Search for Leptoquarks at D0

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Abstract

We present in this paper the current status of searches for leptoquarks at D0. These results include the use of next leading order theoretical predictions for the cross section for pair production of leptoquarks at hadron colliders. We also present a new optimized analysis for first generation leptoquarks with significant increase in sensitivity relative to earlier searches using D0 data. The mass limits derived from this first generation leptoquark search are relevant to the recently reported high mass events at HERA.

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I. INTRODUCTION

Leptoquarks are hypothetical exotic particles with both lepton and color quantum numbers; they are color triplet bosons with fractional charge. They are produced in pairs at hadron colliders via strong interactions. A leptoquark will decay via an unknown coupling, λ, to a lepton and a quark. The production of leptoquark pairs in $p\bar{p}$ collisions is insensitive to λ, and we are not concerned with this coupling as long as it is greater than 10^{-12}; otherwise, the leptoquarks will not decay in our detector and escape detection. We assume that leptoquarks occur in generations; this is to say that leptoquarks of one generation couple exclusively to leptons and quarks of the same generation. For example, a first generation leptoquark will only couple to electrons, electron neutrinos and u or d quarks. With this assumption of generations, we are able to bypass strict bounds ($\geq$ 1 TeV) on leptoquark masses derived from limits on flavor changing neutral currents.

Since leptoquarks are produced dominantly in pairs at hadron colliders, their signature would be two leptons plus two or more jets. A free parameter of the model for leptoquarks is the branching fraction of the leptoquark to charged lepton plus quark, β. For $\beta = 1.0$, leptoquarks decay 100% to a charged lepton plus quark. In the case for a first generation leptoquark pair, the signature would be two isolated electrons (e^+e^-) plus at least two jets. Additional jets could arise from initial state radiation or final state radiation. Since we assume leptoquarks do not couple outside their own generation, for first generation leptoquarks, we would not expect to see muons or evidence of taus in the signature.

Some published and previous preliminary conference limits on leptoquarks masses are shown in tables I and II. These give a brief history of mass limits from the Tevatron. The previously published limits from CDF and DØ have used Leading Order (LO) theory. Next Leading Order (NLO) theory predicts cross sections that are 30-50% higher than LO theory. NLO was used for the CDF limits at recent conferences [7] [8] and will be used in the newest limits presented in this paper from DØ.

II. FIRST GENERATION LEPTOQUARKS

DØ searches for first generation leptoquarks primarily in the dielectron plus two jet and electron plus missing transverse energy ($\not{E}_T$) plus two jet signatures corresponding to the decay modes $eeqq$ and $e\nu qq$. The search for first generation leptoquarks in the dieletron plus two jet signature has been greatly modified since the 1997 Moriond Conferences [7]. After the announcement of the high mass events from HERA [10], DØ has retooled the analysis to increase the acceptance for leptoquarks by increasing the acceptance for electrons and by optimizing the event section for higher mass leptoquarks. The data sample used in this analysis is the full Run I data sample of 123 pb^{-1}. The single electron plus $\not{E}_T$ plus two jets signature search is also optimized at higher masses. We are also using the newly available NLO theory predictions [9] for the production cross section.

The electron identification for one of the two electrons in the dielectron search has been loosened to increase the acceptance for leptoquarks. For the loose selection, the track requirement is removed. This has effectively doubled the acceptance for dielectrons. The relaxing of the track requirement for the one electron does not significantly increase the QCD background relative to the tight-tight electron selection.

The basic $eejj$ event selection is given in the following list:

- two electrons with $E_T > 20$ GeV with $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$,
- two jets with $E_T > 15$ GeV with $|\eta| < 2.5$ where the jets are reconstructed with a cone algorithm using a cone of radius $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$,
- exclude events with dielectron invariant masses between 82 to 100 GeV/c^2.

The dielectron mass cut is a three sigma cut. With this basic selection, we have 101 events in our candidate sample. The main backgrounds come from Drell-Yan, QCD with jets faking electrons, and Top. We estimate 66.8±13.4 events for Drell-Yan, 24.3±3.6 events from QCD, and 1.8±0.7 events from Top for a total of 92.8±13.8 background events.

Further event selection is optimized for leptoquark masses of 200 GeV/c^2 and greater. The optimization is based on signal and background Monte Carlo event samples and on QCD data event samples. Several variables have been studied for the optimization; variables involving sums of energies and transverse energies (E_T) of electrons and jets, variables of event shape, variables of reconstructed invariant masses, and variables involving constraints with leptoquark masses have been used. Systematic grid search [11] and neural network [12] techniques are used for the optimization studies. We approached the optimization in two ways. The first is a discovery search where we optimized signal (S) over the square root of the background (B), $S/\sqrt{B}$. The second is for setting a limit where we maximized the signal for a given target background of about 0.4 events. This level of background gives a probability of about 70% of seeing 0 background events.

We find that a transverse energy variable defined as $S_T = \sum_{\text{jets}} E_T^j + E_T^{e1} + E_T^{e2}$ is the most optimal variable. Here, the jets are required to have $E_T > 15$ GeV to be included in the sum. Figure 1 shows the output of an example grid search. Here is plotted the number of signal events verses the number of background events. Each point in the plot represents a different set of cuts. The electron and jet E_T's are fixed at the basic cut level as given in the figure. The upper line of dots are for the S_T cut. The lower line of dots is for a leptoquark mass constrained variable defined as: DM/M(200) $= \sqrt{(M_{ej1} - M_{LQ}^{200})^2 + (M_{ej2} - M_{LQ}^{200})^2}/M_{LQ}^{200}$. M_{ej1} and M_{ej2} are the invariant masses of the two combinations of the electrons and jets such that the difference in the two masses is minimized, and M_{LQ}^{200} is the mass of a 200 GeV/c^2 mass leptoquark in this example. The wide band of dots is the combination of both variables used in the selection. From this plot we see that that the S_T variable does better than the mass constraint variable at our target background of 0.4 events. We find that a $S_T > 350$ GeV gives a background of about 0.4 events. None of the 101 candidate events pass this cut. The differential and integrated S_T distributions for the data and background predictions are given in Figs. 2 and 3. The background distribution matches well the data distribution.

We have also studied the mass properties of the 101 dielectron candidate event sample. We used a 3C (3 constraint) fit where we require balance of the transverse energy in the event and we require the masses of the two reconstructed electron-jet systems be equal. The combination of electron with jet is chosen such that the difference in masses is minimized before the fitting. The 3C mass fit for a 225 GeV/c^2 mass leptoquark sample ($\beta = 1.0$) can be seen in Fig 4. The peak of the distribution is about 10% low but the mass resolution is good at about 15 GeV/c^2. In Fig. 5 is the 3C fitted mass for the data shown as the points with errors. The background prediction is shown as the solid line histogram. The data and background prediction agree well. The dashed line histogram is the 3C fitted mass for a 200 GeV/c^2 leptoquark sample. We expect about 6 events from a 200 GeV/c^2 mass leptoquark. By comparison we expect about 20 events from a 160 GeV/c^2 mass leptoquark and 3 events from a 225 GeV/c^2 mass leptoquark. All histograms are normalized to 123 pb^{-1}.

One might note the two events at the high end of the mass distribution in Fig. 5. These two events have values of S_T that are significantly lower than our cut of 350 GeV. This can be seen in Fig. 6. Here we plot the S_T variable versus the 3C fitted mass for the background prediction (upper left), for a 225 GeV/c^2 mass leptoquark sample (upper right), and for the data (lower left). The two events in question have S_T's less than about 200 GeV. From Fig. 6 we see that the data and background prediction are again very similar.

Given that we see no dielectron leptoquark signal in our data, we can proceed to set a limit on the production cross section for leptoquark pairs, and by comparing to theory we can set limits on the leptoquark mass. The efficiency for detecting the dielectron plus two or more jet signature from leptoquark pair production as a function of leptoquark mass is given in Fig. 7. The lowest curve is the total efficiency. The errors bars represent the total statistical plus systematic uncertainties of about 13%. These uncertainties are listed here:

- energy scale: 2-5%
- electron identification: 5%
- acceptance: 5%
- gluon radiation: 7%
- parton distribution functions and Q^2: 7%
- luminosity: 5%
- Monte Carlo statistics: 2%

Given the efficiency and uncertainties, we calculate [13] a 95% CL limit on the production cross section times β^2 as a function of leptoquark mass. This is given in Fig. 8. Also given is the NLO theoretical prediction. The band represents the range in cross section prediction as the renormalization scale changes from one half the leptoquark mass (upper boundary: $\mu^2 = 1/4 \times M_{LQ}^2$) to twice the leptoquark mass (lower boundary: $\mu^2 = 4 \times M_{LQ}^2$). The intersection of our experimental limit on the cross section and the lower boundary of the theory prediction gives a 95% CL limit of 225 GeV/c^2 on the mass of the leptoquark for $\beta = 1.0$.

We have also searched for first generation leptoquarks with the single electron plus $\not\!\!E_T$ plus two or more jets signature. Recall that for this signature one leptoquark decays to a electron plus quark, and the other leptoquark decays to electron neutrino plus quark. In this case we are most sensitive to the branching fraction $\beta = 0.5$. We have 103.7 pb^{-1} for this search. The basic event selection is given as follows:

- one electron with $E_T > 25$ GeV, $\mid \eta \mid < 1.2$,
- two jets with $E_T > 25$ GeV, $\mid \eta \mid < 1.0$; a third jet with $E_T > 25$ GeV is allowed in the event; additional jets with $E_T < 25$ GeV are not used to veto events; jets are reconstructed with cone algorithm (R = 0.7),
- $\not\!\!E_T > 40$ GeV, jets and $\not\!\!E_T$ must have $\Delta\phi > 0.25$ and $\mid \pi - \Delta\phi \mid > 0.25$,
- $S_T > 170$ GeV where $S_T = \sum E_T^{jet} + E_T^e$; jets must have $E_T >$ than 15 GeV to be included in sum,
- exclude events with isolated muons, since muons are not part of the first generation leptoquark signature.

With the basic selection we find 32 candidate events. The background sources to this signature are W boson + 2 jets, top, and QCD. The background estimates from these sources are 19.6±4.2 events from W boson + 2 jets, 9.0±2.7 events from top, and 1.1±0.4 from QCD for a total of 29.8±5.0 events.

The transverse mass of the electron and $\not\!\!E_T$ is given in Figs. 9 and 10. The data is given as the points with error bars representing the statistical uncertainties, and the background prediction is the dashed histogram. We see very good agreement between the data and background predictions before and after the H_T cut. The arrow in the figures represents a cut of 100 GeV on $\not\!\!E_T$. This cut eliminates all but one event. This event has an electron plus four jet topology and is in fact a top candidate. This is supported by the background estimates of 0.52±0.28 events from W boson + 2jets, 1.55±0.48 events from top, and 0.41±0.41±0.20 events from QCD for a total background prediction of 2.5±0.6 events.

The last component of the event selection is based on a variable, δM defined as $\delta M = \mid M_{ej} - M_{LQ1} \mid / M_{LQ1}$. M_{LQ1} is the mass of the first generation leptoquark, and M_{ej} is the electron - jet invariant mass. The jet that is chosen from the two or more jets in the event minimizes δM. Optimizations of this variable using signal and background Monte Carlos reveal a cut of $\delta M < 0.2$ is optimal. We find that there are no events left in our sample for leptoquark masses greater than 140 GeV/c^2.

With the signal efficiencies shown in Fig. 11, we calculate the 95% CL limit on the production cross section times $2\beta(1-\beta)$. This is given in Fig. 12 as function of leptoquark mass. The theoretical prediction is the NLO production cross section times $2\beta(1-\beta)$ for $\beta = 0.5$. Our 95% CL limit drops at 140 GeV/c^2 because for masses greater than 140 GeV/c^2 our one remaining event does not survive the δM cut. The intersection of our limit with the lower theoretical prediction ($\mu^2 = 4 \times M_{LQ}^2$) gives a mass limit on first generation leptoquarks of 158 GeV/c^2 for $\beta = 0.5$.

III. SECOND GENERATION LEPTOQUARKS

The search for second generation leptoquarks involves signatures of muons and jets. The search described here is for two isolated muons plus two or more jets. This search uses 94.4 pb^{-1} of data. The basic event selection is the same as the standard DØ dimuon top quark selection [14] which because no direct $\not\!\!E_T$ cut is used also does well for the leptoquark dimuon event selection. The major backgrounds to second generation leptoquarks are Drell-Yan and top. The event selection is listed here:

- two isolated ($R(\mu, jet) > 0.5$) muons with $E_T > 15$ GeV and $\mid \eta \mid < 1.0$,
- two jets with $E_T > 20$ GeV and $\mid \eta \mid < 2.5$,
- $\Delta\phi(\mu_1, \mu_2) < 160^o$ if $\mid \eta_{\mu_1} + \eta_{\mu_2} \mid < 0.5$,
- the dimuon invariant mass, $M_{\mu\mu}$, greater than 10 GeV,
- $H_T(jets) > 100$ GeV,
- Z-kinematic fit probability, $\wp(\chi^2)$, less than 1%.

Here H_T is the sum of the E_T of jets for jets with $E_T > 15$ GeV. The back-to-back cut in ϕ on the muons is for cosmic muon rejection. The H_T cut is intended to significantly reduce the Drell-Yan background. This can be seen in Fig. 13 where we show the H_T distribution for Drell-Yan, top, and leptoquark (M = 160 GeV/c^2) Monte Carlos. We see that the H_T cut of 100 GeV rejects a large portion of the Drell-Yan ($Z \rightarrow \mu\mu$) background. It keeps most of the top and leptoquark events. With these cuts we have one event with an estimated background of 0.97±0.20 events from top and Drell-Yan.

To reduce the top background we consider the ϕ distribution of the two muons and the two highest E_T jets in the candidate events. Top pair ($t\bar{t}$) events producing the dimuon (isolated muons) signature contain $\not\!\!E_T$, the source of which is two neutrinos from the decay of the two W bosons that came from the decay of the $t\bar{t}$ pair. The dimuon signature from second generation leptoquark pair production has no $\not\!\!E_T$ from real sources like neutrinos. It is possible that the neutrinos in the top events will concentrate in one ϕ region of the detector causing the jets and muons to concentrate on the opposite side to balance the event. This will tend to produce a large gap in ϕ between two of the muons or jets. One can imagine a pie cut up into four pieces by the two muon and two jet directions. Using this analogy, a top event could cut out a piece of the pie that is more than half the total pie. Leptoquark events would tend to cut the pie into more equal pieces. The distribution of the maximum ϕ gap is given in Fig. 14 for leptoquark, top, and Drell-Yan Monte Carlo samples. If we require that the maximum ϕ gap be less than 180^o, we reject a significant portion of the top background while we retain nearly all of the leptoquark signal.

With the ϕ-gap cut we have no events left in our sample. The last event is actually a $t\bar{t}$ candidate with a very large ϕ-gap. The total efficiencies for the signal varied from 3.8%±0.5% to 12.6%±1.3% for second generation leptoquark mass that varied from 100 GeV/c^2 to 260 GeV/c^2. The total statistical and systematic errors are 10-15%. We calculate the 95% CL limit on the production cross section time β^2 for second generation leptoquark pairs and compare this to the NLO theory ($\mu^2 = M_{LQ}^2$). In Fig. 15 we show the preliminary 95% CL limit exclusion contour (single line) of β vs second generation leptoquark mass. For $\beta = 1.0$ we have a mass limit of 184 GeV/c^2, and for $\beta = 0.5$ we have a limit of 140 GeV/c^2. The hatched regions are the limits from a previous analysis [5] using only the 1992-1993 (1A) data set.

IV. THIRD GENERATION LEPTOQUARKS

We've searched for signatures of third generation leptoquarks of charge 1/3. These charge 1/3 leptoquarks decay to b quark plus ν_τ. Our search reach for third generation scalar leptoquarks is below the top mass of about 170 GeV/c^2, so we assume that third generation scalar leptoquarks of charge 1/3 decay 100% of the time to b quark plus ν_τ.

In the event selection we require $\not\!\!E_T > 35$ GeV, two jets at least one of which has a muon tag, and topological cuts. The untagged jets are required to have $E_T > 25$ GeV, and the tagged jets are required to have $E_T > 10$ GeV (excluding the muon E_T). We have total efficiencies of 2-5% for third generation leptoquark masses between 100 GeV/c^2 and 300 GeV/c^2. The major background sources to this signature are top, W and Z bosons plus two jets, and QCD multijets. For these cuts we see two events in the full Run 1 data sample (about 20 pb^{-1} for our selected trigger) with an expected total background of 3.1±0.9 events.

In Fig. 16 we show the 95% CL limit on the cross section times $(1-\beta)^2$ as the stars connected by the dotted line as a function of third generation leptoquark mass. The solid line is the NLO theory ($\mu^2 = M_{LQ}^2$) for scalar leptoquarks and the dashed line is the LO theory for vector leptoquarks with Yang-Mills coupling. From this plot we see that we set a limit on the mass of scalar third generation leptoquarks (Q = 1/3) of 98 GeV/c^2, and we set a limit on third generation leptoquarks of 201 GeV/c^2 ($\beta = 0$).

V. CONCLUSION

We have searched for three generations of leptoquarks with diagonal couplings to leptons and quarks. We have found no evidence of a leptoquark signature in the DØ Run I data. A summary of the preliminary mass limits for the three generation of leptoquarks is given in table III.

For the future, we expect that our mass reach for lower β in the second generation search to improve when we add the search for the single muon plus $\not\!\!E_T$ plus jets signature to this analysis. We expect to greatly improve our search reach in both the first and second generation leptoquark searches at low β when we have added our $\not\!\!E_T$ plus jets searches to these analyses. Finally, we will also have limits for vector leptoquarks.

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TABLES

TABLE I. Brief history of published 95% CL mass limits on scalar leptoquarks from hadron colliders.

Experiment	Signature	β	95% CL mass limit (GeV/c^2)
CDF [1]	$eejj$	1.0	113
CDF [1]	$eejj$	0.5	80
DØ [2]	$eejj, e\nu jj$	1.0	130
DØ [2]	$eejj, e\nu jj$	0.5	116
HERA (H1) [3]	ej	1.0	275[1]
CDF [4]	$\mu\mu jj$	1.0	131
CDF [4]	$\mu\mu jj$	0.5	96
DØ [5]	$\mu\mu jj, \mu\nu jj$	1.0	119
DØ [5]	$\mu\mu jj, \mu\nu jj$	0.5	97
CDF [6]	$\tau\tau jj$	Q=4/3,2/3[2]	99

TABLE II. Brief history of 95% CL mass limits on scalar leptoquarks from hadron colliders recently presented at conferences.

Experiment	Signature	β	95% CL mass limit (GeV/c^2)
DØ [7]	$eejj, e\nu jj$	1.0	175
DØ [7]	$eejj, e\nu jj$	0.5	147
DØ [7]	$eejj, e\nu jj$	0.0	81
CDF [8]	$eejj$	1.0	210 (NLO)[3]
DØ [7]	$\mu\mu jj, \mu\nu jj$	1.0	167
CDF [7]	$\mu\mu jj$	1.0	197 (NLO)
DØ [7]	$b\bar{b}\nu_\tau\nu_\tau$	Q = 1/3	80
CDF [7]	$\tau\tau jj$	Q=4/3,2/3	110 (NLO)

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[1] This limit is sensitive to the leptoquark - lepton - quark coupling; limits from HERA assume that $\lambda = \alpha_{\rm em}$.

[2] For this third generation leptoquark limit the Top quarks is not relevant, so β is not relevant.

[3] This limit from CDF uses Next Leading Order (NLO) theory to set limits on the leptoquark mass.

TABLE III. Summary of scalar leptoquark mass limits.

Generation	β	95% CL limit (GeV/c^2)	comment
1rst	1.0	225	NLO ($\mu^2 = 4M_{LQ}^2$)
1rst	0.5	195	NLO ($\mu^2 = 4M_{LQ}^2$)
2nd	1.0	184	NLO ($\mu^2 = M_{LQ}^2$)
2nd	0.5	140	NLO ($\mu^2 = M_{LQ}^2$)
3rd	-	98	Q = 1/3, NLO ($\mu^2 = M_{LQ}^2$)

FIGURES

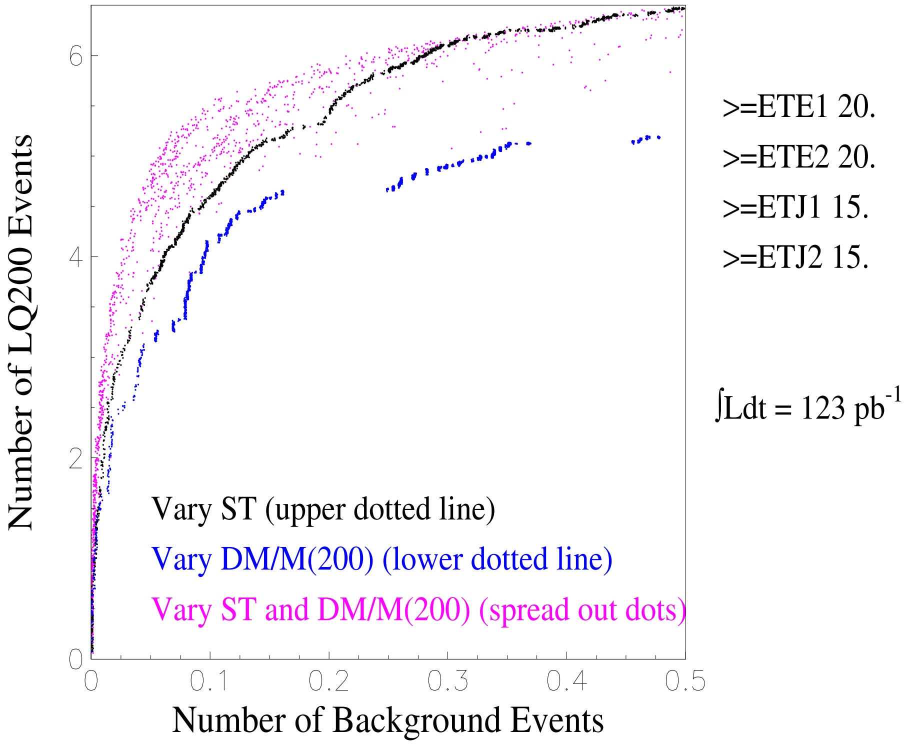

FIG. 1. Output of grid search. We can see by this that the S_T variable alone optimizes the signal to background ratio better than the mass constrained variable, DM/M(200), and the combination of both.

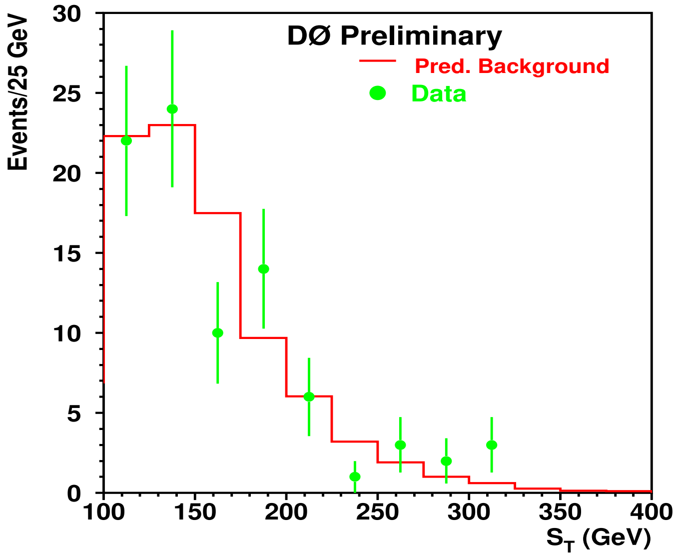

FIG. 2. The differential distribution of S_T for data and background predictions. The basic event selection is applied.

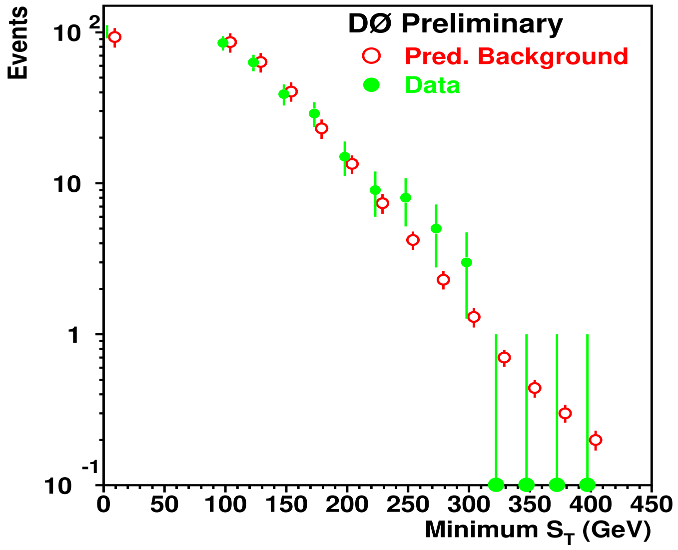

FIG. 3. The integrated distribution of S_T for data and background predictions. The basic event selection is applied.

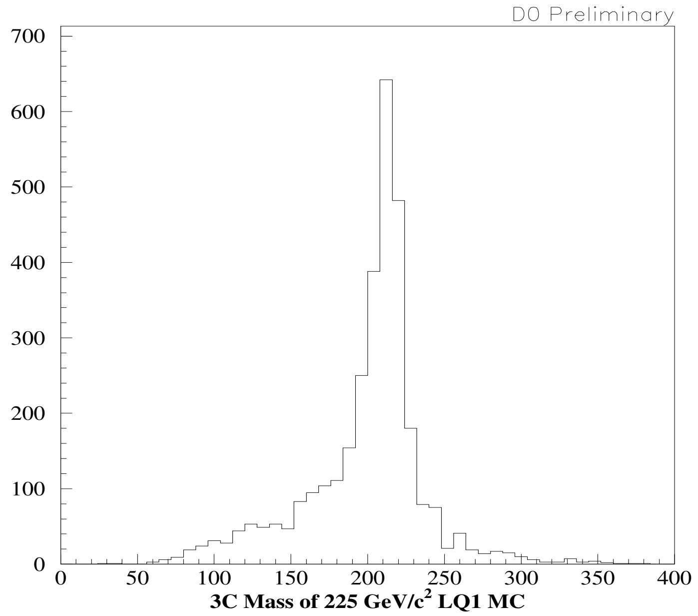

FIG. 4. The 3C mass fit for a 225 GeV/c^2 mass leptoquark sample, $\beta = 1.0$.

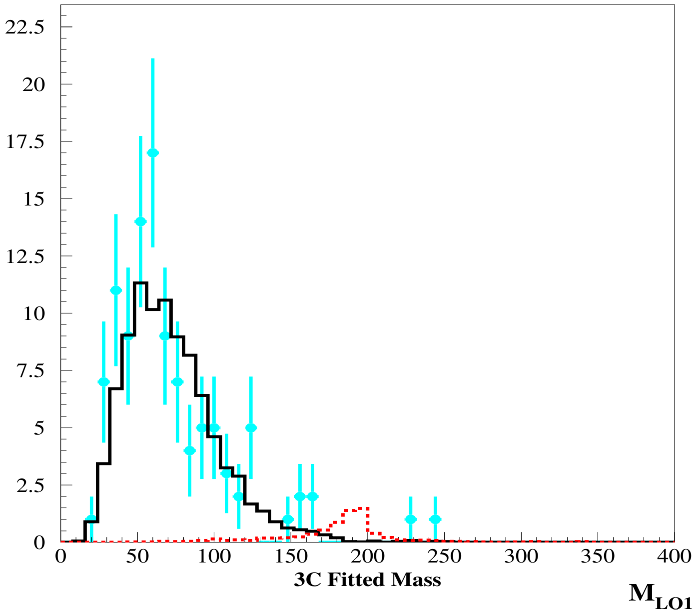

FIG. 5. The 3C mass fit for the data (points) with the basic event selection shown with background prediction (solid line historgram) and 200 GeV/c^2 mass leptoquark sample (dashed line histogram). Preliminary.

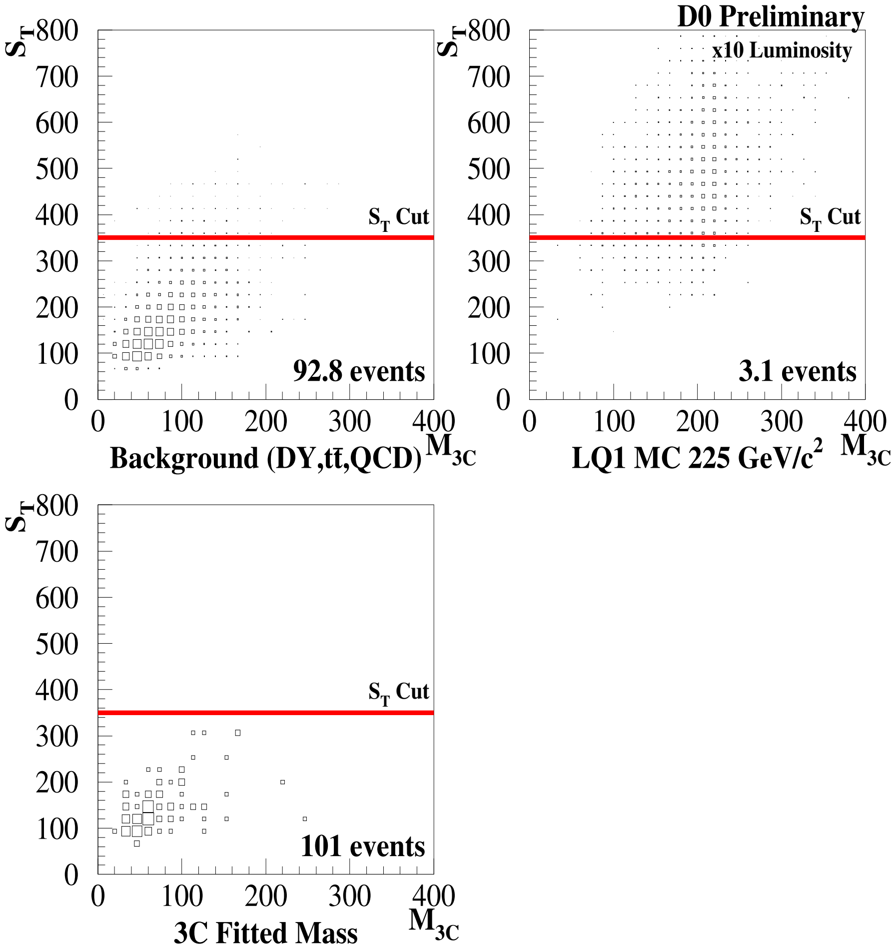

FIG. 6. The S_T vs 3C mass fit for the data with the basic event selection, background prediction, and 225 GeV/c^2 mass leptoquark sample.

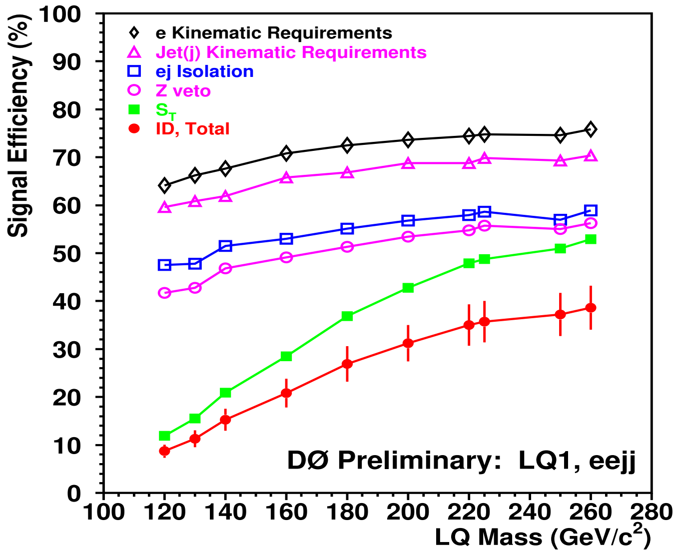

FIG. 7. The efficiency for detection of the dielectron plus two or more jets leptoquark signature.

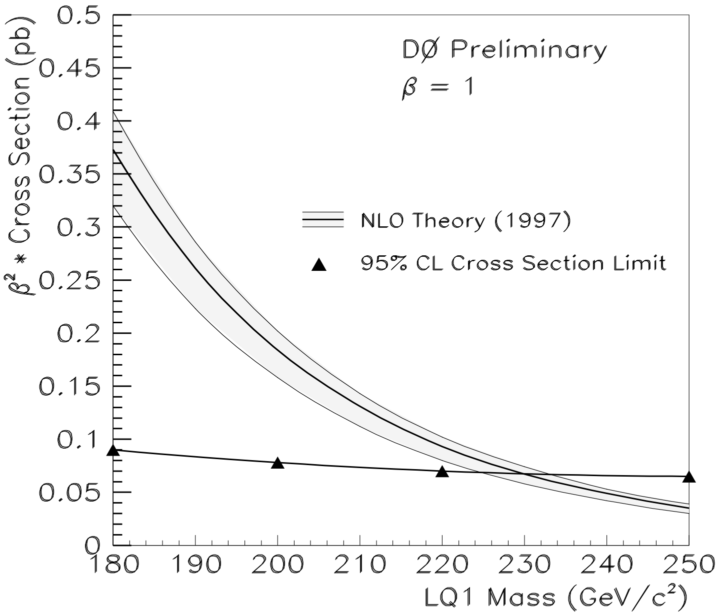

FIG. 8. The 95% CL limit on the production cross section times β^2. Also shown as the band is the NLO theoretical prediction [9].

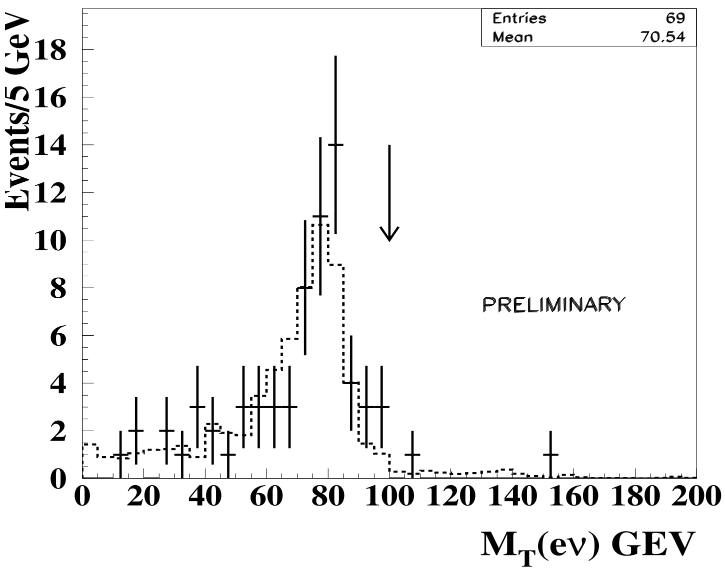

FIG. 9. The $e-\nu$ transverse mass distribution prior to the H_T cut. The number of data events is 69. Data are the crosses, and the dashed histogram is the background prediction. The arrow indicates the mass cut.

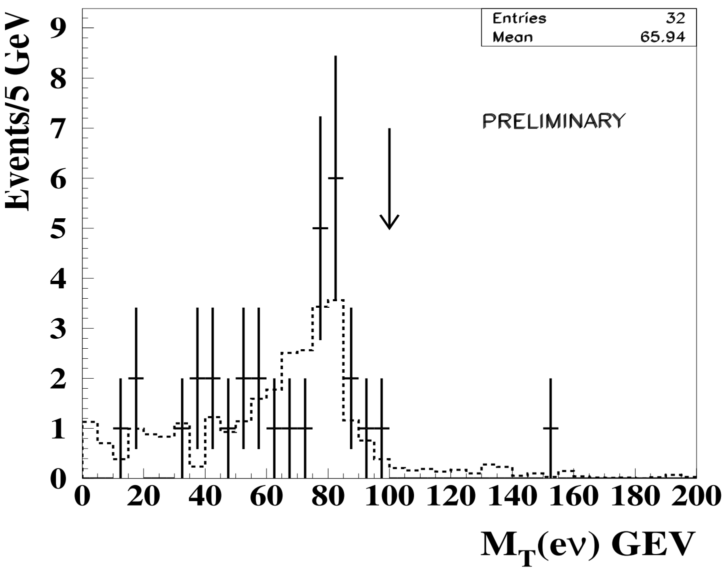

FIG. 10. The $e-\nu$ transverse mass distribution after to the H_T cut. The number of data events is 32. Data are the crosses, and the dashed histogram is the background prediction. The arrow indicates the mass cut.

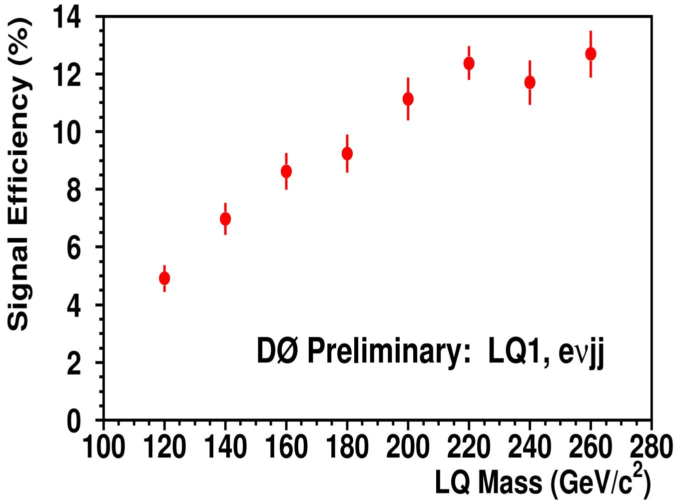

FIG. 11. The efficiency for detection of the electron plus $\not{E}_T$ plus two or more jets leptoquark signature.

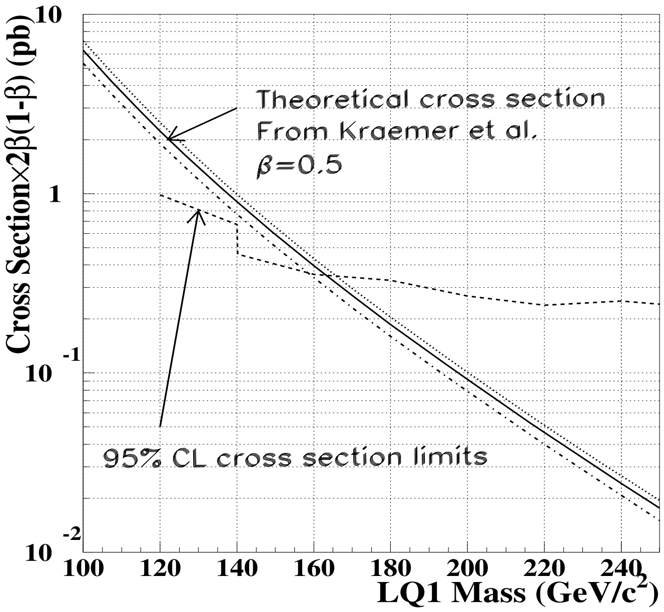

FIG. 12. The 95% CL limit on the production cross section times $2\beta(1-\beta)$ for first generation leptoquarks. Also shown is the NLO theoretical prediction.

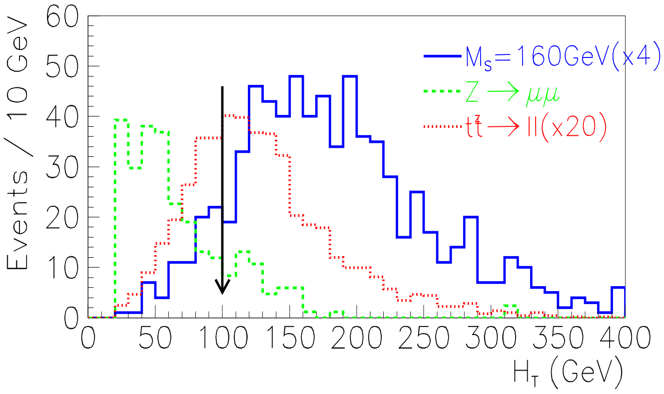

FIG. 13. The H_T distribution for top and Drell-Yan backgrounds and a 160 GeV/c^2 mass leptoquark signal sample. Our cut is indicated by the arrow.

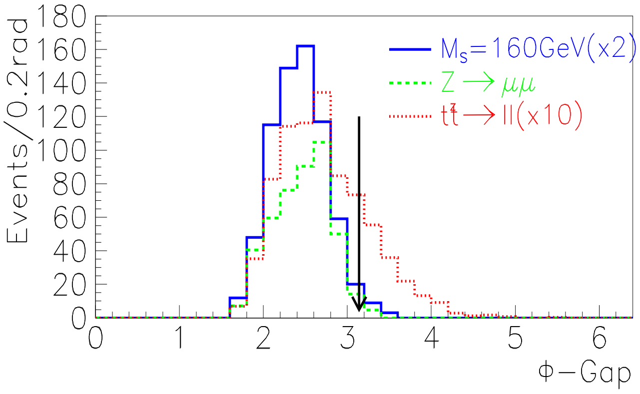

FIG. 14. The ϕ-gap distribution for top and Drell-Yan backgrounds and a 160 GeV/c^2 mass leptoquark signal sample. Our cut is indicated by the arrow.

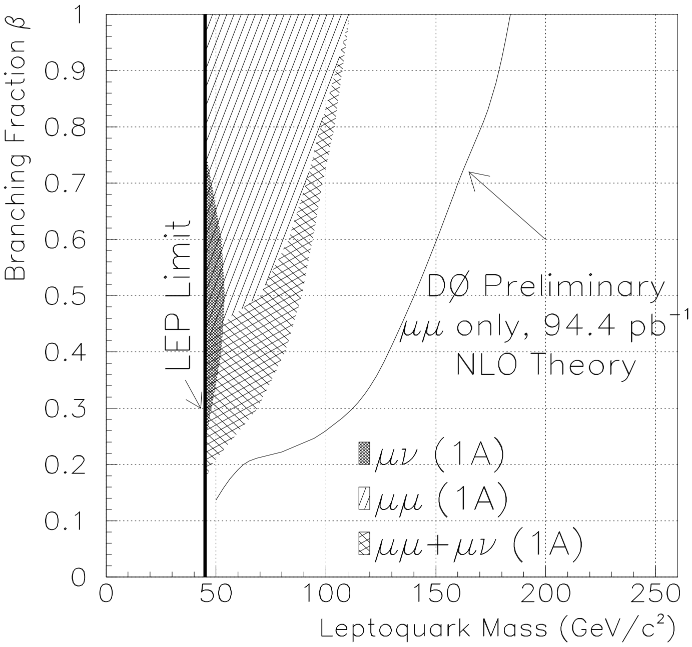

FIG. 15. The 95% CL limit exclusion contour for second generation leptoquarks. Plotted is the branching fraction, β, vs leptoquark mass. We exclude the region to the left of the curve. We use NLO theory ($\mu^2 = M_{LQ}^2$) to determine this contour.

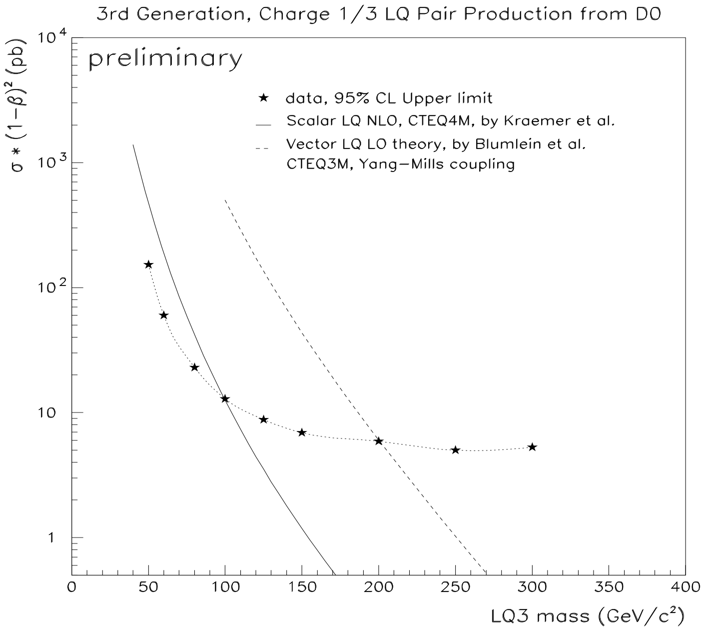

FIG. 16. The 95% CL limit on the production cross section for charge 1/3 third generation leptoquark. We show here as the solid line the NLO theory ($\mu^2 = M_{LQ}^2$) for the scalar leptoquarks. The dashed line is LO theory for vector leptoquarks.