PRAMANA
— journal of
physics

Vol. 62, No. 2
February 2004
pp. 439–450

Unraveling supersymmetry at future colliders

XERXES TATA
Deparment of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA
Email: tata@phys.hawaii.edu

Abstract. After a quick review of the current limits on sparticle masses, we outline the prospects for their discovery at future colliders. We then proceed to discuss how precision measurements of sparticle masses can provide information about how SM superpartners acquire their masses. Finally, we examine how we can proceed to establish whether or not any new physics discovered in the future is supersymmetry, and describe how we might zero in on the framework of SUSY breaking. In this connection, we review sparticle mass measurements at future colliders, and point out that some capabilities of experiments at e^+e^- linear colliders may have been over-stated in the literature.

Keywords. Superparticle discovery at future colliders; sparticle masses as clues to high-scale physics; sparticle spectroscopy at linear colliders.

PACS Nos 14.80.Ly; 12.60.Jv

1. Introduction

Despite its striking success, almost everyone regards the standard model (SM) as an effective theory that need to be augmented by new degrees of freedom once particle collisions at a scale of several hundred GeV to a TeV become experimentally accessible. Although there is no unambiguous indication of the form that this new physics will take, we will assume it to be weak scale supersymmetry [1]. Softly broken supersymmetry provides a calculable and predictive framework, consistent with all observations. The simplest supersymmetric models as well as more elaborate models based on $SO(10)$ unification (these allow for neutrino masses as well as Yukawa coupling unification) naturally account for the measured value of $\sin^2\theta_W$ in LEP experiments, and all models with a conserved R-parity include a promising candidate for dark matter [2], which makes up the bulk of matter in our Universe.

While dimensionless couplings of superpartners are all fixed (in terms of known SM couplings) by supersymmetry, without further assumptions there are $\mathcal{O}(100)$-dimensional parameters that are needed to parametrize the effects of supersymmetry breaking. This is not surprising because without any guidance from data we can only catalogue the effects of supersymmetry breaking. Since many of these dimensional parameters are flavour-violating scalar masses or flavour/CP violating cubic scalar couplings, we would get phenomenologically unacceptable flavour and/or

CP violation if these parameters all have values of $\mathcal{O}(100)$ GeV. This 'negative observation' serves as a starting point for model-building. Unwanted flavour violation can be avoided if,

- sparticles with the same gauge quantum numbers have the same mass parameters (the exact scale at which this degeneracy occurs is unimportant),
- fermion and sfermion mass matrices are diagonalized by the same unitary transformation, or
- superpartners are sufficiently heavy so that loop effects from flavour-violating scalar masses and couplings are sufficiently suppressed.

Many well-studied models adopt the first of these alternatives. In the mSUGRA model all scalars are degenerate at a high scale M_X; within the framework of low-energy gauge-mediated SUSY breaking (GMSB) sparticle masses are proportional to their gauge couplings; within anomaly-mediated SUSY breaking (AMSB) models sparticle masses are determined by the gauge β functions and anomalous dimensions, so that sparticles with the same gauge quantum numbers are again degenerate. In many models, scalar mass parameters are not exactly degenerate when renormalized at $Q = M_{\mathrm{GUT}}$. Although we usually take $M_X = M_{\mathrm{GUT}}$ in the mSUGRA framework, renormalization effects may considerably split the mass parameters of different GUT multiplets if $\ln(M_X/M_{\mathrm{GUT}}) \gtrsim 1$. A similar situation also obtains in the gaugino-mediated SUSY breaking framework. This is a higher dimension theory in which SM supermultiplets are spatially separated (in the extra dimensions) from the SUSY breaking sector, while gauge bosons and gauginos can propagate in the bulk. As a result, gauginos directly 'feel' the effect of SUSY breaking and acquire large masses, while matter scalars only feel SUSY breaking indirectly via their gauge interactions, so that their mass parameters (renormalized at the compactification scale M_{c}) are suppressed. If $\ln(M_{\mathrm{c}}/M_{\mathrm{GUT}}) \gtrsim 1$, renormalization effects lead to substantial values for scalar mass parameters at $Q = M_{\mathrm{GUT}}$ with, e.g. $m_{\tilde{e}_{\mathrm{L}}} \neq m_{\tilde{e}_{\mathrm{R}}}$. Intra-generational splitting (from D-terms) is also expected in SUSY models based on $SO(10)$ gauge symmetry. Sparticle spectroscopy could thus provide clues to the mechanism by which superpartners of SM particles acquire their masses.

A 'bottom-up' vision of the particle physics program for the next two decades would then include the following general steps.

(1) Establish the discovery of new physics.
(2) Figure out what this new physics is – here, we will assume it to be weak scale supersymmetry.
(3) From the experimental values of sparticle masses and couplings, figure out the organizing principle(s) that lead to the observed supersymmetry breaking parameters.

Clearly, this will be a data-driven endeavour which, we hope, will lead to a deeper synthesis of our picture of particles and their interactions, and perhaps even to a new fundamental principle of physics.

2. What do we know today?

No experiment has discovered a superpartner. The negative result of various searches have been interpreted as lower limits on sparticle masses. The most straightforward limits are on masses of charged sparticles from experiments at LEP [3]: $m_{\widetilde{W}_1} > 103$ GeV; $m_{\tilde{e}} > 99$ GeV; $m_{\tilde{\tau}_1} > 85$ GeV; $m_{\tilde{q},\tilde{b},\tilde{t}} \gtrsim 63$–100 GeV, depending on assumptions. The chargino and slepton bounds assume that the mass of the lightest supersymmetric particle (LSP) differs sufficiently from the corresponding sparticle mass. The CDF and D0 experiments at the Tevatron have established [4] the lower limit, $m_{\tilde{g}} \gtrsim 195$ GeV (which moves up to 300 GeV if the squarks are all roughly degenerate with the gluino). The CDF experiment also leads to a lower limit somewhat above 100 GeV (120 GeV) on $m_{\tilde{t}_1}$ ($m_{\tilde{b}_1}$) assuming that the splitting between the squark and $\widetilde{Z}_1$ is larger than about 50 GeV [5].

There are also constraints from low energy experiments. The experimental determination of $B(b \to s\gamma)$ [6], $g_\mu - 2$ [7] and the lower limit on $B(B_s \to \mu^+\mu^-)$ [8] have been used to constrain the parameter space of various models. Very recently, the branching ratio $B(B \to X_{\rm s}\ell^+\ell^-)$ has also been measured [9], and may further constraint SUSY model parameters. It should be kept in mind that these indirect constraints may be very sensitive to details of model assumptions. For instance, even a tiny additional source of flavour violation in the sparticle sector, or departure from exact universality between flavours would lead to significantly different predictions for $b \to s\gamma$ or $B_{\rm s} \to \mu^+\mu^-$ decay rates. Moreover, there appears to be considerable theoretical uncertainty in the evaluation of the SM value of $g_\mu - 2$, and we advise care in drawing inferences from its experimental value.

Models where R-parity is conserved have the LSP as a natural candidate for dark matter, and negative results of dark matter searches have also led to important constraints. Unless lepton number conservation is violated, neutrinoless double beta decay experiments essentially exclude [10] sneutrinos lighter than $\mathcal{O}(1)$ TeV as *galactic* dark matter. Fortunately, many models predict a neutralino LSP. Considerable ranges of model parameters are excluded by the requirement that the neutralinos should annihilate efficiently enough so that their cosmological relic density does not violate observational upper limits on the cosmological parameter Ωh^2 [11]. If we further assume that the observed dark matter is all neutralinos, then the range of Ωh^2 is even more restrictive [11a]. Direct and indirect searches for cold (neutralino) dark matter underway are reviewed in [13].

3. Discovery capabilities of future colliders

Experiments at the Tevatron have been projected to accumulate an integrated luminosity in excess of 15 fb^{-1}. This should enable them to probe $m_{\tilde{g}}$ up to 400 GeV in the $\not\!\!E_{\rm T}$ channel (if squarks are not extremely heavy) [14,15] and, indirectly up to 750 GeV if leptonic signals from $\widetilde{W}_1\widetilde{Z}_2$ production are very enhanced [15]. Unfortunately, there are other ranges of parameters for which the LEP bounds imply that Tevatron experiments will be insensitive to sparticle production. The luminosity upgrade of the Tevatron will increase the reach of stop [16] (sbottom

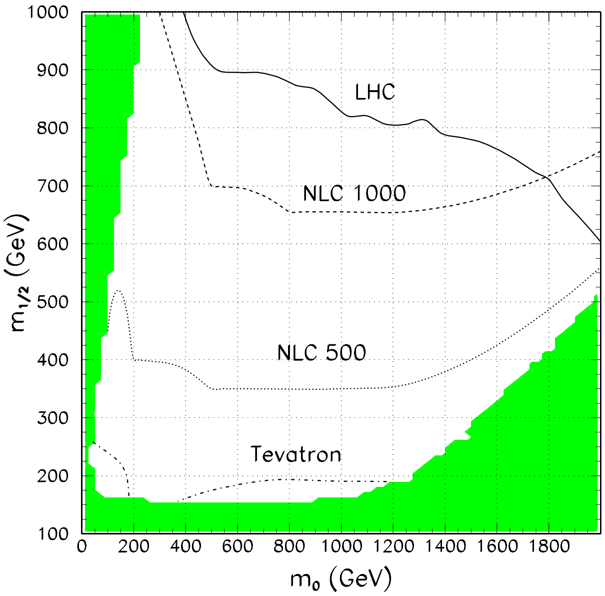

Figure 1. The SUSY reach of an e^+e^- linear collider with $\sqrt{s} = 500$ and 1000 GeV, assuming an integrated luminosity of 30 fb^{-1}. The reach is shown in the m_0–$m_{1/2}$ plane of the mSUGRA model with $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$. For comparison we also show the reach of a luminosity upgrade of the Fermilab Tevatron, assuming 25 fb^{-1} of integrated luminosity, and the CERN LHC for an integrated luminosity of 10 fb^{-1}. The ultimate reach of the LHC may be somewhat larger than that shown in the figure.

[17]) masses to 200/180 (230) GeV assuming that $\tilde{t}_1 \to c\widetilde{Z}_1/\tilde{t} \to b\widetilde{W}_1$ ($\tilde{b}_1 \to b\widetilde{Z}_1$). The sbottom reach is degraded by about 30 GeV if the decay $\tilde{b}_1 \to b\widetilde{Z}_2$ is accessible, and $\widetilde{Z}_2$ mainly decays to hadrons.

The LHC is really the machine of choice for sparticle discovery. For most well-motivated models, experiments at the LHC should be sensitive to gluino and squark masses in excess of 2 TeV assuming an integrated luminosity of just 10 fb^{-1} [18–22]. In GMSB models where either the bino-like neutralino, or $\tilde{e}_R/\tilde{\mu}_R$ is the second lightest sparticle, the presence of isolated photons or hard isolated leptons can be used to reduce SM backgrounds, enhancing the reach to $m_{\tilde{g}} = 3$ TeV [21]. On the down side, if the LSP of the mSUGRA model decays hadronically the gluino mass reach of the LHC may be reduced to about 1.2 TeV [23]. Generally speaking, if squarks and gluinos are lighter than about 1 TeV, SUSY signals should be observable in several jets + leptons $+\not{E}_T$ channels [18–20].

Experiments at e^+e^- colliders should be able to search for charged sparticles (and if they decay visibly, also sneutrinos) with masses up to ~80–95% of their kinematic limit. This can be somewhat extended by processes like $e^+e^- \to \widetilde{Z}_1\widetilde{Z}_{2,3,4}$ or $e^+e^- \to \widetilde{W}_1\widetilde{W}_2$ if these are experimentally accessible. Roughly speaking, as illustrated in figure 1, an e^+e^- collider with an energy of 1.2 TeV has a similar SUSY discovery reach as the LHC [24].

4. Beyond sparticle discovery

4.1 *Establishing the identity of new physics*

Once the discovery of new physics is established, what do we do? First, we have to figure out what this new physics is. Again, assuming the new physics to be SUSY, this may come about via the discovery of several superpartners. At the LHC, this may be possible via the identification of many different signals that are then interpreted as cascade decays of sparticles, or via the identification of several 'kinematic edges' in appropriate energy or mass distributions [25–27]. Logically, this would only establish that there are several new particles. The size of the new physics cross-sections may help us to ascertain whether or not these have strong interactions, and may help us even to ascertain some of their other gauge quantum numbers.

However, to convincingly establish that the new physics is (softly broken) supersymmetry, we have to determine the dimensionless couplings of the new particles and show that these are equal to the corresponding SM couplings [28]. For instance, at tree-level, the coupling $\tilde{g}'$ of $\tilde{e}_\mathrm{R}$ to the electron-bino system has to be the SM hypercharge gauge coupling g'. Establishing this equality is complicated by the fact that the bino is not a mass eigenstate. Nevertheless, it has been shown [29] that under favourable circumstances, experiments at an e^+e^- collider would be able to test this coupling constant relationship at the 1–2% level. If squarks are much heavier than sleptons, radiative corrections lead to substantial value for $\delta g' \equiv g' - \tilde{g}'$. Experimental limits on $\delta g'$ would thus provide an upper bound on the squark mass scale, or if $\delta g'$ can actually be measured, even roughly determine it [30].

4.2 *What can sparticle masses tell us about high-scale physics?*

We have already seen that knowledge of sparticle masses would provide guidance about how superpartners of SM particles acquire their masses. Indeed uncovering how SUSY is broken [31], and how superpartners 'feel the breaking of SUSY' will be a forefront issue if sparticles are discovered. Some mechanisms for the transmission of SUSY breaking are easy to distinguish. For instance, $m_{\tilde{e}_\mathrm{L}} - m_{\tilde{e}_\mathrm{R}}$ is quite different in mSUGRA and GMSB models, and these two frameworks can be distinguished by even a rough determination of these masses. However, small (high scale) intra-generation splittings may be present in other scenarios; e.g., due to $SO(10)$ D-terms, or in the gaugino-mediated SUSY breaking framework. Determining sparticle masses sufficiently precisely can serve to distinguish even these scenarios (as well as others with small inter-generational mass splittings) from one another and from mSUGRA. Indeed, there are many reasons to expect that precise sparticle mass measurements will be useful:

- Recall that even with universal high scale mass parameters which are the hallmark of the mSUGRA framework, $m_{\tilde{e}_\mathrm{R}} \neq m_{\tilde{\tau}_\mathrm{R}}$ because of renormalization effects from tau Yukawa couplings. Also, the Super-Kamiokande atmospheric neutrino data [32] strongly suggest that neutrinos are massive. The well-known see-saw mechanism provides an elegant framework for the small values of neutrino masses implied by these data. Implementation of this mechanism requires that electroweak singlet, right-handed neutrino (RHN) fields exist, and further that neutrinos have Yukawa interactions. As a result, $m_{\tilde{\nu}_e}$ would be expected to differ from $m_{\tilde{\nu}_\tau}$, in much the same way $m_{\tilde{e}_{\rm R}} \neq m_{\tilde{\tau}_{\rm R}}$ in mSUGRA. Exactly how large this difference would be, and which neutrino would be the heaviest, depends on the neutrino Yukawa coupling matrix.

To isolate the effect of neutrino Yukawa couplings on slepton masses, we define [33],

$$\Delta_I = m^2_{\tilde{e}_I} - m^2_{\tilde{\tau}_I}, \tag{1}$$

for $I = {\rm L,R}$. It is then simple to check the 1-loop renormalization group equation ($t = \ln Q$),

$$\frac{\mathrm{d}}{\mathrm{d}t}(2\Delta_{\rm L} - \Delta_{\rm R}) = \frac{4}{16\pi^2} f_\nu^2 X_\nu,$$

valid for $M_{\rm GUT} \geq Q \geq M_N$, where RHNs decouple. If M_N is significantly lower than $M_{\rm GUT} \sim 2 \times 10^{16}$ GeV, effects of neutrino Yukawa couplings can be substantial, and may be detectable if the masses in (1) can be precisely measured. The obvious problem is that $m_{\tilde{\tau}_{\rm L,R}}$ are not the physical masses $m_{\tilde{\tau}_{1,2}}$ that would be experimentally measured. Within mSUGRA, however, $\tilde{\tau}_{1,2} \sim \tilde{\tau}_{\rm R,L}$ leading us to define $\Delta_{1,2}$ as in (1) but with $m_{\tilde{\tau}_{\rm R,L}}$ replaced by $m_{\tilde{\tau}_{1,2}}$. It is optimal [33] to work in terms of the dimensionless variable

$$\delta_{1\nu} = \frac{2\Delta_\nu - \Delta_1}{(m^2_{\tilde{\nu}_e} + m^2_{\tilde{\nu}_\tau} + m^2_{\tilde{e}_{\rm R}} + m^2_{\tilde{\tau}_1})/4},$$

where $\Delta_\nu = m^2_{\tilde{\nu}_e} - m^2_{\tilde{\nu}_\tau}$, which is directly measurable at a linear collider.

Singlet neutrinos (and their superpartners) necessarily occur in SUSY $SO(10)$ models which have recently received considerable scrutiny since they offer the possibility of both gauge and Yukawa coupling unification [34,35]. Within this framework, $f_{\nu_\tau} = f_t$ at $Q = M_{\rm GUT}$ and $\delta_{1\nu} \simeq 0.1$–0.2, to be compared with small and negative [35a] for mSUGRA. The detectability of neutrino Yukawa couplings then depends on whether sparticle masses can be measured accurately enough to allow for a distinction between $\delta_{1\nu} = 0.1$ and $\delta_{1\nu} \simeq 0$. It has been established that $m_{\tilde{\nu}_e}, m_{\tilde{e}_{\rm R}}$ and $m_{\tilde{\tau}_1}$ will be measured to better than a per cent level at linear colliders, and distinction between $\delta_{1\nu} = 0.1$ and $\delta_{1\nu} \simeq 0$ is possible if $m_{\tilde{\nu}_\tau}$ can be determined with a precision of 2–2.5% [33].

- If $\tilde{e}_{\rm L}, \tilde{e}_{\rm R}$ and $\widetilde{W}_1$ are all accessible at an e^+e^- collider, and their masses well measured, experiments at these facilities would directly be able to determine $\delta m^2 \equiv m^2_{\tilde{e}_{\rm R}}(M_{\rm GUT}) - m^2_{\tilde{e}_{\rm L}}(M_{\rm GUT})$. The quantity Δ (and its cousin Δ') introduced in ref. [36] is,

$$\Delta = m^2_{\tilde{e}_{\rm R}} - m^2_{\tilde{e}_{\rm L}} + \frac{m^2_{\widetilde{W}_1}}{2\alpha_2^2(m_{\widetilde{W}_1})} \times \left[\frac{3}{11}\left(\alpha_1^2(m_{\tilde{e}}) - \alpha_1^2(M_{\rm GUT})\right) - 3\left(\alpha_2^2(m_{\tilde{e}}) - \alpha_2^2(M_{\rm GUT})\right)\right],$$

is proportional to δm^2. The running gauge couplings that enter in the expression for Δ are by definition obtained by evolving their experimental values using one-loop renormalization group equations. If both selectrons and the lighter chargino are kinematically accessible at linear colliders, Δ itself is directly determined from experiment. Its value is a measure of the GUT scale selectron mass splitting, assuming that just slepton mass parameters are so split. Determining this slepton mass splitting could provide important input for entangling the underlying SUSY breaking scenario. A 1% measurement of selectron and chargino masses (which is comfortably within the projected capability of linear colliders) would allow δm^2 to be determined precisely enough to be sensitive to the values of GUT scale mass splittings expected from SUSY $SO(10)$ D-terms, and possibly also to the slepton mass splitting expected in models with gaugino-mediated SUSY breaking [36].

- If $\widetilde{W}_1$ and $\widetilde{W}_2$ masses along with production cross-sections and left–right asymmetries can be measured at e^+e^- colliders, a complete reconstruction of the underlying chargino parameters would be possible [37]. Determination of the weak scale soft parameters is the first step towards figuring out the underlying model.
- An interesting bottom-up strategy for the reconstruction of the underlying high-scale physics of SUSY breaking has been suggested in ref. [38]. The idea is to evolve the 'experimentally determined' soft SUSY breaking parameters to high scales and look for patterns between the high-scale values of these parameters. Implementing this strategy appears to require that essentially all sparticle masses and couplings are known with some precision. Such an analysis is thus possible only after all the results from the LHC as well as all the energy upgrades of a linear collider are available. Given this large amount of experimental data, it would be intriguing to explore whether combining the information from various sectors provides new information; e.g. combining the gaugino and scalar lepton sectors to form the quantity Δ mentioned above led to a measure of the intra-generational splitting between slepton mass parameters at $Q = M_{\rm GUT}$.

With these considerations, all providing motivation for precise determination of sparticle masses, let us now discuss how well these will be determined at future experimental facilities.

4.3 *Precision spectroscopy*

It is well-known that sparticle masses can be well-determined in experiments at e^+e^- colliders. However, precision measurements are also possible at the LHC, at least under favourable circumstances [20,26,39]. An instructive illustration of this was provided by an examination of the so-called 'comparison point' studied at Snowmass 96 [39] for the mSUGRA model with $m_0 = 200$ GeV, $m_{1/2} = 100$ GeV, $\tan\beta = 2$, $A_0 = 0$ and $\mu < 0$ [39a]. This yields a gluino of about 300 GeV that dominantly decays via $\tilde{g} \to b\tilde{b}_1$ (88%). Since $\tilde{b}_1$ was dominantly $\tilde{b}_{\rm L}$, it decayed mainly into the $SU(2)$-like mass eigenstate $\widetilde{Z}_2$ (86%). The third unusual feature of this point was that the leptonic decay $\widetilde{Z}_2 \to \ell^+\ell^-\widetilde{Z}_1$ had an enhanced branching fraction of about 16.5% (per lepton flavour). The enormous production cross-section for gluino pairs made it possible to cleanly isolate the decay chain $\tilde{g} \to \tilde{b}_1 b \to \widetilde{Z}_2 bb \to \ell^+\ell^- bb\widetilde{Z}_1$. The dilepton mass distribution from this chain will have a sharp kinematic cut-off at $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$. The large event rate for this cascade led to the conclusion that this kinematic end-point could be determined with a precision limited only by systematic errors, and conservatively estimated to be smaller than 50 MeV [26,39]. Furthermore, because of the large event rate there was a sufficient number of events close to the upper end-point of the dilepton mass distribution, for which $\widetilde{Z}_1$ and the dilepton system is nearly at rest in the rest frame of $\widetilde{Z}_2$. Knowledge of the three-momenta of the two leptons then allows the reconstruction of the corresponding momentum of $\widetilde{Z}_2$ in the lab system. By combining with the momentum of the b jets, $m_{\tilde{b}_1}$ and finally the gluino mass were obtained. It was shown that $m_{\tilde{g}} - m_{\tilde{b}_1}$ could be determined with a precision of about 2 GeV. Other examples of mass reconstruction may be found in the ATLAS TDR. Assuming a model framework, LHC measurements can also be used to determine the underlying parameters, though sometimes measurements may well be consistent with more than one model [20]. It is fair, however, to say that it seems difficult to devise an *a priori* strategy for mass measurements at the LHC because the optimal way to proceed depends strongly on the sparticle spectrum. As illustrated by the specific Snowmass example, this may, however, not be a serious limitation once we have real data.

Precision measurements of sparticle masses at e^+e^- linear colliders were pioneered by the JLC group [40]. Assuming that charged sparticles directly decay to the LSP, they showed that a determination of kinematic end-points made it possible to determine $m_{\tilde{e}_{\rm L,R}}, m_{\tilde{\mu}_{\rm L,R}}, m_{\widetilde{W}_1}$ and $m_{\widetilde{Z}_1}$ with a precision of 1–2%. An integrated luminosity of $\sim$50 fb^{-1} and the availability of $\geq$80% longitudinal electron beam polarization (to reduce SM backgrounds and SUSY contamination) are necessary requirements for these measurements [40a]. It was subsequently shown [42] that cascade decays do not degrade the precision which with slepton and chargino masses may be determined. On the contrary, they provide new opportunities for mass measurements: for instance, if $B(\tilde{\nu}_e \to e\widetilde{W}_1)$ is substantial, $m_{\tilde{\nu}_e}$ can be determined with a precision of $\sim$1% via a determination of the end-points of the energy spectrum of electrons in the final state from $e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e \to e\widetilde{W}_1 e\widetilde{W}_1 \to ee\mu jj + \not\!\!E_{\rm T}$. This final state topology is chosen because it is essentially free of SM background as well as SUSY contamination. It was also shown [29] that, with an integrated luminosity of $\sim$100 fb^{-1}, the determination of kinematic end-points of the tau energy distribution also leads to a similar precision on $m_{\tilde{\tau}_1}$. Using the analogue of the strategy that works so well for determining $m_{\tilde{\nu}_e}$, however, seems to lead to a considerable degradation for a determination of $m_{\tilde{\nu}_\tau}$ or $m_{\tilde{\tau}_2}$ [33].

More recently, in the TESLA TDR it has been suggested that an energy scan of the sparticle production cross-section results in a better determination of sparticle masses than the kinematic determinations described above. Specifically, it is claimed that by measuring this cross-section at ten values of energy in 1 GeV steps starting at the pair production threshold, one can determine $m_{\tilde{e}_{\rm R}}, m_{\tilde{\nu}_e}$ and $m_{\widetilde{W}_1}$ to better than 0.05%, and of $m_{\tilde{\tau}_{1,2}}$ and $m_{\tilde{\nu}_\tau}$ to about 0.4% [43]. The quoted precision assumes an integrated luminosity of 10 fb^{-1} at each energy value, i.e. 100 fb^{-1} in

Table 1. A summary of the projections for tau sneutrino mass measurements (90% CL) for two cases, assuming a 95% longitudinally polarized electron beam. The first row shows our projection with backgrounds and SUSY contamination included, while the second shows the corresponding projection if these backgrounds can be effectively eliminated without loss of signal. For $\tilde{\nu}_e$, both SM background as well as SUSY contamination are insignificant.

	Case I	Case II
$m_{\tilde{\nu}_\tau}$ (500 fb^{-1})	$153^{+12.5}_{-24}$ GeV	$174.9^{+7.1}_{-15.4}$ GeV
	$153^{+11.5}_{-24}$ GeV	$175.4^{+5.6}_{-10.9}$ GeV
$m_{\tilde{\nu}_e}$ (120 fb^{-1})	$157.8^{+0.8}_{-1.2}$ GeV	$178.0^{+0.5}_{-0.8}$ GeV
$m_{\tilde{\nu}_e}$ (500 fb^{-1})	$158.1^{+0.4}_{-0.5}$ GeV	$178.2^{+0.2}_{-0.4}$ GeV

all. Indeed, as discussed in the last subsection, such a precision would enable us to conclude that experiments at proposed linear e^+e^- colliders would be sensitive to (a) intragenerational high-scale mass splittings expected in many models and (b) neutrino Yukawa interactions in the simplest $SO(10)$ SUSY GUT, assuming the usual see-saw mechanism for neutrino masses.

The strong physics motivation for such measurements led us to independently examine [44] the TESLA strategy for determining $m_{\tilde{\nu}_\tau}$ for two examples of mSUGRA model parameters: Case (I): $m_0 = 100$ GeV, $m_{1/2} = 200$ GeV, $\tan\beta = 3$ adopted in the TESLA study [43] and Case (II): $m_0 = 150$ GeV, $m_{1/2} = 170$ GeV, $\tan\beta = 5$ examined in ref. [33]. For both cases, $A_0 = 0$ and $\mu > 0$.

To reduce SUSY contamination and SM backgrounds we confined ourselves to the $\tau\tau\ell jj + \not{E}_{\mathrm{T}}$ final state from the decay $\tilde{\nu}_\tau \to \widetilde{W}_1\tau$ of each sneutrino. We optimistically assumed that it would be possible to efficiently identify taus via vertex separation [43]. Even so, for the scan suggested in [43], we find that at most just over one event with this topology is expected so that this strategy is not viable.

There is another important issue that impacts upon how well masses can be determined. The TESLA strategy to determine $m_{\tilde{\nu}_\tau}$ by fitting to the threshold behaviour of the cross-section is essentially a counting experiment. However, the final state cross-section depends not only on $m_{\tilde{\nu}_\tau}$, but also on an unknown branching fraction that needs to be simultaneously determined from the same experiment. The attainable precision on the sneutrino mass measurement is degraded relative to the case where the branching fraction is known. Indeed, an optimal mass measurement is obtained [44] by dividing the available luminosity between just three or four carefully chosen values of energy. One of these should be at the highest energy of the machine since this will reduce the sensitivity of the cross-section to the mass, and hence give a tight constraint on the branching ratio into the final state. Another of these measurements should be close to the reaction threshold, since the cross-section there is very sensitive to the mass. The other measurements should be at widely spaced points in between [44a]. Optimally, the integrated luminosity should be divided so as to have roughly equal number of events at each of these points.

Using this strategy, even with optimistic assumptions about tau detection, no meaningful measurement of $m_{\tilde{\nu}_\tau}$ is possible with an integrated luminosity of

100 fb^{-1}. The projections for an integrated luminosity of 500 fb^{-1} are summarized in table 1, for the two mSUGRA cases that were examined. We see that even if SUSY contamination can be eliminated, for both cases the precision on $m_{\tilde{\nu}_\tau}$ is considerably worse than the 2–2.5% needed for clear evidence of tau neutrino Yukawa interactions, at least within the simplest see-saw framework. Improving precision by including other channels does not appear possible. Although we have not discussed this in detail, we also show our estimate of how well $m_{\tilde{\nu}_e}$ will be determined. We see that even with 500 fb^{-1} we estimate that the error on $m_{\tilde{\nu}_e}$ will be larger than that claimed in [43]. Here, some improvement may be possible by including signals in other channels.

5. Summary and outlook

With the continued operation of the upgraded Fermilab Tevatron, the imminent start of the LHC, and hopefully, also of a linear e^+e^- collider, we can look forward to exciting discoveries in particle physics over the next two decades. Observational cosmologists have already stolen the lead in this regard. Almost any new discovery will cause us to rethink our ideas. If we find something completely unexpected this will clearly be true. The discovery of extra spatial dimensions will be spectacular. In the (generally assumed to be) unlikely event that experiments conclusively exclude the existence of any Higgs boson up to about 1 TeV (and discover nothing else except signs of a strongly coupled electroweak symmetry breaking sector), this will also be true. If experiments discover a light Higgs boson and several of the anticipated superpartners, we will have new questions to think about: why are baryon and lepton numbers apparently conserved even though we can write renormalizable operators that do not conserve these? Why is there approximate conservation of flavour? Where do neutrino masses come from? Why is μ not much larger than the weak scale? How do superpartners of SM particles get their masses? How do dark matter and dark energy fit in? From the physics viewpoint, the worst case scenario would be to discover a weakly coupled neutral Higgs boson of mass around 125 GeV and nothing else [44b]. It would be hard to decide how one should proceed if this turns out to be the case.

Many new measurements will be needed to elucidate the form of any new physics that is discovered. Further measurements will be needed to figure out the dynamics of SUSY breaking if the new physics is supersymmetry. This will best be accomplished by the combined efforts of the LHC and linear collider collaborations. Indeed, it is worth thinking about archiving the LHC data in a form suitable for subsequent re-analysis in light of information obtained in experiments at a linear collider.

The LHC is not just a broad-band discovery machine for the exploration of the TeV scale – precision measurement of some sparticle properties is also possible at the LHC. A 500 GeV linear collider will almost certainly not be a discovery machine. However, experiments at a linear collider allow a beautiful and systematic program for such measurements and truly complement the capabilities of the LHC. We have noted, however, that some of the claims for the sensitivity of linear collider experiments may have been over-stated. Despite this, we emphasize that experiments at these facilities allow for unique capabilities not available elsewhere. The

LHC and a linear collider together provide a powerful window for exploring physics at high energies, and we can look forward to exciting times ahead.

Acknowledgements

I am grateful to my collaborators and colleagues for what they have taught me about supersymmetry over the years. This research was supported in part by the US Department of Energy Grant DE-FG03-94ER40833.

References

[1] While SUSY is not the only proposal that accommodates a hierarchy, it arguably appears to be the only one where the next scale of new physics can be pushed arbitrarily far
[2] M Nojiri, *Pramana – J. Phys.* **62**, 335 (2004)
[3] Joint LEP2 SUSY Working Group, http://lepsusy.web.cern.ch/lepsusy
E Duchovni, *Pramana – J. Phys.* **62**, (2004) (to appear)
[4] T Affolder *et al*, *Phys. Rev. Lett.* **88**, 041801 (2002)
B Abbot *et al*, *Phys. Rev. Lett.* **83**, 4937 (1999)
A Besson, *Pramana – J. Phys.* **62**, (2004) (to appear)
[5] T Affolder *et al*, *Phys. Rev. Lett.* **84**, 5704 (2000)
[6] K Abe *et al*, *Phys. Lett.* **B511**, 151 (2001)
D Cronin-Hennessy *et al*, *Phys. Rev. Lett.* **87**, 251808 (2001)
R Barate *et al*, *Phys. Lett.* **B429**, 169 (1998)
[7] G Bennett *et al*, *Phys. Rev. Lett.* **89**, 101804 (2002); **89**, 129903 (2002) (erratum)
[8] F Abe *et al*, *Phys. Rev.* **D57**, 3811 (1998)
[9] J Kaneko *et al*, *Phys. Rev. Lett.* **90**, 021801 (2003)
[10] D Reusser *et al*, *Phys. Lett.* **B235**, 143 (1991)
[11] See e.g. H Baer, C Balázs and S Belyaev, *J. High Energy Phys.* **0203**, 042 (2002)
J Ellis *et al*, hep-ph/0303043 (2003)
[11a] Shortly after this conference, the WMAP Collaboration [12] announced that $\Omega h^2 = 0.135^{+0.008}_{-0.009}$, which together with their determination of the baryonic matter density results in $\Omega_{\rm CDM}h^2 = 0.1126 \pm 0.009$. This precise determination should be viewed similarly to the determination of M_Z which really is a model prediction. Usually, μ^2 is fixed so as to obtain the correct value of M_Z. Similarly, the determination of $\Omega_{\rm CDM}h^2$ essentially reduces the dimension of parameter space by 1. We emphasize that even the 'true constraint' from the upper limit on $\Omega_{\rm CDM}h^2$ is a strong restriction
[12] D N Spergel *et al*, arXiv:astro-ph/0302209
[13] K Olive, TASI Lectures on Dark Matter, astro-ph/0301505 (2003)
[14] H Baer *et al*, *Phys. Rev.* **D54**, 5866 (1996)
[15] Report of the SUGRA Working Group of the Supersymmetry/Higgs Workshop, S Abel *et al*, hep-ph/0003154 (2000)
[16] H Baer, J Sender and X Tata, *Phys. Rev.* **D50**, 4517 (1994)
J Sender, PhD thesis, hep-ph/0010025 (2000)
R Demina, J Lykken and K Matchev, *Phys. Rev.* **D62**, 035011 (2000)
[17] H Baer, P Mercadante and X Tata, *Phys. Rev.* **D59**, 015010 (1999)
R Demina *et al*, ref. [16]
[18] H Baer *et al*, *Phys. Rev.* **D52**, 2746 (1995); **D53**, 6241 (1996); **D59**, 055014 (1999)

[19] S Abdullin *et al*, hep-ph/9806366
S Abdullin and F Charles, *Nucl. Phys.* **B547**, 60 (1999)

[20] ATLAS Technical Design Report, CERN-LHCC/99-14 (1999)

[21] H Baer, P Mercadante, X Tata and Y Wang, *Phys. Rev.* **D62**, 095007 (2000)

[22] H Baer *et al*, *Phys. Lett.* **B488**, 367 (2000)

[23] H Baer, C-H Chen and X Tata, *Phys. Rev.* **D55**, 1466 (1997)

[24] J Bagger, U Nauenberg, X Tata and A White, Summary of supersymmetry working group, in *New Directions for High Energy Physics*, edited by D Cassel (1996) Snowmass Summer Study

[25] H Baer *et al*, *Phys. Rev.* **D50**, 4508 (1994)

[26] I Hinchliffe *et al*, *Phys. Rev.* **D55**, 5520 (1997)

[27] M Drees and M Nojiri, *Phys. Rev.* **D63**, 035008 (2001)

[28] J Feng, H Murayama, M Peskin and X Tata, *Phys. Rev.* **D52**, 1418 (1995)

[29] M Nojiri, K Fujii and T Tsukamoto, *Phys. Rev.* **D54**, 6756 (1996)

[30] M Nojiri, D Pierce and Y Yamada, *Phys. Rev.* **D57**, 1539 (1998)
H-C Cheng, J Feng and N Polonsky, *Phys. Rev.* **D57**, 152 (1998)

[31] F Zwirner, *Pramana – J. Phys.* **62**, 497 (2004)

[32] Y Fukuda *et al*, *Phys. Rev. Lett.* **82**, 2644 (1999); **85**, 3999 (2000)

[33] H Baer *et al*, *Phys. Rev.* **D63**, 055011 (2001)

[34] D Auto *et al*, hep-ph/0302155 (2003) and references therein

[35] T Blazek, M Dermisek and S Raby, *Phys. Rev.* **D65**, 115004 (2002) and references therein
S Raby, *Pramana – J. Phys.* **62**, 523 (2004)

[35a] Left–Right mixing in the stau sector makes $\delta_{1\nu}$ negative

[36] H Baer *et al*, *Phys. Rev.* **D63**, 095008 (2001)

[37] S Y Choi *et al*, *Euro. Phys. J.* **C14**, 535 (2000)

[38] G Blair, W Porod and P Zerwas, *Phys. Rev.* **D63**, 017703 (2001); *Euro. J. Phys.* **C27**, 263 (2003)

[39] A Bartl *et al*, ref. [24]

[39a] Although this point has been subsequently excluded by LEP data, it nevertheless provides a good illustration of how experiments at the LHC may lead to very precise determination of some mass differences

[40] JLC-1, KEK Report No. 92-16 (1992)
T Tsukamoto *et al*, *Phys. Rev.* **D51**, 3153 (1995)

[40a] A very precise measurement of the selectron mass would be possible at an e^-e^- collider because of reduced WW background as well as a different $m_{\tilde{e}}$ dependence of the cross-section [41]. Of course, all other sparticle masses would still need to be determined at an e^+e^- collider

[41] J Feng and M Peskin, *Phys. Rev.* **D64**, 115002 (2001)

[42] H Baer, R Munroe and X Tata, *Phys. Rev.* **D54**, 6735 (1996)

[43] TESLA TDR, DESY 2001-011 (2001)
G Blair and H-U Martyn, hep-ph/9910416

[44] J K Mizukoshi *et al*, *Phys. Rev.* **D64**, 115017 (2001)

[44a] Such widely spaced measurements would also be useful for studies of other sparticles, and also of SM processes such as $t\bar{t}$ production close to threshold

[44b] While such a situation can be accommodated in SUSY models [45] with heavy ($\geq$2–3 TeV) sparticles, it would leave an unsatisfactory taste behind

[45] See e.g. H Baer *et al*, *Phys. Rev.* **D64**, 015002 (2001)
D Auto *et al*, ref. [34]