Trilepton signals: the golden channel for seesaw searches at LHC *

F. del Aguila, J.A. Aguilar-Saavedra and J. de Blas

Departamento de Física Teórica y del Cosmos and CAFPE,
Universidad de Granada, E-18071 Granada, Spain

The comparison of samples with different number of charged leptons shows that trilepton signals are the most significant ones for seesaw mediators. As previously pointed out, this is indeed the case for scalar Δ (type II) and fermion Σ (type III) triplets at LHC, which can be discovered in this channel for masses up to $500-700$ GeV and an integrated luminosity of 30 fb^{-1}; whereas fermion singlets N (type I) are marginally observable if there are no further new physics near the TeV scale. However, if there are new gauge interactions at this scale coupling to right-handed neutrinos, as in left-right models, heavy neutrinos are observable up to masses ~ 2 TeV for new gauge boson masses up to ~ 4 TeV, as we discuss in some detail.

PACS numbers: 14.60.St, 13.35.Hb, 14.60.Pq, 13.15.+g

1. Introduction

Large hadron colliders can not directly test light neutrino masses because the energies they probe are of order of several hundreds of GeV, and then much larger than $m_\nu \sim 0.1$ eV. However, they can be sensitive to them in definite models (see, for instance, [1]). In particular, they can produce the seesaw messengers generating the observed neutrino masses, if they have a mass near the electroweak scale $v \simeq 246$ GeV.

The type I seesaw mechanism [2] invokes very heavy neutrino singlets N slightly mixed with the Standard Model (SM) lepton doublets in order to explain the tiny neutrino masses observed in neutrino oscillation experiments. Their leading effects at low energy can be described by the lepton

* Presented by F. del Aguila at "NuFact09", 11th International Workshop on Neutrino Factories, Superbeams and Beta Beams, Chicago, Illinois (U.S.A.), July 20-25, 2009, and the XXXIII International Conference of Theoretical Physics "Matter To The Deepest: Recent Developments in Theory of Fundamental Interactions", Ustroń, Poland, September 11-16, 2009.

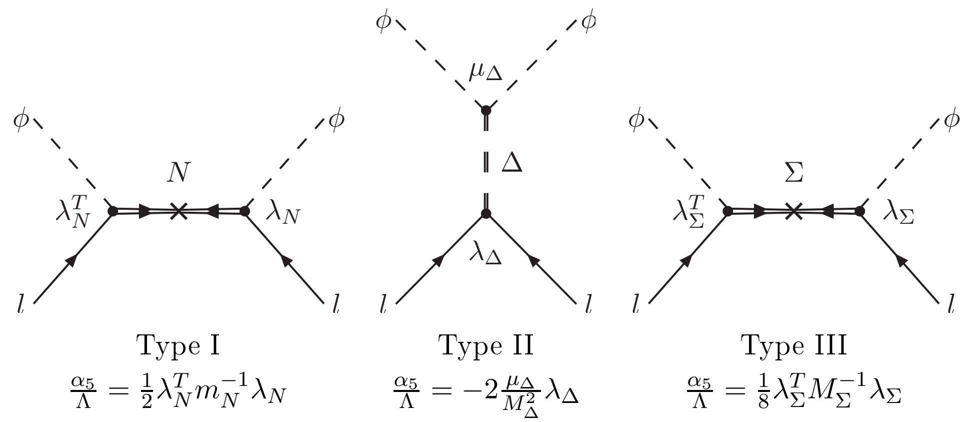

Fig. 1. Tree level seesaw mechanisms.

number violating (LNV) effective operator of dimension 5 resulting from the heavy neutrino integration [3] (see Ref. [4] for notation and definitions)

$$\frac{\alpha_5}{\Lambda}\mathcal{O}_5 = \frac{\alpha_5}{\Lambda}\overline{L_L^c}\tilde{\phi}^*\tilde{\phi}^\dagger L_L \to \frac{\alpha_5}{\Lambda}\frac{v^2}{2}\overline{\nu^c}\nu\,. \tag{1}$$

However, this operator can be also generated by the tree-level exchange of scalar Δ (type II seesaw) [5] and fermion Σ (type III seesaw) [6] triplets. In Fig. 1 we gather the corresponding diagrams and the coefficients of the dimension 5 effective operator α_5/Λ resulting from the heavy particle integration. In order to reproduce the observed neutrino masses, $m_\nu \simeq (\alpha_5/\Lambda)v^2/2$, the effective coupling α_5 must be quite small, of the order of 10^{-12} if the seesaw mediator has a mass $M = \Lambda$ near the electroweak scale (to be eventually at the LHC reach). This implies an effectively small lepton number violation at low energy: rather small λ and/or μ (in the scalar case), and/or a large cancellation between different contributions. (See for further discussion and references [7, 8].)

If seesaw messengers are produced and detected at LHC, the mechanism for neutrino mass generation will be unveiled. The LHC discovery potential for seesaw mediators has been studied in detail for the minimal type I seesaw [9], as well as for extra charged [10, 11] and neutral gauge interactions [12]; whereas simulations for type II seesaw have been performed in Ref. [13], and for type III in Refs. [13–15]. (Parton-level calculations can be found in Refs. [16–19].) In general seesaw messenger production results in multilepton signals, with the significance of each final state depending not only on the signal cross section but also on its SM backgrounds. At this point, it is important to emphasize that there is no new physics process which is background free, even if it violates lepton number or flavour.

For example, within the SM a final state with two charged leptons of the same-sign can be produced in association with two neutrinos balancing the total lepton number plus extra jets, as required by charge conservation. For instance,

$$uu \to W^+ W^+ dd \to \ell^+ \nu \ell^+ \nu dd \,, \tag{2}$$

with $\ell = e, \mu$. If the neutrinos have small transverse momenta their presence (via an observable missing energy $\not{p}_T$) is unnoticed, and the process apparently violates lepton number. The same can be said about lepton flavour violating (LFV) final states, which can be mimicked by SM processes involving opposite-charge W bosons. Apparently LNV backgrounds can be also produced if one charged lepton is missed by the detector, for example, in WZ production with the lepton of different charge from Z decay undetected. A third, less trivial example is $t\bar{t}$ production with $\bar{t}$ decaying semileptonically,

$$q\bar{q}, gg \to t\bar{t} \to W^+ b \, W^- \bar{b} \to jjb \, \ell^- \bar{\nu} \bar{b} \,, \tag{3}$$

and b giving an isolated charged lepton, or viceversa. There is some small probability that charged leptons from $b \to c\ell\nu$ decays have sizeable transverse momenta and small energy depositions in their vicinity, being not possible to effectively distinguish them in such a case from a charged lepton resulting from W or Z decay, except for their typically smaller transverse momenta. [1] Since the $t\bar{t}$ cross section is so large, this process is a sizeable source of same-sign dileptons, being the dominant background in most cases. This makes compulsory to properly take it into account in the simulation. A more detailed and enlightening discussion about how these backgrounds arise can be found in Refs. [9, 20].

As a general rule, it can be said that LNV signals, for instance same-sign dileptons $\ell^\pm \ell^\pm$, have much smaller backgrounds than lepton number conserving (LNC) signals *with equal number of charged leptons*, in this case $\ell^+ \ell^-$. (Signals which conserve lepton but violate flavour number, such as $\ell^+ \ell'^-$, have backgrounds of intermediate size.) But this does not apply when comparing signals and backgrounds with different charged lepton multiplicities, *e.g.*, $\ell^\pm \ell^\pm$, $\ell^\pm \ell^\pm \ell^\mp$ and $\ell^+ \ell^+ \ell^- \ell^-$, as follows from simple arguments and it is confirmed by detailed simulations.

In next section we show with some examples why trilepton signals are the best suited ones for discovery of type II and type III seesaw messengers, as well as of type I if heavy neutrinos couple to a new Z' boson. This is due to their good sensitivity, the best one in most cases, for all seesaw models. (This broad sensitivity in turn implies that the observation or not of other

[1] Note that isolation criteria for electrons and muons must be relaxed at LHC experiments, allowing for a small amount of "calorimeter noise" in order to keep a good acceptance for leptons from W, Z decays.

signals such as same-sign dileptons or four lepton final states is crucial to discriminate between models.) In Section 3 we study multilepton signals from single heavy neutrino production in left-right (LR) models [21], in the large parameter space region where heavy neutrinos predominantly decay into SM bosons $N \to lW/\nu Z/\nu H$. This process has not been previously studied in the literature, which focuses on the region where the three-body decay $N \to lW_R^* \to ljj$ and dilepton final states dominate [10,11].

2. Trilepton versus same-sign dilepton signals and backgrounds

Dilepton and trilepton signals can appear in a variety of production processes involving seesaw messengers. In type I seesaw we can have single N production

$$q\bar{q}' \to W^* \,/\, W' \to \ell^+ N \,, \tag{4}$$

with either a LNC decay $N \to \ell^- W^+$ or a LNV one $N \to \ell^+ W^-$. The subsequent W boson decay results in only two leptons for $W \to q\bar{q}'$ or three for $W \to \ell\nu$. N pair production is also possible if the heavy neutrinos couple to a new Z' boson,

$$q\bar{q} \to Z' \to NN \,, \tag{5}$$

with $NN \to \ell^\pm W^\mp \ell^\mp W^\pm$ (LNC) or $NN \to \ell^\pm W^\mp \ell^\pm W^\mp$ (LNV). The fully hadronic decay $WW \to q\bar{q}' q\bar{q}'$ gives dilepton signals; whereas if one W decays leptonically, three charged leptons are produced. In type II seesaw the processes

$$\begin{aligned} q\bar{q} &\to Z^* \to \Delta^{++}\Delta^{--} \to l_1^+ l_2^+ l_3^- l_4^- \,, \\ q\bar{q}' &\to W^* \to \Delta^{++}\Delta^{-} \to l_1^+ l_2^+ l_3^- \nu \,, \end{aligned} \tag{6}$$

with $l_i = e, \mu, \tau$, produce up to four charged leptons $\ell = e, \mu$. Finally, in type III seesaw we have, for example,

$$q\bar{q}' \to W^* \to E^+ N \,, \tag{7}$$

with $E^+ \to \ell^+ Z / \ell^+ H$ and $N \to \ell^- W^+, \ell^+ W^-$ as in type I seesaw, and the subsequent decays of $Z, H \to q\bar{q}', \nu\bar{\nu}$ and W into hadrons or leptons. In order to understand the relative significance and relevance of the different multilepton signals, several points have to be kept in mind:

First. Not all seesaw models involve heavy Majorana states and large lepton number violation. In particular, inverse type I, III seesaw models [7, 14,22] involve quasi-Dirac heavy neutrinos which in the processes in Eqs. (4), (5) and (7) do not produce final states with same-sign dileptons and no missing energy, but only opposite-sign ones. Still, trilepton signals do not require LNV neutrino decays $N \to \ell^+ W^-$, and are always present.

Second. In some cases, the branching ratio into three leptons is larger than into two same-sign leptons. For instance, in $Z' \to NN$

$$\begin{aligned} \mathrm{Br}(\ell^\pm \ell^\pm \ell^\mp) &\simeq \frac{1}{2} \times \frac{1}{2} \times \frac{2}{9} \times \frac{6}{9} \times 2 \simeq 0.074 \,, \\ \mathrm{Br}(\ell^\pm \ell^\pm) &\simeq \frac{1}{4} \times \frac{1}{4} \times 2 \times \frac{6}{9} \times \frac{6}{9} \simeq 0.055 \,. \end{aligned} \quad (8)$$

Scalar triplet production and decay provides another example. In the light neutrino inverted mass hierarchy the $\Delta^{++} \to l_i^+ l_j^+$, $\Delta^+ \to l_i \nu_j$ decays have approximate branching ratios

$$\begin{aligned} & \mathrm{Br}(\ell^+ \ell^+) \simeq \mathrm{Br}(\ell^+ \nu_\ell) \simeq 0.65 \,, \\ & \mathrm{Br}(\ell^+ \tau^+) \simeq 2\,\mathrm{Br}(\ell^+ \nu_\tau) \simeq 2\,\mathrm{Br}(\tau^+ \nu_\ell) \simeq 0.25 \,, \\ & \mathrm{Br}(\tau^+ \tau^+) \simeq \mathrm{Br}(\tau^+ \nu_\tau) \simeq 0.1 \,. \end{aligned} \quad (9)$$

(For studies of the dependence of these branching ratios on neutrino mixing parameters and the determination of neutrino data from collider observables see Refs. [23].) Then, with a simple counting we obtain

$$\begin{aligned} & \mathrm{Br}(\Delta^{++}\Delta^{--} \to \ell^+ \ell^+ \ell^- \ell^-) \simeq 0.65 \times 0.65 \simeq 0.42 \,, \\ & \mathrm{Br}(\Delta^{++}\Delta^{--} \to \ell^\pm \ell^\pm \ell^\mp) \simeq 0.65 \times 0.25 \times 2 \simeq 0.32 \,, \\ & \mathrm{Br}(\Delta^{++}\Delta^{--} \to \ell^\pm \ell^\pm) \simeq 0.65 \times 0.1 \times 2 \simeq 0.13 \,, \\ & \mathrm{Br}(\Delta^{\pm\pm}\Delta^{\mp} \to \ell^\pm \ell^\pm \ell^\mp) \simeq 0.65 \times (0.65 + 0.12) \simeq 0.5 \,, \\ & \mathrm{Br}(\Delta^{\pm\pm}\Delta^{\mp} \to \ell^\pm \ell^\pm) \simeq 0.65 \times (0.125 + 0.1) \simeq 0.14 \,, \end{aligned} \quad (10)$$

showing that trilepton final states dominate over four lepton and same-sign dilepton ones. For the normal hierarchy the trend is the same, also when secondary leptons from τ decays are included and simple event selection criteria imposed [13].

Third. Even in processes where the branching ratio for $\ell^\pm \ell^\pm \ell^\mp$ is smaller than for $\ell^\pm \ell^\pm$ final states, as for instance in minimal type III seesaw (Eq. (7)), the larger backgrounds in the latter case require more stringent cuts to reduce them making up for the difference in the signal cross sections. In order to illustrate these statements numerically, we collect in Table 1 the number of same-sign dilepton and trilepton events evaluated with a fast detector simulation, and after typical selection cuts to enhance the signal significance for the processes in Eqs. (5) and (7). For comparison, we show both the Majorana and Dirac lepton triplet (labelled Σ_M and Σ_D, respectively) signals, as well as the type I seesaw ones with an extra Z' and a

Majorana or Dirac heavy neutrino (labelled $Z'_\lambda N_{\rm M}$ and $Z'_\lambda N_{\rm D}$). We assume $m_{E,N} = 300$ GeV and $M_{Z'_\lambda} = 650$ GeV. It is apparent that for these cuts same-sign dilepton and trilepton backgrounds are quite similar, altough their relative size depends on the cuts applied. In particular, we observe that the main background for same-sign dileptons (trileptons) comes from the semileptonic (dileptonic) channel in $t\bar{t}$ production, when a b quark gives an isolated charged lepton. As it has been already stressed in the introduction, the fact that a signal violates lepton number does not automatically guarantee the absence of SM backgrounds, nor imply that its background is much smaller than those for other LNC signals with more charged leptons. We

Signals	$\ell^\pm \ell^\pm$	$\ell^\pm \ell^\pm \ell^\mp$	Backgrounds	$\ell^\pm \ell^\pm$	$\ell^\pm \ell^\pm \ell^\mp$
E^+E^- ($\Sigma_{\rm M}$)	1.6	26.3	$t\bar{t}nj$	194	156
$E^\pm N$ ($\Sigma_{\rm M}$)	240.0	192.2	tW	6	6
NN ($Z'_\lambda N_{\rm M}$)	202.1	252.6	$Wt\bar{t}nj$	12	47
			$Zt\bar{t}nj$	3	20
$E_i^+E_i^-$ ($\Sigma_{\rm D}$)	4.2	80.9	$WWnj$	15	0
$E_i^\pm N$ ($\Sigma_{\rm D}$)	12.3	398.3	$WZnj$	24	38
NN ($Z'_\lambda N_{\rm D}$)	8.1	481.9	$ZZnj$	4	5
			$WWWnj$	7	12

Table 1. Number of events in the $\ell^\pm \ell^\pm$ and $\ell^\pm \ell^\pm \ell^\mp$ final states for some signals and their main backgrounds and a luminosity of 30 fb^{-1}, from Ref. [15].

can also observe that, as indicated above, in models with heavy Dirac neutrinos same-sign dileptons are practically absent, but trilepton signals are a factor of two larger than in the Majorana case. In next section we compare dilepton and trilepton final state production for the process mediated by the extra charged boson W_R of a LR model in Eq. (4).

3. Heavy neutrino production in left-right models at LHC

Electroweak precision data constrain heavy neutrino singlets to mix little with SM leptons, $|V_{eN\ (\mu N)}| < 0.05\ (0.03)$ [24], [2] making them difficult to observe at LHC [9]. In models with extra Z' bosons heavy neutrino pair production is possible, leading to dilepton and trilepton signals as shown in the previous section. An alternative widely studied is the LR model, extending the SM gauge symmetry $SU(2)_L \times U(1)_Y$ to $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ and its matter content to include right-handed neutrinos N [21]. Heavy neutrinos can then be produced by W_R exchange with a relatively large cross

[2] This new limit is derived including the CKM constraint, and recent data.

section, as in Eq. (4), without any mixing suppresion. The cross section, assuming $g_R = g_L$ and only one neutrino lighter than the W_R boson, is plotted in Fig. 2 (left). Available studies of the LHC reach for this process [10, 11]

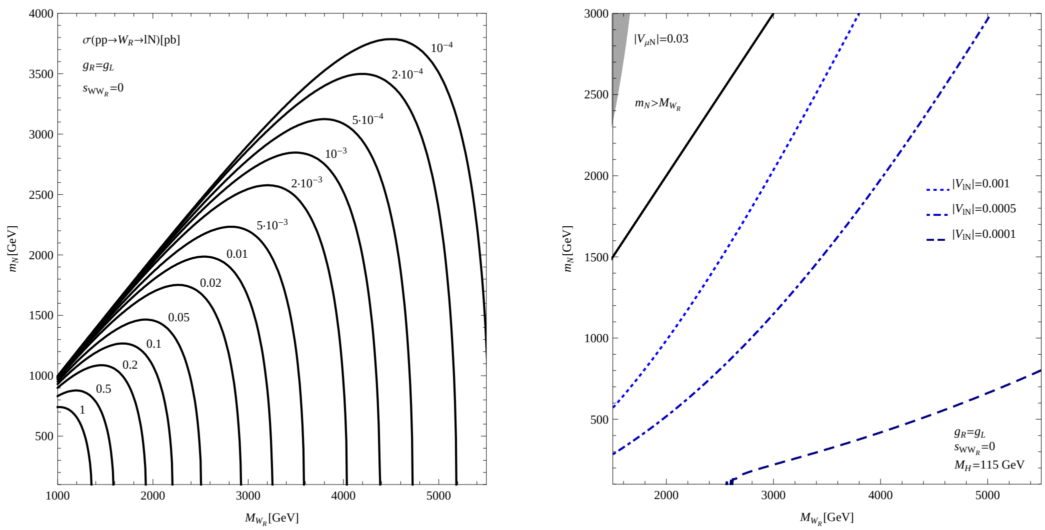

Fig. 2. Left: $pp \to W_R \to lN$ cross section at LHC. Right: N decay branching ratio to W_R^* and SM bosons (see the text).

assume that N only has a three-body decay $N \to lW_R^* \to ljj$. However, this may not be the dominant mode for a relatively large range of LR model parameters. As a matter of fact, N can mainly decay into lW, νZ, νH if V_{lN} or/and the $W - W_R$ mixing s_{WW_R} are sizeable, of order 10^{-4} or larger. The corresponding leptonic charged currents read

$$\begin{aligned} J_{W_R}^{-\ \mu} &\simeq -\frac{g_L}{\sqrt{2}} s_{WW_R} \overline{\nu_L} \gamma^\mu l_L + \frac{g_R}{\sqrt{2}} \left(-V_{lN} \overline{\nu_L^c} \gamma^\mu l_R + \overline{N_R} \gamma^\mu l_R \right) , \\ J_{W}^{-\ \mu} &\simeq \frac{g_L}{\sqrt{2}} \left(\overline{\nu_L} \gamma^\mu l_L + V_{lN} \overline{N_R^c} \gamma^\mu l_L \right) + \frac{g_R}{\sqrt{2}} s_{WW_R} \overline{N_R} \gamma^\mu l_R , \end{aligned} \tag{11}$$

where we only keep the leading terms in the small mixings and omit the flavour indices; and similarly for neutral currents. One can define the branching ratio

$$\mathrm{Br}_R = \frac{\Gamma(N \to lW_R^* \to ljj)}{\Gamma(N \to lW_R^* \to ljj) + \Gamma(N \to lW, \nu Z, \nu H)} , \tag{12}$$

with

$$\Gamma(N \to lW_R^* \to ljj) \simeq N_c \frac{g_R^4}{1024\pi^3} \frac{m_N^5}{M_{W_R}^4} , \tag{13}$$

where we neglect quark masses and sum both lepton channels $\Gamma(N \to l^+ W_R^{-*}) = \Gamma(N \to l^- W_R^{+*})$; whereas

$$\Gamma(N \to lW) \simeq \frac{g_L^2 \, |V_{lN}|^2 + g_R^2 s_{WW_R}^2}{32\pi} \frac{m_N^3}{M_W^2} \left(1 - \frac{M_W^2}{m_N^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_N^2}\right) , \quad (14)$$

and anagolously for $\nu Z, \nu H$ decays. In Fig. 2 (right) we draw the curves for constant $\mathrm{Br}_R = 1/2$ in the $M_{W_R} - m_N$ plane, which depend on the value of $|V_{lN}|^2 + s_{WW_R}^2$. The curve corresponding to the present bound on $|V_{eN}| < 0.05$ (for $s_{WW_R} = 0$) is in the $m_N > M_{W_R}$ upper-half out of the figure. For a given value of $|V_{lN}|^2 + s_{WW_R}^2$, the region on the left of the curve corresponds to $\mathrm{Br}_R > 1/2$, where W_R^* decays start to dominate.

The scenario with $\mathrm{Br}_R \sim 1$ has been widely studied, and we present in Fig. 3 (left) the limits obtained in Ref. [11], assuming a 100 % branching ratio into $N \to ljj$. For the scenario with $\mathrm{Br}_R \sim 0$ we have performed a new simulation extending the generator `Triada` [13] with this process and using `Alpgen` [25] to generate the SM backgrounds. The parton shower Monte Carlo `Pythia` 6.4 [26] is used to add initial and final state radiation and pile-up, and perform hadronisation. The fast detector simulation `AcerDET` [27] is used to simulate a generic LHC detector. Analyses have been performed for different neutrino masses in steps of 100 GeV, using W_R masses of 2.5 or 3 TeV, close to the limits obtained. The selection criteria (with small modifications at some points) are:

$\ell^\pm \ell^\pm \ell^\mp$: three leptons, the same-sign pair with $p_T > 30$ GeV and the third one with $p_T > 10$ GeV; invariant mass of opposite-sign pairs $|m_{\ell^+\ell^-} - M_Z| > 10$ GeV; total invariant mass (adding the missing momentum) $m_{\text{tot}} > 1.5$ TeV.

$\ell^\pm \ell^\pm$: two same-sign leptons with $p_T > 30$ GeV; two jets with $p_T > 20$ GeV; missing energy $\not{p}_T < 50$ GeV; leading lepton with $p_T > 400$ GeV; $m_{\text{tot}} > 1.5$ TeV.

$\ell^+ \ell^-$: two opposite-sign leptons with $p_T > 30$ GeV and $m_{\ell^+\ell^-} > 500$ GeV; two jets with $p_T > 20$ GeV; leading lepton with $p_T > 750$ GeV and leading jet with $p_T > 200$ GeV; $\not{p}_T < 50$ GeV; $m_{\text{tot}} > 2.5$ TeV.

The limits for the dilepton and trilepton final state are presented in Fig. 3 (right), as well as their combination. We observe that same-sign dilepton and trilepton signals have very similar significances despite the larger branching ratio into the former. This is because dilepton backgrounds are also larger and the signal efficiency for $m_N \ll M_{W_R}$ with a highly boosted N is smaller in the dilepton channels, in which the charged lepton from N decay is often

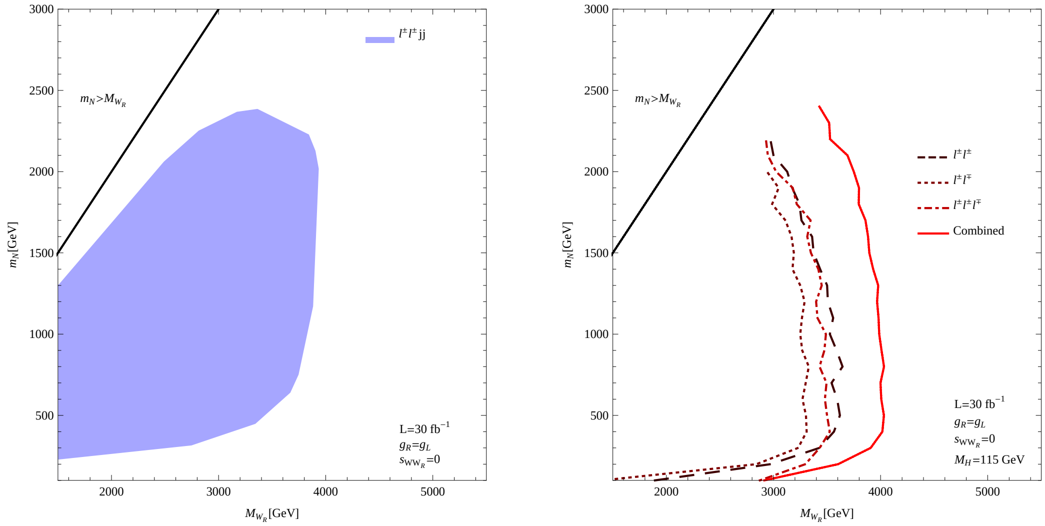

Fig. 3. Left: Discovery limits for 30 fb^{-1} as a function of M_{W_R} and m_N, assuming that N only decays into $l^{\pm} W_R^* \to ljj$, from Ref. [11]. Right: The same, assuming that N decays into SM bosons.

located inside the jets from W hadronic decay. The combination of all final states gives a discovery reach similar to the scenario with W_R^* decaying dominantly into two jets.

We thank discussions with M. Pérez-Victoria. This work has been supported by MEC project FPA2006-05294, Junta de Andalucía projects FQM 101 and FQM 03048, and by the European Community's Marie-Curie Research Training Network under contract MRTN-CT-2006-035505 "Tools and Precision Calculations for Physics Discoveries at Colliders". J.A.A.-S. acknowledges support by a MEC Ramón y Cajal contract.

REFERENCES

[1] W. Porod, M. Hirsch, J. Romao and J. W. F. Valle, *Phys. Rev.* **D63**, 115004 (2001) [hep-ph/0011248].

[2] M. Gell-Mann, P. Ramond and R. Slansky, in *Supergravity*, ed. by P. Van Nieuwenhuizen and D.Z. Freedman (North Holland, Amsterdam, 1979), p.315; S.L. Glashow, in *Quarks and Leptons*, Cargese, 1979, ed. by M. Levy et al. (Plenum, New-York, 1980); T. Yanagida, in Proc. of the *Workshop on the Unified Theory and Baryon Number in the Universe*, ed. by O. Sawada and A.

Sugamoto (KEK report 79-18, Tsukuba, Japan, 1979), p.95; R.N. Mohapatra and G. Senjanovic, *Phys. Rev. Lett.* **44**, 912 (1980).

[3] S. Weinberg, *Phys. Rev. Lett.* **43**, 1566 (1979).

[4] F. del Aguila, J. A. Aguilar-Saavedra, J. de Blas and M. Perez-Victoria, arXiv:0806.1023 [hep-ph]

[5] M. Magg and C. Wetterich, *Phys. Lett.* **B94**, 61 (1980); T. P. Cheng and L. F. Li, *Phys. Rev.* **D22**, 2860 (1980); G. B. Gelmini and M. Roncadelli, *Phys. Lett.* **B99**, 411 (1981); G. Lazarides, Q. Shafi and C. Wetterich, *Nucl. Phys.* **B181**, 287 (1981); R. N. Mohapatra and G. Senjanovic, *Phys. Rev.* **D23**, 165 (1981).

[6] R. Foot, H. Lew, X. G. He and G. C. Joshi, *Z. Phys.* **C44**, 441 (1989); E. Ma, *Phys. Rev. Lett.* **81**, 1171 (1998) [hep-ph/9805219].

[7] F. del Aguila, J. A. Aguilar-Saavedra, J. de Blas and M. Zralek, *Acta Phys. Polon.* **B38**, 3339 (2007) [arXiv:0710.2923 [hep-ph]]; X. G. He, S. Oh, J. Tandean and C. C. Wen, arXiv:0907.1607 [hep-ph].

[8] S. Antusch, C. Biggio, E. Fernandez-Martinez, M. B. Gavela and J. Lopez-Pavon, *J. High Energy Phys.* **0610**, 084 (2006) [hep-ph/0607020]; A. Abada, C. Biggio, F. Bonnet, M. B. Gavela and T. Hambye, *J. High Energy Phys.* **0712**, 061 (2007) [arXiv:0707.4058 [hep-ph]].

[9] F. del Aguila, J. A. Aguilar-Saavedra and R. Pittau, *J. High Energy Phys.* **0710**, 047 (2007) [hep-ph/0703261].

[10] A. Ferrari et al., *Phys. Rev.* **D62**, 013001 (2000).

[11] S. N. Gninenko, M. M. Kirsanov, N. V. Krasnikov and V. A. Matveev, *Phys. Atom. Nucl.* **70**, 441 (2007).

[12] F. del Aguila and J. A. Aguilar-Saavedra, *J. High Energy Phys.* **0711**, 072 (2007) [arXiv:0705.4117 [hep-ph]].

[13] F. del Aguila and J. A. Aguilar-Saavedra, *Nucl. Phys.* **B813**, 22 (2009) [arXiv:0808.2468 [hep-ph]].

[14] F. del Aguila and J. A. Aguilar-Saavedra, *Phys. Lett.* **B672**, 158 (2009) [arXiv:0809.2096 [hep-ph]].

[15] J. A. Aguilar-Saavedra, arXiv:0905.2221 [hep-ph].

[16] A. Datta, M. Guchait and A. Pilaftsis, *Phys. Rev.* **D50**, 3195 (1994) [hep-ph/9311257]; F. M. L. Almeida, Y. A. Coutinho, J. A. Martins Simoes and M. A. B. do Vale, *Phys. Rev.* **D62**, 075004 (2000) [hep-ph/0002024]; O. Panella, M. Cannoni, C. Carimalo and Y. N. Srivastava, *Phys. Rev.* **D65**, 035005 (2002) [hep-ph/0107308]; T. Han and B. Zhang, *Phys. Rev. Lett.* **97**, 171804 (2006) [hep-ph/0604064]; S. Bray, J. S. Lee and A. Pilaftsis, *Nucl. Phys.* **B786**, 95 (2007) [hep-ph/0702294].

[17] K. Huitu, S. Khalil, H. Okada and S. K. Rai, *Phys. Rev. Lett.* **101**, 181802 (2008) [arXiv:0803.2799 [hep-ph]]; P. Fileviez Perez, T. Han and T. Li, arXiv:0907.4186 [hep-ph].

[18] K. Huitu, J. Maalampi, A. Pietila and M. Raidal, *Nucl. Phys.* **B487**, 27 (1997) [hep-ph/9606311]; J. F. Gunion, C. Loomis and K. T. Pitts, [hep-ph/9610237]; A. G. Akeroyd and M. Aoki, *Phys. Rev.* **D72**, 035011

(2005) [hep-ph/0506176]; A. Hektor, M. Kadastik, M. Muntel, M. Raidal and L. Rebane, *Nucl. Phys.* **B787**, 198 (2007) [arXiv:0705.1495 [hep-ph]]; P. Fileviez Perez, T. Han, G. Y. Huang, T. Li and K. Wang, *Phys. Rev.* **D78**, 071301 (2008) [arXiv:0803.3450 [hep-ph]]; P. Fileviez Perez, T. Han, G. y. Huang, T. Li and K. Wang, *Phys. Rev.* **D78** 015018 (2008) [arXiv:0805.3536 [hep-ph]].

[19] R. Franceschini, T. Hambye and A. Strumia, *Phys. Rev.* **D78**, 033002 (2008) [arXiv:0805.1613 [hep-ph]]; A. Arhrib, B. Bajc, D. K. Ghosh, T. Han, G. Y. Huang, I. Puljak and G. Senjanovic, arXiv:0904.2390 [hep-ph]; T. Li and X. G. He, arXiv:0907.4193 [hep-ph].

[20] Z. Sullivan and E. L. Berger, *Phys. Rev.* **D78**, 034030 (2008) [arXiv:0805.3720 [hep-ph]].

[21] J. C. Pati and A. Salam, *Phys. Rev.* **D10**, 275 (1974) [*Erratum-ibid.* **D11**, 703 (1975)]; R. N. Mohapatra and J. C. Pati, *Phys. Rev.* **D11**, 2558 (1975); G. Senjanovic and R. N. Mohapatra, *Phys. Rev.* **D12**, 1502 (1975); see for a review and further references P. Duka, J. Gluza and M. Zralek, *Annals Phys.* **280**, 336 (2000) [hep-ph/9910279].

[22] D. Wyler and L. Wolfenstein, *Nucl. Phys.* **B218**, 205 (1983); R. N. Mohapatra and J. W. F. Valle, *Phys. Rev.* **D34**, 1642 (1986); see for a definite model F. del Aguila, M. Masip and J. L. Padilla, *Phys. Lett.* **B627**, 131 (2005) [hep-ph/0506063]; and for a review and further references E. Ma, arXiv:0908.1770 [hep-ph].

[23] E. J. Chun, K. Y. Lee and S. C. Park, *Phys. Lett.* **B566**, 142 (2003) [hep-ph/0304069]; J. Garayoa and T. Schwetz, *J. High Energy Phys.* **0803**, 009 (2008) [arXiv:0712.1453 [hep-ph]]; M. Kadastik, M. Raidal and L. Rebane, *Phys. Rev.* **D77**, 115023 (2008) [arXiv:0712.3912 [hep-ph]]; A. G. Akeroyd, M. Aoki and H. Sugiyama, *Phys. Rev.* **D77**, 075010 (2008) [arXiv:0712.4019 [hep-ph]]; A. G. Akeroyd and C. W. Chiang, arXiv:0909.4419 [hep-ph].

[24] F. del Aguila, J. de Blas and M. Perez-Victoria, *Phys. Rev.* **D78**, 013010 (2008) [arXiv:0803.4008 [hep-ph]].

[25] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A. D. Polosa, *J. High Energy Phys.* **0307** (2003) 001 [hep-ph/0206293].

[26] T. Sjostrand, S. Mrenna and P. Skands, *J. High Energy Phys.* **0605** (2006) 026 [hep-ph/0603175].

[27] E. Richter-Was, hep-ph/0207355.