DØnote 5110-CONF

Measurement of WZ Diboson Production Cross section in Trilepton Final States at $\sqrt{s} = 1.96$ TeV

The DØ Collaboration
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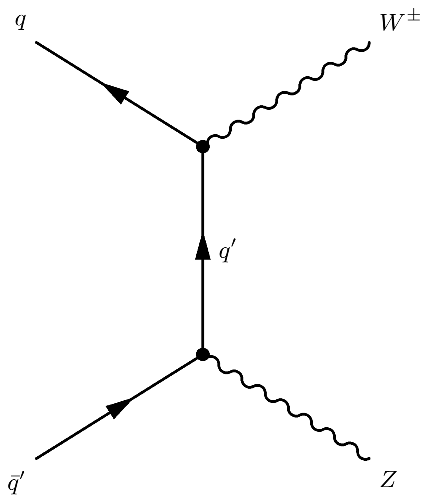
We present a preliminary measurement of the inclusive WZ production cross section in trilepton final states. This analysis utilizes data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected by the DØ experiment at the Fermilab Tevatron from 2002-2006. Twelve trilepton events with WZ decay characteristics are observed in DØ data. With an estimated background of 3.61 ± 0.20 events and integrated luminosities ranging from 760 - 860 pb^{-1} for different trilepton final states, the WZ production cross section is measured to be $3.98^{+1.91}_{-1.53}$ pb, consistent with the Standard Model prediction of 3.68 $\pm$0.25 pb.

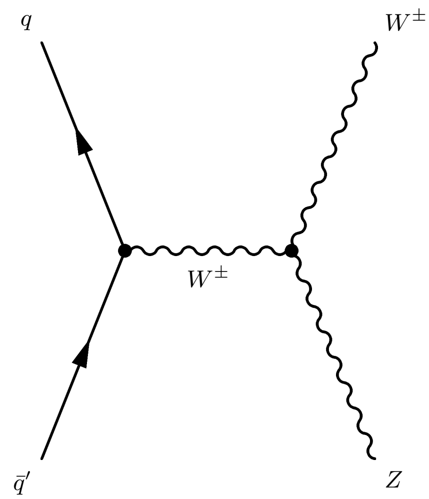
Preliminary Results for Summer 2006 Conferences

I. INTRODUCTION

The electroweak component of the standard model (SM) is based on the non-Abelian gauge group $SU(2)_L \times U(1)_Y$ symmetry transformations, and predicts that the electroweak gauge bosons (W and Z) can interact directly through trilinear and quartic gauge-boson vertices. One of the important tests of the SM is the measurement of such couplings from WZ production in $p\overline{p}$ collisions. This provides a sensitive probe of any low energy remnants of new physics operating at a higher scale, and is therefore complimentary to direct searches of new physics beyond the SM. The WZ production cross section in the standard model depends on the WWZ gauge coupling, shown in the Feynman diagrams for WZ production in $p\bar{p}$ collisions.



(a) t-channel Feyman diagram



(b) s-channel Feynman diagram

FIG. 1: The t- (a) and s- (b) channel tree level Feynman diagrams for WZ production at the Tevatron. The s channel contains that WWZ vertex that allows us to directly measure the coupling strengths of the massive vector bosons to each other. If an anomalous signal is seen then there must be contributing interactions to the WZ final state that are not accounted for in the SM.

In Run I of the Fermilab Tevatron program, the DØ experiment searched for WZ events, and set an upper limit for the WZ cross section of 47 pb [1], compared to the SM prediction of 2.6 pb at $\sqrt{s}$=1.8 TeV. Previously in Run II, an analysis was performed on approximately 0.3 fb^{-1} of data. Three events were observed with an estimated background of 0.71±0.08. The probability of 0.71 events to fluctuate to the observed three candidates is 3.6%, which yields a cross section limit of 13.3 pb at 95% CL (confidence level) (interpreted as a cross section, the value is $4.5^{+3.8}_{-2.6}$ pb)[2].

The predicted cross section for WZ production at $\sqrt{s}$=1.96 TeV is 3.68±0.22 (scale)±0.12 (PDF) pb [3], which is based on the MCFM generator[4] using the latest parton distribution functions (PDF) of CTEQ6_M [5].

The cleanest WZ signals arise from trilepton final states from the the leptonic decay channels of the Z and the W bosons. However, the leptonic decay channels have very low branching ratios, which correspond to only about 0.35% for any given lepton family, and 1.5% for two families of leptons. The trilepton final states include eee, $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$, with an associated neutrino, which is reflected in an imbalance in transverse momentum in the final state (or missing transverse energy, $\not\!\!E_T$, in the DØ detector).

II. APPARATUS OF THE DØ EXPERIMENT

The DØ detector is comprised of several sub-detectors, trigger and data acquisition systems. A magnetic central-tracking system, which consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), is located within a 2 T superconducting solenoid magnet [6]. The SMT has $\approx 800,000$ individual strips with coverage up to pseudorapidity $|\eta| < 3$. The CFT has eight thin coaxial barrels, each supporting two doublet layers of overlapping scintillating fibers of 0.835 mm diameter, one (axial) layer aligned parallel to the collision axis, and the other alternating by $\pm 3^\circ$ pitch relative to the axis. Light signals are transferred via clear fibers to visible light photon counters (VLPC) that have high quantum efficiency.

Central and forward preshower detectors located just outside of the superconducting coil (prior to the calorimetry) are constructed of several layers of extruded triangular scintillator strips that are read out using wavelength-shifting fibers and VLPCs. The calorimeter is composed of three liquid-argon/uranium vessels: a central section (CC) covering $|\eta|$ up to ≈ 1, and two end calorimeters (EC) extending coverage to $|\eta| \approx 4$, each housed in a separate cryostat. In addition to the preshower detectors, scintillators between the CC and EC cryostats provide sampling of developing showers at $1.1 < |\eta| < 1.4$.

A muon system resides beyond the calorimetry, and consists of a layer of tracking detectors and scintillation trigger counters before 1.8 T toroids, followed by two more similar layers after the toroids. Muon tracking at $|\eta| < 1$ relies on 10 cm wide drift tubes, while 1 cm mini-drift tubes are used at $1 < |\eta| < 2$.

Luminosity is measured using plastic scintillator arrays located in front of the EC cryostats, covering $2.7 < |\eta| < 4.4$. The trigger and data acquisition systems are designed to accommodate the high luminosities of the upgraded Fermilab Tevatron in Run II. Based on preliminary information from tracking, calorimetry, and muon systems, the output of the first level of the trigger is used to limit the rate for accepted events to ≈ 1.5 kHz. With more refined information at the second level, the rate is reduced further down to ≈ 800 Hz. These first two levels of triggering rely mainly on hardware and firmware. The third and final level of the trigger, with access to all the event information, uses software algorithms and a computing farm, and reduces the output rate to ≈ 50 Hz, which is written to tape.

III. DATA ANALYSIS

A. Data Sample

This analysis uses data collected at DØ during 2002-2006 and is based on dilepton (ee, $\mu\mu$ and $e\mu$) and dijet events reconstructed using the most recent version of the DØ reconstruction program.

We select events from runs flagged as being of good quality, with all sub-detector systems, including the calorimeter, the muon (when applicable), the CFT, and the SMT systems, operating reliably. Events with luminosity blocks that cannot be normalized are removed.

Based on detailed selection criteria, integrated luminosities for different lepton final states are in this analysis correspond to 860 pb^{-1} for ee final states ,830 pb^{-1} for $ee\mu$ final states , and 760 pb^{-1} for $\mu\mu$ final states.

In di-electron final states, a logical OR of single and di-electron triggers is required to fire. From trigger studies detailed elsewhere [7], for more than one electromagnetic object with p_T greater than 15 GeV, the efficiency is close to 100%. In dimuon final states, single muon triggers are required. Monte Carlo studies with multiple muons yield an efficiency of (91 $\pm$ 9)% for di-muon final states and (98$\pm$2)% efficiency for three muon final states.

B. Event Selection

The characteristic feature of a WZ event is three high-p_T leptons and large $\not\!\!E_T$. We first describe electron and muon identification criteria, and then present the details of WZ event selection.

1. *Electron Identification*

Electrons are identified by the distinctive pattern of energy deposition of electromagnetic showers in the calorimeter and by the presence of a track in the central tracker, that extrapolates from the interaction vertex to a cluster of hits in the calorimeter. The fiducial requirements imposed are $|\eta| < 1.1$ for electrons from CC and $1.5 < |\eta| < 2.5$ for electrons from EC. The transverse momentum of an electron is required to be > 15 GeV.

An acceptable electron must have an electromagnetic-energy (EM) fraction, $f_{\rm EM} > 0.9$, where $f_{\rm EM}$ is a ratio of energy found in the EM cells of the calorimeter to the total energy of a shower. Electron showers are usually compact and contained in the core EM cells. The isolation $\mathcal{I}$ is defined as the ratio of difference between total energy within a cone $R = 0.4(E_{tot})$ and EM energy within a cone $R = 0.2$ ($E_{\rm EM}$), $\mathcal{I} = \frac{E_{tot}(0.4) - E_{EM}(0.2)}{E_{EM}(0.2)}$, where $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, and ϕ is the azimuthal angle. For an isolated electron, $\mathcal{I}$ is required to be < 0.2. An electron likelihood based on tracking and shower shape variables for the showers in the CC and EC is used to compute a probability variable that represents the consistency of a cluster corresponding to that of an electron shower. The selection on this likelihood retains $\approx 95\%$ of all true electrons.

2. Muon Identification

Muons are reconstructed using information from the muon, scintillation, central tracking, and calorimeter detectors. Muons from W and Z boson decays are usually isolated, have large transverse momentum, and have a track in the outer muon spectrometer. A muon reconstructed in the toroid system is required to have a matching track in the central tracker with $p_T > 15$ GeV. The muon isolation selection requires the transverse energies of the calorimeter cells in an annular ring $0.1 < R < 0.4$ around each muon direction to be $\sum_{\text{cells},i} E_T^i < 2.5$ GeV. In addition, the sum of the transverse momenta of all tracks, other than that of the muon, in a cone of $R = 0.5$ around the muon track is required to be < 3.5 GeV.

3. Event Selection

The WZ diboson event selection requires three reconstructed leptons that pass the electron or muon identification criteria outlined in previous sections, and all must originate from the same interaction vertex. The missing transverse energy $\not\!\!E_T$ is required to be > 20 GeV. To avoid confusion between tracks, the separation between any pair of leptons is required to be $R > 0.2$.

To select Z bosons and reduce background, the invariant mass of a like lepton pair has to be within the mass window of 71 GeV to 111 GeV for $Z \rightarrow ee$ events, and 51 GeV to 131 GeV for $Z \rightarrow \mu\mu$ events. These mass windows are set by the respective mass resolutions.

In dimuon events, the pair selected as the Z boson is required to pass an acolinearity cut of greater than 0.05 to minimize cosmic background [9]. For eee and $\mu\mu\mu$ decay channels, the pair of leptons that has an invariant mass closest to the Z mass is regarded as the source of leptons from a Z boson. (The third lepton is thus assumed to originate from a W boson. To reject background from $t\bar{t}$ events, the vector sum of the transverse energies of the leptons and $\not\!\!E_T$, (VET_{had}) is required to be less than 50 GeV.

Applying all selection requirements leaves twelve candidate events.

C. Acceptance and Efficiency

The acceptance for inclusive WZ events is defined to be the acceptance for which all three leptons will be reconstructed within the fiducial volume of the DØ detector and pass the kinematic requirements imposed by the lepton selection and $\not\!\!E_T$ threshold. The acceptance is calculated using Monte Carlo samples generated with the PYTHIA generator and simulated with the GEANT representation of the DØ detector. The acceptances are calculated by counting the number of events that pass all selection criteria, except the lepton identification and the track-matching requirements.

Lepton-identification and track-matching efficiencies are estimated using $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ events. One of the leptons from the Z is required to pass all the lepton selections, and the other lepton is used as an unbiased sample for estimating efficiency. The $Z \rightarrow \ell^+\ell^-$ invariant mass is then fit with a Breit-Wigner function convoluted with a Gaussian function, and an exponential decay function to describe the background.

All identification efficiencies are determined as functions of η, and applied to each lepton in the WZ MC events. The overall acceptance times efficiency (folded with WZ Monte Carlo to properly account for lepton kinematic correlations) for the four channels are summarized in Table I.

Decay Channel	A x ϵ	Syst. Error
eee	0.158	0.012
$ee\mu$	0.167	0.029
$\mu\mu e$	0.175	0.043
$\mu\mu\mu$	0.205	0.033

TABLE I: Summary of acceptance multiplied by efficiency by channel.

D. Estimation of Background

Backgrounds to WZ production are small and originate from various sources. One source of background is $Z + j$ events, in which the jets mimic leptons in the detector. This background is estimated with the following method.

Events are selected using the same criteria as for the WZ sample, except that the requirements for the third lepton are dropped, and these samples therefore include $ee + jets$, $\mu\mu + jets$ and $e\mu + jets$. These 'normalization' samples also include events in which the two leptons were actually mimicked by QCD and thus takes this eventuality into account.

The rates for jets to mimic electrons or muons are then determined using data samples dominated by QCD jets. In dijet events selected on a jet trigger, the first jet is required to pass the standard DØ jet selection criteria (thus, be considered a "good" jet), and the second jet has to be back-to-back with the first jet. The $\not\!\!E_T$ in these events is also required to be small, limiting contributions from W events. The second jet in each event is used as an unbiased source of jets. Any electrons or muons found within $\Delta R < 0.7$ of the axis of the second jet are regarded as background leptons (jets which have been misidentified as leptons). These lepton (background) rates are calculated as a function of jet p_T and of jet η. For the muon channel, the rates at which these 'background leptons' are produced is so small that instead of using the misidentification rate as a function of η, one value averaged over η is used instead. Applying the lepton (background) rates to jets in the dilepton+jets data yields the total background from multijets, summarized with the other backgrounds in Table III D.

In addition to Z+j, ZZ events can mimic WZ events if the energy from one of the leptons is lost, thus mimicking the signature of the neutrino. Top pair events provide a background in which the leptons and $\not\!\!E_T$ are real, though the additional jet activity makes these events unlikely to be selected, due to the cut on the VET$_{HAD}$ energy. Zγ events in which the photon undergoes conversion and has a track associated with it provide an additional background. W+Drell-Yan events, in which the dilepton pair is created by an off-shell, γ^* are also treated as a background. All of these backgrounds are determined from Monte Carlo.

Channel	Source	Estimated background Events ± Stat. ± Syst.
eee	$Z \to ee$ + jets	$0.702 \pm 0.014 \pm 0.056$
	ZZ	$0.058 \pm 0.005 \pm 0.006$
	$Z\gamma$	$0.0004 \pm 0.0003 \pm 0.0001$
	$t\bar{t}$	$0.012 \pm 0.009 \pm 0.002$
	Drell-Yan	$0.188 \pm 0.001 \pm 0.036$
subtotal		$0.960 \pm 0.016 \pm 0.067$
$ee\mu$	$e + \mu+$ jets	$0.029 \pm 0.001 \pm 0.002$
	$Z \to ee+$ jets	$0.077 \pm 0.002 \pm 0.022$
	ZZ	$0.224 \pm 0.004 \pm 0.021$
	$t\bar{t}$	$0.006 \pm 0.006 \pm 0.001$
	Drell-Yan	$0.149 \pm 0.001 \pm 0.042$
subtotal		$0.485 \pm 0.008 \pm 0.052$
$\mu\mu e$	$Z \to \mu\mu+$ jets	$0.699 \pm 0.013 \pm 0.054$
	$e + \mu$ + jets	$0.004 \pm 0.0004 \pm 0.001$
	ZZ	$0.092 \pm 0.002 \pm 0.009$
	$Z\gamma$	$0.001 \pm 0.0007 \pm 0.0001$
	$t\bar{t}$	$0.005 \pm 0.005 \pm 0.001$
	Drell-Yan	$0.161 \pm 0.001 \pm 0.057$
subtotal		$0.963 \pm 0.015 \pm 0.079$
$\mu\mu\mu$	$Z \to \mu\mu$ + jets	$0.078 \pm 0.002 \pm 0.020$
	ZZ	$0.823 \pm 0.011 \pm 0.077$
	$t\bar{t}$	0
	Drell-Yan	$0.302 \pm 0.002 \pm 0.082$
subtotal		$1.203 \pm 0.011 \pm 0.143$
Total		$3.612 \pm 0.026 \pm 0.202$

TABLE II: Estimated background broken down by signal decay channel. The broken down sources have their error separated into their statistical and systematic contributions.

The total background from all sources is estimated to be 3.61 ± 0.20.

IV. CROSS SECTION RESULTS

Decay Channel	Number of Candidates	Overall Efficiency	Expected Signal	Estimated Background
eee	2	0.158±0.012	1.83±0.35	0.960±0.069
$ee\mu$	1	0.167±0.029	1.84±0.52	0.485±0.053
$\mu\mu e$	7	0.175±0.043	1.80±0.63	0.963±0.080
$\mu\mu\mu$	2	0.205±0.033	2.07±0.56	1.203±0.143
Total	12	-	7.54±1.21	3.61±0.20

TABLE III: List of the number of candidate events, overall efficiency, expected signal according to the SM and estimated background in each decay channel.

A total of 7.54±1.21 events are expected from SM WZ production. The probability for the background alone to fluctuate to twelve events is 4.2×10^{-4}. If one translates this background to a Gaussian significance, then this probability corresponds to 3.3 sigma evidence. The probability (with which the background alone would fluctuate to the observed candidates) and significance in each channel is summarized in Table IV. The significance here is calculated using the standard DØ method [8], in which the probability for a Gaussian distributed background is convoluted with the proper Poisson counting probability.

Decay Channel	Probability	Significance (σ)
eee	0.249	0.676
$ee\mu$	0.383	0.296
$\mu\mu e$	7×10^{-5}	3.79
$\mu\mu\mu$	0.338	0.418
Total	4.2×10^{-4}	3.34

TABLE IV: Summary of probability of background to fluctuate to the observed number of candidates, and significance by channel.

To calculate the cross section, since statistics are small, the likelihood for each channel is calculated as a function of cross section, and then combined. The error assessed on the cross section is the 1-sigma (or 68% CL) likelihood difference from the minimum. The likelihood distribution for the combined four channels is shown in Figure 2. From the likelihood, the cross section for WZ production is measured to be $3.98^{+1.91}_{-1.53}$ pb.

V. CONCLUSION

Trilepton final states have been studied using a set of data from 2002-2006 from the DØ detector. Twelve events are observed with an estimated 3.61±0.20 background, which corresponds to a cross section of $3.98^{+1.91}_{-1.53}$pb, consistent with the Standard Model prediction. The probability for the estimated background to fluctuate to the observed events is 4.2×10^{-4}. This in turn translates to 3.3 sigma evidence for WZ production.

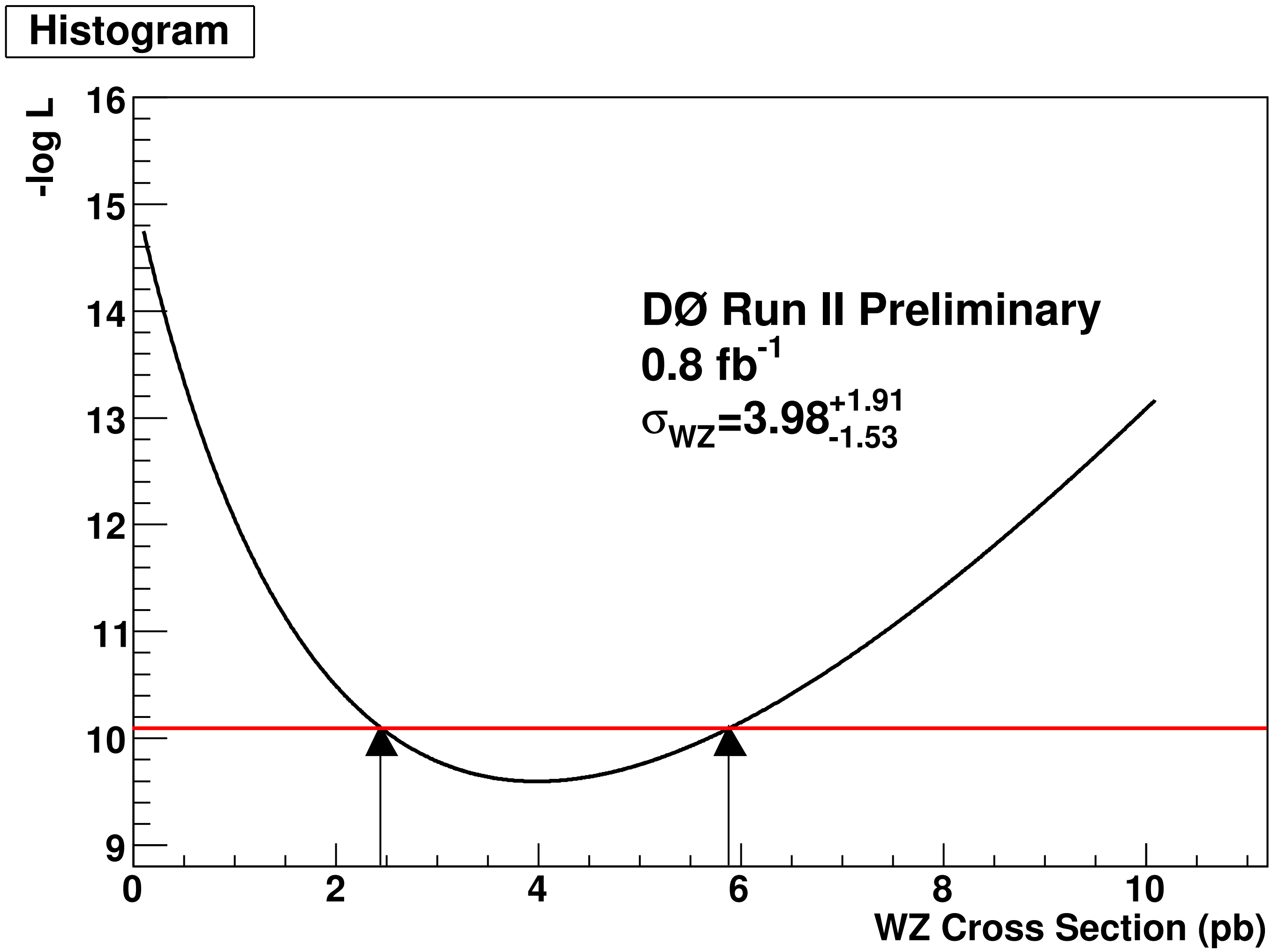


FIG. 2: Combined negative log likelihood as a function of cross section. Arrows indicate the points 0.5 units of likelihood above the minimum, which correspond to the quoted 1σ error on the cross section.

Acknowledgments

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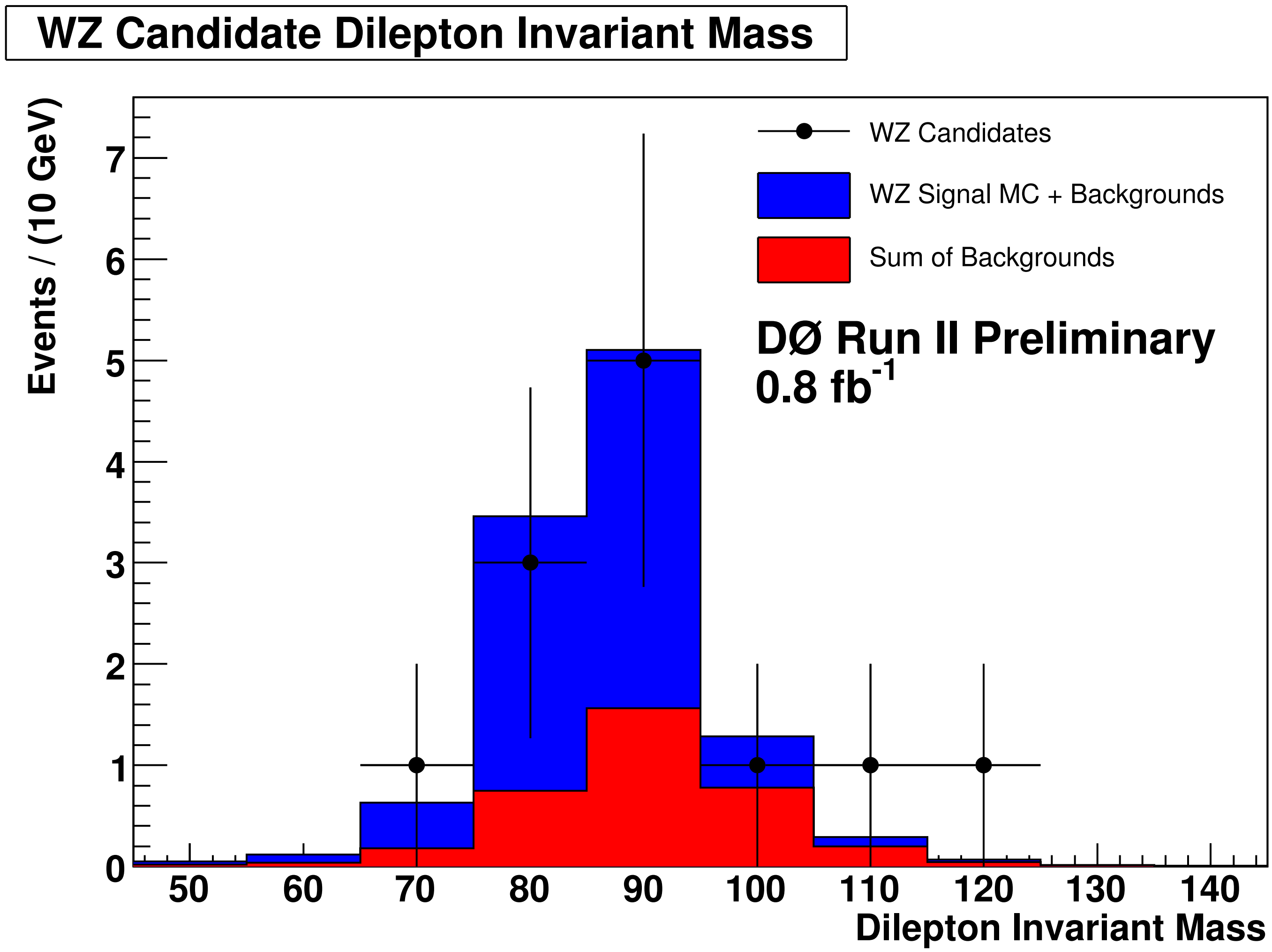

FIG. 3: Dilepton mass of WZ Candidates. The combined background is shown in the solid red histogram, and the combined background and expected signal is shown in solid blue. The data are shown as the black points.

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[7] See the trigger studies wiki page on di-electron triggers: https://plone4.fnal.gov/P1/D0Wiki/tsg/caftrigger/dietriggers.
[8] V. Buescher, *et al.*, DØ Note 4629, 2004.
[9] Acolinearity is the difference of the two muon track from a straight line, *i.e.* $\mathcal{A} \equiv |(\Delta\phi + \Delta\theta) - 2\pi|$.

APPENDIX A: $\mu\mu e$ TIMING INFORMATION

For reference, the timing information and $\Delta\phi$ for each of the seven $\mu\mu e$ events is provided in Table V. All muon times and time differences are inconsistent with cosmic ray bremsstrahlung conversions.

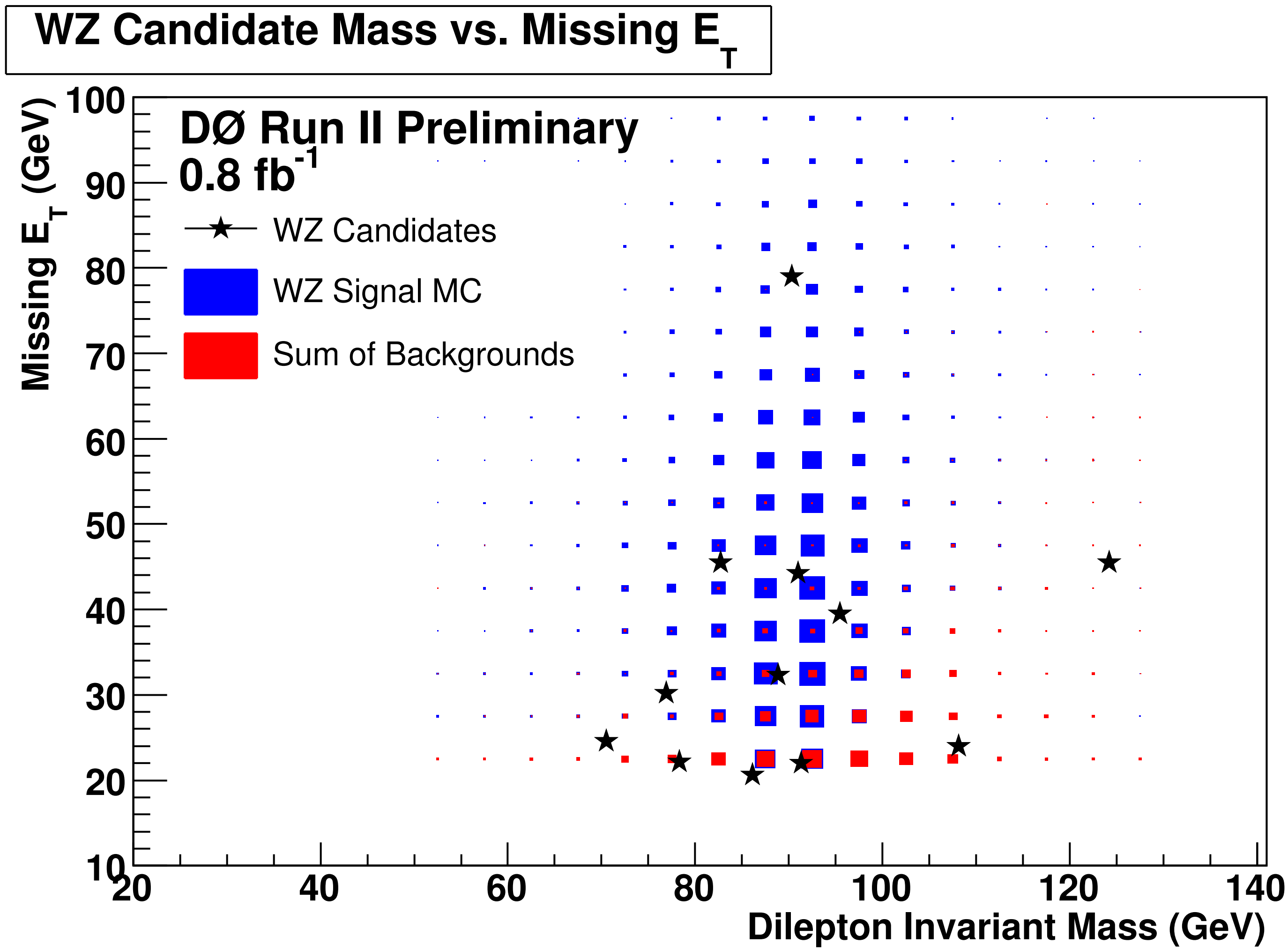

FIG. 4: Missing E_T of WZ Candidates versus Dilepton Mass. The red blocks correspond to the sum of estimated background, and the blue blocks correspond to the signal expectation. The black points are the selected WZ candidates.

Run	Event	$\Delta\phi$	$T_{\mu 1}$(ns)	$T_{\mu 2}$(ns)	ΔT (ns)
207094	10178395	1.77	-2.20	0.70	-2.9
188371	23177216	2.47	0.70	1.77	-1.07
207769	23761167	2.07	-0.24	-0.27	0.03
210156	24837747	1.71	-2.08	0.76	2.84
206332	20605317	3.13	-1.80	-2.25	-0.45
204318	69485771	1.41	1.01	-3.36	4.37
207596	12955559	2.44	2.99	0.92	2.07

TABLE V: Timing and $\Delta\phi$ information for the seven $\mu\mu e$ candidates in data.

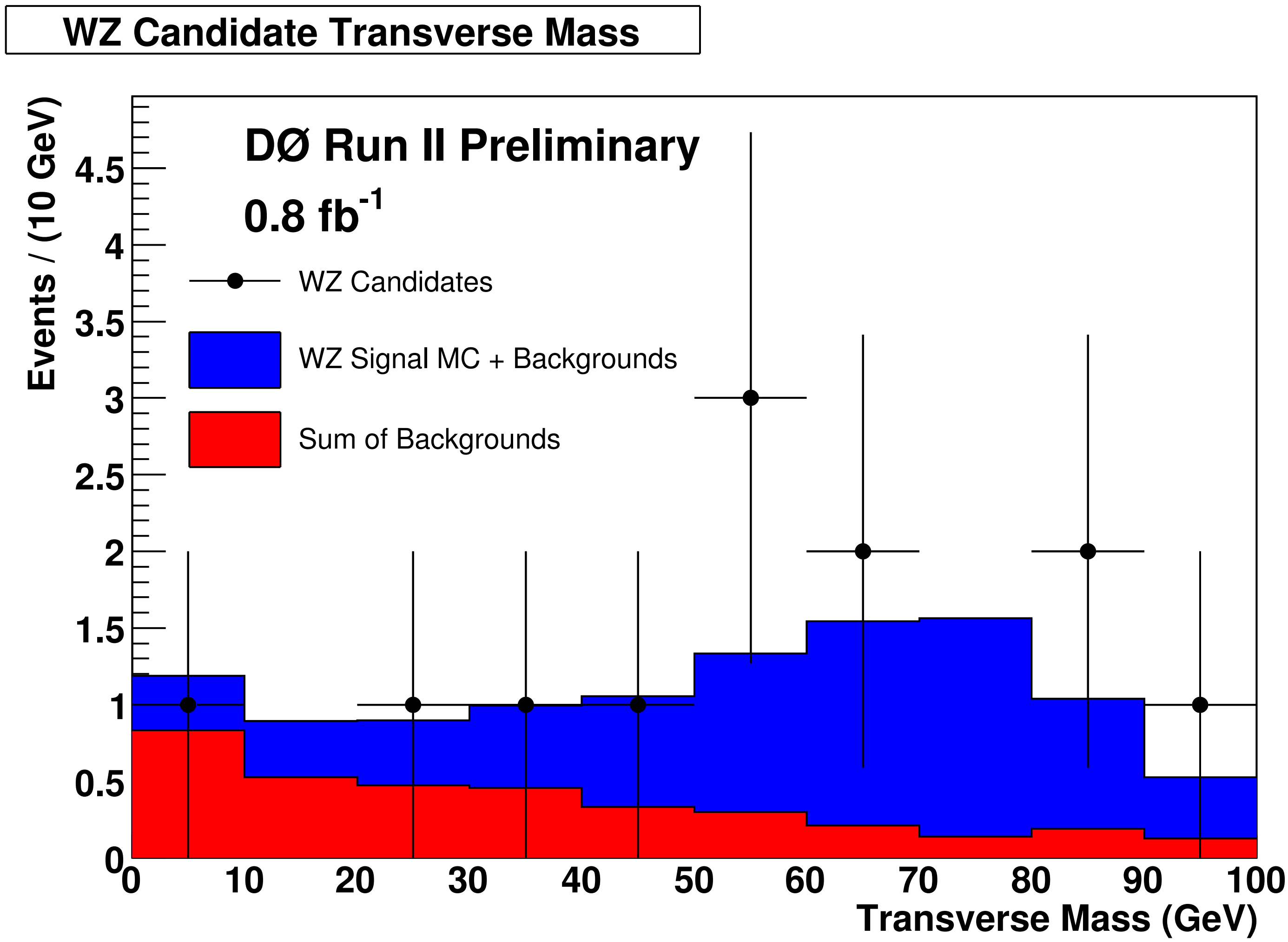

FIG. 5: Transverse mass of the WZ candidates. The red histogram represents the sum of the backgrounds, and the combined signal and background expectation is shown in blue.