First Measurement of the Ratio $B(t \to Wb)/B(t \to Wq)$ and Associated Limit on the Cabibbo-Kobayashi-Maskawa Element $V_{tb}$

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We present the first measurement of the ratio of branching fractions \( R = \frac{B(t \to Wb)/B(t \to Wq)}{\mu} \) from \( p \bar{p} \) collisions at \( \sqrt{s} = 1.8 \text{ TeV} \). The data set corresponds to 109 pb\(^{-1}\) of data recorded by the Collider Detector at Fermilab during the 1992–95 Tevatron run. We measure \( R = 0.944^{+0.031}_{-0.029} \) (stat + syst) or \( R > 0.61 (0.56) \) at 90% (95%) C.L., in agreement with the standard model predictions. This measurement yields a limit on the Cabibbo-Kobayashi-Maskawa quark mixing matrix element \( |V_{tb}| \) under the assumption of three generations and unitarity.

The Cabibbo-Kobayashi-Maskawa matrix \([1]\) is a fundamental component of the standard model of electroweak interactions. However, the matrix elements must be determined experimentally since the model does not constrain their values. Some of the matrix elements have been determined by studying the weak decay of quarks or by deep inelastic neutrino scattering experiments. Until now no direct information has been available for the elements of the top sector. The matrix elements \( |V_{td}| \) and \( |V_{ts}| \) have been indirectly estimated using measurements of processes that probe loop diagrams involving the top quark. Using these indirect measurements and a global fit which includes the additional assumptions of three generations and unitarity the allowed range of \( |V_{tb}| \) is 0.9989–0.9993 (at 90% C.L.) \([2]\). The large value of \( |V_{tb}| \) implies that \( R \), the ratio of branching fractions \( B(t \to Wb)/B(t \to Wq) \) (where \( q \) is a \( d \), \( s \), or \( b \) quark), is close to unity and that the branching ratio for the decay of a top quark to \( Wb \) is nearly 100%. The identification of \( t\bar{t} \) events at the Tevatron allows us to directly check for a possible deviation from the range found by the global fits which would imply the appearance of new physics. The prediction of \( R \) being close to unity has been used in the discovery of the top quark and in the measurement of its cross section but has not been, until now, confirmed experimentally.

In this Letter we present the first direct measurement of \( R \). The result provides additional support for the top quark discovery. Under the assumption of unitarity and three generations, it also provides a constraint on the CKM element \( |V_{tb}| \) obtained by direct measurement in top events. The analysis is performed using 109 pb\(^{-1}\) of proton-antiproton collisions data recorded at a center of mass energy of 1.8 TeV by the Collider Detector at Fermilab (CDF) during the 1992–1995 run of the Tevatron Collider at Fermilab. The CDF detector is described in detail elsewhere \([3]\); here we briefly describe only the components which play a major role in this analysis.

The CDF tracking system consists of three different detectors embedded in a 1.4 T solenoidal magnetic field.
central (|\eta| < 1) lepton (e or \mu) with \( P_T > 20 \text{ GeV}/c \), \( \mathcal{E}_T > 20 \text{ GeV} \), three jets with \( E_T > 15 \) [12] \text{ GeV} within |\eta| < 2 and a fourth jet with \( E_T > 8 \text{ GeV} \) within |\eta| < 2.4. In the dilepton sample we require two leptons (e or \mu) with \( P_T > 20 \text{ GeV}/c \), \( \mathcal{E}_T > 25 \text{ GeV} \) and two jets with \( E_T > 10 \text{ GeV} \) in the region |\eta| < 2.0. Candidate Z events are removed by rejecting events containing same-flavor lepton pairs with opposite charge whose invariant mass lies between 75 and 105 \text{ GeV}/c^2. By construction the two data sets have no overlap. After applying all the selection criteria we find 163 events in the \( l + \text{jets} \) and 9 events in the dilepton sample. The presence of the \( t \rightarrow Wb \) decay is deduced by identifying jets associated with b hadron decays using two distinct algorithms: the SVX tagger and the SLT tagger. The SVX tagging algorithm [9] relies on the long lifetime of b hadrons. It searches for b hadron decay vertices which are significantly displaced from the primary vertex and have three or more associated tracks. If this search fails, tighter quality cuts are applied to the tracks within the jet and vertices with two tracks are also accepted. In both cases, the transverse displacement of the decay vertex from the primary vertex, divided by its uncertainty, is required to be larger than 3. The SVX algorithm is characterized by an efficiency \( (e_i) \) to tag a single b jet in a \( t\bar{t} \) event of \((37.0 \pm 3.7)\% \) and by a fake tagging rate of about 0.5\%. The SLT tagging is performed by looking for \( \text{low-}P_T \) (relatively soft compared to the primary lepton) muons and electrons from semileptonic b hadron decays. The algorithm looks for low transverse momentum electron and muon candidates by matching CTC tracks with \( P_T > 2 \text{ GeV}/c \) with calorimeter clusters and track segments in the muon chambers. Moreover, to classify the event as a \( t\bar{t} \) candidate, the soft lepton is required to be within a conus of radius 0.4 in the \( \eta\phi \) space from one of the four highest-\( E_T \) jets in the event. The SLT algorithm has an efficiency per jet \( (e_i) \) of \((10.2 \pm 1.0)\% \) and a fake tagging rate of about 2\%. Efficiencies for the SLT and SVX algorithms are calculated using the low-\( P_T \) inclusive lepton sample enriched in \( b\bar{b} \) production and Monte Carlo simulation. The background due to fake tags is measured for both algorithms using generic jet samples. A detailed discussion of the algorithms, the determination of the tagging efficiency, and the fake rate can be found in [13].

The unknown ratio of branching fractions, \( R \), is measured by comparing the observed number of tags in the data with expectations based on selection criteria acceptances, tagging efficiencies, and background estimates. In the dilepton sample only SVX tagging is used and the sample is divided into three nonoverlapping bins: events with no \( b \)-tags (bin 0), one and only one \( b \)-tag (bin 1) and two \( b \)-tags (bin 2). The use of SLT tagging in the dilepton data set does not provide any additional statistical gain. In the \( l + \text{jets} \) sample, we use both the SVX and SLT algorithms. Monte Carlo studies [14] indicate that a superior use of the tagging information is obtained by dividing events into the same three bins used for the dilepton sample and then by subdividing the bin with no SVX tags into two bins according to the SLT tagging status. The first bin (bin 00) is populated by events which are tagged by neither the SVX nor the SLT algorithm and the second one (bin 01) contains events with one or more SLT tags and no SVX tags.

The number of observed events in each bin is reported in Table I. The expected number of events, \( N_i \), in each of the bins of the \( l + \text{jets} \) sample can be expressed as a function of the acceptances, tagging efficiencies, and the estimated background by the following set of equations:

\[
\begin{align*}
N_{00} &= n_0 + (1 - e_1)(1 - e_x)n_1 + (1 - e_1^2)(1 - e_x^2)n_2 + F_{00}, \\
N_{01} &= e_1(1 - e_x)n_1 + e_1(2 - e_1)(1 - e_x^2)n_2 + F_{01}, \\
N_1 &= e_xn_1 + 2e_1(1 - e_x)n_2 + F_1, \\
N_2 &= e_x^2n_2 + F_2,
\end{align*}
\]

with \( n_i (i = 0, 1, 2) \), the number of events with \( i b \)-jets in the SVX acceptance, given by

\[
\begin{align*}
n_0 &= N_{\text{top}}[a_0 + (1 - R)a_1 + (1 - R)^2a_2], \\
n_1 &= N_{\text{top}}[Ra_1 + 2R(1 - R)a_2], \\
n_2 &= N_{\text{top}}R^2a_2,
\end{align*}
\]

where \( N_{\text{top}} \) is the total number of \( t\bar{t} \) events in the sample, \( F_i \) is the background in the \( i \)th bin, and \( a_i \) is the fraction of events containing \( i b \) jets \((i = 0, 1, 2)\) in the acceptance. This definition of acceptance, which reflects the way the \( a_i \)'s are related to \( R \) in Eqs. (2a)–(2c), has been chosen in order to be able to use the standard CDF top Monte Carlo (see below) which assumes \( R = 1 \). For the dilepton sample, Eqs. (1a) and (1b) are merged into one because SLT tagging is not used.

The unknown ratio \( R \) is obtained by minimizing the negative logarithm of a likelihood function. Since the \( l + \text{jets} \) and dilepton samples are independent, the global likelihood can be written as

\[
\mathcal{L} = \mathcal{L}_{l+\text{jets}}\mathcal{L}_{\text{dilepton}}
\]

where each of the individual likelihoods is of the form

\[
\mathcal{L}_a = \prod_i p(N_i; \tilde{N}_i) \prod_j G(x_j; \tilde{x}_j, \sigma_j).
\]
In this expression, \( P(N_i; \bar{N}_i) \) is the Poisson probability for observing \( N_i \) events in each bin (the index \( i \) runs from 1 to 4 for the \( l + \) jets sample and from 1 to 3 for the dilepton one) with an expected mean \( \bar{N}_i \) (see Table I). The functions \( G(x_j; \bar{x}_j, \sigma_j) \) are Gaussians in \( x_j \), with mean \( \bar{x}_j \) and variance \( \sigma_j^2 \), and incorporate the uncertainties in the tagging efficiencies, backgrounds, and acceptances into the likelihood functions.

The acceptances and efficiencies are obtained using a \( t\bar{t} \) Monte Carlo \((M_{t\bar{t}} = 175 \text{ GeV}/c^2)\) data set generated using \textsc{pythia} [15], combined with a detailed simulation of the detector response. The total number of \( t\bar{t} \) pairs \((N_{t\bar{t}})\) in the two data samples is left as a free parameter. The acceptances in each bin are normalized with respect to the bin with no \( b \) jets. As a consequence, the trigger and lepton identification efficiencies cancel out in the ratio. We obtain \( r_1 = 11.8 \pm 1.2 \) (14.5 \pm 1.4) and \( r_2 = 38.7 \pm 3.9 \) (58.5 \pm 5.8), where \( r_i = a_i/a_0 \), for the \( l + \) jets (dilepton) sample. The uncertainties in these ratios include contributions from the jet energy scale and from the Monte Carlo modeling of initial and final state radiation.

The background in the untagged sample is mainly due to the associated production of \( W \) bosons with light quark jets. The backgrounds to the SLT and SVX tagged events (background in bin 01 and 1, respectively), are mainly due to the associated production of \( W \) bosons and heavy quarks \((Wb\bar{b}, Wc\bar{c}, Wc)\) and to mistags due to mismeasured tracks. Smaller contributions come from \( b\bar{b} \), diboson production \((WW, ZZ, and WZ)\), \( Z \to \tau\tau \) decays, Drell-Yan lepton pair production and single top quark production. These backgrounds are calculated using a combination of data and Monte Carlo information [14,16]. The initial values of the SVX and SLT backgrounds are a function of the \( t\bar{t} \) content of the \( l + \) jets sample itself, and therefore need to be appropriately corrected [8]. An iterative process is used to account for this effect and has been implemented in the likelihood minimization procedure used to estimate \( R \). Using this procedure as output of the likelihood minimization, we estimate \( F_1 = 3.3^{+5.2}_{-1.2} \) and \( F_{01} = 7.2 \pm 1.6 \) events for the SVX and SLT backgrounds, respectively. In the same way, the background to double SVX tagged events (bin 2) is estimated to be small and amounts to \( F_2 = 0.2 \pm 0.1 \) events. The background in bin 00, \( F_{00} \), is obtained as follows. Defining \( N_{\text{tot}} \) to be the total number of events in the \( l + \) jets data set, \( N_{\text{SVX}} \) the total number of SVX tagged events in this sample, \( F_{\text{SVX}} \) the estimated background and \( \epsilon_{\text{SVX}} \) the SVX event tagging efficiency, the total number of top events is \( N_{tt} = (N_{\text{SVX}} - F_{\text{SVX}})/(\epsilon_{\text{SVX}} R) \). The number of background events before tagging is given by \( F = N_{\text{tot}} - N_{tt} \) and therefore the background in bin 00 is \( F_{00} = F - (F_{01} + F_1 + F_2) \). As above, the estimate is performed iteratively during the likelihood minimization.

The initial background to the dilepton sample has been estimated to be \( 2.4 \pm 0.5 \) [17]. In this sample, we estimate a background of \( 0.10 \pm 0.04 \) events to SVX single tagged events. The double SVX tagged background is negligible \([F_2 = 0 \text{ in Eq. (1d)}]\). In this case, the number of background events is not a function of the \( t\bar{t} \) content of the initial sample and no special correction needs to be applied. As in the \( l + \) jets case, the background in bin 0 is obtained by a subtraction of the tagged background from the total background and amounts to \( 2.3 \pm 0.5 \) events. The resulting number of background events after the likelihood minimization procedure is shown in Table II for both data sets.

The likelihood minimization yields \( R = 0.94^{+0.31}_{-0.24} \text{(stat + syst)} \) or, splitting the statistical and
systematical uncertainties, \( R = 0.94^{+0.26}_{-0.21} \) (stat) \(+0.17_{-0.12} \) (syst).

The negative log-likelihood as a function of \( R \) is shown in Fig. 1. The lower limit on \( R \) is obtained by a numerical integration of the likelihood function and we obtain \( R > 0.61 \) (0.56) at 90\% (95\%) C.L.

The CKM element \( |V_{tb}| \) is directly related to \( R \), although in a model-dependent way. We assume that the top quark decays to non-W final states are negligible [18,19]. Under this assumption \( R \) is related to \( |V_{tb}| \) by

\[
R = \frac{|V_{tb}|^2}{|V_{ts}|^2 + |V_{td}|^2 + |V_{tb}|^2}.
\]

If we assume three generation unitarity, the denominator is equal to unity and therefore \( R = |V_{tb}|^2 \). As a consequence, we obtain \( |V_{tb}| = 0.97^{+0.16}_{-0.12} \) or \( |V_{tb}| > 0.78 \) (0.75) at 90\% (95\%) C.L.

The result, although limited by statistics, represents the first direct measurement of \( R \). The large value of \( R \) that we measure is consistent with standard model expectations and supports the assumption that top quarks decay predominantly to \( b \) quarks. Under the assumption of three generation unitarity, our calculated value of \( |V_{tb}| = 0.97^{+0.16}_{-0.12} \) (\( |V_{tb}| > 0.78 \) at 90\% C.L.) is consistent with indirect limits obtained from global fits.

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[6] The transverse momentum, \( P_T \), is defined as the projection of the momentum onto the plane transverse to the beam axis.

[7] The pseudorapidity, \( \eta \), is defined as \( \eta = -\ln[\tan(\theta/2)] \), where \( \theta \) is the polar angle with respect to the proton beam direction (\( z \) axis).


[11] The missing transverse energy, \( E_T \), is defined as the negative of the vector sum of transverse energy in all calorimeters towers with \( |\eta| < 3.6 \).

[12] The transverse energy, \( E_T \), is defined as the projection of the energy onto the plane transverse to the beam axis.


