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Measurement of the Ratio $\sigma \cdot B(W \rightarrow \tau\nu)/\sigma \cdot B(W \rightarrow e\nu)$, in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We have observed over one hundred events of the type $W \to \tau\nu$ followed by $\tau \to$ hadrons, where the taus are identified by their decay into one or three charged particles. We measure the cross-section times branching ratio for $p\bar{p} \to W \to \tau\nu$ and compare it to the value for $W \to e\nu$ to directly measure the ratio of weak coupling constants g_τ/g_e. We find $g_\tau/g_e = .97 \pm .07$, consistent with lepton universality.

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The universality of lepton couplings to the vector bosons is a direct consequence of SU(2) gauge invariance in the Standard Model[1]. The magnitude of the W-τ coupling at low Q^2 has been extensively studied in the decays of the tau; a recent compilation of results gives $g_\tau/g_e = .967 \pm .017$[2]. A previous direct measurement of g_τ/g_e using W decays is consistent with universality.[3]

In this paper we describe a measurement of the cross-section times branching ratio, $\sigma \cdot B$, for production of W bosons and their decay $W \to \tau\nu$, which affords a test of lepton universality according to the relation:

$$\left(\frac{g_\tau}{g_e}\right)^2 = \frac{\sigma \cdot B(W \to \tau\nu)}{\sigma \cdot B(W \to e\nu)}.$$

Unlike tests of universality derived from the tau lifetime, this constitutes a direct measurement of g_τ/g_e which is free from the uncertainty related to the tau branching ratios. Our measurement is dependent upon the direct identification of tau leptons among the significant background present in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. In particular the taus are positively identified by the observation of characteristic peaks in charged multiplicity at one and three.

This measurement used $4.05\mathrm{pb}^{-1}$ of $p\bar{p}$ collisions at the CDF detector, taken in the 1989 run of the Fermilab Tevatron. The CDF detector is described fully elsewhere.[4] The event selection relies on the characteristic features of the decay $W \to \tau\nu$ and the subsequent hadronic decay of the energetic tau. These include a high transverse momentum track, in a narrow low multiplicity jet, in association with missing transverse energy, $\not{E}_T$.[5]

Two triggers[6] were used in the selection of $W \rightarrow \tau\nu$ events. The first, a missing E_T trigger optimized to select $W \rightarrow e\nu$ events, required $\not{E}_T \geq 25$ GeV and electromagnetic $E_T \geq 8$ GeV in the most energetic cluster. A second selection, the tau trigger[7], was implemented to lower the $\not{E}_T$ threshold and to explicitly select $W \rightarrow \tau\nu$ events. This trigger required a "tau trigger cluster" along with $\not{E}_T \geq 20$ GeV. A tau trigger cluster required a charged track with transverse momentum $P_T \geq 4.8$ GeV/c, matched in azimuth to a cluster in the calorimeter with transverse energy $E_T \geq 10$ GeV, the ratio of energy in the hadronic to electromagnetic calorimeter Had/EM $\geq .125$, and the number of calorimeter towers $N_{towers} \leq 2$, where a tower subtends $\Delta\phi(\text{azimuthal angle}) = 15°$ and $\Delta\eta(\text{pseudorapidity}) = .2$. The tau trigger was in operation for one third of the data taking.

Tau decay reconstruction is designed to distinguish the hadronic final state of the $W \rightarrow \tau\nu$ decay from the QCD jet background. The reconstruction algorithm begins by searching for a seed track in the central tracking chamber with $P_T \geq 5$ GeV/c. Additional tracks with $P_T \geq 1$ GeV/c are included in the cluster if they are within 30° of the seed track. The charged particle multiplicity of the tau is given by the number of tracks within 10° of the seed track (N_{Tracks}), where the choice of 10° gives excellent efficiency for tau decay products with $P_T \geq 1$ GeV/c. The number of tracks between 10° and 30° from the seed track ($N_{Isolation}$) is used as a measure of the isolation of the tau cluster. The energy deposited in the tau calorimeter region, a rectangular region .6 in pseudo-rapidity (η) by 30° in azimuthal angle (ϕ) centered on the seed track, is associated with the tau cluster. Electromagnetic showers, presumably from π^0s, are identified by reconstructing any clusters in a wire and pad strip chamber at electromagnetic shower maximum which are in the tau's calorimeter region. The energy from electromagnetic showers is found using the energy in the calorimeter tower containing the strip chamber cluster, corrected for any charged tracks pointing at the same tower. Two measures of the transverse energy are used: the $E_T(\tau)$ is defined as the calorimeter transverse energy, while $P_T(\tau)$ is defined as the scaler sum of the transverse momentum of charged particles in the 10° cone and the transverse energy of reconstructed electromagnetic showers in the tau's calorimeter region.

The $W \to \tau\nu$ sample is selected by requiring $\not{E}_T \geq 25$ GeV for events from the missing E_T trigger, and $\not{E}_T \geq 20$ GeV for events from the tau trigger; for both there must be one tau cluster with $E_T(\tau) \geq 15$ GeV and $|\eta| \leq 1.1$ in the event. To reduce contamination from QCD backgrounds, the $W \to \tau\nu$ events must also satisfy requirements on global event characteristics: no clusters[8] with $E_T \geq 10$ GeV besides the tau cluster, and no clusters with $E_T \geq 5$ GeV and $\Delta\phi \geq 150°$ from the tau cluster. After these cuts there remains a residual background of very tau-like QCD events, which can be suppressed with the $P_T(\tau)$ variable. Events from the tau trigger with one, two, or three tracks in the signal cone are required to have $P_T(\tau) \geq 17.5$, 20, or 22.5 GeV/c respectively. Finally events where the tau cluster also satisfies a subset of the CDF electron selection cuts[9] are removed to eliminate contamination of the $W \to \tau\nu$ sample by $W \to e\nu$ decays.

The $W \to \tau\nu$ sample is divided into signal and background regions. The signal region includes those clusters with $N_{Track} \leq 3$ and $N_{Isolation} = 0$, while the background region includes those clusters with $N_{Track} \geq 4$ and any $N_{Isolation}$, plus those clusters with $N_{Track} = 2$ and $N_{Isolation} \geq 1$. There are 207 events in the signal region from the missing E_T trigger, and 77 from the tau trigger. Of these, 22 events are common to both samples. The sizes of the signal and background are listed in Table 1. The charged multiplicity for those events with $N_{Isolation} = 0$ is shown in Figure 1; direct evidence for the presence of taus is seen in the excess of events at one and three tracks, as expected for tau decays.

The primary background to the $W \to \tau\nu$ signal comes from QCD jet events in which one parton fragments to satisfy the tau cluster requirements and the other partons are mismeasured - giving the event a substantial amount of $\not{E}_T$. The clusters in Figure 1 with four or more tracks are due to these QCD backgrounds. The amount of background in the $W \rightarrow \tau\nu$ signal region can be estimated by extrapolating from the number of events in the background region. The tau clustering algorithm is applied to a large sample of QCD di-jet events in order to measure the multiplicity distribution of background clusters. The expected number of background events is found by normalizing the QCD di-jet sample to the $W \rightarrow \tau\nu$ sample in the background multiplicity region. The normalization is weighted to account for differences in the E_T spectra.

The normalized multiplicity for clusters from the QCD di-jet sample with $N_{Isolation} = 0$ is also shown in Figure 1. The number of background events in the signal region from QCD jets is $63 \pm 3(\text{stat}) \pm 8(\text{syst})$ for the missing E_T trigger, and $26 \pm 2(\text{stat}) \pm 4(\text{syst})$ for the tau trigger. The statistical error follows from the number of events used to calculate the background normalization factor. The systematic error is taken from the variation in the size of the background for various ranges of $\not{E}_T$ in the QCD di-jet events.

There are also backgrounds to the $W \rightarrow \tau\nu$ sample from $Z \rightarrow \tau\tau$ decays with one lost tau, and from $W \rightarrow e\nu$ decays with a misidentified electron. $Z \rightarrow \tau\tau$ events generated by ISAJET[10] and simulated with the CDF detector simulation indicate that there are 7 ± 2 and 4 ± 1 $Z \rightarrow \tau\tau$ events as background to the two $W \rightarrow \tau\nu$ samples respectively. From the known efficiencies of the electron selection cuts[9], we estimate 5 ± 1 $W \rightarrow e\nu$ events are background to the missing E_T trigger sample only. After we subtract the background from the number of events in the signal region, there are $132 \pm 14 \pm 8$ events from the missing E_T trigger, and $47 \pm 9 \pm 4$ from the tau trigger.

The $W \rightarrow \tau\nu$ detection efficiency is measured with the CDF $W \rightarrow e\nu$ data[9]. The energy deposition and the track from the electron are removed and replaced by a simulated tau, which is allowed to decay using the branching ratios measured by the CELLO collaboration [11]. The decay products are simulated using the CDF detector simulation, and the simulated data is merged with the remainder of the original $W \rightarrow e\nu$ event. The use of real data ensures that the global characteristics of the event are modelled correctly. The simulation of the calorimeter response has been tuned to an accuracy of 5% with a sample of isolated charged tracks and with test-beam charged pions at 7 and 10 GeV [7].

The probability to detect $W \rightarrow \tau\nu$ events can be factored into a part which includes those kinematic and geometrical requirements common to both the $W \rightarrow \tau\nu$ and $W \rightarrow e\nu$ analyses, and a part which applies to just the $W \rightarrow \tau\nu$ sample. The relevant acceptance cuts applied to both $W \rightarrow \tau\nu$ and $W \rightarrow e\nu$ events are: $\mathrm{P_T}(\mathrm{lepton}) \geq 20$ GeV/c, $|\eta|(lepton) \leq 1.0$, and $\mathrm{P_T}(\nu) \geq 20$ GeV. The acceptance for these requirements has been calculated to be $A = .396 \pm .016$[9]. The systematic error in this quantity, largely due to the $\mathrm{P_T}$ distribution of the W boson and the choice of structure functions, will cancel in the ratio $\sigma \cdot \mathrm{B}(W \rightarrow \tau\nu)/\sigma \cdot \mathrm{B}(W \rightarrow e\nu)$.

The second factor, the tau efficiency, includes all the selection cuts made to collect the $W \rightarrow \tau\nu$ sample, after the above acceptance cuts have been applied. We find that 6.4% and 6.8% of events which pass the acceptance cuts, for the missing $\mathrm{E_T}$ and tau samples respectively, pass the $W \rightarrow \tau\nu$ selection cuts and have N_{Track} and $N_{Isolation}$ in the signal region. Two small corrections have been included in the efficiency to account for the differing fiducial regions used in the $W \rightarrow e\nu$ and $W \rightarrow \tau\nu$ analyses and the presence of background in the $W \rightarrow e\nu$ based Monte-Carlo. The total acceptance for $W \rightarrow \tau\nu$ events, including the branching ratio of the tau into hadrons, is $\mathrm{A}(W \rightarrow \tau\nu) = .0161 \pm .0010$ for the missing $\mathrm{E_T}$ sample, and $\mathrm{A}(W \rightarrow \tau\nu) = .0172 \pm .0016$ for the tau sample.

The factors involved in the calculation of the acceptance and its uncertainty are summarized in Table 1. The statistical uncertainty comes from the 2664 $W \rightarrow e\nu$ events used as input for the Monte-Carlo. We take the uncertainty in the knowledge of the energy scale for hadrons in the calorimeter to be ±5%, which leads to an uncertainty in the efficiency for $W \rightarrow \tau\nu$ events to satisfy the $\not{E}_\mathrm{T}$ and $\mathrm{E_T}$ thresholds. There is also an uncertainty from the knowledge of the tau branching ratios into the various exclusive modes. The acceptance varies significantly by mode, with modes with greater numbers of pions, especially neutral pions, having higher acceptance. Uncertainties in the branching ratios are taken from Reference [11], and are used to estimate the change in the efficiency. Finally the Monte-Carlo is used to assess the systematic uncertainty in the tau sample due to the efficiency of the trigger N_{towers} cut and the $\mathrm{P_T}(\tau)$ cut.

In Figure 2 we compare the Monte-Carlo prediction for the track multiplicity, assuming lepton universality, against the measured track multiplicity. The agreement between data and Monte-Carlo is excellent. Other kinematic variables such as $\mathrm{E_T}(\tau)$ and $\mathrm{P_T}(\tau)$ also show very good agreement between data and Monte-Carlo.

Combining the calculated acceptances, the number of $W \rightarrow \tau\nu$ events after a background subtraction, and the integrated luminosity we calculate $\sigma \cdot \mathrm{B}(W \rightarrow \tau\nu)$. To measure the ratio of the W-τ and W-e couplings, the systematic uncertainty from the integrated luminosity and the acceptance has been omitted for both electron and tau $\sigma \cdot \mathrm{B}$, as it cancels in the ratio. We find $\sigma \cdot \mathrm{B} = 2.04 \pm .22(\mathrm{stat}) \pm .18(\mathrm{syst})$ nb from the missing $\mathrm{E_T}$ sample, and $\sigma \cdot \mathrm{B} = 2.08 \pm .40(\mathrm{stat}) \pm .26(\mathrm{syst})$ nb from the tau sample. The results from the two data samples are combined to yield a value of $\sigma \cdot \mathrm{B}(W \rightarrow \tau\nu) = 2.05 \pm .27$. The correlations in the statistical and systematic errors between the two samples have been included. When this is combined with the CDF measurement $\sigma \cdot \mathrm{B}(W \rightarrow e\nu) = 2.19 \pm .04 \pm .11$[9], the ratio of weak coupling constants is found to be $\mathrm{g}_\tau/\mathrm{g}_e = .97 \pm .07$, in agreement with the hypothesis of lepton universality.

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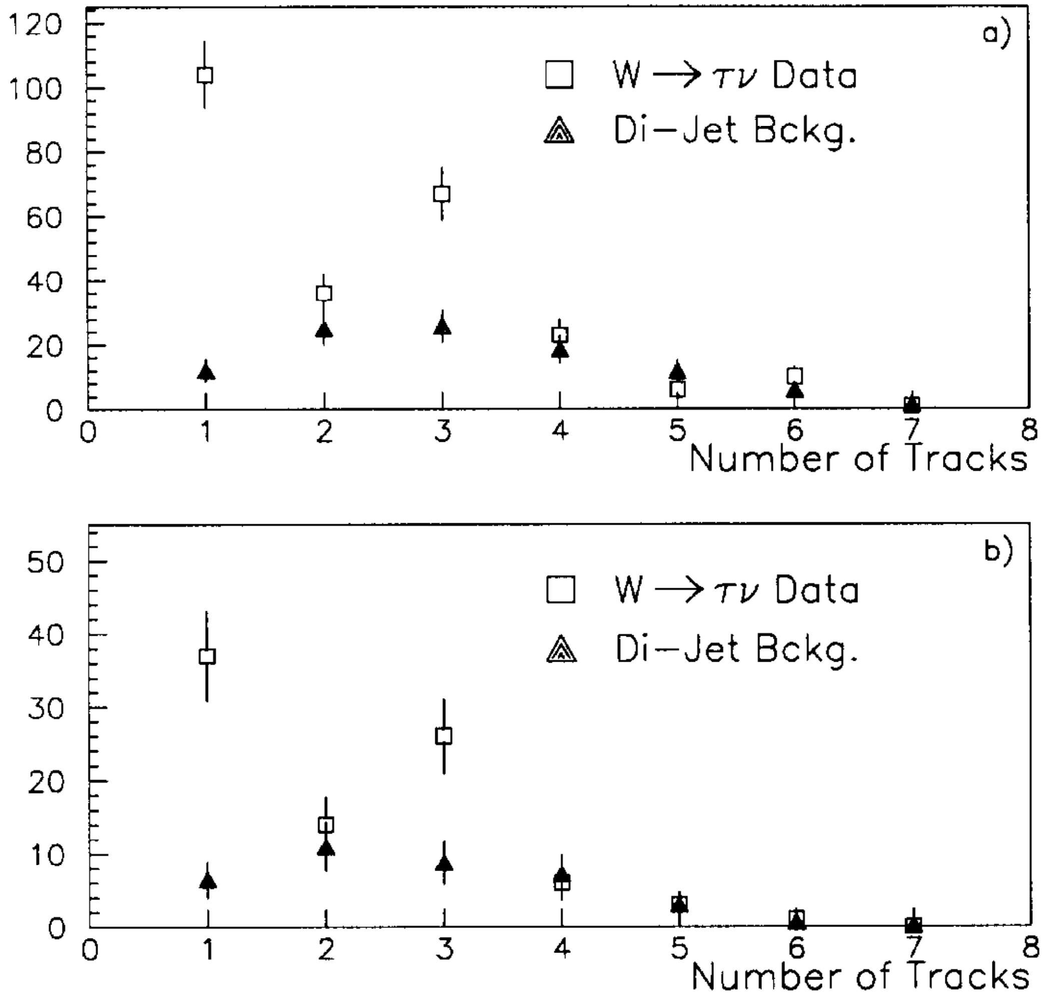

Figure 1: N_{Track} for tau clusters with $N_{Isolation} = 0$, for the $W \rightarrow \tau\nu$ data sample (squares) and the QCD background sample (triangles): a) Missing Et sample, b) Tau sample

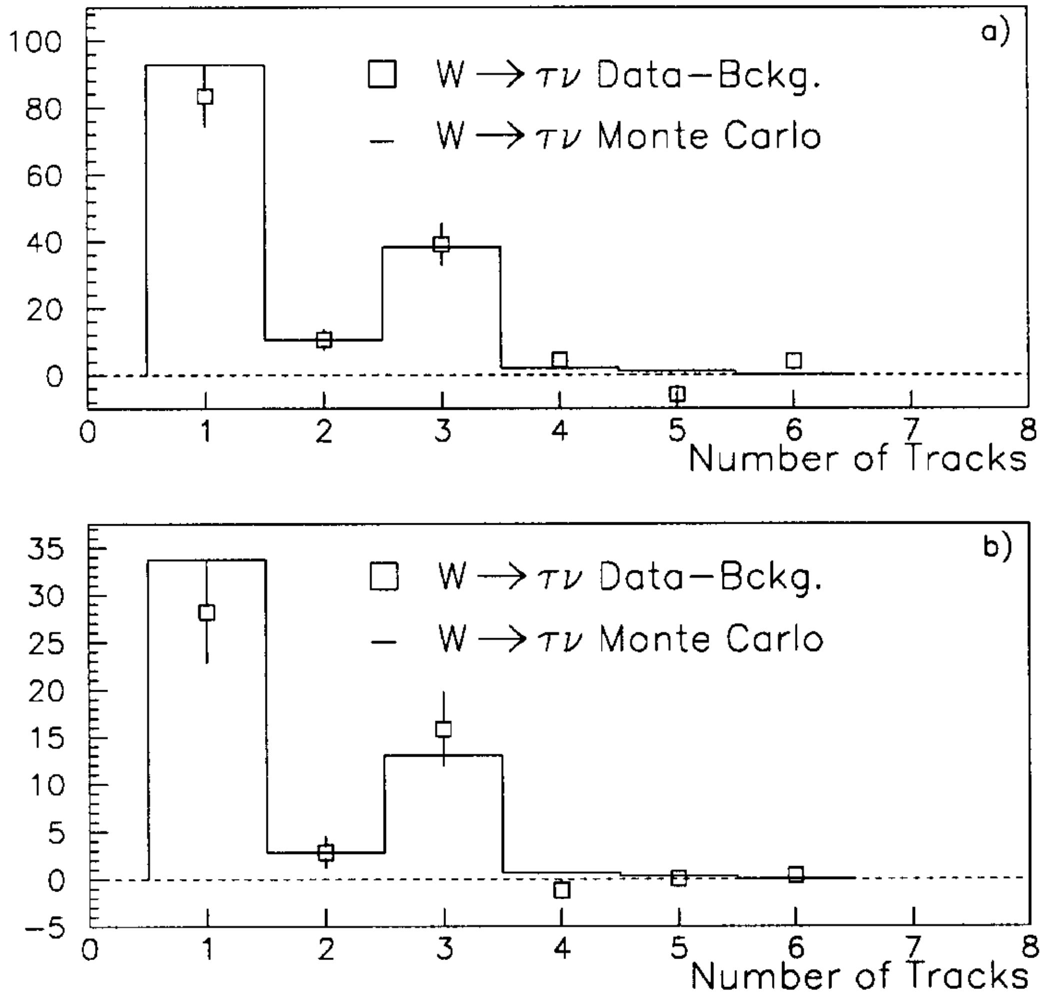

Figure 2: N_{Track} for tau clusters with $N_{Isolation} = 0$, for the $W \to \tau\nu$ data sample with background subtracted (squares) and the monte-carlo prediction (histogram): a) Missing Et sample, b) Tau sample

Table 1: Summary of the $W \to \tau\nu$ analysis

	$\not\!\!E_T$ Sample	Tau Sample
Number of Events		
$W \to \tau\nu$ Data sample	207	77
QCD background	$63 \pm 3 \pm 8$	$26 \pm 2 \pm 4$
$Z \to \tau\tau$ background	7 ± 2	4 ± 1
$W \to e\nu$ background	5 ± 1	–
$N_{W \to \tau\nu}$	$132 \pm 14 \pm 8$	$47 \pm 9 \pm 4$
$A \cdot \epsilon(W \to \tau\nu)$		
$A(W \to \tau\nu)$	.396	
$\tau \to$ hadrons B.R.	.639	
$\epsilon(W \to \tau\nu)$	.0636	.0679
$A \cdot \epsilon(W \to \tau\nu)$	.0161	.0172
Systematic Errors on $A \cdot \epsilon$		
M.C. statistics	$\pm.0005$	$\pm.0005$
N_{tower}, $P_T(\tau)$ cuts	–	$\pm.0008$
B.R. (correlated)	$\pm.0007$	$\pm.0004$
E-scale (correlated)	$\pm.0006$	$\pm.0012$
$\int \mathcal{L} dt$		
Integrated Luminosity	4.015pb^{-1}	1.315pb^{-1}
$\sigma \cdot B$		
$\sigma \cdot B(W \to \tau\nu)$	$2.04 \pm .22 \pm .18$ nb	$2.08 \pm .40 \pm .26$
$\sigma \cdot B(W \to \tau\nu)$ combined	$2.05 \pm .27$ nb	
$\sigma \cdot B(W \to e\nu)$	$2.19 \pm .04$ (stat) $\pm .11$ (syst.) nb	
g_τ/g_e		
g_τ/g_e	$.97 \pm .07$	