Gluino Pair Production in $e^+e^-$ and $\gamma\gamma$ Collisions at CERN CLIC

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Abstract

We confront the generally small cross sections for gluino pair production in $e^+e^-$ annihilation with the much larger ones in photon-photon scattering at a multi-TeV linear collider like CERN CLIC. The larger rates and the steeper rise of the cross section at threshold may allow for a precise gluino mass determination in high-energy photon-photon collisions for a wide range of squark masses and post-LEP SUSY benchmark points.

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Weak-scale supersymmetry (SUSY) is one of the most attractive extensions of the Standard Model (SM) of particle physics. If it is realized in nature, SUSY particles will be discovered either at Run II of the Fermilab Tevatron or within the first years of running at the CERN LHC. Reconstruction of the SUSY Lagrangian and a precise determination of its free parameters will, however, require the clean environment of a linear $e^+e^-$ collider, where in particular the masses, phases, and (electroweak) couplings of sfermions and gauginos will be determined with high accuracy. However, the mass and coupling of the gluino will pose some difficulties, since the gluino couples only to strongly interacting particles and is thus produced only at the one-loop level or in multi-parton final states. In a recent publication, we have investigated gluino pair production through triangular quark/squark loops in $e^+e^-$ annihilation with energies up to 1 TeV, which may become available in the nearer future at linear colliders like DESY TESLA [1]. Due to large cancellation effects, we found that promisingly large cross sections can only be expected for scenarios with large left-/right-handed up-type squark mass splittings or with large top-squark mixing and for gluino masses up to 500 GeV. Small gluino masses of 200 GeV might be measured with a precision of about 5 GeV in center-of-mass energy scans with luminosities of 100 fb$^{-1}$/point.

In this Report, we focus on a multi-TeV linear collider like CERN CLIC with electron (positron) beam polarization of 80% (60%) and integrated luminosity of 1000 fb$^{-1}$/year and compare the generally small production rates in $e^+e^-$ annihilation to the larger ones in photon-photon scattering. Further details on gluino pair production in high-energy photon collisions can be found in Ref. [2]. In the photon collider version of CERN CLIC, 100% polarized laser photons are backscattered from two electron beams, whose helicities must be opposite to those of the laser photons in order to maximize the number of high-energy photons. In the strong fields of the laser waves, the electrons (or high-energy photons) can interact simultaneously with several laser photons. This non-linear effect increases the threshold parameter for $e^+e^-$ pair production to $X = (2 + \sqrt{8})(1 + \xi^2) \simeq 6.5$, which corresponds to laser wavelengths of 4.4 $\mu$m at an $e^+e^-$ center-of-mass energy of 3 TeV [3]. The maximal fractional energy of the high-energy photons is then $x_{\text{max}} = X/(X+1) = 0.86$. Since the low-energy tail of the photon spectrum is neither useful nor well understood, we use only the high-energy peak with $x > 0.8 x_{\text{max}} = 0.693$ and normalize our cross sections such that the expected number of events can be obtained through simple multiplication with the envisaged photon-photon luminosity of 100-200 fb$^{-1}$/year. This requires reconstruction of
the total final-state energy, which may be difficult due to the missing energy carried away by the escaping lightest SUSY particles (LSPs). However, high-energy photon collisions allow for cuts on the relative longitudinal energy in addition to the missing-$E_T$ plus multi-jet, top or bottom (s)quark, and/or like-sign lepton analyses performed at hadron colliders, and sufficiently long-lived gluinos can be identified by their typical $R$-hadron signatures.

We adopt the current mass limit $m_{\tilde{g}} \geq 200$ GeV from the CDF [4] and D0 [5] searches in the jets with missing energy channel, relevant for non-mixing squark masses of $m_{\tilde{q}} \geq 325$ GeV and $\tan \beta = 3$. Since values for the ratio of the Higgs vacuum expectation values, $\tan \beta$, below 2.4 are already excluded by the CERN LEP experiments, and since values between 2.4 and 8.5 are only allowed in a very narrow window of light Higgs boson masses between 113 and 127 GeV [6], we employ a safely high value of $\tan \beta = 10$. For a conservative comparison of the $\gamma\gamma$ and $e^+e^-$ options at CERN CLIC, we maximize the $e^+e^-$ cross section by adopting the smallest allowed universal squark mass of $m_{\tilde{q}} \simeq m_{\text{SUSY}} = 325$ GeV and large top-squark mixing with $\theta_t = 45.195^\circ$, $m_{\tilde{t}_1} = 110.519$ GeV, and $m_{\tilde{t}_2} = 505.689$ GeV, which can be generated by choosing appropriate values for the Higgs mass parameter, $\mu = -500$ GeV, and the trilinear top-squark coupling, $A_t = 648.512$ GeV [7]. The SUSY one-loop contributions to the $\rho$-parameter and the light top-squark mass $m_{\tilde{t}_1}$ are then still significantly below and above the CERN LEP limits, $\rho_{\text{SUSY}} < 0.0012^{+0.0023}_{-0.0014}$ and $m_{\tilde{t}_1} \geq 100$ GeV [8, 9]. For small values of $\tan \beta$, mixing in the bottom squark sector remains small, and we take $\theta_b = 0^\circ$. A full set of Feynman diagrams can be generated and evaluated with the computer algebra packages FeynArts [10] and FormCalc [11].

Fig. 1 shows a comparison of the total cross sections expected in $e^+e^-$ annihilation and $\gamma\gamma$ collisions for gluino masses between 200 and 500 GeV. A light squark mass $m_{\text{SUSY}}$ and large top-squark mixing has been chosen in order to maximize the $e^+e^-$ cross section. Nevertheless, it stays below 0.1 fb and falls steeply with $m_{\tilde{g}}$, so that gluino pair production will be unobservable for $m_{\tilde{g}} > 500$ GeV irrespective of the collider energy. In contrast, the $\gamma\gamma$ cross section reaches around ten fb for a wide range of $m_{\tilde{g}}$. In $e^+e^-$ annihilation the gluinos are produced as a $P$-wave and the cross section rises rather slowly, whereas in $\gamma\gamma$ collisions they can be produced as an $S$-wave and the cross section rises much faster.

The different threshold behavior can be observed even more clearly in Fig. 2 where the sensitivities of $e^+e^-$ and $\gamma\gamma$ colliders to the gluino mass are compared. For the CERN LHC experiments, a precision of $\pm30 \ldots 60$ (12 \ldots 25) GeV is expected for gluino masses of 540
FIG. 1: Gluino pair production cross sections in $e^+e^-$ annihilation (left) and $\gamma\gamma$ collisions (right) as a function of the $e^+e^-$ center-of-mass energy and for various gluino masses. The photon-photon luminosity has been normalized to unity in the high-energy peak.

FIG. 2: Sensitivity of the $e^+e^-$ annihilation (left) and $\gamma\gamma$ scattering cross section (right) to the mass of the pair-produced gluino. The photon-photon luminosity has been normalized to unity in the high-energy peak.
\( e^-(80\%) e^- (80\%) \rightarrow e^- e^- g \bar{g} \)

\[ \sqrt{s} = 2m_\tilde{g}/0.8/0.866 \]

\* Eur.Phys.J.C 22, 535 (2001) \*

\[ \sigma [fb] \]

\[ m_{\tilde{g}} [GeV] \]

\[ \sqrt{s} [GeV] \]

**FIG. 3:** Dependence of the gluino pair production cross section in \( \gamma\gamma \) collisions on the universal squark mass \( m_{SUSY} \) for no squark mixing (thick curves) and maximal top-squark mixing (thin curves). The photon-photon luminosity has been normalized to unity in the high-energy peak. Also shown are the cross sections for the SUSY benchmark points of Ref. [14].

(1004) GeV [12, 13]. If the masses and mixing angle(s) of the top (and bottom) squarks are known, a statistical precision of \( \pm 5 \ldots 10 \) GeV can be achieved in \( e^+e^- \) annihilation for \( m_\tilde{g} = 200 \) GeV for an integrated luminosity of 100 fb\(^{-1}\) per center-of-mass energy point. A precision of \( \pm 2 \ldots 5 \) GeV may be obtained at a CERN CLIC photon collider for \( m_\tilde{g} = 540 \) GeV and an integrated photon-photon luminosity of 50 fb\(^{-1}\) per point, provided that the total final-state energy can be sufficiently well reconstructed. Of course, uncertainties from a realistic photon spectrum and the detector simulation add to the statistical error.

Finally, we demonstrate in Fig. 3 that gluino pair production in \( \gamma\gamma \) collisions depends only weakly on the universal squark mass \( m_{SUSY} \) and even less on the top-squark mixing. This is in sharp contrast to the results obtained in \( e^+e^- \) annihilation [1]. In this plot, the \( e^-e^- \) center-of-mass energy is chosen close to the threshold for gluino pair production and is
varied simultaneously with \(m_{\tilde{g}}\). Also shown in Fig. 3 are several post-LEP SUSY benchmark points, which have recently been proposed within the framework of the constrained MSSM \([14]\). Studies similar to those performed in Fig. 2 show that with the exception of point E, where only about ten events per year are to be expected, the gluino mass can be determined with a precision of \(\pm 20\) GeV (point J) or better.

In conclusion, the reconstruction of the SUSY Lagrangian and the precise determination of its free parameters are among the paramount objectives of any future linear \(e^+e^-\) collider. Determination of the gluino mass and coupling will, however, be difficult, since the gluino couples only strongly and its pair production cross section suffers from large cancellations in the triangular quark/squark loop diagrams. A photon collider may therefore be the only way to obtain precise gluino mass determinations and visible gluino pair production cross sections for general squark masses and would thus strongly complement the physics program feasible in \(e^+e^-\) annihilation.

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