Displaced neutrino jets at the LHeC

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Abstract: Extending the Standard Model with right-handed neutrinos (RHNs) is well motivated by the observation of neutrino oscillations. In the type-I seesaw model, the RHNs interact with the SM particles via tiny mixings with the active neutrinos, which makes their discovery in the laboratory, and in particular at collider experiments in general challenging. In this work we instead consider an extension of the seesaw model with RHNs with the addition of a leptoquark (LQ), and employ a non-minimal production mechanism of the RHN via LQ decay, which is unsuppressed by neutrino mixing. We focus on relatively light RHN with mass $\mathcal{O}(10)$ GeV and LQ with mass 1.0 TeV, and explore the discovery prospect of the RHN at the proposed Large Hadron electron Collider. In the considered mass range and with given interaction strength, the RHN is long lived and, due to it stemming from the LQ decay, it is also heavily boosted, resulting in collimated decay products. The unique signature under investigation is thus a displaced fat jet. We use kinematic variables to separate signal from background, and demonstrate that the ratio variables with respect to energy/number of displaced and prompt tracks are useful handles in the identification of displaced decays of the RHN. We also show that employing a positron beam provides order of magnitude enhancement in the detection prospect of this signature.

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1 Introduction

The observation of neutrino oscillations is a clear indicator for new physics beyond the Standard Model (BSM). A plethora of models exist that aim at explaining the light neutrino masses and mixings, many of which contain Standard Model (SM) gauge singlet right-handed neutrino (RHN). The simplest one among them is the type-I seesaw model [1], where the RHNs are Majorana particles. Being SM gauge singlet RHNs interact with the SM particles only via their mixing with the active neutrinos, referred to as active-sterile mixing, and is proportional to $\sqrt{\frac{m_\nu}{M_N}}$, where $m_\nu$ and $M_N$ are the light neutrino and the RHN mass scale. Since $m_\nu < eV$, this mixing is small, leading to a suppressed production of RHN at colliders, which makes their observation challenging. This limitation can be avoided if RHNs are embedded in a theory framework with a production mechanism that involves unsuppressed interactions of RHN with BSM/SM particles.

Motivated by this, we consider a theory framework that includes a $\tilde{R}_2$ leptoquark (LQ) and Majorana RHN. We consider a mass of 1 TeV for LQ and focus on RHN with low mass $M_N \sim \mathcal{O}(10)$ GeV. The RHN in this framework interacts with the LQ and an up-type quark and can thus be produced from LQ decay. For the considered mass scales, the RHN is heavily boosted and its decay products leptons and jets are collimated, which fail to
satisfy standard isolation criteria, thereby enabling a large radius jet description as the appropriate description to adopt. Additionally, a RHN in the considered mass range is a long lived particle and its decay is displaced from the point of its creation. The final state object of interest is thus a displaced large radius jet, or a fat jet, which is also accompanied by a prompt jet. This signature is not dependent on the violation of lepton number and it therefore can also arise in other variations of LQ extended seesaw models, including in particular sterile neutrinos with inverse/linear/extended seesaw [2–6].

This signature is challenging to probe at the LHC due to its hadronic nature. Therefore, we investigate this signature in a relatively clean environment, i.e., in lepton-hadron collisions at the proposed Large Hadron electron Collider (LHeC) [7]. The LHeC allows for resonant production of a LQ with first-generation coupling [8], cf. also refs. [9, 10]. Moreover, the possibilities of electron polarisation and to use a positron beam provide extra handles to test the nature of the new physics signature [7, 10]. For prompt fat jet study at LHeC see [11], see [12–15] for study on neutrino, lepton jet and light N searches at the LHC in different models.

The paper is organized as follows: first we briefly review the model and the existing constraints on LQ. Following that we discuss the production of RHN at an ep collider LHeC. In the subsequent section, we present a detailed collider analysis and discuss discovery prospect of the unique RHN signature. Finally, we present the summary of the paper.

2 The model

We consider the \( \tilde{R}_2 \) leptoquark model, which contains a scalar LQ, and three RHN states \( (N_i) \). The LQ has two iso-spin components, \( \tilde{R}_3(3, 2, 1/6) = (\tilde{R}_2^3, \tilde{R}_2^{-3})^T \), where the superscript of the components denotes the electromagnetic charge. The following renormalizable terms describe interactions of \( \tilde{R}_2 \) with the SM fermions and \( N_i \) [10, 16–19]:

\[
\mathcal{L}_{LQ} = -Y_{ij} \bar{d}^i_R \tilde{R}_2^a e^a L^b_L + Z_{ij} \frac{\bar{u}^i_L}{\sin \theta_W} \tilde{R}_2^b N^j_R + \text{H.c.} \tag{2.1}
\]

In the above, \( i, j = 1, 2, 3 \) are flavor indices, \( a, b = 1, 2 \) are SU(2)_L indices, and \( N_R \) indicates the right chiral component of \( N \). Upon expansion, eq. (2.1) becomes:

\[
\mathcal{L}_{LQ} = -Y_{ij} \bar{d}^i_R e^a L^b_L \tilde{R}_2^{2/3} + (Y_{\text{PMNS}})_{ij} \bar{d}^i_R e^a L^b_L \tilde{R}_2^{-1/3} + Z_{ij} \frac{\bar{u}^i_L}{\sin \theta_W} N^j_R \tilde{R}_2^{2/3} + (V_{\text{CKM}} Z)_{ij} \frac{\bar{d}^i_R}{\sin \theta_W} N^j_R \tilde{R}_2^{-1/3} + \text{H.c.} \tag{2.2}
\]

Here, \( Y \) and \( Z \) are the 3 × 3 complex Yukawa coupling matrices, \( V_{\text{CKM}} \) and \( U_{\text{PMNS}} \) are the Cabibbo-Kobayashi-Maskawa and Pontecorvo-Maki-Nakagawa-Sakata matrices. To investigate the model signature, it is sufficient to assume that only one generation of RHN couples with leptons and quarks. We consider this to be \( N_1 \) (denoted henceforth as \( N \)), with only \( Z_{11} \neq 0 \), and all other \( Z_{ij} \) being 0. Additionally, we also consider only \( Y_{11} \neq 0 \). Due to the \( Y_{11}, Z_{11} \) couplings \( \tilde{R}_2^{2/3} \) can decay to both \( ed \) and \( Nu \) states. We denote the corresponding branching ratios by \( \beta_{ed} \) and \( \beta_{Nu} \), respectively. Below, we discuss important features of the LQ and RHN decays.
Figure 1. Left panel: branching ratio of LQ vs $Z_{11}$. Right panel: comparison between theory cross-section and the observed limit on eejj cross-section from the LHC. The black line is the 13 TeV LHC limit on $\sigma_{\beta_{ed}}$ [20]. The green, blue, orange lines represent the variation of theory cross-section $\sigma(pp \rightarrow LQLQ) \times \beta_{ed}^2$ w.r.t. LQ mass. The star denotes our chosen benchmark couplings $Y_{11} = 0.2, Z_{11} = 1$, also consistent with the APV bound.

2.1 LQ decays

For non-zero $Y_{11}, Z_{11}$ couplings $\tilde{R}_2^{2/3}$ can decay to both $ed$ and $Nu$ states. The analytical expression for these two-body decays are,

$$\Gamma(LQ \rightarrow ed/Nu) = \frac{|Y_{11}|^2 f_1/|Z_{11}|^2 f_2}{16\pi M_{LQ}^2},$$

where $f_1 = \lambda^2(M_{LQ}^2, m_e^2, m_d^2)(M_{LQ}^2 - m_e^2 - m_d^2)$, $f_2 = \lambda^2(M_{LQ}^2, M_N^2, m_u^2)(M_{LQ}^2 - M_N^2 - m_u^2)$ and $\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$. Note that the LQ $\rightarrow ed$ decay depends on the coupling $Y_{11}$, while LQ $\rightarrow Nu$ depends on $Z_{11}$. Therefore, for $Z_{11} > Y_{11}$, the LQ $\rightarrow ed$ branching ratio is suppressed, which means that the stringent constraints from LHC searches can be alleviated. We show the branching ratios of these two decay modes in the left panel of figure 1 for LQ mass, $M_{LQ} = 1$ TeV and an illustrative RHN mass point, which we also consider for the analysis below. In the right panel of figure 1, we show a comparison of our predicted cross-section with the LHC limits. As shown by the green line, the LHC search for the decay LQ $\rightarrow ed$ constrains LQ mass as $M_{LQ} > 1.80$ TeV, assuming a branching ratio $\beta_{ed} = 1$. Considering smaller branching fractions this lower bound relaxes to, for instance, $M_{LQ} = 1$ TeV when $\beta_{ed} = 0.22$. For $\beta_{ed} = 0.04$ the constraint is even more relaxed. This can be achieved with $Y_{11} = 0.2$ and $Z_{11} = 1$, which we adopt as our benchmark couplings for the collider analysis.

2.2 RHN decay

For the chosen values of the couplings, the dominant decays of $N$ are mediated via an off-shell $\tilde{R}_2$, as we consider a light RHN state with $M_N < M_W$. The SM mediators, such as an off-shell $W, Z, H$, also contribute to the three body decay process. However, their contributions are suppressed for our chosen value of small active-sterile mixing $|V_{eN}| < 10^{-3}$. For the considered mass range $N$ decays to $N \rightarrow e^- u\bar{d}, e^+ u\bar{d}$ via $\tilde{R}_2^{2/3}$ (two-body decays
We consider the tree level lepton flavour violating (LFV) Kaon decay $K_L \rightarrow \mu^- e^+$ via $R_L^{-1/3}$. The partial decay width for $N \rightarrow e^- u \bar{d}/e^+ \bar{u} d$ is:

$$\Gamma(N \rightarrow e^- u \bar{d}/e^+ \bar{u} d) = N_c \frac{|Z_{11}|^2 |Y_{11}|^2 M^4_{LQ}}{512 \pi^3 M^4_{LQ}} \mathcal{I}$$

(2.4)

Here, $\mathcal{I} = I(x_u, x_d, x_e) = \int \frac{(1-x_u)^2}{x_u} \frac{4z}{\pi} (1 + x_u^2 - z)(z - x_d^2 - x_e^2) \lambda^2 \lambda^2 (1, x_u^2, z, x_d^2, x_e^2)$ and $x_u/d/e = \frac{m_u/d/e}{M_N}$, and $N_c = 3$ is the color factor. $N \rightarrow \nu \bar{q} q'$ also has similar dependency on masses and couplings. For $M_N < 50$ GeV, $N$ has a proper decay length $c\tau_N > O(1)$ µm for our chosen benchmark point. In particular, for $M_N = 10$ GeV (20 GeV), $c\tau_N \sim 1$ mm ($c\tau_N \sim 0.01$ mm). On the other hand, for $M_N \geq 50$ GeV, $c\tau_N$ is less than 1 µm, which is below the resolution of the LHeC and also LHC detectors, such that $N$ decay cannot be considered as being displaced. In what follows we focus on the low mass region of RHN, which, together with a LQ mass of 1 TeV dominating its decays, gives rise to a displaced decay signature.

### 2.3 Low energy constraints

Both direct and indirect experimental searches give strong constraints on a LQ state. Very relevant for LQ production at the LHeC is the precision measurement of atomic parity violation (APV), which tightly constrains the LQ coupling to a $d$ quark and $e$ state, as $Y_{11} < 0.34 M_{LQ}/\text{TeV}$ [21]. Evidently, for larger LQ mass the constraint on coupling $Y_{11}$ relaxes. The tree level lepton flavour violating (LFV) Kaon decay $K_L \rightarrow \mu^- e^+$ also gives a tight constraint on the LQ couplings $|Y_{22}Y_{11}| \leq 2.1 \times 10^{-5} (M_{LQ}/\text{TeV})^2$ [21, 22]. Due to our choice of $Y_{22} = 0$, this is not relevant for our study.

The new interactions between RHN and LQ contribute to the neutrinoless double beta decay process may exclude LQ with masses below $O(10)$ TeV for heavy neutrino masses of $O(1)$ GeV [23]. This exclusion depends on the violation of lepton number, however, and could be absent if the neutrino mass matrix would be subject to additional symmetries [24]. In addition, specific structures in the Yukawa matrix in the LQ sector can also relax the contributions from diagrams with LQ and $N$ to neutrinoless double beta decay. We remark further, that the model is not constrained from the measurements of the anomalous magnetic moment of electron due to the absence of mixed-chiral coupling, see e.g. ref. [25].

### 3 LHC searches

#### 3.1 Limits from direct searches for leptoquarks

LQ can be singly produced in proton-proton collisions via the lepton-Quark coupling, $pp \rightarrow \text{LQ} \ell$ where $\ell$ is a lepton. A search for singly produced first-generation scalar LQ at $\sqrt{s} = 8$ TeV by the CMS collaboration excludes $M_{LQ} < 1.73$ TeV for lepton-quark couplings equal to 1 and $\text{BR}(LQ \rightarrow \ell q) = 1$ [26]. In order to conform with the limits from APV we consider $Y_{11} < 0.34$, which relaxes the CMS limit on the LQ mass and allows for $M_{LQ} < 1$ TeV.
LQ can also be pair-produced in proton-proton collisions, which has been investigated in several different channels from the process $pp \to \text{LQLQ} \to \ell j \ell j$ \cite{20, 27}. Non-observation of any signal at $\sqrt{s} = 13$ TeV constrains LQ masses to be larger than 1.8 TeV at 95\% C.L. \cite{20} for LQ coupling exclusively to the first generation fermions. Including several decay channels simultaneously, in particular $\text{LQ} \to \nu j$, relaxes the constraint on the LQ mass, as shown in figure 1. In the following we consider a large branching ratio $\beta_{\nu u} = 96\%$ for $\tilde{R}_2 \to \nu u$ production mode, which leaves a sufficiently small branching ratio $\beta_{\text{ed}}$ for the $\tilde{R}_2 \to \text{de}$ decay to relax the LHC mass-limit to below 1 TeV. As we have mentioned before, these branching ratios can be obtained for $Y_{11} = 0.2, Z_{11} = 1.0$. The point marked in star in the right panel of figure 1 represents this benchmark.

It is important to re-iterate that, as $\beta_{\text{ed}}$ decreases, the branching ratio $\beta_{\nu u}$ becomes large, and LQ $\to Nu$ process could in principle be investigated at the LHC. We remind ourselves that the decay $\tilde{R}_2 \to Nu$ is followed by the decay of $N$ leading to a displaced fat jet for $M_N = \mathcal{O}(10)$ GeV. We find that for our benchmark point the cross-sections for $pp \to \text{LQLQ} \to \nu \nu$, and $pp \to \text{LQLQ} \to \text{ed}\nu u$ at $\sqrt{s} = 13$ TeV are $\sigma = 7.53, 0.31$ fb, respectively, which are much smaller than what we obtain from $ep \to Nu$ at LHeC with $\sigma \sim 20 (100)$ fb for $e^-(e^+)$ polarised beam, as we discuss in section 4.

### 3.2 Limits from other searches

We discuss below the constraints arising from other searches at the LHC that do not particularly target LQ or heavy neutrino, however still relevant for our benchmark point.

- Jet+MET searches. At the LHC, pair production of $\tilde{R}_2^{1/3}$ with subsequent decay to $\nu j$ final state leads to jets + MET signature, which has been studied by the CMS collaboration \cite{28}. Our benchmark point is not excluded by this search, mainly because of the low branching ratio ($\sim 5\%$ for $\tilde{R}_2^{1/3} \to j\nu$). We checked with the ATLAS search for pair-produced gluino (squark) and subsequent decay to 2 quarks (1 quark) + LSP \cite{29}, using the public code CheckMATE \cite{30, 31}. We find that the most sensitive signal region (SR4jm) does not rule out our benchmark point.

The final state jets + MET can also arise from $\tilde{R}_2^{1/3} \to jN (\to \nu jj)$. However, it leads to a different signature including fat-jets in the final state. Other signatures where the final state comprises displaced lepton+jets+MET can arise from $pp \to \tilde{R}_2^{-1/3} \tilde{R}_2^{1/3} \to j\nu jN (\to \nu jj)$. However, due to boosted RHNs (as we show in figure 5), the majority of the leptons fail the selection criteria for isolated leptons, leading to a strongly suppressed cross section of $\sigma \sim 0.03$ fb for this signature.

- Displaced jet searches. Our signal at the LHC is $pp \to \text{LQLQ} \to 2j + 2N$, with subsequent displaced decay of $N \to \nu jj$. For our benchmark, decay products of $N$ being highly collimated require a large jet radius to be reconstructed, i.e., $R = 1$. Thus the signature for this process is $2j$ plus two displaced fat-jets. To the best of our knowledge there are currently no searches that target such signatures.

There exist other searches, however, aiming at discovering long-lived particles that may instead be applicable. The recent CMS search \cite{32} that targets long-lived particle
(LLP) using displaced jets considers the jet-radius $R = 0.4$. This could be sensitive to the scenario under our consideration, i.e. decay of LLP into a single reconstructed jet. We compare the observed limit on the LLP pair-production cross section with our prediction of the LLP pair-production cross section: for LLP with masses below 50 GeV and $c\tau \sim O(1 \text{ mm})$, the 95% C.L. upper limits on the pair production cross-section of the LLP is $\simeq 20\text{ fb}$, which does not test the LLP pair-production cross section for the benchmark ($M_N = 10\text{ GeV}$), which is $\simeq 7.5\text{ fb}$.

### 3.3 Displaced vertex search for heavy neutrinos at the HL-LHC

Heavy neutrinos with long lifetimes give rise to displaced vertices in the detector. These are unique signatures and could be targeted in experimental searches for displaced vertices [33, 34]. We implement a search based on the ATLAS displaced multi-track search in the “DV + electron” channel [35]. Note that the search investigated in [36], designed to probe long lived RHN is not relevant for us, as the search relies on $N \rightarrow l^+l^-\nu$ decay mode, which is suppressed in our case.

We use MadGraph5 aMC@NLO(v2.7) [37] to generate three signal benchmarks for LQ mass of $O(1)\text{ TeV}$ and $M_N = [10, 20, 30]\text{ GeV}$, for the process $pp \rightarrow LQLQ \rightarrow 2j + 2N$, with subsequent decay of $N \rightarrow ejj$. LHE events are further processed with Pythia8 v3.03 [38] for showering and hadronization. The displaced decay positions are extracted from the simulated input LHE files, which are further analyzed within Pythia. Events are required to have an electron within $|\eta| < 2.47$ and $p_T > 120\text{ GeV}$, as well as the reconstruction of a displaced vertex (DV) inside the ATLAS inner tracker, within $4 \text{ mm} < r_{\text{DV}} < 300 \text{ mm}$ and $|z_{\text{DV}}| < 300 \text{ mm}$, where $r_{\text{DV}}$ and $z_{\text{DV}}$ corresponds to the transverse and longitudinal displaced vertex positions. We require the electron to be associated with the DV by truth-matching the electron index with one of the displaced tracks coming from the DV. At least one DV in each event with track multiplicity $N_{\text{trk}} \geq 4$ and invariant mass $m_{\text{DV}} \geq 5\text{ GeV}$, is required, where it is assumed all tracks have the pion mass. Each displaced track from the vertex must have a transverse impact parameter $|d_0| > 2 \text{ mm}$ and $p_T > 1\text{ GeV}$. In addition, paramaterized efficiencies for DVs [39] as a function of track multiplicity and invariant mass are applied to quantify the detector response.

We find efficiencies after all cuts of $[1.7\%, 0.004\%, 0\%]$, yielding $[365, 1, 0]$ number of expected events at the 13 TeV LHC with $3000\text{ fb}^{-1}$ for $M_N = [10, 20, 30]\text{ GeV}$, respectively. Our last two benchmark points are beyond the reach of LHC displaced searches, which can be understood as follows. For our benchmarks, the proper decay distances are $c\tau_N = [1.581, 0.0493, 0.0065]\text{ mm}$. For the last two mass points of 20 and 30 GeV, total decay lengths become too short for the events to pass the ATLAS inner tracker acceptance cuts. This motivates optimised LHC displaced searches to access lower DV positions for this leptoquark model, which is possible at the LHeC, where smaller displacements could be reconstructed [9]. In table 2, we present the cut-efficiencies for the above mentioned displaced search at the HL-LHC, and for comparison also those for displaced fat-jet search at the LHeC, as obtained below.
Figure 2. Sample Feynman diagram for the model signature at the LHeC, the blue circle indicates displaced $N$ decay.

Figure 3. Production cross-section of $ep \to Nu$ with and without 80% left (right) polarised $e^-(e^+)$ beam.

4 Collider analysis for LHeC

4.1 Signal

Our stage is the LHeC with its 7 TeV proton and 60 GeV electron beam and without polarisation, where $N$ is produced via $ep \to Nu$ process. The signal is dominated by resonant $\tilde{R}^{2/3}_2$ production with a cross section of 9.3 fb, followed by the subsequent decay $\tilde{R}^{2/3}_2 \to Nu$ with 96% branching ratio, see figure 2 for sample diagram. This production channel strongly depends on the two couplings $Y_{11}$ and $Z_{11}$. Also the $t$-channel contribution, mediated by $\tilde{R}^{2/3}_2$, contributes sizeably with $\sigma \sim 5.7$ fb. We remark, that the production of $N$ via leptonic mixing is suppressed by mixing square $|V_{eN}|^2 \sim \mathcal{O}(10^{-11})$ and is therefore completely negligible in our model. The associated parton $u$ hadronises and gives rise to a prompt light jet.

We consider both, $e^-$ and $e^+$ in the initial state, which lead to different production cross sections [10] due to a difference in the quark PDFs. This could be a useful handle to fingerprint the signature, if it were to be observed. The production cross sections are shown in figure 3. The cross-sections are fairly large, $\sigma \sim 14,127$ fb for $e^-$ and $e^+$ beam, respectively, and increases even further if polarisation of $e^-/e^+$ beam is being used.

For the considered LQ mass $M_{LQ} = 1$ TeV, and $N$ with mass $M_N \sim \mathcal{O}(10)$ GeV, $N$ is produced with a boost and its proper decay length in the laboratory system is enhanced to $\lambda_N^{lab} = \beta\gamma c\tau_N$, where $\beta\gamma = |p_N|/M_N > 1$ due to RHN momentum $p_N \sim M_{LQ}/2$. We show the distribution of $\lambda_N^{lab}$ in figure 4. As can be seen, $N$ with masses 10, 20 GeV undergoes displaced decays with decay length in the $\mathcal{O}(mm - 100 \ mm)$ range, while for 50 GeV, this is almost a prompt decay.
The boost of $N$ also leads to very small angular separation of its decay products, as shown in figure 5. Of particular interest is the separation between the charged lepton and the jets. As the figure shows, a sizeable fraction of the decays fails to satisfy the standard lepton isolation criterion, $\Delta R(\ell,j) > 0.4$ ($\Delta R$ between other decay products of $N$ also display similar features), which is more pronounced for smaller $M_N$ and implies that the leptons are not sufficiently isolated to be recognized as such. Instead, the $N$ decay products tend to appear as a single jet with somewhat large radius, referred as a “fat jet”. 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:

$$ e^\pm p \rightarrow jN \rightarrow j + j_{N}^{\text{displaced-fat}} \tag{4.1} $$

where $j_{N}^{\text{displaced-fat}}$ denotes the displaced and collimated decay products of the RHN, forming a fat jet, which we refer as a neutrino jet. Among the $N \rightarrow eq\bar{q}', vqq'$ decay modes, we focus
on \(N \rightarrow e^\pm q\bar{q}'\) and include these states in the fat jet description. In terms of sensitivity our results are thus conservative. The chosen decay mode has the added benefit that it allows the reconstruction of \(M_N\). Additional channels \(N \rightarrow \nu q\bar{q}'\) can be vetoed by imposing a missing transverse momentum cut.

Notice that, \(N\) is produced together with a prompt jet with substantial \(p_T\) and moderate \(\eta\) values. This jet emerges from the primary vertex and can be used to determine its three-coordinates. The corresponding uncertainty of this determination is related to the tracking precision, which is \(\mathcal{O}(10) \, \mu m\) [9, 40]. In the subsequent discussion, while designing the cuts, we take for the transverse displacement a detection threshold of 50 \(\mu m\), to be conservative.

### 4.2 Backgrounds

We consider a number of SM backgrounds\(^1\) \(e p \rightarrow ej, eb, \nu j, \nu jj, ebj, ebbb\), shown in table 1. The relevant processes are those involving \(B\)-hadrons, which can give rise to displaced vertices. The light jet background is also important due to its huge cross-section, see table 1. This is especially relevant for the heavier \(N\) which are quasi-prompt due to the short lifetime. The single top production \(e p \rightarrow \nu t\) is already included. Other background involving tau-lepton production \(e p \rightarrow \nu j (W \rightarrow \nu \tau)\) (\(\sigma_\tau = 0.01\) pb with our cuts) can be neglected.

Our main focus is thus on the final states: \(e/\nu + nj + nb\), with \(n_j \geq 1\) and/or \(n_b \geq 1\) being the number of light quarks and \(b\) quarks, respectively.

### 4.3 Simulation and event selection

We use MadGraph5 aMC@NLO(v2.7) [37] to simulate both signal and background samples. For the generation of parton level signal events we implement the LQ model in FeynRules(v2.3) [41] and use the UFO files in MadGraph5 aMC@NLO(v2.7). We implement the following generation level cuts for background event \(p_T(b/j) > 20\ \text{GeV},\ p_T(\ell) > 10\ \text{GeV},\ -4.2 \leq \eta(b/j/\ell) \leq 5,\ \Delta R(jj/\ell j/bb/bj/\ell b) > 0.05\). We also demand transverse momentum \(p_T\) of leading parton \(> 150\ \text{GeV}\) for background events, so that the majority of events populate the signal region. We use Herwig (7.2) [42, 43] to simulate the hadronization and showering of parton level events. For the signal, we consider the RHN decay in Herwig (7.2). We use Rivet (v3.0) [44, 45] for event analysis. For jet formation we use FastJet (v3.3.2) [46]. We reconstruct fat jet using a Cambridge-Aachen algorithm [47] with radius parameter \(R = 1.0\). We did not perform a fast detector simulation, which is not expected to affect our results qualitatively, since the tracking abilities of the detector are extremely good, and the absence QCD backgrounds makes it easy to reconstruct processes event by event. We leave such a study for future work, in particular to test the robustness of our results with respect to detector effects.

We select events according to the following criteria:

- \(N_{\text{jet}} \geq 2\) and \(p_T \geq 50\ \text{GeV}\) for all jets.

\(^1\)We note that instrumental sources of backgrounds (in addition to the SM backgrounds) should also be considered in principle. An accurate and realistic estimation of possible instrumental backgrounds is beyond the scope of this paper. Nevertheless, the absence of large QCD production cross sections lets one expect significantly less background noise compared to the LHC.
We select all the charged final state particles (tracks) with $p_T > 1$ GeV in an event and calculate the transverse displacement $R_T = \sqrt{X^2 + Y^2}$ ($X, Y$ being the coordinates of the production vertex) of each of the tracks from the interaction point (IP). In the left panel of figure 6, we show the distribution of $\log_{10}(R_T/1 \, \text{mm})$ for all tracks associated with both prompt and displaced jets. For both the signal and background event distributions have two similar features. Firstly, tracks with $\log_{10}(R_T/1 \, \text{mm}) \leq -4$ are associated to the prompt jets. Additionally, the tracks with $\log_{10}(R_T/1 \, \text{mm}) \simeq 2.5$ correspond to the tracks emerging from long-lived hadron decay. For signal with $M_N = 10$ GeV, peak at $\log_{10}(R_T/1 \, \text{mm}) \simeq 1.5$ represents the tracks originating from RHN decay. For $M_N = 20$ GeV, two peaks exist in the region $\log_{10}(R_T/1 \, \text{mm}) \geq -4$. The first peak at $\log_{10}(R_T/1 \, \text{mm}) \simeq -1$ correspond to the tracks stemming from the RHN decay vertex, and the latter at $\log_{10}(R_T/1 \, \text{mm}) \simeq 2.5$ indicates tracks from decay of long-lived hadron.

We define the track as a displaced track if the transverse displacement is above the detection threshold, $R_T > 50 \, \mu\text{m}$. Subsequently, we define a ratio

$$r_N = \frac{N_{\text{trk}}(\text{displaced})}{N_{\text{total-trk}}},$$

(4.2)

where $N_{\text{trk}}(\text{displaced})$ and $N_{\text{total-trk}}$ are the number of displaced tracks, and total number of tracks associated to a jet, respectively. Since $N$ is long-lived this ratio is expected to be closer to 1 for jets originating from its decay vertex, while we expect a value $\ll 1$ for any other prompt jet. We also impose a bound $R_T < 312 \, \text{mm}$,\(^2\) so that we consider only decay products appearing in the inner tracker volume [9]. We label the jet having the largest value of $r_N$ as the displaced jet. For $N$ with $M_N \sim 50$ GeV the decays are rather prompt, and $r_N$ can not be reliably used to identify the jet as stemming from $N$ decay.

We further cross-check if the displaced jet is originating from $N$ and hence is a neutrino jet by computing the jet-mass. We identify a jet as the neutrino jet, if its invariant

\(^2\)The (barrel part of the) tracker consists of three inner layers that extend to 312 mm, and three outer strip detectors. Charged particles in the range of $-4.2 < \eta < 5$ leave hits in at least the outer two layers of the strip detectors and can therefore be reconstructed as tracks [9].
mass $M(j_N)$ is closest to $M_N$. The distribution of the variable $M(j_N)$ is shown in the middle panel of figure 6. For background events we show the distribution of the jet mass closest to $M_N = 10$ GeV for illustration. This selection criterion results in a sharp drop after $M(j_N) = 20$ GeV. We find that for $M_N \sim 10, 20$ GeV, the jet with highest $r_N$ is consistent with the invariant mass condition.

- We define a variable $r_E$ as the ratio of the sum of energies of the displaced tracks and sum of energies carried out by all tracks associated to a jet:

  \[
  r_E = \frac{\sum E(\text{displaced-trk})}{\sum E(\text{trk})}.
  \]  \hspace{1cm} (4.3)

We show the distribution of this variable in figure 6 for the jet with highest $r_N$. As can be seen, the distribution for displaced signal and light jet background are complementary in nature, which is instrumental in separating the two. For small $N$ masses majority of the tracks are displaced, leading to a higher energy ratio $r_E$. For light jet background, reverse is true.

- Finally we select those events where the neutrino jet satisfies the following cuts: $r_N \geq 0.5$, $r_E \geq 0.5$, $p_T(j_N) \geq 150$ GeV and $M(j_N) = M_N \pm 3$ GeV.

### 4.4 Results

The signal cross-sections for 10–30 GeV $M_N$ varies as $\sigma^s_i \sim 7.10–7.37 \text{ fb}$ before applying any cut for $e^-$ mode (see table 1). The final cross-sections after all the cuts are $\sigma^f_i \sim 1.6–3.5 \text{ fb}$. Table 2 shows the cut efficiencies for the signal events, including the cut efficiencies for the multi-track displaced vertex search at the HL-LHC discussed in section 3 for comparison. This indicates a better discovery prospects with our proposed displaced fat jet strategy at LHeC. For $M_N = 50$ GeV as the decay is almost a prompt decay, we do not include the

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3 A similar variable based on $p_T$ fraction is defined in the context of emerging jets [48].
result in the table. We find the backgrounds $eb, ej$ are the most relevant ones after cuts, while other backgrounds $e b b / e b b b, e j j / e j j j$ also give sizeable contributions. Applying a veto on missing transverse momentum will further suppress the $\nu j / \nu jj / \nu + 3 j b$ backgrounds. Instead, here we present a conservative estimate. For the $e^+$ mode, the signal cross-section is one order of magnitude larger as compared to $e^-$ mode, while the backgrounds are relatively smaller. The signal sensitivity is calculated as

$$n_\sigma = \frac{\sqrt{\mathcal{L}}}{\sqrt{\sigma_s + \sigma_b}}$$

(4.4)

where $\mathcal{L}$ in fb$^{-1}$ is the required luminosity to achieve $n_\sigma$ significance, $\sigma_s / \sigma_b$ are the after-cut signal/background cross sections. Our findings are summarised in Table 3.

For the considered RHN masses, our signature can be detected with 5$\sigma$ significance with an integrated luminosity $\mathcal{L} < 120$ fb$^{-1}$. With the total integrated luminosity of 1000 fb$^{-1}$ in the $e^-$ mode, excluding our signal at 2$\sigma$ significance can be used to put an upper limit on Yukawa $Y_{11} < 0.067$ for $M_N = 10$ GeV. For higher RHN mass $M_N = 30$ GeV, the limit becomes stringent due to the increase in geometric cut-efficiency ($R_T < 312$ mm).

The table further shows that the $e^+$ mode clearly outperforms the $e^-$ mode as signal sensitivity $n_\sigma$ increases by almost one order of magnitude, and 5$\sigma$ significance can be achieved with luminosities $\mathcal{L} < 2$ fb$^{-1}$ only, for all the mass points considered. With $\mathcal{L} = 1000$ fb$^{-1}$ the upper limit on Yukawa tightens $Y_{11} \leq 0.013$ for $M_N = 30$ GeV. The signal sensitivity can be further improved with polarised $e^-$ and $e^+$ beams due to increase in signal cross-section.

### Table 2
A comparison of signal cut efficiencies between the proposed displaced fat jet search at the LHeC and the multi-track displaced vertex search at the HL-LHC.

| $M_N$ [GeV] | $\epsilon_{\text{LHeC}}$ | $\epsilon_{\text{HL-LHC}}$ |
|-------------|-------------------------|---------------------------|
| 10          | 47.54%                  | 1.7%                      |
| 20          | 46.7%                   | 0.004%                    |
| 30          | 22.4%                   | 0%                        |

### Table 3
$n_\sigma$ is the significance of the proposed signature with only 50 fb$^{-1}$ luminosity. $\mathcal{L}$ is the required luminosity to achieve 5$\sigma$ significance. Numbers without (within) brackets corresponds to $e^-$ ($e^+$) beam, respectively. $Y^{\text{ex}}$ represents 2$\sigma$ exclusion on $Y_{11}$.

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

In this article we considered a model that includes an $\tilde{R}_2$ LQ with $M_{LQ} = 1$ TeV and RHN with a mass of $O(10)$ GeV. The RHN can be produced from resonant LQ decay, with comparatively large cross sections, and also via $t$ channel processes. We studied the prospects of discovering the RHN at the LHeC via a displaced fat jet signature, which is purely hadronic in nature. We perform a detailed analysis of the signal and the different SM background processes. We find that the ratio of energy deposits of the displaced and all possible tracks associated with the displaced jet is instrumental in separating displaced decays of RHN from background. We find that RHN in the considered mass range can be detected at the LHeC with only $\mathcal{L} < 120 (2) \text{ fb}^{-1}$ luminosity with $e^-(e^+)$ beam. We observe that, the use of a positron beam at LHeC clearly enhances the detection prospect of this signature by order of magnitude.

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