DØ Note 5345-CONF

A search for Z/γ^* boson pair production decaying into four leptons

The DØ Collaboration

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We present a search for Z/γ^* boson pair production decaying into $\mu\mu\mu\mu$, $\mu\mu ee$, and $eeee$ final states with approximately 1 fb^{-1} of data collected at the Fermilab Tevatron Collider. After all cuts 1.71 ± 0.11 events are expected with a background of 0.17 ± 0.04 events. One event is observed in the $\mu\mu ee$ channel. A cross section upper limit of 4.3 pb is determined at a 95% confidence level, consistent with the standard model prediction of 1.6 pb.

Preliminary Result for the winter 2007 conferences

I. INTRODUCTION

In the standard model, the lowest order significant Feynman diagram for $p\bar{p} \rightarrow (Z/\gamma^*)(Z/\gamma^*) \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ is shown in Fig. 1. There is no self coupling of Z bosons in the standard model. The pair production of Z/γ^* bosons has never been discovered at a hadron collider, additionally, there are various other processes, for example a sufficiently heavy Higgs boson, that have four lepton final states. Any deviation from the standard model could indicate new physics.

At $\sqrt{s} = 2$ TeV, the predicted $p\bar{p} \rightarrow ZZ$ cross section with one loop corrections is 1.60 pb [1]. Due to the small number of expected Z/γ^* boson pair events and the sensitivity of the acceptance to single lepton cuts, considerable effort was spent optimizing the acceptance and lepton efficiencies for the different channels: $\mu\mu\mu\mu$, $eeee$, and $\mu\mu ee$.

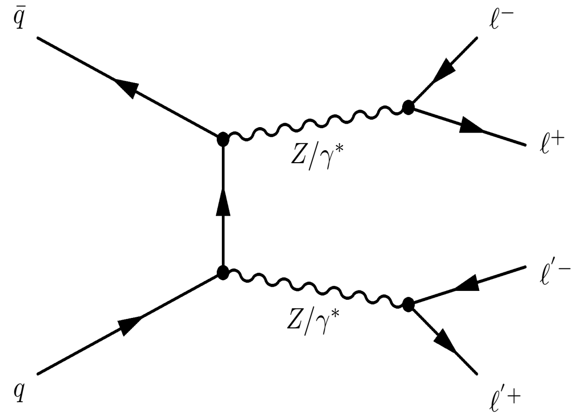

FIG. 1: Lowest order Feynman diagram for $q\bar{q} \rightarrow ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$

Figure 2 shows the invariant mass of one Z/γ^* boson verse the invariant mass of the other Z/γ^* boson for $p\bar{p} \rightarrow (Z/\gamma^*)(Z/\gamma^*) \rightarrow \mu\mu\mu\mu$ at generator level with PYTHIA after the event and muon selection cuts that are described in Section VI A.

The four lepton invariant mass after selection is shown in Fig. 3. Due to phase space considerations, the invariant mass of all four leptons peaks near 200 GeV.

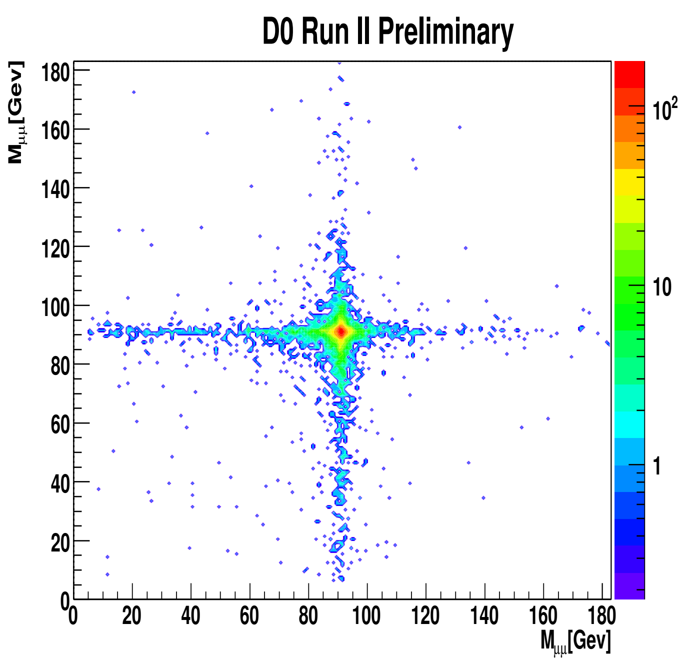

FIG. 2: The invariant mass of one Z/γ^* boson verse the invariant mass of the other Z/γ^* boson from a generator-level Monte Carlo simulation of $p\bar{p} \rightarrow (Z/\gamma^*)(Z/\gamma^*) \rightarrow \mu\mu\mu\mu$ after the muon selection cuts.

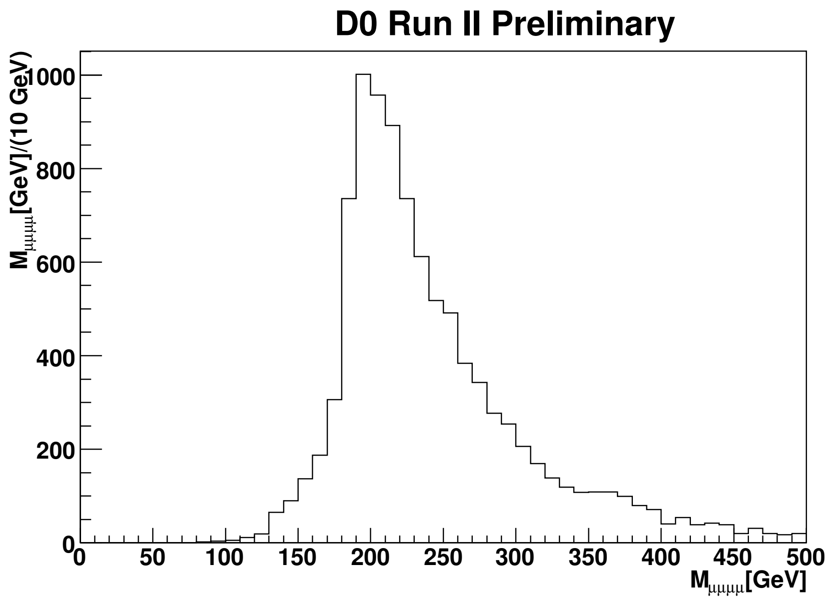

FIG. 3: Invariant mass from all four muons from $p\bar{p} \rightarrow (Z/\gamma^*)(Z/\gamma^*) \rightarrow \mu\mu\mu\mu$ after selection cuts produced with the PYTHIA Monte Carlo generator.

II. THE DETECTOR

The DØ detector has a central-tracking system, consisting of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet [2], with designs optimized for tracking and vertexing at pseudorapidities $|\eta| < 3$ and $|\eta| < 2.5$, respectively. A liquid-argon and uranium calorimeter has a central section (CC) covering pseudorapidities $|\eta|$ up to ≈ 1.1, and two end calorimeters (EC) that extend coverage to $|\eta| \approx 4.2$, with all three housed in separate cryostats [3]. An outer muon system, at $|\eta| < 2$, consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroids, followed by two similar layers after the toroids [4]. The muon system is divided into two main detectors: MUC for $|\eta| < 1.0$, and MUF for $1.0 < |\eta| < 2.0$.

III. THE DATA

The data sets used in this analysis were accumulated between October 2002 and April 2006. Single muon triggers are used as well as single and di-electron triggers. The integrated luminosities [5] after data quality requirements are: (944 ± 58) pb^{-1} for the $\mu\mu\mu\mu$ channel, (1070 ± 65) pb^{-1} for the $eeee$ channel, and (1020 ± 62) pb^{-1} for the $\mu\mu ee$ channel.

IV. EVENT SELECTION

A. The $\mu\mu\mu\mu$ channel

Muons are required to have a central track match and to pass loose quality cuts based on scintillator and wire chamber requirements in the muon system. The track matched to the muon must have $p_T > 15$ GeV. Additionally, muons that are only identified in the muon detector layers before the toroid are required to have calorimeter isolation less than 2.5 GeV to reduce the background from hadronic punch through. Calorimeter isolation for muons is defined as the total transverse energy measured in the calorimeter in the annulus between $R = 0.1$ and $R = 0.4$ centered around the track matched to the muon. The variable R between two objects i and j is defined as $R = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$, where $-\pi < \phi_i - \phi_j < \pi$. No other muon isolation cuts are applied. Muon timing cuts are done to help reduce the background from cosmic rays. Finally the distance of closest approach (DCA) with respect to the beamspot for the track matched to the muon must be < 0.02 cm for tracks with SMT hits and < 0.2 cm for tracks without SMT hits.

This reduces the background from beam halo and cosmic rays. No charge requirement is done due to concerns about charge misidentification for tracks with large p_T.

For the event selection, all six possible pairs of the four muons are required to have $\cos\alpha < 0.96$, where α is the opening angle between the muons. This cut is necessary to remove a background along the MUC and MUF boundary where there is a greater chance for hadron punch through or duplicate muon identification across detector boundaries. The absolute difference between the track vertices along the beam axis z_{vtx} of all muon pairs is required to be less than 3 cm ($|\Delta z_{vtx}| < 3$ cm). This cut helps significantly in reducing the background from the beam halo.

Finally, due to the fact that there are four muons in the final state and because the charge of the muons is not used, there are three possible Z/γ^* boson pair combinations that can be formed. A candidate event is selected if the invariant masses of the muon pairs in at least one of these three choices are both greater than 30 GeV.

B. The $eeee$ channel

Electrons must also have $E_T > 15$ GeV and are restricted to detector $|\eta| < 1.1$ and detector $1.5 < |\eta| < 3.2$. Additionally, electrons were also required to pass identification cuts based on multivariate discriminators derived from calorimeter shower shape and tracking variables. In order to recover some acceptance in detector regions with poor or no tracking coverage, only three of the four electrons were required to have an associated track match. If one electron does not have an associated track, it is instead required to pass tighter shower shape requirements.

Figure 4 shows the efficiency for an electron with $E_T > 15$ GeV to pass a multivariate discriminator with a track match. The efficiency is a strong function of not only η but also the z_{vtx} of the track matched to the electron. The track match requirement greatly reduces the background of jets faking electrons. A mixed selection allowing for an electron without a track match is used to improve the acceptance and control the background.

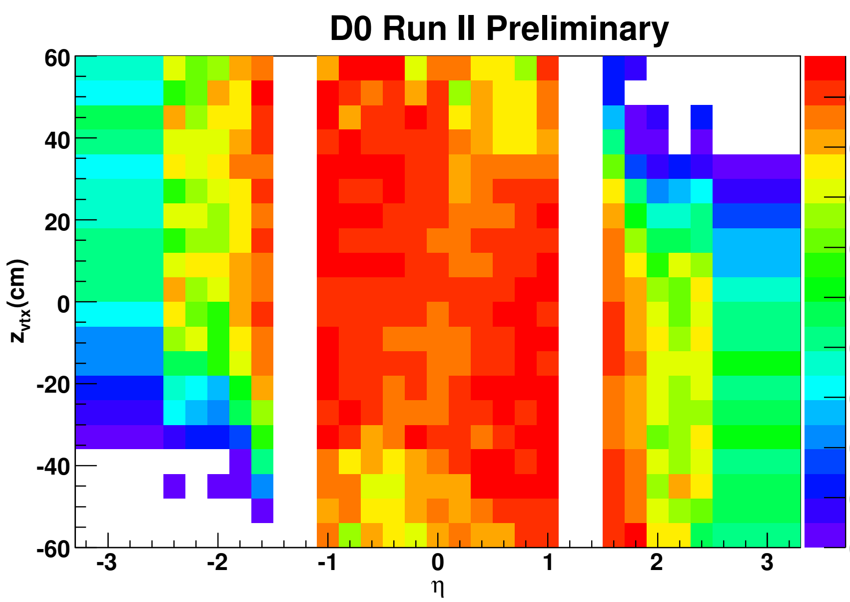

FIG. 4: The efficiency for an electron with $E_T > 15$ GeV to pass a multivariate discriminator with a track match.

Finally, as the four muon channel, there are three Z/γ^* boson pair combinations that can be formed from the electron pairs. A candidate event is selected if the invariant masses of the electron pairs in at least one of these three choices are both greater than 30 GeV.

C. The $\mu\mu ee$ channel

Muons have the same single muon selection cuts as the $\mu\mu\mu\mu$ channel and the electrons have the same E_T cuts and η cuts as the $eeee$ channels. Additionally, the muon pair is required to have $\cos\alpha < 0.96$ and $|\Delta z_{vtx}| < 3$ cm. Both electrons are required to pass the multivariate discriminator with a track match. In order to remove the background from muons radiating photons and the photon faking an electron from the nearby muon track, electrons and muons are required to have $R > 0.2$. The invariant masses of the muon pair and the electron pair are both required to be greater than 30 GeV.

V. THE ACCEPTANCE

The acceptance for each channel is found with PYTHIA and a parametrized Monte Carlo simulation of the detector resolution and detector efficiencies. The resolution for the muon detectors and calorimeter are simulated by smearing four-vectors.

For muons the geometric limit of the muon detectors is about $|\eta| = 2$. This represents the geometry cuts of the muon detector. In some regions at the bottom of the MUC and MUF, the calorimeter has supports to hold it above the floor. These supports limit muon detector coverage. This region called the "hole" region is simulated with the muon identification efficiencies.

The muon kinematic cuts include the $\cos\alpha$ cut and the $p_T > 15$ GeV cut. In addition, muons are required to have a central track match and to pass quality cuts in the muon detector. A summary of the acceptance for the cuts in the $\mu\mu\mu\mu$ channel is shown in Table I.

Selection	Exclusive Acceptance	Cumulative Acceptance
geometry cuts	0.650 ± 0.013	0.650 ± 0.013
$p_T > 15$ GeV	0.804 ± 0.002	0.523 ± 0.011
$cos\alpha < 0.96$	0.923 ± 0.005	0.482 ± 0.010
track match	0.830 ± 0.016	0.400 ± 0.011
muon detector quality cuts	0.700 ± 0.054	0.280 ± 0.023
trigger	0.970 ± 0.030	0.270 ± 0.024
total		0.270 ± 0.024

TABLE I: A summary of the acceptance for each selection cut in the $\mu\mu\mu\mu$ channel.

For electrons, the region between detector $1.1 < |\eta| < 1.5$ where there is little or no EM layer coverage, known as the ICR region, accounts for most of the geometric acceptance loss for electrons. The electron selection limits the spatial separation between any two electrons to $R > 0.4$, and this accounts for some of the kinematic loss. The $E_T > 15$ GeV requirement accounts for most of the kinematic loss. A summary of the acceptance for the cuts in the *eeee* channel is shown in Table II.

Selection	Exclusive Acceptance	Cumulative Acceptance
geometry cuts	0.490 ± 0.005	0.490 ± 0.005
EM cone cut $R > 0.2$	0.935 ± 0.010	0.458 ± 0.007
$E_T > 15$ GeV	0.760 ± 0.001	0.348 ± 0.005
trigger	0.990 ± 0.001	0.345 ± 0.005
electron quality cuts	0.660 ± 0.046	0.228 ± 0.011
total		0.228 ± 0.011

TABLE II: A summary of the acceptance for each selection cut in the *eeee* channel.

For the $\mu\mu ee$ channel the $\cos\alpha$ cut has no effect on the acceptance because the muons both come from the same Z boson and are emitted at relatively large opening angles. For the same reason the EM cone cut has no effect on the acceptance. Electron and muons can spatial overlay with one another; however, this has only a small effect on the acceptance. The ICR geometry cut and the multivariate discriminator with a track match requirement for both electrons have the largest effect on the acceptance. A summary of the acceptance for the cuts in the $\mu\mu ee$ channel is shown in Table III.

VI. BACKGROUNDS

The main sources of backgrounds that produce four leptons in the final state originate from top anti-top quark events, from the production of a Z boson with two jets (Zjj), and from events with a Z boson, a photon, and a jet

Selection	Exclusive Acceptance	Cumulative Acceptance
geometry cuts	0.560 ± 0.006	0.560 ± 0.006
electron and muon separation $R > 0.2$	0.982 ± 0.001	0.550 ± 0.006
$p_T > 15$ GeV	0.780 ± 0.010	0.429 ± 0.007
trigger	0.990 ± 0.010	0.425 ± 0.008
electron and muon quality cuts	0.514 ± 0.046	0.218 ± 0.030
total		0.218 ± 0.030

TABLE III: A summary of the acceptance for each selection cut in the $\mu\mu ee$ channel. Electron quality cuts represents the multivariate discriminator selection with track matches.

($Z\gamma j$). Other electroweak backgrounds with jets or photons in the final state can also contribute such as a W boson and three jets ($Wjjj$). Additionally four QCD jets ($jjjj$) can be a background.

Top anti-top quark events decay into W boson pairs and bottom anti-bottom ($t\bar{t} \to W^+W^-b\bar{b}$) and therefore have a heavy quark bias. However, the jets radiating from initial state gluon radiation in Z boson or W boson production do not have a heavy quark bias. Therefore the background from top quark production and from electroweak production with are determined separately, this last background is called the QCD jet background.

A. The $t\bar{t} \to \ell\ell\ell\ell$ background

The top quark background is determined using PYTHIA and a parametrized Monte Carlo simulation of the detector resolution and detector efficiencies. The W bosons produced from top anti-top production are allowed to decay only into leptons.

In the $\mu\mu\mu\mu$ channel the background for $t\bar{t} \to \mu\mu\mu\mu$ is found to be 0.032 ± 0.016 events. All electrons are required to be isolated so the $t\bar{t}$ background in the $eeee$ channel is negligible. In the $\mu\mu ee$ channel, the W bosons can produce electrons and the bottom quark jets can produce muons. The background for $t\bar{t} \to \mu\mu ee$ is found to be 0.027 ± 0.013 events.

B. The QCD jet background

The background from electroweak production with jets is determined by finding the rate for a jet to produce real or fake leptons. Once the different rates for jets to produce muons and electrons are determined the background from events with electroweak production and jets and events with four or more QCD jets can be determined.

For the $\mu\mu\mu\mu$ channel events are selected with two muons and two jets and the rate for a jet to produce a muon is applied to the jets. The sum of the product of the rates for all these events is the total background. Photons do not fake muons so sources with photons do not contribute to the $\mu\mu\mu\mu$ channel. A background of 0.004 ± 0.001 events from QCD jets is predicted.

In the $eeee$ channel events are selected with three electron candidates that pass the electron selection and one jet. Depending on the type of electrons that are found, a rate for a jet to pass the electron selections is applied to the jet. The sum of the rates from all these events is the total background. A background of 0.065 ± 0.021 events from QCD jets is predicted in the $eeee$ channel.

In the $\mu\mu ee$ channel we select events with two muons, one electron, and one jet. The rate for a jet to produce an electron that pass a multivariate discriminator with a track match is applied to the jet. The total background is the sum of the rates from all these events. A background of 0.007 ± 0.002 events from QCD jets is predicted in the $\mu\mu ee$ channel.

C. The combinatorial background

In the $\mu\mu\mu\mu$ channel and the $eeee$ there is the possibility that a Z boson and a γ^* boson can be produced where the mass of the leptons from the γ^* is less than 30 GeV but the event is nevertheless selected. This is due to the fact that there are more than two leptons of the same family in the final state and the correct mass pair that matches the γ^* cannot be determined. The acceptance is however found with respect to 30 GeV mass cuts on the correct mass pairs. Therefore events that are selected where the real γ^* pair has a mass less than 30 GeV are considered a background. This is called the combinatorial background.

The combinatorial background is found from knowing the correct mass pair from Monte Carlo and counting the number of events that pass the mass selection compared to how many events would have only passed if the correct mass pair were known. In Fig. 2 one can clearly see events that passed the selection in the $\mu\mu\mu\mu$ channel but have invariant mass of the correct Z/γ^* less than 30 GeV. The total combinatorial background is found to be of 0.016 ± 0.003 events in the $\mu\mu\mu\mu$ channel and 0.015 ± 0.003 events in the $eeee$ channel.

A summary of all the backgrounds for each channel can be found in Table IV.

Backgrounds in the $\mu\mu\mu\mu$ channel	Events
$t\bar{t} \to \mu\mu\mu\mu$	0.032 ± 0.016
QCD	0.004 ± 0.001
Muon pairing combinatorics	0.016 ± 0.003
Backgrounds in the $eeee$ channel	Events
$t\bar{t} \to \mu\mu\mu\mu$	negligible
QCD	0.065 ± 0.021
Electron pairing combinatorics	0.015 ± 0.003
Backgrounds in the $\mu\mu ee$ channel	Events
$t\bar{t} \to \mu\mu ee$	0.027 ± 0.013
QCD	0.007 ± 0.002

TABLE IV: A summary of the backgrounds for each channel.

VII. CROSS SECTION LIMIT

When the three channels are combined, the expected number of signal events for $\sigma_{ZZ} = 1.6$ pb is 1.71 ± 0.11 with an expected background of 0.17 ± 0.04 events. A summary of the luminosity, acceptance, background, and signal for each channel can be found in Table V. Correlations in muon and electron acceptances and backgrounds are included when the three channels are combined. One candidate event was found in the $\mu\mu ee$ channel. This is consistent with the number of events expected from the sum of signal plus background. The quality of the muons and electrons in this event are well away from the cut boundaries and the $|\Delta z_{vtx}|$ of all four tracks is well within 1 cm. An event display of this event is shown in Fig. 5. The invariant mass of the electron pairs is 93.4 GeV and the invariant mass of the muon pairs is 33.4 GeV. Due to the low invariant mass of the muon pair this event is a $Z\gamma^*$ candidate. The invariant mass of all four leptons is 150 GeV.

Because the observed yield is consistent with the background prediction we set a limit of 4.3 pb at 95% confidence level on $p\bar{p} \to (Z/\gamma^*)(Z/\gamma^*)$ for an invariant mass requirement on both Z/γ^* bosons of 30 GeV or greater.

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[1] J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999) [arXiv:hep-ph/9905386].

Channel	Luminosity	Acceptance	Background	Signal	N
$\mu\mu\mu\mu$	(944 ± 58) pb^{-1}	0.27 ± 0.02	0.057 ± 0.017	0.46 ± 0.05	0
$eeee$	(1070 ± 65) pb^{-1}	0.23 ± 0.01	0.080 ± 0.017	0.44 ± 0.03	0
$\mu\mu ee$	(1020 ± 62) pb^{-1}	0.22 ± 0.02	0.034 ± 0.014	0.81 ± 0.09	1
Total			0.17 ± 0.04	1.71 ± 0.10	1

TABLE V: A summary of the luminosity, acceptance, background, and signal for each channel. N is the number of candidate events that were found in each channel.

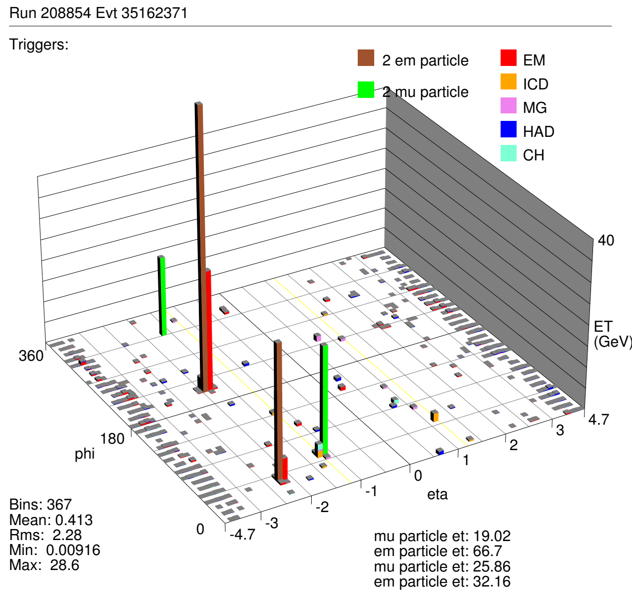

FIG. 5: An event display of the calorimeter energy deposits in E_T verse η and ϕ and the η and ϕ and p_T of the two muons.

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