Prospects for a Low-Mass Higgs Boson

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Abstract. The $SU(2)_L \times U(1)_Y$ gauge theory of the electroweak interactions has enjoyed tremendous success over the past four decades, accurately predicting, or at least accommodating, all high-energy collider data. The gauge group must be broken somehow to $U(1)_{\mathrm{EM}}$, because the unbroken theory predicts massless gauge bosons and massless fermions. The Standard Model incorporates a minimal Higgs sector with a single complex doublet field, to break the symmetry spontaneously, but it is not the only possibility. SUSY Higgses, general two-Higgs-doublet models, and other ideas may prove to model nature better than the minimal model. Many of these models, and even the SM, prefer a light Higgs boson, with a mass between the LEP limit of 114.4 GeV and 200 GeV. The Constrained MSSM favors masses under 120 GeV. A survey of the experimental work so far at LEP and the Tevatron, with estimations of the sensitivity of the upcoming LHC experiments is provided.

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INTRODUCTION

The $SU(2)_L \times U(1)_Y$ gauge theory of electroweak interactions [1] successfully models all collider data taken to date. It is the minimal model that describes the parity-violating weak interactions, and unifies the description of the electromagnetic interaction with the weak interactions. The structure is broadly similar to that of another very successful model, QCD, which has $SU(3)$ as its gauge group. Just as QED predicts a massless photon since a mass term for the photon violates the $U(1)_{\mathrm{EM}}$ gauge symmetry, the electroweak group, if left unbroken, predicts massless $W^{\pm}$ and Z^0 bosons. Furthermore, fermions too must remain massless, as Dirac mass terms for them in the Lagrangian would mix the left-handed states with right-handed ones, and these are known to have different interactions with the weak currents, and hence must have different quantum numbers.

If the electroweak gauge symmetry is spontaneously broken, then the predictive power of the theory is retained, while massive gauge bosons and fermions are allowed. The minimal model breaking $SU(2)_L \times U(1)_Y$ down to $U(1)_{\mathrm{EM}}$ is known as the Higgs mechanism [2], and is incorporated in the Standard Model (SM). It is not the only possibility, however, and given the inability of the SM to explain the nature of dark matter, it is not even the most compelling description. The Higgs boson receives large radiative corrections from loops containing known particles, and these can be counterbalanced by loops containing particles of opposite statistics and hence opposite sign amplitudes. This argument is one of the motivations for supersymmetry, and the prediction of a dark matter candidate is another. The minimal SUSY model, the MSSM, requires two complex

Higgs doublet fields, and has five physical states after symmetry breaking – the CP-even, neutral h^0 and H^0, the CP-odd, neutral A^0, and the charged Higgs bosons H^+ and H^-. One can imagine models with two Higgs doublets even in the absence of supersymmetry, as well as models with Higgs triplets. These latter arise naturally in left-right symmetric scenarios, and predict the presence of doubly-charged Higgs bosons $H^{++/--}$ [3]. Little Higgs models involve introducing new bosons to cancel fermion loops without introducing low-energy supersymmetry, but still require a more exact cancellation for the full radiative corrections at very high energies.

If the Standard Model is the full description of nature (setting aside dark matter for the moment), vacuum stability and triviality bounds place limits on what Higgs boson masses are allowed [4], between approximately 130 GeV and 180 GeV. If new interactions appear only at high energies, these arguments still hold, but become progressively weaker as the scale of new physics gets lower. The argument can be inverted – if a Higgs boson is found with a mass outside of this range, either very light or very heavy, then there is a strong indication for new physics at low mass scales. In fact, some models, such as the MSSM, for many choices of parameters consistent with available data, predict the existence of a Higgs boson which interacts almost exactly like the SM Higgs boson (with only small deviations of decay branching fractions), except that its mass is too light to be accommodated comfortably in the SM with no new interactions.

There are three compelling reasons to study light Higgs bosons (with masses under 200 GeV). The first is the theoretical motivation mentioned above – Higgs bosons are almost guaranteed to exist, and their properties tell us volumes about what other interactions are present in nature. The second reason is that precision electroweak data prefer a light Higgs boson, of mass under about 200 GeV at the 95% confidence level [5]. As of January 2007, the best fit SM $m_H = 80^{+36}_{-26}$ GeV, with $m_H < 153$ GeV at the 95% CL. Including the information from the non-observation of Higgs bosons with masses below 114.4 GeV in direct searches [6], the upper bound on m_H rises to 189 GeV. The third reason for seeking low-mass Higgs bosons is because it is possible to do so at current and planned colliders. LEP could search for Higgs bosons up to a kinematic limit of roughly 115 GeV, determined by the center-of-mass energy of the collider and the necessity of producing Higgs bosons in association with Z^0 bosons. The Tevatron's sensitivity is channel-dependent; the strongest sensitivity corresponds to 114.4 GeV $< m_H <$ 130 GeV, with another strong region of sensitivity near $m_H = 160$ GeV, where the $H^0 \rightarrow W^+W^-$ channel is the most powerful. The LHC is expected to be able to cover the range $m_H < 1$ TeV, although Higgs bosons with some masses will be easier to discover than others. In particular, Higgs bosons with masses under 130 GeV will be more difficult for the LHC experiments.

SEARCHES FOR HIGGS BOSONS AT LEP

The searches for a SM-like Higgs boson at LEP, which closed down at the end of 2000, did not yield evidence for a Higgs boson, although a tantalizing excess of events was reported by the ALEPH experiment [7], corresponding to a bit more than what is expected from a SM Higgs boson with a mass $m_H \approx 115$ GeV. Such excesses were not seen by the other three LEP experiments, and the combined *p*-value, the probability

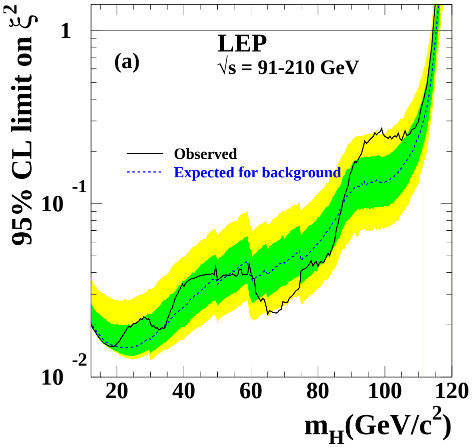

FIGURE 1. Upper limit on the square of the ZZH coupling from the combined searches for a Higgs boson with SM branching fractions and possibly suppressed coupling to the Z^0 boson [6]. The upper limits are expressed as fractions of the SM prediction. The solid black line shows the observed limit as a function of m_H, and the dashed black line shows the median expected limit. The shaded bands show the $\pm 1,2\sigma$ distributions around the expected limits. Discontinuities in the sensitivity arise from the limited m_H search ranges chosen for some analyses on some experiments which did not include the entire sensitive area.

of an upward fluctuation of the background to the data or more, is 9% [6], far higher than the criterion needed to claim evidence. The exclusion of SM-like Higgs bosons with masses below 114 GeV is quite strong, as the large expected signal rate and low backgrounds allow for powerful searches. The coupling limit as a function of m_H is shown in Figure 1. Models with extended Higgs sectors often predict a SM-like Higgs boson but with suppressed couplings to the Z^0 boson. In the MSSM, the ZZH coupling is suppressed by a factor of $\sin(\beta-\alpha)$, where $\tan\beta$ is the ratio of VEV's of the two Higgs doublets, and α is the Higgs mixing angle.

For very light Higgs bosons, the decay branching ratios vary rapidly with mass, as kinematic thresholds are crossed. For exotic models, Higgs bosons may decay invisibly, or via cascades $h^0 \rightarrow A^0A^0$, with A^0 decays to charm, or gluons, or taus. The LEP experiments had a strong advantage of being able to identify boosted Z^0 bosons, fully reconstructed from their leptonic decays, and to infer the properties of recoiling objects, regardless of the decay modes [8]. Strong limits on the Higgsstrahlung process are obtained all the way down to zero mass, but stop at masses above 85 GeV due to the reduced sensitivity of the decay-mode independent search and the falling production cross section. A great many specific models have been tested by direct LEP Higgs boson searches. Neutral MSSM Higgs boson search results are summarized in [9], for CP-conserving and CP-violating scenarios, as well as limits on cross sections multiplied by decay branching fractions which can be applied to any model.

Recently, Roszkowski, Ruiz and Trotta [10] performed a Bayesian analysis scanning over CMSSM parameter space, with a likelihood function which included direct LEP2 Higgs searches, precision EW measurements, $g_\mu - 2$, WMAP cosmic microwave background radiation measurements, the recently-measured B_s mixing rate, $Br(B \rightarrow s\gamma)$, and the limit on $Br(B_s \to \mu^+\mu^-)$ in order to predict the most credible values of the Higgs boson mass in this scenario. Interestingly, almost all of the posterior probability lies below $m_H = 120$ GeV, with SM-like Higgs behavior. The H^0, the A^0 and the $H^\pm$ could have masses up to 4 TeV, however, although masses under 2 TeV are preferred. LEP may have just barely missed discovering a Higgs boson, if the CMSSM is a reasonable approximation to nature. On the other hand, if a SM-like Higgs boson is not found with a mass below approximately 135 GeV, the MSSM is all but ruled out, although there are escape routes and clever parameter choices.

SEARCHES FOR HIGGS BOSONS AT THE TEVATRON

With this in mind, the Tevatron became the focus of Higgs boson searches, as the higher energy of the colliding $p\bar{p}$ beams allows for heavier Higgs bosons to be produced. The difficulty is the large background to most searches. The process $gg \to H^0 \to b\bar{b}$ has the largest production rate and decay branching ratio for light Higgs bosons needed to test the MSSM hypothesis, but it is swamped by the much larger $gg \to b\bar{b}$ process. Instead, associated production of a Higgs boson with a leptonically-decaying vector boson is used, $W^\pm H^0 \to \ell^\pm \nu_\ell b\bar{b}$, $Z^0 H^0 \to \nu\bar{\nu} b\bar{b}$, and $Z^0 H^0 \to \ell^+\ell^- b\bar{b}$ are the most sensitive to Higgs bosons of mass less than about 135 GeV. Another powerful search is the $gg \to H^0 \to W^+W^-$ channel, which also benefits from vector-boson fusion and associated production processes. Typically the leptonic $W^\pm$ boson decays are sought, and little is required of the rest of the event.

The expected sensitivity to a Higgs boson produced with the SM production cross sections was estimated in 2000 [11], and the required luminosity to exclude at the 95% CL, obtain evidence at the 3σ level, or discover at the 5σ level, is shown in Figure 2. The exercise was repeated in 2003 [12] with more realistic Monte Carlo simulations and some data taken with the Run II detector configurations. The projected luminosity requirements are shown in Figure 2 and generally confirm the earlier sensitivity estimations, coming in with slightly more optimistic sensitivity. Systematic uncertainties were not included in the latter study they had not yet been evaluated, nor was the $gg \to H^0 \to W^+W^-$ channel estimated at that time. For the earlier study, systematic uncertainties were expected to scale as $1/\sqrt{\int \mathscr{L} dt}$. One very important change to the expected sensitivities for Higgs boson masses above 135 GeV is the recent calculation of the $gg \to H^0$ production cross section at NNLO [13], which adds approximately 50% more signal rate relative to the NLO cross sections quoted in [11].

The sensitivity projections had a delicate set of requirements to balance – realistic projections require the best estimations of the acceptance and backgrounds, yet it is fully expected that the analysis teams involved in the searches will apply increasingly sophisticated techniques to analyze the data. Furthermore, the detectors continue to be upgraded, even during running. Trigger and data acquisition upgrades are necessary in order to follow the increasing luminosity projections, and DØ finished installing its upgraded inner silicon tracking layer which is expected to improve significantly the b-tagging performance. Low-mass Higgs boson searches presented in 2006 still lack in many cases some of the sophisticated techniques expected to be put to use, such as improved triggers, improved dijet mass resolution techniques, neural nets and

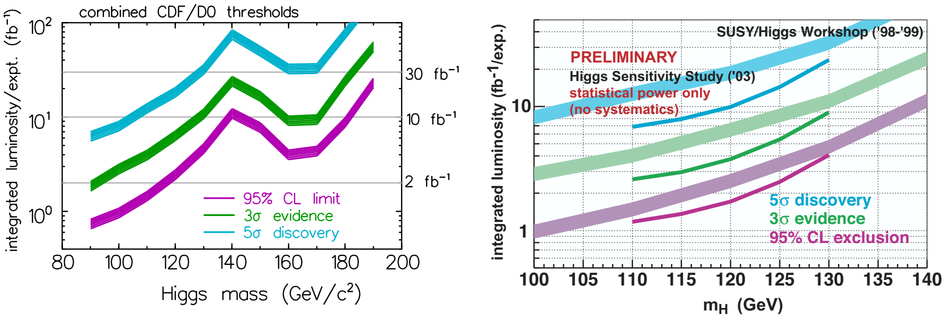

FIGURE 2. Sensitivity projections of the SUSY/Higgs Working Group [11] (left figure) and the Tevatron Higgs Sensitivity Working Group [12] (right figure). Shown are the amounts of integrated luminosity per experiment required in order to achieve an expected sensitivity to a Standard Model Higgs boson at the 95% CL, 3σ evidence, and 5σ discovery level.

matrix element discriminators, forward b-tags and forward leptons, and sophisticated b-tag discriminants. Each of these improvements has an ongoing effort within both collaborations. One example of an improvement which has a significant impact on the sensitivity is splitting the $H^0 \to bb$ channels into single-tagged and double-tagged subsets. This operation improves the sensitivity in two ways: the double-tagged sample has a smaller fraction of mistagged light-flavor and charm jets, and the dijet mass resolution in the double-tagged sample is better.

The status of the Tevatron searches as of ICHEP 2006 is shown in Figure 3. The limits are shown as a multiple of the SM production rate because some channels, such as the bb+missing energy channel, are sensitive to both Z^0H^0 and $W^{\pm}H^0$ production, and the SM ratio is assumed. For ICHEP 2006, DØ analyzed a full 1 fb^{-1} in its $H^0 \to W^+W^-$ channels but about a third of that amount of data in its $H^0 \to bb$ channels. CDF, on the other hand, analyzed a full 1 fb^{-1} for its $H^0 \to bb$ channels but only 360 pb^{-1} for $H^0 \to W^+W^-$. It is a "snapshot" in time – as of April 2007, both CDF and DØ have finished all analyses with 1 fb^{-1}.

The Tevatron collider is performing at record levels, having delivered more than 2 fb^{-1} to the experiments, with stores starting with luminosities frequently exceeding 200×10^{30} cm^2/s. The trigger rates rise faster than the luminosity due to segments of nearby low-energy tracks being falsely reconstructed as high-energy tracks, and due to overlapping energy deposits in the calorimeters passing trigger thresholds more easily. More sophisticated triggering algorithms are studied by CDF and DØ, such as stereo reconstruction of tracks at the trigger level, and better calorimeter clustering algorithms in order to maintain high trigger efficiencies for Higgs bosons at the high projected luminosities.

LOW-MASS HIGGS BOSON SEARCHES AT THE LHC

The ATLAS and CMS experiments offer strong sensitivity to a SM (or SM-like) Higgs boson over the range of masses from 115 GeV up to 1 TeV, and the sensitivities are described in detail in [14] and [15]. Figure 4 shows the expected significance levels in σ

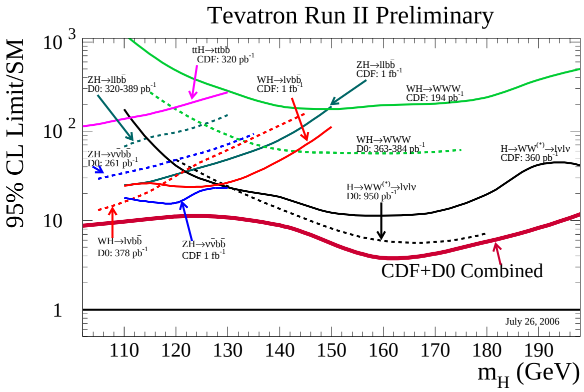

FIGURE 3. Summary status of the CDF and DØ Higgs search limits as of ICHEP 2006. Limits are shown for each of the SM channels separately and combined, as a multiple of the SM production rate.

for both ATLAS and CMS after 30 fb^{-1} have been accumulated by each experiment. The search strategy depends critically on the value of m_H being tested, due to the changing branching fractions of the Higgs boson. For $m_H < 135$ GeV, the sensitivities of the $t\bar{t}H^0 \to t\bar{t}b\bar{b}$ search, the $H^0 \to \gamma\gamma$ search, and the $H^0 \to \tau^+\tau^-$ are similar. Their combination is needed in order to achieve discovery-level sensitivity at 30 fb^{-1}. The associated-production modes $W^\pm H^0$ and Z^0H^0 with $H^0 \to b\bar{b}$ are expected to have poor signal-to-background performance and are not expected to contribute as much to the sensitivity. The possibility of a SM-like Higgs boson with a mass under 135 GeV, a mass range favored by the precision electroweak fits and the CMSSM, and the relative difficulty of discovering such a particle at the LHC, encourages the full development of the Tevatron resources to devote to this search.

At higher masses, however, the sensitivity of ATLAS and CMS rises, as the distinct decay modes $H^0 \to W^+W^- \to \ell^+\nu_\ell \ell'^- \bar{\nu}_{\ell'}$ and $H^0 \to Z^0Z^0 \to \ell^+\ell^-\ell'^+\ell'^-$ become the most important. Vector-boson fusion enhances the production cross section and also supplies forward “tagging jets” which can be used to help distinguish events containing Higgs bosons from the SM W^+W^- backgrounds. ATLAS estimates it may need as little as 1 fb^{-1} of data in order to discover a SM Higgs boson with a mass of 160 GeV. For higher Higgs boson masses still, the full mass reconstruction in the Z^0Z^0 mode allows both a clean separation of signal from the background, as well as a precise measurement of the Higgs boson mass.

EXTENDED AND EXOTIC HIGGS SEARCHES

Even though the current sensitivity of CDF and DØ combined is not yet enough to test for the presence of a SM-like Higgs boson, extended models provide signatures with large enough production rates that they can be detected with 1 fb^{-1}. In particular, the

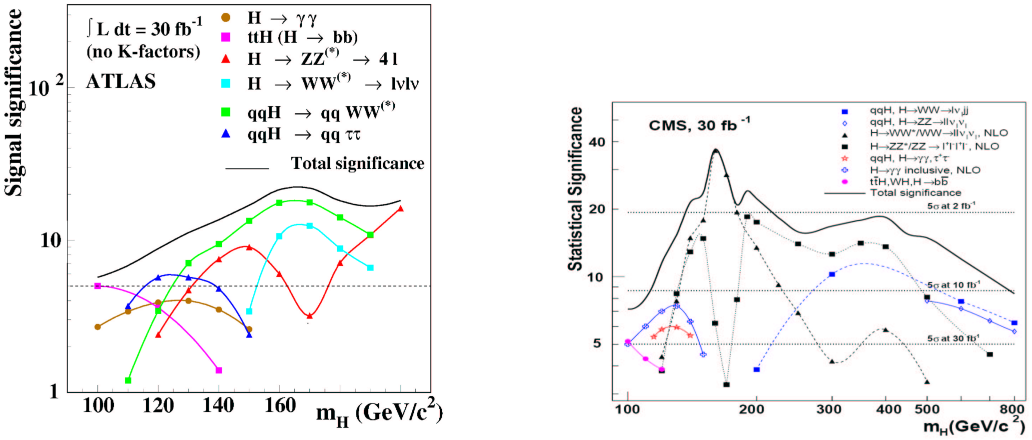

FIGURE 4. Discovery potential for a SM Higgs boson in ATLAS [14] and CMS [15], for the different search channels separately and combined, estimated for an integrated luminosity of 30 fb^{-1}.

production cross section for Higgs bosons produced in association with b quarks, and via a b loop in $gg \to H$ scales roughly as $\tan^2\beta$. Furthermore, at high $\tan\beta$, either the h^0 or the H^0 is expected to have a mass very similar to that of the CP-odd A^0 boson, and thus the expected signal cross section is approximately twice that of just one Higgs boson. These Higgs bosons are expected to decay roughly 10% of the time to tau pairs, and 90% of the time to bb pairs, although model parameter choices can be made which modify both the couplings and the branching ratios [16]. CDF and DØ have recently released searches for the $H^0 \to \tau^+\tau^-$ mode [17][18], using approximately 1 fb^{-1} of data. Both analyses use detailed tau identification algorithms designed to detect leptonically and hadronically decaying tau leptons, and use the reconstructed visible mass of the tau decay products to help separate a Higgs boson signal from the backgrounds (dominantly $Z^0 \to \tau^+\tau^-$). Both searches are sensitive to $\tan\beta \approx 40$ at the 95% CL level. CDF observes an excess of candidates near $m_H = 160$ GeV at a level of 2σ, while DØ observes data which are in agreement with SM background predictions. The excess in CDF is interesting but is not yet very strong.

The LHC has a tremendous potential to discover Higgs bosons in the MSSM. The sensitivity to the lightest CP-even Higgs boson, the h^0 follows that of the SM Higgs sensitivity. If the A^0 is very heavy, however (a few hundred GeV or more), it could be possible that only one Higgs boson is observable, and it would look very SM-like, except perhaps for its low mass. At very high or low values of $\tan\beta$, a charged Higgs boson could be observable at the LHC, and at high $\tan\beta$, ATLAS and CMS can use the $H^0 \to \tau^+\tau^-$ channel to cover H^0 and A^0 masses up to 700 GeV [14].

SUMMARY

The searches for the Higgs bosons of the SM and the MSSM are gaining sensitivity as data are collected by the CDF and DØ collaborations. The LHC, when it collects 30 fb^{-1} of data, will have discovery sensitivity over the entire mass range from the LEP exclusion up to about 1 TeV, and near $m_H = 160$ GeV, the sensitivity is much greater and a discovery can be made with much less luminosity (as little as 1 fb^{-1}). In the Constrained MSSM, the most probable value for the lightest Higgs boson mass is less than 120 GeV [10], where the LHC sensitivity is weakest. A light Higgs boson is also favored by the precision electroweak fits. For these reasons, the Tevatron experiments are optimizing their sensitivity to a low-mass Higgs boson as a top priority. Sensitivity to the heavier Higgs bosons of the MSSM is enhanced at high $\tan\beta$, and Tevatron searches are already probing $\tan\beta \approx 40$. In the next three or four years, we will know quite a lot about electroweak symmetry breaking.

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