quark-lepton families.

Generically speaking, a bilepton is a boson that couples to two leptons, but not to SM quarks, and that carries two units of lepton number. They are present in several beyond-SM scenarios, such as left-right symmetric models, technicolor, and theories of grand unification. The bileptons in which we are interested are doubly charged vector bosons that couple to SM leptons and are predicted when the standard model is embedded in a larger gauge group. The so-called 331 models [2,3] fall into this category, and in this paper we restrict ourselves to this case. However, as will be explained in Sec. II, we expect our results to hold in any model containing vector bileptons.

In bilepton pair production, each of the bileptons will decay to two same-sign leptons. Therefore, they provide an exceptionally clean signature of four isolated high transverse momentum leptons, not necessarily of the same flavor. In this article we explore some of the consequences of this fact at the LHC. We study the actual collider signatures for the process $p, p \rightarrow e^{\mp}e^{\mp}\mu^{\pm}\mu^{\pm}X$ that has no SM background and is for this reason a "golden" channel for finding bileptons. In this process, a bilepton pair is produced via an s or t channel where one of them decays into electrons while the other decays into muons.

The most useful current lower bound on vector bileptons require these particles to be heavier than 740 GeV [4]. This limit has been derived from experimental limits on fermion pair production at LEP and lepton-flavor charged lepton decays. Another useful lower bound is $M_Y > 850$ GeV, a result that was established from muonium-antimuonium conversion [5]. Although more stringent, this limit depends on the assumption that the bilepton coupling is flavor diagonal. In this article we nevertheless consider bilepton masses as low as 400 GeV, following a similar line of reasoning as [6], where the authors argued a lower bound of 350 GeV for doubly charged vector bilepton masses, a limit that is compatible with other low energy bounds [7]. We also allow a larger upper bound for bilepton masses in 331 models than the usual 1 TeV considered by some authors.

The paper is organized as follows. In Sec. II we present our motivations to perform the present study. In Sec. III we explain the numerical procedure for simulating the $p, p \rightarrow e^{\mp}e^{\mp}\mu^{\pm}\mu^{\pm}X$ reaction as well as its validation. In Sec. IV we show relevant experimental observables for the bilepton golden channel. In Sec. V we present the discovery potential for bileptons, calculating mass exclusion limits as a function of the LHC integrated luminosities, including a digression on the prospects for the accelerator's 7 TeV run and for the super LHC (sLHC). We conclude in Sec. VI.

II. MOTIVATIONS

Many interesting channels have been studied in the literature concerning bileptons, but curiously there has been no systematic study on the phenomenology of the bilepton golden channel at the LHC. The authors in [8] did a fairly comprehensive study of bilepton phenomenology at hadron colliders. But in all cases they limited themselves to bilepton pair-production study, disregarding its decays.

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In the present study we go a step further in understanding the actual collider signatures, by considering measurable final states.

A. 331 models

The 331 models are based on the gauge symmetry $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$, hence their name. Their first versions appeared in 1992 [2,3]. There are many interesting aspects of the 331 models worth noticing but the most intriguing one is the explanation of three quark-lepton families, which is the main motivation for expecting bileptons in Nature. This is done via a nontrivial anomaly cancellation in the 331 model that takes place between families, which is achieved by requiring the number of families to be equal to the number of quark colors. The explanation of the number of generations is also arguably one of the main reasons that keep model builders interested in 331 models, since they are one of the few which elegantly address this problem. The 331 models are also the simplest extension of the SM containing bileptons. Other interesting features of the 331 models include (a) they treat the third generation differently than the first two, this leads to an explanation of the heavy top quark mass; (b) they have an automatic Peccei-Quinn symmetry [9], hence they are also able to solve the strong CP problem. Moreover, gauge symmetry $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ is considered a subgroup of the popular E_6 [10] grand unified theory, which can be itself derived from $E_8 \otimes E_8$ [11] heterotic string theory. Finally, it is worth mentioning that contrary to the SM, in 331 models lepton family number is not required to be conserved, only total lepton number. There is already experimental proof that lepton family number is not an exact symmetry via neutrino oscillations and one can regard this as circumstantial evidence for the nonconservation of lepton family number in general. The combination of such intriguing aspects make bileptons desirable candidates to be found in Nature.

Another important point to be discussed is the minimal version of the 331 models. There are different ways in which $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ can be broken down back to the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ SM gauge symmetry. The minimal version corresponds to using minimal Higgs structure to achieve this goal. In this version it is required that the new neutral vector boson Z' mass term be coupled to the bilepton mass, like

$$\frac{M_Y}{M_{Z'}} = \frac{\sqrt{3(1 - 4\sin^2\theta_W)}}{2\cos\theta_W}. \quad (1)$$

Regarding theoretical upper bounds in 331 models there is no consensus in the literature. It was reasoned in [3] that in 331 models, bileptons cannot be significantly heavier than 1 TeV, because of an upper limit in the symmetry breaking scale that is placed by requiring the sine squared of the Weinberg mixing angle (θ_W) to be smaller than $1/4$, which is the same line of argumentation used in [12] to conclude that the Z' mass cannot be itself heavier than 3.1 TeV. Considering the mass relation between Z' and the bilepton, it could be argued that at least the minimal version of the 331 model could be excluded, should bileptons not be detected at the LHC, since any vector bilepton mass heavier than $\sim$840 GeV would violate the Z' mass upper limit via the mass relation between the two gauge bosons given by Eq. (1). This conclusion was challenged in [13]. The argument is as follows. The 331 model predicts that there is an energy scale μ where the model loses its perturbative character. Should experimental data suggest a lower bound on the vector bilepton mass larger than μ, the model would be ruled out. The value of μ is calculated through the condition $\sin^2\theta_W(\mu) = 1/4$, but from this requirement alone it is not possible to know the real value of μ. Then the upper limit on the vector bilepton mass could be, for instance, 3.5 TeV, as has been discussed by [14]. By the same token the 3.1 TeV upper limit in the Z' mass is automatically challenged. Therefore we do not believe it is possible to unambiguously discard *any* 331 model at the LHC (although they could be *discovered* at it), since we consider the bilepton mass upper bound to reasonably lie beyond the accelerator's reach.

For the lower bounds on vector bileptons we consider at least two mass points that violate the general 740 GeV limit imposed by LEP data. As explained by the authors in [6], all the constraints on the 331 parameters coming from experiments involving leptonic interaction should be examined with caution. In the 331 model the leptons mix by a Cabibbo-Kobayashi-Maskawa-like mixing matrix whose elements have not yet been measured, so usually these experiments (and derived limits) apply only when the leptonic mixing matrix is diagonal. Also, in models with an extended Higgs sector some not unrealistic situations could exist in which the scalar bosons contribution to muonium to antimuonium conversion is not negligible. This puts also the possibility of strengthening bilepton experimental limits still at the LHC's 7 TeV run in a new perspective—a possibility that we also discuss in this article.

B. 331 models and supersymmetry

In recent years, a considerable fraction of both the experimental and theoretical communities has dedicated itself to supersymmetry. It is doubtlessly the mainstream subject in particle physics. The 331 models are not *necessarily* supersymmetric. But any renormalizable gauge theory can be extended to a globally supersymmetric model. The 331 models, being anomaly free, are renormalizable and fall of course in this category. Some authors have explored this possibility [15]. Furthermore, as it was argued also in [13], in this model, the hierarchy problem is less severe than in the SM and its extensions since no arbitrary mass scale can be introduced. The masses of fundamental scalars are sensitive to the mass of the heaviest particles that couple directly or indirectly with them. Because in the 331 model the heaviest mass scale is of the order of a few TeVs, there is not a hierarchy problem at all. This feature remains valid when supersymmetry is introduced. Thus, the breaking of the supersymmetry is also naturally at the TeV scale in the 331 model.

C. Model independent vector bilepton searches at the LHC

Ideally one would like to study bileptons in hadron colliders as model independent as possible. For vector bileptons this is not possible as the noninclusion of the Z' boson makes bilepton pair production to violate unitarity, in complete analogy to what happens with $e^+e^- \to W^+W^-$ using only photon exchange. This is another motivation to use the 331 model, although we do not restrain ourselves to the minimal version, allowing M_Y and $M_{Z'}$ to vary independently of one another. Even though model-dependent, our cross sections should approximately be in the same order of magnitude with any other model containing bileptons, since at hadron colliders these particles have to be produced by the same Drell-Yan pair-production process, regardless of the model. Exotic heavy quark exchange can influence this scenario, a possibility we do explore and that makes our conclusions even more general.

III. NUMERICAL IMPLEMENTATION AND VALIDATION

To simulate the bilepton golden channel at the LHC we have implemented the 331 model in the Comphep generator [16]. We followed Ref. [17] to implement the bilepton trilinear gauge interactions and [8] for the Z' couplings with fermions. For the bilepton interaction with leptons we have used the Lagrangian expression given in [18], generating the respective couplings using the Lanhep package [19]. We also take into account bilepton interactions with exotic quarks in the 331 model. For this, we considered the following interactions with the exotic quark sector:

$$\mathcal{L}_Q = -\frac{g}{2\sqrt{2}}[\bar{Q}^c\gamma^\mu(1-\gamma_5)qY_\mu^{++}] + \text{H.c.}, \qquad (2)$$

where Q (D_1, D_2, T_1) is an exotic heavy quark in the 331 model, q is an SM quark, and $g = e/\sin\theta_W$ as in the SM. We considered the respective interaction pairs for (Q, q) to be (D_1, u), (D_2, c), and (T_1, b), where u, c, and b are SM quarks. Our purpose in including such interactions was, besides studying the influence of the heavy quark sector, to guarantee that all relevant quark subprocesses $q\bar{q} \to Y^{++}Y^{--}$ respect unitarity. Since the 331 model itself does not determine the elements of the mixing matrix (which determines how bileptons interact with exotic quarks), this is a reasonable criteria. This was needed for $u\bar{u} \to Y^{++}Y^{--}$, $b\bar{b} \to Y^{++}Y^{--}$, and $c\bar{c} \to Y^{++}Y^{--}$ that violate unitarity otherwise. In Fig. 1, one can see the $u\bar{u} \to Y^{++}Y^{--}$ reaction cross section as a function of the center-of-mass energy. Note that up to energies beyond the LHC designed center-of-mass-energy of 14 TeV, the cross section dependence with energy behaves as expected. We tested this fact for all quarks involved in the proton parton distribution function, CTEQ6l1 [20] that was used for the complete $p, p \to e^\mp e^\mp \mu^\pm \mu^\pm X$ reaction simulation.

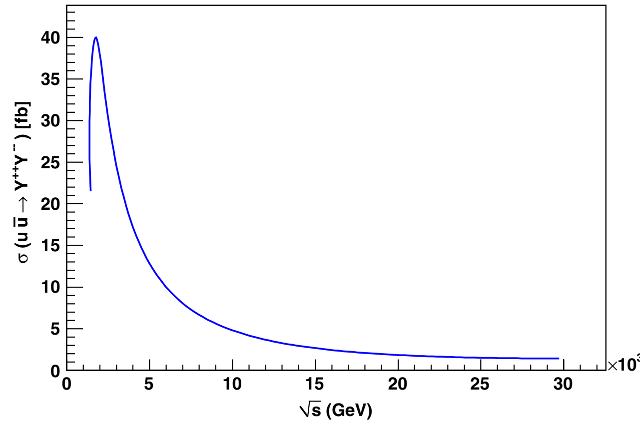

FIG. 1 (color online). $u\bar{u} \to Y^{++}Y^{--}$ cross section as a function of $\sqrt{s}$. The subprocess correctly respects unitarity.

Concerning particle parameters, we considered heavy quark masses to be equal to 400, 600, and 800 GeV (lower bounds on exotic supersymmetric particles impose a lower bound on 331 exotic quark masses to be ~250 GeV [21]) and used 1 TeV for the Z' mass, since 331 Z' masses below 920 GeV were excluded using results from the CDF Collaboration [22]. For the doubly charged bileptons Y^{++} we considered four mass points: 400, 600, 800 GeV and 1 TeV. For each mass point, 10 000 $p, p \to e^\mp e^\mp \mu^\pm \mu^\pm X$ events were generated with Comphep.

The Y^{++}, Z' and exotic quarks widths were calculated directly in Comphep for each mass point. The Z' width for $M_Q = 400$ GeV is $\Gamma_{Z'} \sim 360$ GeV. For the other two exotic quark masses, $\Gamma_{Z'}$ drops to ~ 155 GeV, since Z' decay into exotic quarks becomes kinematically forbidden. The variation of $\Gamma_{Z'}$ with respect to M_Y is of order of 1% between the highest and lowest bilepton mass considered.

To further cross-check our implementation, we reproduced the results from Ref. [8] Fig. 4, for bilepton pair production at the LHC using $M_{Z'} = 1$ TeV. Minor numerical differences in the cross sections can easily be explained by the use of different parton distribution functions.

IV. OBSERVABLES

In what follows, all histograms were produced considering an integrated luminosity of 100 fb^{-1} and the nominal LHC energy of 14 TeV, unless otherwise stated.

A. Cross section and width

Figure 2 shows the total cross section of the $p, p \to e^\mp e^\mp \mu^\pm \mu^\pm X$ process as a function of the doubly charged

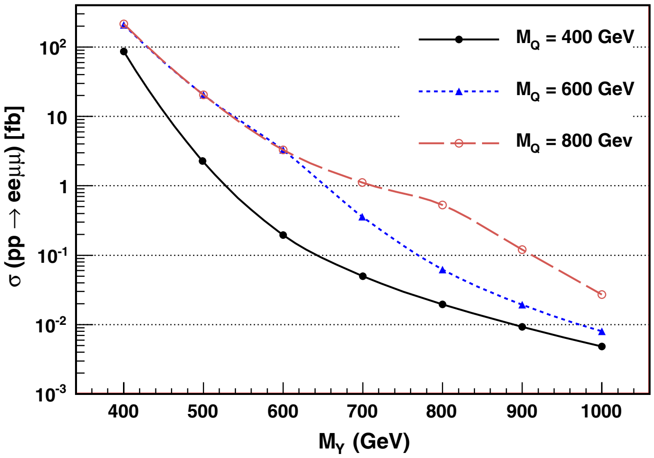

FIG. 2 (color online). Total cross section of the process $p, p \to e^{\mp}e^{\mp}\mu^{\pm}\mu^{\pm}X$ as a function of bilepton mass. The solid (black), dotted (blue), and dashed (red) lines represent the cross section for $M_Q = 400$, $M_Q = 600$, and $M_Q = 800$ GeV, respectively.

bilepton mass, for three different exotic quark masses. Here one can see clear evidence on the problem of the influence of the heavy quark sector on bilepton production. Note that for a bilepton of $M_Y = 800$ GeV the effect on the cross section on having *heavier* exotic quark masses of $M_Q = 800$ GeV as compared to $M_Q = 400$ GeV is to *increase* the cross section of the process by a factor of ~30. We can also see that the $M_Q = 600$ and $M_Q = 800$ curves split at $M_Y = 600$ GeV. This happens because when $M_Y > M_Q$, bilepton decays like $Y^{\pm\pm} \to qQ$ becomes kinematically allowed, which makes the value of $\mathrm{Br}(Y^{\pm\pm} \to l^{\pm}l^{\pm})$ decrease for a given bilepton mass.

Figure 3 shows the bilepton width as a function of bilepton mass for the same exotic quark masses as before. Here we can see how the width increases when new decays are allowed. It is also clear from the plot that the bilepton resonance is very narrow.

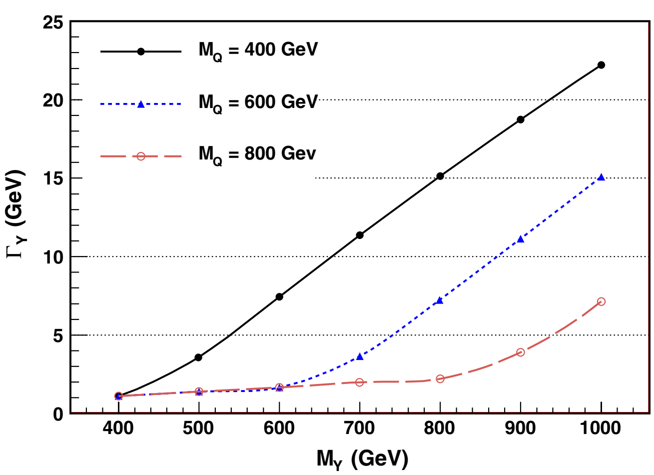

FIG. 3 (color online). Bilepton width as a function of bilepton mass for three different quark mass values.

We admittedly used a very simple approach to the problem of how bileptons and heavy quarks actually mix. However, different ways on determining the values of the mixing matrix between bileptons and heavy quarks could, in principle, intensify such effects even more drastically—an open problem that would deserve a separate study of its own.

B. Pseudorapidity

In order to investigate a more realistic scenario, we require the events that have been generated to pass some selection criteria according to the LHC detectors. First, the four leptons must be within the detectors geometrical acceptance, i.e., $|\eta| < 2.5$ [23]. With this requirement, the fraction of selected events goes from 83% for $M_Y = 400$ GeV to 93% for $M_Y > 900$ GeV. Additionally, we also require each lepton p_T be greater than 20 GeV. The loss of efficiency due to this cut is negligible.

Detailed detector simulations have shown that reconstruction and identification efficiency for dileptons coming from heavy resonances are around 93% for muons and 64% for electrons [23]. In general, muons are much less affected by fake rates from QCD than electrons, which make its identification efficiency higher. In this study, we are considering events with two electron and two muons in the final state, and therefore, based on the above numbers, we take the reconstruction and identification efficiency for this channel to be of 60% ($\epsilon = 0.93 \times 0.64 = 0.60$).

Figure 4 illustrates the electron pair pseudorapidity distribution of the events before and after the selection for $M_Y = 600$ GeV where we can see the fraction of surviving events. The acceptance (geometrical acceptance × efficiency) for this case is 53%, and this changes by ±3% depending on the bilepton mass. The pseudorapidity distribution for muons is similar.

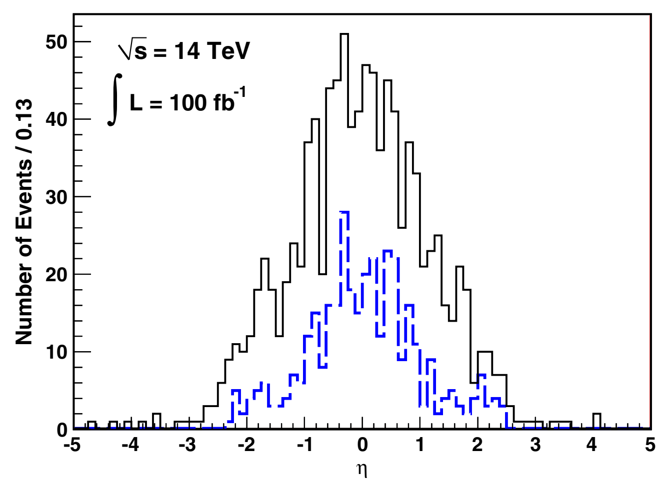

FIG. 4 (color online). Electron pair pseudorapidity distribution for $M_Y = M_Q = 600$ GeV before [solid (black) line] and after [dashed (blue) line] selection.

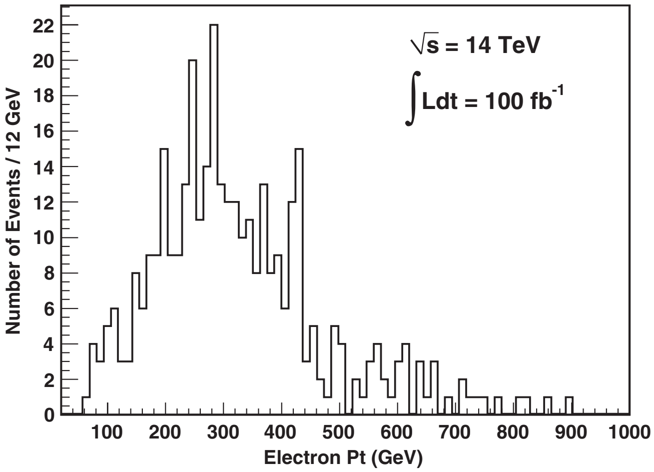

FIG. 5. Electron pair transverse momentum distribution for $M_Y = M_Q = 600$ GeV.

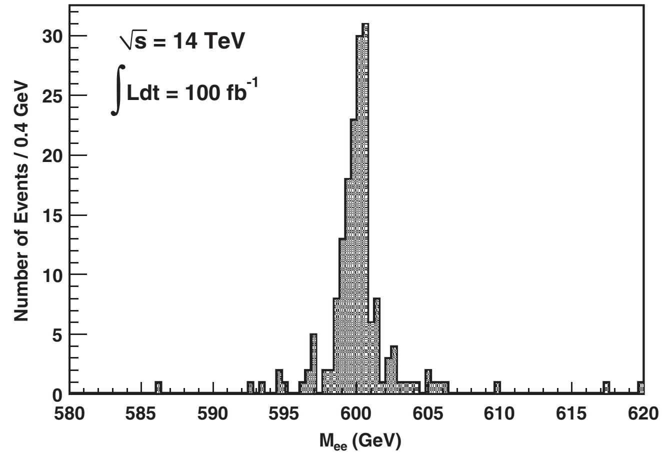

FIG. 7. Invariant mass for electron pair, for a bilepton of 600 GeV.

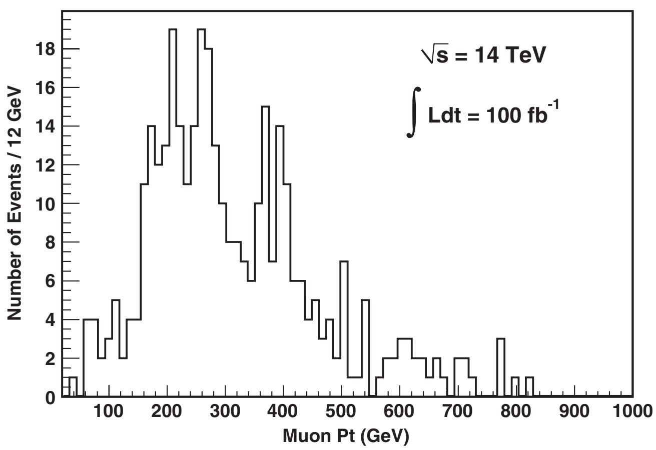

FIG. 6. Muon pair transverse momentum distribution for $M_Y = M_Q = 600$ GeV.

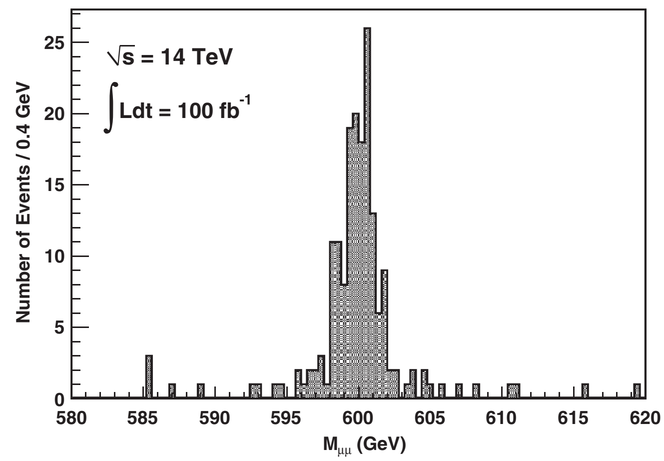

FIG. 8. Invariant mass for muon pair, for a bilepton of 600 GeV.

C. Transverse momentum

Figures 5 and 6, respectively, show the transverse momentum distribution for both the final state selected electrons and muon pairs of the golden channel, where both the doubly charged bilepton and the heavy quarks have a mass of 600 GeV. Typically most of the events are produced in a region between ~200 GeV and 400 GeV but the tail of the distribution has few events going up to 900 GeV for the electron pairs.

D. Invariant mass

When doubly charged vector bileptons are produced in pairs, each bilepton can decay to a pair of same-sign leptons, not necessarily of the same flavor, where each lepton pair will have the same invariant mass distribution. This would be the most compelling evidence of a new resonance coming from a bilepton and very strong evidence of new physics. This is displayed in Figs. 7 and 8 for the final electron and muon pairs, respectively, considering both the bilepton and exotic quarks masses to be equal to 600 GeV. The mean of the invariant mass for both the electrons and muon pairs in the final state unmistakably peaks at 600 GeV, the bilepton mass. Such a plot will, of course, demand several years of data taking such that enough statistics can be gathered, especially for higher bilepton masses, as we will address in the next section.

V. DISCOVERY POTENTIAL AND LIMITS

In order to determine the LHC potential to find bileptons, we calculate the minimal LHC integrated luminosity needed for a five-sigma bilepton discovery. For each bilepton mass, the detector acceptance as stated in Sec. IV B is considered and the 5σ significance is obtained by requiring five events with two electrons and two muons in the final state to be produced. The minimal integrated luminosity $L_{\rm int}$ is given by

$$L_{\rm int} = \frac{5}{\varepsilon(M_Y)\sigma(M_Y)}, \quad (3)$$

where $\varepsilon(M_Y)$ is the detector acceptance and $\sigma(M_Y)$ is the cross section. Figure 9 shows the calculated values of $L_{\rm int}$ as a function of bilepton mass. From the plot, we conclude that an integrated luminosity of order of 10 pb^{-1} is enough for discovering a bilepton of 400 GeV mass, which means that such signal can be observed at the very early days of LHC running with 14 TeV, even in a regime of low luminosity. Depending on the exotic quark mass, luminosities of order 10 fb^{-1} to 100 fb^{-1} are needed to discover bileptons if $M_Y = 800$ GeV. These scenarios can be achieved after 1 yr of LHC operation in low and high luminosity regimes, respectively. Finally, for $M_Y = 1$ TeV, around 10 years of LHC operation at high luminosity would be needed for the resonance observation. This is in contrast with what would happen at the ILC where Møller and Bhabha scattering receive both huge corrections from virtual vector bileptons [24], so that the bilepton mass reach can be as high as $\sim$11 TeV, provided polarized beams are used.

Figure 10 shows the integrated luminosity required for excluding bileptons at 95% C.L. as function of the bilepton mass. For this estimation, we have used the D0 limit calculator [25] to set upper limits on the cross sections that are consistent with the observation of zero events in data, assuming no background. The Bayesian technique is used to set this limits. In this approach, given a posterior probability density function for the signal cross section, the upper limit on the signal cross section $\sigma_{\rm up}$, specified at some confidence level $100 \times \beta\%$, is given by

$$\beta = \int_0^{\sigma_{\rm up}} d\sigma \rho(\sigma k, I), \quad (4)$$

where $\beta = 0.95$, $\rho(\sigma k, I)$ is the posterior probability density function, k is the number of events observed, and I represents prior information available.

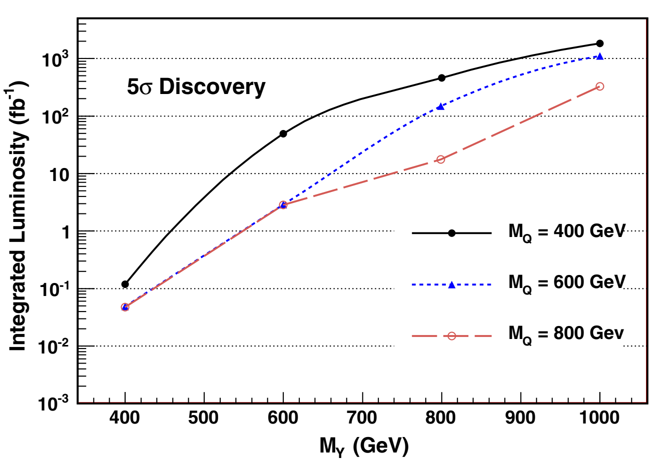

FIG. 9 (color online). Minimal integrated luminosity needed for a 5σ bilepton discovery at the LHC.

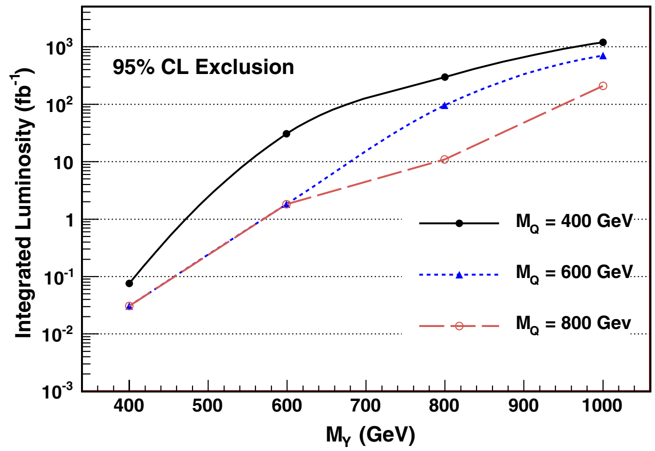

FIG. 10 (color online). Integrated luminosity needed for 95% C.L. bileptons exclusion taking into account acceptance and luminosity uncertainties.

The acceptances values used in this calculation are the same as before. We have assumed an uncertainty of 5% on the acceptance and 10% on the integrated luminosity. It also is assumed that the errors on the acceptance and luminosity are uncorrelated. The obtained limits on the cross section are then translated to limits on the bilepton mass. Comparing Fig. 10 with the discovery plot, we can see that around 60% of the discovery integrated luminosity is needed for excluding bileptons of a given mass.

If a significant signal is observed, the next natural step is to determine the properties of the new particle. In order to check how well the bilepton mass can be reconstructed with the amount of data needed for discovering, we perform an unbinned maximum likelihood fit to the M_{ee} and $M_{\mu\mu}$ distributions for $M_Y = 600$ GeV and $M_Y = 800$ GeV Monte_Carlo (MC) samples, with a fixed exotic quark mass of 600 GeV. The probability density function used in the fits is a Breit-Wigner and two parameters are fitted: the position of the invariant mass peak m and the resonance width Γ. For each bilepton mass, fits are performed to 1000 MC experiments (i.e., 1000 M_{ee} and $M_{\mu\mu}$ distributions) and the mean values of the fitted parameters are reported. The number of events in each MC experiment is fixed to 5. Table I shows the mean, $\bar{m}$, of the fitted mass values and the standard deviation of the m distribution. For both bilepton masses, we see that there is a very good agreement between fitted and true masses in both channels. As expected, the spread of the distribution is larger for

TABLE I. Mean and standard deviation of fitted mass peak for dielectron and dimuon invariant mass distributions.

	$M_Y = 600$ GeV		$M_Y = 800$ GeV	
Channel	$\bar{m}$	σ_m	$\bar{m}$	σ_m
ee	599.9	0.5	799.9	2.4
$\mu\mu$	600.1	0.6	799.9	2.6

$M_Y = 800$ GeV. The bilepton width can also be obtained from the fit at generator level, but it will be dominated by the detector resolution in a more realistic scenario, since bileptons are very narrow resonances.

A. LHC 7 TeV run potential

Considering the LHC's goals until the end of 2012 for a center-of-mass energy of 7 TeV, we estimate the potential for discovering or for setting limits on bilepton masses and couplings at this data taking stage. We consider three scenarios with 1, 5, and 10 fb^{-1} [26] of integrated luminosity. Using the D0 limit calculator and using the same values for acceptance and uncertainties as in the previous sections, we obtain the respective bilepton masses consistent with the observation of zero events for three exotic quark masses: 427, 466, and 483 GeV for $M_Q = 400$ GeV; 478, 534, and 566 GeV for both $M_Q = 600$ GeV and $M_Q = 800$ GeV, from the lowest to the highest integrated luminosity, respectively. These are the doubly charged vector bilepton masses that can be excluded at 95% C.L. The 7 TeV exclusion limits are summarized in Table II.

The 5σ discovery potentials at 5 and 10 fb^{-1} of integrated luminosity are, respectively, found to be 452, 535 GeV for $M_Q = 400$ GeV; 511, 542 GeV for $M_Q = 600$ GeV; and 515, 544 GeV for $M_Q = 800$ GeV. With 1 fb^{-1} the reach is 459 GeV using the highest exotic quark mass. This mass reach is way above the minimum bound of 350 GeV, so such a discovery at this phase is not completely discarded. In any case, even if no discoveries are made at the 7 TeV run, the exclusion limits that will be established are still valuable for setting up the scenario for the 14 TeV run. The 7 TeV discovery reach results are summarized in Table III.

TABLE II. Exclusion limits for doubly charged bileptons with respect to LHC's integrated luminosity and 331 exotic quark masses at the 7 TeV run. Masses are in GeV.

	Integrated luminosity		
M_Q	1 fb^{-1}	5 fb^{-1}	10 fb^{-1}
400	427	466	483
600	478	534	566
800	478	534	566

TABLE III. Discovery mass reach for doubly charged bileptons with respect to LHC's integrated luminosity and 331 exotic quark masses at the 7 TeV run. Masses are in GeV.

	Integrated luminosity		
M_Q	1 fb^{-1}	5 fb^{-1}	10 fb^{-1}
400	415	454	535
600	459	511	542
800	459	515	544

TABLE IV. Discovery mass reach and exclusion limits for doubly charged bileptons with respect to sLHC and 331 exotic quark masses. Masses are in GeV.

M_Q	Discovery	Exclusion
400	1100	1170
600	1150	1220
800	1230	1300

B. sLHC

The upgrade of the LHC machine, also referred to as the sLHC [27] project aims at increasing the peak luminosity by a factor of 10 and delivers approximately 3000 fb^{-1} to the experiments. Although it is rather difficult to foresee what would be interesting to study at the sLHC without having the LHC run at its nominal luminosity first, here we assume that no vector bilepton signals were found at the LHC and explore the sLHC exclusion and discovery potentials for the exotic particles. Using the same techniques described in the previous sections, we find the exclusion potential for three heavy quark masses: 1170 GeV for $M_Q = 400$ GeV, 1220 GeV for $M_Q = 600$ GeV, and 1300 GeV for $M_Q = 800$ GeV. The discovery potential is also increased: 1100 GeV for $M_Q = 400$ GeV, 1150 GeV for $M_Q = 600$ GeV, and 1230 GeV for $M_Q = 800$ GeV. This represents a gain of ~200 GeV in terms of discovery mass reach compared to the default luminosity 14 TeV LHC run. This region is certainly worth exploring since it is still considerably below the upper limit of 3.5 TeV that we discussed in Sec. II. The results for the sLHC are displayed in Table IV.

VI. CONCLUSIONS

We have investigated the LHC potential for discovering or setting limits on doubly charged vector bileptons in different scenarios considering important experimental aspects in the simulation such as detector geometrical acceptance, luminosity uncertainty, and lepton efficiency. By analyzing the observable final state $e^{\mp}e^{\mp}\mu^{\pm}\mu^{\pm}$, we have found that bilepton signatures can already be observed at very early stages of LHC running with 14 TeV, if the bilepton mass is not much greater than 400 GeV. On the other hand, if the bilepton mass lies in the TeV scale, at least 10 yr of the machine operation will be needed for discovering it, if $M_Q > 600$ GeV. The observation of such signal, in combination with Z'_{331} searches in dilepton channel, would provide a very powerful way of discriminating between 331 models and other beyond standard model scenarios that also predict heavy neutral gauge bosons. If no signal is observed, the LHC can extend considerably the current limits on bilepton mass by direct search in the four lepton final state.

At the current LHC energy, 7 TeV, masses up to 566 GeV can be excluded and if 10 fb^{-1} of data is recorded, vector bilepton masses up to 544 GeV could be discovered. We also found that the sLHC can expand the lower exclusion limits up to a mass of 1300 GeV.

We also made a revision on current experimental bounds on bileptons in 331 models and the possibility of results from the LHC to exclude some versions of these models. We found that it is not possible to safely discard any 331 model, including its minimal version, at the LHC. Purely theoretical arguments taken from the literature are used to draw this conclusion.

Furthermore, we investigated how the heavy quark sector of the 331 model influences our results. In some cases a substantial change in the process cross section is observed by varying the value of the heavy quark masses. Since some of the best previous limits on bileptons were coming from experiments containing at least one leptonic beam, we conclude that new results from the LHC will be indispensable in determining to a more accurate extent which models like 331 can be disfavored or discovered. The final state studied in this article will be the best channel to experimentally determine this.

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