Preliminary studies for the search for direct probe of the neutrino mass generation mechanism with the ATLAS detector at LHC

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Summary. — The discovery of neutrino oscillations implies non-null masses which are difficult to accommodate in a natural way through a pure Standard Model (SM) Yukawa coupling to the Higgs field. An interesting Beyond the SM scenario is provided by the Left-Right Symmetric Model (LRSM). The first steps of a new final state search performed with the ATLAS detector at LHC Run 2 data are presented. This search investigates the production of two heavy Majorana neutrinos N which decay in two jets and one lepton each, namely $pp \to NN \to 2\ell 4j$, with the right-handed LRSM Higgs Boson Δ as the dominant mediator.

1. – Theoretical motivation

The Standard Model (SM) of particle physics, despite its experimental success, leaves several fundamental questions unanswered: the large number of free parameters, the nature of dark matter and dark energy, the matter-antimatter asymmetry, the hierarchy problem, and notably, the origin of neutrino masses. Neutrino oscillation experiments have shown that at least two neutrino flavours have non-zero mass, requiring for an extension of the SM [2]. Furthermore, as evident from the Yukawa lagrangian after spontaneous symmetry breaking, the weak interaction is completely asymmetric between right-handed (RH) and left-handed (LH) fields, leaving no mass term generation for the purely LH SM neutrinos.

One approach to extending the SM involves the introduction of seesaw mechanisms. Considering a Majorana mass term, obtained applying the charge conjugation matrix to the LH fermionic fields, a dimension-5 Weinberg operator $\mathcal{O}_5$ can be introduced to accommodate the Majorana neutrino mass. $\mathcal{O}_5$ is non-renormalisable, but this problem can be solved interpreting it as an effective operator produced at low energies by new particles originated from new physics at higher energies. There are three types of seesaw meachanisms, each introducing a multiplet of BSM particles. Within the LRSM, there is the realisation of a Type I + Type II seesaw mechanism, which respectively introduce a fermionic singlet and a scalar triplet. The LRSM introduces a $SU(2)_R$ local symmetry, under which LH fields transform as singlets and RH fields as doublets, making the LRSM gauge group: $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. The Higgs sector is extended by two $SU(2)$ triples, $\Delta_{L,R}$, and a bi-doublet Φ, so that the lightness of LH neutrinos, with mass matrix M_ν, is explained via the seesaw mechanism. The neutrino Dirac mass M_D is generated by the SM-like Higgs and in direct analogy, a "Majorana" Higgs Δ provides the Majorana mass M_N:

$$M_\nu = -M_D^T M_N^{-1} M_D. \tag{1}$$

The neutral field components of Φ (ϕ_1^0 and ϕ_2^0) can mix with the neutral component of Δ (Δ_0) and the mass matrix can be reduced to a 2×2 matrix involving the SM-like Higgs h and the triplet-like Δ

$$\begin{pmatrix} h \\ \Delta \end{pmatrix} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} h_0 \\ \Delta_0 \end{pmatrix}, \tag{2}$$

where $h_0 = Re\ \phi_1^0 + Re\ \phi_2^0$, $c_\theta = cos\theta$ and $s_\theta = sin\theta$. The mixing angle θ depends on m_Δ and typically $s_\theta < 0.2 - 0.4$ for $m_\Delta \lesssim 200\,\text{GeV}$.

It is then possible to probe the origin of the Ns masses with Lepton Number Violating (LNV) decays of Δ, just as the standard SM decays of the Higgs boson h test the origin of charged fermions masses:

$$\text{SM: } \Gamma_{h \to f\bar{f}} \propto m_f^2 \longrightarrow \text{LRSM: } \Gamma_{\Delta \to NN} \propto m_N^2. \tag{3}$$

Exploiting the sizeable mixing of the Higgs boson to the neutral component of the RH triplet Δ, one can expect the production of a pair of heavy Majorana neutrinos: $h/\Delta \to NN$. It is important to note that the SM Higgs can also decay in a couple of Ns [3], acting itself as a portal to LNV, complementary to neutrinoless double-beta decays or the Keung-Senjanović process ($pp \to W_R^* \to \ell N \to \ell\ell jj$), already investigated by the ATLAS Collaboration [4].

2. – Majorana Higgs decays

Because of the Majorana nature of N, each on-shell heavy neutrino decays through an off-shell W_R to a charged lepton or an anti-lepton, with equal probability, and two jets. Thus, half of the events will lead to LNV ($\Delta L = 0, 2$), yielding the Feynman diagram shown in Figure 1.

The region of interest for this search is $m_N < 80\,\text{GeV}$ and $m_\Delta < 200\,\text{GeV}$, for m_{W_R} of the order of 4 TeV. As can be observed from Figure 2 this maximises the production cross-section for the Δ from gluon-gluon fusion and the branching ratio of $\Delta \to NN$.

3. – Event simulation and kinematics studies

The inclusive process $gg \to NN$ was generated with Madgraph5+Pythia8 by the central Monte-Carlo (MC) generation tool of the ATLAS Collaboration [1] following the FeynRules model file from Ref. [5] at a $\sqrt{s} = 13\,\text{TeV}$. The generated events were processed through a simulation [6] of the ATLAS detector geometry and response for its configuration during LHC Run 2 using GEANT4 [7]. Allowing the SM Higgs as mediator of the process yields an $\mathcal{O}(20\%)$ increase in production cross-section. Four initial mass points

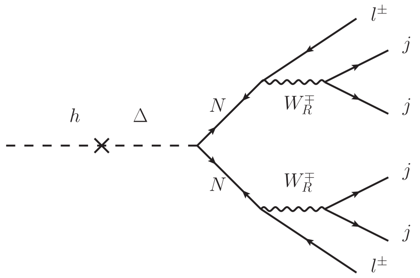

Fig. 1. – Feynman diagram for pair production of N through the Δ resonance which mixes with the SM Higgs boson h. The final state produced involves two leptons and four jets, for a $\Delta L = 0, 2$ signal [3].

were studied: $(m_N, m_\Delta) = [(25,65),(25,100),(25,150),(65,150)]$ GeV. In the generated process, the final state has a high jet multiplicity from hadronic τ decays, and Δ is the main mediator, even when including the SM Higgs. The heavy neutrino decay vertex can be significantly displaced, especially for low m_N, as shown in Eq. 4. Figure 3 shows that the MC results agree well the theory expectation, providing a powerful handle when it comes to signal-background discrimination.

$$c\tau_N \simeq 0.1 \text{ mm} \left(\frac{40 \text{ GeV}}{m_N}\right)^5 \left(\frac{M_{W_R}}{5 \text{ TeV}}\right)^4, \tag{4}$$

Kinematic variables such as the invariant mass of one lepton plus two jets and angular distributions of the two final state leptons, ΔR(ll), are also under study. Figure 4 shows the latter quantity at truth level (left) and after reconstruction (right), proving that this signal characteristic is preserved. The main backgrounds of this process are Z+jets, diboson production, and Drell-Yan processes. Given the very low p_T of the produced leptons, an important contribution comes from mis-identified leptons.

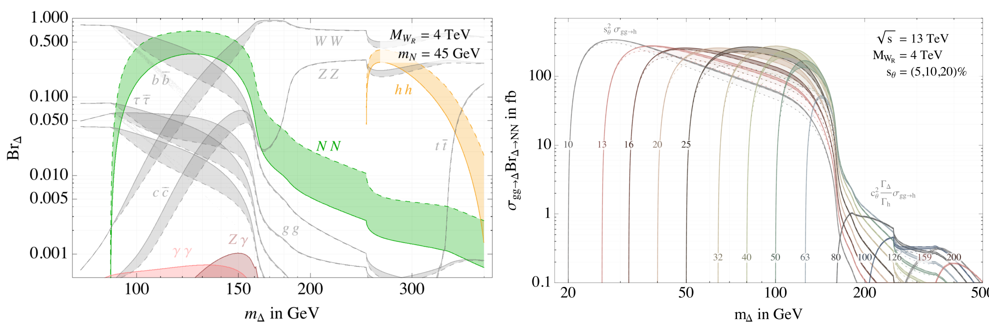

Fig. 2. – Left: Branching ratios of Δ to a pair of Majorana neutrinos (green) with $m_N = 45$ GeV and other SM particles. The shaded areas cover the variation of s_θ from 5% in dashed lines to 10% in solid ones. Right: Production cross-section of heavy Majorana neutrino pairs via Δ gluon fusion. Colours correspond to different masses of N, from 10 to 200 GeV. Figures from [2].

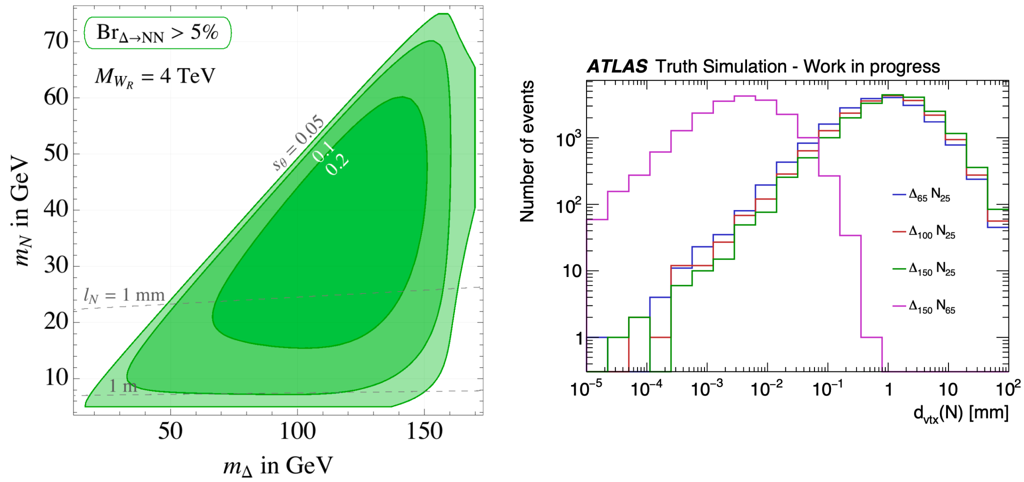

Fig. 3. – Left: Regions where the branching ratio of $\Delta \to NN$ is at least 5%, for $M_{W_R} = 4\,\text{TeV}$. The dashed lines show the lifetime of N in the lab frame [2]. Right: Decay length in the lab frame of the heavy neutrino N as obtained at truth level from MC generation. In the legend the Δ and N masses are indicated, while M_{W_R} is fixed at 4 TeV.

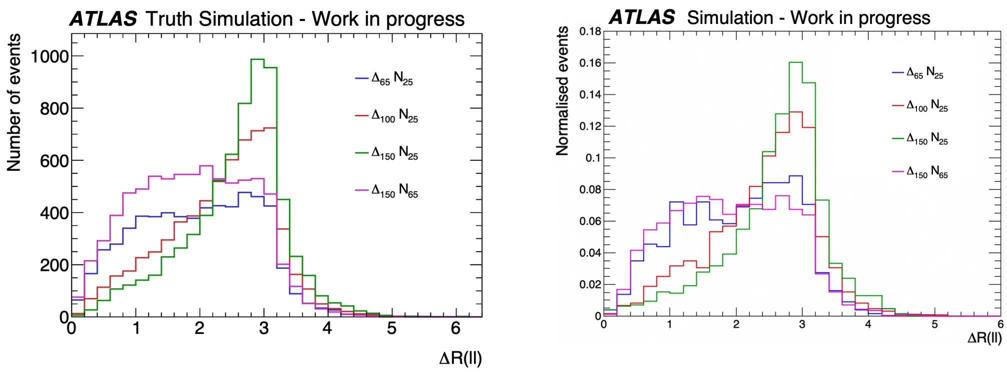

Fig. 4. – Angular distribution of the two leptons in the final state coming from the N decay. The distributions are shown at truth level on the left and after reconstruction on the right.

4. – Summary

The Left-Right Symmetric Model offers a promising framework for physics beyond the SM. The $\Delta \to NN$ process allows exploration of the right-handed sector of the LRSM and opens new parameter space. A new, validated Monte Carlo model is used, and several discriminating features of the final state are being studied, including p_T of the final state particles, missing E_T, lepton number violation, and displaced vertices. Optimization of analysis regions and studies of misidentified leptons and τ contributions are ongoing.

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