REVIEW OF TEVATRON HIGGS RESULTS*

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We present an overview of the analyses performed by the two experiments at the Run II of the Tevatron searching for Higgs boson production. Especial effort has been done in the search for the Higgs boson predicted by the Standard Model. The good performance of the Tevatron would allow the experiments to be sensitive to the presence of the Higgs beyond the LEP limit by the end of Run II. In addition, analyses performed in the framework of models extending the Standard Model are already covering regions not excluded by previous experiments. Results from all these analyses and plans for the future will be discussed.

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1. Introduction

One of the main goals for the Run II of the Tevatron is the search for the Standard Model (SM) Higgs boson. This is the remaining piece to confirm that the SM is the description of the Nature at the lowest scale. Despite the great success of this model, the mechanism breaking the Electroweak symmetry and the way masses of the particles are introduced still need confirmation by the observation and study of the Higgs boson.

In some extensions of the SM, new Higgs bosons appear, whose presence would provide additional confirmation of the Higgs mechanism to break Nature's symmetries. Studies looking for the presence of Higgs bosons from extensions of the SM are also performed at Tevatron for which sensitivity is much larger than that for the SM Higgs boson, and results presented here are already excluding regions of the parameter space that were not previously explored.

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2. Search for the SM Higgs

The Higgs mechanism is the cornerstone of the SM. The success of the model supports the existence of a yet unobserved Higgs boson all of whose properties are predicted except its mass. According to the latest results from LEP, the 95% Confidence Level (C.L.) lower bound on the mass of the Higgs is $m_H > 114^{+69}_{-45}$ GeV/c^2 while fits to the SM parameters prefer a Higgs mass of 89^{+42}_{-30} GeV/c^2. With this information, searches are separated into the low-mass region ($m_H < 130$ GeV/c^2) in which the considered decay is $H \to b\bar{b}$, and the high-mass region ($m_H > 130$ GeV/c^2) with the decay $H \to WW^* \to l\nu l\nu$. In the first region, the decay of the Higgs prevents an inclusive Higgs search to be performed, and the processes to look for are the associated production with a W or Z boson. In the second region, the low multijet background allows the search for the inclusive production of a Higgs boson.

2.1. Low-mass SM Higgs: WH production

The production of a SM Higgs in association with a W boson has been studied by both experiments at the Tevatron. At CDF [1], events are selected from a data sample of 695 pb^{-1} containing an isolated lepton with $p_{\mathrm{T}} > 20$ GeV/c. In addition, it is required that the transverse momentum imbalance, the so-called missing transverse energy ($\not\!\!E_{\mathrm{T}}$), is greater than 20 GeV in order to select events containing a W boson.

Since in the low mass regime the Higgs is expected to dominantly decay into a $b\bar{b}$ pair, jets are reconstructed in the events by applying a cone algorithm with radius 0.4. Jets are required to have transverse energy $E_{\mathrm{T}} > 15$ GeV and $|\eta| < 2$, being the pseudorapidity $\eta = -\ln(\tan(\theta/2))$ and θ the polar angle with respect to the proton beam direction, defining the z axis.

Events are also required to have at least one jet tagged as a b-jet, *i.e.* as containing a b quark. This is done at CDF by requiring a secondary vertex reconstructed from displaced tracks inside the jet. A relatively large displacement of the position of that vertex with respect to that of the interaction is due to long-lived particles in the jet, as it may be the case for a b-hadron. In addition to this selection, a neural-network b-tagger has been used on top of the secondary vertex identification in order to further separate b-jets from jets coming from a c quark or a light-flavour parton.

Estimation of the background containing a real W or Z boson is done using Monte Carlo (MC) samples which are processed in the detector simulation. However, background from multijet processes where no real W produces the lepton and the $\not\!\!E_{\mathrm{T}}$ is estimated using data, by counting the number of events in sideband regions defined using the $\not\!\!E_{\mathrm{T}}$ and lepton-isolation plane.

The search for the Higgs signal is performed in the $W+2$ jet sample, combining the sensitivity from the single b-tagged sample, for which the b-tagging is done using the neural-network b-tagger, and the plain double b-tagged sample. The contamination from light-flavour jets in the double b-tagged sample is small enough to obviate the additional requirement given by the neutral-network b-tagger.

The DØ Collaboration has performed a similar analysis with a data sample of 378 pb^{-1} [2]. Analysis strategy is very similar to that of CDF, requiring an isolated lepton with $p_{\rm T} > 20$ GeV/c, $\not\!\!E_{\rm T} > 25$ GeV and two jets with $p_{\rm T} > 20$ GeV/c and $|\eta| < 2.5$. Jets are reconstructed using a jet cone algorithm with a radius of 0.5.

In the case of the DØ analysis, the b-tagging of jets is performed using a probability algorithm, based on the probability to observe the b lifetime. This algorithm associates a low probability to jets containing tracks with large impact parameter with respect to the primary vertex, as it is expected from b-hadron decays. In the analysis, the jet probability cut is set to less than 1%. If two jets are tagged, the event is selected as double b-tagged. Otherwise the cut is tightened to less than 0.1% and if one jet is then tagged, the event is selected as single b-tagged. These numbers are selected in order to maximise the sensitivity to the Higgs signal.

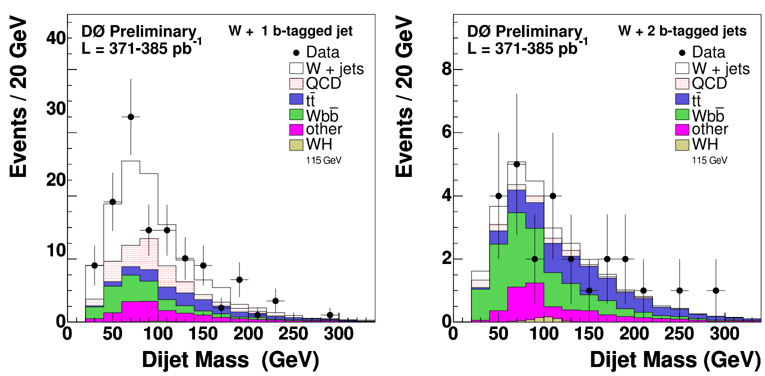

Fig. 1. Dijet invariant mass in the $W+2$ jet events having one tagged b-jet (left) or both of them b-tagged (right) in the Higgs search by the DØ Collaboration. Data (crosses) are compared to the background predictions (stacked histograms).

Results from these analysis are in agreement with the background predictions and no excess that may be attributed to Higgs production is observed. The results are used to obtain upper limits on the cross section for Higgs production. They are discussed in Section 2.4. Distributions of the dijet mass for the single and double tag samples from the DØ analysis are shown in Fig. 1. A good agreement is observed between the data and the predicted background.

2.2. Low-mass SM Higgs: ZH production

When the Higgs is produced in association with a Z boson the most interesting signature is provided by the events with the Z decaying into neutrinos (*invisible* Z) due to the reduction of the background with the $\not{E}_{\mathrm{T}}$ produced and the high enough branching ratio. The main trouble with the analysis is to deal with the sources of backgrounds containing fake $\not{E}_{\mathrm{T}}$, *i.e.* the imbalance in transverse momentum is due to mismeasurement of energy in the detector. This final state has also sensitivity to WH production in the case the final charged lepton is undetected or not properly identified. This is taken into account in the interpretation of the results, and to obtain a combined limit for the existence of the Higgs.

Both experiments have presented results for this search [3, 4]. The analysis by DØ was performed using a sample of 260 pb^{-1} [4]. Selection is done by requiring two jets with $E_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.5$ reconstructed with the iterative-midpoint-Run-II cone algorithm, with a radius of 0.5. The azimuthal angle between the two jets is required to be less than 165°.

In order to deal with the instrumental background, in which the $\not{E}_{\mathrm{T}}$ is mostly due to misreconstruction of the jet energies, DØ makes use of the data in regions where the event reconstruction suggests that transverse momentum imbalance is due to a mismeasured energy, by reconstructing the transverse momentum using both the jets and the tracks in the event [4]. To identify b-jets, an algorithm that uses a jet lifetime probability is applied to the jets in the event. Using the b-tagging algorithm, events are separated into events with a single b-tagged jet with a lifetime probability smaller than 0.1% and events where the two leading jets are b-tagged with probabilities smaller than 1% for the leading jet and 4% for the second jet. The samples are defined exclusively by requiring that events accepted in the single b-tagged sample are not previously accepted in the double b-tagged one.

In the case of CDF, the main background is dealt with by requiring large $\not{E}_{\mathrm{T}}$ and estimated from MC $b\bar{b}$ events. The QCD multijet background is reduced by requiring that no jet is aligned with the $\not{E}_{\mathrm{T}}$ direction. Events are selected in the signal region if they have $\not{E}_{\mathrm{T}} > 70$ GeV and contain at least two jets with $E_{\mathrm{T}} > 25$ GeV and $\eta < 2.4$, one or both of them being b-tagged using the secondary-vertex algorithm described above. Jets were reconstructed using the cone algorithm with radius 0.4.

After checking the good agreement in the control regions, optimization cuts were applied in both analyses to increase the sensitivity to the signal [3, 4]. This selection defines the global signal regions, for which DØ distinguishes between events with exactly one tagged b-jet and those having more than one tagged b-jet. In all these regions, good agreement is found between the observed data and predicted backgrounds. Distributions of the dijet mass for the signal region before the cuts on this variable compared to the background predictions are shown in Fig. 2, showing reasonable agreements between data and backgrounds and no excess that may be attributed to a Higgs boson. Limits on the cross section production were set and they are discussed in Section 2.4.

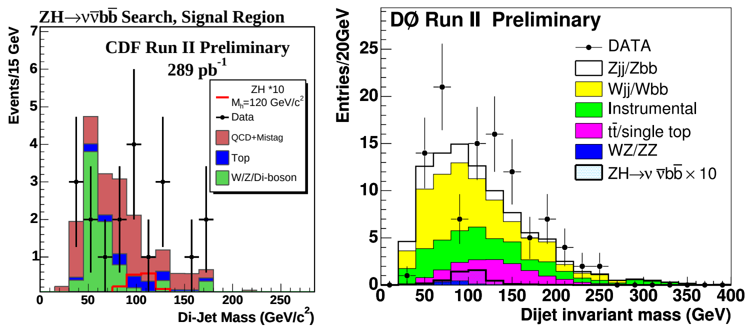

Fig. 2. Dijet Invariant mass distributions for the final selection in the CDF (left) and DØ (right) analyses searching for $ZH \to \nu\bar{\nu}b\bar{b}$. Data is in both cases compared to the predicted backgrounds before setting the cuts on the dijet mass to increase the sensitivity to the signal.

The $ZH \to l^+l^-b\bar{b}$ analysis is not ready at the time of this conference, although it is expected to have results soon. This search provides the cleanest signature for the search. However, sensitivity is reduced due to the small branching ratio of the Z into charged leptons.

2.3. The high-mass SM Higgs

In the high-mass regime, the preferred signature is the leptonic channel containing two opposite-charged leptons and $\not\!\!E_{\mathrm{T}}$ from the decay chain $H \to WW^* \to l^-\bar{\nu}l^+\nu$. The smaller branching ratio for this decay is compensated by the fact that a leptonic channel may be observed using the inclusive production of Higgs.

Given the presence of neutrinos in the decay, the invariant mass cannot be used to separate the background and signal. On the other hand, due to the scalar nature of the Higgs boson, the azimuthal angle between the two leptons is different for the signal than for the dominant backgrounds, concretely the irreducible WW production.

DØ has made the analysis [5] with a sample of 950 pb^{-1} for the decay channels into opposite-sign dielectron or electron+muon channels. In both cases an electron is required with $p_{\mathrm{T}} > 15$ GeV$/c$ and the second lepton, e or μ is required to have $p_{\mathrm{T}} > 10$ GeV$/c$. Drell–Yan production is suppressed by requiring $\not\!\!E_{\mathrm{T}} > 20$ GeV. Additional cuts are applied to reduce contamination of events in which the $\not\!\!E_{\mathrm{T}}$ may be due to misreconstructed energy from jets [5].

CDF has performed this search with a data sample of 360 pb^{-1} using a similar approach [6]. Leptons are selected with $p_{\rm T} > 10$ GeV/c and required to be calorimeter and track isolated, and at least one of them must have $p_{\rm T} > 20$ GeV/c. Cut on $\not\!\!E_{\rm T}$ is introduced to reduce Drell–Yan background and the exact value depends on the signal hypothesis [6]. Additional cuts are used to increase signal to background ratio, some of them depending on the assumed mass for the Higgs.

For both analyses, good agreement is observed between data and SM background expectations for both event yield and kinematic distributions. Given the agreement, 95% C.L. upper limit on the cross section was set as a function of the Higgs mass. With the current data samples and sensitivity, the limit is far above the expected SM cross section, but it is still sensitive to fourth generation models [7].

2.4. Summary of the SM Higgs searches

A good agreement between the data and the expected backgrounds has been observed in all the SM Higgs searches performed at Tevatron during the Run II. The results have been used to obtain 95% C.L. limits for the production of the Higgs in the different channels. In addition, the experiments are currently combining the results from different analysis to obtain a better and global limit. It is expected that both experiments will soon combine their limits to get the global Tevatron limit which will be required to go beyond the LEP limit.

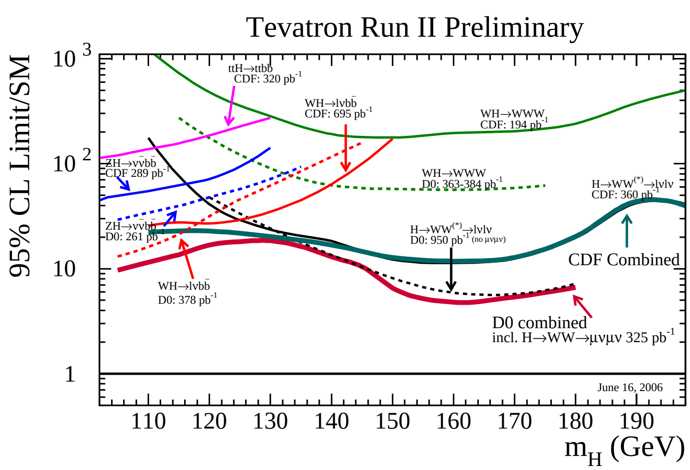

Fig. 3. Cross section limits for Higgs production at Tevatron in Run II as a function of the Higgs mass. The limit is represented in units of the predicted cross section in the SM. Limits are shown individually for each analysis and in the combination performed inside each experiment.

Fig. 3 shows the limits from all the analyses performed by CDF and DØ on Run II in units of the SM cross section. The limits are currently between 3 and 20 times worse than the SM predictions. On the other hand, we expect that with the increased luminosity provided by the Tevatron, data samples will be large enough by the end of the Run II to achieve a sensitivity to observe or exclude the presence of the SM Higgs boson near the current mass limit [8].

3. Search of the neutral MSSM Higgses

In the MSSM, the need for two Higgs doublets in order to provide masses to all the particles leads to the presence of five physical Higgs bosons: two neutral CP-even scalars (h and H): a neutral CP-odd state (A); and two charged states ($H^{\pm}$). The vacuum expectation values of the two Higgs fields is defined as $\tan\beta = v_2/v_1$, where v_1 and v_2 refer to the fields coupling to the down-type and up-type fermions, respectively. Because of this, the coupling of the A boson to down-type quark is enhanced by a factor of $\tan\beta$ relative to that of the SM.

The cross sections for the production of neutral Higgses in association with b quarks is enhanced in many extensions of the SM, such is the case of the MSSM at high $\tan\beta$. Due to the large decay ratio to b quarks, events containing three or four b-jets would represent a clean signature for the presence of Higgses. In addition, searches for the inclusive production of the Higgs are performed looking for the decay into a ditau pair. The branching ratio of this decay is much smaller than for that into b quarks, but the much smaller background makes the analysis sensitive enough to explore regions not previously covered by the experiments.

The analyses performed at Tevatron are sensitive to values of $\tan\beta$ in the range of 50–100, and the sensitivity depends on the Higgs mass. In that region of $\tan\beta$, the A boson is nearly degenerated in mass with either the h or the H and they cannot be distinguished considering the achievable mass resolutions. It is then considered that either of the bosons may be produced. The fact that we do not know the real boson produced is described as the production of a generic boson, ϕ, with the cross section of this process twice of that for the A boson.

3.1. Search for $\phi \to b\bar{b}$

The DØ Collaboration has performed a search for neutral Higgs bosons produced in association with b quarks using 260 pb^{-1} of data [9]. For events having a primary vertex position $|z| < 35$ cm, hadronic jets are reconstructed using a cone algorithm with radius 0.5 and required to have corrected $p_{\mathrm{T}} > 15$ GeV and $\eta < 2.5$.

Events with up to five jets are selected if they contain at least three jets with corrected $p_{\rm T} > 35$, 20 and 15 GeV/c. Jets are tagged as b-jets using a secondary-vertex tagging algorithm. The signal region is selected by requiring that events contain three tagged b-jets, although the sample with two b-jets is used as an auxiliary sample.

Multijet production is the main source of background and was determined from data by normalising the distributions outside the region where signal is expected. In order to model the background containing a mis-tagged jet, the high statistics doubly b-tagged data is used by applying the mis-tag function to non b-tagged jets in this sample. This provides the shape of the multijet background having at least three tagged b-jets.

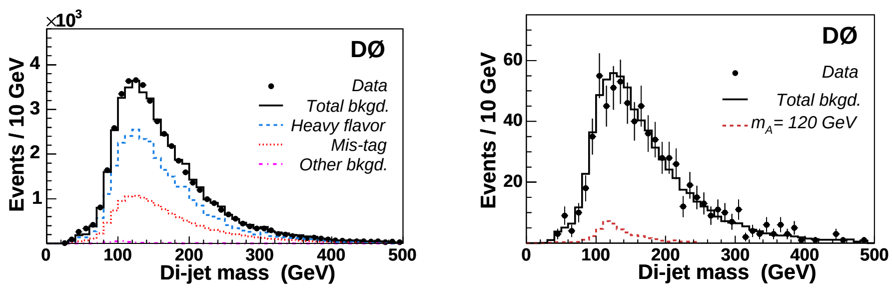

Fig. 4. On the left-hand plot, fit of the invariant mass spectrum of the two leading jets in the sample containing two tagged b-jets to the sum of the backgrounds. On the right-hand plot, invariant mass distribution of the two leading jets in events with at least three tagged b-jets, compared to the estimated background and the Higgs-boson signal that can be excluded at 95% C.L.

Signal samples were generated using PYTHIA and weighted to match the NLO calculation. The final selections are chosen depending on the hypothesised Higgs boson mass in order to optimise the expected signal significance. Plots in Fig. 4 show the distributions obtained for the doubly b-tagged sample and the final selection. Good agreement is obtained for both regions. Results were used to exclude new regions in the parameter space, previously unexplored, down to $\tan\beta = 50$, depending on the mass of the Higgs and the MSSM scenario assumed. We will discuss these limits in Section 3.3.

3.2. Search of $\phi \to \tau\bar{\tau}$

Final states leading to high-mass tau lepton pairs can arise from various physics processes beyond the SM, including the production of neutral Higgs bosons, ϕ, where production rates at the Tevatron could be potentially large enough for an observation.

CDF [10] has performed the search for this signature in a data sample corresponding to 310 pb^{-1} in events with an e or μ from a leptonic decay and one hadronically-decayed tau, τ_h. Reconstruction of hadronic decays of the taus is performed using the properties of jets originating from a tau: these are narrow jets with low multiplicity from neutral and charged particles. The backgrounds are estimated using simulated events, except those where a jet is misidentified as τ_h, which are estimated from the data. Events are selected to satisfy the conditions of $p_{\mathrm{T},e(\mu)} > 10$ GeV/c and $p_{\mathrm{T},\tau_h} > 15$ GeV/c and the lepton and τ_h have opposite charge. Additional kinematic cuts are imposed to reduce the background and optimise the signal selection.

DØ [11] has performed the search on a data sample corresponding to an integrated luminosity between 299 pb^{-1} and 348 pb^{-1}. At least one of the tau leptons is required to decay leptonically and the e or μ is used to accept the event in the online acquisition system. In addition to the $e(\mu)+\tau_h$, DØ also includes the purely leptonic channel where one of the taus decays into an electron and the other into a muon, which also presents very small background.

All background contributions except the contamination from QCD multijet production is estimated using MC events. Normalisation of these backgrounds is obtained by the next-to-leading and next-to-next-to-leading order (for electroweak processes). Contribution from QCD multijet production in which jets are misidentified as leptons, is estimated from data by using like-sign $e+\tau_h$ events (for the $e+\tau_h$ analysis) or by selecting background samples by inverting lepton criteria (for the $\mu+\tau_h$ or $e\mu$ analyses). The total number of events of the background samples is normalised to the data at an early stage of the analysis in a region of phase space where QCD-multijet contamination is the dominant contribution.

The signal is characterised by two leptons, $\not\!\!E_{\mathrm{T}}$ and little jet activity. It would stand out as an enhancement above the background from SM processes in the so called visible mass, defined as

$$M_{\mathrm{vis}} = \sqrt{(p_{\tau_1} + p_{\tau_2} + \not\!p_{\mathrm{T}})^2}\,, \tag{1}$$

$p_{\tau_{1,2}}$ being the four-momenta of the visible tau decay production, and the variable $\not\!p_{\mathrm{T}} = (\not\!\!E_{\mathrm{T}}, \not\!\!E_x, \not\!\!E_y, 0)$ the missing momentum. For the optimization of the signal selection, only the high mass region is used, which is defined as $M_{\mathrm{vis}} > 110$ GeV/c^2 in the $e\mu$ analysis and $M_{\mathrm{vis}} > 120$ GeV/c^2 in the $e/\mu + \tau_h$ analyses. Fig. 5 shows the distributions of the visible mass for the analyses by CDF and DØ comparing the data with the backgrounds and a possible signal. In both cases, good agreement is observed with the expectations from the SM and no excess that may be attributed to a Higgs signal is observed.

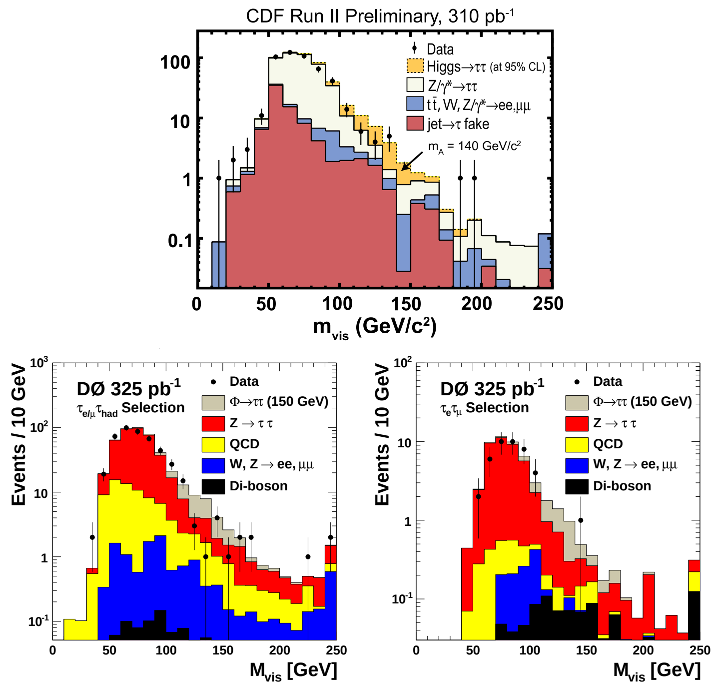

Fig. 5. Distribution of the visible mass $M_{\rm vis}$ for the analysis by CDF (top), and the two options considered by DØ : the one involving hadronic tau decays (bottom left) and one with the $e\mu$ final state (bottom right). Data are compared to the predicted background from the SM and a possible signal.

3.3. Summary of the Neutral MSSM Higgs searches

The results from DØ obtained from the ditau and the four-b analyses are combined and interpreted in a similar MSSM scenario [11] in order to set a global limit to Higgs production. These limits are shown in Fig. 6, where for illustration purposes, they are shown up to $\tan\beta = 100$, ignoring the effects from potentially large higher-order corrections in the very high $\tan\beta$ regime.

Fig. 7 shows the limits obtained from the CDF analysis. The excluded region is compared with the expectations for the analysis with increased luminosity expected for the upcoming years and up to end of Run II. It should be noticed that at some point sensitivity will be limited by systematics and the addition of further data will not represent an incease in the performance of the analysis.

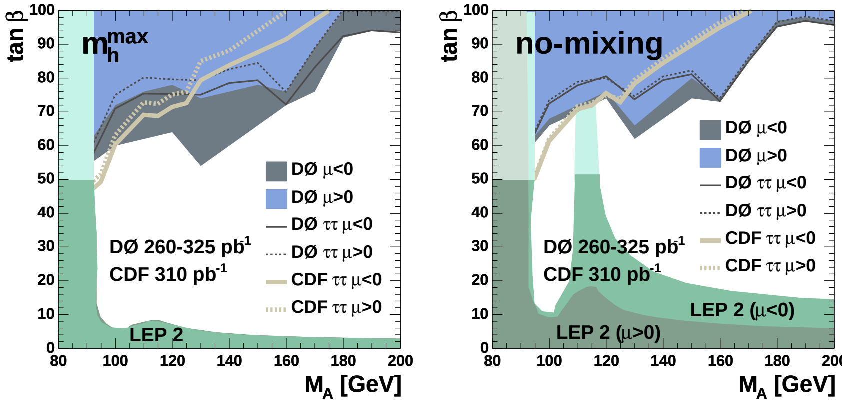

Fig. 6. Region, which is excluded at 95% C.L. by the ditau and four-b searches of the MSSM neutral Higgs boson by the DØ Collaboration, in the $(M_A, \tan\beta)$ plane for the $m_h^{\max}$ (left plot) and the no-mixing scenario (right plot) for $\mu = +0.2$ TeV and $\mu = -0.2$ TeV and assuming a mass of the top quark of 172.7 GeV$/c^2$). The LEP limits extrapolated to the region $\tan\beta > 50$ and those by the ditau channel by CDF are also shown.

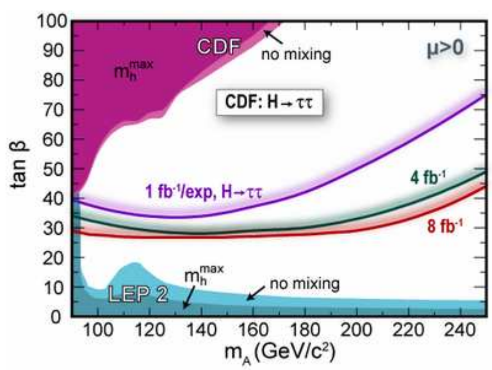

Fig. 7. Excluded regions in the $(M_A, \tan\beta)$ plane for the $m_h^{\max}$ and the no-mixing scenario with $\mu > 0$ and the expectations for increased integrated luminosity samples.

4. Other Higgs searches

Apart from Supersymmetric extensions of the SM, Higgs bosons appear in several models. In some cases the Higgs boson has properties which make them easy to identify in the final state. This is the case of the Doubly-charged Higgses which appear in models with Left–Right symmetry. These doubly-charged Higgses would decay primarily into leptons [12] having the same charge, giving rise to signatures easy to detect in a hadron collider.

CDF has recently performed an analysis searching for doubly-charged Higgs bosons [13] produced in pairs and decaying leptonically, including the presence of τ leptons in the decay. The signature will be the presence of three or four leptons with at least one of them an electron or muon and one of them a hadronic τ.

The background is suppressed requiring high energy in the leptons, *i.e.* that the sum of the transverse momenta of the identified leptons is large. In addition, a veto is set for events containing a pair of leptons whose invariant mass is in the Z peak, $76 < m_{ll} < 106$ GeV/c^2.

After the selection, for a data sample of 350 pb^{-1}, 0.3 (0.4) events are expected for the $e\tau$ ($\mu\tau$) channels coming from SM processes. No event is found in the data and limits on the masses of the doubly-charged Higgses are obtained. As shown in Fig. 8, the obtained limit goes beyond the limits by LEP for the left-handed doubly-charged Higgs, while it is worse for the right-handed one, due to the smaller cross section.

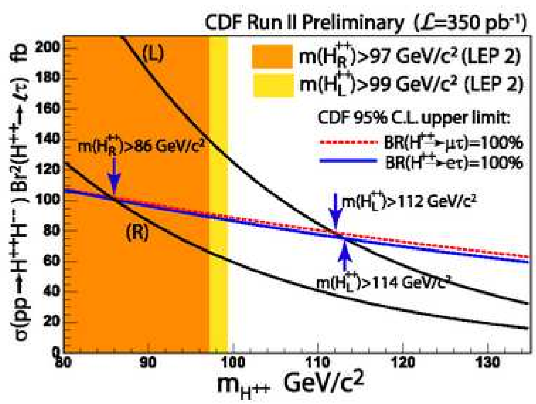

Fig. 8. 95% C.L. curves for $p\bar{p} \to H^{++}H^{--} \to l^+\tau^+l^-\tau^-$. The arrows show the limits for the two analysis, Excluded values by the LEP experiments for the Higgs mass are shown as the coloured region.

It is expected that the use of a larger data sample will increase the sensitivity in this kind of search, in which the exotic signature allows one to greatly reduce the SM background and the main limitation to the sensitivity is given by the cross section of the process.

5. Conclusions

We have presented an overview of the current results on Higgs searches at the Tevatron in Run II. Analyses looking for the SM Higgs show that with increased data samples, sensitivity by the end of Run II may allow exploring mass regions not excluded by the LEP experiments. In searches based on models extending the Standard Model, Tevatron experiments are already exploring regions not previously covered. No hint of the presence of a Higgs boson has been found, and new limits are set that go beyond those set by LEP.

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