DØ Note: 3088
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Top Counting in the Dimuon Channel:

DØ Analysis of Run 1

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ABSTRACT

Using the full Run 1 data set we select for events consistent with $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow \mu^+\nu j\mu^-\overline{\nu}j + X$. We find one candidate event in $104.5pb^{-1}$on an expected background yield of 0.73 ± 0.17 events (± 0.22 when taking into account correlations in systematic errors). For comparison, we expect 0.64 ± 0.06 events for a top mass of 170 GeV/c^2 .

Contents

1 Introduction

This document extends the presentation of the Observation PRL [1] dimuon analysis to cover the entirety of Run 1 (1992-1996) at the Tevatron. An earlier DØ Note fully describes the analysis as of February 1995 [2] and some of the material covered there will be referenced by this DØ Note. It can be found linked to the dimuon web page from the Top analysis web pages at:

http://www-d0.fnal.gov/~raymond/d0_private/top_dimuon.html

2 Data Sample

The data is taken with the DØ detector from May 1992 to February 1996. The total integrated luminosity for the search of $t\bar{t} \rightarrow \mu\mu$ is:

$$10.1\ pb^{-1} \text{ for run 1A, } 84.8 pb^{-1} \text{ for run 1B, } 9.6 pb^{-1} \text{ for run 1C}$$
$$\text{total} = 104.5 \pm 5.6\ pb^{-1}$$

assuming the standard error of 5.3% on the luminosity and applying all corrections for bad runs and Main Ring Veto. At this time, we do *not* include any events occurring during the main ring gates. We are using GOOD_BEAM events only at this time. A search of events occurring during MRBS_LOSS but not during MICRO_BLANK has no additional events passing our full set of selection cuts. This luminosity could be incorporated at a later time with some additional effort.

3 Trigger

The trigger used for obtaining the data sample is MU_JET_xxxx:

Run 1A:

- ≥ 1 Muon $|\eta| < 1.7$ and $p_T > 8$ GeV
- ≥ 1 Jet $\Delta R = 0.7$, $E_T > 15$ GeV

Run 1B:

- ≥ 1 Muon $|\eta| <1.7$ and $p_T >10$ GeV
- ≥ 1 Jet $\Delta R = 0.7$, $E_T>15$ GeV
- cosmic scintillator where applicable

This trigger is also used by the $t\bar{t} \to \mu$+jets analysis. The measured cross section for this trigger is 15-25 *nb*. This selection kept the trigger rate to an acceptable level.

4 Particle ID

A general set of muon identification criteria has been approved for use by the top group. However some flexibility is allowed since muon ID is strongly dependent on the competing background processes. The dimuon muon ID is different from the single high p_T muon top searches only in that the cuts on B.dl and impact parameter are not used.

Muon ID for the dimuon search were the following:

Runs prior to run number 89000. This is before the muon chambers were cleaned with the "zapping" procedure [4].

- Quad ≤ 4
  [IQ(LPMUO+7).LE.4]
  Select only muons in the CF region. (*i.e.*, chambers mounted on toroids parallel to beam.)

- IFW4 ≤ 1
  [IQ(LPMUO+9).LE.1]
  Goodness of fit, defined by cuts on residuals: implying the muon track is consistent with originating from the reconstructed vertex in the bend and non-bend views.

- Not an ASTUB
  [MOD(IQ(LMUOT+4),10).NE.5]
  Requires track to have hits on the outside of the toroid, in the B or C layer chambers.

- (HFrac = 1) .OR. (HFrac $\geq$ 0.7 .AND. EFrac_H > 0)
  [IQ(LPMUO+94).EQ.1.OR.(Q(LPMUO+94).GE.0.7.AND.Q(LPMUO+98).GT.0)]
  Verification from calorimetery of associated energy deposition consistent with that of a 1 mip track. See Ref [3] for definition of the MTC quantities HFrac and EFrac_H.

Runs after run number 89000. After cleaning of muon chambers, EF muon chambers regain efficiency.

- (Quad$\leq$4 .AND. IFW4$\leq$1) .OR. (Quad$\leq$12 .AND. IFW4$\leq$0)
  Require more stringent goodness of fit on track candidates in the EF regions.

- Not an ASTUB

- No hits in SAMUS used.
  Overlap region not used in this analysis.

- (HFrac = 1) .OR. (HFrac $\geq$ 0.7 .AND. EFrac_H > 0)

5 Event Streaming Selection

Dimuon events were selected out of the data in two steps. The first was the Top Group streaming, using the UPDATE_DILEP package. The second phase is putting the streamed events into an ntuple using the package TOP_DILEP. The final event selection is then applied on the ntuple. [Note: All 1A events are DØRECO V11 and all 1B events are DØRECO V12.15 or greater]

5.1 UPDATE_DILEP Streaming

Events were stripped from the Micro DST (MDS) ALL stream data sample using the following selection cuts. Both 1A and 1B have been streamed via the standard UPDATE_DILEP package used by the Top group.

for CF muons	$p_T \geq 12$ GeV Quad ≤ 4 IFW4 ≤ 1 CD Track match .OR. Cal 1NN ≥ 0.5 .OR. MTC Hfrac ≥ 0.6 .OR. MTC Efrac ≥ 0.5
for EF muons	$p_T \geq 12$ GeV Quad ≤ 12 IFW4 $= 0$ MTC Hfrac ≥ 0.6

Since these cuts do not require a T0 float cut or a cut on no SAMUS hits, any muons passing this selection are referred to as 'loose' muons. Total requirement is any two 'loose' muons.

5.2 TOP_DILEP Event Selection and Particle ID

Events from the MDS Dimuon stream selection are then processed and the information put into our dimuon ntuple with no additional requirements. TOP_DILEP is a combined DØUSER package that makes our standard dimuon ntuples used for both Monte Carlo and data. The package comprises the following packages (as used by program builder):

```
$   pbd/frame=d0user/pack=(calor,udst_to_dst,run_select,reco_version_select, -
    c2l2em, compute_mu_quality,cafix,fix_jet_et,compute_em_quality, -
    particle_select,mujets_mu_select,fit_two,top_dilep)/name=top_dilep -
    /zebcom=2000000 /zebstp=2000000/pawc=2000000/switch
```

The reader is referred to the following documentation for details of the above code. The documents are on the Vax clusters under the logical D0$PHYSICS_UTIL$ROOT:[DOCS]. Specifically, TOP_ANALYSIS_PACKAGES.DOC and PARTICLE_SELECT.DOC are applicable.

6 Final Event Selection

6.1 $\mu\mu$ Event Selection

An improvement in muon acceptance compared to that of the analysis published in the observation paper comes from the extension of the geometrical acceptance to include the EF regions of the muon detector (Quad ≥ 5 or approximately $1.0 < |\eta| < 1.7$). Our data sample is broken up into three parts: Run 1A, Run 1B+1C CF-CF, and Run 1B+1C CF-EF.

The Run 1A initial event sample is unchanged from the observation results. The DØRECO version used for the 1A data has no MTC information, so the analysis is unchanged for the muon ID selection in that run period.

The Run 1B+1C sample is broken into two parts depending on the location of the two muons and the run range. Prior to the muon chamber cleaning [4], only CF muons were used. Post cleaning it is possible to include EF muons with a reasonable efficiency. Therefore, our Run 1B+1C sample is divided into events with two CF muons (CF-CF) and post-zap events with one CF muon and one EF muon (CF-EF). No events with two EF muons are included due to trigger inefficiencies, and backgrounds due to combinatorics. Luminosities for the three parts of the data were given in Section 2. The CF-EF region contributes roughly 20% of the final signal acceptance.

The selection criteria are as follows:

- Trigger : Require a MU_JET_xxxx trigger
- 2 muons : $p_T > 15$ GeV/c with muon ID required(see Section 4)
  1 Jet : use 0.5 cone jet algorithm, $E_T > 20$ GeV , $|\eta| < 2.5$
  These kinematic cuts are the first applied and are placed 5 GeV above the threshold requirements of the trigger (muon + jet) and streaming (2 muons) requirements.
- $\Delta\phi(\vec{p}_T^{\,\mu_1}, \vec{p}_T^{\,\mu_2}) < 165^\circ \, for \, |\eta(\vec{p}_T^{\,\mu_1}) + \eta(\vec{p}_T^{\,\mu_2})| < 0.3$
  Cosmic ray rejection designed to reject tracks back to back in both η and ϕ.
- $M_{\mu\mu} > 10$ GeV/c^2
  Cut on the invariant mass of the dimuon pair, $M_{\mu\mu}$. Although momentum resolution prohibits an efficient cut on the Z mass peak, it is an

effective quantity at lower muon p_T to reject low mass pairs representing processes of high p_T J/ψ production with recoil jets.

- $\Delta R\ (\mu, jet) > 0.5$
  We require both muons to be isolated with the above definition. This requirement rejects backgrounds from b and c quark decays to muons.

- 2nd jet $E_T > 20$ GeV , $|\eta| < 2.5$
  Require a second jet reflecting the signal signature of two b quark jets in the final state. This cut along with the H_T cut is effective in reducing all of our background processes, since these processes have only jets from recoil which has a softer jet E_T spectrum.

- $H_T(jets) > 100$ GeV $(\sum |E_T^j|$ of ALL jets $E_T^j > 15$ GeV)
  H_T is a strong discriminator for all top processes.

- $\mathcal{P}(\chi^2) < 0.01$
  The major background to the dimuon signal is the production of high p_T Z bosons. We use a simple kinematic fit and cut on the upper tail probability of a chi-square (χ^2) of the fit. This method is detailed in the DØ Note of Ref. [7].

Table 1 summarizes the effects of the cuts. It shows the events remaining after each cut is applied in progression. We have one candidate event: run 84395, event 15530. Details of this event are given in Table 2, and in event display format in Figure 1. In the candidate event both muons are central and each track has the maximum of ten hits in the muon chambers, a case where the momentum resolution is best modeled and understood. An interesting feature of this event is evident from the end view of the event display. All the muons and jets are in one hemisphere in phi, leaving only missing E_T in the other; a topology highly unlikely to come from the main background of $Z \rightarrow \mu\mu$ production.

Selection cut	events in 100.1 pb^{-1} 1A (CF-CF)	1B+1C (CF-CF)	1B+1C (CF-EF)	Total
1.) Trigger+muon ID+2nd muon 2 high p_T muons, $p_T > 15$ GeV/c 1 jet, $E_T > 20$ GeV , $\|\eta\| < 2.5$	57	606	40	703
2.) Cosmic ray rejection $\Delta\phi(\vec{p}_T^{\mu_1}, \vec{p}_T^{\mu_2}) < 165° for$ $\|\eta(\vec{p}_T^{\mu_1}) + \eta(\vec{p}_T^{\mu_2})\| < 0.3$	53	207	40	300
3.) Invariant Mass Cut $M_{\mu\mu} > 10$ GeV/c^2	28	165	38	231
4.) Muon Isolation $\Delta R\ (\mu, jet) > 0.5$	12	105	29	146
5.) Second Jet requirement 2nd jet $E_T > 20$ GeV , $\|\eta\| < 2.5$	3	19	6	28
6.) H_T Cut $H_T(jets) > 100$ GeV ($\sum \|E_T^j\|$ of ALL jets $E_T^j > 15$ GeV)	1	4	0	5
7.) Z-fitter Cut $\mathcal{P}(\chi^2) < 0.01$	0	1	0	1

Table 1: Number of events passing each level of selection cuts for three run ranges.

Run 84395, Event 15530 (ALL)			
Particle	p_T (GeV)	η	ϕ
Muon 1	56.84	-0.32	2.94
Muon 2	36.97	0.05	2.05
Jet 1	110.67	-0.88	5.03
Jet 2	24.23	0.97	1.95
Jet 3	17.69	1.58	4.29
$\not\!\!E_T^{\rm cal}$	102.64	—	1.67
$\not\!\!E_T$	84.86	—	0.75
H_T	152.58	—	—
Prob(χ^2)	<0.0001	—	—
$M_{\mu\mu}$	43.23	—	—

Table 2: Parameters of Run 1B candidate event 84395_15530 using DØRECO V12.16.

6.2 $t\bar{t} \rightarrow \mu\mu$ efficiency $\times$ branching ratio

The analysis efficiency and expected event yield were calculated from Monte Carlo event samples for values of top mass 110 through 230 GeV in 5 GeV increments. These signal event sets were generated with generator level cuts to produce only those final states with e or μ in the dilepton final states. This method provides for the $W \rightarrow \tau \rightarrow e(\mu)$ contributions to be easily incorporated into the total acceptances. These same event sets are used also by the ee and $e\mu$ analyses. These event sets were produced with the HERWIG 5.7 generator with the CTEQ3M structure functions (and eight mass points with the ISAJET generator for systematic comparison), and processed with DØGEANT using SHOWERLIBRARY, G315TS3. The sets were then processed with the MUSMEAR package and finally with DØRECO version 12.21.

The MUSMEAR package was run with appropriate modeling of muon efficiencies for two distinct run periods, before and after the muon chamber cleaning [4]. We include the following additional factors for muon ID efficiency not modeled in the MC: a factor of 94.1 $\pm$ 1.5% [5] for the efficiency of creating a pmuo bank in the CF region (i.e., reconstructing a muon with IFW4 $\leq$ 1), and an efficiency of 90 $\pm$ 5% [6] for the "phi hole" which is applied only to the integrated luminosity prior to the muon chamber cleaning.

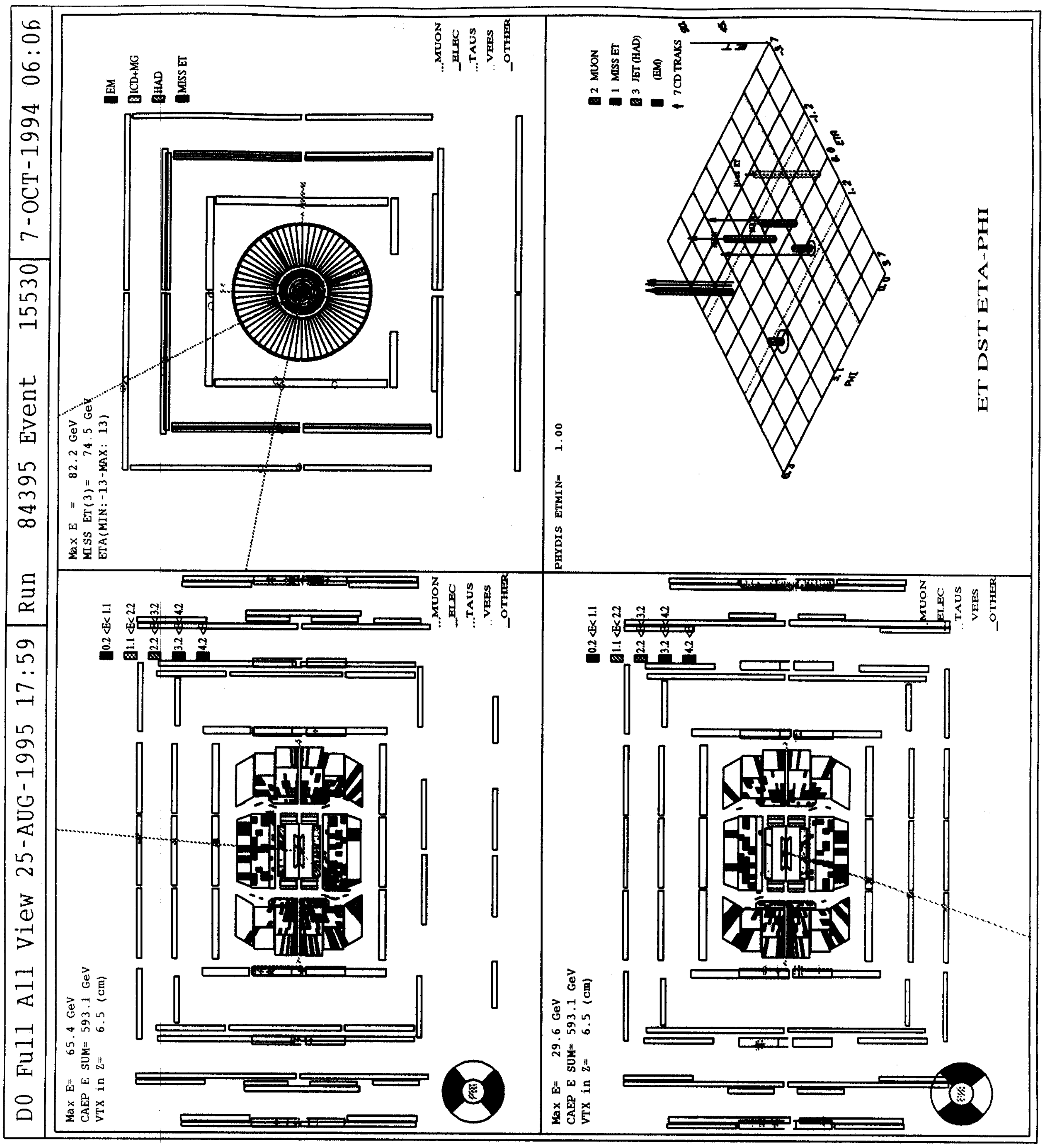

Figure 1: PIXIE Event Display of the Candidate event plotted using uncorrected energies.

M top GeV/c²	Run 1A CF - CF				Run 1B CF - CF				Run 1B CF - EF				Total			
	Accep*BF		events in 10.1 pb⁻¹		Accep*BF		events in 94.4 pb⁻¹		Accep*BF		events in 43.5 pb⁻¹		Accep*BF		events in 104.5 pb⁻¹	
Herwig 5.7		error		error		error		error		error		error		error		error
110	0.00009	0.00002	0.06	0.01	0.00009	0.00000	0.55	0.10	0.00005	0.00001	0.13	0.03	0.00012	0.00002	0.74	0.11
120	0.00014	0.00003	0.06	0.01	0.00017	0.00003	0.64	0.10	0.00011	0.00002	0.19	0.03	0.00022	0.00003	0.88	0.11
130	0.00023	0.00004	0.06	0.01	0.00028	0.00004	0.68	0.10	0.00018	0.00003	0.19	0.03	0.00035	0.00004	0.93	0.11
135	0.00033	0.00005	0.07	0.01	0.00035	0.00005	0.69	0.10	0.00019	0.00003	0.17	0.03	0.00043	0.00005	0.93	0.10
140	0.00041	0.00007	0.07	0.01	0.00047	0.00007	0.74	0.10	0.00023	0.00003	0.17	0.03	0.00055	0.00006	0.98	0.11
145	0.00044	0.00007	0.06	0.01	0.00049	0.00007	0.67	0.09	0.00030	0.00004	0.19	0.03	0.00061	0.00007	0.93	0.10
150	0.00048	0.00008	0.06	0.01	0.00056	0.00008	0.62	0.09	0.00033	0.00005	0.17	0.02	0.00069	0.00007	0.84	0.09
155	0.00061	0.00010	0.06	0.01	0.00070	0.00009	0.64	0.09	0.00034	0.00005	0.14	0.02	0.00083	0.00009	0.84	0.09
160	0.00063	0.00010	0.05	0.01	0.00072	0.00010	0.56	0.08	0.00039	0.00006	0.14	0.02	0.00088	0.00009	0.75	0.08
165	0.00067	0.00010	0.05	0.01	0.00078	0.00010	0.51	0.07	0.00046	0.00006	0.14	0.02	0.00096	0.00010	0.69	0.07
170	0.00076	0.00011	0.04	0.01	0.00087	0.00011	0.48	0.06	0.00047	0.00006	0.12	0.02	0.00106	0.00010	0.64	0.06
175	0.00081	0.00012	0.04	0.01	0.00091	0.00012	0.42	0.05	0.00049	0.00007	0.11	0.01	0.00110	0.00011	0.57	0.06
180	0.00083	0.00013	0.04	0.01	0.00096	0.00013	0.38	0.05	0.00058	0.00008	0.11	0.01	0.00119	0.00012	0.52	0.05
185	0.00089	0.00014	0.03	0.00	0.00104	0.00014	0.35	0.05	0.00057	0.00008	0.09	0.01	0.00126	0.00013	0.47	0.05
190	0.00094	0.00014	0.03	0.00	0.00111	0.00015	0.32	0.04	0.00057	0.00008	0.08	0.01	0.00133	0.00014	0.43	0.04
195	0.00103	0.00016	0.03	0.00	0.00116	0.00015	0.29	0.04	0.00063	0.00009	0.07	0.01	0.00141	0.00014	0.39	0.04
200	0.00100	0.00015	0.02	0.00	0.00116	0.00015	0.25	0.03	0.00054	0.00007	0.05	0.01	0.00137	0.00014	0.32	0.03
205	0.00104	0.00016	0.02	0.00	0.00122	0.00016	0.21	0.03	0.00063	0.00009	0.05	0.01	0.00146	0.00015	0.28	0.03
210	0.00115	0.00017	0.02	0.00	0.00129	0.00017	0.18	0.02	0.00069	0.00009	0.05	0.01	0.00156	0.00016	0.25	0.02
220	0.00122	0.00018	0.01	0.00	0.00140	0.00018	0.15	0.02	0.00075	0.00010	0.04	0.00	0.00169	0.00017	0.20	0.02
230	0.00129	0.00020	0.01	0.00	0.00146	0.00019	0.12	0.02	0.00079	0.00011	0.03	0.00	0.00177	0.00018	0.17	0.02

Figure 2: Table of signal acceptance for HERWIG 5.7 presented for three run ranges/fiducial regions and the total data sample. Here Run 1C is included in the columns marked Run 1B. Errors are the quadrature sum of statistical and systematic.

The table in Figure 2 lists the expected event yields and acceptance × branching fraction for the 21 HERWIG 5.7 Monte Carlo sets, broken down into three run ranges/fiducial regions. Figure 7 is a plot of expected event yield vs. M_{top} for HERWIG 5.7 and ISAJET Monte Carlo for 104.5 pb^{-1}. The cross sections used to calculate event yield are central values reported by Laenen *et al.*, [10].

Monte Carlo Background Event Sets				
Process	Generator	Generator level cuts	# Events	Lum
Z→ $\mu\mu$	ISAJET	$P_T(Z) > 15$ GeV/c	10k	$216 pb^{-1}$
Z→ $\mu\mu$	VECBOS	2 jets$E_T > 10$ GeV	21k	$2.16 fb^{-1}$
Z→ $\tau\tau$	HERWIG 5.7	e or μ final states	53k	$1.97 fb^{-1}$
Z→ $\tau\tau$	PYTHIA	e or μ final states	51k	$1.80 fb^{-1}$
Drell-Yan→ $\mu\mu$	PYTHIA	$M_{ll} > 25$ GeV/c^2	46k	$9.89 fb^{-1}$
$W^+W^- \rightarrow \mu\mu$	ISAJET	e or μ final states	50k	$73.6 fb^{-1}$

Table 3: Event sets used to determine background yields.

7 Background:Estimated events in 104.5 pb^{-1}

Background processes were modeled using one (or more if available for cross checks) of the following event generators: HERWIG, ISAJET, PYTHIA and VECBOS. See Table 3 for specific details of each event set used.

7.1 $Z \rightarrow \mu\mu$ Background

The $Z \rightarrow \mu\mu$ background event yield is estimated from two Monte Carlo event sets. One set uses the ISAJET generator to produce 10000 $Z \rightarrow \mu\mu$ events where at the generator level we require $p_T^Z > 15$ GeV/c . We make such a requirement to enhance the number of jets generated so the event sample contains more events that reflect the actual problematic background (*i.e.*, events with 2 or more jets). Set two is 21000 events generated with the VECBOS generator modified to the ISAJET fragmentation and ZEBRA storage. There is a requirement of at least two jets at the generator level with E_T >10 GeV .

Both sets are processed through DØGEANT using SHOWERLIBRARY. The sets are processed with DØRECO version 12.15 (with mu MC fix). The analysis to determine the cross sections for these event sets is discussed in a following section.

The full selection requirements are applied to these data sets, and the luminosity weighted average is used to determine the estimated event yield for the $Z \rightarrow \mu\mu$ background process. The $Z \rightarrow \mu\mu$ process is by far the largest source of dimuon background contributing 83% of the total in the CF-CF region, and 69% of the total in the CF-EF region.

7.1.1 Determination of the Relative Z Cross Sections

We use the much higher statistics and clean Z peak resolution of the ee channel's Z candidate data events to determine the relative cross section of various Z samples used in the dimuon channel for background calculations. More precisely, we want to determine the cross sections to use to calculate event yield estimates from the ISAJET and VECBOS Monte Carlo event sets where cuts placed at the generator level introduce some uncertainty.

The data sample is a set of 2130 dielectron events that pass good electron quality cuts for each electron. A cut on the M_{ee} invariant mass around the Z mass selects a reasonably clean Z→ee sample:

2130 events pass basic ee event selection and
have $|M_{ee} - 91.0| < 10.0$ GeV [See Fig 3(a) and 3(b)]

Cut on p_T of the 'Z' formed by the two electrons:

490 events pass above and have $p_T^Z > 15.0$ GeV/c [See Fig 3(c)]

Calculate the relative ratio:

$$490/2130 = 0.23 \pm 0.01 \text{ stat.}$$

Using the PDG value for $Z \to \mu\mu$ cross section of 209 pb, our high p_T $Z \to \mu\mu$ ISAJET sample should have a cross section of:

$$209 \text{ x } 0.23 = 48 \pm 2 \text{ pb (stat only)}$$

The VECBOS $Z \to \mu\mu$ + 2jet cross-check starts with the same clean Z→ee's.

2130 events pass basic ee event selection and
have $|M_{ee} - 91.0| < 10.0$ GeV
99 events pass above and have 2 jets > 10 GeV (inclusive)

Calculate the relative ratio:

$$99/2130 = 0.046 \pm 0.004 \text{ stat}$$

Using the PDG value for the $Z \to \mu\mu$ cross section of 209 pb, Our VECBOS $Z \to \mu\mu$ + 2jets should have a cross section of:

$$209 \text{ x } 0.046 = 9.7 \pm 0.9 \text{ pb (stat only)}$$

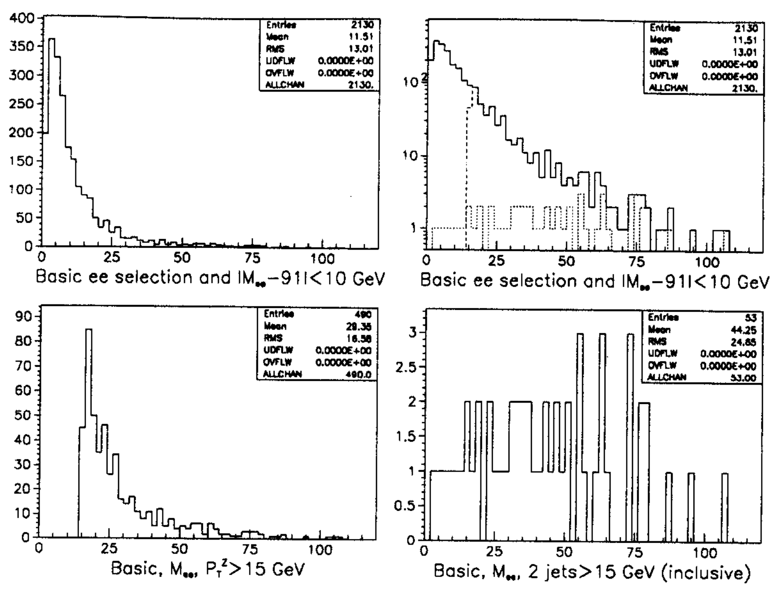

Figure 3: The p_T of the Z ($p_T^Z = p_T^{ee}$) for ee events is shown for (a) basic ee selection and with $|M_{ee} - 91.0| < 10.0$ GeV , (c) same as (a) with a 15 GeV cut on the p_T of the Z, (d) same as (a) with two jets > 15 GeV (inclusive), (b) plots (a),(c),(d) superimposed.

7.1.2 $Z \to \mu\mu$ $\not{E}_T$ Study

The use of the above cross section calculation is supported in part through the comparison of the $\not{E}_T$ and dilepton p_T for the $Z \to \mu\mu$ and $Z \to ee$ data and $Z \to \mu\mu$ Monte Carlo samples. The p_T spectrum of the Z samples should be the same for both data and Monte Carlo to make sure we are cutting on similar shape recoil distributions corresponding to jets. Since the momentum resolution of the muons limits the direct comparison, the p_T of the missing energy is used to represent the $p_T$of the Z. Figure 4 shows the comparison of the $Z \to \mu\mu$ data and the high p_T $Z \to \mu\mu$ ISAJET sample when PNUT4 is used for the $\not{E}_T$. Figure 5 shows the results when comparing the $Z \to ee$ data sample ($p_T^Z = p_T^{ee}$) with the high p_T $Z \to \mu\mu$ ISAJET sample ($p_T^Z = \not{E}_T^{\rm cal}$).

7.2 $Z \to \tau\tau \to \mu\mu$ Background Calculation

The Z→ $\tau\tau$ background event yield is estimated using a set of 51000 Monte Carlo events generated with PYTHIA and 53000 events from HERWIG. Generator cuts are only on the final state particle (similar to the signal sample) with no cuts applied to the kinematic distributions. The cross section is the inclusive cross section times

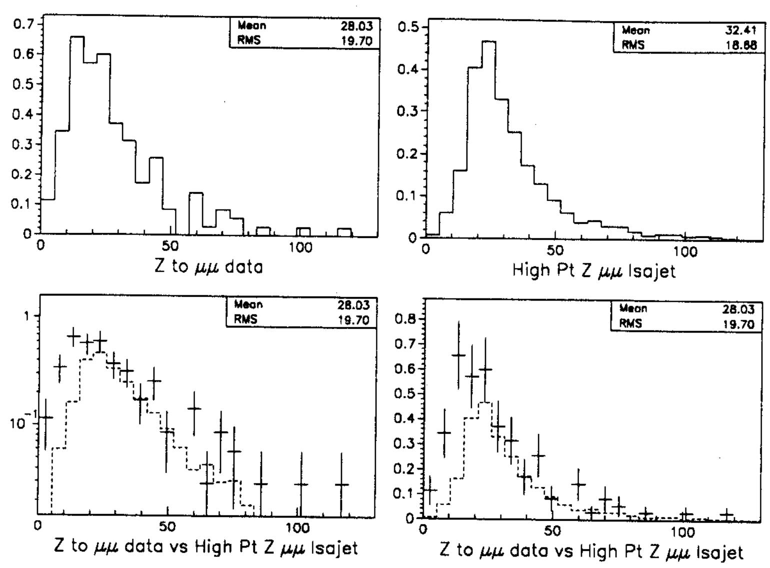

Figure 4: The p_T (using PNUT4) of the Z in $Z \rightarrow \mu\mu$ data and the high p_T $Z \rightarrow \mu\mu$ ISAJET samples. (a) shows $Z \rightarrow \mu\mu$ data, (b) shows $Z \rightarrow \mu\mu$ ISAJET Monte Carlo which has a 15 GeV cut on the p_T of the Z, (c) log scale,(d) linear scale, show the two distributions overlapped. The points are the data.

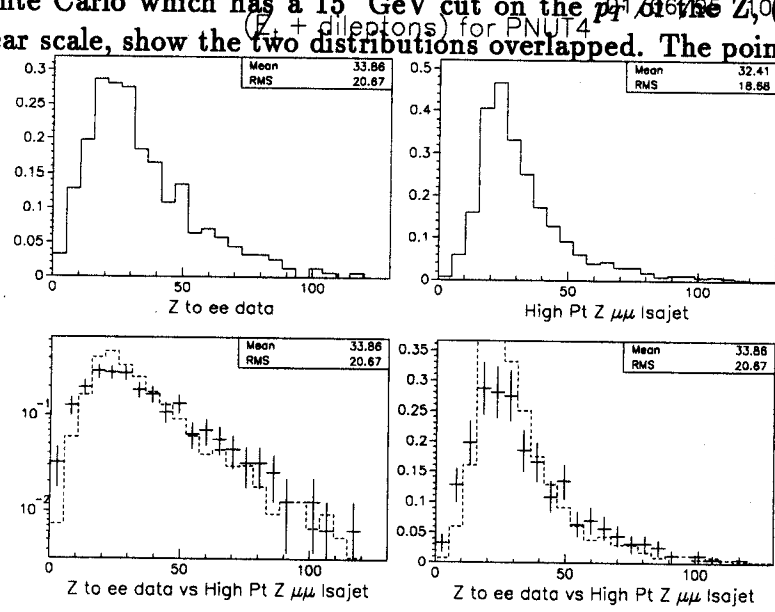

Figure 5: The p_T of the Z in $Z \rightarrow ee$ data ($p_T^Z = p_T^{ee}$) and the high p_T $Z \rightarrow \mu\mu$ ISAJET samples ($p_T^Z = \not{E}_T^{cal}$). (a) shows $Z \rightarrow ee$ data, (b) shows $Z \rightarrow \mu\mu$ ISAJET Monte Carlo which has a 15 GeV cut on the p_T of the Z, (c) log scale,(d) linear scale, show the two distributions overlapped. The points are the data.

a factor to include all $e\mu$ final states.

The similar statistic samples of Z→ $\tau\tau$ Monte Carlo differ in the events passing all dimuon selection requirements. The PYTHIA sample has 4 events passing in the CF-CF, leading to an expected event yield of 0.070 ± 0.038 sys+stat. The HERWIG 5.7, however, has no events passing all selection, leading to an upper limit of 0.044 events at 68% confidence.

A set of dielectron data was selected for comparison with the Monte Carlo event sets. The selection required 2 EM clusters with one passing good electron ID and $70 < M_{ee} < 110$ GeV/c^2 to obtain a good set of Z candidates. Comparing the fraction of events with $H_T > 100$ GeV from the dielectron data set to that of the events passing from each Z→ $\tau\tau$ MC sets (at the pjet level) shows that the PYTHIA H_T distribution is far too hard, and that the HERWIG is slightly soft. Five times more PYTHIA events passed than rate seen in the data, which is an underestimate since the pjets were used for the comparison; resolution effects would make this factor higher.

Our final event yield we use the PYTHIA result with a conservative reduction factor of 4 from the dielectron data comparison. The contribution to the total dimuon background from Z→ $\tau\tau$ is 4.1%.

7.3 Drell-Yan → $\mu\mu$ Background

We also consider the background source Drell-Yan → $\mu\mu$ using a 46000 event set from the PYTHIA Monte Carlo. A generator cut on the steeply falling curve of dilepton mass of 25 GeV/c^2 was made to enhance the region where background is expected while keeping the statistics of the sample manageable. The cross section for this event set is ≈ 64 pb which was determined from the output of PYTHIA and corroborated with DØ data (see Ref [8]). Using this cross section we estimate an event yield of 0.066 ± 0.034 events which corresponds to ≈ 9% of the total background.

7.4 $WW \rightarrow \mu\mu$ Background

The $WW \rightarrow \mu\mu$ background event yield is estimated using a set of 50000 Monte Carlo events generated with PYTHIA. These events were processed with DØGEANT and with version 12.21 of DØRECO. The estimated corresponding integrated luminosity of this set is 73.6 fb^{-1} determined with the calculated cross section for $\overline{p}p \rightarrow WW$ [9] and the branching fractions of $W \rightarrow \mu$ from the PDG. The relevant cross section which we use for this process is:

$$\sigma(WW)(BF(W \rightarrow \mu\ ))^2 = 0.12pb \quad (1)$$

After applying all cuts, 6 events survive the new standard cuts for CF-CF events and 3 events survive for CF-EF events. This translates to an expected event yield of 0.007 ± 0.004 events, or ≈ 1% of the total background.

7.5 Background from QCD and W→ μ+jets inclusive

The 'fake' muon rate for the $\mu\mu$ channel is determined in two parts. First, the number of good, isolated muons per suitable jet is calculated from a data sample. Second, in a muon plus jets sample, find how many jets could actually be replaced by a muon and survive all of the basic selection cuts.

The initial jet sample of 158,885 events is taken from the QCD_JJJ DØDAD stream. 'CF' jets are defined as jets with $E_T > 15$ GeV and $|\eta| < 1.0$. This sample yields 244,341 'CF' jets. It also yields 25 good, isolated, CF muons with $p_T^\mu > 15$ GeV/c . 'EF' jets are defined as jets with $E_T > 15$ GeV and $1.0 > |\eta| > 1.7$. This sample yields 102,148 'EF' jets and 25 good, isolated, EF muons with $p_T^\mu >$ 15 GeV/c .

CF muons per jet = 0.00010
EF muons per jet = 0.00024

In the muon plus jets sample, events are selected from 45 $pb^{-1}$of run 1B data if they pass the trigger and have one good, isolated muon:

MU_JET_xxxx trigger
$p_T^\mu > 15$ GeV/c
Quad(μ) ≤ 4 for CF muons
IFW4 ≤ 1, for CF muons
ΔR (μ-jet)>0.5
Quad(μ) $\geq 5, \leq 12$, for EF muons
IFW4 = 0, for EF muons

There are 12,215 events that pass this selection from a signal sample with an average of 0.7359 'CF' jets per event. There are 957 events from a complementary background sample with an average of 0.7823 jets per event. The combined sample contains all events (duplicates removed) passing this selection in the 45 $pb^{-1}$of run 1B data. These samples yield 9738 jets in total. If I require one good, isolated CF muon and at least one 'CF' jet and the event pass the two jets > 20 GeV and $H_T$cuts without that jet and that the μ-jet pair pass the $\eta - \phi$ cosmic cut then the

Background process	Run 1A	CF - CF	Run 1B	CF - CF	Run 1B	CF - EF		Total
		events in 10.1 pb^{-1}		events in 94.4 pb^{-1}		events in 43.5 pb^{-1}		events in 104.5 pb^{-1}
		quad err		quad err		quad err		quad err [illegible]
Z->mm		0.039 0.016		0.418 0.163		0.102 0.040		0.558 0.168 0.218
Z->tt->mm		0.001 0.000		0.018 0.010		0.010 0.005		0.029 0.011 0.015
DY->mm		0.004 0.002		0.034 0.019		0.028 0.013		0.066 0.023 0.034
WW->mm		0.000 0.000		0.005 0.003		0.001 0.001		0.007 0.003 0.004
QCD/W+j->mm		0.023 0.008		0.033 0.015		0.013 0.002		0.068 0.017 0.025
total		0.066 0.018		0.508 0.164		0.154 0.043		0.728 0.170 0.224

Figure 6: Expected event yields for background processes.Two errors are quoted in the total column, the first is the quadrature sum of the statistical and systematic errors, the second takes into account correlations in the systematic error.

number of such jets is 132 in 73 events. For the EF, a similar series of steps yields 40 jets in 33 events.

Using the pairs of numbers, for CF-CF events with one CF fake muon; 132 jets x 0.00010 x 2.25 yields 0.03 events, where 2.25 normalizes to 90 pb^{-1}. For CF-EF events with one EF fake muon, 40 x 0.00024 x 0.92 = 0.009 events, and CF-EF events with one CF fake muon, 132 x 0.23 x 0.00010 x 0.92 = 0.003 events for a total CF-EF yield of 0.012 events. Here 0.92 normalizes to 41.5 $pb^{-1}$and 0.23 is the ratio (EF muons/CF muons) determined from dimuon top Monte Carlo with $M_{top} = 170$ GeV/c^2 . The Run 1A estimate is unchanged.

This event yield is calculated in such a way to estimate inclusively the backgrounds from :

- $W \to \mu\nu$+jets where one jet contains a muon which then passes the isolation cuts.
- QCD multijets ($b\bar{b}$,$c\bar{c}$) with one heavy quark semileptonic decay (muonic) and the second heavy quark decaying hadronically to produce a jet. The second muon then comes either from the b/c jet or an accompanying gluon jet.
- $Z \to \tau\tau \to \mu$+hadrons where an ISR jet contains the second muon, etc...

Event yield estimates from the data for the above processes are shown in the table in Figure 6 under the entry QCD/W+jets$\to \mu\mu$.

7.6 Background Summary

The summary of all of the backgrounds is shown in the table in Figure 6 by process and broken down by run range. Figure 7 plots the total background event yield, the event yield for each background process and the expected event yield vs. M_{top} for HERWIG 5.7 and ISAJET Monte Carlo for 104.5 pb^{-1}.

An important consistency check is to compare the number of data events at each level of cut to that expected from background and signal. Table 4 shows the data events surviving each cut compared to the total expected background. Also tabulated for comparison is each background by component process and signal events expected for $M_{top} = 170$ GeV/c^2 (HERWIG 5.7). Note that valid comparison starts at cut 3 since we do not currently model or estimate events from cosmic rays or processes that generate low mass pairs. After cut 3 the dominant backgrounds are $Z \rightarrow \mu\mu$ and QCD/$W + jet \rightarrow \mu\mu$ with a 'fake' isolated muon.

The estimate for the QCD/$W + jet \rightarrow \mu\mu$ background at the level of cut 3 is from using muon isolation ($\Delta R\ (\mu, jet) > 0.5$) on a sample of the data free of cosmic ray muons, and defining those events failing the cut as the background in question. Estimates of this background for cuts 5-7 are made by the same method as described in Section 7.4 while backing off one cut at a time. Due to the minimum selection criteria of this method on the muon + jet data set, an estimate for cut 4 is not attempted at this time, however we expect the contribution to less than one event, so the total background is correct within the errors stated.

We use two models for the $Z \rightarrow \mu\mu$ background as outlined in Section 7.1. To calculate the contribution to the total background from $Z \rightarrow \mu\mu$ we use the integrated luminosity weighted average of expected events from each of the two generator event samples. This gives more weight to the VECBOS sample since we run out of statistics in the ISAJET sample. Note that a comparison at cut 5 of these two sets may not be valid as there is a resolution turn on curve for jet $E_T$from the generator level cuts applied to the VECBOS sample, which may underestimate the expected events. The method of weighting relies more on the VECBOS for our final estimate which is a higher yield than that expected of ISAJET, which represents a conservative estimate for the $Z \rightarrow \mu\mu$ contribution.

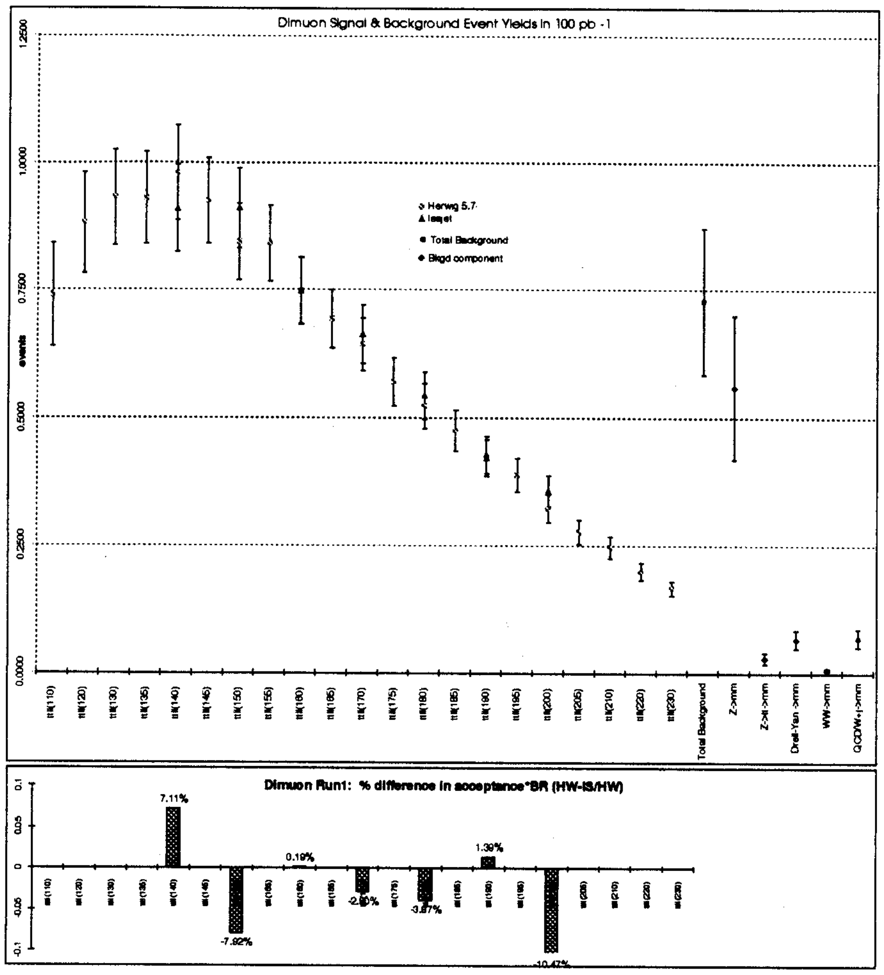

Figure 7: Expected event yield in 104.5 pb^{-1} for signal (HERWIG 5.7 and ISAJET), individual background processes and total background. Errors are systematic + statistical. Lower plot shows percent difference in acceptance between ISAJET and HERWIG relative to HERWIG.

Selection cut	data	total background[1]	$Z \rightarrow \mu\mu$ ISAJET $p_T^Z > 15$	$Z \rightarrow \mu\mu$ VECBOS 2jet $E_T > 15$	QCD/ $W + jet \rightarrow \mu\mu$[2] (1 fake isol μ)
2μ, $p_T^\mu > 15$,μ id +1 jet $E_T > 20$ +MU JET triggers	606		164 ± 50		
cosmic rejection $\Delta\eta < 0.5$ for $\Delta\phi > 160$	207	186 ± 43	137 ± 42		40 ± 9
J/ψ rejection $M_{\mu\mu} > 10$	165	186 ± 43	137 ± 42		40 ± 9
μ isolation $\Delta R_{\mu j} > 0.5$	105	134 ± 39	127 ± 39	generator cuts	no estimate
2^{nd} jet $E_T > 20$	19	13.5 ± 8.0	21.9 ± 7.1	11.8 ± 3.6	0.22 ± 0.10
$H_T > 100$	6	4.6 ± 3.3	8.6 ± 3.1	4.1 ± 1.3	0.03 ± 0.01
Z fitting $Prob(\chi^2) < 1\%$	1	0.51 ± 0.16	0.27 ± 0.28	0.43 ± 0.17	0.03 ± 0.01

Selection cut	data	$t\bar{t} \rightarrow \mu\mu$ M_{top} 170 GeV/c^2	$Z \rightarrow \tau\tau \rightarrow \mu\mu$	Drell-Yan $\rightarrow \mu\mu$	$WW \rightarrow \mu\mu$
2μ, $p_T^\mu > 15$,μ id +1 jet $E_T > 20$ +MU JET triggers	606	1.63 ± 0.21	0.69 ± 0.24	8.87 ± 2.93	0.42 ± 0.14
cosmic rejection $\Delta\eta < 0.5$ for $\Delta\phi > 160$	207	1.50 ± 0.19	0.59 ± 0.20	7.51 ± 2.49	0.38 ± 0.13
J/ψ rejection $M_{\mu\mu} > 10$	165	1.47 ± 0.18	0.59 ± 0.20	7.51 ± 2.49	0.38 ± 0.13
μ isolation $\Delta R_{\mu j} > 0.5$	105	0.88 ± 0.11	0.49 ± 0.17	6.89 ± 2.28	0.32 ± 0.01
2^{nd} jet $E_T > 20$	19	0.72 ± 0.09	0.10 ± 0.04	0.44 ± 0.15	0.05 ± 0.02
$H_T > 100$	6	0.53 ± 0.07	0.02 ± 0.01	0.03 ± 0.02	0.01 ± 0.00
Z fitting $Prob(\chi^2) < 1\%$	1	0.48 ± 0.06	0.02 ± 0.01	0.03 ± 0.02	0.01 ± 0.00

Table 4: Number of dimuon events passing cuts at each level, and number of events of top and background processes expected in $90 pb^{-1}$ (for CF-CF only). (1) Total background is luminosity weighted sum of two $Z \rightarrow \mu\mu$ MC event sets plus the sum of all other contributing backgrounds. (2) QCD/$W + jet \rightarrow \mu\mu$ calculated from $\mu + jets$ data set.

	Signal Errors	Background Errors			
Error Source	$t\bar{t} \to \mu\mu$	$Z \to \mu\mu$	$Z \to \tau\tau \to \mu\mu$	$WW \to \mu\mu$	$QCD\&$ $W + jets$
Statistical	2-8%	24%	24%	41%	15%
Luminosity	5.3%	5.3%	5.3%	5.3%	
Jet Energy Scale	7.7%	24%	24%	24%	-
MC Generator	5%	10%	15%	15%	-
MC Input X-sec	-	10%	15%	15%	-
Mult Int/Noisy	4.7%	3.1%	3.1%	3.1%	-
High $P_T\mu$ efficiency	6.4%	6.4%	6.4%	6.4%	-
Jet Fakes a Muon	-	-	-	-	15%
Z fitter	3%	10%	3%	3%	-
Sys Quad Total	12.5%	30.4%	33.0%	33.0%	15%

Table 5: Errors involved in signal and background calculations.

8 Systematic Error Studies

8.1 Overall Systematic Errors

Table 5 contains a listing of all of the errors relevant in both signal and background calculations. Systematic error assignment for generator dependence is discussed in Ref. [12]

8.2 Errors on Muons

Comparisons of MC to the candidate $Z \to \mu\mu$ data set show good agreement on efficiency of our inclusive Muon ID cuts. We use the same muon ID and systematics as that of the $e\mu$ and μ+jets analyses. The 6.4% estimate includes a luminosity weighted MUSMEAR error (3.5% for CF, 5% for EF), an error for a hole in ϕ in the region of the Main Ring for half the 1B luminosity (an inefficiency not represented by MUSMEAR or GEANT of $90 \pm 5\%$) and an error of 5% on the use of Level 2 turn-on curves used to deduce the efficiency of the trigger on the Monte Carlo events.

8.3 Jet Energy Scale Error

The error on the jet energy scale could not be determined for Monte Carlo using the CAFIX 5.0 one sigma change. This quantity was not calculated correctly in CAFIX 5.0 and DØ Note [11] summarizes the problem and presents an improved calculation of the jet energy scale error using a high/low shift of $\pm(4\% + 1$ GeV$)$ in jet energies. Using this method, a one sigma change in the jet energy scale changes the efficiency for $t\bar{t} \rightarrow \mu\mu$ by 8.6%. In fact, there is little no difference in the efficiency until the H_T cut. This is reasonable considering H_T is the selection cut most sensitive to the jet energy scale.

For the steeply falling jet E_T spectra of the background processes, the one sigma change in jet energy scale has a much greater impact. From studies of the ISAJET $Z \rightarrow \mu\mu$ MC event sample we see a difference in efficiency leading to an assignment of 24% error on the Z and W^+W^- background yields. See Table 5.

8.4 Errors due to Multiple Interactions

The effects of multiple interactions were studied by applying the NOISY package to two Monte Carlo samples. The signal sample is a HERWIG 5.7 set of $t\bar{t}$ to dileptons (includes $\tau \rightarrow e$ or μ) at a mass of 170 GeV/c^2. The background sample was VECBOS $Z \rightarrow \mu\mu + 2$ jets. The NOISY package was then used to add either one or two MBR 'minbias' events onto the original. Standard DØRECO was then applied and TOP_DILEP ntuples filled. The results are shown in the tables below. Table 6 contains the results from the signal sample. Table 7 contains the background sample.

A systematic error is determined by weighting the amount of increase/decrease by the typical instantaneous luminosity distribution of our data sample shown in Fig. 8. This distribution is obtained after the basic selection cuts up through and including muon isolation have been applied. Thus only physics events with the approximate required topology remain. Cosmics and low mass $\mu\mu$ pairs have been removed. The result for the signal is a small shift to decreased acceptance with the additional MBR events overlapped. A 4.7% systematic error is applied to the signal with these results. The background sample is less affected and a systematic of 3.1% is assigned to the $Z \rightarrow \mu\mu$ background. Other backgrounds are simply assigned a systematic of 3.1% as event sets with the NOISY package applied were not available.

Selection cut	$t\bar{t}$ HERWIG 5.7 Sample		
	+0 MBR	+1 MBR	+2 MBR
0.) Number of Events in Sample	4780	4694	4685
1.) Trigger+muon ID+2nd muon 2 high p_T muons, $p_T > 15$ GeV/c , $\|\eta\| < 1.0$ 1 jet, $E_T > 20$ GeV , $\|\eta\| < 2.5$	300	297	280
2.) Cosmic ray rejection $\Delta\phi(\vec{p}_T^{\mu_1}, \vec{p}_T^{\mu_2}) < 165° for$ $\eta(\vec{p}_T^{\mu_1}, \vec{p}_T^{\mu_2}) < 0.3$	271	267	254
3.) Invariant Mass Cut $M_{\mu\mu} > 10$ GeV/c^2	266	262	248
4.) Muon Isolation $\Delta R\ (\mu, jet) > 0.5$	156	149	138
5.) Second Jet requirement 2nd jet $E_T > 20$ GeV , $\|\eta\| < 2.5$	124	119	112
6.) H_T Cut $H_T(jets) > 100$ GeV ($\sum E_T^j$ of ALL jets $E_T^j > 15$ GeV)	90	89	79
7.) Z-fitter Cut $\mathcal{P}(\chi^2) < 0.01$	81	79	72
8.) Trigsim	72.31	70.54	64.24
Fraction Passing (Cut 4)	3.26%	3.17%	2.95%

Table 6: Number of events passing each level of selection cuts for an approximately 4800 event sample of HERWIG 5.7 $t\bar{t}$ with $m_t = 170$ GeV/c^2 . The first column is the base sample. The second column shows the effect of adding via one MBR event to the HERWIG event. The third column shows two added MBR events. Fraction passing is the fraction of events passing cut 4, muon isolation.

Selection cut	$Z \to \mu\mu$ + 2jets VECBOS Sample		
	+0 MBR	+1 MBR	+2 MBR
0.) Number of Events in Sample	4800	4800	4757
1.) Trigger+muon ID+2nd muon 2 high p_T muons, p_T > 15 GeV/c , $\|\eta\| < 1.0$ 1 jet, E_T> 20 GeV , $\|\eta\| < 2.5$	463	464	473
2.) Cosmic ray rejection $\Delta\phi(\vec{p}_T^{\mu_1}, \vec{p}_T^{\mu_2}) < 165° for$ $\eta(\vec{p}_T^{\mu_1}, \vec{p}_T^{\mu_2}) < 0.3$	411	410	414
3.) Invariant Mass Cut $M_{\mu\mu} > 10$ GeV/c^2	411	410	414
4.) Muon Isolation $\Delta R\ (\mu, jet) > 0.5$	342	328	340
5.) Second Jet requirement 2nd jet E_T> 20 GeV , $\|\eta\| < 2.5$	95	94	103
6.) H_T Cut $H_T(jets) > 100$ GeV ($\sum E_T^j$ of ALL jets E_T^j> 15 GeV)	26	27	27
7.) Z-fitter Cut $\mathcal{P}(\chi^2) < 0.01$	5	5	6
8.) Trigsim	4.46	4.46	5.42
Fraction Passing (cut 4)	7.13%	6.83%	7.15%

Table 7: Number of events passing each level of selection cuts. This 4800 event VECBOS $Z \to \mu\mu$ + 2jet sample has no generator level cut on the $p_T$of the Z. The first column is the base sample. The second column shows the effect of adding via NOISY one MBR event to the VECBOS event. The third column shows two added MBR events. Fraction passing is the fraction passing cut 4, muon isolation.

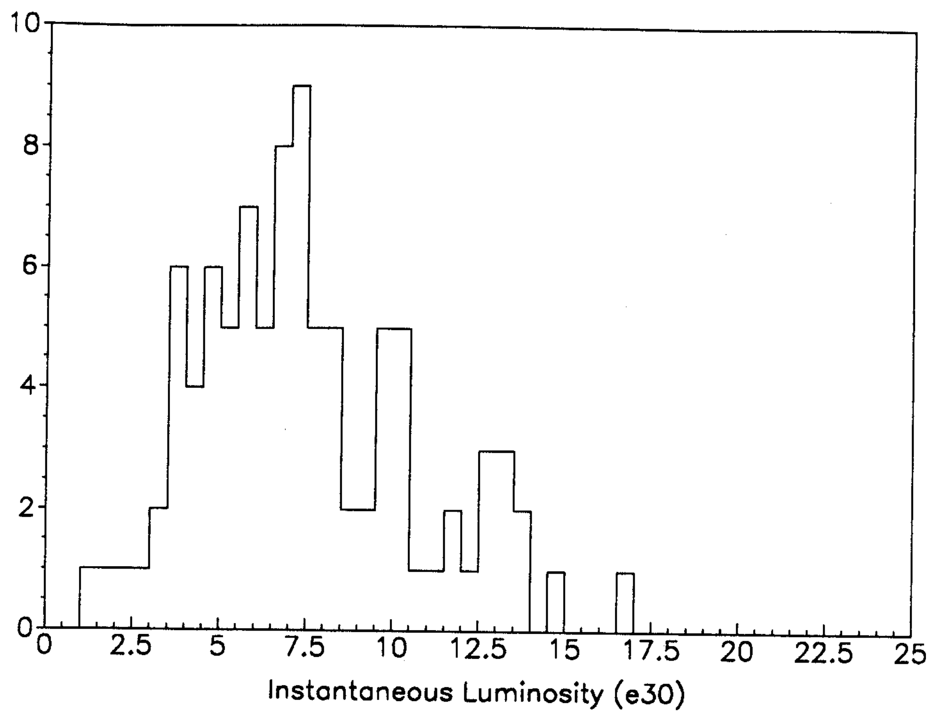

Figure 8: The instantaneous luminosity distribution for the full streamed data sample passing standard event selection up through muon isolation.

8.5 Systematics from Z fitting and Prob(χ^2) cut

Due to the inherent momentum resolution of the DØ muon system, the invariant mass peak of the Z is smeared and a simple cut on M_Z is ineffective in reducing this background. We define a measure of the likelihood that a dimuon event is a $Z \to \mu\mu$ decay as that of the upper tail probability of a chi-square (χ^2) distribution from a Z fit. The chi-square is minimized for the dimuon pair mass to give M_Z and for the missing energy in the calorimeter, $\not\!\!E_T^{cal}$, to equal the p_T of the Z. The variables in the fit are 1/p of both muons and the x and y components of the $\not\!\!E_T^{cal}$. These are floated within their errors.

The routine Z_FIT_MUMU minimizes a chisquare where the p_T of the second muon ($p_T^{\mu 2}$),and the x and y components of $\not\!\!E_T^{cal}$, are a function of p_T of the first muon by solving the kinematic equations in terms of $p_T^{\mu 1}$. Then only $p_T^{\mu 1}$ (the muon with the worst resolution) is floated in the fit within its error.

An overall systematic error of 10% on the $Z \to \mu\mu$ background is arrived at through careful study of the muon momentum resolution and missing E_T resolution parameterizations chosen and used for both data and Monte Carlo, which are the main source of systematic bias when using the Prob(χ^2) distribution as a cut.

For a comprehensive discussion of the Z_FIT_MUMU package, resolution parameterizations, and obtained background rejection and signal efficiencies with errors, the reader is refered to Ref. [7].

9 Summary

Using the full Run 1 data set we select for events consistent with $t\bar{t} \rightarrow W^+\bar{b}W^-b \rightarrow \mu^+\nu j\mu^-\bar{\nu}j + X$. Using the variables of H_T, E_T^{jet2} and the goodness of fit to the $Z \rightarrow \mu\mu$ hypothesis we are able to achieve $S/B = 5/4$ over the main back background process $Z \rightarrow \mu\mu$, and slightly less than $S/B = 1/1$ overall for $M_{top} = 170$ GeV/c^2 .

We find one candidate event in $104.5pb^{-1}$on an expected background yield of 0.73 ± 0.17 events (± 0.22 events if we account for correlations in systematics) where we expect 0.64 ± 0.06 events for a top mass of 170 GeV/c^2 . These results are used in conjunction with seven other top counting analyses to determine the $t\bar{t}$ total cross section in Ref. [15], and in determining the mass of the top from dilepton events Ref. [13] [14].

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