Discriminating New Physics Scenarios at ILC

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Abstract

We discuss the possibility of identifying the effects of graviton exchange in extra dimensions from other new physics scenarios parametrized by the four-fermion compositeness-inspired contact interactions, and *viceversa*, using the polarized differential cross section in high energy e^+e^- annihilation into fermion-pairs.

Many types of new physics (NP) scenarios beyond the Standard Model (SM) are determined by non-standard dynamics involving new forces mediated by exchange of the heavy states with mass scales much greater the electroweak scale. A confirmation of such dynamics would require the experimental discovery of these new heavy objects and the measurement of their coupling constants to ordinary bosons and fermions (quarks and leptons). The current experimental limits on the new, heavy particles are so high, of the order of several (or tens of) TeV, that one cannot expect them to be directly produced at the energies foreseen for proton–proton and electron–positron high energy colliders such as the LHC and the International Linear Collider (ILC). In this situation, the new interactions can manifest themselves only by indirect, virtual, effects represented by deviations of the measured observables from the SM predictions. The problem, then, is to identify from the data analysis the possible new interactions, because different NP scenarios can in principle cause similar measurable deviations, and for this purpose suitable observables must be defined [1].

At "low" energies (compared to the above-mentioned large mass scales) the physical effects of the new interactions are conveniently accounted for,

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in reactions involving the familiar quarks and leptons, by effective *contact-interaction* (CI) Lagrangians [2]. The four-fermion contact interaction scenario can be represented by the following vector-vector dimension-6 effective Lagrangian ($\eta_{\alpha\beta} = \pm 1, 0$; $\alpha, \beta = \mathrm{L}, \mathrm{R}$):

$$\mathcal{L}^{\mathrm{CI}} = 4\pi \sum_{\alpha,\beta} \frac{\eta_{\alpha\beta}}{\Lambda^2_{\alpha\beta}} \left(\bar{e}_\alpha \gamma_\mu e_\alpha\right)\left(\bar{f}_\beta \gamma^\mu f_\beta\right). \tag{1}$$

In the analysis presented below we consider the composite models defined in Table 1. The effective Lagrangian $\mathcal{L}^{\mathrm{CI}}$ should more generally be considered as an effective, "low energy" representation of a variety of non-standard interactions acting at energy scales $\Lambda_{\alpha\beta}$ much larger than the process Mandelstam variables, for example the exchanges of very heavy Z's, leptoquarks, scalar particle exchanges, such as sneutrinos, bi-lepton boson exchanges, anomalous gauge boson couplings, virtual Kaluza–Klein (KK) graviton exchange in the context of gravity propagating in large extra dimensions, exchange of gauge boson KK towers or string excitations, *etc.*

Table 1: Definition of the most common CI models

CI model	η_{LL}	η_{RR}	η_{LR}	η_{RL}
LL	± 1	0	0	0
RR	0	± 1	0	0
LR	0	0	± 1	0
RL	0	0	0	± 1
VV	± 1	± 1	± 1	± 1
AA	± 1	± 1	∓ 1	∓ 1

The interest in studying fermion-pair final states at ILC is driven by the fact that many types of new physics scenarios mentioned above can contribute to these processes. To be specific we will limit our discussion to the fermion-pair production processes

$$e^+ + e^- \to \bar{f} + f \tag{2}$$

$f = l, q$ ($l = \mu, \tau$; $q = c, b$). The processes (2) are chosen as a very sensitive probe, affected in many new physics scenarios. They can be used to search for manifestations of contact interactions and as a very sensitive probe of the graviton exchange effects.

In the ADD large extra dimension scenario [3], only gravity can propagate in at least two extra spatial dimensions, while the SM particles live in the ordinary four-dimensional spacetime and their mutual gravitational interactions are represented by the exchange of a tower of graviton KK states. The summation over the KK spectrum requires the introduction of a ultraviolet cut-off mass scale Λ_H, expected in the (multi) TeV region, and the interaction can be represented by the effective Lagrangian

$$\mathcal{L}^{\rm ADD} = i\frac{4\lambda}{\Lambda_H^4}T^{\mu\nu}T_{\mu\nu}, \tag{3}$$

which is similar to a dimension-8 contact interaction. Here, $T_{\mu\nu}$ is the energy-momentum tensor and the parameter $\lambda = \pm 1$ is usually incorporated.

In this note, we will focus on the discrimination reach on the ADD models of gravity in large, compactified, extra spatial dimensions with respect to the four-fermion contact interactions inspired by compositeness, and *viceversa*, looking at the differential cross sections of fermion pair production at the ILC with longitudinally polarized beams [4, 5]. Also, we here discuss the benefits of longitudinal beams polarization in improving the identification reaches.

Neglecting all fermion masses with respect to the c.m. energy $\sqrt{s}$, the polarized differential cross section can expressed as follows:

$$\frac{d\sigma}{dz} = \frac{D}{4}\left[(1-P_{\rm eff})\left(\frac{d\sigma_{\rm LL}}{dz}+\frac{d\sigma_{\rm LR}}{dz}\right)+(1+P_{\rm eff})\left(\frac{d\sigma_{\rm RR}}{dz}+\frac{d\sigma_{\rm RL}}{dz}\right)\right]. \tag{4}$$

Here, $D = 1 - P_1P_2$, $P_{\rm eff} = (P_1 - P_2)/(1 - P_1P_2)$ and P_1 and P_2 the degrees of longitudinal polarization of the electron and positron beams, respectively, $z \equiv \cos\theta$ with θ the angle between the incoming electron and the outgoing fermion in the c.m. frame, and $d\sigma_{\alpha\beta}/dz$ are the helicity cross sections

$$\frac{d\sigma_{\alpha\beta}}{dz} = N_C\,\frac{3}{8}\,\sigma_{\rm pt}|\mathcal{M}_{\alpha\beta}|^2\,(1\pm z)^2. \tag{5}$$

Conventions are such that the subscripts α and β in the reduced helicity amplitudes $\mathcal{M}_{\alpha\beta}$ indicate the helicities of the initial and final fermions, respectively. The '+' sign applies to the configurations LL and RR, while the '−' sign applies to the LR and RL cases. Also, $\sigma_{\rm pt} = 4\pi\alpha^2_{\rm e.m.}/3s$, and the color factor $N_C \simeq 3(1+\alpha_s/\pi)$ is needed only in the case of quark-antiquark final states.

In the SM the helicity amplitudes, representing the familiar s-channel photon and Z exchanges, are given by $\mathcal{M}^{\rm SM}_{\alpha\beta} = Q_e Q_f + g^e_\alpha\, g^f_\beta\, \chi_Z$, where $\chi_Z = s/(s - M_Z^2 + iM_Z\Gamma_Z) \simeq s/(s-M_Z^2)$ for $\sqrt{s} \gg M_Z$; $g^f_{\rm L} = (I^f_{3L} - Q_f s^2_W)/s_W c_W$ and $g^f_{\rm R} = -Q_f s_W/c_W$ are the SM left- and right-handed fermion couplings to the Z, with $s^2_W = 1 - c^2_W \equiv \sin^2\theta_W$; Q_e and Q_f are the initial and final fermion electric charges. Rather generally, in the presence of non-standard interactions coming from the new, TeV-scale physics, the reduced helicity amplitudes can be expanded into the SM part plus a deviation depending on the considered NP model:

$$\mathcal{M}_{\alpha\beta} = \mathcal{M}^{\rm SM}_{\alpha\beta} + \Delta_{\alpha\beta}, \tag{6}$$

where the quantities $\Delta_{\alpha\beta} \equiv \Delta_{\alpha\beta}({\rm NP})$ represent the contribution of the new interaction. The typical examples relevant to our discussion are the following ones:

a) The ADD large extra dimensions scenario [6]:

$$\begin{aligned} \Delta_{\rm LL}({\rm ADD}) &= \Delta_{\rm RR}({\rm ADD}) = f_G(1-2z), \\ \Delta_{\rm LR}({\rm ADD}) &= \Delta_{\rm RL}({\rm ADD}) = -f_G(1+2z), \end{aligned} \tag{7}$$

where $f_G = \lambda\, s^2/(4\pi\alpha_{\rm e.m.}\Lambda^4_H)$, Λ_H being a phenomenological cut-off on the integration on the KK spectrum.

b) Gravity in TeV^{-1}–scale extra dimensions, where also the SM gauge bosons can propagate there, parameterized by the "compactification scale" M_C [7, 8]:

$$\Delta_{\alpha\beta}({\rm TeV}) = -\left(Q_e Q_f + g^e_\alpha\, g^f_\beta\right)\pi^2/(3\, M^2_C). \tag{8}$$

c) The four-fermion contact-interaction scenario (CI) [2] where, with $\Lambda_{\alpha\beta}$ the "compositeness" mass scales:

$$\Delta_{\alpha\beta}({\rm CI}) = \eta_{\alpha\beta}\, s\,/(\alpha_{\rm e.m.}\Lambda^2_{\alpha\beta}). \tag{9}$$

In cases *b)* and *c)* the deviations are z-independent, whereas in the case *a)* they introduce extra z-dependence in the angular distributions. Current experimental lower bounds on the mass scales M_H and M_C are reviewed, e.g., in Ref. [9] ($M_H > 1.1 - 1.3\,{\rm TeV}$, $M_C > 6.8\,{\rm TeV}$), while those on Λs, of the order of 10 TeV, are detailed in Ref. [10].

Let us assume one of the models, for example the ADD model (7), to be the "true" one, i.e., to be consistent with data for some value of Λ_H. To estimate the level at which it may be discriminated from other, in principle competing NP scenarios ("tested" models), for any values of the relevant mass parameters, say example one of the four-fermion CI models (9), we introduce relative deviations of the differential cross section from the ADD predictions due to the CI in each angular bin denoted as $\sigma^{\rm bin} \equiv \int_{\rm bin}({\rm d}\sigma/{\rm d}z){\rm d}z$, and a corresponding χ^2 function:

$$\Delta(\sigma^{\rm bin}) = \frac{\sigma^{\rm bin}({\rm CI}) - \sigma^{\rm bin}({\rm ADD})}{\sigma^{\rm bin}({\rm ADD})}, \qquad \chi^2(\sigma^{\rm bin}) = \sum_{\rm bins}\left(\frac{\Delta(\sigma^{\rm bin})}{\delta(\sigma^{\rm bin})}\right)^2 . \quad (10)$$

Here, $\delta(\sigma^{\rm bin})$ represents the expected relative uncertainty, which combines statistical and systematic ones, the former one being related to the ADD model prediction. Consequently, the χ^2 of Eq. (10) is a function of λ/Λ_H^4 and the considered η/Λ^2, and we can determine the "confusion" region in this parameter plane where also the corresponding CI model may be considered as consistent with the ADD predictions at the chosen confidence level, so that an unambiguous identification of ADD cannot be made. We choose $\chi^2 < 3.84$ for 95% C.L.

For the numerical analysis, we consider an ILC with $\sqrt{s} = 0.5\,{\rm TeV}$ and time-integrated luminosity $\mathcal{L}_{\rm int} = 100\,{\rm fb}^{-1}$ and $1000\,{\rm fb}^{-1}$; reconstruction efficiencies 95% for l^+l^-, 80% for $b\bar{b}$ and 60% for $c\bar{c}$. We divide the angular range, $|z| < 0.98$ in ten bins. To account for the major systematic uncertainties, we assume $\delta\mathcal{L}_{\rm int}/\mathcal{L}_{\rm int} = 0.5\%$, and $|P_1| = 0.8$ and $|P_2| = 0.6$ with $\delta P_1/P_1 = \delta P_2/P_2 = 0.2$ %. Specifically, we consider the two polarized cross sections with the configurations $(P_1, P_2) = (0.8, -0.6)$ and $(-0.8, 0.6)$, and combine them into the χ^2 also accounting for their mutual statistical correlations.

Fig. 1 shows as an example the "confusion region" between the ADD and the VV models, resulting from the process $e^+e^- \to l^+l^-$, with the above inputs and $\mathcal{L}_{\rm int} = 100\ {\rm fb}^{-1}$, both for unpolarized and polarized beams. In latter case we combine the cross sections with $(P_1, P_2) = (\pm 0.8, \mp 0.6)$. The figure shows that a maximal absolute value of the λ/Λ_H^4 (equivalently, a minimal value of Λ_H) can be found, for which the "tested" VV model hypothesis is expected to be excluded at the 95% C.L. for any value of the CI parameter η/Λ^2. We denote the corresponding ADD mass scale parameter as $\Lambda_H^{\rm VV}$ and call it "exclusion reach" of the VV model. The same procedure can be applied to all other types of

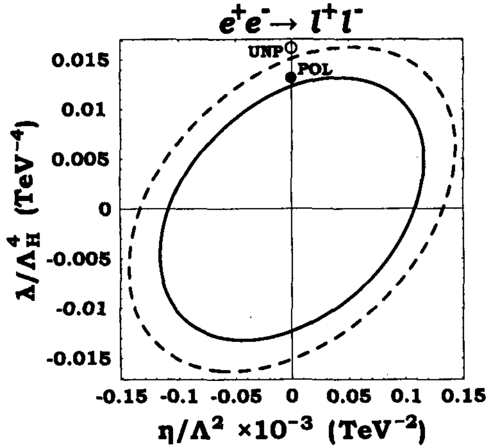

Figure 1: Confusion region (95% C.L.) for ADD and VV models from $e^+e^- \to l^+l^-$ at $\sqrt{s} = 0.5\,\text{TeV}$ and $\mathcal{L}_{\text{int}} = 100\ \text{fb}^{-1}$. Dashed (solid) curve corresponds to unpolarized (polarized) initial beams.

effective contact interaction models considered in Eqs. (9) and (8), and leads to the corresponding "exclusion reaches" Λ_H^{AA}, Λ_H^{RR}, Λ_H^{LL}, Λ_H^{LR}, Λ_H^{RL} and Λ_H^{TeV}. As the final step, the "identification reach" on the ADD scenario can be defined as the minimum of the Λ_H "exclusion reaches", $\Lambda_H^{\text{ID}} = min\{\Lambda_H^{VV}, \Lambda_H^{AA}, \Lambda_H^{RR}, \Lambda_H^{LL}, \Lambda_H^{LR}, \Lambda_H^{RL}, \Lambda_H^{TeV}\}$. Clearly, $\Lambda_H < \Lambda_H^{\text{ID}}$ allows to exclude *all* composite-like CI models as well as the TeV^{-1} gravity model. The results of this kind of analysis for all processes (2) with unpolarized beams as well as polarized beams, and the corresponding "identification reach" on Λ_H, are summarized in Tables 2 and 3.

Analogous χ^2-based procedure outlined above can be applied in turn to all individual processes, sources of the corrections in Eqs. (9) and (8), and distinction reaches on the relevant mass scale parameters can be obtained. One can notice, from Tables 2 and 3, the essential rôle of beam polarization in increasing the discrimination sensitivity on the different NP scenarios.

In conclusion, we have developed a specific approach based on the differential polarized cross sections to search for and identify various new physics scenarios which can be parametrized by effective dimension-6 and dimension-8 contact interactions with uniquely distinct signature.

Table 2: Identification reach (in TeV) on the mass scale parameters (95% C.L.) from the $e^+e^- \to l^+l^-$, $e^+e^- \to \bar{b}b$ and $e^+e^- \to \bar{c}c$ processes at $\sqrt{s} = 0.5$ TeV, $\mathcal{L}_{\text{int}} = 100\,\text{fb}^{-1}$ and the polarizations configurations $(|P_1|, |P_2|)$=(0,0); (0.8,0.6).

model	process		
	$e^+e^- \to l^+l^-$	$e^+e^- \to \bar{b}b$	$e^+e^- \to \bar{c}c$
ADD (Λ_H)	2.7; 2.8	3.0; 3.3	2.7; 3.0
VV (Λ)	57.6; 63.9	20.3; 82.7	56.3; 64.4
AA (Λ)	63.2; 70.2	20.4; 84.7	62.2; 75.5
LL (Λ)	— ; 56.0	— ; 62.2	— ; 59.0
RR (Λ)	— ; 58.0	— ; 61.1	— ; 59.9
LR (Λ)	— ; 57.5	— ; 49.0	— ; 46.9
RL (Λ)	— ; 58.3	— ; 56.2	— ; 53.1
TeV (M_C)	8.8; 14.4	4.5; 7.7	6.0; 8.3

Table 3: Identification reach (in TeV) on the mass scale parameters (95% C.L.) from the $e^+e^- \to l^+l^-$, $e^+e^- \to \bar{b}b$ and $e^+e^- \to \bar{c}c$ processes at $\sqrt{s} = 0.5$ TeV, $\mathcal{L}_{\text{int}} = 1000\,\text{fb}^{-1}$ and the polarizations configurations $(|P_1|, |P_2|)$=(0,0); (0.8,0.6).

model	process		
	$e^+e^- \to l^+l^-$	$e^+e^- \to \bar{b}b$	$e^+e^- \to \bar{c}c$
ADD (Λ_H)	3.2; 3.6	3.7; 4.2	3.2; 3.7
VV (Λ)	92.8; 105.0	26.4; 141.0	84.1; 98.1
AA (Λ)	96.7; 110.5	26.5; 138.7	102.6; 119.9
LL (Λ)	— ; 85.6	— ; 97.2	— ; 89.6
RR (Λ)	— ; 88.7	— ; 101.0	— ; 94.6
LR (Λ)	— ; 93.7	— ; 81.4	— ; 79.5
RL (Λ)	— ; 95.0	— ; 96.5	— ; 89.4
TeV (M_C)	14.3; 22.7	6.9; 12.6	8.8; 13.3

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