Searches for the Higgs Boson

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Searches for this Higgs boson are reaching an exciting time. This proceeding reports the progress on Standard Model Higgs boson searches at the Tevatron and the prospects for Higgs boson searches at the Large Hadron Collider. Also reported are the results of non Standard Model searches and prospects at the Tevatron, Large Hadron Collider and B factories. Included in this result are the first limits on the mass of the Standard Model Higgs boson at high masses beyond the kinematic reach of the Large Electron Positron collider.

1. Introduction

The Higgs boson occupies a unique place in the Standard Model (SM) of particle physics and in many models of beyond the SM (BSM) physics. Experimental evidence shows that the strengths of the electromagnetic (EM) and weak forces are orders of magnitude different at low energies. The SM proposes that EM and weak forces are aspects of a single unified electroweak force with similar coupling strengths governing all the electroweak interactions. The difference in the strength of the EM of weak forces results from the massive nature of the W and Z weak bosons compared to the photon. In the SM the mechanism of electroweak symmetry breaking that results in the difference in strength between EM and weak forces at low energy and gives mass to most of the SM particles is known as the Higgs mechanism. This theory predicts a scalar field and an associated scalar boson, the Higgs boson. The existence of this boson is the primary testable hypothesis of the SM Higgs mechanism. Discovery of the SM Higgs boson would be a key element confirming the predictions of the SM. In addition, many BSM models also predict one or more scalar bosons as part of their electroweak symmetry breaking mechanisms and discovery of those bosons would simultaneously allow us to further understand electroweak symmetry breaking and conclusively prove physics beyond the SM.

In the context of the SM constraints from measuring parameters can be used to predict the Higgs boson mass. These constraints primarily come from measurements of the W boson and top quark masses. The current fit of all electroweak parameters produced by the Large Electron Positron (LEP) Electroweak Working Group predicts that the Higgs mass is $84 + 34 - 26$ GeV\cite{1,2}. At 95% confidence level the Higgs boson mass constrained to be less than 154 GeV. These numbers can be compared to the final limit from the LEP experiments of 114 GeV at 95% confidence level (CL)\cite{3}. This indicates that the Higgs boson mass has a probable value in the area of best sensitivity for the Tevatron experiments. Also of interest is that the central value of the predicted mass of the Higgs boson is below the LEP limit indicating that the Higgs boson might not be of SM origin.

In this proceeding I review the state of experimental searches for the Higgs boson and discuss prospects for finding the Higgs boson at future colliders. The results from the Tevatron are based on an integrated luminosity of up to \(3 \text{ fb}^{-1}\) of \(p\bar{p}\) collisions at 1.96 TeV. Results from the Babar experiment are based on a dedicated run at the \(\Upsilon(3S)\) resonance at the PEPII collider. In this review I begin by discussing the experiments and techniques used to search for the Higgs boson. I then review the status of searches for BSM Higgs bosons, the status of searches for SM Higgs bosons and conclude with prospects for Higgs boson searches at future colliders.

2. Experiments and Techniques

The field of Higgs boson searches is rich and allows for searches at a number of collider experiments. I will primarily review searches performed the the Tevatron experiments CDF and DØ . The Tevatron is a proton-antiproton collider operating at 1.96 GeV. The Tevatron experiments have recorded \(4 \text{ fb}^{-1}\) of integrated luminosity of which up to \(3\text{ fb}^{-1}\) has been analyzed for Higgs boson searches. The CDF and DØ experiments consists of magnetic
spectrometers instrumented with tracking and vertex finding detectors surrounded by electromagnetic calorimeters for measuring the energy of electromagnetic particles such as photons and electrons and hadronic calorimeters for measuring the energy of quark jets, which are in turn surrounded by dedicated chambers for detecting muons. This design in general allows for the measurement of momentum of all charged particles such as electrons and muons, the energy of photons and quark jets, and the detection of displaced vertices’s characteristic of the decay of b flavored hadrons in quark jets. In addition, triggering of interesting events is very important at the high crossing rates of collider experiments. The CDF and DØ experiments have the ability to trigger on leptons and photons as well as the energy of jets and the overall missing energy in the transverse plane. In addition, it is possible to search for lighter Higgs bosons at the dedicated B physics experiments. The dedicated B physics experiments have been primarily running at an energy to produce the Υ(4S) resonance, but recently the Babar experiment has collected smaller datasets at the Υ(3S) and Υ(2S) resonances, which can be used to search for light Higgs bosons. The design of the B physics experiments is similar to the hadron collider experiments, though the typical low track multiplicities of the B physics environment has allowed the detectors to be optimized for higher efficiency and strong particle identification capabilities. Finally, the Large Hadron Collider (LHC) experiments, CMS and ATLAS, will start collecting data soon. The LHC is a 14TeV proton proton collider that will possibly achieve luminosities two orders of magnitude higher than those achieved at the Tevatron. The CMS and ATLAS experiments are similar to the Tevatron experiments though generally have physics object detection capabilities over a larger solid angle. The strong detectors, coupled with the high luminosity and larger cross sections for Higgs boson production makes it likely that the LHC can detect a Higgs boson at any reasonable mass.

Successful Higgs boson searches require excellent detector performance in identifying a variety of physics objects. Signatures that occur in Higgs production and decay include, isolated electrons, muons and photons; tau leptons which can decay to lighter leptons or hadrons; light quark and b quark jets; and missing transverse energy from neutrinos or other undetected particles.

The first step to detecting Higgs boson events is identifying events to be saved for later analysis using triggering systems. A primary set of triggers for many Higgs boson searches are high transverse momentum electron and muon triggers. These triggers generally detect electrons using the electromagnetic calorimeter and muons using dedicated muon chambers. The CDF detector additionally uses their drift chamber to measure the momentum of the muons while the DØ has an array of toroidal magnets that allows the momentum of the muons to be directly measured in the muon detectors. The CDF detector has considerable gaps in solid angle coverage for muons and to a lesser degree electrons. The dedicated charged lepton triggers are supplemented by triggers for missing transverse energy and jets as measured in the calorimeters, which are effective since if a charged lepton is not detected then it will leave a signature of apparent missing transverse energy. For topologies with no charged leptons the CDF and DØ detectors rely purely on the missing energy and jet triggers. In addition, the experiments use dedicated tau lepton triggers, which search for narrow jets identified in the calorimeter accompanied by a small number of charged tracks.

Once events have been triggered and saved for further analysis more sophisticated algorithms can be applied to identifying physics objects of interest. The purest physics objects for Higgs searches involve high transverse momentum electrons and muons. These leptons are identified as well measured tracks with consistent information from the dedicated leptons identification systems. At the DØ detector this strategy allows identification of electrons and muons over a large range of solid angle while at CDF these methods are supplemented by identifying high pt tracks that are either isolated in terms of calorimeter energy along the path of the tracks, indicating muons, or isolated in terms of other tracks around the candidate charged leptons, which can identify muons, electrons and single prong hadronic tau lepton decays. Dedicated tau lepton detection algorithms looks for narrow jets of particles with one or three charged tracks with only a small amount of energy deposited in an annulus around the tau flight direction. Additionally the tau momenta measurement is improved by using both the charged track momentums and the energy in the electromagnetic calorimeters to include energy for neutral pions. Furthermore, this information can all be as input to a Neural Network (NN) to maximize the tau identification performance.

Algorithms for photons primarily require that there is a well measured electromagnetic energy deposit and no corresponding tracks, but more advanced algorithms using information from highly segmented presampling or shower
maximum calorimeter components can be applied to reduce large backgrounds from QCD sources such as neutral pions. Again, this information can all of included in a NN to maximize photon identification performance.

Quark jets are identified as energy clusters in the electromagnetic and hadronic calorimeters by summing the energy in a cone around the highest energy deposit. The energy resolution can be further improved by using tracking information to measure the charged track component of the jets. Quark jets from b quarks are of particular interest in Higgs boson searches. Identification of b quark jets is known as b tagging. The DØ b tagging algorithm combines information in jets such as the decay length of secondary vertices’s, displaced impact parameters of charged tracks, and leptonic decay information in a NN designed to give a continuous output that indicates the likelihood that a jet was produced by a b quark. Several operating points can be utilized from the output to achieve varying levels of efficiency and purity. The CDF experiment employs a b quark identification algorithm based on well identified secondary vertices’s. The invariant mass of the tracks forming the vertex can be used to estimate the percentage of different quark flavors in the background. Additionally CDF employs a jet probability algorithm which uses the displaced impact parameters of charged tracks. CDF does not use leptonic decay information, reserving that information to calibrate the b tagging performance.

Finally missing transverse energy is identified using the vector sum of calorimeter energy corrected by the momentum of muons or charged leptons identified as isolated tracks.

3. BSM Higgs

Many new physics models predict the existence of one or more Higgs bosons. In these models the Higgs boson occupies a similar role in electroweak symmetry breaking as in the SM. One subset of new physics models know as Supersymmetry (SUSY) models has inspired many dedicated searches for BSM Higgs bosons. In the minimal SUSY extension of the SM, MSSM, the Higgs sector is expanded to five Higgs bosons. Three of the five Higgs bosons are neutral with a CP even light Higgs, h, a CP even heavy Higgs, H, and a CP odd Higgs boson, A. The two remaining Higgs bosons are the singly the charged $H^+$ and $H^-$. In these models the coupling of the neutral Higgs bosons to b flavored quarks and $\tau^-$ leptons can be enhance by a factor known as $\tan\beta$. This can enhance both the production of the Higgs bosons, if there are b quarks in the initial state, and the decay to both b quarks and $\tau^+$ leptons. In addition, at certain masses either the light or heavy neutral CP even Higgs bosons can be degenerate with the neutral CP odd Higgs boson and both can be searched for simultaneously. This can result in a significant enhancement of the potential sensitivity for observing a Higgs boson with the production cross section and decay enhanced over SM values by as much as two orders of magnitude.

In addition to standard MSSM models, there are many other BSM models that predict enhanced production of Higgs bosons. For instance, in fermiophobic Higgs models the couplings to fermions are reduced and the Higgs boson decays primarily to bosons. Signals involving photons or W and Z bosons can be distinctive enhancing the sensitivity to detect Higgs bosons produced in these models. In addition, there are models that predicts Higgs bosons below the LEP limits for direct Higgs boson searches, which could be visible at hadron colliders or B factory experiments.

3.1. SUSY Higgs Searches

The Tevatron experiments CDF and DØ have recently performed searches for neutral SUSY Higgs bosons. These searches can be used to put limits on the allowed space in a two dimensional plane of $\tan\beta$ and the $m_A$, the mass of the CP odd neutral Higgs boson. These searches have been performed in three primary channels. The first is an inclusive search for neutral Higgs decays to $\tau^+\tau^-$ pairs. The key issue of this search is optimizing tau identification efficiency and rejection of fake taus from jets. To maximize acceptance the CDF and DØ experiments search for tau leptons in leptonic decays to muons and electrons and hadronic decays and combine them into channels where the final states are either fully leptonic or one tau decays hadronically. The purity of the $\tau^+\tau^-$ signature in this mode gives this search competitive sensitivity. The performance of the tau finding algorithms is optimized using large samples of W and Z boson decays involving tau leptons. The results of the CDF and DØ searches are preliminary
and use 2 fb$^{-1}$ and 2.2 fb$^{-1}$ of integrated luminosity respectively. Both searches place limits on tan $\beta$ to be less than order 50 over a wide range of CP odd Higgs masses. The world’s best limits from the CDF experiment in the space of $m_A$ vs tan $\beta$ for the $m_{A,\text{max}}$ scenario are shown in figure 1. More details on limits in other scenarios and all the analyses described in this proceeding are given on the Babar, CDF and DØ web pages.

The D0 experiment additionally performs a search where the Higgs boson is produced in association with a b quark. The Higgs boson decays to a $\tau^+\tau^-$ pair and the b quark is identified as a jet with properties indicative of the relatively long life or decay patterns of b flavored hadrons using the b tagging algorithm described above. Using these tools the D0 performed a search based on 2.2 fb$^{-1}$ that achieves similar sensitivity to the inclusive searches for Higgs decays to tau pairs.

The CDF and DØ experiments also perform a search for Higgs produced in association with b quarks and decaying to pairs of b quarks. In this search the experiments identify events with three or more jets where at least three of the jets are identified as from b quarks and then search for a peak in the invariant mass distribution of the two highest transverse energy, $E_T$, jets. The key issue of this search is understanding the quark content of the background of events with three or more jets from QCD processes. Since, the b tagging algorithms employed for these searches have substantial mis-identification rates for c quark or lighter quark jets, which vary as a function of jet $E_T$, understanding this background is complex. The two experiments employ different methodologies to achieve this purpose. The CDF experiment employs a b quark identification algorithm solely based on well identified secondary vertices’s and further employs the invariant mass of the tracks forming the vertex to estimate the percentage of different quark flavors in the background. The DØ experiment employs their NN tagger at several operating points in order to create a series of simultaneous equations that can be used to solve for the percentages of quark flavors using the known efficiencies and mis-identification rates at each of the operating points. The sensitivity of these searches is enhanced by the large branching fraction to b quarks, but simultaneously limited by the large background. The CDF and DØ experiments find limits of comparable sensitivity to the tau pair channel in scenarios where the b quark coupling is enhanced.

Figure 1: Limits as a function of $m_A$ vs tan $\beta$ for the neutral SUSY Higgs $\tau^+\tau^-$ search.
3.2. Exotic BSM Higgs Searches

The CDF and DØ experiments conduct a number of searches for fermiophobic Higgs where the Higgs boson will have dominant coupling to bosons. They search for both direct gluon fusion production of Higgs bosons where the Higgs decays to two photons and associated production of a W or Z boson with a Higgs boson where the Higgs boson decays to a pair of oppositely charged W bosons or photons. These searches can be used to search for either fermiophobic or SM Higgs and have been optimized in a model independent way. The sensitivity of such searches to fermiophobic Higgs could be substantially enhanced with a specific optimization for those decays modes.

The DØ collaboration has performed a search for Higgs bosons decaying to two photons. The key element in this search is to reduce the background of QCD jets being misidentified as photons. The DØ search employs a NN based photon identification that substantially reduces the backgrounds in this mode. The resulting search has been benchmarked as a SM Higgs boson search. The sensitivity of the search expressed as the ability to set limits on SM Higgs boson production cross section at 95% confidence level (CL) is 23 times the SM Higgs boson production cross section for a Higgs boson of 115 GeV. This metric of sensitivity will be used throughout to describe the sensitivity of the SM Higgs boson searches. The sensitivity for fermiophobic Higgs boson production has not yet reached the expected fermiophobic Higgs production cross sections for Higgs masses above the LEP limits.

Both the CDF and DØ collaboration perform a search for associated production of the Higgs boson with a W or Z boson. In this search the Higgs boson decays to a pair of W bosons and the signature is same sign charged leptons from one of the associated bosons and one of the W bosons from the Higgs boson decay. These searches are also benchmarked as SM Higgs boson searches and achieve sensitivities of 33 and 20 times the SM Higgs boson production cross section at 160 GeV for the CDF and DØ experiments respectively. Similarly in these modes sensitivity to the cross section for fermiophobic Higgs production has not yet been achieved.

3.3. Low Mass Higgs

The Babar collaboration has performed a search for low mass CP odd Higgs production below a mass of 7.8 GeV. This search utilized the Υ(3S) data set to search for the decay Υ(3S) → γA₀ → γχχ. The neutralinos, χ, are not observed so this results in a signal of a single photon and missing energy consistent with the CP odd Higgs mass. The Babar experiment observes an excess of events, 2.6σ, at a mass of 5.2 GeV. This result could be further investigated using data from the Υ(2S) or using data from other experiments.

4. SM Higgs

In the SM the Higgs boson can be produced with cross sections of order $10^{-3}$ to $1^{-1}$ pb by a variety of processes including direct gluon fusion to Higgs which the largest cross section, associated production with a W or Z boson and vector boson fusion with two associated quarks. The Higgs boson decays with greatest probability to the highest mass available state which leads to dominant decays of on order 90% to b quarks pairs and 10% decays to tau lepton pairs at masses around 115 GeV and dominant decays to W boson pairs at mass around 160 GeV. The cross over point when the b quark pair and W boson pair branching ratios are the same is approximately 135 GeV. This knowledge of the Higgs production and decay characteristics leads to a clear strategy for Higgs boson searches at the Tevatron. At low masses the combination of the dominant gluon fusion production mechanism and b quark pair decay is overwhelmed by a large QCD background and instead we look for associated production with W and Z bosons, where the W and Z bosons decay leptonically. Additionally the tau meson pair decay mode is distinct enough to search for in all production modes. At high Higgs mass we search for gluon fusion Higgs production with decay to W bosons pairs which decay leptonically. Additionally, this decay is distinct enough that the Higgs boson events could be detected in all production modes. In the following subsection I review the various Higgs searches in order of increasing sensitivity.
4.1. Secondary SM searches

In order to maximize sensitivity to the production SM Higgs boson the Tevatron experiments search for the Higgs boson in several decay channels that individually don’t have strong sensitivity to the Higgs boson, but collectively in combination with all the Tevatron SM Higgs boson searches will help achieve the goal of reaching SM sensitivity. These channels typically have enough sensitivity to detect on order less than one Higgs boson candidate per $fb^{-1}$, but will contribute to the overall size of a possible Higgs boson signal. Two such searches have already been discussed; the searches for Higgs decays to pairs of photons or W bosons. The remainder of the searches involve decays to tau leptons or quarks.

The DØ collaboration performs a search for associated production of the Higgs boson with a W boson where the Higgs boson decays to a pair of b quarks and the W boson decays to a tau lepton and a neutrino. This search is the first dedicated search for a Higgs boson in this mode and achieves a sensitivity of 42 times the SM production cross section for a Higgs boson of 115 GeV.

The CDF experiment performs a search for associated production of the Higgs boson with a W or Z boson where the Higgs boson decays to a pair of b quarks and the the vector bosons decays to a pair of quarks. This search is the first search in the four jet mode and achieves a sensitivity of 37 times the SM production cross section for a Higgs boson of 115 GeV.

The CDF experiment performs a search for the Higgs boson decaying to a pair of tau leptons. In this search the Higgs boson is searched for in association with two jets which can occur in associated production with the W or Z boson where the bosons decay to jets, vector boson fusion with two associated quark jets, or gluon fusion where there initial state gluons radiate gluons which forms jets. The two tau leptons decay to either hadrons or lighter charged leptons and at least one of the tau leptons is required to decay to a charged lepton to give a pure enough final state to be distinct from the background. This search is particularly interesting since it was the first search to simultaneously consider these three production mechanisms and it will be an important search mode for low mass Higgs at the LHC. The sensitivity of this search is 25 times the SM production cross section for a Higgs boson of 115 GeV. This search adds 5% sensitivity to the overall CDF combination of SM Higgs searches demonstrating the importance of searching for the Higgs boson in all viable production and decay modes.

4.2. $ZH \rightarrow \ell^+\ell^-b\bar{b}$

The first of the three most highly sensitive low mass Higgs search modes is the search for associated production of a Higgs boson with a Z boson where the Z boson decays to a pair of light charged leptons and the Higgs boson decays to a pair of b quarks. The unique feature of this decay mode is that it is fully reconstructed making it one of the most pure Higgs signals available. Since background is not a primary issue the goal of this search is to maximize b jet tagging and lepton finding efficiency. The CDF and DØ experiments pursue a strategy of using events where both b jets are tagged with a loose high efficiency and low purity tag and events where one jet is b tagged with a tight lower efficiency higher purity tag. In addition, the CDF experiment uses several categories of leptons which are identified with relaxed cuts on the information from the dedicated lepton detectors or are only identified as isolated tracks based on calorimeter isolation. Also CDF uses the fact that the event topology should have no missing transverse energy to correct jet energies using a NN algorithm primarily based on information quantifying whether the observed missing transverse energy is collinear with the jet direction indicating jet energy underestimation. Furthermore, both experiments apply an array of advanced techniques to construct discriminating variables with optimum ability to distinguish signal from background. For instance, multivariate discriminates such as NNs or boosted decision trees (BDTs) are used and additionally the matrix element(ME) technique, where the differential matrix elements of the signal and background processes are used to form an event likelihood that an event with given kinematic properties is signal or background like, is employed. Using integrated luminosities of 2.3 and 2.4 $fb^{-1}$ the $ZH \rightarrow \ell^+\ell^-b\bar{b}$ searches from CDF and DØ have the sensitivity to see approximately two Higgs events or a sensitivity of 11.8 and 12.3 times the SM production cross section for a Higgs boson of 115 GeV respectively.
4.3. $VH \rightarrow METb\bar{b}$

The second of the three most highly sensitive low mass Higgs search modes is the search for associated production of a Higgs boson with a W or Z vector boson, where the Z boson decays to a pair of neutrinos or the W boson decays leptonically and the charged lepton is not observed and the Higgs boson decays to a pair of b quarks. The sum of the two production mechanisms and the large branching ratios involved in the vector boson decays make this search potentially very sensitive. The primary background to this search is QCD dijet events where the jet energy is mis-measured leading to apparent missing energy. The key issue is constructing a model of the QCD background. Both CDF and DØ use the comparison of missing energy as measured by the calorimeter and the tracker to identify events with false missing energy and build a model of the background. The CDF and DØ experiments further pursue a strategy of using events where both b jets are tagged with a loose high efficiency and low purity tag and the CDF experiment additionally uses events where one jet is b tagged with a tight lower efficiency higher purity tag. The CDF experiment uses the H1 which algorithm, which is a technique where track information is used to measure the charged component of the jet energy and improve the overall jet energy resolution. Finally, CDF includes three jet events, which gives acceptance for events where the W boson decays to tau lepton and the tau lepton decays hadronically. The DØ experiment includes these events using the dedicated search described above. For final discrimination between signal and background the experiments apply a NN algorithm in the case of CDF and a BDT in the case of DØ. The combination of these techniques makes this search channel the most sensitive per fb$^{-1}$ in the case of CDF. Using an integrated luminosity of 2.1 fb$^{-1}$ the $VH \rightarrow METb\bar{b}$ searches from CDF and DØ have the sensitivity to see approximately 7 and 4 Higgs events and a sensitivity of 6.3 and 8.4 times the SM production cross section for a Higgs boson of 115 GeV, respectively.

4.4. $WH \rightarrow \ell\nu b\bar{b}$

The most sensitive of the low mass Higgs search modes is the search for associated production of a Higgs boson with a W boson decaying to a charged lepton and a neutrino and the Higgs boson decaying to a pair of b quarks. This production and decay mode enjoys the clear signal of the charged lepton and large branching ratios for the W and Higgs boson decays. Again the key issue is increasing lepton acceptance. The DØ experiment uses its excellent lepton identification system to identify charget light leptons including such features as a logical OR of all muon triggers to give full acceptance over a large range of solid angle and extended use of forward going leptons. CDF supplements its lepton detector coverage using leptons collected on MET and jet triggers where the lepton is identified offline either by using areas of the detector with muon detection systems that are not part of the trigger or identifying leptons as isolated tracks using tracking information, which also gives acceptance for electrons and single charged hadron tau decays. Again both experiments apply an array of advanced techniques to construct discriminating variables including NN, BDT and ME based discriminants. Using an integrated luminosity of 2.7 fb$^{-1}$ and a combination of ME and BDT techniques the CDF experiment achieves the strongest sensitivity of any low mass Higgs search with a sensitivity to 8 Higgs events and 5.6 times the SM production cross section for a Higgs boson of 115 GeV. DØ achieves a sensitivity to Higgs production of 8.5 times the SM production cross section for a Higgs boson of 115 GeV.

4.5. $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^−\bar{\nu}$

The strongest sensitivity of any SM Higgs searches at the Tevatron is achieved in the $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^−\bar{\nu}$ decay mode. In this decay mode the charged leptons have the distinct feature that they tend to be collinear due to the spin correlation of the scalar Higgs boson decaying to vector bosons. The CDF and DØ collaborations perform a search for the WW decay in the gluon fusion and vector boson fusion production modes. The CDF search additionally includes acceptance from associated production of a Higgs boson with a W or Z boson. Again the key issue is maximizing lepton acceptance and DØ uses their full lepton detection system where CDF supplements their lepton detectors with leptons identified using tracking and evidence of a minimum ionization signature in the
calorimeter. The experiments further employ NN based discriminating variables including kinematic information and, in the case of CDF, ME based likelihood discriminants. The DØ collaboration optimizes their analysis based on the flavor of the leptons while CDF divides the analysis in events with 0, 1 or 2 jets. The combination of these techniques gives the CDF and DØ experiments sensitivity to detect 17 and 16 Higgs boson events at 165 GeV, respectively, using an integrated luminosity of $3.0 \, fb^{-1}$. The sensitivity of the experiments to set a 95%CL limit on a Higgs boson mass of 165 GeV are 1.6 and 1.9 times the SM production cross section. In the absence of clear Higgs signature the experiments set observed limits of 1.6 and 2.0 times the SM production cross section.

4.6. SM Higgs Combination of Limits

Substantially improved sensitivity can be achieved by combining the results of the two Tevatron experiments. The two experiments first combine their results within their own collaborations. At low mass this entails combining a large number of channels. At high mass the sensitivity is dominated by the $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ channel. Both collaborations compute both individual and combined limits including systematic uncertainties on theoretical cross sections for backgrounds and signal, efficiencies of trigger and identification algorithms, and uncertainties that can change the shape of the final discriminant distributions such as jet energy scale errors, QCD calculation scale variations, PDF variations and the effects of higher order production diagrams. The systematic uncertainties are included as nuisance parameters and the overall fit to compute the expected and observed cross section limits can constrain these parameters where appropriate. The CDF collaboration uses a Bayesian technique and the DØ collaboration uses a CLs technique to perform the combination. The sensitivity for the production of a Higgs boson of 115 GeV is 3.6 and 4.6 times the SM production cross section for the CDF and DØ collaborations respectively. The High mass results are identical to the results quoted above.

At high mass the CDF and DØ collaboration have combined their results between experiments. The full combination is performed using both the Bayesian and CLs techniques to cross check the results. The expected sensitivity to the SM production cross section is 1.3, 1.2, 1.4 and 1.7 times the SM cross section at masses from 160 to 175 GeV in 5 GeV increments. Based on the expected sensitivities at the masses 160 GeV, 165 GeV and 170 GeV the probability to exclude at least one mass is substantial. At 170 GeV the observed limit excludes the SM cross section for Higgs boson production. Similarly the second limit calculation method excludes a cross section 5% less than the SM cross section for Higgs boson production. Based on the strength of the agreement of these two methods and the good agreement with the the expected sensitivities we report that the production of the SM Higgs boson of 170 GeV is excluded. This exclusion represents the first direct limits on the mass of the SM Higgs boson since the final results from the LEP collaborations. The full results of the high mass combination are given in [6] and summarized in table I.

Two graphical representations showing the 95% CL limits as a ratio to the SM cross section and the confidence level of the limit as a function of mass are shown below.

| Mass (GeV) | Expected 1 | Expected 2 | Observed 1 | Observed 2 |
|-----------|-----------|-----------|-----------|-----------|
| 155       | 1.7       | 1.6       | 1.6       | 1.6       |
| 160       | 1.3       | 1.2       | 1.3       | 1.3       |
| 165       | 1.4       | 1.1       | 0.95      | 1.1       |
| 170       | 1.7       | 1.4       | 1.2       | 1.2       |
| 175       | 2.0       | 1.3       | 1.2       | 1.4       |
| 180       | 2.8       | 1.6       | 1.2       | 1.4       |
| 185       | 3.3       | 2.5       | 1.7       | 2.3       |
| 190       | 4.2       | 3.3       | 2.8       | 3.4       |
| 195       | 4.6       | 4.8       | 2.8       | 3.2       |
| 200       |           | 5.1       | 2.5       | 4.7       |

5. LHC Prospects

Here I briefly comment on the LHC prospects for Higgs boson searches. The LHC experiments have the ability to exclude or observe the SM Higgs boson over a wide rage of masses with high significance. At high masses above
Figure 2: Observed and expected (median, for the background-only hypothesis) 95% C.L. upper limits on the ratios to the SM cross section, as functions of the Higgs boson mass for the combined CDF and DØ analyses. The limits are expressed as a multiple of the SM prediction for test masses (every 5 GeV/c²) for which both experiments have performed dedicated searches in different channels. The points are joined by straight lines for better readability. The bands indicate the 68% and 95% probability regions where the limits can fluctuate, in the absence of signal.

135 GeV an exclusion can be achieved with 1 fb⁻¹. The most difficult range will be low mass where good detector performance and tens of fb⁻¹ will be necessary to reach SM Higgs boson sensitivity for observation. In addition, using SUSY as a benchmark for BSM Higgs boson searches, the LHC has sensitivity to the Higgs boson over a large region of SUSY parameters.

6. conclusion

I have reported on the status of Higgs boson searches and the prospects for searches at future colliders. The Tevatron experiments have reached sensitivity for the production cross section of a SM Higgs boson at high mass and have the potential to reach that sensitivity at all masses of interest. Further, the Tevatron experiments report that the production of the SM Higgs boson of 170 GeV is excluded. With the start of the LHC experiments we expect to have sensitivity to observe the SM Higgs boson at all masses of interest if it exists.

References

[1] [http://lepewwg.web.cern.ch/LEPEWWG/]
[2] We use natural units throughout in which c and hbar are taken as one and energy, momentum, and mass are referred to in units of energy.
Figure 3: Distributions of $1-\text{CL}_S$ as a function of the Higgs boson mass (in steps of 5 GeV/c$^2$) for the combination of the CDF and DØ analyses.

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