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First Generation Leptoquark Search in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

We report on a search for first generation leptoquarks with the DØ detector at the Fermilab Tevatron $p\bar{p}$ collider at $\sqrt{s} = 1.8$ TeV. This search is based on 15 pb^{-1} of data. Leptoquarks are assumed to be produced in pairs and to decay into an electron + quark with branching ratio β. No leptoquark candidates were found. We obtain cross section times branching ratio limits as a function of leptoquark mass. For pair production of scalar leptoquarks, we set a leptoquark mass limit of 133 GeV for $\beta = 1$ and 120 GeV for $\beta = 0.5$ at 95% confidence level.

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Leptoquarks are conjectured exotic particles that carry both color and lepton quantum numbers. They occur in a wide variety of extensions to the Standard Model that connect the quark and lepton sectors [1]. Leptoquarks are fractionally charged and can decay directly to a quark lepton pair. In order to satisfy constraints from flavor changing neutral currents and rare pion and kaon decays, leptoquarks must couple only within one generation and the coupling must be either left or right handed [2]. A first generation leptoquark, S_1, decays into an electron + quark with branching ratio β, or into an electron neutrino + quark with branching ratio (1-β).

We report here on a search for first generation leptoquarks with the DØ detector at the Fermilab Tevatron $p\overline{p}$ collider at $\sqrt{s}$ = 1.8 TeV. Previous searches in $p\overline{p}$ collisions have excluded scalar leptoquarks up to masses of 113 GeV for $\beta = 1$ and up to 80 GeV for $\beta = 0.5$ [3]. Searches by LEP experiments have excluded leptoquarks with masses below about 45 GeV, independent of β [4]. Searches at HERA have ruled out leptoquarks up to approximately 180 GeV, where the unknown quark-lepton-leptoquark vertex coupling, g, is assumed to be the same as the electroweak coupling [5]. Using the notation of Ref. [6], this assumption corresponds to $k = 1$, where k specifies the strength of the leptoquark coupling in terms of the fine structure constant, α, and $g^2 = 4\pi\alpha k$. Studies of $e^+e^- \rightarrow q\overline{q}$ experiments restrict k to be less than 1 for leptoquark masses below 200 GeV [6]. Our reconstruction algorithms require S_1 to decay within a few cm of the primary vertex. With this requirement, we are fully efficient for all values of k greater than 10^{-12}.

The analysis presented here is based on 15 pb^{-1} of data collected during the Tevatron run from August 1992 to May 1993. Pair production of leptoquarks is expected to dominate at the Tevatron, and we have, therefore, chosen to search for leptoquarks produced in this way. The pair production cross section can be calculated using standard QCD methods. We require that at least one of the leptoquarks decays into an electron + quark, since the background is much higher for the mode where both decay into a neutrino + quark. Therefore, we look for events with the following signatures: (1) events with two electrons and two jets or (2) events with one electron, two jets, and large missing transverse energy from the electron neutrino. We use electron to designate both electron and positron, since DØ does not measure the sign of electric charge.

The DØ detector has three major subsystems: central tracking detectors (with no central magnetic field), nearly hermetic liquid argon calorimetry, and a muon spectrometer. The central tracking system is used to identify charged tracks in the pseudorapidity range $|\eta| \leq 3.5$. The liquid argon calorimeters provide full angular coverage for $|\eta| \leq 4$ with sufficiently fine segmentation to provide a good measure of electromagnetic shower shape so that electrons can be separated from jets. From test beam studies, energy resolution is approximately $15\%/\sqrt{\mathrm{E}}$ for electrons and approximately $50\%/\sqrt{\mathrm{E}}$ for hadrons. The muon system consists of drift chambers and magnetized iron toroids. It provides coverage out to $|\eta| \leq 3.3$. A more detailed description of the DØ detector can be found elsewhere [7].

Electrons and jets from leptoquarks tend to be isolated and of relatively high transverse energy, E_T. Electrons are selected using shower shape information and isolation criteria determined from test beam studies, collider data, and Monte Carlo. Electrons are required to have a matching track. The electron energy scale is set using the mass of the Z boson. The relative uncertainty on the electron energy scale is 0.5% . Jets are found with the calorimeter only, using a fixed cone algorithm with radius 0.7 in η, ϕ space. The jet energy scale is set by requiring E_T balance in events with a normal (hadronic) jet and a predominantly electromagnetic jet or photon. The relative uncertainty in the jet energy scale is 10%. The jets are also required to pass loose shape cuts to remove events with extra energy due to electronic noise or accelerator backgrounds [8].

For the process with two electrons and two jets, we require two electrons with $\mathrm{E}_T > 25$ GeV and two jets with $\mathrm{E}_T > 25$ GeV. After these cuts, 9 events are left. In Fig. 1, we show the electron pair mass, M_{ee}, distribution before and after requiring two jets with $\mathrm{E}_T > 25$ GeV. As can be seen, all 9 events have M_{ee} within ± 10 GeV ($\pm 2.5\sigma$) of the Z mass and are consistent with Z + two jet events. No leptoquark candidates remain after excluding events with M_{ee} in the range from 81 GeV to 101 GeV.

The principal backgrounds to this decay mode are: Drell-Yan e^+e^- events with two jets where the e^+e^- are primarily from Z production, QCD multi-jet events where two of the jets fake electrons, and heavy quark events where the heavy quarks decay to electrons and are accompanied by jets. The backgrounds from QCD and charm and bottom quark production are expected to be negligible (less than 0.05 events) for events with two isolated high E_T electrons plus two other jets. We estimate the background from Drell-Yan plus two jet production with M_{ee} outside of the range excluded above to be approximately 0.3 events.

The electron identification efficiency was studied using Z and W events from the data, along with simulated leptoquark events generated using the ISAJET Monte Carlo [9]. The Monte Carlo events were passed through a full simulation of the DØ detector using the GEANT [10] program. The combined efficiency and acceptance for the two electron plus two jet decay mode ranges from 0.62% for 45 GeV leptoquarks to 15.5% for 160 GeV leptoquarks. The relative uncertainty on the overall efficiency ranges from 22.6% for 45 GeV leptoquarks to 9.0% at 160 GeV. It includes the uncertainties on the efficiencies of the shower shape cuts as well as the uncertainties on the energy scales. The jet energy scale uncertainty is the dominant source of the systematic uncertainty on the overall efficiency. The uncertainty on the luminosity is 12%. The 95% confidence level limits on the cross section times branching ratio are given in Fig. 2 for the two electron plus two jet decay mode [11]. A theoretical prediction of the cross section times branching ratio for $\beta = 1$ is also shown. The prediction is based on ISAJET and the MT–LO parton distribution function [12].

For the process with one electron, missing E_T and two jets, we require one electron with $E_T > 20$ GeV, missing $E_T > 20$ GeV and at least two jets, one with $E_T > 15$ GeV and one with $E_T > 10$ GeV. The transverse mass distribution, M_T, of the electron plus missing E_T for these events is shown in Fig. 3. As expected, the figure has a peak in the M_T distribution characteristic of events where a W decays into an electron and a neutrino. Other important backgrounds to this decay mode are: QCD multi-jet events where one of the jets fakes an electron and another is badly measured leading to fake missing E_T, and heavy quark events where one of the heavy quarks decays to an electron which is then accompanied by jets and real missing E_T. The following kinematic cuts reduce all of these backgrounds substantially. We require M_T to be greater than 105 GeV. We require both jets to have E_T > 20 GeV, and the missing E_T to be greater than 40 GeV. The missing E_T is required not to be aligned in azimuth with any jet axis to reduce backgrounds due to poorly measured jets. For comparable leptoquark efficiencies, studies using both data and Monte Carlo show that unequal cuts on electron E_T and missing E_T are more efficient at removing backgrounds than equal cuts. To remove heavy quark and W decays to muons, we eliminate events with muons with $E_T > 15$ GeV and $|\eta| < 1.2$.

After these cuts, no leptoquark candidates remain. The estimated background from W + two jet events and QCD events is approximately 0.9 events. The overall efficiency for the one electron, missing E_T and two jet decay mode ranges from 0.45% for 45 GeV leptoquarks to 12.7% at 140 GeV. The relative uncertainty on the efficiency ranges from 17.3% at 45 GeV to 8.8% at 140 GeV. As before, the jet energy scale uncertainty is the principal source of systematic uncertainty on the overall efficiency. The 95% confidence level limits on cross section times branching ratio [11] are given in Fig. 4. Note that sensitivity to this decay mode vanishes for $\beta = 1$ and $\beta = 0$.

Using cross sections based on ISAJET for scalar leptoquark production with the MT–LO parton distribution function [12], we can obtain limits for the leptoquark mass as a function of β. These limits are shown in Fig. 5. The 95% confidence level lower limit on the mass of a first generation scalar leptoquark for $\beta = 1$ is 133 GeV. The lower limit for $\beta = 0.5$ is 120 GeV. These limits are independent of the unknown quark-lepton-leptoquark coupling for values of $k > 10^{-12}$. Clearly, the mass limits obtained depend on the calculated cross section. For the choice of cross section used in Ref. [3], our limits would be 136 GeV for $\beta = 1$ and 124 GeV for $\beta = 0.5$. Our limits change by roughly 3 GeV for every 10% change in the cross section. Different choices of parton distribution function can vary the cross section by as much as 15% . Corrections due to higher order terms increase the cross section by approximately 10% at 140 GeV [13]. Reference [2] predicts a cross section for leptoquark pair production that is approximately 30% lower than the one used here. For this cross section, our limits become 122 GeV for $\beta = 1$ and 108 GeV for $\beta = 0.5$.

In conclusion, we have searched for pair production of leptoquarks at the Fermilab Tevatron. No leptoquark candidates were observed. We set limits on the leptoquark pair production cross section times branching ratio as a function of mass and limits on leptoquark mass as a function of branching ratio β.

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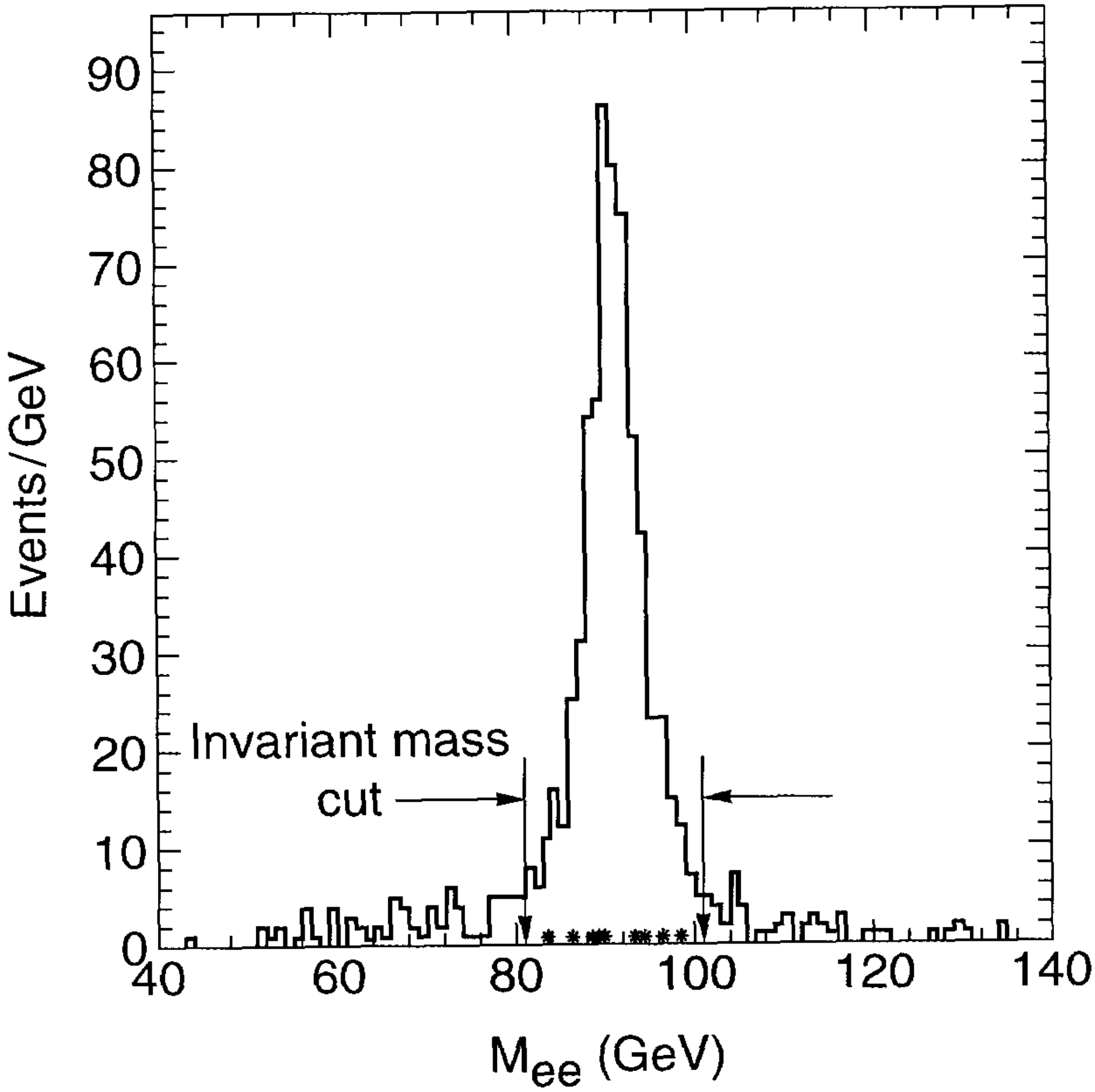

FIG. 1. M_{ee} distribution for events with two electrons with $E_T > 25$ GeV. Stars denote events that also have two jets with $E_T > 25$ GeV. The electron energy scale was set using the mass of the Z boson.

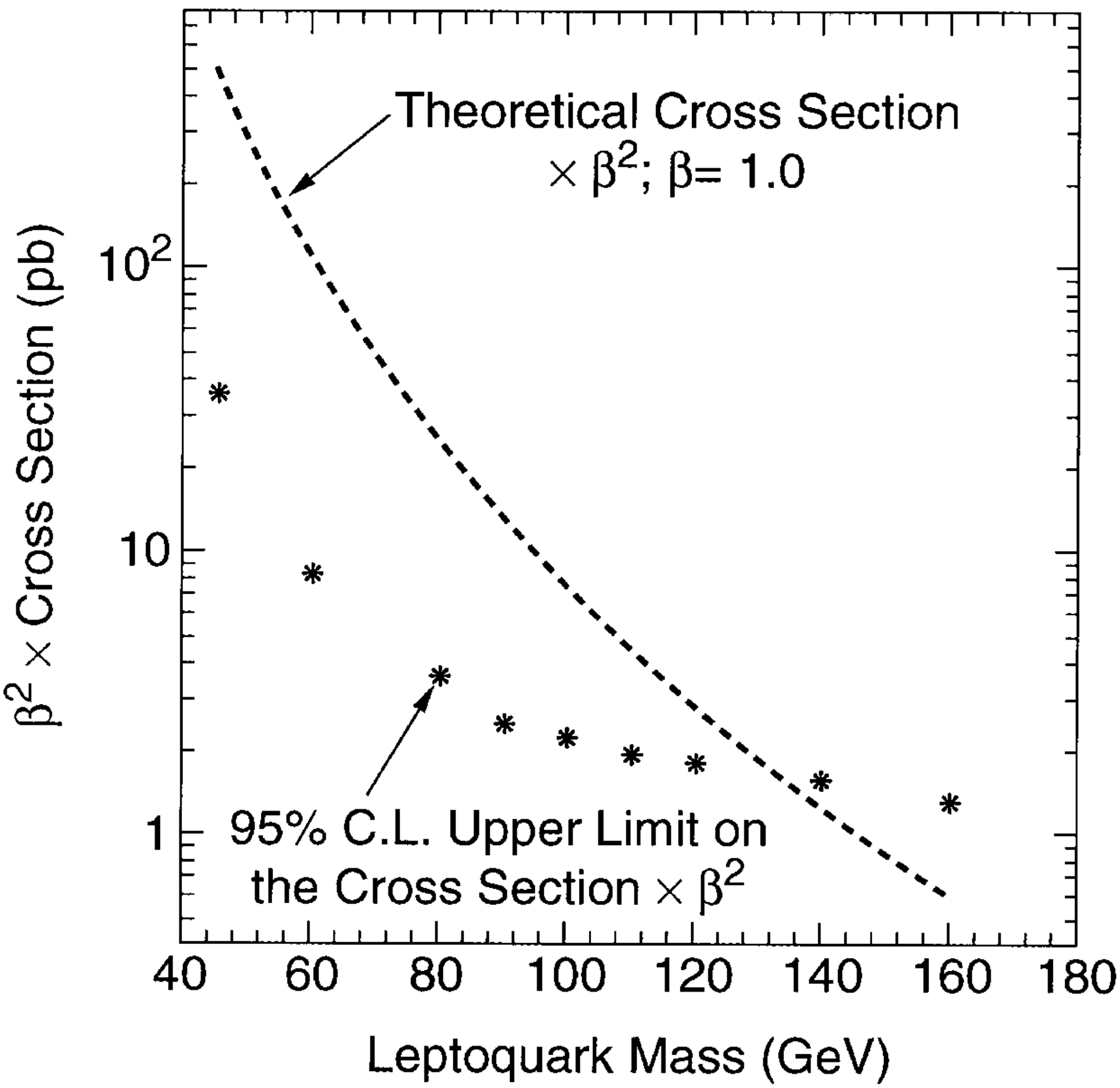

FIG. 2. 95% confidence level limits on the cross section times branching ratio ($\sigma \times \beta^2$) for the two electron plus two jet signature as a function of leptoquark mass. A theoretical prediction of the cross section times branching ratio for $\beta = 1$ is also shown.

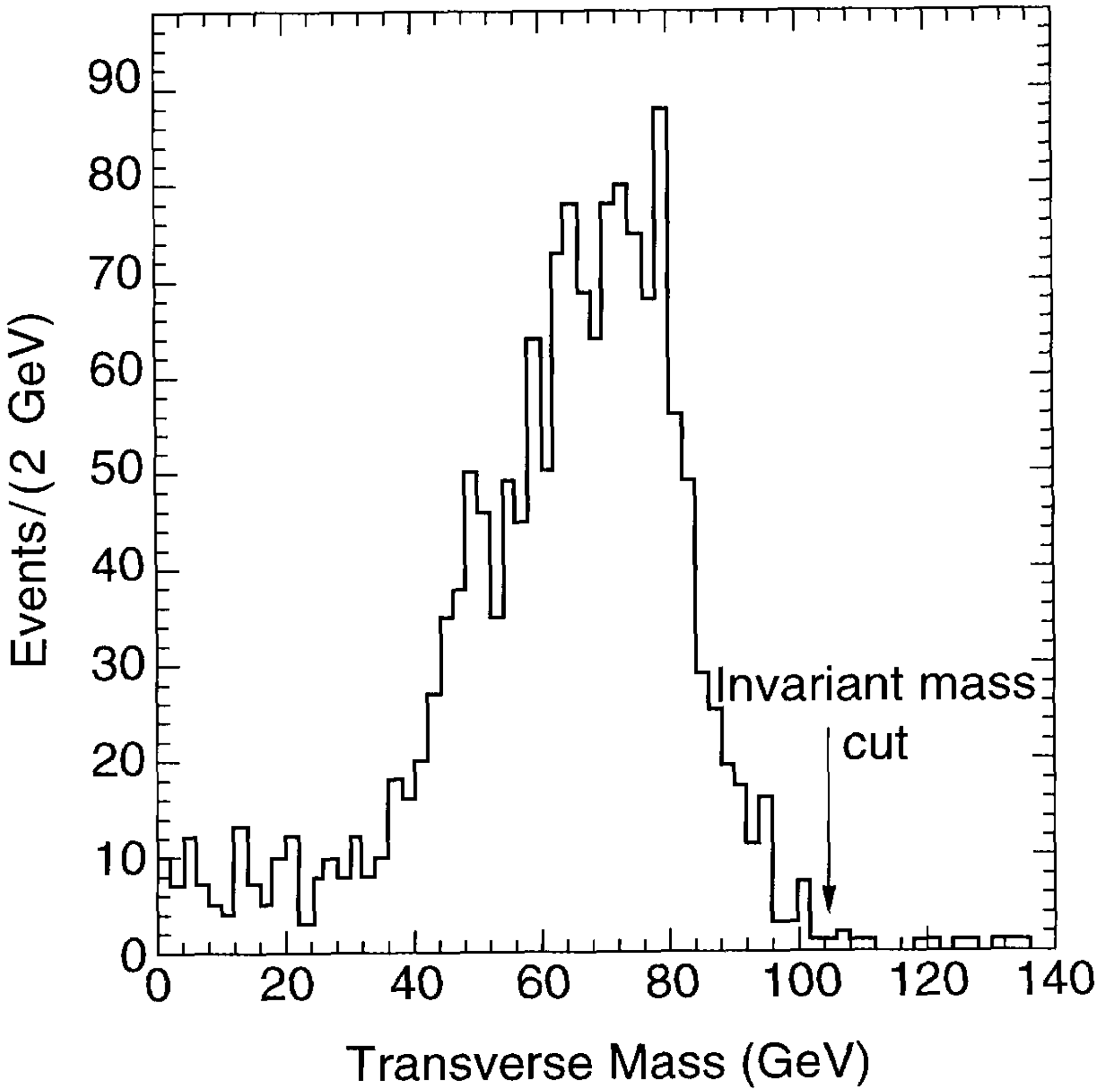

FIG. 3. Electron and missing E_T transverse mass distribution for events with an electron with $E_T > 20$ GeV, missing $E_T > 20$ GeV, one jet with $E_T > 15$ GeV, and a second jet with $E_T > 10$ GeV.

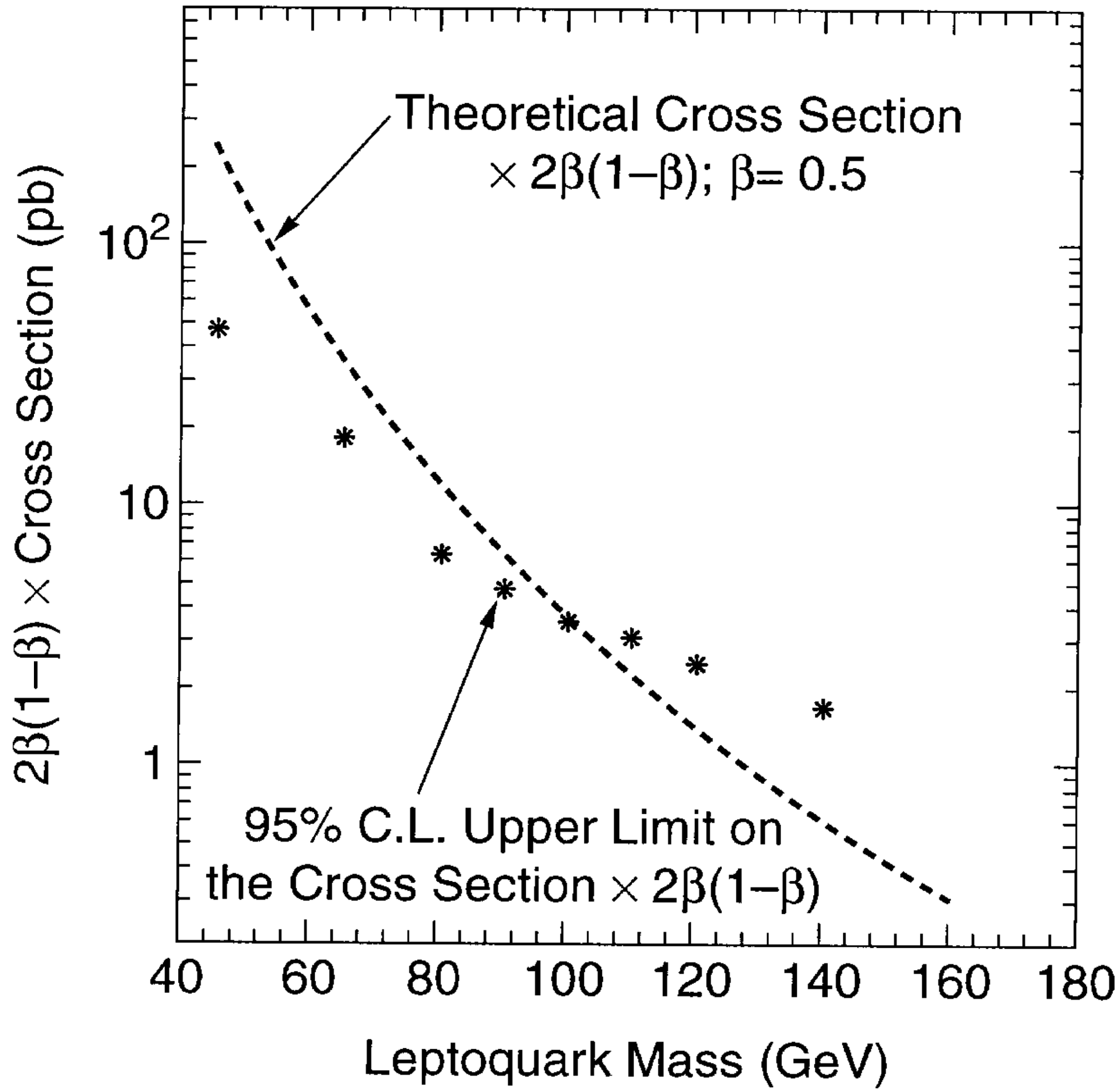

FIG. 4. 95% confidence level limits on the cross section times branching ratio ($\sigma \times 2(1-\beta)\beta$) for the one electron plus two jet plus missing E_T signature as a function of leptoquark mass. A theoretical prediction function of the cross section times branching ratio for $\beta = 0.5$ is also shown.

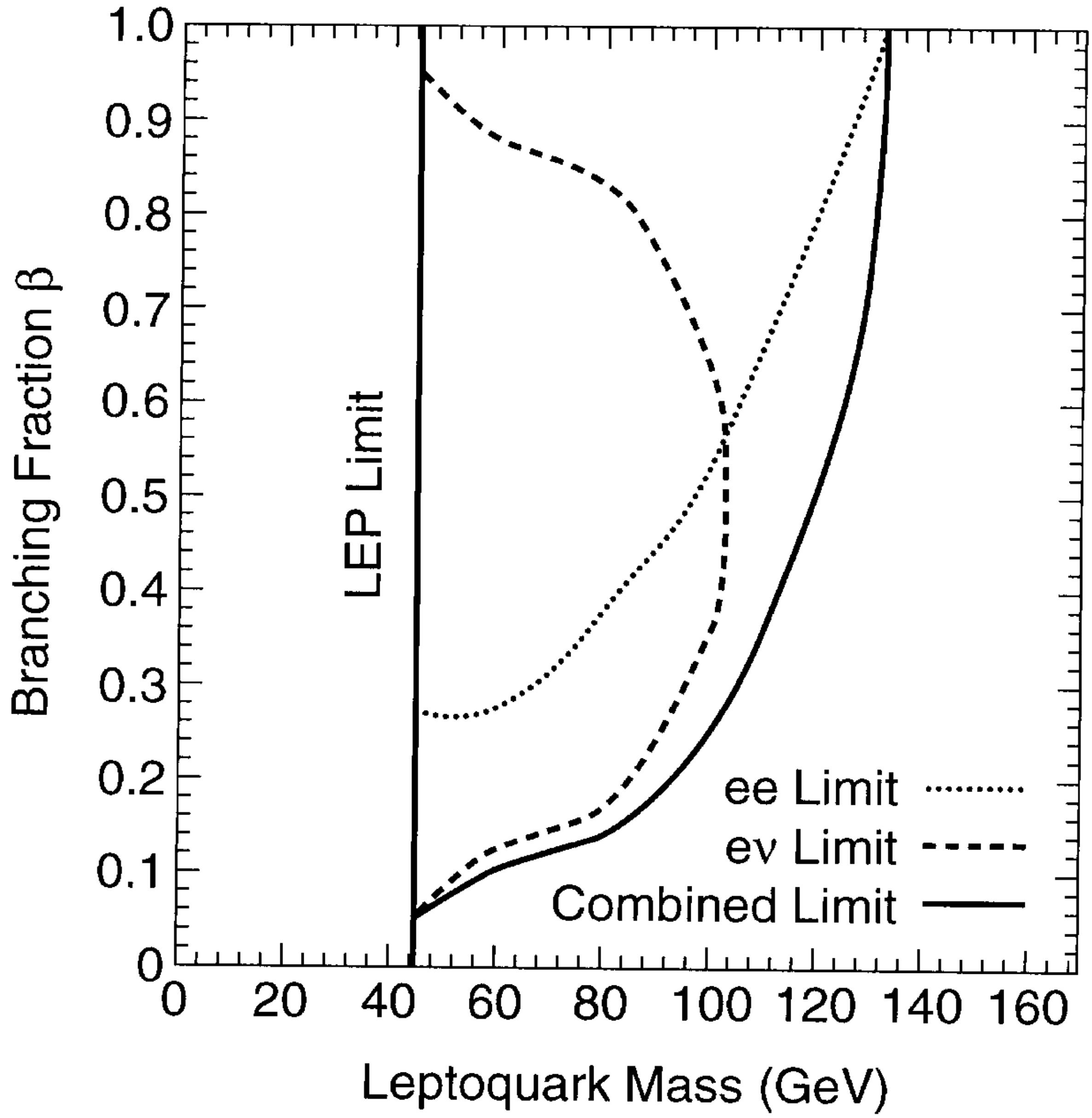

FIG. 5. 95% confidence level lower limit on the leptoquark mass as a function of β. Results are derived using theoretical predictions of the cross section based on ISAJET and the MT–LO particle distribution function.