Neutrino Mass Generation at TeV Scale and New Physics Signatures from Charged Higgs at the LHC for Photon Initiated Processes

Kirtiman Ghosh, Sudip Jana, and S. Nandi

Abstract: We consider the collider phenomenology of a simple extension of the Standard Model (SM), which consists of an EW isospin $3/2$ scalar, $\Delta$ and a pair of EW isospin vector, $\Sigma$ and $\tilde{\Sigma}$, responsible for generating tiny neutrino mass via the effective dimension seven operator. This scalar quadruplet with hypercharge $Y = 3$ has a plethora of implications at the collider. Its signature at TeV scale colliders is expected to be seen, if the quadruplet masses are not too far above the electroweak symmetry breaking scale. In this article, we study the phenomenology of multi-charged quadruplet scalars, in particular, the multi-lepton signatures at the LHC arising from the production and decays of triply and doubly charged scalars. In the context of the Large Hadron Collider (LHC), we studied Drell-Yan (DY) pair production as well as pair production of the charged scalars via photon-photon fusion. For doubly and triply charged scalars, photon fusion contributes significantly for large scalar masses. We also studied collider constraints on the masses of doubly charged scalars in this model. We derive a lower mass limit of 725 GeV on doubly charged quadruplet scalar.

Keywords: Higgs Sector, Collider Phenomenology, Photon Fusion, Neutrino Mass.
1 Introduction

Evidence of physics beyond the Standard Model (SM) have essentially come from one of the most important discoveries namely, the discovery of non-zero tiny neutrino masses. In this paper, we consider a model which naturally accommodate small neutrino masses arising from dimension-7 operators. In order to realize TeV scale seesaw mechanism for the neutrino masses, the model includes a scalar quadruplet and a pair of vector-like fermion triplets. The characteristic signatures of this model at the hadron collider experiments like the Large Hadron Collider (LHC), arise from the production and decay of the triply- and doubly- charged scalars of the scalar quadruplet. In particular, the observation of a triply-charged scalar at the LHC would establish this type of seesaw mechanism as the most promising framework for generating neutrino masses. The charged scalars, in the framework of this model, dominantly decays into charged SM leptons and thus, result into tantalizing same-sign multi-lepton final state at the LHC.

The ATLAS and CMS collaborations at the LHC have already performed dedicated searches [1–5] for like-sign dilepton as a signatures of a doubly charged scalar ($\Delta^{\pm\pm}$). In absence of any significant deviation of data from the SM prediction, bounds are imposed on the mass of $\Delta^{\pm\pm}$ as a function of its decay into lepton pairs. For example, a search [2] for anomalous production of like-sign lepton (electron and muon only) pairs, arise from the production and decay of a doubly charged scalar, $\Delta^{\pm\pm}$, was performed by ATLAS collaboration with 20.3 fb$^{-1}$ of 8 TeV proton-proton collision data. Assuming 100% branching ratio (BR) of $\Delta^{\pm\pm}$ into a pair of leptons of a given flavor, a 95% CL lower limit of 465–550 (370–435) GeV (depending on the lepton flavour) in the context of left-right symmetry
was obtained on the mass of left-(right-)handed $\Delta^{\pm\pm}$. CMS collaboration [4, 5] with 4.93 fb$^{-1}$ (19.7 fb$^{-1}$) integrated luminosity of collected data at the LHC with 7(8) TeV center of mass energy had excluded doubly charged scalar mass below 169–395 (251–530) GeV. The range corresponds to 100% BR into different combinations of same-sign dilepton flavours in the final state, i.e., $e^+e^-, e^+\mu^-, e^+\tau^-, \mu^+\mu^-, \mu^+\tau^-, \tau^+\tau^-$. More stringent limits [1] i.e., 380 (530) GeV for $\Delta^{\pm\pm}_{R(L)}$ decaying into a pair of electrons with 50% BR, are now available from the LHC with 13 TeV center of mass energy and 13.9 fb$^{-1}$ integrated luminosity.

Quadruplet scalars, being charged under the SM gauge group, couple to photon and the SM electroweak (EW) gauge bosons ($Z$ and $W^\pm$). Therefore, these scalars are produced in pairs at the LHC from quark antiquark initial state via a $\gamma/Z/W^\pm$ exchange in the $s$-channel namely, via the Drell-Yan (DY) process. The experimental limits, discussed in the previous paragraph, are obtained assuming DY pair production of doubly charged scalars. However, charged scalars are also produced via $t(u)$-channel photon-photon fusion process. Photon density$^1$ being significantly smaller than the quark and gluon densities, photon fusion contribution to the pair-production of charged scalars was neglected in the literature [6, 7] as well as by the experimental groups [1–5]. However, photon coupling to a pair of charged scalar being proportional to the charge of the scalar, parton level photon fusion cross-sections are enhanced by a factor of $2^4$ and $3^4$ for the doubly and triply charged scalars, respectively. Moreover, photon fusion being a $t(u)$-channel process, falls slowly with parton center of mass energy ($\sqrt{s}$) compared to the $s$-channel DY process. Therefore, for larger masses of doubly and triply charged scalars, photon fusion production could be significant compared to the conventional DY production.

In this work, we have performed a comparative study of DY and photon fusion pair-production of multi charged scalars at the LHC with 13 TeV center of mass energy. And shown for the first time, that the pair production of triply and doubly charged scalars via the photon fusion contributes at a level comparable to the DY-process for large scalar masses. As a consequence, all the LHC search results for charged scalars change dramatically after consideration of photon initiated processes. In the context of present model, we obtained bound on the mass of doubly charged quadruplet scalar from the LHC doubly charged scalar search results and hence, excluded some parts of parameter space. We also studied the production and decay of triply charged scalars at 13 TeV LHC.

This paper is organized as follows. In section 2, we discuss about the model and neutrino masses. In section 3, we briefly discuss the production and decay modes of doubly and triply charged scalars, derive the exclusion limit on the doubly charged scalar mass and hence, on the parameter space, from the LHC 13 TeV results and analyze the characteristic collider signatures of these scalars at the future runs of the LHC. We finally conclude in section 4.

$^1$The inclusion of the photon as a parton inside the proton, with an associated parton distribution function (PDF) is required to include next-to-leading order (NLO) QED corrections. Since $\alpha_S^2$ is of the same order of magnitude as $\alpha_{EM}$ and in the era of precision phenomenology at the LHC when the PDFs are already determined upto NNLO in QCD, consistency of calculations require PDFs which are corrected atleast upto NLO QED.
2 Model and Formalism

In order to realize see-saw mechanism for generating tiny neutrino masses, in addition to
the usual SM matter fields, the model [8] includes two vector-like $SU(2)_L$ triplet leptons
($\Sigma$ and $\bar{\Sigma}$) and an isospin 3/2 scalar ($\Delta$) in the framework of the SM gauge symmetry
$SU(3)_C \times SU(2)_L \times U(1)_Y$. The particle contents along with their quantum numbers are
shown in the Table 1.

<table>
<thead>
<tr>
<th>SU$(3)_C \times SU(2)_L \times U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fermions:</strong> $\begin{pmatrix} u \ d \end{pmatrix} \sim (3, 2, \frac{1}{3}), u_R \sim (3, 1, \frac{2}{3}), d_R \sim (3, 1, -\frac{2}{3})$</td>
</tr>
<tr>
<td>$\begin{pmatrix} \nu_e \ e \end{pmatrix} \sim (1, 2, -1), e_R \sim (1, 1, -2), \nu_R \sim (1, 1, -2)$</td>
</tr>
<tr>
<td>$\Sigma \equiv \begin{pmatrix} \Sigma^{++} \ \Sigma^+ \ \Sigma^0 \end{pmatrix} \sim (1, 3, 2)$, $\bar{\Sigma} \equiv \begin{pmatrix} \bar{\Sigma}^0 \ \bar{\Sigma}^- \ \bar{\Sigma}^{--} \end{pmatrix} \sim (1, 3, -2)$</td>
</tr>
<tr>
<td><strong>Gauge:</strong> $G_{a,a=1-8}, A_{\mu, i=1-3}, B_{\mu}$</td>
</tr>
<tr>
<td><strong>Higgs:</strong> $H \equiv \begin{pmatrix} \phi^+ \ \phi^0 \end{pmatrix} \sim (1, 2, 1)$, $\Delta \equiv \begin{pmatrix} \Delta^{+++} \ \Delta^{++} \ \Delta^+ \ \Delta^0 \end{pmatrix} \sim (1, 4, 3)$.</td>
</tr>
</tbody>
</table>

Table 1. Fermion, gauge and Higgs contents of the model.

The most general renormalizable scalar potential consistent with scalar spectrum of
this model is given by,

$$V(H, \Delta) = \mu_H^2 H^\dagger H + \mu_\Delta^2 \Delta^\dagger \Delta + \frac{\lambda_1}{2} (H^\dagger H)^2 + \frac{\lambda_2}{2} (\Delta^\dagger \Delta)^2 + \lambda_3 (H^\dagger H)(\Delta^\dagger \Delta) + \lambda_4 (H^\dagger \tau_a H)(\Delta^\dagger T_a \Delta) + \{\lambda_5 H^3 \Delta^* + h.c.\}$$

(2.1)

where $\tau_a$ and $T_a$ are the generators of $SU(2)$ in the doublet and four-plet representations,
respectively.

The electroweak symmetry is broken spontaneously once the Higgs acquires the vacuum
expectation value ($VEV$), $v_H$. As was shown in [8], even with positive $\mu_\Delta^2$, due to the
Figure 1. Contour plot for $M_\Delta$ in $\lambda_5 - \tan \alpha$ plane. Mass scale for different color shaded regions is shown in the right side of the figure. Black shaded zone is excluded by current experimental limit.

$\lambda_5$ term in the potential, and the fields $\Sigma$ and $\bar{\Sigma}$, the neutral component of $\Delta$ acquires an induced VEV at the tree level, $v_\Delta = -\lambda_5 v^3/M_\Delta^2$. The experimental limit [9] on $\rho$-parameter gets constrained from the $\rho$ parameter which gets modified as $\rho \approx (1 - 6v_\Delta^2/v_H^2)$ in the presence of non-zero $v_\Delta$ requires $v_\Delta$ to be less than 2 GeV. The masses of neutral ($M_\Delta$) and charged ($M_{\Delta^i}$) component of isospin-3/2 scalars are given by [8, 10]

$$M_\Delta^2 = \mu_\Delta^2 + \lambda_3 v_H^2 + \frac{3}{4} \lambda_4 v_H^2,$$

$$M_{\Delta^i}^2 = M_\Delta^2 - q_i \frac{\lambda_4}{2} v_H^2,$$  \hspace{1cm} (2.2)

where $q_i$ is the (non-negative) electric charge of the respective field. The mass splittings are equally spaced and there are two possible mass orderings. For $\lambda_4$ positive, we have the ordering $M_{\Delta+++} < M_{\Delta++} < M_{\Delta+} < M_{\Delta^0}$ and for $\lambda_4$ negative, we have the ordering $M_{\Delta+++} > M_{\Delta++} > M_{\Delta+} > M_{\Delta^0}$. Due to the $\lambda_5$ term in the potential, there will be small mixing ($\alpha$) between SM Higgs and $\Delta$ and it is given by

$$\tan 2\alpha = \frac{3\lambda_5 v_H^2}{\sqrt{(M_\Delta^2 - M_\delta^2)^2 - 9\lambda_5^2 v_H^4}}.$$ \hspace{1cm} (2.3)

A contour plot for the mass $M_\Delta$ in mixing-coupling plane is shown in Figure 1. The mixing parameter $\alpha$ can be constrained from current experimental limit [11] and it is shown by black shaded zone in Figure 1.
2.1 Origin of Neutrino Masses

Neutrino masses arise \cite{8} from the following Yukawa interactions involving the heavy leptons $\Sigma$ and $\bar{\Sigma}$:

$$L_{\nu\text{-mass}} = Y_i L_i H^* \Sigma + Y_i L_i \Delta \bar{\Sigma} + M_\Sigma \Sigma \bar{\Sigma} + h.c.,$$  \hspace{1cm} (2.4)

where $Y_i$, $\bar{Y}_i$ are Yukawa couplings and $i$ is the generation index. Integrating out the $\Sigma$, $\bar{\Sigma}$ fermions, one obtains an effective dimension-5 neutrino mass operator \cite{6, 8}

$$L_{\text{eff}} = -\frac{(Y_i \bar{Y}_j + Y_j \bar{Y}_i) L_i L_j H^* \Delta}{M_\Sigma} + h.c.$$ \hspace{1cm} (2.5)

The tree level diagram generating this operator is shown in Figure 2(top panel). On the other hand, the 1-loop diagrams in the bottom panel of Figure 2 result into dimension-5 operator which also contribute to the neutrino mass. The detailed structure of the Yukawa interactions are given in \cite{6, 8}. Substituting the EW VEV, $v_H$, for the Higgs doublet and the induced VEV, $v_\Delta$, for the quadruplet in Equation.(2.5), we obtain dimension-7 operator induced neutrino masses, $m_\nu^{\text{tree}}$, as \cite{6, 8},

$$m_{\nu}^{\text{tree}}_{ij} = \frac{(Y_i \bar{Y}_j + Y_j \bar{Y}_i) v_\Delta v_H}{(M_\Sigma M_\Delta^2)},$$  \hspace{1cm} (2.6)

The contribution to the neutrino mass, $m_{\nu}^{\text{loop}}$, from the loop induced dimension-5 operators can be computed as \cite{6}

$$m_{\nu}^{\text{loop}}_{ij} = \frac{3 + \sqrt{3}}{16\pi^2} \frac{\lambda_S v_H^2 M_\Sigma}{(M_\Delta - M_H^2)} \left( \frac{M_\Delta^2 \log \left( \frac{M_\Delta^2}{M_\Sigma^2} \right) - M_H^2 \log \left( \frac{M_H^2}{M_\Sigma^2} \right)}{M_\Sigma^2 - M_\Delta^2} \right).$$  \hspace{1cm} (2.7)

To visualize the relative contribution of the dimension-7 and dimension-5 operators to the neutrino masses, in Figure 3, we present a contour plot of the ratio $m_{\nu}^{\text{loop}}/m_{\nu}^{\text{tree}}$ in the $(M_\Delta - M_\Sigma)$ plane. For smaller values of $M_\Delta$ and $M_\Sigma$, the dimension-7 (tree level) contribution dominates over dimension-5 (loop level) contribution.

For completeness of our study, in Table 3, we present the few benchmark values of $M_\Sigma$, $v_\Delta$, $Y$ and $Y'$ used in our analysis to generate the neutrino masses (presented in the last column of table 3) with correct order of magnitude.

3 Collider Phenomenology

As discussed in the in the previous section, the main motivation for postulation this model is to generate tiny neutrino masses which is achieved by introducing a TeV scale scalar $SU(2)_L$ quadruplet ($\Delta$) and a pair of vector-like $SU(2)_L$ triplet fermions ($\Sigma$ and $\bar{\Sigma}$). The existence of TeV scale multi-charged scalars (component of $\Delta$) and fermions (components of $\Sigma$ and $\bar{\Sigma}$) gives rise to the interesting possibility of probing this particular mechanism for neutrino mass generation at the LHC experiment. In this work, we have studied the production and signatures of the quadruplet scalars, in particular, multi-charged quadruplet scalars at
the LHC. Being a quadruplet under $SU(2)_L$, the multi-charged scalars can only be pair-produced at the LHC. After being produced in pairs, the quadruplet scalars decays into SM particles giving rise to interesting signatures at the collider. The production and decay and hence, the resulting collider signature of the quadruplet scalars are discussed in the following.

3.1 Associated and Pair Production of Charged Higgs

The LHC being a proton-proton collider, the pair production of $\Delta^{\pm\pm}\Delta^{\mp\mp}$, $\Delta^{\pm\pm}\Delta^{\mp\mp}$, and $\Delta^{\pm}\Delta^{\mp}$ takes place via the DY-processes (s-channel $\gamma$ and $Z$ exchanges) [cf. figure 4] with quark anti-quark in the initial state. Being s-channel, Drell Yan pair production cross-sections are significantly suppressed for larger $\Delta^{\pm\pm}/\Delta^{\pm\pm}/\Delta^{\pm\pm}$ masses. However, photo production of charged scalar pairs ($\gamma\gamma \rightarrow \Delta^{\pm\pm}\Delta^{\mp\mp}$, $\Delta^{\pm\pm}\Delta^{\mp\mp}$, and $\Delta^{\pm}\Delta^{\mp}$) takes place.
### Table 2

Order of neutrino mass for different values of yukawa couplings $Y$ and $Y'$ for the representative values of $M_{\Sigma}$ and $v_{\Delta}$. Here $v_H = 174$ GeV.

<table>
<thead>
<tr>
<th>Benchmark Point (BP)</th>
<th>$M_{\Sigma}$ (TeV)</th>
<th>$v_{\Delta}$ (GeV)</th>
<th>$Y$</th>
<th>$Y'$</th>
<th>$m_{\nu}$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP1</td>
<td>2</td>
<td>$10^{-6}$</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
<td>0.017</td>
</tr>
<tr>
<td>BP2</td>
<td>3</td>
<td>$3 \times 10^{-4}$</td>
<td>$10^{-3}$</td>
<td>$10^{-3}$</td>
<td>0.035</td>
</tr>
<tr>
<td>BP3</td>
<td>4</td>
<td>$5 \times 10^{-3}$</td>
<td>$10^{-4}$</td>
<td>$10^{-3}$</td>
<td>0.043</td>
</tr>
<tr>
<td>BP4</td>
<td>2</td>
<td>$3 \times 10^{-5}$</td>
<td>$10^{-3}$</td>
<td>$10^{-2}$</td>
<td>0.052</td>
</tr>
<tr>
<td>BP5</td>
<td>3</td>
<td>$3 \times 10^{-2}$</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
<td>0.035</td>
</tr>
</tbody>
</table>

![Contour plot](image)

- **Figure 3.** Contour plot of the ratio $m_{\nu}^{\text{loop}}/m_{\nu}^{\text{tree}}$ in the $(M_{\Delta} - M_{\Sigma})$ plane.

vis $t(u)$-channel exchange [cf. figure 5] of a charged scalar and hence, is not suppressed by the parton center of mass energy. Moreover, the coupling of photon with a pair of charged scalar being proportional to the charge of the scalar, the matrix element squared of photo productions are enhanced by a factor of $3^4$ and $2^4$ for triply and doubly charged scalars, respectively. However, the pair production of charged scalars at the LHC via photon-photon fusion is suppressed by the small parton density of photon inside a proton.

In fact, the parton density of photon is so small that most of the older versions of PDF’s do not include photon as a parton. However, if we want to include QED correction to the
PDF, inclusion of the photon as a parton with an associated parton distribution function is necessary. And in the era of precision physics at the LHC when PDF’s are determined upto NNLO in QCD, NLO QED corrections are important (since $\alpha_s^2$ is of the same order of magnitude as $\alpha$) for the consistency of calculations. Moreover, as discussed previously, photon-initiated processes could become significant at high energies for some processes. In view of these facts, NNPDF [12, 13], MRST [14] and CTEQ [15] have already included photon PDF into their PDF sets. However, different groups used different approaches for
modeling the photon PDF. For example, the MRST [14] group used a pasteurization for the photon PDF based on radiation off of primordial up and down quarks, with the photon radiation cut off at low scales by constituent or current quark masses. The CT14QED [15] variant of this approach constrains the effective mass scale using $e p \rightarrow e \gamma + X$ data, sensitive to the photon in a limited momentum range through the reaction $e \gamma \rightarrow e \gamma$. The NNPDF [12][13] group used a more general photon parametrization, which was then constrained by high-energy $W$, $Z$ and Drell-Yan data at the LHC.

We have also computed the production of $\Delta^{\pm\pm}$ in association with a $\Delta^{\mp\mp}$. Such a process proceeds through quark anti-quark initial state with the $s$-channel exchange of a $W^\pm$-boson. The couplings relevant for production and decay of doubly- and triply-charged scalars are shown in Table. 3.1. In order to numerically compute the cross-sections, the model has been implemented in CalcHEP package [16]. For the production cross-section, we use parton distribution function (PDF) NNPDF23_lo_as_0130 [12, 13], where the photon PDF\(^2\) is inclusive with the renormalization and factorization scales being chosen to be the invariant mass of the constituent sub-process. We calculate the pair and associated production cross-sections of $\Delta^{\pm\pm}$ and $\Delta^{\mp\mp}$ considering both DY and photon-photon fusion processes. In figure 6, we have shown the pair and associated production cross-sections of $\Delta^{\pm\pm}$ and $\Delta^{\mp\mp}$ at the 13 TeV LHC considering both DY and photon fusion processes. Figure 6 shows that photon fusion significantly contributes to total pair production cross-section of charged scalars for larger masses. For DY process, the QCD correction has been also computed, yielding a NLO K-factor of the order of 1.24 at the LHC energy [1]. But, the noticable fact is that photon-fusion contributes more than the NLO QCD corrections to the DY process for larger masses. The ratio of the two photon contribution relative to the Drell-Yan channel is shown in figure 7. From the plot (figure 7), we can see that for the higher mass region of $\Delta^{\pm\pm}$ and $\Delta^{\mp\mp}$, photon photon fusion contribution becomes much more significant compared to the DY process. As the pair

\begin{table}[h]
\centering
\begin{tabular}{ll}
\hline
Couplings & Values \\
\hline
$A^\mu \Delta^{\pm\pm} \Delta^{\mp\mp}$ & $-3 e (p_1 - p_2)_\mu$ \\
$A^\mu \Delta^{\pm\pm} \Delta^{\mp\mp}$ & $-2 e (p_1 - p_2)_\mu$ \\
$Z^\mu \Delta^{\pm\pm} \Delta^{\mp\mp}$ & $-3 e \cos 2\theta_w (p_1 - p_2)_\mu$ \\
$Z^\mu \Delta^{\pm\pm} \Delta^{\mp\mp}$ & $-2 e (\cos 2\theta_w - 1/2) (p_1 - p_2)_\mu$ \\
$W^\mu \Delta^{\pm\pm} \Delta^{\mp\mp}$ & $\sqrt{3/2} g (p_1 - p_2)_\mu$ \\
$\Delta^{\pm\pm} W^\mp W^\mp$ & $\sqrt{3} g^2 v_\Delta$ \\
$\Delta^{\pm\pm} l^+_i l^+_j$ & $m^2_{ij} / 2\sqrt{3} v_\Delta$ \\
\hline
\end{tabular}
\caption{The couplings relevant for production and decay of doubly- and triply-charged scalars.}
\end{table}

\(^2\)We can also use MRST2004qed_proton [14], CT14 qedinc [15] where the photon PDF is inclusive, including both inelastic and elastic contributions.
production cross section is enhanced by $Q^4$, where $Q$ is the charge of the respective charged scalars, the ratio of the two photon contribution relative to the Drell-Yan channel are much more higher for triply charged Higgs $\Delta^{+++}$. The results of figure.7 and figure.6 can be summarized as follows: there is a significant enhancement in the total pair production cross section arises from the photon fusion processes and thus, photon fusion can not be ignored for a proper LHC for the multi-charged scalars, whereas associated production channels remain unaffected.

![Figure 6](image.png)

**Figure 6.** Pair and associated production cross-sections of $\Delta^{++}$ and $\Delta^{+}$ at the 13 TeV LHC. Red solid (dashed) line is for $\Delta^{++}$ pair production cross section via both DY and photon fusion processes (only DY process) and blue solid (dashed) line is for $\Delta^{+}$ pair production cross section via both DY and photon fusion processes (only DY process). Green dotted line represents associated production cross section of $\Delta^{++}$ and $\Delta^{+}$.

### 3.2 Decay Modes of the Charged Higgs

In this section, we discuss different decay modes of the doubly and triply charged scalars. The representative Feynman diagrams for decay of triply (doubly) charged scalar $\Delta^{+++}$ ($\Delta^{++}$) are shown in figure. 9 (figure. 8). The decay modes of the charged scalars depend on the mass hierarchy between quadruplet scalars. As noted earlier in section 2, there are two possible ordering for the masses of the quadruplet scalars depending on the sign of the parameter $\lambda_4$ in the scalar potential. The two possible decay cascades for the triply and doubly charged scalars (depending on the mass hierarchy) are discussed in the following:

- **Case I**: When $\lambda_4 > 0$, we have $M_{\Delta^{+++}} < M_{\Delta^{++}} < M_{\Delta^+} < M_{\Delta^0}$, so that the triply charged Higgs boson $\Delta^{+++}$ can only decay to $W^\pm l_i^\pm l_j^\pm$ or $W^\pm W^\pm W^\pm$. These decays arise through the diagrams where $\Delta^{+++}$ emits a real $W^\pm$ and an off-shell $\Delta^{++}$ which subsequently decays to either two real $W^\pm$, or two same sign charged leptons. The corresponding decay rates are given by:
Figure 7. The ratio between $\sigma_{\gamma\gamma}$ and leading order $\sigma_{DY}$ for triply and doubly charged Higgs pair production at the 13 TeV LHC.

Figure 8. Feynman diagrams for decay of doubly charged scalar $\Delta^{\pm\pm}$.

$$\Gamma(\Delta^{+++} \to W^+ W^+ W^+) = \frac{3 g^6}{2048 \pi^3} \frac{v_\Delta^2 M_\Delta^5}{m_W^6} I,$$

(3.1)

$$\Gamma(\Delta^{+++} \to W^+ \ell^+ \ell^+) = \frac{g^2}{6144 \pi^3} \frac{M_\Delta \sum_{i} m_i^2}{v_\Delta^2} J,$$

(3.2)
where $I, J$ are dimensionless integrals and $m_i$ stands for the light neutrino masses. In the limit where $M_{\Delta} \gg m_W$, these integrals are approximately equal to one. Since the $W^\pm W^\mp W^\pm$ mode is proportional to $v_\Delta^2$, while the $W^\pm \ell^\mp \ell^\pm$ mode scales as $1/v_\Delta^2$, the former is the dominant one for larger values of $v_\Delta$, while the latter is dominant for smaller values of $v_\Delta$. In figure 10, we have shown the variation of branching ratio for the decay modes of triply charged Higgs $\Delta^{\pm\pm\pm}$ as a function of vev $v_\Delta$ (left) and mass $M_{\Delta}$ (right). We can see from the plot (see figure 10) that when the vev $v_\Delta$ is of order of KeV or less, dominantly decays to $W^\pm \ell^\mp \ell^\pm$.

The doubly charged Higgs $\Delta^{\pm\pm}$ has the following decay modes: $\Delta^{\pm\pm} \rightarrow W^\pm W^\pm, \ell^\pm \ell^\pm, \Delta^{\pm\pm} W^\mp\mp$ and $\Delta^{++} \pi^-$. The partial decay widths are given by,

$$\Gamma (\Delta^{\pm\pm} \rightarrow l^\pm l^\pm) = \frac{|M_{\Delta}^{ij}|^2}{8\pi(1+\delta_{ij})v_\Delta^2}M_{\Delta^{\pm\pm}}, \quad (3.3)$$

$$\Gamma (\Delta^{\pm\pm} \rightarrow W^\pm W^\pm) = \frac{3g^4v_\Delta^2M_{\Delta}^2}{32\pi m_W} \sqrt{1 - \frac{4M_{W}^2}{M_{\Delta^{\pm\pm}}^2}} \left[ 1 - \frac{4M_{W}^2}{M_{\Delta^{\pm\pm}}^2} + 12 \frac{m_W^4}{M_{\Delta^{\pm\pm}}^4} \right], \quad (3.4)$$

$$\Gamma (\Delta^{\pm\pm} \rightarrow \Delta^{\pm\pm} \pi^-) = \frac{3g^4}{32\pi}f_\pi^2 \frac{(\Delta M)^3}{m_W^4}, \quad (3.5)$$

where $M_{\Delta}^{ij}$ is the neutrino mass matrix, $f_\pi = 130$ MeV, $\delta_{ij}$ is the Kronecher’s delta and $l^\pm = e^\pm, \mu^\pm, \tau^\pm$. The decay into $\Delta^{\pm\pm\pm} W^\mp\mp$ is suppressed because of the off-shell $W^\pm$-boson ($W^\pm$) in the final state. We note that the decay width for the decay mode $\Delta^{\pm\pm} \rightarrow l^\pm l^\pm$ is proportional to $1/v_\Delta^2$, the decay width to $W^\pm W^\pm$ final state is proportional to $v_\Delta^2$, while the one to $\Delta^{\pm\pm} \pi^-$ is independent of $v_\Delta$, and proportional to $(\Delta M)^3$. In figure 11, we plot the relative branching ratios of $\Delta^{\pm\pm}$ as a function of $M_{\Delta}$ (right) and $v_\Delta$ (left). For simplicity, we have taken the masses of the quadruplets to

**Figure 9.** Feynman diagrams for decay of triply charged scalar $\Delta^{\pm\pm\pm}$. 
Figure 10. **Left**: Variation of branching ratio (Br) for different decay modes of $\Delta^{\pm\pm\pm}$ as a function of vev $v_\Delta$ for $M_{\Delta^{\pm\pm\pm}} = 300$ (Dotted), 800 (Dashed) and 500 (Solid) GeV. **Right**: Variation of branching ratio (Br) for different decay modes of $\Delta^{\pm\pm\pm}$ as a function of mass $M_{\Delta^{\pm\pm\pm}}$ for $v_\Delta = 40$ KeV (dotted), 100 KeV (dashed) and 1 KeV (Solid). Red and blue lines are for $W^+l^+l^+$ decay and $W^+W^+W^+$ decay respectively.

be the same\(^3\). As expected, for a very small $v_\Delta$, the decay to $l^\pm l^\pm$ dominate, whereas for higher values of $v_\Delta$, the mode $\Delta^{\pm\pi^\pm}$ dominate. For completeness, we have also done the calculation for a small mass splitting of 2.5 GeV and we get that for the vev $v_\Delta \leq 1.5$ KeV the branching ratio to same sign dilepton becomes 100%. The branching ratio study for different decay modes of $\Delta^{\pm\pm}$ for non-degenerate masses of $\Delta$ members can be found in our earlier paper \[7, 8\].

• Case II: When $\lambda_4 < 0$, we have $M_{\Delta^{\pm\pm\pm}} > M_{\Delta^{\pm\pm}} > M_{\Delta^{\pm}} > M_{\Delta^0}$. If the quadruplet components are not degenerate and $\Delta^{\pm\pm\pm}$ is the heaviest member in the quadruplet, then $\Delta^{\pm\pm\pm}$ decays to $\Delta^0$ and SM particles via cascades involving other quadruplet scalars: $\Delta^{\pm\pm\pm} \rightarrow \Delta^{\pm\pm}W^{\pm\pm} \rightarrow W^{\pm\pm}W^{\pm\pm}\Delta^0 \rightarrow W^{\pm\pm}W^{\pm\pm}W^{\pm\pm}\Delta^0$. The other possible decay mode of $\Delta^{\pm\pm\pm}$ is into a $\Delta^{\pm\pm}$ in association with a $\pi^{\pm}$. For large enough mass splitting between the quadruplet scalars, cascade decay dominates over the decay into $\Delta^{\pm\pm\pi^\pm}$.

3.3 Collider Signatures

In this work, we mainly focus on the same-sign dilepton decay mode of $\Delta^{\pm\pm}$. The same-sign dilepton decay of $\Delta^{\pm\pm} \rightarrow l^\pm l^\pm$ is characterized by an invariant mass peak at $m_{\Delta^{\pm\pm}}$ in

\(^3\)Constraints from the $\rho$ parameter dictates the splitting to be $< 38$ GeV \[6, 8\], and can be even smaller depending on the values of $\lambda_4$.\footnote{Constraints from the $\rho$ parameter dictates the splitting to be $< 38$ GeV \[6, 8\], and can be even smaller depending on the values of $\lambda_4$.}
the same-sign dilepton invariant mass distribution. In view of negligible SM background, same-sign dilepton channel characterized by an invariant mass peak in the dilepton invariant mass distribution is considered to be one of the cleanest channel to search at the LHC. Since we are interested mostly on the like-sign dilepton decay of $\Delta^{\pm\pm}$ and the LHC has already searched for a invariant mass peak in the like-sign dilepton invariant mass distribution, it is important to pin down the part of parameter space for which $\Delta^{\pm\pm}$ dominantly decays to dileptons. In figure 12 (left panel), we have shown the contour plot for branching ratio $\text{Br}((\Delta^{\pm\pm} \rightarrow l^\pm l^\pm))$ in $v_\Delta-M_{\Delta^{\pm\pm}}$ plane. Figure 12 (left panel) shows that for low $v_\Delta$, $\Delta^{\pm\pm}$ dominantly decays to dileptons. Therefore, if is possible to exclude low $v_\Delta$ region parameter space of this model from the absence of any new physics same-sign dilepton signature at the LHC with 13 TeV center of mass energy. The exclusion limits in the context

\[\text{Same-sign dilepton in the SM arises from the multiple } W^\pm \text{ and } Z\text{-boson production which are quite suppressed. For example, SSD can arise from 3 } W^\pm\text{-boson (}pp \rightarrow W^\pm W^\pm W^\mp\text{) production followed by leptonic decay of 2 same-sign } W^\pm\text{-boson and hadronic decay of the other. } W^\pm Z\text{ pair production also contributes to the background when both } W^\pm \text{ and } Z\text{-boson decays leptonically and one lepton from } Z\text{-decay falls out side detector coverage. Semi-leptonic decay of } t \bar{t}\text{ pairs also contribute to the SSD background when one } b\text{-quark decays leptonically. Though the leptons from the } b\text{-decay are usually rejected by the lepton isolation criteria, a non-negligible SSD background arises from } t \bar{t}\text{ production due to its huge cross-section at the LHC. Miss identification of a jet as lepton and charge miss-measurement of leptons also contributes to the background. However, all these backgrounds are estimated to be small. Moreover, the background same-sign dileptons are not characterized by any invariant mass peak.} \]
of this model will be discussed in the next section.

![Figure 12](image-url)

**Figure 12.** Contour plot for branching ratio $\text{Br}(\Delta^{\pm\pm} \rightarrow l^{\pm}l^{\pm})$ (left panel) and $\text{Br}(\Delta^{\pm\pm} \rightarrow W^{\pm}l^{\pm}l^{\pm})$ (right panel) in $v_\Delta-M_{\Delta^{\pm\pm}}$ plane. Branching ratio scale is shown in right side of the figure. Red shaded zone in both figure corresponds to $\text{Br}(\Delta^{\pm\pm} \rightarrow l^{\pm}l^{\pm})$ or $\text{Br}(\Delta^{\pm\pm} \rightarrow W^{\pm}l^{\pm}l^{\pm}) \sim 100\%$.

Other characteristic feature of this model is the existence of a triply charged scalar. The pair production cross-section of triply charged scalar is relatively large (see Figure 6) at the LHC because of its enhanced coupling with photon. After being produced, triply charged scalars decays into $W^{\pm}W^{\pm}W^{\pm}$ or $W^{\pm}l^{\pm}l^{\pm}$ depending on the part of parameter space. In figure. 12, we have shown the contour plot for branching ratio $\text{Br}(\Delta^{\pm\pm} \rightarrow W^{\pm}l^{\pm}l^{\pm})$ in $v_\Delta-M_{\Delta^{\pm\pm}}$ plane. Figure. 12 shows that for low $v_\Delta$, $\Delta^{\pm\pm} \rightarrow W^{\pm}l^{\pm}l^{\pm}$ decay dominates over $\Delta^{\pm\pm} \rightarrow W^{\pm}W^{\pm}W^{\pm}$. In both cases, the pair production and decay of $\Delta^{\pm\pm}$ interesting multi-lepton (6,5,4-leptons, same-sign three leptons e.t.c.) final states which will be discussed in the subsequent sections.

### 3.4 Bound on Doubly Charged scalar

In the context of LR-symmetry, the ATLAS Collaboration has recently searched [1] for the doubly-charged scalar decaying into a pair of like-sign leptons in the same-sign dileptons invariant mass spectrum with luminosity 13.9 $fb^{-1}$ at $\sqrt{s} = 13$ TeV. In absence of any significant deviation from the SM background prediction, limits are imposed on the doubly charged scalar pair production cross-section times branching ratio to leptons $(\sigma(\Delta^{++}\Delta^{--}) \times \text{Br}(\Delta^{\pm\pm} \rightarrow l^{\pm}l^{\pm}))$. In the context of LR-symmetric model, the bound on the $\sigma(\Delta^{++}\Delta^{--}) \times \text{Br}(\Delta^{\pm\pm} \rightarrow l^{\pm}l^{\pm})$ corresponds to a lower limit of 570 (420) GeV on the mass of doubly charged $SU(2)_L$ triplet(singlet) scalar assuming its 100% branching ratio to a pair of same-sign electrons.

In the context of our model, the pair production and subsequent leptonic decay of the doubly charged scalar $(\Delta^{\pm\pm})$ gives rise to similar signature at the LHC and hence, our model also should comply with non-observation of any excess in same sign dilepton search. As a result, the model independent limits on $\sigma(\Delta^{++}\Delta^{--}) \times \text{Br}(\Delta^{\pm\pm} \rightarrow l^{\pm}l^{\pm})$ is also
Figure 13. The observed and expected 95% C.L. upper limits of the production cross-section times branching ratio to electrons $[\sigma(\Delta^{++}\Delta^{--}) \times Br(\Delta^{\pm\pm} \rightarrow e^\pm e^\pm)]$ as a function of $M_{\Delta^{\pm\pm}}$ using ATLAS results [1] at $\sqrt{s} = 13$ TeV with 13.9 fb$^{-1}$ integrated luminosity. The theoretical prediction for $\sigma(\Delta^{++}\Delta^{--}) \times Br(\Delta^{\pm\pm} \rightarrow e^\pm e^\pm)$ in the context of present model for a $SU(2)_L$ quadruplet doubly charged scalar are presented by red solid (photon fusion + DY) and dashed (DY-only) lines. In the calculation of the theoretical cross-section, we have assumed $Br(\Delta^{\pm\pm} \rightarrow e^\pm e^\pm) = 100\%$ applicable in our model where the doubly charged scalars are quadruplet under $SU(2)_L$. In Figure 13, we compare theoretical pair production cross-sections of doubly charged quadruplet scalars with 13 TeV ATLAS limit [1] on $\sigma(\Delta^{++}\Delta^{--}) \times Br(\Delta^{\pm\pm} \rightarrow t^\pm t^\pm)$. The solid black line in Figure 13 corresponds to 95% C.L. on upper limit on $\sigma(\Delta^{++}\Delta^{--}) \times Br(\Delta^{\pm\pm} \rightarrow t^\pm t^\pm)$ obtained by ATLAS collaboration with 13 TeV center of mass energy and 13.9 fb$^{-1}$ integrated luminosity. The green and yellow bands correspond to the 1$\sigma$ and 2$\sigma$ bands on the expected limits respectively. As discussed in Section 3.1, the photon fusion contributes significantly to total production cross-section of multi-charged scalar pairs. Therefore, irrespective of origin of $\Delta^{\pm\pm}$, one must incorporate photon fusion contribution to the total pair production cross-section in addition to DY-contribution. However, Ref. [1] considered only DY-production of $\Delta^{\pm\pm}$ pairs in the context of LR-symmetry and hence, significantly under estimated the mass limits on the doubly charged scalars in LR-symmetry [17]. In order to quantify the effect of photon fusion contribution on the bound of $\Delta^{\pm\pm}$ mass, in figure 13, we have presented the theoretical values for $\sigma(\Delta^{++}\Delta^{--}) \times Br(\Delta^{\pm\pm} \rightarrow t^\pm t^\pm)$ in the context of a doubly charged $SU(2)_L$ quadruplet assuming $Br(\Delta^{\pm\pm} \rightarrow e^\pm e^\pm) = 100\%$ for DY-production only (red dashed line) as well as DY plus photon fusion (red solid line). Figure 13 shows that as a result of including photon fusion contribution, there is a significant enhancement on the lower bound of $\Delta^{\pm\pm}$ mass. A brief summary of the 95% CL exclusion limits on $M_{\Delta^{\pm\pm}}$ using ATLAS preliminary results at $\sqrt{s} = 13$ TeV with 13.9
fb$^{-1}$ integrated luminosity is shown in Table 4. It is important to note that there are some uncertainties in photon PDF [12–15] selection. We estimated that the uncertainty in photon PDF selection corresponds to a uncertainty $\pm 13$ GeV on $M_{\Delta^\pm\pm}$ limits.

<table>
<thead>
<tr>
<th>Benchmark Point</th>
<th>Limits on $M_{\Delta^\pm\pm}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta^{\pm\pm} \to e^+e^-$</td>
<td>100% 509 725</td>
</tr>
<tr>
<td>$\Delta^{\pm\pm} \to e^+e^-$</td>
<td>50% 368 521</td>
</tr>
<tr>
<td>$\Delta^{\pm\pm} \to e^+e^-$</td>
<td>33% 330 387</td>
</tr>
</tbody>
</table>

Table 4. Summary of the 95% CL exclusion limits on $M_{\Delta^\pm\pm}$ using ATLAS results at $\sqrt{s} = 13$ TeV with 13.9 fb$^{-1}$ integrated luminosity. DY : Drell-Yan pair production; PF : photon fusion process.

Figure 14. Contour plot of $\sigma(\Delta^{++}\Delta^{--}) \times Br(\Delta^\pm \to e^\pm e^\pm)$ on $v_\Delta$-$M_{\Delta^\pm\pm}$ plane. The crossed region of the plot is excluded from the ATLAS search [1] for same sign dilepton invariant mass peak at 13 TeV center of mass energy and 13.9 fb$^{-1}$ integrated luminosity.

The production cross-section of a pair doubly charged $SU(2)_L$ quadruplet scalars at the LHC is completely determined by the mass of $\Delta^{\pm\pm}$. On the other hand, as discussed in details in Section 3.2, the decay branching ratio of $\Delta^{\pm\pm}$ into a pair of leptons is mainly determined by the induced VEV $v_\Delta$. Therefore, the ATLAS upper bound on $\sigma(\Delta^{++}\Delta^{--}) \times Br(\Delta^{\pm\pm} \to e^\pm e^\pm)$ in Figure 13 can be used to exclude parts $v_\Delta$-$M_{\Delta^\pm\pm}$ plane. In Figure 14, we present contour plot of $\sigma(\Delta^{++}\Delta^{--}) \times Br(\Delta^{\pm\pm} \to e^\pm e^\pm)$ on $v_\Delta$-$M_{\Delta^\pm\pm}$ plane. The
crossed region of Figure 14 is excluded from the ATLAS search [1] for same sign dilepton invariant mass peak at 13 TeV center of mass energy and 13.9 fb$^{-1}$ integrated luminosity.

### 3.5 Characteristic signatures of (multi-)charged scalars at the LHC

![Figure 15](image)

**Figure 15.** Lepton multiplicity distribution after imposing the acceptance cuts summarized in Eqs. (3.7–3.9). We have considered $m_\Delta = 500$ GeV. Left panel corresponds to small $v_\Delta$ and right panel corresponds to large $v_\Delta$.

After discussing the production, decay and collider bounds on the quadruplet scalars, we are now equipped enough to discuss the characteristic collider signatures of these scalars at the future runs of the LHC. As discussed in the previous section, for small $v_\Delta$, multi-charged quadruplet scalars dominantly decay into leptonic final states and hence, give rise to lepton rich signatures at the LHC. On the other hand, for large $v_\Delta$, quadruplet scalars dominantly decay to $W$-bosons and subsequent leptonic decay of $W$-bosons give rise to leptons in the final state. Though, the leptonic final states for large $v_\Delta$ are suppressed by the leptonic branching ratio of the $W$-boson, multi-leptons signatures are considered very promising because of small or negligible SM background. In this work, we have studied multi-leptons signatures of the charged-quadruplet scalars. Since the detection efficiencies of electrons and muons are much higher than the taus, for the rest of this work, we have only considered electrons and muons as leptons. Pair and associated production of doubly and triply charged scalars give rise to final states with 0–6 leptons multiplicity including interesting same-sign dileptons (SSD) and same-sign 3-leptons (SS3L) events. However, before going into the discussion of lepton multiplicity as well as other characteristic kinematic distributions, it is important to list a set of basic requirements for leptons and jets to be visible at the detector.
It should be noted that any realistic detector has only a finite resolution; this applies to both energy/transverse momentum measurements as well as the determination of the angle of motion. For our purpose, the latter effect can be safely neglected\textsuperscript{5} and we simulate the former by smearing the energy with Gaussian functions. The energy resolution function receives contributions from many sources and are, in general, a function of the detector coordinates. We, though, choose to simplify the task by assuming a flat resolution function equating it to the worst applicable for our range of interest \cite{20}, namely,

$$\frac{\Delta E}{E} = \frac{a}{\sqrt{E/\text{GeV}}} \oplus b,$$

where, $a = 100\%$, $b = 5\%$ for jets and $a = 15\%$ and $b = 1\%$ for leptons, and $\oplus$ denotes a sum in quadrature. Keeping in mind the LHC environment as well as the detector

\textsuperscript{5}The angular resolution is, generically, far superior to the energy/momentum resolutions and too fine to be of any consequence at the level of sophistication of this analysis.
configurations, we demand that, to be visible, a lepton or jet must have an adequately large transverse momentum and they are well inside the rapidity coverage of the detector, namely,

\[ p_T^l > 20 \text{ GeV} ; \quad p_T^j > 20 \text{ GeV} , \]
\[ |\eta_l| \leq 2.5 ; \quad |\eta_j| \leq 2.5 . \]  

We demand that a lepton be well separated from other leptons and jets so that they can be identified as individual physics objects. We use the well-known cone algorithm defined in terms of a cone angle \( \Delta R_{ij} \equiv \sqrt{(\Delta \phi_{ij})^2 + (\Delta \eta_{ij})^2} \), with \( \Delta \phi \) and \( \Delta \eta \) being the azimuthal angular separation and rapidity difference between two particles. Quantitatively, we impose

\[ \Delta R_{ll} > 0.4; \quad \Delta R_{lj} > 0.4; \quad \Delta R_{jj} > 0.7. \]

The requirements summarized in Eqs. (3.7–3.9) constitute our acceptance cuts. In order to calculate the production cross-section, simulate subsequent decays and detector resolutions and impose acceptance cuts, we have used a parton-level Monte-Carlo computer code. Pair and associated production of \( \Delta^{\pm\pm} \) and \( \Delta^{\pm\pm\pm} \) are simulated for \( m_\Delta = 500 \text{ GeV} \) and characteristic distributions are presented in the following. For simplicity, we have considered same mass for all the components of the quadruplet.

**Figure 17.** Transverse momentum \( (p_T) \) distributions of hardest and second-hardest same-sign lepton after ordering the leptons according to their \( p_T \) hardness \( (p_T^l > p_T^j) \) for small (left panel) and large (right panel) \( v_\Delta \). \( m_\Delta = 500 \text{ GeV} \) is assumed.

In Fig. 15, we have presented the lepton multiplicity distributions for small (left panel) and large (right panel) \( v_\Delta \). Fig. 15 clearly shows that lepton multiplicity varies between 0 to 6 for both small and large \( v_\Delta \). For small \( v_\Delta \), dileptons and 4-leptons multiplicity final
states dominates over the others and interestingly, most of the dileptons are of same-sign. It is important to note that for small $v_\Delta$, the dominant decay modes of $\Delta^{\pm\pm}$ and $\Delta^{\pm\mp\mp}$ are $l^\pm l^\pm$ and $l^\pm l^\pm W^\pm$, respectively. Therefore, pair and associated production of $\Delta^{\pm\pm}$ and $\Delta^{\pm\mp\mp}$ always result at least 4-leptons (including taus) in final state. Five and six leptons arise when $W$-decays leptonically. Dileptons arise when a pair of tau from the decay of $\Delta^{\pm\pm}$ or $\Delta^{\pm\mp\mp}$ decays hadronically. Since, dileptons signature is a consequence of $\tau$-hadronic decay and the decay of $\Delta^{\pm\pm}$ and $\Delta^{\pm\mp\mp}$ into leptons are flavor conserving, majority of dileptons are same-sign dileptons for small $v_\Delta$. Small number of events with opposite sign dileptons (OSD) arise from the $\Delta^{\pm\mp\mp} \rightarrow \tau^\pm \tau^\pm W^\pm$ as well as $\tau$-hadronic and $W$-leptonic decay. On the other hand, for large $v_\Delta$, $\Delta^{\pm\pm}$ and $\Delta^{\pm\mp\mp}$ dominantly decays to $W$-bosons and subsequent leptonic decays of $W$-bosons give rise to leptonic final states. Therefore, in this case higher lepton multiplicity states are suppressed by the leptonic branching ratios of $W$-boson as can be seen from Fig. 15 (right panel). Moreover, in this case all the dileptons are not necessarily same-sign dileptons as in the case of small $v_\Delta$. However, there is a significant amount of SSD and SS3L for both small and large $v_\Delta$. In Fig. 16, we have presented the parton level jets multiplicity distributions for small (top panel) and large (bottom panel) $v_\Delta$. As expected for small $v_\Delta$, jet multiplicities are usually small. Whereas, for large $v_\Delta$, we have large jet multiplicity final states. However, it is important to note that our computation is done at parton level without incorporating initial state radiation/final state radiation (ISR/FSR). Inclusion of ISR/FSR jets would significantly change the shape of jet multiplicity distributions in Fig 16.

![Figure 18. Invariant mass distributions of same-sign lepton pairs after the acceptance cuts in Eqs. (3.7–3.9).](image-url)

In Fig. 17, we have presented the transverse momentum ($p_T$) distributions of hard-
est and second-hardest same-sign lepton after ordering the leptons according to their $p_T$ hardness ($p_T^1 > p_T^2$). Left and right panel in Fig. 17 corresponds to small and large $v_\Delta$, respectively. For small $v_\Delta$, 500 GeV $\Delta^{\pm\pm}(\Delta^{\pm\pm})$ directly decays to a same-sign lepton pairs (leptons pairs plus $W$-boson) and hence, the lepton transverse momentum in this case are usually large. However, for large $v_\Delta$, leptons arises from the decay of the $W$-boson. As a result, the leptons are soft for large $v_\Delta$ as can be seen from Fig. 17 (right panel).

Moreover, the possibility of getting a second lepton with same-sign is small for large $v_\Delta$ (see Fig. 15).

For small $v_\Delta$, the doubly charge quadruplet scalar decay into a pair of same-sign leptons. Therefore, the characteristic signature for small $v_\Delta$ is a peak in the invariant mass distribution of same-sign leptons. We have considered events with 4-leptons with two positively and two negatively charged leptons and plotted the invariant mass distribution of same-sign dilepton pairs in Fig.18. A invariant mass peak at 500 GeV is clearly visible in Fig.18. It is interesting to notice that the characteristic $\Delta^{\pm\pm}$ invariant mass peak is accompanied by a nearby invariant mass edge. The SSD invariant mass edge at $(m_{\Delta} - m_W)$ for small $v_\Delta$ results from the decay of $\Delta^{\pm\pm\pm}$ into same-sign lepton pairs and a $W$-boson. Therefore, for small $v_\Delta$, the characteristic signature of quadruplet scalars in the framework of this model is a SSD invariant mass peak (at $m_\Delta$) accompanied by a nearby invariant mass edge (at $m_{\Delta} - m_W$). The search for the invariant mass peak in the same-sign dilepton invariant mass distribution is the most promising channel for the discovery of small $v_\Delta$ region of the parameter space. The ATLAS and CMS collaborations of the LHC experiment are actively studying same-sign dilepton invariant mass distributions. In absence of any significant deviation from the SM background prediction at the ATLAS detector, we have already extracted a bound of about 725 GeV on $M_{\Delta^{\pm\pm}}$ in the previous section. With more data, the LHC will be able to probe larger $M_{\Delta^{\pm\pm}}$ regions and observation a invariant mass edge in association with the characteristic SSD invariant mass peak will surely indicate towards a underlying physics model of present kind. However, for large $v_\Delta$, the invariant mass distribution of same-sign lepton pairs do not show any characteristic feature. Moreover, as can be seen from Fig. 15 and Fig. 17, large $v_\Delta$ is corresponding to suppressed and softer multi-leptons in the final state and hence, making the collider phenomenology challenging. The signatures and LHC discovery reach of large $v_\Delta$ part of parameter space is discussed in the following.

3.6 The LHC discovery reach for large $v_\Delta$

The high lepton multiplicity final states namely, 4-leptons, 5-leptons and 6-leptons states, are suppressed by $W$-boson leptonic branching ratio for large $v_\Delta$. However, there are significant amount of dileptons and 3-leptons events. Dileptons and 3-leptons final states suffers from huge SM backgrounds from top-antitop, $\gamma/Z/W$-boson production. However, it is important to note that $t\bar{t}$ and $\gamma/Z/W$-boson productions dominantly give rise to leptons with opposite charges and the SM contributions to SSD and SS3L are very small or neglizible. On the other hand, the signal SSD and SS3L are suppressed (see Fig. 15 left panel) compared to total 2L and 3L final states only by some factor (in particular,
by a factor of 2.5 and 10 for SSD and SS3L, respectively). In view of this facts, we have considered SSD and SS3L for further study.

Figure 19. Missing transverse momentum, $p_T$ (left panel) and effective mass, $M_{\text{eff}}$ (right panel) distributions for SSD and SS3L events after the acceptance cuts.

We have selected events with exactly 2- and 3-leptons with same electric charge for further analysis. For large $v_\Delta$, the lepton arises from the $W^\pm \rightarrow l\nu$ decay. The resulting neutrino remains invisible in the detector and gives rise to missing transverse momentum ($p_T$) signature. The missing transverse momentum defined in terms of the total visible momentum, as,

$$p_T^* = \sqrt{\left(\sum_{\text{vis.}} p_x\right)^2 + \left(\sum_{\text{vis.}} p_y\right)^2}.$$ 

Therefore, the leptonic final states for large $v_\Delta$ are always accompanied by some amount of missing transverse momentum. In Fig. 19, we have presented the missing transverse momentum distributions for SSD and SS3L events after the acceptance cuts. Fig. 19 (right panel) corresponds to the effective mass ($M_{\text{eff}}$) distributions where $M_{\text{eff}}$ is defined as the scalar sum of the $p_T$ of the signal leptons and jets as well as $p_T^*$. In the SM, same sign dilepton and tri-lepton arise mainly from the production of $ttW^\pm$ and multiple gauge boson ($W$ and/or $Z$) productions. $ttW^\pm$ contributes to SSD when $t(\bar{t})$ decays leptonically, $\bar{t}(t)$ decays hadronically and $W^{\pm(-)}$ decays leptonically. On the other hand, $ZW^\pm$ contributes to SSD when both $Z$ and $W$ decays leptonically and one lepton from $Z$-decay falls out side the coverage of the detector ($p_T < 20$ GeV and/or $|\eta| > 2.5$) or do not identified as individual entities ($\Delta R_{ll} < 0.4$ or $\Delta R_{lj} < 0.4$). These backgrounds ($ttW^\pm$ and dibosons) fall in the category of irreducible background since these SM processes contains two same-sign prompt leptons or at least three prompt leptons out of which one
lepton falls out side detector coverage. Contribution to SSD may also arise from events containing electrons with mismeasured charge, mainly from the production of top quark pairs, and events containing at least one fake or non-prompt lepton. The fake or non-prompt lepton mainly originates from heavy-flavour hadron decays in events containing top quarks, or $W$ or $Z$ bosons. For example, production of $t\bar{t}$ pairs may contribute to SSD when $t\bar{t}$ pairs decays semileptonically and the $b$-quark from the hadronically decaying top decays into a lepton. These backgrounds fall into the catagory of reducable backgrounds because the lepton from the heavy-flavour hadron decays is always accompanied by a lots of hadronic activity around it or a jet within close proximity of the lepton and thus, stronger lepton isolation cuts can be used to reduce these backgrounds. The SM background contribution to SSD was studied by ATLAS collaboration [21] in the context of 13 TeV LHC. In order to reduce the SM background contribution to SSD + $p_T$, we have used ATLAS suggested cuts on $p_T > 125$ GeV and $m_{eff} > 650$ GeV as selection cuts. With these set of event selection criteria, dominant SM contribution to the SSD arises from $ZW$ and $t\bar{t}W$ production. We have simulated $ZW$ and $t\bar{t}W$ in association with upto 3 and 4 additional jets, respectively, using ALPGEN [22] and the resulting SSD background cross-section after the selection cuts is estimated to be 0.6 fb at the LHC with 13 TeV center of mass energy.

On the other hand, there is no irreducible source of SS3L in the SM. The contribution to SS3L may arise from $t\bar{t}$, $t\bar{t}W^{\pm}$, $t\bar{t}b\bar{b}$, $t\bar{t}t\bar{t}$ e.t.c. production when one (only for $t\bar{t}W$) or few (all other sources) lepton(s) from heavy-flavour hadron decays are identified as isolated leptons. As discuss in the previous paragraph, lepton isolation cuts significantly reduce this background. Dominant contribution to SS3L background arises from $t\bar{t}W$ when one top
and $W$ decays leptonically and results into like sign lepton and the third like sign lepton comes from the leptonic decay of $b$ hadrons. We have introduced the following selection cuts to study the SS3L signature.

- $p_T^1 > 30 \text{ GeV}$, $p_T^2 > 30 \text{ GeV}$, $p_T^3 > 20 \text{ GeV}$ and $p_T > 50 \text{ GeV}$.

For SS3L background, one or more leptons arise from the decay of heavy-flavour hadrons which cannot be simulated in the framework of parton level Monte-Carlo analysis. Therefore, we have used PYTHIA (v6.4.28) \[23\] to simulate $t\bar{t}W$ production, subsequent decays and hadronization. To reconstruct the jets, we have used FastJet anti-$k_t$ algorithm \[24\] implemented in Fastjet package \[25\] with a cone of $\Delta R = 0.4$ and minimum transverse momentum of 20 GeV. Lepton isolation criteria plays a crucial role for SS3L background. For an isolated lepton, we demand $\sum p_T(\text{hadron})/p_T(\text{lepton}) \leq 0.2$, where the sum is over all hadrons within a cone of $\Delta R \leq 0.2$ around the lepton. Other object reconstruction criteria listed in Eqs. (3.7–3.9) are applied subsequently. With these set of event selection cuts, we have estimated the $t\bar{t}W$ contribution to the SS3L to be less than $10^{-3}$ fb. Therefore, there will be no SS3L background events with the abovementioned set of cuts up to 1000 fb$^{-1}$ integrated luminosity. The signal SSD and SS3L cross-sections after the selection cuts are presented in Fig. 20.

![Figure 21](image_url)  
**Figure 21.** Required luminosity at the 13 TeV LHC for 5σ discovery of quadruplet scalars with large $v_\Delta$ as a function $M_\Delta$.

In order to calculate the discovery reach of the LHC with 13 TeV center of mass energy, we define the signal to be observable over a non-zero background for an integrated luminosity $\mathcal{L}$ if,

$$\frac{N_S}{\sqrt{N_B + N_S}} \geq 5,$$

(3.10)
where, \( N_{S(B)} = \sigma_{S(B)} \mathcal{L} \), is the number of signal (background) events for an integrated luminosity \( \mathcal{L} \). However, if the number of background event is less than one for a integrated luminosity \( \mathcal{L} \) (as in the case of SS3L), then we demand 5 signal event for the discovery. In Fig. 21, we have presented required luminosity of the 13 TeV LHC for 5\( \sigma \) discovery of quadruplet scalar with large \( v_\Delta \) as a function of quadruplet mass. Fig. 21 shows that for lower \( M_\Delta \), SSD is the promising channel however, for \( M_\Delta > 650 \text{ GeV} \), SS3L becomes promising.

4 Summary and Discussions

In this article, we have presented a model, which can generate small neutrino masses via dimension seven effective operators \( LLHH(H^1H)/M^4 \) and can also be probed at the LHC through the multi-lepton signatures. We have investigated the visibility of the triply and doubly charged scalars at the LHC. We have found that the photon photon fusion also contributes to pair production process at a significant level at the LHC due to the substantially enhanced electromagnetic coupling. This, we emphasize in this literature, is comparable to the DY channel, and must be included in a complete and accurate estimate. We consider the spectacular multi-lepton final states driven by the decay of the \( \Delta^{\pm\pm}(\Delta^{\pm\pm}) \) into same sign trileptons (dileptons). These channels not only lead to remarkably background-free signatures of the doubly charged scalars, but also can demonstrate a crucial link between observations at high energy colliders and the discussed mechanism of neutrino mass generation.

The characteristic collider signatures of quadruplet scalars crucially depend on the decays of these scalars and hence, on the value of the induced VEV, \( v_\Delta \). For small \( v_\Delta \), production and decay of quadruplet scalars gives rise to a same-sign dilepton invariant mass peak at \( m_{\Delta^{\pm\pm}} \) which is accompanied by a invariant mass edge at \( m_{\Delta^{\pm\pm}} - m_W \). In absence of any significant deviation in the LHC same-sign dilepton invariant mass data, we derived a bound of about 725 GeV on \( m_{\Delta^{\pm\pm}} \). On the other hand, for large \( v_\Delta \), the pair and associated production of \( \Delta^{\pm\pm} \) and/or \( \Delta^{\pm\pm} \) give rise to softer leptons in the final states with suppressed cross-sections. We have studied SSD and SS3L final states as signatures of quadruplet scalars for large \( v_\Delta \). We found that the LHC with 13 TeV center of mass energy and 100 inverse femtobarn integrated luminosity will be able to probe \( M_\Delta \) upto 600 GeV.

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References