Probing the SUSY breaking scale at an $e^{-}e^{-}$ collider

Uma Mahanta
Mehta Research Institute, Chhatnag Road, Jhusi, Allahabad-211019, India
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If supersymmetry is spontaneously broken at a low-energy scale, then the resulting gravitino will be very light. The interaction strength of the longitudinal components of such a light gravitino to the e-$\tilde{e}$ pair then becomes comparable to that of electroweak interactions. If such a light gravitino is present, it would significantly modify the cross section for $e_L^- e_R^- \to \tilde{e}_L \tilde{e}_R$ from its minimal supersymmetric standard model value. A precision measurement of this cross section could therefore be used to probe the low-energy supersymmetry breaking scale Λ_s. [S0556-2821(99)05101-2]

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If supersymmetry (SUSY) is spontaneously broken at a low-energy scale ($\Lambda_s \approx 1-10$ TeV) then the resulting gravitino is expected to be very light ($m_{3/2} \approx F/M_p \approx 10^{-4}-10^{-2}$ eV). The interaction strength of the longitudinal components of such a light gravitino, i.e., the Goldstino with fermion-sfermion pair, is expected to be of the order of electroweak couplings [1]. Such a light gravitino could lead to new and interesting signatures at forthcoming high-energy colliders. It could also significantly modify the collider expectations for many processes from their corresponding minimal supersymmetric standard model (MSSM) value [2]. Precision measurement of the cross section for such processes can therefore be used to set stringent bounds on the SUSY breaking scale (Λ_s).

A high-energy $e^- e^-$ collider with the provision for polarizing both the incoming electron beams to a high degree provides an ideal environment for such studies. Consider for example, the selectron pair production at an $e^- e^-$ collider. Depending on the polarizations of the incoming electron beams, there are three distinct processes that can be studied namely $e_L e_R \to \tilde{e}_L \tilde{e}_R$, $e_R e_R \to \tilde{e}_R \tilde{e}_R$, and $e_L e_L \to \tilde{e}_L \tilde{e}_L$. In the context of MSSM, the lowest order contribution to the first and second processes arise from the t channel exchange of a $\tilde{B}$ [3], whereas the last process receives nonvanishing contributions both from $\tilde{B}$ and $\tilde{W}_3$ exchanges. In this work, we shall assume for simplicity that the lightest neutralino is gaugino like and more precisely a B-ino. The Majorana nature of $\tilde{B}$ and $\tilde{W}_3$ gives rise to fermion number violating propagators which is crucial for all the three processes to take place. A close examination of the transition amplitudes for $e_L e_L \to \tilde{e}_L \tilde{e}_L$ and $e_R e_R \to \tilde{e}_R \tilde{e}_R$ shows that they arise from the chirality flipping part of the gaugino propagator. They therefore vanish as the relevant gaugino mass approaches zero. However the amplitude for $e_L e_R \to \tilde{e}_L \tilde{e}_R$ arises from the chirality conserving part of the gaugino propagator and therefore it remains finite in the same limit. The longitudinal components of the gravitino behaves as a Majorana fermion and it also interacts with e-$\tilde{e}$ pair through Yukawa interactions just like the electroweak gauginos. The only difference is that the gauge couplings are replaced by the soft gravitino coupling $e_g \approx \tilde{m}_e^2/F$ [4]. Here $\sqrt{F} \approx \Lambda_s$ is the scale for dynamical supersymmetry breaking. Hence, it follows from the above discussion that the existence of a sufficiently light gravitino would modify the cross section for $e_L e_R \to \tilde{e}_L \tilde{e}_R$, but keep the cross sections for the processes $e_L e_L \to \tilde{e}_L \tilde{e}_L$ and $e_R e_R \to \tilde{e}_R \tilde{e}_R$ almost unaffected. Precision measurement of the cross section for $e_L e_R \to \tilde{e}_L \tilde{e}_R$ could therefore be used to set a lower bound on the SUSY breaking scale Λ_s. This however requires that the selectron mass $\tilde{m}_e$ and the B-ino mass ($\tilde{M}$) be known with sufficiently good accuracy from other studies. The selectron mass and the B-ino mass can be determined from the energy distribution of the electron arising from selectron decay.

The Yukawa interactions of B-ino ($\tilde{B}$) and gravitino ($\tilde{G}$) with e-$\tilde{e}$ pair are given by [4]

$$L_1 = \left(\frac{g'}{\sqrt{2}} \bar{\tilde{B}} P_L e \tilde{e}_L^* - \sqrt{2} g' \bar{\tilde{B}} P_R e \tilde{e}_R^* \right) + \text{H.c.}, \tag{1}$$

$$L_2 = e_g \sqrt{2} [\bar{\tilde{G}} P_R e \tilde{e}_R^* + \bar{\tilde{G}} P_L e \tilde{e}_L^*] + \text{H.c.} \tag{2}$$

In the context of MSSM ($e_g \approx 0$), the transition amplitude for $e_L e_R \to \tilde{e}_L \tilde{e}_R$ arises from the t channel exchange of a Bino and is given by $M = M_a + M_b$, where

$$M_a = -g'^2 \overline{v}(p_2,s_2) P_R \frac{p_1 . \gamma - k_1 . \gamma}{t - \tilde{M}^2} P_L u(p_1,s_1), \tag{3}$$

$$M_b = -g'^2 \overline{v}(p_2,s_2) P_L \frac{p_1 . \gamma - k_2 . \gamma}{u - \tilde{M}^2} P_R u(p_1,s_1). \tag{4}$$

Clearly M_a and M_b are the transition amplitudes associated with the direct and crossed diagrams. Here (p_1,p_2) are the momenta of the incoming electrons and (k_1,k_2) are the momenta of the outgoing selectrons. $\tilde{M}$ is the mass of the bino. Squaring the transition amplitude and summing over the incoming electron spins, we get

$$\sum_{s_1,s_2} |M|^2 = \frac{2g'^4}{(t-\tilde{M}^2)^2} [2p_1(p_1-k_1)p_2.(p_1-k_1) - p_1.p_2(p_1-k_1)^2] + \frac{2g'^4}{(u-\tilde{M}^2)^2} [2p_1.(p_1-k_2)p_2.(p_1-k_2) - p_1.p_2(p_1-k_2)^2]. \quad (5)$$

Note that at very high energy where the electron mass can be neglected, there is no interference between M_a and M_b, i.e., the t and u channel amplitudes. For simplicity in this work, we shall ignore any mixing between $\tilde{e}_L$ and $\tilde{e}_R$ and assume that $\tilde{m}_{e_L} = \tilde{m}_{e_R} = \tilde{m}_e$. The above expression for $\Sigma_{s_1,s_2}|M|^2$ then becomes after some algebra

$$\sum_{s_1,s_2} |M|^2 = 2g'^4(ut-\tilde{m}_e^4)\left(\frac{1}{(u-\tilde{M}^2)^2} + \frac{1}{(t-\tilde{M}^2)^2}\right). \quad (6)$$

The contribution of a light gravitino exchange to the transition amplitude for $e_L e_R \to \tilde{e}_L \tilde{e}_R$ is given by

$$\delta M = 2e_g^2 \left(\frac{1}{t}\, \overline{v}(p_2,s_2)(p_1-k_1).\gamma P_L u(p_1,s_1) + \frac{1}{u}\, \overline{v}(p_2,s_2)(p_1-k_2).\gamma P_R u(p_1,s_1)\right). \quad (7)$$

Assuming that δM is small compared to M, we can neglect $|\delta M|^2$ compared to $|M|^2$. We then obtain

$$\sum_{s_1,s_2} |M+\delta M|^2 \approx 2g'^4(ut-\tilde{m}_e^4)\left(\frac{1}{(t-\tilde{M}^2)^2} + \frac{1}{(u-M^2)^2}\right) - 8g'^2 e_g^2 (ut-\tilde{m}_e^4)\left(\frac{1}{t(t-\tilde{M}^2)} + \frac{1}{u(u-\tilde{M}^2)^2}\right). \quad (8)$$

Integrating over all directions, the total cross section for $e_L e_R \to \tilde{e}_L \tilde{e}_R$ to lowest order in e_g^2 becomes $\sigma_{LR} = (\sigma_{LR})_{\mathrm{MSSM}} + \delta\sigma_{LR}$ where

$$(\sigma_{LR})_{\mathrm{MSSM}} = \frac{1}{2\pi s} \frac{\sqrt{s-4\tilde{m}_e^2}}{\sqrt{s}} \frac{g'^4}{4} \left(\frac{a}{b} \ln\frac{a+b}{a-b} - 2\right), \quad (9)$$

and

$$\delta\sigma_{LR} = -\frac{1}{2\pi s} \frac{\sqrt{s-4\tilde{m}_e^2}}{\sqrt{s}} \frac{g'^2 e_g^2}{2} \left(\frac{b^2-a^2}{b(c-a)} \ln\frac{a+b}{a-b} - \frac{b^2-c^2}{b(c-a)} \ln\frac{c+b}{c-b} - 2\right). \quad (10)$$

In the above, $a = \tilde{m}_e^2 - \tilde{M}^2 - s/2$, $b = (\sqrt{s}/2)\sqrt{s-4\tilde{m}_e^2}$, and $c = \tilde{m}_e^2 - s/2$. A sufficiently light gravitino would therefore lower the cross section σ_{LR} from its MSSM value. We find that unless the selectron mass is too close to the threshold, the MSSM contribution to the cross section is quite large. For example, $\tilde{m}_e = 150$ GeV and $\tilde{M} = 100$ GeV yields a cross section of 960 fb. With an integrated luminosity of 50 fb^{-1} per year, we therefore expect around 48000 events. The statistical error in the cross section would therefore be about 0.4% which can be further reduced by increasing the luminosity or the running time. The gravitino contribution to σ_{LR} is bounded by the difference between the experimental value and the MSSM contribution. We therefore need to estimate the theoretical systematic error in the MSSM cross section arising from the uncertainties in $\tilde{M}$ and $\tilde{m}_e$. The values of $\tilde{M}$ and $\tilde{m}_e$ are constrained by the electron energy distribution to lie in a narrow elliptical region with positive correlation [5]. The MSSM cross section decreases with increasing $\tilde{M}$ or $\tilde{m}_e$. The contours of constant σ_{LR} are therefore perpendicular to the uncertainty ellipse. If we assume that M and $\tilde{m}_e$ are both known with an accuracy of 1%, then by using Eq. (9), it can be shown that the systematic error in the MSSM cross section is about 1.5% for the central values $\tilde{M} = 100$ GeV and $\tilde{m}_e = 150$ GeV. Both the systematic error and the statistical error however decreases with decreasing superpartner mass. The condition $|\delta\sigma_{LR}|/(\sigma_{LR})_{\mathrm{MSSM}} \leq 0.01$ could therefore be used to derive an approximate lower bound on $\sqrt{F}$ provided $\tilde{m}_e$ and $\tilde{M}$ are around 100 GeV. We find that for $\tilde{M} = 100$ GeV and $\tilde{m}_e = 150$ GeV, the SUSY breaking scale must be greater than 1.4 TeV, so that the gravitino contribution is below the precision limit for measuring σ_{LR}. The bound corresponds to a center-of-mass energy of 500 GeV. A technically better estimate of the bound can be obtained by using the relation $S/\sqrt{S+B} \leq 2$. Here B is the MSSM background and S is the gravitino contribution to the signal. For $\tilde{m}_e = 150$ GeV, $\tilde{M} = 100$ GeV and an integrated luminosity of 50 fb^{-1}, we then get $\sqrt{F} \geq 1.24$ TeV which is close to the bound obtained by using the relation $|\delta\sigma|/\sigma \leq 0.01$. The angular distribution of the gravitino contribution clearly differs from that of the MSSM contribution, since the former involves a massless propagator and the latter a massive one. Hence, by considering an angular range where the gravitino contribution is enhanced relative to the MSSM contribution, it might be possible to push the lower bound on Λ_s to higher values. What are the implications of our result on known models of low-energy dynamical supersymmetry breaking (DSB)? Recently, a lot of interest has been devoted to the construction of models with gauge mediated SUSY breaking (GMSB) [6] which constitutes an example of low-energy DSB. However for the simplest models of GMSB, the SUSY breaking scale Λ_s lies between 10^2–10^5 TeV. Hence, the process considered in this work will not be able to probe the SUSY breaking scale associated with the simplest versions of GMSB. However there could well be other scenarios of DSB with a SUSY breaking scale close to 1 TeV and superpartners in few hundred GeV range which could fall within the sensitivity reach of the process considered in this work. The supersymmetry breaking in such models has to be communicated to the visible sector by some interactions other than SM gauge interactions.

It should be noted that the selectron pair production cross section at an e^+e^- collider can also be used to set bounds on $\sqrt{F}$. At an e^+e^- collider depending on the polarization of the incoming electron beam, there are two distinct cross sections that can be measured namely σ_L and σ_R. To eliminate the contribution of t channel $\widetilde{W}_3$, the incoming electron beam can be chosen to be right handed. The transition amplitude for σ_R receives contribution from t channel $\widetilde{B}$ exchange and s channel γ and Z exchanges. The contribution of t channel $\widetilde{B}$ exchange has a chirality conserving and a chirality flipping piece. Clearly, the existence of a very light gravitino modifies only the chirality conserving piece. However there are several advantages in using the e^-e^- collision mode for probing the SUSY breaking scale instead of the e^+e^- mode. First, in the context of MSSM at an e^-e^- collider, σ_{LR} gets a contribution only from the t channel $\widetilde{B}$ exchange. However at an e^+e^- collider, σ_R gets a contribution from the t channel $\widetilde{B}$ exchange as well as s channel γ and Z exchanges. The analytical expression for σ_R at an e^+e^- collider is therefore much more complicated than that of σ_{LR} at an e^-e^- collider. Second, the backgrounds to selectron pair production at e^-e^- collider are very small. Most of the major backgrounds to selectron pair production present in e^+e^- are absent in e^-e^- mode. For instance, the W pair production and chargino pair production are prohibited by fermion number conservation. The remaining $e^-\nu W^-$ background originating from the left handed incoming electron beam can be suppressed by imposing suitable kinematic cuts on the transverse energy of the final state electron. These remaining backgrounds can be calculated and subtracted from the total cross section so as to reduce the total uncertainty in the MSSM contribution. Finally at an e^-e^- collider it is possible to polarize both electron beams, whereas at an e^+e^- collider only one of the incoming beams (e^-) can be polarized. This enhances the cross section at an e^-e^- collider by a factor of 2 relative to that at an e^+e^- collider.

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