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PROBING AND IDENTIFYING NEW PHYSICS SCENARIOS AT INTERNATIONAL LINEAR COLLIDER

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ABSTRACT. Many new physics scenarios are described by contact-like effective interactions that can manifest themselves in e^+e^- collisions through deviations of the observables from the Standard Model predictions. If such a deviation were observed, it would be important to identify the actual source among the possible non-standard interactions as many different new physics scenarios may lead to very similar experimental signatures. Here we study the possibility of uniquely identifying the indirect effects of s-channel sneutrino exchange with double polarization asymmetry, as predicted by supersymmetric theories with R-parity violation, against other new physics scenarios in process $e^+e^- \to \mu^+\mu^-$ at the International Linear Collider.

Keywords: Elementary particles, Standard Model, physics beyond the Standard Model.

1. Introduction

Numerous new physics (NP) scenarios, candidates as solutions of Standard Model (SM) conceptual problems, are characterized by novel interactions mediated by exchanges of very heavy states with mass scales significantly greater than the electroweak scale. In many cases, theoretical considerations as well as current experimental constraints indicate that the new objects may be too heavy to be directly produced even at the highest energies of the CERN Large Hadron Collider (LHC) and at foreseen future colliders, such as the e^+e^- International Linear Collider (ILC). In this situation the new, non-standard, interactions would only be revealed by indirect, virtual, effects manifesting themselves as deviations from the predictions of the SM. In the case of indirect discovery the effects may be subtle since many different NP scenarios may lead to very similar experimental signatures and they may easily be confused in certain regions of the parameter space for each class of models.

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 (Eichten, 1983), a Z' boson from models with an extended gauge sector, scalar or vector leptoquarks (Buchmuller, 1987), R-parity violating sneutrino ($\tilde{\nu}$) exchange (Kalinowski, 1997), bi-lepton boson exchanges (Cuypers, 1998), anomalous gauge boson couplings (AGC) (Gounaris, 1997), 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 (Arkani-Hamed, 1998), *etc.* Of course, this list is not exhaustive, because other kinds of contact interactions may be at play.

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 (cross sections and asymmetries). Here we will address the question of whether the effects of the exchange of scalar (spin-0) sparticles can be differentiated at the ILC with a center of mass energy $\sqrt{s} = 0.5 - 1$ TeV and time-integrated luminosity of $\mathcal{L}_{\rm int} = 0.5 - 1$ ab^{-1} in process

$$e^+ + e^- \to \mu^+ + \mu^- \quad (\tau^- + \tau^+), \qquad (1)$$

from those associated with the wide class of other contact interactions mentioned above. For details of the analysis and extended references, see (Tsytrinov, 2012; Moortgat-Pick, 2013).

2. Observables and NP parametrization in $\mu^+\mu^-$ production

For a sneutrino in an R-parity-violating theory, we take the basic couplings to leptons and quarks to be given by

$$\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k. \qquad (2)$$

Here, L (Q) are the left-handed lepton (quark) doublet superfields, and $\bar{E}$ ($\bar{D}$) are the corresponding left-handed singlet fields. If just the R-parity violating $\lambda LL\bar{E}$ terms of the superpotential are present it is clear that observables associated with leptonic process (1) will be affected by the exchange of $\tilde{\nu}$'s in the t- or s-channels. For instance, in the case only one nonzero

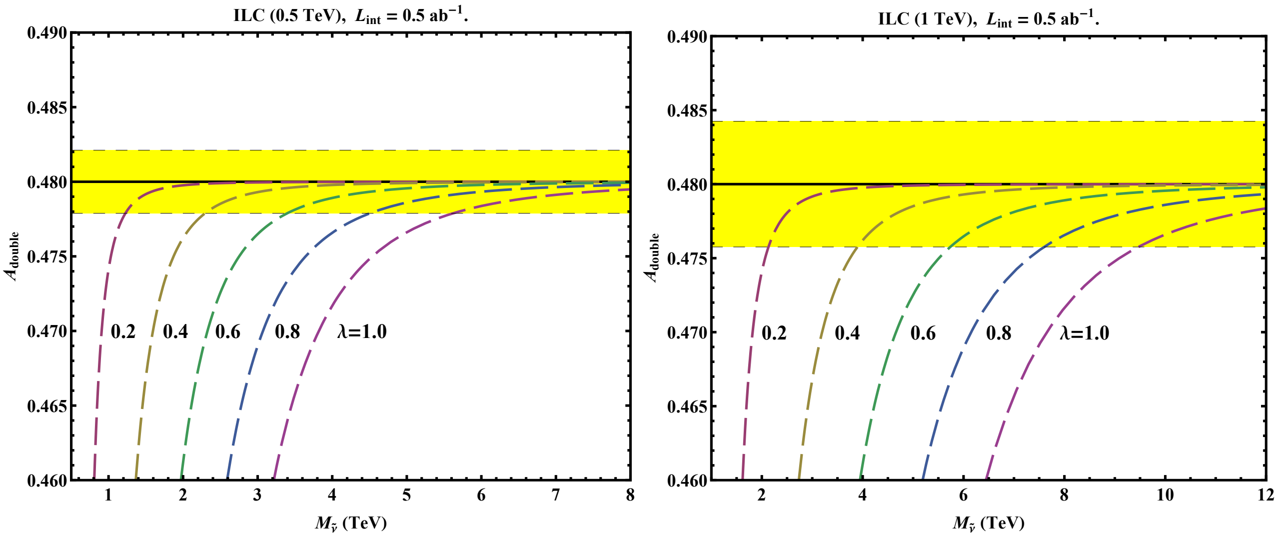

Figure 1: $A^{\tilde{\nu}}_{\rm double}$ asymmetry as a function of sneutrino mass $M_{\tilde{\nu}}$ for different choices of λ (dashed lines) at the ILC with $\sqrt{s} = 0.5$ TeV (left) and $\sqrt{s} = 1.0$ TeV (right), $\mathcal{L}_{\rm int} = 0.5$ ab^{-1}. The horizontal solid line corresponds to $A^{\rm SM}_{\rm double} = A^{\rm CI}_{\rm double} = 0.48$. The expected SM uncertainty shown as yellow bands.

Yukawa coupling is present, $\tilde{\nu}$'s may contribute to, e.g. $e^+e^- \to \mu^+\mu^-$ via t-channel exchange. In particular, if λ_{121}, λ_{122}, λ_{132}, or λ_{231} are nonzero, the $\mu^+\mu^-$ pair production proceeds via additional t-channel sneutrino exchange mechanism. However, if only the product of Yukawa, e.g. $\lambda_{131}\lambda_{232}$, is nonzero the s-channel $\tilde{\nu}_\tau$ exchange would contribute to the $\mu^+\mu^-$ pair final state. Below we denote by λ the relevant Yukawa coupling from the superpotential (2) omitting the subscripts.

With P^- and P^+ denoting the longitudinal polarizations of the electrons and positrons, respectively, and θ the angle between the incoming electron and the outgoing muon in the c.m. frame, the differential cross section of process (1) in the presence of contact interactions can be expressed as ($z \equiv \cos\theta$):

$$\frac{{\rm d}\sigma^{\rm CI}}{{\rm d}z} = \frac{3}{8}\left[(1+z)^2\sigma^{\rm CI}_+ + (1-z)^2\sigma^{\rm CI}_-\right]. \qquad (3)$$

In terms of the helicity cross sections $\sigma^{\rm CI}_{\alpha\beta}$ (with $\alpha,\beta = {\rm L,R}$), directly related to the individual CI couplings $\Delta_{\alpha\beta}$ (see Eq. (7)):

$$\begin{aligned}\sigma^{\rm CI}_+ &= \frac{1}{4}[(1-P^-)(1+P^+)\,\sigma^{\rm CI}_{\rm LL} + \\ &+ (1+P^-)(1-P^+)\,\sigma^{\rm CI}_{\rm RR}], \qquad (4)\\ \sigma^{\rm CI}_- &= \frac{1}{4}[(1-P^-)(1+P^+)\,\sigma^{\rm CI}_{\rm LR} + \\ &+ (1+P^-)(1-P^+)\,\sigma^{\rm CI}_{\rm RL}], \qquad (5)\end{aligned}$$

where the first (second) subscript refers to the chirality of the electron (muon) current. Moreover, in Eqs. (4) and (5):

$$\sigma^{\rm CI}_{\alpha\beta} = \sigma_{\rm pt}|\mathcal{M}^{\rm CI}_{\alpha\beta}|^2, \qquad (6)$$

where $\sigma_{\rm pt} \equiv \sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-) = (4\pi\alpha^2_{\rm em})/(3s)$. The helicity amplitudes $\mathcal{M}^{\rm CI}_{\alpha\beta}$ can be written as

$$\mathcal{M}^{\rm CI}_{\alpha\beta} = \mathcal{M}^{\rm SM}_{\alpha\beta} + \Delta_{\alpha\beta} = Q_e Q_\mu + g^e_\alpha\, g^\mu_\beta\, \chi_Z + \Delta_{\alpha\beta}, \quad (7)$$

where $\chi_Z = s/(s - M^2_Z + iM_Z\Gamma_Z)$ represents the Z propagator, $g^l_{\rm L} = (I^l_{3L} - Q_l s^2_W)/s_W c_W$ and $g^l_{\rm R} = -Q_l s^2_W/s_W c_W$ are the SM left- and right-handed lepton ($l = e,\mu$) couplings of the Z with $s^2_W = 1 - c^2_W \equiv \sin^2\theta_W$ and Q_l the leptonic electric charge. The $\Delta_{\alpha\beta}$ functions represent the contact interaction contributions coming from TeV-scale physics.

The structure of the differential cross section (3) is particularly interesting in that it is equally valid for a wide variety of NP models such as composite fermions, extra gauge boson Z', AGC, TeV-scale extra dimensions and ADD model. Parametrization of the $\Delta_{\alpha\beta}$ functions in different NP models ($\alpha,\beta = {\rm L,R}$) can be found in (Moortgat-Pick, 2013).

The doubly polarized total cross section can be obtained from Eq. (3) after integration over z within the interval $-1 \le z \le 1$. In the limit of s,t small compared to the CI mass scales, the result takes the form

$$\begin{aligned}\sigma^{\rm CI} &= \sigma^{\rm CI}_+ + \sigma^{\rm CI}_- = \\ &= \frac{1}{4}\left((1-P^-)(1+P^+)\,(\sigma^{\rm CI}_{\rm LL} + \sigma^{\rm CI}_{\rm LR}) + \right.\\ &+ \left.(1+P^-)(1-P^+)\,(\sigma^{\rm CI}_{\rm RR} + \sigma^{\rm CI}_{\rm RL})\right). \qquad (8)\end{aligned}$$

It is clear that the formula in the SM has the same form where one should replace the superscript CI $\to$ SM in Eq. (8).

Since the $\tilde{\nu}$ exchanged in the s-channel does not interfere with the s-channel SM γ and Z exchanges, the differential cross section with both electron and positron beams polarized can be written as

$$\frac{d\sigma^{\tilde{\nu}}}{dz} = \frac{3}{8}[(1+z)^2\sigma_+^{\rm SM} + (1-z)^2\sigma_-^{\rm SM} + \\ + \; 2\,\frac{1+P^-P^+}{2}\,(\sigma_{\rm RL}^{\tilde{\nu}} + \sigma_{\rm LR}^{\tilde{\nu}})]. \quad (9)$$

Here, $\sigma_{\rm RL}^{\tilde{\nu}}(=\sigma_{\rm LR}^{\tilde{\nu}}) = \sigma_{\rm pt}\,|\mathcal{M}_{\rm RL}^{\tilde{\nu}}|^2$, $\mathcal{M}_{\rm RL}^{\tilde{\nu}} = \mathcal{M}_{\rm LR}^{\tilde{\nu}} = \frac{1}{2}\,C_{\tilde{\nu}}^s\chi_{\tilde{\nu}}^s$, 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 they read

$$C_{\tilde{\nu}}^s\,\chi_{\tilde{\nu}}^s = \frac{\lambda_{131}\lambda_{232}}{4\pi\alpha_{\rm em}}\,\frac{s}{s - M_{\tilde{\nu}_\tau}^2 + iM_{\tilde{\nu}_\tau}\Gamma_{\tilde{\nu}_\tau}}. \quad (10)$$

Below we will use the abbreviation $\lambda^2 = \lambda_{131}\lambda_{232}$.

As seen from Eq. (9) the polarized differential cross section picks up a z-independent term in addition to the SM part. The corresponding total cross section can be written as

$$\sigma^{\tilde{\nu}} = \frac{1}{4}\,(1-P^-)(1+P^+)\,(\sigma_{\rm LL}^{\rm SM} + \sigma_{\rm LR}^{\rm SM}) + \\ + \; \frac{1}{4}\,(1+P^-)(1-P^+)\times(\sigma_{\rm RR}^{\rm SM} + \sigma_{\rm RL}^{\rm SM}) + \\ + \; \frac{3}{2}\,\frac{1+P^-P^+}{2}\,(\sigma_{\rm RL}^{\tilde{\nu}} + \sigma_{\rm LR}^{\tilde{\nu}}). \quad (11)$$

It is possible to uniquely identify the effect of the s channel sneutrino exchange exploiting the double beam polarization asymmetry defined as (Osland, 2003)

$$A_{\rm double} = \frac{(+,-)+(-,+)-(+,+)-(-,-)}{(+,-)+(-,+)+(+,+)+(-,-)}, \quad (12)$$

where $(+,-) = \sigma(P_1,-P_2)$, ..., and $P_{1,2} = |P^{-,+}|$. From (8) and (12) one finds

$$A_{\rm double}^{\rm SM} = A_{\rm double}^{\rm CI} = P_1P_2 = 0.48, \quad (13)$$

where the numerical value corresponds to electron and positron degrees of polarization: $P_1 = 0.8$, $P_2 = 0.6$. This is because these contact interactions contribute to the same amplitudes as shown in (7). Eq. (13) demonstrates that $A_{\rm double}^{\rm SM}$ and $A_{\rm double}^{\rm CI}$ are indistinguishable for any values of the contact interaction parameters, $\Delta_{\alpha\beta}$, i.e. $\Delta A_{\rm double} = A_{\rm double}^{\rm CI} - A_{\rm double}^{\rm SM} = 0$.

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. All those features in the $A_{\rm double}$ behavior are shown in Fig. 1.

In the numerical analysis, cross sections are evaluated including initial- and final-state radiation by means of the program ZFITTER, together with ZEFIT, with $m_{\rm top} = 175$ GeV and $m_H = 125$ GeV.

As numerical inputs, we shall assume the identification efficiencies of $\epsilon = 95\%$ for $\mu^+\mu^-$ final states, integrated luminosity of $\mathcal{L}_{\rm int} = 0.5$ ab^{-1} with uncertainty $\delta\mathcal{L}_{\rm int}/\mathcal{L}_{\rm int} = 0.5\%$, and a fiducial experimental angular range $|\cos\theta| \leq 0.99$. Also, regarding electron and positron degrees of polarization, we shall consider the following values: $P^- = \pm 0.8$; $P^+ = \pm 0.6$, with $\delta P^-/P^- = \delta P^+/P^+ = 0.5\%$. Discovery and identification reaches on the sneutrino

Table 1: Discovery and identification reaches on sneutrino mass $M_{\tilde{\nu}}$ (95% C.L.) in TeV as a function of λ for the process $e^+e^- \to \mu^+\mu^-$ at the ILC.

$M_{\tilde{\nu}}$ (TeV)	$\lambda = 0.5$	$\lambda = 1.0$
Discovery (ILC 0.5 TeV)	3.0	5.9
ID (ILC 0.5 TeV)	2.4	4.7
Discovery (ILC 1 TeV)	5.1	10.0
ID (ILC 1 TeV)	4.1	8.0
Current limits	0.9	2.0

mass $M_{\tilde{\nu}}$ (95% C.L.) listed in Table 1 are obtained from conventional χ^2 analysis. For comparison, current limits from low-energy data are also shown. From Table 1 one can see that identification of sneutrino exchange effects in the s-channel with $A_{\rm double}$ is feasible in the region of parameter and mass space far beyond the current limits.

3. Concluding remarks

In this note we have studied how uniquely identify the indirect (propagator) effects of spin-0 sneutrino predicted by supersymmetric theories with R-parity violation, against other new physics scenarios in high energy e^+e^- annihilation into lepton-pairs at the ILC in process (1). To evaluate the identification reach on the sneutrino exchange signature, we develop a technique based on a double polarization asymmetry formed by polarizing both beams in the initial state, that is particularly suitable to directly test for such s-channel sneutrino exchange effects in the data analysis.

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References

Arkani-Hamed N. et al.: 1998, *Phys. Lett. B*,,**429**, 263.
Buchmuller W.B. et al.: 1987, *Phys. Lett. B*, **191**, 442.
Cuypers F. et al.: 1998, *Eur. Phys. J. C*, **2**, 503.
Eichten E. et al.: 1983, *Phys. Rev. Lett.*, **50**, 811.
Gounaris G.J. et al.: 1997, *Phys. Rev. D*, **56**, 3970.
Kalinowski J. et al.: 1997, *Phys. Lett. B*, **406**, 314.
Moortgat-Pick G. et al.: 2013, *Phys. Rev. D*, **87**, 095017.
Osland P. et al.: 2003, *Phys. Rev. D*, **68**, 015007.
Tsytrinov A.V. et al.: 2012, *Phys. Lett. B*, **718**, 94.