



**Search for Higgs boson production in dilepton plus missing transverse energy final states with  $8.6 - 9.7 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$**

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We present a search for the Standard Model Higgs boson in dilepton events with large missing transverse energy using  $8.6 - 9.7 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$ , collected with the DØ detector at the Fermilab Tevatron collider. Three leptonic states,  $e^\pm\mu^\mp$ ,  $e^+e^-$  and  $\mu^+\mu^-$ , are considered. No significant excess above the standard model background expectation is observed. Therefore, limits on Higgs boson production are derived at 95% CL. For  $M_H = 165 \text{ GeV}$ , the expected limit is 0.82 relative to the Standard Model yield and the observed limit reaches 1.16 in the same units.

## I. INTRODUCTION

In the Standard Model (SM), the fermions get their mass by explicit couplings between the fermions and the Higgs field. The Higgs field itself induces spontaneous breaking of the electroweak gauge symmetry  $SU(2) \otimes U(1)$ . It gives rise to massive  $W/Z$  bosons and the appearance of an additional scalar boson which we call the Higgs particle. This particle has yet to be discovered. Direct searches at the CERN  $e^+e^-$  collider (LEP) yield a lower limit for the SM Higgs boson mass,  $M_H > 114.4$  GeV [1] at 95% confidence level (CL). A combination of results from the CDF and DØ experiments excludes the SM Higgs boson in the mass range  $156 \text{ GeV} < M_H < 177 \text{ GeV}$  at 95% CL [2]. Indirect constraints from fits to precision electroweak measurements give an upper bound of  $M_H < 185$  GeV [3] at 95% CL when combined with the direct searches from LEP2 (a recent measurement is available [4]). Recently, the LHC experiments have explored a wide range of SM Higgs boson masses. The ATLAS collaboration excludes at 95% CL the ranges 112.9–115.5 GeV, 131–238 GeV and 251–466 GeV [5]. The CMS collaboration excludes at 95% CL the range 127–600 GeV [6].

In this note, we present a search for the Higgs boson in final states containing two leptons ( $e^\pm\mu^\mp$ ,  $e^+e^-$  or  $\mu^+\mu^-$ ) and missing transverse energy ( $\cancel{E}_T$ ), using  $8.6 \text{ fb}^{-1}$  ( $e^+e^-$ ) and  $9.7 \text{ fb}^{-1}$  ( $e^\pm\mu^\pm$ ,  $\mu^+\mu^-$ ) of  $p\bar{p}$  collisions collected with the DØ detector at the Fermilab Tevatron. The combination of these final states has been shown to be most sensitive to a SM Higgs boson of mass  $M_H \sim 160$  GeV [7].

The production of Higgs bosons by gluon fusion is considered, with the subsequent decay  $H \rightarrow WW \rightarrow \ell\nu\ell'\nu'$ , where the  $\ell$  and  $\ell'$  include muons and electrons, as well as  $\tau$  leptons which themselves decay to muons or electrons. The contributions to the  $e^\pm\mu^\pm$ ,  $e^+e^-$ , and  $\mu^+\mu^-$  final states from weak vector boson fusion (VBF) and Higgs production in association with a vector boson ( $WH$  or  $ZH$ ) are also considered.

The preselection, based on the efficient reconstruction of the two leptons, is followed by additional requirements which suppress the large Drell-Yan (DY)  $Z/\gamma^* \rightarrow \ell\ell$  background. A final multivariate analysis based on a random forest of boosted decision trees (BDT) is used to separate the signal from the remaining background. The output of the BDT is the final discriminant used to search for a Higgs boson signal.

## II. DØ DETECTOR

This analysis relies on the efficient identification of muons, electrons, jets and missing transverse energy using many subsystems of the DØ Run II detector [8]. The central tracking system consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T axial magnetic field. The SMT strips have a typical pitch of 50–80  $\mu\text{m}$ , and the design is optimized for tracking and vertexing over the pseudorapidity range  $|\eta| < 3$ , where  $\eta = -\ln(\tan\theta/2)$  with  $\theta$  being the polar angle relative to the proton beam direction. The system has a six-barrel longitudinal structure, with each barrel having a set of four silicon layers arranged axially around the beam pipe, interspersed with sixteen radial disks. In addition, a new layer of silicon sensors (Layer 0 [9]) was added just outside the beam pipe in 2006, and the number of radial disks [10] was changed from sixteen to fourteen. The upgrades to the detector at this time marked the end of Run IIa and the beginning of Run IIb. The CFT has eight thin coaxial barrels, each supporting two doublets of overlapping scintillating fibers of 0.835 mm diameter, one doublet parallel to the beam axis, the other alternating by  $\pm 3^\circ$  relative to the beam axis.

A liquid-argon sampling calorimeter surrounds the central tracking system and consists of a central calorimeter (CC) covering up to  $|\eta| \approx 1.1$ , and two end calorimeters (EC) extending coverage to  $|\eta| < 4.2$ , each housed in separate cryostats. Scintillators between the CC and EC cryostats provide sampling of showers for  $1.1 < |\eta| < 1.4$ .

The muon system is located outside the calorimeters and consists of a layer of tracking detectors and scintillation trigger counters inside toroid magnets which provide a 1.8 T magnetic field, followed by two similar layers behind each toroid. Tracking in the muon system for  $|\eta| < 1$  relies on 10 cm wide drift tubes, while 1 cm mini-drift tubes are used for  $1 < |\eta| < 2$ . The numbers of hits in the wire chambers and in the scintillators of the muon spectrometer are combined to define a muon quality variable, used in the final stage of the analysis.

Trigger and data acquisition systems are designed to accommodate the high luminosities of 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  $\approx 1.5$  kHz. The calorimeter part of the first level of the trigger has been upgraded between Run IIa and Run IIb [11]. At the next trigger stage, with more refined information, the rate is reduced further to  $\approx 0.8$  kHz. These first two levels of triggering rely mainly on hardware. 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  $\approx 100$  Hz, which is written to tape for further analysis.

### III. DATA AND MONTE CARLO SAMPLES

The data sample used in this analysis was collected between April 2002 and September 2011 (Run II) by the DØ detector at the Fermilab Tevatron collider at  $\sqrt{s} = 1.96$  TeV. It corresponds to an integrated luminosity of  $9.7 \text{ fb}^{-1}$  for the  $e^\pm\mu^\pm$  and  $\mu^+\mu^-$  final states after imposing data quality requirements. The  $e^+e^-$  final state analysis is based on data recorded before April 2011, which corresponds to an integrated luminosity of  $8.6 \text{ fb}^{-1}$ . The DØ luminosity is measured with an accuracy of 6.1% using plastic scintillator arrays located in front of the EC cryostats, covering  $2.7 < |\eta| < 4.4$  [12].

Signal and SM background processes are simulated with PYTHIA [13] or ALPGEN [14] using the CTEQ6L1 [15] parton distribution functions (PDF), followed by a detailed GEANT-based [16] simulation of the DØ detector. In order to model the effects of multiple  $p\bar{p}$  interactions, the MC samples are overlaid with events from random  $p\bar{p}$  collisions with similar luminosity profiles and then reconstructed with the same software as the data. The normalization of generated samples is scaled to match the number of events expected, based on the cross sections, which are calculated at the highest available order. For the gluon fusion  $gg \rightarrow H$  process, the cross-section is calculated at NNLO+NNLL level [17], for  $WH$  and  $ZH$  at NNLO [18], and for vector boson fusion at NNLO in the strong coupling constant [19]. All signal cross sections are computed using the MSTW 2008 NNLO PDF set [20]. The PDF uncertainties are assessed according to recommendations of Ref. [21]. The distribution of the transverse momentum of the Higgs boson generated in the gluon fusion process is tuned to match the transverse momentum as calculated by the HQT generator, at NNLL and NNLO accuracy [22].

The main background processes for this analysis are diboson production,  $Z/\gamma^*$  production in leptonic final states,  $W$ +jets/ $\gamma$  production,  $t\bar{t}$  production and multijet production with jets misidentified as leptons. For the  $W$ +jets and  $Z$ +jets backgrounds we use ALPGEN and PYTHIA for diboson and  $t\bar{t}$  production. The background MC samples for inclusive  $W$  and  $Z$  production are normalized using NNLO cross sections calculations of [23] using the NLO CTEQ 6.1 PDF. The  $Z$  boson  $p_T$  distribution is modeled to match the distribution observed in data [24]. We also derive a residual correction for each jet multiplicity bin on this distribution. We correct the  $p_T$  distribution of the  $W$  boson based on measured  $p_T$  of the  $Z$  boson spectrum [24], taking into account the ratio between the  $W$  and  $Z$  bosons  $p_T$  distributions at NLO [25].

In the  $e^+e^-$  and  $e^\pm\mu^\pm$  channels, the  $W$ +jets sample includes contributions from events where a fake electron originates from a jet or a photon. The size of each of these contributions is corrected such that the distribution of the number of hits in the innermost silicon layer (Layer 0) matches that observed in a  $W$ +jets enriched control sample. This sample contains events with two leptons of the same sign and a DY-BDT output (see Sec. V) greater than 0.5 (0-jet bin), -0.45 (1-jet bin) or -0.55 (2-jet bin).

NNLO calculations [26] are used for  $t\bar{t}$  production, while the NLO  $WW$ ,  $WZ$  and  $ZZ$  production cross section values are taken from Ref. [27]. For the main source of background,  $WW$  production, the  $p_T$  of the diboson system is modeled using the MC@NLO simulation [28] and the distribution of the opening angle of the two leptons is corrected to take into account the contribution from gluon fusion [29].

The background due to multijet production, where jets are misidentified as leptons, is determined from data. In order to obtain a high-statistics sample of predominantly multijet events the lepton quality requirements in each channel are inverted. To normalize the multijet sample to the actual multijet contribution in the signal region, and to correct for kinematic bias from reversing the lepton quality requirements, the multijet sample is compared to events which pass all of the signal requirements except that the leptons have the same-sign. As the probability of a jet faking a lepton is independent of charge assuming small charge correlation between the leptons in multijet events, the same-sign sample has the same normalization and kinematics as the actual multijet contribution.

### IV. PRESELECTION

All events satisfying any trigger of the DØ trigger suite are accepted for this analysis. While most events selected in the analysis are triggered by single-lepton and dilepton triggers, additional acceptance is gained by including triggers with jets or missing transverse energy. The simulated background samples are normalized to the number of expected events, based on the integrated luminosity and cross section. Using a Drell-Yan dominated sample in which the statistical uncertainty is smaller than the uncertainty on luminosity, we correct for inefficiencies by comparing the number of Monte-Carlo and data events. This procedure is repeated also for each jet multiplicity, to derive a jet bin dependent Drell-Yan background normalization.

Electrons are identified using calorimeter and tracking information. Electromagnetic showers are identified in the calorimeter by comparing the longitudinal and transverse shower profiles to those of simulated electrons. The showers must be isolated, deposit greater than 90% of their energy in the electromagnetic part of the calorimeter and pass a likelihood criterion that includes a spatial track match and, in the central detector region, an  $E/p$  requirement, where

$E$  is the energy of the calorimeter cluster and  $p$  is the momentum of the track. The value of the likelihood variable is referred to as the electron quality. Electrons are required to be in the acceptance of the calorimeter, and electrons with  $|\eta| > 2.5$  are not considered in this analysis (so that  $|\eta| < 1.1$  or  $1.5 < |\eta| < 2.5$ ). In the dielectron channel, events with one electron in the end-cap calorimeter (EC) are treated separately from events with both electrons in the central calorimeter (CC). This improves the analysis sensitivity as the background composition is different in the two pseudorapidity regions. Events where both the electrons are in the EC are not considered in the analysis due to large background and a small signal contribution. The transverse momentum of electrons is obtained from energy deposits in the calorimeter.

Muon tracks are reconstructed from hits in the wire chambers and scintillators in the muon system and must match a track in the central tracker. To select isolated muons, the scalar sum of the transverse momentum of all tracks, other than that of the muon, in a cone of  $\mathcal{R} = 0.5$  around the muon track is calculated, where  $\mathcal{R} = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$  and  $\phi$  is the azimuthal angle.

The transverse energy deposited in the calorimeter in a hollow cone of  $0.1 < \mathcal{R} < 0.4$  around the muon is also measured. In the  $e^\pm\mu^\mp$  final state, both quantities are required to be  $< 0.15 \times p_T^\mu$ , where  $p_T^\mu$  is the transverse momentum of the muon. In the dimuon final state, the track isolation ( $iso_{track}$ ) is required to be  $iso_{track} < 0.25 \times p_T^\mu$  and the calorimeter isolation ( $iso_{cal}$ ) is required to be  $iso_{cal} < 0.4 \times p_T^\mu$ . In addition, the calorimeter isolation for each muon is required to be  $iso_{cal} < 10$  GeV. In case the muon and the other lepton are closer than  $\Delta\mathcal{R} = 0.5$ , the isolation variables are recomputed. Muons are restricted to the fiducial coverage of the muon system  $|\eta| < 2.0$ . Muons from cosmic rays are rejected by requiring a timing criterion on the hits in the scintillator layers as well as applying restrictions on the position of the muon track with respect to the selected  $p\bar{p}$  interaction point (primary vertex).

Hadronic jets are reconstructed from energy deposits in the calorimeter towers using an iterative midpoint cone algorithm with a cone radius of 0.5 [30]. All calorimeter jets are required to pass a set of quality criteria which are approximately 98% efficient and have at least two reconstructed tracks within  $\Delta R(\text{track, jet-axis}) \leq 0.5$ . Jets are also required to originate from the  $p\bar{p}$  primary vertex (for RunIIb only).

Missing transverse energy,  $\cancel{E}_T$ , is obtained from a vector sum of transverse components of calorimeter energy depositions and corrected for identified muons. Jet energies are calibrated using transverse momentum balance in photon+jet events [31], and the correction is propagated to  $\cancel{E}_T$ .

We select events where the two leptons with highest  $p_T$  ( $\ell_1$  and  $\ell_2$ ) have opposite charge and originate from the same position (within 2 cm) along the beamline; any additional reconstructed lepton is not considered for  $e^+e^-$  and  $\mu^+\mu^-$  channels, whereas in the  $e^\pm\mu^\pm$  channel, a veto is applied on events containing more than two leptons. The requirements for the transverse momenta of the two leptons are the following: in the  $e^+e^-$  and  $\mu^+\mu^-$  channels we select  $p_T^{\ell_1} > 15$  GeV and  $p_T^{\ell_2} > 10$  GeV, while in the  $e^\pm\mu^\mp$  channel we select  $p_T^\mu > 10$  GeV and  $p_T^e > 15$  GeV. In addition, the dilepton invariant mass is required to exceed 15 GeV in all channels. This stage of the analysis is referred to as ‘‘preselection’’. Figs. 1-3 show several kinematic distributions from each dilepton channel after preselection.

The transverse mass is defined as  $M_T = \sqrt{2 \cdot p_T^\ell \cdot \cancel{E}_T \cdot (1 - \cos \Delta\phi(\ell, \cancel{E}_T))}$  and consequently the minimum transverse mass is  $M_T^{\min} = \min(M_T^{\ell_1}, M_T^{\ell_2})$ .

Signal and background composition changes with the jet multiplicity. The sensitivity of the analysis is greatly improved by splitting the events according to the jet multiplicity: no jet, one jet or two jets and more. The subsequent steps of the analysis are then performed for nine separate channels.

The number of events in each jet multiplicity bin at this stage can be found in Table I. In general, good agreement between data and the total expected background contribution is observed. The  $Z/\gamma^*$  contribution and multijet events are the dominant background sources after preselection.

## V. FINAL SELECTION

The dielectron and dimuon channels use a random forest BDT discriminant to remove the dominant  $Z/\gamma^*$  background at the preselection level (DY BDT). The BDT was trained for each Higgs mass point considered in each jet bin separately for dielectron and dimuon channels. The output of the BDT is a single number, which characterizes the event as background-like or signal-like.

The following list of input variables were used for the 0-jet DY BDT:

- $p_T$  of  $\ell_1$ ;
- $p_T$  of  $\ell_2$ ;
- invariant mass of the two leptons;
- azimuthal opening angle between the two leptons,  $\Delta\phi(\ell_1, \ell_2)$ ;

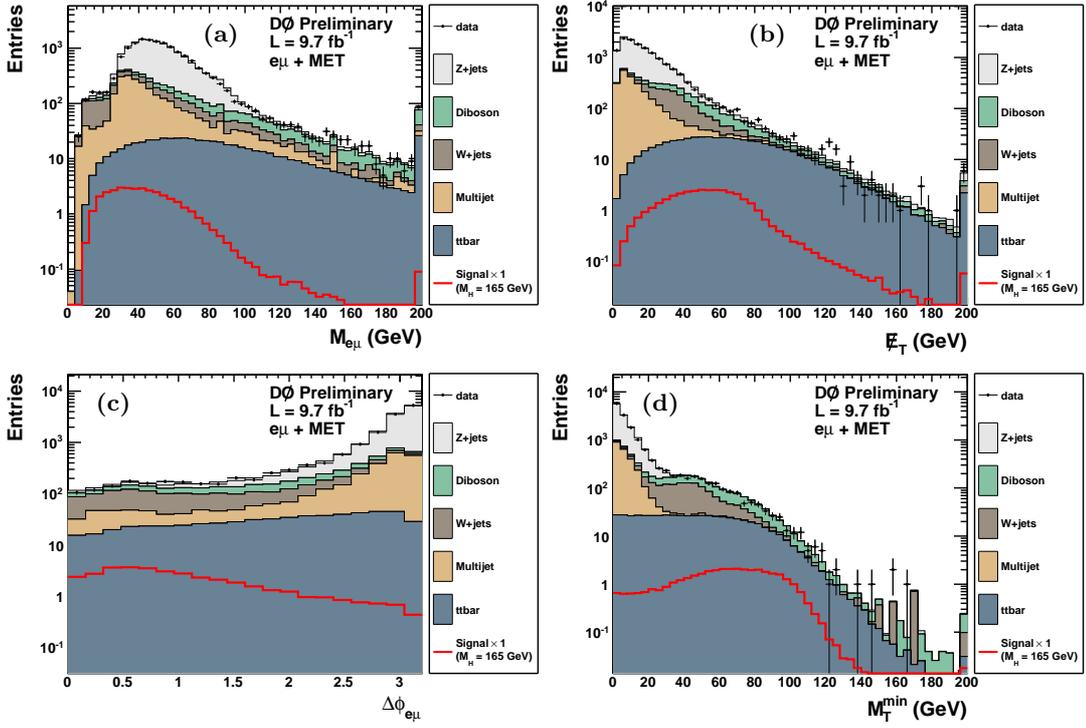


FIG. 1: The (a) dilepton mass, (b)  $E_T$ , (c)  $\Delta\phi$  between the leptons, and (d) minimum transverse mass between either lepton and the  $E_T$ , for the  $e^\pm\mu^\pm$  channel after preselection. In histograms (a),(b) and (d) the last bin includes an overflow.

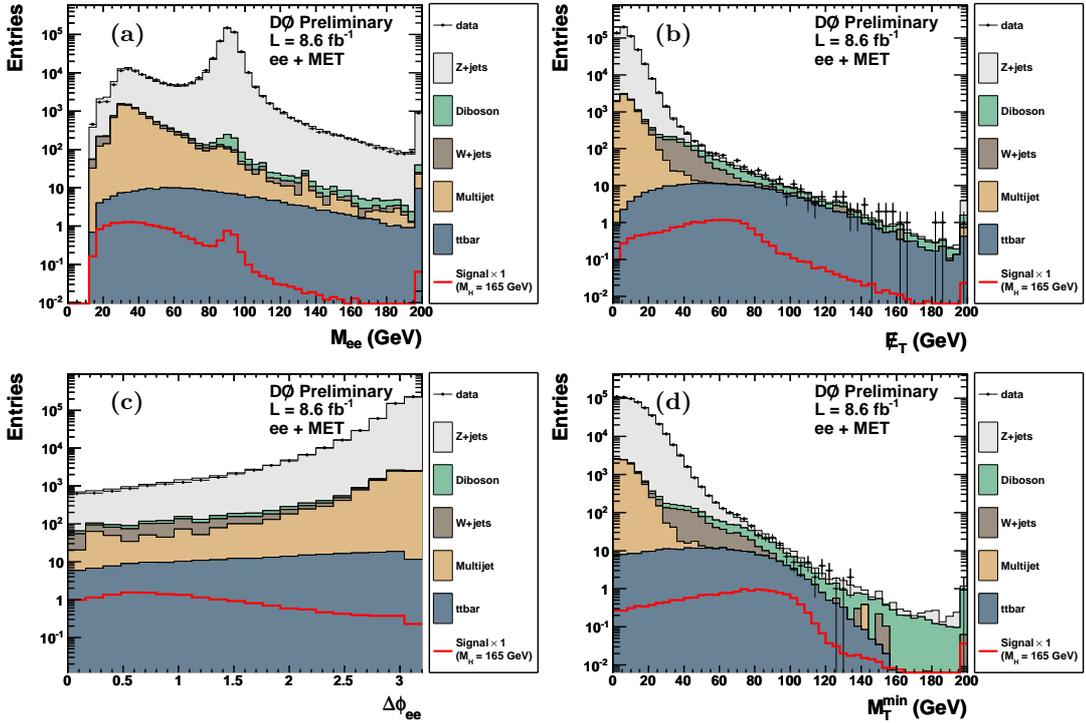


FIG. 2: The (a) dilepton mass, (b)  $E_T$ , (c)  $\Delta\phi$  between the leptons, and (d) minimum transverse mass between either lepton and the  $E_T$ , for the  $e^+e^-$  channel after preselection. In histograms (a),(b) and (d) the last bin includes an overflow.

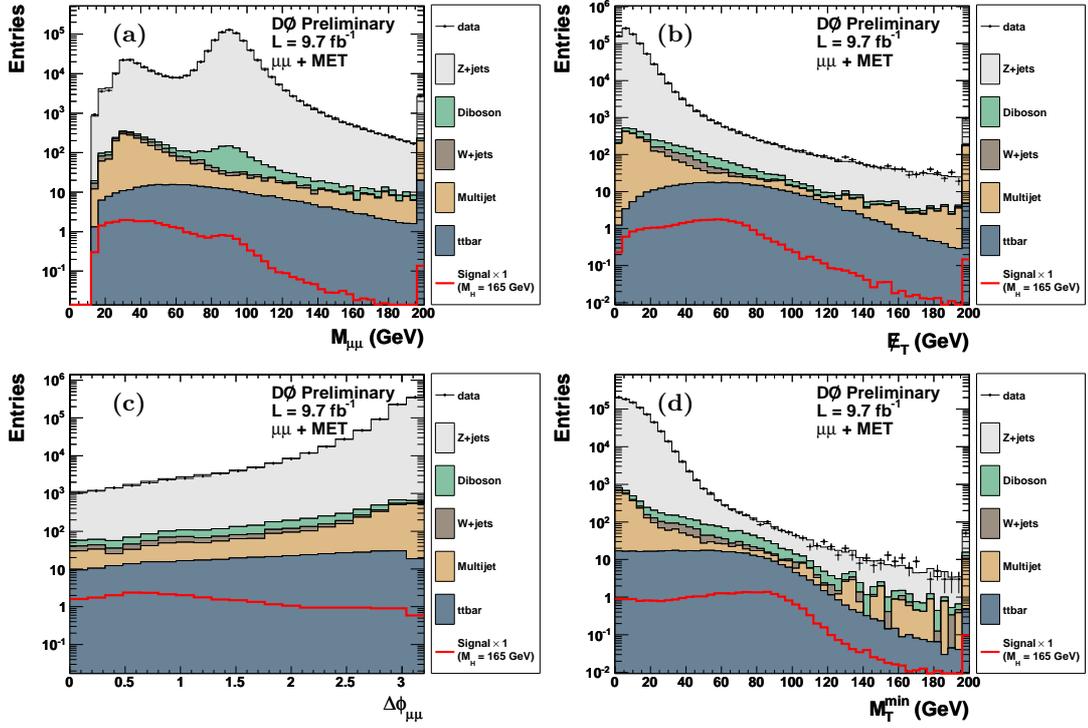


FIG. 3: The (a) dilepton mass, (b)  $\cancel{E}_T$ , (c)  $\Delta\phi$  between the leptons, and (d) minimum transverse mass between either lepton and the  $\cancel{E}_T$ , for the  $\mu^+\mu^-$  channel after preselection. In histograms (a),(b) and (d) the last bin includes an overflow.

TABLE I: Expected and observed number of events for each jet multiplicity bin after preselection in the  $e^\pm\mu^\pm$ ,  $e^+e^-$  and  $\mu^+\mu^-$  final states. The signal assumes a Higgs boson mass of 165 GeV for each jet bin.

	Data	Total Background	Signal	$Z \rightarrow ee$	$Z \rightarrow \mu\mu$	$Z \rightarrow \tau\tau$	$t\bar{t}$	W+jets	Diboson	Multijet
$e^\pm\mu^\pm$ :										
0 jet	12131	12265.7	21.5	343.7	1036.0	7468.3	17.8	960.8	728.4	1710.7
1 jet	2039	2123.7	10.9	54.0	147.5	998.6	174.8	173.7	152.6	422.4
$\geq 2$ jets	766	751.2	5.3	7.2	24.0	148.7	408.7	57.1	25.3	80.2
$e^+e^-$ :										
0 jet	473311	472195.3	8.9	459814.7	-	3935.9	9.4	840.0	424.8	7170.5
1 jet	42480	41795.4	4.6	39975.9	-	258.1	64.0	174.7	151.2	1171.5
$\geq 2$ jets	10151	10213.6	3.5	9280.6	-	99.7	171.2	75.8	153.1	433.2
$\mu^+\mu^-$ :										
0 jet	701086	703360.0	14.2	-	694950.3	5612.6	11.3	359.2	671.8	1754.7
1 jet	95906	96435.5	8.2	-	94828.9	691.6	102.5	76.5	316.3	419.7
$\geq 2$ jets	16483	16945.2	6.5	-	16177.2	108.0	280.6	14.6	259.9	104.9

- opening angle in  $\eta$  and  $\phi$  space between the two leptons,  $\Delta R(\ell_1, \ell_2)$ ;
- $\cancel{E}_T$ ;
- $\cancel{E}_T^{\text{special}} = \begin{cases} \cancel{E}_T & \text{if } \Delta\phi(\cancel{E}_T, \text{nearest lepton or jet}) > \pi/2 \\ \cancel{E}_T \times \sin(\Delta\phi(\cancel{E}_T, \text{nearest lepton or jet})) & \text{otherwise} \end{cases}$
- minimum transverse mass  $m_T^{\text{min}}$ ;
- minimum of azimuthal angle difference between  $\cancel{E}_T$  and each lepton;
- maximum of azimuthal angle difference between  $\cancel{E}_T$  and each lepton;

- transverse mass between  $\cancel{E}_T$  and dilepton pair,  $M_T(\ell_1\ell_2, \cancel{E}_T)$ ;
- $M_{T2}$ , an extension of the transverse mass to a final state with two visible and two invisible particles [32];

The 1-jet DY-BDT uses in addition the following additional variables:

- $\cancel{E}_T^{\text{Scaled}} = \cancel{E}_T / \sqrt{\sum_{\text{jets}} (\Delta E^{\text{jet}} \cdot \sin \theta^{\text{jet}} \cdot \cos \Delta \phi(\text{jet}, \cancel{E}_T))^2}$  (where  $\Delta E$  is the jet energy resolution);
- jet  $p_T$ ;
- azimuthal angle difference between  $\cancel{E}_T$  and the jet;

The 2-jet DY-BDT uses all of the variables for the 0-jet DY-BDT, the jet quantities for the two highest  $p_T$  jets ( $j_1$  and  $j_2$ ), and the following additional variables:

- absolute value of the rapidity difference between the jets,  $\Delta \eta(j_1, j_2)$ ;
- invariant mass of the two jets,  $M(j_1, j_2)$ ;

To reject most of the  $Z/\gamma^*$  background, we require that the discriminant be over some cut value. This value varies for each Higgs mass point in each jet bin. As an example, the DY-BDT discriminant for  $m_H = 165$  GeV is shown in Fig. 4. For the final selection a requirement at 0.9, -0.5 and -0.7 is applied in these distributions for the 0-jet, 1-jet and  $\geq 2$ -jet bin respectively.

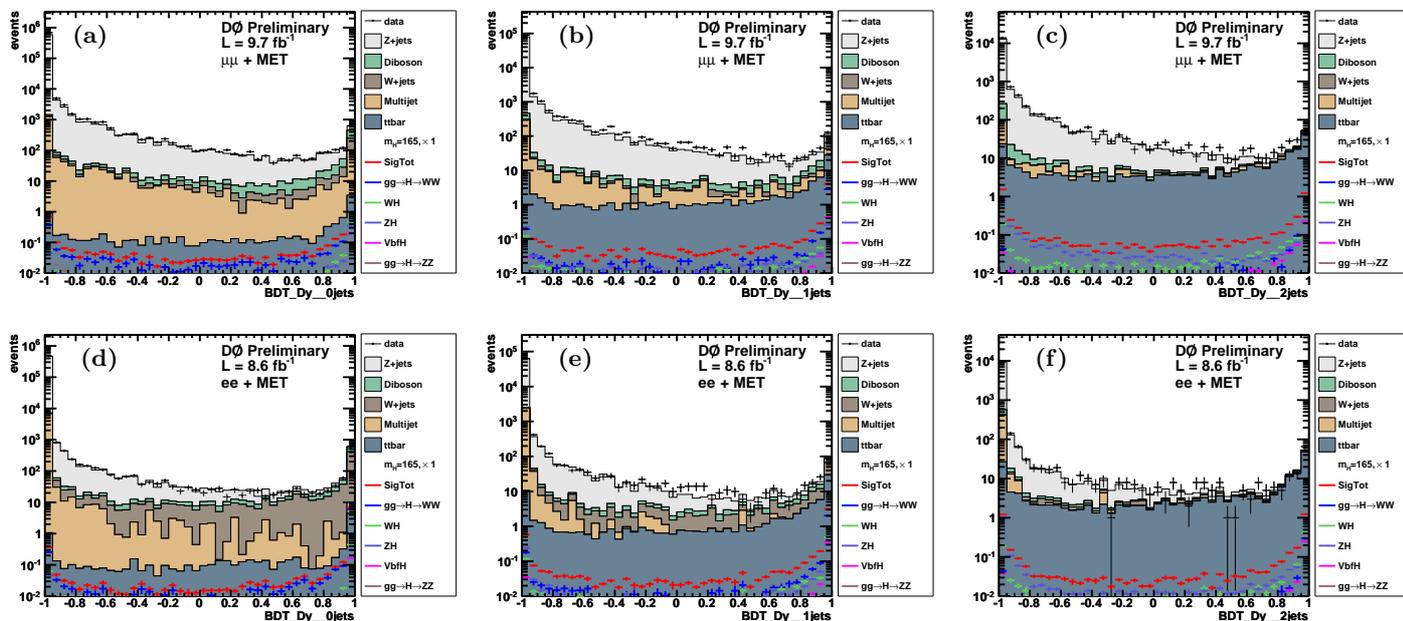


FIG. 4: DY BDT discriminant for  $\mu^+\mu^-$  channel in the (a) 0-jet bin, (b) 1-jet bin, (c)  $\geq 2$ -jet bin and corresponding distributions for the  $e^+e^-$  channel in the (d) 0-jet bin, (e) 1-jet bin and (f)  $\geq 2$ -jet bin. The discriminant shown is trained for a Higgs mass of 165 GeV.

The  $e^\pm\mu^\mp$  channel does not utilize a BDT discriminant to remove the  $Z/\gamma^*$  background, but instead applies kinematic cuts to reduce the dominant backgrounds after preselection. For the signal, large missing transverse energy is expected due to neutrinos in the final state. This is not the case for multijet and  $Z/\gamma^* \rightarrow ee, \mu\mu$  events. In addition, the missing transverse energy is not expected to be aligned with any of the leptons for the signal while for  $Z/\gamma^*$  as well as multijet events this is the case. For the latter, the missing transverse energy is mostly caused by the mismeasured energy of fake leptons, thus the missing transverse energy tends to point in the direction of the fake leptons. In  $Z/\gamma^* \rightarrow \tau\tau$  events, charged leptons and neutrinos follow the direction of the tau leptons due to the large boost, thus the missing transverse energy is also expected to be aligned with the leptons. A quantity that takes into account both the absolute value of the missing transverse energy as well as the angle to the leptons is the minimum transverse mass,

TABLE II: Expected and observed number of events for each jet multiplicity bin after the final selection in the  $e^\pm\mu^\pm$ ,  $e^+e^-$ , and  $\mu^+\mu^-$  final states, assuming  $m_H = 165$  GeV for each jet bin. The numbers in brackets correspond to the efficiency of the final selection with respect to the preselection, shown in Table I, for both the total background and signal. The uncertainty quoted on the total background combines both statistical and systematic uncertainties.

	Data	Total Background	Signal	$Z \rightarrow ee$	$Z \rightarrow \mu\mu$	$Z \rightarrow \tau\tau$	$t\bar{t}$	W+jets	Diboson	Multijet	
$e^\pm\mu^\pm$ :											
0 jet	1266	$1334.1 \pm 128$ (10.9%)	20.1 (93.5%)	6.3	54.6	7.5	12.5	714.7	522.6	15.8	
1 jet	367	$339.8 \pm 44$ (16.0%)	9.3 (85.3%)	3.2	13.4	2.9	108.8	106.0	93.83	11.7	
$\geq 2$	321	$307.1 \pm 43$ (40.9%)	4.1 (77.4%)	0.96	2.8	0.91	250.9	35.0	12.24	4.2	
$e^+e^-$ :											
0 jet	812	$880.6 \pm 80$ (0.1%)	8.0 (89.9%)	128.9	-	5.1	5.9	498.9	222.0	19.8	
1 jet	430	$408.2 \pm 57$ (1.0%)	4.0 (87.0%)	169.5	-	11.7	54.4	114.0	51.6	7.1	
$\geq 2$ jets	365	$355.1 \pm 53$ (3.5%)	2.3 (65.7%)	129.3	-	20.7	140.0	44.8	14.2	5.9	
$\mu^+\mu^-$ :											
0 jet	749	$822.3 \pm 107$ (0.1%)	11.7 (82.3%)	-	257.8	3.7	4.6	175.4	266.3	114.5	
1 jet	660	$635.0 \pm 100$ (0.7%)	5.9 (72.0%)	-	389.1	30.1	62.9	39.0	76.6	37.2	
$\geq 2$ jets	809	$815.3 \pm 146$ (4.8%)	3.6 (55.4%)	-	562.2	11.1	189.8	8.9	26.7	16.6	

$M_T^{\min} = \min(M_T^e, M_T^\mu)$ , and is expected to peak at lower values for  $Z/\gamma^*$  and multijet events compared to the signal. Thus, for the  $e^\pm\mu^\pm$  events a minimum transverse mass exceeding 20 GeV is required, which rejects the majority of the  $Z/\gamma^*$  and multijet backgrounds. An additional requirement of  $M_{T2} > 15$  GeV further reduces these backgrounds.

For the final selection,  $M_T^{\min} > 20$  GeV and  $M_{T2} > 15$  GeV are required for all three jet multiplicity bins. These distributions of  $M_T^{\min}$  and  $M_{T2}$  for the  $e^\pm\mu^\pm$  final state after preselection are shown in Fig. 5 for each jet multiplicity bin.

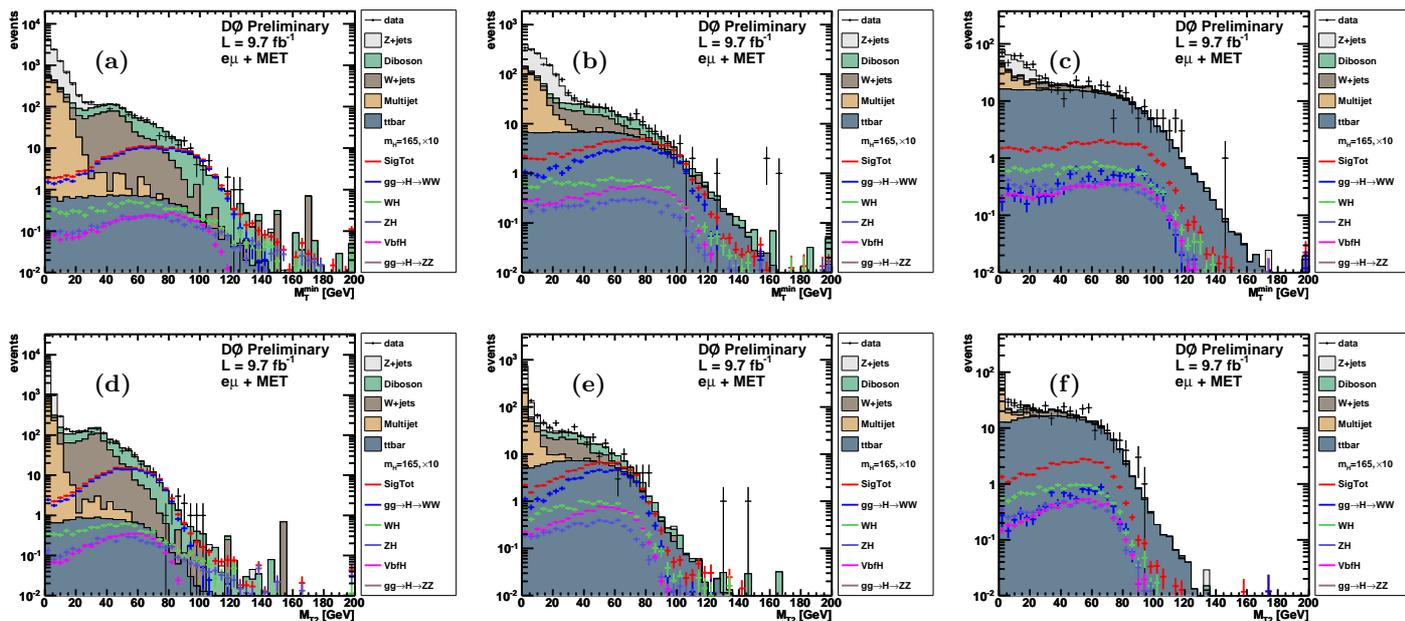


FIG. 5:  $M_T^{\min}$  distribution for the  $e^\pm\mu^\pm$  channel in the (a) 0-jet bin, (b) 1-jet bin, (c)  $\geq 2$ -jet bin.  $M_{T2}$  distribution for the  $e^\pm\mu^\pm$  channel in the (d) 0-jet bin, (e) 1-jet bin, (f)  $\geq 2$ -jet bin.

The number of events at the final selection stage for each of the dilepton states are shown in Table II. In general, good agreement between data and the remaining backgrounds is observed.

## VI. FINAL DISCRIMINANTS

The signal is separated from the remaining background using a second BDT. It uses as inputs all the variables used for the DY discriminant listed above with the addition of the following variables:

- Dielectron
  - electron likelihood
  - number of Layer 0 hits for the minimum quality electron (Run IIb only)
  - number of Layer 0 hits for the maximum quality electron (Run IIb only)
- Electron-muon
  - electron likelihood
  - number of Layer 0 hits for the electron (Run IIb only)
  - muon quality
- Dimuon
  - minimum quality of the two muons
  - the track isolation of each muon

The following additional information is provided for events with jets ( $N_{\text{jets}}$ ):

- Channels with  $N_{\text{jets}} = 1$ 
  - $O(b\text{-tag})$ : the output of a multivariate analysis trained to discriminate jets originating from  $b$ -quarks from those originating from light quarks [33].
- Channels with  $N_{\text{jets}} > 1$ 
  - maximum  $O(b\text{-tag})$
  - minimum  $O(b\text{-tag})$
- All channels
  - the product of charge and pseudorapidity for both leptons

Simulated events are used to train the BDT to differentiate between all Higgs boson signal events, including gluon fusion, associated production and vector boson fusion, and all background events (diboson,  $t\bar{t}$ ,  $W$  boson,  $Z/\gamma^*$ , etc.) in the three jet multiplicities (0, 1, and  $\geq 2$  jet bins), and for each Higgs boson mass considered. The distributions of the final discriminant for separate channels assuming  $M_H = 165$  GeV is shown in Fig. 6, 7 and 8.

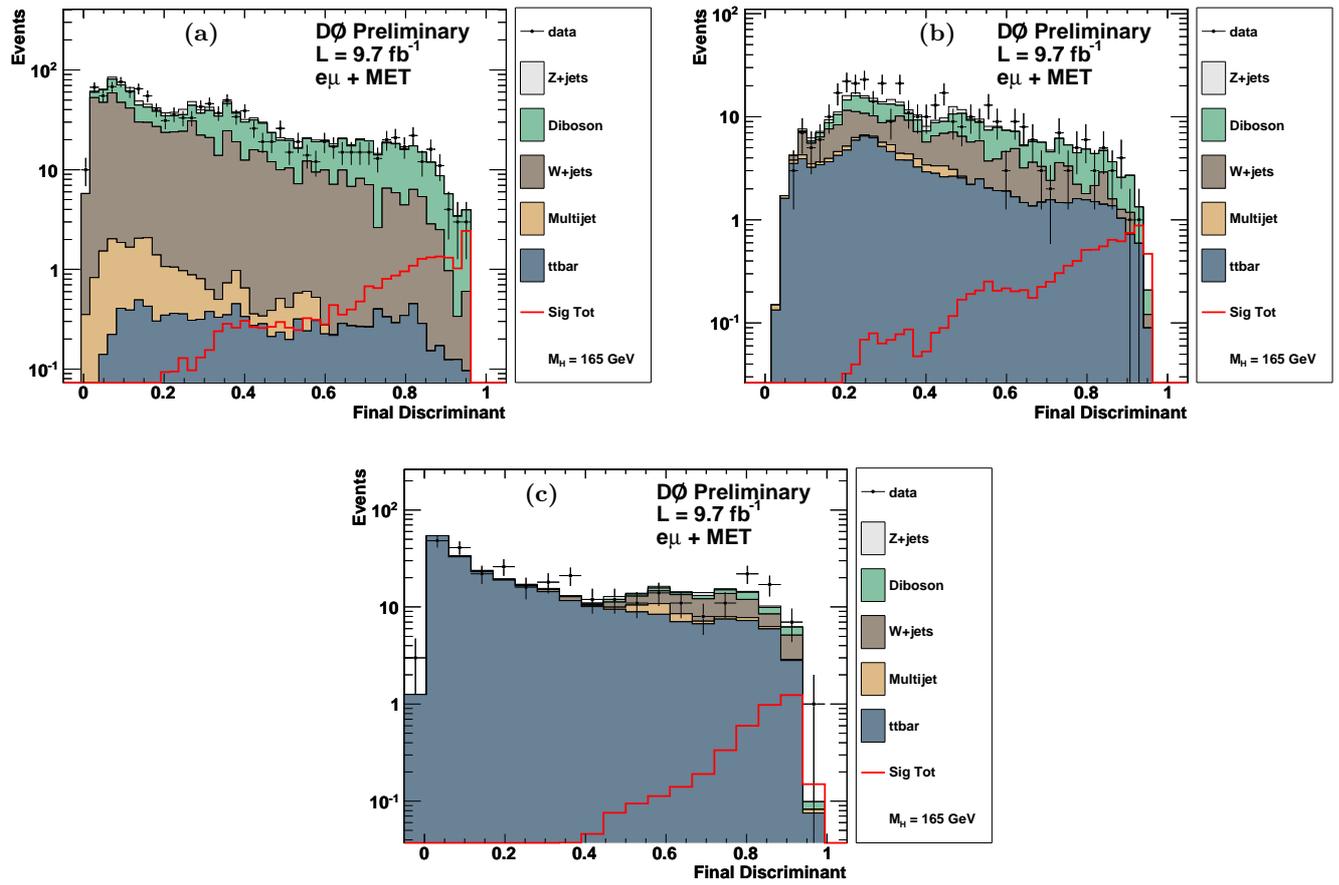


FIG. 6: The final BDT discriminant where  $M_H = 165 \text{ GeV}$  for the  $e^\pm\mu^\pm$  channel with no jet (a), one jet (b) and equal or more than 2 jets (c).

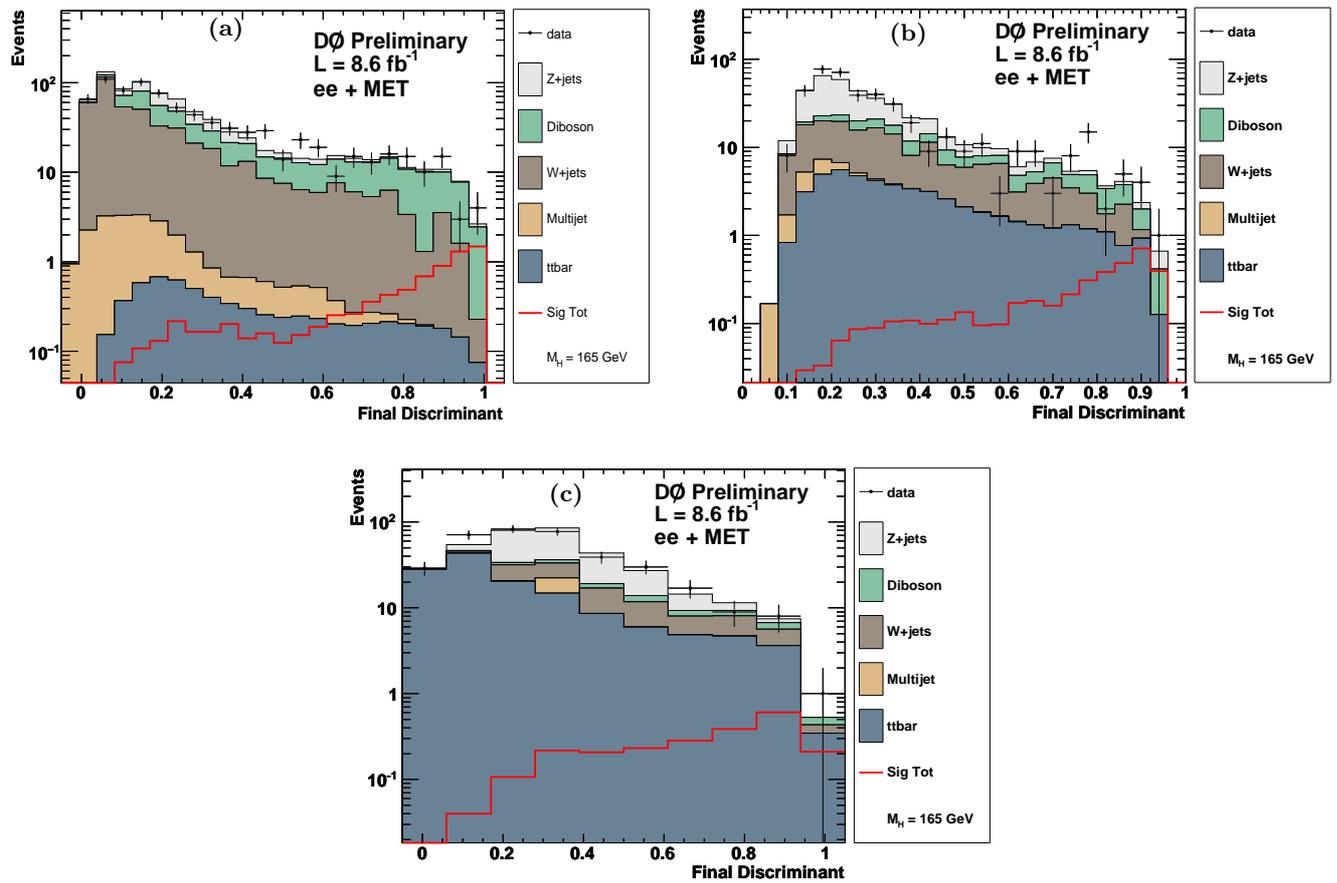


FIG. 7: The final BDT discriminant where  $M_H = 165 \text{ GeV}$  for the  $e^+e^-$  channel with no jet (a), one jet (b) and equal or more than 2 jets (c).

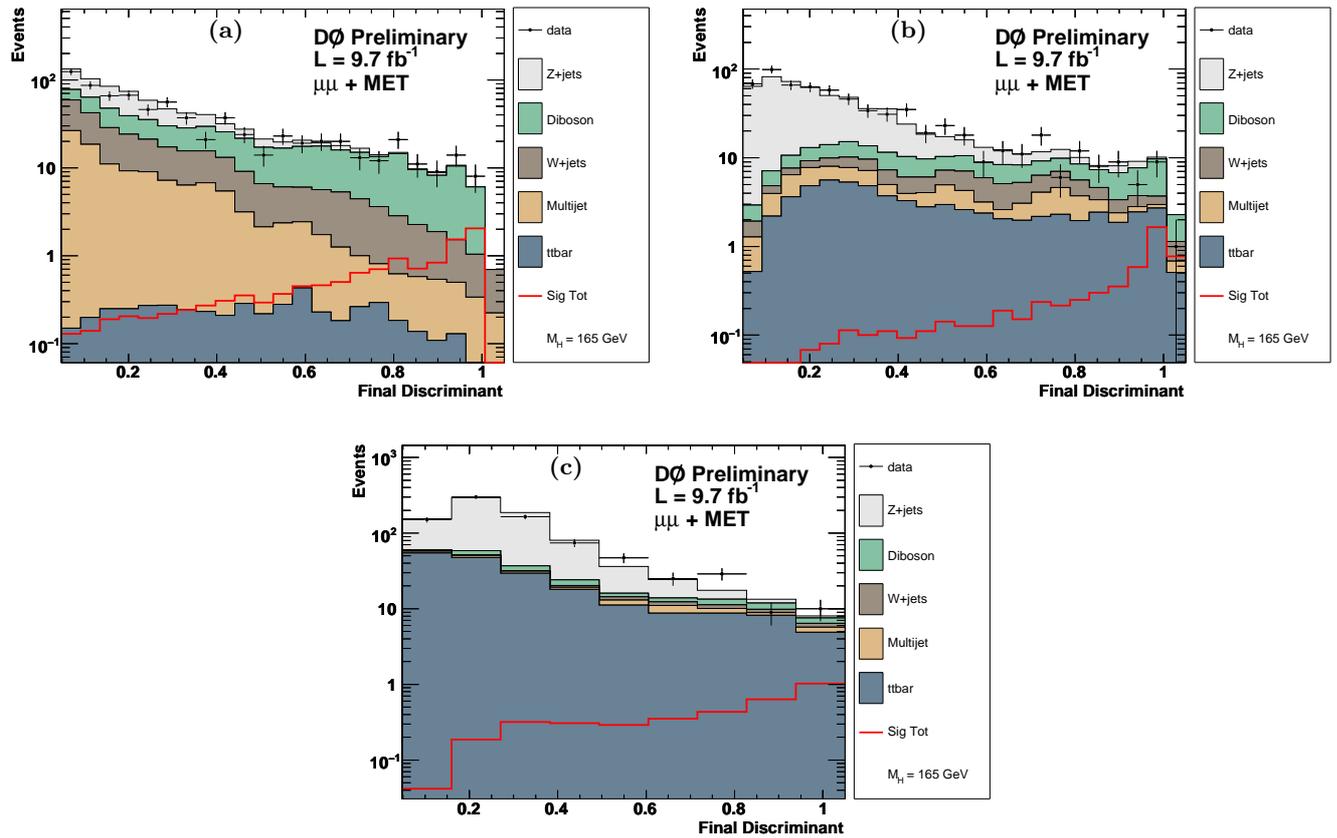


FIG. 8: The final BDT discriminant where  $M_H = 165 \text{ GeV}$  for the  $\mu^+\mu^-$  channel with no jet (a), one jet (b) and equal or more than 2 jets (c).

TABLE III: Expected and observed upper limits at 95% CL for  $\sigma(p\bar{p} \rightarrow H + X)$  relative to the SM for the total combination and separately for the  $e^+e^-$ ,  $e^\pm\mu^\pm$  and  $\mu^+\mu^-$  channels in Run II for  $M_H$  between 115 and 200 GeV.

$M_H =$	115	120	125	130	135	140	145	150	155	160	165	170	175	180	185	190	195	200
Exp. all:	7.72	5.13	3.77	2.96	2.41	2.08	1.76	1.49	1.25	0.88	0.82	1.02	1.23	1.46	1.82	2.41	2.83	3.35
Obs. all:	11.83	7.37	4.23	4.04	3.54	3.01	2.06	1.91	1.75	1.13	1.16	1.42	1.58	1.86	2.22	2.87	3.68	4.26
Exp. $e^\pm\mu^\pm$ :	11.55	7.26	5.22	4.15	3.35	2.86	2.38	2.11	1.73	1.27	1.19	1.47	1.74	2.10	2.64	3.25	3.93	4.65
Obs. $e^\pm\mu^\pm$ :	12.94	7.28	4.87	4.45	3.93	2.65	2.09	1.82	1.60	1.16	1.33	1.51	1.87	2.00	2.87	3.33	3.89	4.55
Exp. $e^+e^-$ :	15.87	11.36	8.30	6.25	4.89	4.22	3.67	3.13	2.67	1.93	1.84	2.10	2.57	3.06	3.63	4.93	5.68	6.61
Obs. $e^+e^-$ :	19.18	13.49	10.24	8.77	6.31	6.51	4.61	4.83	4.51	2.59	2.81	3.32	3.19	4.70	4.46	7.03	8.12	8.91
Exp. $\mu^+\mu^-$ :	14.44	9.54	6.83	5.24	4.31	3.77	3.34	2.85	2.57	1.91	1.77	2.24	2.64	3.18	4.00	5.04	5.50	6.75
Obs. $\mu^+\mu^-$ :	26.28	16.83	11.31	7.54	7.55	6.73	5.68	5.12	3.84	3.34	2.57	3.67	4.24	5.14	6.51	6.66	9.57	10.74

## VII. SYSTEMATIC UNCERTAINTIES

Sources of systematic uncertainties that affect only the normalization are: overall normalization uncertainty due to theoretical cross sections of  $Z$ +jets (4%); theoretical cross section for  $W$ +jets (6%), diboson (6%) and  $t\bar{t}$  (7%); multijet normalization (30%);  $W$ +jets overall normalization (15 to 30%); a  $Z$ +jets jet bin dependent normalization ((2 – 15)%); and jet bin dependent modeling of the  $Z$ +jets background and the  $\cancel{E}_T$  ((5-19)%). The signal  $gg \rightarrow H$  cross-section has different scale and PDF uncertainties depending on the reconstructed jet bin. Using the prescription described in [34], the  $gg \rightarrow H$  cross-section scale/PDF uncertainties range between (13-33)%/(7.6-30)%, depending on the jet bin. We also consider sources of systematic uncertainty which affect the shape of the final discriminant distribution (and quote here the average fractional change across bins of the final discriminant distribution for all backgrounds): jet energy scale (4%); jet resolution (0.5%); jet identification (2%); jet association to primary vertex (vertex confirmation) (2%) and  $b$ -tagging for the heavy-flavor  $t\bar{t}$  sample (4%). Several systematic uncertainties are included which have a small ( $< 1\%$ ) effect on the background model: modeling of diboson production in terms of  $p_T(WW)$  and  $\Delta\phi$  between the leptons, and the  $p_T$  of the vector boson from  $W$ +jets and  $Z$ +jets production. The shape change in the BDT distribution for background due to PDF uncertainties was found to be small and flat. It is taken into account as a 2% systematic uncertainty for all background MC samples.

## VIII. LIMITS

The BDT output distributions in data agree within uncertainties with the expected backgrounds as shown in Fig. 6, 7 and 8. The BDT output distributions are therefore used to set limits on the Higgs boson inclusive production cross section  $\sigma(p\bar{p} \rightarrow H + X)$  assuming SM values for the branching ratios and for the relative cross sections of the various Higgs production mechanisms considered [35]. We calculate limits using a modified frequentist method (CLs), with a log-likelihood ratio (LLR) test statistic [36]. All lepton channels are combined in the limit, but to achieve maximal sensitivity, the nine individual inputs (three leptonic channels, three jet bins) are treated separately. To minimize the degrading effects of systematics on the search sensitivity, the individual background contributions are fit to the data observation by maximizing a profile likelihood function for the background-only and signal-plus-background hypotheses [37].

Table III presents expected and observed upper limits at 95% CL for  $\sigma(p\bar{p} \rightarrow H + X)$  relative to that expected in the SM for each Higgs boson mass considered. Fig. 9 shows expected and observed limits for  $\sigma(p\bar{p} \rightarrow H + X)$  relative to the SM for different Higgs boson masses, while Fig. 10 shows the corresponding LLR distributions. For  $M_H = 165$  GeV, the expected limit is 0.82 relative to the Standard Model yield and the observed limit reaches 1.16 in the same units.

## IX. CONCLUSIONS

A search for the standard model Higgs boson in dilepton ( $e^\pm\mu^\mp$ ,  $e^+e^-$ ,  $\mu^+\mu^-$ ) events with large missing transverse energy using 8.6 to 9.7  $\text{fb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV, collected with the DØ detector at the Fermilab Tevatron collider was presented. No significant excess above standard model background expectations was observed, and upper limits on Higgs boson production were derived.

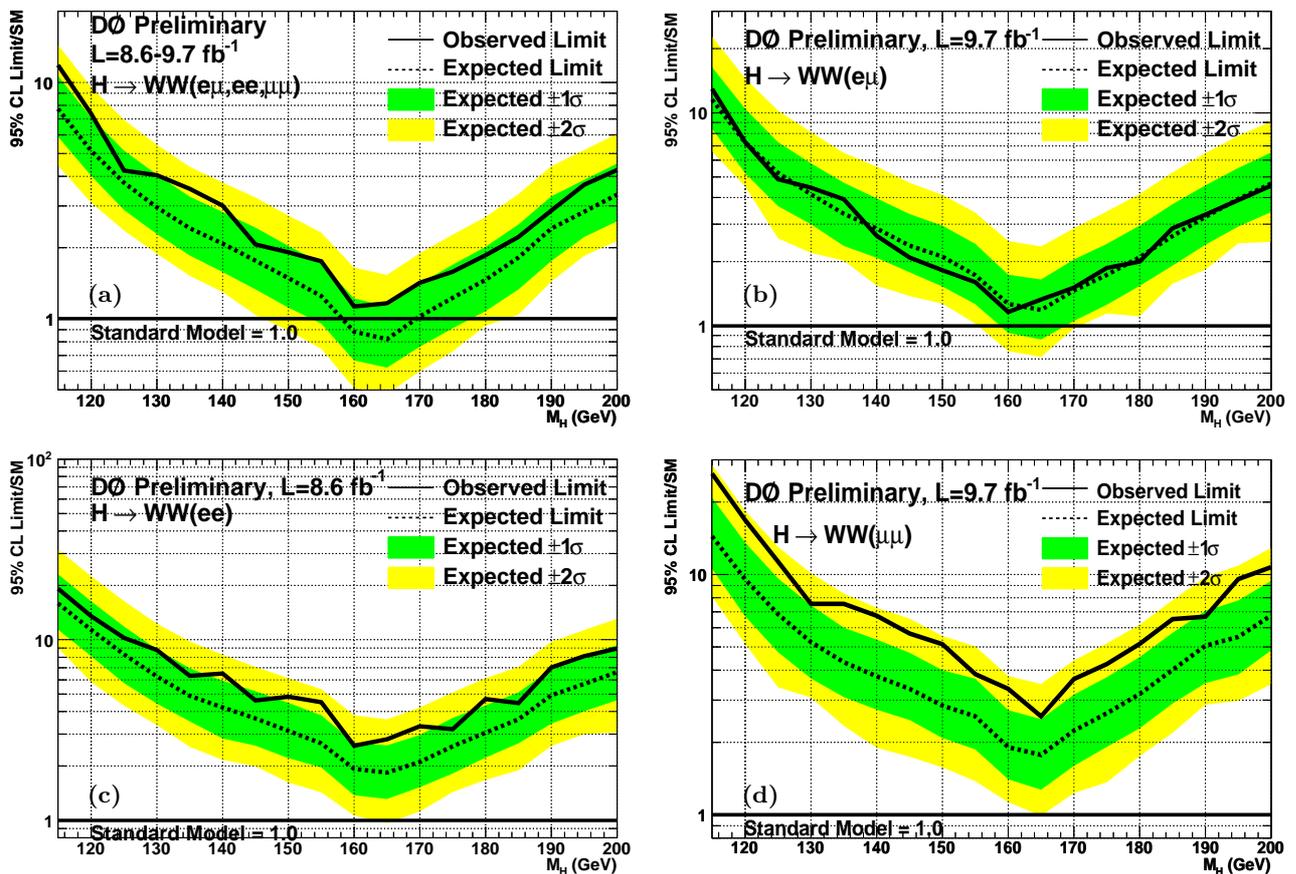


FIG. 9: Excluded cross section ( $\sigma(p\bar{p} \rightarrow H + X)$ ) at 95% CL in units of the SM cross section as a function of  $M_H$  using (a) all channels, (b)  $e^\pm\mu^\pm$  channel, (c)  $e^+e^-$  channel, (d)  $\mu^+\mu^-$  channel.

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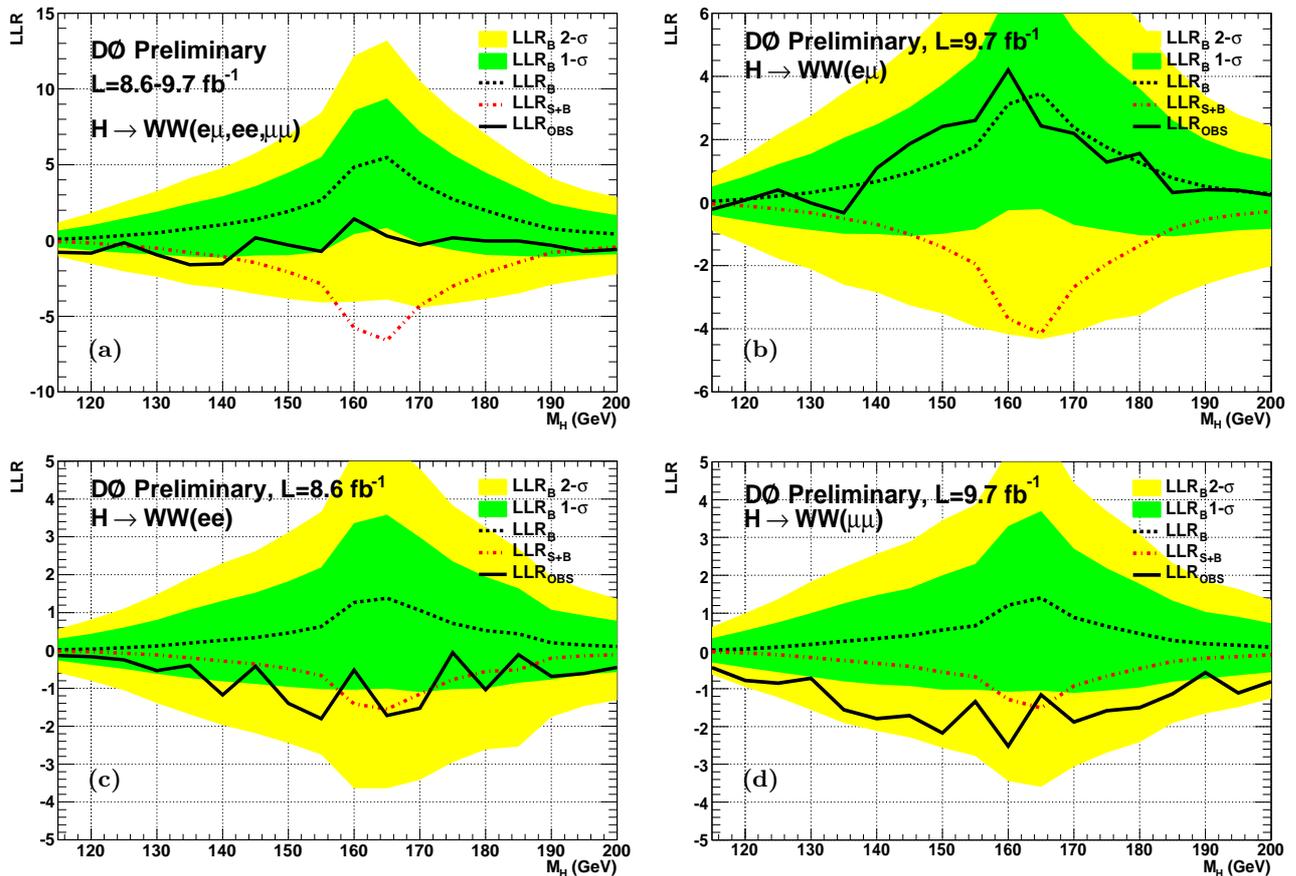


FIG. 10: The observed LLR (solid line) as a function of  $M_H$  using (a) all channels, (b)  $e^\pm\mu^\pm$  channel, (c)  $e^+e^-$  channel, (d)  $\mu^+\mu^-$  channel. Also shown are the expected LLRs for the Background (black dashed line) and Signal+Background (red dashed line) hypotheses, with the green and yellow bands indicating one and two sigma fluctuations of the expected LLR for the Background-only hypothesis.

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