Comparative analysis of the four-fermion contact interactions at e^+e^- and e^-e^- colliders

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Abstract

We study electron-electron contact-interaction searches in the processes $e^+e^- \to e^+e^-, \mu^+\mu^-$ and $e^-e^- \to e^-e^-$ at planned Linear Colliders run in the e^+e^- and e^-e^- modes with both beam longitudinally polarized.

Contact interaction Lagrangians (CI) provide an effective framework to account for the phenomenological effects of new dynamics characterized by extremely high intrinsic mass scales Λ, at the 'low' energies $\sqrt{s} \ll \Lambda$ attainable at current particle accelerators. For the Bhabha scattering process

$$e^+ + e^- \to e^+ + e^-, \tag{1}$$

as well as for Møller scattering

$$e^- + e^- \to e^- + e^-, \tag{2}$$

we consider the flavor-diagonal, helicity conserving $eeff$ contact-interaction effective Lagrangian [1]:

$$\mathcal{L}_{\rm CI} = \frac{1}{1+\delta_{ef}} \sum_{i,j} g^2_{\rm eff}\, \epsilon_{ij} \left(\bar{e}_i \gamma_\mu e_i\right) \left(\bar{f}_j \gamma^\mu f_j\right). \tag{3}$$

In Eq. (3): $i, j = {\rm L, R}$ denote left- or right-handed fermion helicities, $\delta_{ef} = 1$ for processes (1) and (2) and, if we assumed lepton universality, the same Lagrangian, with $\delta_{ef} = 0$, is relevant to the annihilation processes

$$e^+ + e^- \to \mu^+ + \mu^-. \tag{4}$$

The CI coupling constants in Eq. (3) are parameterized in terms of corresponding mass scales as $\epsilon_{ij} = \eta_{ij}/\Lambda_{ij}^2$ and, according to the previous remarks concerning compositeness, one assumes $g_{\rm eff}^2 = 4\pi$. Also, by convention, one takes $|\eta_{ij}| = 1$ or $\eta_{ij} = 0$, leaving the energy scales Λ_{ij} as free, *a priori* independent, parameters.

We notice that for the case of the Bhabha process (1), Eq. (3) envisages the existence of three independent CI models, each one contributing to individual helicity amplitudes or combinations of them, with *a priori* free, and nonvanishing, coefficients (basically, $\epsilon_{\rm LL}, \epsilon_{\rm RR}$ and $\epsilon_{\rm LR} = \epsilon_{\rm RL}$ combined with the $\pm$ signs). The same is true for the Møller process (2). In general, apart from the $\pm$ possibility, for $e^+e^- \to \bar{f}f$ with $f \neq e$ there are four independent CI couplings, so that in the present case of processes (1) and (2) there is one free parameter less. Correspondingly, in principle, a model-independent analysis of the data should account for the situation where the full Eq. (3) is included in the expression for the cross section. Potentially, in this case, the different CI couplings may interfere and such interference could substantially weaken the bounds. To this aim, in the case of the processes (1), (2) and (4) at the Linear Collider (LC) considered here, a possibility is offered by initial beam polarization, that enables us to extract from the data the individual helicity cross sections (or their combinations) through the definition of particular, polarized integrated cross sections and, consequently, to disentangle the constraints on the corresponding CI constants [2, 3]. In this note, we wish to present a model-independent analysis of the CI that complements that of Refs. [3], and is based instead on the measurements of more 'conventional' observables (but still assuming polarized electron and positron beams) such as the differential distributions of the final leptons. We also make a comparison of the results from these three processes.

With P^- and P^+ the longitudinal polarization of the electron and positron beams, respectively, and θ the angle between the incoming and the outgoing electrons in the c.m. frame, the differential cross section of process (1), including γ and Z exchanges both in the s and t channels and the contact interaction (3), can be written in the following form [3]:

$$\frac{d\sigma(P^-,P^+)}{d\cos\theta} = \frac{(1+P^-)(1-P^+)}{4}\frac{d\sigma_{\rm R}}{d\cos\theta} + \frac{(1-P^-)(1+P^+)}{4}\frac{d\sigma_{\rm L}}{d\cos\theta} + \frac{1+P^-P^+}{2}\frac{d\sigma_{{\rm LR},t}}{d\cos\theta}. \tag{5}$$

In Eq. (5):

$$
\begin{aligned}
\frac{d\sigma_{\mathrm{L}}}{d\cos\theta} &= \frac{d\sigma_{\mathrm{LL}}}{d\cos\theta}+\frac{d\sigma_{\mathrm{LR},s}}{d\cos\theta},\\
\frac{d\sigma_{\mathrm{R}}}{d\cos\theta} &= \frac{d\sigma_{\mathrm{RR}}}{d\cos\theta}+\frac{d\sigma_{\mathrm{RL},s}}{d\cos\theta},
\end{aligned}
\tag{6}
$$

with

$$
\begin{aligned}
\frac{d\sigma_{\mathrm{LL}}}{d\cos\theta} &= \frac{2\pi\alpha^2}{s}\left|A_{\mathrm{LL}}\right|^2, \quad \frac{d\sigma_{\mathrm{RR}}}{d\cos\theta}=\frac{2\pi\alpha^2}{s}\left|A_{\mathrm{RR}}\right|^2,\\
\frac{d\sigma_{\mathrm{LR},t}}{d\cos\theta} &= \frac{2\pi\alpha^2}{s}\left|A_{\mathrm{LR},t}\right|^2, \quad \frac{d\sigma_{\mathrm{LR},s}}{d\cos\theta}=\frac{d\sigma_{\mathrm{RL},s}}{d\cos\theta}=\frac{2\pi\alpha^2}{s}\left|A_{\mathrm{LR},s}\right|^2,
\end{aligned}
\tag{7}
$$

and

$$
\begin{aligned}
A_{\mathrm{RR}} &= \frac{u}{s}\left[1+\frac{s}{t}+g_{\mathrm{R}}^2\left(\chi_Z(s)+\frac{s}{t}\chi_Z(t)\right)+2\frac{s}{\alpha}\epsilon_{\mathrm{RR}}\right],\\
A_{\mathrm{LL}} &= \frac{u}{s}\left[1+\frac{s}{t}+g_{\mathrm{L}}^2\left(\chi_Z(s)+\frac{s}{t}\chi_Z(t)\right)+2\frac{s}{\alpha}\epsilon_{\mathrm{LL}}\right],\\
A_{\mathrm{LR},s} &= \frac{t}{s}\left[1+g_{\mathrm{R}}\,g_{\mathrm{L}}\,\chi_Z(s)+\frac{s}{\alpha}\epsilon_{\mathrm{LR}}\right],\\
A_{\mathrm{LR},t} &= \frac{s}{t}\left[1+g_{\mathrm{R}}\,g_{\mathrm{L}}\chi_Z(t)+\frac{t}{\alpha}\epsilon_{\mathrm{LR}}\right].
\end{aligned}
\tag{8}
$$

Here: α is the fine structure constant; $t=-s(1-\cos\theta)/2$, $u=-s(1+\cos\theta)/2$ and $\chi_Z(s)=s/(s-M_Z^2+iM_Z\Gamma_Z)$ and $\chi_Z(t)=t/(t-M_Z^2)$ represent the Z propagator in the s and t channels, respectively, with M_Z and Γ_Z the mass and width of the Z; $g_{\mathrm{R}}=\tan\theta_W$, $g_{\mathrm{L}}=-\cot 2\,\theta_W$ are the SM right- and left-handed electron couplings of the Z, with θ_W the electroweak mixing angle.

With both beams polarized, the polarization of each beam can be changed on a pulse by pulse basis. This would allow the separate measurement of the polarized cross sections for each of the four polarization configurations RR, LL, RL and LR, corresponding to the four sets of beam polarizations $(P^-,P^+)=(P_1,P_2)$, $(-P_1,-P_2)$, $(P_1,-P_2)$ and $(-P_1,P_2)$, respectively, with $P_{1,2}>0$. To make contact to the experiment we take $P_1=0.8$ and $P_2=0.6$, and impose a cut in the forward and backward directions. Specifically, we consider the cut angular range $|\cos\theta|<0.9$ and divide it into nine equal-size bins of width $\Delta z=0.2$ ($z\equiv\cos\theta$). We also introduce the experimental efficiency, ϵ, for detecting the final e^+e^- pair, and according to the LEP2 experience $\epsilon=0.9$ is assumed. The reach

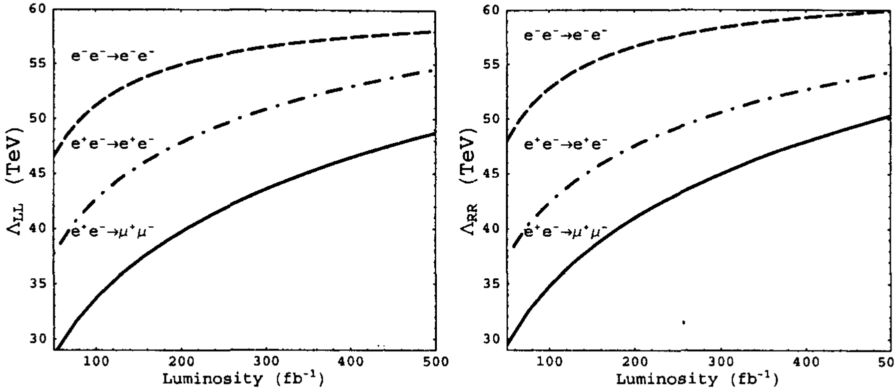

Figure 1: Reach in $\Lambda_{\rm LL}$ and $\Lambda_{\rm RR}$ at 95% C.L. *vs.* integrated luminosity $\mathcal{L}_{\rm int}$ obtained from the model-independent analysis for $e^+e^- \to e^+e^-, \mu^+\mu^-$ and $e^-e^- \to e^-e^-$ at $E_{\rm c.m.} = 0.5$ TeV, $|P^-| = 0.8$ and $|P^+| = 0.6$.

on the CI couplings, and the corresponding constraints on their allowed values in the case of no effect observed, can be estimated by performing χ^2 analysis, assuming the data to be well described by the SM ($\epsilon_{\alpha\beta} = 0$) predictions, i.e., that no deviation is observed within the foreseen experimental uncertainty. The procedure, and the criteria, to derive numerical constraints from the Møller process and muon pair-production process (4) are quite similar. One should notice only that in the case of Møller scattering one can find for the cross section results similar to Bhabha scattering, that can be obtained by crossing symmetry except for the overall normalization factor 1/2 related to identical particles. Also, from Eqs. (5)-(8) one can obtain the cross section for muon pair-production process accounting that it proceeds solely via s-channel exchange.

As for the systematic uncertainty, we take $\delta\mathcal{L}_{\rm int}/\mathcal{L}_{\rm int} = 0.5\%$, $\delta\epsilon/\epsilon = 0.5\%$ and, regarding the electron and positron degrees of polarization, $\delta P_1/P_1 = \delta P_2/P_2 = 0.5$ %. As a criterion to constrain the values of the contact interaction parameters allowed by the non-observation of the corresponding deviations, we impose $\chi^2 < \chi^2_{\rm CL}$, where the actual value of $\chi^2_{\rm CL}$ specifies the desired 'confidence' level. We take the values $\chi^2_{\rm CL}$ =7.82 and 9.49 for 95% C.L. for a three- (Bhabha and Møller processes) and a four-parameter ($\mu^+\mu^-$ pair production) fit, respectively.

In Figs. 1-2 we show the derived limits on the electron contact interactions at a LC with longitudinally polarized beams and using a model-

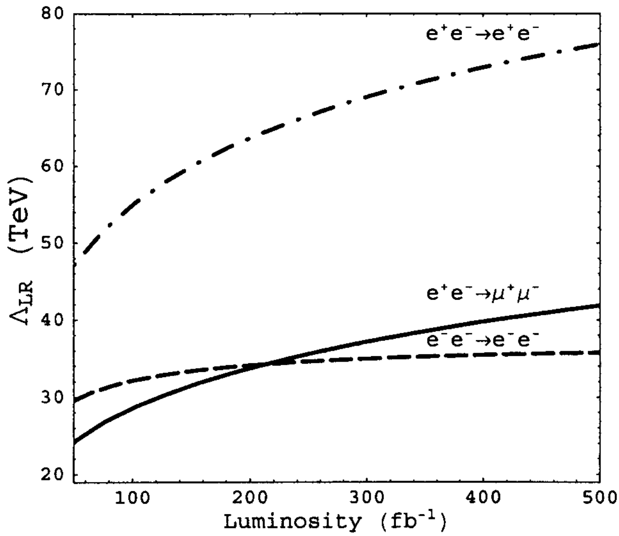

Figure 2: Same as in Fig. 1 but for $\Lambda_{\rm LR}$.

independent analysis that allows to simultaneously account for all independent couplings as non-vanishing free parameters. From these figures one can conclude that the two processes, (1) and (2), are complementary as far as the sensitivity to the individual couplings in a model-independent data analysis is concerned: the sensitivity of Bhabha scattering to $\Lambda_{\rm LR}$ is dramatically higher, while Møller scattering is the most sensitive to $\Lambda_{\rm LL}$ and $\Lambda_{\rm RR}$.

References

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