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Stau searches and measurements with the ILD concept at the International Linear Collider

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The direct pair-production of the τ-lepton superpartner, $\widetilde{\tau}$, is one of the most interesting channels to search for SUSY. First of all the $\widetilde{\tau}$ is with high probability the lightest of the scalar leptons. Secondly the signature of $\widetilde{\tau}$ pair production signal events is one of the most difficult ones, yielding to the "worst" and so most global scenario for the searches. The current model-independent $\widetilde{\tau}$ limits comes from analysis performed at LEP but they suffer from the low energy of this facility. The LHC exclusion reach extends to higher masses for large mass differences, but under strong model assumptions. The ILC, a future electron-positron collider with energy up to 1 TeV, is ideally suited 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 contribution, together with an overview of the current state-of-the-art. A detailed study of the "worst" scenario for $\widetilde{\tau}$ exclusion/discovery, taking into account the effect of the $\widetilde{\tau}$ mixing on $\widetilde{\tau}$ production cross-section and efficiency is presented. For selected benchmarks, the prospect for measuring masses and polarised cross-sections will be shown. The studies were done studying events passed through the full detector simulation and reconstruction procedures of the International Large Detector (ILD) concept at the ILC. The simulation included all SM backgrounds, as well as the machine induced ones.

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[1] On behalf of the ILD Concept Group.
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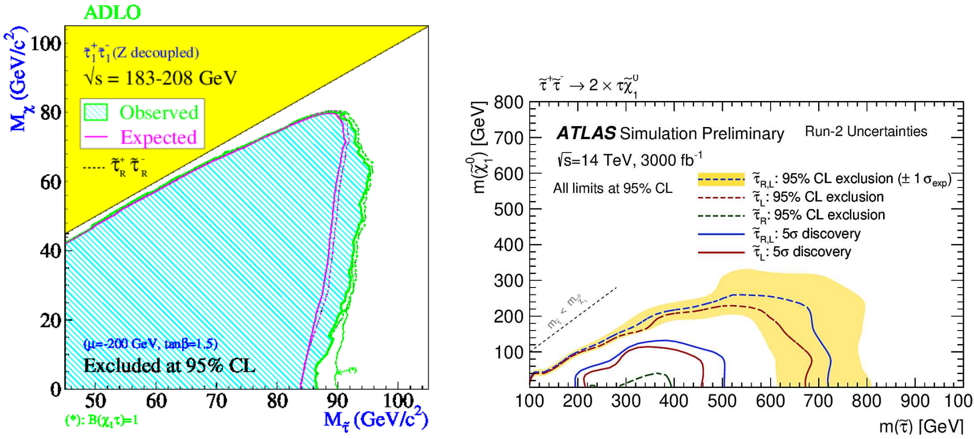
1. Introduccion and limits at other facilities

For evaluating the power of SUSY searches at future facilities, it is beneficial to focus on the lightest accesible particle in the SUSY spectrum and on the most difficult scenario. Since the cosmological constraints requires a neutral and colourles lightest SUSY particle, LSP, the next-to-lightest SUSY particle, the NLSP, would be the first one to be detected, being then the most difficult scenario the NLSP that combines small production cross-section with a difficult experimental signature. The $\widetilde{\tau}$ satisfies both these conditions. As a consequence of the mixing of both $\widetilde{\tau}$ weak hyper-charge states, $\widetilde{\tau}_L$ and $\widetilde{\tau}_R$, it is expected that the lightest of its physical states, $\widetilde{\tau}_1$, will be the lightest slepton, due to the seesaw mechanism. This mixing also points out to a lower cross-section: 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. A difficult experimental signature is due to the fact that its SM partner is unstable, decaying before it can be detected, and, as a further complication, some of its decay products are undetectable neutrinos. 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 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. The most model-independent limit on the $\widetilde{\tau}$ mass comes from the LEP experiments [1]. 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(a), are valid for any mixing and any value of the model-parameters, other than the two masses explicitly shown in the plot. 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 [2].



(a) **(b)**

Figure 1: (a): 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 [1]. (b): 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 [3].

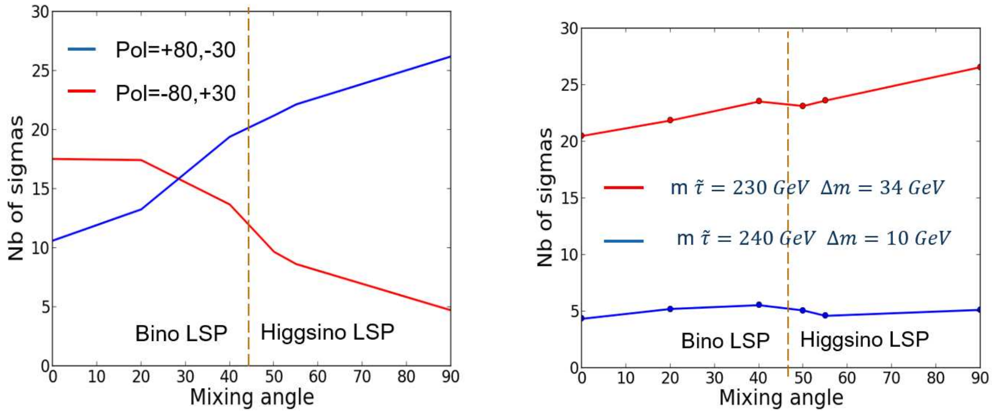
At the LHC, ATLAS and CMS have determined limits on the $\widetilde{\tau}$ mass. They are, however, only valid under certain assumptions: both experiments assume $\widetilde{\tau}_R$ and $\widetilde{\tau}_L$ to be mass-degenerate and that there is no mixing between the weak hyper-charge eigenstates. The future HL-LHC should provide an improvement on the $\widetilde{\tau}$ limits, 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 [3, 4]. 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 lower cross section. These limits, presented in figure 1(b), show that no discovery potential is expected in this case, only exclusion one. 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.

2. Signal and background

Assuming R-parity conservation and 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 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 visible decay products of the two τ's. These signal events are then characterised by a large missing energy and momentum (due to invisible LSPs and neutrinos from both τ-decays), large fraction of the detected activity in the central region of the detector ($\widetilde{\tau}$'s are scalars), un-balanced transverse momentum, large angles between the two τ-lepton directions and zero forward-backward asymmetry (direction of the $\widetilde{\tau}$ does not strongly correlate to that of the visible τ after the decay). The main sources of background, given the generic signal topology 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 both the W's decays to τ and neutrino. 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.

3. Analysis and limits

The study was done assuming an integrated luminosity of 1.6 ab^{-1} at $\sqrt{s} = 500\,\text{GeV}$ for each of the beam polarisations $P(e^-, e^+) = (+80\%, -30\%)$ and $P(e^-, e^+) = (-80\%, +30\%)$, according to the H-20 running scenario for the ILC500 [5]. The "worst" scenario for $\widetilde{\tau}$ exclusion/discovery was analysed taking into account the effect of the $\widetilde{\tau}$ mixing on $\widetilde{\tau}$ production cross-section and efficiency. Signal over background significance as a function of the mixing angle was computed for each polarisation, as shown in figure 2(a), computing the final significance weighting the contribution of both polarisations by the likelihood ratio statistic. The results are plotted in figure 2(b). One can see that rather uniform sensitivity to all mixing angles is obtained, and that for the smallest mass differences - the ones closest to the critical region - a mixing angle around 53°, corresponding to the lowest cross-section for unpolarised beams, can be indeed considered as the worst case also for the ILC conditions.

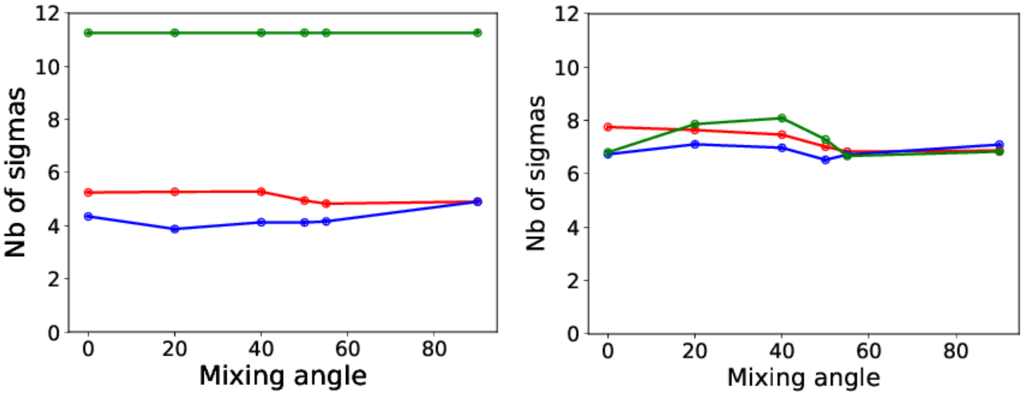


(a) **(b)**

Figure 2: (a): Signal over background significance as a function of the $\widetilde{\tau}$ mixing angle for both main ILC polarisations. (b)Signal over background significance weighting both polarisations using the likelihood-ratio static in the H-20 ILC conditions.

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. The first group of cuts are those in properties that the $\widetilde{\tau}$-events *must* have, meaning cuts in missing energy, visible mass, maximum total momentum and maximum momentum of the jets. An algorithm for τ-identification was also applied. A second group of cuts is based on those properties that the $\widetilde{\tau}$-events *might* have, but will *rarely* be present in background events, allowing to set cuts requiring high missing transverse momentum (P_{Tmiss}), large acoplanarity θ_{acop}, large angle to the beam, and large value of the variable ρ, calculated by first projecting the event on the x-y (transverse) plane, and calculating the thrust axis in that plane. The variable ρ is then the transverse momentum (in the plane) with respect to the thrust axis. The third group of cuts uses properties of some of the “almost irreducible” sources of background, using the highly forward-backward asymmetry of WW events with each of the W’s decaying to a lepton (other than τ) and the visible mass close to M_Z for the ZZ events with one Z decaying to two neutrinos and the second one to a electron or muon pair. 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. 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. For events with mass difference between 3 GeV and the mass of the τ an additional cut requiring an ISR photon was applied.

Overlay tracks can not be neglected in the $\widetilde{\tau}$ studies, since they have similar properties to the visible tracks from the $\widetilde{\tau}$-decays for small mass differences between $\widetilde{\tau}$ and the LSP. They are mainly hadrons with low transverse momentum coming from interactions of real or virtual photons produced by the beams. An algorithm trying to reduce these overlay tracks was developed based on transversal momentum, angular distribution and input parameter significance. Figure 3 shows the significance obtained with and without cuts together with the results from the `SGV` fast simulations [5] (without overlay tracks). For the case with the smallest mass difference, shown in figure 3(a), there is a strong reduction of the significance when adding overlay tracks. For the larger mass-difference ((figure 3(b)), there is only a slight degradation. For both mass differences, the overlay removal procedure ameliorates the sensitivity.



(a) $\Delta(M) = 3$ GeV **(b)** $\Delta(M) = 10$ GeV

Figure 3: Number of sigmas for a $\widetilde{\tau}$ with mass 240 GeV and different mass-differences. The plot assumes H-20 ILC scenario combining both polarisations using the likelihood-ratio statistic. Blue lines correspond to the case with all the tracks and the red ones after rejecting tracks not satisfying the cuts described in the text. The green curves correspond to the study without overlay tracks.

The projection of the limits in the $M_{\widetilde{\tau}}$-ΔM plane is shown in figure 4 [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. The projected HL-LHC limits are also shown. Since they are highly model-dependent, the comparison in this case have to be taken with care. The figure also shows the extrapolation of the ILC limits for the scenarios with centre-of-mass energy 250 GeV and 1 TeV. ILC exclusion and discovery limits are very close to each other and to the ILC kinematic limit.

For specific benchmarks the $M_{\widetilde{\tau}}$ was computed based on the end-point of the spectrum from τ decays and on the $\widetilde{\tau}$ cross-sections, achieving per mil-level precision on the measurements. τ polarisation and $\widetilde{\tau}$ mixing angle were also computed based on the spectrum of the τ decays and $\widetilde{\tau}$ cross-sections and masses, respectively. Percent level precission was reached in those cases [6].

4. 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 worst scenario for $\widetilde{\tau}$-pair production at the ILC was reviewed taking into account ILC beam polarisation conditions. Equal sharing of $P(e^-, e^+) = (+80\%, -30\%)$ and $P(e^-, e^+) = (-80\%, +30\%)$ foreseen in H-20 ensures a quite uniform sensitivity to all mixing angles.

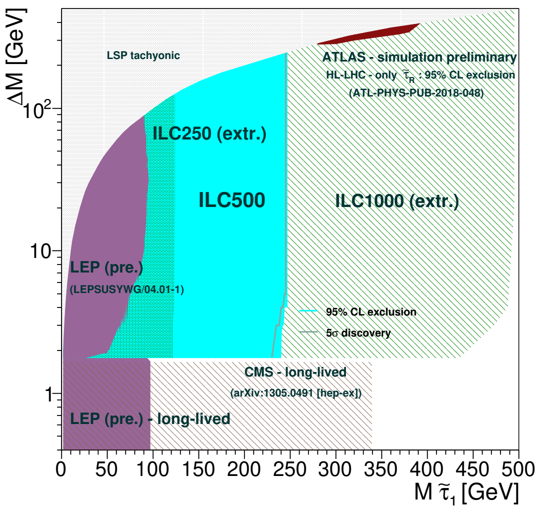


Figure 4: $\widetilde{\tau}$ limits in the $M_{\widetilde{\tau}}$-ΔM plane. ILC results from the current studies are shown together with limits from LEP and LHC. The region with mass differences below the mass of the τ is also shown with LEP and LHC results, even if it is not covered by this study. In addition, the extrapolation of the ILC current results to the ILC 250 GeV and 1 TeV running scenarios is show.

Effect of overlay tracks on signal/background ratio for $\widetilde{\tau}$ searches was analysed. It was found that the effect is considerable, both for small and moderate mass differences. Cuts to mitigate the effect was studied and applied.

If the $\widetilde{\tau}$ exists in the kinematic range of the ILC, precision measurements of $\widetilde{\tau}$ properties could be measured at a few percent level.

References

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