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INDIRECT SEARCH FOR EXCITED ELECTRONS AT LINEAR COLLIDERS

A. OZANSOY
Physics Department,Faculty of Sciences
Ankara University,
Tandoğan, Ankara, TURKEY,
aozansoy@science.ankara.edu.tr

Abstract. - In this work, we study the excited electron contribution to the $e^+e^- \to \gamma\gamma$ pair annihilation process at future high energy linear colliders. Here we assume chiral magnetic couplings of spin-1/2 excited electrons to photons and ordinary electrons. The signal and the corresponding SM background are examined to obtain accessible limits on the excited electron masses and couplings.

1. INTRODUCTION

One of the fundamental questions left open in the Standard Model (SM) is the replication of fermionic families. A natural explanation for the replication of fermionic families is given by the composite theories in which known fermions are composite. The excited leptons and quarks (l^*, q^*) appear as a consequence of the compositeness [1]. In composite models, quarks and leptons are considered as the ground state of a rich spectrum of excited states [2]. The discovery of excited states of fermions would be a direct evidence for the fermionic substructure. Excited leptons with spin and isospin-1/2 are considered as the lowest radial and orbital excitation. Composite models would also imply excited leptons with higher spins [3].

In the present study, in Sec.II we introduce the effective lagrangian describing the gauge interaction of excited leptons with spin-1/2. Excited electron contribution to the process $e^+e^- \to \gamma\gamma$ for future high energy linear colliders namely International Linear Collider (ILC) [4] with $\sqrt{s} = 0.5$ TeV and Compact Linear Collider (CLIC) [5] with $\sqrt{s} = 1, 3$ TeV is given in Sec.III. Our results are summarized in Sec.IV. Excited lepton interaction vertices have been implemented into the simulation program CALCHEP [6] for our calculations.

2. EXCITED LEPTONS

Phenomenologically, a spin-1/2 excited lepton is defined to be a heavy lepton that shares the same leptonic quantum number (flavor) with the corresponding SM lepton. The effective interaction lagrangian that gives the spin-1/2 excited lepton, SM lepton and a gauge boson interaction vertex should respects a chiral symmetry to avoid SM leptons to have a large anomalous magnetic moment [7]. This lagrangian is generally given as [8, 9, 10]

$$L_{ll^*V} = \frac{1}{2\Lambda}\bar{l}^*\sigma^{\mu\nu}\left[gf\frac{\vec{\tau}}{2}.\mathbf{W}_{\mu\nu} + g'f'\frac{Y}{2}B_{\mu\nu}\right]l_L + h.c \tag{1}$$

where, g and g' are the SM couplings, $\mathbf{W}_{\mu\nu}$ and $B_{\mu\nu}$ are gauge tensors for the $SU(2)$ and $U(1)$ gauge fields, $\vec{\tau}$ denotes the Pauli matrices and Y is the weak hypercharge, Λ is the compositeness scale and f and f' are weight factors related to the $SU(2)$ and $U(1)$ gauge groups. In the literature usually it is taken to be $f = f'$ and $f = -f'$. By using the effective lagrangian one can find the interaction vertex factor

$$\Gamma_\mu^{l^*lV} = \frac{e}{2\Lambda}f_V q^\nu\sigma_{\mu\nu}(1-\gamma_5) \tag{2}$$

In Eq.2, q^ν denotes the four-momentum of the vector boson, e is the electromagnetic coupling constant, f_V is a new coupling related to the l^*lV interaction where $V = \gamma, Z, W$. For an excited electron coupling to a photon one can define $f_\gamma = -\frac{1}{2}(f + f')$.

There have been direct and indirect searches for excited fermions at different accelerators. The mass limits for a spin-1/2 excited electron from its single production at HERA H1 experiment is $m^* > 255$ GeV [11], from its pair production at LEP OPAL experiment is $m^* > 103.2$ GeV [12] and from indirect searches at LEP L3 experiment is $m^* > 310$ GeV [13].

3. EXCITED ELECTRON CONTRIBUTION TO THE PROCESS $e^+e^- \to \gamma\gamma$

In e^+e^- colliders excited electrons can be produced in both single [14] and pairs in the $s-$channel and $t-$channel via the exchange of γ, Z. In addition to the direct production of excited electrons at e^+e^- colliders, excited electrons could be searched indirectly as being exchanged on the $t-$channel of the process $e^+e^- \to \gamma\gamma$ [15, 16, 17]. Indirect searches could enlarge the limits on the excited electron mass and couplings beyond the kinematically allowed region of the single production. The discovery regions obtained from $e^+e^- \to \gamma\gamma$ process using unpolarized beams at the LEPII energies ($\sqrt{s} = 175$ and 205 GeV) and at $\sqrt{s} = 500$ GeV were presented in [16].

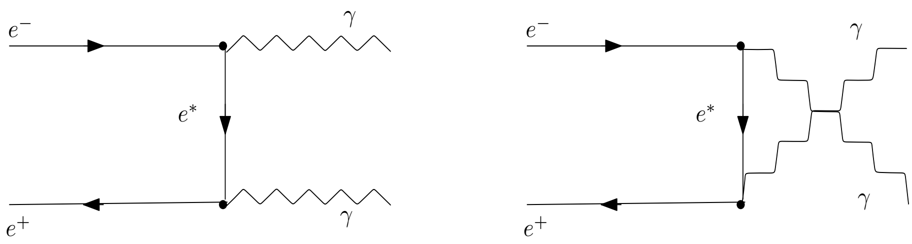

Figure 1: Feynman diagrams shows the excited electron contribution to the process $e^+e^- \to \gamma\gamma$.

The main contribution to the process $e^+e^- \to \gamma\gamma$ comes from QED by means of an ordinary electron exchange at t- and u-channel. The lowest order QED contribution to the cross section is given by

$$(\frac{d\sigma}{d\Omega})_{QED} = \frac{\alpha^2(1+cos^2\theta)}{s(1-cos^2\theta)} \tag{3}$$

In Eq.3, θ is the polar angle of one of the final state photons, α is the fine structure constant and s is the square of the center of mass energy of the collision. The cross section decreases with energy in the QED. In the presence of the non-standard interactions, the cross section grows with the energy. Because of the two photons in the final state the experimental signature of the process is clean, so the $e^+e^- \to \gamma\gamma$ process is a very convenient tool to find some signals for physics beyond the SM. Any deviation from the QED predictions can be interpreted as a sign of new physics beyond the SM. In the presence of an excited electron (e^*), there are four diagrams (two for SM and two for excited electron) contribute to the Born level production of the process $e^+e^- \to \gamma\gamma$. The Feynman diagrams for the excited electron contribution are shown in Fig.1. The differential cross section in the existence of e^* of mass m_{e^*} can be find in [15].

It is essential to consider initial state radiation (ISR) and beamstrahlung phenomena in the future linear collider design. ISR is the photon radiation from incoming electron/positron beams and beamstrahlung is the radiation from the incoming beam caused by its interaction with the field of the other beam moving in the opposite direction. Beamstrahlung spectrum depends on the machine parameters such as bunch sizes, bunch charge and collision energy. The effective energy spectrum of the incoming beam can be found in [18]. In both cases, the initial $e^\pm$ radiates one or more photons which reduce the beam energy and dissipate the beam collimation. The ISR and beamstrahlung photons are mostly collinear with the initial beams. In our calculations we consider the convolution of ISR and beamstrahlung spectra by using the CALCHEP program. The beamstrahlung parameters, Υ and N_γ are given

$$\Upsilon = \frac{5\alpha N E_e}{6m_e^3\sigma_z(\sigma_x+\sigma_y)} \tag{4}$$

Table 1: Linear collider parameters related to the beamstrahlung.

Collider parameter	ILC 500 GeV	CLIC 1 TeV	CLIC 3 TeV
$N(10^{10})$	2	0.4	0.372
$\sigma_x(nm)$	639	115	45
$\sigma_y(nm)$	5.7	1.75	1
$\sigma_z(\mu m)$	300	30	44
Υ	0.05	1.01	4.89
N_γ	1.14	1.04	2.11

$$N_\gamma = \frac{25\alpha^2 N}{12m_e(\sigma_x+\sigma_y)}\frac{1}{\sqrt{1+\Upsilon^{2/3}}} \tag{5}$$

where N is the number of particles in the bunch, E_e and m_e are the energy and mass of the electron, respectively, σ_x and σ_y are the rms beam sizes and σ_z is the bunch length. The beamstrahlung parameters for future linear colliders are presented in Table1. The parameters, $\sigma_x, \sigma_y, \sigma_z$ and N for ILC and CLIC are chosen as in [5, 19, 20]. ISR and beamstrahlung effects on total cross section in the presence of an excited electron to the electron-positron annihilation process are shown in Fig.2.

In Fig.3 one can see the high energy behavior for different Λ scales. When we take the $\Lambda = m^*$ excited electron contribution to the process becomes clearer. However, when Λ is getting bigger values, the difference between the total cross sections calculated for excited electron contributed diagrams and SM diagrams does not seem so big. In Fig.3, $m^* = 350$ GeV and $f = f' = 1$.

It can be seen in Fig.4 that for smaller excited electron masses, the excited electron contribution to the $e^+e^- \to \gamma\gamma$ process becomes bigger. In Fig.4 we assume $\Lambda = m^*$ and $f = f^{'} = 1$.

In the presence of ISR and beamstrahlung, there are extra weak photons along with the initial beam direction therefore they are lost down the beam pipe [21] and evidently there is no matter with tagging such photons. Due to the radiations from initial beams, the center of mass frame of the final state photons is not at rest in the lab, so the events are transformed into the two-photon rest frame to determine the event angle [22, 23]. In order to see the any deviation from the SM predictions, we plot the angular distribution of one of the final state photons for different excited electron masses and for different center of mass energies in Fig.5. In the previous study [15], angular distributions were presented for $\sqrt{s} = 200$ GeV with an excited electron mass of $100, 150$ and 200 GeV. We put some kinematical cuts to obtain the final state photon signal as in [13]. These kinematical cuts are given $E^\gamma > 5$ GeV and $16^o < \theta^\gamma < 164^o$ where E^γ is the photon energy and θ^γ is the polar angle of the photon. In Fig.5, cosθ is defined to be positive, because of the two photons in the final state are identical. For smaller e^* masses deviations from the SM predictions can be easily seen in the angular distribution and the results are in accordance with [15].

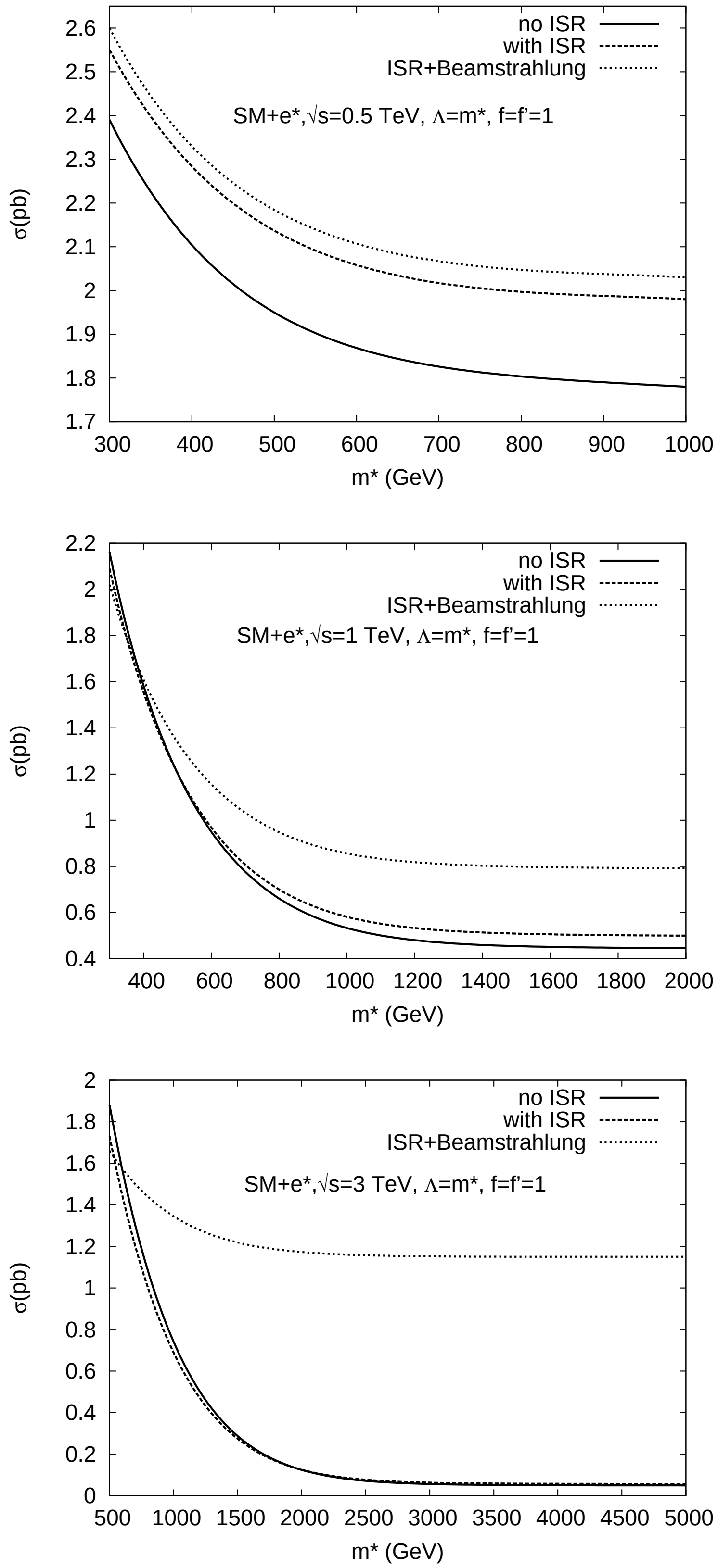

Figure 2: ISR and beamstrahlung effects. The plots are given separately for $\sqrt{s} = 0.5, 1$ and 3 TeV.

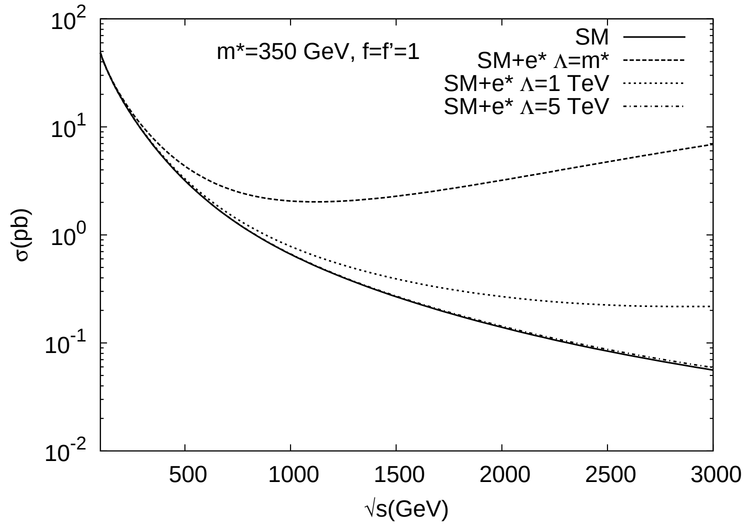

Figure 3: Total cross section in the presence of an excited electron for different Λ scales depending on the center of mass energy.

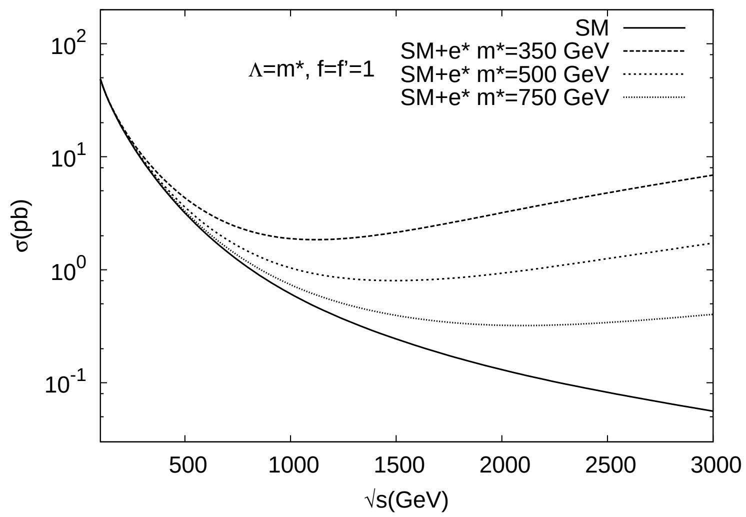

Figure 4: Total cross section in the presence of an excited electron for different e^* masses depending on the center of mass energy.

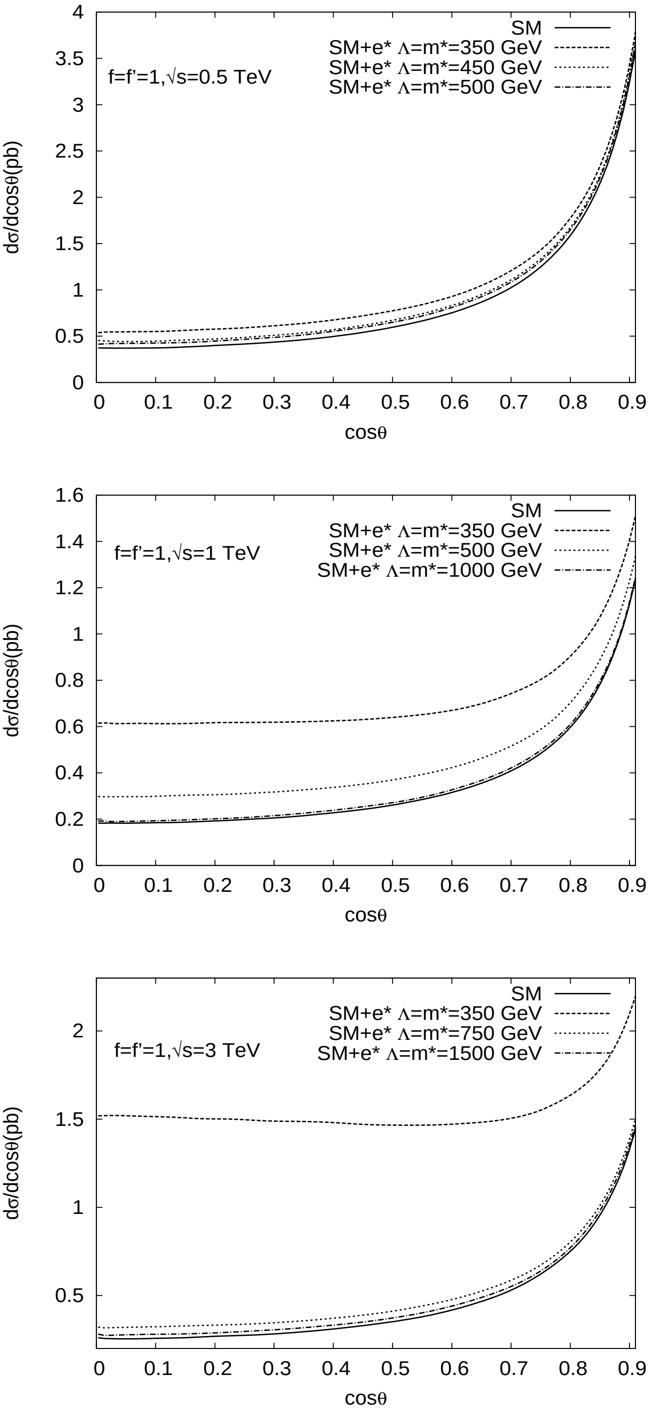

Figure 5: Angular distribution of final state photons. The plots are given separately for $\sqrt{s} = 0.5, 1$ and 3 TeV.

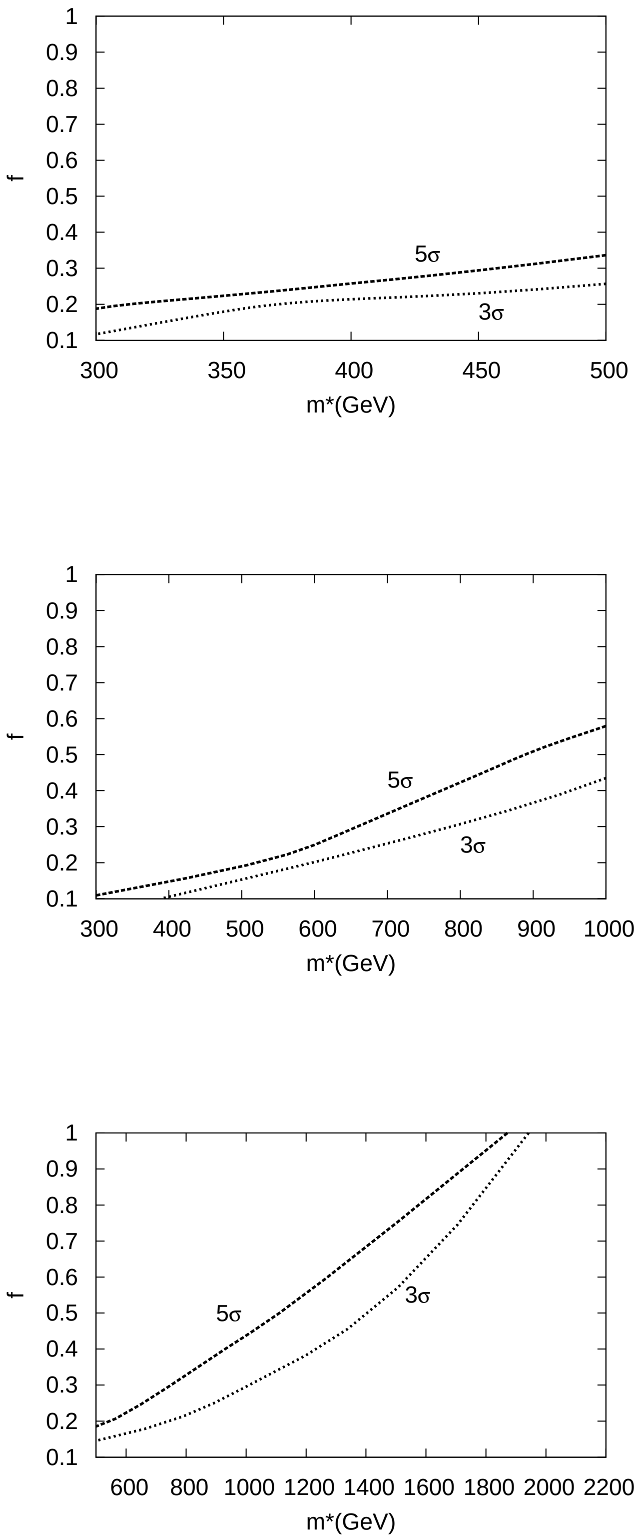

Figure 6: Contour plots. The plots are given separately for $\sqrt{s} = 0.5, 1$ and 3 TeV. The dotted and dashed lines represent the 3σ and 5σ criterias.

To analyze the excited electron contribution to the electron-positron pair annihilation process, we define the statistical signification of the signal,

$$SS = \frac{S - B}{\sqrt{B}} \tag{6}$$

where S corresponds the number of events due to the presence of an excited electron and B corresponds only the number of events of the QED. In the $f - m^*$ parameter space, we plot the contour plots for 3σ and 5σ deviations from the QED predictions considering ISR and beamstrahlung effects. We show our results for the center of mass energies $\sqrt{s} = 0.5$, 1 and 3 TeV in Fig.6, respectively. Concerning the criteria $SS > 3$, with an integrated luminosity (L_{int}) of 2×10^5 pb^{-1} and $\sqrt{s} = 0.5$ TeV ILC can probe excited electron of mass $m^* = 375$ GeV up to the couplings $f = f' = 0.2$. Taking the same criteria, CLIC with $L_{int} = 2.7 \times 10^5$ pb^{-1} and $\sqrt{s} = 1$ TeV can observe excited electron with a mass of 800 GeV up to the couplings $f = f' = 0.3$ and with $L_{int} = 5.9 \times 10^5$ pb^{-1} and $\sqrt{s} = 3$ TeV excited electron with a mass of 1600 GeV can be observed up to the couplings $f = f' = 0.65$.

4.CONCLUSION

In addition to the pair and single production, e^* could also manifest itself in e^+e^- collisions as a virtual state. In the presence of an excited electron the angular distribution of the process $e^+e^- \to \gamma\gamma$ differs from the QED predictions. $e^+e^- \to \gamma\gamma$ process can be used to extend the e^* couplings. Future high energy linear colliders ILC and CLIC could provide an excellent environment for indirect searches for e^*. Higher mass values for smaller couplings can also be achieved. We consider only an excited lepton with spin-1/2 that has chiral magnetic couplings to the electron and the photon. Indirect search for excited spin-3/2 leptons using all data collected by L3 experiment can be found in [17].

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