Search for a fourth generation $t'$ quark in $pp$ collisions at $\sqrt{s} = 1.96$ TeV

V.M. Abazov, 35 B. Abbott, 73 B.S. Acharya, 29 M. Adams, 49 T. Adams, 47 G.D. Alexeev, 35 G. Alkhazov, 39 A. Alton, 61 G. Alversen, 60 G.A. Alves, 2 L.S. Ancu, 34 M. Aoki, 48 M. Aroy, 58 A. Askew, 47 B. Ásman, 41 O. Atramentov, 65 C. Avila, 8 J. BackusMayes, 80 F. Badau, 13 L. Bagby, 48 B. Baldin, 48 D.V. Bandurin, 47 S. Banerjee, 29 E. Barberis, 60 P. Barginer, 56 J. Barreto, 3 J.F. Bartlett, 48 U. Bassler, 18 V. Bazterra, 49 S. Beale, 6 A. Bean, 56 M. Begalli, 3 M. Begel, 71 C. Belanger-Champagne, 41 L. Bellantoni, 48 S.B. Beri, 27 G. Bernardi, 17 R. Bernhard, 52 I. Bertram, 42 M. Beszedes, 43 V.A. Bezzubov, 38 P.C. Bhat, 48 V. Bhatnagar, 27 G. Blazey, 50 S. Blessing, 47 K. Bloom, 64 A. Boehmle, 48 D. Boline, 70 E.E. Boos, 37 G. Borissov, 42 T. Bose, 59 A. Brandt, 76 O. Brandt, 25 R. Brock, 42 G. Brooijmans, 88 A. Bross, 48 D. Brown, 17 J. Brown, 17 X.B. Bu, 48 M. Buehler, 79 V. Buescher, 24 V. Bunichev, 37 S. Burdin, 42 T.H. Burnett, 80 C.P. Buszello, 41 B. Calpas, 15 E. Camacho-Pérez, 32 M.A. Carambas-Lizarraga, 56 B.C.K. Casey, 48 H. Castilla-Valdez, 32 S. Chakrabarti, 70 D. Chakraborty, 50 K.M. Chan, 54 A. Chandra, 78 G. Chen, 56 S. Chevalier-Théry, 18 D.K. Cho, 75 S.W. Cho, 31 S. Choi, 31 B. Choudhary, 28 S. Chiang, 64 D. Claes, 64 J. Clutter, 56 M. Cooke, 48 W.E. Cooper, 48 M. Corcoran, 78 F. Couderc, 18 M.-C. Cousinou, 15 A. Croc, 18 D. Cutts, 75 A. Das, 75 G. Davies, 43 K. De, 76 S.J. de Jong, 34 E. De La Cruz-Burelo, 32 F. Délitou, 18 M. Demarteau, 48 R. Demina, 59 D. Denisov, 38 S. Desai, 48 C. Deterre, 18 K. DeVaughan, 64 H.T. Diehl, 48 M. Diesburg, 48 A. Dominguez, 64 T. Dorland, 80 A. Dubey, 28 L.V. Dudko, 37 D. Duggan, 65 A. Duperrin, 15 S. Dutt, 27 A. Dyshkant, 50 M. Eads, 64 D. Edmunds, 62 J. Ellison, 46 V.D. Elvira, 48 Y. Enari, 17 H. Evans, 52 A. Evdokimov, 71 V.N. Evdokimov, 38 G. Facini, 60 T. Ferbel, 69 F. Fiedler, 24 F. Filthaut, 34 W. Fisher, 52 H.E. Fisk, 48 M. Fortner, 50 H. Fox, 42 S. Fuess, 48 A. Garcia-Bellido, 69 V. Gavrilov, 36 P. Gay, 13 W. Geng, 15, 62 D. Gerbaudo, 66 C.E. Gerber, 49 Y. Gershtein, 65 G. Ginther, 48, 69 G. Golovanov, 35 A. Goussiou, 80 P.D. Grannis, 70 S. Greder, 19 H. Greenlee, 48 Z.D. Greenwood, 58 E.M. Gregores, 4 G. Grenier, 20 Ph. Gris, 13 J.-F. Grivaz, 16 A. Grôhsjean, 18 S. Grünendahl, 48 M.W. Grünewald, 30 T. Guillemin, 16 F. Guo, 70 G. Gutierrez, 48 P. Günterrez, 73 A. Haas, 68 S. Hagopian, 47 J. Haley, 66 L. Han, 7 K. Harder, 44 A. Harel, 69 J.M. Hauptman, 35 J. Hays, 43 T. Head, 44 T. Hebbeker, 21 D. Hedeen, 50 H. Hegab, 74 A.P. Heinson, 46 U. Heintz, 75 C. Hensel, 23 I. Heredia-De La Cruz, 32 K. Herten, 61 G. Hesketh, 44 M.D. Hildreth, 54 R. Hirosky, 79 T. Hoang, 47 J.D. Hobbs, 70 B. Hoeneisen, 12 M. Holhfeld, 24 Z. Hubacek, 10, 18 N. Huske, 17 V. Hynek, 13 I. Iashvili, 97 R. Illingworth, 48 A.S. Ito, 48 S. Jaben, 75 M. Jaffré, 16 D. Janin, 15 A. Jayasinghe, 73 R. Jesik, 43 K. Johns, 45 M. Johnson, 48 D. Johnston, 64 A. Jonckheere, 48 P. Jonsson, 43 J. Josh, 27 A.W. Jung, 80 A. Juste, 40 K. Kaadze, 57 E. Kajfasz, 15 D. Karmanov, 37 P.A. Kasper, 48 I. Katsanos, 64 R. Kehoe, 77 S. Kermiche, 15 N. Kathalayan, 48 A. Khanov, 74 A. Kharchilava, 67 Y.N. Kharzeev, 35 D. Khitatze, 75 M.H. Kirby, 51 J.M. Kohli, 27 A.V. Kozelov, 38 J. Kraus, 62 S. Kulikov, 38 A. Kumar, 67 A. Kupco, 11 T. Kurča, 20 V.A. Kuzmin, 37 J. Kvita, 9 S. Lammers, 52 G. Landsberg, 75 P. Lebrun, 20 H.S. Lee, 31 S.W. Lee, 55 W.M. Lee, 48 J. Lellouch, 17 L. Li, 46 Q.Z. Li, 48 S.M. Lietti, 5 J.K. Lim, 31 D. Lincoln, 48 J. Linemman, 62 V.V. Lipse, 38 R. Lipton, 48 Y. Liu, 7 Z. Liu, 6 A. Lobodenko, 39 M. Lokajícek, 11 R. Lopes de Sa, 70 H.J. Lubatti, 80 R. Luna-García, 32 A.L. Lyon, 48 A.K.A. Maciel, 2 D. Mackin, 78 R. Madar, 18 R. Magaña-Villalba, 32 S. Malik, 64 V.L. Malyshev, 35 V. Maravin, 57 J. Martínez-Ortega, 32 R. McCarthy, 70 C.L. McGivern, 56 M.M. Meijer, 34 A. Melnitchouk, 63 D. Menezes, 50 P.G. Mercadante, 4 M. Merkin, 37 A. Meyer, 21 J. Meyer, 23 F. Miconi, 19 N.K. Mondal, 29 G.S. Muntau, 15 M. Mulhearn, 79 E. Nagy, 15 M. Naimuddin, 28 M. Narain, 45 T. Nayyar, 28 H.A. Neal, 63 J.P. Negret, 8 P. Neustoief, 39 S.F. Novaes, 5 T. Nunnenmann, 25 G. Obrant, 39 J. Orduña, 78 N. Osmany, 15 J. Osta, 54 G.J. Otero y Garzón, 1 M. Padilla, 46 A. Pal, 76 N. Parashar, 53 V. Parihar, 75 S.K. Park, 31 J. Parsons, 68 R. Partridge, 75 N. Parua, 52 A. Patwa, 71 B. Penning, 48 M. Perfilov, 37 K. Peters, 44 Y. Peters, 44 K. Petridis, 44 G. Petrillo, 69 P. Pétron, 16 R. Piegaj, 1 J. Pipkin, 62 M.-A. Pieier, 71 P.L.M. Postema-Lerma, 32 V.M. Podstavkov, 48 P. Polozov, 36 A.V. Popov, 38 M. Prewitt, 78 D. Price, 72 N. Prokopenko, 38 S. Propodopescu, 71 J. Qian, 61 A. Quadt, 23 B. Quinn, 63 M.S. Rangel, 2

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We present a search for pair production of a fourth generation $t'\bar{t}'$ quark and its antiparticle, followed by their decays to a $W$ boson and a jet, based on an integrated luminosity of $5.3 \, fb^{-1}$ of proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV collected by the D0 Collaboration at the Fermilab Tevatron Collider. We set upper limits on the $t'\bar{t}'$ production cross section that exclude at the 95% C.L. a $t'$ quark that decays exclusively to $W$+jet with a mass below 285 GeV. We observe a small excess in the $\mu$+jets channel which reduces the mass range excluded compared to the expected limit of 320 GeV in the absence of a signal.

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Measurements of the partial width of the $Z$ boson to invisible final states at LEP exclude the existence of a fourth neutrino flavor with a mass less than half the $Z$ boson mass [1]. However, this does not exclude the existence of a fourth generation of fermions as long as its neutrino is more massive. Precision electroweak data favor a small mass splitting between the up-type quark of this fourth generation, $t'$, and its down-type partner, $b'$, so that $m(t') - m(b') < m(W)$ [2]. Provided there is moderate mixing between the new fourth generation and the first three generations, the $t'$ quark will predominantly decay to $Wq$, where $q$ includes all standard model down-type quarks.

We report on a search for a fourth generation $t'$ quark...
that is produced in proton-antiproton collisions together with its antiparticle. We assume that the $t'$ quark is a
narrow state that always decays to $Wq$. This search is also sensitive to other new particles that are pair pro-
duced and decay to a $W$ boson plus a jet. We select lep-
ton+jets final states with one isolated electron or muon
with high transverse momentum ($p_T$), a large imbalance in
transverse momentum ($\Delta p_T$), and at least four jets cor-
responding to events in which one of the $W$ bosons decays
to leptons and the other $W$ boson decays to quarks. A
similar search has been carried out by the CDF Collab-
oration in 0.8 fb$^{-1}$ of integrated luminosity [3].

The D0 detector consists of central tracking, calorime-
ter, and muon systems [4, 5]. The central tracking sys-
tem is located inside a 2 T superconducting solenoidal
magnet. Central and forward preshower detectors are lo-
cated just outside of the coil and in front of the calorime-
ters. The liquid-argon/uranium calorimeter is divided
into a central section covering pseudorapidity $|\eta| < 1.1$
and two end calorimeters extending $\eta$ coverage to 4.2.
The calorimeter is segmented longitudinally into elec-
 tromagnetic, fine hadronic, and coarse hadronic sections
with increasingly coarser sampling. The muon system,
located outside the calorimeter, consists of one layer of
tracking detectors and scintillation trigger counters inside
1.8 T toroidal magnets and two similar layers outside the
toroids. A three-level trigger system selects events that
are recorded for offline analysis.

This analysis is based on data corresponding to an in-
tegrated luminosity of 5.3 fb$^{-1}$, collected by the D0 Collab-
oration at the Fermilab Tevatron proton-antiproton col-
lider at a center of mass energy of $\sqrt{s} = 1.96$ TeV. Events
must satisfy one of several trigger conditions, all requir-
ing an electron or muon with high transverse momentum,
in some cases in conjunction with one or more jets. For
all events, the $p_T$ collision point must be reconstructed
with at least three tracks and located within 60 cm of the
center of the detector along the beam direction. Jets are
reconstructed using a midpoint cone algorithm [6] with
cone size $\Delta R = \sqrt{\Delta \eta^2 + (\Delta \phi)^2} = 0.5$, where $\phi$ is the
azimuth, and must have at least two reconstructed tracks
within the jet cone. The jet energy is corrected on av-
average to the total energy of all particles emitted inside
the jet cone. Jets in simulated events are adjusted to
reproduce the reconstruction efficiency and energy reso-
novation and response observed in data. All events must
have at least four jets with $|\eta| < 2.5$, $p_T > 40$ GeV for
the leading jet, and $p_T > 20$ GeV for all other jets. The
momentum carried away by neutrinos is inferred from the
$p_T$ jet, computed from the energies in the cells of the elec-
n tromagnetic and fine hadronic calorimeters and adjusted
for the energy corrections applied to the reconstructed
jets and electrons and for the momentum of any recon-
structed muons, taking into account their energy loss in
the calorimeter.

Electrons are identified as clusters of energy depo-
sitions in the calorimeter that are isolated from other
energy deposits. The electromagnetic section of the cal-
orimeter must contain 90% of their energy, and the
energy deposition pattern must be consistent with that
of an electromagnetic shower. Every electron must be
matched to a reconstructed track with $p_T > 5$ GeV. For
the $e+$jets channel, we require exactly one electron with
$p_T > 20$ GeV and $|\eta| < 1.1$ that originates from the
$p_T$ collision point. We also require $p_T > 20$ GeV and
$|\Delta \phi(e, p_T)| > 2.2 - 0.045 \cdot p_T$/GeV, where $\Delta \phi(e, p_T)$ is
the azimuthal angle between electron and $p_T$, to reject
events with jets that are misidentified as electrons.

Muons are defined as tracks reconstructed in the muon
system matched to tracks in the central tracker. Muons
must be separated from jets and isolated in the calorime-
ter and in the tracker. For the $\mu+$jets channel, we re-
quire exactly one muon with $p_T > 20$ GeV and $|\eta| < 2$
that originates from the $p_T$ collision point. The invari-
ant mass of the selected muon and any other muon must
be less than 70 GeV or more than 110 GeV to reject
$Z(\rightarrow \mu\mu)+$jets events. We require $p_T > 25$ GeV and
$|\Delta \phi(\mu, p_T)| > 2.1 - 0.035 \cdot p_T$/GeV to reject events with
mismeasured muons. More details about the lepton+jets
event selection can be found in Ref. [7].

The two main standard model processes that produce
events with an isolated lepton, $p_T$, and at least four jets
are $t\bar{t}$ and $W+$jets production. The third most impor-
tant source of events arises from mismeasured multijet
events in which a jet is misidentified as an electron or
a muon from heavy flavor decay appears isolated. Sin-
gle top quark, $Z+$jets, and diboson production can also
give rise to such final states but have much smaller cross
sections and/or acceptances.

We use ALPGEN [8] to simulate $t\bar{t}$ production with the
top quark mass set to 172.5 GeV and normalized to the
$Wq$ boson sample to the NNLO cross sec-
tion of 7.48$^{+0.56}_{-0.72}$ pb [10]. Samples of $W+$jets events are
generated using ALPGEN and PYTHIA with a jet-matching
algorithm, following the MLM prescription [11]. Three
subsamples are generated: $Wb\bar{b}$, $Wc\bar{c}$, and $W+$light par-
tons. The $Wc$ subprocesses are included in the $W+$light parton sample with massless charm quarks. We fix the
relative normalization of $Wb\bar{b}$, $Wc\bar{c}$, and $W+$light parton
samples to match NLO cross sections [12]. The $Z(\rightarrow ee$, $\mu\mu$, $\tau\tau)$+jets samples are generated with ALPGEN and
PYTHIA and broken up into $Zb\bar{b}$, $Zc\bar{c}$, and $Z+$light parton
samples in the same way as the $W+$jets samples. We fix
their relative normalization to NLO predictions and nor-
malize the total $Z$ boson sample to the NNLO cross sec-
tion [13]. We simulate single top quark production using the
COMHEP-SINGLETOP [14] Monte Carlo event gener-
ator with the top quark mass set to 172.5 GeV and nor-
malize to the NNLO cross section with NNLO threshold
corrections in the $s$ and $t$-channels of 3.3 pb [15]. Dibo-
sion samples are generated with PYTHIA. Their NLO cross
sections are 12.3 pb for \(WW\), 3.7 pb for \(WZ\), and 1.4 pb for \(ZZ\) production \[12\]. The CTEQ6L1 parton distribution functions \[16\] are used for all Monte Carlo samples. We simulate detector effects using the GEANT \[17\] program. Events from random collisions are added to all simulated events to account for detector noise and additional \(p\bar{p}\) interactions. The events are reconstructed with the same program as the data.

To define the background model, we estimate the number of multijet events that enter the final data sample using a data driven method \[18\]. We compute the number of multijet events in the \(e+\)jets and \(\mu+\)jets samples separately. We then subtract the multijet and all other backgrounds, except the \(W+\)jets background, from the data, based on their calculated cross sections, and normalize the \(W+\)jets contribution to the remaining number of events. This corresponds to scaling the total number of \(W+\)jets events expected by a factor 1.3, which is consistent with NLO expectations. Table I summarizes the resulting composition of the data sample. When we test for the presence of a \(t'\) quark signal, we fix the relative normalizations of the \(W+\)jets, \(Z+\)jets, single top quark, and diboson backgrounds, as given in Table I, but float their overall normalization.

**TABLE I: Composition of the final data sample with systematic uncertainties.** The number of \(W+\)jets events is chosen to equalize the total number of events observed and expected.

| Source       | \(e+\)jets | \(\mu+\)jets |
|--------------|-------------|--------------|
| \(t\bar{t}\) production | 678\(\pm\)76  | 508\(\pm\)55  |
| Single \(t\) production | 12\(\pm\)4  | 8\(\pm\)3   |
| \(W+\)jets | 503\(\pm\)87  | 648\(\pm\)59  |
| \(Z+\)jets | 41\(\pm\)7  | 40\(\pm\)7   |
| \(WW, WZ, ZZ+jets\) | 25\(\pm\)5  | 21\(\pm\)5   |
| Multijets | 173\(\pm\)42  | 43\(\pm\)18  |
| Data | 1431 | 1268 |

To simulate the signal, we use \(t\bar{t}\) production in PYTHIA and force the decay \(t' \rightarrow Wb\). However, since we do not identify \(b\) jets in this analysis, our results are also applicable to \(t'\) quarks decaying to a \(W\) boson and a light down-type quark. We generate events at 13 \(t'\)-mass values between 200 and 500 GeV. We set the total width of the \(t'\) quark to 10 GeV. This is smaller than the resolution for reconstructing the \(t'\) mass, which ranges between 50 GeV at \(m_{t'} = 200\) GeV and 100 GeV at \(m_{t'} = 500\) GeV. Therefore, the exact value of the width does not affect the analysis.

We define \(H_T\) as the scalar sum of \(p_T\) and of the transverse momenta of all jets and the charged lepton. A kinematic fit to the \(t\bar{t}\rightarrow t\nu b q\bar{q}'\bar{b}\) hypothesis reconstructs the mass \(m_{t\bar{t}}\) of the \(t'\) quark. We use the two-dimensional histograms of \(H_T\) versus \(m_{t\bar{t}}\) to test for the presence of signal in the data and to compute 95% C.L. upper limits on the \(t\bar{t}\) production cross section as a function of \(t'\)-mass. Figure I shows the scatter plots observed in data and expected from \(t\bar{t}\) production, \(\bar{t}\) production, and from all other background sources. For each hypothesized value of the \(t'\) mass, we fit the data to background-only and to signal+background hypotheses. We then use the likelihood ratio \(L = -2 \log(P_{S+B}/P_B)\) as the test statistic, where \(P_{S+B}\) is the Poisson likelihood to observe the data under the signal+background hypothesis and \(P_B\) is the Poisson likelihood to observe the data under the background-only hypothesis. For the background-only hypothesis, we fit three components to the data: \(t\bar{t}\) production constrained to its theoretical cross section, the multijets background constrained to the number of events given in Table I and \(W+\)jets and all other backgrounds in the proportions given in Table I. For the signal+background fit we add the \(t\bar{t}\) cross section as a parameter to the fit. The fit can discriminate between background and signal contributions because their distributions in the \(H_T\) and \(m_{t\bar{t}}\) variables are different. For each hypothesis we also vary the systematic uncertainties given in Table I subject to a Gaussian constraint to their prior values to maximize the likelihood ratio \[19\].

**FIG. 1:** \(H_T\) versus \(m_{t\bar{t}}\) for (a) data, (b) background, (c) \(t\bar{t}\)-production, and (d) \(t\bar{t}\) signal with \(m(t') = 325\) GeV. The bins at the upper and right edges of the plots also contain overflows.

We use the CLs method \[20\] to determine the cross section limits. Using pseudoexperiments, we determine the probability to measure values of \(L\) that are larger than the value observed in the data sample for a \(t'\) signal, \(CL_{s+b}\), and for no \(t'\) signal, \(CL_b\). The value of the \(t'\) pair production cross section for which \(1 - CL_{s+b}/CL_b = 0.95\) is the 95% C.L. upper limit. We repeat this procedure for each \(t'\) mass point.

Table I summarizes the sources of systematic uncertainties included in the limit calculation. The first four uncertainties affect the normalization of the components of our signal and background models. All other uncer-
tainties affect the selection efficiency. When estimating the effect of uncertainties in the jet energy scale, the jet identification efficiency, and the jet energy resolution, we also vary the shapes of the \( H_T \) and \( m_{\text{fit}} \) distributions. No uncertainties are given for the \( W+\text{jets} \) background because its normalization is a free parameter of the fit.

| Source          | \( t'\bar{t'} \) | \( t\bar{t} \) | multijets |
|-----------------|-----------------|-----------------|-----------|
| \( tt \) cross section | —               | 9%              | —         |
| Multijets normalization  | —               | —               | (25-50)%  |
| Integrated luminosity | 6.1%            | 6.1%            | —         |
| MC model         | —               | 4.3%            | —         |
| Trigger efficiency | \( \leq 5\% \) | \( \leq 5\% \) | —         |
| \( pp \) collision point reconstruction | 1.6% | 1.6% | — |
| Lepton identification | (3-4)% | (3-4)% | — |
| Jet energy calibration | (1-2)% | (2-5)% | — |
| Jet energy resolution | (1-2)% | (2-3)% | — |
| Jet identification | 1% | (1-3)% | — |

We first analyze the \( e+\text{jets} \) and \( \mu+\text{jets} \) data separately. Figure 2 shows the distributions of \( H_T \) and \( m_{\text{fit}} \) from the standard model backgrounds and a 325 GeV \( t' \) quark signal compared to data. There is no visible excess in the \( e+\text{jets} \) data. In the \( \mu+\text{jets} \) data we observe a small excess of events over standard model expectations. We can fit the data best with a \( t'\bar{t'} \) production cross section of 3.2 \( \pm 1.1 \) times the theoretical cross section for a \( t' \) quark mass of 325 GeV. The value of \( 1 - CL_b \) for the data gives the probability of getting a local deviation of at least this size from the standard model expectation in the absence of physics beyond the standard model. We find a \( p \) value of 0.007, corresponding to 2.5 Gaussian-equivalent standard deviations.

Figure 3 shows the resulting cross section limits compared to the limits expected in the absence of \( t'\bar{t'} \) production and to the predicted NLO \( t' \) pair production cross section as a function of the mass of the \( t' \) quark for (a) \( e+\text{jets} \), (b) \( \mu+\text{jets} \). The shaded regions around the expected limit represent the \( \pm 1 \) and \( \pm 2 \) standard deviation bands.

In conclusion, we searched for pair production of a \( t' \) quark and its antiparticle followed by their decays into a \( W \) boson and a jet. We do not see a signal consistent with \( t'\bar{t'} \) production, although we observe a small excess of events in the \( \mu+\text{jets} \) channel. Combining the \( e+\text{jets} \) and \( \mu+\text{jets} \) channels, we exclude at 95\% C.L. \( t'\bar{t'} \) production for \( t' \) quark mass values below 285 GeV.

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FIG. 4: Same as Fig. 3 but for both channels combined.

[1] The ALEPH, DELPHI, L3, OPAL, and SLD Collaborations and working groups, Physics Reports 427 (2006) 257.
[2] G.D. Kribs, Phys. Rev. D 76, 075016 (2007); O. Eberhardt, A. Lenz, and J. Rohrwild, Phys. Rev. D 82, 095006 (2010).
[3] T. Aaltonen et al. (CDF Collaboration), Phys. Rev. Lett. 100, 161803 (2008).
[4] S. Abachi et al. (D0 Collaboration), Nucl. Instrum. Methods Phys. Res. A 338, 185 (1994).
[5] V.M. Abazov et al. (D0 Collaboration), Nucl. Instrum. Methods Phys. Res. A 565, 463 (2006).
[6] G. Blazey et al., in Proceedings of the Workshop: “QCD and Weak Boson Physics in Run II” edited by U. Baur, R.K. Ellis and D. Zeppenfeld, FERMILAB-Pub-00/297 (2000).
[7] V.M. Abazov et al. (D0 Collaboration), submitted to Physical Review D, arXiv:1101.0124.
[8] M. L. Mangano et al., J. High Energy Phys., 07, 001 (2003); we use version 2.11.
[9] T. Sjostrand, S. Mrenna, and P. Skands, J. High Energy Phys., 05, 026 (2006); we use version 6.409.
[10] S. Moch and P. Uwer, Phys. Rev. D 78, 034003 (2008).
[11] S. Höche et al., hep-ph/0602031.
[12] Computed with MCFM: J. Campbell, R.K. Ellis, Phys. Rev. D 65, 113007 (2002).
[13] R. Hamberg, W.L. van Neerven, and W.B. Kilgore, Nucl. Phys. B359, 343 (1991) and erratum in B644, 403 (2002). The cross section was corrected to include the $\gamma^*$ contribution.
[14] E.E. Boos et al., Phys. Atom. Nucl. 69, 1317 (2006).
[15] N. Kidonakis, Phys. Rev. D 74, 114012 (2006).
[16] J. Pumplin et al., J. High Energy Phys., 07, 012 (2002); D. Stump et al., J. High Energy Phys., 10, 046 (2003).
[17] R. Brun and F. Carminati, CERN Program Library Long Writeup W5013, 1993 (unpublished).
[18] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. D 76, 092007 (2007).
[19] W. Fisher, FERMILAB-TM-2386-E.
[20] T. Junk, Nucl. Instrum. Methods Phys. Res., A 434, 435 (1999).
[21] M. Cacciari et al., J. High Energy Phys., 04, 068 (2004).