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Little Higgs model effects in $\gamma\gamma \to \gamma\gamma$

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Abstract. Though the predictions of the standard model (SM) are in excellent agreement with experiments, there are still several theoretical problems associated with the Higgs sector of the SM, where it is widely believed that some new physics will take over at the TeV scale. One beyond the SM theory which resolves these problems is the Little Higgs (LH) model. In this work we have investigated the effects of the LH model on $\gamma\gamma \to \gamma\gamma$ scattering [1].

Keywords. Little Higgs model; linear collider.

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1. Introduction

It has been known for some time that the $\gamma\gamma \to \gamma\gamma$ scattering amplitude at high energies will be a very useful tool in the search for new particles and interactions in an e^+e^- linear collider operated in the $\gamma\gamma$ mode. In the SM the $\gamma\gamma \to \gamma\gamma$ amplitudes will have one-loop contributions mediated by charged fermions (leptons and quarks) and W-bosons. At large energies ($\sqrt{s_{\gamma\gamma}} \geq 250$ GeV) it is known that the W contributions dominate over the fermionic contributions and that the dominant amplitudes are predominantly imaginary. Therefore, we expect that any new physics effects in the $\gamma\gamma \to \gamma\gamma$ process may come from the interference terms between the predominantly imaginary SM amplitudes and new physics effects to these amplitudes.

The SM has been very successful in explaining all electroweak interactions probed so far, where the SM requires a Higgs scalar field to achieve the electroweak symmetry breaking. Note that the mass of the Higgs scalar is not protected by any symmetry. In fact the Higgs mass diverges quadratically when quantum corrections in the SM are taken into account. This gives rise to a 'fine tuning' problem in the SM. The precision electroweak data demands the lightest Higgs boson mass to be ~200 GeV! In order for this to happen we need to invoke some symmetries which will protect the Higgs mass to a much higher scale (possibly GUT scale). To resolve the 'fine tuning' problem it is expected that some new physics should takeover from the SM at the TeV scale. The favoured model, supersymmetry, addresses this problem by introducing a symmetry between bosons and fermions. Recently, a new approach has been advocated, the approach popularly known as the 'little Higgs models', which addresses some of the problems in the SM by making the Higgs boson a pseudo-Goldstone boson of a symmetry which is broken at some higher scale Λ. For a review of the LH models, see refs [2,3]. However, LH models were severely constrained by precision EW data. The basic problem with these kinds of models was the way in which new physics was coupled to the SM. To resolve these problems, a class of models with another symmetry, named T-parity, was introduced. These classes of models were investigated in ref. [3]. These T-parity models had another advantage in that they provided a very useful dark matter candidate. In our work [1] we have analyzed $\gamma\gamma \rightarrow \gamma\gamma$ in both the LH and LH with T-parity models.

2. The $\gamma\gamma \rightarrow \gamma\gamma$ cross-sections

The process $\gamma(p_1, \lambda_1)\gamma(p_2, \lambda_2) \rightarrow \gamma(p_3, \lambda_3)\gamma(p_4, \lambda_4)$ can be represented by 16 possible helicity amplitudes $F_{\lambda_1\lambda_2\lambda_3\lambda_4}(\hat{s}, \hat{t}, \hat{u})$, where p_i and λ_i represent the respective momenta and helicities; $\hat{s}$, $\hat{t}$ and $\hat{u}$ are the usual Mandelstam variables. By the use of Bose statistics, crossing symmetries and demanding parity and time-invariance, these 16 possible helicity amplitudes can be expressed in terms of just three amplitudes, namely (the relationships between the various helicity amplitudes is given in Appendix A of our paper [1]) $F_{++++}(\hat{s}, \hat{t}, \hat{u}), F_{+++-}(\hat{s}, \hat{t}, \hat{u}), F_{++--}(\hat{s}, \hat{t}, \hat{u})$. As such, the cross-section for this process can be expressed as [4]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau \mathrm{d}\cos\theta^*} = \frac{\mathrm{d}\bar{L}_{\gamma\gamma}}{\mathrm{d}\tau} \left\{ \frac{\mathrm{d}\bar{\sigma}_0}{\mathrm{d}\cos\theta^*} + \langle\xi_2\xi_2'\rangle \frac{\mathrm{d}\bar{\sigma}_{22}}{\mathrm{d}\cos\theta^*} + [\langle\xi_3\rangle\cos 2\phi + \langle\xi_3'\rangle\cos 2\phi] \right.$$

$$\times \frac{\mathrm{d}\bar{\sigma}_3}{\mathrm{d}\cos\theta^*} + \langle\xi_3\xi_3'\rangle \left[\frac{\mathrm{d}\bar{\sigma}_{33}}{\mathrm{d}\cos\theta^*} \cos 2(\phi + \phi') + \frac{\mathrm{d}\bar{\sigma}_{33}'}{\mathrm{d}\cos\theta^*} \cos 2(\phi - \phi') \right]$$

$$\left. + [\langle\xi_2\xi_3'\rangle \sin 2\phi' - \langle\xi_3\xi_2'\rangle \sin 2\phi'] \frac{\mathrm{d}\bar{\sigma}_{23}}{\mathrm{d}\cos\theta^*} \right\}, \tag{1}$$

where $\mathrm{d}\bar{L}_{\gamma\gamma}$ describes the photon–photon luminosity in the $\gamma\gamma$ mode and $\tau = s_{\gamma\gamma}/s_{ee}$. Note that ξ_2, ξ_2', ξ_3 and ξ_3' are the Stokes parameters. To obtain the total cross-section from the above expressions, the integration over $\cos\theta^*$ has to be done in the range $0 \leq \cos\theta^* \leq 1$. However, the whole range of θ^* will not be experimentally observable. Hence, for our numerical estimates we will restrict the scattering angle to $|\cos\theta^*| \leq \sqrt{3}/2$. The process $\gamma\gamma \rightarrow \gamma\gamma$ proceeds through the mediation of charged particles. In the SM these charged particles were charged gauge bosons (W), quarks and charged leptons. In the LH model, in addition to the charged gauge bosons and fermions, we also have charged scalars. The analytical expressions of the contributions from fermions, gauge bosons and scalars to the helicity amplitudes are given in ref. [4] and are quoted in Appendix A of our paper [1]. In our work we have analyzed the effects of the LH models on various polarized cross-sections defined in eq. (1).

3. Results and conclusions

As the $\gamma\gamma \to \gamma\gamma$ scattering proceeds through loops, both in the SM and in the LH models (where these loops intermediate particles are pair produced), in the SM these are dominated by W loops, leading to a peak in the SM cross-sections around the threshold of the W pair production [4]. Similarly, in the LH model, the dominant contribution will come from the new heavy W-boson and the Higgs particles (especially those that are doubly charged, as the amplitudes are proportional to the fourth power of the charge), once we exceed the threshold for the pair production of these particles. As such, we have plotted the various cross-sections for a range of energies ($\sqrt{s_{\gamma\gamma}}$) well above the threshold for the SM W-bosons, but in the vicinity of the pair production energy for the new particles in the LH models. Note further, that we have integrated our differential cross-sections in the angular range $30^\circ \leq \theta^* \leq 150^\circ$.

As expected, the deviation in the SM value of the cross-sections becomes visible around the threshold of the pair production of LH particles, where the present constraints on the LH models force the masses of all the new heavy particles to be of the order of TeV.

In all cases we can get substantial deviations in the cross-sections due to LH effects. However, σ_3 and σ'_{33} provide the most interesting results (as given in figures 1 and 2), where σ_3 is the only cross-section with pronounced 'dips'. The location of these 'dips' is dependent on the model parameters. The other feature of note in these plots is the pronounced peaks in the σ'_{33} cross-section. The SM values of the cross-sections σ_3 and σ'_{33} are relatively small as compared to the other cross-sections. However, the LH effects in these two cross-sections are very striking. These effects mainly depend upon the LH parameter f (the symmetry breaking scale of the global symmetry).

Though the results we have presented are rather generic, they can be used as a probe for heavy charged gauge bosons and charged scalars. In our results we have tried to focus ourselves to the range of cm energy ($\sqrt{s_{\gamma\gamma}}$) which is close to the threshold of the pair production of the particles. The deviations from SM results as shown will not be observable in the proposed international linear collider (ILC), but will be easily probed in a multi-TeV e^+e^- compact linear collider (CLIC); where it is proposed to build an e^+e^- linear collider with a center-of-mass energy from 0.5 to 3 TeV. Generically such a mode should lead to $\gamma\gamma$ collisions at cm energies $E_{\rm cm}^{\gamma\gamma} \leq 0.8 E_{\rm cm}^{ee}$. Furthermore, the polarized cross-sections σ_3 and σ'_{33} can be used to test the spin structure of the particle loops which are responsible for the $\gamma\gamma \to \gamma\gamma$ process [4]. In summary the $\gamma\gamma \to \gamma\gamma$ process is a very clean process which shall provide a very useful tool for testing LH-type models.

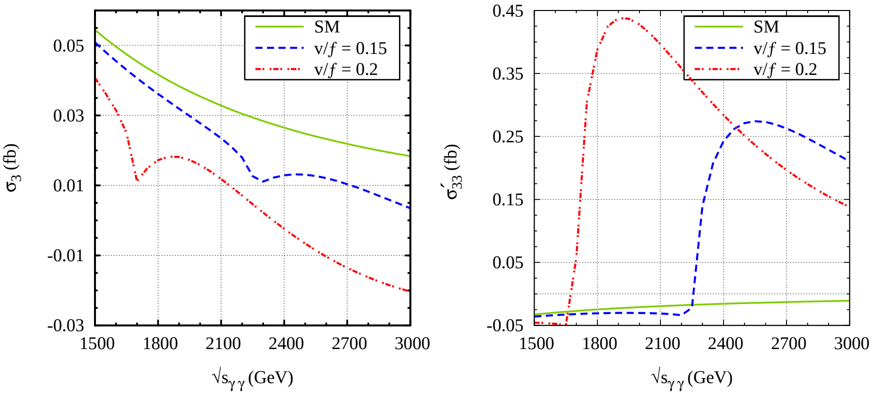

Figure 1. Results for the cross-sections integrated in the range $30 \leq \theta^* \leq 150$ for various values of v/f. Other LH model parameters are: $x_L = 0.2, s = s' = 0.6$.

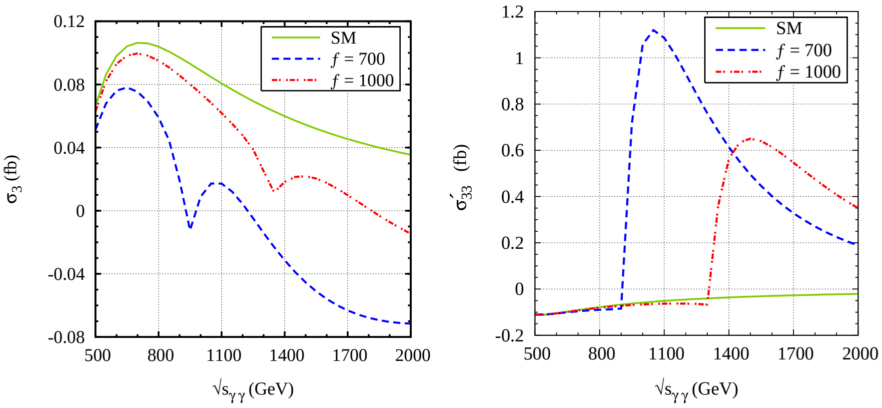

Figure 2. Results for the cross-sections integrated in the range $30 \leq \theta^* \leq 150$ for various values of v/f in LH model with T-parity.

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