MSSM studies using sfermions at a Linear Collider

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Abstract

The experimental signatures for sfermion production at a linear collider operating at $\sqrt{s} = 500$ GeV is presented. The methods to extract their cross-section, masses, mixing angles, and decay-properties are discussed, and how to use these measurements to constrain the parameters of SUSY, in particular the mSUGRA.

1 Introduction

One of the most interesting topics for a future linear e^+e^- collider is super-symmetry (SUSY)[1], the proposed symmetry between fermions and bosons that would stabilize the loop-corrections of the Higgs mass, without unnatural fine-tuning. It also would solve the hierarchy problem, and appears as a possible low-energy manifestation of super-gravity and super-string theory[2].

Many versions of super-symmetric theories can be constructed, but the one with minimal particle content is the one that is by far been most widely studied. In this version of SUSY, MSSM (the Minimal Supersymmetric extension to the Standard Model)[3], each standard model particle is accompanied by a super-symmetric partner with the opposite statistic (fermion partners to the SM bosons, and boson partners to the SM fermions). In addition, one finds that the Higgs sector must contain at least two doublets, and in MSSM one assumes that there is indeed this minimal required number[4]. Hence, in the MSSM one has one sfermion for each fermion (ie. six squarks, three sneutrinos, and there charged leptons), one fermion partner to each gauge-boson (the gauginos), and one fermion partner to each Higgs (the Higgsinos). The gauginos and Higgsinos mix to give rise to the physical states, the two charginos and the four neutralinos.

The absence of observed boson-partners of the standard model fermions and vice-versa shows that SUSY must be broken. To preserve the properties solving the hierarchy and naturalness problems, SUSY-breaking must occur in a quite specific way (so-called soft-breaking). Two proposed mechanisms for such soft breaking of SUSY are gravity mediated SUSY-breaking (mSUGRA) and gauge mediated SUSY-breaking (GMSB). Both these senarii reduce the number of parameters of the MSSM by a large factor. In mSUGRA there will only be five independent GUT-scale parameters [5]:

- $M_{1/2}$, the common gaugino mass.
- M_0, the common scalar mass.
- $\tan\beta$, the ratio of the two Higgs VEV's.
- A, the SUSY breaking tri-boson coupling.
- μ, the Higgs mass-parameter.

Furthermore, if SUSY is invoked to explain why one Higgs mass-parameter is driven negative, and hence electro-weak symmetry breaking, $|\mu|$ can be expressed in terms of the other parameters. It's sign will remain undetermined, however[6].

In this note, I will concentrate on the scalar partners to the SM fermions - the sfermions - and what precision measurements of these particles could reveal about SUSY. I will specialize to the case mSUGRA, and to the aspects that are less likely to be explored at the LHC.

2 The scenario

The context of the studies in present note is the following: When a linear collider becomes operational, LHC will have been taking data for several years. This will mean that *if SUSY exists, LHC will have discovered it.* Only very particular choices of the SUSY parameters would denigrate this statement. However, it is quite possible that the LHC experiments will not be able to make precision measurements of the SUSY parameters. Whether this will be the case or not depends on if there are several cascade decay-chains available in the SUSY spectrum. Without the lever-arm of studies of cascade-decays, a hadron-collider will be penalized by the large background from the spectator quarks, and from the lack of knowledge of the exact energy and polarization state of the partons actually interacting[7].

Following the proposed TESLA parameters, the linear collider is assumed to run at E_{CMS} = 500 GeV, and to deliver an integrated luminosity of 500 fb^{-1} per annum. It is also assumed that the option of having polarized beams is pursued[8].

There are certain states that will be hard to discover at LHC, in particular the lightest neutralino, and the sleptons (in particular the stau). However, discovering these states at the LC will not be a primary argument for it's construction: a machine with much less luminosity would be sufficient for this. Typical production cross-sections for sfermions of a mass of some hundred GeV are around 10-100 fb, and the selection efficiencies are at least around 20% . Hence, a integrated luminosity of a few fb^{-1} would be enough for their discovery.

On the other hand, it is quite likely that the colored sfermions (the squarks) will be to heavy to be observed at TESLA. The possible exclusion to this are the third generation squarks (the stop and the sbottom) where important mixing effects might make them much lighter than the other squarks.

Hence, the primary topic for a linear collider will be to *measure* the properties of SUSY particles, and thereby extracting detailed information on the SUSY-parameters.

3 Sfermions

At a linear collider, sfermions are pair-produced in the s-channel, except the selectron, for which also t-channel neutralino-exchange contributes. In this note, I assume that R-parity [10] is conserved, which implies that sfermions will decay into a fermion and a neutralino or a chargino. It also implies that the lightest SUSY particle (the LSP) is stable, and neutral, the latter due to cosmological constraints. The most likely candidate for the LSP is the lightest neutralino, $\tilde{\chi}^o_1$. The LSP will interact only little with ordinary matter, and will escape the detector without being seen.

The ino produced in the sfermion decay might be the LSP, in which case the only visible particle will be the fermion: $\tilde{f} \to \tilde{\chi}^o_1 f$. Or, it could be a heavier state which would then in turn decay into the LSP, possibly in a multi-step cascade: $\tilde{f} \to \tilde{\chi}^{\pm} f' \to \tilde{\chi}^o f' X$ or $\tilde{f} \to \tilde{\chi}^o_2 f \to \tilde{\chi}^o_1 f X$. In this case, also the decay products of the heavier inos will be detected. In most of the mSUGRA parameter space, the right-handed sfermions tend to decay directly to the corresponding fermion and the LSP, while the left-handed super-partners tend to decay in a cascade, whenever this is kinematically allowed[9]. In any of the cases, the typical signal for sfermion production is the observation of a pair of acollinear fermions, possibly accompanied by jets, and large missing energy and large momentum imbalance (due to the presence of the LSP).

Due to the fact that leptons are easily identified, one will be able to separate the different flavours of sleptons, except in the case of a decay $\tilde{l} \to \tilde{\chi}^{\pm}\nu \to \tilde{\chi}^o \nu X$. For squarks, this will be much more difficult. One will need to have very good b-tagging capabilities, and a good theoretical understanding of the squark hadronization mechanism.

3.1 Sfermion masses in mSUGRA

Several mechanisms are in play when the sfermions attain their weak-scale masses[11]:

Firstly, at the GUT scale, the mass of all sfermions are given by the common free parameter M_0.

Secondly, when the masses are evolved from the GUT-scale to the weak scale according to the appropriate renormalization group equations, a contribution proportional to $\mathrm{M}_{1/2}$ will appear. This arrises due to gauge-loops, and is always positive. The colored sfermions - the squarks - get substantially larger such contributions that the un-colored sleptons. The weak iso-spin doublets gets larger contributions than the singlets, and hence the super-partners to the left-handed and the right-handed fermions are not expected to be degenerate in mass: The left-handed partners are expected to be heavier than the right-handed ones.

Thirdly, if the Yukawa couplings are large at the the GUT scale, they will also vary appreciably when changing scale to the weak scale. This running will induce contributions to the third generation sfermion masses. These contributions will be negative, showing up as a coefficient less than unity multiplying M_0.

Finally, due both to Yukawa couplings and SUSY-breaking tri-linear couplings, the weak iso-spin states of the third generation tend to mix, yielding a lighter physical state below the lightest un-mixed state.

Hence, it is very likely that sleptons are appreciably lighter than squarks, and are the ones to concentrate most on. Possibly, also the stop and/or the sbottom will be light, due to mixing.

3.2 The slepton mass spectrum

The generic mass-matrix for the sleptons can be written as [12]:

$$\mathcal{M} = \begin{pmatrix} m^2_{LL} & m^2_{LR} \\ m^2_{LR} & m^2_{RR} \end{pmatrix}$$

where the elements can be expressed in the mSUGRA parameters as

$$m_{LL}^2 = 0.5M_{1/2}^2 + a_L M_0^2 + D - terms$$

$$m_{RR}^2 = 0.15M_{1/2}^2 + a_R M_0^2 + D - terms$$

$$m_{LR}^2 = m_l\,(A - \mu\tan\beta)$$

Here it can directly be seen that mixing is expected only for staus, since the off-diagonal term is proportional to the lepton-mass. The selectron and smuon masses are expected to be degenerate, and equal to m_{LL} and m_{RR} for the left- and right-handed partners, respectively. The factors a_L and a_R depend on the size of the Yukawa couplings at the GUT scale. For selectrons and smuons, both will be unity, but for staus they might be substantially less. In eg. ref[13] a SO(10) scenario with GUT-scale Yukawa-unification is presented, and the authors find typical values to be $a_L = 0.65$ and $a_R = 0.32$. By diagonalization of the mass-matrix for the staus, one finds that the stau mixing angle is given by:

$$\frac{\tan^2\theta_{mix} - 1}{\tan\theta_{mix}} = \frac{m_{LL}^2 - m_{RR}^2}{m_{LR}^2}$$

and by finding the eigen-values that:

$$m_{\tilde{\tau}_1}^2 = \frac{1}{2}\left(m_{LL}^2 + m_{RR}^2 - (m_{LL}^2 - m_{RR}^2)\frac{\tan^2\theta_{mix} + 1}{\tan^2\theta_{mix} - 1}\right)$$

From this, one sees that the iso-mass^2 curves will be straight lines in the $M_{1/2}^2$–M_0^2 plane, and hence the iso-mass curves will be conic sections in the $M_{1/2}$–M_0 plane. For the smuons and the selectrons, the slope of these lines are fixed, while for the stau the slope changes with the mixing angle. Figure 1 shows how a simultaneous observation of a right-handed and a left-handed slepton would yield quite precise values for M_0 and $M_{1/2}$. Figure 2 shows the case of an observation of a stau and a right-handed smuon. Note that the preferred point in the $M_0 - M_{1/2}$ plane depends very sensitively to the exact value of the stau mixing angle.

3.3 The slepton decay-properties and production cross-sections

Since the sfermions are scalars, if follows that the momentum distribution of the fermion follows a flat distribution centered at

$$< P > = \frac{E_{beam}}{2}\left(1 - \left[m_{\tilde{\chi}}/m_{\tilde{f}}\right]^2\right)$$

and with a width

$$\Delta = 2 < P > \left(1 - \sqrt{1 - \left[m_{\tilde{f}}/E_{beam}\right]^2}\right)$$

Hence, measuring the width and position of the visible decay-products yields information on both the mass of the sfermion, and of the ino into which it decays. From the formula, one sees that the lowest (highest) possible fermion momentum is:

$$p_f^{min(max)}(m_{\tilde{f}}, m_{\tilde{\chi}}) = \frac{E_{beam}}{2}\left(1 - \left[m_{\tilde{\chi}}/m_{\tilde{f}}\right]^2\right)\left(1 \underset{(+)}{-} \sqrt{1 - \left[m_{\tilde{f}}/E_{beam}\right]^2}\right)$$

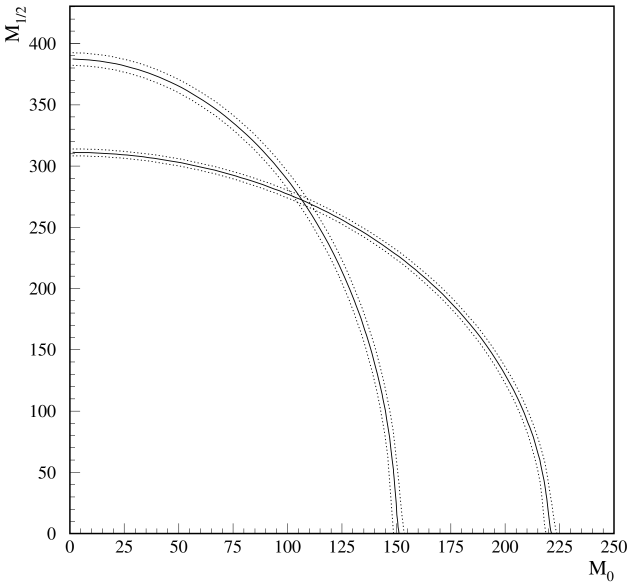

Figure 1: *The iso-mass curves in the $M_0 - M_{1/2}$ plane for a right-handed slepton of mass 150 GeV/c^2 and a left-handed one with a mass of 220 GeV/c^2. Error-bands of $\pm$ 2 GeV/c^2 are also shown. The effect of D-terms have been neglected.*

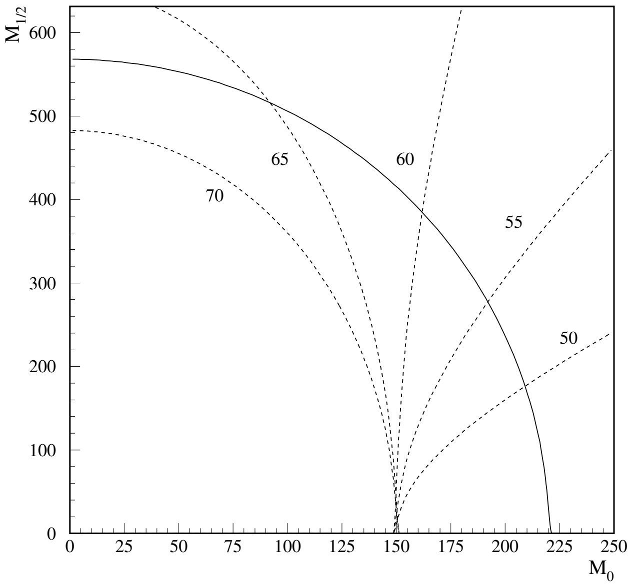

Figure 2: *The iso-mass curves in the $M_0 - M_{1/2}$ plane for a stau of mass 150 GeV/c^2 and for the mixing-angles indicated in the figure (dashed lines) and a right-handed smuon with a mass of 220 GeV/c^2 (solid line). The effect of D-terms have been neglected, and $a_L = a_R = 1$.*

In the case of the stau, the tau will decay, and the spectrum of it's decay products will probe the polarization state of the tau, and thereby the nature of the stau. For instance, in the case of $\tau \to \pi\nu$, the pion momentum will be distributed according to:

$$f_p(x) = \frac{1}{p_\tau^{max} - p_\tau^{min}} \begin{cases} \ln\frac{p_\tau^{max}}{p_\tau^{min}} + P_\tau\left(2x\left[\frac{1}{p_\tau^{min}} - \frac{1}{p_\tau^{max}}\right] - \ln\frac{p_\tau^{max}}{p_\tau^{min}}\right) & \text{if } 0 < x < p_\tau^{min} \\ \ln\frac{p_\tau^{max}}{x} + P_\tau\left(-2x\frac{1}{p_\tau^{max}} - \ln\frac{p_\tau^{max}}{x} + 2\right) & \text{if } p_\tau^{min} < x < p_\tau^{max} \end{cases}$$

In this formula, P_τ is the average polarization of the tau, which depends both on the stau-mixing and neutralino mixing [14]:

$$P_\tau = \frac{a_R^2 - a_L^2}{a_R^2 + a_L^2}$$

where

$$a_R = -\cos\theta_{mix}\frac{gm_\tau}{\sqrt{2}M_W\cos\beta}N_{13} - \sin\theta_{mix}\frac{2g}{\sqrt{2}}\tan\theta_W N_{11}$$

$$a_L = \cos\theta_{mix}\frac{g}{\sqrt{2}}\left(N_{12} + \tan\theta_W N_{11}\right) - \sin\theta_{mix}\frac{gm_\tau}{\sqrt{2}M_W\cos\beta}N_{13}$$

N_{11}, N_{12}, N_{13} is the Bino, neutral Wino, and Higgsino content of the lightest neutralino, respectively. Note that β enters only via the Higgsino component.

The momentum spectrum of the pion in decays of staus with mass 150 GeV/c^2 into a pion and an LSP of mass 100 GeV/c^2 is shown in figure 3, for different average polarizations and two beam-energies (155 and 250 GeV). For a given number of observed events, the sensitivity for P_τ is larger if the accelerator is operated closer to the threshold, but the cross-section is also lower, so the optimal point for this measurement will be a compromise between these two factors.

The distribution of the angle between the the two visible fermions can also be calculated, and can be shown to depend only on the mass of the the sfermion, not that of the ino[15]. Figure 4 shows the distribution of this angle for a few slepton masses at E$_{CMS}$ = 500 GeV.

Also due to scalar nature of the sfermions, their angular distribution is isotropic (except the t-channel contribution to selectron production). As a consequence, the distribution of the decay products is also isotropic, which is very helpful to reduce background: most backgrounds tend to be forward-peaked.

For $\sqrt{s}$ well above M$_Z$, the production cross-section of the sleptons is proportional to $\beta^3/s = 8\left(E_b^2 - m_{\tilde{l}}^2\right)^{3/2}/E_b^5$ [16]. The proportionality factor depends in complicated (but well-known) way on the sfermion mixing, the beam polarization, and, for the selectrons, on the neutralino mixing. Hence, if the mixing is known, a precise measurement of the cross-section yields a measurement of the sfermion mass, or vice-versa. In the case of the smuon and the first and second generation squarks, the mixing is negligible, and the cross-section directly gives the mass. For the third generation sfermions, and for the selectron, one can use the fact that the dependence of the cross-section on mixing angle is different for different beam-polarizations. Therefore, if the measurement is done with different beam polarizations, also the mixing angles will be accessible. This is illustrated in figure 5 (from [17]), which presents a simultaneous determination of mass and mixing for the stop.

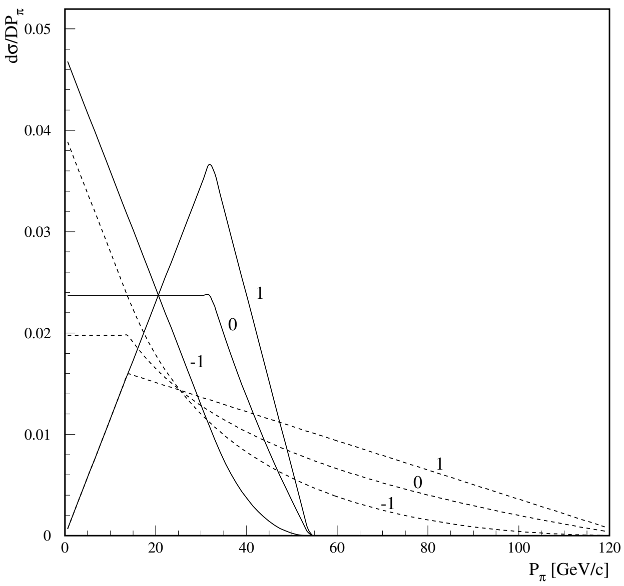

Figure 3: *Pion momentum spectrum in $\tilde{\tau} \to \tau\tilde{\chi}^o_1 \to \pi\nu\tilde{\chi}^o_1$, at different average polarizations as indicated above the curves. The solid line is for E_{CMS}=310 GeV, and the dashed is for E_{CMS}=500 GeV. The stau mass is 150 GeV/c^2 and the LSP mass is 100 GeV/c^2.*

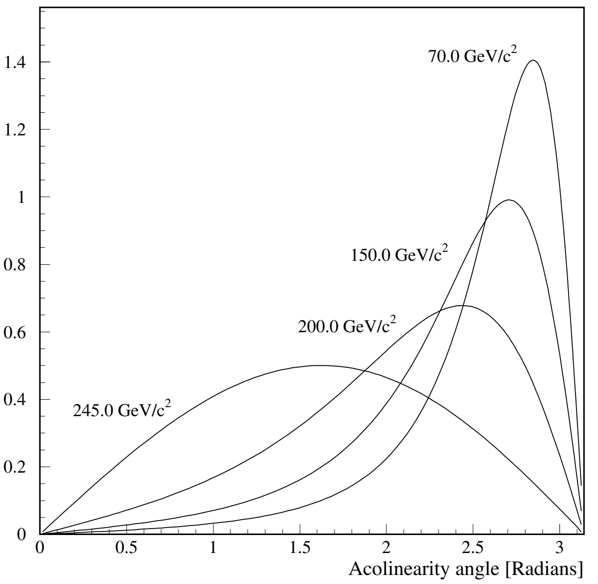

Figure 4: *Acollinearity angle distribution between the observed leptons from decays of sleptons with the masses indicated next to the curves. The CMS energy is 500 GeV.*

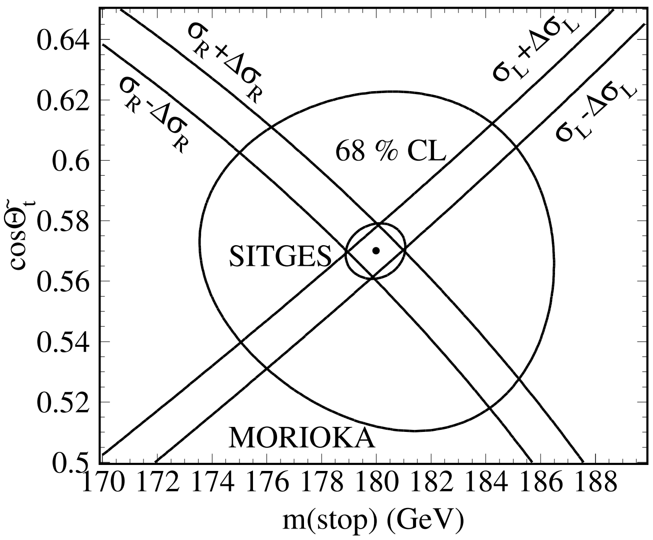

Figure 5: *Stop mass and mixing. The two bands indicate the iso-cross-section curves for opposite beam-polarizations. The widths of the bands indicate the experimental precision found in the study [17].*

It should be noted that the rise of the cross-section has a rather slow (β^3) dependence on the beam-energy. This, once again, is due to the scalar nature of the sfermions. Whether a threshold-scan or a measurement of the decay-product spectrum will yield the highest precision on the slepton mass depends very strongly on the the mass: The higher the mass, the lower the precision will be from the threshold. This is illustrated in figure 6, where the cross-section for $\tilde{\tau}_R$ (from SUSYGEN [18]) is shown as a function of E_{CMS} for a few different masses. Note the pronounced decrease of the slope as the mass increases.

4 Meassuring sfermion properties and extracting mSUGRA parameters

The discussion in the previous sections shows that the mass of the sfermions is accessible alone from the acolinearity distribution, and for un-mixed states from the total cross-section. From the decay-spectrum, it is accessible together with the mass of the ino it decays to, and from the cross-section at different beam-polarizations, it can be measured together with the mixing angle for mixed states. The mass of mixed states can also be measured together with the mixing-angle by measuring the cross-section at several CMS energy. By studying specific decay-channels of the τ lepton in $\tilde{\tau}$ decays, the average polarization of the τ can be found, which in turn gives access to a certain combination of $\tilde{\tau}$ and neutralino mixings.

If $M_{1/2}$ is small - just above the limit from chargino production at LEP200 - either both of the left and right partners of the leptons will be kinematically accessible at TESLA, or none of them: If eg. $M_{1/2} = 130$, then $m_{\tilde{l}_R}$ will be below 250 GeV/c^2 if M_0 is less than 245, and $m_{\tilde{l}_R}$ will be below the same limit as long as M_0 is less than 232.

The observation of both states of an un-mixed sfermion would yield a simultaneous

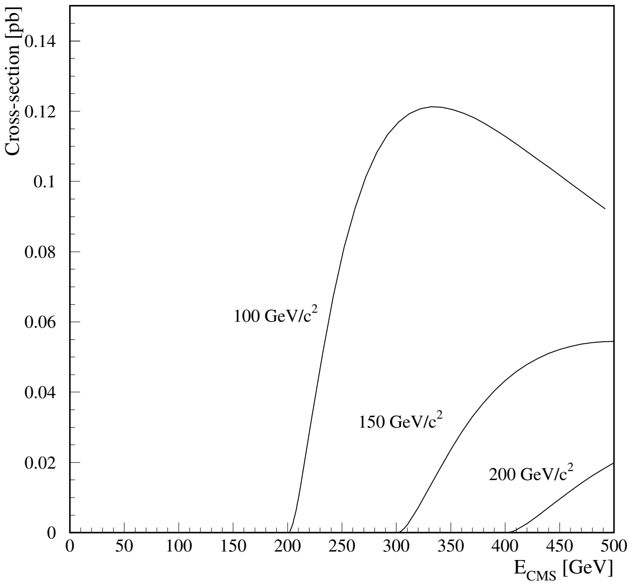

Figure 6: *Production cross-sections for $\tilde{\tau}_R$ as a function of E_{CMS}. The curves indicate the behaviour for three different stau-masses, as indicated in the figure*

measurement of M_0 and $M_{1/2}$ with a precision of the same order as the mass-measurements of the two sfermions. If also a eg. the $\tilde{\tau}$ is observed, and at a different mass from the other sleptons, the mixing-angle will be measured to a high precision as well, and hence also the off-diagonal element in the $\tilde{\tau}$ mass-matrix, ie. the value of $A - \mu \tan\beta$. In addition, the LSP mass will also be measured (from the decay spectrum), and, quite likely, the masses and branching ratios of one or several heavier inos. This implies further constraints on ino mixings. To this can be added the selectron cross-section (a measure of the $e\tilde{e}\chi^o$ vertex), the polarization measurement in stau decays, and EW-symmetry breaking relation. Hence, in this scenario, mSUGRA will be largely over-constrained from the sleptons alone. The only situation that would denigrate this conclusion is if the only ino accessible is the LSP, and it is a pure gaugino. In that case, there is little sensitivity to $\tan\beta$.

If $M_{1/2}$ is large, only the lighter states will be accessible: for $M_{1/2}$ above 350, even a vanishing M_0 yields m_{LL} above 250 GeV/c^2. In this case - where only the lighter states are observed - M_0 and $M_{1/2}$ might still be evaluated, provided that the $\tilde{\tau}$ has a substantial mixing (and that it is measured!). The precision will be lower due to the rapid change of the $\tilde{\tau}$ iso-mass curves with the mixing angle. The measurements of the $e\tilde{e}\chi^o$ strength, the LSP mass, and the tau-polarization are still possible, albeit with less redundancy. Hence, also in this case the full set of mSUGRA parameters can be found from the sleptons alone, except in the case of no cascade decays and a pure gaugino LSP.

Finally, it should be noted that even is *only the stau* is observed, it might be possible to measure all the mSUGRA parameters, if the EW symmetry breaking relation is assumed. The stau alone provides at least four quantities: $m_{\tilde{\tau}}$, θ_{mix}, m_{LSP} and P_τ. If cascade-decays occur, then more ino-masses and branching ratios will be added to the list. If no cascades occur, there will be no redundancy, so a study of the stau alone will not be able to rule out alternative models for soft SUSY breaking in favour mSUGRA, except if the alternative model has even less free parameters.

5 Expected measurement precision

The precision of the cross-section measurement can be estimated by studying the performance of the LEP200 searches for sleptons, and scale to the situation at TESLA. The cross-sections for sleptons of masses accessible at TESLA are in the range 10-100 fb. At LEP200, the efficiency for the signal is typically in the range 20-40 %, and the total background remaining after the signal-selection cuts is around 5-10 fb. Most of the SM background contributions scale with $1/\sqrt{s}$ between the LEP200 and TESLA range. The W^+W^- background, dominating at LEP200, is less similar to the signal at TESLA energies, since it becomes more forward-peaked. It therefore seems quite probable that a background rate corresponding to 1-2 fb would be attainable at TESLA. These numbers yield between 1000 and 20000 signal events per year, with less than 1000 background events. This would give a relative error on the cross-section between 0.7 and 4 %.

If a simple β^3/s dependence of the cross-section is assumed (ie. ignoring the effect of the Z-pole and of ISR), one finds that the optimal sensitivity to the mass, at a fixed integrated luminosity, is attained if the accelerator is tuned to run at $E_b=\sqrt{2}m_{\tilde{l}}$. The error on the mass will be proportional to $m_{\tilde{l}}^2$:

$$\Delta(m_{\tilde{l}}) \approx 10^{-3}\frac{m_{\tilde{l}}^2}{\sqrt{\epsilon\int\mathcal{L}}}$$

with masses in GeV/c^2 and integrated luminosity in fb^{-1}. The error on the mass obtainable from the decay-product spectrum obtained at $E_b=\sqrt{2}m_{\tilde{l}}$ will also scale with $m_{\tilde{l}}^2$, with a proportionality factor slightly lower. Hence, an error of the order of 1 GeV/c^2 is expected for masses of 100 GeV/c^2 at TESLA. By measuring the cross-section at several energies, the information from the change in shape of the cross-section curve with sfermion energy (cf. figure 6) will also be exploited, and the error will be reduced. In fact, a detailed study [19] shows that with a scan with 10 energy-points and 10 fb^{-1} per point, an error of 400 MeV/c^2 can be attained for a smuon of 176 GeV/c^2. The authors also find an error of 200 Mev/c^2 from the decay-spectrum for the same smuon mass. The study in [17] shows that for a 180 GeV/c^2 stop at minimum production cross section, $\Delta m = 1$ GeV and $\Delta\cos(\theta_{mix}) = 0.009$ can be attained. In [14], a study of the measurement error of P_τ is performed. The authors find that an error of 0.08 is attainable for an integrated luminosity of 100 fb^{-1}. In their study, they use several τ decay-modes, not only $\tau\to\pi\nu$.

6 Summary

In this note, I have summarized to properties of sfermion production and decays at TESLA. As they are the most likely ones to be accessible at $\sqrt{s}$=500 GeV, I've mostly concentrated on sleptons. How the experimental masses, cross-sections, mixing-angles, and polarizations can be used to to extract the parameters of SUSY within the mSUGRA frame-work has also been discussed, both in the low and high $M_{1/2}$ region. The conclusion of this discussion is that in the low region, mSUGRA can be studied in great detail by the sleptons alone, eg. both $M_{1/2}$ and M_0 can be measured to a precision of the same order as that of the slepton masses themselves. Also in the high region, mSUGRA can be studied to some detail. Even is the lightest stau is the only sfermion accessible, quite some insight can be gained. Finally, indicative numbers and rules-of-thumb for the attainable experimental precisions were given.

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