Testing low energy supersymmetry breaking at LHC

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Abstract

If supersymmetry has anything with our World it should be spontaneously broken. There is a class of phenomenologically acceptable models in which supersymmetry breaking scale is low, i.e. at TeV energy scale. In that case one has a possibility to probe the sector responsible for supersymmetry breaking which should contain goldstino (Goldstone fermion) and its superpartners – scalar and pseudoscalar sgoldstinos. Interactions of these particles with Standard Model fields are suppressed by the SUSY breaking scale. We discuss possible experimental program for study the low-energy SUSY breaking scenario at LHC.

1 Introduction

Supersymmetry is a very attractive idea which results in phenomenologically interesting class of the Standard Model (SM) extensions (see, e.g., [1] and references therein). At the moment these models are under extensive study at the LHC. However, exact supersymmetry predicts equal masses for superpartners which is not phenomenologically acceptable. Thus, SUSY, if it has any relation to Nature, should be spontaneously broken. There were proposed several mechanisms to do that. An additional *hidden* sector is introduced where supersymmetry gets broken. The fields of this *hidden* sector are assumed to have no direct (renormalizable) interactions with the SM fields. Besides, some additional fields – messengers – are needed. Their role is to transmit supersymmetry breaking effects from hidden to visible sector. The characteristic energy scale for messenger interactions M varies depending on SUSY breaking mechanism. For gravity mediated models this scale is the Planck scale, while for gauge mediated models the scale M is around the masses of new gauge bosons.

Goldstone theorem tells us that if a usual global symmetry gets spontaneously broken then there should exist a massless boson in the spectrum of the theory. Supersymmetric version of this theorem states that when SUSY is spontaneously broken then there should be a massless fermion – goldstino ψ [2]. In the simplest case the superpartner of goldstino is a complex scalar $\phi = \frac{1}{\sqrt{2}}(S + iP)$ which has two degrees of freedom – scalar S and pseudoscalar P sgoldstinos. Goldstino and sgoldstinos are unified in a single supermultiplet $\Phi = \phi + \sqrt{2}\theta\psi + \theta^2 F_\phi$, where F_ϕ – is an auxiliary field. This last field component can be expressed in terms of other physical fields of the model. However, its special role is that when SUSY gets spontaneously broken this auxiliary field F_ϕ acquires non-zero vacuum expectation value $\langle F_\phi \rangle = F$. The quantity $\sqrt{F}$ has dimension of energy and called scale of supersymmetry breaking.

When standard setup of MSSM (Minimal Supersymmetric Standard Model) or its extensions is considered it is implicitly assumed that the messenger scale M and the SUSY breaking scale $\sqrt{F}$ is much larger then the electroweak scale m_{EW}. And in this case one can safely neglect interactions with goldstino supermultiplet. However, it is possible [3, 4, 5, 6] to have

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the scale $\sqrt{F}$ not very far from electroweak scale, around several TeV. In this case one should include interactions of MSSM fields with goldstino and sgoldstinos. When gravity interactions are turned on goldstino becomes a longitudinal component of gravitino which acquires a mass $m_{3/2} = \sqrt{8\pi/3}F/M_{Pl}$ [7]. Sgoldstinos which are massless at tree level also become massive because of loop quantum corrections. And it is natural in the setup of low-energy supersymmetry breaking to have their masses below electroweak scale. Searching for these particles at the LHC could give us knowledge about the scale of supersymmetry breaking of which MSSM has no information at all. Here we point out several interesting signatures to probe this scenario at LHC and estimate the sensitivity of its experiments to the scale of supersymmetry breaking.

2 Sgoldstino interactions and decays

Goldstino low-energy interactions with MSSM fields are governed by supersymmetric version of Goldstone theorem and the corresponding interaction lagrangian reads [7]

$$\mathcal{L}_\psi = \frac{1}{F} J^\mu_{SUSY} \partial_\mu \psi,$$

where J^μ_{SUSY} is a supercurrent. Sgoldstino interactions with the fields of MSSM sector can be obtained via spurion technique (see e.g. [5]) and the corresponding lagrangian can be obtained from the following effective interactions

$$\mathcal{L}_\Phi = \mathcal{L}_{\Phi-gauge} + \mathcal{L}_{\Phi-superpotential} + \mathcal{L}_{\Phi-K\ddot{a}hler}$$

$$\mathcal{L}_{\Phi-gauge} = \frac{1}{2}\int d^2\theta\ \Phi \cdot \sum_{gauge} \frac{M_\alpha}{F} \mathrm{Tr} W^\alpha W^\alpha + h.c.,$$

$$\mathcal{L}_{\Phi-superpotential} = \int d^2\theta\ \Phi \cdot \epsilon_{ij} \left(\frac{B}{F} H^i_D H^j_U + \frac{A^L_{ab}}{F} L^i_a E^c_b H^j_D + \frac{A^D_{ab}}{F} Q^i_a D^c_b H^j_D + \frac{A^U_{ab}}{F} Q^i_a U^c_b H^j_U \right) + h.c.$$

$$\mathcal{L}_{\Phi-K\ddot{a}ler} = -\int d^2\theta d^2\bar{\theta}\ \Phi^\dagger \Phi \cdot \sum_{matter} \frac{m^2_{kl}}{F^2} \Phi^\dagger_k \mathrm{e}^{g_1 V_1 + g_2 V_2 + g_3 V_3} \Phi_l,$$

where the sum in the second line goes over all gauge groups and the sum in the fourth line goes over all matter supermultiples of the MSSM. The parameters M_α, B, $A^{L,D,U}_{ab}$, m^2_{kl} become soft supersymmetry breaking constants after spontaneous SUSY breaking. Explicit expressions for interactions of component fields after integrating over $\theta, \bar{\theta}$ can be found in Ref. [8]. Here we note that sgoldstino interactions are generically suppressed by unknown high energy scale $\sqrt{F}$. *So, to probe such a scenario high statistics and high luminosity is needed.*

Let us turn to phenomenology of goldstino supermultiplet. First of all, note that the mass of gravitino is very small in the case of low-energy SUSY breaking. For instance, for $\sqrt{F} \sim 10$ TeV one obtains $m_{3/2} \sim 10^{-2}$ eV ! So, gravitino is the lightest supersymmetric particle (LSP) in this scenario. In the case of models with conserved R-parity goldstino is odd with respect to this symmetry and should be produced in pairs in collisions of SM particles. On the other hand, sgoldstinos have even R-parity and thus, production of sgoldstinos is less suppressed as compared to the gravitino production.

A typical picture of branching ratios of sgoldstino is presented in Fig. 1 for the following values of soft SUSY breaking parameters fixed at the electroweak scale: $M_1 = 400$ GeV, $M_2 = 800$ GeV, $M_3 = 1200$ GeV, $A = 700$ GeV (see Ref [9] for details). Branching ratios are governed by the interactions of sgoldstinos to SM fields and hierarchy of soft parameters. One can see that it is preferable for light sgoldstino to decay into gauge bosons and into the heaviest among the possible fermions, while for heavier ($m_{S(P)} \gg m_W, m_t$) sgoldstinos – decay into gravitinos become important and even dominant. Let us note that this branchings pattern does not depend on supersymmetry breaking scale $\sqrt{F}$, but can change when we vary soft SUSY breaking parameters [9], in particular, such decay channels as $S \to PP$, $S \to hh$ or decays involving superpartners can play important role, but we do not discuss here this possibility.

3 Possible signatures of light sgoldstinos at LHC

Sgoldstino interactions with SM particles are very similar to those of the Higgs boson. However, the hierarchy of the corresponding coupling constants is quite different. It is well known that for the Higgs boson the dominating production mechanism at LHC is gluon-gluon fusion even though there are no tree level Higgs coupling to gluons and it appears at one-loop level. For sgoldstino this coupling constant is present already at tree level and it is proportional to the gluino mass. Thus, one can expect that gluon-gluon fusion will be the dominant production channel for sgoldstino as well. This is indeed the case and calculations show that other production channels interesting for the Higgs boson are suppressed by 3-4 orders of magnitude [9, 10]. Example of production cross section for channel $pp \to S \to \gamma\gamma$ is presented in Fig. 2 for different values of $\sqrt{F}$. Comparing this cross section to known $\gamma\gamma$ Standard Model background (see, e.g. [12]) one can conclude that with the high integrated luminosity $L = 3000$ fb^{-1} the models with low energy scale of SUSY breaking can be probed till $\sqrt{F} \sim$ 20-30 TeV depending on hierarchy of soft SUSY breaking parameters.

Another interesting channel is production of sgoldstino in proton-proton collisions in association with an additional jet. Corresponding production cross section is suppressed only by factor of α_s while additional jet can help to suppress the SM background. The case of $\gamma\gamma$ final state is discussed in Ref. [11] and sensitivity to the scale of SUSY breaking for a typical set of soft parameters is presented in Fig. 3.

For relatively light sgoldstinos with masses in a few GeV range it is possible to look for their signatures not in direct production but in decays of some SM particles especially in FCNC decays because of sometimes negligible SM background. Flavor violating decays of SM particles involving sgoldstino were considered in Refs. [11, 13, 14, 15, 16, 18]. They are generally governed by squark or slepton soft mass matrices squared and by soft SUSY-breaking trilinear coupling constants. For sgoldstinos of masses less than several GeV their main decay channels are $\gamma\gamma$, $\pi\pi$, $\tau^+\tau^-$, $c\bar{c}$, $\mu^+\mu^-$ etc. The decay mode to muon-antimuon pair is particularly of interest for CMS studies and in some models (especially in models with nonuniversal hierarchy of the soft parameters) branching to muons can reach about 10% [13].

In the Figs. 4 and 5 we present the results for branching ratios of the the decays $B^0 \to SP$, $B_s \to SP$, $B^0 \to K^0 SP$ and $B^0 \to K^* SP$ as functions of the mass of scalar sgoldstino, when the mass of pseudoscalar sgoldstino is fixed to be $m_P = 0.4$ GeV. Here we consider unitary limit, i.e. we put all masses of superpartners equal to the scale of supersymmetry breaking, which we take to be $\sqrt{F} = 10$ TeV. The details of calculation can be found in Ref. [17]. One can see that searches for these decays in which sgoldstinos go into muon-antimuon pairs could put considerable limits on the models with low-energy supersymmetry breaking.

4 Conclusions and outlook

We discussed interesting applications of the phenomenology of sector responsible for spontaneous supersymmetry breaking which can reveal itself in the case of low-scale supersymmetry breaking. In this scenario low energy theory contains along with usual MSSM lagrangian also goldstino supermultiplet which consists, in the simplest case, of the singlet (almost) massless fermion - goldstino, and two singlet scalars – sgoldstinos. We described several interesting signatures for such a scenario which could be interesting for experiments at LHC. For heavy sgoldstinos (with masses larger than 50-100 GeV it seems that the most effective way to search for them is direct production in proton-proton collisions which proceed in a similar way as for

Higgs boson. While for very light sgoldstinos it is very intriguing to look for these particles in rare flavor violating decays of heavy B. One of the interesting and clear signatures for these searches can be the decays $B^0 \to SP$, $B_s \to SP$, $B^0 \to K^0 SP$ and $B^0 \to K^* SP$ where sgoldstinos eventually decay into muon-antimuon pair. The sensitivity to the scale of supersymmetry breaking at high integrated luminosity of LHC $L \sim 3000$ fb^{-1} can reach $20-30$ TeV depending on parameters of the model.

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References

[1] S. P. Martin, In *Kane, G.L. (ed.): Perspectives on supersymmetry II* 1-153 [hep-ph/9709356].

[2] D. V. Volkov and V. P. Akulov, JETP Lett. **16** (1972) 438 [Pisma Zh. Eksp. Teor. Fiz. **16** (1972) 621]. D. V. Volkov and V. P. Akulov, Phys. Lett. B **46** (1973) 109.

[3] G. F. Giudice and R. Rattazzi, Phys. Rept. **322** (1999) 419 [hep-ph/9801271]; S. L. Dubovsky, D. S. Gorbunov and S. V. Troitsky, Phys. Usp. **42** (1999) 623 [Usp. Fiz. Nauk **169** (1999) 705] [hep-ph/9905466].

[4] J. R. Ellis, K. Enqvist and D. V. Nanopoulos, Phys. Lett. B **147** (1984) 99; J. R. Ellis, K. Enqvist and D. V. Nanopoulos, Phys. Lett. B **151** (1985) 357.

[5] A. Brignole, F. Feruglio and F. Zwirner, Nucl. Phys. B **501** (1997) 332 [hep-ph/9703286].

[6] A. Brignole, J. A. Casas, J. R. Espinosa and I. Navarro, Nucl. Phys. B **666** (2003) 105 [hep-ph/0301121].

[7] S. Deser and B. Zumino, Phys. Rev. Lett. **38** (1977) 1433. E. Cremmer, B. Julia, J. Scherk, S. Ferrara, L. Girardello and P. van Nieuwenhuizen, Nucl. Phys. B **147** (1979) 105.

[8] D. S. Gorbunov and A. V. Semenov, "CompHEP package with light gravitino and sgoldstinos," hep-ph/0111291.

[9] D. S. Gorbunov and N. V. Krasnikov, JHEP **0207** (2002) 043 [hep-ph/0203078].

[10] E. Perazzi, G. Ridolfi and F. Zwirner, Nucl. Phys. B **590** (2000) 287 [hep-ph/0005076].

[11] S. V. Demidov and D. S. Gorbunov, Phys. Atom. Nucl. **69** (2006) 712 [hep-ph/0405213].

[12] Z. Bern, L. J. Dixon and C. Schmidt, Phys. Rev. D **66** (2002) 074018 [hep-ph/0206194].

[13] D. S. Gorbunov, Nucl. Phys. B **602** (2001) 213 [hep-ph/0007325].

[14] S. V. Demidov and D. S. Gorbunov, JETP Lett. **84** (2007) 479 [hep-ph/0610066].

[15] D. Gorbunov, V. Ilyin and B. Mele, Phys. Lett. B **502** (2001) 181 [hep-ph/0012150].

[16] D. S. Gorbunov and V. A. Rubakov, Phys. Rev. D **73** (2006) 035002 [hep-ph/0509147].

[17] S. V. Demidov and D. S. Gorbunov, arXiv:1112.5230 [hep-ph], to appear in PRD.

[18] D. S. Gorbunov and V. A. Rubakov, Phys. Rev. D **64** (2001) 054008 [hep-ph/0012033].

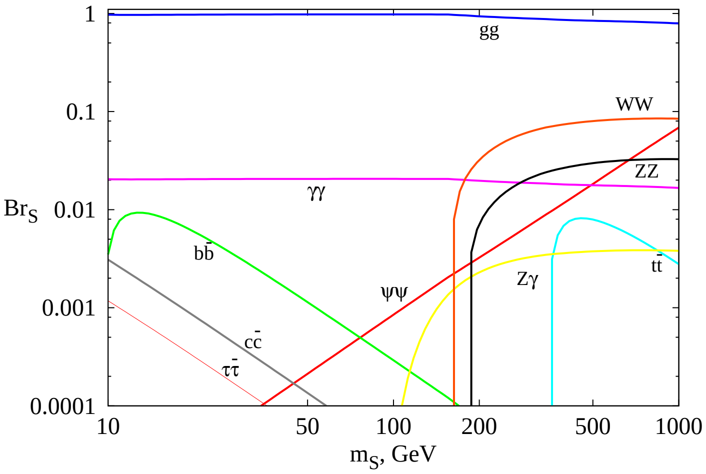

Figure 1: Typical picture of branching ratio of scalar sgoldstino into SM particles.

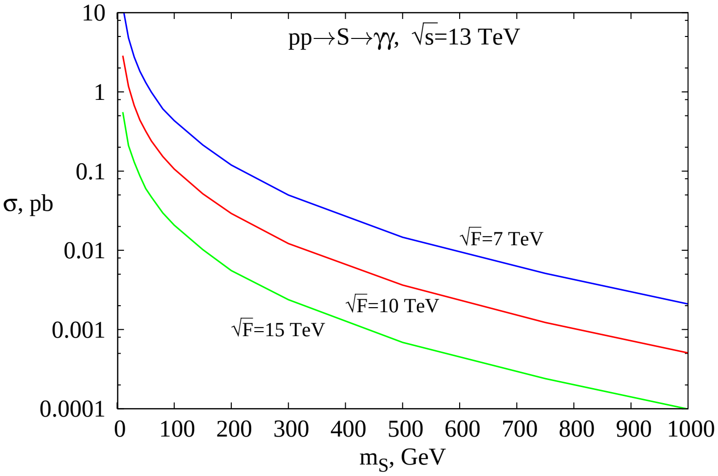

Figure 2: Sgoldstino production cross section for $pp \to S \to \gamma\gamma$. The soft supersymmetry breaking parameters are the following: $M_1 = 400$ GeV, $M_2 = 800$ GeV, $M_3 = 1200$ GeV, $A = 700$ GeV.

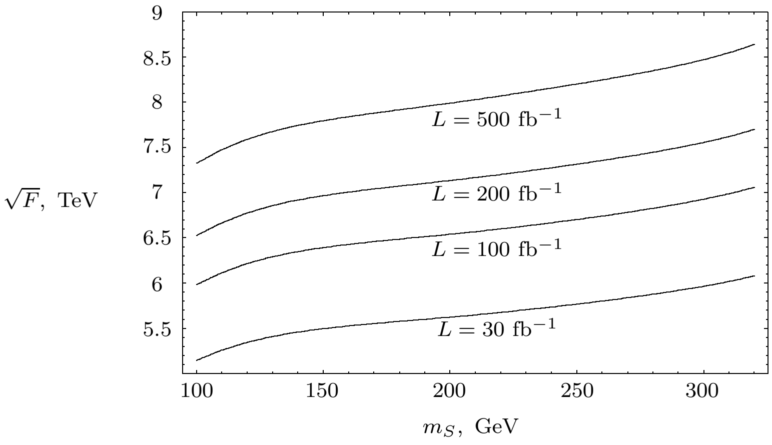

Figure 3: Sensitivity of LHC to the scale of SUSY breaking $\sqrt{F}$ in channel $pp \to S(S \to \gamma\gamma) + jet$. See details in Ref. [11].

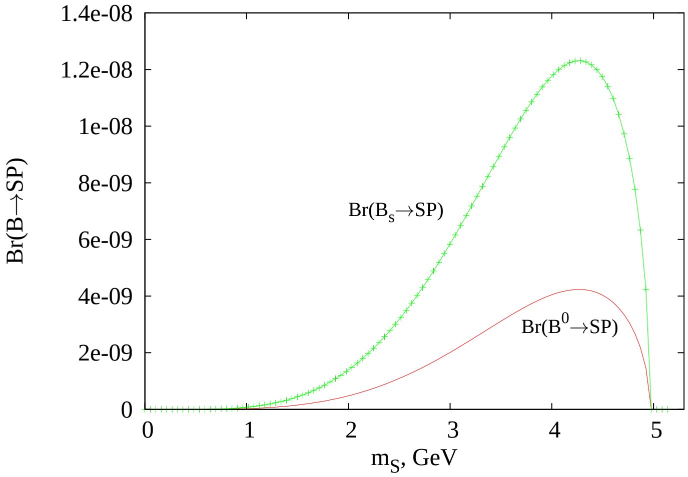

Figure 4: Branching ratios of the decays $B^0 \to SP$ and $B_s \to SP$ as functions of the mass of scalar sgoldstino m_S.

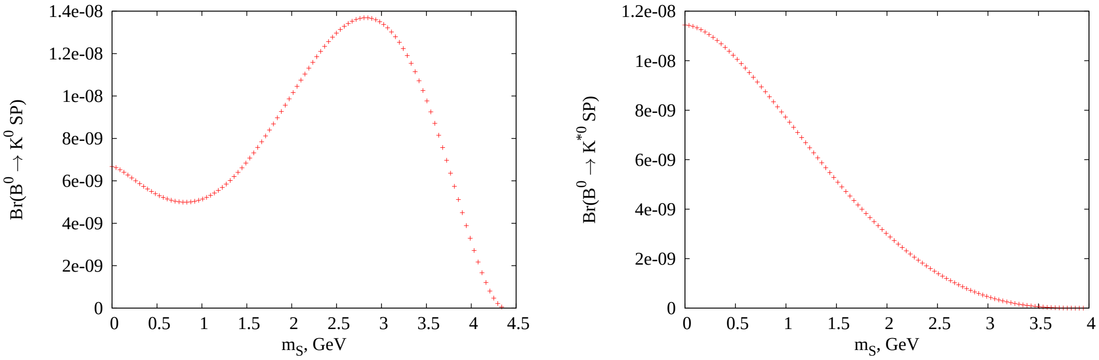

Figure 5: Branching ratio of the decay $B^0 \to K^0 SP$ (left) and $B^0 \to K^* SP$ (right) as functions of the mass of scalar sgoldstino m_S.