IL NUOVO CIMENTO Vol. 32 C, N. 3-4 Maggio-Agosto 2009
DOI 10.1393/ncc/i2009-10477-5

Colloquia: IFAE 2009

Type-III see-saw at the LHC

R. Franceschini
ITPP, EPFL - CH-1015, Lausanne, Switzerland

(ricevuto il 19 Settembre 2009; pubblicato online il 24 Novembre 2009)

Summary. — In this contribution I shall discuss the LHC production and decay of $SU(2)_L$ triplets responsible for the generation of neutrino masses through type-III see-saw. I shall discuss how the study of the specific channels can reveal leptonic flavor violation and leptonic number violation. I shall also discuss how the measure of the lifetime of the see-saw messengers and the ratio of rates of specific decay modes can provide an upper-bound on the lightest neutrino mass.

PACS 14.60.St – Non-standard-model neutrinos, right-handed neutrinos, etc.
PACS 14.60.Hi – Other charged heavy leptons.

1. – Introduction

The smallness of the observed neutrino masses suggests that they are more likely generated at an energy scale many orders of magnitude above the TeV scale that is going to be explored by the LHC pp collider. Nevertheless nothing prevents that the particles that mediate neutrino masses have TeV scale masses. If this is the case the LHC has a potential to unveil some feature of the neutrino mass generation mechanism. In this contribution I will concentrate on the generation mechanism known as Type-III see-saw, that is to say the generation of neutrino mass through the tree-level exchange of fermionic $SU(2)_L$ triplets of zero hypercharge coupled to the ordinary neutrinos as in the following Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}_i i \not{D} N_i + \frac{M_{ij}}{2} N_i^a N_j^a + \lambda_N^{ij} N_i^a (L_j \cdot \varepsilon \cdot \tau^a \cdot H + \text{h.c.}), \quad (1)$$

where the $SU(2)_L$ gauge index a runs over $\{1,2,3\}$, τ^a are the Pauli matrices and ε is the permutation tensor ($\varepsilon_{12} = +1$) and i, j are flavor indexes. Gauge covariant derivatives are defined as $D = \partial + igA^A T^A$; the lepton doublets $L = (\nu, e_L)$ and the Higgs doublet $H = (h_+, h_0)$ have hypercharge $Y = -1/2$ and $Y = 1/2$, respectively, and transform as a 2 under $SU(2)_L$. In order to deal with the breaking of $SU(2)_L$, we choose the usual unitary gauge where $h_+ = 0$ and $h_0 = v + h/\sqrt{2}$ with $v = 174\,\text{GeV}$.

Working in the basis of N_i mass eigenstates, where $M_{ij} = \mathrm{diag}(M_1, M_2, M_3)$ with $0 < M_1 \le M_2 \le M_3$ and choosing light neutrino masses such that $0 \le m_1 \le m_2 \le m_3$ one can define the parameters $\tilde{m}_i \equiv |\sum_j \lambda_{ij}^2 v^2/M_i|$ that tell how fast N_i decays: $\Gamma_i = \tilde{m}_i M_i^2/(8\pi v^2)$. The $\tilde{m}_i$ are unknown, but together with neutrino masses they must satisfy the following constraints:

$$\tilde{m}_i \ge m_1, \qquad \sum_i \tilde{m}_i \ge \sum_{i=1}^{3} m_i. \tag{2}$$

These inequalities show that any measurement or bound on the parameters $\tilde{m}_i$ provides a bound on the degree of degeneracy of the spectrum of the neutrinos and a measurement of the $\tilde{m}_i$ of *all* the see-saw messengers has the potential to discriminate between the inverted hierarchical and normal hierarchical neutrino mass spectrum.

The Yukawa coupling of the Higgs generates Lagrangian terms $\lambda v\, \nu_\ell N_0$ and $\sqrt{2}\lambda v N^+ \ell_L$ that are mass-mixing term for N_0, ν_ℓ and $N_\pm$, ℓ_L. The only relevant effect of the mixings is to generate $SU(2)_L$-breaking couplings between the N^a, the SM leptons and the heavy Z, $W^\pm$ vectors that "eat" the Goldstone components of the Higgs. This coupling affects the decay properties of the Ns and therefore is of key importance to establish a link between LHC phenomenology and neutrinos.

In the following I shall focus on the lightest of the heavy triplet, N_1, the one which is most probable to be produced at the LHC. I denote as ℓ the unknown combination of flavors e, μ, τ coupled to N_1 and from now on I will drop the index $_1$ on M and N.

2. – Production and decay

Production at LHC is dominated by gauge couplings with the dominant partonic process being

$$q\bar{q}^{(\prime)} \to Z^0, W^\pm \to N^+N^-, N^\pm N^0. \tag{3}$$

Unfortunately the production mechanism is completely unrelated to the mechanism of neutrino mass generation and at best one can extract some information about the see-saw messengers through the production rate, which is expected to be larger in the case of a fermion as opposed to the case of a scalar. In the range of masses M between 100 GeV and 1 TeV the total production cross-section is between few pb and few fb, with $pp \to N^+N^0$ being the dominant channel.

The decay properties of the Ns are indeed more interesting for neutrinos. In fact there are two main classes of decays, those mediated by gauge interactions, $N^\pm \to N^0 W^{\pm *}$, and those mediated by the Yukawa interactions that are generated as described in the previous section by the spontaneous symmetry breaking of $SU(2)_L$.

Gauge decays are possible only for the $N^\pm$ and are suppressed by the small mass difference between the $N^\pm$ and the N^0 that yields an almost constant partial width [1]. The main $N^\pm$ gauge decay is $N^\pm \to N^0\pi^\pm$ and when Yukawa modes are negligible it yields a lifetime $\tau \simeq 1\,\mathrm{cm}$. The short track resulting by the interaction of $N^\pm$ with the detector and the softness of the emitted pion render this decay nearly undetectable, therefore gauge decays can be seen only through indirect effect to be discussed in the next section.

Yukawa decays are possible for both the Ns. All the partial widths of the Yukawa modes depend only on M, the Higgs mass m_h and $\tilde{m}_1$ with the latter bringing in a connection with properties of the neutrinos [2]. The $N^\pm$ decays dominantly through Yukawa

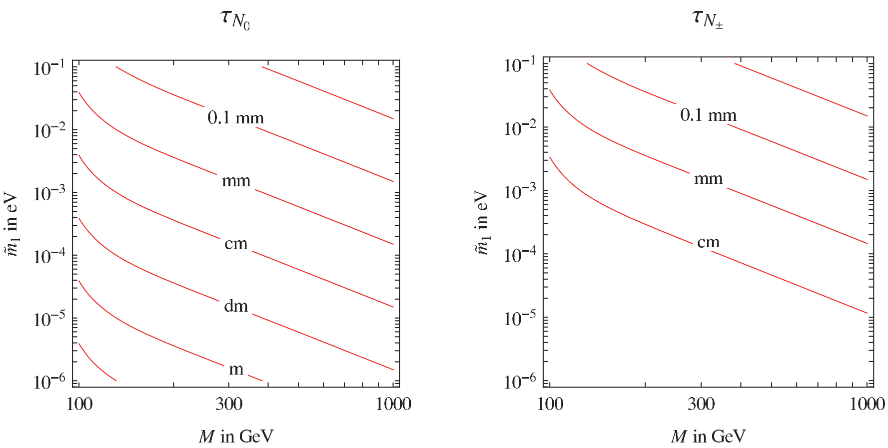

Fig. 1. – Lifetime of the charged and neutral components of the $SU(2)_L$ triplet N.

modes when $\tilde{m}_1 > 10^{-4}$ eV while the N^0 has only Yukawa decays and therefore when $\tilde{m}_1$ is too small it is stable on the scale of detector size. Figure 1 shows the exact dependence of the lifetimes of N^0 and $N^{\pm}$ on their mass, M, and $\tilde{m}_1$. Since the parameter M can be determined studying distributions of p_T, invariant mass and transverse mass of the decay products a measurement of the lifetime of the N is a direct measurement of $\tilde{m}_1$.

3. – Collider signatures

Among the possible signatures for the production of a N we shall concentrate on the detection of decay modes with leptonic flavor violation (LFV) and leptonic number violation (LNV).

As representative of the LFV signals we study

$$pp \to (N^+ \to \ell_1^+ Z^0)(N^0 \to \ell_2^- W^+) \to 4j \ell_1^+ \ell_2^- , \tag{4}$$

where j means a generic light quark or gluon originated jet and by ℓ_i we denote a single component of the unknown flavor mixture coupled to the triplet N of interest. This process is characterized by a lepton of large $p_T \sim M$, the absence of missing transverse energy, $\not{E}_T$, and peaks in the invariant mass of pairs of jets due to presence of W and Z bosons in the intermediate state.

SM processes can produce a background (BG) for this search. The main background process is $pp \to t\bar{t}2j \to 2j2b\ell_1\ell_2\not{E}_T$. Requiring leptons and jets with angular separation $\Delta R > 0.4$, within the detector acceptance $\eta < 5$ and with $p_T^j > 20\,\text{GeV}$ and $p_T^l > 70\,\text{GeV}$ one can estimate the signal and the background at the partonic level using MADGRAPH [3] and ALPGEN [4]. For $M = 250\,\text{GeV}$ this partonic study yields a signal cross-section of 8 fb *versus* a BG cross-section of 36 fb. Taking into account all the relevant BG processes, including those generated by detector effects, ref. [5] found that for $M = 300\,\text{GeV}$ a 5 σ discovery in this channel needs 80/fb of integrated luminosity at 14 TeV. We notice that this channel has the feature to manifest LFV without LNV, providing an independent test of the two violations and possibly a distinction between type-II and type-III see-saw (however other testable differences exist, for a recent review see [5]).

As representative of the LNV signals we study the process

$$pp \to (N^+ \to \ell^+ Z^0)(N^0 \to \ell^+ W^-) \to 4j\ell^+\ell^+. \tag{5}$$

This process has the same features of that studied for the LFV, but benefits of lower backgrounds as processes like $t\bar{t}$ production contribute only because of detector effects like charge misidentification and rare semi-leptonic decays of the top quark. The background can be reduced with cuts similar to those used for the LFV process. Reference [5] studied the LHC reach in this channel using the full list of background and including detector effects. They find that an integrated luminosity of 2/fb at 14 TeV is sufficient for a 5 σ discovery.

The low level of background of this channel allows to imagine a measurement of $\tilde{m}_1$ through the ratio of the rate of gauge and Yukawa decays. In fact when a gauge decay happen in the chain equation (5) the N^+N^0 system is effectively replaced by a N^0N^0 system which produces the charged leptons $\ell^+\ell^+$ with a different rate. In particular the necessary decay is $N^0N^0 \to \ell^+\ell^+W^-W^-$ as opposed to $N^+N^0 \to \ell^+\ell^+W^-Z$. Thus a measure of $\Gamma(WW\ell^+\ell^+)/\Gamma(WZ\ell^+\ell^+)$ is sensitive to $\tilde{m}_1$.

4. – Conclusions

Type-III see-saw involves fermionic $SU(2)_L$ triplets that can be produced at the LHC and can decay in a LFV and LNV fashion. We studied the reach of LHC for the detection of these decay modes. The result is that LNV final states with same-sign leptons are observables at the LHC with as low as 2/fb of integrated luminosity.

I outlined two possible ways to measure the combination of Yukawa couplings $\tilde{m}_1$, that through eq. (2) provides an upper bound for the lightest neutrino mass, and therefore sets a bound on the degree of degeneracy of neutrino spectrum. The first method involves a measure of $\Gamma(WW\ell^+\ell^+)/\Gamma(WZ\ell^+\ell^+)$ in the LNV signal, the other involves a measure of the lifetime of the see-saw messengers. As detector effects are of primary importance for the tagging of W and Z and for lifetime measurements of long-lived objects both the methods proposed require a detailed study by the experimental collaborations.

In principle *all* the see-saw messengers could be produced at the LHC and therefore not only $\tilde{m}_1$ could be measured, but all the $\tilde{m}_i$ of the involved triplets. If this is the case, eq. (2) can be used to upper-bound the sum of the light neutrino masses, that is to say to distinguish between the two experimentally allowed types of hierarchical neutrino spectra.

REFERENCES

[1] Cirelli M. *et al.*, *Nucl. Phys. B*, **787** (2007) 152.
[2] Franceschini R. *et al.*, *Phys. Rev. D*, **78** (2008) 033002.
[3] Maltoni F. and Stelzer T. (MadGraph), *JHEP*, **0302** (2003) 027; Stelzer T. and Long W. F., *Comput. Phys. Commun.*, **81** (1994) 357; Alwall J. *et al.*, *JHEP*, **0709** (2007) 028.
[4] Mangano M. L. *et al.* (AlpGen), *JHEP*, **0307** (2003) 001.
[5] del Aguila F. and Aguilar-Saavedra J. A., arXiv:0808.2468 [hep-ph].