Feasibility of Detecting Leptoquarks Decaying to Neutrinos Plus Jets in the Mass Range 100 to 200 GeV Using the CDF Detector

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ABSTRACT

Many extensions to the Standard Model of particle physics predict the existence of particles with the properties of both leptons and quarks. The CDF and D0 collaborations have searched for these particles in the past; leptoquarks have not yet been observed so lower limits on leptoquark mass have been established. This lower bound is least stringent in the region of low charged lepton branching ratio. We developed new searching criteria specifically for leptoquarks with a low branching ratio and mass between 100 and 200 GeV. We found that while leptoquark sensitivity was relatively independent of the minimum missing transverse energy, it was affected by the minimum jet energy. We chose a minimum jet energy that maximized our sensitivity and used our optimized cuts to obtain the expected upper limit on the leptoquark cross section for several luminosities. We obtained limits that were consistent with D0’s recent work for a luminosity of 100 pb$^{-1}$.

I. INTRODUCTION
In the Standard Model, the fundamental constituents of matter are divided into leptons, such as the electron, and quarks, which make up larger particles such as the proton. Leptons possess lepton number and quarks possess baryon number; both lepton and baryon number are conserved in all processes. Thus, the number of quarks and leptons in a system, after accounting for antiparticles, is constant. However, grand unified theories, supersymmetry, and string theory predict the existence of particles with the characteristics of both leptons and quarks [1]. These particles, called leptoquarks, would have both baryon and lepton number. Leptoquarks, like quarks and leptons, could be arranged in generations; first generation particles include the electron, electron neutrino, up quark, and down quark, whereas third generation particles include the tau particle, tau neutrino, top quark, and bottom quark.

Leptoquarks may be produced via a standard gauge coupling or via a Yukawa coupling [1]. A gauge coupling occurs when a particle and its antiparticle annihilate, producing a burst of energy. If this energy is adequately large, a new particle-antiparticle pair can be produced. For example, if a proton and an antiproton with sufficient energies collide, they may produce a leptoquark-antileptoquark pair. Yukawa couplings, on the other hand, may be probed in particle colliders such as HERA, where protons and electrons are accelerated toward each other. In this scenario, a quark from a proton and an electron may fuse into a single leptoquark. At one point leptoquarks
were believed to have been observed at HERA, but the number of leptoquark-like events was found to be statistically insignificant [1].

We should be able to detect leptoquarks using their decay signatures. A leptoquark will decay into a quark and a lepton. The quark will form a hadron jet, a large stream of composite particles such as pions, protons, and neutrons, which is then detected by the hadron calorimeter of an experiment. It is also possible to detect the lepton if it is an electron, muon, or tau particle. However, if the lepton is a neutrino, it cannot be directly detected because neutrinos have no electric charge, no color (or strong charge), and virtually no mass. The only evidence of a neutrino’s existence is an imbalance in the measured final momenta of a collision. We can separate possible leptoquark events from background events by looking for these characteristics as well as some additional criteria.

The D0 and CDF collaborations have used this approach to look for leptoquarks at the Tevatron Collider, a facility at the Fermi National Accelerator Laboratory. No leptoquarks have been found so far, but their work has eliminated the possibility of leptoquarks with masses less than 98 GeV (Fig. 1) [2-6]. Note that the lower bound on leptoquark mass is smaller for $\beta$, the charged lepton branching ratio, near 0. The branching ratio $\beta$ indicates the probability that an emitted lepton will be an electron, muon, or tau particle rather than a neutrino; thus, the lower bound on leptoquark mass is small for double neutrino emission. We plan to focus on this region, looking
for leptoquark events in the mass range 100 to 200 GeV. The sought
signature is missing transverse energy, or neutrinos, plus jets ($\nu\bar{\nu}jj$).

We use a combination of criteria to separate leptoquark objects
from background collisions; many of these cuts are similar to those
used by the D0 collaboration [4]. For example, we require the missing
transverse energy of the event to exceed 40 GeV, that there be no
fewer than two and no more than three jets with an energy above
15 GeV, and that jets be separated by at least $45^\circ$ and no more
than $165^\circ$. We are testing the efficiency of these cuts on simulated
leptoquark and background events, and we will use these results to
fine tune our cuts. We will, for instance, adjust the minimum miss-
ing transverse energy and the minimum jet energies until we achieve
the highest sensitivity to leptoquarks, which requires maximizing the
quantity

$$S/\sqrt{S+B}$$

where S is the signal and B is the background. Once we have finalized
our cuts, we will apply them to real data, and determine whether it
is possible for leptoquarks with low $\beta$ and masses between 100 GeV
and 200 GeV to exist.

II. THEORY

As previously mentioned, leptoquarks may be produced via a
standard gauge coupling or via a Yukawa coupling. For processes
sought using the CDF detector, there are five first-order Feynman
diagrams for standard gauge couplings and one-first order diagram for Yukawa couplings (Fig. 2). We were able to determine a cross section for leptoquark production using these diagrams. We also used this approach to determine the cross sections of various other events, such as the production of W and Z bosons, top quarks, and QCD background.

The efficiency of our cuts is the ratio of selected events to total events:

$$\epsilon = \frac{N_{\text{sel}}}{N_{\text{tot}}}.$$  \hfill (2)

Our goal is a high efficiency for selecting leptoquark events, and a low efficiency for any other event. We use these efficiencies along with the events’ cross sections to estimate how many events would be observed in a collider:

$$N_{\text{obs}} = \sigma \epsilon L.$$  \hfill (3)

Here $\sigma$ is the cross section and $L$ is the integrated luminosity.

The quantity we seek to maximize is the sensitivity (Eq. 1). To compute the sensitivity, we needed values for the expected number of observed leptoquark events and the number of observed background events, which we obtained using Eq. 3 and the results of our cuts. We estimated the uncertainty associated with the background in the
following manner:

\[ \text{Uncertainty} = \sqrt{\frac{N_{\text{pass}}}{N_{\text{tot}}}} \]  

(4)

where \( N_{\text{pass}} \) is the number of events that pass our cuts.

We are more sensitive to third generation leptoquarks, as illustrated by the higher mass limits on third generation leptoquarks. For this reason, we simulated third generation leptoquarks, which decay into third generation particles; for instance, a bottom quark and a tau neutrino. We used cuts that are not generation specific, but will eventually add bottom quark tagging, or b tagging.

III. PROCEDURE

Our first step was to simulate leptoquark and background events using the Pythia event generator [7]. The cdfSim program was used for our detector simulator, Production for event reconstruction, and Stntuple for event analysis. The last three programs are part of the 4.6.0 version of the CDF software. Large numbers of events were needed to determine the efficiency and decrease statistical effects; we used between 5,000 and 60,000 events for each leptoquark mass and 200,000 and 700,000 events for each background type. The third generation leptoquarks generated had masses of 100, 125, 150, 175, and 200 GeV, and background events included quantum chromodynamics, W and Z bosons, and W and Z bosons with jets. Larger numbers
of background events were required because our cuts eliminate all but a fraction of one percent. In fact, we are still statistically limited on the QCD background. At the same time, these background events have cross sections up to six orders of magnitude larger than the leptoquark cross sections; thus, a single selected event results in a large statistical deviation unless the total number of events is very large (Eq. 2).

In selecting our basic cuts, we generally followed the example of the D0 collaboration [5]. Our criteria stipulate that the missing transverse energy be greater than a certain minimum energy, and that there be exactly two or three jets with an energy exceeding another minimum energy, with no other jets above the lower energy of 7 GeV. A complete listing of our cuts is provided in Table I. We included in our cuts an electron veto (those events with electrons did not pass), which in turn required us to determine which events had electrons. The list of criteria determining whether a particle is an electron is in Table II [8].

In our attempts to maximize the sensitivity, we varied the specifics of our cuts, including the values of the minimum missing transverse energy and minimum jet energy. Once we finalized our cuts, we then used the function of experimental sensitivity as a function of background to determine the upper limits on the number of leptoquark events [9]. Our lack of experimental data led us to assume that the number of observed events of all types was the same as the predicted
number of background events, $B$. When this number of events was 15 or less, we used Feldman and Cousins' data for the averaged upper limit on the number of signal events at the 95\(^{\circ}\) confidence level [9]. When this number was larger than 15, we used the approximation

$$N_{ul} = 2\sqrt{N_b}. \quad (5)$$

We obtained this approximation from the gaussian distribution of background events. Eq. 5 breaks down for small $N_b$, but because we did not apply it to numbers smaller than 15, we avoided this problem. Once we had obtained an upper limit on the signal, we used it to determine the upper limit on the cross section:

$$\sigma_{ul} = N_{ul}/\epsilon L. \quad (6)$$

This upper limit, when plotted as a function of leptoquark mass, allowed us to determine the region on the mass vs. $\beta$ plot that we have investigated. If this area extends beyond the shaded regions in Fig. 1, then we have improved the sensitivity of leptoquark detection.

**IV. RESULTS**

We found the dependence of the sensitivity on the minimum missing transverse energy to be relatively small (Fig. 3). Before the addition of the QCD background, the sensitivity slowly decreased from 30 GeV to 40 GeV, and decreased a little more rapidly from 40 GeV
to 60 GeV. However, the statistical fluctuations caused by the few QCD background events passing (around 0 or 1 per 718130 events) dwarfed the variation in the sensitivity. We chose to use a minimum missing transverse energy of 40 GeV, even though this value does not reflect a sensitivity maximum.

Varying the minimum jet energy, on the other hand, had a noticeable effect (Fig. 4). Note that the abrupt jumps in the sensitivity for high energy values correspond to statistical variations; we had only a few, or even zero, events selected for the QCD background. Ignoring these fluctuations, we did find what appeared to be a sensitivity maximum at 35 GeV. Thus, we chose to use a minimum jet energy of 35 GeV for our final analyses.

We had intended to use electron production to differentiate between leptoquark events and W and Z boson events. W and Z bosons tend to decay into electrons, while the leptoquark events we are selecting for decay into neutrinos. We found, however, that after making the necessary cuts to determine whether a particle was an electron (Table II), only three and five percent of the W and Z boson events, respectively, contained electrons, compared to two percent of the leptoquark events. Thus, cutting events based on the presence of electrons did not make a pronounced difference in the sensitivities.

We obtained values for the cross section upper limits using the procedure mentioned earlier. We estimated the error in the background events using Eq. 4. We obtained upper and lower bounds
for the number of background events by adding and subtracting this error from the number of predicted events. We carried these bounds through our calculation; the results are upper and lower bounds on the cross section limit, as depicted in Fig. 5. We then translated these results into a $\beta$ vs. leptoquark mass plot, as seen in Fig. 6.

V. CONCLUSIONS

If no leptoquarks are found in the regions described by Fig. 6, and the number of observed events agrees with our approximation, then the leptoquark mass limit will be extended to 105 GeV for an integrated luminosity of 100 pb$^{-1}$. This limit of 105 GeV is slightly larger than the preexisting value of 98 GeV. However, we did not incorporate the uncertainty in the background limit into the calculation of the upper limit.

Because we are interested in second and third generation leptoquarks, we plan to implement heavy flavor tagging in addition to our cuts to search for those leptoquarks in particular. This will aid in eliminating $W$ and $Z$ bosons. However, top quark events also produce heavy flavor quarks, so we need to investigate this effect as well.

VI. ACKNOWLEDGMENTS

Acknowledgment is made to Dr. Darin Acosta and Dmitri Tsybychev for simulating the leptoquark and background events used, and to Dr. Darin Acosta for invaluable assistance and explanations in every aspect of this study. Thanks are also due to the Univer-
sity of Florida and the NSF for hosting and funding this Research Experience for Undergraduates project.
REFERENCES


TABLE I: Cuts used in our selection of leptoquark events.

<table>
<thead>
<tr>
<th>LQ Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Missing transverse energy $E_T \geq 40$ GeV</td>
</tr>
<tr>
<td>$0.1 \leq$ jet em fraction $\leq 0.9$</td>
</tr>
<tr>
<td>$N_J = 2$ or $3$ ($E_T \geq 35$ GeV, $</td>
</tr>
<tr>
<td>No other jets with $E_T &gt; 7$ GeV</td>
</tr>
<tr>
<td>$\min \Delta \phi(E_T, j) &gt; 45^\circ$</td>
</tr>
<tr>
<td>$\Delta \phi(E_T, j_1) &lt; 165^\circ$</td>
</tr>
<tr>
<td>$45^\circ &lt; \Delta \phi(j_1, j_2) &lt; 165^\circ$</td>
</tr>
<tr>
<td>Electron veto</td>
</tr>
</tbody>
</table>

TABLE II: Cuts used to identify electrons.

<table>
<thead>
<tr>
<th>Electron Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse energy $E_T &gt; 10$ GeV</td>
</tr>
<tr>
<td>Energy/momentum $E/P &lt; 2$</td>
</tr>
<tr>
<td>Hadronic energy/electromagnetic energy $HAD/EM &lt; 0.1$</td>
</tr>
<tr>
<td>Balance LSHR $&lt; 0.2$</td>
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</table>
Fig. 1: Lower mass limits for (a) first generation leptoquarks, (b) second generation leptoquarks, and (c) third generation leptoquarks, compiled from references 2 through 6. The abscissa is leptoquark mass, and the ordinate is the branching ratio $\beta$, the probability that the lepton produced in decay is an electron, muon, or tau rather than a neutrino.

Fig. 2: The first-order Feynman diagrams for leptoquark production in the CDF detector via standard gauge and Yukawa couplings.

Fig. 3: Sensitivity to leptoquark production as a function of the minimum missing transverse energy.

Fig. 4: Sensitivity to leptoquark production as a function of the minimum jet energy.

Fig. 5: Cross section as a function of leptoquark mass, together with over and underestimates. The middle curve was obtained by using our background data in conjunction with Feldman and Cousins’ table [9]. There is not a way to incorporate the uncertainty in the background into this 95% confidence limit; we elected to simply add and subtract the uncertainty and obtain two additional curves. We used the most conservative of the limits in our subsequent calculations. The cross section theory curve is included.

Fig. 6: The regions under the curves depict areas of possible investigation for luminosities of 100, 150, 300, 500, and 1000 pb$^{-1}$ (see Fig. 1). If no leptoquarks are found with our data, the limits depicted in Fig. 1a will be expanded to include these regions.
FIG. 1
FIG. 2
\textbf{Leptoquark Sensitivity}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Leptoquark Sensitivity}
\end{figure}

FIG. 3
Leptoquark Sensitivity

- M = 100 GeV
- M = 125 GeV
- M = 150 GeV
- M = 175 GeV
- M = 200 GeV

FIG. 4
FIG. 5

95% CL Limit for Third Generation LQs (β = 0)
Excluded regions

FIG. 6