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**SEARCHING FOR SUPERSYMMETRY
AT HIGH-ENERGY COLLIDERS**

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Searching for Supersymmetry at High-Energy Colliders

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Recent developments in searches for supersymmetric particles at future e^+e^- and hadron colliders are reviewed. The detection of supersymmetric particles is studied for two scenarios: a) direct decays to the lightest supersymmetric particle, which escapes detection and therefore leads to large missing transverse energy, and b) cascade decays of heavy supersymmetric particles containing gauge bosons among their decay products. The implications arising from searches for supersymmetric particles at LEP will also be discussed.

1. Introduction

Despite of the great success of the Standard Model (SM) in describing available data on fundamental particle interactions, there are still many reasons for postulating a supersymmetric extension of the SM. Supersymmetric theories [1] address the outstanding problems of the SM, particularly those associated with electroweak symmetry-breaking (the Higgs sector) and the origin of elementary-particle mass scales. A large number of new particles are predicted which should have masses ≤ 1 TeV. The detection of supersymmetric particles (sparticles) has therefore received a lot of attention in various physics studies for future colliders [2].

Searches for sparticles have already been performed at existing colliders (the CERN $p\bar{p}$ Collider, the FNAL Tevatron, PEP at SLAC, and PETRA at DESY), and will soon be carried out at e^+e^- colliders at $\sqrt{s} = 100$ GeV (LEP at CERN and the SLC at SLAC). Present limits are not yet problematic for low-energy supersymmetry, and the sparticle masses may still be too high for them to be produced at the CERN $p\bar{p}$ Collider, at the Tevatron, at LEP, and at the SLC. If this is the case, it will be necessary to await the next generation of high-energy colliders, which will be the first machines to probe parton-parton collisions at energies of the order of 1 TeV. Possible future hadron colliders are UNK, the LHC, and the SSC at $\sqrt{s} = 6, 16$, and 40 TeV, respectively. Several e^+e^- colliders are under discussion, for instance the TLC at SLAC and CLIC at CERN, at $\sqrt{s} = 1$ and 2 TeV, respectively. (See Ref. [2].)

In the next section we give a brief summary of the searches for sparticles carried out at existing colliders. Section 3 addresses the issue of observing sparticles at LEP/SLC. In Section 4 we discuss the possibilities offered by the next generation of colliders to discover supersymmetry, taking into account the relative importance of $\sqrt{s}$ and of the luminosity of the machines under discussion. The searches for sparticles presented here — like the searches for any other new physics — should be considered as bench-mark studies that are necessary in order to compare the physics potentials of different new machines in the multi-TeV energy range.

2. Supersymmetric Models and Current Limits

Sparticle production in e^+e^- and hadron colliders has been discussed extensively in published articles [1–3]. We will recall a few important features that are relevant for our

Fig. 1 Limits on squark and gluino mass (90% CL) obtained by UA1. Also shown are preliminary results from CDF [6].

discussion of sparticle detection. The conservation of a new quantum number, known as R-parity, has the following phenomenological consequences: i) sparticles must be pair-produced, e.g. $pp \rightarrow \tilde{g}\tilde{g} + X$, $e^+e^- \rightarrow \tilde{\ell}^+\tilde{\ell}^-$; ii) each sparticle must decay into a lighter sparticle, e.g. $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$, $\tilde{e} \rightarrow e\tilde{\gamma}$; iii) the lightest sparticle (LSP) must be stable.

Electroweak symmetry-breaking includes mixing between gauginos and Higgsinos of the same charge. Thus the photino, the zino, and the neutral Higgsinos (the weak eigenstates) mix to produce (in order of increasing mass) the mass eigenstates $\tilde{Z}_1^0$, $\tilde{Z}_2^0$, $\tilde{Z}_3^0$, and $\tilde{Z}_4^0$ (neutralinos). Similarly the winos and charged Higgsinos mix to give mass eigenstates $\tilde{W}_1^\pm$ and $\tilde{W}_2^\pm$ (charginos). Several analyses assume that the lightest neutralino $\tilde{Z}_1^0$ is the LSP, and take it to be a pure photino ($\tilde{Z}_1^0 = \tilde{\gamma}$). However, the LSP could be a mixture of $\tilde{\gamma}$, $\tilde{H}^0$, and $\tilde{Z}^0$. The LSP is expected to have a very small interaction cross-section and would normally escape detection, thus resulting in a missing transverse energy (E_T) event signature. The amount of E_T depends on the assumed decay modes, i.e. for direct decay into the LSP (e.g. $\tilde{q} \rightarrow q\tilde{\gamma}$), one expects large E_T , whereas for cascade decays, where the LSP appears at the end of the decay chain, only a soft E_T spectrum is expected. A complete survey of all the parameter space for the minimal supersymmetric model has been performed for hadron colliders [4] and has recently become available also for e^+e^- colliders [5].

The best current limits on squark and gluino masses come from hadron colliders (the CERN $p\bar{p}$ Collider and the Tevatron). The analyses performed [6] assumed the LSP to be a light, stable photino. The squark and gluino decay modes depend on their masses, e.g. $m_{\tilde{g}} > m_{\tilde{q}}$: $\tilde{q} \rightarrow q\tilde{\gamma}$, $m_{\tilde{g}} < m_{\tilde{q}}$: $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$. Under these assumptions (i.e. direct decay to the LSP), the final state contains large E_T and at least two high- E_T jets. The limits published by UA1 are shown in Fig. 1, together with the preliminary results from the CDF Collaboration presented at this conference. UA2 reports somewhat weaker limits compared with those of UA1 for the same model assumption, but in addition it has considered the possibility of an unstable photino. In this case, UA2 obtains $\tilde{g}$ and $\tilde{q}$ limits that are comparable to those of UA1. In the future, it is expected to obtain a mass reach of ~ 200 GeV for strongly interacting sparticles at the Tevatron. Searches for $e^+e^- \rightarrow \tilde{\ell}^+\tilde{\ell}^-$ established [7] the lower limit, $m_{\tilde{\ell}} \geq 20$ GeV. More stringent limits have been reported; they are, however, more model-dependent, e.g. $m_{\tilde{e}} > 67$ GeV for $m_{\tilde{\gamma}} = 0$ GeV [7].

3. Searches for Supersymmetry on the Z^0

For LEP and the SLC, one expects sparticle masses $\leq E_{\text{beam}}$ to be accessible for associated produced sparticles. However, selectrons with masses larger than the beam energy could

be produced singly in the process $e^+e^- \rightarrow \tilde{e}^+\tilde{\gamma}e^-$. The single-slepton ($\tilde{e}, \tilde{\mu}$) production at the Z^0 peak has been investigated by Hidaka et al. [8]. These authors conclude that for $5 \leq m_{\tilde{\gamma}} \leq 25$ GeV, a detectable number of $\tilde{e}$ ($\tilde{\mu}$) are expected, even if their masses substantially exceed the beam energy (e.g. $m_{\tilde{e}} = 63.5$ GeV for $m_{\tilde{\gamma}} = 5$ GeV). The detection limits have been obtained using suitable cuts to eliminate all possible backgrounds and assuming an integrated luminosity of 830 pb^{-1} . For a more realistic assumption of 200 pb^{-1} , the obtained mass reach is reduced by only ~ 5 GeV.

In the framework of low-energy supergravity models, the Z^0 can have sizeable branching ratios into pairs of neutralinos [9]. The decay of the heavier neutralino produces very distinctive signatures. Assuming that the lightest physical neutralino χ' is the LSP, the following decay modes of the heavier neutralino χ' are considered:

$$e^+e^- \rightarrow Z^0 \rightarrow \chi\chi', \text{ with } \chi' \rightarrow h^0 \text{ (or } \gamma \text{ or } f\bar{f}) \chi,$$

where h^0 is the Higgs boson that is predicted to be lighter than the Z^0 in the minimal supersymmetric models. If the h^0 is light ($m_{h^0} \leq 40$ GeV), the decay $\chi' \rightarrow h^0\chi$ is by far the dominant mode. In this case, supersymmetry would lead to a sizeable enhancement of the rate for $Z^0 \rightarrow H + E$, expected from SM Higgs production. On the other hand, if $m_{h^0} \geq 40$ GeV, the other two decay channels $(\gamma \text{ or } f\bar{f})\chi$ become important. As pointed out by Barbieri et al. [9], the search for these very characteristic events at the Z^0 is a crucial test of the electroweak fermionic gauge sector of supersymmetric models, and it can be carried out already in the near future.

In minimal supersymmetry there are five physical Higgs bosons: a charged pair ($H^\pm$), two neutral scalars (h^0, H^0), h^0 being by definition the lightest, and a pseudoscalar (A^0). Supersymmetry imposes strong constraints on the parameters of the Higgs sector. For example [10], given $m_{H^\pm}$ and the ratio of the vacuum expectation values (v_2/v_1) of the two Higgs fields, one can calculate the other Higgs masses. As illustrated in Fig. 2, the h^0 is predicted to be always lighter than the Z^0 .

It has been shown by Giudice [11] that LEP can set a lower bound on m_{h^0} if one considers the processes $Z^0 \rightarrow h^0\mu^+\mu^-$ and $Z^0 \rightarrow h^0A^0$ simultaneously. The production of h^0 is strongly dependent on the ratio v_2/v_1 . If h^0 is light with respect to the Z^0 , then either $v_2/v_1 \approx 1$ or A^0 is light. A large value of v_2/v_1 implies that h^0 and A^0 are approximately degenerate in mass. Therefore, if $v_2/v_1 \approx 1$, then h^0 mimics the ordinary minimal SM Higgs boson, and if v_2/v_1 is large, then the decay $Z^0 \rightarrow h^0A^0$ becomes available. Similar results apply to the Higgs search in e^+e^- collisions at LEP 200 energies [11].

Fig. 2 Masses of h^0 (dashed line), H^0 (solid line), and A^0 (dotted line) as a function of $m_{H^\pm}$ at fixed $v_2/v_1 = 1.5$ [10].

Even if the sparticle masses are larger than a few hundred GeV, nearly all low-energy supersymmetric models imply the existence of at least a light Higgs scalar with mass less than $O(m_{\chi})$. The experimental verification of the existence of an enlarged Higgs sector will be very important. Therefore the non-observation of a neutral Higgs boson up to LEP 200 energies would put rather tight constraints on possible supersymmetric parameters.

4. Sparticle Production at Future pp and e^+e^- Colliders

A survey of supersymmetric particle production mechanisms in high-energy hadron and e^+e^- collisions can be found in Refs. [1] to [5]. Some examples of sparticle production cross-sections in pp collisions at $\sqrt{s} = 40$ TeV are shown in Fig. 3a as a function of the sparticle mass [12]. Squarks and gluinos should be copiously produced at the LHC/SSC. For example, for a total integrated luminosity of $10^{40} \text{ cm}^{-2} = 10 \text{ fb}^{-1}$ (corresponding to one year of running at $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$), we expect $\sim 10^4$ gluino pairs to be produced at the SSC for $m_{\tilde{g}} = 1.5$ TeV or at the LHC for $m_{\tilde{g}} = 1$ TeV. Figure 3b shows examples of sparticle production cross-sections in e^+e^- collisions as a function of $\sqrt{s}$ [13]. For example, at $\sqrt{s} = 2$ TeV and for 10 fb^{-1} , $\sim 30 \mu\mu$ events ($m_{\tilde{\mu}} = 0.8$ TeV) and $\sim 600 \tilde{e}\tilde{e}$ events ($m_{\tilde{e}} = 0.8$ TeV) are predicted. These numbers have to be compared with the ~ 220 events per year expected from $e^+e^- \rightarrow \mu^+\mu^-$. Clearly, for e^+e^- colliders, high luminosity ($> 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$) is required in order to maintain the physics reach for sparticles.

Fig. 3 Supersymmetric particle production cross-sections: a) as a function of sparticle masses for pp collisions at $\sqrt{s} = 40$ TeV [12]; b) as a function of $\sqrt{s}$ for e^+e^- collisions [13].

4.1 Searches for gluinos and squarks in pp collisions

The sparticle signatures, as discussed above, depend on the details of the assumed masses and decay patterns. The 'classical' signature of large E_T plus two or more high- E_T jets results from the assumption that $\tilde{q}$ and $\tilde{g}$ will decay directly to the LSP. Although these signatures should remain valid at LHC and SSC energies, it has been emphasized [4] that for large squark and gluino masses, direct decays to the LSP become less important; instead, the decays to the heavier neutralinos ($\tilde{Z}_1^0$) and charginos ($\tilde{W}_1^\pm$) become dominant.

Fig. 4 Branching ratios of a 1 TeV gluino into $q\bar{q}\tilde{Z}_i^0$ or $q\bar{q}'\tilde{W}_i^\pm$, as a function of the supersymmetric Higgs mass parameter μ , for $v_2/v_1 = 1.5$, taken from Barnett et al. [4]. The solid line corresponds to the decay into the LSP.

An example of predicted branching ratios of a 1 TeV gluino into $q\bar{q}\tilde{Z}_i^0$ or $q\bar{q}'\tilde{W}_i^\pm$ is given in Fig. 4. The $\tilde{Z}_i^0$'s and $\tilde{W}_i^\pm$'s from the $\tilde{g}$ and $\tilde{q}$ decay will in turn decay into lighter charginos and neutralinos, and eventually into the LSP. These cascade decays generally occur for both of the produced gluinos and squarks, and result in a large variety of possible final states, often containing $W^\pm$ or Z^0 bosons in a complex event topology. The predicted branching ratios for these decays depend on details of the sparticle mass spectrum and on the gaugino couplings, and are therefore subject to model parameters.

We first discuss the detailed Monte Carlo simulations carried out for LHC energies [2, 14], where squarks and gluinos are assumed to decay directly to a light photino ($\tilde{q} \rightarrow q\tilde{\gamma}$ and $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$) giving the signature of large E_T plus two or more high- E_T jets. Figure 5a shows the E_T distribution for squark pair production ($m_{\tilde{q}} = 1$ TeV, histogram) and for the total expected background from SM physics (points with error bars). The contributions from QCD heavy-flavour production (dominant for $E_T < 0.5$ TeV, mainly from top production) and from Z^0 and W decays (dominant for high E_T , mainly from $Z^0 \rightarrow \nu\bar{\nu}$) are shown separately. The background rate from the t -quark at large E_T was found to be insensitive to the assumed t -quark mass ($m_t = 40$ and 200 GeV were used). Figure 5a shows that the SM background at large E_T is of the same order as the signal. These backgrounds can be reduced by i) a cut on E_T , ii) rejecting events containing muons or isolated electrons ($p_T(e, \mu) > 15$ GeV), and iii) by topology cuts [e.g. number of jets ($E_T > 250$ GeV), circularity C , difference in azimuthal angle between the E_T direction and the direction of the highest- E_T jet, etc.]. Figure 5b shows an example of the E_T spectrum using one of these possible event selections ($C > 0.25$, $N_{\text{jet}} > 3$). The resulting signal-to-background ratios are typically $\sim 10:1$ at large E_T . Similar results were obtained with selections based on other topology variables. Taking into account all the uncertainties involved in the above calculations, it was concluded that squark and gluino masses up to ~ 1 TeV are potentially accessible for 10 fb^{-1} integrated luminosity.

At SSC energies, the signal cross-sections for $\tilde{q}$ and $\tilde{g}$ masses above 1 TeV are much larger; the background cross-sections have, however, a relatively small increase. Extrapolating the LHC studies to SSC energies, one expects a discovery limit of $\sim 1.5\text{--}2$ TeV for the gluino and the squark mass. This strong $\sqrt{s}$ dependence of the signal cross-section triggered the question whether the disadvantage of the LHC's low energy, compared with the higher energy of the SSC, could be offset by running the LHC at higher luminosity.

The LHC parameters allow a luminosity of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at 5 ns bunch spacing, which leads to an average of ~ 15 inelastic interactions per bunch crossing [2, 14]. The

Fig. 5 Missing transverse energy distributions at $\sqrt{s} = 17$ TeV [14]: a) for squark pair production for a squark mass of 1 TeV (histogram) and for SM backgrounds (points with error bars), and b) after final selection cuts for squark (solid histogram) and gluino (dashed histogram) production and for the total background (points with error bars). A squark or gluino mass of 1 TeV is assumed.

analysis described above has been extended to a study of the feasibility of searching for $\tilde{g}$ and $\tilde{q}$ in such an environment of multiple interactions. A detailed simulation of event pile-up was performed for the case of gluino pair production ($m_{\tilde{g}} = 1$ TeV) [14]. It was found that the E_T distribution and the jet topology (at high E_T^{jet} , after reducing the jet cone size and raising the threshold on cells contributing to the jet) remained essentially unchanged when pile-up was added. Representative selections of gluinos and squarks showed that signal-to-background ratios similar to those found at lower luminosity could be obtained. Therefore, provided the experimental problems associated with running at high luminosity can be overcome, an extension of the discovery limits for $\tilde{g}$ and $\tilde{q}$ of masses ~ 2 TeV should be feasible at the LHC.

The branching ratio for the direct decay of gluinos to the LSP approaches 14% for $m_{\tilde{g}} \geq 0.6$ TeV [4]. Thus in $\tilde{g}\tilde{g}$ production for large $m_{\tilde{g}}$, where both $\tilde{g}$'s decay directly into the LSP, the total gluino event rate is only $\sim 2\%$. The dominant decay of a heavy gluino is into heavier charginos and neutralinos (see Fig. 4). These states will, in turn, decay into lighter charginos and neutralinos until the LSP is reached. As mentioned before, the final states produced will often contain $W^\pm$ or Z^0 bosons, which probably offer the best promise of detection.

A study of gluino final states containing Z^0 's was carried out for SSC energies (Barnett et al. in Berkeley Workshop [2]). The following decay chain for both gluinos has been used:

$$pp \rightarrow \tilde{g}\tilde{g} + X, \quad \tilde{g} \rightarrow q\bar{q}\tilde{Z}_i^0, \quad \tilde{Z}_i^0 \rightarrow \tilde{Z}_j^0 Z^0 \quad (Z^0 \rightarrow \ell^+\ell^-).$$

The final state therefore contains at least four hard jets, plus four charged leptons, plus the decay products (including some E_T) of the $\tilde{Z}_j^0$. For a gluino mass of 0.75 TeV, the signal after selection cuts was 56 events, compared with a background from $pp \rightarrow Z^0 Z^0 + \text{jets}$ of 0.5 ± 0.3 events. Other possible backgrounds considered are high- p_T Z^0 production ($pp \rightarrow qZ^0 + \text{jets}$) and QCD jet production ($pp \rightarrow qqg$), where each quark radiates a Z^0 boson. These backgrounds were not explicitly evaluated, but are expected to be small. Thus, from these complex decay modes, it is possible to find event signatures that give promising

results for signal-to-background ratios. Other signatures that clearly deserve further investigation have been pointed out in the literature [4].

4.2 Searches for sparticles in e^+e^- collisions

First we discuss studies carried out for CLIC energies ($\sqrt{s} = 2$ TeV), where sparticles are assumed to decay directly to a light photino. The processes investigated in detail were [2, 13]

$$e^+e^- \rightarrow \tilde{X}\tilde{X}, \tilde{X} \rightarrow X\tilde{\gamma} (\tilde{X} = \tilde{e}, \tilde{\mu}, \tilde{\tau}, \tilde{q}); \text{ and } e^+e^- \rightarrow \tilde{W}^+\tilde{W}^-.$$

The characteristic signatures of these processes are events with missing energy, and dijets or dilepton final states that are acollinear and acoplanar. These event characteristics have been used in selection cuts to distinguish signals from backgrounds. The backgrounds considered are $e^+e^- \rightarrow \ell^+\ell^-\gamma$, W^+W^- , and WZ , which are not overwhelming as in pp collisions. It was concluded [13] that the detection of almost the full sparticle spectrum up to masses of $\sim 90\%$ of the beam energy ($m \approx 0.9$ TeV) would be possible at CLIC, provided an integrated luminosity of 50 fb^{-1} ($L = 5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$) can be achieved. In addition, the cleanliness of sparticle production in e^+e^- collisions compared with pp collisions allows the physical properties of the new particles to be measured. For example, the spin of the smuon could be determined by measuring the average angular distribution of the muons as shown in Fig. 6a for $m_{\tilde{\mu}} = 0.5$ TeV. Figure 6b shows the threshold behaviour of the $\tilde{\mu}\tilde{\mu}$ cross-section for $m_{\tilde{\mu}} = 0.5$ TeV. Measurements at different energies above threshold should allow a determination of the smuon mass with an error of 2%, as also shown in Fig. 6b.

The first detailed studies of signals resulting from cascade decays of heavy $\tilde{\ell}$, $\tilde{\nu}$, $\tilde{W}_L^\pm$, and $\tilde{Z}_1^0$ in high-energy e^+e^- collisions have recently been performed [5]. An example of predicted branching ratios for $\tilde{e}_L$ as a function of selectron mass is plotted in Fig. 7. Heavy sleptons lead to events with at least one very hard electron ($p_T \approx m_{\tilde{e}}/2$) and two or more large- p_T vector bosons, with possible additional hadronic or leptonic activity. It was concluded that at CLIC, for 10 fb^{-1} , sleptons ($\tilde{e}, \tilde{\nu}$) with masses up to ~ 0.8 TeV can be

Fig. 6 a) Measured average angular distribution of two muons at $\sqrt{s} = 2$ TeV. The solid line corresponds to the expected distribution for a spin-0 smuon of 0.5 TeV mass; the dashed line is the expectation for a spin-1/2 particle. b) Total $\mu\mu$ cross-section as a function of beam energy, for $m_{\tilde{\mu}} = 0.5$ TeV. The bars represent the statistical errors in the cross-section measurements with the indicated luminosities [13].

Fig. 7 Branching fractions for $\tilde{e}_L$ decays into various gauginos as a function of $m_{\tilde{e}_L}$, for $v_2/v_1 = 0.5$ and the supersymmetric Higgsino mass $m = m_W/2$ [5]. The solid line corresponds to the decay into the LSP.

discovered. Identification of $\tilde{W}_I^\pm$ and $\tilde{Z}_I^0$ is somewhat more difficult owing to the absence of the primary hard lepton. The expected signature of two W 's, together with additional hadronic activity in these events, should allow a separation from the background. From rate arguments, however, one has to identify the vector bosons through their hadronic decays, which is possible in e^+e^- collisions, as was concluded in a study of searches for heavy leptons at CLIC [15]. As expected, the detection of signals from cascade decays is easier in e^+e^- collisions because of the absence of large QCD backgrounds. A detailed background evaluation, as performed in the searches discussed in Ref. [13], would be welcome.

As pointed out by Leike [16], measurements of the chargino production threshold together with longitudinal polarization asymmetries would lead to very severe restrictions on the supersymmetry parameters. To perform such a study, a total of $\geq 300 \text{ fb}^{-1}$ are needed, as well as polarized beams — a project which clearly cannot be realized in the near future.

5. Conclusions

A comparison of expected supersymmetry signatures at multi-TeV e^+e^- and pp colliders has been presented. Detailed studies of signals and backgrounds have been performed for the direct decays of sparticles into the LSP. Promising signals have been proposed for cascade decays of heavy sparticles, but a detailed background evaluation is needed. Strongly interacting particles are a domain for hadron colliders, whereas e^+e^- colliders have larger physics reaches for weakly interacting particles, demonstrating the complementarity between the machines under discussion.

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