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CONSTRAINTS ON DOUBLY CHARGED HIGGS INTERACTIONS AT LINEAR COLLIDER

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Abstract

Production of a single doubly charged Higgs boson Δ^{--} in polarized e^+e^- and $e^+\gamma$ collision modes of the linear collider have been investigated. The mass range of Δ^{--} to be probed extends up to the collision energy. The diagonal lepton number violating Yukawa coupling h_{ee} will be tested at least three orders of magnitude more strictly than in present experiments.

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1. *Introduction.* Discovery of a doubly charged scalar particle in future colliders would be a definite signal of new physics beyond the Standard Model (SM). One of the most attractive theories in which such particles are present is the left-right symmetric (LR) electroweak theory [1]. This theory, based on the gauge symmetry group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, was proposed to offer a dynamical solution to the parity violation of weak interaction. The presence of triplet representations of Higgs fields, i.e. SU$(2)_R$ triplet Δ_R and SU$(2)_L$ triplet Δ_L, provides a simple explanation to the lightness of neutrinos via the see-saw mechanism [2]. The triplet scalars do not couple to quarks and their couplings to leptons break the lepton number by two units, leading to a clear decay signature of the doubly charged scalars, namely a same sign pair of leptons.

In literature several experimental tests of lepton number violating interactions mediated by virtual doubly charged bosons have been reported. There are two unknown parameters on which the obtained constraints depend: the mass of the scalar $M_{\Delta^{--}}$ and a coupling constant h_{ij}, where $i, j = e, \mu$ (no constraints are available for the τ leptons). Assuming that the rest energy of the scalar is large compared with the interaction energy, the constraints one can derive from the present measurements are upper limits for quantities of the type $h_{ij}h_{i'j'}/M^2_{\Delta^{--}}$.

The present experimental constraints are the following (see [3] and references therein). The most stringent constraint comes from the upper limit for the flavour changing decay $\mu \to \overline{e}ee$:

$$h_{e\mu}h_{ee} < 3.2 \times 10^{-11}\ \mathrm{GeV}^{-2} \cdot M^2_{\Delta^{--}}. \tag{1}$$

From non-observation of the decay $\mu \to e\gamma$ follows the constraint

$$h_{e\mu}h_{\mu\mu} \lesssim 2 \cdot 10^{-10}\ \mathrm{GeV}^{-2} \cdot M^2_{\Delta^{--}}. \tag{2}$$

From the Bhabha-scattering cross section at SLAC and DESY the following bound on the h_{ee} coupling was established:

$$h^2_{ee} \lesssim 9.7 \times 10^{-6}\ \mathrm{GeV}^{-2} \cdot M^2_{\Delta^{--}}. \tag{3}$$

For the coupling $h_{\mu\mu}$ the extra contribution to $(g-2)_\mu$ yields the limit

$$h_{\mu\mu} \lesssim 2.5 \cdot 10^{-5}\ \mathrm{GeV}^{-2} \cdot M^2_{\Delta^{--}}, \tag{4}$$

and the muonium transformation to antimuonium converts into a limit

$$h_{ee}h_{\mu\mu} \lesssim 5.8 \cdot 10^{-5}\ \mathrm{GeV}^{-2} \cdot M^2_{\Delta^{--}}. \tag{5}$$

We will point out in this paper that in a linear collider (LC) currently under discussion one can obtain much more stringent constraints than those quoted above by considering single production of Δ^{--}.

2.*Production of a single doubly charged scalar.* The single production of doubly charged scalars in lepton colliders has been previously studied by several authors [4, 5, 6]. The production in *ep* collisions at Hera was considered in [7]. In high energy *pp* collisions at LHC the triplet Δ^{--} can be produced via WW fusion process which has been studied in [8]. The rate of this process is suppressed either by the large mass of the right-handed gauge boson W_R or by the small left-handed triplet vacuum expectation value (vev) v_L. In $e^-\gamma$ mode the production reaction is

$$e^-\gamma \to l^+\Delta^{--}. \tag{6}$$

The photon beam can be obtained by scattering laser pulses off the electron beam [9]. The achievable monochromaticity and polarization rate are comparable with the electron beam ones [10]. In e^+e^- collisions a single Δ^{--} can be produced in

$$e^+e^- \to e^+l^+\Delta^{--}. \tag{7}$$

In the e^-e^- collision mode a single Δ^{--} will be produced in s-channel anihilation. If the mass of Δ^{--} were known in advance, e.g. from the other LC collision modes or LHC experiments, one could adjust the collision energy suitably to have a very large production cross section at pole. In this way one would be capable to probe extremely small values of the coupling constant h_{ee}, as was shown in [6].

In this paper we will investigate the sensitivity of linear collider to the mass and couplings of a doubly charged Higgs scalar in the single production reactions (6) and (7). We present our results for several collision energies ($\sqrt{s}$ = 360, 500, 800 and 1600 GeV), and we take into account polarization of the initial state particles. Unlike previous authors [5] we do not use any approximations to calculate the cross sections of process (7) and keep lepton masses explicitly in the formulae. We will perform our analysis in the framework of the left-right symmetric model, where doubly charged scalars appear most naturally, but our results are applicable to any model with scalar bileptons [11].

3. *The model.* Let us present some basic features of the $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model. In this model leptons are assigned to doublets of gauge groups $SU(2)_L$ and $SU(2)_R$ according to their chirality:

$$\Psi_L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L = (2,1,-1), \quad \Psi_R = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_R = (1,2,-1), \tag{8}$$

and similarly for the other families. The minimal set of fundamental scalars consists of a bidoublet Φ, one $SU(2)_L$ triplet Δ_L and one $SU(2)_R$ triplet Δ_R. Their quantum numbers are $\Phi = (2,2,0)$, $\Delta_L = (3,1,2)$ and $\Delta_R = (1,3,2)$. This set of scalars allows for a manifest left-right symmetry of the Lagrangian and leads to a consistent symmetry breaking scheme.

The Higgs bidoublet and triplets

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}, \quad \Delta_{L,R} = \begin{pmatrix} \Delta^+_{L,R} & \sqrt{2}\Delta^{++}_{L,R} \\ \sqrt{2}\Delta^0_{L,R} & -\Delta^+_{L,R} \end{pmatrix}, \tag{9}$$

acquire non-vanishing vacuum expectation values given by

$$\langle\Phi\rangle = \tfrac{1}{\sqrt{2}} \begin{pmatrix} \kappa_1 & 0 \\ 0 & \kappa_2 \end{pmatrix}, \quad \langle\Delta_{L,R}\rangle = \tfrac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix}. \tag{10}$$

The vev of the bidoublet Φ breaks the Standard Model symmetry $SU(2)_L \times U(1)_Y$ and generates Dirac mass terms to fermions through the Yukawa Lagrangian $\bar{\Psi}^i_L(f_{ij}\Phi + g_{ij}\tilde{\Phi})\Psi^j_R +$

h.c., where $\tilde{\Phi} = \sigma_2 \Phi^* \sigma_2$. The left-handed triplet vev v_L is forced to be small due to its contribution to the ρ parameter. The right-triplet Δ_R breaks the $SU(2)_R \times U(1)_{B-L}$ symmetry to $U(1)_Y$ and at the same time the discrete $L \leftrightarrow R$ symmetry. The vev v_R gives masses to W_R as well as to the doubly charged scalars $\Delta^{--}_{L,R}$. It also provides right-handed neutrinos with large Majorana mass terms via the Yukawa Lagrangian

$$\mathcal{L}_Y = h_{ij}(\Psi^T_{iR} C \sigma_2 \Delta_R \Psi_{jR} + \Psi^T_{iL} C \sigma_2 \Delta_L \Psi_{jL}) \quad + \text{ h.c.}, \tag{11}$$

where $\Psi_{iR,L} = (\nu_{iR,L}, l_{iR,L})$ and i, j are flavour indices. This mass Lagrangian combined with the Dirac mass terms from the bidoublet Yukawa couplings gives rise to the see-saw mechanism of neutrino masses [2], which is an attractive way to produce very light neutrinos.

The processes we are interested in have their origin in the Yukawa Lagrangian (11) that contains interactions between the doubly charged Higgses and leptons. The strength of the interaction is scaled by the unknown Yukawa coupling constants h_{ij} which, in general, are not flavour diagonal allowing for lepton number violating interactions. The present constraints on these couplings were listed above.

The two doubly charged Higgses $\Delta^{--}_{L,R}$ have different chiral couplings to leptons. Their masses are expected to be comparable with each other because they derive both from similar terms of the scalar potential [12]. Since their production processes are the same we shall concentrate in the following only on the production of Δ^{--}_R. Therefore we assume that the electron beam is always 100% right-handedly polarized. This is, of course, a simplification which is motivated by the very high polarization rate achievable in the LC. Using a right-handedly polarized electron beam has the benefit that at the same time one swiches off most of the SM background processes which would otherwise mask the discovery of new particles.

4. *Production rates.* Feynman diagrams contributing to the reaction (6) are depicted in Fig.1. As can be expected the dominant contribution to the cross section comes from the diagram with a t-channel exchange of a lepton. It is important to emphasize that to get physically meaningful results one must take into account the masses of the leptons when calculating the helicity amplitudes of the process. The reason for that is twofold. Firstly, neglecting the lepton masses would make the total cross section to diverge in the backward direction. Secondly, one may expect that with proper angular cuts one can estimate the partial cross section for the central region of the detector to be correct when the lepton masses are neglected. In this case the partial cross section is an increasing function of the doubly charged Higgs mass M_Δ and approaches a constant value when M_Δ approaches the collision energy. This unphysical behaviour is cured when the masses are taken into account.

In Fig.2 we plot the total cross section of the process (6) in the case when the final state lepton is an electron as a function of M_Δ for two different photon beam polarizations and for four different collision energies $\sqrt{s_{e\gamma}}$ =300, 420, 670, 1450 GeV, which correspond to the energies $\sqrt{s_{ee}}$ =360, 500, 800, 1600 GeV of the e^+e^- collider, respectively. The Yukawa coupling constant is taken to have the value $h_{ee} = 0.1$. The cross section is large for the whole kinematical range of the LC. When the photon beam has linear polarization of $\tau = -1$ the cross section is a decreasing function of M_Δ, for the photon beam polarization of $\tau = 1$ the behaviour is quite the opposite, the cross section increasing with M_Δ almost up to the kinematical threshold. Due to the t-channel electron exchange the differential cross section of the process is strongly peaked in the backward direction and most of the produced Δ_R^{--}'s have momenta almost parallel to the beam axis.

Feynman diagrams contributing to the process (7) are depicted in Fig.3. Note that there are also crossed digrams if both of the final state fermions are electrons. We have neglected diagrams involving neutral Higgs bosons as they are strongly suppressed due to the negligible couplings of Higgses to electrons and the large Higgs masses. We have also checked that at the LC energies the diagrams mediated by Z bosons are suppressed compared with the graphs involving photons and can be neglected. Therefore, the process (6) can be regarded as the subprocess of the reaction (7).

One can estimate the total cross section of the process (7) using equivalent particle approximation (EPA) [13] and integrating the cross section of the process (6) over the photon spectrum of EPA as was done in [5]. However, because of the delicate effects of small fermion masses in this case, the EPA is expected to give only very rough estimates of the total cross section and to fail to predict further details of the process. Therefore, we have calculated the cross section of the process (7) exactly keeping lepton masses non-zero both in the amplitude and in the phase space formulae. Indeed, the behaviour of the process (7) cannot be predicted by studying the process (6). The individual contribution to the cross section of each separate graph in Fig.3 is huge, but they cancel by several orders of magnitude due to destructive interference terms. The distribution of produced doubly charged particles is peaked strongly in the forward direction.

In Fig.4 we plot the total cross section of the process (7) in the case when both final state fermions are electrons as a function of M_Δ for collision energies of $\sqrt{s_{ee}} = 360$, 500, 800, 1600 GeV assuming different longitudinal polarizations of the positron beam. The triplet Yukawa coupling constant is taken to be $h_{ee} = 0.1$ in these plots. The cross section for the right-handedly polarized positron beam is larger than the one for the left-handedly polarized positrons for almost all testable M_Δ range. Close to the kinematical limit the difference can be more than one order of magnitude. Only for relatively small M_Δ values the situation is the opposite but in this case the cross sections are comparable in size. Clearly, with the chosen parameters one can test Δ_R^{--} masses almost up to the kinematical threshold.

In order to discover Δ_R^{--} at the LC one has to detect its decay products. The decays of doubly charged Higgs bosons have been studied e.g. in [8]. With reasonable assumptions on the masses of Higgs bosons and various mixing angles the main decay modes were found to be $\Delta_R^{--} \to l_1^- l_2^-$ and $\Delta_R^{--} \to W_R^- W_R^-$, where $l_{1,2}$ denote leptons. Since for the Δ_R mass range we are considering the latter decay is kinematically forbidden, we assume in the following that Δ_R^{--} decays 100% to leptons. The experimental signature of the decay is then the same sign lepton pair with no missing energy, including lepton number violating final states, e.g. $\mu^-\mu^-$ or $e^-\mu^-$.

As can be seen in Fig.5., for a light Δ_R^{--} the distribution of a produced lepton l^- is peaked in the backward (process (6)) or forward (process (7)) direction, for larger masses the distribution becomes more flat. This is an expected behaviour since the heavier the particles, the less boosted they are along the beam axis. Assuming the coverage of the detector to be $|\cos\theta| < 0.95$ one can detect about 60% of the final state leptons if $M_\Delta = 100$ GeV and considerably more for larger masses.

The opening angle between the two produced leptons strongly depends on the mass of Δ_R^{--}. For heavy Δ_R^{--} the final state leptons are almost back to back while for 100 GeV Higgs boson the opening angle is restricted to be $\cos\theta_{12} \lesssim 0.5$. This implies that one of the leptons can always be detected. Taking into account the rather small losses of the decay products, clear experimental signatures (lepton number violation, no missing energy) and almost no background from the SM, the doubly charged Higgs is hard to miss in LC if it is produced.

5. *Sensitivity to* $|\Delta L| = 2$ *couplings.* Let us finally analyse the sensitivity of the LC to the triplet Yukawa couplings h_{ij}. The couplings can be tested either in the production processes or in the decays of the Higgs bosons. Since our first interest is the production of Δ_R^{--} we will assume that the Higgs boson mass is in the LC energy range. If Δ_R^{--} will not be seen in the collider experiments one will be able to put an upper bound on the couplings.

The present constraints (3), (4) and (5) do not yield any essential restriction on the diagonal couplings h_{ee} and $h_{\mu\mu}$ for the scalar masses above the electroweak scale, and as large values of the couplings as $\mathcal{O}(1)$ are allowed. The off-diagonal coupling $h_{e\mu}$ is instead restricted by (1) well below unity in the whole mass range covered by the LC. At the LC one will be able via the reactions (7) and (6) to improve these constraints substantially. Furthermore, in addition to the non-diagonal $h_{e\mu}$ coupling one will be able to probe also the non-diagonal coupling $h_{e\tau}$, for which there are no bounds at all from low energy processes.

Let us first consider the reaction (6). The primary lepton created in the process will remain undetected as it is radiated almost parallel to the beam axis. One cannot tell whether this particle is a positron, antimuon or antitau. Therefore, the quantity which one can test in the reaction is actually the sum $h_{ee}^2 + h_{e\mu}^2 + h_{e\tau}^2$. The upper bound obtained for this sum is, of course, the upper bound of each individual term of the sum separately.

Assuming the integrated luminosities of $e^-\gamma$ collisions to be $L = 5,\ 10,\ 20,\ 40$ fb^{-1} and that for the discovery of Δ_R^{--} one needs ten events, we obtain the upper bounds plotted in Fig.6. As one can see from the figure, the sensitivity of the LC on the quantity $(h_{ee}^2 + h_{e\mu}^2 + h_{e\tau}^2)^{1/2}$ is on the level of 10^{-3} almost up to the threshold value of the Δ_R^{--} mass. In other words,

$$h_{ee},\ h_{e\mu},\ h_{e\tau} \lesssim 10^{-3} \tag{12}$$

for $M_{\Delta^{--}} \lesssim \sqrt{s_{e\gamma}}$. Among the present constraints only (1), also presented in the plot, competes with these bounds and does so only at the low mass values. For the coupling $h_{e\tau}$ no bounds exist from the present experiments.

For the same Δ_R^{--} mass, the cross section of the process (7) is roughly two orders of magnitude smaller than the cross section of the process (6), implying that the constraints obtained for $(h_{ee}^2 + h_{e\mu}^2 + h_{e\tau}^2)^{1/2}$ are correspondingly weaker, although the higher luminosities $L = 20,\ 50,\ 100,\ 200$ fb^{-1} of e^+e^- slightly compensate the lack in cross section. The resulting bounds are presented in Fig.7.

6.*Summary.* We have studied in the framework of the left-right symmetric model the single production of a doubly charged Higgs boson via the reactions $e^-e^+ \to e^+l^+\Delta^{--}$ and $e^-\gamma \to l^+\Delta^{--}$ at the LC. We found that the testable range of Δ_R^{--} mass extends almost up to the collision energy. A negative search of the double charged scalar will lead to constraints for the lepton number violating Yukawa couplings substantially more stringent than the present ones.

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Figure caption

Fig.1 Feynman diagrams of the process $e^-\gamma \to l^+\Delta^{--}$ in the left-right model.

Fig.2 Total cross section of the process $e^-\gamma \to e^+\Delta^{--}$ as a function of Higgs boson mass M_Δ for different beam polarizations and collision energies as indicated in figure.

Fig.3 Feynman diagrams contributing to the process $e^-e^+ \to e^+l^+\Delta^{--}$ in the left-right model.

Fig.4 Total cross section of the process $e^-e^+ \to e^+e^+\Delta^{--}$ as a function of Higgs boson mass M_Δ for different beam polarizations and collision energies as indicated in figure.

Fig.5 Angular distribution of final state leptons produced in decays of doubly charged Higgs boson Δ_R^{--}. Production processes and masses of the Higgs boson are shown in figure.

Fig.6 Achievable constraints on triplet Yukawa couplings from the process $e^-\gamma \to l^+\Delta_R^{--}$ for different collision energies as functions of the scalar mass. The most stringent present constraint from low energy experiments is also drawn.

Fig.7 Achievable constraints on triplet Yukawa couplings from the process $e^-e^+ \to e^+l^+\Delta_R^{--}$ for different collision energies as functions of the scalar mass. The most stringent present constraint from low energy experiments is also drawn.

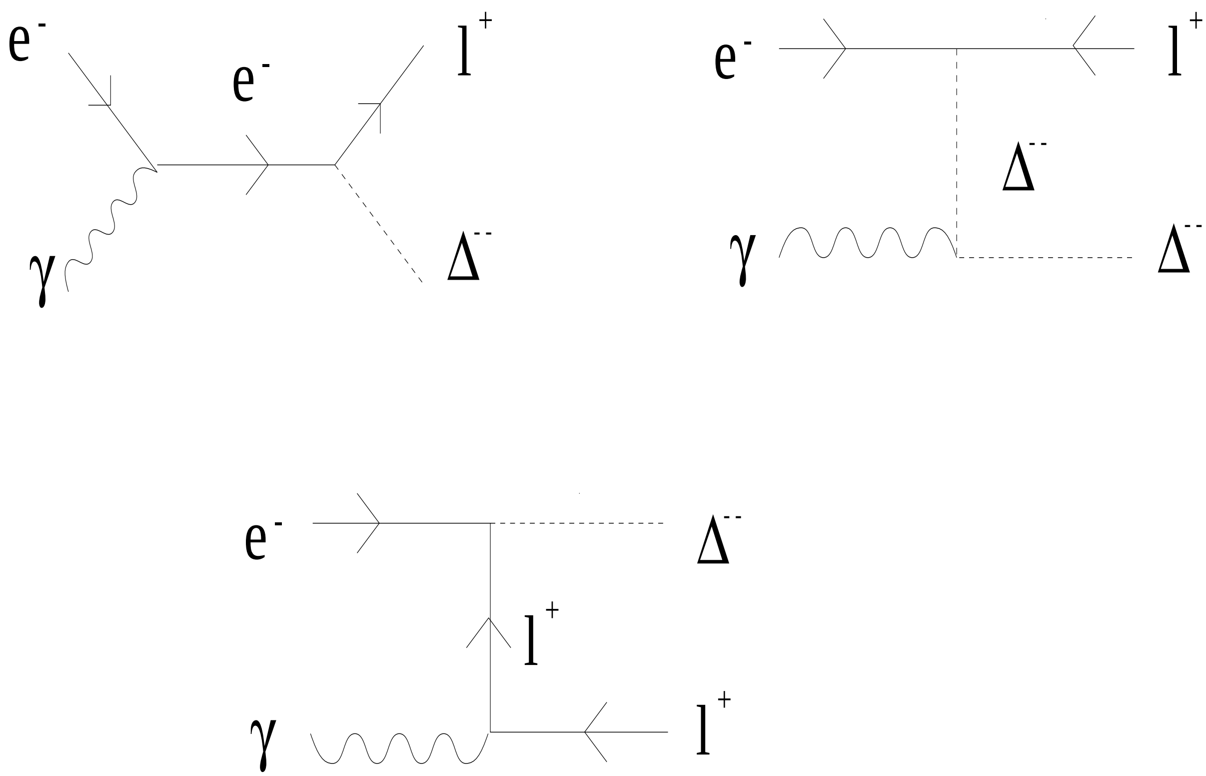
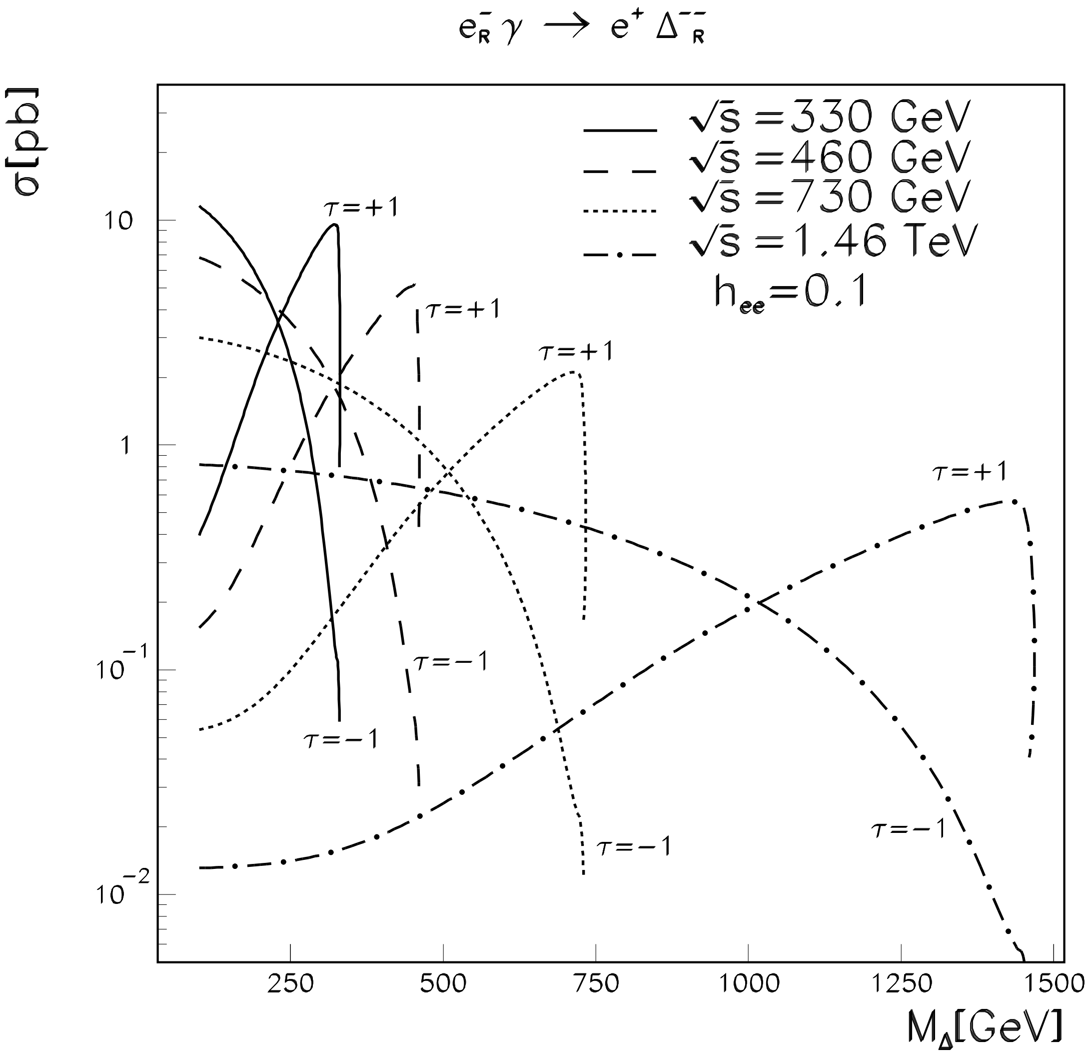
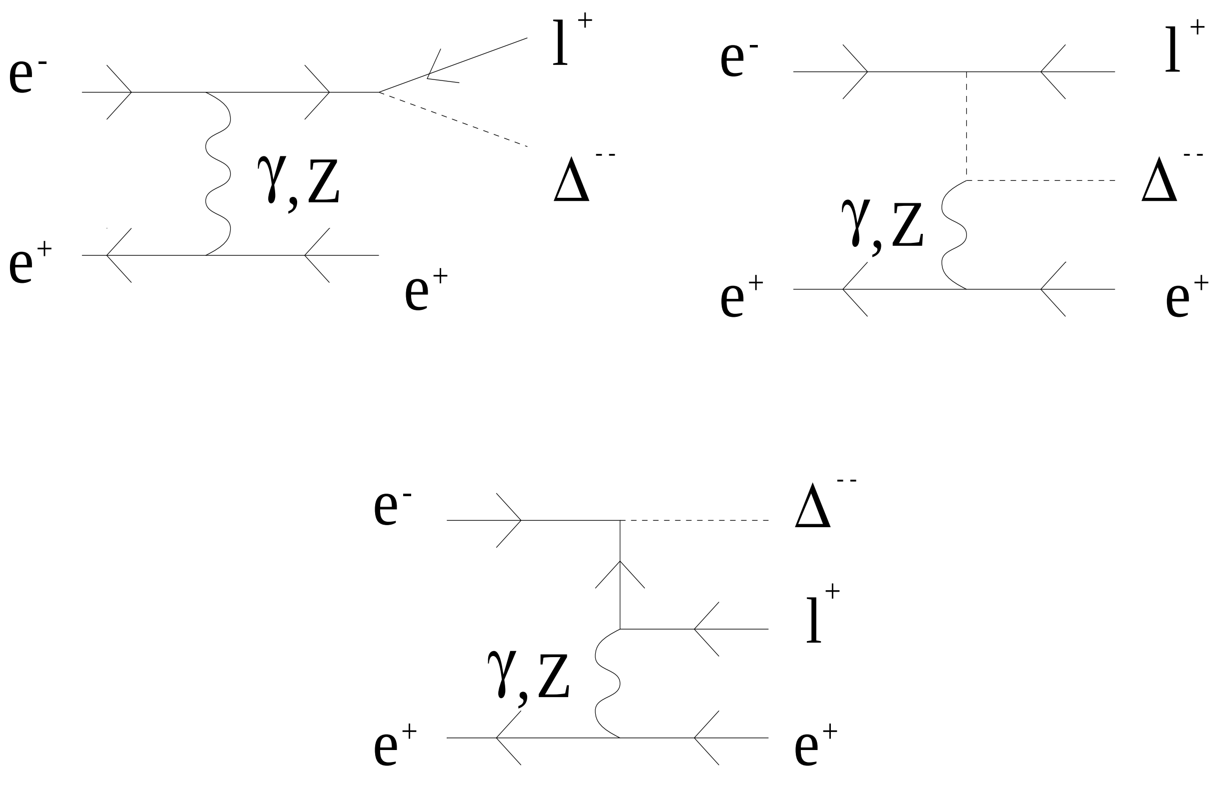


Figure 1:



e⁻_R γ → e⁺ Δ⁻⁻_R
σ[pb]
√s =330 GeV
√s =460 GeV
√s =730 GeV
√s =1.46 TeV
h_ee=0.1
τ=+1
τ=+1
τ=+1
τ=+1
τ=−1
τ=−1
τ=−1
τ=−1
10
1
10⁻¹
10⁻²
250
500
750
1000
1250
1500
M_Δ[GeV]

Figure 2:



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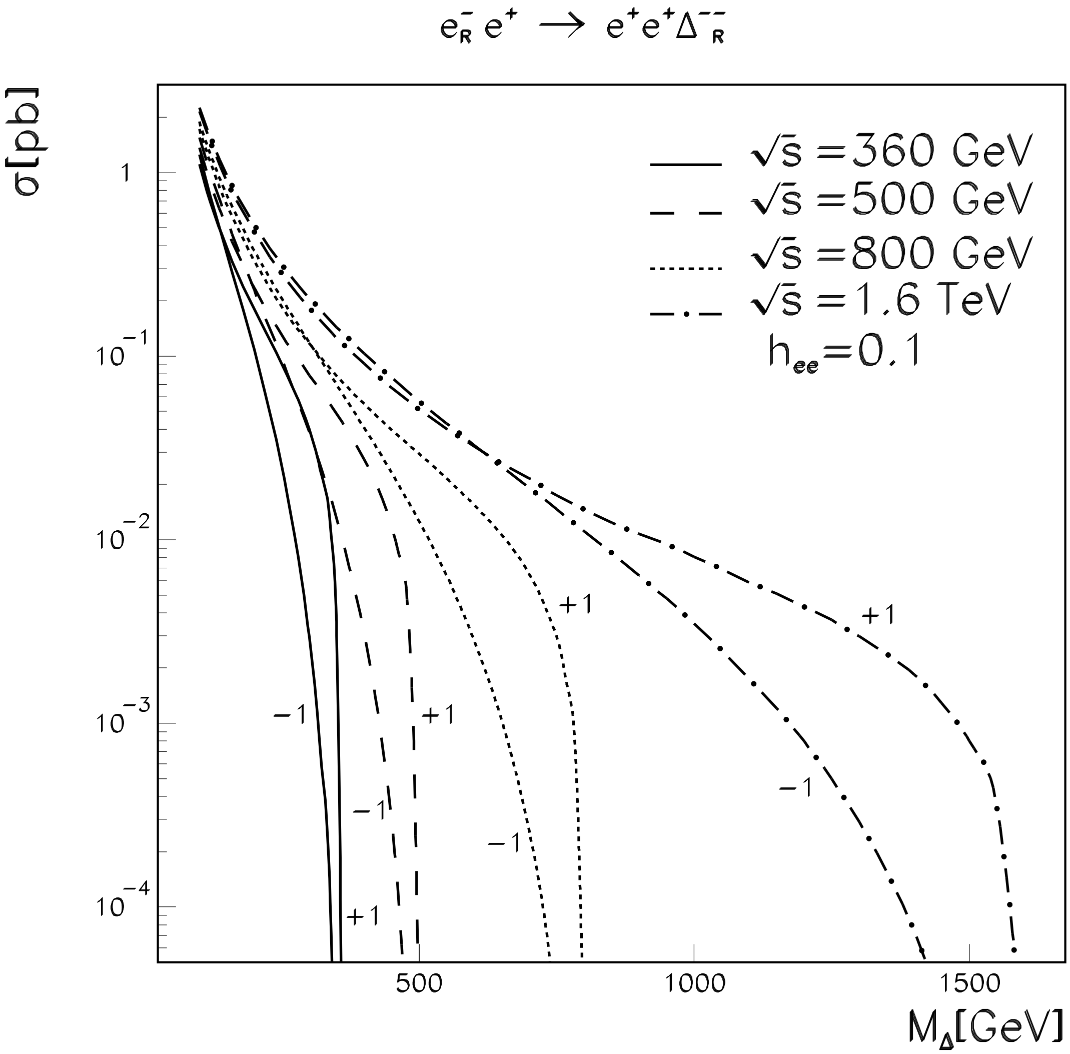
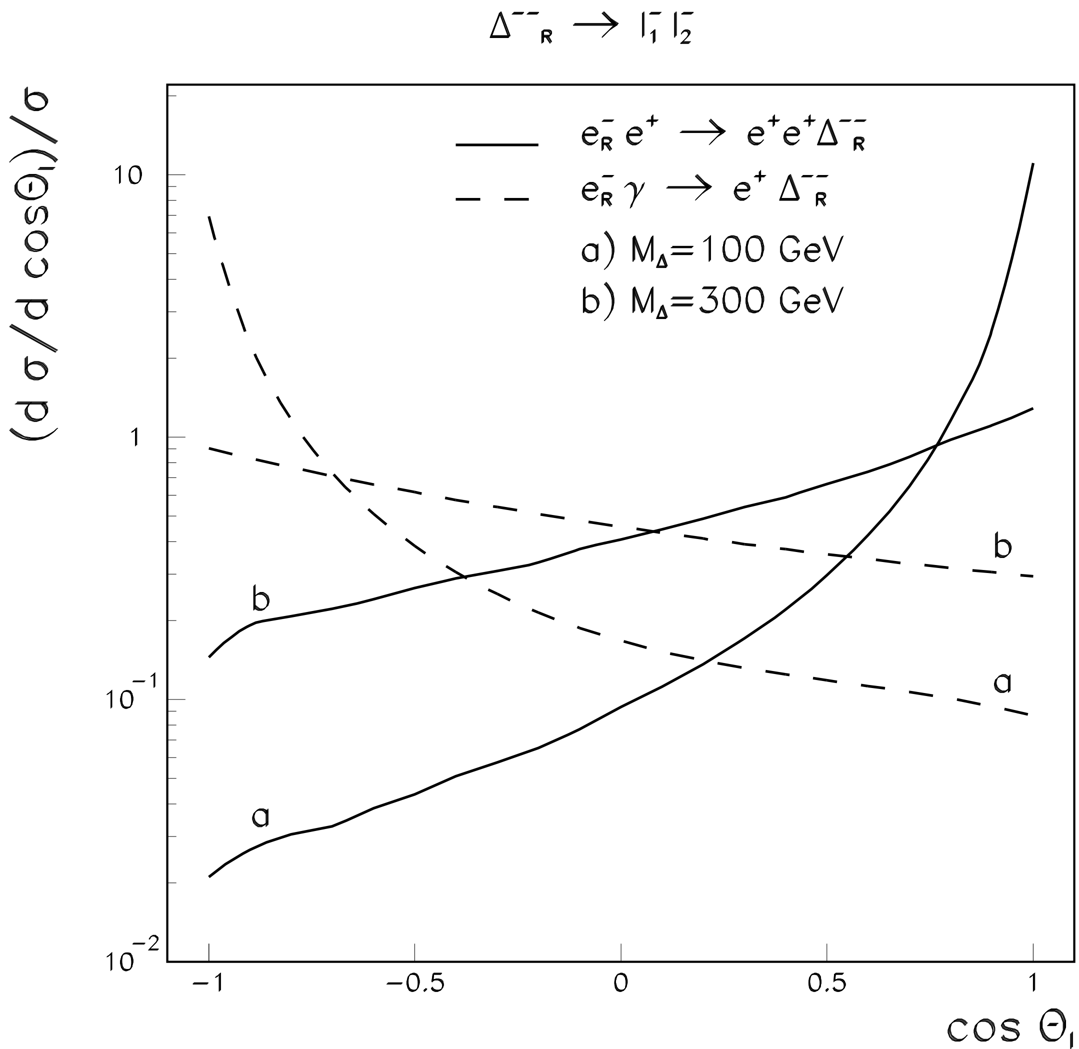


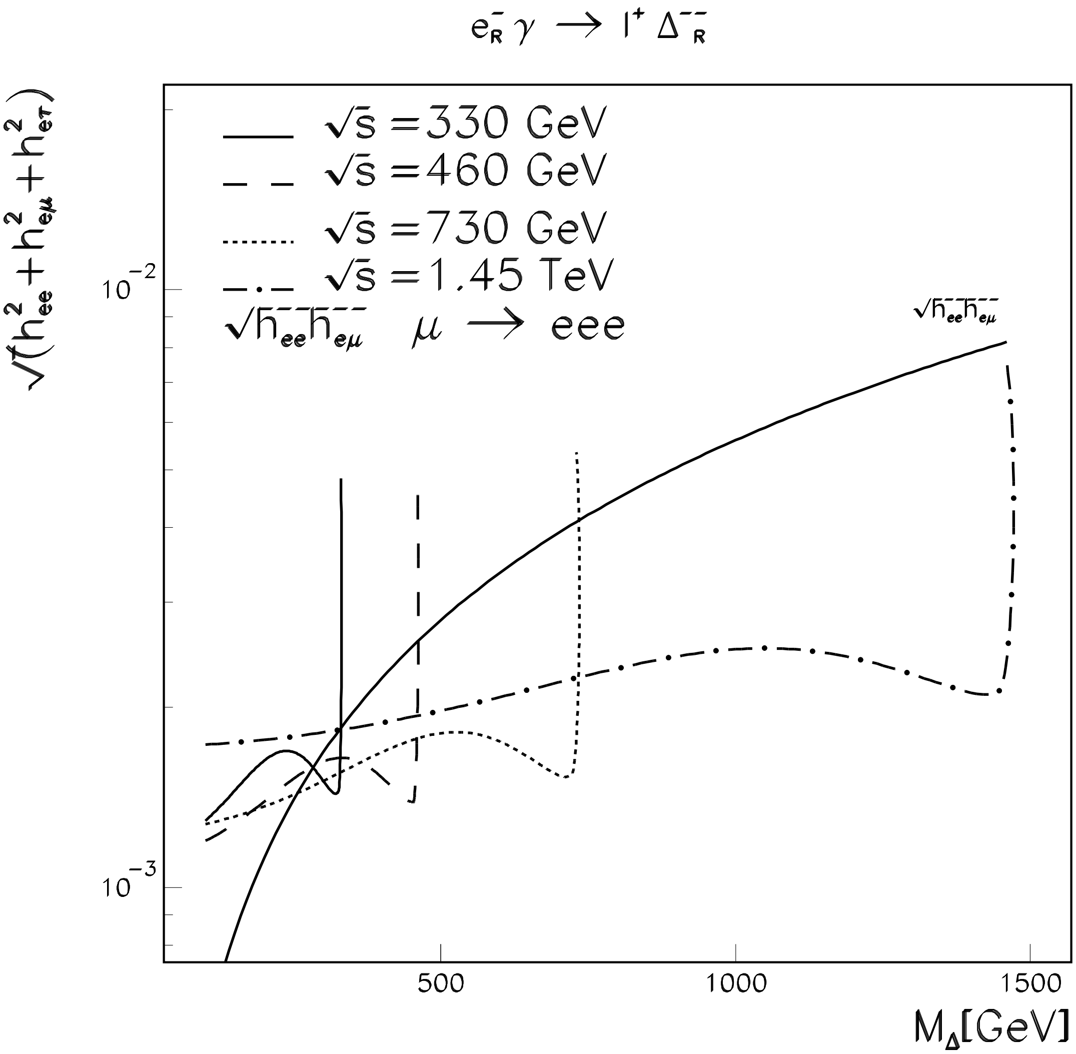
e⁻_R e⁺ → e⁺e⁺Δ⁻⁻_R
σ[pb]
1
10^-1
10^-2
10^-3
10^-4
√s =360 GeV
√s =500 GeV
√s =800 GeV
√s =1.6 TeV
h_ee=0.1
+1
−1
500
1000
1500
M_Δ[GeV]

Figure 4:



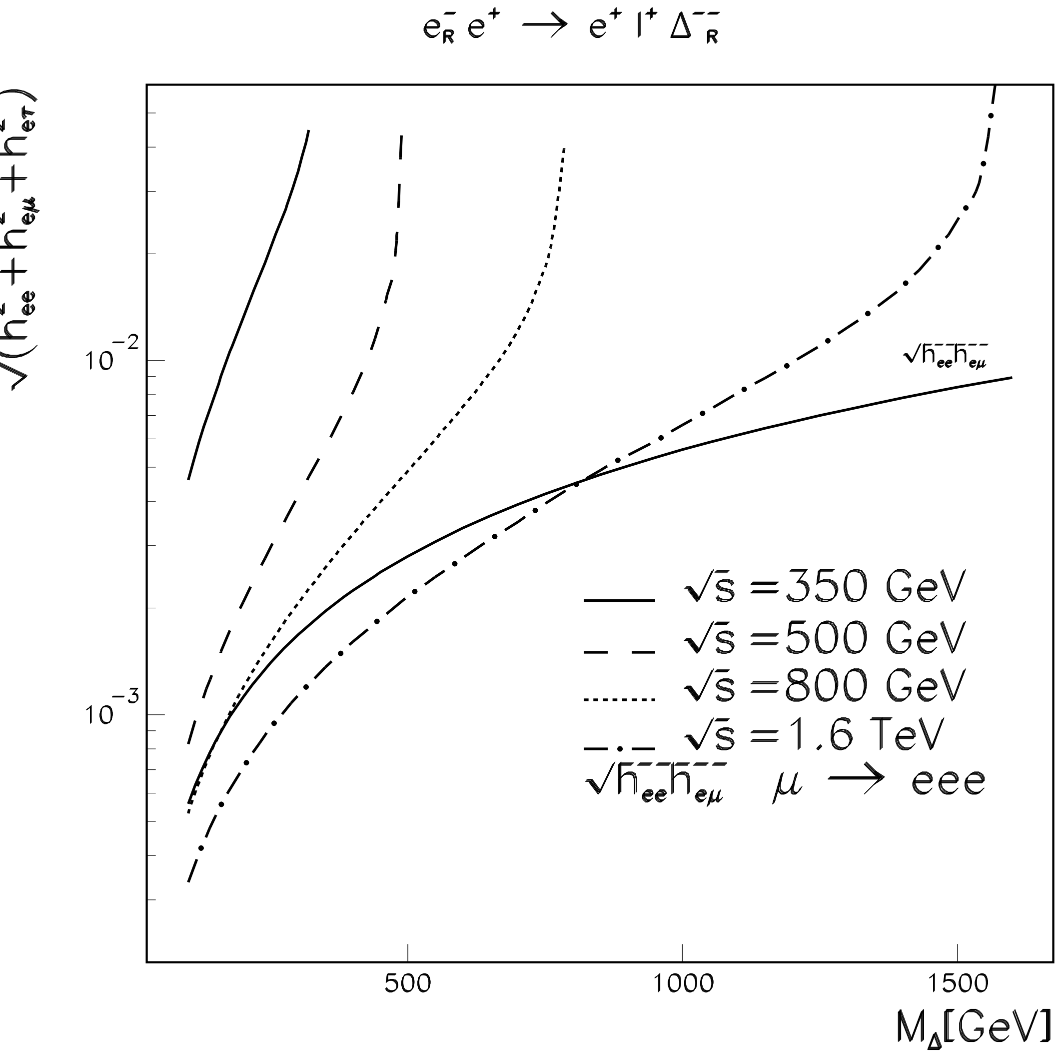
$\Delta^{--}{}_R \to l_1^- l_2^-$
$(d\sigma/d\cos\Theta_l)/\sigma$
$e_R^- e^+ \to e^+ e^+ \Delta_R^{--}$
$e_R^- \gamma \to e^+ \Delta_R^{--}$
a) M_Δ=100 GeV
b) M_Δ=300 GeV
10
1
10^{-1}
10^{-2}
−1
−0.5
0
0.5
1
b
a
b
a
$\cos\Theta_l$

Figure 5:



$e_R^- \gamma \rightarrow l^+ \Delta_R^{--}$
$\sqrt{(h_{ee}^2+h_{e\mu}^2+h_{e\tau}^2)}$
$\sqrt{s}$ =330 GeV
$\sqrt{s}$ =460 GeV
$\sqrt{s}$ =730 GeV
$\sqrt{s}$ =1.45 TeV
$\sqrt{h_{ee}h_{e\mu}}$ $\mu \rightarrow eee$
$\sqrt{h_{ee}h_{e\mu}}$
10^{-2}
10^{-3}
500
1000
1500
M_Δ[GeV]

Figure 6:



$e_R^- e^+ \rightarrow e^+ l^+ \Delta_R^{--}$
$\sqrt{(h_{ee}^2+h_{e\mu}^2+h_{e\tau}^2)}$
10^{-2}
10^{-3}
$\sqrt{h_{ee}^{--}h_{e\mu}^{--}}$
$\sqrt{s}=350$ GeV
$\sqrt{s}=500$ GeV
$\sqrt{s}=800$ GeV
$\sqrt{s}=1.6$ TeV
$\sqrt{h_{ee}^{--}h_{e\mu}^{--}}$ $\mu \rightarrow eee$
500
1000
1500
M_Δ[GeV]

Figure 7: