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Squark Mass Determination at a Future Linear Collider*

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ABSTRACT

Present mass limits allow the possibility that squarks may be produced a future linear e^+e^- collider. In this talk we discuss the prospects for precision studies of squark masses at such a facility. Both direct and cascade decay scenarios are discussed. By exploiting the clean environment and polarizable beams of linear e^+e^- colliders, we find that squark mass determinations at the level of a few GeV are possible for a number of regions in parameter space.

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1. Introduction

The discovery of supersymmetry will open a new chapter of experimental studies aimed at accurately determining the parameters of the SUSY sector. It is therefore worth thinking about whether it will be possible to extract from NLC events information about the underlying parameters of SUSY with enough accuracy to be of genuine use in trying to piece together physics at the GUT/Planck/string scales. Several talks in this conference have discussed this question, focussing on gaugino and slepton studies [1,2]. They have shown how the parameters for these sectors of the theory can be determined with enough precision to make nontrivial tests of GUT supergravity models. It is also possible that squarks may be produced at a future linear collider. Present limits [3] allow the possibility that squarks may also be pair produced at future linear colliders. In this talk we assume they are produced and address the issue of precision measurements of squark masses. A more complete account of this work can be found in ref. 4.

2. Squarks in the MSSM

Measurement of squark masses allows one to determine the squark soft SUSY breaking terms, and thus to probe the mechanism of supersymmetry breaking. Soft breaking terms for different species of squarks can in principle be unrelated to one another. The minimal assumptions of supergravity phenomenology often include the assumption of a universal scalar mass at the GUT scale. This leads to definite relations among the physical squark masses, including a left-right splitting and a splitting of the third generation. A 10 GeV L-R splitting is a benchmark. Precision mass measurements would be needed to test these relations.

Experimental studies of squarks will depend in detail on their decay modes. We make the standard assumptions that (a) R-parity is conserved, so the LSP is stable, (b) the LSP is the lightest neutralino, $\tilde{\chi}_1^0$. We then have the following possibilities for squark decay: a direct decay to the gluino, $\tilde{q} \to q\tilde{g}$, a direct decay to the LSP, $\tilde{q} \to q\tilde{\chi}_1^0$, or, if the squark is massive enough, a cascade decay into one of the heavier neutralinos or a chargino, $\tilde{q} \to q'\tilde{\chi}_2^0$ or $\tilde{q} \to q'\tilde{\chi}_1^{\pm}$, followed by the subsequent decays $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0(q\bar{q}, l\bar{l}, \nu\bar{\nu})$ or $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0(q\bar{q}, \nu\bar{l})$. Which decay is prevalant will depend on the parameters (μ, M_2), which determine the masses and composition of the $\tilde{\chi}^0, \tilde{\chi}^{\pm}$. We will assume here that the gluino is heavier than the squark, so that $\tilde{q} \to q\tilde{g}$ is forbidden. Gluino decay will require a seperate analysis beyond the scope of this talk.

For direct decays to the LSP, the experimental signature is two acoplanar jets with large $\not{p}_T$. Most SM backgrounds could be eliminated with cuts in $\not{p}_T$ and the acoplanarity angle, θ_{acop} [5], and most remaining 2 jet backgrounds could be eliminated by requiring the 2 jet invariant mass to be incompatible with the W. In our analysis, we apply the cuts $\not{p}_T > 35$ GeV, $\theta_{acop} < 150^o$. For cascade decays we will have additional jets or leptons in the final state.

For this study, we use a simple parton level Monte Carlo to simulate squark production and decay, then smear quark jets with a detector resolution of $\sigma_E^{\rm had}/E = 50\%/\sqrt{E}$ (E in GeV). We simulate 1 year runs with a luminosity of 10 fb^{-1}/year. Squark masses of 220 GeV are used, and $\sqrt{s} = 500$ GeV is assumed. We use two generations of squarks with a left-right mass splitting. The third generation of squarks requires a seperate analysis and is discussed in other talks [1].

The (μ, M_2) plane is divided into regions characterized by allowed decay channels. The regions are shown in Fig. 1 for $m_{\tilde{q}} = 220\,\mathrm{GeV}$. The hatched regions violate $m_{\tilde{\chi}_1^0} < m_{\tilde{q}}$, and the cross-hatched regions are experimentally ruled out. In the section labeled 4, the squarks can decay to four or more of the neutralinos/charginos. The only two-body decays kinematically allowed in region 1 are those directly to the LSP. In regions 2 and 3, squarks may also decay to either $\tilde{\chi}_2^0$ or $\tilde{\chi}_1^{\pm}$. In region 2, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^{\pm}$ are all dominated by their gaugino components, while in region 3, they are Higgsino-like. It should also be noted that our assumption that the squarks are lighter than gluinos, together will the assumption of the unification of gaugino masses, implies that our analysis is only valid above the dotted line in Fig. 1.

3. Examples

We first consider an example where only direct decays to the LSP are allowed. For the sake of concreteness, we take the point $(\mu, M_2) = (-500\,\mathrm{GeV}, 300\,\mathrm{GeV})$. The quark jet from the decay of the scalar particle $\tilde{q} \to q'\tilde{\chi}_1^0$ will have a flat energy distribution. With knowledge of the LSP mass, which should be known from the study of slepton decay to about 1 GeV [1], measurement of these endpoints determines the squark mass. This is essentially the same analysis applied to slepton studies. In practice the endpoints will be smeared by hadronization and detector resolution, and one must make a fit to extract the mass. While this analysis is adequate, it does not make use of the correlations between the jets in an event. One way to use this information is as follows: with knowledge of the center of mass energy and the LSP mass, one can for each event find the lowest kinematically allowed squark mass consistent with the observed jet momenta, called $m_{\tilde{q}}^{min}$. The distribution of $m_{\tilde{q}}^{min}$ is sharply peaked near the value of the actual squark mass. Making a fit to this quantity gives somewhat more precise results. In the case at hand, a likelihood fit to our event simulation determines the squark mass to within 0.5 GeV at 95% CL.

One noteworthy feature of squark mass measurements in this region is that,

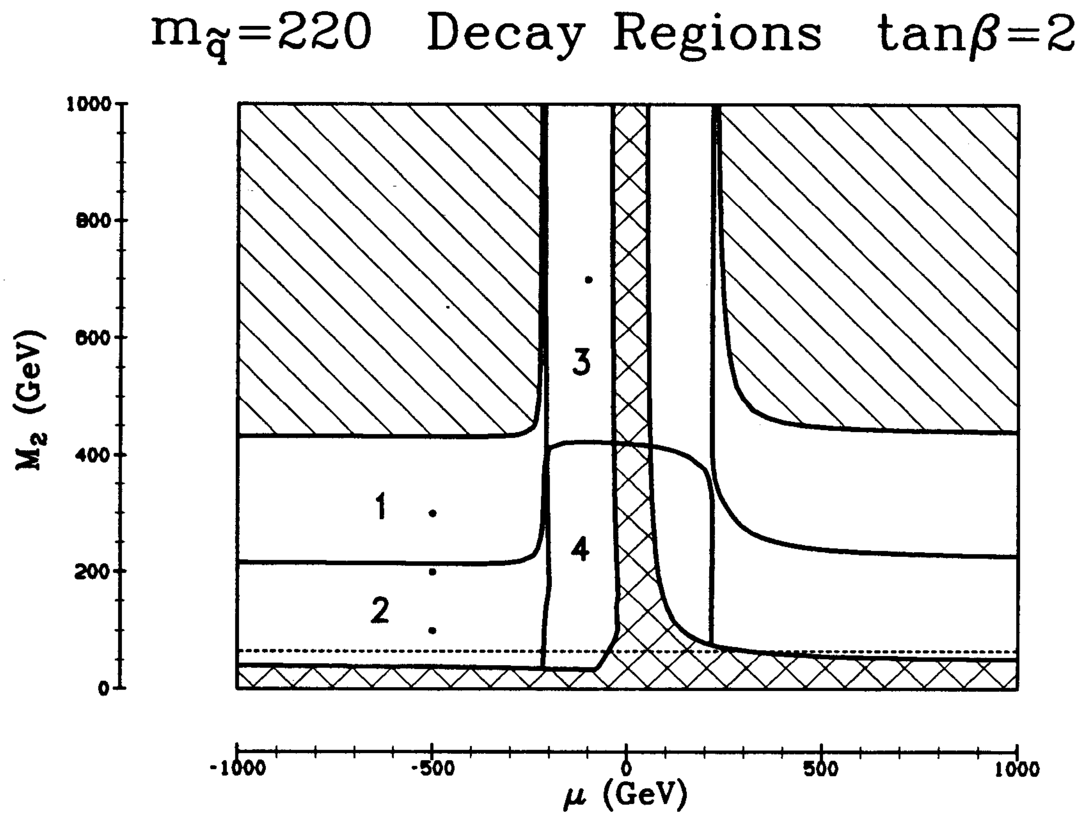

Figure 1. The M, μ plane organized according to regions of similar squark decays. Dots represent examples treated in the text. Regions with $\mu > 0$ are qualitatively similar to their $\mu < 0$ counterparts.

since both left- and right-handed squarks have identical decay channels, a direct comparison can be made to determine left-right mass splittings. The left- and right-handed squarks can be isolated using polarized beams, and systematic errors should largely cancel for the ratio of their masses.

We must now address the question of whether, for a point in parameter space with multiple decay channels present simultaneously, one can still extract squark masses with precision. This can be done if we can isolate the jets coming from the initial squark decays from those from the decays of heavy neutralinos/charginos. We discuss how this is done for several examples.

We will begin with examples from the region of parameter space labelled region 2. Here the LSP is primarily $\tilde{B}$, and squarks have new decay channels through $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$. Right handed squarks, which have a large coupling to the $\tilde{B}$, will decay almost exclusively directly to the LSP. Left handed squarks have more complex decays. We take $(\mu, M_2) = (-500\,\text{GeV}, 200\,\text{GeV})$, and find branching ratios $\text{BR}(\tilde{u}_L \rightarrow \tilde{\chi}_1^0) =$

58%, BR($\tilde{u}_L \to \tilde{\chi}_2^0$) = 28%, BR($\tilde{u}_L \to \tilde{\chi}_1^\pm$) = 14%, and similarly for down type squarks. The masses of $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^\pm$ are 103, 206, and 206 GeV, respectively. This is a fairly typical cascade scenario, and the jet energy spectrum is plotted in Fig. 2. We see a superposition of jets from the different squark decays and from the neutralino/chargino decays. In this case, there are a substantial number of events where both squarks decay directly to the LSP. These may be isolated efficiently by selecting 2 jet events with no isolated leptons. Events involving a decay to $\tilde{\chi}_2^0$ followed by the emission of two neutrinos will also be of this form (but will lie in a different energy range, as seen in Fig. 2). Having isolated this subset of events, the analysis of region 1 may be applied, in this case determining the squark mass to 1.6 GeV at 95% CL.

In cases where direct decays are not dominant, the analysis must rely on cascade events. Such is the case for the point in region 2 $(\mu, M_2) = (-500\,\mathrm{GeV}, 100\,\mathrm{GeV})$. Here the masses of $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^\pm$ are 53, 108, and 108 GeV, respectively, and the branching ratios are BR($\tilde{u}_L \to \tilde{\chi}_1^0$) = 7%, BR($\tilde{u}_L \to \tilde{\chi}_2^0$) = 61%, and BR($\tilde{u}_L \to \tilde{\chi}_1^\pm$) = 32%. As long as the leptonic branching fractions of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ are signifigant, there will be a substantial number of 2 jet events (plus leptons). Since $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ are nearly degenerate in this region, we need not distinguish between them kinematically. We can apply the analysis of region 1 to the 2 jet events, replacing the LSP mass with the chargino mass. The effectiveness of this analysis depends on the leptonic branching fractions of $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$. If $m_{\tilde{l}} < m_{\tilde{\chi}_1^\pm}$, they will decay through sleptons or sneutrinos predominantly. If this is not the case, the branching fractions will depend on a number of off-shell diagrams. For a slepton/sneutrino mass of 200 GeV, we find by direct calculation BR($\tilde{\chi}_2^0 \to q\bar{q}$) = 20%, BR($\tilde{\chi}_2^0 \to l\bar{l}$) = 31%, BR($\tilde{\chi}_2^0 \to \nu\bar{\nu}$) = 49%, BR($\tilde{\chi}_1^\pm \to q'\bar{q}$) = 62%, and BR($\tilde{\chi}_1^\pm \to l\nu$) = 38%. There are many leptonic decays, so we may apply the analysis of 2 jet events. Of 1319 e_L^- polarized events that pass the $\not{p}_T$ and θ_{acop} cuts, 754 are 2 jet events (+ leptons). 32% of these actually contain direct decays to the LSP, but about half of these can be removed by demanding consistency with the kinematics of double cascade decays. This leaves 623 events, with 81% correctly identified. Analysing these determines the squark masses to 2.4 GeV at 95% CL. If the slepton mass is lower, this analysis will improve.

We look at a final example in region 3, where the LSP is higgsino dominated, and $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^\pm$ are close in mass. For the representative point $(\mu, M_2) = (-100\,\mathrm{GeV}, 700\,\mathrm{GeV})$, the masses of $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^\pm$ are 98, 111, and 106 GeV, respectively. It is now difficult to distinguish the different types of decays. The simplest approach is to plot all jet energies. Jets coming from decays of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ will have a soft energy spectrum, and can be eliminated with an energy cut. The remaining spectrum will contain three overlapping flat distributions with three endpoints. The relative positions of the endpoints are known provided the mass differences of $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ are known, so one can fit the distribution to obtain the squark mass. In the

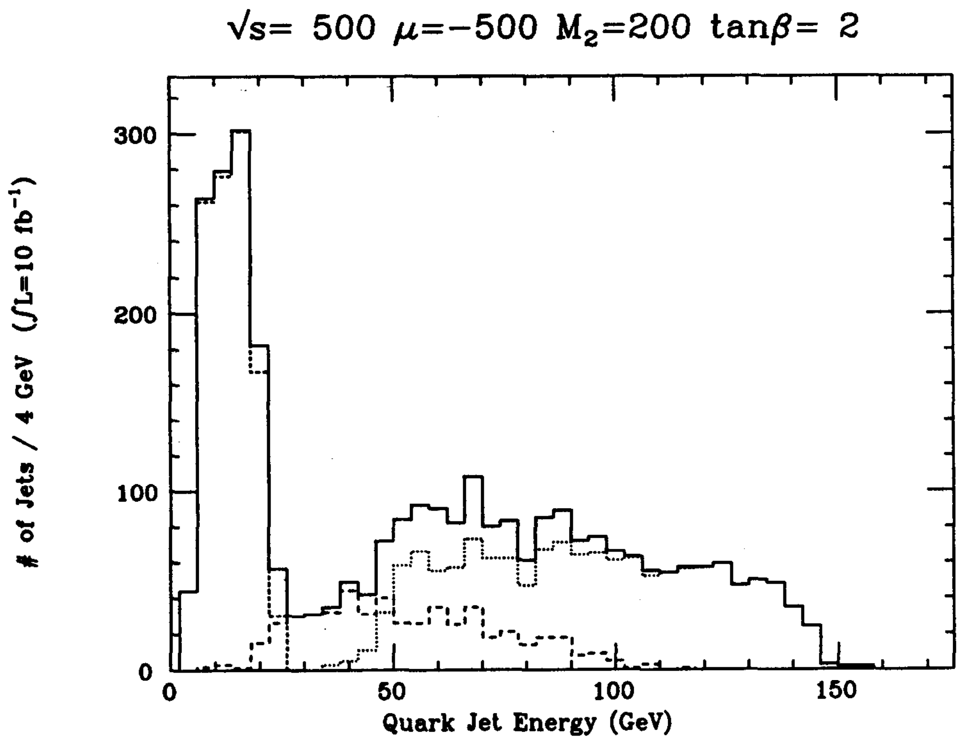

Figure 2. Jet energy distributions for an example described in text. The solid line is for all jets, dotted line is for jets from direct LSP decay, small dashed line is for jets from squark decay to neutral/chargino, large dashed line is for jets from the decay of neutral/charginos.

present example, the fit gives $m_{\tilde{q}}$ to within 1.2 GeV at 95% CL.

Finally, a few remarks are in order regarding the extension of this work to higher energy colliders and more massive squarks. When the (μ, M_2) plane is partitioned for decays of a heavier squark, the region where cascade decays are allowed is enlarged. Also, in a substantial portion of this region, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ may decay to the LSP and on-shell Z's and W's. If $m_{\tilde{l}} > m_{\tilde{\chi}_1^\pm}$ the W's and Z's will insure that cascade decays are predominantly hadronic. However, W and Z mass reconstruction may be applied to 4 jet events to isolate primary decay jets a large fraction of the time.

4. Conclusions

In this talk we have shown that, even if complex decay patterns are present, future linear e^+e^- colliders offer an opportunity for precision squark mass measurements. Potential accuracy could be of the order 1-2 GeV. However, this analysis has been carried out at the parton level only, and more realistic simulations are needed.

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