

Search for single-top-quark production in  $p\bar{p}$  collisions at  $\sqrt{s}=1.8$  TeV

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We search for standard model single-top-quark production in the  $W$ -gluon fusion and  $W^*$  channels using  $106 \text{ pb}^{-1}$  of data from  $p\bar{p}$  collisions at  $\sqrt{s}=1.8 \text{ TeV}$  collected with the Collider Detector at Fermilab. We set an upper limit at 95% confidence level (C.L.) on the combined  $W$ -gluon fusion and  $W^*$  single-top cross section of 14 pb, roughly six times larger than the standard model prediction. Separate 95% C.L. upper limits in the  $W$ -gluon fusion and  $W^*$  channels are also determined and are found to be 13 and 18 pb, respectively.

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The observation of the top quark in  $p\bar{p}$  collisions at the Fermilab Tevatron has relied on pair production through the strong interaction, typically  $q\bar{q} \rightarrow t\bar{t}$ . A top quark can also be produced singly, in association with a  $b$  quark, through the electroweak interaction [1]. The two dominant “single-top” processes are “ $Wg$ ” (i.e.  $W$ -gluon fusion,  $qg \rightarrow t\bar{b}q'$ ) and “ $W^*$ ” ( $q\bar{q}' \rightarrow t\bar{b}$ ). Within the context of the standard model, a measurement of the rate of these processes at a hadron collider allows a determination of the Cabibbo-Kobayashi-Maskawa matrix element  $V_{tb}$  [2]. Assuming  $|V_{tb}|=1$ , the predicted cross sections for  $Wg$  and  $W^*$  are 1.7 pb [3] and 0.7 pb [4], respectively, compared to 5.1 pb for  $t\bar{t}$  pair production [5]. The DØ Collaboration has recently published 95% confidence level (C.L.) upper limits of 22 pb on  $Wg$  and 17 pb on  $W^*$  production [6]. In this Rapid Communication we report on two searches: one for the two single-top processes combined, and the other for each process separately.

The expected final state of a single-top event consists of  $W$ -decay products plus two or more jets, including one  $b$ -quark jet from the decay of the top quark. In  $W^*$  events, we expect a second  $b$ -quark jet from the  $W^*t\bar{b}$  vertex. In  $Wg$  events, a second jet originates from the recoiling light quark and a third jet is produced through the splitting of the initial-state gluon into  $b\bar{b}$ . This  $b$ -quark jet is produced at a larger absolute value of pseudorapidity [7] and lower transverse momentum than the second  $b$ -quark jet in  $W^*$  events [1].

Single-top processes are harder to observe than  $t\bar{t}$  production because their cross section is smaller and their final state, containing fewer jets, competes with a larger  $W$ +multijet background from QCD. *A priori* we do not expect sensitivity to the standard model cross section in the presently available data. However, a number of new physics processes could enhance the single-top production rate, motivating a search [8–10]. For example, current Collider Detector at Fermilab (CDF) data are expected to be sensitive to a new flavor gauge boson with mass below  $1 \text{ TeV}/c^2$  [9].

Our measurement uses  $106 \pm 4 \text{ pb}^{-1}$  of data from  $p\bar{p}$  collisions at  $\sqrt{s}=1.8 \text{ TeV}$  collected with the Collider Detector at Fermilab between 1992 and 1995 (“run I”). The detector is described in detail elsewhere [11]. We restrict our single-

top search to events with evidence of a leptonic  $W$  decay: an isolated [12] electron (muon) candidate with  $E_T(P_T) > 20 \text{ GeV}(\text{GeV}/c)$  and missing transverse energy [13]  $\cancel{E}_T > 20 \text{ GeV}$  from the neutrino. We remove events that were identified in a previous CDF analysis [14] as  $t\bar{t}$  dilepton candidates. Events with a second, same-flavor and opposite-charge lepton that forms an invariant mass with the first lepton between 75 and 105  $\text{GeV}/c^2$  are rejected as likely to have come from  $Z^0$  boson decays. Furthermore, to reject those dilepton  $t\bar{t}$  or  $Z^0$  candidates where one lepton fails our electron or muon identification, we also remove events that contain a track with  $P_T > 15 \text{ GeV}/c$  and charge opposite that of the primary lepton, and such that the total  $P_T$  of all tracks in a cone of radius  $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$  around this track is less than 2  $\text{GeV}/c$  [15]. Jets are formed as clusters of calorimeter towers within cones of fixed radius  $\Delta R = 0.4$ . Events are required to have one, two, or three jets with  $E_T > 15 \text{ GeV}$  and  $|\eta| < 2.0$ ; at least one jet must be identified as likely to contain a  $b$  quark (“ $b$ -tagged”) using displaced-vertex information from the silicon vertex detector (SVX) [15]. If a second jet in the event is also  $b$ -tagged, either in the SVX or by the presence of a soft lepton indicative of semi-leptonic  $b$  decay, the event is labeled “double-tag,” otherwise it is labeled “single-tag.” The above event selection cuts are common to our combined and separate searches for the two single-top processes. Additional cuts are applied within each analysis.

We first describe our search for single-top production in the  $Wg$  and  $W^*$  channels combined. The expected signal significance is improved by requiring the invariant mass  $M_{l\nu b}$ , reconstructed from the lepton, neutrino, and highest- $E_T$   $b$ -tagged jet, to lie in a window around the top quark mass,  $140 < M_{l\nu b} < 210 \text{ GeV}/c^2$ . The neutrino momentum is obtained from the  $\cancel{E}_T$  and the constraint that  $M_{l\nu} = M_W$  [16]. The variable  $M_{l\nu b}$  discriminates against both non-top and  $t\bar{t}$  backgrounds, in the latter case because combinatorial errors in assigning partons to final-state jets broaden the  $M_{l\nu b}$  distribution compared to single top.

We determine the efficiency of our selection criteria from events generated by the PYTHIA Monte Carlo program [17] and subjected to a CDF detector simulation. The acceptance times branching ratio is  $(1.7 \pm 0.3)\%$  for each of the two single-top processes. The largest contributions to the acceptance uncertainties come from lepton triggering and identification (10%), and  $b$ -tagging (10%). Combining these acceptances with the cross sections predicted by theory [3,4] and the size of the CDF Run I dataset, we expect a total signal yield of 4.3 events.

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TABLE I. Expected numbers of signal and background events passing all cuts in the  $W$ +jets data sample, compared with observations. The uncertainties on the expected numbers of single-top events do not include uncertainties on the theoretical cross section calculations.

Process	Combined search	Separate search	
	$W+1,2,3$ jets	Single-tag	Double-tag
$Wg$	$3.0 \pm 0.6$	$1.4 \pm 0.3$	$0.04 \pm 0.01$
$W^*$	$1.3 \pm 0.2$	$0.55 \pm 0.15$	$0.32 \pm 0.06$
$t\bar{t}$	$8.4 \pm 2.7$	$1.4 \pm 0.5$	$0.7 \pm 0.2$
non-top	$54 \pm 12$	$10 \pm 2$	$1.6 \pm 0.4$
Total	$67 \pm 12$	$14 \pm 2$	$2.7 \pm 0.5$
Observed	65	15	6

Expectations for signal and background rates are listed in the second column of Table I. We estimate the  $t\bar{t}$  background from a HERWIG Monte Carlo calculation [18] followed by a detector simulation. Normalizing to the theoretically predicted cross section,  $\sigma_{t\bar{t}} = 5.1 \pm 0.9$  pb [5], we expect  $8.4 \pm 2.7$   $t\bar{t}$  events to survive our selection criteria, where the uncertainty includes theoretical and acceptance contributions.

The largest component of the non- $t\bar{t}$  background in the SVX-tagged  $W$ +jets sample is inclusive  $W$  production in association with heavy-flavor jets (e.g.  $p\bar{p} \rightarrow Wg$ , followed by  $g \rightarrow b\bar{b}$ ). Additional sources include ‘‘mistags,’’ in which a light-quark jet is erroneously identified as heavy flavor, ‘‘non- $W$ ’’ (e.g. direct  $b\bar{b}$  production), and smaller contributions from  $WW, WZ$ , and  $Z$ +heavy-flavor [15]. The mistag and non- $W$  rates are estimated from data, the

TABLE II. Systematic uncertainties on the fit result for  $\beta_s$  in the combined search ( $Wg+W^*$ ), and for  $\beta_{Wg}$  and  $\beta_{W^*}$  in the separate search (see text). The  $\delta n$  columns list fractional uncertainties due to signal normalization effects and the  $\Delta S$  columns list absolute uncertainties due to effects on the shapes of the fitted distributions.

Source	$Wg+W^*$		$Wg$		$W^*$	
	$\delta n$	$\Delta S$	$\delta n$	$\Delta S$	$\delta n$	$\Delta S$
Jet $E_T$ scale	0.01	0.25	0.01	0.02	0.01	0.06
Initial-state radiation	0.02	0.15	0.06	0.07	0.06	0.13
Final-state radiation	0.03	0.02	0.07	0.02	0.05	0.01
Parton distributions	0.04	0.02	0.01	0.03	0.01	0.02
Signal generator	0.02	0.25	0.08	0.03	0.07	0.12
Background model	-	0.04	-	0.12	-	0.18
Top mass	0.04	0.01	0.01	0.12	0.00	0.35
Trigger and lepton identification	0.10	-	0.10	-	0.10	-
$b$ -tag efficiency	0.10	-	0.10	-	0.10	-
Luminosity	0.04	-	0.04	-	0.04	-
Total	0.16	0.39	0.19	0.19	0.18	0.44

$W$ +heavy-flavor rates from Monte Carlo normalized to data, and the smaller sources such as diboson production from Monte Carlo normalized to theory predictions [15]. The total non-top background expectation is  $54 \pm 12$  events. The uncertainty on our background includes the effect of varying the top mass by its uncertainty of  $\pm 5$  GeV/ $c^2$ .

To measure the combined  $Wg + W^*$  single-top production cross section, we use a kinematic variable whose distribution is very similar for the two single-top processes and is different for background processes: the scalar sum  $H_T$  of  $E_T$  and the transverse energies of the lepton and all jets in the event. We perform an unbinned maximum-likelihood fit of the  $H_T$  distribution from data to a linear superposition of the expected  $H_T$  distributions from single-top signal,  $t\bar{t}$  and non-top backgrounds. We model the shape of the  $H_T$  distribution for all sources of non-top background with VECBOS-generated [19] events containing a  $W$  plus two partons that we force to be a  $b\bar{b}$  pair. We have checked that VECBOS reproduces the  $H_T$  and  $M_{l\nu b}$  distributions for the  $b$ -tagged  $W+1$ -jet data before the  $M_{l\nu b}$  cut, a sample in which the non-top backgrounds are expected to dominate. In the search sample, the observed  $H_T$  distribution agrees with the spectrum derived from Monte Carlo calculations when the latter are normalized to the *a priori* predicted numbers of events (Fig. 1).

We set an upper limit on the cross section using the likelihood function

$$\mathcal{L}(\beta_s, \beta_{t\bar{t}}, \beta_{nt}) = G_1(\beta_{t\bar{t}})G_2(\beta_{nt})\mathcal{L}_{\text{shape}}(\beta_s, \beta_{t\bar{t}}, \beta_{nt}),$$

where  $\beta_s, \beta_{t\bar{t}}$  and  $\beta_{nt}$  are fit parameters representing, respectively, factors by which the standard model cross section predictions for single-top,  $t\bar{t}$  and non-top must be multiplied to fit the data. The functions  $G_1$  and  $G_2$  are Gaussian densities constraining the background factors  $\beta_{t\bar{t}}$  and  $\beta_{nt}$  to unity, and  $\mathcal{L}_{\text{shape}}$  represents the joint probability density for observing the  $N_{\text{obs}}$  data events at their respective values of  $H_T$ :

$$\mathcal{L}_{\text{shape}}(\beta_s, \beta_{t\bar{t}}, \beta_{nt}) = \frac{\mu_{\text{fit}}^{N_{\text{obs}}} e^{-\mu_{\text{fit}} N_{\text{obs}}}}{N_{\text{obs}}!} \prod_{i=1}^{N_{\text{obs}}} \frac{\beta_s F_s(H_{Ti}) + \beta_{t\bar{t}} F_{t\bar{t}}(H_{Ti}) + \beta_{nt} F_{nt}(H_{Ti})}{\mu_{\text{fit}}}.$$

In this expression,  $\mu_{\text{fit}} \equiv \beta_s \mu_s + \beta_{t\bar{t}} \mu_{t\bar{t}} + \beta_{nt} \mu_{nt}$ , where  $\mu_s, \mu_{t\bar{t}}$  and  $\mu_{nt}$  are the predicted numbers of events, and  $F(H_T)$  are smoothed  $H_T$  distributions for signal and background, normalized to unity. The maximum of  $\mathcal{L}$  is obtained for  $\beta_s = 2.0 \pm 1.8$ , where the uncertainty is statistical only and includes the effect of correlations with the other fit parameters.

To extract Bayesian upper limits on the single-top production rate, we construct a probability distribution  $f(\beta_s)$  by maximizing  $\mathcal{L}(\beta_s, \beta_{t\bar{t}}, \beta_{nt})$  with respect to  $\beta_{t\bar{t}}$  and  $\beta_{nt}$  for each value of  $\beta_s$ , and multiplying the result with a flat prior distribution for  $\beta_s$ . We then convolute  $f(\beta_s)$  with two Gaussian smearing functions. The first one has width  $\beta_s \delta n$ , where  $\delta n$  is the sum in quadrature of all the normalization uncertainties listed in Table II. The width of the second smearing Gaussian is the sum in quadrature of all the sys-



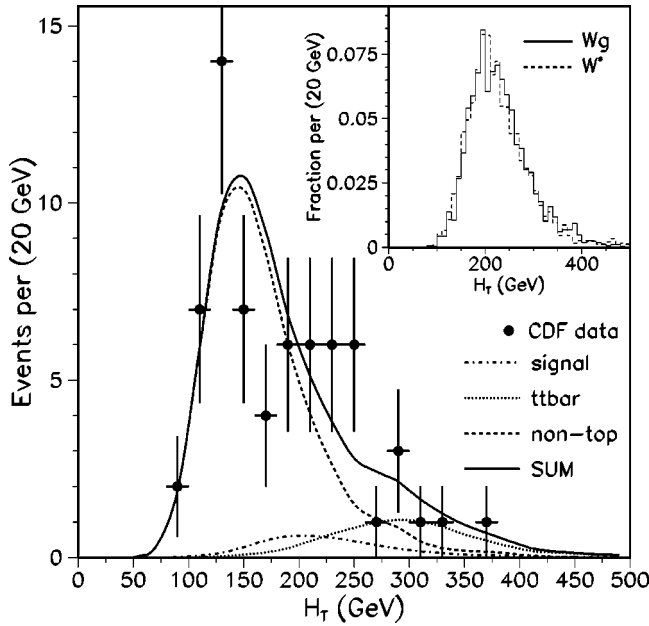


FIG. 1. The  $H_T$  distribution for data in the combined search, compared with smoothed Monte Carlo predictions for signal and backgrounds (second column in Table I).  $H_T$  is the scalar sum of  $E_T$  and the transverse energies of the lepton and all jets in the event. The inset shows that the Monte Carlo modeling of  $H_T$  is very similar for both signal processes.

tematic uncertainties relative to the shape of the  $H_T$  distribution ( $\Delta S$  in Table II). Finally, the smeared distribution is integrated to find the 95% C.L. upper limit on single-top production. We find this limit to be  $\beta_s^{95} = 5.9$ , corresponding to a cross section of 14 pb.

Because of significant differences in the final-state kinematics of the two single-top processes, it is possible to search for them separately. This is interesting, because an exotic single-top production mechanism may contribute to one and not the other, for example a heavy  $W'$  decaying to a  $t\bar{b}$  quark pair adding to the apparent  $W^*$  rate [10]. For the separated search, we use events in the  $W+2$ -jets sample only and consider two non-overlapping subsamples. The first one consists of single-tag events in which the reconstructed top mass lies in the window  $145 < M_{l\nu b} < 205$  GeV/ $c^2$ , and the second consists of double-tag events. The expected compositions, calculated in the same way as for the combined analysis, are shown in the last two columns of Table I: in the single-tag sample,  $Wg$  is about 2.5 times larger than  $W^*$ ; in the double-tag sample,  $W^*$  is about 7.5 times larger than  $Wg$ .

The  $Wg$  component in the single-tag sample can be measured by considering that the light-quark jet in  $Wg$  events is about twice as likely to be in the same hemisphere as the outgoing (anti)proton beam when a top (anti)quark is produced. Thus the product  $Q \times \eta$  of the primary lepton charge and the untagged jet pseudorapidity has a strongly asymmetric distribution. In the double-tag sample, the  $W^*$  component can be extracted from the distribution of  $M_{l\nu b}$ . In this case, since both jets are tagged, the  $b$ -jet with the largest  $\eta$  ( $-\eta$ ) is used in forming  $M_{l\nu b}$  for a  $t(\bar{t})$  decay, as determined by the sign of the primary lepton in the event, an

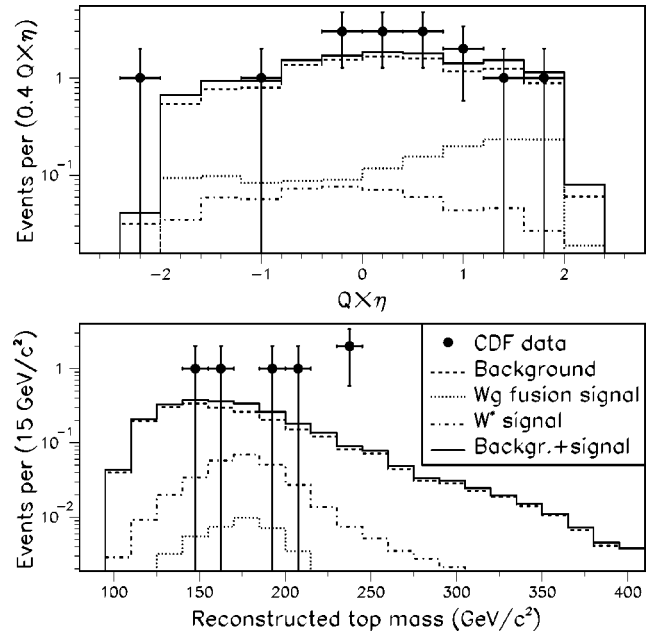


FIG. 2. Top: distribution of the product  $Q \times \eta$  of the lepton charge and the untagged jet pseudorapidity for single-tag  $W+2$ -jets events. Bottom: distribution of the reconstructed top mass for double-tag events. The data are compared with expectations for signal and backgrounds (third and fourth columns in Table I).

assignment that is expected to be correct 64% of the time. The  $Q \times \eta$  and  $M_{l\nu b}$  distributions for the data are compared to expectations for signal and background in Fig. 2. For the separate  $Wg$  and  $W^*$  searches, we use a HERWIG Monte Carlo calculation to model our signals.

A binned maximum-likelihood fit is used to extract the amounts of  $Wg$  and  $W^*$  present in the  $W+2$ -jets data. The likelihood function has the following form:

$$\begin{aligned} \mathcal{L}(\beta_{Wg}, \beta_{W^*}, \beta_{t\bar{t}1}, \beta_{t\bar{t}2}, \beta_{nt1}, \beta_{nt2}) \\ = G_1(\beta_{t\bar{t}1}) G_2(\beta_{nt1}) \mathcal{L}_1(\beta_{Wg}, \beta_{W^*}, \beta_{t\bar{t}1}, \beta_{nt1}) \\ \times G_3(\beta_{t\bar{t}2}) G_4(\beta_{nt2}) \mathcal{L}_2(\beta_{Wg}, \beta_{W^*}, \beta_{t\bar{t}2}, \beta_{nt2}), \end{aligned}$$

where the fit parameters are factors by which the predicted numbers of  $Wg$  ( $\beta_{Wg}$ ),  $W^*$  ( $\beta_{W^*}$ ), single-tag  $t\bar{t}$  ( $\beta_{t\bar{t}1}$ ), double-tag  $t\bar{t}$  ( $\beta_{t\bar{t}2}$ ), single-tag non-top ( $\beta_{nt1}$ ) and double-tag non-top ( $\beta_{nt2}$ ) events must be multiplied to fit the data. The  $G_i$  functions are Gaussian constraints on the normalizations of the various backgrounds,  $\mathcal{L}_1$  is a binned Poisson likelihood for the  $Q \times \eta$  distribution of single-tag events, and  $\mathcal{L}_2$  is a binned Poisson likelihood for the  $M_{l\nu b}$  distribution of double-tag events.

The result of the maximum-likelihood fit for the single-top content of the data is  $-0.6_{-4.0}^{+4.8}$   $Wg$  events and  $7.6_{-4.8}^{+5.9}$   $W^*$  events. The systematic uncertainties are listed in Table II. We extract upper limits on the individual single-top processes in the same way as for the combined search. At the 95% C.L., we find upper limits of 13 and 18 pb on single-top

production in the  $Wg$  and  $W^*$  channels, respectively. These two limits are correlated since they are derived from the same likelihood function.

In summary, we conclude that electroweak  $t\bar{b}$  production is out of reach in the Run I CDF data set. At the 95% C.L., we set an upper limit on the combined  $Wg + W^*$  single-top cross section of 14 pb. Separate 95% C.L. upper limits in the  $Wg$  and  $W^*$  channels are 13 and 18 pb, respectively.

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- [1] S.S.D. Willenbrock and D.A. Dicus, *Phys. Rev. D* **34**, 155 (1986); S. Dawson and S. Willenbrock, *Nucl. Phys.* **B284**, 449 (1987); C.-P. Yuan, *Phys. Rev. D* **41**, 42 (1990); R.K. Ellis and S. Parke, *ibid.* **46**, 3785 (1992); D. Carlson and C.-P. Yuan, *Phys. Lett. B* **306**, 386 (1993).
- [2] T. Stelzer and S. Willenbrock, *Phys. Lett. B* **357**, 125 (1995).
- [3] T. Stelzer, Z. Sullivan, and S. Willenbrock, *Phys. Rev. D* **58**, 094021 (1998). All cross sections we quote are for a fixed top quark mass of 175 GeV/ $c^2$ .
- [4] M.C. Smith and S.S. Willenbrock, *Phys. Rev. D* **54**, 6696 (1996).
- [5] R. Bonciani *et al.*, *Nucl. Phys.* **B529**, 424 (1998). The authors cite  $\sigma_{t\bar{t}} = 5.06^{+0.13}_{-0.36}$  pb at  $\sqrt{s} = 1.8$  TeV for a top quark mass of 175 GeV/ $c^2$ . We use a linear plot to assess the effect on the cross section of the uncertainty on the top mass; in quadrature with the uncertainty above, this gives an uncertainty on  $\sigma_{t\bar{t}}$  of  $\sim 18\%$ .
- [6]  $D\bar{D}$  Collaboration, V.M. Abazov *et al.*, *Phys. Lett. B* **517**, 282 (2001).
- [7] In the CDF coordinate system,  $\theta$  is the polar angle with respect to the proton beam direction and  $\phi$  is the azimuth. The pseudorapidity  $\eta$  is defined as  $-\ln \tan(\theta/2)$ . The transverse momentum of a particle is  $P_T = P \sin \theta$  and its transverse energy is  $E_T = E \sin \theta$ .
- [8] F. Larios and C.-P. Yuan, *Phys. Rev. D* **55**, 7218 (1997).
- [9] G. Burdman, R.S. Chivukula, and N. Evans, *Phys. Rev. D* **62**, 075007 (2000).
- [10] J.L. Rosner and E. Takasugi, *Phys. Rev. D* **42**, 241 (1990); T.M.P. Tait and C.-P. Yuan, *ibid.* **63**, 014018 (2001).
- [11] F. Abe *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **271**, 387 (1988); D. Amidei *et al.*, *ibid.* **350**, 73 (1994); P. Azzi *et al.*, *ibid.* **360**, 137 (1995).
- [12] A lepton is “isolated” if the nonlepton  $E_T$  in an  $\eta$ - $\phi$  cone of radius 0.4 centered on the lepton is less than 10% of the lepton’s  $E_T$  or  $P_T$ .
- [13] Missing transverse energy  $\cancel{E}_T$  is defined as the magnitude of  $-\sum_i E_T^i \hat{n}_i$ , where  $\hat{n}_i$  is a unit vector in the azimuthal plane that points from the beamline to the  $i$ th calorimeter tower.
- [14] CDF Collaboration, F. Abe *et al.*, *Phys. Rev. Lett.* **80**, 2779 (1998).
- [15] CDF Collaboration, F. Abe *et al.*, *Phys. Rev. Lett.* **79**, 3819 (1997).
- [16] This procedure generally yields two solutions for the neutrino  $P_z$ . We use the solution with the smallest absolute value. In cases where the solutions are complex conjugate, we use their real part.
- [17] T. Sjöstrand, *Comput. Phys. Commun.* **82**, 74 (1994). We use PYTHIA version 5.6.
- [18] G. Marchesini and B.R. Webber, *Nucl. Phys.* **B310**, 461 (1988); G. Marchesini *et al.*, *Comput. Phys. Commun.* **67**, 465 (1992). We use HERWIG version 5.6.
- [19] F.A. Berends, W.T. Giele, H. Kuijff, and B. Tausk, *Nucl. Phys.* **B357**, 32 (1991).