DØnote 4526-CONF

Measurement of $\sigma(p\bar{p} \to Z/\gamma^*)\cdot\text{Br}(Z/\gamma^* \to \tau\tau)$ at $\sqrt{s} = 1.96$ TeV at DØ

The DØ Collaboration
URL http://www-d0.fnal.gov
(Dated: August 2, 2004)

We measure the cross section for Z production times the branching fraction $\sigma\cdot\text{Br}(Z \to \tau\tau)$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The measurement was performed in the channel in which a τ decays into $\mu\nu_\mu\nu_\tau$, and the other into hadrons $+\,\nu_\tau$ or $e\nu_e\nu_\tau$. The data sample corresponds to an integrated luminosity of 207 pb^{-1} collected with the DØ detector at the Tevatron between September 2002 and April 2004. The final sample has 1946 candidate events with a 55% background from misidentified τ's. From this we obtain $\sigma\cdot$Br=256±16(stat.)±17(sys.)±16(lum.) pb, which is in agreement with the Standard Model prediction.

Preliminary Results for Summer 2004 Conferences

I. INTRODUCTION

We describe a measurement of $\sigma\cdot$Br$(Z \to \tau\tau)$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV based on an event sample containing a τ candidate that is back-to-back in azimuth with respect to a single isolated μ (τ could be $\tau \to$ hadrons $+\ \nu_\tau$ or $\tau \to e\nu_e\nu_\tau$). This measurement is of interest not only as a test of our ability to identify τ's but also because any excess over the expected $\sigma\cdot$Br could be an indication of a source other than Z's for $\mu\tau$ pair events. The data were collected between September 2002 and April 2004 requiring single μ triggers. Periods of data-taking with the DØ detector not fully operational were removed. The remaining data corresponds to an integrated luminosity of 207 pb^{-1}.

II. THE τ CANDIDATE IDENTIFICATION

Unlike the other leptons, the τ has a life time of the order 10^{-13} s and therefore decays before reaching any of the DØ detectors. For the τ candidate identification we used the neural network (NN) package from the ROOT example applications [1], which consists of a standard back propagation method, especially suitable for particle physics classification tasks. We chose the simplest configuration of a network, i.e., one consisting of a single input layer containing several nodes (one for each input variable), a single hidden layer containing several nodes, and a single output. There are no connections between any two nodes of a given layer, nor are there any direct connections between the input nodes and the output.

Three separate NNs were trained using 100,000 single τ MC events, uniformely distributed in visible p_T, ϕ and η, with 10 GeV $<$ visible $\mathrm{p_T} < 60$ GeV and $-3 < \eta < 3$, each one of the NN corresponding to a certain τ type. We define a τ as being of "type 1" if it has a single track associated with a calorimeter cluster, but no EM subclusters (a cluster in the electro-magnetic (EM) part of the calorimeter). This corresponds to a τ that decays into $\mathrm{h}^\pm + \nu_\tau$ or $\mu^\pm\nu_\mu\nu_\tau$, as well as to $\mathrm{h}^\pm +$ a number of $\pi^0\mathrm{s} + \nu_\tau$ if none of the $\pi^0 s$ formed an EM subcluster. A "type 1" τ can come as well from the decay to $e^\pm\nu_e\nu_\tau$, if the electron failed to form an EM subcluster, or to $\geq$3 charged prongs if none of the other tracks was reconstructed. A "type 2" τ is one that consists of a single track with calorimeter cluster and EM subclusters, corresponding mainly to $\mathrm{h}^\pm +$ a number of $\pi^0\mathrm{s} + \nu_\tau$ decays, but also $\mathrm{h}^\pm + \nu_\tau$ in case there is an early showering of the charged hadron leading to the formation of EM subclusters, $e^\pm\nu_e\nu_\tau$ or $\mu^\pm\nu_\mu\nu_\tau$ where the μ radiated a photon. Finally, a "type 3" τ has 2 (2-pr.) or 3 tracks with the invariant mass consistent with the τ mass and a calorimeter cluster, corresponding to a 3-prong decay of the τ. A track is associated with a tau in all these cases if it is the highest p_T track reconstructed within a cone ($R < 0.3$). Additional tracks from the (R<0.3) cone are associated with the τ as well if they satisfy the requirement of being consistent with tau mass. Table I shows the input variables that were used for the training of the three NNs.

TABLE I: Input variables for the 3 NNs, corresponding to the 3 types of τs (yes/no=variable is/is not used)

	profile[a]	iso[b]	ettr/ettsum[c]	EM12isof[d]	$p_T^{\tau trk1}/(E_T^\tau \cdot iso)$[e]	$p_T^{\tau trk}/E_T^\tau$	e1e2/E_T^τ[f]	$\delta\alpha$/3.1416[g]
type 1	yes	yes	yes	yes	no	yes	no	no
type 2	yes	yes	yes	no	yes	no	yes	yes
type 3	yes	yes	yes	no	no	yes	yes	yes

[a]profile $= (E_{T_1} + E_{T_2})/E_T$, where E_{T_1} and E_{T_2} are the E_T of the two most energetic calorimeter towers
[b]iso $= (E_T(R < 0.5) - E_T(R < 0.3))/E_T(R < 0.3)$, where $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ and $\Delta\phi$, $\Delta\eta$ are differences between the ϕ and η of a calorimeter tower and the direction of the jet cone axis.
[c]ettr $= \Sigma p_T^{trk}$, for trk within a R<0.5 cone and not associated with the τ, ettsum$=\Sigma p_T^{\tau trk}$
[d]EM12isof $= (EM_1 + EM_2)/E$ in a R<0.5 cone, where EM_1 and EM_2 are the energies deposited in the first two layers of the EM calorimeter
[e]$p_T^{\tau trk1}$=p_T of the highest p_T track associated with the τ, E_T^τ=E_T of the calorimeter cluster associated with the τ
[f]e1e2 $= \sqrt{\mathrm{ettsum} \cdot \mathrm{E_T^{EM}}}$, where E_T^{EM} is the transverse energy deposited in the EM layer of the calorimeter
[g]$\delta\alpha = \sqrt{(\Delta\phi/sin\theta)^2 + \Delta\eta^2}$, where Δ's are between $\Sigma\tau$-tracks and Σem-clusters; ϕ is the opening angle between the τ tracks and the EM cluster, if any, while θ is the azimutal angle of the calorimeter cluster centroid; the τ-mass is therefore given by e1e2$\cdot\delta\alpha$

Note that the input variables for the NNs were chosen to minimize dependence on the energy of the τ. Distributions for some of these variables are shown in Fig. 1. The τ pT denotes the visible p_T of the τ. "QCD pT $>$ 20" is a notation for MC QCD events with the requirement that the $p_T^{\mathrm{jet}} > 20$ GeV for all jets in the event. Since the QCD jets are reconstructed with larger cone sizes ($R < 0.7$), the energy in the narrow cone ($R < 0.3$) of the τ candidate makes them more similar to τ leptons in the kinematic region 10 $<$ visible τ pT $<$ 20 GeV. The requirement on the data events is to have a non-isolated μ with $p_T > 15$ GeV in the event. Figure 2 shows the NN output distributions for background (τ-candidates in events with non-isolated μ's) and $Z \to \tau\tau$ Monte Carlo.

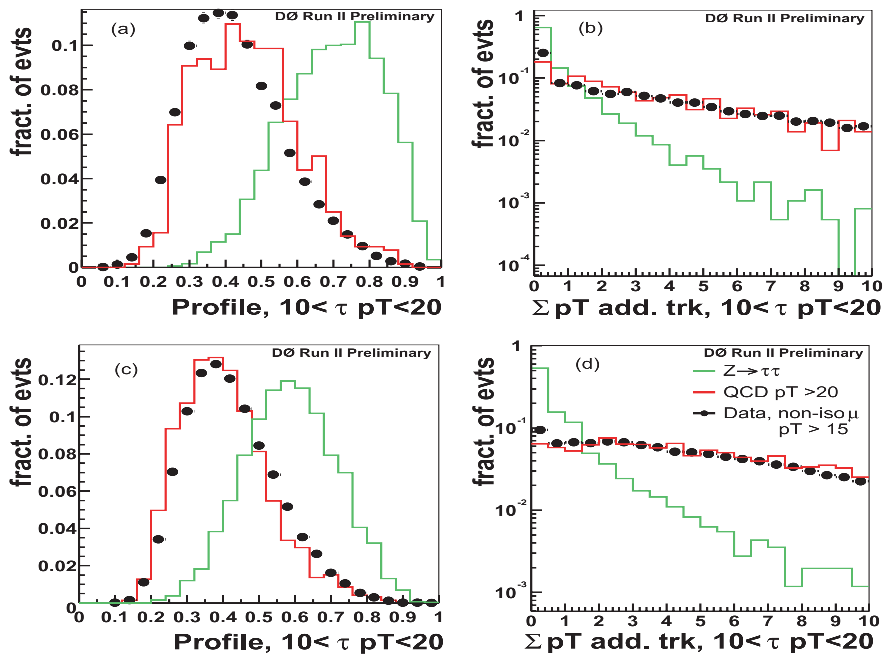

FIG. 1: Examples of distributions of input variables for data, QCD background and $Z \to \tau\tau$ MC; (a) and (c) represent the profile for type 2 and 3 τ-candidates respectively, while (b) and (d) are the Σp_T of the additional tracks (not associated with the τ) in a cone (R< 0.5) for types 2 and 3 respectively.

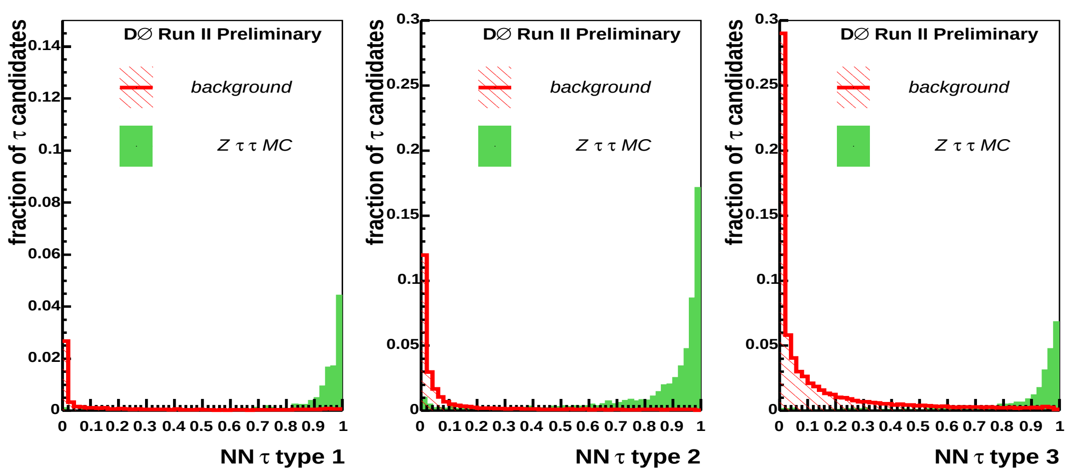

FIG. 2: NN output distributions for different τ-candidate types. The ratio of signal to background is arbitrary, but the relative amounts of type 1, type 2 and type 3 events in background and signal are not. The sums of signal and background in each plot have been normalized to one, respectively.

III. EVENT SELECTION

For analysis we used a sample of events selected from data by requiring at least one μ with local (measured in the μ detectors) or central (measured with the central tracking detectors) $p_T > 8$ GeV (1MUloose sample). A special filter was used at this stage of preselection to choose only events with one isolated μ matched to a central track. Table II shows the cuts applied at different stages of the event selection.

The event sample resulting from the selection at Stage 2 is split in two: μ and τ of opposite sign charge (OS), and μ and τ of same sign charge (SS). The OS sample has most of the signal. The SS sample is pure background that can be used to predict the expected contribution from QCD jets background to the OS sample (mainly from $b\bar{b}$ jets and some $W \to \mu\nu$ + jet). The other main source of background, μ pairs from Drell-Yan processes, contributes only

TABLE II: Different cuts applied at each stage of the event selection

	Preselection	Selection - Stage 1	Selection - Stage 2
number of loose μ	$\geq$1	$\geq$1	=1
p_T^{μ}	$>$ 8 GeV (local or central)	$>$ 5 GeV (central)	$>$ 12 GeV (central)
μ isolation[a]	required	required	required
$p_T^{\tau_{trk}}$		$>$ 3.5 GeV	$>$ 3.5 GeV
E_T^{τ} -type 1 & 3 (type 2)[b]		$>$ 5 GeV ($>$ 5 GeV)	$>$ 10 GeV ($>$ 5 GeV)
$\Sigma p_T^{\tau_{trk}}$ - type 1 & 3 (type 2)			$>$ 7 GeV ($>$ 5 GeV)
τ-rms[c]		$<$ 0.25	$<$ 0.25
$\lvert\phi_\mu - \phi_\tau\rvert$			$>$ 2.5
R_{trk}^{τ}[d]			$>$ 0.7
NN output		$>$ 0.3	$>$ 0.3
trigger selection[e]			required
Number of selected events	11,722,731	589,648	8,562

[a]E(R< 0.1) < 4 GeV and E(R< 0.4)-E(R< 0.1) < 4 GeV and track isolation: (<3 tracks in (R< 0.7))
[b]E_T^{τ} is the E_T of the calorimeter cluster that is a τ candidate (τ-cluster)
[c]τ-rms=$\sqrt{\sum_{i=1}^{n}\frac{\Delta\phi_i^2 E_{T_i}}{E_T}+\frac{\Delta\eta_i^2 E_{T_i}}{E_T}}$, where i=1,..,n is the calorimeter tower number; the τ-rms is the energy weighted width of the cluster
[d]$R_{trk}^{\tau} = (E^{\tau} - E_{CH}^{trk})/p_T^{trk}$, where E_{CH}^{trk} is the energy deposited in the Coarse Hadronic (CH) calorimeter in a 5x5 window around the tau track
[e]triggers used: single μ at L1, 3 or 5 GeV μ at L2, 10 GeV track at L3

to the OS sample. In the case of type 3 τ-candidates with only 2 tracks reconstructed, the event is included only if both tracks have the same charge (since we need to separate samples by the charge of μ and τ's). A final cut on the NN output at 0.8 reduced the sample to 1946 events.

IV. BACKGROUNDS

The predominant background is from $b\bar{b}$ events that were not removed by the μ isolation requirement and one of the jets satisfies all τ selection criteria. The other main sources of background are $W \to \mu\nu$ + jets with one jet misidentified as τ and $Z \to \mu\mu$ with one of the μ's misidentified as a τ.

A. QCD background

The $b\bar{b}$ QCD background is removed by subtracting the distributions of SS μ-τ pairs from OS pairs. One needs to test the assumption that the number of SS events is equal to the number OS in QCD background events. For this study 800,000 events were picked from the 1MUloose sample without a μ isolation requirement. The measurement was done by looking at τ-candidates which were back-to-back in azimuth with a non-isolated muon and had a NN output between 0.3 and 0.8. The observed excess of OS over SS events in this background sample was 4$\pm$2 %. The number of events in the SS sample is 909, therefore we calculate that the number of QCD background events in the OS sample is 945$\pm$36.

B. *W*+jet background

The $W \to \mu\nu$ + jets is a source of events with isolated muons and τ candidates from misidentified jets. A significant part of this background is removed by requiring back-to-back in azimuth pairs, a NN cut and subtracting SS from OS distributions. But we do expect an excess of OS over SS because a high percentage of W + 1 jet events come from quark jets. One can estimate the number of $W \to \mu\nu$ events in the data by selecting a sample that can be expected to have large contribution from that channel and negligible contributions from the Z channels. If we require an isolated μ with $p_T > 20$ GeV, 0.3<NN<0.8, and $|\phi_\mu - \phi_\tau| < 2.0$ we can expect mostly QCD and $W \to \mu\nu$ events to contribute. Using the fact that we expect the ratio between the difference of OS and SS events and the sum of OS and SS events to be 2$\pm$1% for QCD and 26$\pm$3% for $W \to \mu\nu$ (number obtained by applying the same cuts to a sample of 638,000 $W \to \mu\nu$ MC events and looking at the excess of OS over SS events), we can extract N$_W$=754$\pm$227 $W \to \mu\nu$ events in the data with the above cuts by solving the linear equations:

$$N_W + N_{QCD} = N_{OS} + N_{SS} = 2870$$
$$0.26 * N_W + 0.02 * N_{QCD} = N_{OS} - N_{SS} = 238.$$

This is to be compared with the amount predicted from MC $W \to \mu\nu$: N_W^{MC}=919±37. N_W is the total number of W events (summed over types) in this data sample and N_{QCD} the total number of QCD events. The error on N_W derived from data is taken as the systematic error from this background. With this we calculate that the number of $W \to \mu\nu$ + jets background events which we expect in the signal sample is 48±14 events.

C. $\mu^+\mu^-$ background

Requiring $p_T^\mu > 12$ GeV will decrease the low mass background observed for isolated $\mu^+\mu^-$ pairs, but a substantial number with mass above 24 GeV remain. Requiring events to have only one loose reconstructed μ removes some of the $\mu^+\mu^-$ background but still leaves a significant number of τ-candidates that are really μ that have not been identified as such. From the NN output distribution for τ-candidates that overlap with a μ candidate, which also peaks very sharply at 1, we conclude that the variables chosen for NN have little discriminating power between μ and τ. As given in Table II, an effective variable to differentiate a high p_T μ from a single prong τ is R_{trk}^τ, since most of the taus leave all their energy in the calorimeter before reaching the CH layer, as opposed to the muons. Imposing the requirement R_{trk}^τ >0.7 removes 70% of the overlaps. The cut is effective in removing Z events but less so for low mass pairs. We estimate the background contribution from $\mu^+\mu^-$ pairs after all cuts to be 80±17 events. This error is taken as the systematic error for this background.

V. EXTRACTING $Z \to \tau\tau$ SIGNAL

The total background in OS events is estimated by summing $1.04 \cdot N_{SS} + N_{W\to\mu\nu} + N_{\mu^+\mu^-}$(normalized to the expected number of events with non-identified $2^{nd}\mu$) and is calculated to be 479±22 events. The factor 1.04 accounts for the excess of OS over SS in QCD background. Fig. 3 shows that subtracting the background NN distribution from OS NN distribution one obtains a NN distribution consistent with that expected for $Z \to \tau\tau$ events.

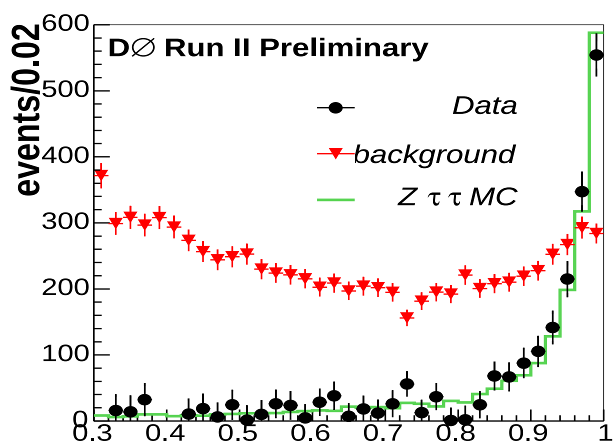

FIG. 3: NN output distributions for τ candidates: estimated background (triangles), prediction from $Z \to \tau\tau$ Monte Carlo (green line) and OS with estimated background subtracted (bold dots).

Observed and predicted distributions for M(μ,τ_{trk}), p_T^μ and E_T^τ are shown in Fig. 4, 5, and 6. The τ 4-momenta used for M(μ,τ) is calculated by summing the p_T of the τ tracks and the energy in the EM portion of the calorimeter associated with the τ.

In Table III we give the number of observed events as a function of the NN output cut for each τ type separately and compare the number of signal events to the $Z \to \tau\tau$ MC predictions. The number of MC events is normalized to the total observed with NN>0.8. The number of observed events are consistent within statistics with the number of expected events for each type. Table IV shows the efficiency for reconstructing $Z \to \tau\tau$ MC within the acceptance and taking into account the efficiencies of all cuts that were applied, as well as the branching ratios of $\tau \to \mu$ and $\tau \to$ different types of τ, all as a function of NN cut.

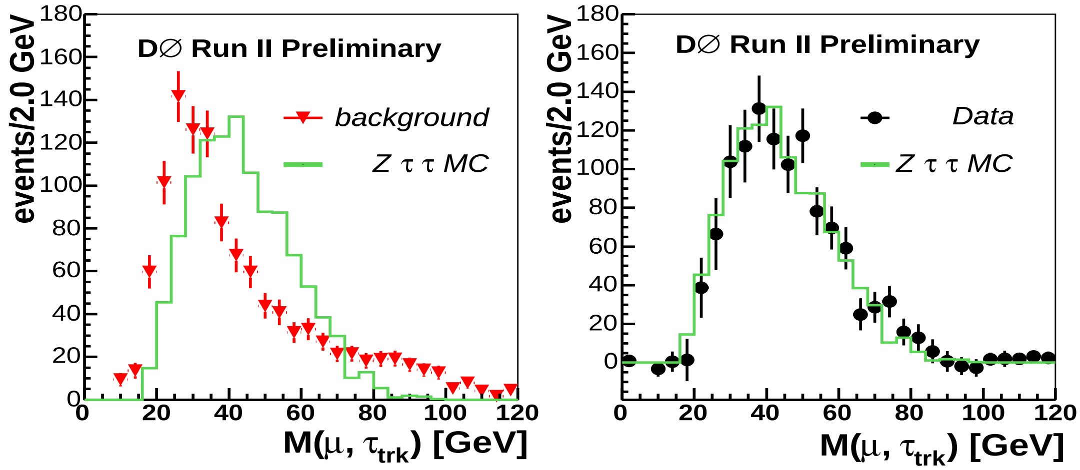

FIG. 4: Invariant mass distribution of the μ and the τ track for background and $Z \to \tau\tau$ MC normalized to the background distribution (left), and OS - estimated background data overlayed on $Z \to \tau\tau$ MC normalized to the signal distribution (right).

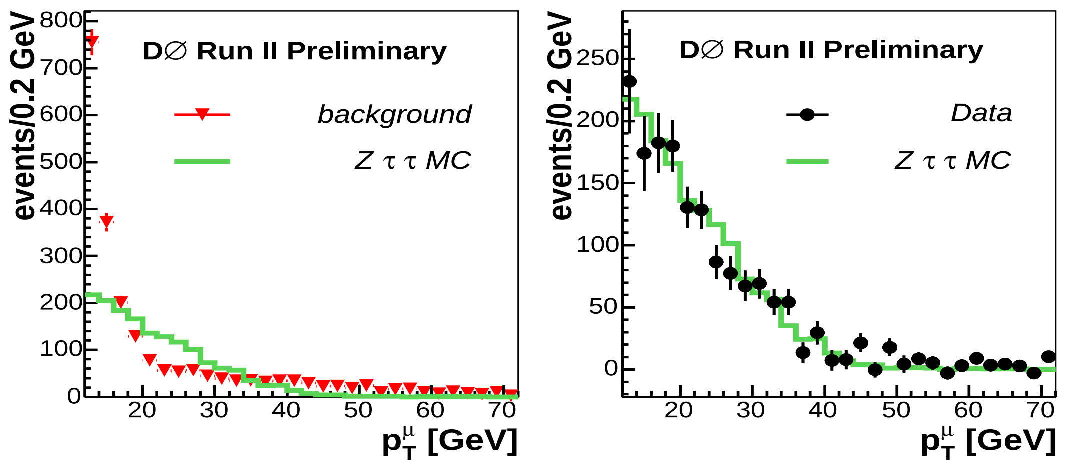

FIG. 5: p_T distribution of the μ for background and $Z \to \tau\tau$ MC normalized to the background distribution (left), and OS with estimated background subtracted data overlayed on $Z \to \tau\tau$ MC normalized to the signal distribution (right).

VI. CORRECTING THE MC EFFICIENCIES

To correct the MC efficiencies for differences in efficiencies between data and MC, every event is given a weight. This weight corrects for differences in tracking efficiency, muon reconstruction efficiency and trigger efficiencies, all obtained by studying the $Z \to \mu\mu$ channel. The error on the data/MC correction factor is the sum of the statistical and systematic error of all its components. Events are then thrown out of the MC sample using a random number generator according to the event weight. The efficiency determined with this procedure is applied in the cross section calculation. In comparing data and signal plus background, all events are used as differences between the distributions in the complete and the efficiency corrected sample were not seen.

The efficiency of the muon isolation cuts was found to be compatible in data and MC. For this comparison, di-muon events were selected. The Z-peak was fitted with a gaussian on an exponential background to extract the number of Z candidates for three classes of events: no isolation requirement, at least one isolated muon and both muons isolated. From the ratio of doubly-isolated sample to the inclusive sample the efficiency of the isolation requirement was determined to be 0.804$\pm$0.002 in data and 0.772$\pm$0.001 in MC.

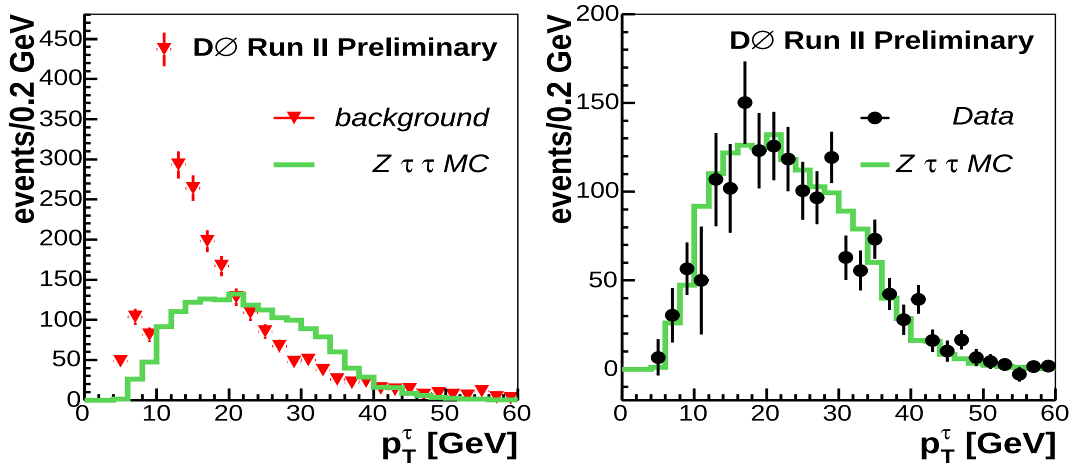

FIG. 6: Visible p_T distribution of the τ-candidates for background and $Z \to \tau\tau$ MC normalized to the background distribution (left), and OS with estimated background subtracted data overlayed on $Z \to \tau\tau$ MC normalized to the signal distribution (right).

TABLE III: Number of signal events compared to MC prediction, for each τ type and different NN cuts

NN cut	type 1	type 2	type 3
>0.3[a]	457 - 248 - (58)	1655 - 914 - (94)	2946 - 2342 - (134)
signal[b]	141±27	610±51	376±74
predicted[c]	136	644	314
> 0.8[a]	341 - 176 - (42)	798 - 251 - (56)	807 - 482 - (31)
signal [b]	116±23	481±33	275±36
predicted[c]	111	511	250
>0.9[a]	260 - 119 - (35)	559 - 137 - (40)	453 - 240 - (15)
signal [b]	101±20	377±27	188±27
predicted[c]	105	428	209

[a]numbers given as N_{OS} - N_{SS} - (N($\mu^+\mu^-$ backg. + $W \to \mu\nu$ backg.)), N_{OS} and N_{SS} = no. of events in the OS respectively SS samples
[b]signal = N_{OS} - 1.04·N_{SS} - N($\mu^+\mu^-$ backg. + $W \to \mu\nu$ backg.)
[c]prediction is based on using the total number of signal events with NN>0.8 and the efficiencies in Table IV

VII. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties for background estimates are derived from the uncertainties given for each estimate in Section IV.

The systematic uncertainties in the NN were estimated using two methods. In the first method we recalculate the NN output for MC $Z \to \tau\tau$ after scaling the NN input variables (removing the energy dependent part). The error is determined from the change in efficiency when the difference between the extracted signal and MC distributions for a given variable change by $\delta\chi^2 = 1$. A systematic uncertainty for the NN of 2 % is calculated by adding the contributions from scaling each variable by the amount mentioned above (for the distribution of that variable), keeping all other variables unscaled.

For the second method, we constructed 100 ensembles out of a sample of 3000 $Z \to \tau\tau$ MC events by splitting the distributions of most input variables into 10 bins with equal numbers of events and then let the number in each bin fluctuate according to the expected error from the difference between MC and signal extracted from data. We used a set of 2000 (accepted) MC events from which events in any given bin were randomly removed for downward fluctuations. Another set of 1000 events were randomly selected to add to the set of 2000 events for upward fluctuations. Only one variable at a time was allowed to fluctuate. The total NN systematic uncertainty obtained by this method is 2.6 %. For the calculation of the total systematic uncertainty, the value obtained with the second method was used.

The error on the energy scale was found by rescaling the p_T^τ distribution and recalculating the NN output. This includes also the effect from the p_T cut. We do not correct the data or MC for jet energy scale. The difference between the jet energy scale calculated for MC and the jet energy scale calculated for data is taken to be the

TABLE IV: Total efficiencies for MC $Z \to \tau\tau$ as a function of τ type and NN cut

NN cut	type 1	type 2	type 3 (2-pr)	total
>0	0.46%	2.18%	1.03% (0.20%)	3.67%
>0.3	0.43%	2.03%	0.99% (0.16%)	3.45%
>0.8	0.35%	1.61%	0.79% (0.11%)	2.75%
>0.9	0.33%	1.35%	0.66% (0.09%)	2.35%
Trigger ϵ		65.0% ± 2.0%		
$\epsilon_{data}/\epsilon_{MC}$ [a]		92.5% ± 3.2%		

[a] $\epsilon_{data}/\epsilon_{MC}$ is the ratio of data reconstruction efficiency to Monte Carlo reconstruction efficiency

systematic uncertainty in the energy scale.

The acceptance calculated using the values for the scaling parameters that give the minimum χ^2 when fitting the scaled MC distribution with the data decreases by 0.5%. The uncertainty on the acceptance due to the energy scale is calculated by scaling the MC energies within uncertainties and evaluating the acceptance for the scaled energies.

The systematic uncertainties are summarized in Table V.

TABLE V: Systematic errors on $\sigma(Z \to \tau\tau)$

rms cut	<1%
Energy Scale	2.5%
NN (excluding Energy scale)	2.6%
QCD background	2%
$\mu\mu$ background	2%
$W \to \mu\nu$ background	1.7%
$\epsilon_{data}/\epsilon_{MC}$(from τ id)	2.5%
$\epsilon_{data}/\epsilon_{MC}$ (from μ id)	2%
Trigger	3%
Total	6.5%

VIII. RESULT ON $\sigma\cdot$ Br ($Z \to \tau\tau$)

The cross section times branching ratio for $Z \to \tau\tau$ is given by (no. of signal events)/($\epsilon_{TOT} \cdot \int \mathcal{L}dt$) where $\epsilon_{TOT} = \epsilon_{MC-reco} \times \epsilon_{trigger} \times \Delta(MC, data)$ and $\int \mathcal{L}dt$ represents the integrated luminosity for the sample we studied . From Table IV we get $\epsilon_{TOT} = 0.0275 \times 0.65 \times 0.925 = 0.0165$. The sum of OS events of all τ types, after subtracting estimated backgrounds, gives 872±54 signal events. The integrated luminosity for the two single μ triggers used is 207 pb^{-1} with a 6.5% systematic error. Thus we obtain

$$\sigma \cdot Br(Z \to \tau\tau) = 256 \pm 16(\text{stat.}) \pm 17(\text{sys.}) \pm 16(\text{lum.})\ \text{pb}.$$

This value agrees within errors with the Standard Model prediction.

Fig. 7 illustrates the number of τ-candidates as a function of τ-candidate type which were found for background (most left three bars), predicted from $Z \to \tau\tau$ Monte Carlo (most right three bars) and found in the OS sample after substracting the estimated background (middle three bars).

Acknowledgments

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the Department of Energy and National Science Foundation (USA), Commissariat à L'Energie Atomique and CNRS/Institut National de Physique Nucléaire et de Physique des Particules (France), Ministry for Science and Technology and Ministry for Atomic Energy (Russia), CAPES, CNPq and FAPERJ (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), CONICET and UBACyT (Argentina), The Foundation for Fundamental Research on Matter (The Netherlands), PPARC (United

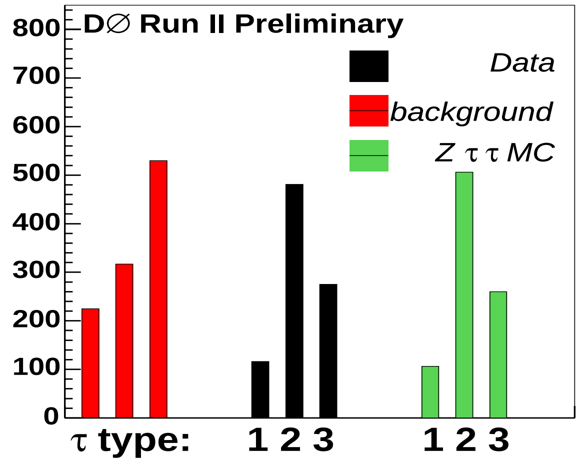

FIG. 7: Number of τ-candidates as a function of τ-candidate type for background (τ-candidates in SS events), predicted from $Z \to \tau\tau$ Monte Carlo and found in the OS sample after substracting the estimated background.

Kingdom), Ministry of Education (Czech Republic), Natural Sciences and Engineering Research Council and West-Grid Project (Canada), BMBF (Germany), A.P. Sloan Foundation, Civilian Research and Development Foundation, Research Corporation, Texas Advanced Research Program, and the Alexander von Humboldt Foundation.

[1] Jean-Pierre Ernenwein http://e.home.cern.ch/e/ernen/www/NN/index.html