



A Search for WH Production at $\sqrt{s} = 1.96$ TeV with 1 fb^{-1} of Data

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A search for WH production in $p\bar{p}$ collisions at a center of mass energy $\sqrt{s} = 1.96$ TeV is presented. An integrated luminosity of 1.0 fb^{-1} , accumulated by the DØ experiment at the Tevatron collider, was used. Events containing one lepton, missing transverse energy and two or three jets, with at least one of them being b -tagged, are considered. In the single and double b -tagged sample, good agreement between data and the Standard Model is observed. No excess being observed, we set combined upper limits on $\sigma(p\bar{p} \rightarrow WH) \times B(H \rightarrow b\bar{b})$ from 1.1 pb to 1.4 pb for Higgs masses ranging from 105 to 145 GeV (0.9 to 1.2 in expected limits). For $m_H = 115$ GeV, the observed (expected) upper limit is 1.3 (1.1) pb, to be compared to the standard model expected cross section of 0.13 pb.

Preliminary Results for Winter 2007 Conferences

I. INTRODUCTION

For Higgs searches, the most sensitive production channel at the Tevatron for a Higgs mass (m_H) below ~ 135 GeV is the associated production of a Higgs boson with a W boson. The DØ collaboration has published a search for such production in the $e\nu b\bar{b}$ decay channel using 174 pb^{-1} of integrated luminosity [1]. An update of that result using the $e\nu b\bar{b}$ and $\mu\nu b\bar{b}$ decay channels and a larger dataset of 0.4 fb^{-1} has been presented [2]. The CDF collaboration has published a similar search on 320 pb^{-1} of data [3], and recently presented an update of the search with 1 fb^{-1} of data [4].

Both e and μ channels are also studied here. As in Ref. [2], the channels are separated in events having exactly one “tight” b -tagged jet, and those having two “loose” b -tagged jet (with no overlap). The resulting four channels are analyzed independently to optimize the sensitivity and then combined. In parallel, the four equivalent channels in $W + 3$ jet events are also studied as a control sample.

The data set corresponds to an integrated luminosity of 1.0 fb^{-1} and consists of data recorded between April 2002 and February 2006. One lepton, missing transverse energy \cancel{E}_T to account for the neutrino in the W boson decay and two or three jets are required, with at least one of them being b -tagged. Dominant backgrounds to the WH signal are $W +$ heavy flavor production, $t\bar{t}$ and single-top quark production.

II. DATA SAMPLE

The analysis relies on the following components of the DØ detector: a magnetic central-tracking system, which consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet [5]; a liquid-argon/uranium calorimeter made of a central section (CC) covering pseudorapidity $|\eta|$ up to ≈ 1.1 , and two endcap calorimeters (EC) extending coverage to $|\eta| < 4.0$, all housed in separate cryostats [6], with scintillators between the CC and EC cryostats providing sampling of developing showers at $1.1 < |\eta| < 1.4$; a muon system which resides beyond the calorimetry, and consists of a layer of tracking detectors and scintillation trigger counters before 1.8 T toroids.

The luminosity is measured using plastic scintillator arrays located in front of the EC cryostats, at $2.7 < |\eta| < 4.4$. The uncertainty on the measured luminosity is 6%. We reject data periods in which the quality of tracking (CFT and SMT), the calorimeter or muon system data may be compromised. The resulting luminosity (1.0 fb^{-1}) is about 10% lower than the total recorded luminosity during the period considered in this analysis.

The trigger and data acquisition systems are designed to accommodate the large luminosity of Run II. The events used in this analysis are triggered in the electron channel by a single trigger requiring an electromagnetic (EM) object and one jet (EM+jet). Triggers are taken into account in the simulation through event reweighting with an efficiency derived from data, and parameterised as a function of lepton azimuthal angle φ and η , and jet p_T . This efficiency is in average $\sim 90\%$ for the events passing our requirements.

In the muon analysis we accept events from any trigger, since we expect close to 100% of our events to be triggered by our redundant triggering system (single muons, muon+jets, topological triggers). This is verified using a combination of single-muon triggers for which a full analysis is completed. The efficiency of this trigger combination is measured using a tag-and-probe method on di-muons Z events with an uncertainty of 3%, and is $\sim 70\%$ for the events passing our requirements. This efficiency is consistent with the increase in statistics (47% in average) that we observe in all channels when accepting events from any trigger, both in data and in simulation, within $\pm 3\%$ for the high statistics channels, and within $\pm 10\%$ channels for the (low statistics) b -tagged channels. The shape of all distributions remains unchanged within the acceptance systematic uncertainty originating mainly from the jet energy scale uncertainty. We thus use this sample for the final analysis, after attributing an additional 10% uncertainty on the trigger systematic in this channel.

III. SIMULATED DATASETS

Background and signal processes have been generated by different event generators as listed below. The PYTHIA [7] event generator using the CTEQ6L1 [8] leading-order parton distribution functions, has been used to generate the following processes:

- Diboson processes: $WW \rightarrow \ell\nu jj$; $WZ \rightarrow \ell\nu jj$; $WZ \rightarrow jj\ell\ell$; inclusive decays of ZZ ($\ell = e$ or μ)
- $WH \rightarrow \ell\nu b\bar{b}$ production ($\ell = e, \mu, \text{ or } \tau$)

The following processes are simulated using other generators:

- W + jets and Z + jets events are generated with ALPGEN [9] (with PYTHIA radiation and showering), since ALPGEN yields a better description of processes with high jet multiplicity. ALPGEN samples have been produced using the MLM parton-jet matching prescription [9] and are generated in bins of light parton multiplicity. $W(Z)$ + jets samples contain Wjj and Wcj processes, whilst $Wb\bar{b}$ and $Wc\bar{c}$ are generated separately.
- $Wb\bar{b}$ and $Wc\bar{c}$ events are generated with ALPGEN requiring 2 heavy-flavoured parton jets with $p_T > 0$ GeV and $|\eta| < 5.0$, and “light parton” (u, d, s , and g) jets with $p_T > 8$ GeV separated in η - φ by $\Delta R (\equiv \sqrt{\Delta\eta^2 + \Delta\varphi^2}) > 0.4$
- $Zjj \rightarrow \ell\ell jj$, $Zb\bar{b} \rightarrow \ell\ell b\bar{b}$ and $Zc\bar{c} \rightarrow \ell\ell c\bar{c}$ ($\ell = e, \mu$ or τ) are generated with ALPGEN.
- $t\bar{t}$ (lepton+jet and dilepton channels) production is generated with ALPGEN.
- Single-top events (s -channel (tb) and t -channel (tbq)) are generated using COMPHEP [10].

All the generated events were processed through the $D\bar{O}$ detector simulation (based on GEANT [11]) and the reconstruction software.

The simulated events have been reweighted with trigger efficiencies and with all the efficiency ratios of data to simulation (scale factors). Depending on the efficiency considered these scale factors are constant or have a dependency on the event kinematics which is then taken into account.

The simulated background processes are absolutely normalized to the SM prediction of their cross section except W + jets which are normalized to data. The normalization factor data/MC ~ 0.97 (0.85) in the W +2 jet (W +3 jet) sample, when we use the Next-to-Leading-Order (NLO) K-factor of 1.35 for the simulated Wjj sample, determined using the program MCFM [12]. The normalization factor is derived after subtracting all other expected background processes from data, and is done independently in the 2 and 3 jet bin.

The K-factor used for $Wb\bar{b}$ and for $Wc\bar{c}$ has been empirically determined to be 1.75 ± 0.35 , by adjusting the total number of background events to the data in the W +2 jet sample, with at least one tight b -tagged jet. This is compatible with a MCFM calculation on $Wb\bar{b}$ using parton $p_t > 8$ GeV, which gives 1.97. This computed K-factor was not used since our LO simulated sample use asymmetric cuts at the generator level: 8 GeV on light partons, 0 GeV on b and c -quarks. The same K-factors have been used for the corresponding Z + jet processes.

IV. EVENT SELECTION

The analysis is based on the selection of events with exactly one electron (muon) with $p_T > 20$ GeV and detector $|\eta| < 1.1$ (< 2.0), missing transverse energy $\cancel{E}_T > 20$ GeV and two or three jets, with $p_T > 20$ GeV (after jet energy scale corrections) and $|\eta| < 2.5$. Only events having a primary z -vertex within ± 60 cm of the nominal interaction point and at least three attached tracks are retained for analysis.

A. Lepton reconstruction and identification

The leptons used in the analysis are identified in two steps. 1) The lepton candidates are first required to pass the “loose” identification criteria, which for the electron are: energy fraction deposited in the EM calorimeter > 0.9 , ratio of the energy in the hollow cone having external and internal radii of $R = 0.4$ and 0.2 around the electron candidate direction, divided by the candidate energy < 0.15 , shower shape requirements, and matching of an EM cluster to a track having $p_T > 5$ GeV. For the muon, we require hits in each layer of the muon system, scintillator hits timing cuts to veto cosmics, matching between the muon track and a central track, and isolation from jets to reject muons from semi-leptonic hadron decays. 2) The loose leptons then undergo a final, “tight” selection: tight electrons have to satisfy a likelihood test developed on well-controlled samples, that takes as input seven quantities sensitive to the EM nature of the particles; tight muons must satisfy stricter isolation criteria requiring low calorimeter and tracking activity around the muon candidate. The inefficiencies induced by the lepton identification and isolation criteria are determined from dielectron and dimuon samples.

The final selection uses only tight leptons, whilst the sample of loose leptons is used for instrumental and semi-leptonic background determination

B. Instrumental and semi-leptonic background

The instrumental and semi-leptonic backgrounds, so-called “QCD” background in the following, are estimated from the data. The instrumental background is important in the electron channel, where a jet with high EM fraction can

pass the electron identification criteria. The semi-leptonic background is important in the muon channel, when the muon from a semi-leptonic heavy quark decay is mis-identified as being isolated.

To estimate the number of events containing a jet passing the final electron identification criteria we determine the probability p_{tight}^{loose} for a loose electron candidate originating from a jet to pass the likelihood test. This is done on data, using a sample of events having two jets back to back in φ ($|\pi - \Delta\varphi| < 0.2$), low $\cancel{E}_T (< 10 \text{ GeV})$, and in which one of the jets has an EM fraction smaller than 0.7 and to be in the central calorimeter ($|\eta| < 1.1$) and far from the calorimeter modules boundaries. The other jet is required to satisfy the loose electron requirements. The probability p_{tight}^{loose} is obtained by dividing the number of events containing at least one electron candidate passing the likelihood test by the total number of events of the sample. This probability is determined as a function of the p_T of the candidate electron. We proceed similarly in the muon channel to determine the semi-leptonic background. We use the same selection criteria, but require a loose muon to be back-to-back in φ with a jet.

The QCD background is then estimated for every differential distribution: this p_T -dependent probability is used in the so-called matrix method that we apply to our final sample and to the loose sample. This method allows to derive the QCD background directly from data, once p_{tight}^{loose} and the lepton identification efficiency are known [13].

The p_T distribution of the lepton in the $W + 2$ jet sample is shown in Fig.1a,b and compared to the expectation: at low p_T the contamination of QCD background is significant. The shape and magnitude of the distribution is well reproduced by the ALPGEN simulation of the $W +$ jets processes, after adding the QCD background and other standard model (SM) backgrounds detailed in the previous section.

C. Missing E_T and Jet properties

To select W decays we require large missing transverse energy, $\cancel{E}_T > 20 \text{ GeV}$. \cancel{E}_T is calculated from the calorimetric cells except unclustered cells in the coarse hadronic layers and is corrected for the presence of any muons. All energy corrections to muons or to jets are propagated into \cancel{E}_T .

The transverse mass $m_T = \sqrt{2p_T^\ell p_T^\nu (1 - \cos(\varphi_\ell - \varphi_\nu))}$ of the W boson can be reconstructed from the charged lepton and neutrino (ν) kinematics quantities, in which the neutrino 4-vector is approximated by the missing transverse energy 4-vector. The distributions of the scalar and missing transverse energy are shown in Fig.1c,d and compared to the expectation.

The jets used in this analysis are cone-type jets with a radius of $R = 0.5$. Identification requirements ensure that the jet energy distribution in the various layers of the calorimeter is reasonable and that the jets are not due to spurious energy deposits. The difference in efficiency of the jet identification requirement between data and simulation is taken into account in the overall jet reconstruction efficiency scale factor.

We have studied standard kinematic distributions and for example, the p_T distributions of the leading jet and next to leading jet in $W + 2$ jet events are shown in Fig. 2a and b. The η distribution of the leading jet in the $W + 2$ jet events is shown in Fig. 2c. The dijet invariant mass is shown in Fig. 2d. The shape of the distributions are described, within systematic errors, over the complete kinematic range for all jets.

V. b -TAGGING RESULTS

The primary goal of this analysis is the search for WH production with two b jets in the final state. Thus we focus on the identification of b -jets in our selected events. For tagging heavy flavored jets the $D\mathcal{O}$ neural network (NN) b -tagging algorithm has been used. It is based on the combination of seven b -hadron lifetime observables.

We start with a loose NN operating point, which corresponds to a fake rate, i.e. the fraction of “light” partons (u, c, s, g) mistakenly tagged as heavy-flavoured jets by the tagger, of about 4.5% for a jet p_T of 50 GeV. If two jets are tagged the event is selected as double-tagged. Otherwise the operating point is tightened to a value corresponding to a fake rate of about 0.5%, and the event can then be selected as an “exclusive” single b -tag, simply called single b -tag in the following. We are thus left with two disjoint samples, one “loose” double-tag (DT) and one “tight” single-tag (ST) which simplifies their combination, done afterwards to improve the significance of a potential signal. The operating points have been selected based on the optimal combined sensitivity to a WH signal.

The efficiencies for identifying a jet containing a B hadron of the loose and tight operating points are about $70 \pm 1\%$ and $48 \pm 1\%$, respectively. The efficiency has been determined relative to taggable jets, i.e jets having at least 2 good quality tracks, of which one has $p_T > 1 \text{ GeV}$ and another $p_T > 0.5 \text{ GeV}$. The jet taggability is typically 80% in a two jet QCD sample with an uncertainty of 3% per jet. The ratio between the expected taggability \times tagging efficiency in data vs. simulation is used, to reweight (per jet) the simulated events in which one or more jets is tagged. The systematic uncertainty on this scale factor is 4-7% for heavy quarks (b, c) and 25% when mis-tagging “light” partons.

	$W + 2$ jets	$W + 2$ jets (1 b jet)	$W + 2$ jets (2 b jets)	$W + 3$ jets	$W + 3$ jets (1 b jet)	$W + 3$ jets (2 b jets)
WH	5.58 ± 0.81	1.90 ± 0.30	1.67 ± 0.32	1.18 ± 0.17	0.39 ± 0.06	0.38 ± 0.07
WZ	408.1 ± 56.7	22.8 ± 3.6	7.0 ± 1.24	80.3 ± 10.0	5.1 ± 0.7	2.1 ± 0.4
$Wb\bar{b}$	974.3 ± 249.4	293.1 ± 77.6	81.4 ± 23.1	223.1 ± 56.7	66.1 ± 17.4	25.9 ± 7.2
$t\bar{t}$	252.5 ± 59.8	90.5 ± 22.3	54.4 ± 14.5	358.0 ± 84.0	121.2 ± 29.6	100.0 ± 26.2
Single top	110.9 ± 21.5	43.0 ± 8.8	14.9 ± 3.4	32.5 ± 6.2	11.4 ± 2.3	7.4 ± 1.7
QCD Multijet	2581.3 ± 387.2	158.4 ± 29.7	26.0 ± 8.0	492.7 ± 73.9	41.0 ± 7.5	13.8 ± 5.3
$W + \text{jets (light,c)}$	20289 ± 2304	291.0 ± 84.5	35.8 ± 11.9	2608 ± 316	62.9 ± 18.5	16.4 ± 5.4
Total expectation	24616 (n.t.d.)	898.7 ± 121.0	219.6 ± 31.0	3795 (n.t.d.)	307.7 ± 39.8	165.7 ± 28.2
Observed Events	24617	872	222	3795	271	151

TABLE I: Summary table for the $W + 2,3$ jet final state. Observed events in data are compared to the expected number of $W + 2$ jet events before tagging, after one tight b -tag, and after 2 loose b -tags. First (last) three columns, $W + 2(3)$ jet channel. Expectation originates from the simulation of WH (with $m_H = 115$ GeV), dibosons (WW, WZ, ZZ , labeled WZ in the table), $Wb\bar{b}$ production, top production ($t\bar{t}$ and single-top), QCD multijet background and “ $W + \text{jet}$ ” production, which contains light and c quarks. All Z processes are fully simulated, and included in the corresponding W categories. The processes $W(Z)b\bar{b}$ and WH are counted separately. “n.t.d.” stands for “normalized to data”.

In Fig. 3a and b are shown the distributions of the p_T and ΔR of the b -tagged jets for the $W + 2b$ -jet events. The observed agreement in both cases indicates that simulation, which includes the different Standard Model processes, describes the data well.

In total, we observe 872 (271) single b -tagged events in the $W + 2(3)$ jet channel, to be compared to 899 ± 121 (308 ± 40) expected events, as detailed in Table I.

When requiring only one b -tagged jet, the background due to $W + 2$ non- b quark jets, $t\bar{t}$ and QCD processes is a factor two larger than the contribution of the rare processes which can be studied with the upgraded Tevatron: $Wb\bar{b}$, single-top or Higgs production. To improve the signal to background ratio, we study single-tagged and double-tagged events separately.

In the $W + 2(3)$ jet sample, the 222 (151) events observed in the DT channel are to be compared to an expected Standard Model background of 220 ± 31 (166 ± 28) events, as detailed in Table I. In conclusion, the expectation describes the data well in all channels.

VI. SYSTEMATIC UNCERTAINTIES

The experimental systematic uncertainties due to efficiencies (i.e. the uncertainty on the ratio data/simulation of the efficiencies) or to the propagation of other systematic uncertainties (trigger, energy calibration, smearing), which affect the signal and standard model backgrounds (QCD background excepted) are summarized as follows:

- 3-10% uncertainty for the trigger efficiency derived from the data sample used in this analysis;
5-6% uncertainty for the lepton identification and reconstruction efficiency
- 6-12% uncertainty on the acceptance due to the jet identification and jet energy scale uncertainty.
5% for the acceptance uncertainty due to jet modelling (fragmentation).
- 3% for the jet taggability, 6-15% for the b -tagging efficiency, per heavy quark jet. For the light quark jets the uncertainty is 25%; this translates into an uncertainty on the total background of the exclusive single-tag sample of 7% (negligible for double-tag)

Overall, the experimental systematic uncertainty on the acceptance varies between 16 and 24% depending on the process and the channel (18% for WH in the DT channel).

The total uncertainty on the QCD background is 18% in the ST channel, and about 35% in the DT channel, due to the low statistics of QCD background events in the DT sample, as determined by the matrix method.

The luminosity error is treated separately and amounts to 6%. The uncertainty on the cross sections of the background processes is 18% for $t\bar{t}$ production, 16% for single-top production, 6% for WZ and WH production, and 22% for $W + \text{heavy flavor jets}$.

VII. WH CROSS SECTION LIMIT

The expected contribution from the $b\bar{b}$ decay of a standard model Higgs boson of 115 GeV, produced in association with a W boson is shown in Fig. 4a,b for the ST $W+2,3$ jet channel, and in Fig. 4c,d for the DT $W+2,3$ jet channels. It amounts to a total of 2.29 (2.05) events in the ST (DT) channels. With the amount of background still present, we cannot yet detect this small signal so we proceed to set limits using the $W + 2$ jet events. Each subchannel is analyzed independently. Limits are then derived from the invariant dijet mass distribution of the four individual analyses ($e, \mu, \text{ST}, \text{DT}$) done with the $W + 2$ jet events.

Limits are calculated at 95% confidence level using the semi-Frequentist CL_s approach with a Poisson log-likelihood ratio test statistic [14, 15]. The impact of systematic uncertainties is incorporated through marginalization of the Poisson probability distributions for signal and background via Gaussian distribution. All correlations in systematic uncertainties are maintained amongst channels and between signal and background. The expected distributions for background are evaluated by minimizing a profile likelihood function, referencing the shape and rate of the observed distributions in the sideband regions.

The log-likelihood ratio (LLR) distributions for the $WH \rightarrow \ell\nu b\bar{b}$, (i.e. after combining the four individual $W + 2$ jet subchannels) is shown in Fig. 5a. Included in the figure are the LLR values for the signal+background hypothesis (LLR_{s+b}), background-only hypothesis (LLR_b), and the observed data (LLR_{obs}). The shaded bands represent the 1 and 2 standard deviation departures for LLR_b . The cross section limit obtained for $\sigma(p\bar{p} \rightarrow WH) \times B(H \rightarrow b\bar{b})$ is 1.3 pb at 95% C.L. for a Higgs boson mass of 115 GeV. The corresponding expected upper limit is 1.1 pb. The same study is performed for four other Higgs mass points: 105, 125, 135, and 145 GeV. The corresponding observed and expected limits are given in Table II. The ratio of these limits to the standard model expected values is shown in Fig. 5b. The limits obtained in this analysis are displayed in Fig. 6, where they

m_H (GeV)	expected limit (pb)	observed limit (pb)
105	1.22	1.41
115	1.13	1.34
125	1.02	1.21
135	0.95	1.21
145	0.87	1.13

TABLE II: 95% C.L. expected and observed limits on $\sigma(p\bar{p} \rightarrow WH) \times B(H \rightarrow b\bar{b})$ as a function of the Higgs mass.

are compared to the previously published results of DØ on 174 pb^{-1} of data [1], CDF on 320 pb^{-1} of data [3], and to the expected preliminary limits of DØ (0.4 fb^{-1}) [2] and CDF (1.0 fb^{-1}) [4]. The improvement in sensitivity obtained with this analysis is significant, in particular in the region where we have best sensitivity for low Higgs mass discovery, i.e. 115–135 GeV, with a ratio of observed (expected) limit to the SM cross section of ~ 10.6 (~ 8.8) for $m_H = 115$ GeV. This result is also compared to another WH analysis [16] performed by the DØ collaboration on a slightly smaller dataset (0.9 fb^{-1}), and using the event selection optimized for single-top [17], which has a higher relative contribution than WH in the single-tag channel. Although such selection is not optimal for WH , the sensitivity of that search is similar to the sensitivity of the “cut-based” analysis described in this note, due to the application of advanced selection techniques, using a discriminant based on all the available kinematic information, in the so called “matrix-element” approach. The application of the matrix-element approach on the optimized selection presented here, will lead in the near future to a further improvement in sensitivity.

VIII. SUMMARY

The $\ell + \cancel{E}_T + 2$ or 3 jets final state has been studied in 1.0 fb^{-1} of data taken between April 2002 and February 2006, to search for WH production,

We observe 222 $W+2$ jet events with both jets b -tagged using a neural network b -tagging algorithm, which has high efficiency. The production rate of these double b -tagged events is in agreement with the expectation from standard model backgrounds, within statistical and systematic errors, both in $W + 2$ and $W + 3$ jet events.

The number of events with a W boson candidate and two jets in which one of the jets has been b -tagged with a tighter tagging operating point, and which does not belong to the double-tag sample is 872 for an expectation of 899

± 122 events. The single b -tagged production rate is consistent with the simulated expectation and the kinematic distributions of these events are well described by the simulation.

The total expectation for Higgs production in this analysis amounts to 3.6 events, if $m_H = 115$ GeV. To search for Higgs bosons of similar masses, we have combined all channels (e, μ, ST, DT) in $W + 2$ jet events, and derived limits from the invariant dijet mass distributions, using the CL_S method. We set upper cross section limits between 1.1 and 1.4 pb at 95% C.L. (0.9 to 1.2 pb for the expected limits) on $\sigma(p\bar{p} \rightarrow WH) \times B(H \rightarrow b\bar{b})$ for Higgs masses between 105 and 145 GeV. For $m_H = 115$ GeV, the observed (expected) limit is 1.3 (1.1) pb, to be compared to the standard model cross section expectation of 0.13 pb.

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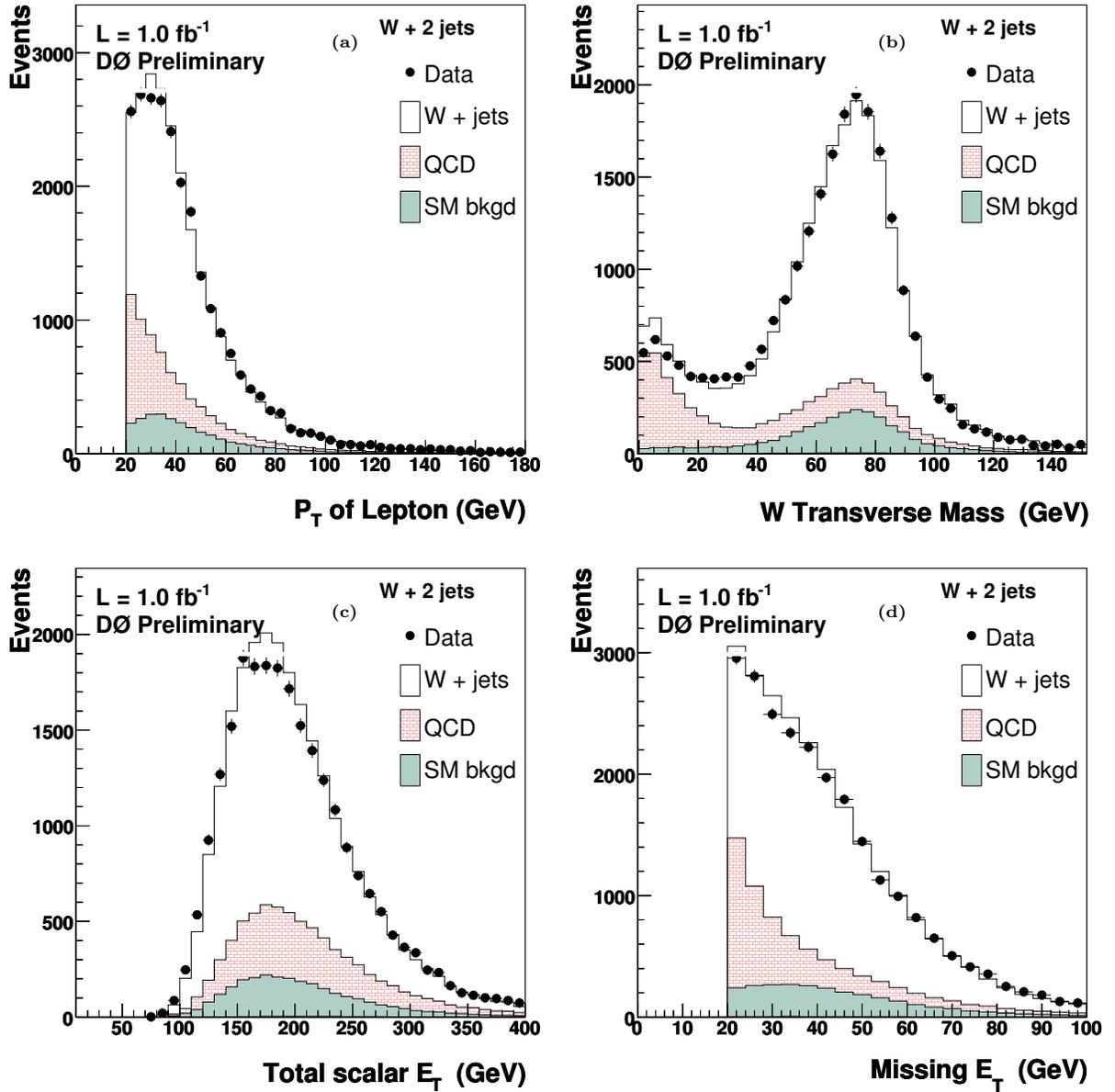


FIG. 1: Distributions of the lepton momentum (a), the transverse W mass (b), the scalar (c) and missing transverse energy (d) compared to the simulated expectation in the $W + 2$ jet event sample. The simulation is normalized to the integrated luminosity of the data sample using the expected cross sections (absolute normalization) except for the $W + \text{jets}$ sample which is normalized on the "untagged sample" to the data, taking into account all the other backgrounds.

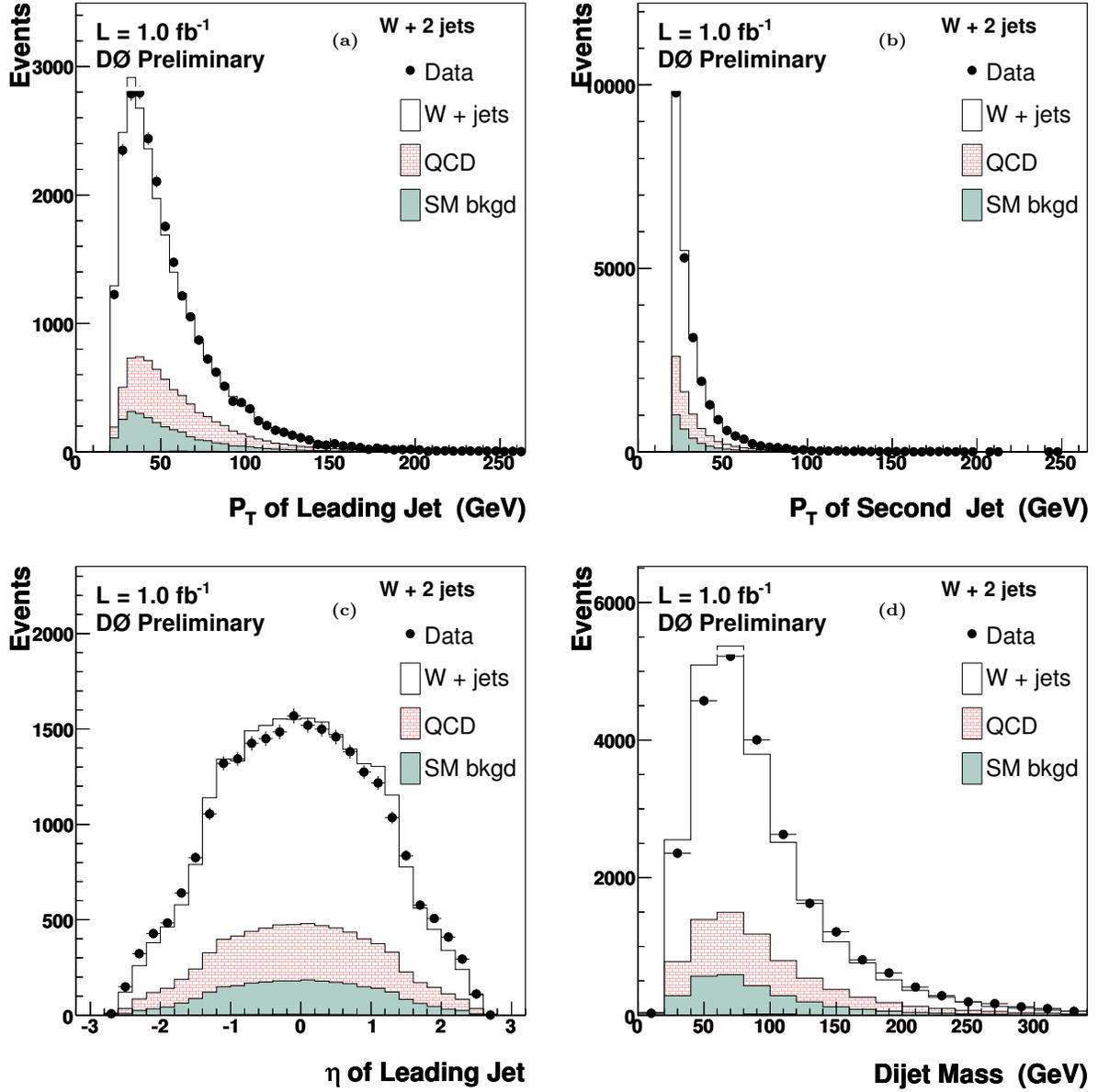


FIG. 2: Distribution of the p_T of the leading (a) and next to leading (b) jet, of the pseudorapidity of the leading jet (c) and of the dijet mass (d) between the two jets in the $W + 2$ jet sample compared with the simulated expectation. The simulation is normalized to the integrated luminosity of the data sample using the expected cross sections (absolute normalization) except for the $W + \text{jets}$ sample which is normalized on the "untagged sample" to the data, taking into account all the other backgrounds.

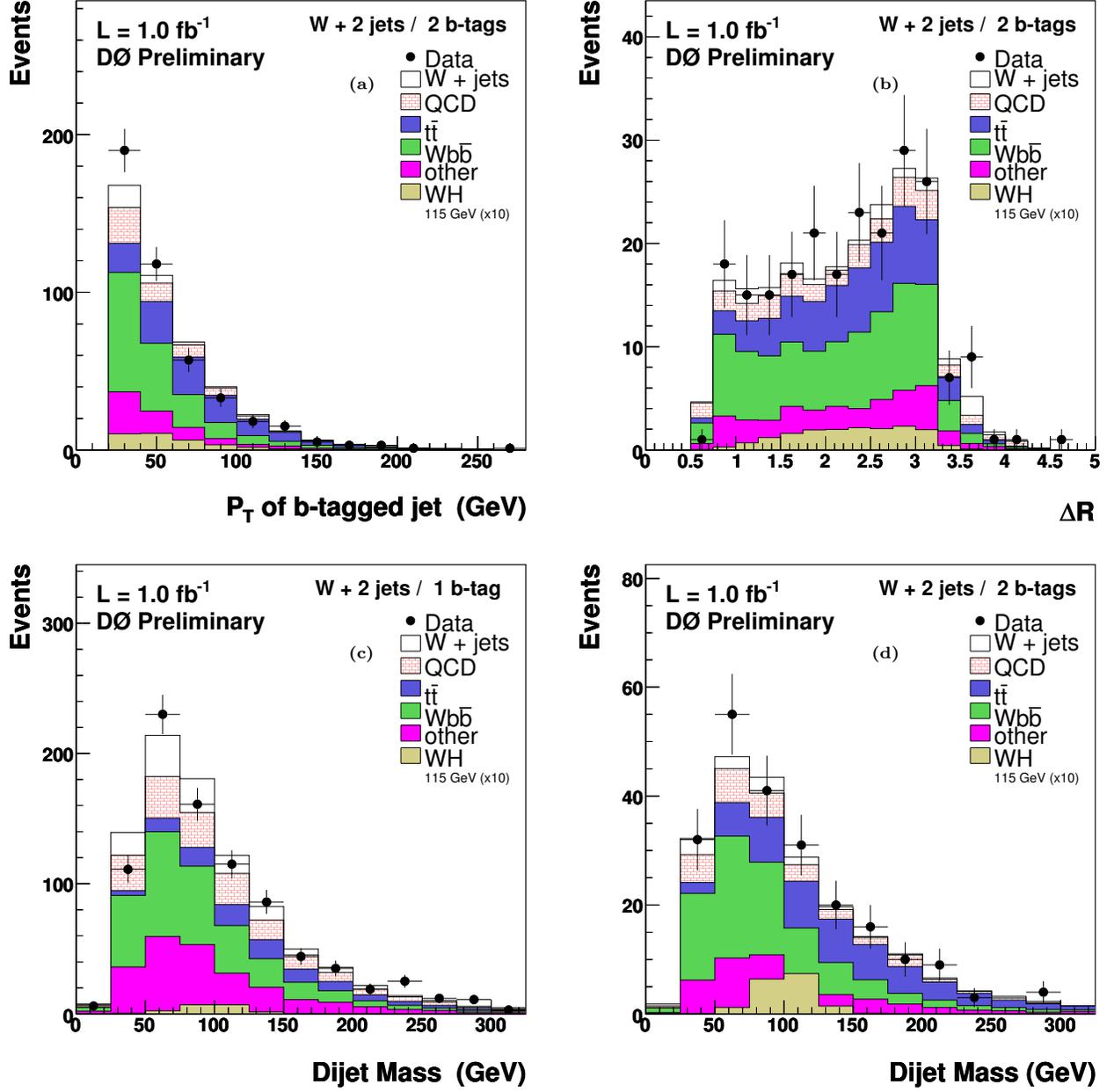


FIG. 3: (a,b): Distributions for the $W + 2$ jet events having at least two jets b -tagged: a) b -tagged jets momentum; b) ΔR between the two leading b -jets. c) (d) Dijet invariant mass in $W + 2$ jet events having exactly one (two) jet b -tagged; The data are compared to the different simulated processes. The simulation is normalized to the integrated luminosity of the data sample using the expected cross sections (absolute normalization) except for the $W + \text{jets}$ sample which is normalized on the "untagged sample" to the data, taking into account all the other backgrounds. Also shown is the contribution expected for standard model WH production with $m_H = 115$ GeV, multiplied by a factor 10.

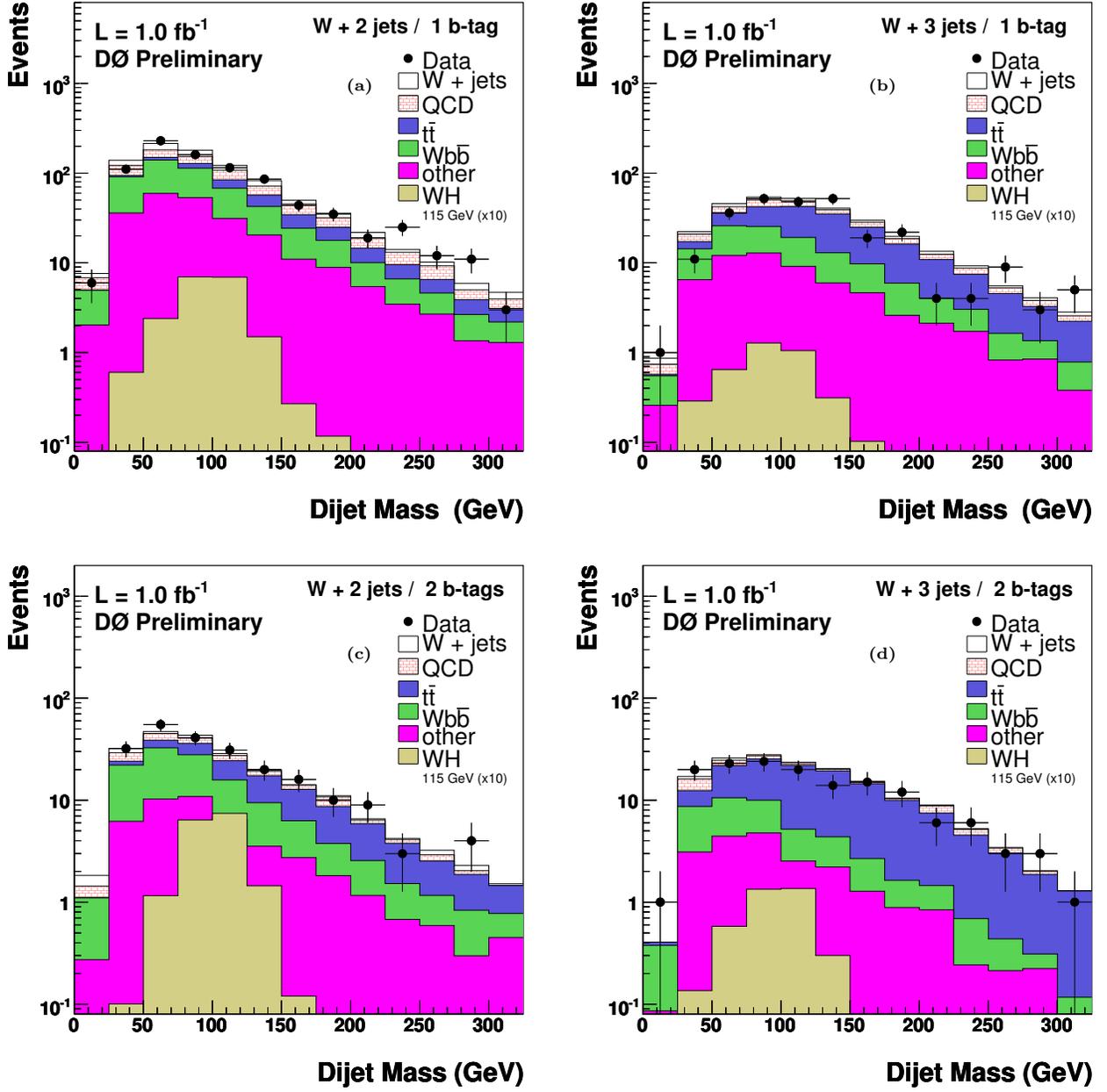


FIG. 4: a) (b) dijet invariant mass in $W + 2(3)$ jet events when exactly one jet is b -tagged. c) (d) same distributions when at least 2 jets are b -tagged. The simulated processes are normalized to the integrated luminosity of the data sample using the expected cross sections (absolute normalization) except for the $W + \text{jets}$ sample which is normalized on the “untagged sample” to the data, taking into account all the other backgrounds. The backgrounds labelled as “other” in the figure are dominated by single-top production. Also shown is the contribution expected for standard model WH production with $m_H = 115 \text{ GeV}$, multiplied by a factor 10.

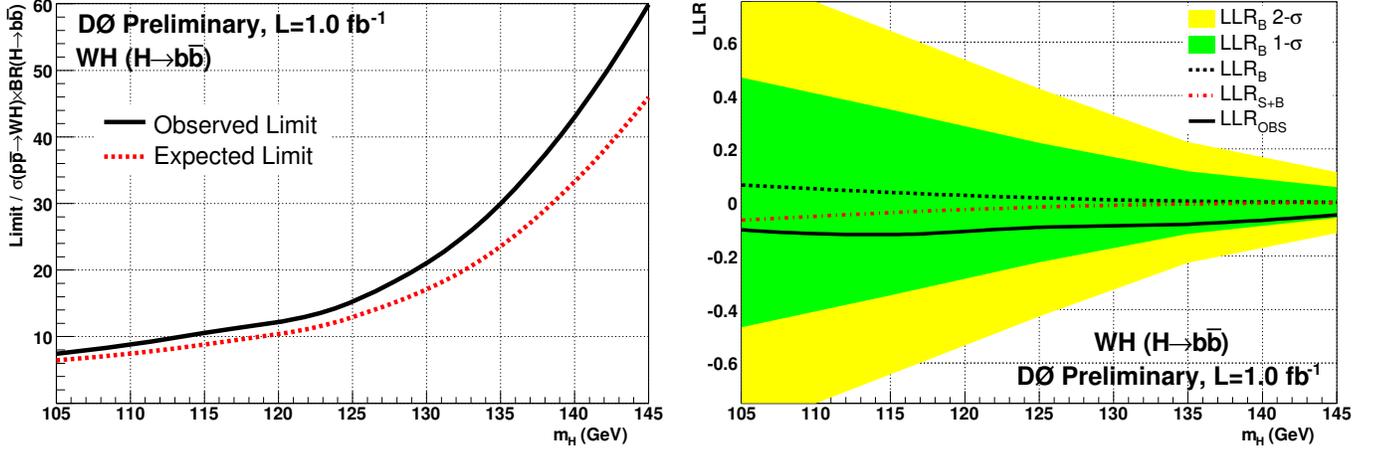


FIG. 5: a) Expected (median) and observed 95% CL cross section ratios for this “Cut-Based” $WH \rightarrow \ell\nu b\bar{b}$ analysis in the $m_H = 105 - 145$ GeV mass range; b) Log-likelihood ratio distribution for this analysis.

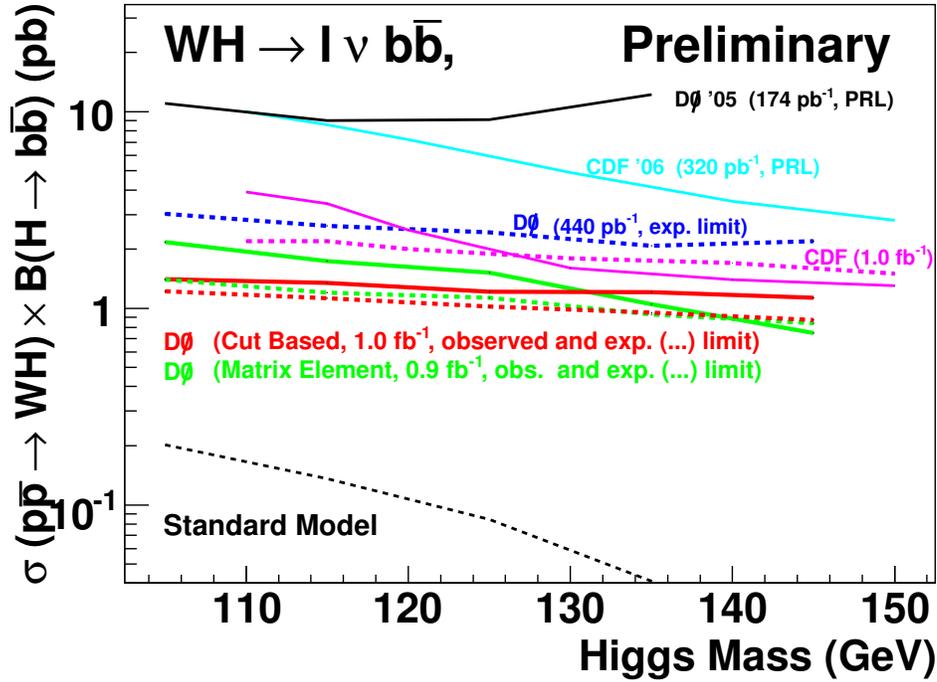


FIG. 6: 95% confidence level upper cross section limits on WH production derived after combining all $W + 2$ jet channels (W boson decaying into a electron/muon + neutrino and Higgs into $b\bar{b}$) vs. Higgs mass. This analysis is labeled “Cut-Based” and is compared to the “Matrix Element” result also obtained by $D\phi$. Previous results, and the Standard Model expectation, are also shown, see text for details.