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Probing Gauge-Mediated Supersymmetry Breaking Through Polarized Electron Beams in an e^+e^- Collider

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Abstract

Using the facts that in Gauge-Mediated Supersymmetry Breaking schemes, masses of the right and the left sfermions can differ widely, and the gravitino is the Lightest Supersymmetric Particle, we show that it is possible to obtain unambiguous signatures of such schemes in a high energy e^+e^- collider if one looks at the asymmetries in the cross-sections for certain final states with left-and right-polarized beams.

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While the search for supersymmetry (SUSY) as a fundamental symmetry of nature continues to be an area of intense activity in high energy physics, it is not clear that even the discovery of superpartners of the existing particles will answer a crucial question on the subject, namely how is SUSY broken so that we have a consistent phenomenology. The popular paradigm, as embodied in models based upon supergravity (SUGRA), is that SUSY is broken in a ‘hidden sector’ and the breaking is conveyed to the observable sector through gravitational interaction, resulting in a gravitino (the spin-3/2 partner of the graviton) with a mass of the order of the electroweak scale [1]. In this picture, all superparticle decays culminate into the production of the lightest supersymmetric particle (LSP) which is stable. In most models the LSP is a mixture of the spin-1/2 superpartners of the photon, the Z-boson and the two neutral Higgs bosons in the theory, and is designated as the lightest ‘neutralino’. Characteristic signals with such an ‘invisible’ LSP have been widely explored [2].

Another scenario which has lately received a lot of attention is one where the Standard Model (SM) gauge group itself may act as the carrier of SUSY breaking [3, 4, 5, 6, 7]. For this, one requires a ‘messenger sector’ which inherits the hidden sector effects through a separate set of interactions decoupled from the observable sector, at a scale that can be as low as $\mathcal{O}(10 - 100)$ TeV. The gauginos and sfermions acquire their masses through ordinary gauge interactions with the messenger sector at the one- and two-loop levels respectively [8]. This mechanism is referred to as Gauge Mediated SUSY Breaking (GMSB). The recently renewed interest in GMSB is partially due to the observation of a single $e^+e^- \gamma\gamma + \cancel{p}_T$ event at the Collider Detector at Fermilab (CDF) experiment, which can be explained in this scenario [4]. Another advantage of such a scenario is that flavour-diagonal sfermion masses are induced at a rather low energy scale. Consequently, flavour changing neutral currents (FCNC) are naturally suppressed, which is a distinct advantage over the conventional SUGRA models.

The messenger sector in GMSB models consists of lepton and quark superfields, and one (in extended GMSB models, more than one) superfield (S). The scalar as well as the auxiliary component of S acquire finite vacuum expectation values (VEV) when SUSY is broken in the messenger sector. The hidden sector and the interactions between the hidden and the messenger sector are

responsible for giving VEVs to S . The messenger lepton and quark superfields must be in a GUT representation (like a $5 + \bar{5}$ or $10 + \bar{10}$ of $SU(5)$ or $SO(10)$ respectively) to preserve the successful prediction of $\sin^2 \theta_W$.

To find out from experiments which one is the real SUSY breaking scheme, perhaps the most important thing to remember is that the gravitino in GMSB is decoupled from the SUSY breaking mechanism, and can be so light as to be considered massless compared to the electroweak scale. Consequently, the gravitino becomes the LSP now. The erstwhile LSP now becomes the next lightest SUSY particle (NLSP) which can decay to its SM partner and the gravitino. This decay mode normally does not affect other particles as the gravitational coupling is extremely weak.

While there have been several attempts in recent times to focus upon distinctive signals of GMSB [5], we want to point out here that a very interesting way will be to explore the final states in a high energy e^+e^- -annihilation experiment with a polarized electron beam. This method utilizes the fact that the masses of left- and right-handed sleptons in GMSB are bound to be widely apart, as a consequence of their different $SU(2) \times U(1)$ quantum numbers which in turn dictate the gauge interactions with the messenger sector. This should be compared with SUGRA models where, except for the stau and the stop, all left-handed sfermions are nearly degenerate with the corresponding right-handed ones. The same principle sometimes causes a right-handed slepton to be the NLSP in GMSB, instead of a neutralino. We demonstrate that in either case one may expect to get widely asymmetric signals with polarized electron beams, which provide a clear distinction to the GMSB scenario. Here we demonstrate our predictions in the context of a linear collider with $\sqrt{s} = 500 GeV$, because (i) the expected efficiency of electron polarization is quite high ($\approx 90\%$) there, and (ii) such an energy range covers a large part of the parameter space of a GMSB scenario.

We consider a minimal GMSB scenario where there is a single symmetry-breaking superfield S in the messenger sector. The masses induced for the gauginos ($M_{1/2}$) and the sfermions (M_0), induced at one- and two-loop levels respectively, depend crucially on two quantities. These are M , the messenger mass scale, and Λ , the ratio between the VEV's of the auxiliary and scalar components of S . The expressions for the induced masses are [6]

$$M_{\frac{1}{2}}(M) = N_m f_1(\Lambda/M) \frac{\alpha_i(M)}{4\pi} \Lambda, \quad (1)$$

$$M_0^2(M) = 2N_m f_2(\Lambda/M) \sum_{i=1}^3 k_i C_i \left(\frac{\alpha_i(M)}{4\pi} \right)^2 \Lambda^2, \quad (2)$$

with the messenger scale threshold functions

$$f_1(x) = \frac{1+x}{x^2} \log(1+x) + (x \rightarrow -x), \quad (3)$$

$$f_2(x) = f_1(x) - \frac{2(1+x)}{x^2} \left[Li_2\left(\frac{x}{1+x}\right) - \frac{1}{4} Li_2\left(\frac{2x}{1+x}\right) \right] + (x \rightarrow -x). \quad (4)$$

In (1), $C_i = 0$ for all gauge singlets and equals to $4/3$, $3/4$, $(Y/2)^2$ for scalars falling in the fundamental representations of $SU(3)$, $SU(2)$ and $U(1)$ respectively ($Y = 2(Q - T_3)$ is the usual weak hypercharge), and $k_i = 1, 1, 5/3$ for these three groups respectively (our α_1 is not GUT-normalized). N_m is the number of messenger generations; for one pair of $5 + \bar{5}$, $N_m = 1$, while for one pair of $10 + \bar{10}$, $N_m = 3$ (these are the two values we will work with). Once the mass terms are obtained in this way, one can evolve them down to the electroweak scale. Thus, all the slepton, squark chargino and neutralino masses can be obtained from four inputs, viz. M , Λ , μ (the Higgsino mass parameter) and $\tan \beta$ (the ratio of the two Higgs VEV's). The latter two are treated as free parameters here. Of course, one has to diagonalize the chargino and neutralino mass matrices in order to get the physical masses for them. We have also taken care of the usual D -term and sfermion threshold corrections while evolving the sfermion mass down to the electroweak scale. Equations (1) and (2) indicate that in general the lightest neutralino is the NLSP for $N_m = 1$ whereas for higher N_m , the fact that $M_0 \sim N_m^{1/2}$ tends to make the right-handed sleptons the NLSP [9]. However, the mass spectrum also depend crucially upon the diagonalisation of the neutralino mass matrix, and, as is evident from the samples listed in Table 1, in some cases the lightest neutralino is the NLSP even for $N_m = 3$.

Now, first consider the situation where the NLSP is a neutralino. The production of a pair of such NLSPs will be followed by each decaying into a photon and a gravitino leading to the signal $\gamma\gamma + \cancel{p}_T$. The analysis is simpler if one assumes the NLSP to be Bino-dominated, which is indeed the case for a large region of the parameter space. Using polarized electron beams in a high-energy

e^+e^- -collider, the rate for such a signal is not the same for left- and right electron beams. This is because neutralino pair production receives contributions from a t-channel diagram mediated by a selectron. In this scheme, the right selectron (which is going to be in the propagator when a right electron is involved) is normally much lighter than a left selectron, as a result of which the t-channel contribution is larger with a right-polarized electron beam. The s-channel contribution on the other hand is nearly independent of electron polarization. At high energies ($\sim 500\text{GeV}$) the t-channel contributions dominate over s-channel unless the selectron is excessively heavy. Thus if one defines $\sigma_{L(R)}^{\gamma\gamma}$ as the cross section for $e^+e^- \rightarrow \gamma\gamma + \cancel{p}_T$ with a left(right)-polarized electron and a specific \cancel{p}_T -cut, then $\sigma_R^{\gamma\gamma}$ is bound to be larger than $\sigma_L^{\gamma\gamma}$. The effect is rather nicely described by an asymmetry parameter defined as

$$\mathcal{A}^{\gamma\gamma} = \frac{\sigma_L^{\gamma\gamma} - \sigma_R^{\gamma\gamma}}{\sigma_L^{\gamma\gamma} + \sigma_R^{\gamma\gamma}} \quad (5)$$

All systematic effects cancel out in the asymmetry $\mathcal{A}^{\gamma\gamma}$ which is plotted in Figure 1 for a centre-of-mass energy of 500 GeV and different values of the GMSB parameters. Note that such left-right asymmetries for exclusive final states can be measured very precisely [10]. Here we have applied a \cancel{p}_T -cut of 30 GeV for demonstration; the qualitative features do not depend qualitatively on the cut. Basically, the quantity Λ controls the masses induced in the observable sector; the dependence on M is only through the way it affects the evolution of the coupling and mass parameters from SUSY breaking scale in the messenger sector down to the electroweak scale. This latter dependence is relatively minor. On the other hand, a higher Λ is instrumental in causing a larger left-right mass splitting between selectrons, thereby leading to increasing negative values of $\mathcal{A}^{\gamma\gamma}$.

The backgrounds come mainly from $\gamma\gamma Z$ -production followed by invisible decays of the Z . The total cross-section for such final states is about 2×10^{-3} pb, which is rather small for most of the parameter range here. In addition, the backgrounds do not have any asymmetry since they arise from chirality-preserving gauge interactions. Nonetheless, they can reduce $\mathcal{A}^{\gamma\gamma}$ by enhancing the denominator if the backgrounds are comparable to the signals. To alleviate such possibilities, we show here a rather conservative scan over parameters, showing only those cases where the signal is not less than 0.01 pb. We find that sufficiently large asymmetries are still predicted over a wide

region.

Consider next the other situation, where right sleptons are the NLSPs. This happens for most of the parameter space for $N_m = 3$. To be very precise, here the three right slepton generations are lighter than any other superparticle and are practically degenerate unless one considers the fact that in the case of a stau there is a non-negligible left-right mixing that makes the lighter stau the true NLSP. It is easy to see, however, that even then our arguments go through when it comes to asymmetric production of right selectrons with polarized electron beams. This is because, even though a stau may be lighter than it, a right selectron has no other way to decay but into an electron and the gravitino. The consequent signal from a pair of right selectrons then is $e^+e^- \rightarrow e^+e^- + \cancel{p}_T$. Again, the rates with a left-polarized electron beam is highly suppressed because the t-channel becomes ineffective. Thus one expects a large negative asymmetry in $\sigma_{L(R)}^{ee}$, defined as the cross section for $e^+e^- + \cancel{p}_T$ with a left(right) electron beam, and with a suitable \cancel{p}_T -cut so as to make the signal identifiable. The production of left-handed selectrons cannot give rise to final states of this type.

There is however another point here. Unlike in the case with the $\gamma\gamma + \cancel{p}_T$ final state, here we have a substantial contribution coming from W-pair production (the next largest background is from Z-pairs and is down by roughly one order). This contribution receives an enhancement with left-handed electrons because of t-channel effects. The net effect is thus to cancel the asymmetry arising from GMSB, not to speak of the relative suppression it causes to our signals in the total cross-section. What we have done, therefore, is to define the relevant asymmetry more carefully, in the following way:

$$\mathcal{A}^{ee} = \frac{\sigma_L^{tot} - \sigma_R^{tot}}{\sigma_L^{tot} + \sigma_R^{tot}} \quad (6)$$

where $\sigma_{L(R)}^{tot} = \sigma_{L(R)}^{ee} + \sigma_{L(R)}^{WW}$, $\sigma_{L(R)}^{WW}$ being the contributions to the same final states from a W-pair.

Plots of \mathcal{A}^{ee} , defined in this manner, are presented in Figure 2, also drawn with a \cancel{p}_T -cut of 30 GeV. Again, to avoid the error due to Z-pair backgrounds etc., we have made the rather conservative choice of only those regions in the parameter space where the SUSY cross-sections are at least 40% of the corresponding W-induced rates. As is evident from the graphs, even then the asymmetry

is quite spectacular. Starting from large negative values, \mathcal{A}^{ee} gradually becomes positive as the selectron mass increases, and asymptotically approaches the standard model value of ≈ 1 for very large values of M/Λ . This is because the corresponding kinematic suppression for high selectron masses makes the GMSB effects progressively insignificant with respect to the SM effects. However, a large region of the parameter space shows an unambiguously measurable asymmetry, much in the same way as is $\mathcal{A}^{\gamma\gamma}$ discussed above. It should be mentioned that both the graphs are drawn assuming a 100% polarization efficiency of the e^- beam and completely unpolarized e^+ beam.

The range in the parameter space that is covered in our rather conservative approach here includes practically the entire region within the reach of the Large Hadronic Collider (LHC). If, therefore, it is expected that a SUSY signal is observed at the LHC, then one may aspire to resolve the uncertainty regarding the SUSY breaking mechanism by performing experiments with polarized electrons at a high-energy e^+e^- linear collider.

We end this discussion with a few remarks. We have shown only two cases of NLSP production here. Situations where non-NLSP superparticles are produced and subsequently decay into via the NLSP channel to a gravitino can also have significant asymmetries for exclusive final states. For example, with a neutralino NLSP, the production of right selectron pairs can lead to the asymmetric $e^+e^- + \cancel{p}_T$ signal. Similar signals follow from pair-produced neutralinos when a right selectron is the NLSP. Also, though we have not shown any results for $N_m = 2$, this particular case deserves closer attention as over a large region of the parameter space, the right slepton and the lightest neutralino are nearly degenerate, and the resulting signals can be quite interesting. A detailed study of the above points will be reported in a subsequent paper.

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Table 1

N_m	μ	$\tan \beta$	M (TeV)	Λ (TeV)	M_{χ^0} (GeV)	$M_{\tilde{e}_R}$ (GeV)
1	300	2	100	50	61	91
1	900	2	50	25	33	54
2	500	2	50	25	66	68
2	500	20	100	50	139	127
2	800	2	50	25	68	68
3	100	2	100	50	72	150
3	100	20	50	25	62	84
3	800	2	500	50	199	154
3	900	20	500	100	40	52

Some sample mass values for the lightest neutralino and the right selectron with different GMSB parameters.

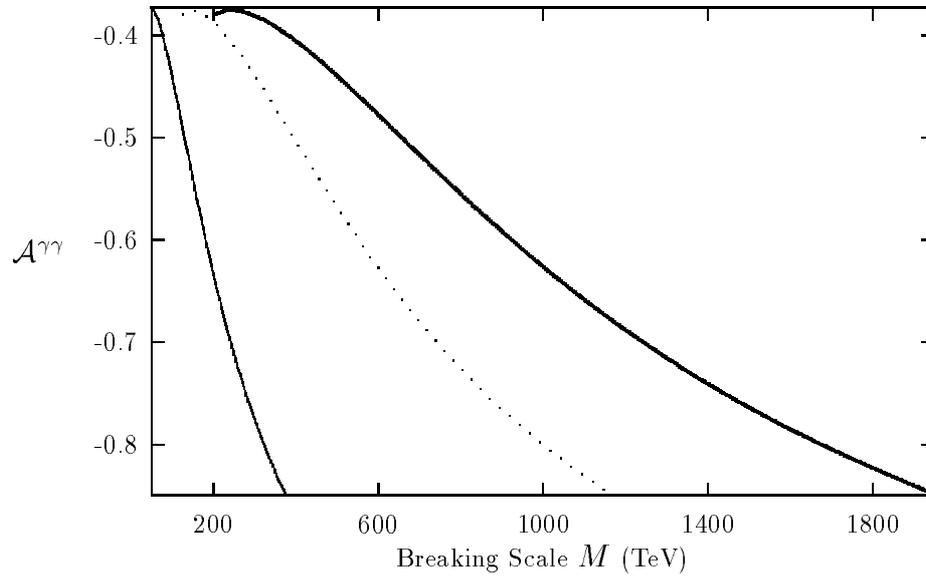


Fig 1(a)

Plot of $\mathcal{A}^{\gamma\gamma}$ vs M , with $\mu = 300$ and $\tan \beta = 10$. The lines from left to right are for $M/\Lambda = 2, 6, 10$ respectively.

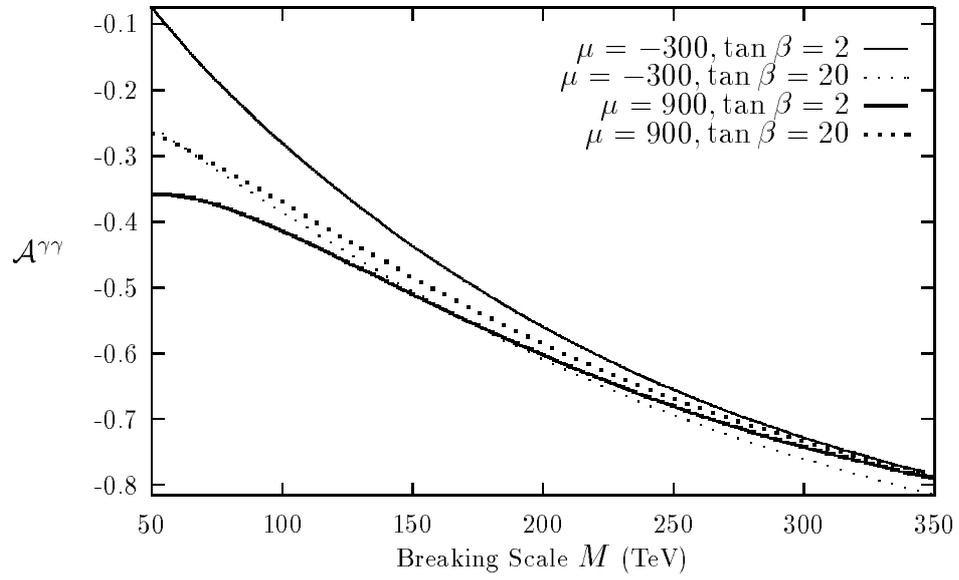


Fig 1(b)

Same as in Fig 1(a) with $M/\Lambda = 2$ and varying μ and $\tan \beta$.

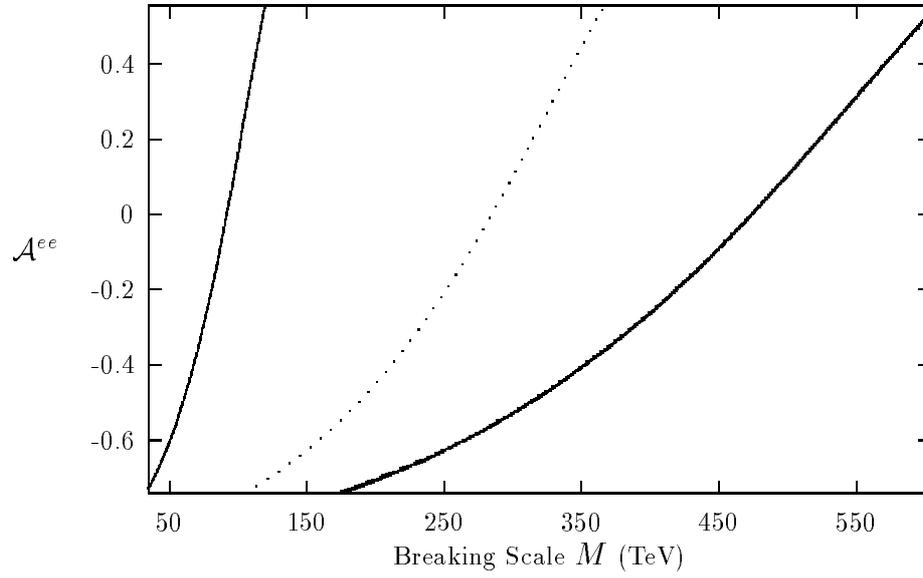


Fig 2(a)

Plot of \mathcal{A}^{ee} vs M , with $\mu = 300$ and $\tan \beta = 10$. The lines from left to right are, as in Fig 1(a), for $M/\Lambda = 2, 6, 10$ respectively.

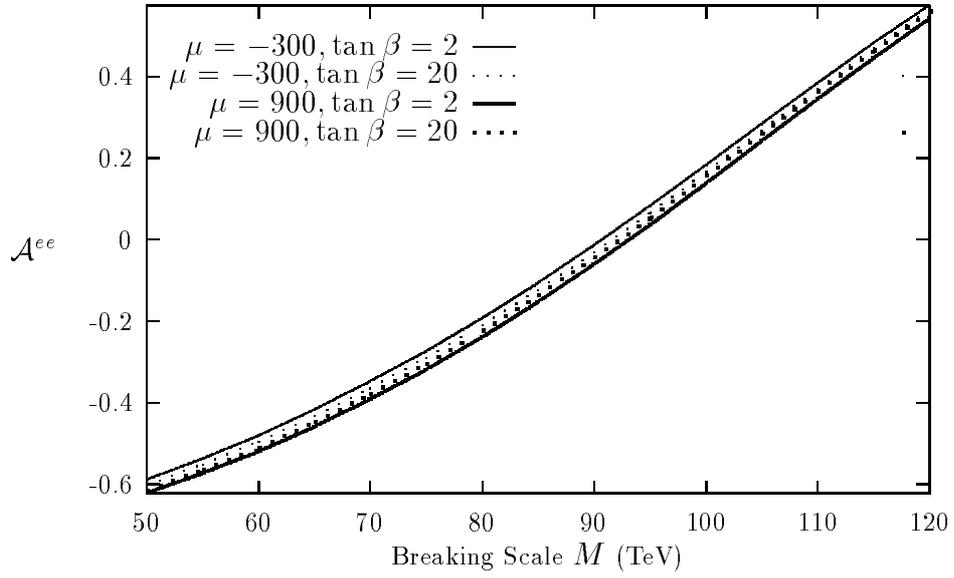


Fig 2(b)

Same as in Fig 2(a) with $M/\Lambda = 2$ and varying μ and $\tan \beta$.