Search for second generation leptoquarks in the dimuon plus dijet channel of $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV

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F. Abe,[17] H. Akimoto,[39] A. Akopian,[31] M. G. Albrow,[7] A. Amadon,[5] S. R. Amendolia,[27] D. Amidei,[20] J. Antos,[33] S. Aota,[37] G. Apollinari,[31] T. Arisawa,[39] T. Asakawa,[37] W. Ashmanskas,[18] M. Atac,[7] P. Azzi-Bacchetta,[25] N. Bacchetta,[25] S. Bagdasarov,[31] M. W. Bailey,[22] P. de Barbaro,[30] A. Barbaro-Galtieri,[18] V. E. Barnes,[29] B. A. Barnett,[15] M. Barone,[9] G. Bauer,[19] T. Baumann,[11] F. Bedeschi,[27] S. Behrends,[3] S. Belforte,[27] G. Bellettini,[27] J. Bellinger,[40] D. Benjamin,[35] J. Bensinger,[3] A. Beretvas,[7] J. P. Berge,[7] J. Berryhill,[5] S. Bertolucci,[9] S. Bettelli,[27] B. Bevensee,[26] A. Bhatti,[31] K. Biery,[7] C. Bigongiari,[27] M. Binkley,[7] D. Bisello,[25] R. E. Blair,[1] C. Blocker,[3] S. Blusk,[30] A. Bodek,[30] W. Bokhari,[26] G. Bolla,[29] Y. Bonushkin,[4] D. Bortoletto,[29] J. Boudreau,[28] L. Breccia,[2] C. Bromberg,[21] N. Bruner,[22] R. Brunetti,[2] E. Buckley-Geer,[7] H. S. Budd,[30] K. Burkett,[20] G. Busetto,[25] A. Byon-Wagner,[7] K. L. Byrum,[1] M. Campbell,[20] A. Caner,[27] W. Carithers,[18] D. Carlsmith,[40] J. Cassada,[30] A. Castro,[25] D. Cauz,[36] A. Cerri,[27] P. S. Chang,[33] P. T. Chang,[33] H. Y. Chao,[33] J. Chapman,[20] M. -T. Cheng,[33] M. Chertok,[34] G. Chiarelli,[27] C. N. Chiou,[33] F. Chlebana,[7] L. Christofek,[13] M. L. Chu,[33] S. Cihangir,[7] A. G. Clark,[10] M. Cobal,[27] E. Cocca,[27] M. Contreras,[5] J. Conway,[32] J. Cooper,[7] M. Cordelli,[9] D. Costanzo,[27] C. Couyoumtzelis,[10] D. Cronin-Hennessy,[6] R. Culbertson,[5] D. Dagenhart,[38] T. Daniels,[19] F. DeJongh,[7] S. Dell'Agnello,[9] M. Dell'Orso,[27] R. Demina,[7] L. Demortier,[31] M. Deninno,[2] P. F. Derwent,[7] T. Devlin,[32] J. R. Dittmann,[6] S. Donati,[27] J. Done,[34] T. Dorigo,[25] N. Eddy,[20] K. Einsweiler,[18] J. E. Elias,[7] R. Ely,[18] E. Engels, Jr.,[28] W. Erdmann,[7] D. Errede,[13] S. Errede,[13] Q. Fan,[30] R. G. Feild,[41] Z. Feng,[15] C. Ferretti,[27] I. Fiori,[2] B. Flaugher,[7] G. W. Foster,[7] M. Franklin,[11] J. Freeman,[7] J. Friedman,[19] H. Frisch,[5] Y. Fukui,[17] S. Gadomski,[14] S. Galeotti,[27] M. Gallinaro,[26] O. Ganel,[35] M. Garcia-Sciveres,[18] A. F. Garfinkel,[29] C. Gay,[41] S. Geer,[7] D. W. Gerdes,[15] P. Giannetti,[27] N. Giokaris,[31] P. Giromini,[9] G. Giusti,[27] M. Gold,[22] A. Gordon,[11] A. T. Goshaw,[6] Y. Gotra,[28] K. Goulianos,[31] H. Grassmann,[36] L. Groer,[32] C. Grosso-Pilcher,[5] G. Guillian,[20] J. Guimaraes da Costa,[15] R. S. Guo,[33] C. Haber,[18] E. Hafen,[19] S. R. Hahn,[7] R. Hamilton,[11] T. Handa,[12] R. Handler,[40] F. Happacher,[9] K. Hara,[37] A. D. Hardman,[29] R. M. Harris,[7] F. Hartmann,[16] J. Hauser,[4] E. Hayashi,[37] J. Heinrich,[26] W. Hao,[35] B. Hinrichsen,[14] K. D. Hoffman,[29] M. Hohlmann,[5] C. Holck,[26]

R. Hollebeek,[26] L. Holloway,[13] Z. Huang,[20] B. T. Huffman,[28] R. Hughes,[23] J. Huston,[21] J. Huth,[11] H. Ikeda,[37] M. Incagli,[27] J. Incandela,[7] G. Introzzi,[27] J. Iwai,[39] Y. Iwata,[12] E. James,[20] H. Jensen,[7] U. Joshi,[7] E. Kajfasz,[25] H. Kambara,[10] T. Kamon,[34] T. Kaneko,[37] K. Karr,[38] H. Kasha,[41] Y. Kato,[24] T. A. Keaffaber,[29] K. Kelley,[19] R. D. Kennedy,[7] R. Kephart,[7] D. Kestenbaum,[11] D. Khazins,[6] T. Kikuchi,[37] B. J. Kim,[27] H. S. Kim,[14] S. H. Kim,[37] Y. K. Kim,[18] L. Kirsch,[3] S. Klimenko,[8] D. Knoblauch,[16] P. Koehn,[23] A. Köngeter,[16] K. Kondo,[37] J. Konigsberg,[8] K. Kordas,[14] A. Korytov,[8] E. Kovacs,[1] W. Kowald,[6] J. Kroll,[26] M. Kruse,[30] S. E. Kuhlmann,[1] E. Kuns,[32] K. Kurino,[12] T. Kuwabara,[37] A. T. Laasanen,[29] S. Lami,[27] S. Lammel,[7] J. I. Lamoureux,[3] M. Lancaster,[18] M. Lanzoni,[27] G. Latino,[27] T. LeCompte,[1] S. Leone,[27] J. D. Lewis,[7] P. Limon,[7] M. Lindgren,[4] T. M. Liss,[13] J. B. Liu,[30] Y. C. Liu,[33] N. Lockyer,[26] O. Long,[26] C. Loomis,[32] M. Loreti,[25] D. Lucchesi,[27] P. Lukens,[7] S. Lusin,[40] J. Lys,[18] K. Maeshima,[7] P. Maksimovic,[11] M. Mangano,[27] M. Mariotti,[25] J. P. Marriner,[7] G. Martignon,[25] A. Martin,[41] J. A. J. Matthews,[22] P. Mazzanti,[2] P. McIntyre,[34] P. Melese,[31] M. Menguzzato,[25] A. Menzione,[27] E. Meschi,[27] S. Metzler,[26] C. Miao,[20] T. Miao,[7] G. Michail,[11] R. Miller,[21] H. Minato,[37] S. Miscetti,[9] M. Mishina,[17] S. Miyashita,[37] N. Moggi,[27] E. Moore,[22] Y. Morita,[17] A. Mukherjee,[7] T. Muller,[16] P. Murat,[27] S. Murgia,[21] M. Musy,[36] H. Nakada,[37] I. Nakano,[12] C. Nelson,[7] D. Neuberger,[16] C. Newman-Holmes,[7] C.-Y. P. Ngan,[19] L. Nodulman,[1] A. Nomerotski,[8] S. H. Oh,[6] T. Ohmoto,[12] T. Ohsugi,[12] R. Oishi,[37] M. Okabe,[37] T. Okusawa,[24] J. Olsen,[40] C. Pagliarone,[27] R. Paoletti,[27] V. Papadimitriou,[35] S. P. Pappas,[41] N. Parashar,[27] A. Parri,[9] J. Patrick,[7] G. Pauletta,[36] M. Paulini,[18] A. Perazzo,[27] L. Pescara,[25] M. D. Peters,[18] T. J. Phillips,[6] G. Piacentino,[27] M. Pillai,[30] K. T. Pitts,[7] R. Plunkett,[7] A. Pompos,[29] L. Pondrom,[40] J. Proudfoot,[1] F. Ptohos,[11] G. Punzi,[27] K. Ragan,[14] D. Reher,[18] M. Reischl,[16] A. Ribon,[25] F. Rimondi,[2] L. Ristori,[27] W. J. Robertson,[6] T. Rodrigo,[27] S. Rolli,[38] L. Rosenson,[19] R. Roser,[13] T. Saab,[14] W. K. Sakumoto,[30] D. Saltzberg,[4] A. Sansoni,[9] L. Santi,[36] H. Sato,[37] P. Schlabach,[7] E. E. Schmidt,[7] M. P. Schmidt,[41] A. Scott,[4] A. Scribano,[27] S. Segler,[7] S. Seidel,[22] Y. Seiya,[37] F. Semeria,[2] T. Shah,[19] M. D. Shapiro,[18] N. M. Shaw,[29] P. F. Shepard,[28] T. Shibayama,[37] M. Shimojima,[37] M. Shochet,[5] J. Siegrist,[18] A. Sill,[35] P. Sinervo,[14] P. Singh,[13] K. Sliwa,[38] C. Smith,[15] F. D. Snider,[15] J. Spalding,[7] T. Speer,[10] P. Sphicas,[19] F. Spinella,[27] M. Spiropulu,[11] L. Spiegel,[7] L. Stanco,[25] J. Steele,[40] A. Stefanini,[27] R. Ströhmer,[7a] J. Strologas,[13] F. Strumia, [10] D. Stuart,[7] K. Sumorok,[19] J. Suzuki,[37] T. Suzuki,[37] T. Takahashi,[24] T. Takano,[24] R. Takashima,[12] K. Takikawa,[37] M. Tanaka,[37] B. Tannenbaum,[22] F. Tartarelli,[27] W. Taylor,[14] M. Tecchio,[20] P. K. Teng,[33] Y. Teramoto,[24] K. Terashi,[37] S. Tether,[19] D. Theriot,[7] T. L. Thomas,[22] R. Thurman-Keup,[1] M. Timko,[38] P. Tipton,[30] A. Titov,[31] S. Tkaczyk,[7] D. Toback,[5] K. Tollefson,[19] A. Tollestrup,[7] H. Toyoda,[24] W. Trischuk,[14] J. F. de Troconiz,[11] S. Truitt,[20] J. Tseng,[19] N. Turini,[27] T. Uchida,[37] F. Ukegawa,[26] J. Valls,[32] S. C. van den Brink,[28] S. Vejcik, III,[20] G. Velev,[27] R. Vidal,[7] R. Vilar,[7a] D. Vucinic,[19]

R. G. Wagner,[1] R. L. Wagner,[7] J. Wahl,[5] N. B. Wallace,[27] A. M. Walsh,[32] C. Wang,[6] C. H. Wang,[33] M. J. Wang,[33] A. Warburton,[14] T. Watanabe,[37] T. Watts,[32] R. Webb,[34] C. Wei,[6] H. Wenzel,[16] W. C. Wester, III,[7] A. B. Wicklund,[1] E. Wicklund,[7] R. Wilkinson,[26] H. H. Williams,[26] P. Wilson,[5] B. L. Winer,[23] D. Winn,[20] D. Wolinski,[20] J. Wolinski,[21] S. Worm,[22] X. Wu,[10] J. Wyss,[27] A. Yagil,[7] W. Yao,[18] K. Yasuoka,[37] G. P. Yeh,[7] P. Yeh,[33] J. Yoh,[7] C. Yosef,[21] T. Yoshida,[24] I. Yu,[7] A. Zanetti,[36] F. Zetti,[27] and S. Zucchelli[2]

(CDF Collaboration)

[1] *Argonne National Laboratory, Argonne, Illinois 60439*

[2] *Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*

[3] *Brandeis University, Waltham, Massachusetts 02254*

[4] *University of California at Los Angeles, Los Angeles, California 90024*

[5] *University of Chicago, Chicago, Illinois 60637*

[6] *Duke University, Durham, North Carolina 27708*

[7] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

[8] *University of Florida, Gainesville, FL 32611*

[9] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*

[10] *University of Geneva, CH-1211 Geneva 4, Switzerland*

[11] *Harvard University, Cambridge, Massachusetts 02138*

[12] *Hiroshima University, Higashi-Hiroshima 724, Japan*

[13] *University of Illinois, Urbana, Illinois 61801*

[14] *Institute of Particle Physics, McGill University, Montreal H3A 2T8, and University of Toronto, Toronto M5S 1A7, Canada*

[15] *The Johns Hopkins University, Baltimore, Maryland 21218*

[16] *Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*

[17] *National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan*

[18] *Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*

[19] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

[20] *University of Michigan, Ann Arbor, Michigan 48109*

[21] *Michigan State University, East Lansing, Michigan 48824*

[22] *University of New Mexico, Albuquerque, New Mexico 87131*

[23] *The Ohio State University, Columbus, OH 43210*

[24] *Osaka City University, Osaka 588, Japan*

[25] *Universita di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*

[26] *University of Pennsylvania, Philadelphia, Pennsylvania 19104*

[27] *Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*

[28] *University of Pittsburgh, Pittsburgh, Pennsylvania 15260*

[29] *Purdue University, West Lafayette, Indiana 47907*

[30] *University of Rochester, Rochester, New York 14627*

[31] *Rockefeller University, New York, New York 10021*

[32] *Rutgers University, Piscataway, New Jersey 08855*

[33] *Academia Sinica, Taipei, Taiwan 11530, Republic of China*

[34] *Texas A&M University, College Station, Texas 77843*

[35] *Texas Tech University, Lubbock, Texas 79409*

[36] *Istituto Nazionale di Fisica Nucleare, University of Trieste/ Udine, Italy*

[37] *University of Tsukuba, Tsukuba, Ibaraki 315, Japan*

[38] *Tufts University, Medford, Massachusetts 02155*

[39] *Waseda University, Tokyo 169, Japan*

[40] *University of Wisconsin, Madison, Wisconsin 53706*

[41] *Yale University, New Haven, Connecticut 06520*

We report on a search for second generation leptoquarks (Φ_2) using a data sample corresponding to an integrated luminosity of 110 pb^{-1} collected at the Collider Detector at Fermilab. We present upper limits on the production cross section as a function of Φ_2 mass, assuming that the leptoquarks are produced in pairs and decay into a muon and a quark with branching ratio β. Using a Next-to-Leading order QCD calculation, we extract a lower mass limit of $M_{\Phi_2} > 202(160)$ GeV/c^2 at 95% confidence level for scalar leptoquarks with β=1(0.5).

Leptoquarks are hypothetical bosons which carry both baryon and lepton quantum numbers and mediate interactions between quarks and leptons. They appear in many extensions to the Standard Model, *e.g.* GUT, superstring, horizontal symmetry, compositeness or technicolor [1]. Leptoquarks which combine quarks and leptons of different generations result in flavor changing neutral currents, which are known to be highly suppressed [2]. While these FCNC constraints do not exclude such leptoquarks, they restrict them to very high masses. For example, in the Pati-Salam model [3], the masses are expected in the multi-TeV range, and indirect searches for such leptoquarks have been made [4]. For this search, we assume that the leptoquarks couple only to leptons and quarks of the same generation. This leads to the classification of leptoquarks of three generations, denoted as Φ_i, $i = 1, 2, 3$ in this report.

In $p\overline{p}$ collisions, leptoquarks can be pair-produced by gluon-gluon fusion or $q\bar{q}$ annihilation [5]. The contribution to the production rate from direct Φql coupling is suppressed relative to the dominant QCD mechanisms [5]. The coupling strength to gluons is determined by the color charges of the particles, and is model-independent in the case of scalar leptoquarks. The production of vector leptoquark pairs is also possible. However, vector leptoquarks have model-dependent trilinear and quadratic couplings to the gluon field [6]. In typical cases the production cross section is orders of magnitude larger than for scalar leptoquarks. The acceptance for vector and scalar leptoquark detection is similar, resulting in much more stringent limits on the vector leptoquark mass.

In this analysis, we report on a direct search for pair produced second generation scalar leptoquarks. The possible decay channels are:

$$\begin{aligned} \Phi_2 &\to q_2\mu^{\pm}, && \text{branching ratio } \beta \\ \Phi_2 &\to q_2\nu_{\mu}, && \text{branching ratio } 1-\beta \end{aligned} \qquad (1)$$

where β is the branching ratio to charged lepton decay, and q_2 is a second generation quark (c, s). Our search for Φ_2 production is based on events having a topology including two muons and at least two jets ($\Phi_2\overline{\Phi_2} \to \mu^+\mu^- jj$). The production rate of this decay mode is proportional to β^2.

A previous CDF study [7] excluded $M_{\Phi_2} < 131(96)$ GeV/c^2, for $\beta = 1.0(0.5)$ using an integrated luminosity of 19 pb^{-1}. A limit has also been published by D∅ [8], which excludes $M_{\Phi_2} < 119(89)$ GeV/c^2 for $\beta = 1(0.5)$. Searches at LEP-1 have excluded leptoquarks with masses below 45 GeV/c^2 independent of β [9]. Here we present a new limit using an integrated luminosity of 110 pb^{-1} collected during the 1992-93 and 1994-95 Tevatron runs (including the 19 pb^{-1} of the previous CDF study). Searches have also been made for first and third generation leptoquark production at the Tevatron [10], LEP [9] and HERA [11]. The H1 and ZEUS experiments at HERA have reported the observation of an excess of events at high Q^2 [12]. The interpretation of the excess as the production of a first generation leptoquark has been ruled out for large β by the Tevatron results [10].

The CDF detector is described in full detail elsewhere [13]. Only the detector subsystems that are important in this analysis are mentioned here. The momenta of muons are measured in the Central Tracking Chamber (CTC), a 2.76 m diameter cylindrical drift chamber. It is surrounded by a 1.4 T super-conducting solenoidal magnet, covering a pseudo-rapidity (η) range up to 1.1, which allows precision measurements of the transverse momenta (p_T) of charged particles. Inside the CTC a vertex tracking chamber (VTX) allows event vertex reconstruction using tracks over the range $|\eta| < 3.25$. Jets are detected by the calorimeters, which are divided into a central barrel ($|\eta| < 1.1$), end plugs ($1.1 < |\eta| < 2.4$), and forward/backward modules ($2.4 < |\eta| < 4.2$). Outside the calorimeters, Central Muon drift chambers (CMU) in the region $|\eta| < 0.6$ provide muon identification. Outside the CMU lie the Central Muon Upgrade chambers (CMP), with additional steel between the CMU and CMP detectors to reduce the background from hadrons in the muon sample. The region of $0.6 < |\eta| < 1.0$ is covered by the Central Muon Extension (CMX) chambers.

We use the PYTHIA Monte Carlo generator [14] with the CTEQ4M parton distribution functions [16] and the renormalization and factorization scales defined as $Q^2 = p_T^2$, together with the CDF detector simulation package, to study the detailed properties of the signal for Φ_2 masses between 100 and 240 GeV/c^2. The signal selection criteria are set according to the kinematic distributions (*e.g.* the p_T of the muons and E_T of the jets) of decay products determined by Monte Carlo studies, optimised to eliminate the background with a minimal loss of signal events [15].

We select events from several different central single-muon triggers [13] with p_T thresholds of 9 or 12 GeV/c. From these events an exclusive dimuon sample is selected by requiring events with two muons satisfying $p_T > 30$ GeV/c (μ_1) and $p_T > 20$ GeV/c (μ_2). We do not require the two muons to have opposite charge because at very high p_T the charge determination is not reliable. One of the muons is required to have a track from the CTC that matches with a stub in the fiducial region of the central muon detectors (within 2 cm for CMU, and 5 cm for CMU/CMP). The muon satisfying this criterion is defined as a 'tight' muon. The other muon can be either a tight muon or a 'loose' muon. A loose muon is defined as a CTC track that deposits less than 2 GeV of electromagnetic energy and less than 6 GeV of hadronic energy in the calorimeter tower that it traverses. To ensure good track quality, the track is required to traverse at least 75% of the CTC in the radial direction, and be matched to an interaction vertex determined by the VTX to better than 5.0 cm in the Z direction. Both muons are required to be isolated, defined as $I < 2$ GeV, where I is the sum of transverse energies of all calorimeter towers (excluding the one traversed by the muon) within a cone of $\Delta R = 0.4$ around the direction of the muon, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and ϕ is the azimuthal angle.

The total dimuon identification efficiency, averaged over the data sample, lies between 79% at $M(\Phi_2) = 100$ GeV/c^2 and 74.5% at $M(\Phi_2) = 240$ GeV/c^2, with the dependence on mass being due to the efficiency of the minimum ionizing requirement. The combined average identification and trigger efficiency is approximately 70% over the mass range $100 < M(\Phi_2) < 240$ GeV/c^2.

From this high-p_T dimuon event sample, we require ≥ 2 jets with $E_T^{(1)} > 30$ GeV and $E_T^{(2)} > 15$ GeV, respectively. Jets are reconstructed by an algorithm using a fixed cone in $\eta - \phi$ space. A detailed description of the algorithm can be found in Ref. [17]. For this analysis a cone of 0.7 is used. Both jets are required to be reconstructed in the region $|\eta| < 2.4$. Jet energy corrections, due to the calorimeter non-linearity, energy deposited outside the jet cone, underlying energy from other interactions, and the detector geometrical dependence, are applied to determine the $\mu - jet$ invariant mass. The Z^0 and other resonances such as the J/ψ or Υ are removed by rejecting events with a dimuon invariant mass in the regions $76 < M_{\mu\mu} < 106$ GeV/c^2 and $M_{\mu\mu} < 11$ GeV/c^2. After applying these requirements, we are left with a sample of 11 events.

Cosmic rays can fake high-p_T dimuon events; however such muons take a finite time to traverse the detector, generally entering from the top of the detector and exiting at the bottom. We use the hadronic calorimeter TDC information and a measurement of the opening angle of the two muons to reject cosmic ray events. None of the 11 selected events is identified as a cosmic ray event.

The numbers of events surviving each selection criterion are listed in Table I. A total of 11 events passing the final selection are shown in Figure 1, plotted in the muon-jet invariant mass plane ($M_{\mu j}^1$ v.s. $M_{\mu j}^2$). From two muons and two jets, there are two possible muon-jet pairings. We choose the combination having the smallest invariant mass difference to determine the leptoquark mass for possible candidate events. The reconstructed leptoquark candidates of a pair should have equal mass, within the experimental mass resolution σ_r.

We therefore search for leptoquark candidates by selecting events in a $3\sigma_r$ mass resolution region of the $M_{\mu j}^1$ vs. $M_{\mu j}^2$ plane around any given mass, as shown in Fig. 1. The mass resolution, estimated from Monte Carlo studies, depends on the event geometry and the total event energy. Consequently, it varies with the leptoquark mass. For example, the maximum values for the mass resolutions are $\sigma_r(\Phi_2 = 120$ GeV/$c^2) = 21.2$ GeV/c^2 and $\sigma_r(\Phi_2 = 240$ GeV/$c^2) = 46.5$ GeV/c^2. The asymmetric mass resolution (oval-shaped regions shown in Figure 1) results primarily from the detector resolution, but also includes a small probability of misidentifying the jet when additional jets exist in the collision, and cases for which a wrong muon-jet pairing combination is chosen.

The backgrounds for the Φ_2 search include higher order Drell-Yan processes, heavy flavor decay (from $\bar{b}b$ or $\bar{t}t$ in the dimuon channel), WW, or $Z \to \tau^+\tau^-$. An additional background results from W plus multi-jet events with a fake muon from energetic hadrons penetrating the shielding to reach the muon chambers, or with a hadron decay to a muon. These background processes are studied using relevant Monte Carlo events samples and actual data samples where possible. The major background is from Drell-Yan processes (we expect $\sim$ 12 events for 110 pb^{-1}) for which the final state includes a muon pair ($Z^0/\gamma \to \mu^+\mu^-$) plus two or more jets from initial or final state radiation. There is a small contribution from $\bar{t}t$ ($\sim$ 1.3 events). Other backgrounds are negligible due to large muon p_T and jet E_T requirements ($\bar{b}b$ and $Z \to \tau^+\tau^-$), muon isolation requirements (W plus jets), and small cross section (WW). The total estimated background is 14 ± 1.8 for an integrated luminosity of 110 pb^{-1}, before applying the 3 σ_r mass cut. This mass requirement reduces the background substantially, since in the background events the reconstructed muon-jet invariant masses are not correlated. For example, we have estimated the background contribution to be only 0.3 events for M(Φ_2) = 200 GeV/c^2 for the 110 pb^{-1} data sample.

In the final result, we do not apply a background subtraction procedure, giving the most conservative estimate of the cross section limit. The number of expected events, N, is given by

$$N = \mathcal{L} \cdot \beta^2 \cdot \sigma(M_{\Phi_2}) \cdot \varepsilon_{total}, \qquad (2)$$

where $\mathcal{L}$ is the total integrated luminosity of the sample, β is the decay branching ratio to the charged lepton plus quark channel, $\sigma(M_{\Phi 2})$ is the cross section for a given mass, and ε_{tot} is the overall efficiency. We evaluate the factors entering the overall efficiency as a function of Φ_2 mass using actual event samples where possible and otherwise simulated event samples. As shown in Table II, it increases monotonically with M(Φ_2), from 9% at M(Φ_2) = 100 GeV/c^2 to 22% at M(Φ_2) = 240 GeV/c^2.

Possible systematic uncertainties of the measured cross section limit have been studied. The major source comes from a limited understanding of the initial and final state gluon radiation. We have used Monte Carlo samples with and without gluon radiation to determine the cross section uncertainty due to this effect. The uncertainty decreases as the Φ_2 mass increases, and it is estimated to be 10% for M(Φ_2) = 160 GeV/c^2. A systematic uncertainty also results from the Q^2 scale and the structure functions used. We compute this effect by varying the Q^2 scale between 1/4 and 4 of the default value ($Q^2 = p_T^2$), and by using other structure functions (CTEQ2L [18] and MRS(A) [19]). The jet energy scaling uncertainty, which results from detector performance limitations is determined by including a 10% energy uncertainty in the Monte Carlo reconstruction. Other sources of uncertainty, resulting from the detector simulation and the limitation of Monte Carlo statistics, are relatively small. The uncertainty on the luminosity measurement is 7.2%. The total systematic uncertainty varies with Φ_2 mass, and is computed to be 15% at $M_{\Phi 2} = 120$ GeV/c^2 and 10% at $M_{\Phi 2} = 240$ GeV/c^2, as listed in Table II.

We compute the 95% confidence level (C.L.) limits on $\sigma(p\bar{p} \to \Phi_2\bar{\Phi}_2)\beta^2$, including systematic uncertainties with no background subtraction, as a function of the leptoquark mass (see Table II and Figure 2). The cross section limit for a given Φ_2 mass does not depend on the coupling λ, and therefore the mass limit does not depend on the choice of the theoretical model but only on β. A theoretical Next-to-Leading order (NLO) cross section calculation [20] is also shown in Figure 2, where the band represents the main uncertainty of the calculation coming from the Q^2 value. Comparing the cross section limit to this calculation, a limit of $M_{\Phi_2} > 202(160)$ GeV/c^2 for $\beta = 1.0(0.5)$ is derived.

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Type of selection	Number of events remaining
Total number of sample	30934
1^{st} muon selection (tight cut)	6844
2^{nd} muon selection (loose cut)	4153
2 jet cuts	937
Jet E_T cut	64
Invariant Mass cut	11
Cosmic ray cut	11

TABLE I. The number of events surviving each cut, using an integrated luminosity of 110 pb^{-1} from CDF data. The estimated total background from Standard Model sources is 14 ± 1.8 events.

Φ_2 mass (GeV/c^2)	120	160	200	240
Total signal detection efficiency,ε_{tot}	0.13	0.17	0.20	0.22
Systematic error on ε_{tot}	0.019	0.023	0.023	0.023
Number of candidate events	1	0	0	1
Estimated background	3.8	1.1	0.3	0.1
σ (at 95% C.L.) in pb	0.34	0.16	0.13	0.19

TABLE II. Results for different Φ_2 masses for an integrated luminosity of 110 pb^{-1} from CDF data. No background subtraction is made in the cross section evaluation. The candidate satisfying M(Φ_2) > 200 GeV/c^2 was previously published [6].

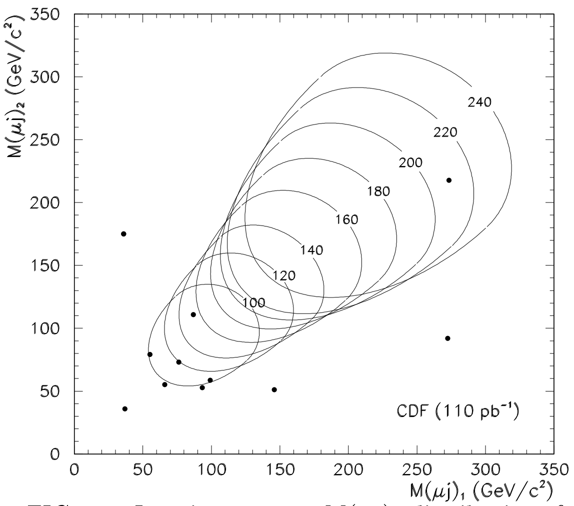

FIG. 1. Invariant mass $M(\mu j)$ distribution for events before applying the mass requirement. A total of 11 candidate events are displayed on the $M(\mu j)_2$ versus $M(\mu j)_1$ plane. The oval configuration shows the limit of the mass requirement for Φ_2 masses between 100 and 240 GeV/c^2. $M(\mu j)_1$ is the invariant mass with the higher p_T muon, while $M(\mu j)_2$ is that with the lower p_T muon.

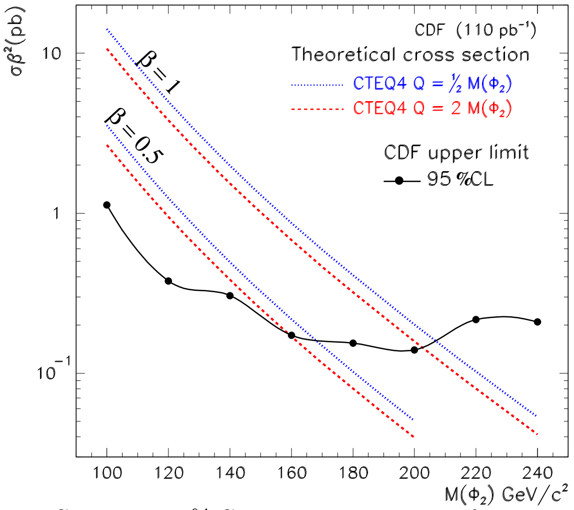

FIG. 2. The 95% C.L. cross section limit for Φ_2 production for an integrated luminosity of 110 pb^{-1}. The theoretical cross section curves [17] for $\beta = 0.5$ and 1.0 are super-imposed.

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