Coloron-assisted Leptoquarks at the LHC

Yang Bai\textsuperscript{a} and Joshua Berger\textsuperscript{b}

\textsuperscript{a} Department of Physics, University of Wisconsin, Madison, WI 53706, USA
\textsuperscript{b} SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA

Recent searches for a first-generation leptoquark by the CMS collaboration have shown around 2.5\sigma deviations from Standard Model predictions in both the eejj and evjj channels. Furthermore, the eejj invariant mass distribution has another 2.8\sigma 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 evjj events at around 2.1 TeV.

PACS numbers: 12.60.-i,14.80.Sv

\textbf{Introduction.} First-generation leptoquark searches \cite{1} and right-handed W gauge boson plus a heavy neutrino searches \cite{2} from the CMS collaboration have both shown interesting deviations from the Standard Model (SM) predictions in recent analyses. In this paper, we explore these excesses and develop a potential new physics model that can explain them.

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 \cite{3,4}, \( S_1 \) (in the notation of Ref. \cite{5}), can have two different decay channels, \( S_1 \rightarrow e^+\bar{u} \) and \( S_1 \rightarrow \nu_e d \). After they are pair-produced at the LHC via QCD interactions, the final states at colliders are eejj, evjj and \( \nu\nujj \). The former two channels have been searched for and are reported to deviate from the SM at 2.4\( \sigma \) and 2.6\( \sigma \) respectively after imposing kinematic cuts to optimize a 650 GeV leptoquark \cite{1}. 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, \( m_{ejmin} \). The cuts optimized for a 650 GeV leptoquark are \( S_T > 850 \) GeV, \( m_{ee} > 155 \) GeV and \( m_{ejmin} > 360 \) GeV, for which there are 36 observed events with \( 20.49 \pm 2.14 \pm 2.45 \) (syst) expected background events, which amounts to a 2.4\( \sigma \) deviation from the SM prediction. In the evjj channel, the missing transverse energy in the event, \( E_T^{miss} \), and the electron-neutrino transverse mass, \( m_{T,\nu\nu} \), are also used to select events. After imposing the cuts, \( S_T > 1040 \) GeV, \( E_T^{miss} > 145 \) GeV, \( m_{ej} > 555 \) GeV and \( m_{T,\nu\nu} > 270 \) GeV, there are 18 observed events in contrast to of \( 7.54 \pm 1.20 \pm 1.07 \) (syst) expected background events, representing a 2.6\( \sigma \) excess over the SM prediction.

In the \( W_R^+ \) 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 \( pp \rightarrow W_R \rightarrow eN_e \rightarrow eejj \). The signal selection cuts differ from the cuts in the previous leptoquark searches. The cuts (beyond pre-section) include \( m_{ee} > 200 \) GeV and \( m_{eejj} > 600 \) GeV \cite{2}. The invariant mass distribution of \( m_{eejj} \) 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 2.8\( \sigma \) local excess from the SM prediction \cite{2}.

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 evjj 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 \cite{6}. From Table 4 and Table 5 of Ref. \cite{1}, the leptoquark model predicts 125.85 and 37.22 events in the eejj and evjj channels after the final selection cuts, implying 48.6\% and 28.8\% signal acceptances, respectively. Within the leptoquark model, one therefore obtains \( \sigma(pp \rightarrow eejj) \sim 1.6 \) fb for the eejj channel and \( \sigma(pp \rightarrow evjj) \sim 1.9 \) 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 \( \sigma(pp \rightarrow resonance \rightarrow eejj) \sim 1 \) 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.

**Coloron-assisted Leptoquark Model.** Noting the approximately equal excesses in the $eejj$ and $e\nu jj$ channels, we consider a scalar leptoquark with $(3, 1)_{1/3}$ under the SM gauge group. Following the notation in Ref. [5], we have the interaction of

$$g_{ij}^q g_{ij}^q i\tau_2 \ell_L^i S_1. \quad (1)$$

For the flavor assumption $g_{ij}^q \approx g_{ij}^q \delta_{ij}$ with $g_{1i}^q > g_{2i}^q$, 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 $\nu_j$ with equal branching ratios. Other operators like $\bar{u}^i_R e e R \bar{S}_1$ 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 [7–10]. 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 $G_\mu = \cos \theta G_1 + \sin \theta G_2$, and the massive coloron $G_\mu' = -\sin \theta G_1 + \cos \theta G_2$. 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. [11–13 for recent studies). All the SM quarks couple to site number one, so one has the coupling of $G'$ to quarks

$$g_s \tan \theta \bar{q} \gamma^\mu T^a G_\mu' q. \quad (2)$$

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

$$i g_{S1} g_s G_\mu' \left[ S_1 T^a \partial^\mu S_1' - (\partial^\mu S_1) T^a S_1' \right], \quad (3)$$

with $g_{S1} = \xi/\tan \theta$ for generalized to a multi-site model and $S_1$ allowed to sit on 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.

The coloron can decay into quarks as well as leptoquarks. The partial decay widths of $G'$ into the five light flavors, $tt$, and leptoquarks are given by

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

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

$$\Gamma(G' \to S_1 S_1') = \frac{g_{S1}^2 \alpha_s}{24} \frac{M_{G'}}{M_{G'}} \left( 1 - \frac{4M_{S1}}{M_{G'}} \right)^{3/2}. \quad (6)$$

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:

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

![FIG. 1. The production cross sections of coloron times its various decay branching ratios. The solid lines have $M_{S1} = 550$ GeV with $\xi = 1.0$, while the dotted lines have $M_{S1} = 650$ GeV with $\xi = 0.15$. The black and horizontal line is the constraint from the narrow dijet resonance searches [11]. The two green five-pointed stars are the benchmark model points to fit the data.](image)

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 [2]), the production cross section is $\sigma(pp \to G') \approx 1780 \times \tan^2 \theta \, \text{fb}$. Using the MSTW [13] PDFs as well as the calculated branching ratios, we show $S_1 S_1'$ and $jj$ production cross sections from $G'$ in Fig. 1. 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 $M_{S1} = 550$ GeV the dijet has a constraint of $\tan \theta < 0.32$, while for the model with $\xi = 0.15$ and $M_{S1} = 650$ GeV the dijet has a constraint of $\tan \theta < 0.19$ (see also Ref. [10] for more constraints on other coloron masses without a leptoquark). The current $t\bar{t}$ resonance searches [17] are not sensitive enough to constrain the model parameters $\xi$.

**Fit to Data.** We parameterize the model first with three phenomenological parameters, $\sigma_{SC2} \equiv \sigma(pp \rightarrow G' \rightarrow S_1 S_1')$, $Br_{ej} \equiv Br(S_1 \rightarrow ej)$ and $Br_{\nu j} \equiv Br(S_1 \rightarrow \nu j)$ to fit the three excesses. The signal acceptances for cases not studied in [1] are estimated by implementing the coloron model in [18], generating events at LO using MadGraph [19], showering and hadronizing using Pythia [20], and simulating the detector using PGS [21]. The selection cuts as outlined in [1] and [2] are applied to the PGS events and the signal acceptance is extracted. The acceptances for two benchmark leptoquark masses
| LQ Mass (GeV) | Production | LQ $eejj$ | LQ $\nu ejj$ | $WR + N_e$ |
|--------------|------------|-----------|--------------|-----------|
| 550          | QCD        | 0.45      | 0.08         | 0.04      |
| Coloron (2.1 TeV) | 0.60 | 0.18 | 0.55 |
| 650          | QCD        | 0.49      | 0.29         | 0.08      |
| Coloron (2.1 TeV) | 0.64 | 0.45 | 0.58 |

TABLE I. 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 [1]. For the $WR + N_e$ search, the acceptance is for the selected events to have $1.8 \, \text{TeV} < m_{eejj} < 2.2 \, \text{TeV}$ [2].

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 $1.8 \, \text{TeV} < m_{eejj} < 2.2 \, \text{TeV}$ bin in the $WR + N_e$ 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

$$\sigma_{SG} = 63.0 \, \text{fb}, \quad \text{Br}_{ej} = 0.12, \quad \text{Br}_{ejj} = 0.15. \quad (8)$$

for a leptoquark mass of 550 GeV and

$$\sigma_{SG} = 17.8 \, \text{fb}, \quad \text{Br}_{ej} = 0.21, \quad \text{Br}_{ejj} = 0.13. \quad (9)$$

for a leptoquark mass of 650 GeV. A $\chi^2$ fit shows that the model with leptoquark mass 550 GeV is consistent with $\text{Br}_{ej} = \text{Br}_{ejj}$, while the model with leptoquark 650 GeV is consistent with $\text{Br}_{ej} = 2 \, \text{Br}_{ejj}$. Either scenario is a plausible result of electroweak symmetry. In terms of the parameter $\tan \theta$ and from Fig. 1, the required production cross sections can match to $\tan \theta = 0.19$ and $\tan \theta = 0.17$ for $M_{S1} = 550 \, \text{GeV}$ and $M_{S1} = 650 \, \text{GeV}$, respectively.

Although we only use the total excess numbers of events to fit our model, we also show the $m_{ejj}$ distribution in the $eejj$ final state of the leptoquark search in Fig. 2 the $m_{ejj}$ distribution in the $evjj$ final state of the leptoquark search in Fig. 3 and the $m_{eejj}$ distribution in the $WR + N_e$ search in Fig. 4. Comparing fitted results with two different leptoquark masses, one can see that the current data does not have enough statistics to constrain the leptoquark mass.

**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 $evjj$ 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 ($\nujj$) 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, 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 $\sigma \times Br \sim 1 - 20$ 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. (9) and (10) 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 $S_1 \rightarrow \tau^+ \tau^-, \nu\bar{\nu}$, which currently has less stringent limits. Simply due to the leptoquark quantum numbers, other possibilities are restricted. The simplest ones include baryon-number violating couplings or additional $j + \text{MET}$ 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.

**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 [2] can capture the quantitative features of the $e\nu jj$ data presented in [1] at the level of current uncertainties. In fact, our simulated results of the $W_R + N_e$ model show a broad peak structure in $m_{e\nu jj}$ after the selection cuts of the leptoquark search [1]. There could exist other event topologies to provide the similar signatures (see Ref. [25] for more event topologies). A similar model that added a $e\nujj$ 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 ($\ell\ell, jj, \ell jj$ and $\ell j$, as well as the leptoquark combination).

**Acknowledgements.** We thank John Chou, Bryan Dahmes, Jared Evans, Paddy Fox, Francesco Romeo, Francesco Santanastasio and Haijun Yang for useful discussion. YB is supported by the U. S. Department of Energy under the contract DE-FG-02-95ER40896. SLAC is operated by Stanford University for the US Department of Energy under contract DE-AC02-76SF00515. We thank the Aspen Center for Physics, under NSF Grant No. PHY-1066293, where this work is generated and finished.

[1] CMS Collaboration, *Search for Pair-production of First Generation Scalar Leptoquarks in pp Collisions at sqrt s = 8 TeV*, Tech. Rep. CMS-PAS-EXO-12-041, CERN, Geneva, 2014.

[2] CMS Collaboration, V. Khachatryan et. al., *Search for heavy neutrinos and W bosons with right-handed couplings in proton-proton collisions at sqrt(s) = 8 TeV*, arXiv:1407.3683.

[3] J. C. Pati and A. Salam, *Lepton Number as the Fourth Color*, Phys.Rev. D10 (1974) 275–289.

[4] J. L. Hewett and T. G. Rizzo, *Much ado about leptoquarks: A Comprehensive analysis*, Phys.Rev. D56 (1997) 5709–5724, hep-ph/9703337.

[5] W. Buchmuller, R. Ruckl, and D. Wyler, *Leptoquarks in Lepton - Quark Collisions*, Phys.Lett. B191 (1987) 442–448.

[6] M. Kramer, T. Plehn, M. Spira, and P. Zerwas, *Pair production of scalar leptoquarks at the CERN LHC*, Phys.Rev. D71 (2005) 057503, hep-ph/0411038.

[7] C. T. Hill, *Topcolor: Top quark condensation in a gauge extension of the standard model*, Phys.Lett. B266 (1991) 419–424.

[8] C. T. Hill and S. J. Parke, *Top production: Sensitivity to new physics*, Phys.Rev. D49 (1994) 4454–4462, hep-ph/9312324.

[9] R. Chivukula, A. G. Cohen, and E. H. Simmons, *New strong interactions at the Tevatron?*, Phys.Lett. B380 (1996) 92–98, hep-ph/9603311.

[10] E. H. Simmons, *Coloron phenomenology*, Phys.Rev. D55 (1997) 1678–1683, hep-ph/9608269.
