Signatures of $\tilde{R}_2$ class of leptoquarks at the upcoming ep colliders

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We explore the signatures of the $\tilde{R}_2$ class of leptoquark (LQ) models at the proposed e^-p and e^+p colliders. We carry out an analysis for the proposed colliders, LHeC, and FCC-eh, with center of mass (c.m.) energy 1.3 TeV and 3.46 TeV, respectively. For $\tilde{R}_2$ class of LQ models, there are a number of final states that can arise from LQs production and their subsequent decays. In this report we do a detailed cut-based analysis for the $l^\pm j$ final state. We also discuss the effect of polarized electron and positron beams on LQ production and in turn on $l^\pm j$ production. At LHeC, the final state $l^+ j$ has a very good discovery prospect. We find that, with only 100 fb^{-1} of data, one can probe LQs of masses up to 1.2 TeV with 5σ significance, even with a generic set of cuts. On the contrary, at FCC-eh, one can probe LQ masses upto 2.2 TeV (for e^- beam) and 3 TeV (for e^+ beam), at more than 5σ significance with luminosity 1000 fb^{-1} and 500 fb^{-1} , respectively.

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I. INTRODUCTION

LQs are hypothetical particles which can emerge from the unification of quarks and leptons in the Pati-Salam model [1]. LQs also exist in grand unified theories based on $SU(5)$ [2] and $SO(10)$ [3–5]. TeV scale LQs can also exist in extended technicolor models [6–9]. Under the Standard Model (SM) representation, there are twelve types of LQs, six of them are scalar, while the other six are vector type of LQs [10]. We consider the scalar LQ $\tilde{R}_2$ charged as $(3, 2, 1/6)$ under SM gauge group. The advantage with $\tilde{R}_2$ type of scalar LQ is that in addition to the coupling with the lepton and jet, the model also has right handed (RH) neutrinos coupled to the LQ. Hence, this model provides unique signatures, that can be tested in different collider and noncollider experiments. Moreover, the $\tilde{R}_2$ also allows matter stability at tree level [11,12]. Discovery prospect of $\tilde{R}_2$ has been studied in dilepton final state at the LHC [13]. There have been several searches for other types of LQs. In Ref. [14], both single and pair production of scalar LQs (with $Q_{\text{EM}} = 1/3, 5/3$) have been studied with the decay

mode, $LQ \rightarrow tl$. This study shows that in the pair production channel, 5σ significance can be achieved at HL-LHC for LQ mass upto 1.7 TeV. When LQ couples to only left-handed leptons, 5σ reach can extend beyond 2 TeV. Pair production of LQs (S_3 and U_1) and their subsequent decay to $t\bar{t} + \cancel{E}_T$ has been studied in Ref. [15]. As stated in this search, a U_1 (S_3) LQ can be excluded with mass upto 1.96 TeV (1.54 TeV) or observed with mass upto 1.83 TeV (1.41 TeV), at HL-LHC. In Ref. [16], pair production LQs (S_3) and their decay to a $\mu\mu jj$ final state has been explored at future hadron colliders. The 5σ discovery sensitivity of HL-LHC have been estimated to be 1.9 TeV. In Ref. [17], a recast of heavy resonance search at LHC has been performed in the $\tau\tau$ and $\tau\nu$ channels. Also, the exclusion limit on the coupling of a scalar LQ (S_1 , which is motivated by the B-anomalies) as a function of its mass, has been placed. A review on other class of LQs, which are proposed to address B-anomalies has been presented in Ref. [18].

LQ's can be most easily tested at ep colliders. At ep colliders such as LHeC [19,20] and FCC-eh [20,21], LQs can be resonantly produced. LHeC and FCC-eh are the proposed ep colliders, planned to operate with c.m. energies $\sqrt{s} = 1.3 \text{ TeV}$ and $\sqrt{s} = 3.46 \text{ TeV}$, respectively. LHeC (FCC-eh) will use electron and possibly positron beams of 60 GeV, to collide with the 7 TeV (50 TeV) proton beam. There are numerous important phenomenological beyond the standard model studies for ep colliders which have been performed and listed in Ref. [22].

For the specific type of LQ model, that we consider in this paper, the LQ can decay to a lepton and a jet, as well as, to a jet and a RH neutrino. The decay of the LQ into a

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lepton and a jet, and the decay to a jet and RH neutrino with subsequent decays of RH neutrino give rise to many possible final states. In this work, we have studied in detail the final state $l^\pm j$. We have considered both the scenarios of electron and positron beams. We show that with judicious application of selection cuts, the final state $l^\pm j$ has very good discovery prospects at LHeC and FCC-eh colliders. We find that, we can probe the LQ mass up to 1.2 TeV at more than 5σ significance with e^+ beam at LHeC. For FCC-eh, we can easily probe LQ mass up to 2.2 TeV (3 TeV) with e^- (e^+) beams.

The paper is organized as follows: First we review the model and the existing constraints on LQs. Following this, we discuss the production of a LQ at an ep collider and compare with that at the LHC. In the subsequent sections, we present a detailed collider analysis and discuss the discovery prospects of the final state $l^\pm j$. Finally, we conclude.

II. MODEL

We consider an extension of the SM with a single scalar LQ, $\tilde{R}_2(3, 2, 1/6) = (\tilde{R}_2^{\frac{2}{3}}, \tilde{R}_2^{-\frac{1}{3}})^T$. This is a genuine LQ ($F = 3B + L = 0$). The superscript of $\tilde{R}_2$ denotes the electromagnetic (em) charge. In the presence of the RH neutrinos $N_R(1, 1, 0)$, the LQ has additional interaction [10,23–25],

$$\mathcal{L} = -Y_{ij}\bar{d}_R^i \tilde{R}_2^q e^{ab} L_L^{j,b} + Z_{ij}\bar{Q}_L^{i,a} \tilde{R}_2^q N_R^j + \text{H.c.}, \quad (1)$$

where $a, b = 1, 2$ are $SU(2)_L$ indices. Upon expansion, the Lagrangian becomes

$$\mathcal{L} = -Y_{ij}\bar{d}_R^i e_L^j \tilde{R}_2^{2/3} + (YU_{\text{PMNS}})_{ij}\bar{d}_R^i \nu_L^j \tilde{R}_2^{-1/3} + (V_{\text{CKM}}Z)_{ij}\bar{u}_L^i N_R^j \tilde{R}_2^{2/3} + Z_{ij}\bar{d}_L^i N_R^j \tilde{R}_2^{-1/3} + \text{H.c.}, \quad (2)$$

where $i, j = 1, 2, 3$ are flavor indices. Y and Z are the Yukawa couplings. U_{PMNS} and V_{CKM} represent the Pontecorvo-Maki-Nakagawa-Sakata and the Cabibbo-Kobayashi-Maskawa matrices. For simplicity, we assume that both the Yukawa couplings are diagonal, $Y_{ij} = \delta_{ij}Y_{ii}$ and $Z_{ij} = \delta_{ij}Z_{ij}$, where $i, j = 1, 2, 3$. Hence in our model a LQ couples to the same generation of lepton and quark. Although, most of the collider bounds on LQ mass and coupling are derived assuming that only one generation is present at a time, our model can have nonzero couplings of LQ to fermions of more than one generation. In the next section, we review the existing constraints on LQ mass and couplings.

III. CONSTRAINTS ON LQ MASS AND COUPLINGS

Tight constraints exist on $\tilde{R}_2$ type of scalar LQ's mass and coupling from both the collider experiments as well as

low energy experiments such as those searching for atomic parity violation and lepton flavor violating decays, $K_L \rightarrow \mu^- e^+$ etc. Below, we summarize present bounds on LQ mass and couplings.

A. Atomic parity violation

There are tight bounds on Yukawa couplings Y_{de} and Y_{ue} from atomic parity violation (APV) experiments, which have been explained in Refs. [26,27]. Following Ref. [26], the present bound on the coupling Y from atomic parity violation are $Y_{de} < 0.34 \frac{M_{\text{LQ}}}{1 \text{ TeV}}$ and $Y_{ue} < 0.36 \frac{M_{\text{LQ}}}{1 \text{ TeV}}$. Hence for larger LQ mass the allowed values of Yukawa couplings will also be large. Note that, these bounds are derived with the assumption that only one of the Yukawa coupling is present at a time.

B. $K_L \rightarrow \mu^- e^+$

The tree level lepton flavor violating (LFV) process $K_L \rightarrow \mu^- e^+$ gives tight constraints on the diagonal couplings of $\tilde{R}_2^2$. Specifically this tree level process constrains the product of Yukawa couplings $|Y_{s\mu}Y_{de}^*|$. Following Refs. [26,28], the experimental upper bound on the decay mode $K_L \rightarrow \mu^- e^+$ results in the bound on the product of Yukawas and is given by $|Y_{s\mu}Y_{de}^*| \leq 2.1 \times 10^{-5} \frac{M_{\text{LQ}}}{1 \text{ TeV}}$. Therefore, couplings of first two generations are tightly constrained.

C. Collider bounds

The present tightest collider bounds on LQs come from LHC [29–34]. LHC has specifically looked for the final states $pp \rightarrow \text{LQLQ} \rightarrow lj lj$ with the assumption that LQ decays to the final state lj with 100% branching ratio. LHC constrains first [34], second [30], and third generation [29] of LQs considering l to be e, μ , or τ . From the non-observation of any new physics at LHC, the LQs with mass up to 1.435 TeV have been ruled out for the first generation at 95% C.L. [34].

In Fig. 1, we have shown the Feynman diagrams for LQ pair production at LHC. For smaller values of Yukawa coupling Y , LQ pair production is dominated by the gluon-initiated diagrams, whereas for relatively larger Yukawa coupling Y , the t-channel quark-initiated diagram can dominate. In Fig. 2, we have shown present limit on scalar LQ pair-production times branching fraction to ej final state as a function of LQ mass. This bound corresponds to that from CMS experiment with $\sqrt{s} = 13 \text{ TeV}$ and integrated luminosity 35.9 fb^{-1} [34]. Black and red lines represent observed and expected limits. Note that, Ref. [34] also studies the $e\nu jj$ channel. For $\beta = 0.5$, using the $e\nu jj$ channel alone, LQ masses are excluded below 1.195 TeV. It also gives a limit on LQ mass combining both the channels $eejj$ and $e\nu jj$. In our analysis we have chosen

FIG. 1. Upper panel: Feynman diagram for the gluon-initiated LQ pair-production process at LHC. Lower panel: the same, but for the quark-initiated processes.

the values of Yukawa couplings and LQ mass according to this combined limit presented in Fig. 9 of Ref. [34].

Note that, assuming 100% branching ratio to ej final state (which implies $Z_{11} = 0$), bound on LQ mass is 1.435 TeV. If the branching ratio β to ej is less than 100% (which is of course possible if LQ has additional interactions such as $LQ-\nu j$, $LQ-jN_i$), the bound on LQ mass can be lowered. For example, to be consistent with

FIG. 2. Present limit on scalar LQ pair-production times branching fraction to $eejj$ final state as a function of mass for first generation LQs from CMS experiment with $\sqrt{s} = 13$ TeV and luminosity 35.9 fb^{-1} . The red and black lines are the expected and observed limits. The green line is the theory prediction.

TABLE I. Values of different model parameters used in the analysis for $M_{LQ} = 1$ TeV.

Benchmarks	M_{LQ}	M_{N_i}	Y	Z
BP ₁	1000	100	(0.34,0,0)	(1.03,0,0)

TABLE II. LQ mass, corresponding to the maximum allowed value of Y_{11} consistent with APV and lower bound on Z_{11} according to LHC constraint.

M_{LQ}	Y_{11}	Z_{11}
687	0.233	1.29
860	0.29	1.27
1000	0.34	1.03
1110	0.377	0.84
1204	0.41	0.65

LHC, flavour and APV constraints, for LQ mass of 1 TeV, one can choose the coupling $Y_{11} = 0.34$ and $Z_{11} = 1.03$. We have shown this benchmark BP₁ in Table I. For different LQ masses we have chosen different benchmark points consistent with all the existing constraints, which have been summarized in Table II.

In the next section, we discuss about the LQ production at colliders.

IV. LQ PRODUCTION

At an ep collider, scalar LQs can be resonantly produced through s-channel process, as shown in the upper panel of Fig. 3. LQs can also mediate t-channel process $ep \rightarrow lj$, as

FIG. 3. Feynman diagram for the lj production in e^-p collider.

FIG. 4. Single LQ production at LHC.

shown in the lower panel of Fig. 3. Single or pair production of LQs is also possible at pp colliders such as LHC. We have shown the Feynman diagrams for pair production and single production of LQs at LHC in Fig. 1 and Fig. 4, respectively. A comparison between production cross section of LQ at LHeC and LHC has been presented in the upper panel of Fig. 5. Here we have shown the cross section for single LQ production at LHeC, as well as both the single and pair production cross section at LHC, for various LQ masses. For this comparison, electron and proton beams are fixed at 60 GeV and 7 TeV, respectively. For LQ mass upto 1.2 TeV, the single LQ production at ep collider clearly dominates over the single and pair production of LQ at LHC. For LQ mass $M_{LQ} > 1.2$ TeV, single LQ production at LHC dominates. In the lower panel of Fig. 5, we have given the comparison of single LQ production at e^-p and e^+p colliders. For this comparison we have fixed the electron or positron beam at 60 GeV and for proton beam we have taken 7 TeV and 50 TeV. From this plot, it is evident that LQ production at e^+p collider is larger than that at the e^-p collider for the chosen mass range. This occurs as the $\frac{2}{3}$ charged LQ couples with $e^- - \bar{d}$ and $e^+ - d$, respectively and a quark parton distribution function is larger than that for antiquark.

We also compute the production cross section for the channel lj with both polarized and unpolarized electron and positron beams to show how much the cross sections differ. There is a relative enhancement in l^-j (l^+j) production cross sections at e^-p (e^+p) collider when the electron (positron) beam is dominantly left (right)-polarized. We have shown

FIG. 5. Upper panel: comparison of single LQ production at LHeC with respect to single or pair production of LQ at LHC. Lower panel: cross section for single LQ production at e^+p and e^-p collider for various proton beam energies. The electron or positron beam has been fixed at 60 GeV. In both these cases, the coupling Y_{de} has been varied as $0.34 \frac{M_{LQ}}{1 \text{ TeV}}$, in agreement with the APV constraints. For these plots we have considered $Z_{11} = 0$.

our results in Fig. 6 for both LHeC and FCC-eh case. We can see that the production rates improve by almost a factor of 2 over the entire range of the LQ mass in the case of polarized electron or positron beams. This enhancement occurs due to the couplings $e_L^- - \tilde{R}_2^{\frac{2}{3}} - \bar{d}$ and $e_R^+ - \tilde{R}_2^{\frac{2}{3}} - d$ at e^-p and e^+p colliders, respectively. Hence at e^-p and e^+p colliders, LQ predominantly couples with left polarized electron and right polarized positron, respectively.

In Fig. 7, we present a density plot which shows the variation of cross section for the process $e^-p \rightarrow l^-j$ with the variation of $\tilde{R}_2 - e - d$ coupling (Y_{11}) and mass of the LQ (M_{LQ}). Here the $\tilde{R}_2 - N_R - u$ coupling (Z_{11}) is fixed to 1.03 and mass of the right-handed neutrino (M_{N_1}) is assumed to be 100 GeV. The dashed curves represent the constraints on Y_{11} , for Z_{11} equal to 0.42, 0.62 and 1.03, from LHC search [34]. Region below each dashed curve is allowed for respective value of Z_{11} . Blue region in $Y_{11} - M_{LQ}$ plane is disallowed due to limit on Y_{11} from APV. Here we consider c.m. energy $\sqrt{s} = 1.3$ TeV. As we can see, a 700 GeV mass LQ is still allowed, for $Y_{11} = 0.238$

FIG. 6. Production cross section of l^-j (l^+j) with and without 80% left(right)- polarized electron (positron) beam. The dotted and solid lines represent the variation of production cross section with and without the polarized electron or positron beam. Upper panel is for LHeC and lower panel is for FCC-eh. In both these cases, the coupling Y_{de} has been varied as $0.34 \frac{M_{LQ}}{1 \text{ TeV}}$, in agreement with the APV constraints and we have fixed $Z_{11} = 0$.

and $Z_{11} = 1.03$. Finally, in the next section we present our analysis for the model signature $ep \rightarrow lj$.

V. ANALYSIS

We consider the process $e^\pm p \rightarrow l^\pm j$ as the signal. The dominant background for this process comes from the SM processes $e^\pm p \rightarrow l^\pm j, l^\pm jj$. The analysis is carried out with $\sqrt{s} = 1.3$ TeV of LHeC and $\sqrt{s} = 3.46$ TeV of FCC-eh. To simulate the signal samples, we implement the model in FeynRules(v2.3) [35]. The UFO output is then fed in MadGraph5_aMC@NLO(v2.6) [36] that generates the parton-level events. We perform parton showering and hadronization with PYTHIA6 [37] and carry out the detector simulations with DELPHES(v3.4.1) [38]. Finally data analysis and plotting is done in ROOT(v6.14/04) [39].

We apply the following basic cuts $p_T(l) > 10$ GeV, $p_T(j) > 20$ GeV, $|\eta(l)| < 5$, $|\eta(j)| < 5$, $\Delta R_{ll} > 0.4$, $\Delta R_{jj} > 0.4$, $\Delta R_{lj} > 0.4$ for event generation in MadGraph5.

Figs. 8 and 9 show the normalised distributions of different kinematical variables (transverse momentum of

FIG. 7. Variation of $\sigma(e^-p \rightarrow l^-j)$ in Y_{l1} - M_{LQ} plane. Blue region is disallowed from atomic parity violation. The upper region corresponding to each of the dashed ($Z_{11} = 0.42$), dotted ($Z_{11} = 0.62$), and dotted-dashed ($Z_{11} = 1.03$) line is disallowed from 13 TeV LHC search [34], where we consider the combined limit on branching ratio from [34]. The color bar indicates the cross section for $e^-p \rightarrow l^-j$ for 60 GeV electron and 7 TeV proton beam. We consider BP_1 for this plot.

the leading lepton, leading jet, as well as the invariant mass distribution of the leading jet and leading lepton) for LHeC and FCC-eh, respectively. We have shown these distributions for BP_1 . For LHeC and FCC-eh, the distributions of background sample are similar for both the e^- and e^+ case. For LHeC, the distributions of signal sample for e^- and e^+ beam are different. For e^- beam there are two peaks, one lies in the lower p_T region and the other in the higher p_T region. The peak lying in the lower p_T region corresponds to the off-shell production of LQ. For e^+ beam there is no second peak which implies that the off-shell production of LQ is less than that in case of e^- beam. This occurs since for e^-p (e^+p) collider, LQ couples to $e^- - \bar{d}$ ($e^+ - d$). The d quark carries greater fraction of proton momentum. From Fig. 9 it is evident that for FCC-eh there are no such differences between the use of e^- and e^+ beams due to availability of enough c.m. energy for LQ mass 1 TeV.

In Table III, we have shown the variation of signal and background cross sections after applying different selection cuts one by one at LHeC for BP_1 . Before applying any selection cuts, the signal and background cross sections for the channel $e^-p \rightarrow l^-j$ ($e^+p \rightarrow l^+j$) are 4.0164 fb (39.23 fb) and 2180 fb (1440 fb),¹ respectively. Note that due to the initial and final state radiations, additional jets

¹Note that, for the SM background, at the event generations level we impose two additional cuts on transverse momentum of leading lepton and jet, which are $p_T(l_1) > 200$ GeV and $p_T(j_1) > 200$ GeV to have better statistics as the SM background cross section is very large.

FIG. 8. Normalized distribution of transverse momentum of leading lepton $p_T(l_1)$, leading jet $p_T(j_1)$, invariant mass of leading lepton and jet $M(l_1 j_1)$ for both signal and background with c.m.energy $\sqrt{s} = 1.3$ TeV. Here the parameter set given in Table I is considered.

FIG. 9. Normalized distribution of transverse momentum of leading lepton $p_T(l_1)$, leading jet $p_T(j_1)$, invariant mass of leading lepton and jet $M(l_1 j_1)$ for both signal and background with c.m.energy $\sqrt{s} = 3.46$ TeV. Here the parameter set given in Table I is considered.

TABLE III. Signal ($e^\pm p \rightarrow l^\pm j$) and background cross sections after different selection cuts at LHeC for BP₁.

	$e^- p \rightarrow l^- j$		$e^+ p \rightarrow l^+ j$	
	σ^{sig} [fb]	σ^{bkg} [fb]	σ^{sig} [fb]	σ^{bkg} [fb]
Before cut	4.016	2180	39.23	1440
$c_1: N_j \geq 1 + N_l \geq 1$	3.01	1644	29.85	1079
$c_2: c_1 + p_T(l_1) \geq 400$	0.365	13.98	11.77	6.54
$c_3: c_2 + p_T(j_1) \geq 400$	0.275	9.51	8.92	4.48
$c_4: c_4$	0.25	5.13	8.3	2.534
$+ M_{LQ} - M_{lj} \leq 100$				
Significance for $\mathcal{L} = 1 \text{ fb}^{-1}$	0.107		2.5	

will be present in the final states considered. For signal selection we demand at least one lepton and one jet in the final state. Then we impose a cut on transverse momentum of leading jet and lepton, i.e., $p_T(j_1) \geq 400$ GeV and $p_T(l_1) \geq 400$ GeV. This significantly reduces the background cross section. Finally we select the signal events by demanding a window on lepton-jet invariant mass in between $M_{LQ} \pm 100$ GeV. After imposing all cuts the signal cross section for the channel $e^- p \rightarrow l^- j$ ($e^+ p \rightarrow l^+ j$) is reduced to one sixteenth (one fifth) of its initial value. Similarly Table IV represents the result for FCC-eh. We calculate the statistical significance using the expression: $S = \frac{s}{\sqrt{s+b}}$, where s and b are number of signal and background events after all cuts, respectively.

VI. RESULTS

We discuss the discovery prospects of LQs at LHeC and FCC-eh in the mass range 700 GeV–1200 GeV and 1 TeV–3 TeV, respectively. In the upper panel of Figs. 10 and 11, we have shown the signal cross section after all the cuts at LHeC and FCC-eh, respectively. In the lower panel of Fig. 10, we have shown the required luminosity ($\mathcal{L}$) to achieve 3σ and 5σ significance versus M_{LQ} for LHeC. Yukawa coupling Y_{11} has been fixed to its upper limit, $0.34 \frac{M_{LQ}}{1 \text{ TeV}}$ for a given M_{LQ} according to APV constraint. Z_{11} has been fixed to its lower limit for given M_{LQ} and Y_{11} , according to the upper bound from LHC search. For $M_{LQ} \geq 1 \text{ TeV}$, we use the same selection cuts as given in Table III. For $M_{LQ} < 1 \text{ TeV}$, we again apply the same set of cuts except the cuts c_2 and c_3 . Here cuts c_2 and c_3 are defined as $c_1 + p_T(l_1) \geq 300$ GeV and $c_2 + p_T(j_1) \geq 300$ GeV, respectively.

Similarly, Fig. 11 shows the variation of required luminosity ($\mathcal{L}$) to achieve 3σ and 5σ significance, as a function of M_{LQ} for FCC-eh. For $M_{LQ} < 2 \text{ TeV}$, we use same selection cuts as given in Table IV. For $M_{LQ} \geq 2 \text{ TeV}$, we define c_2 and c_3 as $c_1 + p_T(l_1) \geq 800$ GeV and $c_2 + p_T(j_1) \geq 800$ GeV, respectively.

TABLE IV. Signal ($e^\pm p \rightarrow l^\pm j$) and background cross sections after different selection cuts at FCC-eh for BP₁.

	$e^- p \rightarrow l^- j$		$e^+ p \rightarrow l^+ j$	
	σ^{sig} [fb]	σ^{bkg} [fb]	σ^{sig} [fb]	σ^{bkg} [fb]
Before cut	395.08	10900	1246.4	9597
$c_1: N_j \geq 1 + N_l \geq 1$	354.41	9836.93	1119.03	8652.58
$c_2: c_1 + p_T(l_1) \geq 400$	180	839.141	578.13	611.459
$c_3: c_2 + p_T(j_1) \geq 400$	129.97	618.963	417.26	441.812
$c_4: c_3$	119.9	141.112	383.59	90.279
$+ M_{LQ} - M_{lj} \leq 100$				
Significance for $\mathcal{L} = 1 \text{ fb}^{-1}$	7.42		17.6

FIG. 10. Upper panel: Signal cross section after cut. Lower panel: Required luminosity to reach 3σ and 5σ significance versus mass of the LQ with c.m.energy 1.3 TeV. Since at LHeC c.m.energy is low to get a better signal cross section we use the optimum values of the couplings for a given LQ mass, which are given in Table II.

FIG. 11. Upper panel: Signal cross section after cut. Lower panel: Required gs for all LQ masses as given in Table I for $M_{LQ} = 1 \text{ TeV}$.

We find that, this final state has reasonably good discovery prospect even after giving a generic set of cuts. For LHeC with e^- beam, its difficult to probe LQ due to small cross section. From the lower panel of Fig. 10, it is evident that to probe higher LQ masses with 5σ significance, the required luminosity is very high in spite of smaller SM background, as the signal cross section is itself small for higher LQ masses. On the contrary, for LHeC with e^+ beam, due to larger signal cross sections, it is possible to probe the LQ mass upto 1.2 TeV at more than 5σ significance with integrated luminosity less than 100 fb^{-1} .

For FCC-eh, even with e^- beam, we can probe LQ mass up to 2.3 TeV at more than 5σ significance with integrated

luminosity less than 1000 fb^{-1} . For higher LQ masses, the required luminosity to probe with 5σ significance increases quickly. For the case of e^+ beam, due to enhanced cross section we can very easily probe the LQ mass up to 3 TeV at more than 5σ significance with integrated luminosity less than 500 fb^{-1} . Note that, the production cross section of $\tilde{R}_2$ at the ep colliders and its decay vary with respect to the Yukawa couplings (Y_{11} and Z_{11}). Therefore, the discovery reach of LHeC and FCC-eh presented in this analysis depend on the chosen values of Yukawa couplings. Several studies have been carried out to predict the discovery prospect of other types of LQs at HL-LHC. The studies [14,16] shows that, scalar LQs of masses upto 2 TeV can be discovered at HL-LHC.

Finally, we would like to point out that as with the polarized electron or positron beams, lj production cross sections are enhanced by almost a factor of two, we can probe even higher LQ masses compared to the case of unpolarized beams. We evaluate the asymmetry between the production cross section of LQ at e^+p and e^-p colliders, which is defined as $\mathcal{A}_{ep} = \frac{\sigma(e^+p) - \sigma(e^-p)}{\sigma(e^+p) + \sigma(e^-p)}$. It is found to be positive (which is evident from the upper panel of Figs. 10 and 11), consistent with the fermion number of $\tilde{R}_2$ LQ.

VII. CONCLUSIONS

In this work we study the discovery prospect of $\tilde{R}_2$ class of LQ models at the proposed ep colliders such as LHeC and FCC-eh. This type of LQ can be copiously produced at ep colliders, due to its interaction with the electron and down type quarks. There are many possible final states for this type of LQ model. We specifically focus on LQ production and its decay to a lepton and a jet. For this final state, we expect higher statistical significance at an ep collider compared to pp collider due to higher production cross section as well as lower SM backgrounds. We find that at LHeC with e^+ beam, we can probe the LQ mass upto 1.2 TeV at more than 5σ significance. For FCC-eh, with e^- beam we can probe LQ mass upto 3 TeV with 5σ significance, but the required luminosity is large. On the contrary, at FCC-eh with e^+ beam, we can easily probe the LQ mass up to 3 TeV at more than 5σ significance with nominal integrated luminosity. Note that at an ep collider, polarization of the electron or positron beams can result in a substantial increase in the LQ production and the resulting lepton-jet production cross sections.

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