Leptoquark Pair Production at the Fermilab Tevatron: Signal and Backgrounds

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Abstract

We perform a simulation of scalar leptoquark pair production at the Tevatron ($\sqrt{s} = 1.8$ TeV and $\mathcal{L} = 100$ pb$^{-1}$) with ISAJET. We also investigate the dominant sources of Standard Model background: $Z^*jj$, $ZZ$, $WZ$ production and heavy quark $t\bar{t}$. We find that the $Z^*jj$ background is dominant. We also evaluate the signal-to-background ratio and find a discovery reach of 130 GeV (170 GeV) for a branching ratio of $BR(LQ \rightarrow eq) = 0.5$ ($BR = 1$).
I. INTRODUCTION

Symmetry considerations such as family replication, anomaly cancellation and symmetry between generations are the main motivations behind the prediction of leptoquarks. They are color-triplet particles which possess baryon number ($B$) and lepton number ($L$). They arise in various extensions of the Standard Model (SM): GUT’s [1], Strongly Coupled Standard Model [2], composite models [3], superstring-inspired models [4], where they appear as scalar, vector or even fermionic particles.

Leptoquarks (LQs) could in principle be produced in $e^+e^-$ [5], $e\gamma$ [6], $ep$ [7] and hadron colliders [8,9,10,11]. But hadron colliders have two advantages: the production is almost insensitive to the Yukawa coupling and the available center-of-mass energy ($\sqrt{s}$) is much higher. We perform our calculations with the Tevatron in mind, taking $\sqrt{s} = 1.8$ TeV and $L = 100$ pb$^{-1}$. The current limits imposed on first generation LQ mass by the D0 collaboration are 133 GeV for BR$\left(LQ \rightarrow eq\right) = 1$ and 120 GeV for BR$\left(LQ \rightarrow eq\right) = 0.5$ and BR$\left(LQ \rightarrow \nu q\right) = 0.5$ [12]. The object of the present paper is to evaluate the importance of SM background ($Z^* jj$ where the $Z$ is virtual, $ZZ$, $WZ$ and $t\bar{t}$ events) when producing a pair of scalar leptoquarks in the context of an $E_6$ model. So far, these major sources of background have only been identified [10] but no quantitative analysis has been made. We implemented leptoquark data into the ISAJET event generator to achieve this goal.

In this paper, we look at the pair production of first generation $E_6$ scalar leptoquarks with $Q = -1/3$ and evaluate the importance of the SM sources of background for this signal. In the next section, we first describe the $E_6$ model. In Section 3, we give the details of our simulation for the detector and the calorimeter plus the kinematic cuts that are imposed. The LQ signal and the SM backgrounds ($Z^* jj$, $ZZ$, $WZ$ and heavy quark pair production) are discussed in Section 4. We analyze the results in Section 5 and conclude in the following section.

II. FRAMEWORK

Up to now, the SM provides a satisfactory description of phenomenology. However, many problems still remain. Among them, we find gauge hierarchical and fine tuning problems, no explanation for the existence and the number of fermion families and too many parameters to be extracted from experiment.

In the context of an $E_6$ model [13], the low-energy limit of an $E_8 \otimes E_8'$ heterotic string theory, the gauge hierarchical and fine tuning problems no longer appear due to the supersymmetric nature of the theory. In $E_6$ superstring models, each matter supermultiplet lies in the fundamental 27 representation which may explain the replication of fermion families. Another attractive feature of the model lies in the predictions it makes about low-energy physics. The 27 representation possess the following $SO(10)$ and $SU(5)$ contents:

$$27 = [16 + 10 + 1] = [10 + \bar{5} + 1] + [\bar{5} + \bar{5}] + [1].$$  \hspace{1cm} (1)

The particles belonging to this representation can be arranged as:

$$27 = [(u^c, Q, e^+) + (L, d^c) + \bar{\nu}^c] + [(D, H) + (D^*, H^*)] + N$$  \hspace{1cm} (2)
where we have the usual quarks and leptons and their superpartners along with new particles such as two five-plets \((D, H)\) and \((D^*, H^*)\) and an \(SU(5)\) superfield singlet \(N\). In particular, the superfields \(D\) and \(D^*\) are two \(SU(3)\) triplets and \(SU(2)\) singlets with electromagnetic charge \(-1/3\) and \(+1/3\) respectively. They possess \(B = \pm 1/3\) and \(L = \pm 1\). Contrary to the usual notation, those particles are supersymmetric and we denote their non-supersymmetric partners as \(\tilde{D}\) and \(\tilde{D}^*\). Thus, scalar leptoquarks come out naturally for an \(E_6\) model. Restricting our study to the first generation of fermions, the Yukawa Lagrangian will take the form:

\[
\mathcal{L}_Y = \lambda_L \tilde{D}^* (\bar{e}_L u_L + \nu_L d_L) + \lambda_R \tilde{D} \bar{e}_L \bar{u}_L + \text{h.c.} \tag{3}
\]

where \(\lambda_L\) and \(\lambda_R\) are chosen to be equal to the electromagnetic charge otherwise there would be important effects in the process \(e^+ e^- \rightarrow q \bar{q}\) arising from the LQ exchange.

### III. EVENT SIMULATION

#### A. Detector and calorimeter

We use ISAJET, a Monte-Carlo event simulator, to model the experimental conditions at the Tevatron. We simulate a toy detector with the following characteristics for the calorimeter:

- cell size: \(\Delta \eta \times \Delta \phi = 0.1 \times 0.0875\),
- pseudorapidity range: \(-4 < \eta < 4\),
- hadronic energy resolution: \(70\% / \sqrt{E}\),
- electromagnetic energy resolution: \(15\% / \sqrt{E}\).

#### B. Kinematic cuts

In order to qualify as a jet, any hadronic shower must satisfy the following kinematic cuts:

- lie within a cone of radius \(R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.7\),
- have a transverse energy \(E_T > 25\) GeV,
- have a pseudorapidity \(|\eta_j| \leq 3\).

Similarly, we must impose some cuts on the leptons. More specifically, electrons are considered isolated if they:

- are separated from any jet by \(R \geq 0.3\),
• have a transverse momentum $p_T > 25$ GeV,
• have a pseudorapidity $|\eta| \leq 2.5$.

Our calculations are performed using the PDFLIB distribution functions of Morfin and Tung (M-T B2) with $\Lambda = 191$ GeV [13].

IV. SIGNAL AND BACKGROUNDS

A. Leptoquark signal

We study the pair production of $E_6$ scalar leptoquarks with $Q = -1/3$ decaying into an up quark and an electron or into a down quark and an electron neutrino with branching ratios of $BR(LQ \to eq) = BR(LQ \to \nu q) = 0.5$. For comparison, we also consider the case of a leptoquark decaying into an up quark and an electron with $BR(LQ \to e\nu) = 1$. In both cases, we assume a Yukawa coupling with $k = 1$ in $\alpha_Y = k\alpha_{em}$.

The leptoquark pair production can occur via two different channels, either via $q\bar{q}$ annihilation $q\bar{q} \to \tilde{D}\tilde{D}^*$ or gluon fusion $gg \to \tilde{D}\tilde{D}^*$. The corresponding Feynman diagrams are shown in Fig. 1. For the details of the calculation of the cross section, we refer the reader to Ref. [11]. We expect the first of these channels to dominate at the Tevatron.

In the case $BR = 0.5$, we obtain three different signals [10]:

(a) 2 jets + $e^+e^-$
(b) 2 jets + $p_T$
(c) 2 jets + $e^\pm + p_T$.

The most distinctive of these signals [10] should be (a) but apart from that, very little is known about the signal and backgrounds expected from the SM. The background for signal (b) and (c) should be more important due to the missing transverse momentum ($p_T$). For the purposes of this paper, we therefore restrict ourselves to 2 jets + $e^+e^-$. For simplicity, we impose the same $E_T$ cut values on the jets and the leptons: 25 GeV, 30 GeV, 35 GeV, 40 GeV.

B. SM Backgrounds

The most probable sources of background as identified by Refs. [11] are (1) $Z^*jj$, (2) $ZZ$, $WZ$ and (3) $t\bar{t}$ production (in which the top is decaying into a $W$ and a $b$ quark). Backgrounds from $bb$ and $c\bar{c}$ are ignored. Previous estimates have shown them to be negligible [4]. The Feynman diagrams of the background processes are shown in Fig. 2.

1. $Z^{*}jj$ background

The $Z^{*}jj$ background proceed through a Drell-Yan virtual $Z$ (producing a pair of leptons) along with two jets: $p\bar{p} \to Z^{*}jj \to e^+e^-jj$ where $j = q, \bar{q}, g$. We consider this background for an invariant mass of the lepton pair ranging from 100 GeV to 260 GeV.
2. ZZ and WZ background

Other possible sources of background come from the production of a pair of Z bosons with one of the Z decaying into a lepton pair and the other one decaying into a pair of quarks and/or the production of a Z and a W with the Z decaying into a lepton pair and the W decaying into a pair of quarks. We calculated those backgrounds and found them negligible. The small magnitude of this background can be explained by the fact that ZZ and WZ productions are suppressed by $\alpha_{W}^2$, where $\alpha_{W}$ is the weak coupling with respect to the LQ process and the $t\bar{t}$ background which involve only strong interactions and a factor of $\alpha_{s}^2$ with $\alpha_{s} \simeq 0.1$. Therefore, we will not consider those background processes any further. In any case, the study of the invariant mass of the pairs could single them out.

3. $t\bar{t}$ background

The final background process we consider comes from $t\bar{t}$ where the top is decaying into a bottom, an electron and a neutrino, $\nu_e$. The presence of neutrinos implies a $p_T$ and a less energetic electron. However, our analysis has shown that this process can provide some very energetic jets and thus be an important source of background. We consider $M_{t}$=175 GeV.

V. DISCOVERING LEPTOQUARKS AT THE TEVATRON

In Fig. 3, we first show the results for the total cross section for the leptoquark signal (2 jets + $e^+e^-$) as a function of the leptoquark mass, $M_{LQ}$ (solid lines). For comparison, we also show the $t\bar{t}$ background (dashed lines) evaluated at $M_{t}$=175 GeV as well as the $Z^*jj$ background (dot-dashed lines) integrated over an invariant mass of the lepton pair ranging from 100 GeV to 260 GeV. The $Z^*jj$ signal dominates the background while the $t\bar{t}$ signal is relatively small. Requiring a statistical significance $\geq 5\sigma$, where $\sigma = N_{signal}/\sqrt{N_{bckg}}$, we find that the leptoquark signal dominates the background for leptoquark masses up to 150 GeV (200 GeV) for $BR = 0.5$ ($BR = 1$). These ranges are found to be insensitive to the value of $E_T$ as long as it remains in the region $25$ GeV $\leq E_T \leq 40$ GeV.

The $t\bar{t}$ background is higher than the heavy quark background predicted by D0 coming from $c\bar{c}$ and $b\bar{b}$ due to the masses of the particles involved. The relevance of this background can be associated to the available transverse energy which is comparable to that in the leptoquark process analyzed in this work. The absence of missing $p_T$ is however characteristic in the LQ case. In fact, such a cut increases the signal-to-background ratio even more but reduces the signal by about 10%. However, since the $t\bar{t}$ background is not significant here, we chose not to include this cut in the rest of the analysis.

In general, one expects that in leptoquark production there will be a strong lepton-jet correlation due to the leptoquark decay while such correlation should be absent in $t\bar{t}$ and $Z^*jj$ backgrounds. Indeed, even if the signal and background total cross-section were comparable in magnitude, there can still be a detectable signal in the form of a peak in the invariant mass distribution of the lepton-jet pairs. The distribution in the invariant mass of the lepton-jet pairs are presented in Figs. 4-5 for the various processes for $E_T = 25$ GeV and 35 GeV respectively. The invariant mass $M_{ej}$ was calculated by pairing the most energetic electron.
with the least energetic jet. This particular choice is based on the reasonable assumption that the two leptoquarks will emerge with approximately the same energy and that this lepton-jet pair will correspond to the decay products of the same leptoquark. Each figure displays the leptoquark signal for leptoquark mass inputs of $M_{LQ} = 130$ GeV (solid lines), $M_{LQ} = 150$ GeV (dashed lines) and $M_{LQ} = 170$ GeV (dash-dotted lines) as well as the background due to the $Z^*jj$ (dash-dot-dot-dotted lines) and the $t\bar{t}$ (dotted lines) processes. Here, we have applied an invariant mass cut on the lepton pairs with $81 \text{ GeV} \leq M_{e^+e^-} \leq 101 \text{ GeV}$ in order to eliminate the events near the $Z^0$ peak and minimize the $Z^*jj$ background. 

We see from Figs. 4-5 that the optimal $E_T$ cut is 25 GeV. An $E_T$ cut of 35 GeV reduces the background significantly. Our results show the expected strong lepton-jet correlation in the leptoquark signal. The $Z^*jj$ background is mostly concentrated between $50 \leq M_{ej} \leq 100$ GeV but remains the dominant background for all values of the invariant mass. The $5\sigma$ statistical significance is satisfied for $M_{LQ} = 130$ and 150 GeV with an $E_T$ cut of 25 GeV.

In order to estimate the relative importance of the signal to the background near the peak in the $M_{ej}$ distribution, we calculate the partial cross section $\Delta \sigma$ within a bin of width $\Delta M_{ej} = 60$ GeV around $M_{ej} = M_{LQ}$ as a function of the invariant mass of the electron-jet pair for $E_T = 25$ GeV. The calculations repeated for several intermediate values of $M_{LQ}$ and are shown in Fig. 6. We can then see more clearly how that the signal-to-background ratio is affected by the leptoquark mass. Also, we find that the $5\sigma$ statistical significance condition is satisfied for $M_{LQ} \leq 150$ GeV.

Coming back to figure 3, we can estimate the discovery reach of scalar leptoquarks at the Tevatron. To that effect, we require a minimum of 10 events in addition to the $5\sigma$ statistical significance condition imposed on the background. The integrated luminosity for the Tevatron current run is 100 pb$^{-1}$ which leads to a discovery mass limit of 130 GeV for $E_T = 25$ GeV (Fig. 3). A similar estimate can be easily carried for leptoquarks that decay with $BR(LQ \rightarrow eq) = 1$ by arguing that the cross section for the production of 2 jets $+ e^+e^-$ is four times larger in this case. Accordingly, the discovery reach is increased up to 170 GeV. On the other hand, the proposed luminosity upgrades of the Tevatron should enhance significantly the signal and increase the discovery reach to approximately 200 GeV for $BR = 0.5$ (with a luminosity 2 fb$^{-1}$).

Summarizing, we carried out a simulation for first-generation scalar leptoquark pair production within the context of an $E_6$ model taking into account the SM backgrounds for the most promising signal, i.e. 2 jets $+ e^+e^-$. The results are found to be sensitive on the choice of $E_T$ cut for the jets and while background is dominated by the $Z^*jj$ process, it does not overwhelm the signal for leptoquarks at the Tevatron. We find a discovery mass limit of 130 GeV ($BR = 0.5$) and 170 GeV ($BR = 1$) for an optimum $E_T$ cut of 25 GeV.

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FIGURES

FIG. 1. Feynman diagrams for leptoquark pair production via ((a), (b)) $q\bar{q}$ annihilation and
((c), (d), (e), (f)) gluon fusion.

FIG. 2. Examples of Feynman diagrams for (a) $Z^*jj$, (b) $ZZ$ pair and (c) $t\bar{t}$ production.

FIG. 3. Integrated cross section for the production of 2 jets + $e^+e^-$ as a function of the leptoquark mass for $E_T = 25$ GeV. The full line corresponds to the leptoquark signal versus the leptoquark mass ($M_{LQ}$), the dash-dotted line to the total $Z^*jj$ background and the dashed line to $t\bar{t}$ background for $M_t=175$ GeV.

FIG. 4. Distribution of the invariant mass of the lepton-jet pair for the production of 2 jets + $e^+e^-$ for $E_T = 25$ GeV. The solid, dashed and dashed-dotted lines correspond to the leptoquark signal with $M_{LQ}=130$, 150 and 170 GeV respectively. The dash-dot-dot-dotted lines correspond to the $Z^*jj$ background and the dotted lines to $t\bar{t}$ background (at the bottom of the plot).

FIG. 5. Same as Fig. 3 but for $E_T = 35$ GeV.

FIG. 6. Partial cross section within a bin of width $\Delta M_{ej}=60$ GeV around $M_{ej} = M_{LQ}$ as a function of the invariant mass of the electron-jet pair for $E_T = 25$ GeV.
Figure 1
Figure 2
Figure 6

$E_T = 25 \text{ GeV}$

$\Delta \sigma (fb)$ vs $M_{ej} (GeV)$