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

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Kelly,[34] C. L. Kim,[20] S. K. Kim,[43] A. Klatchko,[15] B. Klima,[14] C. Klopfenstein,[7] V. I. Klyukhin,[37] B. Knuteson,[23] V. I. Kochetkov,[37] J. M. Kohli,[36] D. Koltick,[38] A. V. Kostritskiy,[37] J. Kotcher,[4] A. V. Kotwal,[12] J. Kourlas,[30] A. V. Kozelov,[37] E. A. Kozlovski,[37] J. Krane,[29] M. R. Krishnaswamy,[45] S. Krzywdzinski,[14] S. Kunori,[25] S. Lami,[44] R. Lander,[7] F. Landry,[27] G. Landsberg,[14] B. Lauer,[19] A. Leflat,[28] H. Li,[44] J. Li,[46] Q. Z. Li-Demarteau,[14] J. G. R. Lima,[40] D. Lincoln,[26] S. L. Linn,[15] J. Linnemann,[27] R. Lipton,[14] Y. C. Liu,[33] F. Lobkowicz,[41] S. C. Loken,[23] S. Lökös,[44] L. Lueking,[14] A. L. Lyon,[25] A. K. A. Maciel,[10] R. J. Madaras,[23] R. Madden,[15] L. Magaña-Mendoza,[11] S. Mani,[7] V. Manankov,[28] H. S. Mao,[14,†] R. Markeloff,[32] T. Marshall,[18] M. I. Martin,[14] K. M. Mauritz,[19] B. May,[33] A. A. Mayorov,[37] R. McCarthy,[44] J. McDonald,[15] T. McKibben,[17] J. McKinley,[27] T. McMahon,[35] H. 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(Received 30 October 1997)

We have searched for first generation scalar leptoquark (LQ) pairs in the $e\nu$ + jets channel using $p\bar{p}$ collider data ($\int L\,dt \approx 115\ \mathrm{pb}^{-1}$) collected by the D0 experiment at the Fermilab Tevatron during 1992–1996. The analysis yields no candidate events. We combine the results with those from the ee + jets and $\nu\nu$ + jets channels to obtain 95% confidence level (C.L.) upper limits on the LQ pair production cross section as a function of mass and of β, the branching fraction to a charged lepton. Comparing with the next-to-leading order theory, we set 95% C.L. lower limits on the LQ mass of 225, 204, and 79 GeV/c^2 for $\beta = 1$, $\frac{1}{2}$, and 0, respectively. [S0031-9007(98)05381-2]

PACS numbers: 14.80.–j, 12.60.–i, 13.85.Rm

One of the remarkable features of the standard model (SM) is the symmetry between quarks and leptons that leads to cancellation of chiral anomalies and renders the SM renormalizable. This symmetry might be explained by a more fundamental theory that relates quarks and leptons. Several extensions [1] of the SM include leptoquarks (LQ), color-triplet bosons which carry both lepton (ℓ) and quark (q) quantum numbers. The masses and coupling strengths of leptoquarks that couple to all three fermion generations are severely constrained by low energy experiments [2] and by HERA [3]. Therefore, in this Letter we consider only LQ that couple to the first generation. The excess of events at high Q^2 in e^+p collisions reported [4] by the H1 and ZEUS experiments at HERA, and its possible interpretation [5] as evidence for production of first generation scalar leptoquarks with a mass near 200 GeV$/c^2$, have stimulated much interest in these particles.

Leptoquarks would be dominantly pair produced via strong interactions in $p\bar{p}$ collisions, independently of the unknown LQ-ℓ-q Yukawa coupling. Each leptoquark would subsequently decay into a lepton and a quark. For first generation leptoquarks, this leads to three possible final states: ee + jets, $e\nu$ + jets, and $\nu\nu$ + jets, with rates proportional to β^2, $2\beta(1-\beta)$, and $(1-\beta)^2$, respectively, where β denotes the branching fraction of a leptoquark to an electron and a quark (jet). The CDF [6,7] and D0 [8,9] Collaborations have both searched for first generation scalar leptoquarks. The recent analyses [9,7] of the ee + jets decay channel yielded 95% confidence level (C.L.) lower limits on the leptoquark mass of 225 GeV$/c^2$ (D0) and 213 GeV$/c^2$ (CDF). In this Letter we present an analysis of the $e\nu$ + jets final state (which has maximum sensitivity at $\beta = \frac{1}{2}$), using 115 ± 6 pb^{-1} of collider data collected at the Fermilab Tevatron at $\sqrt{s} = 1.8$ TeV during 1992–1996. We also present a reinterpretation of our search [10] for top squark pairs as a search for leptoquarks in the $\nu\nu$ + jets decay channel. We combine the results from all three decay channels to obtain lower limits on the leptoquark mass as a function of β.

The D0 detector [11] consists of a central tracking system including a transition radiation detector, a uranium/liquid-argon calorimeter, and a muon spectrometer. The data used in this analysis were collected with triggers which required the presence of an electromagnetic object, with or without jets and missing transverse energy ($\not{E}_T$). The combined efficiency of the triggers is greater than 98% for LQ masses above 80 GeV$/c^2$. Off-line event selection requires one electron with transverse energy $E_T^e > 20$ GeV and pseudorapidity $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$, $\not{E}_T > 30$ GeV as the signature for a neutrino, and two or more jets reconstructed using a cone algorithm (cone radius $\mathcal{R} \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.7$, where ϕ is the azimuthal angle) with $E_T^j > 20$ GeV and $|\eta| < 2.5$. To reduce the effects of jet energy mismeasurements, we require the $\not{E}_T$ vector to be separated from the jets by $\Delta\phi > 0.25$ radians if $\not{E}_T < 120$ GeV. To suppress background from heavy quark events, we reject events that contain muons. These selection criteria define our base sample.

An electron is identified by its pattern of energy deposition in the calorimeter, the presence of a matching track in the central tracking detectors, and ionization in the central detectors. The efficiency for finding an electron is calculated to be $(61 \pm 4)\%$, using $Z(\rightarrow ee)$ + jets events which are similar in topology to the signal. All kinematic quantities in the event are calculated using the event vertex determined by the electron.

We use the ISAJET [12] Monte Carlo (MC) event generator to simulate LQ signal events for masses (M_{LQ}) between 80 and 220 GeV$/c^2$ in 20 GeV$/c^2$ steps. The PYTHIA [13] MC program is used to simulate signal events with $M_{\mathrm{LQ}} = 200$ GeV$/c^2$ to study systematic errors arising from differences in modeling of the gluon radiation and parton fragmentation. The leptoquark production cross sections used are from recent next-to-leading order (NLO) calculations [14]. The dominant W + jets background is simulated using the VECBOS [15] event generator (with the HERWIG [16] program used for fragmenting the partons). The background from multijet events containing a jet which is misidentified as an electron, and with $\not{E}_T$ arising from the mismeasurement of jet energies, is modeled using multijet data. The probability for a jet to be misidentified as an electron (the fake probability) is estimated [9] to be $(3.50 \times 0.35) \times 10^{-4}$. The background from $t\bar{t}$ decays into one or two electrons plus two or more jets, and is simulated using the HERWIG MC program with a top quark mass of 170 GeV$/c^2$. All MC event samples are processed through the D0 detector simulation based on the GEANT [17] package.

In the base sample of 1094 events, we estimate the number of $t\bar{t}$ events to be 12 ± 4 using the measured $t\bar{t}$ production cross section of 5.5 ± 1.8 pb [18]. The multijet background is estimated to be 75 ± 15 events, using a sample of events with three or more jets with $\not{E}_T > 30$ GeV. This is done by multiplying the fake probability by the number of ways the events satisfy the selection criteria with one of the jets passing the electron E_T and η requirements. After the estimated numbers of $t\bar{t}$ and multijet background events are subtracted, the number of events with transverse mass of the electron and neutrino ($M_T^{e\nu}$) below 110 GeV$/c^2$ is used to obtain an absolute normalization for the W + jets background. This background is then largely eliminated by requiring $M_T^{e\nu} > 110$ GeV$/c^2$. After this cut, 14 events remain in the final data sample. The estimated background is 17.8 ± 2.1 events, of which 11.7 ± 1.8, 4.1 ± 0.9, and 2.0 ± 0.7 events are from W + jets, multijets, and $t\bar{t}$ production, respectively. Leptoquark pair production would yield 24 events in this sample, if $M_{\mathrm{LQ}} = 120$ GeV$/c^2$ and $\beta = \frac{1}{2}$. Assuming all 14 events to be signal, LQ

production for masses below 120 GeV/c^2 can be excluded at the 95% C.L. for $\beta = \frac{1}{2}$ with no further optimization.

We have identified two additional variables that provide significant discrimination between signal and the remaining background. They are the scalar transverse energy sum $S_T \equiv E_T^e + E_T^{j_1} + E_T^{j_2} + \not{E}_T$, where $E_T^{j_{1,2}}$ are the transverse energies of the two leading jets, and a mass variable $\frac{dM}{M}(M_{\rm LQ}) \equiv \min(\frac{|M_{ej_1} - M_{\rm LQ}|}{M_{\rm LQ}}, \frac{|M_{ej_2} - M_{\rm LQ}|}{M_{\rm LQ}})$, where $M_{\rm LQ}$ is an assumed LQ mass and $M_{ej_{1,2}}$ are the invariant masses of the electron with the first and second leading jets.

To find the optimal selection cuts, we adopt the criterion [9] of maximizing the MC signal efficiency for a fixed expected background of approximately 0.4 events. In the low mass range ($M_{\rm LQ} \leq 120$ GeV/c^2), where LQ production rates are high, requiring $S_T > 400$ GeV is sufficient. For $M_{\rm LQ} > 120$ GeV/c^2, we use neural networks (NN) since they provide higher efficiency than an S_T cut alone. At each mass, $M_{\rm LQ}$, where we have generated MC events, we use a three layer feed-forward neural network [19] with two inputs [S_T and $\frac{dM}{M}(M_{\rm LQ})$], five hidden nodes, and one output [$\mathcal{D}_{\rm NN}(M_{\rm LQ})$]. We train each NN using simulated LQ events as the signal [with desired $\mathcal{D}_{\rm NN}(M_{\rm LQ}) = 1$] and a mixture of W + jets, multijet, and $t\bar{t}$ events as background [with desired $\mathcal{D}_{\rm NN}(M_{\rm LQ}) = 0$]. Cuts on $\mathcal{D}_{\rm NN}(M_{\rm LQ})$ that yield background estimates closest to the desired background are obtained by varying $\mathcal{D}_{\rm NN}(M_{\rm LQ})$ in steps of 0.05. The background after the cut ranges between 0.29 ± 0.25 and 0.61 ± 0.27 events as shown in Table I. The errors in the background estimates include the effects of uncertainties in jet energy scale, fake probability, and $t\bar{t}$ production cross section. The signal detection efficiencies calculated using simulated LQ events passing the selection requirements are also shown in Table I. The errors on the signal efficiencies include uncertainties in trigger and particle identification efficiencies, jet energy scale, effects of gluon radiation and parton fragmentation in the signal modeling, and finite MC statistics. No data events pass the cuts.

To demonstrate that the backgrounds are reliably modeled, comparisons of the data and combined background in the variables $M_T^{e\nu}$ and $\mathcal{D}_{\rm NN}(180)$ are shown in Fig. 1 for the base sample.

Figures 2(a)–2(c) show the two-dimensional distributions of $\frac{dM}{M}(180)$ vs S_T for simulated LQ signal events with $M_{\rm LQ} = 180$ GeV/c^2, the combined background, and data. The contours corresponding to constant values of $\mathcal{D}_{\rm NN}(180)$ demonstrate the separation achieved between signal and background. The distribution of $\mathcal{D}_{\rm NN}(180)$ for data is compared with the predicted distributions for background and signal in Fig. 2(d). It is clear that the data are described well by background alone. The highest $\mathcal{D}_{\rm NN}(180)$ observed in the final data sample is 0.79.

Using Bayesian statistics, we obtain a 95% C.L. upper limit on the leptoquark pair production cross section for $\beta = \frac{1}{2}$ as a function of leptoquark mass. The results are shown in Table I. The statistical and systematic uncertainties in the efficiency, the integrated luminosity, and the background estimation are included in the limit calculation with Gaussian prior probabilities. The measured 95% C.L. cross section upper limits for LQ pair production, corrected for the branching ratio with $\beta = \frac{1}{2}$, for various LQ masses are plotted in Fig. 3 together with the NLO calculations [14]. The intersection of the limit curve with the lower edge of the theory band (renormalization scale $\mu = 2M_{\rm LQ}$) is at 0.19 pb, leading to a 95% C.L. lower limit on the LQ mass of 175 GeV/c^2.

An analysis of the $\nu\nu$ + jets channel is accomplished by making use of our published search (with $\int L\,dt \approx 7.4$ pb^{-1}) for the supersymmetric partner of the top quark [10]. Three events survive the selection criteria ($\not{E}_T > 40$ GeV, two jets with $E_T^j > 30$ GeV, and no isolated electrons or muons) consistent with the estimated background of 3.5 ± 1.2 events, mainly from W/Z + jets production. The efficiencies of the event selection for $M_{\rm LQ} = 60$, 80, and 100 GeV/c^2 are calculated to be 1.1%, 2.2%, and 3.9%, respectively, using signal MC

TABLE I. Signal detection efficiencies, estimated backgrounds, and measured 95% C.L. upper limits on the production cross section from the $e\nu$ + jets channel analysis. The NLO cross sections (with $\mu = 2M_{\rm LQ}$) from Ref. [14] times $2\beta(1-\beta) = \frac{1}{2}$ for $\beta = \frac{1}{2}$ are also shown.

Leptoquark mass (GeV/c^2)	Signal efficiency (%)	Estimated background (events)	95% C.L. upper limit (pb)	NLO theory (pb)
80	0.3 ± 0.1	0.60 ± 0.27	10.88	17.98
100	1.2 ± 0.2	0.60 ± 0.27	2.59	5.34
120	2.5 ± 0.3	0.60 ± 0.27	1.15	1.90
140	6.7 ± 1.0	0.54 ± 0.25	0.43	0.77
160	10.9 ± 1.2	0.61 ± 0.27	0.25	0.34
180	14.7 ± 1.2	0.29 ± 0.25	0.18	0.16
200	19.4 ± 1.7	0.43 ± 0.27	0.14	0.08
220	21.5 ± 1.7	0.41 ± 0.27	0.13	0.04

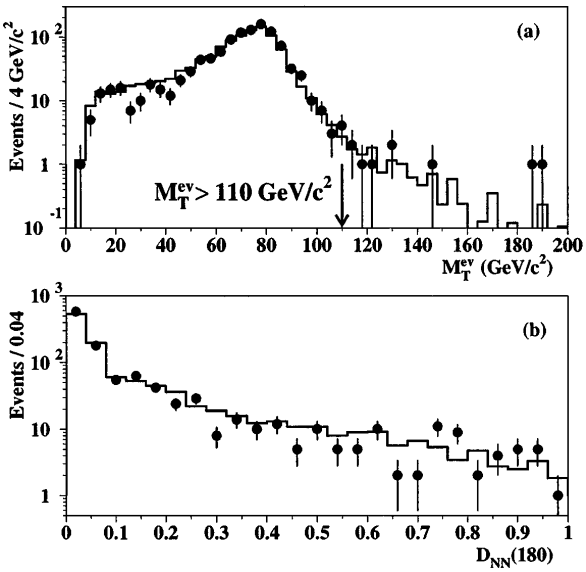

FIG. 1. (a) $M_T^{e\nu}$ and (b) $\mathcal{D}_{\rm NN}(180)$ distributions for data (points) and background (histograms), after all cuts except on $M_T^{e\nu}$ and $\mathcal{D}_{\rm NN}(180)$. The arrow in plot (a) shows a cut on $M_T^{e\nu}$, as described in the text.

events generated with the ISAJET generator and processed through the detector simulation based on GEANT. The systematic errors in the signal acceptance are calculated

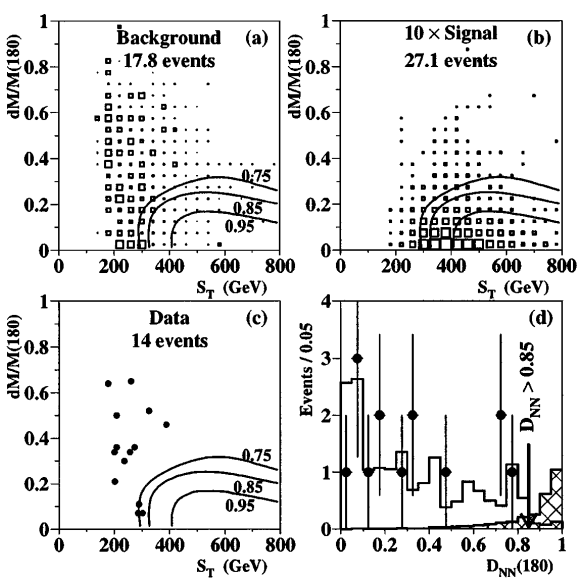

FIG. 2. Distributions of $\frac{dM}{M}(180)$ vs S_T for (a) predicted background, (b) simulated LQ events ($M_{\rm LQ} = 180$ GeV/c^2), and (c) data, after all cuts except that on $\mathcal{D}_{\rm NN}(180)$. The contours correspond to $\mathcal{D}_{\rm NN}(180) = 0.75$, 0.85, and 0.95. The box area is proportional to the number of events in the bin, with the total number of events normalized to 115 pb^{-1}. Plot (d) shows distributions of $\mathcal{D}_{\rm NN}(180)$ for data (solid circles), background (open histogram), and expected LQ signal for $M_{\rm LQ} = 180$ GeV/c^2 (hatched histogram). The arrow in plot (d) shows the chosen cut on $\mathcal{D}_{\rm NN}(180)$, as described in the text.

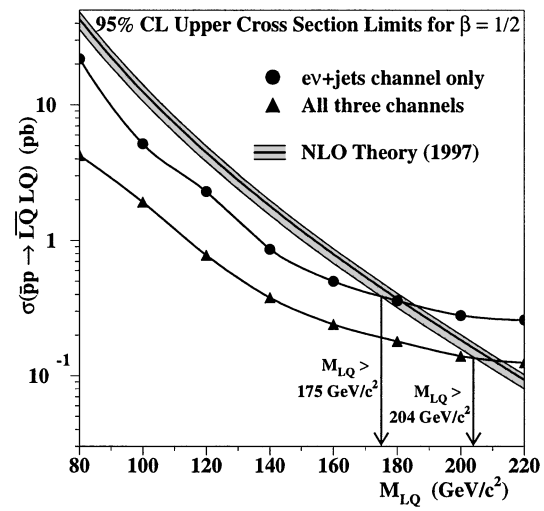

FIG. 3. Measured 95% C.L. upper limits on the leptoquark pair production cross section (see text) in the $e\nu$ + jets channel (circles) and all three channels combined (triangles) for $\beta = \frac{1}{2}$. Also shown are the NLO calculations of Ref. [14] where the central line corresponds to $\mu = M_{\rm LQ}$, and the lower and upper lines to $\mu = 2M_{\rm LQ}$ and $\mu = \frac{1}{2}M_{\rm LQ}$, respectively.

as in Ref. [10]. This analysis yields the limit $M_{\rm LQ} >$ 79 GeV/c^2 at the 95% C.L. for $\beta = 0$.

Combining the ee + jets, $e\nu$ + jets, and $\nu\nu$ + jets channels, we calculate 95% C.L. upper limits on the LQ pair production cross section as a function of LQ mass for various values of β. These cross section limits for $\beta = \frac{1}{2}$ (shown in Fig. 3), when compared with NLO theory, yield a 95% C.L. lower limit on the LQ mass of 204 GeV/c^2. The lower limits on the LQ mass derived as a function of β, from all three channels combined, as well as from the

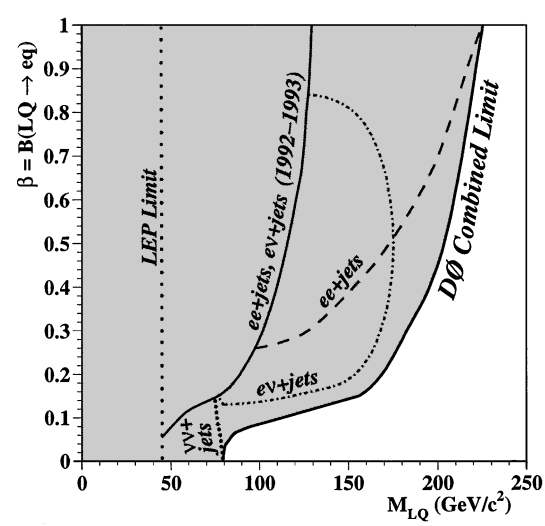

FIG. 4. Lower limits on the first generation scalar leptoquark mass as a function of β, based on searches in all three possible decay channels for LQ pairs. Limits from CERN Large Electron-Positron Collider (LEP) [20] and from our previous analysis [8] of 1992–1993 data are also shown. The shaded area is excluded at 95% C.L.

individual channels, are shown in Fig. 4. These results can also be used to set limits on pair production of any heavy scalar particle decaying into a quark and an electron or a neutrino, in a variety of models.

In conclusion, we have presented a search for first generation scalar leptoquark pairs in the $e\nu$ + jets decay channel. Combining the results with those from the ee + jets and $\nu\nu$ + jets channels, we exclude leptoquarks with mass below 225 GeV/c^2 for $\beta = 1$, 204 GeV/c^2 for $\beta = \frac{1}{2}$, and 79 GeV/c^2 for $\beta = 0$, at the 95% C.L. Our results exclude (at the 95% C.L.) the interpretation of the HERA high Q^2 event excess via s-channel scalar LQ production with LQ mass below 200 GeV/c^2 for values of $\beta > 0.4$. Our limits on LQ mass as a function of β can also be used to constrain new LQ models [21].

We are grateful to M. Krämer for discussions and detailed cross section information and to J. L. Hewett and T. G. Rizzo for helpful discussions. We thank the staffs at Fermilab and collaborating institutions for their contributions to this work, and acknowledge support from the Department of Energy and National Science Foundation (U.S.A.), Commissariat à L'Energie Atomique (France), State Committee for Science and Technology and Ministry for Atomic Energy (Russia), CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), and CONICET and UBACyT (Argentina).

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[1] J.C. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974); H. Georgi and S. Glashow, Phys. Rev. Lett. **32**, 438 (1974); also see J. L. Hewett and T. G. Rizzo, Phys. Rep. **183**, 193 (1989), and references therein.

[2] See, e.g., M. Leurer, Phys. Rev. D **49**, 333 (1994).

[3] H1 Collaboration, S. Aid *et al.*, Phys. Lett. B **369**, 173 (1996); ZEUS Collaboration, M. Derrick *et al.*, Z. Phys. C **73**, 613 (1997).

[4] H1 Collaboration, C. Adloff *et al.*, Z. Phys. C **74**, 191 (1997); ZEUS Collaboration, J. Breitweg *et al.*, Z. Phys. C **74**, 207 (1997).

[5] See, e.g., J. L. Hewett and T. G. Rizzo, Phys. Rev. D **56**, 5709 (1997), and references therein.

[6] CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **48**, 3939 (1993).

[7] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **79**, 4327 (1997).

[8] D0 Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **72**, 965 (1994).

[9] D0 Collaboration, B. Abbott *et al.*, Phys. Rev. Lett. **79**, 4321 (1997).

[10] D0 Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **76**, 2222 (1996).

[11] D0 Collaboration, S. Abachi *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **338**, 185 (1994).

[12] F. Paige and S. Protopopescu, BNL Report No. 38034, 1986 (unpublished). We used ISAJET version 7.22 with CTEQ2L parton distribution functions.

[13] T. Sjöstrand, Comput. Phys. Commun. **82**, 74 (1994). We used PYTHIA version 5.7.

[14] M. Krämer, T. Plehn, M. Spira, and P. M. Zerwas, Phys. Rev. Lett. **79**, 341 (1997).

[15] F. A. Berends *et al.*, Nucl. Phys. **B357**, 32 (1991).

[16] G. Marchesini *et al.*, Comput. Phys. Commun. **67**, 465 (1992). We used HERWIG version 5.7.

[17] R. Brun and F. Carminati, CERN Program Library Writeup W5013, 1993 (unpublished). We used GEANT version 3.15.

[18] D0 Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **79**, 1203 (1997).

[19] D0 Collaboration, P. C. Bhat, in *Proceedings of the 10th Topical Workshop on Proton-Antiproton Collider Physics*, edited by R. Raja and J. Yoh (AIP Press, New York, 1995), p. 308, and references therein; C. Peterson, T. Rögnvaldsson, and L. Lönnblad, Comput. Phys. Commun. **81**, 185 (1994). We used JETNET version 3.0.

[20] See, e.g., P. Mättig, Report No. CERN-PPE/96-187.

[21] See, e.g., J. L. Hewett and T. G. Rizzo, hep-ph/9708419.