LC–TH–2001–007
February 21, 2001

Fermion-Pair Production at a Linear Collider – A Sensitive Tool for New Physics Searches

Sabine Riemann
DESY Zeuthen
Platanenallee 6, D-15738 Zeuthen, Germany

Abstract

Indications of new physics phenomena in fermion-pair production are tested for a linear collider. A general approach in terms of contact interactions is discussed as well as the influence of leptoquark exchange, Z' exchange and extra spatial dimensions. The rôle of electron and positron polarization is considered, systematic errors are taken into account.

1 Introduction

Since the discovery of neutral currents the Standard Model has been confirmed with an excellent accuracy exploiting the e^+e^- annihilation up to 210 GeV; on the Z resonance cross sections and asymmetries are measured with a precision of a few 0.1% [1]. The validity of the Standard Model has been verified at the one-loop level of electroweak corrections, partially up to leading terms of two-loop corrections. Despite this impressive result there is some doubt that the Standard Model could be the final answer questing the source of the existing world of particles. The search for signals from new interactions and particles remains one of the main tasks in all experiments of elementary particle physics. Although the study of the process $e^+e^- \to f\bar{f}$ is not primarily devoted to the search for new phenomena, it guarantees a good sensitivity to deviations from the Standard Model expectations. The clear signature of the final states in the detector as well as the relatively high statistics of these processes allow measurements of cross sections and asymmetries down to the percent level and better. If new physics beyond the Standard Model exists it could be found with fermion-pair production at e^+e^- colliders operating far below the production threshold of new particles.

In this note the rôle of fermion-pair production at a linear collider working between 500 GeV and 1 TeV is studied regarding the possibility to obtain new physics or to find hints for potential sources of deviations from the Standard Model and symmetry breaking.

In particular, the sensitivity of this process is discussed for phenomena like four-fermion contact interactions as a general case, for new neutral gauge bosons, for leptoquarks, R-parity violationg scalar particles and extra spatial dimensions. It will be shown how polarization of at least one beam helps to disentangle sources of new physics. If new physics exists at the TeV scale new particles will be discovered with LHC. These potential LHC results are taken into account to study some aspects of the new phenomena. It will be shown that the indirect searches with fermion-pair production and the direct searches at LHC are complementary.

2 Measurements of $f\bar{f}$ final states

2.1 Observables

In general, Standard Model processes can be fully described and parametrized by helicity amplitudes:

$$\frac{d\sigma}{d\cos\theta} = \sum_{i,j=\mathrm{L,R}} \rho_{i,j}|\mathcal{A}_{i,j}|^2 \tag{1}$$

with

$$\mathcal{A}^{ef}_{i,k} = \left(Q_e Q_f + C^e_i C^f_k \chi\right)\frac{t}{s}; \quad i,k = \mathrm{L,R}; \quad i \neq k,$$

$$\mathcal{A}^{ef}_{i,i} = \left(Q_e Q_f + C^e_i C^f_i \chi\right)\frac{u}{s}; \quad i = \mathrm{L},\mathrm{R} \tag{2}$$

and

$$\begin{aligned} \chi(s) &= \frac{s}{s - m_\mathrm{Z}^2 + is\Gamma_\mathrm{Z}/m_\mathrm{Z}}; \quad \chi(t) = \frac{t}{t - m_\mathrm{Z}^2}, \\ C^f_\mathrm{L} &= v_f + a_f, \quad C^f_\mathrm{R} = v_f - a_f. \end{aligned}$$

s, t and u are the Mandelstam variables, $t = -s/2(1 - \cos\theta)$ and $u = -s/2(1 + \cos\theta)$, Q_f is the electrical charge of the fermion and C^f_L, C^f_R are the left- and right-handed couplings of the Z to fermions. An interaction with vector and axialvector couplings is fully specified measuring the following observables: total cross section, σ_{tot}, forward-backward asymmetry, $A_{FB} = (\sigma_F - \sigma_B)/\sigma_{tot}$, the left-right asymmetry, $A_{LR} = (\sigma_L - \sigma_R)/\sigma_{tot}$ and the polarisation asymmetry, $A^{pol}_{FB} = [(\sigma_L - \sigma_R)_F - (\sigma_L - \sigma_R)_B]/\sigma_{tot}$. With $\sigma_{i,j} \propto |\mathcal{A}^{ef}_{i,j}|^2$ the observables are built by the relations:

$$\begin{aligned} \sigma_{tot} &= \sigma_\mathrm{LL} + \sigma_\mathrm{LR} + \sigma_\mathrm{RR} + \sigma_\mathrm{RL} \\ \sigma_{FB} &= \sigma_\mathrm{LL} - \sigma_\mathrm{LR} + \sigma_\mathrm{RR} - \sigma_\mathrm{RL} \\ \sigma_{LR} &= \sigma_\mathrm{LL} + \sigma_\mathrm{LR} - \sigma_\mathrm{RR} - \sigma_\mathrm{RL} \\ \sigma^{pol}_{LR} &= \sigma_\mathrm{LL} - \sigma_\mathrm{LR} - \sigma_\mathrm{RR} + \sigma_\mathrm{RL} \end{aligned} \tag{3}$$

Equations (3) define a system that allows to determine the helicity amplitudes.

If new interactions contribute to s-, t- or u-channel exchange, the helicity amplitudes are modified. The corresponding formulae are given in the following sections. A more complicated situation arises in case of extra spatial dimensions. The effective interactions of spin-2 gravitons with the standard particles distort the angular dependence on $(1 \pm \cos^2\theta)$ in (2) (see also [2]).

In general, new physics interactions (NP) in the process

$$e^+e^- \to \gamma, Z, NP \to f\bar{f} \tag{4}$$

are described by

$$\frac{d\sigma}{d\cos\theta} = \frac{d\sigma^\mathrm{SM}}{d\cos\theta} + \frac{d(\sigma^\mathrm{SM} \otimes \sigma^\mathrm{NP})}{d\cos\theta} + \frac{d\sigma^\mathrm{NP}}{d\cos\theta}. \tag{5}$$

2.2 Cuts and Uncertainties

2.2.1 QED corrections

The measurements of cross sections and asymmetries or alternatively, the measurements of differential cross sections can be analyzed in a combined fit to search indirectly for new physics.

For the analyses the QED corrections are unfolded,

$$\sigma(s) = \int \sigma^{Born}(s', s) R(s') dv, \tag{6}$$

where $R(s')$ is the radiation function and new physics contributions are taken into account in σ^{Born}.

In order to increase the sensitivity to new phenomena one has to avoid the radiative return to the Z peak; the rediative tail enhances the cross section dramatically. Hence, the signals from new physics which are expected to be small are diluted completely. A cut on $s' = (1-\Delta)s$,

$$\Delta = \frac{E_\gamma}{E_{beam}} < 1 - \frac{m_{Z^2}}{s}, \tag{7}$$

ensures that only 'pure' high energy events are included into the analysis. For the energies of a TESLA collider a cut of $\Delta = 0.6$ is applied.

2.2.2 Polarization

With polarized beams a very effective study of Standard Model and new physics processes becomes possible. Different mechanisms can be switched on or off, so that the background rates can be reduced (or studied) or new particles and interactions can be disentangled. In fermion-pair production polarized electrons couple to chirally flipped positrons, hence, the total cross section is affected only by the statistical weight. With both electrons and positrons polarized the total annihilation cross section can be increased up to a factor 2, $\sigma_{e^+,e^-} = 2 \times \sigma_{unpol} = 2 \times \sigma_{e^-}$. It will be shown in the following sections that polarization will increase the sensitivity to new interactions and will help to distinguish between models.

For the TESLA collider an electron polarization of $P_{e^-} = 0.8$ is foreseen. If both electrons and positrons are polarized, it is convenient to introduce a generalized polarization,

$$P = \frac{-P_{e^-} + P_{e^+}}{1 - P_{e^+}P_{e^-}}. \tag{8}$$

The corresponding error of P is given by error propagation and smaller than the error of the separate polarisation measurements, δP_{e^-} and δP_{e^+}. With P_{e^+}=60% (40%) and P_{e^-}=80% a generalized polarization of 95% (91%) is reached. Simultaneously, the uncertainties of the polarisation measurements, i.e. $\delta P_{e^-}/P_{e^-} = \delta P_{e^+}/P_{e^+}$=0.5%, are reduced to the common polarization error of $\delta P/P$=0.13% (20%). The accuracy of the polarization measurement is important for the uncertainty of A_{LR}:

$$\begin{aligned} \Delta A_{LR} &= \sqrt{(\Delta_{stat}A_{LR})^2 + (\Delta_{syst}A_{LR})^2} && (9) \\ &= \sqrt{\frac{1 - P^2 A_{LR}^2}{NP^2} + A_{LR}^2(\frac{\Delta P}{P})^2} && (10) \end{aligned}$$

It is easy to see that the accuracy of polarization measurement could dominate the error of A_{LR}. With positron polarization the influence of this systematic error can be substantially reduced.

2.2.3 Estimation of Uncertainties

Whereas the lepton-pairs can be easily identified in the detector, hadronic final states have to be separated from the large W^+W^- background. With right-handed electrons and left-handed positrons the W^+W^- production can be supressed substantially.

Starting with the experience of LEP and the studies of [3, 4, 5] the following parameters and errors are assumed to study the sensitivity to new physics:

- $\sqrt{s} = 0.5$ TeV, 0.8 TeV, 1 TeV
- $\mathcal{L}_{int}$ =1 ab^{-1}, $\Delta\mathcal{L}/\mathcal{L} = 0.5\%$, 0.2%
- ee $\rightarrow \mu\mu$:
  selection efficiency: $\epsilon = 0.95$
  $\Delta sys = \Delta\epsilon^{\mu}/\epsilon^{\mu} = 0.5\%$, 0.2% (0.1%)
- ee $\rightarrow$ *hadrons* (light quarks):
  selection efficiency: $\epsilon = 0.90$
  $\Delta sys = \Delta\epsilon^{had}/\epsilon^{had} = 0.5\%$; 0.02% (0.1%)
- ee $\rightarrow$ bb:
  selection efficiency: $\epsilon = 0.60$
  $\Delta sys = \Delta\epsilon^{b}/\epsilon^{b} = 1.0\%$; 0.5%
- ee $\rightarrow$ cc:
  selection efficiency: $\epsilon = 0.40$
  $\Delta sys = \Delta\epsilon^{c}/\epsilon^{c} = 1.5\%$; 1%
- fiducial volume:
  leptons, hadrons: $|\cos\theta| < 0.98$
  flavour tagging: $\cos\theta < 0.9$

The studies were done for electron polarization of $P_{e^-} = 80\%$. Positron polarization is taken as 0% and 60% (40%). The error of the polarization measurement is varied: $\delta P_{e^-}/P_{e^-} = \delta P_{e^+}/P_{e^+}$ =1.0%, 0.5% (0%).

Due to the high luminosity the indirect search limits are restricted by the systematic errors. Therefore, in some of the results also the limits are given for the unrealistic case without systematic errors.

2.2.4 Scaling Law

New interactions are probed by performing a combined χ^2-fit to all observables taking into account statistical and systematic uncertainties and potential correlations.

The sensitivity to new physics is dominated by the interference of Standard and new physics contributions and depends on the uncertainty $\Delta\sigma_i$ of the measurements,

$$\chi^2 = \frac{[\sigma_i(SM) - \sigma_i(SM+NP)]^2}{\Delta\sigma_i^2} < \chi^2_{min} + \Delta\chi^2, \tag{11}$$

σ_i are the measured observables. This allows to estimate the scaling of the sensitivity to new physics with the center-of-mass energy and with the luminosity. Taking into account only the statistical errors the sensitivity scales with

$$\frac{m_X}{g_X} \propto \sqrt{\Delta_{stat}\sigma} \propto (L_{int} \cdot s)^{1/4}. \tag{12}$$

If systematic errors are not negligable this behavior is changed:

$$\Delta_{stat}\sigma \to \Delta_{stat}\sigma\sqrt{1 + \Delta^2_{sys}\sigma/\Delta^2_{stat}\sigma} \tag{13}$$

Further, the combination of all available observables will increase the sensitivity. But it is very difficult to estimate this influence because different observables show different sensitivities to the special models of new interactions and depend on top of that on the final state. An example for the sensitivity of observables to Z′ models for different final states can be found in [6].

3 Sensitivity to Contact Interactions

Fermion compositeness or exchange of very heavy new particles can be described in general by four-fermion contact interactions [7],

$$\mathcal{L}_{CI} = \sum_{i,j=\mathrm{L,R}} \eta_{ij} \frac{g^2}{\Lambda^2_{ij}} (\bar{\mathrm{e}}_i \gamma^\mu \mathrm{e}_i)(\bar{f}_j \gamma^\mu f_j). \tag{14}$$

The strength of interaction is by convention $g^2/4\pi = 1$ and models are considered by choosing $|\eta_{ij}| = 1$ or $|\eta_{ij}| = 0$. Table 1 gives an overview about the models considered here. The helicity amplitudes in Eq.(2) are modified;

$$\begin{aligned}
\mathcal{A}^{ef}_{i,k} &= \left(Q_e Q_f + C^e_i C^f_k \chi + \eta_{i,k} \frac{s}{\alpha} \frac{1}{\Lambda^2}\right) \frac{t}{s}; \quad i,k = \mathrm{L,R}; \quad i \neq k, \\
\mathcal{A}^{ef}_{i,i} &= \left(Q_e Q_f + C^e_i C^f_i \chi + \eta_{i,i} \frac{s}{\alpha} \frac{1}{\Lambda^2}\right) \frac{u}{s}; \quad i = \mathrm{L,R}
\end{aligned} \tag{15}$$

The contact scale Λ can be interpreted as effect of new physics like new gauge bosons, leptoquarks, scalar quarks etc. and resolved by

$$\frac{1}{\Lambda^2} \propto \frac{g^2}{m_X^2}. \tag{16}$$

Model	$\eta_{\rm LL}$	$\eta_{\rm RR}$	$\eta_{\rm LR}$	$\eta_{\rm RL}$
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
V0	±1	±1	0	0
A0	0	0	±1	±1

Table 1: Models of contact interaction.

Different error scenarios are assumed to study the sensitivity reach for contact interactions in $\mu^+\mu^-$, $b\bar{b}$, $c\bar{c}$ and hadronic final states. Assuming an integrated luminosity of 1 ab^{-1} at 500 GeV, the search reaches are shown in Figures 1 and 2. Considering hadronic final states it is assumed that contact interactions contribute with the same strength to all quarks ($e^+e^- \rightarrow q\bar{q}$) or alternatively, only to one flavour, ($e^+e^- \rightarrow u\bar{u}, d\bar{d}$). The case that all systematic errors are assumed to be zero demonstrates an upper limit of search reaches with the considered scenarios.

4 Sensitivity to Leptoquarks

The kinematical limit of direct searches for leptoquarks of first generation is $m_{LQ} < \sqrt{s}/2$ for leptoquark pair production [8] and nearly $m_{LQ} \approx \sqrt{s}$ for single leptoquark production [9]. For $m_{LQ} > \sqrt{s}$ leptoquarks could show up by their virtual exchange in t- or u-channel in $q\bar{q}$ production [10]. Hence, the measurements of hadronic final states are sensitive to $g_{L,R}/m_{LQ}$ and limits on leptoquark masses in dependence on their couplings can be derived. These indirect searches extend the sensitivity reaches up to a multiple of the centre-of-mass energy. In Table 2 the limits (95% C.L.) of indirect leptoquark searches at $\sqrt{s} = 500$ GeV are summarized assuming electromagnetic coupling strength, $g_{L,R} = \sqrt{4\pi\alpha}$. An integrated luminosity of $\mathcal{L} =$ 1 ab^{-1}, $P_{e^+} = 0.4$ and the following error scenarios are assumed:

- (A) $\Delta\mathcal{L}/\mathcal{L} = 0.5\%$, $\Delta P_{e^+}/P_{e^+} = \Delta P_{e^-}/P_{e^-}$=1.0%, $\Delta^{had}_{sys} = 0.5\%$;
- (B) $\Delta\mathcal{L}/\mathcal{L} = 0.5\%$, $\Delta P_{e^+}/P_{e^+} = \Delta P_{e^-}/P_{e^-}$=0.5%, $\Delta^{had}_{sys} = 0.5\%$;
- (C) $\Delta\mathcal{L}/\mathcal{L} = 0.2\%$, $\Delta P_{e^+}/P_{e^+} = \Delta P_{e^-}/P_{e^-}$=0.5%, $\Delta^{had}_{sys} = 0.1\%$:

Furthermore, limits on Yukawa couplings of leptoquarks depending on the mass can be derived. The expected sensitivities are shown in Figure 3 for error scenario B.

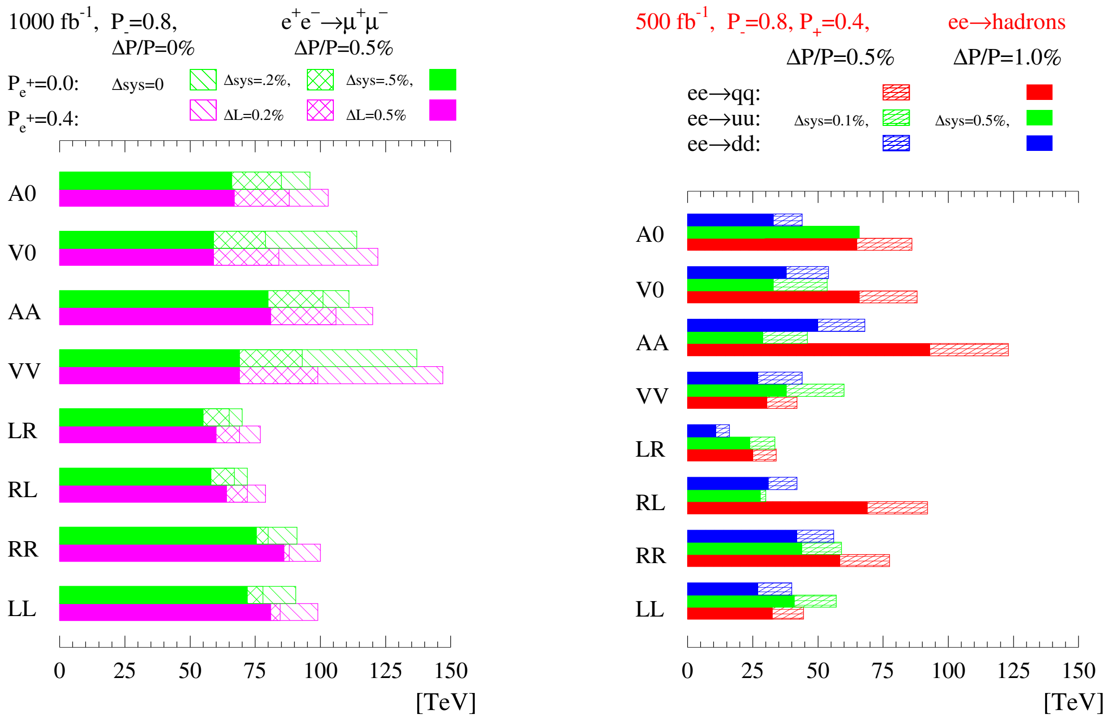

Figure 1: Expected sensitity reaches for contact interactions (95% C.L.) for $\sqrt{s}$ = 500 GeV based on $\mu^+\mu^-$ and $q\bar{q}$ final states.

errors	S_0(L)	S_0(R)	$\tilde{S}_0$(R)	$S_{1/2}$(L)	$S_{1/2}$(R)	$\tilde{S}_{1/2}$(L)	S_1(L)
A	2.44	2.63	2.55	1.45	2.29	0.23	1.47
B	3.20	3.49	3.40	1.89	3.04	0.26	1.82
C	3.40	3.57	3.42	2.02	3.07	0.28	2.23
	V_0(L)	V_0(R)	$\tilde{V}_0$(R)	$V_{1/2}$(L)	$V_{1/2}$(R)	$\tilde{V}_{1/2}$(L)	V_1(L)
A	2.25	3.59	3.78	1.23	0.68	0.47	4.47
B	2.80	4.79	4.98	1.45	0.69	0.48	5.86
C	3.42	4.82	5.10	1.72	0.69	0.48	6.06

Table 2: Indirect leptoquark search reaches (95% C.L.) assuming $g_{L,R} = \sqrt{4\pi\alpha}$. The process $e^+e^- \to$ hadrons at $\sqrt{s}$ = 500 GeV is considered. The error scenarios A,B,C are explained in the text.

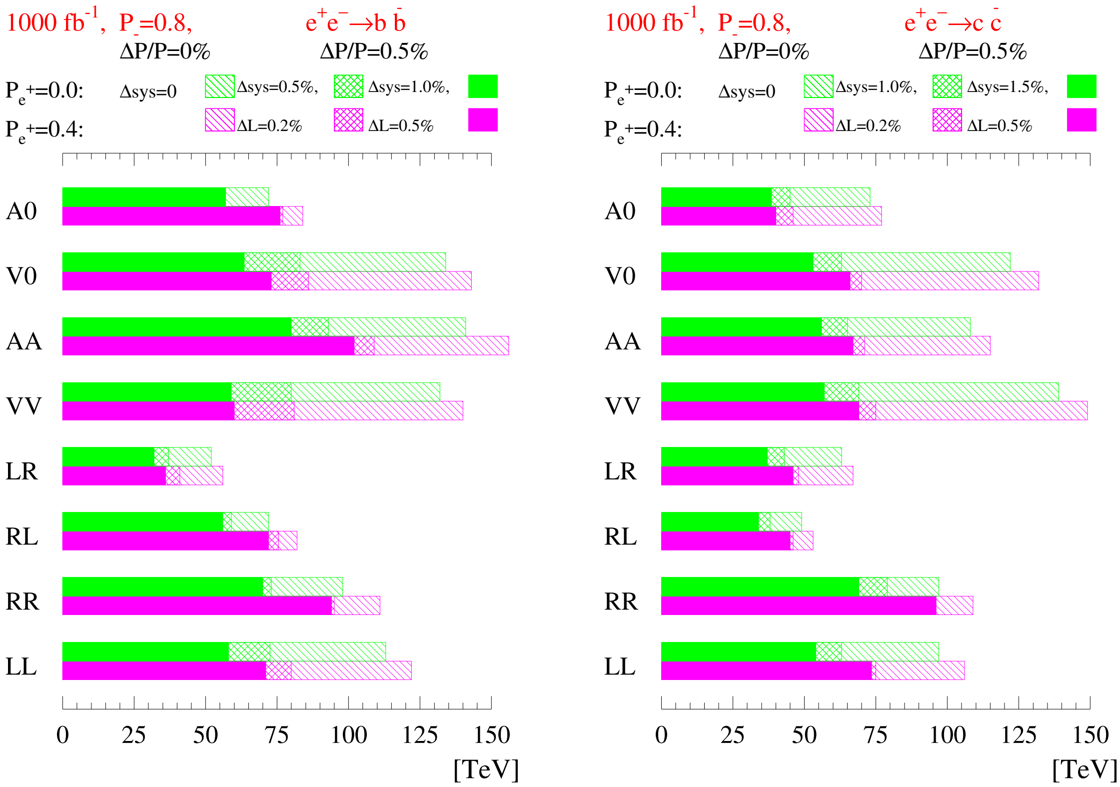

Figure 2: Expected sensitity reaches for contact interactions (95% C.L.) for $\sqrt{s}$ = 500 GeV based on $b\bar{b}$ and $c\bar{c}$ final states.

It should be remarked that the leptoquarks $\tilde{S}_{1/2}$ and $\tilde{V}_{1/2}$ interfere with the helicity amplitudes that are suppressed in the SM. Hence, the sensitivity of indirect searches to these leptoquarks is small.

Similar to the virtual effects of leptoquarks also R-parity violating scalar quarks can be exchanged in the t- or u-channel [10] in the process $e^+e^- \to$ hadrons. The most general supersymmetric ansatz contains R-parity violation in the trilinear couplings of the superfield,

$$W = \lambda'_{ijk} L^i_{\mathrm{L}} Q^j_{\mathrm{L}} \bar{D}^k_{\mathrm{R}}. \tag{17}$$

Left-handed up-type quarks couple like $\tilde{S}_{1/2}$ leptoquarks and right-handed down-type quarks couple like S_0 with left-handed couplings. Hence, limits in Table 2 correspond also for scalar quarks with $\lambda'_{1jk} = \sqrt{4\pi\alpha}$. Limits on λ'_{1jk} depending on the mass $m_{\tilde{q}}$ can be obtained from Figure 3. The sensitivity to $\lambda'_{1jk}/m_{\tilde{q}}$ can be substantially improved by including the $b\bar{b}$, $c\bar{c}$ and $t\bar{t}$ final states in addition to the hadronic cross sections only.

5 Sensitivity to Neutral Extra Gauge Bosons

Extra neutral gauge bosons (Z') are predicted breaking grand unified theories down to the Standard Model gauge group. Some subgroups survive unbroken at the TeV scale and propose the existence of new gauge bosons Z′ (Z_{R}), W' (W_{R}). Popular models arise from breaking $E_6 \to SU(3) \times SU(2) \times U(1) \times U(1)_{Y'}$ and $SO(10) \to SU(3) \times SU(2)_{\mathrm{L}} \times SU(2)_{\mathrm{R}} \times U(1)$.

Recent studies demonstrate that additional neutral gauge bosons can be produced at hadron colliders up to 4 TeV [11]; this is beyond the search reaches of an e^+e^- collider. Nevertheless, a Z′ can be probed by its virtual effects on cross sections and asymmetries. In this note the sensitivity of fermion-pair production to a potential Z′ exchange is updated using the input described in subsection 2.2.3. Former studies can be found in [5, 6, 12, 13, 14, 15, 16, 17]. Analyses of LEP data show that a potential ZZ′ mixing is restricted to few 10^{-3} [18]. Hence, it is set to zero in the following.

Neutral gauge bosons contribute to the helicity amplitudes (2) as follows:

$$\begin{aligned} \mathcal{A}^{ef}_{i,k} &= \left(Q_e Q_f + C^e_i C^f_k \chi + C'^e_i C'^f_k \chi'\right) \frac{t}{s}; \quad i,k = \mathrm{L,R}; \quad i \neq k, \\ \mathcal{A}^{ef}_{i,i} &= \left(Q_e Q_f + C^e_i C^f_i \chi + C'^e_i C'^f_i \chi'\right) \frac{u}{s}; \quad i = \mathrm{L,R} \end{aligned} \tag{18}$$

with

$$\begin{aligned} \chi'(s) &= \frac{s}{s - m^2_{Z'} + is\Gamma_{Z'}/m_{Z'}} \\ C'^f_{\mathrm{L}} = v'_f + a'_f, &\quad C'^f_{\mathrm{R}} = v'_f - a'_f \end{aligned} \tag{19}$$

The couplings of different Z′ models can be found e.g. in [5, 12].

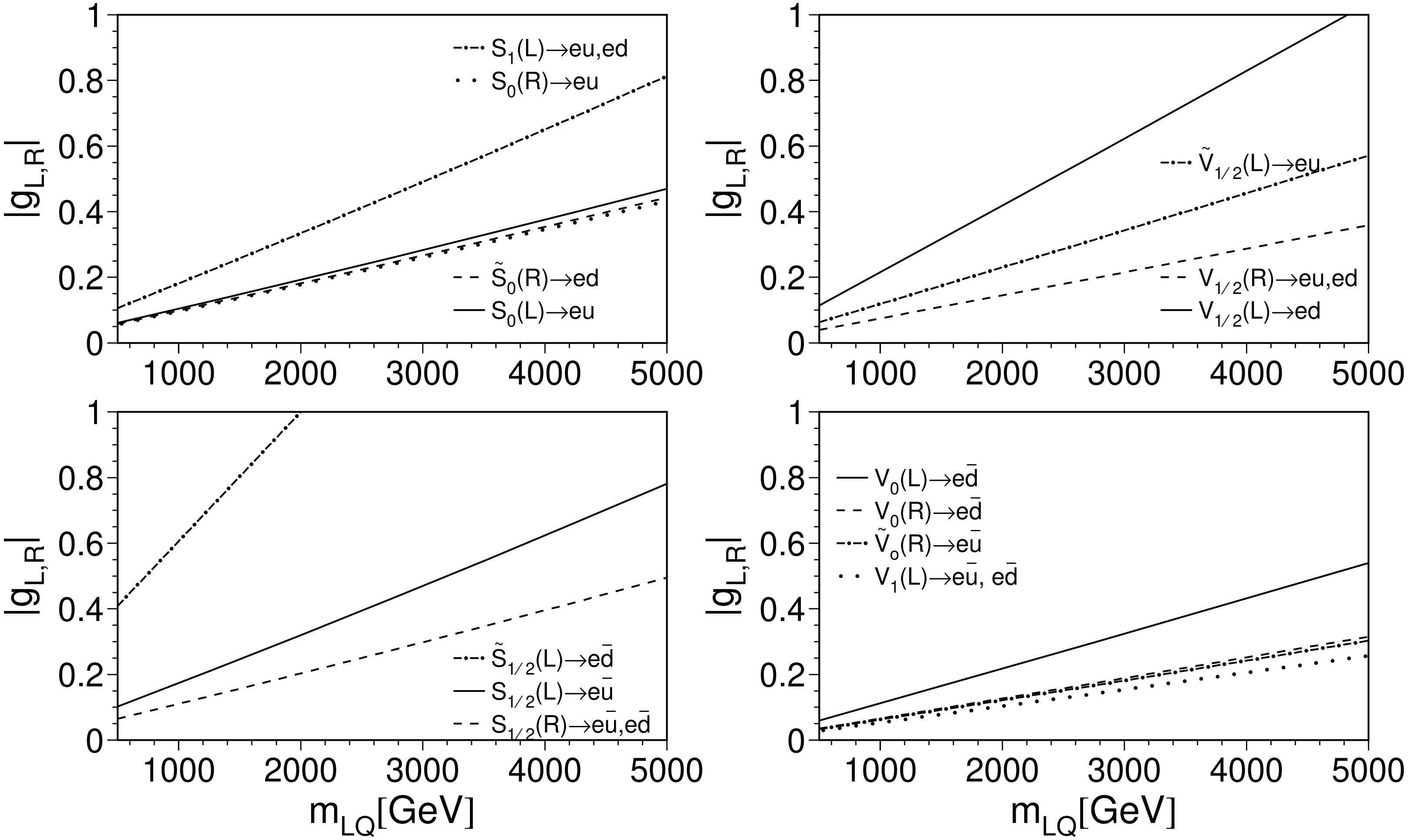

Figure 3: Expected sensitivity reaches (95% C.L.) for Yukawa couplings $g_{L,R}$ of leptoquarks depending on m_{LQ}. The process $e^+e^- \to$ hadrons at $\sqrt{s} = 500$ GeV is considered.

Figure 4 shows the sensitivity to usual Z′ models in comparison to the expected search reach of LHC [11] for $\mathcal{L} = 1$ ab^{-1}, $P_{e^+} = 0.6$, $P_{e^-} = 0.8$ and two error scenarios:

- case A: $\Delta P_{e^\pm}/P_{e^\pm} = 1.0\%$, $\Delta\mathcal{L}/\mathcal{L} = 0.5\%$, $\Delta^{sys}_{lep} = 0.5\%$, $\Delta^{sys}_{had} = 0.5\%$;
- case B: $\Delta P_{e^\pm}/P_{e^\pm} = 0.5\%$, $\Delta\mathcal{L}/\mathcal{L} = 0.2\%$, $\Delta^{sys}_{lep} = 0.2\%$, $\Delta^{sys}_{had} = 0.1\%$;

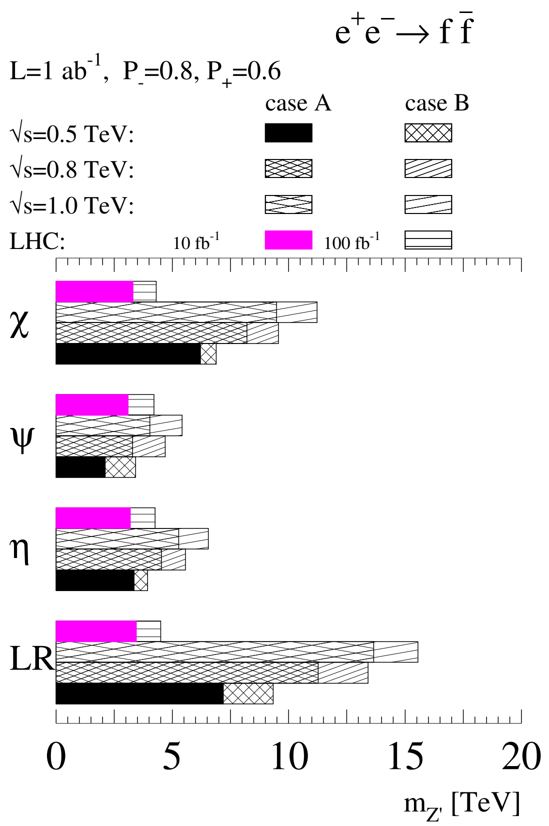

Figure 4: Expected sensitivity reaches for Z′ masses for the models χ, ψ, η and LR from a linear collider and from LHC. The measurements of leptonic and hadronic final states are combined. The error scenarios A and B are explained in the text.

Below a Z′ resonance measurements of fermion-pair production are sensitive only to the ratio of Z′ couplings and Z′ mass. Therefore, limits on the Z′ mass can be obtained only in dependence on a model with given Z′ couplings. For the popular E_6 and LR models mass sensitivities between $4 \cdot \sqrt{s}$ and $14 \cdot \sqrt{s}$ are reached. Thus, a LC operating at 800 GeV exceeds the sensitivity of the LHC to a potential Z′ for these models. If a Z′ will be detected at LHC its origin can be found by determining the Z′ couplings. Figure 5 demonstrates for a linear collider the resolution power between Z′ models assuming that the mass of the new boson is measured at LHC.

Leptonic final states are considered and lepton–universality is supposed. A two-fold ambiguity remains. Without beam polarization, $P_{e^-} = P_{e^+} = 0$, this ambiguity is 4-fold.

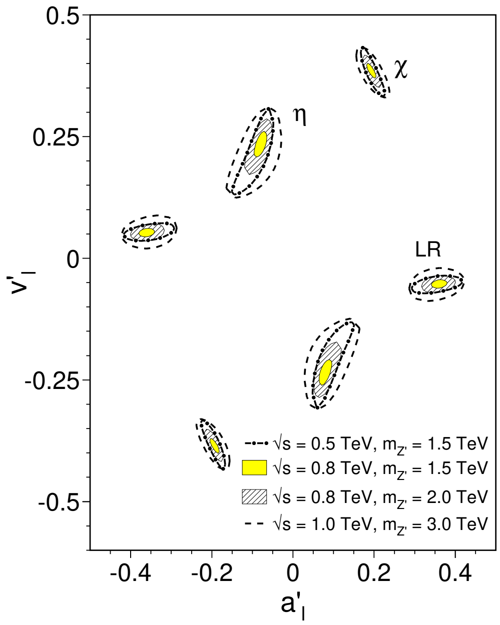

Figure 5: Expected resolution power (95% C.L.) to reconstruct Z′ models based on the measurement of Z′ couplings to leptons. It is assumed that the Z′ mass is known from LHC measurements.

There is still a remarkable sensitivity to Z′ models even if the Z′ is too heavy to be detected at LHC. A determination of normalized couplings,

$$a_f^N = a'_f \sqrt{\frac{s}{m_{Z'}^2 - s}}, \quad v_f^N = v'_f \sqrt{\frac{s}{m_{Z'}^2 - s}}, \tag{20}$$

allows to conclude to a potential Z′ for $m_{Z'} > 4$ TeV. Figures 6 demonstrate the reconstruction of the Z′ model without knowledge of the Z′ mass depending on the final state fermions, beam polarization and systematic uncertainties. Positron beam polarization will improve only slightly the resolution power for Z′ models in case of leptonic final states, but it will enhance the resolution power considering hadronic final states. More details about the influence of polarization as a tool to disentangle models can be found [6, 19].

6 Sensitivity to Extra Spatial Dimensions

Recent theoretical developments exploit the geometry of extra spatial dimensions to explain the gauge hierarchy [2, 20]. As a consequence, near the weak scale gravitons

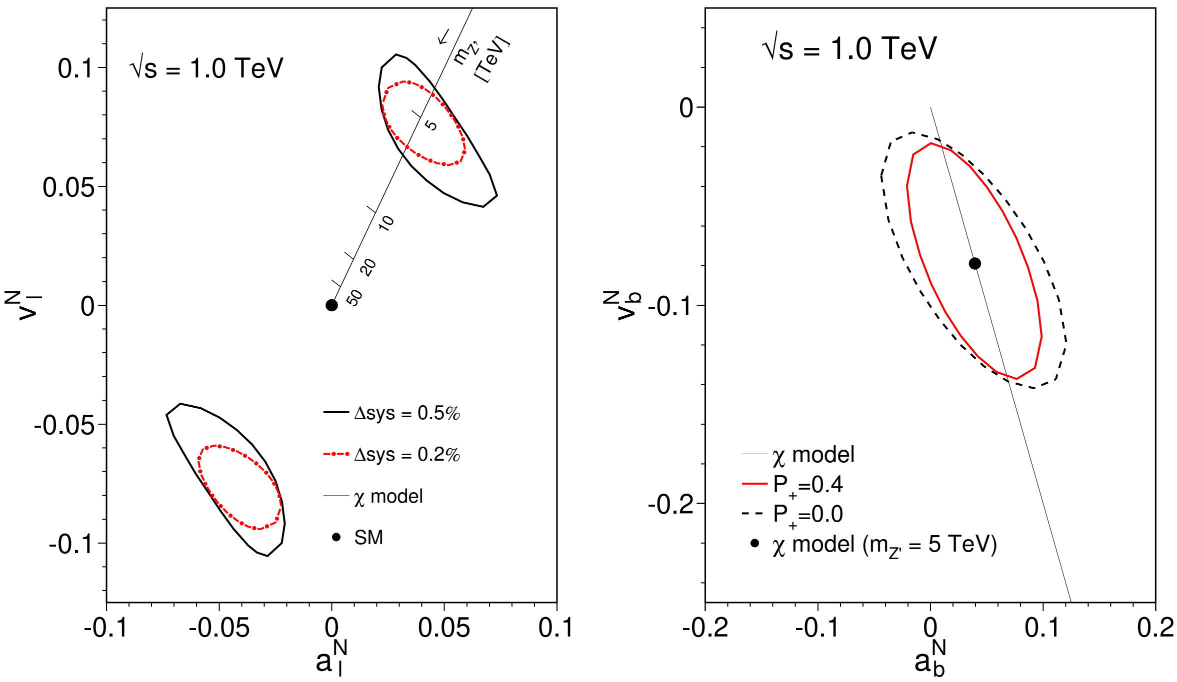

Figure 6: Expected resolution power (95% C.L.) to reconstruct a Z′ realized in the χ model based on the measurement of leptonic (left side) and $b\bar{b}$ final states (right side). The Z′ mass is assumed to be unknown.

become strong interacting in extra spatial dimensions. In the 4-dimensional space-time gravitons are weak and only observable as projection onto a wall. The spin-2 gravitons, that propagate in 4+δ dimensions interact with Standard Model particles in the normal 4 dimensions with a sizable strength, related to λ/M_D^4. λ is a model parameter and taken as ± 1. The virtual interaction of gravitons in fermion pair production leads to modifications of the angular distributions as it is demonstrated in Figures 7 for a scale of extra dimensions $M_D = 2$ TeV. The sensitivity to these effects of low-scale gravity is shown in Table 3 for $\sqrt{s} = 500$ GeV, 800 GeV and $\mathcal{L} = 1$ ab^{-1} for different positron polarizations.

	M_D [TeV]			
$\sqrt{s}$	0.8 TeV	0.5 TeV		
P_{e^+}	0.6	0.6	0.4	0.0
ee→ $\mu\mu$	5.8	4.1	4.0	3.8
ee→ bb	7.1	5.0	4.7	4.4
ee→ cc	7.1	5.1	4.7	4.4
combined	8.0	5.6	5.3	4.9

Table 3: Sensitivity in M_D for indirect effects in fermion pair production; $\mathcal{L} = 1$ ab^{-1}, $\sqrt{s} = 0.5$ TeV and $P_{e^-} = 0.8$.

7 Summary

Fermion pair production is sensitive to a variety of new phenomena. New interactions would manifest by their interferences with photon and Z boson exchange and lead to deviations from the Standard Model expectations. The combination of measurements of the different observables for the $f\bar{f}$ final states as well as their angular distributions can be exploited to probe new interactions and to disentangle the source of new physics up to a multiple of the available centre-of-mass energies. In this context the polarization of electrons and also of the positrons will be an important tool.

A crucial point in the analyses are the systematic errors. The high luminosity and the good reconstruction efficiencies will lead to statistical errors on the permille level. That implies that the systematic errors will dominate and limit the search reaches for new phenomena. Therefore, it will be important to minimize the systematic errors, e.g. the error of the polarization measurement as well as the error of the luminosity measurement and of the data reconstruction.

The sensitivity of indirect searches done with a linear collider is complementary to the searches of LHC. Results of the LHC experiments can be used to specify the source of new interactions with the linear collider. Otherwise, the sensitivity reach

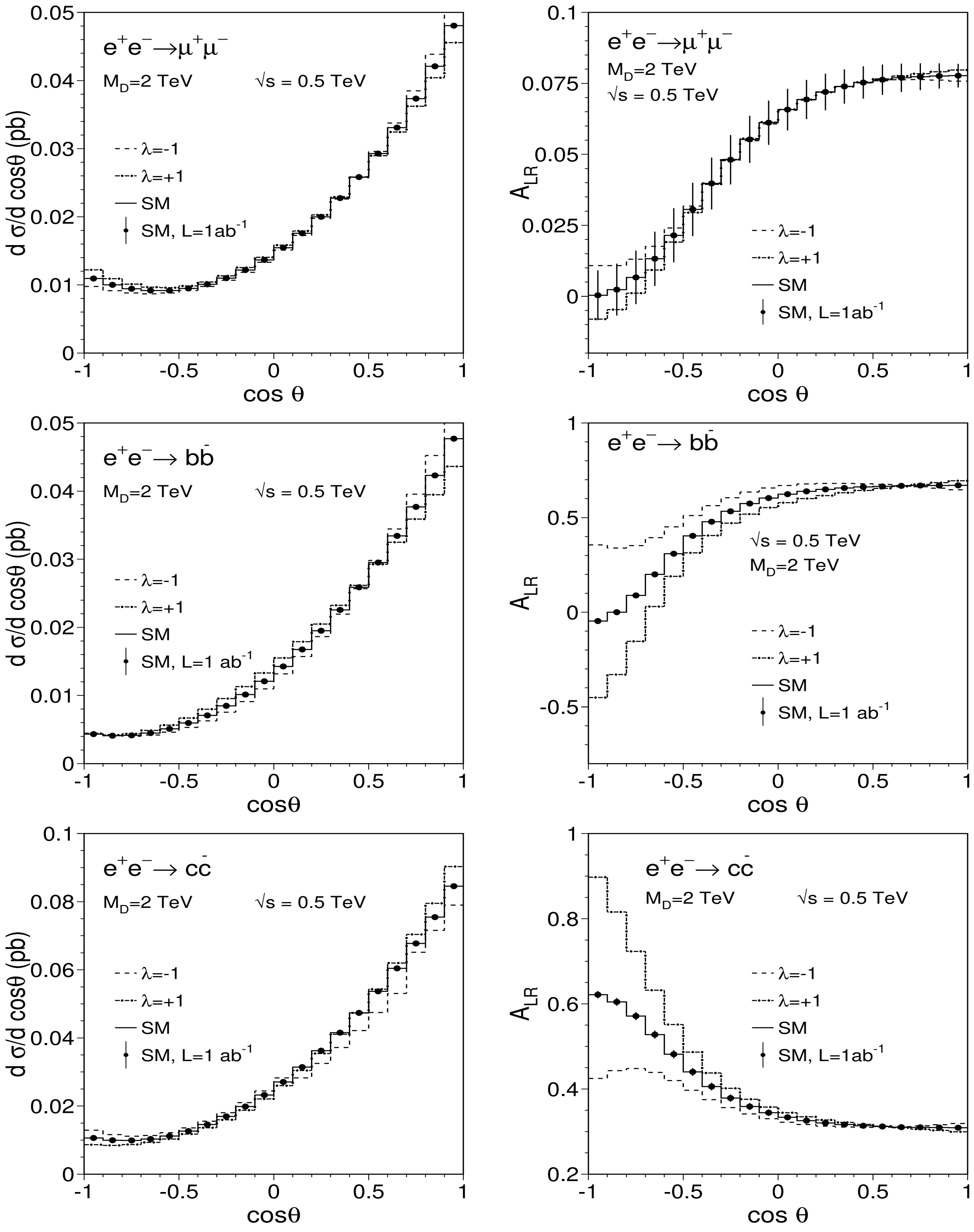

Figure 7: Expected modifications of angular distrubutions due to universal extra dimensions.

of the linear collider will exceed the direct search reaches of LHC for some of new phenomena. To get a complete information about particles and forces both colliders will be needed.

References

[1] LEP Collaborations ALEPH, DELPHI, L3 and OPAL and the Lineshape Subgroup of the LEP Electroweak Working Group, CERN-EP/2000-153; December 19, 2000; LEP Collaborations ALEPH, DELPHI, L3 and OPAL, the LEP Electroweak Working Group and the SLD Heavy Flavor and Electroweak Groups CERN-EP-2000-016, January 21, 2000.

[2] Hewett, J.A., Phys. Rev. Lett. **82** (1999) 4765 and references therein.

[3] R. Hawkings, LC-PHSM-2000-021.

[4] S. Bethke, Nucl. Phys. Proc. Suppl. **64** (1998) 54 and Saariselka Workshop 1991, pp. 575-610

[5] A. Djouadi, A. Leike, T. Riemann, D. Schaile and C. Verzegnassi, Z. Phys. **C 56** (1992) 289.

[6] A. Leike, S. Riemann, Z. Phys. **C75** (1997) 341.

[7] Eichten E., Guptal A.K. and Peskin M.E., Phys. Rev. Lett. **50** (1983) 811.

[8] J. Blümlein, R. Rückl, Phys. Lett. **B 304** (1993) 337; R. Rückl, R. Settles, H. Spiesberger, hep-ph/9709315.

[9] J.L. Hewett, Phys. Lett. **B 227** (1989) 178; M.A. Doncheski and S. Godfrey, hep-ph/9612385.

[10] Kalinowski J., R. Rückl R., Spiesberger H., Zerwas P., Z. Phys. **C 74** (1997) 595.

[11] S. Godfrey, Phys. Rev. **D 51** (1995) 1402; ATLAS Collaboration, Technical Design Report, Report CERN-LHCC-99-15 (May 1999).

[12] A. Leike, S. Riemann, T. Riemann, LMU-91-06, hep-ph/9808374.

[13] A. Leike, S. Riemann, T. Riemann, Phys. Lett. **B 291** (1992) 187.

[14] S. Riemann, Proceedings of the 1996 DPF / DPB Summer Study on New Directions in High-energy Physics, hep-ph/9610513.

[15] S. Riemann, hep-ph/9710564.

[16] S. Riemann, Proceedings of 4th International Workshop on Linear Colliders (LCWS 99), Sitges, Spain, 28 Apr - 5 May 1999.

[17] S. Riemann, Proceedings LCWS2000, Fermilab 2000.

[18] L3 Collaboration, O. Adriani et al., Phys. Lett. **B 306** (1993) 187; DELPHI, Collaboration, P. Abreu et al., Z. Phys. **C 47** (1995) 603; S. Riemann, Balholm 1997, "Beyond the standard model 5", 387.

[19] R. Casalbuoni, S. De Curtis, D. Dominici, R. Gatto and S. Riemann, LC-TH-2000-006, hep-ph/0001215.

[20] G.F. Giudice, R. Ratazzi and J.D. Wells, Nucl. Phys. **B 544** (1999) 3; S. Cullen and M. Perelstein, Phys. Rev. Lett. **83** (1999) 268; L. Hall and D. Smith, Phys. Rev. **D 60** (1999) 085008; V. Barger, T. Han and R.J. Zhang, Phys. Lett. **B 461** (1999) 34; C. Hanhart, D.R. Philips, S. Reddy and M.J. Savage, nucl-th/0007016; T. Han, J. Lykken, and R.J. Zhang, Phys. Rev. **D 59** (1999) 105006.