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Journal

Physics Letters B, 518

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Publication Date

2001-08-22

Superlight gravitinos in electron-photon collisions

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Abstract

Motivated by recent studies of supersymmetry in higher-dimensional spaces, we discuss the experimental signatures of a superlight gravitino (mass $\leq 10^{-3}$ eV). We concentrate on the process $e^- \gamma \rightarrow \tilde{e}_R \tilde{G}$ as a probe of supersymmetry, where a single heavy superpartner and a superlight gravitino are produced. The fact that there is only one heavy superpartner in the final state in this process would require a lower center-of-mass energy for on-shell production compared to conventional pair production. For instance, for a 500 GeV machine, we find that a positive signal will be found if the supersymmetry breaking scale is less than about 2 TeV. If no positive signal is found, this process puts a bound on the supersymmetry breaking scale.

July 2001

The gravitino is a spin 3/2 superpartner to the graviton. The massless gravitino has two spin degrees of freedom, the +3/2 and the -3/2 helicity components. When supersymmetry is spontaneously broken, the gravitino acquires a mass, denoted by $m_{3/2}$. The precise value of $m_{3/2}$ is model dependent. One possible way in which supersymmetry can be broken spontaneously is by the F component vacuum expectation value of a hidden sector superfield, $Z = (z, \chi, F)$. (z is a scalar, χ is a spin 1/2 fermion and F is an auxiliary field.) The massive gravitino has four spin degrees of freedom, and the two additional (longitudinal) ones are supplied by the goldstino, χ . In this case, the mass of the gravitino is

$$m_{3/2} = \frac{\langle F \rangle}{\sqrt{3}M_{\text{pl}}}, \quad M_{\text{pl}} = (8\pi G_N)^{-1/2} \approx 2.4 \times 10^{18} \text{ GeV}. \quad (1)$$

The scale of supersymmetry breaking, $\langle F \rangle$, and hence the mass of the gravitino, are presently not known. It is instructive to note what the different schemes of supersymmetry-breaking imply for $m_{3/2}$. Weak-scale supersymmetry breaking and some extra dimensions theories can give superlight gravitinos [1, 2], $m_{3/2} \lesssim 10^{-3} \text{ eV}$, $\sqrt{F} \lesssim 10^3 \text{ GeV}$; Gauge Mediation, $m_{3/2} \approx 1 \text{ eV} - 10 \text{ keV}$, $\sqrt{F} \approx 10^5 - 10^7 \text{ GeV}$; Generic Gravity Mediation, $m_{3/2} \approx 10 \text{ keV} - 10 \text{ TeV}$, $\sqrt{F} \approx 10^7 - 10^{12} \text{ GeV}$; Anomaly Mediation, $m_{3/2} > 10 \text{ TeV}$, $\sqrt{F} > 10^{12} \text{ GeV}$.

There are collider, cosmological and astrophysical bounds on the mass of the gravitino. The current LEP bound due to non-observation of any deviation from the Standard Model is $m_{3/2} \gtrsim 10^{-5} \text{ eV}$ [3]. The constraints from the cooling of stars excludes the region $10^{-2} \text{ eV} \lesssim m_{3/2} \lesssim 10^2 \text{ eV}$ [4]. There is thus a window $10^{-5} \text{ eV} \lesssim m_{3/2} \lesssim 10^{-2} \text{ eV}$ for the mass of the gravitino and we focus on this range of masses and analyze its implications for electron-photon collisions. As we will discuss in the following section, the production cross-section is inversely proportional to the square of $m_{3/2}$ (equivalently, $\sigma \sim 1/F^2$) and thus superlight gravitinos become interesting at next generation colliders.

Owing to the Goldstone equivalence theorem, at energies much bigger than $m_{3/2}$, the production cross-section of the longitudinal helicity components (+1/2 and -1/2) is approximately equal to the production cross-section of the goldstino, χ , that was eaten. The correction is of order $m_{3/2}/E$ where E is the energy of the process. To get the amplitudes for the production of the longitudinal helicity components of the gravitino, it is sufficient to replace the gravitino field ψ_μ by,

$$\psi_\mu \sim i\sqrt{\frac{2}{3}} \frac{1}{m_{3/2}} \partial_\mu \tilde{G}, \quad (2)$$

where \tilde{G} is the goldstino. We focus on the goldstino production (+1/2 and -1/2 components)

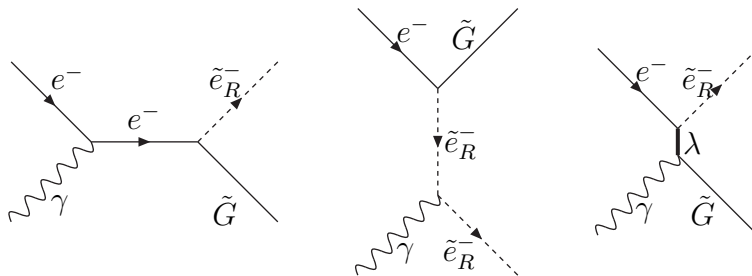
since the production amplitude is proportional to $1/F$ which is significantly stronger than the $1/M_{\text{pl}}$ coupling for the $+3/2$ and $-3/2$ helicity components. This can be seen from the Lagrangian given below.

We focus on a scenario in which the gravitino is the superlight LSP, \tilde{e}_R the NLSP, and all other superpartners are much heavier. This is for instance the case in the model [1, 2] constructed in the Randall-Sundrum scenario [5]. In this framework, we live on a 3-dimensional brane in AdS space, an idea motivated by the need to generate two hierarchically different scales, M_{pl} and M_{weak} . The hierarchically different masses of the gravitino and the gaugino are determined directly [2] from the poles in the propagators on the brane. This computation gives a superlight gravitino and gauginos with TeV scale masses. The scalars also get TeV scale masses due to radiative corrections. A more intuitive reason [2] for the superlight gravitino appeals to the conjectured AdS/CFT correspondence. In the CFT picture, Supersymmetry breaking is due to a strongly coupled sector charged under the Standard Model gauge group, which results in a tree-level gaugino mass of TeV scale. The gravitino coupling to the CFT has a $1/M_{\text{pl}}$ suppression and hence gets a mass of order $\text{TeV}^2/M_{\text{pl}}$.

For the Goldstino production in the process $e^- \gamma \rightarrow \tilde{e}_R \tilde{G}$, it is sufficient to work with an effective global supersymmetric lagrangian. The relevant terms in this effective lagrangian are [3, 6, 7]

$$L \supset -\frac{\tilde{m}^2}{|M|} \left[\frac{M}{F} (\tilde{e}_R \bar{e} P_L \tilde{G}) + \frac{M^*}{F^*} (\tilde{e}_R^* \tilde{G} P_R e) \right] - \sqrt{2} i g (\tilde{e}_R^* \bar{\lambda} P_R e - \tilde{e}_R \bar{e} P_L \lambda) \\ - \frac{1}{4\sqrt{2}} \tilde{G} [\gamma^\mu, \gamma^\nu] \lambda \left[\text{Re} \left(\frac{M}{F} \right) F_{\mu\nu} - \text{Im} \left(\frac{M}{F} \right) \tilde{F}_{\mu\nu} \right] + i g A_\mu (\tilde{e}_R^* \partial^\mu \tilde{e}_R - \partial^\mu \tilde{e}_R^* \tilde{e}_R) \quad (3)$$

where \tilde{m}^2 is the \tilde{e}_R mass squared, \tilde{G} the Goldstino, e the electron, and M the mass of the gaugino λ . The gaugino is included above, since it contributes to the effective four point vertex, as shown in the Feynman diagrams below:



For producing \tilde{e}_R the incoming e^- must be right handed. The photon helicities can be $+$ or $-$. The amplitudes for these two photon helicities in the center-of-mass frame are

$$\mathcal{M}_+ = \frac{e\tilde{m}^2}{F} \sqrt{\frac{2p}{E}} \left[\left(1 + \frac{4E^2}{\tilde{m}^2}\right) \sqrt{\frac{1 - \cos\theta}{2}} - \frac{\sin\theta \sqrt{\frac{1+\cos\theta}{2}}}{(1 + \cos\theta) + \tilde{m}^2/2Ep} \right], \quad (4)$$

$$\mathcal{M}_- = \frac{e\tilde{m}^2}{F} \sqrt{\frac{2p}{E}} \left[\frac{-\sin\theta \sqrt{\frac{1+\cos\theta}{2}}}{(1 + \cos\theta) + \tilde{m}^2/2Ep} \right], \quad (5)$$

where θ is the angle made by the \tilde{e}_R with respect to the incoming e^- , E is the incoming e^- beam energy, $p \equiv |\mathbf{p}|$ is the 3-momentum magnitude of the \tilde{e}_R , \tilde{m} is the \tilde{e}_R mass, and $e = \sqrt{4\pi\alpha}$. The cross-sections in the center-of-mass frame are,

$$\frac{d\sigma_{\pm}}{d\cos\theta} = \frac{(1 - \tilde{m}^2/4E^2)}{128\pi E^2} |\mathcal{M}_{\pm}|^2. \quad (6)$$

We are concentrating on the process $e^- \gamma \rightarrow \tilde{e}_R \tilde{G}$ as a probe of supersymmetry, since on-shell production requires the center-of-mass energy of the collision only be greater than the mass of one heavy superpartner (\tilde{e}_R) as opposed to twice this in conventional pair production of heavy superpartners. The \tilde{e}_R produced decays promptly to an e^- and a \tilde{G} (the \tilde{G} escapes the detector unseen). Thus the experimental signature in the detector is $e^- + \cancel{E}$. This is similar to the signal of $\tilde{e}_R \chi_1^0$ production in $e^- \gamma$ collisions [8, 9, 10].

The background is due to the Standard Model processes: $e^- \gamma \rightarrow e^- Z \rightarrow e^- \nu \bar{\nu}$ and $e^- \gamma \rightarrow W^- \nu_e \rightarrow e^- \nu_e \bar{\nu}_e$. The background can be reduced significantly by placing appropriate cuts and by using polarized beams as will be discussed later. Helicity amplitudes for the background are given in [11] and [12].

The high energy photons needed for the $e^- \gamma$ collisions are produced by Compton back scattering a low-energy laser beam from a second electron beam. The Compton back scattered photons have an energy spread as shown in Fig. 1, with data from the package Pandora [13].

In the following, we present results for two machine designs:

- “500 GeV collider”: Collision of 250 GeV (+0.8 polarized) electrons with the photons whose spectrum is shown in Fig. 1. We denote this as a 500 GeV machine since the maximum electron-photon center-of-mass energy is close to, but somewhat less than 500 GeV. That is, the 250 GeV electron beam collides against backscattered photons

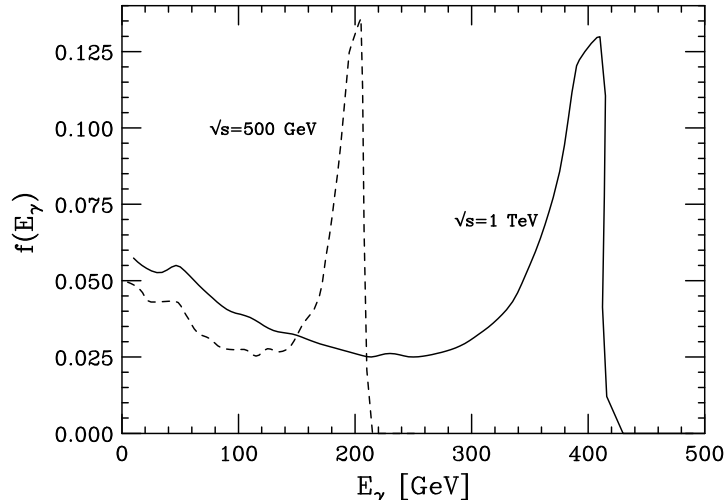


Figure 1: The Compton back scattered photon spectra obtained by scattering 1 eV photons with polarization -1.0 on (i) 250 GeV electrons and (ii) 500 GeV electrons. The electron beams have polarization $+0.8$.

with maximum beam energy slightly less than 250 GeV, yielding a maximum center of mass energy for $e^- \gamma$ collisions slightly less than 500 GeV.

- “1TeV collider”: Collision of 500 GeV ($+0.8$ polarized) electrons with the photons whose spectrum is shown in Fig. 1, with center-of-mass energy slightly less than 1 TeV.

We used the package Pandora [13] to obtain the results in this section with the unpolarized cross-sections verified with Pythia and our own Monte Carlo code. Fig. 2 shows the differential cross-section as a function of $\cos \theta$ and $|\mathbf{p}|$ of the outgoing e^- for the case of a 500 GeV collider. The cross-section shown is for the production of the e^- after factoring in the branching fraction to e^- . θ is measured from the direction of the incident e^- beam. The background is reduced by applying a theta cut to accept events in the range $10^\circ < \theta < 125^\circ$, and a momentum cut is employed to accept events with $|\mathbf{p}_e| > 100 \text{ GeV}$ for the case of $\tilde{m} = 250 \text{ GeV}$. A different momentum cut is found to be optimal for other choices of \tilde{m} .

Fig. 3 shows the dependence of the cross-section on the mass of the selectron. It should be noted that the selectron production cross-section scales as $1/(\sqrt{F})^2$ as can be inferred from eq. 3.

Fig. 4 shows the reach of a 500 GeV collider and a 1 TeV collider for luminosities of 100 fb^{-1} and 500 fb^{-1} . Momentum and angle cuts were placed on the outgoing electron to suppress the background and enhance the reach. The 500 GeV collider curve shows the

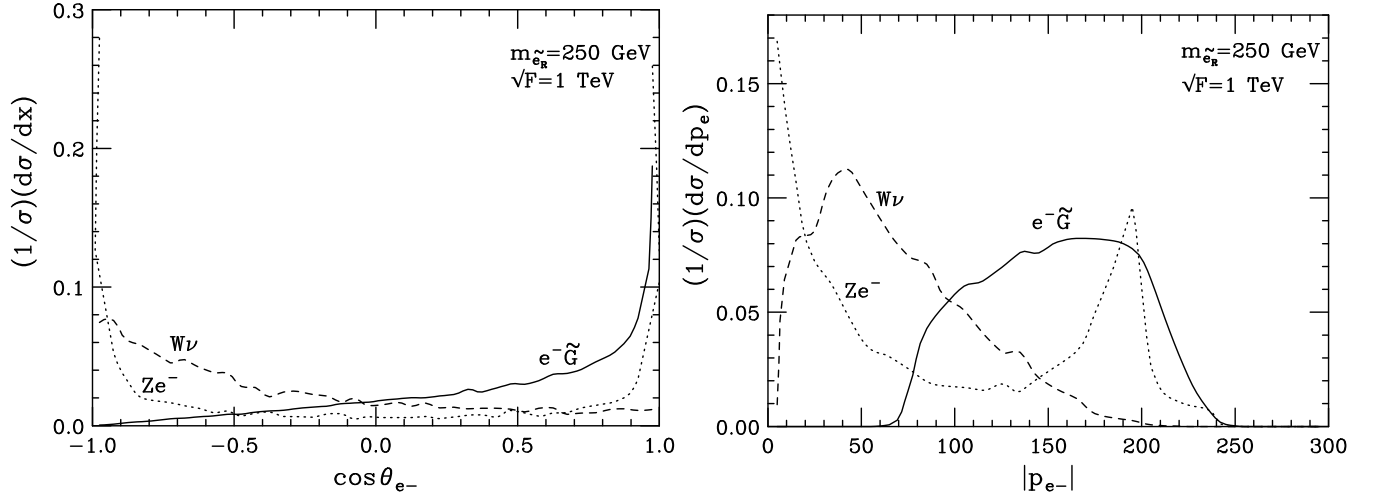


Figure 2: The differential signal and background cross-sections as a function of the outgoing $e^- \cos(\theta)$ and $|\mathbf{p}|$. The signal cross-section is shown for a representative choice of ($\tilde{m} = 250$ GeV, $\sqrt{F} = 1$ TeV).

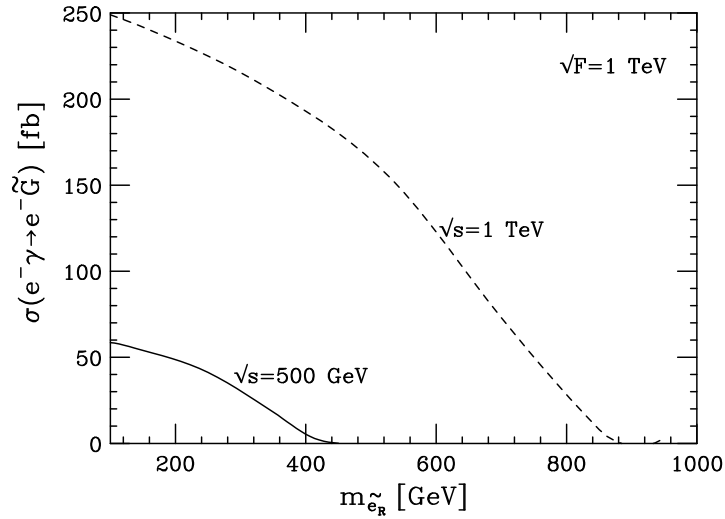


Figure 3: The dependence of the \tilde{e}_R production cross-section on \tilde{m} for a 500 GeV collider and a 1 TeV collider.

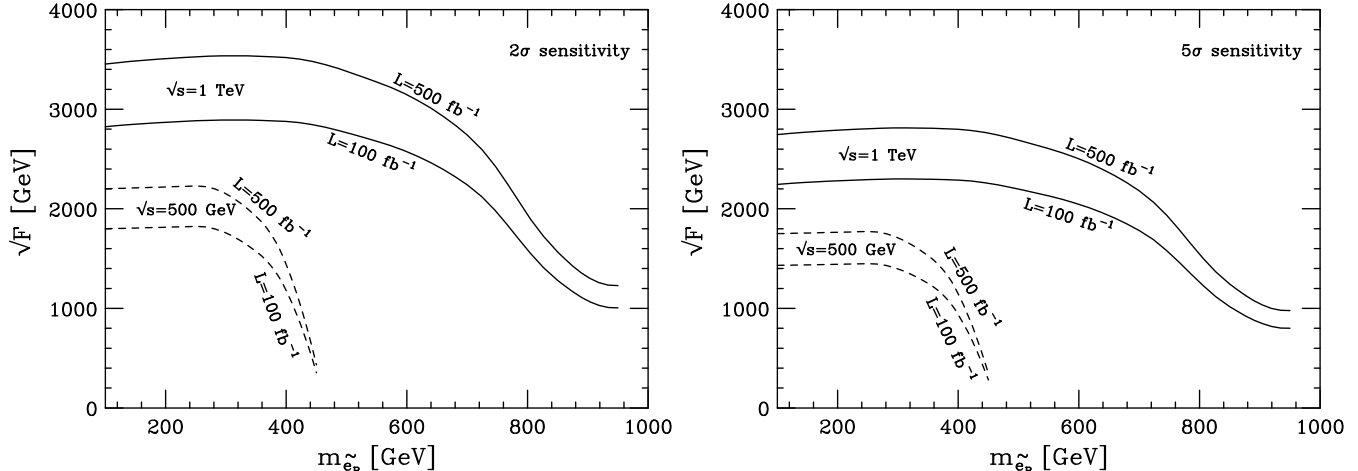


Figure 4: 2σ (left) and 5σ (right) reach for a 500 GeV collider and a 1 TeV collider with luminosities of 100 fb^{-1} and 500 fb^{-1} .

reach after making the theta cut $10^\circ < \theta < 125^\circ$ and the $|\mathbf{p}|$ cuts: $(\tilde{m}(\text{GeV}), |\mathbf{p}|(\text{GeV})) \rightarrow (100,50), (150,50), (250,100), (350,125), (400,150), (450,150)$. The 1 TeV collider curve is with the same theta cut, $10^\circ < \theta < 125^\circ$, and a momentum cut at 100 GeV. The plot on the left shows a 2σ exclusion contour; if a positive signal is not found, the region below the line would be excluded. In the plot on the right, the region below the lines will result in a 5σ excess over background.

We have presented the mode $e^-\gamma \rightarrow \tilde{e}_R \tilde{G}$ as a probe of supersymmetry and as a means of glean insight into the scale of supersymmetry breaking. The advantage of this mode over conventional pair production is that this requires just the mass of one heavy superpartner in the center of mass before it is produced on-shell.

Polarized beams can offer tremendous advantages for suppressing $W^-\nu$ and Ze^- backgrounds. This results in the excellent reach for probing the supersymmetric breaking scale \sqrt{F} . Our studies indicate that the reach for a 500 GeV (1 TeV) machine design is nearly 2 TeV (3 TeV) with 500 fb^{-1} of integrated luminosity.

Another useful way to search for light gravitinos is through $e^+e^- \rightarrow \tilde{G}\tilde{G}\gamma$ production. A finite cross-section is still possible even if all the other superpartners are extremely heavy. The current LEP lower bound on \sqrt{F} from this process is around 200 GeV [3] ($\sqrt{s} = 183 \text{ GeV}$ with 60 pb^{-1} of data). Extrapolating this to an e^+e^- linear collider with 100 fb^{-1} gives a \sqrt{F} reach of $\sim 750 \text{ GeV}$ for a 500 GeV collider and $\sim 1 \text{ TeV}$ for a 1 TeV collider. This estimate is for an unpolarized e^+e^- machine and can be improved upon by using polarized beams

to reduce the background. The reach of the upgraded Tevatron is ~ 410 GeV and that of the LHC ~ 1.6 TeV [14]. Although our signal of single gravitino production is sensitive to somewhat higher values of \sqrt{F} , the $\tilde{G}\tilde{G}\gamma$ signal does not require another accessible superpartner and should be considered complementary.

This study was done with a realistic Compton backscattered photon energy spectrum. Only primary backscatters were considered and secondary scatters ignored. Including secondary scatters gives a higher luminosity in the low-energy tail of the photon energy spectrum and its effect on the reach should be minimal.

Acknowledgements: SG wishes to acknowledge Lawrence Livermore Lab for financial support, and M. Peskin for help implementing the helicity amplitudes into Pandora. We also wish to thank T. Gherghetta, J. Gronberg, J. Gunion, A. Konechny, S. Mrenna and B. Murakami for valuable discussions.

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