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ELECTROWEAK CONSTRAINTS ON SEE-SAW MESSENGERS AND THEIR IMPLICATIONS FOR LHC

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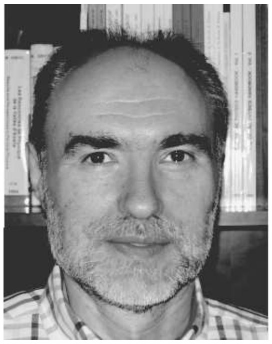

We review the present electroweak precision data constraints on the mediators of the three types of see-saw mechanisms. Except in the see-saw mechanism of type I, with the heavy neutrino singlets being mainly produced through their mixing with the Standard Model leptons, LHC will be able to discover or put limits on new scalar (see-saw of type II) and lepton (see-saw of type III) triplets near the TeV. If discovered, it may be possible in the simplest models to measure the light neutrino mass and mixing properties that neutrino oscillation experiments are insensitive to.

1 Introduction

As it is well known, the original see-saw mechanism [1], nowadays called of type I, explains the smallness of the light neutrino masses $|m_\nu| \sim 1$ eV invoking a very heavy Majorana neutrino $M_N \sim 10^{14}$ GeV:

$$|m_\nu| \simeq \frac{v^2 |Y|^2}{M_N} \simeq |V|^2 M_N , \tag{1}$$

where $|Y| \sim 1$ is the corresponding Yukawa coupling and $v \simeq 246$ GeV the electroweak vacuum expectation value. For reviews see [2,3]. Alternatively, if the heavy scale is at the LHC reach $M_N \sim 1$ TeV, it requires a very small heavy–light mixing angle $|V| \sim 10^{-6}$. In its simplest form the model cannot be tested at large colliders, because the heavy neutrino N is a Standard Model (SM) singlet and only couples to SM gauge bosons through its mixing V. Hence it is produced through the vertex $-\frac{g}{\sqrt{2}} \bar{\ell} \gamma^\mu V_{\ell N} P_L N W_\mu$, with ℓ a charged lepton, with a cross section proportional to $|V_{\ell N}|^2$, which is strongly suppressed. See Fig. 1-(I). There are two other types of see-saw mechanism giving tree level Majorana masses to the light neutrinos ν, as shown

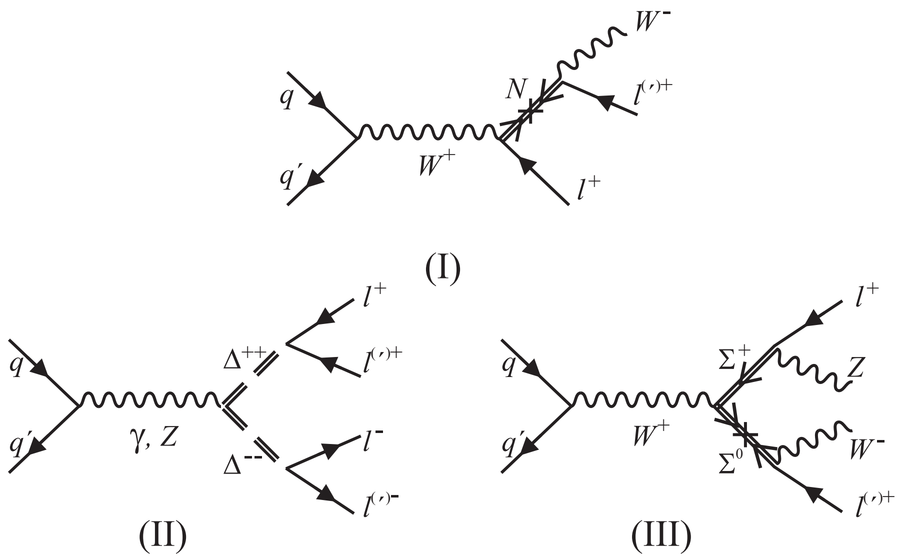

Figure 1: Examples of production diagrams for same-sign dilepton signals, $l^{+} l^{(\prime)+} X$, mediated by the three types of see-saw messengers.

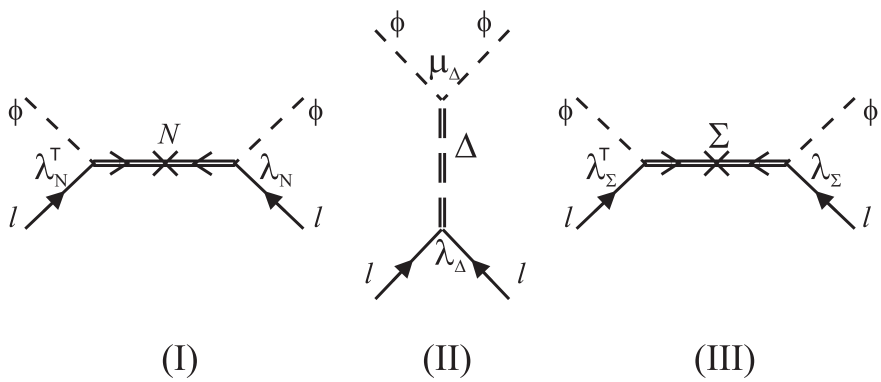

Figure 2: See-saw mechanisms of type I, II and III. λ_N, λ_Δ and λ_Σ are the Yukawa coupling matrices in the Lagrangian terms $\overline{l_L}\tilde\phi\lambda_N^\dagger N_R$, $\overline{\tilde l_L}\lambda_\Delta(\vec\tau\cdot\vec\Delta)l_L$ and $\overline{\vec\Sigma_R}\lambda_\Sigma(\tilde\phi^\dagger\frac{\vec\tau}{2}l_L)$, respectively, with $\overline{\tilde l_L} = l_L^T C i\sigma_2$ and C the spinor charge conjugation matrix. Whereas μ_Δ is the coefficient of the scalar potential term $\tilde\phi^\dagger(\vec\tau\cdot\vec\Delta)^\dagger\phi$.

in Fig. 2. In all cases the extra particles contribute at low energies to the dimension 5 lepton number (LN) violating operator[4]

$$(O_5)_{ij} = \overline{(l_L^i)^c}\,\tilde\phi^*\,\tilde\phi^\dagger l_L^j \to \frac{v^2}{2}\overline{(\nu^i)^c}\,\nu^j \qquad (\text{with } l = e, \mu, \tau \text{ and } \tilde\phi = i\sigma_2\phi^*)\,; \tag{2}$$

which gives Majorana masses to light neutrinos after spontaneous symmetry breaking. The see-saw of type II[5] in Fig. 2 is mediated by an $SU(2)_L$ scalar triplet Δ of hypercharge $Y = 1$, implying three new complex scalars of charges $Q = T_3 + Y$: Δ^{++}; Δ^{+}; Δ^{0}. The see-saw of type III[6] exchanges an $SU(2)_L$ fermion triplet Σ of hypercharge $Y = 0$, assumed to be Majorana and containing charged leptons $\Sigma^\pm$ and a Majorana neutrino Σ^0. The main difference for LHC detection is that the see-saw messengers for these last two mechanisms can be produced by unsuppressed processes of electroweak size (Fig. 1). Their decay, even if suppressed by small couplings, can take place within the detector due to the large mass of the new particle. All three types of see-saw messengers produce LN conserving as well as LN violating signals, but the former have much larger backgrounds. On the other hand, same-sign dilepton signals, $l^\pm l^{(\prime)\pm} X$, do not have to be necessarily LN violating. Thus, in the example in Fig. 1–(II), the decay coupling needs not be very small because it is only one of the factors entering in the LN violating expression for masses (see Table 1). In fact, this process is LN conserving as we can

Table 1: Coefficients of the operators up to dimension 6 arising from the integration of the heavy fields involved in each see-saw model. The parameters $_3$ and $_5$ are the coefficients of the scalar potential terms $(\ ^\dagger\ )(\tilde{\ }^\dagger\tilde{\ })$ and $(\tilde{\ }^\dagger T_i\tilde{\ })(\ ^\dagger\ _i\ )$, respectively, and $(\ _e)_{jj}$ the diagonalised SM charged-lepton Yukawa couplings. The remaining parameters are defined in the caption of Fig. 2.

Coefficient	Type I	Type II	Type III
$_4$		$2\frac{\lvert\ \rvert^2}{M^2}$	
$\frac{(\ _5)_{ij}}{}$	$\frac{1}{2}\frac{(\ _N^T)_{ia}(\ _N)_{aj}}{M_{N_a}}$	$2\frac{(\ )_{ij}}{M^2}$	$\frac{1}{8}\frac{(\ ^T)_{ia}(\ )_{aj}}{M_a}$
$\frac{(\ ^{(1)}_{l})_{ij}}{^2}$	$\frac{1}{4}\frac{(\ _N^\dagger)_{ia}(\ _N)_{aj}}{M_{N_a}^2}$		$\frac{3}{16}\frac{(\ ^\dagger)_{ia}(\ )_{aj}}{M_a^2}$
$\frac{(\ ^{(3)}_{l})_{ij}}{^2}$	$\frac{(\ ^{(1)}_{l})_{ij}}{^2}$		$\frac{1}{3}\frac{(\ ^{(1)}_{l})_{ij}}{^2}$
$\frac{(\ ^{(1)}_{ll})_{ijkl}}{^2}$		$2\frac{(\ )_{jl}(\ ^\dagger)_{ki}}{M^2}$	
$\frac{}{^2}$		$6(\ _3+\ _5)\frac{\lvert\ \rvert^2}{M^4}$	
$\frac{^{(1)}}{^2}$		$4\frac{\lvert\ \rvert^2}{M^4}$	
$\frac{^{(3)}}{^2}$		$4\frac{\lvert\ \rvert^2}{M^4}$	
$\frac{(\ _e)_{ij}}{^2}$			$\frac{4}{3}\frac{(\ ^{(1)}_{l})_{ij}}{^2}(\ _e)_{jj}$

conventionally assign LN equal to 2 to . There are other processes that do violate LN, e.g. when one of the doubly-charged in Fig. 2–(II) decays into W W. Then, what does violate LN is the corresponding W W vertex, which is proportional to the coupling of the only LN violating term in the fundamental Lagrangian $\tilde{\ }^\dagger(\tilde{\ })^\dagger$, with total LN equal to 2. In the examples in Fig. 1–(I, III) LN is violated in the decay (mass) of the heavy neutral fermion.

In conclusion, all the three mechanisms produce same-sign dilepton signals, but only the last two are observable at LHC [7,8,9,10,11,12,13] in minimal models. Heavy neutrino singlets in particular non-minimal scenarios could also be observed, as described in Section 3.

In the following we first review the experimental constraints on the parameters entering the three see-saw mechanisms, and then the LHC reach for the corresponding see-saw messengers. Complementary reviews on this subject have been presented by other speakers at this Conference (see F. Bonnet, T. Hambye and J. Kersten in these Proceedings).

2 Electroweak precision data limits on see-saw messengers

The low energy effects of the see-saw messengers can be described by the effective Lagrangian

$$\mathcal{L}_{e} = \mathcal{L}_4 + \frac{1}{}\mathcal{L}_5 + \frac{1}{^2}\mathcal{L}_6 + \dots; \quad (3)$$

where is the cut-off scale, in our case of the order of the see-saw messenger masses M, and the different terms contain gauge-invariant operators of the corresponding dimension. The non-zero terms up to dimension 6 are [14,15]

$$\mathcal{L}_4 = \mathcal{L}_{SM} + \ _4\ \ ^\dagger\ \ ^2; \quad (4)$$

$$\mathcal{L}_5 = (\alpha_5)_{ij}\overline{(l_L^i)^c}\tilde{\phi}^*\tilde{\phi}^\dagger l_L^j + \mathrm{h.c.}; \quad (5)$$

$$\begin{aligned}\mathcal{L}_6 = \Big[& (\alpha_{\phi l}^{(1)})_{ij}\left(\phi^\dagger i D_\mu \phi\right)\left(\overline{l_L^i}\gamma^\mu l_L^j\right) + (\alpha_{\phi l}^{(3)})_{ij}\left(\phi^\dagger i \sigma_a D_\mu \phi\right)\left(\overline{l_L^i}\sigma^a\gamma^\mu l_L^j\right) \\ & + \left(\alpha_{e\phi}\right)_{ij}\left(\phi^\dagger\phi\right)\left(\overline{l_L^i} e_R^j \phi\right) + (\alpha_{ll}^{(1)})_{ijkl}\frac{1}{2}\left(\overline{l_L^i}\gamma^\mu l_L^j\right)\left(\overline{l_L^k}\gamma_\mu l_L^l\right) + \mathrm{h.c.} \\ & + \alpha_\phi^{(1)}\left(\phi^\dagger\phi\right)\left((D_\mu\phi)^\dagger D^\mu\phi\right) + \alpha_\phi^{(3)}\left(\phi^\dagger D_\mu\phi\right)\left((D^\mu\phi)^\dagger\phi\right) + \frac{1}{3}\alpha_\phi\left(\phi^\dagger\phi\right)^3\Big]; \end{aligned} \quad (6)$$

where we choose the basis of Buchmüller and Wyler to express the result[16]. l_L stands for any lepton doublet, e_R for any lepton singlet, and ϕ is the SM Higgs doublet. In Table 1 we collect the explicit expressions of the coefficients in terms of the original parameters for each type of see-saw (see Fig. 2 and the table caption for definitions).

Only the dimension 6 operators can give deviations from the SM predictions for the electroweak precision data (EWPD). The operators of dimension 4 only redefine SM parameters. The one of dimension 5 gives tiny masses to the light neutrinos, and contributes to neutrinoless double β decay. An important difference is that the coefficient α_5 involves LN-violating products of two λ's or of μ and λ, while the other coefficients depend on $\lambda\lambda^\dagger$ or $|\lambda|^2$. Therefore, it is possible to have large cancellations in α_5 together with sizeable coefficients of dimension six[14,15]. Type I and III fermions generate the operators $O_{\phi l}^{(1,3)}$, which correct the gauge fermion couplings. Type II scalars, on the other hand, generate 4-lepton operators and the operator $O_\phi^{(3)}$, which breaks custodial symmetry and modifies the SM relation between the gauge boson masses. EWPD are sensitive to all these effects and put limits on the see-saw parameters.

There are two classes of processes, depending on whether they involve neutral currents violating lepton flavour (LF) or not. The first class puts more stringent limits[17,18], but only on the combinations of coefficients entering off-diagonal elements. The second class is measured mainly at LEP[19] and constrains the combinations in the diagonal entries[20]. The LF violating limits are satisfied in types I and III if N and Σ mainly mix with only one charged lepton family. In Table 2 we collect the bounds from EWPD on the N and Σ mixings with the SM leptons $V_{\ell N,\ell\Sigma}$[20], and in Table 3 their product including the LF violating bounds[17,18]. These

Table 2: Upper limit at 90 % confidence level (CL) on the absolute value of the mixings. The first three columns are obtained by coupling each new lepton with only one SM family. The last one corresponds to the case of lepton universality: three new lepton multiplets mixing with only one charged-lepton family each, all of them with the same mixing angle. All numbers are computed assuming $M_H \geq 114.4$ GeV.

Coupling	Only with e	Only with μ	Only with τ	Universal
$V_{\ell N} = \frac{v(\lambda_N^\dagger)_{lN}}{\sqrt{2}M_N} <$	0.055	0.057	0.079	0.038
$V_{\ell\Sigma} = \frac{v(\lambda_\Sigma^\dagger)_l}{2\sqrt{2}M_\Sigma} <$	0.019	0.017	0.027	0.016

values update and extend previous bounds on diagonal entries for N[21,22] (see also[23].) Their dependence on the model parameters entering in the operator coefficients in Table 1 is explicit in the first column of Table 2. All low energy effects are proportional to this mixing, and the same holds for the gauge and Higgs couplings between the new and the SM leptons, responsible of the heavy lepton decay (and N production if there is no extra NP). An interesting by-product of a non-negligible mixing of the electron or muon with a heavy N is that the fit to EWPD prefers a Higgs mass M_H higher than in the SM, in better agreement with the present direct limit. This is so because their contributions to the most significative observables partially cancel[24], so that

Table 3: Upper limit at 90 % CL on the absolute value of the products of the mixings between heavy singlets N and triplets Σ with the SM leptons, $VV^\dagger$, entering in low energy processes. Row and column ordering corresponds to $e;\mu;\tau$.

$\lvert V_{\ell N} V^*_{\ell' N}\rvert <$			$\lvert V_{\ell\Sigma} V^*_{\ell'\Sigma}\rvert <$		
0.0030	0.0001	0.01	0.0004	1.1×10^{-6}	0.0005
0.0001	0.0032	0.01	1.1×10^{-6}	0.0003	0.0005
0.01	0.01	0.0062	0.0005	0.0005	0.0007

both the mixing and M_H can be relatively large without spoiling the agreement with EWPD. The new 90 % CL on M_H increases in this case[20] up to ~ 260 GeV (see also[25,26]). In all other cases the limit stays at ~ 165 GeV.

In type II see-saw a crucial phenomenological issue is the relative size of $(\lambda_L)_{ij}$ and λ_H for $M_\Delta \sim 1$ TeV. The ν masses are proportional to their product, $(m_\nu)_{ij} = 2v^2 \frac{(\lambda_L)_{ij}\lambda_H}{M_\Delta^2}$, which gives the strength of the LN violation. If λ_H is small enough, $(\lambda_L)_{ij}$ can be relatively large and saturate present limits on LF violating processes, eventually showing at the next generation of experiments. If instead $(\lambda_L)_{ij}$ are very small, the flavour structure appears only in the mass matrix. The present limits are reviewed in[15]. Neglecting LF violating bounds (i.e., assuming that $(\lambda_L)_{ee}$ is small enough not to give a too large $\mu \to eee$ decay rate), λ_H and λ_L are constrained by the T oblique parameter and four-fermion processes, respectively. From a global fit to EWPD (see[20] for details on the data set used) we obtain the following limits at 90 % CL:

$$\frac{|\lambda_H|}{M_\Delta^2} < 0.048\,\text{TeV}^{-1}; \quad \frac{|(\lambda_L)_{e\mu}|}{M_\Delta} < 0.100\,\text{TeV}^{-1}. \tag{7}$$

3 Dilepton signals of see-saw messengers

The previous limits apply to any particle transforming as the corresponding see-saw messenger, independently of whether it contributes or not to light neutrino masses. As indicated above, in minimal models the tight restriction imposed by ν masses (Eq. 1) gives much more stringent limits for the mixings of TeV-scale see-saw messengers. However, these limits can be avoided if additional particles give additional contributions to neutrino masses that cancel the previous ones, for instance if the fermionic messengers are quasi-Dirac, i.e. a nearly degenerate Majorana pair with appropriate couplings[27]. The EWPD limits are in this case relevant for production and detection of type I messengers N, but the signals are different because they conserve LN to a very large extent[14,28]. On the other hand, type II and III messengers with masses near the TeV can be produced and detected at LHC even in minimal models. Let us discuss the three types of see-saw mechanism in turn.

3.1 Type I: Fermion singlets N

As already explained, a type I heavy neutrino N with a mixing saturating the EWPD limit cannot be Majorana, unless extra fields with a very precise fine tuning keep the ν masses small enough[29]. Unnatural cancellations allowing for LN-violating signals are also possible in principle. In this case a fast simulation shows that LHC can discover a Majorana neutrino singlet with $M_N \simeq 150$ GeV for $|V_{eN}| \sim 0.054$ (near the EWPD limit)[8], assuming an integrated luminosity $L = 30\ \text{fb}^{-1}$.

Such a signal can be also observed for much smaller mixings and larger masses if there is some extra NP [30], especially if the extra particles can be copiously produced at LHC [31]. This is the case, for instance, if the gauge group is left-right symmetric and the new W_R^0 has a few TeV mass. Then $pp \to W_R^0 \to \ell N \to \ell\ell^0 W$ is observable, even with negligible mixing $V_{\ell N}$, for M_N and $M_{W_R^0}$ up to 2.3 TeV and 3.5 TeV, respectively,[32] for an integrated luminosity $L = 30$ fb ^{1}. Similarly, if the SM is extended with a leptophobic Z^0, the process $pp \to Z^0 \to NN \to \ell\ell^0 WW$ can probe Z^0 masses[33] up to 2.5 TeV, and M_N up to 800 GeV.

3.2 Type II: Scalar triplets

$SU(2)_L$ scalar triplets can be produced through the exchange of electroweak gauge bosons with SM couplings, and then they may be observable for masses near the TeV scale (see for reviews [3;31]). Although suppressed, their decays can occur within the detector for these large masses. In Fig. 1-(II) we display one of the possible processes. The search strategy and LHC potential depend on the dominant decay modes. These are proportional to the vacuum expectation value $j< \;^0 > j \quad v$, as for example[9] $\to W \quad W$, or to $(\quad)_{ij}$, as[11] $\to l \; l^{(0)}$.
can also decay into W if kinematically allowed (see [10]). All these di erent decay channels make the phenomenological analysis of single and pair production quite rich [12]. The EWPD limit in Eq. 7 translates into the bound $v = \frac{v^2 j \quad j}{\sqrt{2} M^2} < 2$ GeV. This is to be compared with $jm \; j = 2\sqrt{2}v \; j \; j \quad 10^{9}$ GeV, which gives a much more stringent constraint for non-negligible . Dilepton (diboson) decays are dominant for $v < (>) v^c \quad 10^{4}$ GeV. If for instance is of the same size as the charged lepton Yukawa couplings $10^{2} \quad 5 \quad 10^{6}$, v varies from $5 \quad 10^{8}$ to 10^{4} GeV, below the critical value v^c, and decays mainly into leptons. In this case the LHC reach for M has been estimated, based on statistics, to be 1 TeV for an integrated luminosity $L = 300$ fb ^{1}. In Fig. 3 we plot the invariant mass distribution $m_{\ell\ell}$ of same-sign dilepton pairs containing the lepton of largest transverse momentum for $M = 600$ GeV. As this fast simulation analysis shows, the SM background is well separated from the signal, and the LHC discovey potential strongly depends on the light neutrino mass hierarchy. For the simulated sample we nd 4 (44) signal events for the normal mass hierarchy NH (inverted IH), well separated from the main backgrounds: $t\bar{t}nj$ (1007 events), $Zb\bar{b}nj$ (91 events), tW (68 events), and $Zt\bar{t}nj$ (51 events). We get rid of other possible backgrounds like $ZZnj$ requiring no opposite-sign dilepton pairs with an invariant mass in the range $M_Z \quad 5$ GeV. For larger v values, with dominant non-leptonic decays, the corresponding reach estimate based on statistics is 600 GeV. Note that only in the leptonic case LHC is sensitive to the see-saw avour structure. Near the critical value, one could in principle extract information on the structure and on the global scale of the see-saw.

Tevatron Collaborations have already established limits on the scalar triplet mass assuming that $\to l \; l$ 100% of the time: At the 95% CL $M > 150$ GeV for only decaying to muons[34], and an integrated luminosity $L = 1.1$ fb ^{1}.

3.3 Type III: Fermion triplets

Not so much attention has been payed to the study of the LHC reach for $SU(2)_L$ fermion triplets . Up to very recently a similar electroweak process, the production of a heavy vector-like lepton doublet[35], had to be used to guess that LHC could be sensitive to $M \quad 500$ GeV. A dedicated study [13] estimates that an integrated luminosity $L = 10$ fb ^{1} should allow to observe LN violating signals (see Fig. 1-(III) for a relevant process) for $M < 800$ GeV. Vector-like fermion triplets couple to SM leptons proportionally to its mixing V_{l}, which is 10^{6} according to Eq. 1 if is at the LHC reach 1 TeV. So, one can eventually improve the analysis using the displaced vertex signatures of their decays.

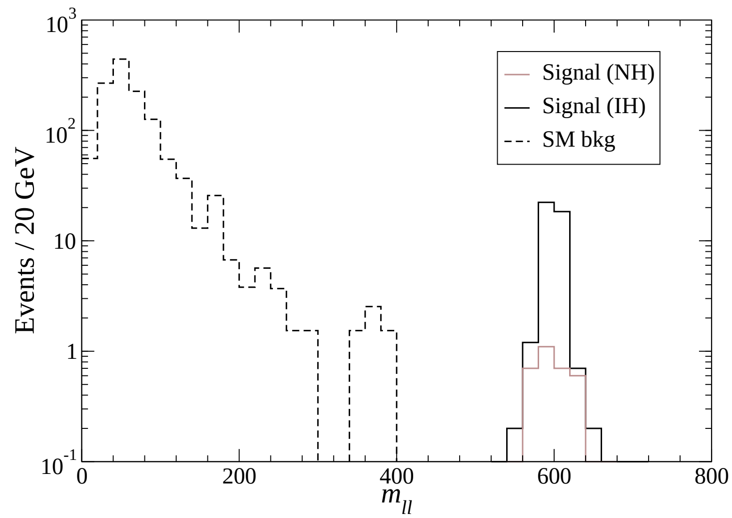

Figure 3: Same-sign dilepton invariant mass distributions for M = 600 GeV and normal (NH) and inverted (IH) mass hierarchies, assuming an integrated luminosity L = 300 fb^{1}.

4 Conclusions

Same-sign dilepton signals $l\,l^{(0)}\,X$ will allow to set significative limits on see-saw messengers at LHC, as illustrated in Table 4. The estimates for M and M are mainly based on statistics,

Table 4: LHC discovery limit estimates for see-saw messengers, assuming an integrated luminosity L = 30;300 and 10 fb^{1} for N; and , respectively. See Section 3 for a detailed explanation.

	M_N	M	M
LHC reach (in GeV)	150	600 1000	800

and a more detailed analysis is needed to confirm them.

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References

1. P. Minkowski, Phys. Lett. B 67, 421 (1977); T. Yanagida, Proceedings of the Workshop on Unified Theories and Baryon Number in the Universe, eds. A. Sawada and A. Sugamoto (Tsukuba, 1979); M. Gell-Mann, P. Ramond and R. Slansky, Proceedings of the Supergravity Stony Brook Workshop, eds. P. Van Niewenhuizen and D. Freedman (New York, 1979); S.L. Glashow, NATO Adv. Study Inst. Ser. B Phys. 59, 687 (1979); R. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44, 912 (1980).
2. R.N. Mohapatra et al, Rept. Prog. Phys. 70, 1757 (2007).
3. M. Raidal et al, arXiv:0801.1826 [hep-ph].

4. S. Weinberg, Phys. Rev. Lett. 43, 1566 (1979).
5. W. Konetschny and W. Kummer, Phys. Lett. B 70, 433 (1977); T. P. Cheng and L. F. Li, Phys. Rev. D 22, 2860 (1980); J. Schechter and J. W. F. Valle, Phys. Rev. D 22, 2227 (1980); see also E. Ma and U. Sarkar, Phys. Rev. Lett. 80, 5716 (1998).
6. R. Foot, H. Lew, X. G. He and G. C. Joshi, Z. Phys. C 44, 441 (1989).
7. T. Han and B. Zhang, Phys. Rev. Lett. 97, 171804 (2006).
8. F. del Aguila, J. A. Aguilar-Saavedra and R. Pittau, JHEP 0710, 047 (2007).
9. J. F. Gunion, R. Vega and J. Wudka, Phys. Rev. D 42, 1673 (1990).
10. A. G. Akeroyd and M. Aoki, Phys. Rev. D 72, 035011 (2005); see also S. Chakrabarti, D. Choudhury, R. M. Godbole and B. Mukhopadhyaya, Phys. Lett. B 434, 347 (1998).
11. A. Hektor, M. Kadastik, M. Muntel, M. Raidal and L. Rebane, Nucl. Phys. B 787, 198 (2007); M. Kadastik, M. Raidal and L. Rebane, arXiv:0712.3912 [hep-ph].
12. P. Fileviez Perez, T. Han, G. Y. Huang, T. Li and K. Wang, arXiv:0803.3450 [hep-ph]; arXiv:0805.3536 [hep-ph].
13. R. Franceschini, T. Hambye and A. Strumia, arXiv:0805.1613 [hep-ph].
14. F. del Aguila, J. A. Aguilar-Saavedra, J. de Blas and M. Zralek, Acta Phys. Polon. B 38, 3339 (2007).
15. A. Abada, C. Biggio, F. Bonnet, M. B. Gavela and T. Hambye, JHEP 0712, 061 (2007).
16. W. Buchmuller and D. Wyler, Nucl. Phys. B 268, 621 (1986); C. Arzt, M. B. Einhorn and J. Wudka, Nucl. Phys. B 433, 41 (1995).
17. S. Antusch, C. Biggio, E. Fernandez-Martinez, M. B. Gavela and J. Lopez-Pavon, JHEP 0610, 084 (2006).
18. A. Abada, C. Biggio, F. Bonnet, M. B. Gavela and T. Hambye, arXiv:0803.0481 [hep-ph].
19. W. M. Yao et al. [Particle Data Group], J. Phys. G 33, 1 (2006), and 2007 partial update for the 2008 edition available on the PDG WWW pages http://pdg.lbl.gov/.
20. F. del Aguila, J. de Blas and M. Perez-Victoria, arXiv:0803.4008 [hep-ph].
21. S. Bergmann and A. Kagan, Nucl. Phys. B 538, 368 (1999).
22. D. Tommasini, G. Barenboim, J. Bernabeu and C. Jarlskog, Nucl. Phys. B 444, 451 (1995).
23. P. Langacker and D. London, Phys. Rev. D 38, 886 (1988).
24. W. Loinaz, N. Okamura, T. Takeuchi and L. C. R. Wijewardhana, Phys. Rev. D 67, 073012 (2003).
25. G. Cynolter and E. Lendvai, arXiv:0804.4080 [hep-ph].
26. I. Gogoladze, N. Okada and Q. Sha , arXiv:0805.2129 [hep-ph].
27. D. Wyler and L. Wolfenstein, Nucl. Phys. B 218, 205 (1983); see also S. Bray, J. S. Lee and A. Pilaftsis, Nucl. Phys. B 786, 95 (2007).
28. J. Kersten and A. Y. Smirnov, Phys. Rev. D 76, 073005 (2007).
29. G. Ingelman and J. Rathsman, Z. Phys. C 60, 243 (1993); F. del Aguila, J. A. Aguilar-Saavedra, A. Martinez de la Ossa and D. Meloni, Phys. Lett. B 613, 170 (2005).
30. F. del Aguila, S. Bar-Shalom, A. Soni and J. Wudka, arXiv:0806.0876 [hep-ph]; see also S. Bar-Shalom, G. Eilam, T. Han and A. Soni, arXiv:0803.2835 [hep-ph].
31. F. del Aguila et al, arXiv:0801.1800 [hep-ph].
32. S. N. Gninenko, M. M. Kirsanov, N. V. Krasnikov and V. A. Matveev, Phys. Atom. Nucl. 70, 441 (2007); see also J. M. Frere, T. Hambye and G. Vertongen, arXiv:0806.0841 [hep-ph].
33. F. del Aguila and J. A. Aguilar-Saavedra, JHEP 0711, 072 (2007).
34. V. M. Abazov et al. [D0 Collaboration], arXiv:0803.1534 [hep-ex]; see also V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 93, 141801 (2004); D. E. Acosta et al. [CDF Collaboration], Phys. Rev. Lett. 93, 221802 (2004).
35. F. del Aguila, L. Ametller, G. L. Kane and J. Vidal, Nucl. Phys. B 334, 1 (1990).