Type II Seesaw at LHC: the Roadmap

Alejandra Melfo, 1, 2 Miha Nemevšek, 2, 3 Fabrizio Nesti, 2 Goran Senjanović, 2 and Yue Zhang 2

1 Universidad de Los Andes, Mérida, Venezuela
2 International Center for Theoretical Physics, Trieste, Italy
3 J. Stefan Institute, Ljubljana, Slovenia
(Dated: December 27, 2012)

In this Letter we revisit the type-II seesaw mechanism based on the addition of a weak triplet scalar to the standard model. We perform a comprehensive study of its phenomenology at the LHC energies, complete with the electroweak precision constraints. We pay special attention to the doubly-charged component, object of collider searches for a long time, and show how the experimental bound on its mass depends crucially on the particle spectrum of the theory. Our study can be used as a roadmap for future complete LHC studies.

Introduction. The modern day understanding of the origin and the smallness of neutrino mass is based on the see-saw mechanism [1]. The most natural source for this mechanism is provided by the Left-Right symmetric theories [2], which require the existence of the $SU(2)_L$ (and $SU(2)_R$) triplets with hypercharge $Y = 2$. Left-Right symmetry can be realized either at low scale, or embedded in a grand unified theory such as $SO(10)$. It turns out that once the see-saw mechanism is turned on, the $SU(2)_L$ triplet gets a small vacuum expectation value, even if it is very heavy. One can even contemplate the possibility that this triplet is the only low-energy remnant of the new physics beyond the standard model (SM), in which case one talks of the Type II see-saw mechanism [6].

An appealing feature of what could otherwise be seen as an ad-hoc hypothesis is the minimalism and the predictivity of this scenario, namely, the fact that the Yukawa couplings determine the neutrino mass matrix. This would become particularly important if the triplet were to lie in the TeV region, for then its decays could directly probe the neutrino masses and mixings.

The doubly charged component of the triplet has been the focus of attention due to its possibly spectacular signatures at colliders [7]: if Yukawa couplings are sufficiently large, it will decay predominantly into same-sign charged leptons which is a clear signature of Lepton Number Violation (LNV). The same sign leptons at colliders are a generic high energy analogue of the neutrinoless double beta decay as a probe of LNV, envisioned in [8].

Both, CDF and D0 performed a search of the doubly charged component [9]. However, only the pair production of the doubly charged components was considered. The latest search at CMS [10] takes into account the associated production with the singly charged component but assumes the triplet spectrum to be degenerate. None of them have taken into account the full complexity of its production and decay modes. An attempt in this direction was made in [11]. Here we provide a global view of the phenomenological implications of the Type II seesaw scenario at hadron colliders, in particular at the LHC.

We perform the first electroweak high precision study and demonstrate the strong dependence of the above CMS limit on the spectrum of the scalar triplet. In particular we find that the quoted limit on the order of $250 - 300$ GeV can go down all the way to $100$ GeV for the mass split around $20 - 30$ GeV. In what follows we discuss and quantify our results.

The model. Let us start by summarizing the salient features of the Type II see-saw mechanism. Besides the usual SM particle content, the model requires the existence of a $Y = 2$ $SU(2)_L$ triplet $\Delta$. When its neutral component $\Delta^0$ acquires a vev $v_\Delta$, it generates a Majorana mass for the neutrinos through the Yukawa term

$$\frac{M_{ij}^\nu}{v_\Delta} L^\dagger_i C i \sigma^2 \Delta L_j + \text{h.c.},$$

where $L_i$ is a left-handed lepton doublet, $C$ the charge conjugation operator and

$$M_{\nu} = U^* m_{\nu} U^\dagger,$$

is the neutrino mass matrix in the basis where the charged lepton masses are diagonal. Here $m_{\nu}$ stands for the neutrino masses and $U$ is the PMNS lepton mixing matrix. The complete potential for the scalars, including the Higgs doublet $H$, is

$$V = - m_H^2 H^\dagger H + m_\Delta^2 \text{Tr} \Delta^\dagger \Delta + (\mu H^\dagger i \sigma_2 \Delta^* H + \text{h.c.}) + \lambda_1 (H^\dagger H)^2 + \lambda_2 (\text{Tr} \Delta^\dagger \Delta)^2 + \lambda_3 (\text{Tr} H^\dagger \Delta)^2 + \lambda_4 H^\dagger H \text{Tr} \Delta^\dagger \Delta + \beta H^\dagger H \Delta \Delta^\dagger H,$$

and the triplet vev is $v_\Delta = \mu v^2/\sqrt{2} m_\Delta^2$, where $v$ is the SM Higgs vev. Thus a small $v_\Delta$ is technically natural, as its size is controlled by the $\mu$ parameter which is only self-renormalized. A non-vanishing $v_\Delta$ spoils the $\rho$ parameter, which requires $v_\Delta$ smaller than a few GeV.

The triplet components then follow the sum rules

$$m_{\Delta^+}^2 - m_{\Delta^0}^2 - m_{\Delta^+}^2 \simeq m_{\Delta^0}^2 - m_{\Delta^+}^2 \simeq \beta v^2/4,$$

$$m_S \simeq m_A = m_{\Delta^0},$$

1 For instance, in the case of left-right symmetry, it is known that the scale must be $M_W \gtrsim 2.5$ TeV [3] on theoretical grounds and 1.7 TeV [4, 5] on experimental grounds.
where $m_S$ and $m_A$ are the masses of the scalar (S) and pseudoscalar (A) components of $\Delta^0$. The triplet components are separated by equal mass square difference, and there is an upper limit on the splitting from the perturbativity of $\beta$. These rules are valid up to tiny $O(v^2/\mu^2)$ corrections.

We first focus on smaller values $v_\Delta \lesssim 10^{-3}$ GeV, relevant for probing the connection with neutrino masses at LHC and later on comment on larger $v_\Delta$ and quantify its upper bound.

**Probing the flavor structure.** The doubly charged scalar $\Delta^{++}$ plays a central role in the physics of this model. In particular, its decays into same-sign charged leptons probe the neutrino masses and mixings. This is clear from (1), and is made explicit in the decay rate

$$\Gamma_{\Delta^{++}\rightarrow \ell_i\ell_j} = \frac{m_{\Delta^{++}}}{8\pi(1 + b_{ij})} \left| \frac{(U^* m_\nu U^*)_{ij}}{v_\Delta} \right|^2.$$  

This connection between the collider physics and the low energy processes has been studied extensively [12, 13]. If this were the only mode, one could probe the Yukawa structure through branching ratios to different flavor modes. In addition, the decay of the singly-charged component $\Delta^+ \rightarrow \ell_i \nu$ may also serve as a possible channel to determine the Yukawa structure.

**Probing the neutrino mass scale.** By probing the flavour structure as above one also measures the ratio of neutrino masses, so that by using neutrino oscillation data one might infer the absolute neutrino mass scale. There is also a chance of directly measuring the absolute mass scale at LHC. In fact, the other decay mode,

$$\Gamma_{\Delta^{++}\rightarrow W^+W^+} = \frac{g^4 v_\Delta^2}{8\pi m_{\Delta^{++}}} \left( 1 - \frac{4M_W^2}{m_{\Delta^{++}}^2} \right)^2 \left[ 1 + \left( \frac{m_{\Delta^{++}}^2}{2M_W^2} - 1 \right)^2 \right]$$

opens up for a non-vanishing $v_\Delta$. Higgs triplet with gauge boson fusion production and decay at the LHC has been studied in [14]. If large enough this channel would thus enable the determination of $v_\Delta$. The critical value is obtained for $\Gamma_{\Delta^{++}\rightarrow \ell_i\ell_j} = \Gamma_{\Delta^{++}\rightarrow W^+W^+}$ which gives $v_\Delta = 10^{-4} \div 10^{-3}$ GeV, see Fig. 1.

**The decay phase diagram.** The triplet mass sum rules in Eqs. (4) and (5) allow for only two scenarios,

**Case A:** $m_{\Delta^0} \geq m_{\Delta^+} \geq m_{\Delta^{++}}$  

**Case B:** $m_{\Delta^{++}} > m_{\Delta^+} > m_{\Delta^0}$.  

When the triplet components are not degenerate, the cascade channels $\Delta^0 \rightarrow \Delta^+W^- \rightarrow \Delta^{++}W^-$ and $\Delta^{++} \rightarrow \Delta^+W^+ \rightarrow \Delta^0W^+W^+$ for case A and $\Delta^{++} \rightarrow \Delta^+W^- \rightarrow \Delta^0W^-W^+$ (for case B) are open [11, 13]. These processes have been overlooked in previous experimental studies due to the assumption of the degeneracy.

In Fig. 1 we provide a phase diagram separating the regions where different decay modes play a dominant role. We take as an example scenario B with $m_{\Delta^{++}} = 150$ GeV, and consider the $\Delta^{++}$ decays. It shows that for moderate mass splits, the cascade channels become important and one basically loses the same-sign dilepton channel. Once the mass difference is large enough, cascade decays quickly dominate. Similar decaying phase diagrams hold also for $\Delta^+ \rightarrow \ell_1 \nu \ell_2$ in case B and $\Delta^0$ in case A. On the other hand, for the lightest triplet component there are only two possibilities: it decays either into leptons or gauge bosons. The mass splits have thus a dramatic impact on the direct search limits on the doubly-charged scalar masses, as we show below.

**Electroweak precision tests: a lesson on spectra.** Let us take this model seriously as an effective theory at the LHC, so that any other new physics is effectively decoupled. Then, high precision electroweak study is a must. We apply the general formulae in [15] to the case of the triplet. The dominant constraint comes from the oblique parameter $T$ which is governed by the mass differences. The essential role in this analysis is thus played by the sum rules in (4) and (5), which eliminate two arbitrary mass scales. The first message from EWPT is that the mass split may be large. In particular, for very light SM Higgs the mass difference can range from zero to roughly 50 GeV. Actually, many of the studies assumed the degeneracy (or tiny mass difference) among the members of the triplet. Although this is possible for a light SM Higgs, it is strongly disfavored for larger masses, beyond 200 GeV. For instance, a very heavy Higgs of 400 GeV requires the mass difference to be bigger than $\sim 40$ GeV. The reason for this is that the heavy SM Higgs contribution to the $T$ parameter has to be compensated by a splitting of the triplet components. There is also an
The analogous curve for $Z$ for SM Higgs mass 130 GeV (left panel) and 300 GeV (right panel). The (green) region excluded by the DWPT and plays a similar role as a heavy Higgs boson (but with $m_D$). These constraints further ensure that the triplet Yukawa couplings are small enough so that the above EWPT constraints, i.e. the regions favored by electroweak precision tests, are brought together with the collider phenomenology, see also [22].

**Current LHC limits.** The CMS collaboration has published the latest data on four lepton final states, with a luminosity of 980 pb$^{-1}$ at $\sqrt{s} = 7$ TeV, in [10]. No excess over the SM prediction is observed and an updated lower limit on the mass of the doubly-charged Higgs is set. The analysis is performed assuming degeneracy of the triplet components. In the following, we perform an estimate of the limit in the full parameter space. We generate the events for the pair and associated production of all the $\Delta$’s using MadGraph 4.4.57 [17], decay them with BRIDGE 2.23 [18] and then do the showering and detector simulation with Pythia-PGS 2.1.8 [19, 20]. We adopt the K-factor from [21] to account for next-to-leading order correction to the production. We focus on the four lepton final states and implement the same cuts as in [10]. These cuts may be further optimized for different event topologies of cascade decays, however we would expect only a minor increase of the bound, due to the rather small triplet splitting. For illustration purposes we take the triplet vev $v_\Delta = 10^{-6}$ GeV and nearly degenerate light neutrino masses (corresponding to the sample point BP3 in [10]).

We summarize in Fig. 2 the limits on the masses of the charged components, along with the theoretical constraints, i.e. the regions favored by electroweak precision tests at 95% CL, for SM Higgs mass of 130 GeV and 300 GeV. The updated lower limit on $m_{\Delta^{++}}$ for relatively large $v_\Delta$, is independent of the SM Higgs boson mass.

In case A, we find a lower limit of 240 GeV on the doubly-charged Higgs mass for the degenerate case. This is to be contrasted with the CMS limit of 258 GeV using four-lepton final states only, probably due to the use of different statistics. For moderately large mass splits this limit can be increased by as much as 50 GeV, compared to the degenerate case. We note the analysis can be further improved by combining both the three- and four-lepton final states, as done by the CMS collaboration, see also [22].

For case B on the contrary, the limit goes down all the way to $m_{\Delta^{++}} \gtrsim 100$ GeV (for $v_\Delta > 10$ eV). In this case, all the $\Delta$ states cascade to $\Delta^0$ and further to neutrinos. Current missing energy data do not yet possess large enough luminosity to set here a relevant limit.
We would like to emphasize that: i) the above bounds from CMS data are valid only for small enough \( v_\Delta \lesssim 10^{-4} \) GeV; ii) the bounds become splitting independent only for very tiny \( v_\Delta \), as shown by the dashed line with \( v_\Delta = 1 \) eV.

**A look from the right perspective.** As said in the introduction this scenario can emerge naturally in the context of LR symmetric theories. First, the sum rule for \( \Delta_L \) remains. Second, \( \Delta_{R}^+ \) gets eaten by \( W_R^+ \), therefore the cascades do not occur and the limits on \( \Delta_{R}^+ \) mass set by CDF and D0 \([9]\) remain perfectly valid.

In the LR theory, the neutrino mass situation is more complicated since in general there are both contributions from type-I and type-II seesaw. In other words, the decay formulae Eq. (6) gets simply modified by the right-handed neutrino masses, mixings and the right-handed triplet vev. Nonetheless, as long as the competition between the decays into charged leptons and two \( W \) bosons exists, our conclusion on the \( m_{\Delta^{++}} \) limit obviously holds true. Actually, the same conclusion applies in any theory with such phenomena.

**Implications for the SM Higgs search.** The crucial couplings to probe in the Higgs potential are those between the Higgs doublet and the triplet. For instance the \( \beta \) parameter is responsible for the splitting of the triplet masses, while in a certain region of the Higgs mass, the \( \alpha \) and \( \beta \) couplings can be probed through the Higgs decays to \( \Delta \)’s \([23]\).

As is well known, a heavy SM Higgs is inconsistent with EWPT, unless there is new physics near the electroweak scale. In the context of the type II seesaw, this implies large splits between the components of the triplet. When the Higgs is heavier than twice the triplet mass, the \( h \to \Delta \Delta \) channel opens up and may affect the other branching ratios appreciably. As shown in Fig. 3, the branching ratio of SM Higgs decay to \( W^+W^- \) could be reduced for SM Higgs heavier than 200 GeV, and the current limits from the Higgs search at hadron colliders should be modified. Interestingly, the decay to doubly-charged components can in turn serve as another clean discovery channel for the SM Higgs boson. The opposite case with Higgs decaying into neutral components with the invisible width controlled by \( \alpha \) could easily explain recent evidence for \( m_h \approx 144 \) GeV.

**What next?** In this letter, we offered a systematic study of the collider phenomenology for the type-II seesaw mechanism. We showed how the recently set LHC limit changes dramatically when one moves away from the assumed benchmark points. We believe that our results will be a useful roadmap for future experimental analysis. We end with a few suggestions for further exploration.

- The missing energy channels relevant for case B require further in-depth study, with more statistics.
- One could try to probe the larger values of \( v_\Delta \approx 10^{-4} \times 10^{-2} \) GeV where the di-lepton decay channels give rise to displaced vertices, possibly leading to simultaneous visibility of both these and WW decay channels.

To close, we believe that our work strengthens further the case for LHC being also a neutrino machine.

**Acknowledgements.** We are grateful to Georges Azuelos, Dilip K. Ghosh, Ivica Puljak, Beate Heinemann, Louise Skinnari and Martina Hurwitz for their interest in our work. We thank the BIAS institute for the warm hospitality and support. YZ thanks the Aspen Center for Physics for hospitality during the final stages of this work.

**Note added on \( h \to \gamma\gamma \).** After this work was submitted for publication, both ATLAS and CMS reported \([24]\) a tentative evidence of the Higgs boson, with a mass about 126 GeV, at 2-3 \( \sigma \) CL. In particular, the \( h \to \gamma\gamma \) branching ratio is found to be roughly twice as large as the SM prediction. This feature seems to persist in the combined 7 and 8 TeV dataset \([25]\). Also, a new paper \([26]\) appeared discussing the \( h \to \gamma\gamma \) branching ratio in the type-II seesaw model. It claims the compatibility with the experimental result for rather large positive values of the quartic coupling \( \alpha \sim O(1-2) \) or larger, depending on the masses of the charged components, \( \Delta^{\pm\pm} \).

A new window in agreement with the above LHC results is opened here. As illustrated in Fig. 4, a moderate value \( \alpha \approx -0.5 \) can do the job, as long as the doubly-charged scalar is light, \( m_{\Delta^{++}} \approx 100 \) GeV. This shows how crucial it is to take the cascade decays into account, which is the only way to have such light \( \Delta^{++} \), as discussed at length in this paper.
FIG. 4. Contours of $Br(h \rightarrow \gamma\gamma)$ in the Type II seesaw model, for fixed $\beta = -0.18$. The horizontal contour with $\alpha = 0$ is approximately equal to the SM prediction $Br(H \rightarrow \gamma\gamma) = 0.2\%$. We find this branching ratio can be enhanced by a factor of 2, for $\alpha \approx -0.5$ and $m_{\Delta^{++}} \lesssim 120$ GeV.

[1] P. Minkowski, Phys. Lett. B 67 (1977) 421; R.N. Mohapatra, G. Senjanović, Phys.Rev.Lett. 44 (1980) 912; S. Glashow, in Quarks and Leptons, Cargèse 1979, eds. M. Lévy, et al., (Plenum, 1980, New York); M. Goldberger, P. Ramond, R. Slansky, proceedings of the Supergravity Stony Brook Workshop, New York, 1979, eds. P. Van Nieuwenhuizen, D. Freeman (North-Holland, Amsterdam); T. Yanagida, proceedings of the Workshop on Unified Theories and Baryon Number in the Universe, Tsukuba, 1979, eds. A. Sawada, A. Sugamoto, KEK Report No. 79-18, Tsukuba.

[2] J.C. Pati, A. Salam, Phys. Rev. D 10 (1974) 275; R.N. Mohapatra, J.C. Pati, Phys. Rev. D 11 (1975) 2558; G. Senjanović, R.N. Mohapatra, Phys. Rev. D 12 (1975) 1502; G. Senjanović, Nucl. Phys. B 153 (1979) 334.

[3] G. Beall, M. Bander, A. Soni, Phys. Rev. Lett. 48 (1982) 848; for latest studies and further references therein, see A. Maiezza et al., Phys. Rev. D82 (2010) 055022; Y. Zhang et al., Nucl. Phys. B802 (2008) 247.

[4] M. Nemšек et al., Phys. Rev. D83 (2011) 115014.

[5] The CMS collaboration, CMS-PAS-EXO-11-002.

[6] M. Magg, C. Wetterich, Phys. Lett. B94 (1980) 61; G. Lazarides, Q. Shafi, C. Wetterich, Nucl. Phys. B181 (1981) 287; R.N. Mohapatra, G. Senjanović, Phys. Rev. D23 (1981) 165; T.P. Cheng, L.-F. Li, Phys. Rev. D22 (1980) 2860.

[7] G. Azuelos, K. Benslama, J. Ferland, J. Phys. G 32 (2006) 73; T. Han et al., Phys. Rev. D 76 (2007) 075013; A.G. Akeroyd, M. Aoki, H. Sugiyama, Phys. Rev. D 77 (2008) 075010.

[8] W.-Y. Keung, G. Senjanović, Phys. Rev. Lett. 50 (1983) 1427; For a review and further references, see G. Senjanović, Riv. Nuovo Cim. 034 (2011) 1; G. Senjanović, [arXiv:1012.4104 [hep-ph]].

[9] D. Acosta et al. [ CDF Collaboration ], Phys. Rev. Lett. 95 (2005) 071801. V.M. Abazov et al. [D0 Collaboration], arXiv:1106.4250 [hep-ex],

[10] The CMS collaboration, CMS-PAS-HIG-11-001, CMS-PAS-HIG-11-007.

[11] A.G. Akeroyd, H. Sugiyama, Phys. Rev. D84 (2011) 035010 and references therein.

[12] E.J. Chun, K.Y. Lee, S.C. Park, Phys. Lett. B566 (2003) 142, J. Garayoa, T. Schwetz, JHEP 0803 (2008) 009; M. Kadastik, M. Raidal, L. Rebane, Phys. Rev. D77 (2008) 115023.

[13] P. Fileviez Perez et al., Phys. Rev. D78 (2008) 015018.

[14] S. Godfrey, K. Moats, Phys. Rev. D81 (2010) 075026.

[15] L. Lavoura, L.-F. Li, Phys. Rev. D49 (1994) 1409.

[16] A.G. Akeroyd, M. Aoki, H. Sugiyama, Phys. Rev. D79 (2009) 113010; T. Fukuyama, H. Sugiyama, K. Tsumura, JHEP 1003 (2010) 044.

[17] J. Alwall et al., JHEP 0709 (2007) 028.

[18] P. Meade, M. Reece, [hep-ph/0703031].

[19] T. Sjostrand, S. Mrenna, P.Z. Skands, Comput. Phys. Commun. 178 (2008) 852.

[20] http://www.physics.ucdavis.edu/~conway/research/software/pgs/pgs4-general.htm.

[21] M. Muhlleitner, M. Spira, Phys. Rev. D 68 (2003) 117701.

[22] A.G. Akeroyd, C.-W. Chiang, N. Gaur, JHEP 1011 (2010) 005.

[23] A.G. Akeroyd, S. Moretti, arXiv:1106.3427 [hep-ph].

[24] The ATLAS collaboration, Report No. ATLAS-CONF-2011-161; The CMS collaboration, Report Nos. CMS-PAS-HIG-11-030.

[25] The ATLAS collaboration, Report No. ATLAS-CONF-2012-168; S. Chatrchyan et al., Phys. Lett. B716, 30 (2012) [arXiv:1207.7235 [hep-ex]].

[26] A. Arhrib, R. Benbrik, M. Chabab, G. Moultaka and L. Rahili, JHEP 1204, 136 (2012) [arXiv:1112.5453 [hep-ph]].