Trimuon production at the LHC

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(Received 16 December 2019; published 28 January 2020)

No process without a standard model (SM) background has been observed so far. As a tool in the study of a class of models containing doubly charged vector bileptons, we propose one such process that, violating lepton flavor number conservation, has no contribution from the SM: $pp \to \mu^+\mu^+\mu^- e^-$. By carefully isolating the parameters to keep them free, we are able to acquire a notion of how a possible PMNS-like matrix present in the relevant charged current parametrization could affect the observables. We find that an interesting section of the space of parameters can be explored at the current LHC in the specified conditions.

DOI: 10.1103/PhysRevD.101.015024

I. INTRODUCTION

The Large Hadron Collider (LHC) has reached an excited stage of a large amount of data collection. Even though conclusive hints for new physics have been evasive, current data and the data that are expected to be collected at the high-luminosity (HL) stage open the possibility of turning the LHC into a precision machine.

In this paper, we explore the prospects for the LHC to discover doubly charged vector bileptons with the current luminosity. Most of the processes considered to find new physics have a SM background. This is not the case for the process $pp \to \mu^+\mu^+e^-e^-(e^+e^+\mu^-\mu^-)$ [1], or the trimuon events $pp \to \mu^+\mu^+\mu^-e^-$, both of which violate the conservation of lepton flavor number, which is conserved to all orders in perturbation theory within the SM. Hence, having no background, this sort of process may be the smoking gun of new physics and, specifically, of the discovery of doubly charged particles, which are, in many models, the biggest candidates to trigger these processes.

Doubly charged particles appear in multiple scenarios beyond the standard model (BSM) with extended gauge groups; they may be scalars, fermions, or vectors: see Ref. [2] and references therein. Among the possibilities, the most interesting one is the case of doubly charged *vector* bosons, because (i) their couplings with leptons have almost the same intensity as the $W^\pm$ of the SM, and (ii) this kind of particle is a very rare feature in models of new physics. They occur, for example, in the minimal 3-3-1 model (m331 for short) [3–5], and in $SU(15)$ grand unification [6,7].

If these sorts of particles do exist, then resonances in like-sign leptons' invariant mass could be observed at the LHC [8] in the (sub)process $U^{++} \to \ell^+\ell^+$. Interesting cases include when $pp \to e^+e^+\mu^-\mu^-$ [1] and when $pp \to \mu^+\mu^+\mu^-\mu^-$ [9,10].

This paper is organized as follows: In Sec. II, we write down the interactions relevant for our analysis. In Sec. III, we describe the method and present our results. Our conclusions are presented in Sec. IV.

II. INTERACTIONS

The lepton-lepton-bilepton interaction that is relevant to the present analysis is the following:

$$\mathcal{L}_{\ell\ell} = -i\frac{g}{4\sqrt{2}}\bar{\ell}^c\gamma^\mu(A-\gamma_5 B)\ell U_\mu^{--} + \text{H.c.} \tag{1}$$

For general A and B matrices, this is a model-independent parametrization for vector and axial interactions. We will focus here on a large class of models in which the charged lepton mass matrix is diagonalized by a biunitary transformation given by $\hat{M}^\ell = V_L^{\ell\dagger}M^\ell V_R^\ell$, defining $\ell'_{L,R} = V^\ell_{L,R}\ell_{L,R}$ and $\hat{M}^\ell = \text{diag}(m_e, m_\mu, m_\tau)$, where the primed fermions are symmetry eigenstates and the unprimed ones are mass eigenstates. In this scenario, A is an antisymmetric matrix given by $A = V_U - V_U^T$, while B is symmetric and obeys $B = V_U + V_U^T$, where $V_U = (V_R^\ell)^T V_L^\ell$.

In a model-independent way, the significant production mechanism of the bileptons is through Drell-Yan-like processes. We will need the bilepton-bilepton-Z interaction, generally given by

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$$\mathcal{L}_{UUZ} = i\frac{g}{2}f(g,v)\{U^{++}_{\mu}[U^{--}_{\alpha}(\partial_{\mu}Z_{\alpha}) - Z_{\alpha}(\partial_{\mu}U^{--}_{\alpha})] + U^{--}_{\nu}[Z_{\alpha}(\partial_{\nu}U^{++}_{\alpha}) - U^{++}_{\alpha}(\partial_{\nu}Z_{\alpha})] + Z_{\alpha}[U^{++}_{\mu}(\partial_{\alpha}U^{--}_{\mu}) - U^{--}_{\mu}(\partial_{\alpha}U^{++}_{\mu})]\}, \quad (2)$$

where $f(g,v)$ is a dimensionless function of the gauge coupling constants and of the vacuum expectation values of the model. Distinctive possible values for $f(g,v)$ include (i) $f(g,v) = 2c_W$, which is the corresponding value of the SM W^+W^-Z vertex, and (ii) $f(g,v) = -(1-4s_W^2)/c_W$, which is the vertex of the m331 model in a possible SM limit [11] if we use $g_X^2/g^2 = s_W^2/(1-4s_W^2)$, where g_X, g are the gauge coupling constants of $U(1)_X$ and $SU(3)_L$, respectively, and s_W, c_W are the sine and cosine of the weak angle. Below we will consider only the latter case. Notice that in the m331 model, the vector bilepton is Z-phobic.

The last required Lagrangian is that of the bilepton-bilepton-photon interaction, which is

$$\mathcal{L}_{UUA} = i2Q_e(g)\{U^{++}_{\mu}[U^{--}_{\alpha}(\partial_{\mu}A_{\alpha}) - A_{\alpha}(\partial_{\mu}U^{--}_{\alpha})] + U^{--}_{\nu}[A_{\alpha}(\partial_{\nu}U^{++}_{\alpha}) - U^{++}_{\alpha}(\partial_{\nu}A_{\alpha})] + A_{\alpha}[U^{++}_{\mu}(\partial_{\mu}U^{--}_{\mu}) - U^{--}_{\mu}(\partial_{\alpha}U^{++})]\}; \quad (3)$$

here $Q_e(g)$ is the expression for the fundamental charge within the considered model, which, in general, is a function of the coupling constants. In our calculations, we will set $Q_e(g) = gs_W$, which is the corresponding electrical charge of the SM and also of the m331 when using, again, $g_X^2/g^2 = s_W^2/(1-4s_W^2)$.

III. LHC PHENOMENOLOGY

As mentioned before, we will focus on the phenomenology of the vector bileptons at the LHC energy and luminosity. We note that in all the previous analysis, only a diagonal version of Eq. (1) has been considered, and consequently, the trimuon final-state case was not specifically studied either. This may be too restrictive an imposition, since, taking the m331 model as an illustration, it is not possible to assume that the charged lepton mass matrix is in the diagonal basis. This is because to generate the correct mass of these particles, it is necessary to have two contributions arising from different scalar multiplets: a triplet η and a sextet S. The mass matrix coming from the Yukawa interactions between the leptons and the triplet is antisymmetric, while that from the sextet is symmetric. If we choose only the symmetric matrix (forgetting the sextet), the neutrino mass matrix becomes proportional to the charged lepton one, so that they are diagonalized by the same transformations, which, in turn, causes the resulting PMNS matrix to be unity.

In turn, this theoretically (probably) inescapable mixing causes the study of these processes to be very difficult as a consequence of the number of free parameters. For this reason, we perform a study of the trimuon end state with more general nondiagonal mixing matrices, considering only the contribution of the bilepton $U^{\pm\pm}$ together with the SM particles. Of course, we stress that in this case the unitarity of the model is not manifest, but we already know possible ultraviolet completions, say those in Refs. [3,4] or Ref. [7]. Eventually, directed studies of specific models should take all contributions into account.

A. The method

In order to obtain exclusion contours in the two-dimensional parameter space $M_U \times (V_U)_{e\mu}$, where V_U is the unitary matrix introduced below Eq. (1), we study the process $pp \to e^-\mu^-\mu^+\mu^+$ (and its charge mirrored end-state conjugate), which, obviously, has no SM background, and hence may be easily distinguished if it does happen at all in the current experimental reach. However, further simplifications are needed if we are to be able to perform this study without arbitrarily fixing unknown parameters.

We start by recalling that we are considering only contributions containing the $U^{\pm\pm}$ and the SM particles. Diagrams are shown in Fig. 1.

At this point, we would be left with five free parameters: the boson's mass and the three angles and one phase that parametrize a 3×3 unitary matrix—all the matrix elements influence the results, if not explicitly in the vertex, through the particle's width. The next obvious choice of simplification is to make the matrix real, eliminating in this way the phase. At last, we decide to study the case of a symmetric V_U, ending up with three parameters to deal with: the mass and the two real numbers that are the degrees of freedom (d.o.f.) of a 3×3 symmetric orthogonal matrix (actually, there is still one more discrete d.o.f. that labels one of four different solutions of the orthogonality conditions for the

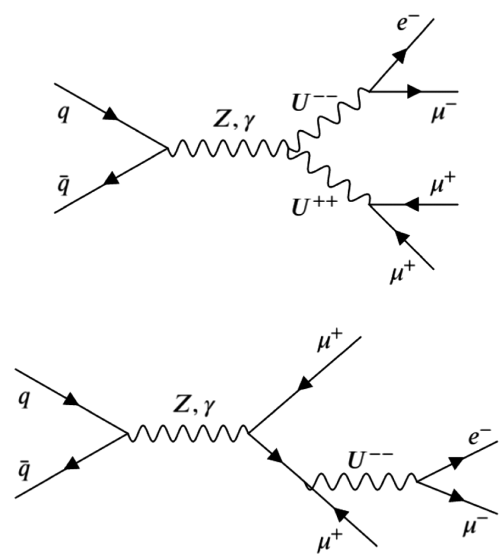

FIG. 1. Representatives of the considered diagrams.

four other matrix elements in terms of two specified ones, but this is not an issue). We stress that these assumptions, although not more strong than necessary for any similar analysis in the present phenomenological context, are not the most general case or a prediction of a specific model.

A consequence of imposing a symmetry condition on V_U is that there are no vectorial interactions between the bilepton and the leptons, since, again, $A = V_U - V_U^T$.

Our goal is to learn what is the behavior of the signal upon the variation of the parameters $m_{U^{\pm\pm}}$ and $(V_U)_{e\mu}$. To do so, we choose the third free parameter from the analysis above to be $(V_U)_{ee}$, which we fix at four different benchmark values: $(V_U)_{ee} = \{0.001, 0.01, 0.1, 0.9\}$. We then perform one bidimensional scan for each value of $(V_U)_{ee}$, for values within 100 GeV $\leq m_{U^{\pm\pm}} \leq$ 1200 GeV in steps of 50 GeV and $0.001 \leq (V_U)_{e\mu} \leq 0.9$—except for $(V_U)_{ee} = 0.9$, when $(V_U)_{e\mu}$ goes up to ∼0.43—through 12 strategically chosen points, with every other matrix element being in each point determined as a solution of the orthogonality constraints. Using the Monte Carlo generator MadGraph, we generated 10 000 events for each of the 1035 points in the parameter space, with the following cuts on transverse momentum, rapidity, and opening angle between leptons:

$$1500\ \text{GeV} > p_{T_\ell} > 30\ \text{GeV}, \qquad |\eta_\ell| < 2.5, \qquad \Delta R_{\ell\ell} > 0.4 \tag{4}$$

at a center-of-mass energy $\sqrt{s} = 13$ TeV and an integrated luminosity of $\mathcal{L} = 140\ \text{fb}^{-1}$. The resulting total cross section of each point is multiplied by 2, to accommodate the charge-reversed end state $pp > e^+\mu^+\mu^-\mu^-$, which has identical numerical results in our case of $(V_U)_{ij} = (V_U)_{ji}$ and is experimentally distinguishable from the original process in principle.

B. Results

The results are presented in Figs. 2 and 3. The y axis is rescaled by a square-root function for better readability of the smaller values of $(V_U)_{e\mu}$. Since there is no background, we present directly contours of the number of events instead of confidence levels. The shown contours in Fig. 2 refer to the occurrence of three events, so that the region to the left of the curves may, in the respective case, be eliminated with a confidence level of 95% (in a Poisson statistic basis and without systematic uncertainties).

We observe that the contour is roughly identical for all $(V_U)_{ee}$, which happens because the orthogonality constraints obligate the matrix elements to conspire in such a way that when [for fixed $(V_U)_{e\mu}$] $(V_U)_{\mu\mu}$ increases, making the numerator of the cross section larger, the width decreases (roughly) exactly the right amount to make it stay the same. We see that the highest mass that may be eliminated in the specified conditions is ∼1100 GeV, for $(V_U)_{e\mu} \sim 0.52$.

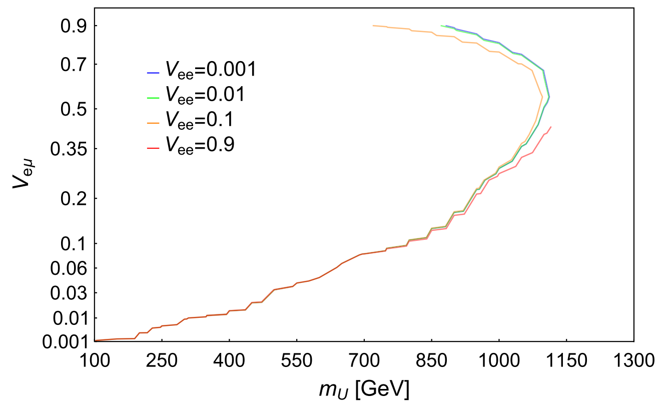

FIG. 2. Occurrence of three events for each value of $(V_U)_{ee}$ considered. The region to the left of the curves may be experimentally eliminated with a 95% confidence level.

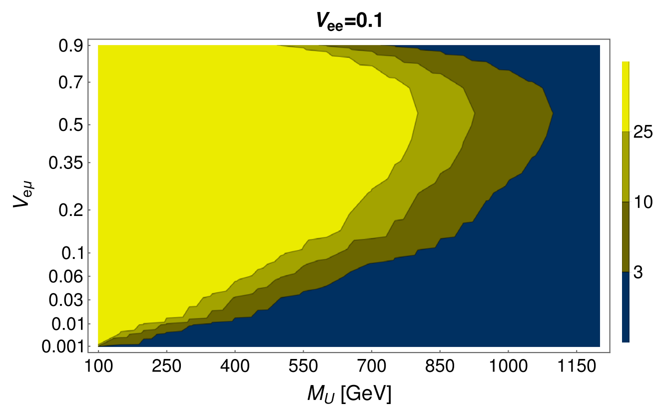

FIG. 3. A more detailed example of the behavior of the number of events. The shown plot is for $(V_U)_{ee} = 0.1$.

IV. CONCLUSIONS

We see that at $\sqrt{s} = 13$ TeV and $\mathcal{L} = 140\ \text{fb}^{-1}$, the trimuon end state may be adequate to explore the possibility of doubly charged vectors with masses up to the TeV scale in favorable cases. Had we chosen to use the SM WWZ vertex for the UUZ interaction, which would be an equally sensible choice, the results would indicate that higher masses could be explored, since in the m331 the U is Z-phobic. By adding other contributions due to the other particles of a given model, unless a fine-tuned negative interference happens, our result that a vector bilepton can be observed at the LHC should not be affected.

Of course, there might be processes that could, theoretically, impose lower limits that are higher than those obtained in this work for the mass of the doubly charged bileptons. One example we have noted is the purely leptonic $\mu \to e\bar{e}e$ decay, which, by an analytical calculation, we observe to be able to explore masses up to 5 TeV if the vector bilepton contribution to that process is predominant [12]. However, in the mentioned reference a heavy sextet was assumed, and the only d.o.f. active at low energies were the three scalar triplets. In contrast, if the d.o.f. of the scalar sextet are active at low energy, light (neutral or doubly charged) scalars may induce large contributions to the $\mu \to e\bar{e}e$ decay, possibly relieving the lower limit for the mass of the boson U.

Concerning the trimuon events, we recall that many years ago this kind of process was apparently observed in several experiments using neutrino-nucleon scattering [13–15]. At that time, it was difficult to accommodate these events in electroweak models with a $SU(2) \otimes U(1)$ symmetry, but not in those with a $SU(3) \times U(1)$ one [16,17]. However, further experiments do not confirm the existence of these events with neutrino energies larger than 100 GeV [18]. If they do occur in nature, perhaps they could be observed at the LHC.

The objective of the present paper was to study the contribution of the vector bilepton alone to a hadronic process with lepton flavor violation, so that we could also make a more skeptical assessment of the unavoidable mixing matrix. Nevertheless, we emphasize that a given closed model that contain such bileptons could accommodate a great number of still free parameters, which makes a truly skeptical phenomenological analysis very complicated, and that eventually, a more detailed study, including more d.o.f. of each said model, cannot be avoided.

We conclude that it is worth continuing to study such processes in a model-dependent way to see, among other things, if, as we expect, there is no negative interference that can suppress the contribution of the vector bilepton $U^{\pm\pm}$, and we urge the LHC to search for this sort of resonance in the context of such models.

ACKNOWLEDGMENTS

M. B. would like to thank CNPq for the financial support, and especially Rodolfo M. Capdevilla for many useful discussions. V. P. would like to thank CNPq for partial support and is also thankful for the support of FAPESP funding Grant No. 2014/19164-6.

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