Displaced Neutrino Jets at the LHeC

G. Cottin, O. Fischer, S. Mandal, M. Mitra & R. Padhan

invisibles
neutrinos, dark matter & dark energy physics
Invisibles 2021 Workshop

Abstract

The Standard Model (SM) singlet right-handed neutrinos (RHNs) are essential fields in many neutrino mass models. In type-I seesaw model, RHNs interact with SM particles via suppressed mixings, which makes their discovery at collider experiments in general challenging. We instead explore a non-minimal production mechanism of the RHN via leptoquark decay at the proposed Large Hadron electron Collider. We consider a long lived and heavily boosted RHN, that leads to a displaced fat jet signature. We show that the track based variables are useful in the identification of such signature. Employing a positron beam further provides order of magnitude enhancement in the signal sensitivity.

The Model

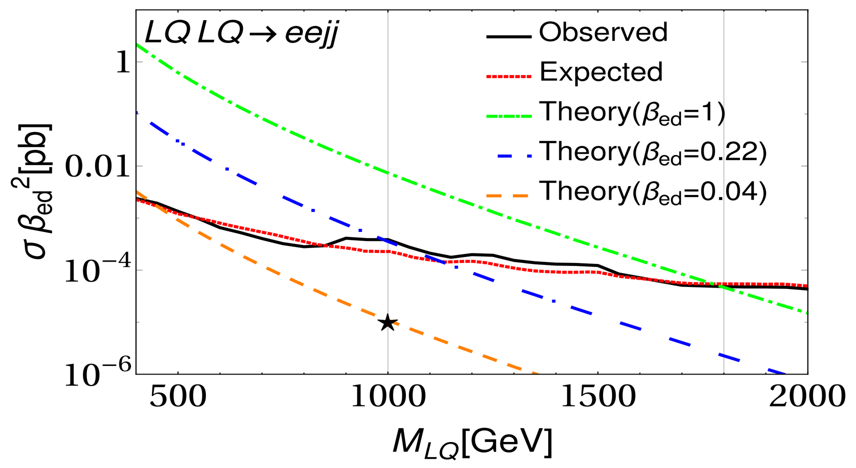
The $\tilde{R}_2$ leptoquark (LQ) model contains a scalar LQ $\tilde{R}_2$, and three RHN states N_i. The LQ has two iso-spin components $\tilde{R}_2(3,2,1/6) = (\tilde{R}_2^{\frac{2}{3}}, \tilde{R}_2^{-\frac{1}{3}})^T$, where superscript denotes the electromagnetic charge. The interactions of $\tilde{R}_2$ with the SM fermions and N_i are, [W. Buchmuller *et al.*]

$$\mathcal{L}_{LQ} = -Y_{ij}\bar{d}^i_R e^j_L \tilde{R}_2^{2/3} + (YU_{\text{PMNS}})_{ij}\bar{d}^i_R \nu^j_L \tilde{R}_2^{-1/3} + Z_{ij}\bar{u}^i_L N^j_R \tilde{R}_2^{2/3} + (V_{\text{CKM}}Z)_{ij}\bar{d}^i_L N^j_R \tilde{R}_2^{-1/3} + \text{H.c.}$$

We consider only one of the 3 RHNs, $Z_{11} \neq 0$, $Y_{11} \neq 0$ and other Y_{ij}, $Z_{ij} = 0$. Thus $\tilde{R}_2^{2/3}$ can decay to both ed and Nu states, with branching ratios (BRs) β_{ed} and β_{Nu}, respectively.

Constraints

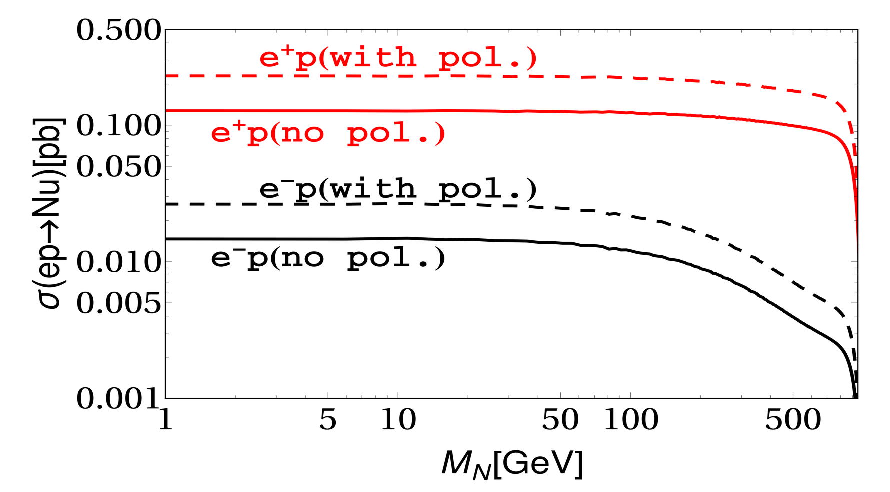
- From Atomic parity violation experiment : $Y_{11} < 0.34\frac{M_{LQ}}{1\,\text{TeV}}$. [I. Dorsner *et al.* JHEP (2014)]
- From LQ search in channel $pp \to \text{LQ LQ} \to \ell j \ell j$, at $\sqrt{s} = 13$ TeV LHC : $M_{LQ} > 1.8$ TeV for $\beta_{ed} = 1$. This limit can be relaxed if $\beta_{ed} < 1$ as shown in figure below. Star mark represent our benchmark: $M_{LQ} = 1$TeV, $Y_{11} = 0.2$ and $Z_{11} = 1$.



[G. Aad *et al.* (ATLAS), JHEP (2020)]

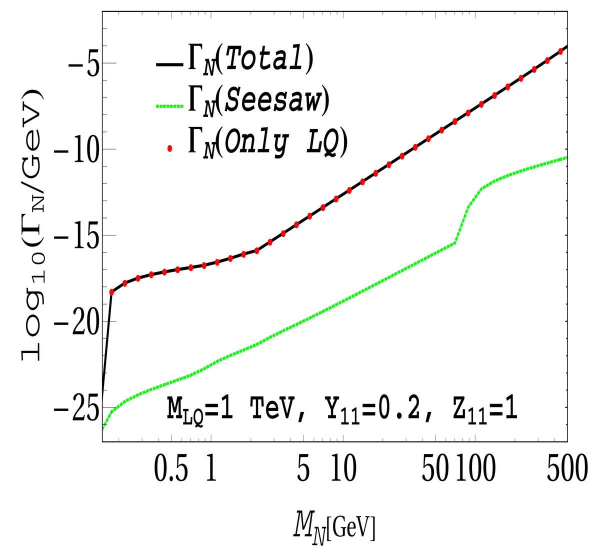
Production of RHN @LHeC

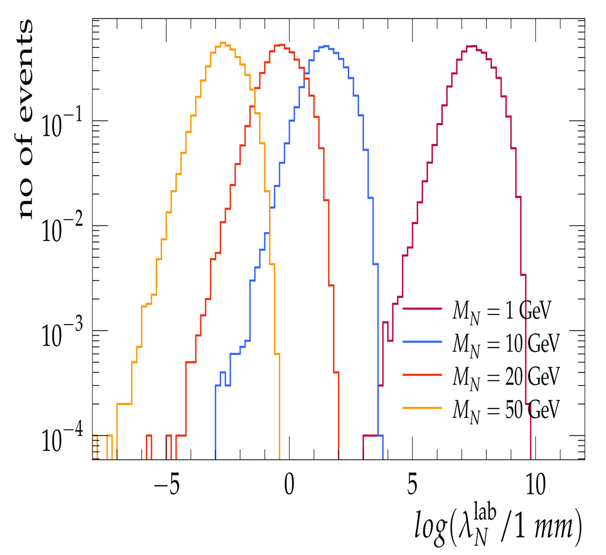
- The production of N, $e^-p \to Nu$ is dominated by LQ mediated channels. Production via leptonic mixing completely negligible.
- As evident from figure below, use of e^+ beam instead of e^- beam, enhances the cross-sections, which can be increased further if polarised beam is used.



RHN decay

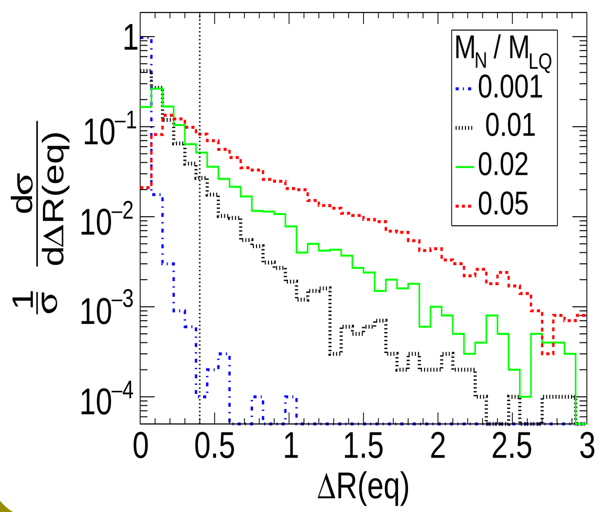
- For the chosen mass scales, the dominant decays of N are mediated via an off-shell $\tilde{R}_2$. The contributions of SM mediators are suppressed by small mixings of N with SM neutrinos.
- The partial decay widths are, $\Gamma(N \to e^-u\bar{d}/e^+\bar{u}d) = N_c\frac{|Z_{11}|^2|Y_{11}|^2 M_N^5}{512\pi^3 M_{LQ}^4}\mathcal{I}$. The BRs for $N \to eq\bar{q}'$ and $N \to \nu q\bar{q}'$ are 50% each.
- For $M_N = 10(20)$ GeV, $c\tau_N \sim 1(0.01)$ mm. For $M_N \geq 50$ GeV, $c\tau_N < 1\ \mu m$, which is below the resolution of the LHeC detector, such that N decay cannot be considered as being displaced. Decay length in the laboratory system is $\lambda_N^{\text{lab}} = \beta\gamma c\tau_N$, where $\beta\gamma = |p_N|/M_N > 1$.

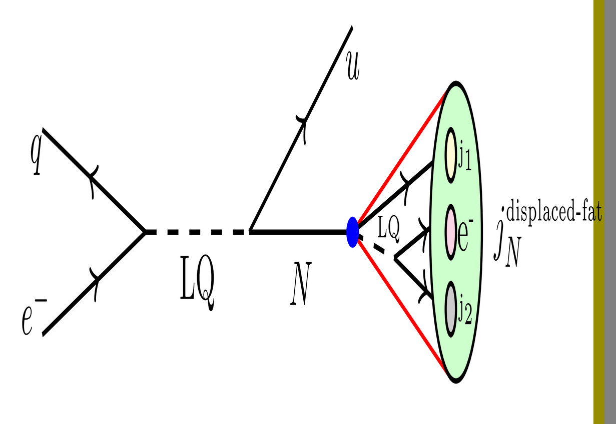




Displaced Fatjet

N with $M_N \sim \mathcal{O}(10)$ GeV will be boosted as it is produced from a LQ of mass $M_{LQ} = 1$ TeV. This leads to very small angular separation between its decay products. The $\Delta R(eq)$ distribution of closest lepton-quark pair, shows that a sizeable fraction of the decays fails to satisfy the standard lepton isolation criterion, $\Delta R(\ell, j) > 0.4$. Hence, N decay products can be reconstucted as a single large radius jet, called as a "fatjet". Thus, the very specific signature under investigation is a fat jet that originates from a RHN displaced vertex and is accompanied by a prompt jet: $e^{\pm}p \to jN \to j + j_N^{\text{displaced-fat}}$, where $j_N^{\text{displaced-fat}}$ denotes the displaced and collimated decay products of the RHN.





Event Simulation and Results

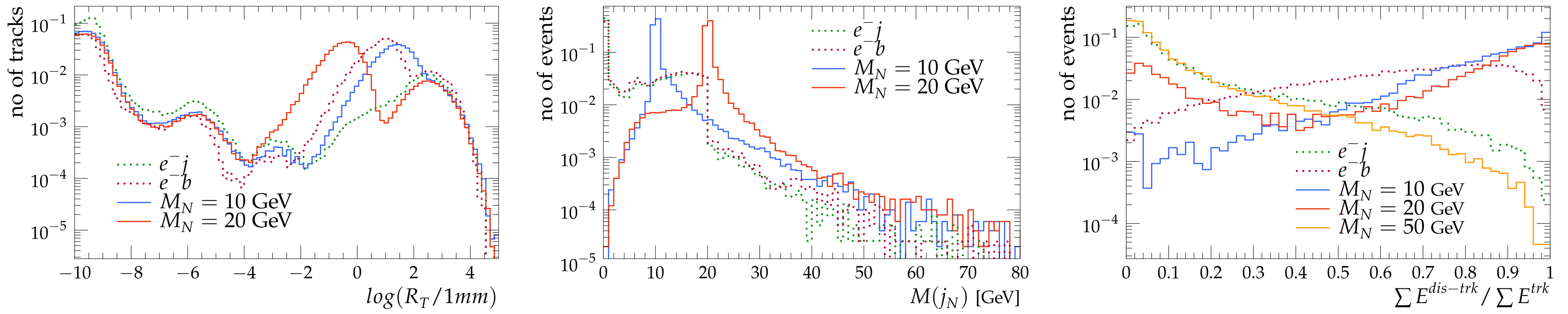


Figure 1: Distribution of various observables for signal and e^-j, e^-b background. Left, Middle, and right panel: R_T distribution of the tracks, invariant mass distribution of j_N, distribution of r_E for displaced jet.

Selection cuts:

- Transverse displacement: $\mathbf{R_T = \sqrt{X^2 + Y^2}}$ Displaced track $\Rightarrow 50\,\mu m < R_T < 312\ mm$. [LHeC, FCC-he Study Group]
- $p_T(trk) > 1$ GeV.
- $\mathbf{r_N = \frac{N_{trk}(displaced)}{N_{total-trk}}}$. Jet with highest $r_N \Rightarrow$ displaced jet (j_N). $\mathbf{r_E = \frac{\Sigma E(displaced-trk)}{\Sigma E(trk)}}$. In r_E distribution signal and light jet background are complimentary to each other.
- Events are select with $N_{jet} \geq 2$ and $p_T \geq 50$ GeV for all jets. Further cuts on displaced jet: $\mathbf{r_N \geq 0.5}$, $\mathbf{r_E \geq 0.5}$, $\mathbf{p_T(j_N) \geq 150}$ GeV and $\mathbf{M(j_N) = M_N \pm 3}$ GeV.

M_N	n_σ	$\mathcal{L}$ [fb^{-1}]	$\mathcal{Y}^{ex}$
10 GeV	6.0 (41.5)	34.0 (0.7)	0.067 (0.035)
20 GeV	4.7(39.7)	56.8 (0.8)	0.059 (0.017)
30 GeV	3.3 (30.4)	116.6 (1.3)	0.047 (0.013)

Table 1: n_σ is the signal significance with 50 fb^{-1} luminosity. $\mathcal{L}$ is the required luminosity to achieve 5σ significance. $\mathcal{Y}^{ex}$ represents 2σ exclusion on Y_{11}. Numbers without (within) brackets corresponds to e^- (e^+) beam, respectively.

Summary

For our benchmark, RHN can be probed with only $\mathcal{L} < 120\ (2)$ fb^{-1} using e$^-$(e$^+$) beam, at the LHeC. For $M_{LQ} > 1$ TeV, the same signature can be studied at FCC-he as well as at pp colliders.

Reference

G. Cottin, O. Fischer, S. Mandal, M. Mitra & R. Padhan, arXiv: 2104.13578 [hep-ph].

Contact Information

Rojalin Padhan. **Email:** rojalin.p@iopb.res.in
Web : https://www.iopb.res.in/