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Sneutrino identification in tau pair production at ILC with polarized beams

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Abstract. Many scenarios of new physics can lead to deviations of the observables (cross sections, asymmetries) from the Standard Model predictions in e^+e^- collision. The possibility of uniquely identifying the indirect effects of s-channel sneutrino exchange, as predicted by supersymmetric theories with R-parity violation, against other new physics scenarios in high-energy electron-positron annihilation into tau pairs at the International Linear Collider has been studied.

1. Introduction

A wide range of new physics (NP) scenarios, beyond the Standard Model (SM), are characterized by novel interactions mediated by exchanges of very heavy states with mass scales significantly greater than the electroweak scale. Theoretical considerations and current experimental constraints indicate that the new objects may be too heavy to be directly produced at the CERN LHC and at the planned e^+e^- International Linear Collider (ILC). Thus, the non-standard interactions would only be revealed by indirect effects manifesting themselves as deviations from the predictions of the SM. In the case of indirect discovery many different NP scenarios may lead to very similar experimental signatures. There are many very different NP scenarios that predict new particle exchanges which can lead to contact interactions (CI) which may show up below direct production thresholds. These are compositeness, a Z' boson from models with an extended gauge sector, scalar or vector leptoquarks, R-parity violating sneutrino ($\tilde{\nu}$) exchange, bi-lepton boson exchanges, anomalous gauge boson couplings (AGC), virtual Kaluza–Klein (KK) graviton exchange in the context of gravity propagating in large extra dimensions, exchange of KK gauge boson towers or string excitations, *etc.*[1]. Of course, this list is not exhaustive, because other kinds of contact interactions may be at play. The purpose of the present analysis is to develop the tools that can be used to differentiate these scenarios at high energy e^+e^- colliders.

If R-parity is violated it is possible that the exchange of sparticles can contribute significantly to SM processes and may even produce peaks or bumps in cross sections if they are kinematically accessible. Below threshold, these new spin-0 exchanges may make their manifestation known via indirect effects on observables. Here we will investigate the question of whether the effects of the exchange of scalar (spin-0) sparticles can be differentiated at linear colliders from other contact interactions mentioned above [2].

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For a sneutrino in an R-parity-violating theory, we take the basic couplings to leptons to be given by $\lambda_{ijk} L_i L_j \bar{E}_k$. Here, L are the left-handed lepton doublet superfields, and $\bar{E}$ are the corresponding left-handed singlet fields. In this case observables associated with leptonic process

$$e^+ + e^- \to \gamma, Z, \tilde{\nu}_\mu \to \tau^+ + \tau^-, \tag{1}$$

will be affected by the exchange of $\tilde{\nu}$'s in the s-channel. If only the product of Yukawa coupling $\lambda_{121}\lambda_{323}$ is nonzero the s-channel $\tilde{\nu}_\mu$ exchange would contribute to the $\tau^+\tau^-$ pair final state.

2. Observables and numerical analysis

2.1. Polarized e^+, e^- beams

With P^- and P^+ denoting the longitudinal polarizations of the electrons and positrons the doubly polarized total cross section for the process (1) in the presence of contact interactions can be expressed as

$$\begin{aligned} \sigma^{\rm CI} = \sigma_+^{\rm CI} + \sigma_-^{\rm CI} &= \frac{1}{4}\,[(1-P^-)(1+P^+)\,(\sigma_{\rm LL}^{\rm CI} + \sigma_{\rm LR}^{\rm CI}) \\ &+ (1+P^-)(1-P^+)\,(\sigma_{\rm RR}^{\rm CI} + \sigma_{\rm RL}^{\rm CI})]. \end{aligned} \tag{2}$$

For the SM it has the same form where one should replace the superscript CI $\to$ SM. In Eq. (2) the helicity cross sections $\sigma_{\alpha\beta}^{\rm CI} \propto |\mathcal{M}_{\alpha\beta}^{\rm CI}|^2$ $(\alpha, \beta = {\rm L}, {\rm R})$ are directly related to the individual CI couplings $\Delta_{\alpha\beta}$. Here the helicity amplitudes $\mathcal{M}_{\alpha\beta}^{\rm CI}$ can be written as $\mathcal{M}_{\alpha\beta}^{\rm CI} = \mathcal{M}_{\alpha\beta}^{\rm SM} + \Delta_{\alpha\beta}$. The $\Delta_{\alpha\beta}$ functions represent the contact interaction contributions coming from TeV-scale physics mentioned above [2].

Since the $\tilde{\nu}$ exchanged in the s-channel does not interfere with the s-channel SM γ and Z exchanges, the corresponding total cross section can be written as

$$\begin{aligned} \sigma^{\tilde{\nu}} &= \frac{1}{4}\,(1-P^-)(1+P^+)\,(\sigma_{\rm LL}^{\rm SM} + \sigma_{\rm LR}^{\rm SM}) + \frac{1}{4}\,(1+P^-)(1-P^+)\,(\sigma_{\rm RR}^{\rm SM} + \sigma_{\rm RL}^{\rm SM}) \\ &+ \frac{3}{2}\,\frac{1+P^-P^+}{2}\,(\sigma_{\rm RL}^{\tilde{\nu}} + \sigma_{\rm LR}^{\tilde{\nu}}). \end{aligned} \tag{3}$$

Here, $\sigma_{\rm RL}^{\tilde{\nu}} = \sigma_{\rm LR}^{\tilde{\nu}} \propto |\mathcal{M}_{\rm RL}^{\tilde{\nu}}|^2$, $\mathcal{M}_{\rm RL}^{\tilde{\nu}} = \mathcal{M}_{\rm LR}^{\tilde{\nu}} = \frac{1}{2}\,C_{\tilde{\nu}}^s \chi_{\tilde{\nu}}^s$, and $C_{\tilde{\nu}}^s$ and $\chi_{\tilde{\nu}}^s$ denote the product of the R-parity violating couplings and the propagator of the exchanged sneutrino. For the s-channel $\tilde{\nu}_\tau$ sneutrino exchange: $C_{\tilde{\nu}}^s\,\chi_{\tilde{\nu}}^s = (\lambda^2/(4\pi\alpha_{\rm em}))\,(s/(s - M_{\tilde{\nu}_\tau}^2 + iM_{\tilde{\nu}_\tau}\Gamma_{\tilde{\nu}_\tau}))$, where $\lambda^2 = \lambda_{121}\lambda_{323}$.

To uniquely identify the effect of the s-channel sneutrino exchange the double beam polarization asymmetry can be used:

$$\begin{aligned} A_{\rm double} &= \frac{\sigma(P_1,-P_2) + \sigma(-P_1,P_2) - \sigma(P_1,P_2) - \sigma(-P_1,-P_2)}{\sigma(P_1,-P_2) + \sigma(-P_1,P_2) + \sigma(P_1,P_2) + \sigma(-P_1,-P_2)} \\ &= P_1P_2 \cdot \frac{(\sigma_{\rm LL}^{\rm SM} + \sigma_{\rm LR}^{\rm SM} + \sigma_{\rm RR}^{\rm SM} + \sigma_{\rm RL}^{\rm SM}) - 3(\sigma_{\rm LR}^{\tilde{\nu}} + \sigma_{\rm RL}^{\tilde{\nu}})}{(\sigma_{\rm LL}^{\rm SM} + \sigma_{\rm LR}^{\rm SM} + \sigma_{\rm RR}^{\rm SM} + \sigma_{\rm RL}^{\rm SM}) + 3(\sigma_{\rm LR}^{\tilde{\nu}} + \sigma_{\rm RL}^{\tilde{\nu}})}, \end{aligned} \tag{4}$$

where $P_1 = |P^-|$, $P_2 = |P^+|$. For the whole set of contact interactions, with the exception of the s-channel sneutrino exchange, $A_{\rm double}^{\rm SM} = A_{\rm double}^{\rm CI} = P_1P_2 = 0.48$, where $P_1 = 0.8$, $P_2 = 0.6$. This is because these contact interactions contribute to the same amplitudes as SM. Thus, $A_{\rm double}^{\rm SM}$ and $A_{\rm double}^{\rm CI}$ are indistinguishable for any values of the contact interaction parameters. On the contrary, the $\tilde{\nu}$ exchange in the s-channel will force this observable to a smaller value, $\Delta A_{\rm double} = A_{\rm double}^{\tilde{\nu}} - A_{\rm double}^{\rm SM} \propto -P_1P_2\,|C_{\tilde{\nu}}^s\chi_{\tilde{\nu}}^s|^2 < 0$. The value of $A_{\rm double}$ below P_1P_2 can provide a signature of scalar exchange in the s-channel.

2.2. Unpolarized e^+, e^- beams

Alternatively, if the tau spins can be analyzed [3, 4], a spin-spin correlation can be formed which is sensitive to the spin of any new particle exchanged in s-channel of the process

$$e^+ + e^- \to \tau^+(h') + \tau^-(h), \tag{5}$$

where h (h') denotes the helicity of τ^- (τ^+). The spin-spin correlation, B_{ZZ}, as introduced in [3], can be written as:

$$\begin{aligned} B_{ZZ} &= \frac{\sigma(+,-)+\sigma(-,+)-\sigma(+,+)-\sigma(-,-)}{\sigma(+,-)+\sigma(-,+)+\sigma(+,+)+\sigma(-,-)} \\ &= \frac{(\sigma^{\rm SM}_{\rm LL}+\sigma^{\rm SM}_{\rm LR}+\sigma^{\rm SM}_{\rm RR}+\sigma^{\rm SM}_{\rm RL})-3(\sigma^{\tilde\nu}_{\rm LR}+\sigma^{\tilde\nu}_{\rm RL})}{(\sigma^{\rm SM}_{\rm LL}+\sigma^{\rm SM}_{\rm LR}+\sigma^{\rm SM}_{\rm RR}+\sigma^{\rm SM}_{\rm RL})+3(\sigma^{\tilde\nu}_{\rm LR}+\sigma^{\tilde\nu}_{\rm RL})}. \end{aligned} \tag{6}$$

This quantity is unity in the SM as well as in CI models but can be substantially smaller when s-channel scalars are present as shown in Fig. 1.

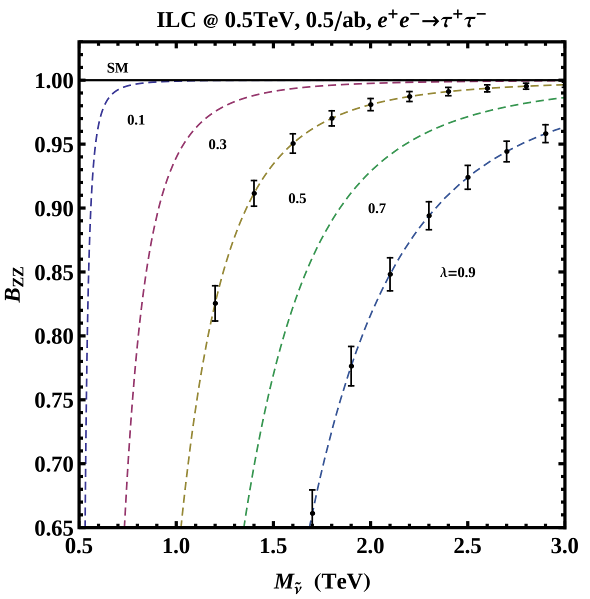

Figure 1. B_{ZZ} asymmetry as a function of sneutrino mass $M_{\tilde\nu}$ for different choices of λ. The error bars indicate the expected uncertainty (2σ-level) for ILC with $\sqrt{s} = 0.5$ TeV and $\mathcal{L}_{\rm int} = 0.5$ ab^{-1}.

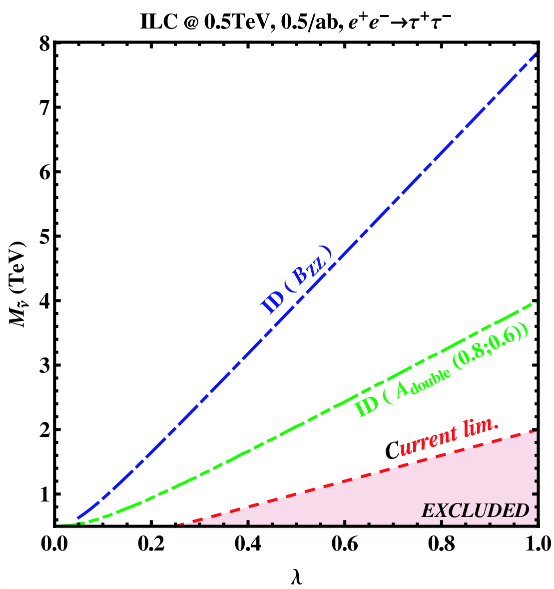

Figure 2. Identification reach on $M_{\tilde\nu}$ (95% C.L.) as a function of λ for the process $e^+e^- \to \tau^+\tau^-$ at the ILC with $\sqrt{s} = 0.5$ TeV and $\mathcal{L}_{\rm int} = 0.5$ ab^{-1}. Radiative corrections were included.

Identification reaches on the sneutrino mass $M_{\tilde\nu}$ (95% C.L.) plotted in Fig. 2 are obtained from χ^2 analysis of $A_{\rm double}$ and B_{ZZ} asymmetries. For comparison, current limits from low-energy data are also shown. The reach obtained using spin-spin correlation technique discussed above is superior to that found by examination of the double spin asymmetry $A_{\rm double}$.

3. Concluding remarks

We studied the possibility of uniquely identifying the indirect effects of s-channel sneutrino exchange, as predicted by supersymmetric theories with R-parity violation, against other new physics scenarios in high-energy electron-positron annihilation into tau pairs at the International

Linear Collider. New physics outlined above can lead to qualitatively similar alterations in SM cross sections and angular distributions but differ in detail. These detailed differences provide the key to the two major tools that are useful in accomplishing our task: (i) an asymmetry formed by polarizing both initial beams,$A_{\rm double}$, and (ii) spin-spin correlation, B_{ZZ}.

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