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LNV Meson Decays and Displaced Decay Searches to Probe Heavy Neutral Leptons in Leptoquark Assisted Seesaw Model

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Abstract

Lepton number violating (LNV) three and four-body meson decays, such as $M_1^+ \to \ell_i^+ \ell_j^+ M_2^-$ and $M_1^+ \to M_2 \ell_i^+ \ell_j^+ M_3^-$, which are mediated by right handed (RH) neutrinos can be used as a probe to test their Majorana nature. These three and four-body meson decays are resonantly enhanced if the mass scale of RH neutrino falls in the range $M_N \sim \mathcal{O}(100\,\text{MeV} - 1\,\text{GeV})$. For masses in the $\mathcal{O}(10\,\text{GeV})$ range, the RH neutrinos can be tested via their displaced decays at colliders. In this letter, we propose to probe low mass RH neutrinos by looking at these novel signal topologies. We would analyse three and four body rare meson decays, and the displaced decays of heavy neutrinos in a $\tilde{R}_2$ type of leptoquark (LQ) model, both for *ep* and *pp* colliders.

Frontiers: Primary: NF03 and TF11. Secondary: NF05

Origin of the proposal: In various seesaw models, the inclusion of SM singlet heavy RH neutrinos to the SM particle content is one of the best motivated way to account for the observed neutrino masses and the PMNS mixing. The RH neutrino mass scale can vary in a wide range. For mass $M_N \sim \mathcal{O}(1\,\text{GeV})$, searches through LNV meson decays $M_1^+ \to \ell_i^+ \ell_j^+ M_2^-$ and $M_1^+ \to M_2 \ell_i^+ \ell_j^+ M_3^-$ are more relevant. For mass range larger than $M_N \sim 10$ GeV, collider searches are the best probes. In basic seesaw models with heavy neutrinos, such as, Type-I seesaw, or inverse seesaw, the production of the heavy neutrinos crucially depend on the mixing between the light and heavy neutrinos, and hence are suppressed due to the stringent constraint on these mixings from different direct and indirect experiments, as well as, light neutrino mass measurements.

Another variation of seesaw model is the LQ assisted neutrino mass model, where $\tilde{R}_2$ scalar LQ charged as (3,2,1/6) under SM gauge group [1] is present. In addition to the coupling with the lepton and jet, the model also contains RH neutrinos coupled to the LQ. The benefit of this model is that, as compared to the conventional seesaw model, RH neutrino productions in this model can be significantly large.

Objective: We propose to look for heavy neutrinos in this $\tilde{R}_2$ LQ model via a number of processes.

- **LNV meson decays:** Rare meson decays work as an interesting probe of lepton number violation. The LNV meson decays such as $M_1^+ \to \ell_1^+ \ell_2^+ M_2^-$ and $M_1^+ \to M_2 \ell_1^+ \ell_2^+ M_3^-$ are sensitive to the low RH neutrino mass scale (in the few 100 MeV-few GeV range) [4, 5]. In this mass range, the processes, mediated via the RH neutrinos, are resonantly enhanced. The rare LNV meson decays are complementary to the collider searches which are sensitive to GeV - TeV mass scale of the RH neutrinos.

  In this work, we propose to look for three body meson and tau decays, mediated via the LQ and RH neutrinos. Being free from any nuclear matrix uncertainty, these rare decays can be more accurately evaluated compared to $0\nu\beta\beta$. Albeit their small decay rates, they may be accessible at various ongoing and proposed beam dump and collider experiments. Few of them are NA62 (K^+), SHiP(D, D_s), MATHUSLA(B,D), FCC-ee(B), Belle-II(B) etc.

  We also propose to persue a study on the four body LNV meson decay $M_1^+ \to M_2 \ell_1^+ \ell_2^+ M_3^-$ for this model. Four body meson decays are suppressed compared to three body meson decays due to phase space suppression. However, if the transition M_1^+ to M_2 is Cabibbo favoured then the four body meson decays can have sizable rate. One such example is $B_c^+ \to B_s^0 \ell_1^+ \ell_2^+ \pi^-$ decay mode [6]. For the $c \to s$ decay, it will be a Cabibbo favoured transition. Hence, the mode $B_c^+ \to B_s^0 \ell_1^+ \ell_2^+ \pi^-$ is expected to have a significantly large branching fraction.

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In evaluating the proposed signal, we plan to take into account the following points:

– The effect of detector length: the LNV meson decays are mediated via LQ and RH neutrinos. For small masses of RH neutrinos in the MeV range, the decay width of the RH neutrinos will be very small. Hence, the neutrinos will have displaced decays. The number of signal events within the detector crucially depend on the detector length [4]. In view of this, it is preferable to consider large detector length for beam dump experiments.

– Interference effect: the branching ratios of the LNV meson decays change dramatically, if more than one RH neutrino state with almost degenerate masses contribute in these processes [7, 8]. The predictions for LNV and lepton number conserving (LNC) meson decay rates can widely differ due to the interference amongst the contributions of different RH neutrinos. In this case the ratio of LNV and LNC decay rate can vary between 0 to 1. We would like to explore this interference effect in detail.

- **Collider Searches:** We are interested to explore the discovery prospect of the RH neutrino (N) at the proposed ep colliders, LHeC and FCC-he via the production channel $ep \to jN$. In conventional seesaw models, the same final state can be obtained from a charged current process. The cross section for this process is governed by the mixing angle (V) between light neutrinos and N. Direct and indirect experimental probes, as well as, light neutrino mass measurements severely constrain this mixing angle. Therefore the production cross section is small. For the mass of RH neutrino $M_N = 50$ GeV and $V \sim 10^{-6}$, cross section is $\mathcal{O}(10^{-6}$ fb). On the other hand, depending upon the coupling of $\tilde{R}_2$ with j and N, the production cross-section in $\tilde{R}_2$ model can be significantly large, as compared to the conventional seesaw models [3]. This cross section will further increase if e^+ beam is used instead of e^- beam [2]. Use of polarized e^- or e^+ beam is another way to get relatively enhanced cross section.

Depending upon the hierarchy between M_N and $M_{\rm LQ}$, several signatures will arise from the channel $ep \to jN$. When M_N is not very small relative to $M_{\rm LQ}$, we will get resolved decay products from N decay ($N \to l^\pm jj$), which leads to a standard lepton + multi-jet signature. If $M_N << M_{\rm LQ}$, N will be highly boosted. Therefore, all the decay products of N will be collimated forming a large radius jet referred as fat-jet. A very light N with a macrosopic decay length and $M_N << M_{\rm LQ}$ can further lead to a displaced fatjet. If M_N is few tens of GeV and $M_{\rm LQ} \geq 1$ TeV, N will decay inside the tracking detector and hence can be probed via displaced vertex search. These are few of the interesting signatures to search for RH neutrinos and LQ. We propose to analyse these different possibilities.

Summary: RH neutrinos are essential ingredient of various seesaw models. Depending on the different mass ranges of RH neutrino, it can be tested in few different experiments. For mass scale $M_N \sim 1$ GeV, RH neutrinos and their Majorana nature can be probed via LNV meson decays. One can expect to observe these rare decays in various beam dump, as well as, collider experiments. For mass range $M_N \geq 10$ GeV, we propose to search for RH neutrinos in LQ mediated RH neutrino production channel $ep \to jN$ at the proposed ep colliders, LHeC and FCC-he. Due to huge enhancement in the RH neutrino production, this model is expected to provide better discovery prospect.

References

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