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Associated single photons and doubly-charged scalars at linear e^-e^- colliders

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Abstract. Doubly-charged scalars, predicted in many models having exotic Higgs representations, can in general have lepton-number violating (LFV) couplings. We show that by using an associated monoenergetic final state photon seen at a future linear e^-e^- collider, we can have a clear and distinct signature for a doubly-charged resonance. The strength of the $\Delta L = 2$ coupling can also be probed quite effectively as a function of the recoil mass of the doubly-charged scalar.

Keywords. Doubly-charged Higgs; associated photon; initial state radiation.

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Doubly-charged scalars arise in a number of physics scenarios [1,2], the most common models to accommodate such scalars are those with triplet Higgs. An added feature often associated with doubly-charged Higgs is the possibility of lepton-number violation. This basically consists of $\Delta L = 2$ couplings with leptons of the form

$$L_Y = ih_{ij}\Psi_{iL}^T C\tau_2\Phi\Psi_{jL} + \text{h.c.}, \tag{1}$$

where $i, j = e, \mu, \tau$ are generation indices, the Ψ's are the two-component left-handed lepton fields, and Φ is the triplet with $Y = 2$ weak hypercharge. This leads to mass terms for neutrinos once the neutral component ϕ^0 of Φ acquires a vacuum expectation value (VEV):

$$M_{ij}^{\nu} \sim h_{ij}v' \tag{2}$$

v' being the triplet VEV. Constraints on the ρ-parameter put strong limits on the triplet VEV [3] translating into limits on the L-violation Yukawa couplings from the expected ranges of neutrino masses. Such limits usually constrain the collider signals for doubly-charged scalars sought through $\Delta L = 2$ interactions.

We point out the usefulness of looking for doubly-charged scalars in an e^-e^- collider, in the radiative production channel. Resonant production of ϕ^{--} requires one to know its mass with reasonable accuracy to start with, and tune the center-of-mass energy of the colliding electrons accordingly. In addition, precise identification of a doubly-charged resonance will also depend on its decay products, which depend on the parameters of the L-violating sector. In general, one can have the decays

$$\phi^{--} \to W^-W^-, l^-l^-, W^-\phi^-, \phi^-\phi^-.$$

A degeneracy among the triplet components is often a consequence of theories, albeit in a model-dependent fashion. If we thus neglect the last two channels listed above, we still have the W^-W^- and l^-l^- channels, of which the first is controlled by the triplet VEV v' and the second, by the coupling h_{ll}. When the first mode is dominant, it requires careful analysis of the W-decay products in order to isolate signatures of resonant production. It is thus desirable to have supplementary channels in mind while looking for doubly-charged scalars. With this in view, we have calculated the rates for the process

$$e^-e^- \longrightarrow \phi^{--}\gamma \longrightarrow X\gamma$$

at a $\sqrt{s} = 1$ TeV e^-e^- machine, concentrating on the hard single photon in the final state. This photon will be monochromatic if a doubly-charged resonance is produced, irrespective of what it decays into. Furthermore, one is no more required to tune the electron–electron center-of-mass energy at a fixed value. For our analysis, taking the radiative production of the scalar ϕ^{--} as the benchmark process, we concentrate only on the flavor diagonal coupling h_{ee}. In our numerical estimate, we have chosen the coupling strength to be $h_{ee} = 0.1$ which respects the most stringent bounds coming from muonium–antimuonium conversion results which for flavor diagonal coupling is $h < 0.44M_{\phi}^{\pm\pm}$ TeV^{-1} at 90% CL. The on-shell radiative production of a doubly-charged scalar gives an almost monochromatic photon of energy

$$E_\gamma = \frac{s - M_{\phi^{--}}^2}{2\sqrt{s}} \tag{3}$$

which stands out against the continuum background of the standard model (SM). We assume that the h_{ii} couplings are of equal strength. The total decay width of ϕ^{--} thus obtained is very miniscule ($\sim$1.2 GeV) for a 1 TeV scalar mass when compared to the machine energy and allows one to use the narrow-width approximation.

The major SM background that contributes to the above process is the radiative Moller scattering process: $e^- + e^- \to \gamma + e^- + e^-$ which, although a continuum background, could *prima facie* be large enough to wash away the monochromatic peak. The event selection criteria, therefore, are largely aimed at suppressing this continuum background. We impose the following set of cuts.

- Rapidity cut on the final state particles: $|\eta(e^-)| < 1.5$ and $|\eta(\gamma)| < 2.5$
- Minimum cut on energies: $E(\gamma) > 20$ GeV, $E(e^-) > 5$ GeV
- To ensure that the final state particles are well separated in space for the detectors to resolve events: $\delta R > 0.2$

Using the above cuts we make an estimate of the SM background and the signal. We focus on the main trigger, viz. the photon. In figure 1a we show the distribution of the photon energy, where we have superposed the differential cross-section for

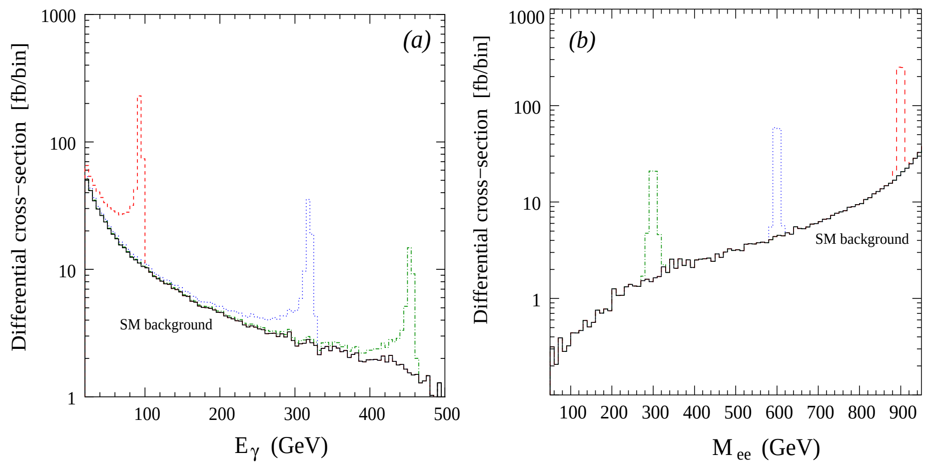

Figure 1. Differential cross-sections against (**a**) photon energy E_γ and (**b**) invariant mass of electron pair M_{ee}. The dash-dot-dash (green) line corresponds to $M_{\phi^{--}} = 300$ GeV, dotted (blue) line corresponds to $M_{\phi^{--}} = 600$ GeV and the dashed (red) line corresponds to $M_{\phi^{--}} = 900$ GeV respectively. The bin size is chosen to be 5 GeV in (**a**) and 10 GeV in (**b**).

signal+background in each bin over the SM background. A pronounced peak can be seen in the photon energy distribution, due to the monochromaticity of the photon, corresponding to the recoil energy against the scalar resonance through the relation of eq. (3). To make our analysis realistic, we have smeared the photon energy by a Gaussian function whose half-width is guided by the resolution of the electromagnetic calorimeter [4,5] and also incorporated the effects of ISR which often results in substantial broadening of the peak. We show the resulting peak for three choices of scalar mass (300, 600, 900 GeV). Alternatively, in figure 1b, we also show the invariant mass distribution of the ee pair for the above choice of parameters and as expected the distribution peaks corresponding to the mass of scalar.

In figure 2a we plot the energy distribution of the photon once again but here we only look at the final state hard transverse photon in $e^-e^- \to \gamma + \phi^{--} \to \gamma + X$. The distribution again shows peaks corresponding to the recoil against the massive scalars, irrespective of the knowledge of the decay products of the scalar. In fact, our signal here receives a relative boost as it is not suppressed by considering any further decay since $\mathrm{BR}(\phi^{--} \to X) = 100\%$. The fact that looking at a single photon against the backdrop of a continuum background makes it possible to identify a LFV ($\Delta L = 2$) process in a model independent way, makes this signal worth studying at a future e^-e^- collider and running the linear collider in this mode.

Since the rates for the signal depend directly on the eeH coupling squared, in figure 2b we show the strength of the coupling for which the peaks would stand out against the fluctuations in the SM background. In our analysis we have assumed a luminosity of $\mathcal{L} = 100\ \mathrm{fb}^{-1}$. The fact that we are not looking at any specific final state arising from ϕ^{--} decay improves the reach of this search channel. However, if a direct resonance is excited then that would invariably translate into a much

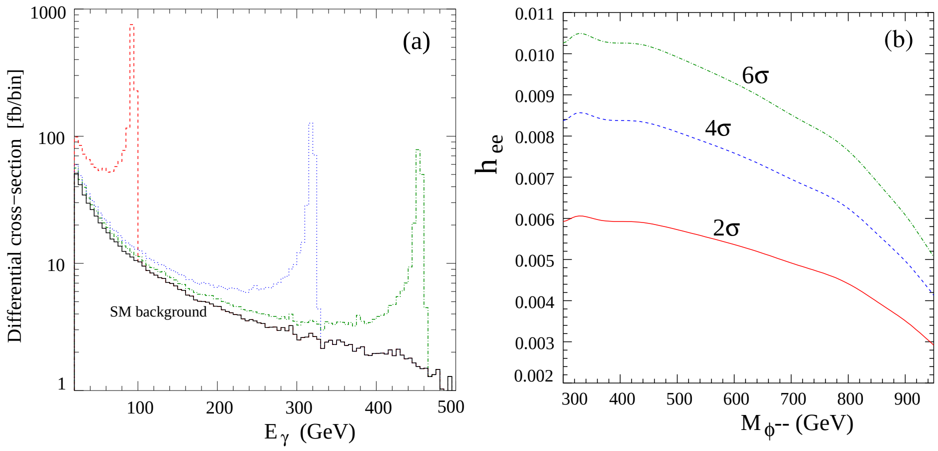

Figure 2. (**a**) Differential cross-sections against photon energy E_γ when $\phi^{--} \rightarrow X$ (anything). The dash-dot-dash (green) line corresponds to $M_{\phi^{--}} = 300$ GeV, dotted (blue) line corresponds to $M_{\phi^{--}} = 600$ GeV and the dashed (red) line corresponds to $M_{\phi^{--}} = 900$ GeV respectively. (**b**) Illustrating the reach of the coupling constant at which the resonances in the E_γ distribution can be identified over the fluctuations in the SM background. The assumed luminosity is 100 fb^{-1}.

stronger probe of the coupling strength. Nonetheless, our analysis is not dependent on the tuning of $\sqrt{s}$ of the machine to hit a resonance and hence serves as a more robust proposition. For luminosity higher than what we have used, this reach can be further enhanced.

To summarise, the cleanliness of central photon detection at a high energy linear collider can be very helpful in identifying a doubly-charged scalar. The peaks in the hard photon energy can be helpful in two ways. First, one does not need to tune the two electron beams, and can therefore work without a prior knowledge of the ϕ^{--} mass. Secondly, this method is shown to work even if the ϕ^{--} dominantly decays into states that are not clean enough for the resonance to be identified. Thus, as soon as one succeeds in reducing the SM backgrounds, one can clearly see $\Delta L = 2$ interactions, just by looking at the accompanying hard photon. Not only doubly-charged scalars but also more exotic resonances such as bileptons are amenable to detection in this manner.

This talk was based on an earlier work and for further details one is suggested to look at ref. [6].

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