$\widetilde{\tau}$ Searches at the ILC

M. T. Núñez Pardo de Vera, M. Berggren, J. List

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M.T. Núñez Pardo de Vera[*1], M. Berggren[1], and J. List[1]

[1]*DESY*

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Abstract

The direct pair-production of the superpartner of the τ-lepton, the $\widetilde{\tau}$, is one of the most interesting channels to search for SUSY in. First of all, the $\widetilde{\tau}$ is likely to be the lightest of the scalar leptons. Secondly the signature of $\widetilde{\tau}$ pair production signal events is one of the experimentally most difficult ones, thereby constituting the "worst" possible scenario for SUSY searches. The current model-independent $\widetilde{\tau}$ limits comes from analyses performed at LEP but they suffer from the limited energy of this facility. Limits obtained at the LHC do extend to higher masses, but they are only valid under strong assumptions. ILC, a future electron-positron collider with energy up to 500 GeV and upgrade capability[1], is a promising facility for SUSY searches. The capability of the ILC for determining exclusion/discovery limits for the $\widetilde{\tau}$ in a model-independent way is shown in this paper, together with an overview of the current state-of-the-art. Results of the last studies of $\widetilde{\tau}$ pair-production at the ILC are presented, showing the improvements with respect to previous results[2].

1 Introduction

Supersymmetry (SUSY) [1][2][3][4][5] is one of the most promising candidates for new physics. It could explain or at least give some hint at solutions to current problems of the Standard Model (SM), such as the gauge hierarchy problem, the nature of Dark Matter or the possible theory-experiment discrepancy of the muon magnetic moment. SUSY is a symmetry of spacetime relating fermions and bosons. For every SM particle it introduces a superpartner with the same quantum numbers except for the spin. The spin differs by half a unit from the value of its SM partner. A new parity, R-parity, is commonly introduced in SUSY, which has a crucial impact in SUSY phenomenology. R-parity takes an even value for SM particles and odd value for the SUSY ones. Multiplicative R-parity conservation [3], assumed in most of the SUSY models, implies that the SUSY particles are always created in pairs and that the lightest SUSY particle (the LSP) is stable and, when cosmological constraints are taken into account, also neutral. An important point in this kind of studies is the fundamental SUSY principle stating that each SUSY particle

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[*]Corresponding author: maria-teresa.nunez-pardo-de-vera@desy,de

[1]The initial ILC energy is planned to be 250 GeV.

[2]Talk presented at the International Workshop on Future Linear Colliders (LCWS2021), 15-18 March 2021. C21-03-15.1.

[3]The introduction and conservation of this symmetry is inspired by flavour physics constraints since the most general SUSY Lagrangian induces flavour-changing neutral interactions that are avoided imposing R-parity conservation.

couples as its corresponding SM particle. This allows to know the cross sections for SUSY pair production solely from the knowledge of initial centre-of-mass energy of the collider and the masses of the involved SUSY particles.

2 SUSY searches

Considerable efforts have been and are being devoted to the search of SUSY at different facilities. Searches at hadron colliders, such as the LHC, are mainly sensitive to the production of coloured particles, gluino and squarks. They are most probably the heaviest ones. The search of the lighter colour-neutral SUSY states, such as sleptons, charginos or neutralinos, at hadron colliders is challenged by the much smaller cross sections, and high backgrounds. Mass limits have been obtained at the LHC, but they are only valid if many constraints on the model parameters are fulfilled. Lepton colliders, like LEP, have a higher sensitivity to the production of colour-neutral SUSY states, but the searches up to now were limited by the beam energy. Limits computed at these facilities are however valid for any value of the model parameters not shown in the exclusion plots. The future International Linear Collider (ILC) [6], an electron-positron collider operating at centre-of-mass energies of $250 - 500\,\mathrm{GeV}$ and with upgrade capability to $1\,\mathrm{TeV}$, is seen as an ideal environment for SUSY studies. SUSY searches at the ILC would profit from the high electron and positron beam polarisations, 80% and 30% respectively, a well defined initial state (in 4-momentum and spin configuration), a clean and reconstructable final state, near absence of pile-up, hermetic detectors (almost 4π coverage) and trigger-less operation, which is a huge advantage for precision measurements and unexpected signatures.

3 Motivation for $\widetilde{\tau}$ searches

For evaluating the power of SUSY searches at future facilities, it is beneficial to focus on the lightest particle in the SUSY spectrum that could be accessible. Since the cosmological constraints requires a neutral and colourles LSP, the next-to-lightest SUSY particle, the NLSP, would be the first one to be detected. The NLSP can only decay to the LSP and the SM partner of the NLSP (or *via* it's SM partner, if the LSP-NLSP mass-difference is smaller than the mass of the SM partner). This already makes the NLSP production special: heavier states might well decay in cascades, and thus have signatures that depend strongly on the model. Furthermore, there is only a finite set of sparticles that could be the NLSP, so a systematic search for each possible case is feasible. This also means that one can a priori estimate which will be the most difficult case, namely the NLSP that combines small production cross-section with a difficult experimental signature. The $\widetilde{\tau}$ satisfies both these conditions. Therefore, studies of $\widetilde{\tau}$ production might be seen as the way to determine the guaranteed discovery or exclusion reach for SUSY: any other NLSP would be easier to find.

The $\widetilde{\tau}$ is the super-partner of the τ. Like for any other fermion or sfermion, there are two weak hyper-charge states, $\widetilde{\tau}_R$ and $\widetilde{\tau}_L$. For the fermions the chiral symmetry assures that both weak hyper-charge states are degenerate in mass. However this symmetry does not apply to sfermions, since they are scalars, rather than fermions. Hence there is no reason to expect that $\widetilde{\tau}_R$ and $\widetilde{\tau}_L$ would have the same mass. Furthermore, mixing between the weak hyper-charge states yields the physical states. The strength of the couplings involved in the mixing of states depend on the fermion mass and hence only the third generation of the sleptons, $\widetilde{\tau}$, will mix [4]. As a

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[4]This is also the case for the squarks, where the third generation, the stop the and the sbottom, will also mix.

consequence of the mixing the lightest $\widetilde{\tau}$, $\widetilde{\tau}_1$, would most likely be the lightest slepton, due to the seesaw mechanism. The mass of the lightest physical (mixed) state would be smaller than the mass of any un-mixed weak hyper-charge state. The cross section of the $\widetilde{\tau}$ also differs from the one of the τ, not only due to phase-space limitations - the $\widetilde{\tau}$ being more massive than the τ - but also due to the mixing. In e^+e^- colliders, assuming R-parity conservation, the $\widetilde{\tau}$ will be pair-produced, with contribution of the s-channel only, via Z^0/γ exchange. The strength of the $Z^0/\gamma\,\widetilde{\tau}\,\widetilde{\tau}$ coupling depends on the $\widetilde{\tau}$ mixing, reaching its minimum value when the coupling $\widetilde{\tau}_1\,\widetilde{\tau}_1\,Z^0$ vanishes, which will lead to the worst possible scenario in $\widetilde{\tau}$ and, in general, in slepton searches. Another property making the search of $\widetilde{\tau}$ the worst case, is the fact that its SM partner is unstable. It decays before it can be detected, and, as a further complication, some of its decay products are undetectable neutrinos. This on one hand makes the identification more difficult than the direct decay to electrons or muons, and on the other hand, since the decay products are only partially detectable, that blurs kinematic signatures. The search of a light $\widetilde{\tau}$ is also theoretically motivated: SUSY models with a light $\widetilde{\tau}$ can accommodate the observed relic density, by enhancing the $\widetilde{\tau}$-neutralino coannihilation process.

4 Limits at LEP, LHC and previous ILC studies

The most model-independent limit on the $\widetilde{\tau}$ mass comes from the LEP experiments [7]. They set a minimum value that ranges from 87 to 93 GeV depending on the mass difference between the $\widetilde{\tau}$ and the neutralino, not smaller than 7 GeV. These limits, shown in figure 1, are valid for any mixing and any value of the model-parameters, other than the two masses explicitly shown in the plot.
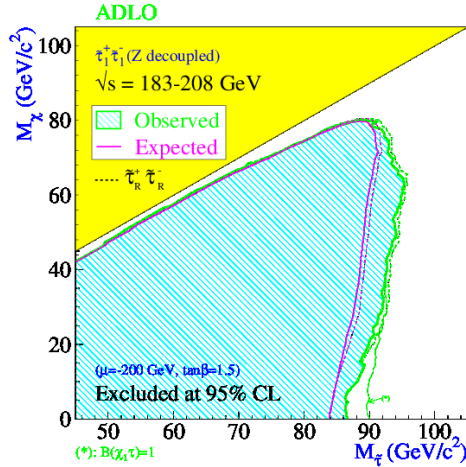

Figure 1: 95% CL exclusion limits for $\widetilde{\tau}$ pair production obtained combining data collected at the four LEP experiments with energies ranging from 183 GeV to 208 GeV. From [7].

An analysis by the DELPHI experiment, targeted at low mass differences, excludes a $\widetilde{\tau}$ with mass below 26.3 GeV, for any mixing, and any mass difference larger than the τ mass [8]. At the LHC, ATLAS and CMS have determined limits on the $\widetilde{\tau}$ mass, analysing data from Run 1 and Run 2 [9] [10]. These limits, however, are only valid under certain assumptions. Both experiments assume $\widetilde{\tau}_R$ and $\widetilde{\tau}_L$ to be mass-degenerate. This is a very unlikely scenario, the running of the $\widetilde{\tau}_R$ and $\widetilde{\tau}_L$ masses from the GUT scale to the weak scale follows renormalisation group equations

with β-functions that are inevitably different for the two weak hyper-charge states. They also assume that there is no mixing between the weak hyper-charge eigenstates, which is again very improbable. The mixing will yield to cross section of the lightest physical state smaller than that of any unmixed state. Putting together $\widetilde{\tau}_R$ and $\widetilde{\tau}_L$ by adding the cross sections, ATLAS excludes $\widetilde{\tau}$ masses between approximately 120 and 390 GeV for a nearly massless neutralino[5]. Under the same conditions, CMS extends the lower limit to 90 GeV closing the gap with the LEP limit. Analysis of a pure $\widetilde{\tau}_L$ pair production set limits between 150 and 310 GeV from ATLAS data and up to 125 GeV from CMS; both limits again assume a nearly massless neutralino. The future HL-LHC should provide an improvement on the $\widetilde{\tau}$ limits provided by ATLAS and CMS, not only because of an increase of the luminosity but also because of an expected gain in sensitivity to direct $\widetilde{\tau}$ production due to the use of different analysis methods. Simulation studies have already been performed in both experiments [11] [12]. Upper limits for $\widetilde{\tau}$ masses are indeed increased by about 300 GeV, but they suffer from the same constraints as the previous studies. ATLAS adds limits for pure $\widetilde{\tau}_R$ pair production, that could be considered the closest case to the physical lightest $\widetilde{\tau}$ since it is likely to be the lightest of the two weak hyper-charge states and is the one with the lowest cross section. These limits, presented in figure 2, show that no discovery potential is expected in this case, only exclusion potential. They do not have exclusion potential for $\widetilde{\tau}$ co-annihilation scenarios, a highly motivated scenario if SUSY is to provide a viable DM candidate: Such a scenario requires that the $\widetilde{\tau}$-LSP mass difference is small, $\lesssim 10$ GeV. $\widetilde{\tau}$ searches at the ILC have been also performed in previous studies [13]. They assume an integrated luminosity of 500 fb^{-1} at $\sqrt{s} = 500$ GeV and average beam polarisations of $P(e^-, e^+) = (+80\%, -30\%)$. The same beam polarisations are used in the current studies, since the signal to background ratio is favoured, but the luminosity is increased to the one corresponding the the foreseen running scenario, 1.6 ab^{-1}. The limits presented in that study do not have a dedicated analysis for low mass differences between the $\widetilde{\tau}$ and the LSP, ΔM, and are only valid down to ΔM 3-4 GeV. The exclusion limit goes up to 240 GeV with a discovery potential up to 230 GeV for large mass differences.

5   Conditions and tools

The study was done assuming an integrated luminosity of 1.6 ab^{-1} at $\sqrt{s} = 500$ GeV with beam polarisations $P(e^-, e^+) = (+80\%, -30\%)$, according to the H-20 running scenario in the ILC500 benchmark [14] [6]. The polarisation was selected due to the increase of the signal to background ratio, as will be shown in the description of the analysis. The study assumes R-parity conservation and a 100% decay of the $\widetilde{\tau}$ to τ and the lightest neutralino, the LSP in this case. In order to select the worst scenario, the $\widetilde{\tau}$ mixing angle was set to 53 degrees, corresponding to the lowest cross section due to the suppression of the s-channel with Z exchange in the $\widetilde{\tau}$ pair production. The SGV fast detector simulation [15], adapted to the ILD concept [16] at ILC, was used for detector simulation and event reconstruction. Signal events were generated inside SGV using Pythia 6.422 [17]. The generated background event samples were those of the standard "DBD" production [18]. They were generated with Whizard 1.95 [19], and were written in stdhep format. These files were read by SGV, and passed through the same detector simulation and reconstruction as the signal samples. The relevant information of the reconstructed events

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[5]100% decay to $\widetilde{\tau}$ and neutralino is assumed, as it is in the analysis presented in this paper

[6]$\sqrt{s}$=500 GeV, total integrated luminosity 4 ab^{-1} with 1.6 ab^{-1} for $P(e^-, e^+) = (-80\%, +30\%)$ and $P(e^-, e^+) = (+80\%, -30\%)$, 0.4 ab^{-1} for $P(e^-, e^+) = (+80\%, +30\%)$ and $P(e^-, e^+) = (-80\%, -30\%)$
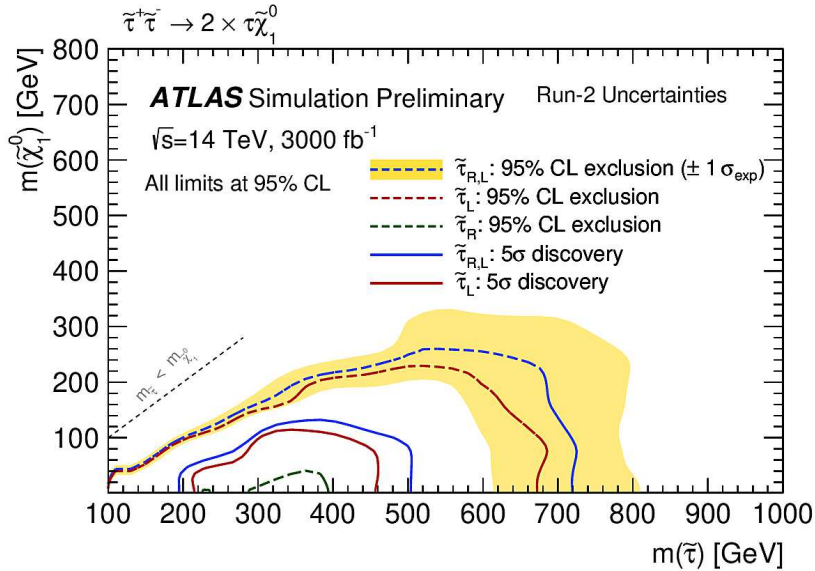
Figure 2: 95% CL exclusion and discovery potential for $\widetilde{\tau}$ pair production at the HL-LHC, assuming $\widetilde{\tau}_L^+\widetilde{\tau}_L^- + \widetilde{\tau}_R^+\widetilde{\tau}_R^-$ production, $\widetilde{\tau}_L^+\widetilde{\tau}_L^-$ production or $\widetilde{\tau}_R^+\widetilde{\tau}_R^-$ production. From [11].

were written to Root files.

6   Signal characterisation

Assuming R-parity conservation and assuming that the $\widetilde{\tau}$ is the NLSP, $\widetilde{\tau}$'s will be produced in pairs via Z^0/γ exchange in the s-channel and they will decay to a τ and an LSP (assuming mass differences above the mass of the τ, as is done in this study). The LSP, as already mentioned, is stable and weakly interacting, hence it will leave the detector without being detected. The τ, with a lifetime of the order of 2.9 x 10^{-13} s, will decay before leaving any signal in the detectors. The only detectable activity in the signal events is therefore the decay products of the two τ's. Signal events are then characterised by a large missing energy and momentum, not only due to the invisible LSPs but also to the neutrinos from both τ-decays. Since the $\widetilde{\tau}$'s are scalars and hence isotropically produced, these events have a large fraction of the detected activity in the central region of the detector. The $\widetilde{\tau}$'s must also be rather heavy, so they will not have a large boost in the lab-frame, and since the LSP is also quite heavy, the direction of the $\widetilde{\tau}$ does not strongly correlate to that of the visible τ after the decay. As a consequence the two τ-leptons are expected to go in directions quite independent of each other resulting in events with un-balanced transverse momentum, large angles between the two τ-lepton directions and absence of forward-backward asymmetry. These properties are however not necessarily present in any event - the two τ's could accidentally happen to be back to back, for example.

7   Main background sources

The main sources of background, given the generic signal topology, i.e. two τ's and an anseen

recoil system, are SM processes with real or fake missing energy. They can be classified into "irreducible" and "almost irreducible" sources. The first are events with two τ's and real missing energy, i.e. neutrinos. The main contribution to this group are ZZ events with one Z decaying to two neutrinos and the other to two τ's, and fully leptonic WW events, where at most one of the W's decays to τ and neutrino. ZWW and ZZZ events decaying to two τ's and four neutrinos are not an issue due to their low cross sections. The second group of events are those which are not really two τ's and neutrinos, but after reconstruction looks very similar. They are events with two soft τ-jets, with two other leptons plus true missing energy or two τ's plus fake missing energy. The main sources for events with true missing energy in this group are τ pair production, with the τ's decaying such that most energy goes to the neutrinos, ZZ events where one of the Z's decays to an electron or a muon pair and the other one to neutrinos, and WW events with each W decaying to an electron or muon and a neutrino. The background with fake missing energy comes mainly from τ pair production with Initial State Radiation (ISR) at very low angles, events with two τ's and two very low angle electrons (below the acceptance of the BeamCAL) in the final state and events where two τ's are produced by a $\gamma\gamma$ interaction and not from an e^+e^- one; in that case there is not really missing energy but an initial state with much less energy than that of the electron-positron interactions.

8 General cuts

Taking into account the signal signature and the main background sources, different cuts have been designed in order to separate the signal from the background.

Since the study was focused on small differences between the $\widetilde{\tau}$ and LSP masses[7], $M_\tau < \Delta M < 11\,\text{GeV}$, the absence of signal in the calorimeter closest to the beam pipe (the BeamCAL) was required as a pre-selection step before applying the following cuts.

The first group of cuts are those in properties that the $\widetilde{\tau}$-events *must* have. Since the two LSP's from the $\widetilde{\tau}$-decays are invisible to the detector, signal events have to have a missing energy greater than two times the mass of the LSP and the visible mass can not be bigger than this quantity. Also a cut in the maximum total momentum, smaller than 70% the beam momentum is applied for the same reason. The multiplicity of the event can also be constrained taking into account that the visible part comes only from the decays of the two τ's and maybe an ISR photon. For that reason the number of charged particles is asked to be between 2 and 6, with only 2 or 3 clusters identified as τ's and a total charge between -1 and 1. An specific algorithm for τ-identification was also applied. This algorithm consists in a first set of conditions requiring to have a pattern of charged tracks typical for τ-decay, *viz.* exactly two jets (obtained with the DELPHI tau-finder [8]) with charged particles, 1 or 3 charged particles in each charged jet, jet-charge ± 1, and opposite charge between both jets. A set of conditions is devoted to the reduction of background from sources with leptons not from τ-decays. To reduce the background of single W production in eγ events, with W decaying to τ and neutrino, none of the jets should consist of a single positron (this cut takes into account the polarisation selected for the study). This background together with the background from $WW \to e\nu_e\mu\nu_\mu$ and from $\gamma\gamma$ events with a beam-remnant deflected to larger angles is further reduced by rejecting those events in which the most energetic jet consists of a single electron. The two charged jets were also required to neither be made by single leptons with the same flavour nor to have one hadronic jet and

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[7]Larger mass differences were also analysed in order to cross-check and try to improve the limits from the previous studies.

one leptonic. This algorithm reduces the signal efficiency by 38% but with a reduction of the background of the order of 94%, depending on the region of the SUSY parameter space one is working with. The last cut in this first group of cuts is on the maximum momentum of the jets. Since the $\tilde{\tau}$-decay is a two body decay, it is possible to determine the maximum and minimum momentum of each of the decay products as a function of the $\tilde{\tau}$ mass, the mass of LSP and the centre-of-mass energy of the collider. The cut in the minimum momentum can not be applied due to the presence of neutrinos in the τ decay, with the corresponding decrease of observable momentum. The maximum value can be used even if it is smeared by the missed neutrinos. The expression for the maximum jet momentum is given by:

$$P_{max} = \frac{\sqrt{s}}{4}(1 - \left(\frac{M_{LSP}}{M_{\tilde{\tau}}}\right)^2)(1 + \sqrt{(1 - \frac{4M_{\tilde{\tau}}^2}{s})}) \tag{1}$$

Excluding the cut applied by the τ-identification algorithm, the signal efficiency for each of the cuts is at least 95% at all model points.

A second group of cuts is based on those properties that the $\tilde{\tau}$-events *might* have, but will *rarely* be present in background events. As already pointed out, the $\tilde{\tau}$'s are scalars, and therefore isotropically produced, while the backgrounds are either fermions or vector bosons, and tend to be produced at small angles to the beam axis. This allows to set cuts requiring events with high missing transverse momentum, large acoplanarity, high angles to the beam and high values of the variable ρ. The latter is calculated by first projecting the event on the x-y (transverse) plane, and calculating the thrust axis in that plane. ρ is then the transverse momentum (in the plane) with respect to the thrust axis. The cut in ρ helps to reject events with two τ's back-to-back in the transverse projection with the *visible* part of the decay of one of the τ's in the direction of its parent, while the other τ decays with the *invisible* ν closely aligned with the direction of its parent. These events fake the signal topology, having a large missing transverse momentum and high acoplanarity, but would have a small value of ρ. The values at which the cut in these properties is set depends on the $\tilde{\tau}$ mass and the mass difference between the $\tilde{\tau}$ and the LSP. Cutting in these properties has a certain cost in efficiency but improves the signal-to-background ratio.

The third group of cuts uses properties of some of the "almost irreducible" sources of background. WW events with each of the W's decaying to a lepton (not τ) and a neutrino are highly forward-backward asymmetric; they can be almost entirely removed by requiring the sum of the product of the charge and the cosine of the polar angle of the two most energetic jets to be above -1. ZZ events with one Z decaying to two neutrinos and the second one to a electron or muon pair are highly suppressed demanding a visible mass more than 4 GeV from the Z mass, since the visible mass in those events equals the Z mass quite precisely.

A last cut is based on a property that the signal often *does not* have, *viz.* sizeable energy detected at low angles to the beam. Events with more than 2 GeV detected at angles lower than 20 degrees to the beam axis are therefore rejected. This cut is however not useful for small mass differences.

After applying these cuts the main sources of remaining background are WW events with each W decaying to $\tau\nu$ and events with four fermions in the final state coming from $\gamma\gamma$ interactions, mostly $\tau\tau$ events.

The selected polarisation plays an important role in the capability of excluding/discovering the different regions of the SUSY space. Table 1 shows the number of signal and background events for a specific spectrum point for the two main ILC running polarisations and for unpolarised beams. Since the polarisation of the τ coming from the $\tilde{\tau}$ decays was not considered in this study,

the difference in the number of signal events comes only from the dependence of the cross section on the polarisation. This is also the main factor for the difference in WW events, ee → $\tau\nu\tau\nu$. One can see that the signal-to-background ratio is clearly enhanced in the selected polarisation. Taking the definition of exclusion at 95% CL as $S > 2\sqrt{S+B}$, with S and B the number of signal and background events respectively, it is also shown that unpolarised beams would allow neither exclusion nor discovery. Polarisation is not only important in the enhancement of the signal over background but also plays an important role in the parameter determination.

Table 1: Remaining signal and background events after the application of the selection cuts for $M_{\widetilde{\tau}}$=47 GeV and mass difference with the LSP of 10 GeV.

Polarisation	Signal	ee → $\tau\nu\tau\nu$	$\gamma\gamma \to \tau\tau$ll	$\gamma\gamma \to$ llll
$P(e^-, e^+) = (+80\%, -30\%)$	7.4	1.7	0.2	0.02
$P(e^-, e^+) = (-80\%, +30\%)$	5.7	28	0.2	0.02
Unpolarised	6	12	0.2	0.02

The cuts described above are mainly suited for mass differences up to 3 GeV. When the mass difference is between 3 GeV and the mass of the τ [8] the kinematic of the signal events is very close to that of the $\gamma\gamma$ background events and the described cuts are not enough for discovering/excluding the signal. An additional cut was done based on the Initial State Radiation photons (ISR). Events with isolated photons with high transverse momentum were selected, allowing to extension of the limits into the region under study. This cut is effective against the remaining $\gamma\gamma$ background because these events become candidates due to fake missing transverse momentum. If the presence of an ISR is requested, the incoming electron or positron that emitted the ISR must have recoiled against the ISR. Since this is a scattering process, not an annihilation one, the electron (positron) is still present in the final state. Therefore, if it is required to see a high transverse momentum ISR, the final state electron (positron) will have acquired a transverse momentum big enough to be deflected into the BeamCAL, and thus to have been rejected already at the pre-selection stage. On the other hand, if the ISR was emitted from an electron or positron that was subsequently annihilated into a Z, as is the case for the signal process, the transverse momentum of the ISR is included in the decay products of the Z, and no signal is expected in the BeamCAL.

9   Exclusion/discovery limits

The exclusion and discovery limits extracted from this study are shown in figure 3.

They assume the lightest $\widetilde{\tau}$ to be the NLSP and the lightest neutralino the LSP, and are valid for any $\widetilde{\tau}$ mixing angle. Results from previous ILC studies, computed for 500 fb^{-1} total integrated luminosity, are also shown for comparison, as well as an extrapolation of the current results from 1.6 ab^{-1} to 500 fb^{-1}. The comparison of these two curves shows that the extension of the limits is not only due to an increase of the total integrated luminosity but also to an improvement of the analysis. The main reason of this improvement is the application of individual limits depending on the $\widetilde{\tau}$ mass and the mass difference. The previous studies were only making a difference for mass differences above or below 10 GeV and were not optimised for the low mass difference

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[8]For mass differences below the mass of the τ the lifetime of the $\widetilde{\tau}$ increases exponentially and the study has to be done based on a signature of long-lived particles travelling through the detector.
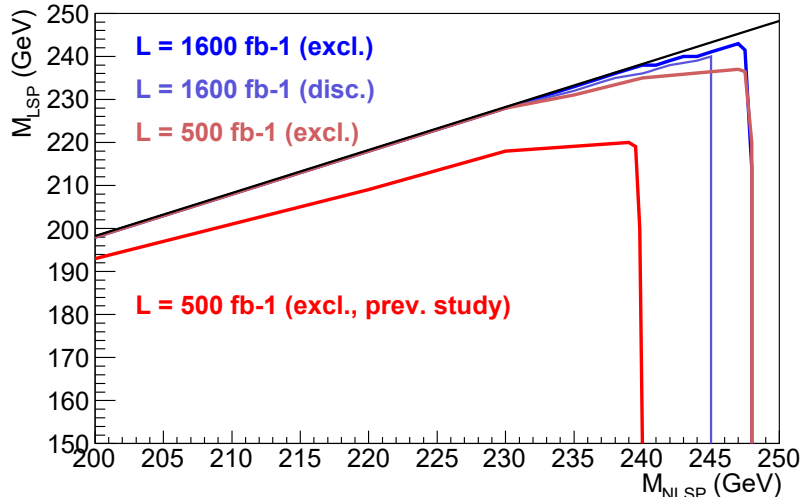
Figure 3: Exclusion and discovery $\widetilde{\tau}$ limits as a function of the $\widetilde{\tau}$ and LSP masses. Exclusion limits from previous ILC studies are also shown, as well as an extrapolation of the currents limits to 500 fb^{-1} total integrated luminosity.

region. Another difference in the analysis is a change in the τ-identification algorithm, excluding events with two jets consisting of single leptons of the same flavour or one jet being hadronic and other leptonic, which was found to be necessary for the exclusion/discovery of some points. It is also relevant to compare these results with the current $\widetilde{\tau}$ limits coming from LEP. Figure 4 shows this comparison. LEP limits are also valid for any value of the not shown model parameters.

The projection of the limits in the $M_{\widetilde{\tau}}$-ΔM plane is shown in figure 5. The region for mass differences below the mass of the τ, not included in the current study, is shown for completeness. In the region with ΔM larger than M_τ exclusion and discovery ILC limits are compared to the ones from LEP. Since the LHC limits are highly model-dependent, the comparison in this case have to be taken with care. Limits considering only the $\widetilde{\tau}_R$-pair production are shown, as, while still being optimistic, they are the closest to the ones expected for the lightest $\widetilde{\tau}$ at minimal cross-section. For the region with ΔM smaller than M_τ results from LEP and LHC are shown. LEP studies cover not only the region where the $\widetilde{\tau}_1$ travels through the detector without decaying but also the region with decays at a certain distance from the production vertex. In those regions acoplanar leptons, tracks with large impact parameters and kinked tracks are looked for, depending on the $\widetilde{\tau}_1$ lifetime [20] [21]. Figure 6 extends the previous one adding the extrapolation of the ILC limits for the scenarios with centre-of-mass energy 250 GeV and 1 TeV.

10 Outlook and conclusions

The capability of the ILC for excluding/discovering $\widetilde{\tau}$-pair production up to a few GeV below the kinematic limit, without model dependencies and even in the worst scenario, has been shown. The study has been done assuming the $\widetilde{\tau}$ mixing angle to be the one corresponding to the lowest cross section for unpolarised beams. This is also the mixing angle that gives the smallest number of signal events when simply combining the samples with polarisations $P(e^-, e^+) = (+80\%, -30\%)$ and $P(e^-, e^+) = (-80\%, -30\%)$ with equal integrated luminosity, as it is planned in the ILC
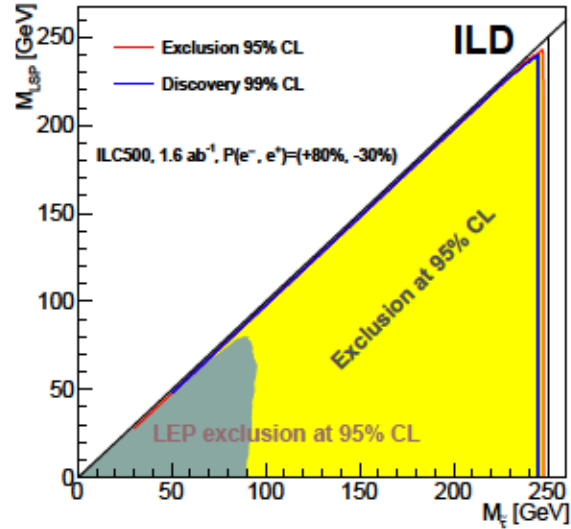
Figure 4: Exclusion and discovery $\tilde{\tau}$ limits from the current studies compared to the ones from LEP studies.
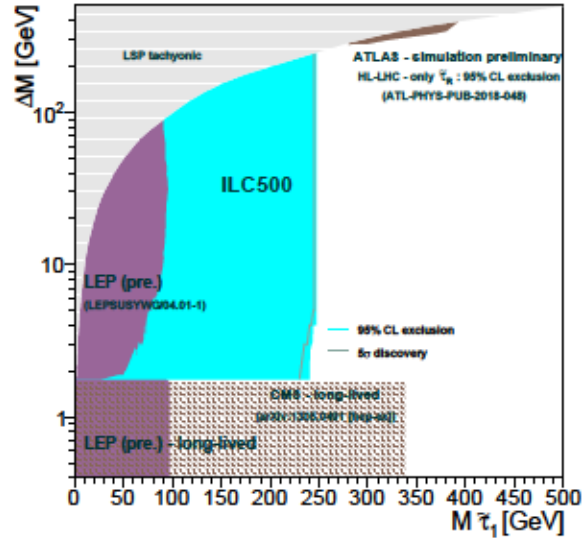

Figure 5: $\tilde{\tau}$ limits in the $M_{\tilde{\tau}}$-ΔM plane. ILC results from the current studies are shown together with limits from LEP and LHC. The region with mass differences below the mass of the τ is also shown with LEP and LHC results, even if it is not covered by this study.
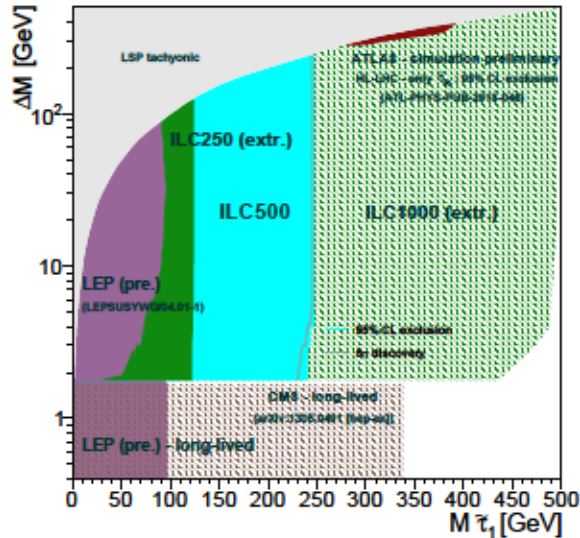
Figure 6: $\tilde{\tau}$ limits in the $M_{\tilde{\tau}}$-ΔM plane with the extrapolation of the ILC current results to the ILC 250 GeV and 1 TeV running scenarios.

running scenarios. However, due to the clear enhancement of the signal-to-background ratio with the polarisation $P(e^-, e^+) = (+80\%, -30\%)$, as shown in table 1, only this dataset was used for the calculation of the limits. The study will be extended taking into account the contribution of both polarisations. In this extension we will consider different $\tilde{\tau}$ mixing angles for confirming the one corresponding to the worst scenario. Without considering the polarisation of the τ coming from the $\tilde{\tau}$ decay, as it is done in the present study, the number of detected signal events for each mixing angle and each beam polarisation depends only on the cross section for $\tilde{\tau}$-pair production in those conditions. However the signal efficiency is affected by the τ polarisation due to the effect on the momentum distribution of the τ-decays, being softer or harder depending on the neutralino mixing angle. This effect will be also considered in the extension of the study, being an important point in the determination of the worst scenario. The calculation of the exclusion/discovery limits in the region with mass differences below the τ mass, meaning an exponential increase of the $\tilde{\tau}$ lifetime and consequently a study of long-lived particles going through or decaying in different parts of the detector, is also foreseen.

11 Acknowledgements

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