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A Measurement of the $W \rightarrow \tau\nu$ Production Cross Section in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

We report on a measurement of $\sigma(p\overline{p} \to W + X) \cdot B(W \to \tau\nu)$ in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron. The measurement is based on an integrated luminosity of 18 pb^{-1} of data collected with the DØ detector during 1994–1995. We find that $\sigma(p\overline{p} \to W + X) \cdot B(W \to \tau\nu) = 2.22 \pm 0.09$ (stat) ± 0.10 (syst) ± 0.10 (lum) nb. Lepton universality predicts that the ratio of the tau and electron electroweak charged current couplings to the W boson, g_τ^W/g_e^W, be unity. We find $g_\tau^W/g_e^W = 0.980 \pm 0.031$, in agreement with lepton universality.

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The measurement of the W boson production cross section times branching ratio to τ lepton and neutrino, $\sigma(p\overline{p} \to W+X) \cdot B(W \to \tau\nu)$, can be used with the corresponding result from the electron channel, $\sigma(p\overline{p} \to W + X) \cdot B(W \to e\nu)$, to test one of the fundamental concepts in the standard model: the universality of the leptonic couplings to the weak charged current. Such "lepton universality" is a direct consequence of SU(2) gauge symmetry and the assumption that the leptons transform as left-handed SU(2) doublets, making its characterization a basic test of the underlying structure of the theory. Previous tests of τ-e universality at high Q^2 ($Q^2 \approx M_W^2$) have been obtained from the direct measurements of $\sigma_W \cdot B(W \to \tau\nu)$ and $\sigma_W \cdot B(W \to e\nu)$ by the UA1 [1], UA2 [2] and CDF [3] collaborations. Results from the CERN e^+e^- collider (LEP) on the couplings of Z bosons to charged leptons also support three-generation lepton universality to a precision of 0.5% [4].

In this Letter we report a new measurement of $\sigma(p\overline{p} \to W + X) \cdot B(W \to \tau\nu)$ using data collected with the DØ detector during the 1994–1995 Fermilab Tevatron collider run at a $p\overline{p}$ center-of-mass energy of $\sqrt{s} = 1.8$ TeV. The integrated luminosity [5] for the τ trigger used for this measurement is $\int \mathcal{L}dt = 18.04 \pm 0.79$ pb^{-1}. The DØ detector is described in detail in Ref. [6]. The detector consists of a non-magnetic tracking system, a uranium/liquid-argon calorimeter with segmentation $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in pseudorapidity and azimuth, and an iron toroid muon spectrometer.

In DØ the τ lepton is identified through its hadronic decay modes into final states consisting of one or three charged hadrons plus neutral particles. The τ decay products are highly boosted, forming a very narrow hadronic jet. The signature for $W \to \tau\nu$, with $\tau \to \nu +$ hadrons, is therefore an isolated and very narrow hadronic jet with low charged particle multiplicity, accompanied by a large amount of missing transverse energy $\not\!\!E_T$, determined from the energy deposition in the calorimeter within $|\eta| < 4.5$.

The τ trigger requires $\not\!\!E_T > 16$ GeV, a leading (highest E_T) narrow jet with transverse energy $E_T > 20$ GeV and $0.05 < f_{\mathrm{EM}} < 0.95$, where f_{EM} is the fraction of the jet energy in the electromagnetic calorimeter. The trigger also requires no jet with $E_T > 15$ GeV within 0.7 radians in ϕ of the direction opposite to that of the leading jet, or within 0.5 radians in ϕ of the $\not\!\!E_T$ direction, where ϕ is the azimuthal angle. In addition, a single interaction requirement is applied at the trigger level.

In the offline analysis, jets are reconstructed using a cone algorithm with radius $\mathcal{R} = 0.7$ in η-ϕ space, where η is the pseudorapidity. $W \to \tau\nu$ events are selected by requiring one jet satisfying (i) $25 < E_T < 60$ GeV, (ii) jet width $\mathcal{W} \leq 0.25$, where

$$\mathcal{W} = \sqrt{\sum_{i=1}^{n} \frac{\Delta\phi^2 E_{Ti}}{E_T} + \sum_{i=1}^{n} \frac{\Delta\eta^2 E_{Ti}}{E_T}}$$

and $i = 1, \ldots, n$ indicates the calorimeter η-ϕ tower number, (iii) $0.10 < f_{\mathrm{EM}} < 0.95$, ($iv$) $|\eta| \leq 0.9$, (v) one to seven reconstructed tracks within a 0.2×0.2 road in η-ϕ space around the jet axis, (vi) at least one track within 0.1 radian in ϕ of the center of gravity of the jet, (vii) jet quality cuts involving the longitudinal and lateral distribution of the energy within the jet, and ($viii$) profile $\mathcal{P} \geq 0.55$, where

$$\mathcal{P} = \ (E_{T1} + E_{T2}) \ / \ E_T,$$

and E_T, E_{T1} and E_{T2} are the transverse energy of the jet and the two towers within the jet with the largest E_T, respectively. The profile variable exploits the fine calorimeter segmentation and good energy resolution of the DØ detector. The very narrow jets from hadronic τ decays lead to high values of $\mathcal{P}$. QCD processes yield events with wider jets, and therefore lower values of $\mathcal{P}$ (Fig. 1).

In addition, the event must have (*i*) $\not\!\!E_T > 25$ GeV, (*ii*) a z vertex position within 60 cm of the detector center, (*iii*) no electrons or muons with $E_T > 15$ GeV, (*iv*) no jets with $E_T \geq 8$ GeV within 0.5 radians of the $\not\!\!E_T$ direction, (*v*) no jets with $E_T \geq 8$ GeV within 0.7 radians in ϕ of the direction opposite to that of the τ jet, and (*vi*) no jet with $E_T > 15$ GeV in addition to the τ jet.

The τ lepton identification is very sensitive to electronic noise in the calorimeter and to the underlying event. A data-based Monte Carlo (DBMC), using $W \rightarrow e\nu$ data, was developed to model $W \rightarrow \tau\nu$ events with actual noise and underlying event effects. We replace the electron from W boson decays with a Monte Carlo τ, which was generated with the same kinematics as the electron, forced to decay hadronically, and then passed through a detector simulation based on the GEANT Monte Carlo program [7]. The tracking hits along the electron track and the calorimeter cells associated with the electron cluster are replaced by the simulated Monte Carlo τ information. In this way, only the τ decays and the response of the detector to the τ decay products are simulated with a Monte Carlo, and noise and underlying event effects are taken directly from the data.

The dominant background in the $W \rightarrow \tau\nu$ final sample is from QCD events in which one of the jets mimics a τ jet, and the energies of the other jets fluctuate to give $\not\!\!E_T$. We estimate this QCD background using the $\mathcal{P}$ distribution. The cuts to select the "QCD background sample" are similar to those used to select the $W \rightarrow \tau\nu$ sample, but without the $\mathcal{P}$ or $\not\!\!E_T$ requirements or the requirement that there be no jet with $E_T > 15$ GeV in addition to the leading jet. The "τ sample" is the final $W \rightarrow \tau\nu$ sample before the $\mathcal{P}$ cut. We define the

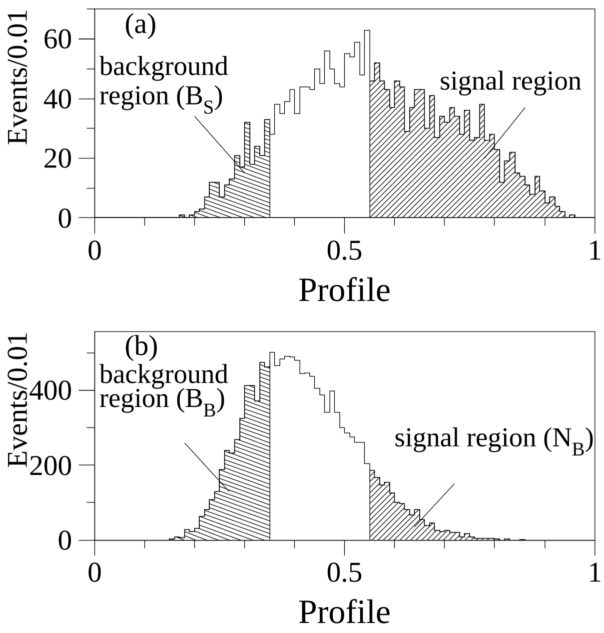

FIG. 1. The $\mathcal{P}$ distributions of (a) the τ sample from data, and (b) the QCD background sample.

region with $\mathcal{P} < 0.35$ as the "background region," and the region with $\mathcal{P} > 0.55$ as the "signal region," as shown in Fig. 1 for both the τ sample and the QCD background sample. We find that the $\mathcal{P}$ distribution of the background sample is uncorrelated with $\not\!\!E_T$, leading jet E_T or the number of jets in the event. From the DBMC $W \to \tau\nu$ studies only $\sim 1\%$ of $W \to \tau\nu$ events are in the background region. The number of background events in the signal region of the τ sample ($N_{\rm QCD}$) can be calculated as

$$N_{\rm QCD} = N_B \times (B_S/B_B),$$

where $N_B = 1834$ is the number of events in the signal region of the QCD background sample, $B_B = 4422$ is the number of events in the background region of the QCD background sample, and $B_S = 253$ is the number of events in the background region of the τ sample. We obtain $N_{\rm QCD} = 106 \pm 7$ (stat) $\pm\, 5$ (syst) events [8]. The systematic error is estimated from the dependence of the average profile on $\not\!\!E_T$ in the background region of the QCD background sample. We compared the $\mathcal{P}$ distribution in the background region between the QCD background sample and the τ sample. Their shapes agree very well – the Kolmogorov-Smirnov probability that the two distributions are from the same parent distribution is 0.94. This assures us of the validity of normalizing the background region in the QCD background sample to the background region in the τ sample. As another consistency check, we divided the τ and QCD background samples into bins in E_T of the τ jet and calculated $N_{\rm QCD}$ separately for each E_T bin. We estimated $N_{\rm QCD}$ to be 107 events using this method. We also checked the $\mathcal{P}$ distribution in $\not\!\!E_T$ bins. We see no significant dependence of $\mathcal{P}$ on $\not\!\!E_T$.

The QCD background estimate also includes W/Z+jet events in which a jet is misidentified as a τ jet and the $\not\!\!E_T$ arises from either a W leptonic decay or from unreconstructed muons in $Z \to \mu\mu$ decays, which result in $\not\!\!E_T$ in the calorimeter. The background from Z+jet events in which $Z \to \nu\nu$ is also included in the QCD background estimate. The $W \to e\nu$ background, in which the electron is misidentified as a τ, is estimated to be 3 ± 1 events.

Electronic noise in a calorimeter cell may simulate a narrow jet and also give a large $\not\!\!E_T$. When an underlying event track is very close to the noise jet, it mimics a τ event. The background from noise events is estimated by using the same method that was used to calculate $N_{\rm QCD}$, but using the distribution of $\Delta\phi$, the difference in ϕ of the τ jet and the closest track, instead of the $\mathcal{P}$ distribution. We defined $\Delta\phi > 0.1$ as the background region. This gives the number of background noise events in the final τ sample to be 81 ± 14.

Another source of background is $Z \to \tau\tau$, where one of the τ leptons decays hadronically. We studied this background using the ISAJET [9] generator and the GEANT-based DØ simulation program. Applying the same cuts as those used in the $W \to \tau\nu$ event selection, we estimate that 32 ± 5 $Z \to \tau\tau$ events are present in our final data sample. The number of background events is summarized in Table I.

There are 1202 events passing all the selection cuts. For these events Fig. 2(a) shows the τ jet E_T distribution. Figure 2(b) shows the distribution of the transverse mass calculated from the τ jet and the $\not\!\!E_T$ for the τ sample after QCD background subtraction. Figure 2(b) also shows the comparison with DBMC events, normalized to the data, passing the same cuts. The distribution of jet width ($\mathcal{W}$) can also be used to confirm the selection of $W \to \tau\nu$ events. Figure 3 compares the $\mathcal{W}$ distribution for DBMC τ jets and QCD jets before and after the profile ($\mathcal{P}$) cut. Figure 3(b) also shows the $\mathcal{W}$ distribution for τ jets from the final

TABLE I. Summary of the $\sigma(p\overline{p} \to W + X) \cdot B(W \to \tau\nu)$ measurement.

$N_{\rm obs}$	1202
Backgrounds (No. events):	
QCD $\pm$(stat)$\pm$(syst)	$106 \pm 7 \pm 5$
Electronic noise	81 ± 14
$Z \to \tau\tau$	32 ± 5
$W \to e\nu$	3 ± 1
Total Background (No. events)	222 ± 17
$A \cdot \epsilon$	0.0379 ± 0.0017
$\int \mathcal{L}dt$ (pb^{-1})	18.04 ± 0.79
$\sigma_W \cdot B(W \to \tau\nu)$ (nb)	
$\pm$ (stat),(syst),(lum)	$2.22 \pm 0.09 \pm 0.10 \pm 0.10$

data sample with the QCD background subtracted. The $\mathcal{W}$ distribution of the final data sample is clearly different from that of the QCD jet sample, and agrees well with the DBMC $W \to \tau\nu$ prediction.

The acceptance A is determined by applying the geometric and kinematic cuts on ISAJET Monte Carlo τ leptons, giving $A = 0.2903 \pm 0.0007$. The efficiency ϵ is determined by applying the trigger requirements and the offline cuts on the DBMC $W \to \tau\nu$ sample, giving $\epsilon = 0.1307 \pm 0.0034$. The trigger efficiency for the events passing the offline selection is 0.9941 ± 0.0020. The above uncertainties are from Monte Carlo statistics and are treated as

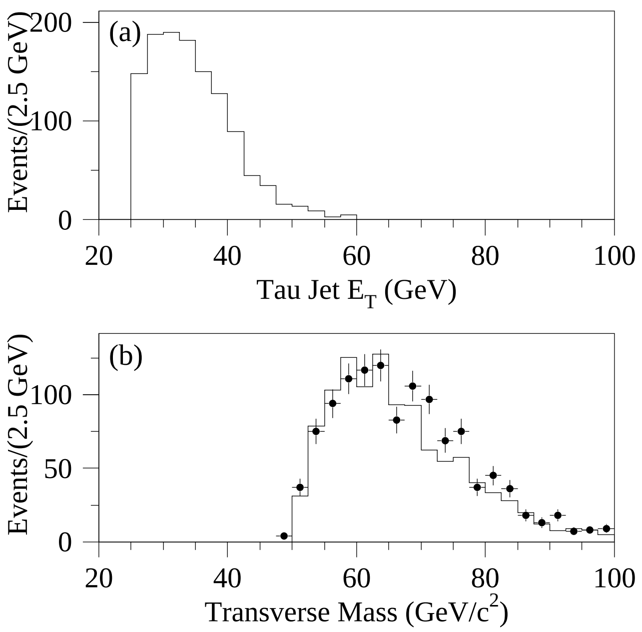

FIG. 2. (a) The τ jet E_T distribution for data passing all the selection cuts, and (b) the distribution of the transverse mass of the τ jet and the $\not\!\!E_T$ for DBMC events (histogram) and for data (points) passing all the selection cuts and with QCD background subtraction.

systematic. Two additional sources contribute to systematic uncertainties in $A\cdot\epsilon$. First, the 3% uncertainty in the energy scale [10] results in an uncertainty of 2.8% on $A\cdot\epsilon$. Second, the uncertainty due to τ branching fraction uncertainties is calculated by varying the branching fractions of the various exclusive τ decay modes by their measurement errors [4], subject to the constraint that the sum of all τ decay branching fractions add up to 1. This variation results in an uncertainty of 2.0% on $A\cdot\epsilon$. The final value of $A\cdot\epsilon$ is 0.0379 ± 0.0017.

The cross section times branching ratio for $p\overline{p} \to W + X$, with $W \to \tau\nu$, is calculated using the formula

$$\sigma_W \cdot B(W \to \tau\nu) = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{\int \mathcal{L}dt \cdot B(\tau \to \nu + \mathrm{hadrons}) \cdot A \cdot \epsilon},$$

where N_{obs} is the number of events in the final data sample, N_{bkg} is the estimated background, A is the acceptance, ϵ is the efficiency, $\int \mathcal{L}dt$ is the integrated luminosity, and $B(\tau \to \nu + \mathrm{hadrons}) = (64.69 \pm 0.22)\%$ [4]. We measure

$$\sigma_W \cdot B(W \to \tau\nu) = 2.22 \pm 0.09 \pm 0.10 \pm 0.10 \text{ nb},$$

where the uncertainties are statistical, systematic, and due to the luminosity uncertainty, respectively.

We can determine the ratio of the tau and electron electroweak charged current couplings to the W boson, g_τ^W and g_e^W, from

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

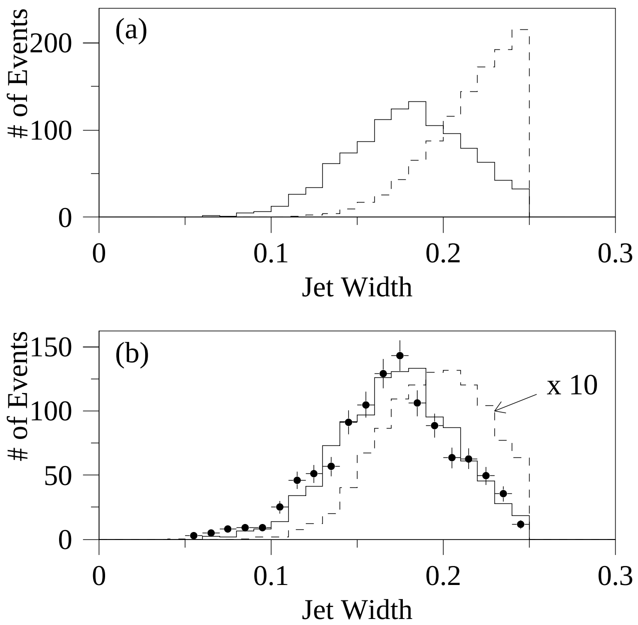

FIG. 3. The distribution of jet width for DBMC τ jets (solid histogram) and QCD jets (dashed histogram) (a) before the profile cut (with arbitrary scale), and (b) after the profile cut. The $\mathcal{W}$ distribution for data (points) is also shown in (b). The QCD distribution in (b) has been scaled up by a factor of 10.

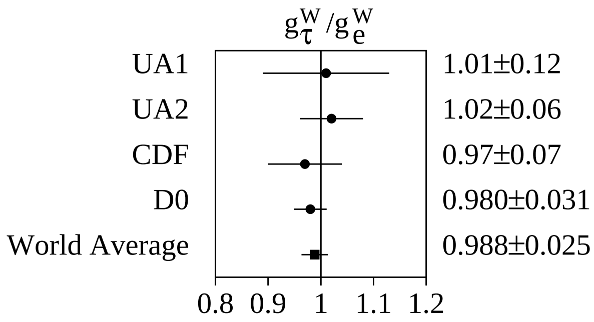

FIG. 4. g_τ^W/g_e^W from UA1 [1], UA2 [2], CDF [3], and this measurement (DØ).

Taking the ratio of $\sigma_W \cdot B(W \to \tau\nu)$ and $\sigma_W \cdot B(W \to e\nu)$ completely cancels the luminosity error. Using our measurement [11] of $\sigma_W \cdot B(W \to e\nu) = 2.31 \pm 0.01 \pm 0.05 \pm 0.10$ nb for data collected during the same Tevatron collider run, we find

$$\begin{aligned} g_\tau^W/g_e^W &= 0.980 \pm 0.020\ (\text{stat}) \pm 0.024\ (\text{syst}) \\ &= 0.980 \pm 0.031. \end{aligned}$$

Our measurement is in good agreement with lepton universality, which requires that $g_\tau^W/g_e^W = 1$. Figure 4 shows the results for g_τ^W/g_e^W from other experiments, along with the value determined by the DØ experiment and the weighted average of the four experiments, which is 0.988 ± 0.025. The average was calculated assuming systematic errors are uncorrelated among the four experiments.

In summary, we have used the DØ detector to identify τ leptons in $p\overline{p}$ collisions, have measured the cross section times branching ratio $\sigma(p\overline{p} \to W + X) \cdot B(W \to \tau\nu)$, and have used this result to test τ-e universality at high Q^2 ($Q^2 \approx M_W^2$) to a precision of 3%.

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