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Novel Leptoquark Pair Production @LHC

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I discuss asymmetric leptoquark pair production mechanism at the Large Hadron Collider to advocate its potential relevance in providing reliable constraints on the leptoquark parameter space. The main feature of this production mechanism is that the two leptoquarks that are produced in proton-proton collisions through a t-channel lepton exchange are not charge conjugates of each other. This distinguishes asymmetric leptoquark pair production from conventional leptoquark pair production even though the final state signatures can be exactly the same in both instances. I spell out prerequisite conditions for the asymmetric leptoquark pair production mechanism to be operational and enumerate all possible combinations of leptoquark multiplets that can potentially generate it. Finally, I demonstrate effects of the asymmetric pair production signature inclusion by recasting existing leptoquark pair production search results within the S_1, S_3, R_2, S_1+S_3, and S_1+R_2 leptoquark extensions of the Standard Model, where I assume that all these leptoquarks exclusively couple to electrons and the first generation quarks via a single Yukawa coupling.

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1. A novel mechanism

I present, in what follows, a novel mechanism of leptoquark pair production at hadron colliders that has been recently introduced in Ref. [1] and further investigated in Refs. [2, 3]. The main feature of this novel mechanism that distinguishes it from the usual leptoquark pair production at, for example, the Large Hadron Collider (LHC) is a fact that the two leptoquarks LQ_1 and LQ_2 that are produced in proton-proton collisions through a t-channel exchange of a lepton do not comprise a charge conjugate pair, i.e., $\mathrm{LQ}_1 \neq (\mathrm{LQ}_2)^*$. This is a primary reason why I refer to it as an asymmetric leptoquark pair production.

Since asymmetric leptoquark production mechanism can yield the same final state as the conventional pair production, it can affect interpretation of existing and future experimental search results. I will, for definiteness, discuss effects of this novel production mechanism within the context of scalar leptoquark extensions of the Standard Model (SM). I accordingly present in Table 1 a list of pertinent scalar leptoquark multiplets and associated transformation properties under the SM gauge group $SU(3) \times SU(2) \times U(1)$. The chirality of both quarks and leptons that the scalar leptoquark couples to is denoted with R and L for right- and left-chiral fields, respectively, in the third column of Table 1. The convention is such that the first (second) letter, in that column, denotes chirality of quarks (leptons). A fermion number F of scalar leptoquark multiplets is also specified in Table 1, where F is defined as the sum of the lepton number and three times the baryon number of leptons and quarks that a given leptoquark couples to. Leptoquarks with $F = -2$ exclusively couple/decay to quarks and leptons whereas $F = 0$ leptoquarks couple/decay to quark-antilepton or antiquark-lepton pairs.

$(SU(3), SU(2), U(1))$	LQ SYMBOL	CHIRALITY TYPE (LQ-q-l)	F
$(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	S_3	LL	-2
$(\mathbf{3}, \mathbf{2}, 7/6)$	R_2	RL, LR	0
$(\mathbf{3}, \mathbf{2}, 1/6)$	$\tilde{R}_2$	RL	0
$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	$\tilde{S}_1$	RR	-2
$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	S_1	LL, RR	-2

Table 1: Scalar leptoquark multiplets, chiralities of the leptoquark interactions with the SM quark-lepton pairs, and associated leptoquark fermion numbers.

The hyper-charge normalization is $Q = I_3 + Y$, where Q corresponds to electric charge in units of the positron charge, I_3 stands for the diagonal generator of $SU(2)$, and Y represents $U(1)$ hyper-charge operator. The electric charge eigenvalues of scalar leptoquarks in Table 1 are thus $S_3^{+4/3}$, $S_3^{+1/3}$, $S_3^{-2/3}$, $R_2^{+5/3}$, $R_2^{+2/3}$, $\tilde{R}_2^{+2/3}$, $\tilde{R}_2^{-1/3}$, $\tilde{S}_1^{+4/3}$, and $S_1^{+1/3}$. I will denote leptoquarks using this notation and furthermore write that $(\mathrm{LQ}^{+Q})^* = \mathrm{LQ}^{-Q}$ and $(\mathrm{LQ}^{-Q})^* = \mathrm{LQ}^{+Q}$.

There are several prerequisite conditions for the asymmetric leptoquark pair production mechanism under consideration to be operational [1]. First, it requires non-negligible Yukawa coupling(s) between leptoquarks and the SM quarks and leptons. Second, this mechanism is relevant whenever there exist at least two leptoquark states LQ_1 and LQ_2 originating from the same or two different leptoquark multiplets that couple to a lepton of the same chirality and flavor. This, then, leads to a simple schematic representation shown in Fig. 1 of all possible minimal leptoquark combinations that can potentially generate asymmetric pair production at hadron colliders and, consequentially, LHC.

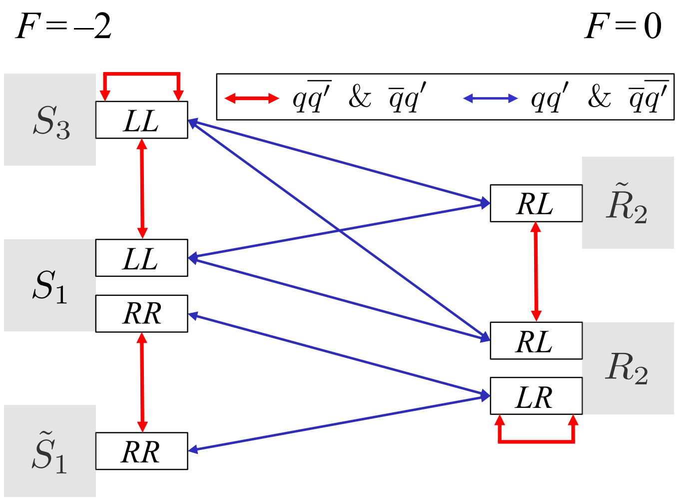

Figure 1: Schematic classification of potential sources of asymmetric leptoquark pair production.

The double-headed arrows in Fig. 1 connect those leptoquark multiplets that can simultaneously couple to a lepton of the same flavor and chirality and can thus generate asymmetric leptoquark pair production. These arrows are color-coded either blue or red to distinguish between two different initial state configurations behind the relevant asymmetric pair production processes. If the two leptoquarks LQ_1 and LQ_2 have different fermion numbers, i.e., $\Delta F = |F(\mathrm{LQ}_1)| - |F(\mathrm{LQ}_2)| = \pm 2$, the initial states are of the qq' and $\overline{q}\,\overline{q'}$ nature, where q and q' denote the quark fields and can, in principle, be equal to u, d, s, c, and b. These scenarios are indicated with blue double-headed arrows in Fig. 1. If, on the other hand, leptoquarks have the same fermion number, i.e., $\Delta F = 0$, the initial states are of the $q\overline{q'}$ and $\overline{q}q'$ nature, where, again, $q, q' = u, d, s, c, b$. The $\Delta F = 0$ scenarios are depicted with red double-headed arrows in Fig. 1.

In view of all these requirements, I note that it is entirely possible to have a new physics scenario with only one scalar leptoquark multiplet and only one non-zero Yukawa coupling and still be able to asymmetrically produce leptoquark pairs at the LHC [1]. There are two such scenarios, as indicated in Fig. 1. One is generated if a single non-zero Yukawa coupling exists between R_2 and any right-chiral charged lepton. The other one requires presence of a single non-zero Yukawa coupling for S_3. An all-encompassing classification of diagrams that generate asymmetric pair production is given in Fig. 2, whereas Tables 2 and 3 provide associated nomenclature for the $\Delta F = |F(\mathrm{LQ}_1) - |F(\mathrm{LQ}_2)| = \pm 2$ and $\Delta F = |F(\mathrm{LQ}_1)| - |F(\mathrm{LQ}_2)| = 0$ scenarios, respectively.

There is no interference between asymmetric and conventional leptoquark pair production at the amplitude level even though the final state signatures of both processes can be exactly the same. I will accordingly focus attention solely on the asymmetric pair production cross sections that can thus be simply added, if and when appropriate, to the conventional pair production cross sections. The leading order cross sections, in QCD, are

$$\sigma^{\mathrm{pair}}_{q_1 q_2}(y_{q_1}, y_{q_2}, m_{\mathrm{LQ}_1}, m_{\mathrm{LQ}_2}) = a_{q_1 q_2}(m_{\mathrm{LQ}_1}, m_{\mathrm{LQ}_2})|y_{q_1} y_{q_2}|^2, \quad (1)$$

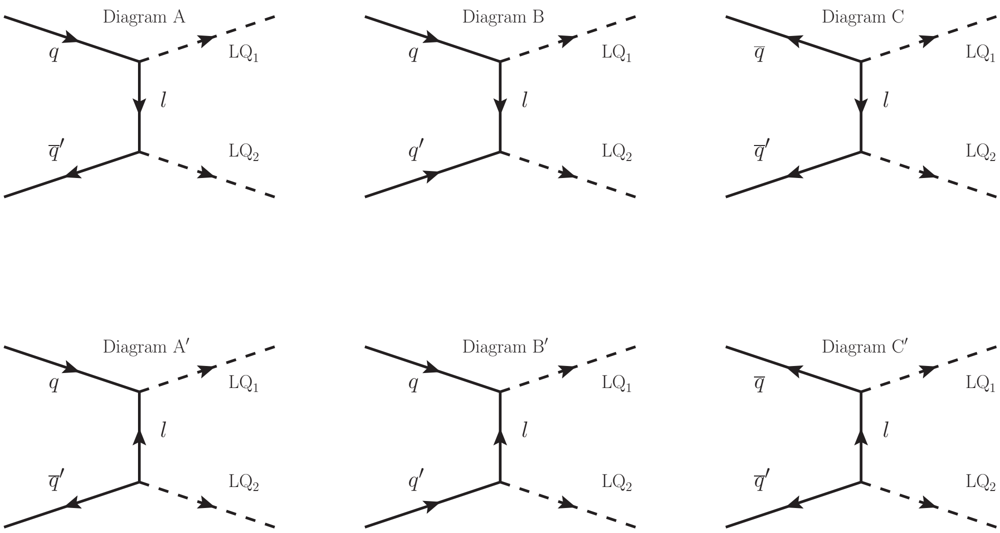

Figure 2: Types of diagrams for asymmetric production. q, q', l, LQ_1, and LQ_2 for $\Delta F = |F(\text{LQ}_1) - |F(\text{LQ}_2)| = \pm 2$ and $\Delta F = |F(\text{LQ}_1)| - |F(\text{LQ}_2)| = 0$ are specified in Tables 2 and 3, respectively. Here l refers to a charged lepton or a neutrino.

where $q_1, q_2 = u, \overline{u}, d, \overline{d}, s, \overline{s}, c, \overline{c}, b, \overline{b}$. Here, leptoquark LQ_i of mass m_{LQ_i} couples to a quark q_i and a lepton l of a given chirality and flavor with strength y_{q_i}, where $i = 1, 2$. Note that the cross sections of Eq. (1) do not depend on whether LQ_1 couples to a quark q_1 while LQ_2 couples to a quark q_2 or vice versa. This is only relevant for subsequent leptoquark decays. The cross sections of Eq. (1) also do not depend on the type of lepton that leptoquarks LQ_1 and LQ_2 simultaneously couple to. They are proportional to a square of the product $|y_{q_1} y_{q_2}|$ and can thus be trivially rescaled as a function of Yukawa couplings once they are determined for one particular value of $|y_{q_1} y_{q_2}|$ product.

I will always assume that LQ_1 and LQ_2 are mass-degenerate, i.e., $m_{\text{LQ}_1} = m_{\text{LQ}_2} \equiv m_{\text{LQ}}$, and furthermore take all Yukawa couplings to be real. These two assumptions allow one to introduce cross section $\sigma^{\text{pair}}_{q_1 q_2}(y_{q_1}, y_{q_2}, m_{\text{LQ}})$ that is symmetric in flavor, i.e., $\sigma^{\text{pair}}_{q_1 q_2} \equiv \sigma^{\text{pair}}_{q_2 q_1}$, where

$$\sigma^{\text{pair}}_{q_1 q_2}(y_{q_1}, y_{q_2}, m_{\text{LQ}}) = \sigma^{\text{pair}}_{q_1 q_2}(y_{q_1}, y_{q_2}, m_{\text{LQ}_1} = m_{\text{LQ}_2} \equiv m_{\text{LQ}}, m_{\text{LQ}_2}). \tag{2}$$

There are fifteen cross sections $\sigma^{\text{pair}}_{q_1 q_2}(y_{q_1}, y_{q_2}, m_{\text{LQ}})$ of interest, at the LHC, when the initial states are quark-quark pairs and twenty five when the initial states are quark-antiquark pairs. The quark-quark initiated cross sections are given in Fig. 3 under the assumption that $|y_{q_1} y_{q_2}| = 1$, where $q_1 = u, d, s, c$ and $q_2 = u, d, s, c, b$, while the quark-antiquark initiated cross sections are given in Fig. 4 under the same assumption that $|y_{q_1} y_{q_2}| = 1$, but, this time around, with $q_1 = u, d, s, c$ and $q_2 = \overline{u}, \overline{d}, \overline{s}, \overline{c}, \overline{b}$. I also include in Figs. 3 and 4, for comparison purposes, conventional scalar leptoquark pair production cross section at the LHC that is evaluated under the assumption that the leptoquark Yukawa couplings are negligible but still large enough to ensure prompt leptoquark

Diagram Type	q	$\overline{q'}$	l	LQ$_1$	LQ$_2$	LQ scenario
A	u_L	$\overline{d}_L$	ℓ_R	$R_2^{+5/3}$	$R_2^{+2/3}$	21cm R_2
A	d_L	$\overline{u}_L$	ℓ_R	$R_2^{-2/3}$	$R_2^{-5/3}$	
A′	d_L	$\overline{u}_L$	ν_L	$S_3^{-1/3}$	$S_3^{-2/3}$	41cm S_3
A′	u_L	$\overline{d}_L$	ν_L	$S_3^{+2/3}$	$S_3^{+1/3}$	
A′	d_L	$\overline{u}_L$	ℓ_L	$S_3^{-4/3}$	$S_3^{+1/3}$	
A′	u_L	$\overline{d}_L$	ℓ_L	$S_3^{-1/3}$	$S_3^{+4/3}$	
A	d_R	$\overline{u}_R$	ℓ_L	$\widetilde{R}_2^{+2/3}$	$R_2^{-5/3}$	42cm $\widetilde{R}_2$+R_2
A	u_R	$\overline{d}_R$	ℓ_L	$R_2^{+5/3}$	$\widetilde{R}_2^{-2/3}$	
A	d_R	$\overline{u}_R$	ν_L	$\widetilde{R}_2^{-1/3}$	$R_2^{-2/3}$	
A	u_R	$\overline{d}_R$	ν_L	$R_2^{+2/3}$	$\widetilde{R}_2^{+1/3}$	
A′	d_R	$\overline{u}_R$	ℓ_R	$\widetilde{S}_1^{-4/3}$	$S_1^{+1/3}$	22cm $\widetilde{S}_1$+S_1
A′	u_R	$\overline{d}_R$	ℓ_R	$S_1^{-1/3}$	$\widetilde{S}_1^{+4/3}$	
A′	d_L	$\overline{u}_L$	ν_L	$S_1^{-1/3}$	$S_3^{-2/3}$	42cm S_1+S_3
A′	u_L	$\overline{d}_L$	ν_L	$S_3^{+2/3}$	$S_1^{+1/3}$	
A′	u_L	$\overline{d}_L$	ℓ_L	$S_1^{-1/3}$	$S_3^{+4/3}$	
A′	d_L	$\overline{u}_L$	ℓ_L	$S_3^{-4/3}$	$S_1^{+1/3}$	

Table 2: Asymmetric production with $q\overline{q'}$ and $\overline{q}q'$ initial states. See Fig. 2 for the diagram type.

decay. This particular cross section is simply denoted with $\sigma_{\rm QCD}^{\rm pair}(m_{\rm LQ})$ to stress that it is purely QCD induced and it is represented by a thick dashed black curve in both Figs. 3 and 4.

The asymmetric leptoquark pair production cross sections of Figs. 3 and 4 are extracted from the new physics scenarios of Fig. 1. These scenarios are implemented using FeynRules [4] and subsequently imported in MadGraph5_aMC@NLO framework [5] to produce numerical results for $m_{\rm LQ}$ values between 1.6 TeV and 2.6 TeV. I exclusively use the `nn23lo1` PDF set [6] to generate leading order cross sections for the center-of-mass energy of proton-proton collisions set at 13 TeV, where the factorisation (μ_F) and renormalization (μ_R) scales are taken to be $\mu_F = \mu_R = m_{\rm LQ}/2$.

One can observe from Fig. 3 that the quark-quark initiated asymmetric pair production cross sections of mass-degenerate scalar leptoquarks LQ$_1$ and LQ$_2$, i.e., when $\Delta F = |F(\mathrm{LQ}_1)| - |F(\mathrm{LQ}_2)| = \pm 2$ and $m_{\mathrm{LQ}_1} = m_{\mathrm{LQ}_2} = m_{\mathrm{LQ}}$, can be comparable to or be even substantially larger than the QCD driven leptoquark pair production cross section at the LHC if at least one of the leptoquarks couples to a valence quark and the product of relevant Yukawa cuplings is of order one. In the case of the quark-antiquark initiated asymmetric pair production cross sections the only truly relevant scenarios, once again, are those where the initial quark is a valence quark.

With these preliminary considerations out of the way I now turn towards quantitative analysis of the asymmetric pair production mechanism within several concrete scenarios of new physics.

Diagram Type	$q/\overline{q}$	$q'/\overline{q'}$	l	LQ$_1$	LQ$_2$	LQ scenario
B′	d_R	u_L	ℓ_R	$\widetilde{S}_1^{-4/3}$	$R_2^{+5/3}$	42cm $\widetilde{S}_1$+R_2
B′	d_R	$\overline{d}_L$	ℓ_R	$\widetilde{S}_1^{-4/3}$	$R_2^{+2/3}$	
C′	$\overline{u}_L$	$\overline{d}_R$	ℓ_R	$R_2^{-5/3}$	$\widetilde{S}_1^{+4/3}$	
C′	$\overline{d}_L$	$\overline{d}_R$	ℓ_R	$R_2^{-2/3}$	$\widetilde{S}_1^{+4/3}$	
B	u_R	d_L	ν_L	$R_2^{+2/3}$	$S_1^{-1/3}$	82cm S_1+R_2
B	u_R	u_L	ℓ_L	$R_2^{+5/3}$	$S_1^{-1/3}$	
B	u_L	u_R	ℓ_R	$R_2^{+5/3}$	$S_1^{-1/3}$	
B	d_L	u_R	ℓ_R	$R_2^{+2/3}$	$S_1^{-1/3}$	
C	$\overline{d}_L$	$\overline{u}_R$	ν_L	$S_1^{+1/3}$	$R_2^{-2/3}$	
C	$\overline{u}_L$	$\overline{u}_R$	ℓ_L	$S_1^{+1/3}$	$R_2^{-5/3}$	
C	$\overline{u}_R$	$\overline{u}_L$	ℓ_R	$S_1^{+1/3}$	$R_2^{-5/3}$	
C	$\overline{u}_R$	$\overline{d}_L$	ℓ_R	$S_1^{+1/3}$	$R_2^{-2/3}$	
B	d_R	u_L	ℓ_L	$\widetilde{R}_2^{+2/3}$	$S_1^{-1/3}$	22cm S_1+$\widetilde{R}_2$
C	$\overline{u}_L$	$\overline{d}_R$	ℓ_L	$S_1^{+1/3}$	$\widetilde{R}_2^{-2/3}$	
B	u_R	d_L	ℓ_L	$R_2^{+5/3}$	$S_3^{-4/3}$	62cm S_3+R_2
B	u_R	u_L	ℓ_L	$R_2^{+5/3}$	$S_3^{-1/3}$	
B	u_R	d_L	ν_L	$R_2^{+2/3}$	$S_3^{-1/3}$	
C	$\overline{d}_L$	$\overline{u}_R$	ℓ_L	$S_3^{+4/3}$	$R_2^{-5/3}$	
C	$\overline{u}_L$	$\overline{u}_R$	ℓ_L	$S_3^{+1/3}$	$R_2^{-5/3}$	
C	$\overline{d}_L$	$\overline{u}_R$	ν_L	$S_3^{+1/3}$	$R_2^{-2/3}$	
B	d_R	d_L	ℓ_L	$\widetilde{R}_2^{+2/3}$	$S_3^{-4/3}$	62cm S_3+$\widetilde{R}_2$
B	d_R	u_L	ℓ_L	$\widetilde{R}_2^{+2/3}$	$S_3^{-1/3}$	
B	d_R	u_L	ν_L	$\widetilde{R}_2^{-1/3}$	$S_3^{+2/3}$	
C	$\overline{d}_L$	$\overline{d}_R$	ℓ_L	$S_3^{+4/3}$	$\widetilde{R}_2^{-2/3}$	
C	$\overline{u}_L$	$\overline{d}_R$	ℓ_L	$S_3^{+1/3}$	$\widetilde{R}_2^{-2/3}$	
C	$\overline{u}_L$	$\overline{d}_R$	ν_L	$S_3^{-2/3}$	$\widetilde{R}_2^{+1/3}$	

Table 3: Asymmetric production with qq' and $\overline{q}\overline{q'}$ initial states. See Fig. 2 for the diagram type.

1.1 Case studies

I discuss five different leptoquark extensions of the SM and derive, for several particular realisations of these extensions, accurate limits using one specific experimental search. More specifically, I recast the ATLAS Collaboration analysis [7] of the leptoquark pair production searches via $pp \to \mathrm{LQ}\overline{\mathrm{LQ}} \to jjee$, where j is taken to generically represents a light jet, i.e., $j = u, \overline{u}, d, \overline{d}, s, \overline{s}$, while it is implicitly understood that ee stands for oppositely charged electron pair. All five scenarios provide a setting for pedagogical illustration of various phenomenological intricacies associated with the leptoquark pair production signatures.

First of these five scenarios involves a presence of a single scalar leptoquark S_1. The second scenario of new physics is an R_2 extension of the SM, where R_2 multiplet comprises two states,

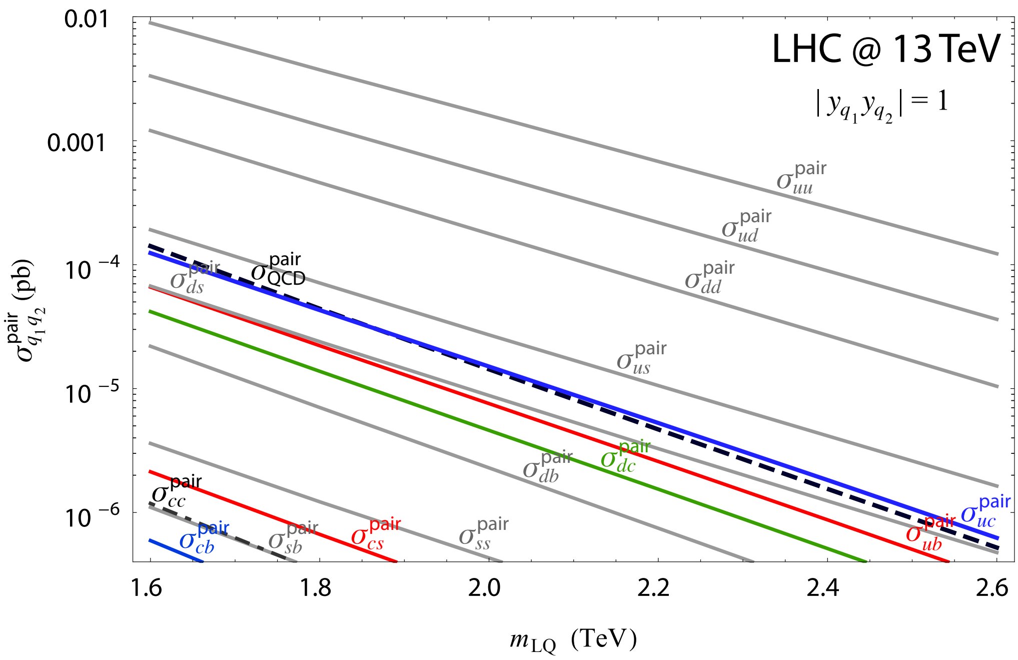

Figure 3: Asymmetric leptoquark pair production cross sections $\sigma^{\rm pair}_{q_1 q_2}(y_{q_1}, y_{q_2}, m_{\rm LQ})$ for quark-quark initial states, where $q_1 = u, d, s, c$ and $q_2 = u, d, s, c, b$.

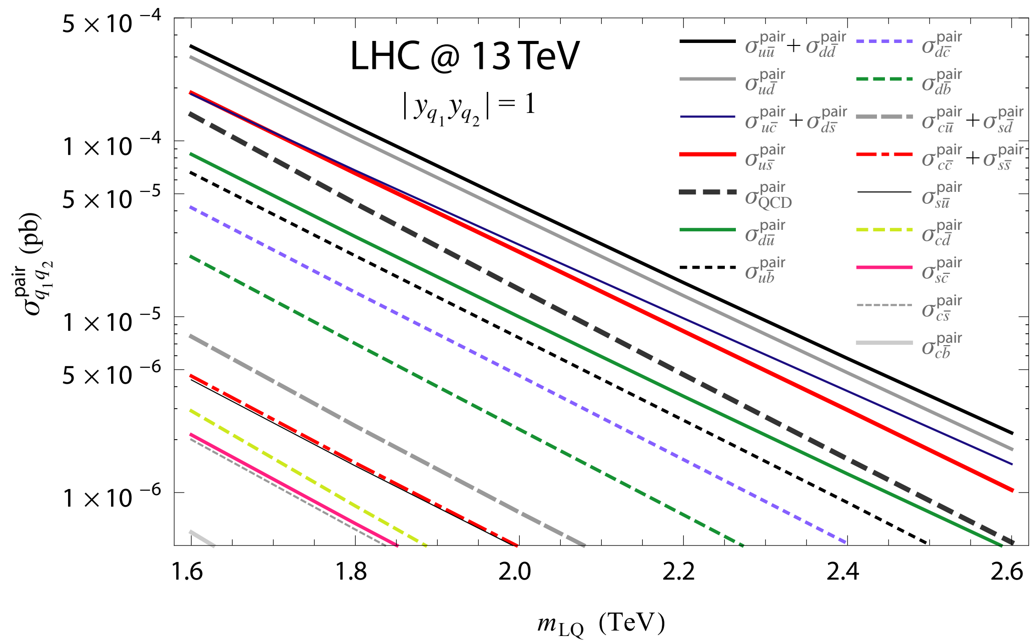

Figure 4: Asymmetric leptoquark pair production cross sections $\sigma^{\rm pair}_{q_1 q_2}(y_{q_1}, y_{q_2}, m_{\rm LQ})$ for quark-antiquark initial states, where $q_1 = u, d, s, c$ and $q_2 = \bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}$.

i.e., $R_2^{+5/3}$ and $R_2^{-2/3}$. Third scenario extends the SM particle content with both S_1 and R_2 while forth scenario concerns addition of an S_3 leptoquark multiplet to the SM particle content, where S_3 contains scalars $S_3^{+4/3}$, $S_3^{+1/3}$, and $S_3^{-2/3}$. Fifth scenario regards simultaneous extension of the SM with both S_1 and S_3. Again, I will assume that all these leptoquarks exclusively couple to electrons and the first generation quarks.

Relevant parts of the S_1 lagrangian, for this study, are

$$\begin{aligned}\mathcal{L}_{S_1} &= + y_{1\,ij}^{LL} \bar{Q}_L^{C\,i,a} S_1 \epsilon^{ab} L_L^{j,b} + y_{1\,ij}^{RR} \bar{u}_R^{C\,i} S_1 e_R^j + \text{h.c.} \\ &= -(y_1^{LL} U)_{ij} \bar{d}_L^{C\,i} \nu_L^j S_1^{+1/3} + (V^* y_1^{LL})_{ij} \bar{u}_L^{C\,i} e_L^j S_1^{+1/3} + y_{1\,ij}^{RR} \bar{u}_R^{C\,i} e_R^j S_1^{+1/3} + \text{h.c.},\end{aligned} \tag{3}$$

where $a, b(=1,2)$ are $SU(2)$ indices, V is a Cabibbo–Kobayashi–Maskawa (CKM) mixing matrix, and U represents a Pontecorvo–Maki–Nakagawa–Sakata (PMNS) unitary mixing matrix. I set the CKM matrix to be an identity matrix whereas the exact form of the PMNS matrix is irrelevant for subsequent discussion as long as it resides entirely in the neutrino sector. Note that the CKM matrix, in this convention, is in the up-type quark sector.

Pertinent parts of the R_2 lagrangian are

$$\begin{aligned}\mathcal{L}_{R_2} &= - y_{2\,ij}^{RL} \bar{u}_R^i R_2^a \epsilon^{ab} L_L^{j,b} + y_{2\,ij}^{LR} \bar{e}_R^i R_2^{a\,*} Q_L^{j,a} + \text{h.c.} \\ &= - y_{2\,ij}^{RL} \bar{u}_R^i e_L^j R_2^{+5/3} + (y_2^{RL} U)_{ij} \bar{u}_R^i \nu_L^j R_2^{+2/3} + \\ &\quad + (y_2^{LR} V^\dagger)_{ij} \bar{e}_R^i u_L^j R_2^{-5/3} + y_{2\,ij}^{LR} \bar{e}_R^i d_L^j R_2^{-2/3} + \text{h.c.}.\end{aligned} \tag{4}$$

One can note that all unitary transformations of the right-chiral fermions can be completely absorbed, for both the S_1 and R_2 scenarios, into associated Yukawa coupling matrices. I accordingly take all unitary transformations of right-chiral quarks and charged leptons to be unphysical in this study.

The S_3 Lagrangian, in my notation, is

$$\begin{aligned}\mathcal{L}_{S_3} &= y_{3\,ij}^{LL} \bar{Q}_L^{C\,i,a} \epsilon^{ab} (\tau^k S_3^k)^{bc} L_L^{j,c} + \text{h.c.} \\ &= -(y_3^{LL} U)_{ij} \bar{d}_L^{C\,i} \nu_L^j S_3^{+1/3} - (V^* y_3^{LL})_{ij} \bar{u}_L^{C\,i} e_L^j S_3^{+1/3} + \\ &\quad + \sqrt{2} (V^* y_3^{LL} U)_{ij} \bar{u}_L^{C\,i} \nu_L^j S_3^{-2/3} - \sqrt{2} y_{3\,ij}^{LL} \bar{d}_L^{C\,i} e_L^j S_3^{+4/3} + \text{h.c.},\end{aligned} \tag{5}$$

where τ^k, $k = 1,2,3$, are Pauli matrices and I define $S_3^{+4/3} = (S_3^1 - iS_3^2)/\sqrt{2}$, $S_3^{+1/3} = S_3^3$, and $S_3^{-2/3} = (S_3^1 + iS_3^2)/\sqrt{2}$ to be electric charge eigenstates.

Once again, in all of these scenarios I will always assume a presence of a single non-zero Yukawa coupling to an electron and the first generation quarks for each of these leptoquark multiplets, if and when they are featured, in order to simplify discussion.

1.1.1 Case study: $S_1(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$

Let me first address the S_1 scenario.

- If $y_{1\,11}^{LL} \equiv y$ is the only non-zero Yukawa coupling present in Eq. (3), the corresponding branching ratios for the S_1 decays are $B(S_1^{\pm 1/3} \to j\nu) = 1/2$ and $B(S_1^{\pm 1/3} \to je) = 1/2$. A recast of the ATLAS Collaboration analysis [7] of the leptoquark pair production search via $pp \to \text{LQ}\overline{\text{LQ}} \to jjee$ process at 13 TeV center-of-mass energy of proton-proton collisions, using an integrated luminosity of 139 fb^{-1}, then yields a limit on the mass of S_1 leptoquark, as a function of $y \equiv y^{LL}_{1\,11}$, which is rendered with a thick dashed black curve in Fig. 5. The exclusion region is to the left of that curve and it is based on the ATLAS Collaboration observed 95% C.L. limit. The Yukawa dependent limit of Fig. 5, for small values of $y^{LL}_{1\,11} \equiv y$, needs to agree with the outcome of the ATLAS Collaboration analysis when $B(S_1^{\pm 1/3} \to je) = 1/2$, i.e. $m_{\mathrm{LQ}} \geq 1380$ GeV, which is based on the next-to-leading order cross section in QCD calculation [7]. I accordingly rescale the leading order simulation when presenting the limits in Fig. 5 and note that the cross section obtained in that way indeed corresponds to the next-to-leading order cross section in QCD as given in Ref. [8]. I also plot in Fig. 5 the leptoquark parameter constraint with a vertical thin dashed black line if one would use $\sigma^{\mathrm{pair}}_{\mathrm{QCD}}(m_{\mathrm{LQ}})$ instead of the Yukawa dependant cross section, for this particular branching fraction scenario. That vertical line is additionally marked with "w/o t-channels" to stress exclusion of the t-channel lepton exchange diagrams during evaluation of $\sigma^{\mathrm{pair}}_{\mathrm{QCD}}(m_{\mathrm{LQ}})$.

There are two subtleties with regard to the $y^{LL}_{1\,11} \equiv y \neq 0$ case. First, there are two t-channel contributions towards the S_1 pair production that need to be included in this analysis. One contribution is due to the first term in the second line of Eq. (3) and it is $d\bar{d}$ initiated. The other contribution is $u\bar{u}$ initiated and it is due to the second term in the second line of Eq. (3). Another subtlety concerns the CKM mixing matrix placement. Namely, if the CKM matrix is taken to be in the up-type quark sector it would induce coupling between S_1, a charm quark, and an electron through the second term in the second line of Eq. (3). This would primarily impact the branching ratio $B(S_1^{\pm 1/3} \to je)$ by reducing it to 80% of its initial value and would also introduce $B(S_1^{\pm 1/3} \to ce)$ at the level of 10%. These changes in branching fractions would consequentially impact interpretation of the ATLAS Collaboration analysis [7] that can distinguish between light jets and, for example, a c-quark induced jet. The bounds on the S_1 parameter space would accordingly shift to the left in Fig. 5. The placement of the CKM mixing matrix in the down-type quark sector, on the other hand, would not produce any such shift.

- If $y^{RR}_{1\,11} \equiv y$ is the only non-zero Yukawa coupling in Eq. (3), one gets that $B(S_1^{\pm 1/3} \to je) = 1$ and the correct interpretation of the ATLAS Collaboration results [7] would correspond to a bound rendered with a thick dashed blue curve in Fig. 5. This bound, for small values of $y^{RR}_{1\,11} \equiv y$, yields $m_{\mathrm{LQ}} \geq 1790$ GeV [7] and thus coincides with the constraint presented with a vertical thin dashed blue line that is generated if one were to use $\sigma^{\mathrm{pair}}_{\mathrm{QCD}}(m_{\mathrm{LQ}})$ instead of the more appropriate $\sigma^{\mathrm{pair}}_{u\bar{u}}(y, m_{\mathrm{LQ}})$ to interpret the ATLAS Collaboration analysis.

Note that the exclusion regions, in these two cases, feature negative interference effects, first discussed in detail in Ref. [9], for intermediate values of Yukawa couplings $y^{LL}_{1\,11} \equiv y$ and $y^{RR}_{1\,11} \equiv y$.

1.1.2 Case study: $R_2(\mathbf{3}, \mathbf{2}, 7/6)$

I discuss, in what follows, scenarios when $y^{RL}_{2\,11}$ and $y^{LR}_{2\,11}$ in Eq. (4) are switched on, individually, while all other Yukawa matrix elements are taken to be negligible.

- If one turns on Yukawa coupling $y^{RL}_{2\,11} \equiv y$ in Eq. (4), one has that $B(R_2^{\pm 5/3} \to je) = 1$ and $B(R_2^{\pm 2/3} \to j\nu) = 1$. Since members of the R_2 multiplet need to be mass-degenerate

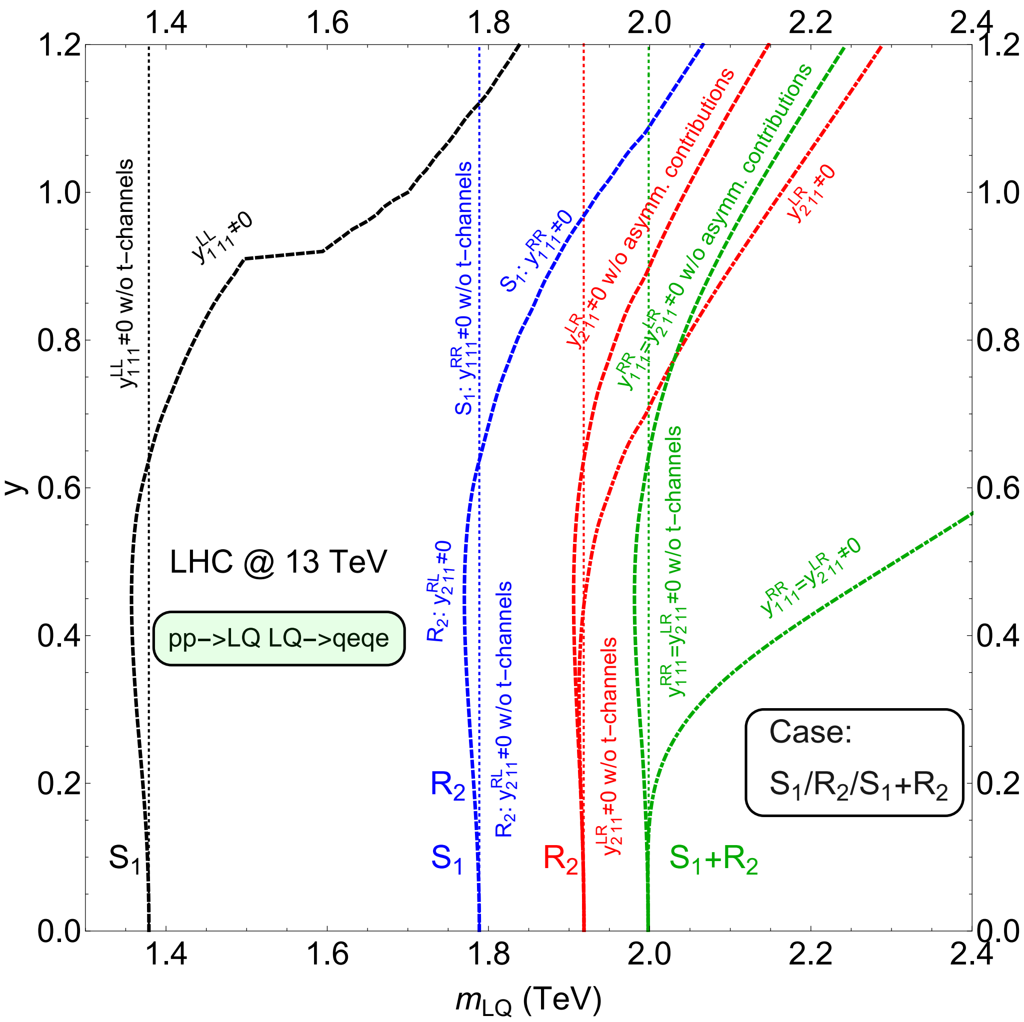

Figure 5: The leptoquark parameter space limits for the S_1, R_2, and S_1+R_2 scenarios extracted from the $pp \to \mathrm{LQ}\overline{\mathrm{LQ}} \to jjee$ process search [7] performed at 13 TeV center-of-mass energy of proton-proton collisions at the LHC, using an integrated luminosity of 139 fb^{-1}. See text for more details.

for all practical purposes, the limit on the $R_2^{\pm 5/3}$ parameter space, as extracted from the ATLAS Collaboration pair production analysis [7], should also be applicable to $R_2^{\pm 2/3}$ and vice versa. If I furthermore take into account the fact that the experimental limit on $pp \to R_2^{+5/3} R_2^{-5/3} \to jjee$ is certainly more relevant than the limit that could be extracted from $pp \to R_2^{+2/3} R_2^{-2/3} \to jj\nu\nu$, the constraint on the viable $R_2^{\pm 5/3}$ and $R_2^{\pm 2/3}$ parameter spaces is given with a thick dashed blue curve in Fig. 5. Note that this particular limit on the $R_2^{\pm 5/3}$ and $R_2^{\pm 2/3}$ parameter spaces, when $y_{2\,11}^{RL} \equiv y \neq 0$, is the same as for S_1 leptoquark when $y_{1\,11}^{RR} \equiv y \neq 0$.

- If $y_{2\,11}^{LR} \equiv y \neq 0$, one has that $B(R_2^{\pm 5/3} \to je) = 1$ and $B(R_2^{\pm 2/3} \to je) = 1$. Since the pair productions of both components of R_2 produce the same final state, i.e., $pp \to R_2^{+5/3} R_2^{-5/3} \to jjee$ and $pp \to R_2^{+2/3} R_2^{-2/3} \to jjee$, one needs to take that into account. Naive combination of these two processes, i.e., based purely on the $\sigma^{\rm pair}_{\rm QCD}(m_{\rm LQ})$ value, results in a bound given by a vertical thin dashed red line in Fig. 5 and yields $m_{\rm LQ} \geq 1920$ GeV. If one furthermore includes the Yukawa dependence of the cross sections to pair produce both components of R_2 multiplet, one obtains a limit rendered in a thick dashed red curve in Fig. 5. It should be noted that the generation of the thick dashed red curve denoted with "w/o asymm. contributions" calls for separate evaluation of cross sections for both $pp \to R_2^{+5/3} R_2^{-5/3} (\to jjee)$ and $pp \to R_2^{+2/3} R_2^{-2/3} (\to jjee)$ and their subsequent addition. Since $R_2^{-5/3}$ couples to the up quark while $R_2^{-2/3}$ couples to the down quark, these two cross sections, as functions of $y^{LR}_{2\,11} \equiv y$, are clearly not identical.

Note, however, that simple addition of cross sections to produce $R_2^{+5/3} R_2^{-5/3}$ and $R_2^{+2/3} R_2^{-2/3}$ pairs does not account for the asymmetric pair production mechanism effects that I want to advocate. To take into account asymmetric pair production one also needs to include cross sections for $pp \to R_2^{+5/3} R_2^{-2/3} (\to jjee)$ and $pp \to R_2^{-5/3} R_2^{+2/3} (\to jjee)$. Relevant diagrams for these two processes are presented in Fig. 6. The diagrams of Fig. 6 explicitly show that the two leptoquarks that are produced do not comprise a charge conjugate pair.

If one combines both the conventional and asymmetric pair production cross sections, and applies the constraints obtained by the ATLAS Collaboration on the $pp \to {\rm LQ}\overline{\rm LQ} \to jjee$ process [7], one obtains a proper bound rendered with a thick dot-dashed red curve in Fig. 5. The relevance of the asymmetric contribution is self-evident.

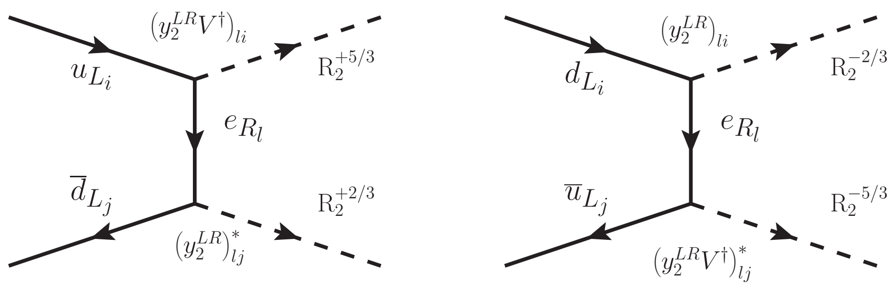

Figure 6: Asymmetric pair production for the case of R_2 leptoquark.

1.1.3 Case study: $S_1(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$+$R_2(\mathbf{3}, \mathbf{2}, 7/6)$

Since both S_1 and R_2 multiplets can couple to the SM leptons of both chiralities, there are four different scenarios to consider even if only one Yukawa coupling for each of these two multiplets is turned on at a given time. I will, for simplicity, investigate only one of these four possibilities for the $jjee$ final state scenario.

- If one takes that $y^{RR}_{1\,11} = y^{LR}_{2\,11} \equiv y \neq 0$, it is clear that all three leptoquarks decay into the same final state, i.e., $B(S_1^{\pm 1/3} \to je) = B(R_2^{\pm 5/3} \to je) = B(R_2^{\pm 2/3} \to je) = 1$. If one furthermore assumes that the masses of S_1 and of the two charged components in R_2 are the same, one obtains that a pure QCD cross section generates bound given with a vertical thin dashed green line whereas a simplistic addition of cross sections for processes $pp \to S_1^{+1/3} S_1^{-1/3} (\to jjee)$, $pp \to R_2^{+5/3} R_2^{-5/3} (\to jjee)$, and $pp \to R_2^{+2/3} R_2^{-2/3} (\to jjee)$ yields a bound given by a thick dashed green curve in Fig. 5. These bounds are based on the observed 95% C.L. limits, as given by the ATLAS Collaboration results on the $pp \to \mathrm{LQ}\overline{\mathrm{LQ}} \to jjee$ process search [7], and yield $m_{\mathrm{LQ}} \geq 2000\,\mathrm{GeV}$ in the small Yukawa coupling limit. Since the ATLAS Collaboration analysis [7] provides results for the leptoquark masses up to 2 TeV only, I conservatively assume that the observed limits above 2 TeV would have the ATLAS Collaboration 2 TeV level values.

If one finally includes all six asymmetric contributions, i.e., $pp \to S_1^{\pm 1/3} R_2^{\pm 5/3} (\to jjee)$, $pp \to S_1^{\pm 1/3} R_2^{\pm 2/3} (\to jjee)$, and $pp \to R_2^{\pm 5/3} R_2^{\mp 2/3} (\to jjee)$, one obtains a bound given by a thick dot-dashed green curve in Fig. 5. Once again, the importance of inclusion of the asymmetric contribution is self-evident.

1.1.4 Case study: $S_3(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$

- I assume that $y^{LL}_{3\,11} \equiv y$ of Eq. (5) is the only non-zero Yukawa coupling and take all three leptoquarks within S_3 multiplet to be degenerate in mass that I denote by m_{LQ}. The branching fractions for the S_3 components, when $y^{LL}_{3\,11} \neq 0$, are accordingly $B(S_3^{\pm 4/3} \to je) = 1$, $B(S_3^{\pm 2/3} \to j\nu) = 1$, $B(S_3^{\pm 1/3} \to je) = 1/2$, and $B(S_3^{\pm 1/3} \to j\nu) = 1/2$.

  If one is to use the ATLAS Collaboration results on the $pp \to \mathrm{LQ}\overline{\mathrm{LQ}} \to jjee$ process [7] to generate accurate constraints on the S_3 parameter space, one needs to take into account several factors. Namely, in the regime of the QCD dominated leptoquark pair production, i.e., for small $y^{LL}_{3\,11}$, there are two different processes that yield the $jjee$ final state. These are $pp \to S_3^{+4/3} S_3^{-4/3} \to jjee$ and $pp \to S_3^{+1/3} S_3^{-1/3} \to jjee$, where the $S_3^{+4/3} S_3^{-4/3}$ pair goes exclusively into $jjee$ whereas the $S_3^{+1/3} S_3^{-1/3}$ pair decays into $jjee$ only 25% of the time. If $y^{LL}_{3\,11}$ is not small, one needs to include conventional t-channel contributions [9]. These contributions, however, are not the same for $pp \to S_3^{+4/3} S_3^{-4/3}$ and $pp \to S_3^{+1/3} S_3^{-1/3}$ since the former process is $d\bar{d}$ initiated whereas the latter one is both $u\bar{u}$ and $d\bar{d}$ initiated. Moreover, the $S_3^{\pm 4/3}$ couplings to the quark-lepton pairs are always a factor of $\sqrt{2}$ larger than that of $S_3^{\pm 1/3}$ due to the $SU(2)$ symmetry of the SM. If one accounts for all these intricacies, one obtains the Yukawa dependent limit given in Fig. 8 with a thick dashed red curve. A vertical thin dashed red line in Fig. 8, on the other hand, denotes a naive limit if one uses purely QCD dominated leptoquark pair production cross sections and yields $m_{\mathrm{LQ}} \geq 1830\,\mathrm{GeV}$.

  Previous considerations do not incorporate potential asymmetric production contributions towards the $jjee$ final state. There are, in general, four asymmetric pair production contributions in any S_3 scenario and I present associated diagrams in Fig. 7. Two diagrams in the second row of Fig. 7 can give the $jjee$ final state via $pp \to S_3^{-4/3} S_3^{+1/3} \to jjee$ and $pp \to S_3^{+4/3} S_3^{-1/3} \to jjee$ with 50% probability, each, where $pp \to S_3^{-4/3} S_3^{+1/3}$ and $pp \to S_3^{+4/3} S_3^{-1/3}$ are $u\bar{d}$ and $d\bar{u}$ initiated, respectively. If one accounts for these effects, one obtains a limit given in Fig. 8 with a thick dot-dashed red curve. It is this limit that represents correct interpretation of the ATLAS Collaboration results on the $pp \to \mathrm{LQ}\overline{\mathrm{LQ}} \to jjee$ process [7] when $y^{LL}_{3\,11} \equiv y$ of Eq. (5) is the only non-zero Yukawa coupling. Again, the importance of the asymmetric production inclusion is self-evident.

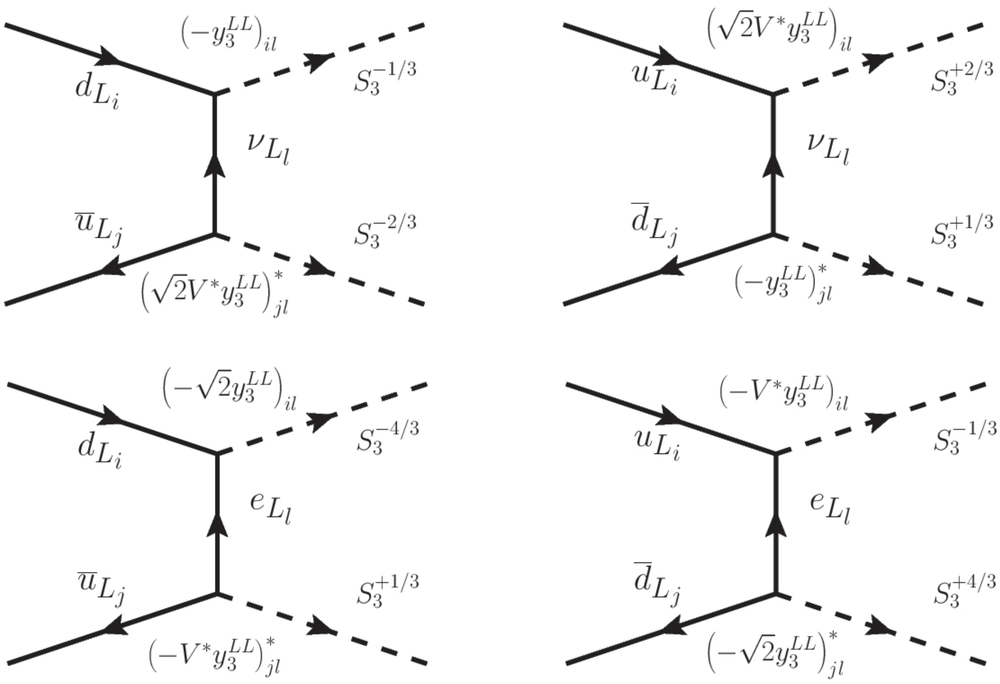

Figure 7: Asymmetric pair production for the case of S_3 leptoquark.

1.1.5 Case study: $S_1(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$+$S_3(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$

Since S_3 couples exclusively to the left-chiral leptons I assume that the only non-zero Yukawa couplings in this scenario, comprising S_1 and S_3 leptoquarks, are $y^{LL}_{1\,11}$ and $y^{LL}_{3\,11}$.

- If $y^{LL}_{1\,11} \neq 0$ and $y^{LL}_{3\,11} \neq 0$, the branching fractions of leptoquarks are $B(S_3^{\pm4/3} \to je) = 1$, $B(S_3^{\pm2/3} \to j\nu) = 1$, $B(S_3^{\pm1/3} \to je) = 1/2$, $B(S_3^{\pm1/3} \to j\nu) = 1/2$, $B(S_1^{\pm1/3} \to je) = 1/2$, and $B(S_1^{\pm1/3} \to j\nu) = 1/2$. I furthermore assume that S_1 and the components of S_3 are degenerate in mass and also take that $y^{LL}_{1\,11} = y^{LL}_{3\,11} \equiv y$ to simplify discussion.

  A naive QCD limit on the parameter space of this scenario, set by the ATLAS Collaboration data on the $pp \to \mathrm{LQ}\overline{\mathrm{LQ}} \to jjee$ process [7], is presented in Fig. 8 with a vertical thin dashed green line and corresponds to $m_{\mathrm{LQ}} \geq 1860\,\mathrm{GeV}$. If I also include the usual t-channel contributions for both S_1 and S_3, I obtain the limit given with a thick dashed green curve in Fig. 8.

  In order to numerically evaluate the asymmetric pair production contributions one needs to account for $pp \to S_3^{-4/3}S_3^{+1/3} \to jjee$ (50%), $pp \to S_3^{+4/3}S_3^{-1/3} \to jjee$ (50%), $pp \to S_3^{-4/3}S_1^{+1/3} \to jjee$ (50%), $pp \to S_3^{+4/3}S_1^{-1/3} \to jjee$ (50%), $pp \to S_3^{-1/3}S_1^{+1/3} \to jjee$ (25%) and $pp \to S_3^{+1/3}S_1^{-1/3} \to jjee$ (25%), where I specify in parentheses the associated

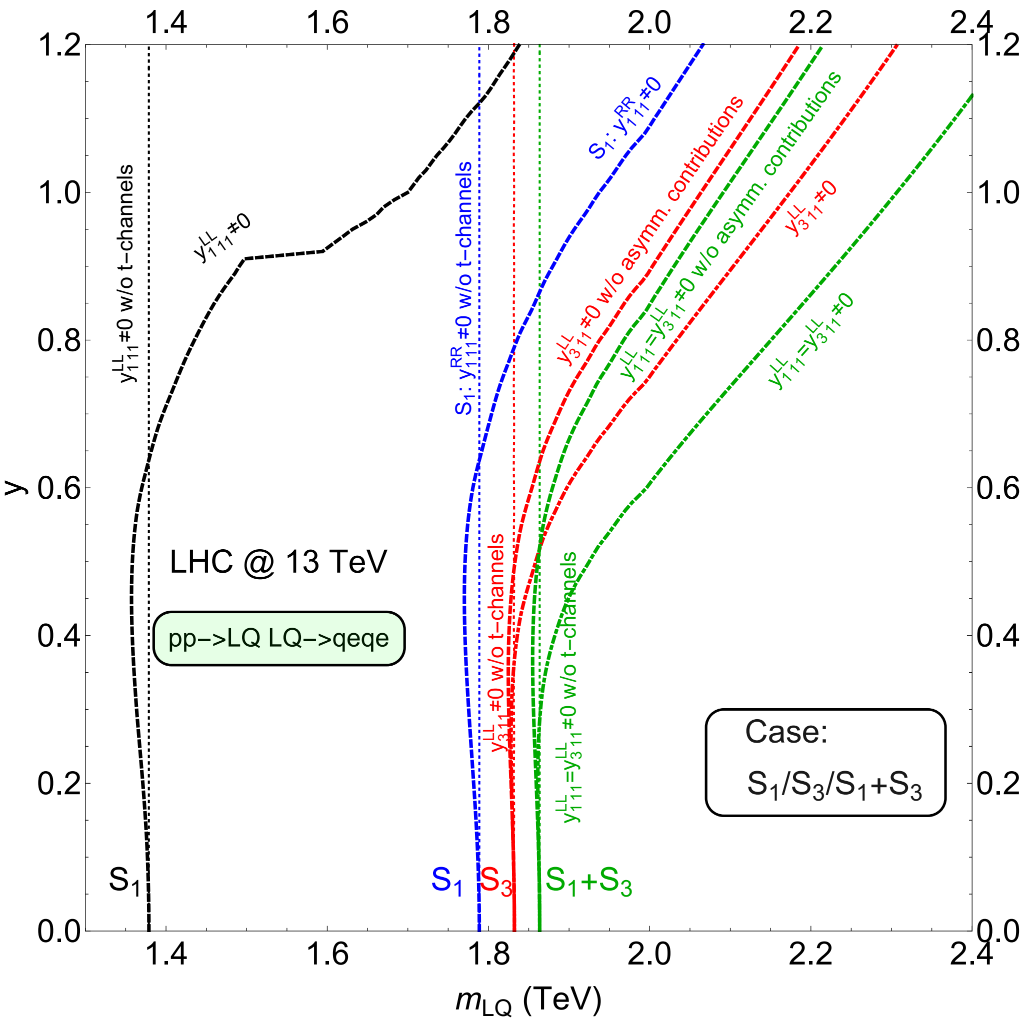

Figure 8: The leptoquark parameter space limits for the S_1, S_3, and S_1+S_3 scenarios extracted from the $pp \to \mathrm{LQ}\overline{\mathrm{LQ}} \to jjee$ process search [7] performed at 13 TeV center-of-mass energy of proton-proton collisions at the LHC, using an integrated luminosity of 139 fb^{-1}. See text for more details.

decay rate into the $jjee$ final state for each of these processes. Note that the last two processes are both $u\bar{u}$ and $d\bar{d}$ initiated. In fact, S_1+S_3 scenario is the only $\Delta F = 0$ scenario that features asymmetric production initiated with the $q\overline{q'}$ combination, where both q and q' are of the same type of flavor. Moreover, these same-flavor contributions always come in pairs as they are simultaneously generated by the up-type and down-type quarks. This is the reason why I opted to present combinations $\sigma^{\text{pair}}_{u\bar{u}} + \sigma^{\text{pair}}_{d\bar{d}}$, $\sigma^{\text{pair}}_{u\bar{c}} + \sigma^{\text{pair}}_{d\bar{s}}$, $\sigma^{\text{pair}}_{c\bar{u}} + \sigma^{\text{pair}}_{s\bar{d}}$ and $\sigma^{\text{pair}}_{c\bar{c}} + \sigma^{\text{pair}}_{s\bar{s}}$ in Fig. 4 instead of individual $q\overline{q'}$ contributions.

If one properly includes all the relevant processes that yield the $jjee$ final state, one obtains a limit on the S_1+S_3 scenario parameter space that is given by a thick dot-dashed green curve in Fig. 8. The parameter space to the left of that curve is excluded by the ATLAS Collaboration search for the $pp \to \mathrm{LQ}\overline{\mathrm{LQ}} \to jjee$ process [7].

2. Conclusions

This work discusses the asymmetric leptoquark pair production mechanism at the LHC. A sharp difference between the conventional leptoquark pair production and the asymmetric one is that for the latter, which is produced via t-channel lepton exchange, the pairs of produced leptoquarks are not conjugate states of each other. I spell out necessary conditions for an operational asymmetric leptoquark pair production mechanism and catalog all possible combinations of leptoquark multiplets that can potentially generate it. I also demonstrate how to properly combine asymmetric and conventional pair production mechanism effects by considering several scenarios where the SM is extended with either one or two scalar leptoquark multiplets. I finally advocate, using a recast of available experimental searches, that contributions from asymmetric pair production should be included when deriving reliable constraints on leptoquark parameter space as well as be used when attempting to perform correct identification of these promising new physics sources.

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