Search for events with leptonic jets and missing transverse energy in p\(p\) collisions at \(\sqrt{s} = 1.96\) TeV

V.M. Abazov,35 B. Abbott,73 M. Abolins,62 B.S. Acharya,29 M. Adams,48 T. Adams,46 G.D. Alexeev,35 G. Alkhazov,39 A. Alton,61 G. Alves,60 G.A. Alves,2 L.S. Anuc,34 M. Aoki,47 Y. Arnould,14 M. Arov,57 A. Askew,46 B. Åsman,40 O. Atramentov,65 C. Avila,8 J. BackusMayes,80 F. Badaud,13 L. Bagly,47 B. Baldin,47 D.V. Bandurin,46 S. Banerjee,20 E. Barberis,60 P. Baringer,55 J. Barretto,2 J.F. Bartlett,47 U. Bassler,18 S. Beale,94 A. Bean,55 M. Begalli,3 M. Begel,71 C. Belanger-Champagne,40 L. Bellantoni,47 J.A. Benitez,62 S.B. Beri,27 G. Bernardi,17 R. Bernhard,22 I. Bertram,41 M. Besançon,18 R. Beuselinck,42 V.A. Bezzubov,38 P.C. Bhat,47 V. Bhatnagar,27 G. Blazey,49 S. Blessing,46 K. Bloom,64 A. Boehmlein,47 D. Boline,70 T.A. Bolton,56 E.E. Boos,37 G. Borissov,41 T. Bose,59 A. Brandt,76 V.O. Brandt,23 R. Brock,62 G. Brooijmans,68 A. Bross,47 D. Brown,17 J. Brown,17 X.B. Bu,7 D. Buchholz,50 M. Buehler,79 V. Buescher,24 V. Bunichev,37 S. Burdin,43 T.H. Burnett,80 C.P. Buszello,42 B. Calpak,15 S. Calvet,16 E. Camacho-Pérez,22 M.A. Carrasco-Lizarraga,32 E. Carrera,46 B.C.K. Casey,47 H. Castilla-Valdez,32 S. Chakrabarti,70 D. Chakraborty,49 K.M. Chan,53 A. Chandra,78 G. Chen,55 S. Chevalier-Théry,18 D.K. Cho,75 S.W. Cho,31 S. Choi,31 B. Choudhary,28 T. Christoudias,42 S. Cihangir,47 D. Claes,64 J. Clutter,55 M.O. Cooper,75 W.E. Cooper, M. Corcoran,78 F. Couderc,18 M.-C. Cousinou,55 A. Croc,18 D. Cutts,75 M. Ćwiok,30 A. Das,44 G. Davies,42 K. De,76 S.J. de Jong,34 E. De La Cruz-Burelo,33 F. Déliot,18 D. DeMaet,65 M. Demarteau,47 R. Demina,69 D. Denisov,47 S.P. Denisov,38 S. Desai,47 K. DeVaughan,64 H.T. Diehl,47 M. Diesburg,47 A. Dominguez,64 T. Dorland,80 A. Dubey,28 L.V. Dudko,37 D. Duggan,65 A. Duperrin,15 S. Dutt,27 A. Dyshkant,49 M. Eads,64 D. Edmunds,62 J. Ellison,45 V.D. Elvira,47 Y. Enari,17 S. Eno,55 H. Evans,51 A. Evdokimov,51 V.N. Facini,48 A.V. Ferapontov,75 T. Ferbel,58,69 F. Fiedler,24 F. Filthaut,34 W. Fisher,62 H.E. Fisk,47 M. Fortner,49 H. Fox,41 S. Fuess,47 T. Gadfort,71 A. Garcia-Bellido,69 V. Gavrilo,36 P. Gay,13 W. Geist,19 W. Geng,15,62 D. Gerbaudo,66 C.E. Gerber,48 Y. Gerstein,47,69 G. Ginther,47,69 G. Golovanov,35 A. Goussion,80 P.D. Grammis,70 S. Greder,19 H. Greenlee,47 Z.D. Greenwood,57 E.M. Gregoreys,4 G. Grenier,20 Ph. Gris,13 J.-F. Grivaz,16 A. Grohsjean,18 S. Grinendahl,47 M.W. Grünwald,30 F. Gu,70 W.E. Cooper,75 M. Corcoran,78 F. Courderc,18 M.-C. Cousinou,55 A. Croc,18 J. Haley,60 L. Han,7 K. Harder,43 A. Harel,69 J.M. Hauptman,54 J. Hays,42 T. Hebbeker,21 D. Hedin,49 H. Hegab,74 A.P. Heinson,45 U. Heintz,75 C. Heusel,23 I. Heredia-De La Cruz,32 K. Herner,61 G. Heseketh,60 M.D. Hildreth,53 R. Hirosky,79 T. Hoang,46 J.D. Hobbs,70 B. Hoeveisen,12 M. Höhlfeld,24 S. Hossain,73 Z. Hubacek,10 N. Huse,17 V. Hynek,10 I. Iashvili,67 R. Illingworth,47 A.S. Itó,47 S. Jabeen,75 M. Jaffré,16 S. Jain,87 D. Jamin,15 R. Jesik,42 K. Johns,44 M. Johnson,47 D. Johnston,64 A. Jonckheere,47 P. Jonsson,42 J. Joshi,27 A. Juste,47 K. Kaadze,56 E. Kajfasz,17 D. Karmanov,37 P.A. Kasper,47 I. Katsanos,64 R. Keohoe,77 S. Kermiche,15 N. Khalatyan,47 A. Khanov,74 A. Kharchilava,67 Y.N. Khartcheev,35 D. Khattidze,75 M.H. Kirby,50 J.M. Kohli,27 A.V. Kozelov,38 J. Kraus,62 A. Kumar,67 A. Cupo,11 T. Kurča,20 V.A. Kuzmin,37 J. Kvišta,9 S. Lambers,51 G. Landsberg,75 P. Lebrun,49 H.S. Lee,31 S.W. Lee,54 W.M. Lee,47 J. Lellouch,17 L. Li,45 Q.Z. Li,47 S.M. Lietti,5 J.K. Lim,31 D. Lincoln,47 J. Linnemann,62 V.V. Lipaev,38 R. Lipton,47 Y. Liu,7 Z. Liu,6 A. Lobodon,59 M. Lokajíček,11 P. Love,41 H.J. Lubatti,80 R. Lima-Garcia,32 A.L. Lyon,47 A.K.A. Maciel,2 D. Mackin,78 R. Madar,18 R. Magaña-Villalba,32 S. Malik,64 V.L. Malyshev,35 Y. Maravin,56 J. Martínez-Ortega,32 R. McCarthy,70 C.L. McGivern,55 M.M. Meijer,34 A. Melnitchouk,63 D. Menezes,29 P.G. Mercadante,4 M. Merkin,37 A. Meyer,21 J. Meyer,23 N.K. Mondal,20 G.S. Muanza,15 M. Mulhearn,79 E. Nagy,42 M. Naimuddin,28 M. Narain,73 R. Nayar,28 H.A. Neal,61 J.P. Negret,8 P. Neustroev,39 H. Nilsen,22 S.F. Novoa,5 T. Nummennnen,25 G. Obrant,39 D. Opromoleno,56 J. Orduna,32 N. Osman,42 J. Osta,53 G.J. Otero y Garzón,1 M. Owen,43 M. Padilla,45 M. Pangilinan,75 N. Parashar,52 V. Parihar,75 S.K. Park,31 J. Parsons,68 R. Partridge,75 N. Parua,51 A. Patwa,71 B. Penning,47 M. Perfilov,37 K. Peters,43 Y. Peters,43 G. Petripollio,66 P. Pétrikov,46 E. Pigniana,1 J. Piper,62 M.-A. Pleier,71 P.L.M. Podesta-Lerma,32 V.M. Podstavkov,47 M.-E. Pol,2 P. Polozov,36 A.V. Popov,38 M. Prewitt,78 D. Price,51 S. Protopopescu,71 J. Qian,61 A. Quadt,23 B. Quinn,63 M.S. Rangel,16 K. Ranjan,28 P.N. Ratoff,41 I. Razumov,38 P. Renkel,77 P. Rich,43 M. Rijssenbeek,70 I. Ripp-Baudot,19 F. Rizatdinova,74 M. Rominsky,47 C. Royon,18 P. Rubinov,47 R. Ruchti,53 G. Saposnik,36 G. Sajot,14 A. Sánchez-Hernández,32 M.P. Sanders,25 B. Sanghi,47 A.S. Santos,5
G. Savage,47 L. Sawyer,57 T. Scanlon,42 R.D. Schamberger,70 Y. Scheglov,39 H. Schellman,50 T. Schliephake,26 S. Schlobohm,80 C. Schwanenberger,43 R. Schwienhorst,62 J. Sekaric,55 H. Severini,73 E. Shabalina,23 V. Shary,18 A.A. Shehukin,38 R.K. Shivpuri,28 V. Simak,10 V. Sirotenko,47 P. Skubic,73 P. Slattery,69 D. Smirnov,53 K.J. Smith,67 G.R. Snow,64 J. Snow,72 S. Snyder,71 S. Sönder-Rembold,43 L. Sonnenschein,21 A. Sopczak,41 M. Sosebee,76 K. Soustruznik,9 B. Spurlock,76 J. Stark,14 V. Stolin,36 D.A. Stoyanova,36 E. Strauss,70 M. Strauss,73 D. Strom,48 L. Stutte,47 P. Svoisky,34 M. Takahashi,43 A. Tanasijczuk,1 W. Taylor,6 M. Titov,18 V.V. Tokmenin,35 D. Tsybychev,70 B. Tuchming,18 C. Tully,66 P.M. Tuts,68 L. Uvarov,39 S. Uvarov,39 S. Uzunyan,49 R. Van Kooten,51 W.M. van Leeuwen,33 N. Varelas,48 E.W. Varnes,44 I.A. Vasilyev,38 P. Verdier,20 L.S. Vertogradov,35 M. Verzocchi,47 M. Vesterinen,80 D. Vilanova,45 M. Vobis,57 D.R. Wood,60 T.R. Wyatt,53 Y. Xie,47 C. Xu,61 S. Yacoob,50 R. Yamada,47 W.-C. Yang,43 T. Yasuda,47 Y.A. Yatsumenko,35 Z. Ye,47 H. Yin,7 K. Yip,71 H.D. Yoo,75 S.W. Youn,47 J. Yu,76 S. Zelitch,79 T. Zhao,80 B. Zhou,61 J. Zhu,61 M. Zielinski,69 D. Zieminska,51 and L. Zivkovic,68
(The D0 Collaboration*)

1Universidad de Buenos Aires, Buenos Aires, Argentina
2LAFAEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
3Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
4Universidade Federal do ABC, Santo André, Brazil
5Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil
6Simon Fraser University, Vancouver, British Columbia, and York University, Toronto, Ontario, Canada
7University of Science and Technology of China, Hefei, People’s Republic of China
8Universidad de los Andes, Bogotá, Colombia
9Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic
10Czech Technical University in Prague, Prague, Czech Republic
11Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
12Universidad San Francisco de Quito, Quito, Ecuador
13LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
14LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
15CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
16LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
17LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France
18CEA, Ifri, SPP, Saclay, France
19IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
20IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
21IIH. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
22Physikalisches Institut, Universität Freiburg, Freiburg, Germany
23II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
24Institut für Physik, Universität Mainz, Mainz, Germany
25Ludwig-Maximilians-Universität München, München, Germany
26Fachbereich Physik, Bergische Universität Wuppertal, Wuppertal, Germany
27Panjab University, Chandigarh, India
28Delhi University, Delhi, India
29Tata Institute of Fundamental Research, Mumbai, India
30University College Dublin, Dublin, Ireland
31Korea Detector Laboratory, Korea University, Seoul, Korea
32CINVESTAV, Mezco City, Mexico
33FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands
34Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands
35Joint Institute for Nuclear Research, Dubna, Russia
36Institute for Theoretical and Experimental Physics, Moscow, Russia
37Moscow State University, Moscow, Russia
38Institute for High Energy Physics, Protvino, Russia
39Petersburg Nuclear Physics Institute, St. Petersburg, Russia
40Stockholm University, Stockholm and Uppsala University, Uppsala, Sweden
41Lancaster University, Lancaster LA1 4YB, United Kingdom
42Imperial College London, London SW7 2AZ, United Kingdom
43The University of Manchester, Manchester M13 9PL, United Kingdom
We present the first search for pair production of isolated jets of charged leptons in association with a large imbalance in transverse energy in $p\bar{p}$ collisions using 5.8 fb$^{-1}$ of integrated luminosity collected by the D0 detector at the Fermilab Tevatron Collider. No excess is observed above Standard Model background, and the result is used to set upper limits on the production cross section of pairs of supersymmetric chargino and neutralino particles as a function of “dark-photon” mass, where the dark photon is produced in the decay of the lightest supersymmetric particle.

PACS numbers: 12.60.Jv, 14.80.Ly

Hidden-valley models contain a hidden sector that is very weakly coupled to standard-model (SM) particles. By introducing new low-mass particles in the hidden sector, these models have been shown to provide coherent interpretation of possible astrophysical anomalies, and accommodate discrepancies in direct searches for dark matter. The impact of the hidden valley particles should be observable in high-energy collisions. Although details of the hidden sector can affect the phenomenology, the force carrier in the hidden sector, the dark-photon ($\gamma_D$), must have a mass $< 2$ GeV, and generally decays into SM charged-fermion (or pion) pairs. In many models, $\gamma_D$ has a short lifetime, and does not travel an observable distance ($< 1 \mu$m) before decaying. If supersymmetry (SUSY) is realized in Nature, there will be partners for both the SM and the hidden sector particles. If the lightest SUSY particle (LSP) of the hidden sector ($\tilde{X}$) is lighter than the lightest SM SUSY partner (SM-LSP), the SM-LSP can decay...
promptly into particles of the hidden sector, and always will do so if $R$-parity is conserved. The D0 collaboration has reported a search for such a decay, with one SM-LSP decaying to a SM photon and $\tilde{X}$, and the other to $\gamma_D$ and $\tilde{X}$. However, the SM-LSP might decay predominantly into hidden sector particles, thereby yielding two or more $\gamma_D$ in each event, as indicated in Fig. 1. Pair-produced dark photons could also arise from rare decays of Z bosons and Higgs bosons. Single dark photons should also be produced directly in association with a jet, as in SM prompt-photon production. This process is difficult to detect at a hadron collider, while high-luminosity low-energy $e^+e^-$ colliders could be more effective in observing such events.

Since hidden-sector particles have small mass and they are produced with high velocities, their decays through the hidden sector can produce jets of tightly collimated particles from decays of $\gamma_D$. If $M(\gamma_D) < 2m(\pi)$, the jets will consist only of charged leptons. Even for larger $M(\gamma_D)$, the lepton content of these jets will be high, and we therefore refer to them as leptonic jets ($l$-jets). For the proposed scenario, every SUSY event will have at least two $l$-jets and a large imbalance in transverse energy ($E_T$) from the escaping $\tilde{X}$ and possibly also from other escaping dark particles. Radiation of additional $\gamma_D$ in the hidden sector can dilute the $l$-jet signatures, by producing final-state particles in $l$-jets that are softer, less tightly collimated, and less isolated.

In this Letter, we present a search for events with two $l$-jets and large $E_T$ in data collected using the D0 detector during Run II of the Fermilab Tevatron Collider, corresponding to an integrated luminosity of 5.8 fb$^{-1}$. Depending on whether the $\gamma_D$ decays to muons or electrons, the $l$-jet can appear either as a “muon $l$-jet” or an “electron $l$-jet” in the detector. To reconstruct muon $l$-jets, we demand a muon-track candidate with hits in all three layers of the outer D0 muon system and a matching track with $p_T > 10$ GeV in the central tracker. An electron $l$-jet must contain a central track with $p_T > 10$ GeV that matches an electromagnetic (EM) calorimeter cluster with transverse energy $E_T^{EM} > 15$ GeV within a cone of radius $R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.2$. EM clusters are formed using a simple cone algorithm of $R = 0.4$ and require $> 95\%$ of the energy to be deposited in the EM section of the calorimeter. The calorimeter isolation variable $I_T = [E_T^{EM}(0.4) - E_T^{EM}(0.2)]/E_T^{EM}(0.2)$ must be $I_T < 0.2$, where $E_T^{EM}(0.4)$ is the total transverse energy in a cone of radius $R = 0.4$, corrected for contributions from the underlying event, and $E_T^{EM}(0.2)$ is the transverse EM energy in a cone of radius $R = 0.2$. The central “seed” track matched to the muon or EM cluster is required to have at least one hit in the silicon detector. When the seed track is matched to both a muon and an EM cluster, the $l$-jet is defined as a muon $l$-jet. Next, a companion track of opposite electric charge from the seed track, and within $z = 1$ cm of the seed track at its distance of closest approach to the beamline, is required to have $p_T > 4$ GeV and be within $R < 0.2$ of the seed track. If more than one such companion track is found, we use the one with smallest $R$. No explicit requirements are made on the distances of closest approach of tracks to the collision point, thus the $l$-jet reconstruction efficiency remains high for $\gamma_D$ decay radii up to $\approx 1$ cm. We then choose the pair of $l$-jet candidates with seed tracks separated by $R > 0.8$ that have the largest invariant mass of any pair of seed tracks in the event.

The MadGraph MC event generator, with PYTHIA for showering and hadronization, is used to simulate the signal, and these Monte Carlo (MC) events are then processed through the full GEANT3-based D0-detector simulation and event reconstruction software. SUSY events generated using SPSS parameters of the gauge-mediated-SUSY-breaking (GMSB) model are used as a benchmark. The efficiency to reconstruct many tightly-collimated tracks is difficult to determine from data, and we therefore assume that all neutralinos decay directly into a single $\gamma_D$ and the dark gaugino LSP $X$, giving just two leptons per $l$-jet. The $X$ would, most naturally, have a similar mass as $\gamma_D$, so we assume $m(X) = 1$ GeV. More complicated hidden-sector options are studied using MC simulation and are discussed below.

The analysis requires two $l$-jet candidates (either muon or electron) in each event. The three classes of $\mu\mu$, $e\mu$, and $ee$ $l$-jets are analyzed separately, and contain 7344, 19014, and 30642 candidate events, respectively. Each event is assigned to just one class, with preference of choice given to $\mu\mu$, then $e\mu$, and then $ee$, since muon $l$-jets have less background. All collected events are used in the analysis, but most pass single or di-lepton triggers. Following offline selections, the trigger efficiency for signal is $> 90\%$.

The main background to $l$-jets is from multijet production, but electron $l$-jets also have a contribution.
from photon production with subsequent conversion to $e^+e^-$. Such backgrounds cannot be calculated reliably using simulation, and are therefore determined from data. We exploit the tight collimation of $l$-jets to distinguish them from multijet background, through track and calorimeter-isolation criteria. The “track isolation” is defined by a scalar sum over $p_T$ of tracks with $p_T > 0.5$ GeV, $z < 1$ cm from the seed track at its distance of closest approach to the beamline, and within an annulus $0.2 < R < 0.4$ relative to the seed track. Muon $l$-jet calorimeter isolation ($I_\mu$, defined in Ref. [23], relies on the transverse energies of all calorimeter cells within $R < 0.4$, excluding cells within $R < 0.1$ of either the seed muon or its companion track. For electron $l$-jet isolation, we employ the EM cluster-isolation $I_e$, defined above. A reliable estimate of background requires that the $l$-jet isolation requirements not bias the kinematics, such as distributions in $E_T$ or $p_T$ of $l$-jets. Both types of $l$-jets require the track isolation to be $I < 2$ GeV, which does not significantly bias the background. Calorimeter-isolation criteria are chosen as linear functions of $p_T$ values of the $l$-jet, such that the fraction of rejected background is large, but weakly dependent on $E_T$, as discussed below. For EM clusters, we choose $I_e < 0.085 \times p_T - 0.53$ (in GeV units), which rejects 90% of the background. For muon $l$-jets we use the scalar sum of $p_T$ values of the muon and companion tracks as a measure of $l$-jet $p_T$, and require $I_\mu < 0.066 \times p_T + 2.35$ (in GeV units), which rejects 94% of the background. We compare the $E_T$ distribution in data with just one isolated $l$-jet to those containing two (not necessarily isolated) $l$-jets. The two distributions are observed to be very similar, which indicates that the kinematic bias on $E_T$ from $I_e$ and $I_\mu$ requirements is indeed small. We therefore use the $E_T$ distribution in data without isolation requirements as background for the data with two isolated $l$-jets, since both samples are dominated by similar multijet processes.

Finally, we require $E_T > 30$ GeV for the search sample, where $E_T$ is calculated using only calorimetric information, and not corrected for any detected muons, as muon reconstruction is unreliable in $l$-jets because of the presence of nearby tracks. We scale the $E_T$ distribution in the data sample without isolation criteria so that the total number of events with $E_T < 15$ GeV matches that in the isolated data sample, see Fig. 2. The ratio $R_f$ defined as the number of events in each search channel with $E_T > 30$ GeV divided by the scaled number of events with $E_T < 15$ GeV in each respective background is given in Table I. The value of $R_f$ is important since if a signal

| Chan. | $R_f$ | $N_{obs}$ | $N_{pred}$ | $A(\%)$ | $\varepsilon(\%)$ | $\sigma_{stat} \times B$, fb |
|-------|-------|-----------|-----------|---------|----------------|------------------|
| $\mu\mu$ | 0.33 | 3 | 8.6±4.5 | 50 | 12 | $B_\mu^2$ | 20 | $35^{+26}_{-21}$ |
| $e\mu$ | 0.37 | 11 | 17.5±4.2 | 53 | 15 | $2E_eB_\mu$ | 19 | $30^{+19}_{-15}$ |
| $ee$ | 0.04 | 7 | 10.2±1.7 | 45 | 20 | $B_e^2$ | 13 | $19^{+11}_{-9}$ |

FIG. 2: (color online) The $E_T$ distribution for events with (a) two isolated muon $l$-jets, (b) one muon and one electron $l$-jet, and (c) two electron $l$-jets. The data are presented by the black points, and the shaded bands represent the expected background, with red showing the correlated part of the systematic uncertainty from normalization and blue the full uncertainty. The SPS8 MC contribution for signal (see text) is scaled to an integrated content of 10 events. The highest bin contains all events with $E_T > 90$ GeV.

TABLE I: The ratio $R_f$ of events with two $l$-jets and $E_T > 30$ GeV divided by the number with $E_T < 15$ GeV in the non-isolated data sample (see text); events observed and predicted from background in each channel; the acceptance of the chosen SPS8 [23] SUSY MC point, and the reconstruction efficiency, given in %; branching ratios ($B$) for each channel, calculated from $B_e$ and $B_\mu$ in Table I. Finally, limits on cross sections times $B$ from the inclusive $l$-jet search.
TABLE II: Branching ratio (B) into electrons and muons of γ_D as a function of its mass. Mass windows for a search for γ_D, and the efficiency for a reconstructed, isolated l-jet to be found in each mass window, for electron and muon l-jets.

| M(γ_D) (GeV) | B_e/B_µ | ΔM(l-jet)(GeV) | Eff. ee/µµ (%) |
|--------------|---------|----------------|----------------|
| 0.15         | 1.00/0.00 | 0.0–0.3        | 81/–           |
| 0.3          | 0.53/0.47  | 0.1–0.4        | 82/88          |
| 0.5          | 0.40/0.40  | 0.3–0.6        | 81/89          |
| 0.7          | 0.15/0.15  | 0.4–0.8        | 85/89          |
| 0.9          | 0.27/0.27  | 0.6–1.1        | 82/91          |
| 1.3          | 0.31/0.31  | 0.9–1.4        | 72/79          |
| 1.7          | 0.22/0.22  | 1.0–1.8        | 73/76          |
| 2.0          | 0.24/0.24  | 1.3–2.2        | 73/83          |

has a E_T spectrum similar to that of the background, this analysis would be largely insensitive, regardless of the size of the signal. The total background for a signal having f_1 events with E_T < 15 GeV and f_2 events with E_T > 30 GeV is a factor of (f_1/f_2) × R_f larger than for the case of no signal. For the benchmark signals considered, (f_1/f_2) × R_f ≪ 1, and the correction is therefore ignored.

We separate the detection efficiency into three components (Table II): (i) the branching ratio (B) for an event to have at least two l-jets in the μμ, eμ, or ee channel, obtained from the expected γ_D branching fractions [13]. (ii) the acceptance (A) for both l-jets to have the seed and companion tracks within |η| < 1.1 for electrons and < 1.6 for muons, with p_T > 10 and 4 GeV, respectively, and E_T (calculated in MC as the vector sum of transverse momenta of all stable particles in the hidden sector, neutrinos, and muons) > 30 GeV, and (iii) the efficiency (ε) to reconstruct both l-jets in the acceptance, to pass the isolation criteria for both l-jets, and to have reconstructed E_T in excess of 30 GeV. The acceptance and reconstruction efficiency do not vary significantly with M(γ_D).

With no excess observed above the expected background at large E_T (see Fig. 2), we set limits on l-jet production cross sections, using a likelihood fitter [24] that incorporates a log-likelihood ratio statistic [25]. Limits at the 95% CL on cross section times B, calculated separately for the μμ, eμ, and ee channels, using the observed numbers of events, predicted backgrounds, and detection efficiencies and acceptances, are given in Table II. Systematic uncertainties are included for signal efficiency (20%), background normalization (20–50%), and luminosity (6.1%). The uncertainty on the signal efficiency is dominated by the uncertainty in the tracking efficiency for neighboring tracks in data. The background uncertainty is dominated by the small remaining kinematic bias on the E_T arising from the isolation criteria.

When the track multiplicity in any l-jet is small, the leading track and its companion track are likely to originate from the decay of the same dark photon, so we also examine the invariant mass of the seed and its companion track (M(γ_D)) in events with two isolated l-jets and E_T > 30 GeV (Fig. 3). The backgrounds are normalized by scaling the events passing all selections but with E_T < 20 GeV to data with E_T > 30 GeV outside of the mass windows defined in Tab. II thus R_f is irrelevant for this second analysis. The selection of background events is loosened to E_T < 20 GeV for this resonance search to increase the statistics of the sample. Limits on cross sections are calculated in various ranges of l-jet mass, ΔM(l-jet), as shown in Tab. III and Fig. 4.

The dependence of the efficiency for reconstructing and identifying l-jets on parameters of the hidden sector is studied using MC simulation. Additional MC samples are used for examining the neutralino decay into a dark Higgs boson that decays into two dark photons, leading to more, but softer, leptons in l-jets. Efficiency for these states decreases by ≈50% at large M(γ_D), for both elec-
tron and muon $l$-jets. The point $M(\gamma_D) = 0.7$ GeV also has a $\approx 50\%$ lower efficiency, due to the large branching fraction of $\gamma_D$ to hadrons. MC events are also generated with additional radiation in the hidden sector. Raising the dark coupling ($\alpha_D$) from 0 to 0.3 reduces the efficiency by up to 20%, independent of $M(\gamma_D)$. According to MC simulation, the $l$-jet identification criteria maintain good efficiency even for more complicated behavior in the hidden sector.

In summary, we have performed a search for events with two tightly collimated jets consisting mainly of charged leptons and large $E_T$ in 5.8 fb$^{-1}$ of integrated luminosity. The invariant mass of the $l$-jets, formed by a seed track and a companion track was also examined for a resonant signal. No evidence was observed for such signals, and upper limits were set, as a function of $M(\gamma_D)$, on the production cross section for SUSY particles decaying to two $l$-jets and large $E_T$.

We thank A. Falkowski, J. Ruderman, M. Strassler, S. Thomas, I. Yavin, and J. Wacker for many useful discussions and guidance. We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); STFC and the Royal Society (United Kingdom); MSMT and GACR (Czech Republic); CRC Program and NSERC (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); and CAS and CNSF (China).

![Cross section limit vs Dark photon mass](image)

**FIG. 4:** (color online) Limit on the observed cross section (blue, solid curve) for the three channels combined, corrected for SPS8 acceptance, as a function of $M(\gamma_D)$. Also shown are the observed (blue, circles) and expected (red, squares) combined limit determined using the measured masses of the seed and companion tracks in both $l$-jets, for each mass window studied (from Table III). Limits are weaker when the dark photon branching ratio to hadrons is larger, particularly near the $\rho$ and $\phi$ resonances.

[1] T. Han et al., J. High Energy Phys. 07, 008 (2008); M. Strassler and K. Zurek, Phys. Lett. B 651, 374 (2007).
[2] D.P. Finkbeiner and N. Weiner, Phys. Rev. D 76 083519 (2007).
[3] N. Arkani-Hamed et al., Phys. Rev. D 79 015014 (2009).
[4] A.A. Abdo et al., Phys. Rev. Lett. 102, 181101 (2009).
[5] O. Adriani et al., Nature 458, 607 (2009).
[6] J. Chang et al., Nature 456, 362 (2008).
[7] R. Bernabei et al. (DAMA/LIBRA Collaboration), Eur. Phys. J. C 56, 333 (2008).
[8] Z. Ahmed et al. (CDMS II Collaboration), Science 327 (5973), 1619 (2010).
[9] M. Baumgart et al., J. High Energy Phys. 04, 014 (2009).
[10] D.S.M. Alves et al., [arXiv:0903.3945 [hep-ph]] [Phys. Lett. B (to be published)].
[11] A. Katz and R. Sundrum, J. High Energy Phys. 06, 003 (2009).
[12] A. Falkowski et al., [arXiv:1002.2952 [hep-ph]].
[13] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 103, 081802, (2009).
[14] C. Cheung et al., J. High Energy Phys. 04, 116 (2010).
[15] B. Aubert et al. (BaBar Collaboration), [arXiv:0808.2821]
[16] B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. 103, 081803 (2009).
[17] J. D. Bjorken et al., Phys. Rev. D 80 075018 (2009).
[18] V. M. Abazov et al. (D0 Collaboration), Nucl. Instrum. Methods Phys. Res. A 565, 463 (2006).
[19] D0 uses a right-handed coordinate system, with the $z$-axis pointing in the direction of the proton beam and the $y$-axis pointing upwards. The pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$, where $\theta$ is the polar angle.
[20] J. Alwall et al., J. High Energy Phys. 09, 028 (2007).
[21] T. Sjostrand et al., Comput. Phys. Commun. 135, 238 (2001).
[22] R. Brun and F. Carminati, CERN Program Library Long Writeup W5013, 1993 (unpublished).
[23] The lightest neutralino mass for this SUSY point is $\approx 140$ GeV and the second neutralino and the chargino masses are both $\approx 265$ GeV; B.C. Allanach et al., Eur. Phys. J. C 25, 113 (2002).
[24] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 103, 061801 (2009).
[25] W. Fisher, FERMILAB-TM-2386-E.