Same-sign tetra-leptons in type II seesaw at the LHC

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In type II seesaw model of neutrino mass generation, we study a remarkable signal of same-sign tetra-lepton (SS4L) signal at the Large hadron collider. When doubly charged Higgs is lightest, the heavier singly charged or neutral Higgs boson produces a doubly charged Higgs boson through its fast gauge decay. This leads to a novel signature of same-sign tetra-leptons resulting from a pair production of same-sign doubly charged Higgs bosons. We study production cross section for the SS4L signal in parameter space of the mass splitting among triplet components and the triplet vacuum expectation value at the LHC.

I. INTRODUCTION

One of the important question in particle physics is the origin of neutrino masses and mixing. In type II seesaw model [1], Higgs triplet coupling to lepton doublet can generate neutrino mass terms once it develops non-trivial vacuum expectation value. A distinct feature of this model is the presence of doubly charged Higgs bosons which can give a very clean signal at collider experiments [2]–[3]. Moreover it can also explain the deviation in Higgs-to-diphoton rate as measured by CMS and ATLAS [4].

In this work [5], we study a novel signature of same-sign tetra-leptons (SS4L) allowed in some parameter space of the type II seesaw model that has not been studied so far. When the mass splitting among triplet components is sizable and the doubly charged Higgs boson is the lightest, the electroweak gauge interaction allows a fast decay of the neutral or singly charged component of the Higgs triplet into the lighter singly or doubly charged component. Therefore, pair-produced Higgs triplet components can end up with a pair of same-sign doubly charged Higgs bosons leading to same-sign tetra-leptons if their leptonic Yukawa coupling is larger than the ratio of the triplet and doublet Higgs vacuum expectation values.

The SS4L final state, which is almost background free, provides an excellent new channel to test the model and probe sizes of the Higgs triplet vacuum expectation value and the mass splitting among the Higgs triplet components at the LHC.

II. THE TYPE II SEESAW MODEL

In this model, the Higgs sector of the Standard Model is extended with a $Y = 2$ $SU(2)_L$ scalar triplet Δ in addition to a SM-Higgs doublet Φ. The leptonic part of the Lagrangian which generates neutrino masses is

$$\mathcal{L}_Y = f_{\alpha\beta} L_\alpha^T C i\tau_2 \Delta L_\beta + \text{H.c.}, \tag{1}$$

and the scalar potential is

$$\begin{aligned} V(\Phi,\Delta) &= m^2\Phi^\dagger\Phi + \lambda_1(\Phi^\dagger\Phi)^2 + M^2\text{Tr}(\Delta^\dagger\Delta) + \lambda_2\left[\text{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\text{Det}(\Delta^\dagger\Delta) + \lambda_4(\Phi^\dagger\Phi)\text{Tr}(\Delta^\dagger\Delta) \\ &+ \lambda_5(\Phi^\dagger\tau_i\Phi)\text{Tr}(\Delta^\dagger\tau_i\Delta) + \left[\frac{1}{\sqrt{2}}\mu(\Phi^T i\tau_2\Delta\Phi) + \text{H.c.}\right]. \end{aligned} \tag{2}$$

After the electroweak symmetry breaking with $\langle\Phi^0\rangle = v_0/\sqrt{2}$, the μ term in Eq. (2) gives rise to the vacuum expectation value of the triplet $\langle\Delta^0\rangle = v_\Delta/\sqrt{2}$ where $v_\Delta \approx \mu v_0^2/\sqrt{2}M^2$ with μ being real and positive.

There are seven physical massive scalar eigenstates denoted by $H^{\pm,\pm}$, $H^\pm$, H^0, A^0, h^0. Under the condition that $|\xi| \ll 1$ where $\xi \equiv v_\Delta/v_0$, the mixing among doublet and triplet components is too small and thus the first five states are mainly from the triplet and the last from the doublet. We write the masses of the Higgs bosons as

$$\begin{aligned} M_{H^{\pm\pm}}^2 &= M^2 + 2\frac{\lambda_4-\lambda_5}{g^2}M_W^2 \\ M_{H^\pm}^2 &= M_{H^{\pm\pm}}^2 + 2\frac{\lambda_5}{g^2}M_W^2 \\ M_{H^0,A^0}^2 &= M_{H^\pm}^2 + 2\frac{\lambda_5}{g^2}M_W^2\,. \end{aligned} \tag{3}$$

The mass of h^0 is given by $m_{h^0}^2 = 4\lambda_1 v_\Phi^2$ as usual.

The mass splitting among triplet scalars can be approximated as

$$\Delta M \approx \frac{\lambda_5 M_W^2}{g^2 M} < M_W \,. \tag{4}$$

Furthermore, the sign of the coupling λ_5 determines two mass hierarchies among the triplet components: $M_{H^{\pm\pm}} > M_{H^\pm} > M_{H^0/A^0}$ for $\lambda_5 < 0$; or $M_{H^{\pm\pm}} < M_{H^\pm} < M_{H^0/A^0}$ for $\lambda_5 > 0$. In this work, we focus on the scenario, where the doubly charged scalar $H^{\pm\pm}$ is the lightest and thus it decays only to $l_\alpha^\pm l_\beta^\pm$ or $W^\pm W^\pm$, while H^0/A^0 ($H^\pm$) decays mainly to $H^\pm W^{\mp *}$ ($H^{\pm\pm} W^{\mp *}$) unless the mass splitting ΔM is negligibly small. For more details, see, e.g., Ref. [6].

The mass splitting δM_{HA} between H^0 and A^0 plays a crucial role for SS4L signal. The μ term in Eq. (2), which is lepton number violating, generates not only the triplet VEV v_Δ but also $\delta M_{HA} \equiv M_{H^0} - M_{A^0}$:

$$\delta M_{HA} = 2 M_{H^0} \frac{v_\Delta^2}{v_0^2} \frac{M_{H^0}^2}{M_{H^0}^2 - m_{h^0}^2} \,. \tag{5}$$

For a preferable choice of v_Δ, δM_{HA} can be comparable to the total decay rate of the neutral scalars, Γ_{H^0/A^0}, enhancing the SS4L signal.

III. DECAYS OF TRIPLET SCALARS

Depending on the triplet mass splitting ΔM and the triplet vacuum expectation value v_Δ, the triplet scalars have different decay properties. When H^{++} is the lightest, the possible decay channels for the triplet scalars are shown in Table. I. The decays of triplet scalars can be classified into three modes, a) di-leptonic mode: which is proportional to Yukawa coupling f, b) quark/di-boson mode: controlled by $\xi = v_\Delta/v_0$, and c) gauge decay: due to $SU(2)$ gauge interaction which dominates if allowed kinematically.

H^0	A^0	H^+	H^{++}
$\to t\bar{t}/b\bar{b}$	$\to t\bar{t}/b\bar{b}$	$\to t\bar{b}$	$\to \ell^+\ell^+$
$\to \nu\bar{\nu}$	$\to \nu\bar{\nu}$	$\to \ell^+\nu$	$\to W^+W^+$
$\to ZZ$	$\to Zh^0$	$\to W^+Z$	
$\to h^0h^0$	$\to H^\pm W^{\mp^*}$	$\to W^+h^0$	
$\to H^\pm W^{\mp^*}$		$\to H^{++}W^{-^*}$	

TABLE I: Possible decay channels for the triplet Higgs bosons for $\lambda_5 > 0$.

In Fig. 1, we show phase diagrams for H^+ and H^{++} decays in the plane of ΔM and v_Δ. In the left panel, the brown, the gray and the purple regions show the branching fractions for the decays $H^+ \to H^{++}W^{-^*}$, $H^+ \to \ell^+\nu$ and $H^+ \to \{t\bar{b}, W^+Z, W^+h\}$, respectively. In the right panel, the brown and the gray regions show the branching fractions for the decays $H^{++} \to W^+W^+$ and $H^{++} \to \ell^+\ell^+$ respectively. In both panels, the dark-colored regions denote the parameter space where the branching fraction is greater than 99% and the light-colored regions denote the parameter space where the branching fraction is between 50%-99%.

As it can be seen from Fig. 1, the leptonic decay BF of H^+ is dominant for small values of $v_\Delta < 0.1$ MeV and always greater than 0.99. However, for moderate mass splitting $\Delta M > 5$ GeV, the gauge decay of H^+ starts becoming large at $v_\Delta = 0.1$ MeV and at ΔM around 10-20 GeV, large parameter space opens up for this decay. Hence, for moderate v_Δ (around 1 keV-10 MeV), large mass splitting is allowed for the BF larger than 99%. On the other hand, for large v_Δ and low mass splitting, rest of the decays viz., ($H^+ \to t\bar{b}, W^+Z, W^+h$) have appreciable contributions and thus BF($H^+ \to H^{++}W^{-^*}$) goes down.

In the case $H^{\pm\pm}$, for $v_\Delta < 0.1$ MeV, it is completely dominated by leptonic decay i.e., $H^{\pm\pm} \to \ell^\pm\ell^\pm$ while for $v_\Delta > 1$ MeV, it is dominated by the di-W decay. These BFs are completely independent of the mass splitting ΔM as the $H^{\pm\pm}$ is the lightest.

Similarly, in Fig. 2, we show phase diagrams for H^0 and A^0 decays in the plane of ΔM and v_Δ. In the left panel, the brown, the gray and the purple regions show the BFs for the decays $H^0 \to \nu\bar{\nu}$, $H^0 \to H^+W^{-^*}$, and $H^0 \to \{t\bar{t}, b\bar{b}, ZZ, h^0h^0\}$ respectively. In the right panel, the brown, the gray and the purple regions show the BFs for the decays $A^0 \to \nu\bar{\nu}$, $A^0 \to H^+W^{-^*}$, and $A^0 \to \{t\bar{t}, b\bar{b}, Zh^0\}$ respectively. In both panels, the

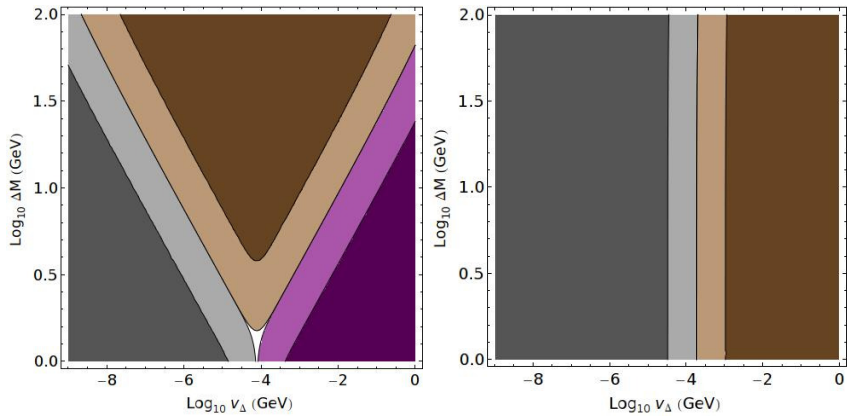

FIG. 1: Phase diagrams for H^+(left) and H^{++}(right) decays in the type II seesaw model for $\lambda_5 > 0$ with $M_H^{++} = 300$ GeV. The dark-colored regions denote the branching fraction larger than 99%.

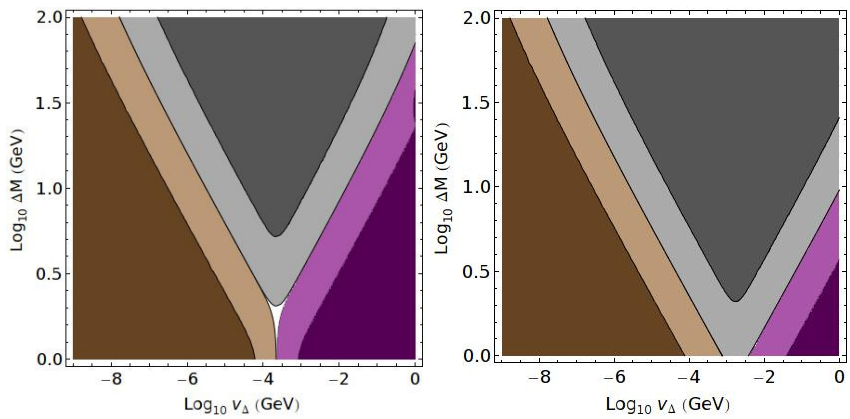

FIG. 2: Phase diagrams for H^0(left) and A^0(right) decays in the type II seesaw model for $\lambda_5 > 0$ with $M_H^{++} = 300$ GeV. The dark-colored regions denote the branching fraction in the range of 49%-50%.

dark-colored regions denote the parameter space where BF is between 49%-50% and the light-colored regions denote the parameter space where the BF is between 20%-49%.

IV. SAME-SIGN TETRA-LEPTONS AT THE LHC

In this section, we study a new possibility of probing the type II seesaw model at the LHC through a remarkable signal of four same-sign leptons which are either positively or negatively charged. The processes which contribute to such a signal are as follows:

1. $q'\bar{q} \to W^* \to H^\pm H^0/A^0$ proceeded by $H^\pm \to H^{\pm\pm}W^{\mp^*}$ and $H^0/A^0 \to H^\pm W^{\mp^*} \to H^{\pm\pm}W^{\mp^*}W^{\mp^*}$;
2. $q\bar{q} \to Z^* \to H^0A^0$ proceeded by $H^0/A^0 \to H^\pm W^{\mp^*} \to H^{\pm\pm}W^{\mp^*}W^{\mp^*}$.

Out of all the triplet pairs produced in the above three processes, only some fraction of them eventually give same-sign $H^{\pm\pm}$ pairs which is controlled by the neutral scalar mixing parameter as will be discussed below.

In the limit of lepton number conservation i.e. $\mu, v_\Delta \to 0$, the SS4L final state cannot occur, due to the canceling interference between H^0 and A^0 [7]. However, the above processes 1 and 2 are allowed when there is a finite mass difference δM_{HA} (5) violating lepton number. Like as in the B^0-$\bar{B}^0$ system, this phenomenon occurs as H^0 and A^0, sharing the same final states, can mix together . If they undergo sufficient oscillation before they decay, i.e., $\delta M_{HA} \gtrsim \Gamma_{H^0/A^0}$, the lepton number violating production of SS4L becomes sizable. This

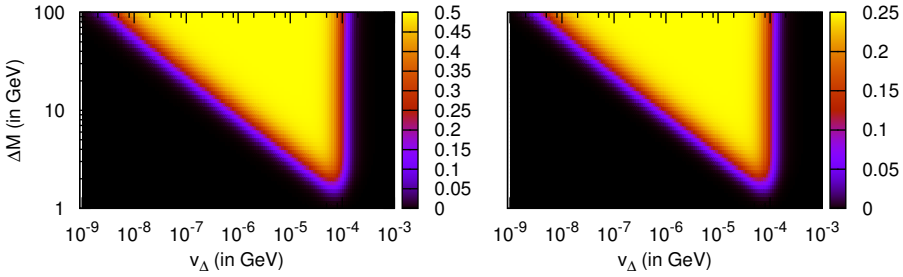

FIG. 3: Product of branching fractions for processes 1 (left), and 2 (right).

effect is controlled by the usual oscillation parameter x_{HA}:

$$x_{HA} \equiv \frac{\delta M_{HA}}{\Gamma_{H^0/A^0}} \,. \tag{6}$$

Using the narrow width approximation for the calculation of the H^0-A^0 interference term, we obtain the cross-sections for the processes 1 and 2 as follows:

$$\begin{aligned} \sigma\left(4\ell^\pm + 3W^{\mp^*}\right) &= \sigma\left(pp \to H^\pm H^0 + H^\pm A^0\right) \left[\frac{x_{HA}^2}{1+x_{HA}^2}\right] \mathrm{BF}(H^0/A^0 \to H^\pm W^{\mp^*}) \\ &\times \left[\mathrm{BF}(H^\pm \to H^{\pm\pm} W^{\mp^*})\right]^2 \left[\mathrm{BF}(H^{\pm\pm} \to \ell^\pm \ell^\pm)\right]^2 ; \end{aligned} \tag{7}$$

$$\begin{aligned} \sigma\left(4\ell^\pm + 4W^{\mp^*}\right) &= \sigma\left(pp \to H^0 A^0\right) \left[\frac{2+x_{HA}^2}{1+x_{HA}^2}\frac{x_{HA}^2}{1+x_{HA}^2}\right] \mathrm{BF}(H^0 \to H^\pm W^{\mp^*}) \\ &\times \mathrm{BF}(A^0 \to H^\pm W^{\mp^*}) \left[\mathrm{BF}(H^\pm \to H^{\pm\pm} W^{\mp^*})\right]^2 \left[\mathrm{BF}(H^{\pm\pm} \to \ell^\pm \ell^\pm)\right]^2 . \end{aligned} \tag{8}$$

As expected, the cross-sections vanish for $x_{HA} \to 0$ recovering the lepton number conserving limit. In the limit of $x_{HA} \gg 1$ (the maximal lepton number violation), the mixing factors become one and the SS4L numbers are controlled only by the branching fractions of H^0 and A^0.

The cross section for SS4L signal depend on v_Δ through decay branching fractions. In Fig. 3, we show product of BFs which occur in the evaluation of cross-section for processes 1 (left figure) and for process 2 (right figure) in $\Delta M - v_\Delta$ plane. One can see from these figures that large parameter space are favourable. In Fig. 4 (bottom), we show sum of cross-sections for processes 1 and 2 which can finally give same-sign tetra-leptons. The cross-sections are independent of v_Δ and steadily decreases with the rise of ΔM. In Fig. 4 (top), we show cross-sections for $\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ signal at LHC8 and LHC14 in the $\Delta M - v_\Delta$ plane. The Fig. 4 (top) is obtained by superposing the Figs. 4 (bottom) and 3 and multiplying with the oscillation factor as in Eqs. (7,8). The doubly charged Higgs mass is taken to be 400 GeV. One can see from Fig. 4 that the same-sign tetra-lepton cross-section is maximized for $v_\Delta = (10^{-4} - 10^{-5})$ GeV and $\Delta M = (1-2)$ GeV in accordance with the rough estimate. If the parameter region happens to be near the limited bright region in Fig. 4, one can find in addition for SS4L allowing to get information about v_Δ and ΔM.

Now we choose a benchmark point with $v_\Delta = 7 \times 10^{-5}$ GeV, $\Delta M = 1.5$ GeV and $M_{H^\pm\pm} = 400$ GeV which gives $\delta M_{HA} = 3.68 \times 10^{-11}$ GeV, $\Gamma_{H^0/A^0} = 3.73 \times 10^{-11}$ GeV, and thus $x_{HA}^2/(1+x_{HA}^2) = 0.79$.

So far, we have not distinguished among flavors of charged leptons i.e., e, μ, τ in our analysis. However, we know that at the LHC, τ leptons are more difficult to identify. τ leptons can decay leptonically $\tau \to e\nu_e\bar{\nu}_\tau$ and $\tau \to \mu\nu_\mu\bar{\nu}_\tau$ with branching fractions of 17% each. These e's and μ's are less energetic than their parent τ's. On the other hand, decays $H^{\pm,\pm} \to e^\pm e^\pm/\mu^\pm\mu^\pm/e^\pm\mu^\pm$ are much cleaner and produce the two energetic e and μ closer to invariant mass $M_{H^{\pm\pm}}$. For the collider analysis including lepton flavor dependence, we consider the full neutrino mass matrices calculated for the NH and IH, respectively. In the NH case, the BF of the $H^{\pm\pm}$ decay to the e and μ final states is only 32%, and thus $H^{\pm\pm}$ decay mainly to same-sign τ pairs. Of course, the leptonic decays of these τ's to e/μ are included in our analysis. On the other hand, for the IH case, the $H^{\pm\pm}$ decay BF to the e and μ final states is 60% and thus we expect to have more SS4L signal events compared to the NH case.

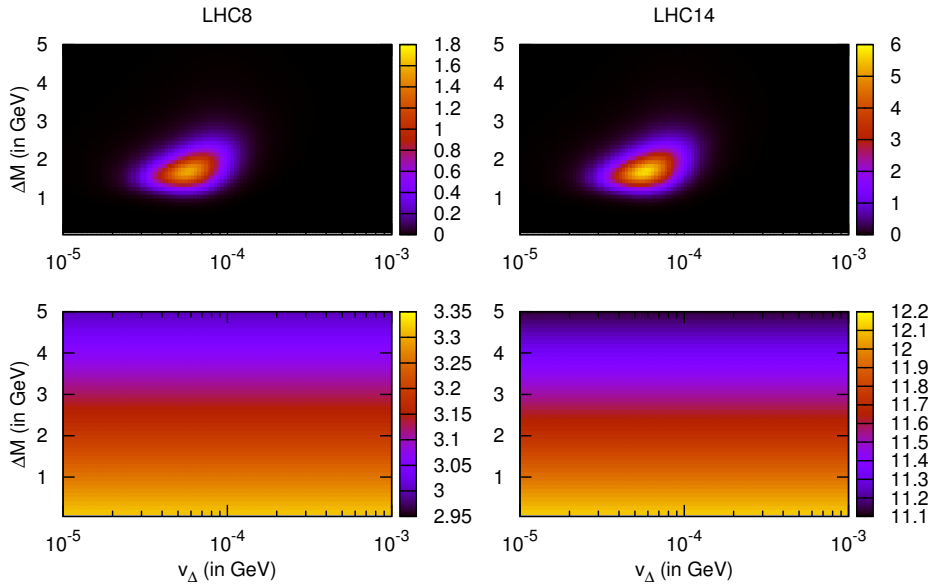

FIG. 4: Bottom panels show cross-sections (in fb) for $H^{\pm}H^{0}/H^{\pm}A^{0}/H^{0}A^{0}$ production, and top panels for same-sign tetra-lepton events. Left (right) panels are for LHC8 (LHC14).

The only potential background can come from multi W productions demanding four $W^{\pm}$ decaying leptonically. At the lowest order, cross-section is proportional to α_{EW}^{7} and, at one loop, would be suppressed by $\alpha_{S}^{2}\alpha_{EW}^{8}$ times loop-suppression factor. Thus, the background for SS4L final states is practically zero at the LHC.

Since there is negligible background, the selection criteria for the leptons are very trivial. So, the basic cuts like $p_T > 20$ GeV and $|\eta| <2.5$ for all leptons would be sufficient to detect our signal. We use `CTEQ6L` parton distribution function (PDF) and the renormalization/factorization scale is set at $2M_{H^+}$. We use `CALCHEP` to generate the parton level events for the relevant processes and `PYTHIA` for fragmentation and initial/final state radiations.

The SS4L signal for $M_{H^{++}} = 400$ GeV might be barely observable at LHC8 for the IH case, but the event number is too small to reconstruct its mass. But, at LHC14 with 100 fb^{-1} of integrated luminosity there would be enough number of events to look for the doubly charged Higgs mass of $M_{H^{++}} = 400$ GeV. Assuming the criteria of 10 signal events for the claim of discovery, we find that $H^{\pm\pm}$ with mass $M_{H^{\pm\pm}}$ as large as 600 GeV and 700 GeV can be probed for NH and IH scenario respectively at the LHC14 with 100 fb^{-1} of integrated luminosity.

	Pre-selection	Selection
$\ell^{\pm}\ell^{\pm}\ell^{\pm}\ell^{\pm}$ (LHC8-NH)	4	3
$\ell^{\pm}\ell^{\pm}\ell^{\pm}\ell^{\pm}$ (LHC8-IH)	9	8
$\ell^{\pm}\ell^{\pm}\ell^{\pm}\ell^{\pm}$ (LHC14-NH)	110	94
$\ell^{\pm}\ell^{\pm}\ell^{\pm}\ell^{\pm}$ (LHC14-IH)	240	210

TABLE II: Number of events for SS4L signals before and after selection cuts for both NH and IH scenarios at LHC8 and LHC14 with 15 fb^{-1} and 100 fb^{-1} of integrated luminosities respectively.

In Fig. 5, we plot the reconstructed $H^{\pm\pm}$ mass from the sample of selected SS4L events for both NH and IH neutrino mass scenarios at LHC14 with 100 fb^{-1} integrated luminosity. The peaks in all plots correspond to $H^{\pm\pm} \to ee/e\mu/\mu\mu$ decays while the broad part (off-peak) of distribution correspond to τ decays.

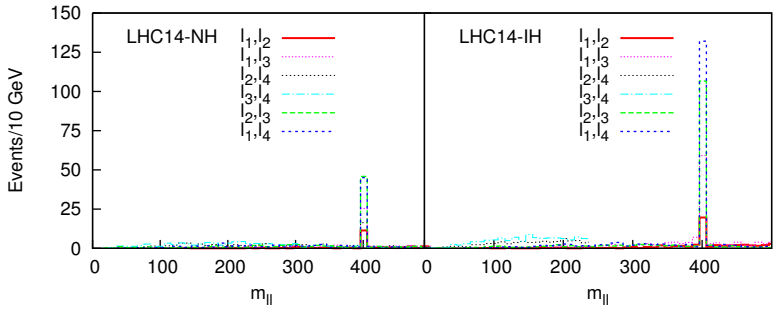

FIG. 5: Invariant mass from $4\ell^{\pm}$ final states.

V. CONCLUSION

We point out that a remarkable signal of SS4L, $l^{\pm}l^{\pm}l^{\pm}l^{\pm}$, is allowed in the type II seesaw mechanism. Such a signal at the LHC strongly depends on the mass splitting ΔM and the triplet vev v_{Δ} When the doubly charged component $H^{\pm\pm}$ is the lightest, larger ΔM allows more efficient gauge decay of the neutral component to the singly charged one and then to the doubly charged one. Thus, a pair production of the triplet components at colliders can end up with producing $H^{\pm\pm}H^{\pm\pm}$ whose branching fraction to SS4L becomes larger for smaller v_{Δ}. Another crucial ingredient for increasing the SS4L signal number is the H^0-A^0 mixing parameter x_{HA} which becomes smaller for smaller v_{Δ} and larger ΔM. Therefore, there appear optimal values of the model parameters which maximize the same-sign tetra-lepton signal.

After studying such a behavior in the $\Delta M - v_{\Delta}$ plane, we identified a benchmark point with $\Delta M = 1.5$ GeV and $v_{\Delta} = 7 \times 10^{-5}$ GeV for maximized the signal numbers at the LHC. After making the typical selection cuts to identify four same-sign leptons, we have shown that one can obtain sizable event numbers for $M_{H^{\pm\pm}} = 400$ GeV with integrated luminosity of 100 fb^{-1} at the LHC14 to reconstruct the doubly charged Higgs mass in both cases of the normal and inverted neutrino mass hierarchy.

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