First Measurement of $\sigma(pp \to Z)\cdot Br(Z \to \tau\tau)$ at $\sqrt{s} = 1.96$ TeV

We present a measurement of the cross section for $Z$ production times the branching fraction to $\tau$ leptons, $\sigma \cdot Br(\tau^{+}\tau^{-})$, in $p\bar{p}$ collisions at $\sqrt{s}=1.96$ TeV in the channel in which one $\tau$ decays into $\mu\nu\bar{\nu}$ and the other into hadrons+$\nu$ or $e\nu\bar{\nu}$. The data sample corresponds to an integrated luminosity of 226 $\pm$ 15(stat)$\pm$18(sys)$\pm$15(lum) pb collected with the DØ detector at the Fermilab Tevatron collider. The final sample contains 2008 candidate events with an estimated background of 55%. From this we obtain $\sigma \cdot Br(\tau^{+}\tau^{-}) = 237 \pm 15(stat) \pm 18(sys) \pm 15(lum)$ pb, in agreement with the standard model prediction.

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Measurements of the $Z$ boson production cross section times the leptonic branching fraction ($\sigma \cdot Br$) in $p\bar{p}$ collisions can be used to test standard model (SM) predictions. The $\sigma \cdot Br$ to $e^{+}e^{-}$ and $\mu^{+}\mu^{-}$ in $p\bar{p}$ collisions has been measured by the UA1 and UA2 collaborations at $\sqrt{s} = 630$ GeV [1], by the CDF collaboration at $\sqrt{s} = 1.8$ TeV and $\sqrt{s} = 1.96$ TeV [2], and by the DØ collaboration at $\sqrt{s} = 1.8$ TeV [3]. The $Z$ boson branching ra-
tio to $\tau^+\tau^-$ has been measured with high precision by the CERN $e^+e^-$ collider (LEP) experiments \cite{4}. These measurements are in good agreement with SM expectations and lepton universality. We report here the first measurement of $\sigma\cdot\text{Br}(Z \rightarrow \tau^+\tau^-)$ in $p\bar{p}$ collisions. This measurement is a test of the SM and verifies that the DØ detector can identify $\tau$ leptons in the energy range covered by $Z$ boson decays, which could be critical in the search for non-SM signals such as supersymmetric (SUSY) particles in certain regions of the SUSY parameter space, or heavy resonances decaying into fermion pairs with enhanced coupling to the third generation.

The DØ Run II detector is fully described in \cite{5}; a more succinct description of details relevant to this measurement can be found in \cite{6}. The $Z \rightarrow \tau^+\tau^-$ candidate selection strategy focused on one $\tau$ lepton decaying to muon by triggering on the single muon using a three-level triggering system. The first level used the timing and position information in the muon scintillator system to find muon candidates. The second level used digital signal processors to form segments defined in the muon drift chambers. The third level used software algorithms executed on a computer farm to reconstruct tracks in the central tracking system and required at least one track with transverse momentum $p_T > 10$ GeV. The integrated luminosity of the selected sample is 226 pb$^{-1}$ determined with a 6.5% uncertainty \cite{7}.

After full reconstruction, the events were required to have an isolated muon with $p_T^\mu > 12$ GeV and a $\tau$ candidate. The muon isolation required less than 4 GeV in the calorimeter in a cone $R<1$ and at least one associated track with $E_T$ in the EM section of the calorimeter belonging to the $\tau$-cluster. Finally, subclusters were constructed from the cells in the EM section of the calorimeter belonging to the $\tau$-cluster. The minimum $E_T$ required for an EM subcluster was 800 MeV. Three types of $\tau$ candidates were identified according to tracking and calorimetry information:

1. single track with no subclusters in the electromagnetic (EM) section of the calorimeter ($\pi$-like),
2. single track with EM subclusters ($\rho$-like), or
3. more than one associated track.

No attempt was made to separate hadrons from electrons (which can contribute to both $\tau$-type 1 and $\tau$-type 2).

Additional requirements (which depend on the $\tau$-type) imposed on the selected events to enhance the signal-to-background ratio are shown in Table I. The background increases rapidly with decreasing $p_T^\mu$ or decreasing $E_T^\tau$. It is significantly lower for $\tau$-type 2 than for the other $\tau$-types, so a lower $E_T^\tau$ cut is warranted for that $\tau$-type. The longitudinal shape variable $R^\tau_{trk}$ (defined in Table I caption) is used to remove misidentified muons because it has a distribution that peaks at much lower values for muons than for $\tau$ leptons.

The $\tau$ leptons from a $Z$ boson decaying to hadrons + $\nu_\tau$ have average visible energy ($E^\tau$) of the order of 25 GeV and need to be separated from a very large background of jets. To further reduce the jet background, a neural network (NN) \cite{8} consisting of a single input layer containing several nodes (one for each input variable), a single hidden layer with the same number of nodes, and a single output node was used. A separate NN was trained for each type using a Monte Carlo (MC) sample of single $\tau$ leptons uniformly distributed in $E_T$ and $\eta$ and overlaid with a minimum bias event for signal \cite{9}, and jets recoiling against non-isolated muons from data for background. The NN input variables were chosen to minimize the dependence on the $\tau$ energy and to exploit the narrow width of the energy deposition in the calorimeter, the low track multiplicity, the low $\tau$ mass, and the fact that $\tau$ leptons from $Z$ boson decays are well isolated. The NN input variables were:

\begin{table}
\centering
\begin{tabular}{|c|c|}
\hline
Selection & applied to the $\tau$-types \\
\hline
only one $\mu$ & all \\
p$T^\mu > 12$ GeV & all \\
$\mu$ isolation & all \\
E$_T^\mu > 10(5)$ GeV & 1 and 3 (2) \\
$\Sigma_{i=1}^n E_{trk}^i > 7(5)$ GeV & 1 and 3 (2) \\
rms$_{a,b} < 0.25^a$ & all \\
$|\phi_\mu - \phi_\tau| > 2.5$ & all \\
R$^\tau_{trk} > 0.7^b$ & 1 and 2 \\
\hline
\end{tabular}
\caption{Event pre-selection cuts}
\end{table}

\begin{enumerate}
\item profile = $(E_{T^1} + E_{T^2})/E_T^\tau$, where $E_{T^1}$ and $E_{T^2}$ are
\end{enumerate}
the $E_T$ of the two most energetic calorimeter towers. Used for all $\tau$-types.

2. $caliso = (E_T^{\mu} - E_T^{core})/E_T^{core}$. A calorimeter isolation parameter used for all $\tau$-types.

3. $trkiso = \Sigma p_T^{trk}/\Sigma p_T^{\tau}$, where $p_T^{trk}$ ($p_T^{\tau}$) is the $p_T$ of a track within a $R < 0.5$ cone not associated (associated) with the $\tau$ candidate. A track isolation parameter used for all $\tau$-types.

4. $(E_{EM1} + E_{EM2})/E_\tau$ in a $R < 0.5$ cone, where $E_{EM1}$ and $E_{EM2}$ are the energies deposited in the first two layers of the EM calorimeter. A parameter used for $\tau$-type 1 to reject jets with one energetic charged track and soft $\pi^0$ mesons.

5. $p_T^{\tau}$ / $E_T^{\tau}$, where $p_T^{\tau}$ is $p_T$ of the highest $p_T$ track associated with the $\tau$. Used for $\tau$-type 1 and 3.

6. $p_T^{\tau}$ / $(E_T^{\tau}$-caliso). A parameter used for $\tau$-type 2 that measures the correlation between track and energy deposition in isolation annulus.

7. $e_{12} = \sqrt{\Sigma p_T^{trk} \cdot E_T^{EM} / E_T^{\tau}}$, where $E_T^{EM}$ is the transverse energy deposited in the EM layers of the calorimeter. Used for $\tau$-types 2 and 3.

8. $\delta \alpha = \sqrt{(\Delta \theta / \sin \theta)^2 + (\Delta \phi)^2}$, where the differences are between $\Sigma \tau$-tracks and $\Sigma$-EM-clusters. In the small angle approximation the observed $\tau$ mass is given by $e_{12} \cdot E_T^{\tau} \cdot \delta \alpha$. Used for $\tau$-types 2 and 3.

The dominant background is from multijet (QCD) processes, mainly from $b\bar{b}$ events where the muon isolation requirement is met and a jet satisfies the $\tau$ selection criteria. The other sources of background are $W \rightarrow \mu \nu +$ jets and $Z/\gamma^* \rightarrow \mu^+ \mu^-$ with one of the muons misidentified as a $\tau$ lepton. The $R_{trk}^{\tau} > 0.7$ cut removed 70% of the $\mu^+ \mu^-$ background while keeping 98% of the signal. The number of events that did not satisfy this criterion was used to estimate the background from misidentified muons remaining in the sample after the cut.

The selected 29,021 events were separated into two samples: $\mu$ and $\tau$ of opposite charge sign (OS), and $\mu$ and $\tau$ of same charge sign (SS). The OS sample contains the signal. The SS sample is dominated by background and was used to predict the QCD background distributions in the signal sample. From detailed studies of a sample of data with non-isolated muons, we established that this procedure is sound if one accounts for a small excess of OS over SS events that varies somewhat with the $\tau$-type. The correction factors ($f_i$, where $i$ denotes the $\tau$-type) were determined to be $1.06 \pm 0.06$, $1.09 \pm 0.03$, and $1.03 \pm 0.02$, by taking the ratio of OS to SS data in the non-isolated muon sample. There was no observable dependence of $f_i$ as function of $E_T^{\tau}$, of NN output ($NN$) values, or of the muon parameters. An overall 3% systematic uncertainty was added for the extrapolation to the $NN > 0.8$ region. These factors do not fully account, however, for the contribution from $W \rightarrow \mu \nu +$ jets, which have a larger excess of OS over SS and different distributions. The additional contribution of this channel to the signal sample is estimated from PYTHIA [9] MC samples. The MC is normalized using the OS and SS data with $p_T^{\tau} > 20$ GeV, $|\phi_\mu - \phi_\tau| < 2.0$, and $0.3 < NN < 0.8$ (in this region $W \rightarrow \mu \nu$ events dominate over the QCD background).

Figure 1 shows the $NN$ distributions for each $\tau$-type (and the sum) for the signal sample, the predicted background and the result of adding the predicted signal (from $Z/\gamma^* \rightarrow \tau \tau$ MC [9]) to the background. Table II shows the total number of events observed and predicted before and after the final cut $NN > 0.8$. Distributions of background subtracted data are in very good agreement with those expected from $Z \rightarrow \tau \tau$ MC. Figure 2 compares the expected $E_T^{\tau}$ and $p_T^{\tau}$ (adding all $\tau$-types) signal distributions to the predicted background distributions, and to the distributions obtained by subtracting the predicted background from the signal sample distributions.

The total event efficiency ($\epsilon_{TOT}$) summed over $\tau$-types 1, 2, and 3 is 1.52% for $M_{\tau\tau}$ greater than 60 GeV. The total efficiency accounts for all losses due to branching ratios, geometrical acceptance, reconstruction and trigger efficiencies. It is corrected for the small difference between MC and data reconstruction efficiencies. The contributions of the three $\tau$-types to the signal in the final data sample are 13%, 58%, and 29%. 

FIG. 1: NN output distributions for: (a) $\tau$-type 1, (b) $\tau$-type 2, (c) $\tau$-type 3, and (d) the sum over all the $\tau$-types.
The QCD background is estimated by multiplying the number of SS events by $f_{1}$ (described in the text).

The predicted number of $Z/\gamma^{\ast}\rightarrow\tau^{+}\tau^{-}$ events is based on a theoretical cross section of $257\pm9$ pb for $M_{\tau\tau}>60$ GeV [10] plus 3.5% predicted from MC for the number of events expected with $M_{\tau\tau}<60$ GeV.

The QCD background is estimated by multiplying the number of SS events and the theoretical cross section of 257.

TABLE III: Systematic uncertainties on $\sigma\cdot Br(Z/\gamma^{\ast}\rightarrow\tau^{+}\tau^{-})$

| Energy Scale | 2.5% |
| NN | 2.6% |
| QCD background | 3.5% |
| $Z/\gamma^{\ast}\rightarrow\mu\mu$ background | 2% |
| $W\rightarrow\mu\nu$ background | 2.3% |
| $Z/\gamma^{\ast}\rightarrow\tau\tau$ MC | 1.5% |
| PDF$^{a}$ | 1.7% |
| $\epsilon_{data}/\epsilon_{MC}$ | 2.1% |
| Trigger | 3.5% |
| Total | 7.5% |

$^{a}$Efficiency uncertainty due to uncertainty in parton distribution function (PDF).

$^{b}\epsilon_{data}/\epsilon_{MC}$ is the ratio of data to MC reconstruction efficiency.

The systematic uncertainty due to the NN performance (2.6%) was estimated by generating ensembles of Monte Carlo events in which the number of events in each bin of distributions of NN input variables was allowed to fluctuate by the uncertainties in the difference between MC distributions and the background-subtracted data distributions. The distributions of NN input variables are in good agreement with those predicted adding $Z/\gamma^{\ast}\rightarrow\tau^{+}\tau^{-}$ MC and the estimated background; two are shown in Fig. 3.

The QCD systematic uncertainty (3.5%) is due to the uncertainty in determining $f_{1}$. The uncertainty in the $Z/\gamma^{\ast}\rightarrow\mu^{+}\mu^{-}$ and $W\rightarrow\mu\nu$ backgrounds (2.0% and 2.3%) come from the statistical uncertainty in determining their contribution, while the $Z/\gamma^{\ast}\rightarrow\tau^{+}\tau^{-}$ MC systematic uncertainty reflects limited signal MC statistics. The value of $\epsilon_{data}/\epsilon_{MC}$ was determined by: i) comparing tracking and isolation efficiencies between $Z\rightarrow\mu^{+}\mu^{-}$ MC events and $Z\rightarrow\mu^{+}\mu^{-}$ data events, and ii) comparing the ratio of two- to three-prong events between background subtracted data and $Z/\gamma^{\ast}\rightarrow\tau^{+}\tau^{-}$ MC in $\tau$-type 3 candidates. The $\epsilon_{data}/\epsilon_{MC}$ systematic uncertainty is the statistical uncertainty in those comparisons. The trigger efficiencies were estimated using $Z\rightarrow\mu^{+}\mu^{-}$ data, the systematic uncertainty comes from the statistical uncertainty in that data; the uncertainties include dependencies on $\eta$ and $\phi$. Systematic uncertainties from

The cross section times branching ratio for $Z/\gamma^{\ast}\rightarrow\tau^{+}\tau^{-}$ is given by $N_{signal}/(\epsilon_{TOT}\cdot\int L\,dt)$ where $N_{signal}$ is given by the number of signal events and $\int L\,dt$ is the integrated luminosity of the sample studied. $N_{signal} = 865 \pm 55$ (statistical uncertainty only) is the number of OS events of all $\tau$ types after selecting the events with $NN > 0.8$, subtracting the estimated background (see Table II), and subtracting the number of expected events in the sample with $M_{\tau\tau}$ less than 60 GeV (3.5%).

The systematic uncertainties on the cross section measurement are listed in Table III. The uncertainty (2.5%) due to the energy scale was estimated from the change in the acceptance when scaling the energy in MC events by the energy difference between MC and data (as determined by the $p_{T}$ imbalance in photon + jet events).
all other sources are less than 1%. Thus we obtain

\[ \sigma \cdot \text{Br}(Z/\gamma^* \to \tau\tau) = 252 \pm 16(\text{stat}) \pm 19(\text{sys}) \text{ pb} \]

for \( M_{\tau\tau} \) greater than 60 GeV. The quoted statistical uncertainty is the uncertainty from OS and SS statistics (excluding the uncertainties on the correction factors). This yields, after removing the \( \gamma^* \) contribution,

\[ \sigma \cdot \text{Br}(Z \to \tau\tau) = 237 \pm 15(\text{stat}) \pm 18(\text{sys}) \pm 15(\text{lum}) \text{ pb} \]

good in agreement with the NNLO standard model prediction of 242±9 pb [10].

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ADDITIONAL PLOTS

FIG. 3: Distributions for OS data, background and background plus signal of two NN input variables before [(a), (b)] and after [(c), (d)] \( NV > 0.8 \) cut: (a), (c) profile; (b), (d) caliso.

FIG. 4: The distribution of the mass between the muon and the tau-track for type 1 and 2 taus.
FIG. 5: NN output distributions for data, background and $Z \rightarrow \tau\tau$ MC, summed over all types (finer bins than Fig. 1).

FIG. 6: Number of events by $\tau$-type for background, background-subtracted data and $Z \rightarrow \tau\tau$ MC.