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Coloron-assisted leptoquarks at the LHC

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ABSTRACT

Recent searches for a first-generation leptoquark by the CMS collaboration have shown around 2.5σ deviations from Standard Model predictions in both the $eejj$ and $e\nu jj$ channels. Furthermore, the $eejj$ invariant mass distribution has another 2.8σ excess from the CMS right-handed W plus heavy neutrino search. We point out that additional leptoquark production from a heavy coloron decay can provide a good explanation for all three excesses. The coloron has a mass around 2.1 TeV and the leptoquark mass can vary from 550 GeV to 650 GeV. A key prediction of this model is an edge in the total m_T distribution of $e\nu jj$ events at around 2.1 TeV.

1. Introduction

Leptoquarks have long been predicted by grand unification models such as the Pati–Salam model [1]. These models can explain the non-trivial structure of the Standard Model (SM). On the other hand, the solutions to the "gauge hierarchy problem" generically requires new physics beyond the SM at the TeV scale. The Randall–Sundrum (RS) model uses a warped extra-dimension to naturally generate an exponential hierarchy between the electroweak and the Planck scales [2]. One of the predictions of the RS model is Kaluza–Klein (KK) modes including a KK-gluon with TeV-scale masses. Implementing the Pati–Salam model in warped extra-dimension setup can provide a realistic unified model without a hierarchy problem. This class of models predicts both leptoquarks and KK-gluon as well as their interactions [3]. Following the spirit of deconstruction of extra dimensions [4,5], we study the phenomenology of a simple two-site model with interactions between a coloron (or KK-gluon) and leptoquarks, demonstrating non-trivial correlations for searches at the Large Hadron Collider (LHC).

Recently, first-generation leptoquark searches [6] and right-handed W gauge boson plus a heavy neutrino searches [7] from the CMS collaboration have both shown interesting deviations from the SM predictions in recent analyzes. In this paper, we also explore these excesses and point out that they may be explained by a coloron plus leptoquark scenario.

In the first-generation leptoquark searches, the CMS has studied 19.6 fb^{-1} integrated luminosity of data at the 8 TeV LHC. A first-generation leptoquark [1,8], S_1 (in the notation of Ref. [9]), can have two different decay channels, $S_1 \to e^+\bar{u}$ and $S_1 \to \nu_e\bar{d}$. After they are pair-produced at the LHC via QCD interactions, the final states at colliders are $eejj$, $e\nu jj$ and $\nu\nu jj$. The former two channels have been searched for and are reported to deviate from the SM at 2.4σ and 2.6σ respectively after imposing kinematic cuts to optimize a 650 GeV leptoquark [6]. For the $eejj$ channel, in addition to basic pre-selection, additional cuts are imposed on the scalar sum of the p_T of the two electrons and the two leading jets, S_T, the invariant mass of the two electrons, m_{ee} and the minimum of electron-jet invariant mass of the two leptoquark candidates after choosing the combination with the smaller difference between the two electron-jet masses, m_{ej}^{min}. The cuts optimized for a 650 GeV leptoquark are $S_T > 850$ GeV, $m_{ee} > 155$ GeV and $m_{ej}^{min} > 360$ GeV, for which there are 36 observed events with $20.49 \pm 2.14 \pm 2.45\,(\text{syst})$ expected background events, which amounts to a 2.4σ deviation from the SM prediction. In the $e\nu jj$ channel, the missing transverse energy in the event, E_T^{miss}, and the electron–neutrino transverse mass, $m_{T,e\nu}$, are also used to select events. After imposing the cuts, $S_T > 1040$ GeV, $E_T^{miss} > 145$ GeV, $m_{ej} > 555$ GeV and $m_{T,e\nu} > 270$ GeV, there are 18 observed events in contrast to of $7.54 \pm 1.20 \pm 1.07\,(\text{syst})$ expected background events, representing a 2.6σ excess over the SM prediction.

In the $W_R^\pm$ plus a heavy neutrino N_e search with 19.7 fb^{-1} integrated luminosity at the 8 TeV LHC, a similar final state $eejj$ has been used to probe $pp \to W_R \to eN_e \to eejj$. The signal selection cuts differ from the cuts in the previous leptoquark searches. The cuts (beyond pre-section) include $m_{ee} > 200$ GeV and $m_{eejj} >$

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600 GeV [7]. The invariant mass distribution of $m_{\rm eejj}$ shows an excess at around 2 TeV. For the bin from 1.8 TeV to 2.2 TeV, around 14 events have been observed with approximately 4.0 expected background events. Keeping only the statistical uncertainty, this amounts to 2.8σ local excess from the SM prediction [7].

Since the intriguing excesses in the $eejj$ channel happen in both leptoquark and $W_R + N_e$ searches, the immediate question is whether both excesses can be explained by the same model. The $W_R + N_e$ model cannot produce significant $e\nu jj$ events, so we restrict ourselves to models producing two leptoquarks from a combination of QCD and resonant production channels. We will later comment on models with an event topology similar to the $W_R + N_e$ model.

Before introducing a detailed model and fitting to the data, we introduce a few order of magnitude estimates regarding the data. For the leptoquark search, we consider the QCD-produced leptoquark model and use it to give a rough sense of the excess, though other signal models generally only have comparable acceptances at the order of magnitude level. The NLO QCD production cross-section for a 650 GeV leptoquark is 13.2 fb [10]. From Table 4 and Table 5 of Ref. [6], the leptoquark model predicts 125.85 and 37.22 events in the $eejj$ and $e\nu jj$ channels after the final selection cuts, implying 48.6% and 28.8% signal acceptances, respectively. Within the leptoquark model, one therefore obtains $\sigma(pp \to eejj) \sim 1.6$ fb for the $eejj$ channel and $\sigma(pp \to e\nu jj) \sim 1.9$ fb. The acceptance in the $W_R + N_e$ search is roughly independent of the chain leading to the $eejj$ final state and indicates a production cross-section of $\sigma(pp \to \text{resonance} \to eejj) \sim 1$ fb, though this can include a contribution from non-resonant production. The similarity of these cross-sections points to a common origin for all three excesses, as well as electroweak symmetry relations between the electron and neutrino signatures. We explore both of these possibilities in greater detail in this paper.

The remainder of this paper is structured as follows. We begin by introducing a coloron model that can be consistent with all current data. We then fit this model to the current excesses. Given the model details, we make several predictions for follow up searches. We conclude by briefly discussing some alternatives and their distinguishing features.

2. Coloron-assisted leptoquark model

Noting the approximately equal excesses in the $eejj$ and $e\nu jj$ channels, we consider a scalar leptoquark with $(\bar{3}, 1)_{1/3}$ under the SM gauge group. Following the notation in Ref. [9], we have the interaction of

$$g_{1L}^{ij} \bar{q}_L^{c\,i}\, i\tau_2\, \ell_L^j\, S_1 \,. \tag{1}$$

For the flavor assumption $g_{1L}^{ij} \approx g_{1L}^i \delta^{ij}$ with $g_{1L}^1 > g_{1L}^2, g_{1L}^3$, the S_1 mainly couples to the first-generation quarks and leptons. Because the $SU(2)_W$ symmetry, the leptoquark could decay into ej and $\nu_e j$ with equal branching ratios. Other operators like $\bar{u}_R^c e_R S_1$ may break this branching ratio relation.

One simple extension of the leptoquark model which includes resonant production is to introduce a coloron, which is a massive color-octet gauge boson [11–16]. A diagram for the resonant leptoquark production mode is shown in Fig. 1. For a simple two-site model with $SU(3)_1 \times SU(3)_2 \to SU(3)_c$ from a Higgs mechanism, we have the massless gluon $G_\mu = \cos\theta\, G_{1\,\mu} + \sin\theta\, G_{2\,\mu}$ and the massive coloron $G'_\mu = -\sin\theta\, G_{1\,\mu} + \cos\theta\, G_{2\,\mu}$. The two gauge couplings satisfy $h_1 \cos\theta = g_s$ and $h_2 \sin\theta = g_s$ as well as $h_1/h_2 = \tan\theta$. In this paper, we will ignore other potential color-octet scalars in the renormalizable coloron model (see Ref. [17–19] for recent studies). All the SM quarks couple to site number one, so one has the coupling of G' to quarks

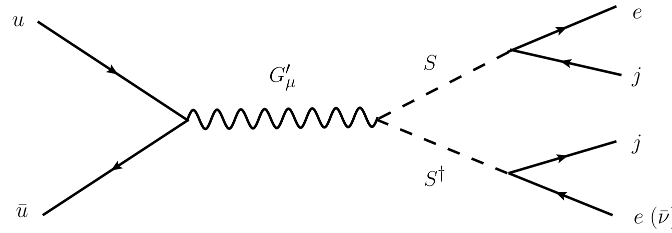

Fig. 1. Feynman diagram of the full process of resonant production of leptoquarks and subsequent decay into the $eejj$ ($e\nu jj$) final state.

$$g_s \tan\theta\, \bar{q}\, \gamma^\mu\, T^a\, G'^a_\mu\, q \,. \tag{2}$$

Depending on the site at which the leptoquark couples, one can have

$$i\, g_{S_1}\, g_s\, G'^a_\mu \left[S_1 T^a \partial^\mu S_1^\dagger - (\partial^\mu S_1) T^a S_1^\dagger \right] , \tag{3}$$

with $g_{S_1} = \xi/\tan\theta$ for generalized to a multi-site model and S_1 allowed to sit on a site beyond the two sites of G'. For S_1 just coupling to site number two, one has $\xi = 1.0$. We will not consider the case with S_1 sitting on the site number one as it cannot provide a sufficient signal cross section to be an explanation for the observed excess.

In this class of models, there is no coupling of the form GGG' generated at the renormalizable level. There is an accidental Z_2 symmetry within the gauge boson sector that exchanges $SU(3)_1$ and $SU(3)_2$. After the breaking of the two $SU(3)$ symmetries into color symmetry, this symmetry manifests as a residual Z_2 symmetry under which G' is odd, but G is even. Resonant production via a gluon initial state is only generated by non-renormalizable operators and is therefore neglected.

The coloron can decay into quarks as well as leptoquarks. The partial decay widths of G' into the five light flavors, $t\bar{t}$ and leptoquarks are given by

$$\Gamma(G' \to jj) = \frac{5\,\alpha_s}{6} \tan^2\theta\, M_{G'} \,, \tag{4}$$

$$\Gamma(G' \to t\bar{t}) = \frac{\alpha_s}{6} \tan^2\theta\, M_{G'} \left(1 + \frac{2m_t^2}{M_{G'}^2}\right) \left(1 - \frac{4m_t^2}{M_{G'}^2}\right)^{1/2} , \tag{5}$$

$$\Gamma(G' \to S_1 S_1^\dagger) = \frac{g_{S_1}^2\, \alpha_s}{24} M_{G'} \left(1 - \frac{4M_{S_1}^2}{M_{G'}^2}\right)^{3/2} . \tag{6}$$

For the production of G', we can use the narrow width approximation (for $0.15 < \tan\theta < 1/\sqrt{2}$, $\Gamma_{G'}/M_{G'} < 0.1$) to estimate the production cross section for producing a G' in the s-channel:

$$\sigma(q\bar{q} \to G') \approx \frac{8\pi^2\, \alpha_s\, \tan^2\theta}{9\, M_{G'}} \delta\left(\sqrt{\hat{s}} - M_{G'}\right) . \tag{7}$$

At the 8 TeV LHC and for $M_{G'} = 2.1$ TeV (the location of the most significant excess in the $eejj$ invariant mass distribution [7]), the production cross section is $\sigma(pp \to G') \approx 1780 \times \tan^2\theta$ fb. Using the MSTW [21] PDFs as well as the calculated branching ratios, we show $S_1 S_1^\dagger$ and jj production cross sections from G' in Fig. 2. In the same plot, we also show the current constraints from dijet narrow resonance searches from CMS with 19.6 fb^{-1} data. For the model with $\xi = 1.0$ and $M_{S_1} = 550$ GeV the dijet has a constraint of $\tan\theta < 0.32$, while for the model with $\xi = 0.15$ and $M_{S_1} = 650$ GeV the dijet has a constraint of $\tan\theta < 0.19$ (see also

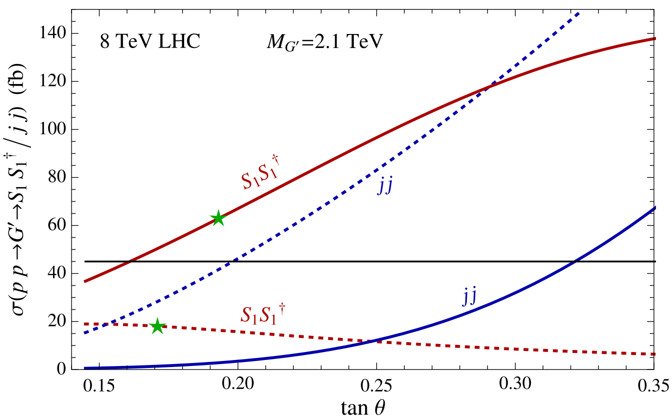

Fig. 2. The production cross sections of coloron times its various decay branching ratios. The solid lines have $M_{S_1} = 550$ GeV with $\xi = 1.0$, while the dotted lines have $M_{S_1} = 650$ GeV with $\xi = 0.15$. The black and horizontal line is the constraint from the narrow dijet resonance searches [20]. The two green five-pointed stars are the benchmark model points to fit the data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

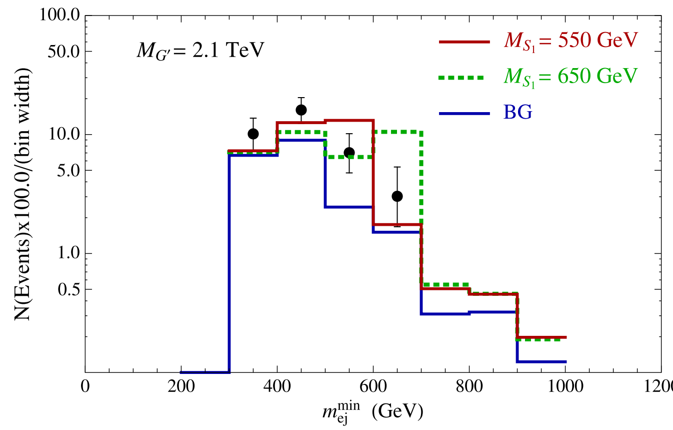

Fig. 3. A comparison of the data and the signal plus background m_{ej}^{min} distributions from the leptoquark search in the *eejj* final state. The fitted results in Eq. (8) and Eq. (9) are used for two benchmark leptoquark masses. The data and the SM background are taken from [6].

Table 1
The acceptances for two benchmark leptoquark masses, for the three different searches, and for QCD and coloron-mediated productions. For the leptoquark searches, the acceptances are for the final selection of the cuts optimized for a 650 GeV leptoquark [6]. For the $W_R + N_e$ search, the acceptance is for the selected events to have 1.8 TeV $< m_{eejj} <$ 2.2 TeV [7].

LQ mass	Production	LQ *eejj*	LQ *νejj*	$W_R + N_e$
550 (GeV)	QCD	0.45	0.08	0.04
	Coloron (2.1 TeV)	0.60	0.18	0.55
650 (GeV)	QCD	0.49	0.29	0.08
	Coloron (2.1 TeV)	0.64	0.45	0.58

Ref. [22] for more constraints on other coloron masses without a leptoquark). The current $t\bar{t}$ resonance searches [23] are not sensitive enough to constrain the model parameters in Fig. 2.

3. Fit to data

We parametrize the model first with three phenomenological parameters, $\sigma_{SG} \equiv \sigma(pp \to G' \to S_1 S_1^\dagger)$, $\mathrm{Br}_{ej} \equiv \mathrm{Br}(S_1 \to ej)$ and $\mathrm{Br}_{\nu j} \equiv \mathrm{Br}(S_1 \to \nu j)$ to fit the three excesses. The signal acceptances for cases not studied in [6] are estimated by implementing the coloron model in `FeynRules` [24], generating events at LO using `MadGraph` [25], showering and hadronizing using `Pythia` [26], and simulating the detector using `PGS` [27]. The selection cuts as outlined in [6] and [7] are applied to the `PGS` events and the signal acceptance is extracted. This procedure was validated by comparing the $Z +$jets prediction obtained in by this prediction with that presented in [6]. Agreement is found at the 10% level. The acceptances for two benchmark leptoquark masses are shown in Table 1. The acceptances are for the final selection cuts optimized for a 650 GeV leptoquark in the leptoquark searches and for selected events falling in the 1.8 TeV $< m_{eejj} <$ 2.2 TeV bin in the $W_R + N_e$ search. Since there are three searches and three parameters in this procedure, we solve for optimal parameters that fit the central values of the excesses under the acceptances we calculated. Taking the coloron mass to be fixed at 2.1 TeV, we find parameters

$$\sigma_{SG} = 63.0\ \text{fb}\,, \quad \mathrm{Br}_{ej} = 0.12\,, \quad \mathrm{Br}_{\nu j} = 0.15\,, \tag{8}$$

for a leptoquark mass of 550 GeV and

$$\sigma_{SG} = 17.8\ \text{fb}\,, \quad \mathrm{Br}_{ej} = 0.21\,, \quad \mathrm{Br}_{\nu j} = 0.13\,, \tag{9}$$

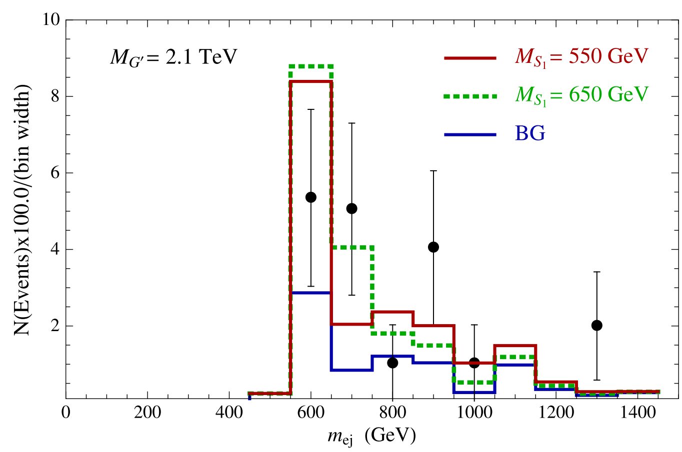

Fig. 4. The same as Fig. 3 but in terms of m_{ej} in the $e\nu jj$ channel of the leptoquark search.

for a leptoquark mass of 650 GeV. A χ^2 fit shows that the model with leptoquark mass 550 GeV is consistent with $\mathrm{Br}_{ej} = \mathrm{Br}_{\nu j}$, while the model with leptoquark 650 GeV is consistent with $\mathrm{Br}_{ej} = 2\,\mathrm{Br}_{\nu j}$. Either scenario is a plausible result of electroweak symmetry. In terms of the parameter $\tan\theta$ and from Fig. 2, the required production cross sections can match to $\tan\theta = 0.19$ and $\tan\theta = 0.17$ for $M_{S_1} = 550$ GeV and $M_{S_1} = 650$ GeV, respectively.

Although we only use the total excess numbers of events to fit our model, we also show the m_{ej}^{min} distribution in the *eejj* final state of the leptoquark search in Fig. 3, the m_{ej} distribution in the $e\nu jj$ final state of the leptoquark search in Fig. 4 and the m_{eejj} distribution in the $W_R + N_e$ search in Fig. 5. Comparing fitted results with two different leptoquark masses, one can see that the current data does not have enough statistics to constraint the leptoquark mass. The two models, however, both provide a better fit to the data. Though we do not have sufficient information about systematic uncertainties to do a complete goodness-of-fit test, we do find that the Poisson likelihood for the model points tested to yield the observed distributions in Figs. 3–5 is higher. This test indicates that our two model points improve the fit at a distribution level, as well as at the level of counts in the searches that see an excess. The Poisson likelihoods for the two models, as well as the SM, to yield the data as shown in Table 2.

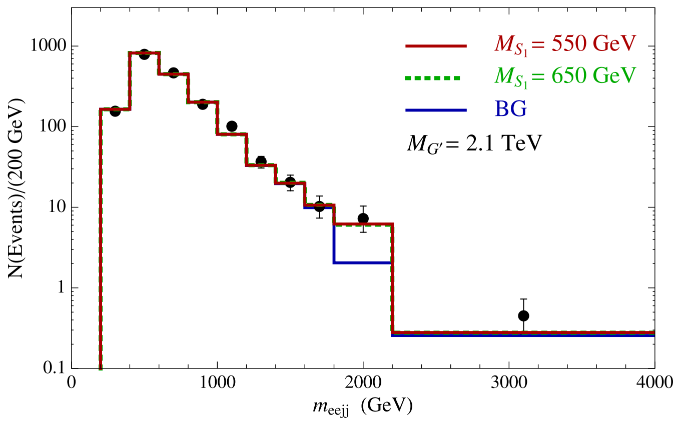

Fig. 5. The same as Fig. 3 but in terms of $m_{\rm eejj}$ after imposing cuts used in the $W_R + N_e$ search. The data and the SM background are taken from [7].

Table 2
The value of $-2\log L$ for the SM and the two leptoquark + coloron models to yield the observed data in the $m_{\rm ej}$ and $m_{\rm eejj}$ distributions, assuming all the bins are uncorrelated and neglecting unknown bin-by-bin systematic uncertainties. All signal models include a 2.1 TeV coloron.

Leptoquark search, $eejj$ final state, $m_{\rm ej}^{\rm min}$ distribution	
SM	27.96
550 GeV LQ	21.75
650 GeV LQ	26.94
Leptoquark search, $e\nu jj$ final state, $m_{\rm ej}$ distribution	
SM	40.49
550 GeV LQ	28.32
650 GeV LQ	27.59
W_R search, $m_{\rm eejj}$ distribution	
SM	73.42
550 GeV LQ	66.74
650 GeV LQ	66.62

4. Predictions and further searches

These results have several implications for further searches, which we now briefly outline. Most obviously, the ATLAS experiment should be sensitive to any excesses in all three channels studied here. In addition, assuming the best fit coloron model, ATLAS and CMS should see the following signatures:

- A bump in the $e\nu jj$ invariant mass distribution. Assuming a leptoquark mass, one can reconstruct events in this channel. If one cannot determine the leptoquark mass, one should still see an edge at ~ 2.1 TeV in the m_T (constructed by summing the three visible particle transverse momenta and missing transverse momentum) distribution;
- A dijet + MET ($\nu\nu jj$) cross-section of $\sim 0.5 - 2.4$ fb depending on the scenarios. The current limit on this signature is 17 fb and 32 fb in the two scenarios respectively [28], assuming the coloron production channel has the same acceptance as a squark. This assumption is likely badly violated due to the harder objects in coloron events;
- A dijet (or $t\bar{t}$) resonance with a mass 2.1 TeV with $\sigma \times {\rm Br} \sim 1 - 20$ fb, again depending on the leptoquark mass scenarios.

The current searches can be improved to confirm our coloron + leptoquark model. For example, one can find a bump in the invariant mass distribution of $e + j$ pairs selected from events in the 2.1 TeV peak of the $W_R + N_e$ search. Additionally, events coming from a resonance typically have a larger S_T, so a tighter S_T cut would enhance the signature of any resonant production model in any of the channels.

The above predictions are a required consequence of any incarnation of the coloron model. There are, however, other possible signatures that are more dependent on the detailed structure of the model. Most importantly, there must be other decay modes for the leptoquark, as the listed branching fractions in Eqs. (8) and (9) to first generation leptons do not add up to 100%. Depending on the flavor model, the leptoquark can also decay into other generations of leptons and quarks, for instance $S_1 \to \tau^+\bar{t}, \nu_\tau\bar{b}$, which currently has less stringent limits [29,30]. Simply due to the leptoquark quantum numbers, other possibilities are restricted. The simplest ones include baryon-number violating couplings or additional j + MET channels with the MET from a pair of dark matter particles. The former are constrained by the absence of proton decay, while the later has no stringent constraints so far and will be probed by the dijet + MET search. More exotic channels are also possible, including cascades to additional jets, but all final states will include jets along with possible leptons and/or MET.

One final possibility hinted at by the data is that the leptoquark decay branching ratios to electrons and neutrinos may be the same, indicating a coupling only to the left-handed leptons. To fully assess this possibility, one requires a more precise determination of the masses.

5. Discussion and conclusions

The coloron plus leptoquark model is one well-motivated possible explanation for the observed excess, but other models may also fit the data and have qualitatively different additional signatures. For example, a model with the decay topology of the $W_R + N_e$ model studied in [7] can capture the quantitative features of the $eejj$ data presented in [6] at the level of current uncertainties. In fact, our simulated results of the $W_R + N_e$ model show a broad peak structure in $m_{\rm ej}^{\rm min}$ after the selection cuts of the leptoquark search [6]. There could exist other event topologies to provide the similar signatures (see Ref. [31] for more event topologies). A similar model that added an $e\nu jj$ decay mode could account for the data in that channel as well. The construction of a specific model with this topology is beyond the scope of this work. Nevertheless, this quasi-degeneracy should be probed further by examining the various possible resonant combinations of the final state particles ($\ell\ell$, jj, ℓjj and $\ell\ell j$, as well as the leptoquark combination).

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.physletb.2015.04.046.

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