

Exploring New Physics Through Contact Interactions in Lepton Pair Production at a Linear Collider

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If a contact interaction type correction to a Standard Model process is observed, studying its detailed properties can provide information on the fundamental physics responsible for it. Assuming that such a correction has been observed in lepton pair production at a 500 GeV – 1 TeV linear collider, we consider a few possible models that could explain it, such as theories with large and TeV-scale extra dimensions and models with lepton compositeness. We show that using the measured cross-sections and angular distributions, these models can be distinguished with a high degree of confidence.

1. Introduction

All known solutions to the gauge hierarchy problem of the Standard Model (SM) require the appearance of new particles at energy scales around 1 TeV. It is not guaranteed, however, that these new particles can be produced directly at the proposed 500 GeV linear collider (LC). Only for supersymmetric theories are there strong arguments that at least some superpartners should be kinematically accessible at such a collider [1]. In the case of composite Higgs models and models with extra dimensions, the situation is far less certain. It is possible that all the new states predicted in these theories are too heavy and cannot appear in the final state at a 500 GeV LC. In fact, for models with large extra dimensions, current experimental constraints most likely rule out the possibility that string Regge excitations could be lighter than 500 GeV. In this case, the only direct effect of extra dimensions would be the enhanced rate of events with missing energy due to graviton emission. These events, however, provide only very limited amount of information about the fundamental theory. Moreover, this signature could be mimicked by gravitino emission processes in certain supersymmetric models, so one would need additional handles to disentangle the underlying physics [2]. In this situation, it is important to look for indirect effects of new physics, that is, the effects of new heavy particles appearing as virtual states. For example, processes such as Bhabha scattering or other lepton pair production,

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

could receive an additional contribution from the exchange of a heavy state X . Because such additional contributions come from short-distance physics and do not possess poles in the accessible range of any kinematic variables, they are referred to as *contact interactions*. By carefully examining the total cross section and angular distribution of these processes, it should be possible to not only find deviations from the Standard Model, but also gain some information about the nature of the state X , such as its spin and couplings.

In this report, we will assume that the cross section of process (1) was found to deviate from the Standard Model prediction. We will then consider several possible explanations for this deviation, such as models with lepton substructure, models with TeV-scale strings, and models in which gauge fields can propagate in the extra dimensions. Our main goal is to determine how well one can discriminate between these possibilities, given the measurement of the total cross section and angular distributions of the final-state particles.

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2. Models with Contact Interactions

The unpolarised cross section formula for Bhabha scattering can be written in the form

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s} \left[u^2(|A_{LL}|^2 + |A_{RR}|^2) + 2t^2|A_{RL,s}|^2 + 2s^2|A_{RL,t}|^2 \right], \quad (2)$$

where

$$\begin{aligned} A_{LL} &= \frac{1}{s} + \frac{1}{t} + \frac{(\frac{1}{2} - \sin^2\theta_W)^2}{\sin^2\theta_W \cos^2\theta_W} \left(\frac{1}{s - M_Z^2} + \frac{1}{t - M_Z^2} \right) + \Delta_{LL}, \\ A_{RR} &= \frac{1}{s} + \frac{1}{t} + \frac{\sin^2\theta_W}{\cos^2\theta_W} \left(\frac{1}{s - M_Z^2} + \frac{1}{t - M_Z^2} \right) + \Delta_{RR}, \\ A_{RL,s} &= \frac{1}{s} - \frac{(\frac{1}{2} - \sin^2\theta_W)}{\cos^2\theta_W} \frac{1}{s - M_Z^2} + \Delta_{RL,s}, \\ A_{RL,t} &= \frac{1}{t} - \frac{(\frac{1}{2} - \sin^2\theta_W)}{\cos^2\theta_W} \frac{1}{t - M_Z^2} + \Delta_{RL,t}, \end{aligned} \quad (3)$$

and the Δ_a functions represent the contact interaction corrections coming from TeV-scale physics. For this study we have considered the following models:

Models with composite leptons [3], where the contact interaction terms are given by

$$\Delta_{LL} = 2 \frac{\eta_{LL}}{\alpha\Lambda^2}, \quad \Delta_{RR} = 2 \frac{\eta_{RR}}{\alpha\Lambda^2}, \quad \Delta_{RL,s} = \Delta_{RL,t} = \frac{\eta_{RL}}{\alpha\Lambda^2}. \quad (4)$$

Here $\eta_a = \{+1, 0, -1\}$ parametrise the helicity structure of the contact interactions, and Λ is the scale of compositeness. We will study two possibilities:

(VV) the vector-vector model with $\eta_{LL} = \eta_{RR} = \eta_{RL} = +1$,

(AA) the axial-axial model with $\eta_{LL} = \eta_{RR} = -\eta_{RL} = +1$.

Models with large extra dimensions have two sources from which contact interactions may arise. The first contribution is from the virtual effect of string Regge excitations of the photon and the Z boson. This has been computed in [4] using a simple string toy model. The corrected Bhabha scattering cross section is given by

$$\frac{d\sigma}{d\cos\theta}(e^+e^- \rightarrow e^+e^-) = \frac{d\sigma}{d\cos\theta} \Big|_{SM} \times \left(1 - \frac{\pi^2}{3} \frac{st}{M_s^4} + \dots \right), \quad (5)$$

where M_s is the string scale. The second contribution comes from virtual graviton exchange, and was analysed in [5, 6, 7]. This effect could be sizable because of the large number of Kaluza-Klein (KK) modes of the graviton that contribute. The Δ_a functions in this case are given by

$$\begin{aligned} \Delta_{LL} = \Delta_{RR} &= \frac{\lambda}{\pi\alpha M_H^4} \left[\left(u + \frac{3}{4}s\right) + \left(u + \frac{3}{4}t\right) \right], \\ \Delta_{RL,s} &= -\frac{\lambda}{\pi\alpha M_H^4} \left(t + \frac{3}{4}s\right), \quad \Delta_{RL,t} = -\frac{\lambda}{\pi\alpha M_H^4} \left(s + \frac{3}{4}t\right), \end{aligned} \quad (6)$$

where M_H is the quantum gravity scale as defined in [6]. Here we will study two models:

(SR) The String Regge model, where the contribution of the Regge states is dominant, as is necessarily the case if physics at the TeV scale is described by weakly coupled string theory.

(KK+, KK-) The KK graviton model with $\lambda = +1$ or -1 , where we assume that the Regge contribution is for some reason suppressed, and the virtual graviton exchange dominates.

Models with TeV-scale extra dimensions (TeV) may allow the Standard Model gauge bosons to propagate in the additional dimensions. In these models, contact interactions arise from the

exchange of virtual KK excitations of the photon and the Z boson. Using the formalism of [8], we obtain

$$\begin{aligned}\Delta_{LL} &= -\frac{1}{2} \frac{1}{\cos^2 \theta_W \sin^2 \theta_W} \frac{V}{M_W^2}, & \Delta_{RR} &= -2 \frac{1}{\cos^2 \theta_W} \frac{V}{M_W^2}, \\ \Delta_{RL,s} &= \Delta_{RL,t} = -\frac{1}{2} \frac{1}{\cos^2 \theta_W} \frac{V}{M_W^2},\end{aligned}\quad (7)$$

where in the case of one extra dimension V is directly related to the compactification scale M_c :

$$V = \frac{\pi^2}{3} \frac{M_W^2}{M_c^2}. \quad (8)$$

For more than one extra dimension, the relation between V and M_c depends on the details of the TeV-scale physics, and it is more useful to work in terms of V itself. In this study we give all results in terms of M_c .

Analogous formulas can be obtained for $\mu^+\mu^-$ and $\tau^+\tau^-$ final states. Since phenomenology of string models with multiple generations has not been studied in detail, we will not consider the effects of Regge states in these channels.

3. Analysis

The theoretical formulas (2) – (7) have been implemented in PANDORA [9] to scan the scale parameters of our models (referred to as VV, AA, SR, KK+, KK– and TeV in the following). At each scan point the angular distribution of the produced leptons is studied calculating the expected number of events in 10 bins of $\cos \theta$, with a cut of $|\cos \theta| < 0.9$ imposed on the outgoing electron polar angle in the case of Bhabha scattering. The ratio of the predicted new physics cross-section to the SM cross-section for electron and muon pair production is shown in Figure 1 for all the models considered at a 500 GeV LC.

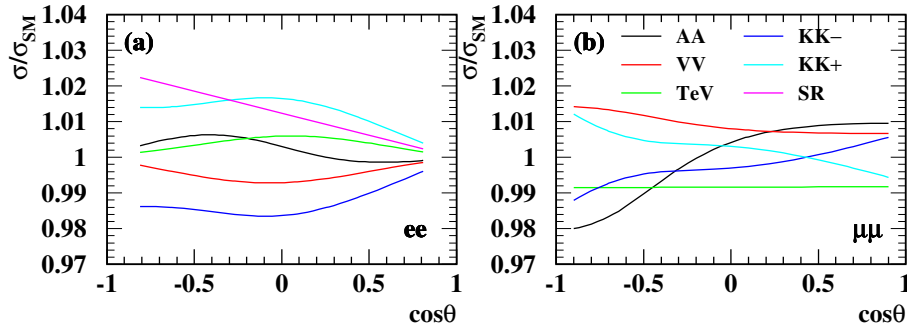


Figure 1: Ratio of the predicted new physics cross-section to the SM cross-section for (a) electron and (b) muon pair production as a function of the lepton polar angle for the models AA ($\Lambda=70$ TeV), VV ($\Lambda=84$ TeV), TeV ($M_c=14$ TeV), KK+ ($M_H=3.4$ TeV), KK– ($M_H=3.4$ TeV) and SR ($M_s=1.7$ TeV) at a 500 GeV LC. The scale parameters have been chosen to be at the sensitivity reach with 100 fb^{-1} integrated luminosity.

For each considered model and parameter value 100–1000 Monte Carlo (MC) experiments are generated using Poisson statistics. These are in turn compared to all theoretical models (including SM) by calculating the χ^2 of the MC and the predicted theoretical distributions, accounting for a fully correlated systematic error of 2% as well. (We will use the term *true model* for the model which is assumed to be true, ie. which was used to generate the MC experiments.) We define the confidence level (CL) at which a model with a given parameter can be excluded by the ratio of its χ^2 probability to the highest χ^2 probability for any model with any parameter considered:

$$1 - CL = \mathcal{P}(\chi^2) / \max(\mathcal{P}(\chi^2)) \quad (9)$$

The expected CL is computed as the median value for all the MC experiments generated with the same model and parameter value.

4. Results

For each new physics model considered, we have calculated the maximum value of the scale parameter for which the Standard Model hypothesis is expected to be excluded at the 95% CL. We list these limits, for three sample values of the LC energy and luminosity, in Table I. The corresponding limits for the exclusion of *all* models but the true one are inevitably somewhat lower, as shown in the Table II. This effect is more pronounced when only one channel is analysed, as is necessarily the case for the SR model where at present theoretical calculations only exist for Bhabha scattering. In most cases, however, combining all the channels allows one to distinguish between the theoretical models almost up to the SM sensitivity reach of Table I, with the model selection sensitivity reach of Table II being only about 5-15% lower. In Figure 2 we plot $1 - CL$ corresponding to the best fit for each tested model in the electron pair final state as a function of the scale parameter of the true model for the case of a 500 GeV LC with 100 fb^{-1} luminosity.

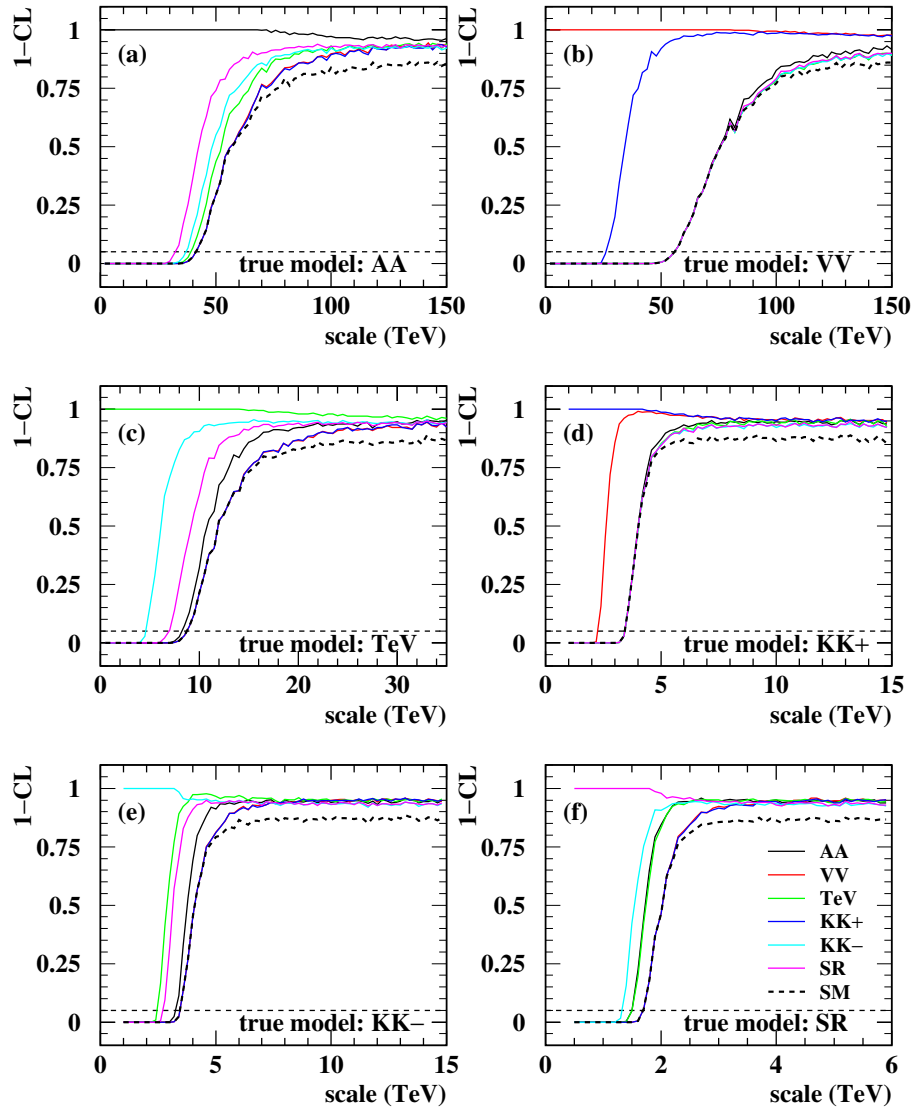


Figure 2: Best expected $1 - CL$ for each tested model, using the electron pair final state only, as a function of the scale parameter of the true model (a) AA, (b) VV, (c) TeV, (d) KK^+ (e) KK^- and (f) SR at a 500 GeV LC with an integrated luminosity of $\mathcal{L} = 100 \text{ fb}^{-1}$.

Measurements of electron, muon and tau final states provide complementary information, and combining them significantly improves model selection sensitivity. This is illustrated by Figure 3, which shows the $1 - CL$ values as a function of the model scale parameter with the assumption that

Table I Highest scale parameter values of the true model for which the SM hypothesis is expected to be excluded at the 95% CL for different LC energies and luminosities. The first numbers correspond to the results using all final states and the second using only electron pairs.

true model	scale parameter (TeV)		
	$\sqrt{s}=500$ GeV $\mathcal{L}=100 \text{ fb}^{-1}$	$\sqrt{s}=500$ GeV $\mathcal{L}=500 \text{ fb}^{-1}$	$\sqrt{s}=1$ TeV $\mathcal{L}=500 \text{ fb}^{-1}$
AA (Λ)	71 / 41	105 / 61	149 / 86
VV (Λ)	85 / 56	128 / 83	178 / 118
TeV (M_c)	14 / 8.5	21 / 13	29 / 18.5
KK+ (M_H)	3.4 / 3.4	4.1 / 4.1	7.1 / 7.0
KK- (M_H)	3.4 / 3.4	4.2 / 4.2	7.1 / 7.1
SR (M_s)	- / 1.7	- / 2.1	- / 3.5

Table II Highest scale parameter values of the true model for which all other model hypotheses are expected to be excluded at the 95% CL for different LC energies and luminosities. The first numbers correspond to the results using all final states and the second using only electron pairs. The second best model is given in the last column.

true model	scale parameter (TeV)			
	$\sqrt{s}=500$ GeV $\mathcal{L}=100 \text{ fb}^{-1}$	$\sqrt{s}=500$ GeV $\mathcal{L}=500 \text{ fb}^{-1}$	$\sqrt{s}=1$ TeV $\mathcal{L}=500 \text{ fb}^{-1}$	second best model
AA (Λ)	68 / 32	101 / 48	142 / 70	KK+ / SR
VV (Λ)	74 / 26	111 / 37	157 / 54	KK+
TeV (M_c)	12 / 4.2	18 / 6.5	25.5 / 9.5	KK-
KK+ (M_H)	3.2 / 2.3	3.9 / 2.7	6.7 / 4.8	VV
KK- (M_H)	3.2 / 2.4	3.9 / 3.0	6.6 / 5.1	TeV
SR (M_s)	- / 1.3	- / 1.6	- / 2.7	KK-

model KK- is realized with $M_H=3$ TeV. While separately none of the measurements can exclude the other models, together they do so with a high confidence level. Note that the sharp peak in $1 - CL$ for the true model at the true parameter value indicates that not only the model can be recognised, but the value of its scale parameter can be estimated with a reasonable precision. Of course, this measurement becomes less precise for higher values of the scale parameter.

5. Conclusions

Many models of physics beyond the Standard Model predict new particles at the TeV scale. Even if the collider energy is not sufficient to produce these particles directly, their virtual exchanges can still lead to observable effects, such as contact-interaction type corrections to Standard Model processes. If such a correction is observed, studying it carefully can provide important information about the physics at and above the TeV scale. In this study, we have considered a few well-motivated theoretical models which predict contact interaction corrections to lepton pair production processes. We have shown that for a wide range of model parameters, measuring lepton pair production cross-sections and angular distributions at a 500 GeV – 1 TeV linear collider with realistic integrated luminosities will allow to unambiguously determine which of the candidate models is correct. In fact, we find that whenever a significant deviation from the Standard Model is seen, the model selection can be performed with a high degree of certainty. Combining the measurements with electron, muon and tau final states is crucial for model selection.

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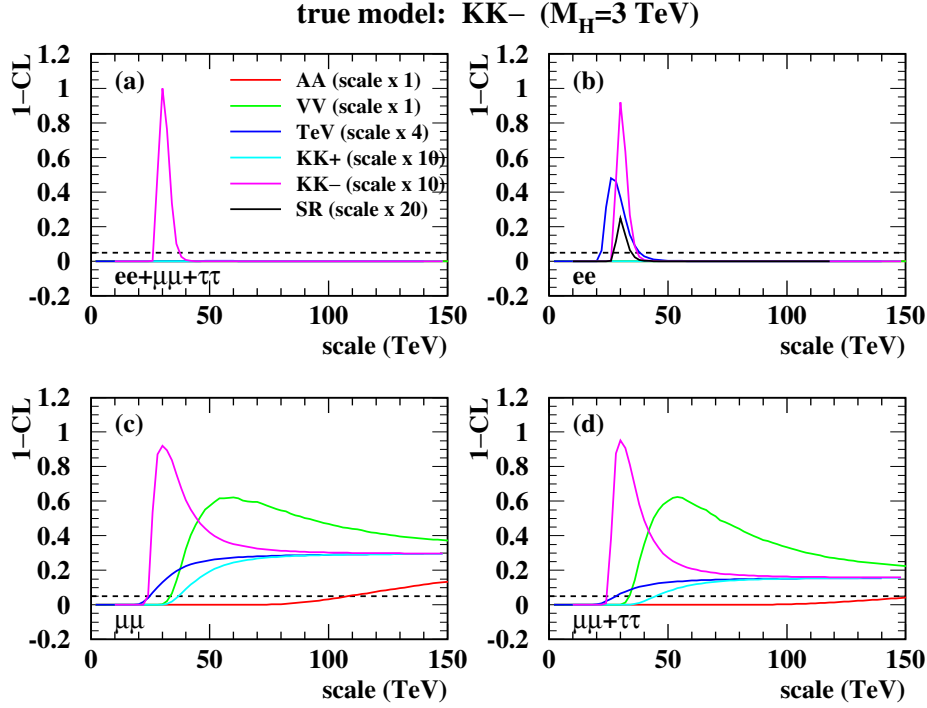


Figure 3: Expected $1 - CL$ as a function of the scale parameter of the tested model using (a) all three cross-section measurements, (b) the electron pair, (c) the muon pair and (d) the muon and tau pair measurements at a 500 GeV LC with an integrated luminosity of $\mathcal{L} = 100 \text{ fb}^{-1}$. The true model assumed is KK⁻ with $M_H=3$ TeV. Note that for better visibility the scale parameters have been multiplied by 1–20 as indicated in the figure.

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