Displaced vertices in GMSB models at LHCb

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We consider minimal Gauge Mediated Supersymmetry Breaking models at which the next to lightest supersymmetric particle is a neutralino with a large enough decay length to be detected at the CERN Large Hadron Collider. We analyze the potential of the LHCb experiment to determine the discovery reach for such models and found that the LHCb will be able to probe such models up to the energy breaking scale of $\Lambda = 130$ TeV.

PACS numbers: 14.80.Nb, 13.85.Rm, 12.60.Jv

I. INTRODUCTION

Elucidating the electroweak breaking sector of the Standard Model (SM) constitutes a major challenge for the Large Hadron Collider (LHC) at CERN. Supersymmetry provides an elegant way to stabilize the Higgs boson scalar mass against quantum corrections provided supersymmetric states are not too heavy, with some of them expected within reach for the LHC. Searches for supersymmetric particles constitute an important item in the LHC agenda [1–10], as many expect signs of supersymmetry (SUSY) to be just around the corner and, indeed, some SUSY searches has been done recently by the ATLAS experiment [11]. However, the first searches up to $\sim 5 \, \text{fb}^{-1}$ at the LHC interpreted within specific frameworks, such as Constrained Minimal Supersymmetric Standard Model (CMSSM) or minimal supergravity (mSUGRA) indicate that squark and gluino masses are in excess of $\sim 1$ TeV [12].

Despite intense efforts over more than thirty years, little is known from first principles about how exactly to realize or break supersymmetry. As a result one should keep an open mind as to which theoretical framework is realized in nature, if any. Here, we consider gauge mediated supersymmetry breaking models (GMSB) in which SUSY is broken in a hidden sector by messanger fields which interacts with the SM sector through gauge mediated interactions [13, 14]. In these scenarios, the lightest supersymmetrical particle (LSP) is the gravitino, presenting a mass below the keV scale, while the next-to-lightest supersymmetrical particle (NLSP) is, most of the time, the lightest neutralino. Since, in most of the parameter space spectrum, the coupling between the gravitino and the lightest neutralino is small, the decay length of the NLSP is usually large and it may produce displaced vertices that can be detected at LHC.

The LHCb experiment consists of a front-end detector mainly designed to investigate b-physics and, therefore, is very sensitive to performing displaced vertices searches. In this work, we consider the capability of the LHCb to detect displaced vertices coming from the lightest neutralino decays in the framework of GMSB models. The paper is organized as follows. In Sec. II, we present a brief resume of the caracteristcs of GMSB models, pinpointing the large decay length of the NLSP. In Sec III, we show the details of our signal simulation and the analysis of the results. Finally, in Sec. IV, we draw our conclusions and comments regarding recent ATLAS and CMS higgs search results.

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II. GAUGE MEDIATED SUPERSYMMETRY BREAKING MODELS

Gauge Mediated Supersymmetry Breaking models are well motivated, since they can solve the SM hierarchy problem by the introduction of supersymmetric partners, as well as the SUSY flavour problem by the gauge mediation. GMSB models assume that SUSY is dynamically broken by the introduction of messanger fields in a hidden sector where they couple with the SM fields through gauge mediated interactions. In this way, such GMSB models are defined by six parameters

\[ \Lambda, M_m, \tan \beta, \text{sign}(\mu), N_5, C_{grav}, \]

where \( \Lambda \) is the energy scale of the breaking, \( M_m \) is the messenger mass scale, \( \mu \) is the Higgs mass term, \( \tan \beta \) is the ratio between the Higgs field vacuum expectation values (vevs), \( N_5 \) is the number of messenger chiral supermultiplets and \( C_{grav} \) is the scale factor of the gravitino mass. In the minimal realization of GMSB we take \( N_5 = 1 \) and \( C_{grav} = 1 \).

In such models the gravitino is the lightest supersymmetric particle and the next to LSP is commonly the lightest neutralino, \( \tilde{\chi}_1^0 \), and it usually decays into a gravitino via the following channels

\[ \tilde{\chi}_1^0 \rightarrow \tilde{G} + \gamma; \]
\[ \tilde{\chi}_1^0 \rightarrow \tilde{G} + Z^0; \]
\[ \tilde{\chi}_1^0 \rightarrow \tilde{G} + h^0. \]

Due to the smallness of the neutrino-gravitino coupling, the lightest neutralino may have a lifetime long enough to decay far from the primary vertex of LHC generating a displaced vertex. We show in figure 1 the neutralino decay length distribution for several values of \( M_m \), for \( \Lambda = 80 \) TeV, \( (\mu) > 0 \) and \( \tan \beta = 30 \). Therefore, we can anticipate that the neutralino decay vertex can be observed at the LHCb within a large fraction of the parameter space.
Our analysis aim to study the LHCb experiment potential to probe the lightest neutralino decays exploring its detached vertex signature. We simulated the SUSY particle production using PYTHIA version 6.4.23 where all the properties of GMSB models were included using the SLHA format. The relevant masses, mixings, branching ratios and decay lengths were generated using the SPHENO code.

In our studies we followed the same basic strategy presented in. We used a toy calorimeter roughly inspired by the actual LHCb detector. We assumed a front-end detector with a pseudo-rapidity coverage between $\eta = 1.8$ and $\eta = 4.9$. The calorimeter resolution was included by smearing the energies with an error

$$\frac{\Delta E}{E} = 0.10 \pm 0.01,$$

for leptons. For jets with pseudo-rapidity $\eta > 3$ we have used

$$\frac{\Delta E}{E} = 1.0 \pm 0.10,$$

while for $\eta < 3$ we considered

$$\frac{\Delta E}{E} = 0.5 \pm 0.03.$$

The calorimeter segmentation was assumed to be $\Delta \eta \otimes \Delta \varphi = 0.10 \times 0.098$. Jets were reconstructed using the cone algorithm in the subroutine PYCELL with $\Delta R = 0.7$ and jet seed with a minimum transverse energy $E_{T,mn} = 2$ GeV.

Our analyzes start by selecting events that pass some typical triggers employed by the ATLAS/CMS collaborations, i.e. an event to be accepted should fulfill at least one of the following requirements:

- the event contains one electron or photon with $p_T > 20$ GeV;
- the event has an isolated muon with $p_T > 6$ GeV;
- the event exhibits two isolated electrons or photons with $p_T > 15$ GeV;
- the event has one jet with transverse momentum in excess of 100 GeV;
- the events possesses missing transverse energy greater than 100 GeV.

We then require the existence of, at least, one displaced vertex that is more than $5\sigma$ away from the primary vertex – that is, the detached vertex is outside the ellipsoid

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

where the $z$-axis is along the beam direction. We used the ATLAS expected resolutions in the transverse plane ($\delta_{xy} = 20 \mu m$) and in the beam direction ($\delta_z = 500 \mu m$). To ensure a good reconstruction of the displaced vertex we further required that the lightest neutralino decays within the tracking system, i.e., within a radius of 500 mm and $z$-axis length of 500 mm. In our model the decay lengths are such that this last requirement is almost automatically satisfied; see figure.

We studied the displaced vertices coming from the neutralino decay into $\tilde{G} + Z^0$ with the $Z^0$ subsequently decaying into either a lepton pair or a quark pair. Usually, the $\tilde{G} + \gamma$ decay mode has an on-shell photon and does not produce any displaced vertices, while the $G + h^0$ mode has a very small branching ratio in comparison with our main $Z^0$ mode. Therefore, our main signal contains a displaced vertex either with a opposite sign lepton pair our a jet pair with
Figure 2: LHCb reach for detecting displaced vertices in the plane $\Lambda \times M_m$. The left panel presents the reach for detecting displaced vertices including only leptons in the final state, while the right one stands for the reach with only jets in the final state. The blue(red)(green) squares stand for luminosities of 2(1)(0.5)fb$^{-1}$. In this figure we considered $\tan \beta = 30$, and $\text{sgn}(\mu) > 0$.

high invariant mass. In addition to the basic cuts described above we further required the lepton and jet pair have an invariant mass

$$M_{\text{inv}} > 20 \text{ GeV},$$

(4)
to avoid possible Standard Model (SM) backgrounds. In the case of a lepton pair signal, we further require the both lepton are isolated within a cone of $\Delta R = 0.4$. In this sense, we believe that, apart from instrumental provoked displaced vertices, our signal is essentially background free.

In the left panel of Fig. 2 we depict the LHCb reach using only the lepton pair channel in the plane $\Lambda \times M_m$, with $\tan \beta = 30$ and $\text{sgn}(\mu) > 0$ for different luminosities. The smallness of this signal is due to the lepton isolation requirement which cuts out most of the signal. On the other hand, the jet reconstruction is less restrictive and the LHCb sensitiveness to this channel is higher, as we can observe from the right panel of Fig. 2. Fig. 3 shows the combined LHCb reach, using both lepton and jet pair signals, in the plane $\Lambda \times M_m$, with $\tan \beta = 30$ and $\text{sgn}(\mu) > 0$ for different luminosities. We can see that for luminosities $> 1\text{fb}^{-1}$ the LHCb will be capable of detect displaced vertex signal compatible with GMSB models with breaking scales up to $\Lambda \sim 130 \text{ TeV}$.

IV. CONCLUSIONS

We have analyzed the LHCb potential to detect the lightest neutralino decay via displaced vertices in a scenario with GMSB models. In such models, for a large range of values in the plane $\Lambda \times M_m$, one can have sizeable displaced vertices containing the final states $\ell^+ \ell^-$, ($\ell = e, \mu, \tau$) and di-jets for luminosities that the LHCb will reach in a near future. We saw that the LHCb is capable of probe such models up to $\Lambda < 130 \text{ TeV}$ with a small dependence of the messenger mass $M_m$.

Recent Higgs search results has been performed by ATLAS and CMS experiments at CERN [21] with a result of a Higgs boson with a mass of 125 GeV. However, further studies show that the properties of the detected Higgs
boson may not comply with a SM Higgs. In minimal GMSB models considered here, the lightest Higgs mass is hardly heavier than 118 GeV. Nevertheless, in order to make GMSB models viable, one can think in extensions of the minimal GMSB model where the Higgs mass can receive contributions to be consistent with data. For instance, one can introduce mixings among the messengers and matter that can enlarge the Higgs mass up to the experimental value even in the range of the $\Lambda \times M_m$ plane considered here. Although such models may change the spectroscopy of SUSY, specially in the third family scalar sector, we believe their phenomenology would still be similar to those considered here, since we are mainly interested in the lightest neutralino decay.

Acknowledgments

M.B.M. would like to thank the Departamento de Física–Matemática of Institute of Physics of University of São Paulo for their hospitality.

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