IC/HEP/04-9

Higgs Results From DØ

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Abstract. Preliminary results obtained by the DØ Collaboration on searches for Higgs bosons at Run II of the Tevatron, within as well as beyond the Standard Model, are discussed. The data, corresponding to integrated luminosities of up to 191 pb^{-1}, are compared to theoretical expectations. No excess of signal above the expected background is observed in any of the various final states examined, instead new limits at 95 % Confidence Level are presented.

INTRODUCTION

The search for Higgs bosons is one of the main challenges for particle physics and as such a high priority for the upgraded DØ detector at Run II of the Tevatron. A discovery of the Standard Model (SM) Higgs may be within reach by the end of Run II, thanks to recently improved accelerator performance. Indirect constraints on the mass, from fits to the global set of electroweak data, favor a light SM Higgs boson of 117 GeV with an upper limit of 251 GeV at 95% Confidence Level [1]. The direct searches at LEP have already excluded SM Higgs masses below 114.4 GeV [2].

Higgs boson production cross sections in the SM are small at Tevatron energies in this mass region, of the order of 1 - 0.1 pb, depending on the production mechanism. Gluon fusion, gg → H, is the dominant production mechanism. However, for masses below 135 GeV, where H → $b\bar{b}$ decays dominate, the QCD background is overwhelming. The smaller but cleaner channels of associated ZH and WH production with the vector bosons decaying into leptons can instead be used for direct searches. $H \rightarrow WW^{(*)}$ decays, with subsequent electronic and/or muonic decays of the Ws, provide a promising search channel at higher Higgs masses, even though the leptonic branching ratio is small.

Even though it would require several fb^{-1} of data to discover or exclude the SM Higgs at the Tevatron [3], the modest luminosities of less than 200 pb^{-1} collected and analyzed so far by the DØ experiment are nonetheless useful to optimize detector performance and study background processes, both critical issues for a future discovery.

Furthermore, some models beyond the SM predict larger Higgs cross sections and cleaner search channels, some within reach even with the present data set. The Minimal Supersymmetric extension of the Standard Model (MSSM) contains five physical Higgs bosons [4]. Two of them are CP even scalars, h and H, of which h is the lighter and SM like. The other three consist of a charged Higgs pair, $H^{+/-}$, and a

CP-odd scalar, A, the mass of which is one of two free parameters of the model at tree level. The production cross section of the Higgs in the MSSM is proportional to the square of the second free parameter of the model, tanβ, the ratio of the vacuum expectation values of the Higgs doublets, ν_u and ν_d. A large value of tanβ could hence result in significantly increased Higgs cross sections compared to the SM. The charged Higgs bosons would mainly decay to τν while the dominant decay of the neutral bosons would be h/H/A → $b\bar{b}$ (90%), followed by h/H/A → $\tau^+\tau^-$ (10%). Searches for b(b)h/H/A production with a final state of three (four) b-jets are therefore, already at present luminosities, well motivated by this model. Indeed, this may well be the main search channel for Higgs at the Tevatron, of great interest well before the luminosities reach the levels needed for the SM searches.

Other possible extensions to the SM, 4th generation [5], TopColor [6] and Fermiophobic [7] Higgs models, could lead to enhanced decays of $H \rightarrow WW^{(*)}$ and/or $H \rightarrow \gamma\gamma$ (the latter is negligible in the SM). Furthermore, Left-Right symmetric and Higgs triplet models [8], predict the existence of doubly charged Higgs bosons, $H^{++/--}$, which would result in very clean like-sign muon signatures when pair produced. There are consequently a number of Higgs searches worthwhile to pursue already with the lower luminosities of the initial years of Run II at the Tevatron.

WH ASSOCIATED PRODUCTION

Associated WH production, with the W decaying to a charged lepton and a neutrino, provides the perhaps most promising channel for SM Higgs searches at Run II. DØ reports new preliminary results for the electron channel [9]. The analysis selects candidate events by identifying the W through its decay to an electron and a neutrino. The events are required to have a central, isolated electron with $p_T > 20$ GeV, missing transverse energy > 25 GeV and at least two jets with $E_T > 20$ GeV in a pseudo rapidity region of $|\eta| < 2.5$. Nearly 2,600 such $W \rightarrow e\nu + \geq 2$ jet candidate events are selected in 174 pb^{-1} of data. Good agreement between data and MC is observed for the various kinematic properties of these events. The reconstructed transverse W mass distribution is shown in figure 1a. The W + 2 jets processes are generated with the ALPGEN [10] parton generator, interfaced with PYTHIA [11], and then passed through the detailed detector simulation. The cross sections are normalized to MCFM Next to Leading Order calculations [12]. The QCD background is evaluated from the data, while remaining SM processes are generated with PYTHIA. After requiring at least two b-tagged jets, 8 events remain in data, while 8.3 ± 2.2 are expected from the SM simulations. For consistency, different b-tag algorithms, both impact parameter and secondary vertex based, were tested and found to give similar results after applying the b-tag requirements. In order to further suppress the dominant $t\bar{t}$ background, only events with exactly two jets, both of them tagged as b-jets, are retained in the final analysis. Figure 1b shows the di-jet invariant mass distribution of the final sample. 2 events are observed in data while 2.5 ± 0.5 events are expected from SM simulations. The background is dominated by $Wb\bar{b}$ production (1.4 ± 0.4) with a non-negligible contribution from $Wc\bar{c}/j\bar{j}$ (0.4 ± 0.1), $t\bar{t}$

and single top processes (0.6 ± 0.2). Upper limits at 95% C. L. are set on the $Wb\bar{b}$ production cross section, $\sigma[Wb\bar{b}] < 20.3$ pb, and, in the absence of an observed excess of signal, as well on the WH associated production cross section, $\sigma[WH(\rightarrow b\bar{b})] < 12.4$ pb for a Higgs mass of 115 GeV. Systematic errors (26%) on the $Wb\bar{b}$ cross section include uncertainties from MC simulations (15%), the jet energy scale (14%), b-tagging (11%), jet identification (7%), trigger and electron identification (5%) and the electromagnetic energy scale (5%) and are expected to be smaller for the WH signal. The results presented here are superior to similar Run I measurements [13].

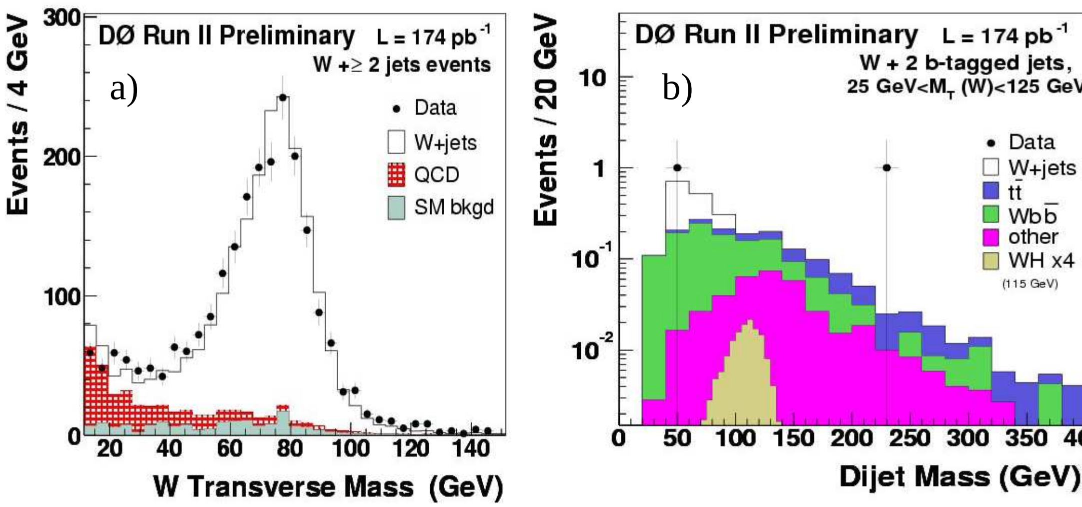

FIGURE 1. a) The transverse mass distribution for electron + missing E_T + jets events. b) The di-jet mass spectrum when both jets are tagged as b-jets. The light grey histogram corresponds to four times the expected SM Higgs signal at 115 GeV. Neither of the two observed final candidates is in the expected Higgs mass window.

MEASUREMENT OF THE σ[Z + b]/σ[Z + j] CROSS SECTION RATIO

Z boson production in association with one or more b-jets is, from a Higgs search perspective, for several reasons an important process to study. First, it probes the b-quark content of the proton parton distribution functions. Second, it is a dominant background to ZH associated production searches and finally, it is also an important benchmark process for non-SM Higgs searches in b(b)h/A/H associated production. Figure 2a shows two examples of Leading Order ZQ (Zj) diagrams.

DØ has analyzed electron and muon decays of Z bosons, in data corresponding to integrated luminosities of 184 (electron channel) and 152 (muon channel) pb^{-1}, and presents a new preliminary measurement of the cross section ratio, σ[Z + b-jet]/σ[Z + jet] [14]. Many systematic uncertainties affecting the total cross sections cancel in the cross section ratio measurement. The event selection requires two isolated leptons with $p_T > 15$ GeV within $|\eta| < 2.5$ (electron channel) or $p_T > 20$ GeV within $|\eta| < 2$ (muon channel). The Z mass peak is used to select signal events while the side bands are used for the background evaluation. Events are further required to have a jet with $E_T > 20$ GeV within $|\eta| < 2.5$. Simulations are done with PYTHIA or ALPGEN interfaced with PYTHIA and then passed through the detailed detector response. The QCD and mis-tag background is estimated from the data. The total rate in the Z + jet sample, including light quarks and gluon jets, is normalized to data while the relative content of b- and c-jets is taken from the NLO calculations [15], since the b-tag algorithm cannot distinguish between b- and c-jets. The fraction of events with one b-tagged jet is then measured in data, correcting for the tag rates of the algorithm. Figure 2b shows the E_T spectrum of the b-tagged jets in the selected Z+j sample.

The preliminary measurement of the cross section ratio is σ[Z + b-jet]/σ[Z + jet] = $0.024 \pm 0.005(\text{stat.})\ ^{+0.005}_{-0.004}(\text{syst.})$, compared to a predicted value of ~ 0.02 from theory [15]. The systematic errors include uncertainties due to the jet tagging efficiency (16%), the jet energy scale (11%), background estimations (6%) and assumptions on the relative fraction of b- and c-jets (3%). This measurement is the first of its kind.

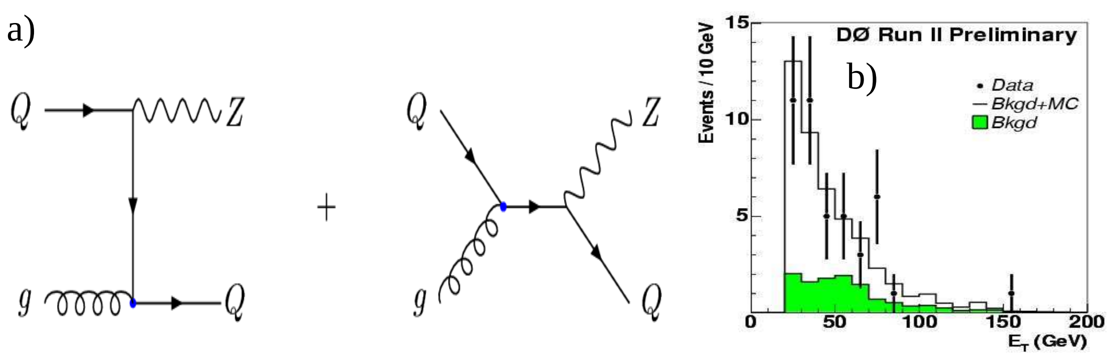

FIGURE 2. a) Two examples of Leading Order ZQ (Zj) production diagrams. b) Transverse energy spectrum of the b-tagged jets in the Z+j sample. The error bars represent the statistical error.

HIGGS SEARCHES IN $H \rightarrow WW^{(*)} \rightarrow l^+\nu l^-\nu$ FINAL STATES

At Higgs boson masses above 135 GeV, where the $H \rightarrow WW^{(*)}$ decay mode is kinematically possible, leptonic decays of W pairs provide a promising search channel with manageable backgrounds. The signature of the signal consists of two isolated, oppositely charged leptons together with a large missing E_T. The background processes include $Z/\gamma^*(\rightarrow l^+l^-)$ + jets, WW, WZ, W + jets, $t\bar{t} \rightarrow bl^+\nu\bar{b}l^-\bar{\nu}$ and QCD production.

DØ has analyzed ~ 180, 160 and 150 pb^{-1} of data in the ee, eμ and μμ final states respectively [16]. Selected events must have two isolated leptons with $p_T > 12$ and 8 GeV (ee/eμ channels) or $p_T > 20$ and 10 GeV (μμ channel), missing $E_T > 20$ GeV (ee/eμ channels) or missing $E_T > 30$ GeV (μμ channel). Z candidates and energetic jets are rejected from the analysis. Simulations are done with PYTHIA and passed through the detailed detector response, except for the QCD contribution which is evaluated from the data. The rates are normalized to the NLO cross section values. Good agreement between data and MC is observed at each step of the event selection. Figure 3a shows the missing E_T spectrum in the di-muon final states after event pre-selection (p_T and isolation criteria). Direct reconstruction of the Higgs mass is not possible in this analysis, due to the two neutrinos in the final state. Instead, the spin-correlations between the decay products of the Higgs boson may be employed to suppress the background. The charged leptons from the signal events tend to be collinear and hence the azimuthal opening angle between them is particularly useful in rejecting background. Figure 3b shows the distribution of the azimuthal opening angle between the electron and muon after all cuts have been applied.

The final data samples of ee, eμ and μμ final states contain 2, 2 and 5 events, respectively, while 2.7 ± 0.4, 3.1 ± 0.3 and 5.3 ± 0.6 events are expected from MC. The background in the eμ sample consists of WW production (2.51 ± 0.05), W + jets (0.34 ± 0.02), WZ (0.11 ± 0.01) and $t\bar{t}$ (0.13 ± 0.01). The signal acceptance is between 0.02 and 0.2 depending on the Higgs mass and final state. In the absence of an observed excess of signal, limits are set at 95% C.L. on the Higgs boson production cross section times branching ratio into W bosons as illustrated in figure 3c.

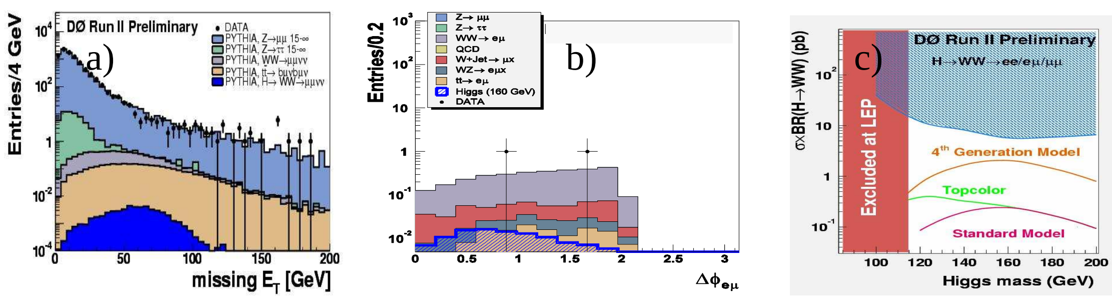

FIGURE 3. a) The missing transverse energy distribution in the di-muon sample after event pre-selection . b) Distribution of the azimuthal opening angle between electron and muon; dark (blue) histograms in both plots correspond to a Higgs signal of 160 GeV. c) Excluded cross section times branching ratio to W-pairs, σ x BR(H → WW$^{(*)}$), along with the expectations from SM Higgs boson production and the 4th generation and TopColor models.

LIMITS ON NEUTRAL SUSY HIGGS AT HIGH tanβ

The main production mechanism for neutral Higgs bosons in MSSM would be through diagrams of gg, qq → ϕ + $b\bar{b}$ → $b\bar{b}b\bar{b}$, where ϕ = h, H, A. The branching ratio of ϕ → $b\bar{b}$ is around 90%. The event selection of this search [17] is accordingly applied to the multi-jet event sample collected by DØ, corresponding to an integrated luminosity of 131 pb^{-1}. Candidate events are required to contain at least three jets with the exact E_T thresholds optimized separately for different Higgs mass hypotheses and final state jet multiplicities. It is further required that at least three jets are identified as b-jets. A signal is then looked for in the invariant mass spectrum of the two leading b-tagged jets. Figure 4a shows the invariant mass spectrum of selected events. Simulations are performed with PYTHIA or ALPGEN interfaced with PYTHIA and passed through the detailed detector simulation program. The dominant background is multi-jet production and is estimated from the data outside the signal search region. The signal acceptance is found to be 0.2-1.5 % depending on the Higgs mass and number of jets. No indication of a signal was detected and instead preliminary exclusion limits at a 95% C. L. were calculated. Figure 4b shows the values of tanβ which are excluded by this analysis.

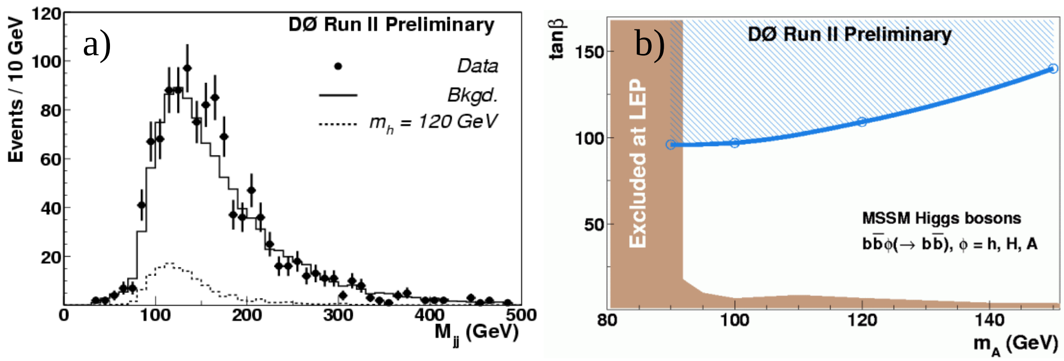

FIGURE 4. a) The invariant mass distribution of the leading two b-jets for data and background. The dotted histogram illustrates a Higgs signal of 120 GeV at the 95 % C.L. limit. b) The excluded values of tanβ from this search along with the region already excluded by previous searches at LEP [18].

LIMITS ON NON-SM h→γγ PRODUCTION

The branching of Higgs to photons is negligible in the SM. Some extensions to the SM however predict a large branching of h → γγ. A Fermiophobic Higgs does not couple to fermions at all and a TopColor Higgs has a zero coupling to all fermions except the top quark. Such models would hence result in an enhanced rate of Higgs bosons decaying to photons.

DØ has searched for Higgs bosons in γγ final states in data corresponding to an integrated luminosity of 191 pb^{-1} [19]. The event selection includes two isolated photons with $p_T > 25$ GeV within $|\eta| < 1.05$ (Central Calorimeter) or $1.5 < |\eta| < 2.4$ (End Calorimeter). The combined transverse momentum of the two photons is further required to be larger than 35 GeV. Figure 5a shows the mass spectrum of the two photons in the selected events. 97 events are selected with one photon in the CC and one in the EC with a total expected background of 68.8 ± 45.8 events. The background is dominated by QCD (64.0 ± 45.7 events) with a small contribution of Drell-Yann and γγ (3.0 ± 3.0 and 1.8 ± 0.1 events respectively). The dominant uncertainty in the background estimation is the measurement of the photon mis-identification rate (~30%). Taking the uncertainties into account there is no clear evidence of an excess in this search and hence exclusion limits are calculated using counting experiments on optimized sliding mass windows. The resulting preliminary limits on $B(h \rightarrow \gamma\gamma)$ as a function Higgs mass can be seen in Figure 5b and c.

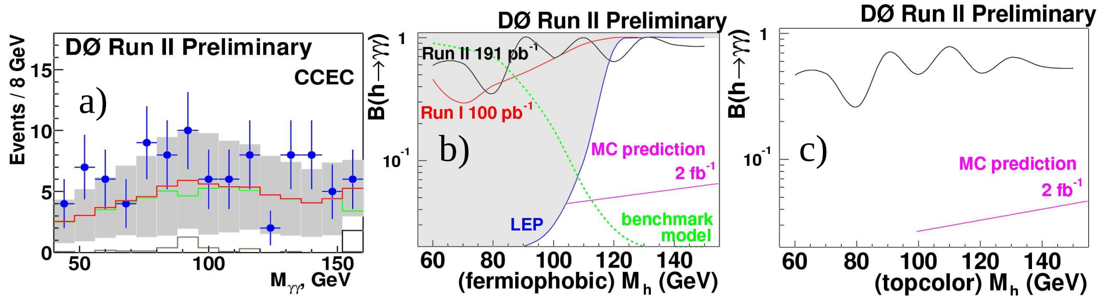

FIGURE 5. a) The invariant mass spectrum of selected $\gamma\gamma$ events. The dots are data and the red histogram is the total background with the grey shaded area indicating the uncertainty. The open green, grey and black histograms represent the QCD, Drell-Yann and $\gamma\gamma$ components of the background respectively. b) Exclusion limits on $B(h \rightarrow \gamma\gamma)$ versus fermiophobic Higgs mass. The Run I exclusion [20] based on 100 pb^{-1} of DØ data is included in the plot, as is the exclusion from the LEP searches [21] and the combined DØ and CDF prediction [22] from MC with 2 fb^{-1} of Run II data. The expected branching of Higgs to two photons versus Higgs mass in the benchmark fermiophobic Higgs model is also shown. c) Exclusion limits on $B(h \rightarrow \gamma\gamma)$ versus topcolor Higgs mass along with the combined DØ and CDF MC prediction with 2 fb^{-1}.

LIMITS ON H^{++}/H^{--}

Doubly charged Higgs bosons, H^{++}/H^{--}, appear in Left Right symmetric and Higgs triplet models. The leading order pair production mode at the Tevatron is: $qq \rightarrow Z/\gamma^* \rightarrow H^{++}H^{--}$ and the dominant decay mode of the doubly charged Higgs bosons is like signed leptons. Same sign muon decays have low SM background and hence provide a clean environment for this new physics search.

Di-muon triggered events in 107 pb^{-1} of data collected by the DØ experiment have been analyzed [23]. The muon identification requires isolated muons with an associated track from the central tracking system. The muon momentum is given by the central track. At least two muons are required to have $p_T > 15$ GeV in $|\eta| < 2$ and an invariant mass larger than 30 GeV. The acolinearity in the transverse direction of the two leading muons is required to be larger than $\pi/5$ to reject $Z \rightarrow \mu\mu$, semi-leptonic b-decays and remaining cosmic muons. Finally, there must be at least one pair of muons with like-sign charges. Figure 6 shows the di-muon mass spectra at different steps of the event selection procedure. Two candidates pass the final event selection with an expected background of 0.34 from SM processes. Figure 7 shows the confidence level of the signal as a function of the charged Higgs mass for left and right handed Higgs bosons. Assuming a 100% branching ratio into muons, this analysis results in a preliminary lower mass limit on a left (right) handed doubly charged Higgs boson of 116 (95) GeV[*]. Systematic uncertainties, including contributions from luminosity (10%), theory (10%) and efficiencies (5%), are taken into account in the calculated limit.

[*] An updated analysis with improved limits has recently been approved for publication [24].

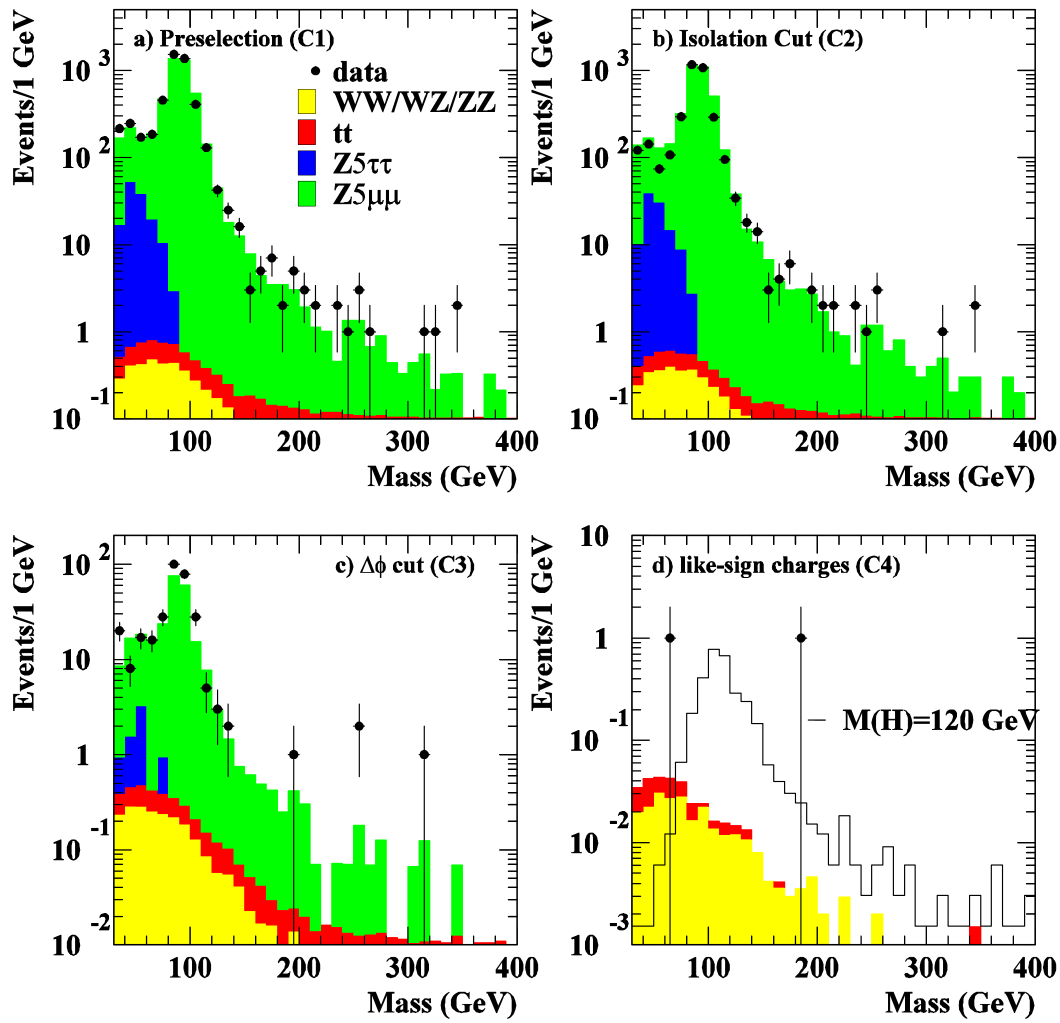

FIGURE 6. Distribution of the di-muon mass for data compared to the sum of the different MC background processes. a) After pre-selection. b) After isolation cut. c) After acolinearity cut. d) After like-sign cut. The open histogram shows the expected signal of a left-handed doubly charged Higgs boson at 120 GeV.

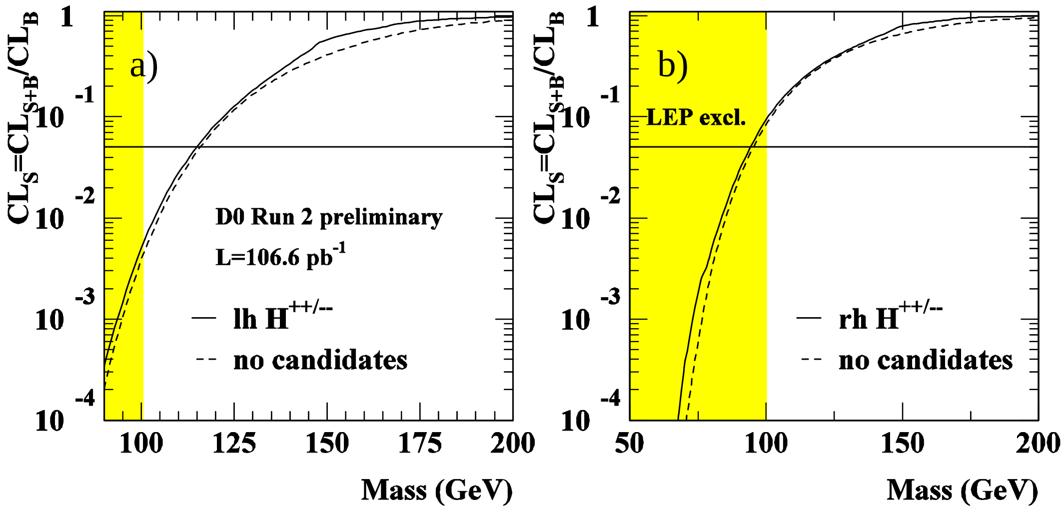

FIGURE 7. The confidence level of the signal, $CL_S = CL_{S+B}/CL_B$, as a function of the Higgs mass of a) the left-handed and b) the right-handed doubly charged Higgs boson. The mass region below 100 GeV is excluded by LEP [25]. The dashed curve shows CL_S in the case of no candidates.

CONCLUSIONS

The new preliminary results presented at this conference by the DØ Collaboration, together with the recent performance of the Tevatron, are very encouraging for the Higgs searches at Run II. The preliminary limits already set on the WH and $H \rightarrow WW^{(*)}$ production processes in the SM are unmatched or superior to Run I results. Furthermore, the searches for Higgs bosons beyond the SM, in the MSSM scenario and other extensions, have produced new preliminary limits on b(b)h/A/H, $h \rightarrow \gamma\gamma$ and H^{++}/H^{--}.

Having successfully accomplished these first probing searches for the Higgs at Run II, we are confidently looking forward to exploring the full 0.5 fb^{-1} of data that has already been written to tape.

ACKNOWLEDGMENTS

I would like to thank my colleagues from the DØ collaboration for providing material for this talk and the organizers of Hadron Collider Physics 2004 for a most stimulating conference.

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