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Sensitivity to sgoldstino states at the future linear e^+e^- and photon colliders

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Abstract

Sensitivity to the supersymmetric scalar states ϕ at the future linear e^+e^- and photon colliders is discussed. In particular it is illustrated a search strategy for massive sgoldstinos, the supersymmetric partners of the goldstino.

1 Introduction

In the Supersymmetric extension of the Standard Model, once Supersymmetry is spontaneously broken the gravitino $\tilde{G}$ can acquire a mass absorbing the degrees of freedom of the goldstino. The mechanism is analogous to the spontaneous breaking of the electroweak symmetry in the Standard Model, when Z and W bosons acquire mass absorbing the goldstone bosons.

A very light gravitino $\tilde{G}$ as predicted by supersymmetric models [1] has been searched for at LEP and Tevatron experiments [2, 3] and the sensitivity to its signatures of an experiment at a future linear collider has been studied [4]. Limits on the $\tilde{G}$ mass are related to the supersymmetry-breaking scale $\sqrt{F}$.

It has been pointed out [5] that in such supersymmetric extensions of the Standard Model with a light gravitino, the effective theory at the weak scale must contain also the supersymmetric partner of the goldstino, called sgoldstino. The production of this particle, which could be massive, may be relevant at the LEP and Tevatron energies [6] if the supersymmetry-breaking scale and the sgoldstino mass are not too large. Two states are considered in [5, 6], S CP-even and P CP-odd. Assuming R-parity conservation, it has to be noticed that, while the goldstino is R-odd, the sgoldstino is R-even and therefore it can be produced together with Standard Model particles.

At LEP 2 sgoldstino signatures have been searched for by the DELPHI experiment [7] and preliminary results from CDF [8] show the higher sensitivity of hadron colliders. None of the two searches found an evidence for such states.

At an e^+e^- collider one of the most interesting channels for the production of such scalars (from now on the symbol ϕ will be used to indicate a generic state) is the process $e^+e^- \rightarrow \phi\gamma$ which depends on the ϕ mass m_ϕ and on $\sqrt{F}$:

$$\frac{d\sigma}{dcos\theta}(e^+e^- \rightarrow \phi\gamma) = \frac{|\Sigma|^2 s}{64\pi F^2}\left(1 - \frac{m_\phi^2}{s}\right)^3 (1 + cos^2\theta) \tag{1}$$

where θ is the scattering angle in the centre-of-mass and

$$|\Sigma|^2 = \frac{e^2 M_{\gamma\gamma}^2}{2s} + \frac{g_Z^2(v_e^2 + a_e^2)M_{\gamma Z}^2 s}{2(s - m_Z^2)^2} + \frac{e g_Z v_e M_{\gamma\gamma} M_{\gamma Z}}{s - m_Z^2} \tag{2}$$

with $v_e = sin^2\theta_W - 1/4$, $a_e = 1/4$ and $g_Z = e/(sin\theta_W cos\theta_W)$. The parameters $M_{\gamma\gamma}$ and $M_{\gamma Z}$ are related to the diagonal mass term for the $U(1)_Y$ and $SU(2)_L$ gauginos M_1 and M_2:

$$M_{\gamma\gamma} = M_1 cos^2\theta_W + M_2 sin^2\theta_W, \;\; M_{\gamma Z} = (M_2 - M_1) sin\theta_W cos\theta_W. \tag{3}$$

Other interesting processes are due to $\gamma\gamma$- or gg-fusion occurring, respectively, at e^+e^- and hadron colliders. In both cases the production cross sections are proportional to the corresponding widths:

$$\sigma(e^+e^- \rightarrow e^+e^-\phi) \propto \sigma_0^{\gamma\gamma} = \frac{4\pi^2}{m_\phi^3}\Gamma(\phi \rightarrow \gamma\gamma), \sigma(p\bar{p} \rightarrow \phi) \propto \sigma_0^{gg} = \frac{\pi^2}{8m_\phi^3}\Gamma(\phi \rightarrow gg) \tag{4}$$

and they can be obtained, respectively, from the photon and gluon distribution functions.

The decay modes $\phi \to \gamma\gamma$ and $\phi \to gg$ widths are

$$\Gamma(\phi \to \gamma\gamma) = \frac{m_\phi^3 M_{\gamma\gamma}^2}{32\pi F^2} \tag{5}$$

and

$$\Gamma(\phi \to gg) = \frac{m_\phi^3 M_3^2}{4\pi F^2} \tag{6}$$

where M_3 is the gluino mass.

As noticed in [6] the production formulae are similar in form to those for a light SM Higgs production in Born approximation where $\Gamma(H \to \gamma\gamma)$ and $\Gamma(H \to gg)$ substitute the ϕ widths. It is straightforward to apply the same correspondence between these two different physical cases to the ϕ production on photon colliders. With a reverse substitution, an effective production cross section in the narrow-width approximation can be deduced from the studies of Higgs Physics at a $\gamma\gamma$ collider [9]:

$$\sigma^{eff} = \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} \frac{m_\phi}{L_{\gamma\gamma}} \times \frac{4\pi^2 \Gamma(\phi \to \gamma\gamma)}{m_\phi^3} \tag{7}$$

where $dL_{\gamma\gamma}/dW_{\gamma\gamma}$ is the luminosity spectrum in the two photon center-of-mass $W_{\gamma\gamma}$ and $L_{\gamma\gamma}$ is defined as the luminosity at the high $\gamma\gamma$ energy peak.

All the above formulae depend on model dependent mass parameters. In [5] two sets for these parameters are considered to give numerical examples. They are reported in Table. 1.

	M_1	M_2	M_3
1)	200	300	400
2)	350	350	350

Table 1: Two choices for the gaugino mass parameters (in GeV) relevant for the sgoldstino production and decay.

The total width for a large interval of the parameter space is dominated by $\Gamma(\phi \to gg)$ and it is narrow (below the few GeV order) except for the region with small $\sqrt{F}$ where the production cross section is expected to be very large.

In this note the sensitivity to these states of an experiment at a e^+e^- linear collider with a center-of mass energy of 500 GeV and the sensitivity of an experiment at a photon collider obtained from the same energy primary e^+e^- beams are evaluated. An integrated luminosity of 500 fb^{-1} for the e^+e^- collisions is considered with a reduction factor for the $\gamma\gamma$ interactions.

2 e^+e^- collider

The search for these scalars at a future linear collider can be an upgrade of the analysis done at LEP where the two decay channels $\phi \to \gamma\gamma$ and $\phi \to gg$ were considered [7]. For the present sensitivity evaluation only the dominant channel is considered. The $\phi \to gg$

decay gives rise to events with one photon and two jets. An irreducible background from $e^+e^- \to q\bar{q}\gamma$ events is associated to this topology and therefore the signal must be searched for as an excess of events over the background expectations for every mass hypothesis.

To select $gg\gamma$ candidate events the following selection criteria can be defined:

- an electromagnetic energy cluster identified as photon with a polar angle $\theta > 20°$; the angle between the photon and the nearest jet must be greater than $10°$;
- no electromagnetic cluster with $\theta < 5°$;
- to remove $\gamma\gamma$ fusion events: the total multiplicity > 10; the charged multiplicity > 5; the energy in transverse plane $> 0.12 \cdot \sqrt{s}$; the sum of absolute values of track momentum along thrust axis $> 0.20 \cdot \sqrt{s}$;
- to remove Bhabha background: reject the events with electromagnetic cluster with $E > 0.45 \cdot \sqrt{s}$ and low track multiplicity;
- to reduce $q\bar{q}\gamma$ events: $|cos(\theta_p)| < .995$ where θ_p is the polar angle of missing momentum; the visible energy greater than $0.60 \cdot \sqrt{s}$; reject events with c or b tag;
- to remove WW background the events are reconstructed forcing into 2 jets topology but removing from jetization the tracks associated to the photon cluster. Events are removed if $y_{cut} > 0.02$.

The polar angle acceptance for a $\phi\gamma$ signal produced as in (1) is about 80%. It has been evaluated by generating 4-vectors corresponding to the prompt photon and to the ϕ decay products. Considering the DELPHI results [7], the selection efficiency inside the acceptance region is assumed to be of the order of 50 %.

The associated photon is monochromatic (except for the region with small $\sqrt{F}$ where the production cross-section is expected to be very large) for a given center-of-mass energy. Therefore the signal can be detected as a peak in the photon energy distribution of the selected events. In addition, the photon energy could be determined very precisely by means of kinematic constraints if a final state three body topology is assumed. However, the presence of the beamstrahlung (2.8% of mean beam-energy loss [10]) induces a smearing on the photon energy which is comparable with or larger than the experimental resolution. On the other hand, the signal can be searched for directly in the jet-jet invariant mass distribution. Clearly the detector performance plays a crucial role in the optimal search strategy. Here a jet energy resolution following the $\sigma_E^{jet}/E = 40\%/\sqrt{E} \oplus 2\%$ dependence and an error of about one degree in the jet angle reconstruction is assumed. With these assumptions the direct mass search is convenient or comparable w.r.t. the recoil photon search. The mass resolution is given in Fig. 1.

The background rate depends on the considered ϕ mass hypothesis as it can be seen in Fig. 2 where the reconstructed jet-jet invariant mass of $q\bar{q}\gamma$ events generated with PYTHIA [11] in the acceptance region is shown. The events are scaled in order to reproduce the number of expected events with an integrated $L_{e^+e^-}$ luminosity of 500 fb^{-1}. However the statistical fluctuations are not reproduced.

Given the background event distribution as function of m_ϕ and the detection efficiency for any ϕ mass hypothesis it is possible to estimate a 95% Confidence Level cross section limit for the ϕ production cross section. Only statistical fluctuations are considered here.

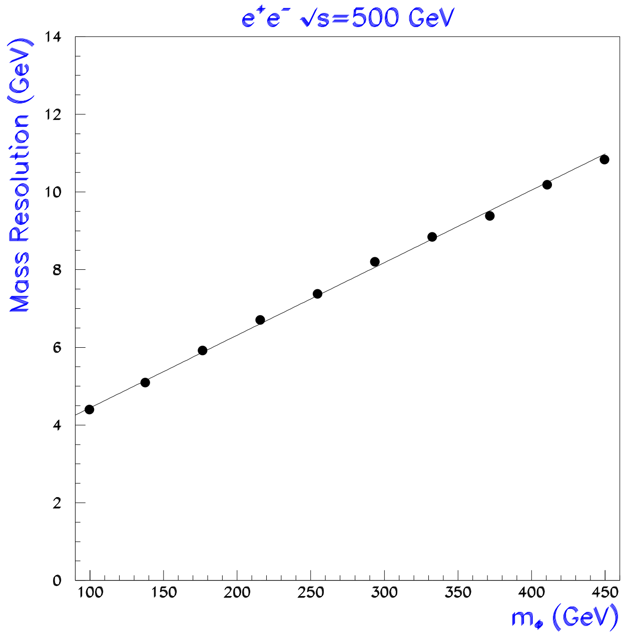

Figure 1: Mass resolution as function of the considered ϕ mass hypothesis. The full line corresponds to a linear fit.

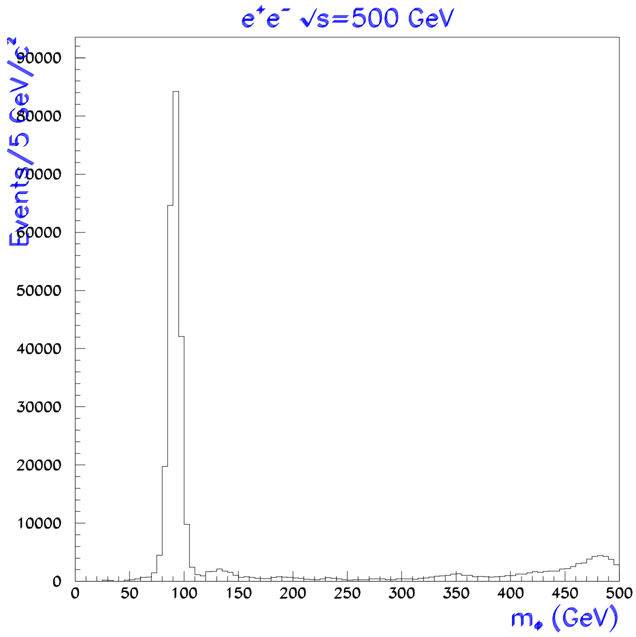

Figure 2: Jet-jet invariant mass spectrum for the $q\bar{q}\gamma$ events.

The bin to bin fluctuations on the number of background events due to the reduced Monte Carlo statistics are removed by a spline function.

By comparing the experimental limits with the production cross section computed from (1) it is possible to determine a 95% Confidence Level excluded region on the parameter space and a 5 σ discovery region. The beamstrahlung effects which are more relevant than the Initial State Radiation one's are taken into account. The limit and the 5 σ regions are shown in Fig. 3. The ϕ width for all the considered m_ϕ values is smaller than the experimental resolution in all the points corresponding to the limit curves. Therefore the limit has been computed integrating the signal only over the experimental resolution. The region where the expected width is larger than the experimental resolution is indicated in Fig. 3. For $m_\phi < 420$ it is possible to cover this region of parameter space given the high cross section. This is no more true for $m_\phi > 420$ GeV where the decreasing cross section and the increasing width result in a drop of experimental sensitivity.

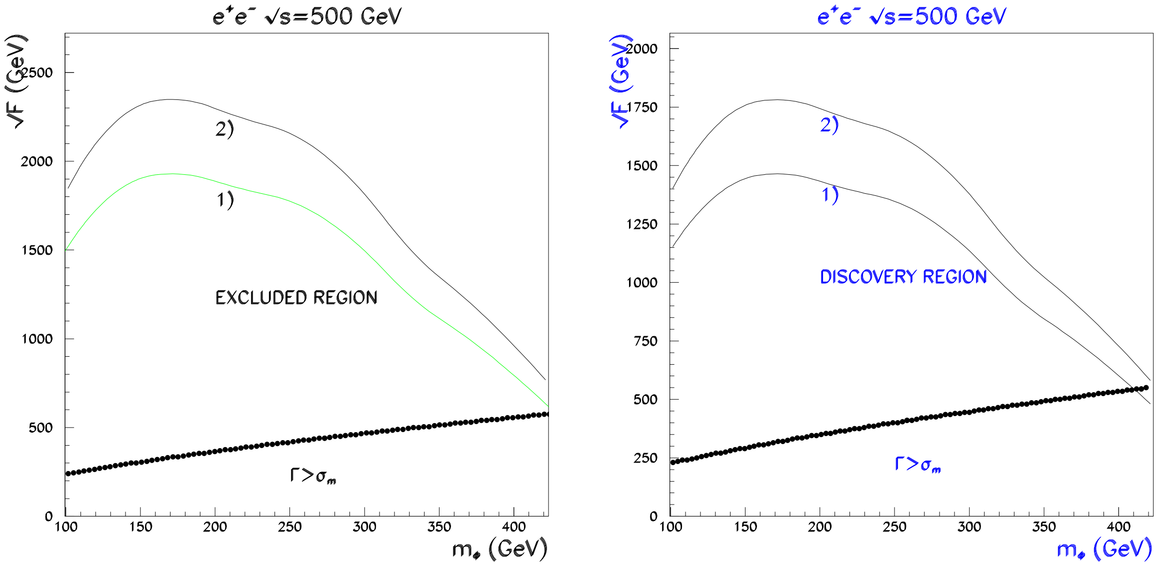

Figure 3: Exclusion region at the 95% Confidence Level and > 5 σ signal discovery region in m_ϕ $\sqrt{F}$ space for the two sets of parameters of Tab. 1. The thick lines indicate the region where the decay width Γ is larger than the experimental resolution.

In the near future the Fermilab Tevatron Collider is expected to increase the luminosity by a factor ~ 20 [12] and consequently an increase of about 1.5 in their $\sqrt{F}$ limits can be envisaged. The limits shown in Fig. 3 are then competitive with the future improved Tevatron results.

At e^+e^- colliders, additional information can be obtained by searching for the associated ϕZ^0 production as described in [5]. As far as the production cross section is considered, competitive results are expected in the $m_\phi < \sqrt{s} - m_Z$ region. However, since this channel has a different final state topology requiring a more sophisticated analysis, it is not considered here.

3 $\gamma\gamma$ collider

The effective cross section given in eq. (7) depends on the luminosity factor $f_L = \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} \frac{m_\phi}{L_{\gamma\gamma}}$. In the photon collider projects [13] there are several possible scenarios concerning the photon energy spectra. It may be desirable a photon energy distribution peaked as much as possible toward the primary electron/positron energy. In [9] $f_L = 7$ is assumed and $L_{\gamma\gamma}$ is taken as the integral luminosity for $z > z_{min} = 0.65$ where $z = W_{\gamma\gamma}/2E_e$ and E_e is the primary electron beam energy. The luminosity high energy peak is expected to have a FWHM of $\sim 10-15\%$ with a sharp edge at $z \sim 0.8$. Therefore the unexcluded $m_\phi - \sqrt{F}$ parameter space achievable at these machines with $2E_e = 500$ GeV ensures that the ϕ width is negligible.

The effective cross section obtained with $f_L = 7$ is much higher (several orders of magnitude, depending on m_ϕ) than the $e^+e^- \to \phi\gamma$ cross section with the same parameters. Considering the photon and gluon decay channels, the signal would appear as a peak of two high energy photons or jets with no transversal missing energy. The two jets final state has to compete with large Standard Model background which can be suppressed using polarized photon beams with polarizations λ_1, λ_2: $\sigma(\gamma\gamma \to q\bar{q}) \propto 1 - \lambda_1\lambda_2$ while $\sigma(\gamma\gamma \to \phi) \propto 1 + \lambda_1\lambda_2$. However, taking into account QCD corrections [14, 15], the $q\bar{q}g$ final state with unresolved gluon jet gives rise to a sizeable background which may be hard to reject. Therefore, despite of the smaller decay branching ratio, only the two photons final state which has a very little Standard Model background is considered here.

The selection of events with two collinear high energetic photons is rather simple and the LEP experience can be used [16]. An efficient way to select photons and to reject electrons is to require two energy clusters in the electromagnetic calorimeter not associated to hits in the vertex detector. Events with tracks detected in the other tracking devices only in one hemisphere can be accepted to recover photon conversions. Other requirements are:

- acollinearity between the e.m. clusters smaller than 30°;
- acoplanarity smaller than 5°;
- polar angle $\theta > 30°$;
- $E_\gamma > 0.9 \cdot z_{min} \cdot E_e$.

The detection efficiency is very high ($> 90\%$) in the region $W_{\gamma\gamma}/2E_e > z_{min}$ and the acceptance for the decay of a scalar particle is 86%.

The irreducible Standard Model background of $\gamma\gamma \to \gamma\gamma$ events has been discussed in [17, 18]. In the $W_{\gamma\gamma}$ region above 200-250 GeV the cross section is in the range 8-14 fb for $\theta > 30°$ and then, assuming $L_{\gamma\gamma} \sim 0.15 \cdot L_{e^+e^-}$, the number of expected events is of the order of 600-1000. As a consequence any New Physics signal has to exceed the corresponding statistical error (which is of the order of 3 to 4 %) and the systematic uncertitude including the precision on the background calculation. For the present sensitivity study an overall background uncertitude of 5 % is assumed, leaving more detailed analysis of the signal and background including the comparison of their angular distributions to a later stage. With these assumptions, the sensitivity to a scalar state decaying in two photons is given by the expected 95 % Confidence Level limit on the cross section times branching ratio and it is

$$\sigma(\gamma\gamma \to \phi) \times B.R.(\phi \to \gamma\gamma) < 1 \text{ fb}$$

at the 95 % Confidence Level for $m_\phi \sim 400$ GeV.

This value is obtained following the hypothesis that the whole luminosity is collected at the maximal energy spectrum available with 250 GeV electron beams. The actual sensitivity for several ϕ mass hypothesis depends on the machine run strategy, on the available energy spectrum and on the photon beam polarization. Nevertheless, taking the given limit just as an evaluation of the order of magnitude for the sensitivity, it is worth investigating the effect on the supersymmetry breaking scale from (5) and (7). In particular, defining as a reference cross-section-branching-ratio-product the value σB obtained with $M_{\gamma\gamma} = 350$ GeV and a 10% branching ratio to two photons, the limit on $\sqrt{F}$ and the 5 σ signal can be expressed in terms of the ratio $R = \sigma^{eff} \times B.R.(\phi \to \gamma\gamma)/\sigma B$. They are then proportional to $R^{\frac{1}{4}}$ as shown in Fig. 4. The sensitivity is clearly much larger than the one expected at the e^+e^- machines.

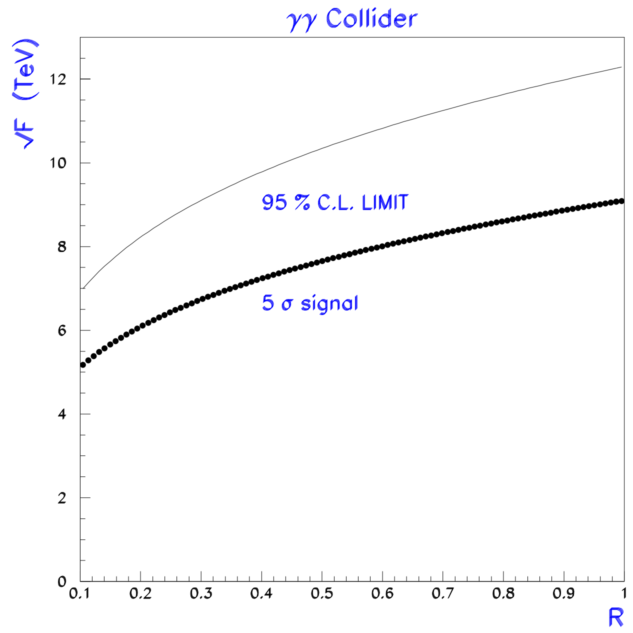

Figure 4: Limit at 95 % Confidence Level on the supersymmetry breaking scale and 5 σ signal (thick line) for the production of a ~ 400 GeV ϕ scalar state as function of the ratio R.

4 Conclusions

The sensitivity to the supersymmetric scalar ϕ at the future linear e^+e^- and photon colliders is such that unexplored parameter space regions can be investigated. The e^+e^- machines with center of mass energy of 500 GeV can set limits for the production of sgoldstino scalars up to about 420 GeV. These limits are competitive w.r.t. the expected future results from the Tevatron RUN II. The sensitivity at the photon colliders obtained from the same electron-positron beam energy is expected to be much higher for $m_\phi \sim 400$ GeV.

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