

Finding the Higgs boson through supersymmetryF. de Campos,^{1,*} O. J. P. Éboli,^{2,†} M. B. Magro,^{2,3,‡} D. Restrepo,^{4,5,§} and J. W. F. Valle^{4,||}¹*Departamento de Física e Química, Universidade Estadual Paulista, Guaratinguetá-SP, Brazil*²*Instituto de Física, Universidade de São Paulo, São Paulo-SP, Brazil.*³*Centro Universitário Fundação Santo André, Santo André-SP, Brazil.*⁴*AHEP Group, Instituto de Física Corpuscular-C.S.I.C./Universitat de València, Edificio Institutos de Paterna, Apt 22085, E-46071 Valencia, Spain*⁵*Instituto de Física, Universidad de Antioquia, Colombia*

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The study of displaced vertices containing two b-jets may provide a double discovery at the Large Hadron Collider (LHC): we show how it may not only reveal evidence for supersymmetry, but also provide a way to uncover the Higgs boson necessary in the formulation of the electroweak theory in a large region of the parameter space. We quantify this explicitly using the simplest minimal supergravity model with bilinear breaking of R-parity, which accounts for the observed pattern of neutrino masses and mixings seen in neutrino oscillation experiments.

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I. INTRODUCTION

By opening the exploration of the new territory of physics at the terascale, the CERN Large Hadron Collider (LHC) is likely to shed light upon the main open puzzle in particle physics, namely, the origin of mass and the nature of electroweak symmetry breaking. Supersymmetry (SUSY) provides an elegant way of justifying the electroweak symmetry breaking mechanism in terms of an elementary Higgs particle, alleviating the so called hierarchy problem [1]. The Higgs boson and the existence of supersymmetry therefore stand out as the main missing pieces in our understanding of fundamental forces, and a lot of effort has been put into their direct observation. Indeed the search for the Higgs boson and for supersymmetry constitutes the main topic in the agenda of the LHC.

In contrast, so far the only established evidence for physics beyond the standard model (SM) has been the discovery of neutrino masses and oscillations [2], which has culminated decades of painstaking efforts.

Here we stress that these two issues may be closely related. Indeed, low-energy supersymmetry with broken R-parity [3] provides a plausible mechanism for the origin for neutrino masses and mixings. Indeed, as the bilinear model best illustrates [4], in contrast to the simplest seesaw schemes [5], these may be tested at particle accelerators like the LHC.¹

Here we consider the simplest ansatz to introduce R-parity breaking in supersymmetry, characterized by an additional bilinear violating (BRpV) term in the superpotential [9]. It provides the simplest effective description of a more complete picture containing additional neutral heavy lepton [10] superfields whose scalars drive the spontaneous breaking of R-parity [11].

Our focus here is on the specific case of a minimal gravity mediated supersymmetry breaking model with bilinear R-parity violation: BRpV-mSUGRA model for short. In this model, the lightest supersymmetric particle (LSP) is no longer stable. Current neutrino oscillation data indicate that the strength of the BRpV term is small [9], hence the LSP decay length is expected to be long enough to provide a displaced vertex at the LHC [12,13]. For a low Higgs mass the dominant decay is into $b\bar{b}$, however at the LHC the overwhelming QCD background makes this signal irrelevant when the Higgs is produced in the standard way. In supersymmetry the Higgs can be produced after the decay chains of the next-to-lightest supersymmetric particle. In the R-parity conserving case for specific spectrum and supersymmetric production, the additional jets and the missing energy can allow the discovery of the Higgs in the b channel [14]. The same features also hold in our case, but in addition now the Higgs can be produced from the lightest neutralino, leading to events with a displaced vertex with two large invariant mass b-jets. The signal of a neutralino into a Higgs and a neutrino is therefore free of SM backgrounds if the neutralino decays inside the pixel detector and well outside the interaction point. Here we show explicitly that this is the case.²

In this work we analyze the potential of the LHC to survey the existence of the Higgs boson using a novel

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¹Such a model has no conventional neutralino dark matter, though other possible dark matter candidates may be envisaged such as the axion [6], the majoron [7], the axino, or the gravitino [8].

²In fact the LHCb Collaboration is considering the possibility of searching for b's originating outside the interaction point [15].

signal: a b-jet pair coming from displaced vertices generated by the lightest neutralino decays within the BRpV-mSUGRA model. We demonstrate that the LHC reach is capable of uncovering a supersymmetric Higgs in a fair region of the $M_{1/2} \otimes M_0$ parameter plane.

II. MODEL DESCRIPTION

The BRpV model is described by the superpotential

$$W_{\text{BRpV}} = W_{\text{MSSM}} + \varepsilon_{ab} \epsilon_i \hat{L}_i^a \hat{H}_u^b, \quad (1)$$

in which the standard minimal supersymmetric model (MSSM) is supplemented by three extra bilinear terms characterized by three new parameters (ϵ_i), one for each fermion generation. In addition to these we must also include new soft supersymmetry breaking terms (B_i) in whose presence the bilinears become physical parameters that cannot be rotated away [16],

$$V_{\text{soft}} = V_{\text{MSSM}} - \varepsilon_{ab} B_i \epsilon_i \tilde{L}_i^a \tilde{H}_u^b. \quad (2)$$

The new terms in the BRpV Lagrangian (ϵ_i , B_i) lead to the explicit violation of lepton number as well as R-parity. Furthermore, the sneutrino fields acquire a vacuum expectation value (VEV) when we minimize the scalar potential.

In BRpV models the terms presenting explicit lepton number violation, as well as the sneutrino vacuum expectation values, generate mixing among neutrinos and neutralinos giving rise to one tree-level neutrino mass. The other two neutrino masses are generated through loop diagrams [9]. One can show that, indeed, the resulting neutrino masses and mixings provide a good description of all current neutrino oscillation data [2].

For the sake of definiteness, we assume mSUGRA as the model of supersymmetry breaking, implying universality of the soft breaking terms at unification. In this case, our model depends upon 11 free parameters, namely

$$M_0, M_{1/2}, \tan\beta, \text{sign}(\mu), A_0, \epsilon_i, \quad \text{and} \quad \Lambda_i, \quad (3)$$

where $M_{1/2}$ and M_0 are the common gaugino mass and scalar soft SUSY breaking masses at the unification scale, A_0 is the common trilinear term, and $\tan\beta$ is the ratio between the Higgs field VEV's. For convenience, we trade the soft parameters B_i by $\Lambda_i = \epsilon_i v_d + \mu v_i$, where v_i is the vacuum expectation value of the sneutrino fields, since the Λ_i 's are more directly related to the neutrino masses; for further details see [9].

The bilinear R-parity violating interaction gives rise to mixings between SM and SUSY particles that lead to decay of the LSP into SM particles. In a large fraction of the parameter space the lightest neutralino is the LSP and it can decay into leptonic final states $\nu \ell^+ \ell'^-$, where $\ell = e, \mu, \text{ or } \tau$, as well as into semileptonic final states $\ell q' \bar{q}$ or $\nu q \bar{q}$. For sufficiently heavy neutralinos these decays are dominated by two-body channels like νZ , $\ell^\pm W^\mp$, and νh with h being the lightest CP-even Higgs boson; for further

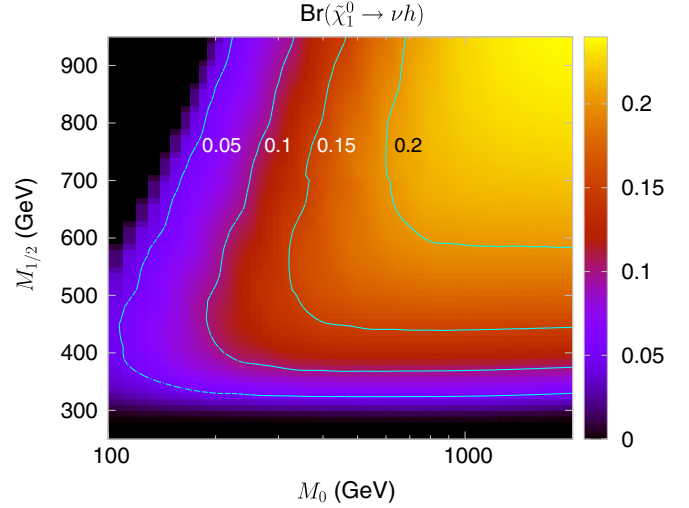


FIG. 1 (color online). $\text{Br}(\tilde{\chi}_1^0 \rightarrow h\nu)$ as a function of $M_{1/2} \otimes M_0$ for $\tan\beta = 10$, $A_0 = -100$ GeV, and $\mu > 0$.

details see [13,17,18]. In the region where the stau is the LSP the detached vertex signal disappears completely since the stau possesses a very small decay length.

In contrast, a salient feature of our BRpV model is that neutralino LSP's exhibit a rather large decay length, ranging from a few millimeters to tenths of millimeters for $M_{1/2}$ varying from 200 GeV to 1 TeV. Such large decay lengths lead to the production of detached vertices at the LHC which constitute a smoking gun of this kind of model.

In this work, we analyze the two-body lightest neutralino decay into the lightest Higgs boson h^0 as a Higgs discovery channel

$$\tilde{\chi}_1^0 \rightarrow h\nu. \quad (4)$$

If the lightest neutralino lives long enough it will be detached from the primary interaction point leaving a displaced vertex as signal at the LHC. Since the Higgs boson h decays mostly into a b-quark pair we expect a displaced vertex with two b-jets as a characteristic signature for Higgs production.

We present, in Fig. 1, the lightest neutralino branching ratio to $h\nu$ as a function of $M_{1/2} \otimes M_0$ for $\tan\beta = 10$, $A_0 = -100$ GeV, and $\mu > 0$.³ Here we focus on the situation where the lightest neutralino is heavier than h , so the neutralino Higgs decay channel opens for $M_{1/2} \gtrsim \mathcal{O}(300)$ GeV for our choice of parameters. The maximum value of the branching ratio for this channel is about 22%; for an illustration of the full behavior of neutralino decays see, for example, Refs. [13,17,18]. This figure tells us that, for fixed values of $M_{1/2}$, the LSP branching ratio into Higgs-neutrino pairs initially grows with increasing M_0 , stabilizing for M_0 in excess of a few hundred GeV. On the

³We note that in the upper left dark region the stau is the LSP and in what follows we will not consider this region.

other hand, the importance of this decay increases with $M_{1/2}$ for moderate and large values of M_0 .

III. SIGNAL AND BACKGROUNDS

In order to simulate the Higgs production we calculate all R-parity violating branching ratios and SUSY spectra using the package SPHENO [19]. We used PYTHIA version 6.408 [20] to generate events, using the SPHENO output in the SLHA format [21]. In order to have a rough simulation of the detector response we smeared the track energies, but not their directions, with a Gaussian error given by $\Delta E/E = 0.10/\sqrt{E} + 0.01$ (E in GeV) for leptonic tracks and $\Delta E/E = 0.5/\sqrt{E} + 0.03$ for all hadronic tracks.

Displaced vertices at the LHC were identified requiring that the neutralino decays away from the primary vertex point, that is, outside an ellipsoid centered at the primary vertex

$$\left(\frac{x}{5\delta_{xy}}\right)^2 + \left(\frac{y}{5\delta_{xy}}\right)^2 + \left(\frac{z}{5\delta_z}\right)^2 = 1, \quad (5)$$

where the z axis is along the beam direction. To be conservative we assumed the ellipsoid size to be 5 times the ATLAS experiment's expected precision in both directions for the semiconductor tracker [22] which are $\delta_{xy} = 20 \mu\text{m}$ and $\delta_z = 500 \mu\text{m}$. To reconstruct the vertices we required that visible tracks coming from neutralino decays must have an intersection inside a sphere determined by the tracking detector resolution which we assumed to be $10 \mu\text{m}$ [22]. Furthermore, we considered only the charged tracks inside the pseudorapidity region of $|\eta| < 2.5$.

Since the Higgs production in the LSP decay is characterized by the presence of two b-tagged jets we looked for events with at least one displaced vertex containing at least one jet tagged as a b-jet. In our analyses we considered a b-tagging efficiency up to 50%.

In order to ensure that the detached vertex events are properly recorded we accepted only events that pass very simple trigger requirements. We further required the events to present an isolated electron (muon) with $p_T > 20(6) \text{ GeV}$, or the presence of a jet with $p_T > 100 \text{ GeV}$, or missing transverse energy in excess of 100 GeV .

For our analysis we have fixed $\tan\beta = 10$, $A_0 = -100 \text{ GeV}$, and $\mu > 0$. For this choice of parameters, the Higgs mass lies in the range $110 \text{ GeV} \lesssim M_h \lesssim 120 \text{ GeV}$ when we vary M_0 and $M_{1/2}$. Since we are only interested in detached jets coming from Higgs decays, we have further required that the jet-jet invariant mass is around the Higgs mass value.

Within the SM framework displaced vertices originate from decays of long lived particles like B 's and τ 's, and consequently its visible decay products exhibit a rather small invariant mass. In contrast, in our BRpV model, the displaced vertices are associated with the LSP decay and will have in general a large invariant mass associated

with them. Therefore, physical SM processes do not lead to sizable backgrounds to the detached Higgs searches due to large difference in the invariant mass of the visible products. However, BRpV LSP decays into νZ are a potential source of background for the Higgs signal.

As an illustration we show in Fig. 2 the jet-jet invariant mass distribution of all displaced vertices exhibiting jets. As we can see, a cut on the invariant mass outside the range $100 \text{ GeV} < M_{\text{inv}} < 125 \text{ GeV}$ eliminates a good fraction of supersymmetric backgrounds coming, for instance, from the neutralino decay into W and Z bosons as well as the three-body $b\bar{b}\nu$ channel. The physical background can be further suppressed by requiring that at least one of the jets associated with the displaced vertex is tagged as a b-jet. Moreover, these requirements ensure that SM backgrounds coming from the decay of long lived particles are also efficiently eliminated. There remain instrumental backgrounds [23] which require a full detector simulation along the lines we have described above; this simulation is beyond the scope of the present work.

In Fig. 3 we show that almost all vertices containing b-jets come from neutralino decay via Higgs and that our invariant mass cut will eliminate the νZ background, while keeping a large fraction of the signal events. We checked that the events passing the LHC triggers and all the above cuts come from the signal events $\tilde{\chi}_1^0 \rightarrow \nu h$ with the physics background being negligible.

In order to estimate the LHC reach for Higgs search coming from displaced vertex signal in BRpV-mSUGRA

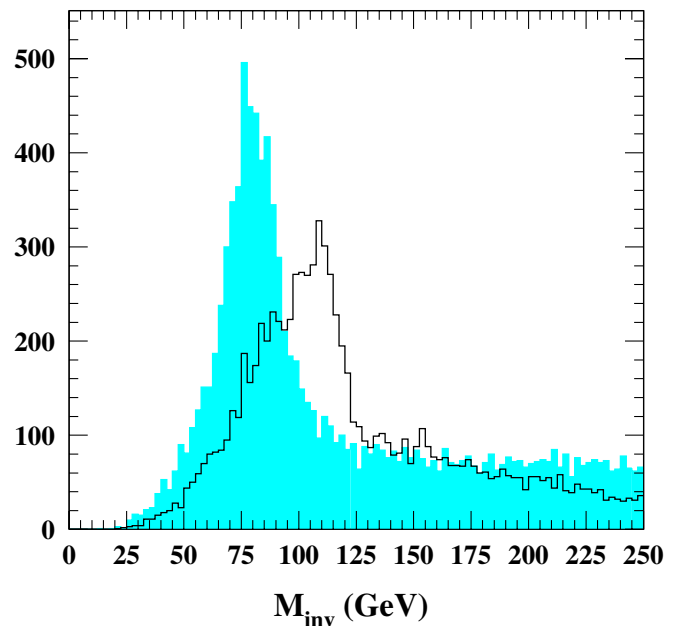


FIG. 2 (color online). Jet pair invariant mass distribution in GeV. The light blue (grayish) histogram stands for the background where the lightest neutralino decays via W and Z bosons and the other histogram stands for the channels where the lightest neutralino decays into $b\bar{b}$ pairs.

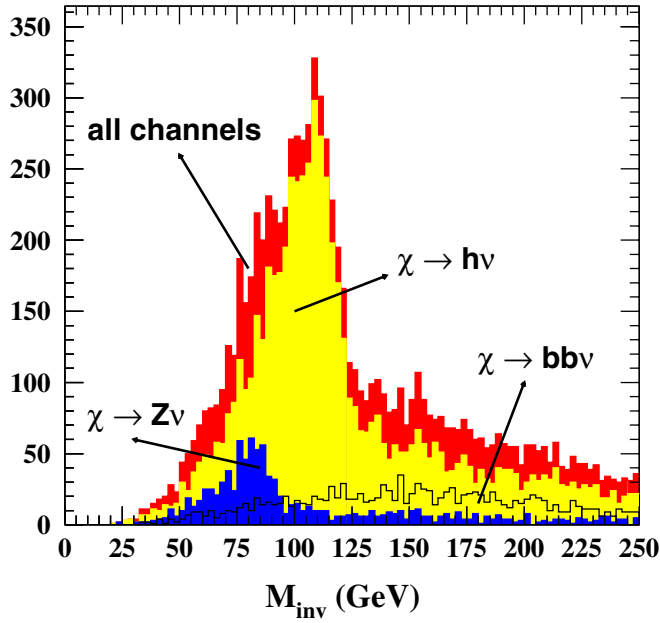


FIG. 3 (color online). Invariant mass distribution in GeV of the neutralino decaying into b-jet pairs separated into its several channels.

models we considered a few scenarios. In the optimistic analysis we assumed that there is no event coming from instrumental backgrounds or overlapping events and took the b-tagging efficiency to be 50%. In this case we required that the signal must have more than five events since no background is expected and present our result in the $M_{1/2} \otimes M_0$ plane for integrated luminosities of 10 and 100 fb^{-1} . We also considered three additional scenarios. In the first one we studied the impact of a lower b-tagging efficiency (30%) but we still assumed that the process is background free. In the second case we assumed that there are five background events originating from instrumental errors and overlapping events and required a 5σ signal for a 50% b-tagging efficiency. Finally, in the last scenario we assumed the same background as in the last case, lowering however the b-tagging efficiency down to 30%.

IV. RESULTS

In Fig. 4 we depict the LHC discovery reach for the Higgs displaced vertex signal in our most optimistic scenario. The shaded (yellow) region at the bottom stands for points already excluded by direct LEP searches while the upper left corner of the $M_{1/2} \otimes M_0$ plane, the (red) shaded area has staus as LSP [13], and hence is not covered by the present analysis. The region around $M_{1/2} = 200$ GeV has no signal due to the fact that the neutralino mass is smaller than the Higgs mass in it, therefore, being forbidden the two-body LSP decays into Higgs-neutrino pairs.

From Fig. 4 one can see that the ATLAS and CMS experiments will be able to look for the signal up to $M_{1/2} \sim 700(900)$ GeV for a LHC integrated luminosity of

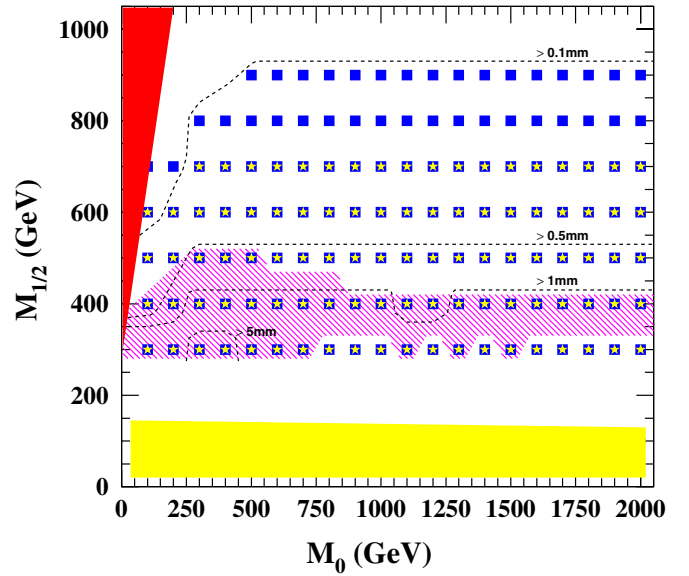


FIG. 4 (color online). LHC reach for Higgs search in displaced vertices for the BRpV-mSUGRA model in the plane $M_{1/2} \otimes M_0$ assuming $\tan\beta = 10$, $A_0 = -100$ GeV, and $\mu > 0$. The yellow stars (blue squares) represent the reach for an integrated luminosity of 10(100) fb^{-1} while the crosshatched region corresponds to the reach of the LHCb experiment for an integrated luminosity of 10 fb^{-1} . The (yellow) shaded region at the bottom stands for points excluded by direct LEP searches, while the (red) upper left area represents a region where the stau is the LSP. Note that the black lines delimit different regimes of LSP decay length.

10(100) fb^{-1} . Notice that the LHC Higgs discovery potential is almost independent of M_0 . For a fixed value of $M_{1/2}$ the LSP total production cross section decreases as M_0 increases, however, the LSP branching ratio into Higgs-neutrino pairs increases with M_0 , therefore, both effects tend to cancel and produce the observed behavior. Moreover, this figure also exhibits the average decay length of the neutralino, demonstrating that its decay takes place inside the vertex detector, ensuring a good vertex reconstruction.

We have also estimated the reach expected at LHCb for our Higgs search proposal. The crosshatched region in Fig. 4 indicates the LHCb reach for 10 fb^{-1} . Because of the strong cut on the pseudorapidity required by this experiment, the reach for 2 fb^{-1} is severely depleted and only a small region of the parameter space is covered, i.e., $300 \text{ GeV} \leq M_{1/2} \leq 350 \text{ GeV}$ and $200 \text{ GeV} \leq M_0 \leq 500 \text{ GeV}$.

Tagging b-jets emanating from a detached vertex is certainly a more intricate procedure, therefore, we also considered a lower b-tagging efficiency in our analyses. Figure 5 contains the reach of LHC for Higgs search using a b-jet reconstruction efficiency of 30%, instead of 50% used of Fig. 4, however, we still assumed that the search is background free. Comparing Figs. 4 and 5, one can see that

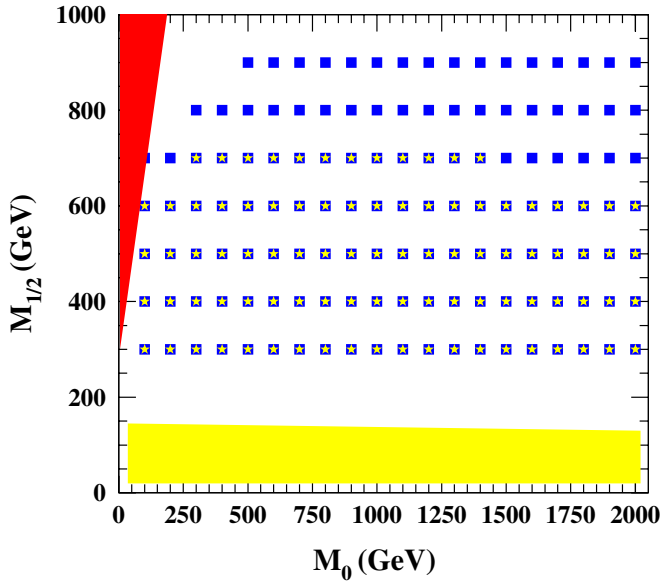


FIG. 5 (color online). Same as Fig. 4 using a b-jet reconstruction efficiency of 30% with no background events.

the LHC reach in this second case is mildly affected by this change for an integrated luminosity of 10 fb^{-1} , while the changes are minute at higher integrated luminosities.

A study of the instrumental backgrounds and the effect of overlapping events does require a full detector simulation, which is beyond the scope of this work. In order to assess the impact of existence of nonphysical backgrounds we considered that these backgrounds give rise to five background events for both integrated luminosities used in our studies. In Fig. 6 we present the 5σ LHC Higgs

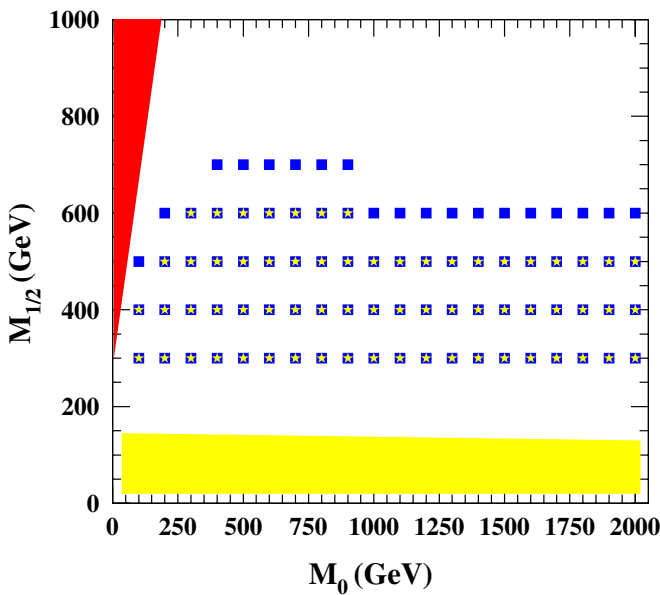


FIG. 6 (color online). Same as Fig. 4 using a b-jet reconstruction efficiency of 50% and assuming the existence five background events for both integrated luminosities.

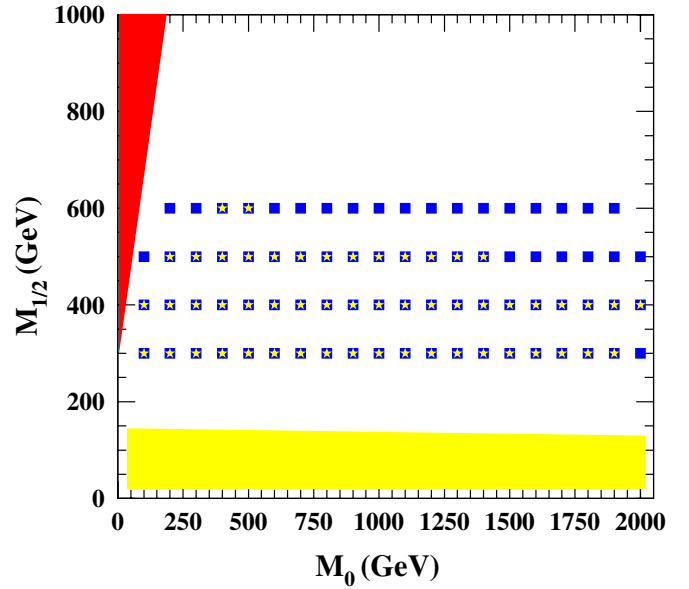


FIG. 7 (color online). Same as Fig. 4 using a b-jet reconstruction efficiency of 30% and five background events.

discovery potential assuming a b-jet reconstruction efficiency of 50% and five background events. We can see from this figure that the existence of background events does lead to a substantial reduction of the LHC reach for Higgs in displaced vertices.

In Fig. 7 we present the reach of LHC for Higgs search in a very pessimistic scenario that exhibits a lower b-jet reconstruction efficiency of 30%, as well as the presence of five background events. In this case we observe a more severe reduction of the LHC reach that is reduced to $M_{1/2} = 600 \text{ GeV}$ at most. This large depletion of the LHC search potential follows from the need of a large number of signal events to establish the signal given the fast decrease of the SUSY production cross section with increasing $M_{1/2}$. In this sense, the 100 fb^{-1} case is more affected since the production cross section exhibits a steep decrease for $M_{1/2} \gtrsim 700 \text{ GeV}$.

V. CONCLUSIONS

In summary we have seen how the search for displaced vertices containing b-tagged jets at the LHC may not only provide evidence for supersymmetric particles but also lead to the discovery of the Higgs boson of the electroweak theory. We have given a quantitative analysis within the simplest minimal supergravity model with bilinear breaking of R-parity, which accounts for the observed pattern of neutrino masses and mixings observed in current neutrino oscillation experiments. Similar variant schemes can be envisaged where, for example, supersymmetry and/or electroweak breaking is realized differently.

In an optimistic background free scenario, the Higgs search in LSP decays can be carried out for LSP masses

up to 300 (380) GeV for an integrated luminosity of $10(100) \text{ fb}^{-1}$. We showed that this result is robust against variations of the assumed b-tagging efficiencies. Notwithstanding, the results change drastically if instrumental backgrounds are present. Assuming the existence of five background events reduces the LHC reach to LSP masses of 210 (250) GeV at the low (high) luminosity run.

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