ASSOCIATED SINGLE PHOTONS AS SIGNALS FOR A DOUBLY CHARGED SCALAR 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. The basis of most searches for this charged scalar has been to look for its direct production and its subsequent decay to like-sign final state leptons. In this work 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 and also determine its mass rather precisely. We also estimate the strength of the $\Delta L = 2$ coupling which can be probed in this way at $\sqrt{s} = 1$ TeV, as a function of the recoil mass of the doubly-charged scalar.
The absence of the Higgs boson from the cupboard containing *particle trophies* discovered by experimentalists, still leaves a scope of speculation as to what would eventually be the possible structure for $SU(2) \times U(1)$-breaking. Thus scenarios with extended Higgs sectors, ranging from ones with two or more doublets to those with other representations of $SU(2)$, are often considered. Doubly charged scalars arise in a number of such scenarios [1, 2]. The most common models to accommodate such scalars are those with triplet Higgs. Triplets can be made part of the electroweak symmetry breaking sector in purely phenomenological studies [3–5]. On the other hand, they may be indispensable in some special theories such as the simplest versions of Little Higgs models [6], where the Higgs is envisioned as a pseudo-goldstone boson, and the triplets are required to cancel the quadratic divergence to the Higgs mass.

An added feature often associated with doubly-charged Higgs is the possibility of lepton-number violation. This basically consists in $\Delta L = 2$ couplings with leptons of the form

$$L_Y = i h_{ij} \Psi_i^T C \tau_2 \Phi \Psi_j + h.c.$$  \hspace{1cm} (1)

where $i, j = e, \mu, \tau$ are generation indices, the $\Psi$'s are the two-component left-handed lepton fields, and $\Phi$ is the triplet with $Y = 2$ weak hypercharge and is given by the $2 \times 2$ matrix of the scalar fields:

$$
\begin{pmatrix}
\phi^+/\sqrt{2} & \phi^{++} \\
\phi^0 & -\phi^+/\sqrt{2}
\end{pmatrix}
$$

This leads to mass terms for neutrinos [1, 7] once the neutral component $\phi^0$ acquires a vacuum expectation value (vev):

$$M^\nu_{ij} \sim h_{ij} v'$$  \hspace{1cm} (2)

$v'$ being the triplet vev. Since constraints on the $\rho$-parameter [8] puts strong limits on the the triplet vev [9] in general, this immediately translates to limits on the L-violation Yukawa couplings from the expected ranges of neutrino masses [10]. Such limits usually constrain the collider signals for doubly-charged scalars sought through $\Delta L = 2$ interactions. Of course, there are models where the limits from the $\rho$-parameter can be avoided [11] by postulating real as well as complex triplets at the same time, and assuming a custodial symmetry relating
their vev [3]. Although such a custodial symmetry has been found to be preserved in higher-order corrections from the scalar potential [12], its stability against corrections via gauge coupling is not obvious. Thus it is safe to abide by the constraints on both the triplet vev $\langle \phi^0 \rangle$ and the quantities $h_{ij}\langle \phi^0 \rangle$ in an analysis related to collider signals.

In this paper we point out the usefulness of looking for doubly-charged scalars in an $e^-e^-$ collider, in the radiative production channel. A linear collider with, say, $\sqrt{s} = 1$ TeV can operate for part of its run-time in the electron mode, where certain signals can be remarkably free from backgrounds. Also, this mode is perhaps ideal for exploring scenarios with $\Delta L = 2$ couplings. As for doubly-charged scalars, their resonant production in $e^-e^-$ as well as $\mu^-\mu^-$ have been already studied [11,13]. However, resonant production of the $\phi^--$ 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 [14], which depend on the parameters of the L-violating sector. In general, one can have the decays

- $\phi^-- \rightarrow W^-W^-$
- $\phi^-- \rightarrow l^-l^-$
- $\phi^-- \rightarrow W^-\phi^-$
- $\phi^-- \rightarrow \phi^-\phi^-$

Of these, the third mode, if kinematically possibly, is dominant as it is driven by gauge coupling. However, 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. Furthermore, the analysis becomes complicated in case the $\phi^-\phi^-$ can decay into a $\phi^-$ or a pair of them.

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

$$e^-e^- \rightarrow \phi^--\gamma \rightarrow X\gamma$$
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 [15]. And finally, one can use such a study of monochromatic single photons in $e^-e^-$ collision to include the search for doubly-charged objects other than the scalar discussed above, an example being bilepton resonances [16].

For our analysis, taking the radiative production of the scalar $\phi^{--}$ as the benchmark process, we concentrate only on the flavor diagonal coupling $h_{ee}$. Others, especially the non-diagonal couplings, are subject to very stringent bounds from rare decay processes of $\mu^\pm$ and $\tau^\pm$ leptons. The rare decay studies [17] provide bounds on the product of couplings as:

$$h_{e\mu} h_{ee} < 3.2 \times 10^{-11} \text{ GeV}^{-2} M_{\phi^{\pm\pm}}^2$$  \hspace{1cm} (3)

$$h_{e\mu} h_{\mu\mu} < 2.0 \times 10^{-10} \text{ GeV}^{-2} M_{\phi^{\pm\pm}}^2$$  \hspace{1cm} (4)

The relevant bounds in our case are the following upper bounds, which come from Bhabha scattering [18]:

$$h_{ee}^2 \sim 6.0 \times 10^{-6} \text{ GeV}^{-2} M_{\phi^{\pm\pm}}^2$$  \hspace{1cm} (5)

and from $(g-2)_\mu$ measurements [19]:

$$h_{\mu\mu}^2 \sim 2.5 \times 10^{-5} \text{ GeV}^{-2} M_{\phi^{\pm\pm}}^2$$  \hspace{1cm} (6)

Much stringent upper bounds exist from the measurements of muonium-antimuonium transition [20] in the form of the product of the couplings:

$$h_{ee} h_{\mu\mu} \sim 2.0 \times 10^{-7} \text{ GeV}^{-2} M_{\phi^{\pm\pm}}^2$$  \hspace{1cm} (7)

The above bounds allow for small value of doubly-charged scalar mass with small coupling constant. In our numerical estimate, we have chosen the coupling strength to be $h_{ee} = 0.1$ which is consistent with the limits obtained from Bhabha scattering [21,22] and also respects the most stringent bounds coming from muonium-antimuonium conversion results which for flavor diagonal coupling is $h < 0.44 M_{\phi^{\pm\pm}} \text{ TeV}^{-1}$ at 90% C.L. The latter bound however, can be relaxed in different new physics models [23].

As has been mentioned already, on-shell radiative production of a doubly-charged scalar gives an almost monochromatic photon of energy

$$E_\gamma = \frac{s - M_{\phi^{\pm\pm}}^2}{2\sqrt{s}}$$  \hspace{1cm} (8)
which stands out against the continuum background of the standard model (SM). In the discussions to follow based on our work, we show how, by simply tagging on the isolated photon in the final state without bothering about the the other associated particles, and looking at the line spectrum superposed on the continuum background, leads to clear signals for the production of a doubly-charged scalar.

Before we present the results of our analysis, it may be noted that there exist studies on the doubly-charged scalar in the context of hadron colliders [24] and in different modes of operation of linear colliders other than $e^−e^−$ collision [13,25] and $e^+e^−$ mode [26], such as the $eγ$ and $γγ$ modes [27]. Although these works point out interesting ways of producing doubly-charged scalars either singly or in pair, the latter are somewhat restrictive in mass reach, considering the fact that a back-scattered photon carries a fraction of the initial electron beam energy. Moreover, there is an unavoidable kinematic suppression in pair-production in the $γγ$ channel, in spite of the spectacular enhancement of rates due to the electric charge(s). Also, another possible channel for associated production of a doubly charged Higgs in $e^−e^−$ collisions has been looked at in ref [28]. In this work we show that we can probe the full energy reach of the collider in its fundamental mode of running, and is only restricted by the phase-space restrictions due to the kinematic cuts used for the selection of events. Hardness and transversality cuts on the photon in our final state are presumed to avoid any confusion with initial state radiation (ISR) or beamstrahlung photons.

Figure 1: Feynman graphs corresponding to single production of a doubly-charged scalar along with an associated photon in $e^−e^−$ collisions.

The Feynman diagrams contributing to the associated photon process are shown in Figure 1. It is worth mentioning here that since they involve clashing fermion lines, one has to be careful while writing down the Feynman amplitudes and carefully handle the charge conjugation operator appearing in the Feynman rules for the $eeH$ vertices. Using the properties
of the charge conjugation operator $C$, it is a matter of simple algebra to write down the matrix amplitude squares for the different graphs in Figure 1. The above process is also a clear indicator of a $\Delta L = 2$ process. We look at this process in the context of a $\sqrt{s} = 1$ TeV linear $e^-e^-$ collider. As discussed earlier, we consider decay of the doubly-charged scalar to like signed leptons only and that too of the same flavor. We assume that the $h_{ii}$ couplings are of equal strength and so the branching ratio $\text{BR}(\phi^{--}\rightarrow l_i^-l_i^-) = 1/3$ for $i = 1, 2, 3$. In this work we have consistently chosen the coupling strength to be $h_{ee} = 0.1$ and we calculate the decay width of the doubly-charged scalar assuming the decays to leptons only. In other words, we assume the triplet $vev$ to be very small, so it hardly contributes to the decay mode of $\phi^{--}\rightarrow W^-W^-$ which is directly proportional to the triplet $vev$ squared $(v'^2)$ and we have also neglected the other possible decay modes of $\phi^{--}$ as pointed out earlier. We find that the total decay width obtained is very miniscule ($\sim 1.2$ GeV) for a 1 TeV scalar mass when compared to the machine energy. So we can use the narrow-width approximation and consider on-shell production of the doubly-charged scalar and its subsequent decay to $e^-e^-$. The major SM background that contributes to the above process is the radiative Moller scattering process:

$$e^- + e^- \rightarrow \gamma + e^- + e^-$$

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. Since we do not want the final state particles to be too close to the beam pipe, one needs to have a rapidity cut on the final state particles:

$$|\eta(e^-)| < 3.0 \quad \text{and} \quad |\eta(\gamma)| < 2.5$$

We also demand a hard photon in the final state, which is the main focus of our work. This is obtained by imposing a cut on the minimum photon energy:

$$E(\gamma) > 20 \text{ GeV}$$

A minimum energy is also demanded for both the final state electrons:

$$E(e^-) > 5 \text{ GeV}$$
Figure 2: Differential cross-sections for (a) signal with $|\eta_e| < 3.0$, (b) signal+background and SM background with $|\eta_e| < 3.0$ and (c) signal+background and SM background with $|\eta_e| < 1.5$, against electron rapidity $\eta_e$.

The above criteria help us in suppressing the continuum background to a considerable extent. Finally we would like the detectors to register and resolve events for the different particles and hence all the final state particles should be well separated in space and satisfy:

$$\delta R > 0.2$$

where $(\delta R)^2 \equiv (\Delta \phi)^2 + (\Delta \eta)^2$ with $\Delta \eta$ and $\Delta \phi$ respectively denoting the separation in rapidity and azimuthal angle for the pair of particles under consideration. Using the above cuts we make an estimate of the SM background and the signal. The background has been generated using the MadEvent Monte Carlo generator [29]. It is found that the background is quite large compared to the signal with a cross-section of about 3216 $fb$. In Figure 2 we
show the distribution for the differential cross-section as a function of the electron rapidity. It is worth noticing that the SM background is symmetric in the binwise distribution for \( \eta(e^-) \) of the final state electron and is peaked away from the central region of the rapidity distribution (Fig 2(b)), which means that they are more in the forward direction. This is expected due to the strong t-channel radiative contribution to Moller scattering. On the same curve we also show the distribution for the signal+background for two different values of the doubly-charged scalar mass, \( m_{\phi^{--}} = 300 \text{ GeV} \) and 750 GeV. In contrast to the background, we find that the signal is peaked at the central region, which is clear from Fig 2(a) where we have plotted the signal alone and this peaking becomes more pronounced as the mass of the \( \phi^{--} \) increases. Infact for the low mass there does not seem to be much difference in the rapidity distribution but as the mass is increased to a higher value, the difference shows up with the signal peaked centrally. This can be easily understood if we look at the kinematics of production. The higher the mass of the \( \phi^{--} \), the less boost it will have and hence the decay products will come out back-to-back. Using this as a cue, we can actually implement a more stronger cut on the rapidity of the electron which will throw the signal into prominence. We find that a cut of

\[
|\eta(e^-)| < 1.5
\]
is good enough to kill the background by about 80% while the signal goes down only by about 45% for low masses ($\sim 300$ GeV) and by about 10% for large masses ($\sim 900$ GeV) for the doubly-charged scalar. With the kind of luminosity expected at future linear colliders we expect that the event rates would be considerable even if low mass state is realized and although the signal might drop by $40\%-50\%$, it will still stand out against the much reduced background due to this cut. To highlight this we implement the cut and plot the distribution

\begin{table}
| Cut on $\eta_e$ | $|\eta| < 3.0$ | $|\eta| < 1.5$ |
|----------------|----------------|----------------|
| $M_{\phi^\pm\pm}$ (GeV) | $\sigma_B$ (fb) | $\sigma_S$ (fb) | $\sigma_B$ (fb) | $\sigma_S$ (fb) |
| 300 | 65.5 | 35.4 |
| 400 | 72.7 | 47.9 |
| 500 | 84.8 | 62.5 |
| 600 | 3216.0 | 614.0 | 84.1 |
| 700 | 146.1 | 122.2 |
| 800 | 235.6 | 204.7 |
| 900 | 524.9 | 468.8 |

Table 1: Cross-sections for signal and the SM background corresponding to the two choices of rapidity cut on the final state electron.

Next, we focus on the main trigger, viz. the photon. In Fig 4(a) we show the distribution of the photon energy, where we have superposed the differential cross-section for signal+background in each bin over the SM background. A pronounced peak can be seen in Fig 4(c). It is clearly visible how the signal is enhanced compared to the background with this cut. We have demonstrated the signal+background for three different masses for the doubly-charged scalar, $m_{\phi^\pm\pm} = 300, 600, 900$ GeV. We also show the significance of the cut in Fig 4 by plotting the ratio of the cross-sections of the signal+background ($\sigma_{S+B}$) with the SM background ($\sigma_B$), for both the choices of the cut on electron rapidity, as a function of the doubly-charged scalar mass. The graph clearly highlights the enhancement in the signal to background ratio and reflects the increase in the cross-section as we go higher in scalar mass. In Table 1, we list the cross-sections (rounded off to the nearest integer) for different masses corresponding to the respective cuts imposed on the electron rapidity for a more quantitative outlook.
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.8. 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 [30, 31]:

$$\frac{\Delta E}{E} = \frac{14\%}{\sqrt{E}}$$

Moreover, we have fully incorporated the effects of ISR [32] which often results in substantial broadening of the peak, due to the spread in the effective center of mass energy available for our process. We have used CompHEP [33] to include ISR effects for the SM background. We show the resulting peak for three choices of scalar mass (300, 600, 900 GeV). Alternatively, in Fig 4(b), 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.

Here the half-width of the Gaussian function used for smear is [30, 31]:

$$\frac{\Delta E}{E} = \frac{15\%}{\sqrt{E}} + 0.01$$

In Fig 5 we plot the energy distribution of the photon once again. But here we assume that we do not have prior knowledge of the decay products of the doubly-charged scalar. In
other words, we only look at the final state hard transverse photon in

\[ e^- e^- \rightarrow \gamma + \phi^{--} \rightarrow \gamma + X \]

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 the \( BR(\phi^{--} \rightarrow X) = 100\% \). Through Fig.4 and Fig.5 we have shown that a single associated photon will show peaks in its energy distribution over the continuum background of SM, if a doubly-charged scalar is produced with mass \( M_{\phi^{--}} < \sqrt{s} \). We only demand that no electron in the final state can have a rapidity whose absolute value is greater than 1.5. 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, we can make an estimate of the strength of the coupling which can give substantial rates for identification of the peaks in the photon energy distribution. We do this for the case when \( \phi^{--} \rightarrow X \)

Figure 5: Differential cross-sections against photon energy \( E_\gamma \) 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. The binsize is 5 GeV.
Figure 6: Illustrating the reach of the coupling constant at which the resonances in the $E_\gamma$ distribution can be identified over the fluctuations in the SM background. The assumed luminosity is $100 \text{ fb}^{-1}$.

and in Fig. We show the strength of the coupling for which the peaks would stand out against the fluctuations in the SM background at $2\sigma, 4\sigma$ and $6\sigma$ level. In our analysis we have assumed a luminosity of $\mathcal{L} = 100 \text{ fb}^{-1}$, easily achievable at future linear colliders. We have also done this analysis based on the smear in photon energies due to finite resolution of the detector as well as ISR effects, as mentioned earlier. A bin of width 10 GeV about the signal peak in photon energy has been identified for each $M_{\phi^{-}-\phi^{-}}$. We then look at the fluctuations in the SM background in that bin and compare the corresponding rate for the signal. This procedure has been repeated for different coupling strengths. The fact that we are not looking at any specific final state arising from $\phi^{-}-\phi^{-}$ decay improves the reach of this search channel. Our analysis suggests that the peaks in the photon distributions will be distinguishable for coupling strengths as low as $0.006(0.010)$ for scalar mass of 300 GeV at $2\sigma(6\sigma)$ level and to about $0.0034(0.006)$ for scalar mass of 900 GeV at $2\sigma(6\sigma)$. This estimate far overwhelms the simple method of comparing total rates of signal and background and restricting the coupling strength in the parameter space. It is also worth mentioning that if one is to assign a certain order of detection efficiency $\epsilon$, with the final states then the
above reach atmost scales by $\epsilon^{-1/4}$. However, if a direct resonance is excited then that would invariably translate into a much stronger probe of the coupling strength [11]. Nonetheless, our analysis is not dependent on the tuning of the $\sqrt{s}$ 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. While it is true that final states such as $(\mu^-\mu^-)$ can be completely background-free, 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 $\phi^{--}$ mass. Secondly, this method is shown to work even if the $\phi^{--}$ 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 (using, for example, the electron rapidity cut), 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.

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