Testing the $R_{D^{(*)}}$ anomaly at the LHeC

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Received: 1 June 2021 / Accepted: 13 December 2021 / Published online: 22 December 2021

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Abstract B-Physics anomalies have recently raised renewed interest in leptoquarks, predicted in several theoretical frameworks. Under simplifying but conservative assumptions, we show that the current limits from LHC searches together with the requirement to explain the observed value for $R_{D^{(*)}}$ constrain the R_2 leptoquark mass to be in the range of $800 \leq m_{R_2} \leq 1000$ GeV. We study the search for R_2 at the LHeC via its resonance in the $b\tau$ final state by performing a cut-and-count analysis of the signal and the dominant Standard Model backgrounds. We find that the LHeC has an excellent discovery potential for the R_2 leptoquark even for couplings to the first generation as small as $\mathcal{O}(10^{-2})$.

1 Introduction

Over the last years the LHCb collaboration has consolidated the existence of the so-called flavor anomalies which are being corroborated by the Belle and Babar collaborations. These anomalies consist of excesses or deficiencies in ratios of branching ratios of semileptonic B meson decays. Notable are recent updates from LHCb for the measurements of the so-called $R_{D^{(*)}}$ observable, defined as $\text{Br}(\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau)/\text{Br}(\bar{B} \rightarrow D^{(*)}l^-\bar{\nu}_l)$ [1], and the measurement of CP averaged observables in $\text{Br}(B \rightarrow K^{(*)}\mu^+\mu^-)/\text{Br}(B \rightarrow K^{(*)}e^+e^-)$ in restricted range of q^2 , also referred to as the $R_{K^{(*)}}$ observable, cf. the recent publications by the LHCb collaboration [2–4].

The flavor anomalies have led to renewed theoretical interest in leptoquarks (LQ), which were introduced in the context of quark-lepton unification [5–8], and are capable of addressing at least subsets of these anomalies. LQs can be scalar or

vector bosons, and are classified according to their transformation properties under the SM gauge groups [9, 10].

Their color charge allows for LQ's to be produced in pairs at the LHC and searched for via their decay products (see, for example, Refs. [11, 12]). They can also be searched for via indirect effects in many other observables (cf. Ref. [13] and references therein). The LHC collaborations impose strong constraints on LQ's that couple exclusively to first and second generation fermions [14–18] as well as to the third generation fermions, with recent results in [19, 20]. No signal has been found up to now, apart from a moderate excess in the $\mu\nu jj$ final state (cf. the discussion in Ref. [21]). However, these results are most constraining assuming a large branching ratio to the final state considered.

LQ's can be produced via their Yukawa couplings as a single resonance in electron-proton collisions, provided they couple to the first generation of fermions. The planned Large Hadron electron Collider (LHeC) [22] has been shown to have a very good sensitivity to a LQ [23] because of the low background rates and the clean environment. The LHeC is thus an excellent laboratory to study these hypothetical particles. Signatures with leptons and jets from R_2 leptoquarks at the LHeC have been studied in Refs. [24, 25], wherein the authors found a good discovery potential already with 100 fb^{-1} of integrated luminosity.

In this paper we consider a minimal scenario that is motivated by the $R_{D^{(*)}}$ anomaly, namely the LQ called R_2 . We revisit the LHC bounds on the model parameters and discuss the prospects to discover and study this particle at the LHeC.

2 The leptoquark model

An overview of the possible LQ solutions to the flavor anomalies has been presented in Ref. [26]. We focus here on the scalar LQ called R_2 . The general scalar potential is given in

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Fig. 1 Feynman diagram denoting the contribution of the R_2 leptoquark to the b quark decay into $c\tau\nu_\tau$ final state, mediated by its component $\omega^{(2/3)}$. This contribution can in principle explain the observed anomaly in the b meson decays called $R_{D^{(*)}}$. For details, see text

Ref. [27]. The R_2 has following representation under the SM gauge groups:

$$R_2 = \left(\frac{\omega^{5/3}}{\omega^{2/3}} \right) \sim (3, 2, 7/6). \quad (2.1)$$

The two components, ω^q , are the two eigenstates under the electric charge with eigenvalues q . We notice that the scalar potential allows for a mass splitting between the two eigenstates, which is limited to $\Delta m \leq \mathcal{O}(100)$ GeV due to the oblique parameters [27].

Its gauge representation allows the R_2 to interact with the quarks and leptons via Yukawa interactions:

$$\mathcal{L} \supset -(y_1)_{ij} \bar{u}_R^i R_2^a \epsilon^{ab} L_L^{j,b} + (y_2)_{ij} \bar{e}_R^i R_2^{a*} Q_L^{j,a} + \text{h.c.} \quad (2.2)$$

In the interaction terms above we introduced the couplings y_1 and y_2 , which are arbitrary complex 3×3 Yukawa matrices. The interaction terms in Eq. (2.2) can be cast into the mass basis:

$$\begin{aligned} \mathcal{L} \supset & -(y_1)_{ij} \bar{u}_R^i e_L^j \omega^{5/3} + (y_1 U)_{ij} \bar{u}_R^i v_L^j \omega^{2/3} \\ & + (y_2 V^\dagger)_{ij} \bar{e}_R^i u_L^j \omega^{5/3*} + (y_2)_{ij} \bar{e}_R^i d_L^j \omega^{2/3*} + \text{h.c.} \end{aligned} \quad (2.3)$$

Here U and V stand for the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) and the Cabibbo–Kobayashi–Maskawa (CKM) matrices, respectively. Furthermore, $Q_i = \left[(V^\dagger u_L)_i, d_{Li} \right]^T$ and $L_i = \left[(U v_L)_i, \ell_{Li} \right]^T$ denote quark and lepton $SU(2)_L$ doublets, whereas u_L, d_L, ℓ_L and ν_L are the fermion mass eigenstates.

We consider a minimalistic structure of the Yukawa couplings. For LQ masses around the TeV we need that both y_1^{23}, y_2^{33} are $\mathcal{O}(1)$ in order to explain $R_{D^{(*)}}$ according to Eq. (2.7) below. In addition, we require a small but non-zero value for y_2^{11} to allow for production in electron-proton collisions.¹ The other coupling constants are set to $y_i^{jk} = 0$ for

¹ While not necessary to explain the $R_{D^{(*)}}$ anomaly, this coupling has been shown to be able at least in principle to address the $R_{K^{(*)}}$ anomaly also [28].

simplicity. This fixes the Yukawa matrices as follows:

$$y_1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_1^{23} \\ 0 & 0 & 0 \end{pmatrix}, \quad y_2 = \begin{pmatrix} y_2^{11} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_2^{33} \end{pmatrix}. \quad (2.4)$$

This particular choice of the Yukawa texture allows us to escape several stringent flavor physics constraints as outlined below, and it makes the explanation of $R_{D^{(*)}}$ particularly simple.

2.1 The R_2 leptoquark and the $R_{D^{(*)}}$ anomaly

The couplings y_1 and y_2 contribute to tree-level diagrams where a b -quark decays according to $b \rightarrow q\ell\bar{\ell}'$. This allows in principle the explanation of the $R_{D^{(*)}}$ anomaly, as is shown diagrammatically in Fig. 1, simply by enhancing the decay $B \rightarrow D\tau\nu$ over the SM prediction with a $\omega^{2/3}$ induced contact interaction. We consider the following effective Hamiltonian in order to confront the LQ contributions with the experimental data

$$\begin{aligned} \mathcal{H}_{\text{eff}} = & \frac{4G_F}{\sqrt{2}} V_{cb} \left[(\bar{\tau}_L \gamma^\mu \nu_L) (\bar{c}_L \gamma_\mu b_L) + g_S(\mu) (\bar{\tau}_R \nu_L) \right. \\ & \left. \times (\bar{c}_R b_L) + g_T(\mu) (\bar{\tau}_R \sigma^{\mu\nu} \nu_L) (\bar{c}_R \sigma_{\mu\nu} b_L) \right] + \text{h.c.} \end{aligned} \quad (2.5)$$

where $g_{S,T}$ denote the Wilson coefficients induced by the R_2 LQ state mediating the tree-level semileptonic decay (cf. Fig. 1). At the matching scale $\mu = m_\omega = m_{R_2}$, integrating out the $\omega^{2/3}$, the expression for $g_{S,T}$, can be expressed as:

$$g_S(\mu = m_{R_2}) = 4g_T(\mu = m_{R_2}) = \frac{y_1^{23} (y_2^{33})^*}{4\sqrt{2}m_{R_2}^2 G_F V_{cb}}. \quad (2.6)$$

It was found e.g. in [29] that with Yukawa couplings satisfying the condition

$$\frac{|y_1^{23}| |y_2^{33}|}{m_{R_2}^2} \in (0.80, 1.32) \times (1 \text{ TeV})^{-2} \quad (2.7)$$

the numerical value of $R_{D^{(*)}}$ can be explained in this model at the 2σ confidence level.

2.2 Experimental constraints

Atomic parity violation: The precise measurement of atomic parity violation (APV) puts strong limits on the R_2 coupling to down quarks and electrons [30,31]:

$$y_2^{11} < 0.34 \frac{m_{R_2}}{1 \text{ TeV}}. \quad (2.8)$$

Lepton flavor violation: The R_2 LQ can induce tree-level lepton flavor violating decays, such as $B_d \rightarrow e\tau$ and $B \rightarrow$

$\pi e \tau$. The lepton-flavor violating decay rate for the process $B_d \rightarrow \tau^- e^+$ can be expressed as [32]:

$$\Gamma_{B_d \rightarrow \tau^- e^+} = \frac{|y_2^{33} y_2^{11*}|^2}{256\pi} \frac{m_{B_d}^3 f_{B_d}^2}{m_{R_2}^4} \hat{m}_\tau^2 (1 - \hat{m}_\tau^2). \quad (2.9)$$

The current experimental bound on the branching ratio for the process $B_d \rightarrow \tau^- e^+$ is 2.8×10^{-5} at 90% CL [33]. This leads to a bound on the Yukawa couplings as $|y_2^{33} y_2^{11*}|^2 < 1.05 \times 10^{-2} \left(\frac{m_{R_2}}{\text{TeV}}\right)^4$ (see details in [32] for the flavor constraints). The differential decay rate for the lepton-flavor violating decay $B \rightarrow \pi \tau^\pm e^\mp$ can be written as [32]:

$$\begin{aligned} \frac{d\Gamma}{ds} (B \rightarrow \pi \tau^\pm e^\mp) &= \frac{|y_2^{33} y_2^{11*}|^2}{(16\pi)^3 m_{R_2}^4} m_B^3 \lambda^{1/2} \left(1 - \frac{m_\tau^2}{s}\right)^2 \\ &\times \left[\frac{\lambda}{3} f_+^\pi(s)^2 \left(2 + \frac{m_\tau^2}{s}\right) + \frac{m_\tau^2}{s} f_0^\pi(s)^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \right], \end{aligned} \quad (2.10)$$

where s is the squared momentum difference between the two outgoing leptons, $f_{+,0}^\pi$ denote the form factors and $\lambda \equiv \lambda(1, m_\pi^2/m_B^2, s/m_B^2)$ and $\lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + bc + ca)$. The experimental upper limit on the branching ratio for the process $B \rightarrow \pi e \tau$ is 7.4×10^{-5} [33], which imposes a bound on the couplings as $|y_2^{33} y_2^{11*}|^2 < 1.9 \times 10^{-2} \left(\frac{m_{R_2}}{\text{TeV}}\right)^4$ at 90% CL.

Further constraints from rare lepton flavor violating processes exist, cf. Ref. [34]. For instance, the semi-leptonic tau lepton decays $\tau \rightarrow e\pi^0, e\eta, e\eta', e\rho$ strongly constrain the product of the coupling constants $y_2^{13} \cdot y_2^{11}$. Similarly, rare lepton-flavor-violating decays $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$ strongly constrain the product of the coupling constants y_2^{33} with y_1^{31} and y_1^{32} , respectively. These flavor-related constraints require that at most one large entry may exist in any row or column of the Yukawa matrices y_1 and y_2 .

LHC searches in di-lepton di-jets: At the LHC the R_2 components can be produced in pairs directly from the gluons in proton–proton collisions. In particular, at the LHC with $\sqrt{s} = 13$ TeV, this allows for large production cross sections for LQ masses that are at the TeV scale. The production and decay of a pair of LQ's gives rise to final states with two leptons and two jets. We consider the relevant limits from Refs. [15, 16], which depend on the branching ratios into the considered final state(s). The dominant decay modes of the R_2 leptoquark for our Ansatz are:

$$\omega^{(2/3)} \begin{cases} \xrightarrow{y_1} c\nu_\tau \\ \xrightarrow{y_2} b\tau, de \end{cases} \quad \omega^{(5/3)} \begin{cases} \xrightarrow{y_1} c\tau \\ \xrightarrow{y_2} t\tau, ue. \end{cases} \quad (2.11)$$

In general, when the two R_2 components have different masses they are being constrained separately by the LHC searches for different final states. Reference [20] summarises a search for LQ in channels with top quarks and tau leptons, which is a decay channel driven by the coupling y_2^{33} in our model, a branching ratio of 100% is excluded for LQ masses up to around 1.4 TeV, while masses around one TeV are possible if the branching ratio into this final state is at most 10%. Such small branching ratios are possible because of additional decay channels like $\omega^{5/3} \rightarrow \omega^{2/3} + W^{(*)}$ [35], which can yield a branching ratio for $\omega^{5/3} \rightarrow t\tau W^{(*)}$ of 10% or less. In the following we focus on the phenomenology of the $\omega^{2/3}$ and ignore $\omega^{5/3}$, which does not contribute directly to the $R_{D^{(*)}}$ anomaly (cf. Fig. 1). The scalar $\omega^{(5/3)}$ decaying into boosted tops and light leptons with 100% branching ratio can be tested for masses up to around 2 TeV at the HL-LHC [36].

LHC searches for di-leptons: Limits from ATLAS searches for di-leptons [37, 38] apply to our LQ model since R_2 contributes to the process $pp \rightarrow l^+ l^-$ in a t -channel diagram. In particular, of non-zero y_2^{11} the non-resonant di-lepton process $pp \rightarrow e^+ e^-$ is created, whereas larger values of y_1^{23}, y_2^{33} lead to $pp \rightarrow \tau^+ \tau^-$ process. For the di-lepton bounds, we analyze the cross section for the process $pp \rightarrow \ell_i^+ \ell_j^-$ due to t -channel R_2 LQ exchange using the MadGraph5aMC@NLO [39] event generator and compare the quoted observed limits [37] on the cross-section to derive the limits on the Yukawa coupling of the R_2 LQ.

LHC searches for jets plus missing energy: Also this kind of search applies to the LQ model, which contributes to the process $pp \rightarrow \nu \bar{\nu} j$, where the R_2 is exchanged in a t -channel process and the jet originates from the initial state radiation of the quarks. To recast the limit from the recent 13 TeV ATLAS monojet study [40], we adopt the acceptance criteria from the analysis, defining jets with the anti- k_t jet algorithm and radius parameter $R = 0.4$, $p_{Tj} > 30$ GeV and $|\eta| < 2.8$ via FASTJET [41]. Events with identified muons with $p_T > 10$ GeV or electrons with $p_T > 20$ GeV in the final state are vetoed. In order to suppress the W + jets and Z + jets backgrounds, we select the events with $E_T > 250$ GeV recoiling against a leading jet with $p_{Tj1} > 250$ GeV, $|\eta_{j1}| < 2.4$, and azimuthal separation $\Delta\phi(j_1, \mathbf{p}_{T,miss}) > 0.4$. Events are vetoed if they contain more than four jets. We find that the limit from monojet searches on the Yukawa coupling is less stringent than the limits from the di-lepton searches. We also estimate the projected limits for HL-LHC with an integrated luminosity of 3 ab^{-1} by scaling appropriately the number of data and background events. These projected sensitivities are shown in Fig. 2.

Fig. 2 Projection of the LHC constraints at the 95% confidence level on the y_2^{33} - m_{R_2} parameter space. For the recasting of the limits, $y_1^{23} = 1$ has been set, and $y_2^{11} \ll 1$ assumed. The red area denotes parameter combinations where the $R_{D^{(*)}}$ can be explained according to Eq. (2.5). For details on the LHC constraints, see text

2.3 Evaluation of model parameter space

We fix the coupling parameter $y_1^{23} = 1$ and evaluate the LHC constraints as follows: For a given mass we translate the limits on the branching ratio into a limit of the corresponding coupling constant. This yields e.g. upper limits on y_2^{33} from the searches for τb final states, and also from the recasted di-tau searches. The constraints from the LQ searches are shown via the solid green and purple regions in Fig. 2. Also shown in the figure are extrapolations for these searches where we naively rescaled the search results to the HL-LHC's final integrated luminosity of 3 ab^{-1} . The constraints resulting from the LHC searches leave a region of parameter space where the R_2 is not excluded at the LHC for masses above 800 GeV. We remark that we assume $y_2^{11} \ll 1$ such that the limits from the first generation searches are always met.

We evaluate the parameter region wherein the $R_{D^{(*)}}$ anomaly can be explained within one sigma: To be definite, also here we fix the coupling parameter $y_1^{23} = 1$, and for a given mass m_{R_2} we calculate y_2^{33} such that the condition in Eq. (2.7) is satisfied. This region is denoted by the red band in Fig. 2. We remark, that this choice minimises the experimental constraints on the parameter space in our Ansatz, as the corresponding searches for the final states relating to y_1 couplings are weaker compared to the ones related to the y_2 couplings.

A region of parameter space exists wherein the $R_{D^{(*)}}$ anomaly can be addressed and that is not excluded by current LHC searches. We show this region for three different benchmark masses $m_{R_2} = 800, 900, 1000 \text{ GeV}$ in Fig. 3 as projections on the y_2^{11} vs y_2^{33} parameter plane, including the current constraints.

We emphasise that while our setup requires y_1^{23} and y_2^{33} to be $\mathcal{O}(1)$, one may consider additional non-zero coupling constants conforming to the other constraints. Considering such additional non-zero coupling constants adds to the decay channels of the R_2 components, subsequently reducing their branching ratios for the dominant channels and thus relaxing the constraints from $\tau b \tau b$ and $\nu j \nu j$ searches. Our setup can therefore be considered conservative.

3 R_2 searches at the LHeC

As mentioned above, the R_2 LQ can be produced as an s-channel resonance in the electron-proton collisions of the LHeC when its Yukawa coupling to the first-generation fermions y_2^{11} is non zero, and when its mass is below the centre-of-mass energy of about 1.3 TeV. The resulting cross section, for a given hypothetical mass, is then proportional to the square of this Yukawa coupling, and the LHeC's sensitivity to it depends on the integrated luminosity, which we consider to be 1 ab^{-1} .

3.1 The LQ signal

The signal of interest at the LHeC is determined via the dominant branching ratios of the LQ, namely the $\bar{b}\tau^-$ and $\bar{c}\tau^-$ final states, which have the characteristic Breit-Wigner peak in the invariant mass distribution. In the following we focus on the τb final state, as shown in Fig. 4. As benchmark points we fix $y_1^{23} = 1$, $y_2^{11} = 0.1$ and we choose masses and the remaining couplings such that they are compatible with the $R_{D^{(*)}}$ anomaly and the LHC constraints (see Figs. 2 and 3). This defines the following set of parameters: masses of 800, 900 and 1000 GeV, and $y_2^{33} = 0.7$, $y_2^{33} = 0.75$ and $y_2^{33} = 0.85$, respectively. With these parameter values, the branching ratio $R_2 \rightarrow e^- j$ is below 1% and therefore this scenario evades the LHC limits on first generation leptoquarks [15, 18].

For the simulation of the production of the R_2 LQ samples, the Monte Carlo event generator MadGraph5_aMC@NLO version 2.4.3 is employed with the leading order UFO model from [42]. Parton showering and hadronization are performed by Herwig7.21 [43, 44]. For fast detector simulation, Delphes [45] and its LHeC detector card [46, 47] are used. Because there is no irreducible SM process with only $b\tau$ in the final state, the level of expected background will be very small and will depend on fake tagging of b and τ jets. Flavor tagging efficiencies and mis-identification are therefore very important ingredients in our analysis. Since they are not well known for the LHeC detector, we assume, for definiteness, a detector performance comparable to what is conservatively typically obtained at the LHC [48, 49]. Concretely we use the tau tagging efficiency of 40% for jets from hadronic tau decays in a range $|\eta| < 3$ and a mis-tagging probability of

Fig. 3 Projection of Fig. 2 in the parameter space plane y_2^{33} vs y_2^{11} for three different values of m_{R_2} . The limit from atomic parity violation is from Eq. (2.8). All limits are at 95% the confidence level, except for $B_d \rightarrow e\tau$, which is at 90%

Fig. 4 Feynman diagram denoting resonant R_2 production at the LHeC. This process requires non-zero coupling parameters y_2^{11} and y_2^{33}

1% from light jets. Furthermore we also assume that isolated electrons can be mis-identified as tau hadronic jets with a probability of 2.5%. For the tagging of b-jets we use an efficiency of 75% in the pseudorapidity range $|\eta| < 3$ and the mistagging from c-jets with 5% probability.

3.2 Background processes

We consider background processes at leading order (see Table 1) which give rise to true or mis-identified b or τ jets. Like for the signal, event samples are also generated using MadGraph, Herwig and Delphes. The dominant background is found to be the neutral current (NC) process $e^- p \rightarrow e^- j$ where the electron is potentially mis-identified as a tau-jet and the final state jet either originates from a b quark or is mis-identified as a b-jet. The SM background $e^- p \rightarrow \nu \tau \nu b$ or $e^- p \rightarrow \nu \tau \nu \bar{b}$, using respectively 5-flavour or 4-flavor scheme parton distribution functions, includes single top production ($e^- b \rightarrow \nu t$; $t \rightarrow Wb$; $W \rightarrow \tau \nu$). Other backgrounds considered are: the charged current process $e^- p \rightarrow \nu jj$ and processes with a vector boson in the final

state: $e^- p \rightarrow \nu Z j$, and $e^- p \rightarrow \nu W^- j$, $e^- p \rightarrow e^- Z j$ with $W \rightarrow \tau \nu$ or $Z \rightarrow \tau \tau$.

3.3 Analysis and results

The R_2 LQ mass is reconstructed from the 4-vectors of the tau-tagged jet and the b-tagged jet. Because of the presence of a neutrino in a tau-jet, its energy is underestimated. However, assuming that the missing transverse momentum of the event is due to the tau neutrino, and that the forward angle (or pseudorapidity) of the neutrino is the same as that of the tau-tagged jet, the tau-jet 4-vector is corrected for the presence of the invisible neutrino. This leads to a considerable improvement in the reconstructed τb mass. Figure 5 shows some kinematical distributions of the R_2 signal events.

Figure 6 shows the distributions of missing transverse energy and reconstructed LQ mass, before the selection, for the benchmark case of mass 800 GeV and for the background, for an integrated luminosity of 100 fb^{-1} . We apply the following simple and minimal set of selection criteria to enhance the signal over the background:

- Presence of τ -jet and b -jet candidates in the final state, with a $p_T > 50 \text{ GeV}$. The missing transverse momentum is further required to be in the direction of the τ -tagged jet: $\Delta\phi(\mathbf{E}_T^{\text{miss}}, \tau) < 0.2$. This is because, in case of a leptonic decay, the b -tagged jet, which is expected to be essentially back-to-back with the τ -tagged jet, may also include neutrinos. This requirement also ensures that the neutral channel process with an isolated electron, and the process $e^- p \rightarrow \nu \tau \nu b(\bar{b})$ will be strongly suppressed. For the LQ signal with $m_{R_2} = 800 \text{ GeV}$, the correspond-

Table 1 Cross sections for the benchmark signals and for background processes, after conditions applied at generation level

Process	Conditions	Cross section (fb)
$e^- p \rightarrow R_2(800 \text{ GeV}) \rightarrow \bar{b}\tau$	$p_T(b, \tau) > 200 \text{ GeV}$	5.37
$e^- p \rightarrow R_2(900 \text{ GeV}) \rightarrow \bar{b}\tau$	$p_T(b, \tau) > 200 \text{ GeV}$	1.55
$e^- p \rightarrow R_2(1.0 \text{ TeV}) \rightarrow \bar{b}\tau$	$p_T(b, \tau) > 200 \text{ GeV}$	0.602
$e^- p \rightarrow e^- j$	$p_T(j) > 200 \text{ GeV}, p_T(e^-) > 50 \text{ GeV}$	2205
$e^- p \rightarrow \nu jj$	$p_T(j) > 200 \text{ GeV}$	23.0
$e^- p \rightarrow \nu W^- j, W^- \rightarrow \tau^- \bar{\nu}$	$p_T(j) > 200 \text{ GeV},$	4.10
$e^- p \rightarrow e^- W^+ j, W^+ \rightarrow \tau^+ \nu$	$p_T(j) > 200 \text{ GeV}, p_T(e^-) > 50 \text{ GeV}$	2.91
$e^- p \rightarrow e^- Z j, Z \rightarrow \tau^+ \tau^-$	$p_T(j) > 200 \text{ GeV}, p_T(e^-) > 50 \text{ GeV}$	1.33
$e^- p \rightarrow \nu Z j, Z \rightarrow \tau^+ \tau^-$	$p_T(j) > 200 \text{ GeV}$	1.05
$e^- p \rightarrow \nu \nu \tau b$ (5F)	$p_T(b, \tau) > 100 \text{ GeV}$	1.69
$e^- p \rightarrow \nu \nu \tau b \bar{b}$ (4F)	$p_T(b, \tau) > 100 \text{ GeV}$	0.30

Fig. 5 Kinematic distributions from the production of the R_2 leptoquark. Left: the reconstructed mass before (blue) and after (red) correction for the neutrino in the tau-tagged jet; center: transverse momentum

of the tau-tagged (blue) and b-tagged jet (red); right: pseudorapidity distribution of the tau-tagged jet (blue) and the b-tagged jet (red)

ing selection efficiency is 16.9%. The background, dominated by the neutral current process $e^- p \rightarrow e^- j$ with mis-identification of the electron as a τ and the jet as a b jet, becomes 0.074 fb.

- (b) Because of the presence of neutrinos, missing transverse energy is expected. Its distribution is concentrated at low values for the main neutral current background, $e^- p \rightarrow e^- j$ (Fig. 6, left). We require $E_T^{miss} > 50 \text{ GeV}$. The selection efficiency for $m_{R_2} = 800 \text{ GeV}$ is then reduced to 9.9%. The background is now suppressed by a further factor of 20 and is dominated by the process $e^- p \rightarrow \nu \nu \tau b$.
- (c) For a hypothetical mass m_{R_2} of the R_2 resonance, the reconstructed invariant mass of the tau and b candidate jets must be in the range $m_{R_2} - 100 \text{ GeV} < m_{\tau b} < m_{R_2} + 50 \text{ GeV}$. The selection efficiency in the mass region around 800 GeV becomes 5.2% with a background suppressed by a further factor of 11.

With the application of the above selection criteria, the background becomes totally negligible. In the absence of background, a discovery limit will be obtained by requiring a 95% probability of observing 5 events, meaning that the *expected* number of signal events should be at least 10.5. Since it is not possible to estimate systematic errors, we also consider the case of a minimum of 10 observed events, corresponding to a minimum *expected* number of signal events of 17. Given that the production cross section is proportional to $(y_2^{11})^2$, these limits can further be translated to a 95% confidence level limit on y_2^{11} (Table 2). Note that if 5 (10) events are in fact observed when no background is expected, we can conclude that the expected number is, at 95% CL, greater than 1.37 (5.43) events and therefore still smaller upper limits will be deduced.

A comment on the choice of coupling constants is in order: for a given mass the product $y_1^{23}(y_2^{33})^*$ is fixed according to Eq. (2.7) to account for the observation of $R_{D^{(*)}}$. It is y_2^{33} that gives rise to the final state considered here. For y_1^{23} coupling

Fig. 6 Distributions of (left) missing transverse energy after the requirement of the presence of τ and b jets, and (right) reconstructed LQ mass, after applying selection criterion (a) (see text). An integrated

luminosity of 100 fb^{-1} is assumed: red: benchmark signal of R_2 of mass 800 GeV; green: neutral current $e^- p \rightarrow e^- j$; blue: $e^- p \rightarrow \nu \tau b(\bar{b})$; magenta: charged current $e^- p \rightarrow \nu j j$; shaded: all backgrounds

Table 2 Number of expected events from the benchmark signals with $y_1^{23} = 1$ and $y_2^{11} = 0.1$, and from backgrounds, for an integrated luminosity of 1 ab^{-1} after selection discussed in the text. Based on a mean

expected observed signal of 5 or 10 events, the predicted limits on the coupling y_2^{11} are also shown

Mass	800 GeV	900 GeV	1 TeV
Signal	306 ($y_2^{33} = 0.7$)	68 ($y_2^{33} = 0.75$)	12 ($y_2^{33} = 0.85$)
95% limit on y_2^{11} (5 observed events)	0.024	0.03	0.093
95% limit on y_2^{11} (10 observed events)	0.021	0.050	0.12

values smaller (bigger) than 1, the resulting sensitivity of this channel is enhanced (reduced). In general, the process $\omega^{2/3} \rightarrow c\nu$ could add to the discovery prospects due to the large transverse momentum and missing energy of the signal. We leave the detailed exploration of this channel for future work.

We remark that a naïve extrapolation of the LHC limits to the HL-LHC with a target luminosity of 3 ab^{-1} closes completely the remaining parameter space for the $\omega^{2/3}$ that is compatible with an explanation of the $R_{D^{(*)}}$ anomaly. Thus, the R_2 could be discovered in both collider environments simultaneously, with the LHC proving its color charge, and the clean environment of the LHeC enabling a study of the other elements of the Yukawa coupling matrix through the less prominent branching fractions.

4 Conclusions

The R_2 Leptoquark, motivated by several theoretical frameworks, is not excluded by current LHC searches for masses around 1 TeV when it has several decay channels including the third generation fermions. Such a leptoquark can explain the $R_{D^{(*)}}$ anomaly in B-physics and it could be discovered

at the LHC. In this paper we investigated the possibility to test the R_2 at the LHeC via its resonance in the $b\tau$ final state, which does not have a parton level background in the SM.

We quantified the LHeC's sensitivity to the R_2 Yukawa coupling that parameterizes its interactions with the first generation fermions via a MC study. This study includes hadronization, a fast detector simulation, and conservative assumptions on the flavor tagging capabilities of the LHeC detector.

For our analysis we included a number of SM backgrounds. The dominant background is found to be the neutral current (NC) process $e^- p \rightarrow e^- j$ due to mis-tagging, and it can be well suppressed with simple kinematic cuts, for instance, on the invariant mass.

We find that the LHeC has a good discovery potential for R_2 couplings with the first generation larger than $\mathcal{O}(10^{-1} - 10^{-2})$ in the considered mass range, which is complementary to the LHC. Our results are conservative in the sense that additional decay channels for the R_2 would enlarge the viable parameter space for mass and couplings, and add further signal channels at the LHeC.

Acknowledgements OF and SJ are thankful for stimulating discussions at the 3rd FCC physics and experiments workshop at CERN.

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: All the data are completely included and properly cited in our article and we do not use or produce any external data. Given that this work is theoretical, no data is necessary.]

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Funded by SCOAP³.

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