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Leptoquark production at LHC

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Abstract. Leptoquarks are hypothetical bosonic particles with a unique property; they can transform quarks into leptons and vice versa. There is a large number of scientific articles that cover questions of the leptoquark production and ways of their detection at Large Hadron Collider (LHC). LHC can produce leptoquarks in several different ways. The production mechanism that is best studied in literature is the pair production which is dominant for small Yukawa couplings. However, with the increase of the Yukawa couplings, the phenomenology of leptoquarks becomes more interesting and diverse. Namely, for large Yukawa couplings there are also additional leptoquark production mechanisms: t-channel production, single production, Drell-Yan di-lepton production and a resonant production. Moreover, there has recently been introduced a novel leptoquark production mechanism that is of the t-channel topology which gives asymmetric leptoquark pairs in the final state. The novel production mechanism has the potential to be complementary to other leptoquark production mechanisms in limiting certain parts of the parameter space that is described by the relevant Yukawa couplings and leptoquark masses. This article will provide the most recent studies of that particular leptoquark production mechanism at LHC.

1. Introduction

Leptoquarks are hypothetical particles that have the ability to transform quarks into leptons and vice versa. This transformation is possible because in Grand Unification Theories (GUT) there is not only the unification of forces but also a unification of matter, so that quarks and leptons become elements of a higher symmetry multiplet, which then results in the transition of a lepton to a quark and vice versa. Therefore, the discovery of leptoquarks would represent a signal for the unification of matter. Accordingly, leptoquarks are a very interesting source of new physics and are often present in phenomenological extensions of the Standard Model [1].

Leptoquarks are bosonic particles that can have spin zero ($s = 0$) - scalar leptoquarks and spin one ($s = 1$) - vector leptoquarks (which are not in the focus of my research). A list of five possible scalar leptoquark multiplets is given in table 1, where their names are shown in the first column. In the brackets of the second column are listed their associated transformation properties under the gauge group of the Standard Model $SU(3) \times SU(2) \times U(1)$. The first two numbers show how the field in question transforms under $SU(3)$ and $SU(2)$, respectively, and to distinguish them from ordinary numbers they are always in bold. Leptoquarks are triplets (antitriplets) of colour and can be triplets, dublets or singlets under $SU(2)$ (as indicated by the subscript in the leptoquark multiplet symbol). The third number in the brackets represents the transformation under $U(1)$ and is indeed a number, the so-called hyper-charge Y. As shown in table 1, the sign $\sim$ is used to distinguish leptoquarks that have the same transformation properties under

Table 1. List of five possible scalar leptoquark multiplets: S_3, R_2, $\tilde{R}_2$, $\tilde{S}_1$ and S_1. See text for details.

LQ Symbol	$SU(3) \times SU(2) \times U(1)$	F
S_3	$(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	-2
R_2	$(\mathbf{3}, \mathbf{2}, 7/6)$	0
$\tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, 1/6)$	0
$\tilde{S}_1$	$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	-2
S_1	$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	-2

$SU(2)$ and different hyper-charges (see, for example, scalar leptoquark multiplets R_2 and $\tilde{R}_2$). The hyper-charge Y is connected to the electric charge Q through a relation:

$$Q = I_3 + Y, \tag{1}$$

where I_3 is the diagonal generator of the $SU(2)$ gauge group. Thus, the electric charge eigenvalues of scalar leptoquark multiplets in table 1 are: $S_3^{+4/3}$, $S_3^{+1/3}$, $S_3^{-2/3}$, $R_2^{+5/3}$, $R_2^{+2/3}$, $\tilde{R}_2^{+2/3}$, $\tilde{R}_2^{-1/3}$, $\tilde{S}_1^{+4/3}$ and $S_1^{+1/3}$.

The last column of table 1 lists the fermion numbers F, specially introduced for leptoquarks. The fermion number is the sum of the three times the baryon number B and the lepton number L of leptons and quarks that a given leptoquark couples to:

$$F = 3B + L. \tag{2}$$

As shown in table 1, the possible values for the fermion number are: $F = -2$ and $F = 0$. A leptoquark with a fermion number $F = -2$ exclusively couples (decays) into a quark and a lepton, while a leptoquark with a fermion number $F = 0$ couples (decays) into a quark and antilepton or antiquark and a lepton.

2. Leptoquark production mechanisms at LHC

There is a large number of scientific articles that cover questions of the leptoquark production and ways of their detection at Large Hadron Collider (LHC). LHC can produce leptoquarks in several different ways that are analysed next.

2.1. Pair production of leptoquarks

The production mechanism that is best studied in literature is the pair production of leptoquarks [2–10]. There are two processes of this type at the LHC. The first process is the gluon-gluon fusion

$$g + g \to LQ + LQ^* \tag{3}$$

shown in figure 1. The products of proton-proton collisions through this mechanism are the leptoquark LQ and its charge-conjugate LQ^*. The second process of the leptoquark pair production at LHC is the quark-antiquark annihilation (see figure 2)

$$q + \bar{q} \to LQ + LQ^* \tag{4}$$

where q represents a quark ($q = u, d, s, c, b$) from one proton and $\bar{q}$ an antiquark from another proton which collide. Of course, as in gluon-gluon fusion, there is a leptoquark-antileptoquark pair in the final state of this process.

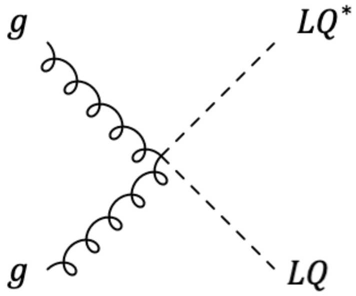

Figure 1. Feynman diagram relevant for the gluon-gluon fusion.

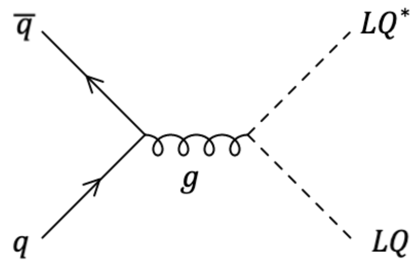

Figure 2. Feynman diagram relevant for the quark-antiquark annihilation.

Since there are a very few antiquarks compared to the number of quarks in proton-proton collisions characteristic for the LHC, the leading pair production process is then the gluon-gluon fusion.

The leptoquark pair production at the LHC is dominant for small Yukawa couplings. In other words, the conventional leptoquark pair production at LHC is dominant only when the leptoquarks are not strongly coupled to Standard Model quarks and leptons. However, with the increase of the Yukawa couplings, the phenomenology of leptoquarks becomes more interesting and diverse. Namely, for large Yukawa couplings there are also additional leptoquark production mechanisms.

2.2. t-channel production

First on the list is t-channel leptoquark production. This mechanism is realized through the quark-antiquark annihilation process shown in figure 3, where y (y^*) represents Yukawa coupling of a quark q (antiquark $\overline{q}$) and a lepton l with the leptoquark LQ (antileptoquark LQ^*).

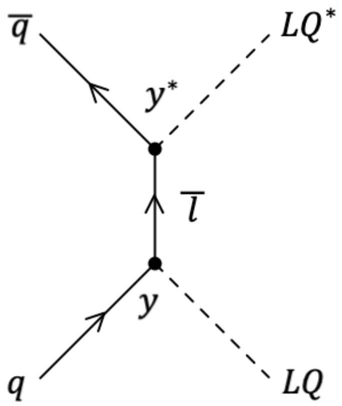

Figure 3. Feynman diagram relevant for the t-channel leptoquark production.

Accordingly, the products of proton-proton collisions through the t-channel mechanism are leptoquark LQ and its charge-conjugate LQ^*.

2.3. Single leptoquark production

The next production mechanism is the single leptoquark production [11–14], when a gluon g from one proton collides with a quark q from another proton creating only one leptoquark LQ

and a lepton l in the final state. Process of the single leptoquark production looks like

$$g + q \to LQ + l. \tag{5}$$

Feynman diagrams that correspond to the single leptoquark production are given by figures 4 and 5. Figure 4 shows the s-channel, while the figure 5 shows the t-channel of the single scalar

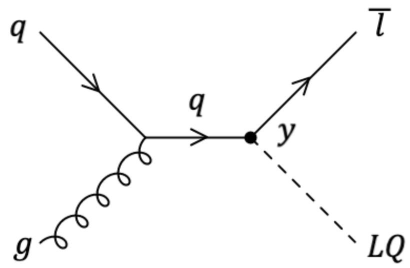

Figure 4. Feynman diagram relevant for the s-channel single leptoquark production mechanism.

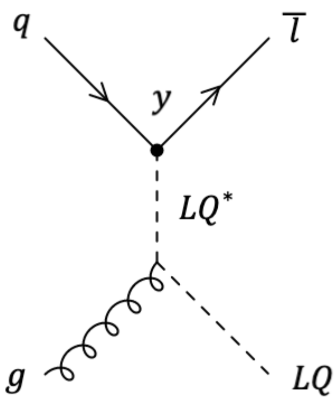

Figure 5. Feynman diagram relevant for the t-channel single leptoquark production mechanism.

leptoquark production mechanism. In both cases, y is the Yukawa coupling of a quark and a lepton with the leptoquark.

2.4. Drell-Yan di-lepton production

The scalar leptoquarks can be produced both directly, as it has been presented so far, and indirectly. Indirect leptoquark production takes place in processes of the Drell-Yan type [15–20]; through the quark-antiquark annihilation

$$q + \overline{q} \to l^+ l^- \tag{6}$$

with two oppositely charged leptons l^+ and l^- in the final state. Feynman diagram that corresponds to the Drell-Yan di-lepton production mechanism is given by figure 6.

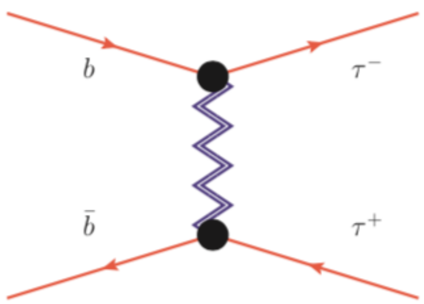

Figure 6. Feynman diagram relevant for the Drell-Yan di-lepton leptoquark production [15].

Figure 6 is taken from the article [15] and it shows the process of the b-quark and $\overline{b}$-antiquark annihilation where two oppositely charged leptons τ^- and τ^+ are created in the final state.

2.5. Resonant leptoquark production

As presented thus far, the processes usually studied at LHC are quark and/or gluon initiated in proton-proton collisions. However, there are several recent scientific articles [21–24] that claim that there is a possibility of studying lepton initiated processes at the LHC. This means that there is yet another scalar leptoquark production mechanism at LHC, the so-called resonant production. The simplest process of this type (see figure 7 taken from the article [24]) consists of the collison of the lepton l from one proton and quark q from another, creating a single leptoquark LQ that decays into a lepton and a quark:

$$l + q \to LQ \to l + q. \tag{7}$$

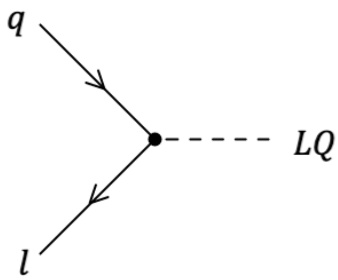

Figure 7. Feynman diagram relevant for the resonant leptoquark production [24].

3. Novel leptoquark pair production at LHC

Let us return to figure 3 which shows the relevant Feynman diagram for the conventional t-channel leptoquark production mechanism. As shown on the diagram, there are quark q and antiquark $\overline{q}$ in the initial state, while the products of the proton-proton collisions through this mechanism are two leptoquarks: leptoquark LQ and its charge-conjugate LQ^* in the final state. Therefore, this production mechanism can be called the symmetric t-channel leptoquark production.

However, it has already been stated that in proton-proton collisions characteristic for the LHC, there are a very few antiquarks compared to the number of quarks, so the authors of the article [25] came up with the idea of having two quarks in the initial state of the pair production mechanism that is of the t-channel topology, whereby the quarks do not have to be the same flavour. For example, see figures 8 and 9, where u is the up quark and d is the down quark. The idea of having two quarks in the initial state makes this novel leptoquark production mechanism ideal for studying at LHC.

As shown in the Feynman diagrams given in figures 8 and 9, the novel production mechanism can be, for example, uu or ud initiated, respecitively. The products of the proton-proton collisions through this mechanism are two different leptoquarks: leptoquark LQ_1 and leptoquark LQ_2. It can be seen that leptoquarks LQ_1 and LQ_2 have an explicitly labeled electric charge with superscripts; $LQ_1^{+5/3}$ and $LQ_2^{-1/3}$ for the uu initiated production and $LQ_1^{+2/3}$ and $LQ_2^{-1/3}$ for the ud initiated novel pair production mechanism. Of course, y_1 and y_2 in the relevant Feynman diagrams represent the non-negligible Yukawa couplings between these two leptoquarks and the Standard model quarks in the initial state and the lepton exchanged in the t-channel.

The most important fact to emphasize is that the leptoquark LQ_1 is not the antiparticle of the leptoquark LQ_2 and vice versa. In other words, the products of the proton-proton collisions through novel leptoquark production mechanism are two leptoquarks LQ_1 and LQ_2 that are not charge conjugates of each other. Therefore, this leptoquark production mechanism is called the asymmetric t-channel leptoquark production at LHC.

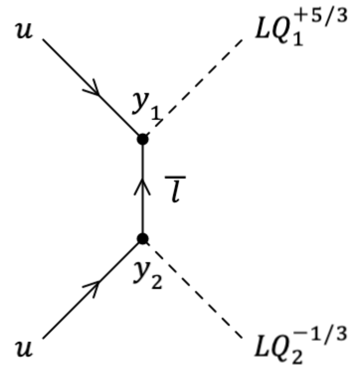

Figure 8. Relevant leading order Feynman diagram for the asymmetric leptoquark pair production at LHC that is uu initiated.

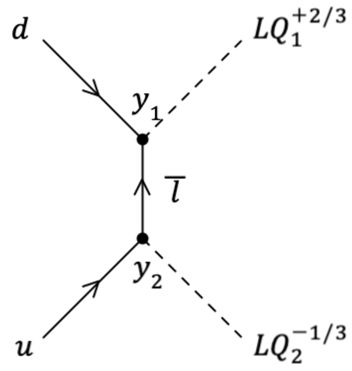

Figure 9. Relevant leading order Feynman diagram for the asymmetric leptoquark pair production at LHC that is ud initiated.

The article [25] also presents the physics potential of this novel asymmetric production mechanism by a detailed analysis of the $S_1 - R_2$ mass-degenerate ($m_{R_2} = m_{S_1} = m_{LQ}$) scalar leptoquark pair production for which one needs the leading order Feynman diagrams given by figures 8 and 9. In the article is shown a comparison between the cross section σ_{uu} of the uu initiated asymmetric leptoquark pair production

$$pp \to R_2^{+5/3} + S_1^{-1/3}, \tag{8}$$

the cross section of the conventional leptoquark pair production $\sigma_{\mathrm{P}u}$ for the processes:

$$pp \to S_1^{+1/3} + S_1^{-1/3} \tag{9}$$

$$pp \to R_2^{+5/3} + R_2^{-5/3} \tag{10}$$

and single production cross section $\sigma_{\mathrm{S}u}$ for the processes:

$$pp \to S_1^{+1/3} + \mu^- \tag{11}$$

$$pp \to S_1^{-1/3} + \mu^+ \tag{12}$$

$$pp \to R_2^{+5/3} + \mu^- \tag{13}$$

$$pp \to R_2^{-5/3} + \mu^+. \tag{14}$$

An identical comaparison has been made between the cross section σ_{ud} of the ud initiated asymmetric leptoquark pair production

$$pp \to R_2^{+2/3} + S_1^{-1/3}, \tag{15}$$

the cross section of the conventional leptoquark pair production $\sigma_{\mathrm{P}d}$ for

$$pp \to R_2^{+2/3} + R_2^{-2/3} \tag{16}$$

and single production cross section $\sigma_{\mathrm{S}d}$ for the processes:

$$pp \to R_2^{+2/3} + \mu^- \tag{17}$$

$$pp \to R_2^{-2/3} + \mu^+. \tag{18}$$

As a result, the authors obtained a parametric space (see figures 10 and 11 taken from the article [25]) in which asymmetric production mechanism dominates over all conventional production mechanisms both for uu:

$$\sigma_{uu} > \sigma_{\mathrm{S}u} > \sigma_{\mathrm{P}u} \tag{19}$$

and ud case:

$$\sigma_{ud} > \sigma_{\mathrm{S}d} > \sigma_{\mathrm{P}d}. \tag{20}$$

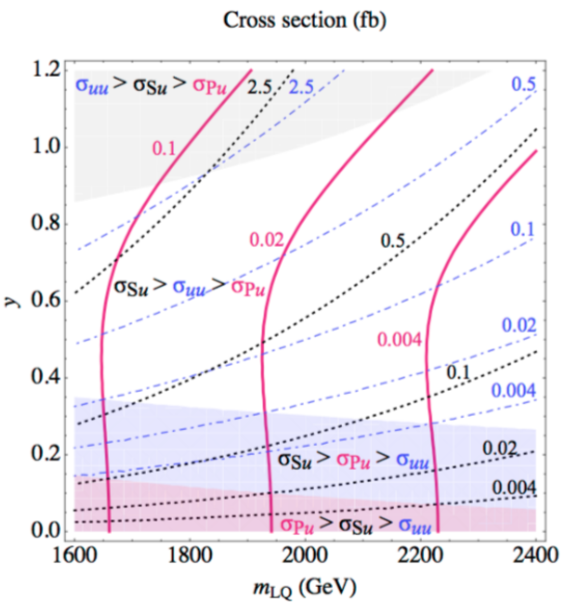

Figure 10. The contours of constant value cross section for the asymmetric pair production σ_{uu}, conventional pair production σ_{Pu} and single production σ_{Su} as fuction of leptoquark mass m_{LQ} and Yukawa coupling y. Values of cross sections are expressed in femtobarn units.

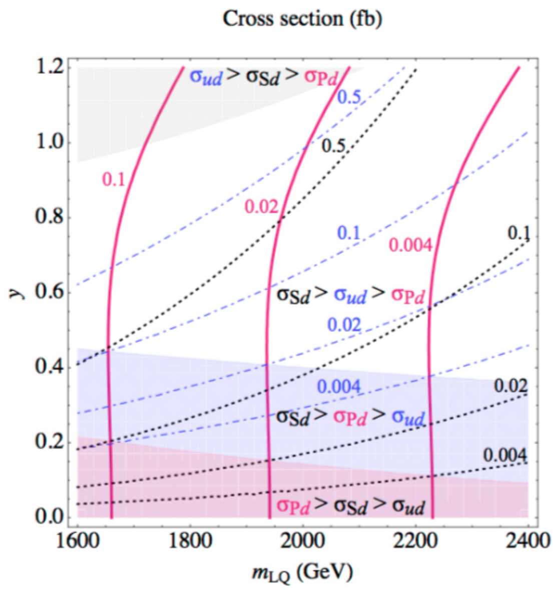

Figure 11. The contours of constant value cross section for the asymmetric pair production σ_{ud}, conventional pair production σ_{Pd} and single production σ_{Sd} as fuction of leptoquark mass m_{LQ} and Yukawa coupling y. Values of cross sections are expressed in femtobarn units.

4. Conclusions

This article provides an overview of all leptoquark production mechanisms at LHC that have been known in the literature so far. Although there is a large number of scientific articles covering leptoquark production mechanisms, the article [25] recently showed that the asymmetric pair production has the potential to be more important than other leptoquark production mechanisms in limiting certain parts of the leptoquark parameter space that is described by the relevant Yukawa couplings and leptoquark masses. This has been done by analyzing one specific example of $S_1 - R_2$ asymmetric leptoquark production that is quark-quark initiated.

In table 1 it can be seen that the fermion numbers of the produced scalar leptoquarks in question differ by two

$$|F(R_2) - F(S_1)| = 2. \tag{21}$$

Translated into leptoquark language, this means that the quark-quark initiated asymmetric leptoquark production will occur when leptoquarks S_3 or $\tilde{S}_1$ or S_1 are combined with either leptoquark R_2 or leptoquark $\tilde{R}_2$.

However, quark-quark initiated asymmetric leptoquark pair production is not the only possibility for this novel production mehanism. Looking at table 1, two different leptoquarks LQ_1 and LQ_2 which are not charge conjugates of each other, with equal fermion numbers

$$|F(LQ_1) - F(LQ_2)| = 0 \tag{22}$$

can also be produced through the asymmetric pair production. This process would be quark-antiquark initiated. Therefore, the authors plan to analyze and systematize all possible combinations that lead to asymmetric leptoquark pair production at LHC in their future work.

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