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Search for the SM Higgs Boson at the Fermilab Tevatron

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We present the results of searches for the standard model (SM) Higgs boson (H) in data collected by the CDF II and D0 experiments at the Fermilab Tevatron. Individual searches performed by the two collaborations, targeting several decay modes of the Higgs boson, are combined, with $p\bar{p} \to H \to b\bar{b}$ and $p\bar{p} \to H \to W^+W^-$ contributing dominantly to search sensitivity below and above $\sim$135 GeV/c^2 respectively. The searches are performed in data samples of $p\bar{p}$ collision events corresponding to integrated luminosities of up to 10 fb^{-1}. In combination, we observe a significant excess of data events compared to the expected contribution of background processes, in the mass range $115 < m_H < 140$ GeV/c^2, with a local significance of 3.0 standard deviations at $m_H = 120$ GeV/c^2.

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1. Introduction

In the standard model of particle physics (SM), electroweak symmetry breaking gives rise to the Higgs boson (H). Searches aiming to provide confirmation of the existence of this particle have drawn the effort of particle physicists for many years, with the goal of discovery remaining elusive prior to the summer of 2012. The two LHC experiments, CMS and ATLAS, have each recently reported observation [1, 2] of a particle with a mass of approximately $\sim 125\ \mathrm{GeV}/c^2$. The LHC observations draw much of their significance from excesses in searches for the decays $H \to \gamma\gamma$ and $H \to ZZ$, while searches for the dominant decay mode at $\sim 125\ \mathrm{GeV}/c^2$, $H \to b\bar{b}$, have not yet achieved sufficient sensitivity to shed light on the presence or absence of a Higgs boson signal on their own.

In contrast, at the Tevatron, sensitivity to a low-mass Higgs boson ($m_H \leq 135\ \mathrm{GeV}/c^2$) is derived mainly in searches for $H \to b\bar{b}$. As such, the results of these searches serve as a source of complimentary knowledge- in particular, containing the potential to shed light on the coupling of the Higgs boson to fermions.

Here, we summarize the result of a new combination of searches performed by the CDF and D0 collaborations. The results presented here are derived from combination of individual direct searches which target a multitude of final event topologies consistent with the decays of the Higgs boson, including $H \to b\bar{b}$, $H \to ZZ$, $H \to \tau^+\tau^-$, $H \to W^+W^-$, and $H \to \gamma\gamma$. Several of the individual searches combined here, have been updated with expanded datasets and/or improved analysis methods compared to the searches combined previously [3]. A list of the analysis channels (where each "channel" is a search conducted in an exclusive event sample determined by the targeted final state topology) contributing to the combined result is provided in Tables I and II of reference [4], along with references to documents providing technical details which are omitted here in the interest of brevity.

In the following sections, we summarize the primary features of Tevatron searches, and present the results of the combination of individual direct searches for the SM Higgs boson.

2. Contributing Channels

While the individual search channels differ in terms of the specific analysis techniques employed, they do share several features in common. In particular, many of the channels utilize selection criterion designed to enhance both Higgs boson acceptance and background process rejection. In addition, a multivariate technique, typically an artificial neural network (ANN) or boosted decision tree (BDT), is employed to increase separation between the predicted signal and expected background in the selected data samples. Both selection and multivariate techniques are developed using simulated signal and background processes or signal-deficient (control) data samples. Although multivariate methods may be employed at several stages during a search (for example to identify energetic leptons, or b-quark jets), the output of the "final" multivariate method, evaluated for each H boson candidate data event, is binned producing the distribution (often denoted as the "final discriminant") which is used in the extraction of 95% confidence level (CL) upper limits on the rate of the signal process. One such distribution is produced for each Higgs boson mass (m_H) hypothesis analyzed. We consider values of m_H between 100 and 200 GeV/c^2 in 5 GeV/c^2 steps.

The upper limits are expressed in multiples of the predicted SM cross section $\times$ branching ($\sigma_{SM} \times BR$) ratio of the signal process. The CDF collaboration utilizes a Bayesian technique [5], while the D0 collaboration employs a Modified Frequentist technique [6] to extract the upper limits on the signal process rate. When compared, the two statistical techniques produce limits which agree to within 1% on average, and within 10% for a given mass hypothesis.

Signal samples are simulated with the PYTHIA [7] Monte Carlo program, with CTEQ5L and CTEQ6L1 [8] leading-order (LO) parton distribution functions with corrections to the simulations included to account for the differences with respect to recent higher-order calculations as described in reference [4]. The signal samples are normalized assuming the Higgs boson production cross sections listed in Table III of reference [4]. The Higgs boson decay branching ratios are set to those of references [9, 10].

The particular combination of background processes expected to contribute to a channel varies based on the specific selection criterion applied. Significant backgrounds are expected from QCD multijet events and SM electroweak processes. The multijet contribution, instrumental in nature, is measured by both CDF and D0 in isolated (from predicted Higgs boson signal) data samples. Electroweak processes are simulated using any of several Monte Carlo programs, including PYTHIA [7], ALPGEN [11], MC@NLO [12], and HERWIG [13]. The expected contribution from these backgrounds to the candidate Higgs boson sample is determined by normalizing the simulated samples to experimental measurements or next-to-leading order calculations. When not included by the generating program, parton showering is added to the simulated processes with PYTHIA. Simulated samples utilized by the CDF and D0 searches are interfaced to GEANT-based detector simulations [14].

Systematic uncertainties are incorporated into the statistical techniques during the extraction of the upper limits on the signal rate. Uncertainties may be correlated across channel and experiment, can affect the expected rates of signal and background processes, and are capable of modifying the shape of the distributions used in the extraction of upper limits. Uncertainties arising from the measurement of integrated luminosity, signal production rates, background normalization, multijet background modeling, and selection efficiencies are considered, among others. In combination, systematics are found to degrade sensitivity to a Higgs boson signal by roughly 10 to 20% for most analysis channels.

In the following subsections, we briefly highlight the key features of several analyses included in the combined result to be presented below.

2.1 ZH Searches

Searches for the associated production of a Higgs boson with a Z boson at the Tevatron select candidate events based on their consistency with the expected topology of a $H \to b\bar{b}$ decay. Tevatron ZH searches can be divided into two major categories. One set of searches target the decay of the Z boson into a pair of electrons or muons ($Z \to \ell\ell$), while the other considers Z boson decays to neutrino pairs ($Z \to \nu\nu$).

CDF and D0 searches for $H \to b\bar{b}$ with and $Z \to \ell\ell$, select events with at least two isolated leptons and two energetic jets. At least one of the two jets is required to be consistent with a jet arising from the hadronization of a b-quark. Both CDF and D0 searches are notable for the introduction of methods designed to improve the dijet mass resolution. CDF employs an artificial neural network to correct jet energies while D0 extracts the dijet mass based on a kinematic fit to the objects (jets+leptons) in each event. Both techniques improve the dijet mass resolution by roughly 15%, enhancing sensitivity to the ZH signal by a similar factor.

The ZH searches with $Z \to \nu\nu$ select candidate events with two or more jets and a significant transverse energy imbalance ($\not{E}_T$). As multijet backgrounds are a significant contribution to this event topology, the CDF and D0 collaborations both utilize preselection multivariate techniques optimized for the rejection of QCD events. These methods reduce the multijet backgrounds by up to 90% while retaining a significant fraction of the expected signal. Both CDF and D0 analyses include the expected contribution from WH processes in these searches. As the probability for a charged lepton from a W boson decay to escape detection is not negligible, WH signal can contribute up to 50% of the total SM Higgs boson signal expected for a search in the $\not{E}_T$+$H \to b\bar{b}$ event topology.

2.2 WH Searches

The WH search modes target $H \to b\bar{b}$ with the leptonic decay of a W boson, $W \to \ell\nu$, in events consistent with the jets + charged lepton + $\not{E}_T$ topology. To maintain orthogonality with the candidate samples selected in ZH searches, the WH channels reject events with more than one charged lepton of significant energy. The D0 collaboration's WH search includes the additional signal contribution from the $VH \to VWW \to \ell\bar{\nu}jjjj$ process, where “j" is a jet and V represents a Z or W boson.

2.3 $H \to WW$ Searches

In searches for $H \to WW$, candidate events are required to contain significant $\not{E}_T$ and a pair of oppositely charged leptons. CDF and D0 searches in this mode feature several “sub-channels", dividing candidate events into categories based on the number of jets or the flavor of the identified leptons. The D0 analysis introduces WW-enriched and WW-depleted sub-channels, dividing events based on the output of a multivariate decision tree, contributing to the approximately 5-10% sensitivity boost achieved in this iteration of the analysis. CDF extends the analysis selection to trilepton and same-sign dilepton topologies in order to accommodate additional signal from $W/Z+H \to WW$ processes.

2.4 $H \to \tau\tau$ Searches

CDF performs a search for direct $gg \to H$ (where g is a gluon) with the Higgs boson decaying to a pair of oppositely-charged τ leptons. The search also includes the expected contribution from associated WH and ZH production. Similarly, D0 includes $H \to \tau\tau$ signal in a dedicated search for VH processes.

2.5 $H \to \gamma\gamma$ Searches

The signal contribution from $H \to \gamma\gamma$ is considered by CDF and D0 searches in two-photon event topologies. CDF examines the diphoton invariant mass distribution for a peak consistent with the predicted Higgs boson signal. While the CDF search utilizes the diphoton invariant mass spectrum in the extraction of upper limits on the signal rate, D0 utilizes the output distribution of a boosted decision tree.

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3. Results

The statistical techniques mentioned above, with care taken to account for systematics correlated between the two experiments, are applied to the collection of final discriminants produced by the analysis channels from each experiment. The combined 95% CL upper limits on the signal production rate as a function of m_H, as obtained from the combination of all Tevatron search channels, are displayed in figure 1. The combined result excludes the regions $100 < m_H < 103$ GeV/c^2 and $147 < m_H < 180$ GeV/c^2 at the 95% CL. As visible in figure 1, there is an excess of data events beyond the expected total background in the mass range $115 < m_H < 140$ GeV/c^2. The minimum p-value obtained at $m_H = 120$ GeV/c^2 corresponds to a local significance of 3.0 standard deviations, which moves to 2.5 standard deviations after adjustment for the look-elsewhere effect.

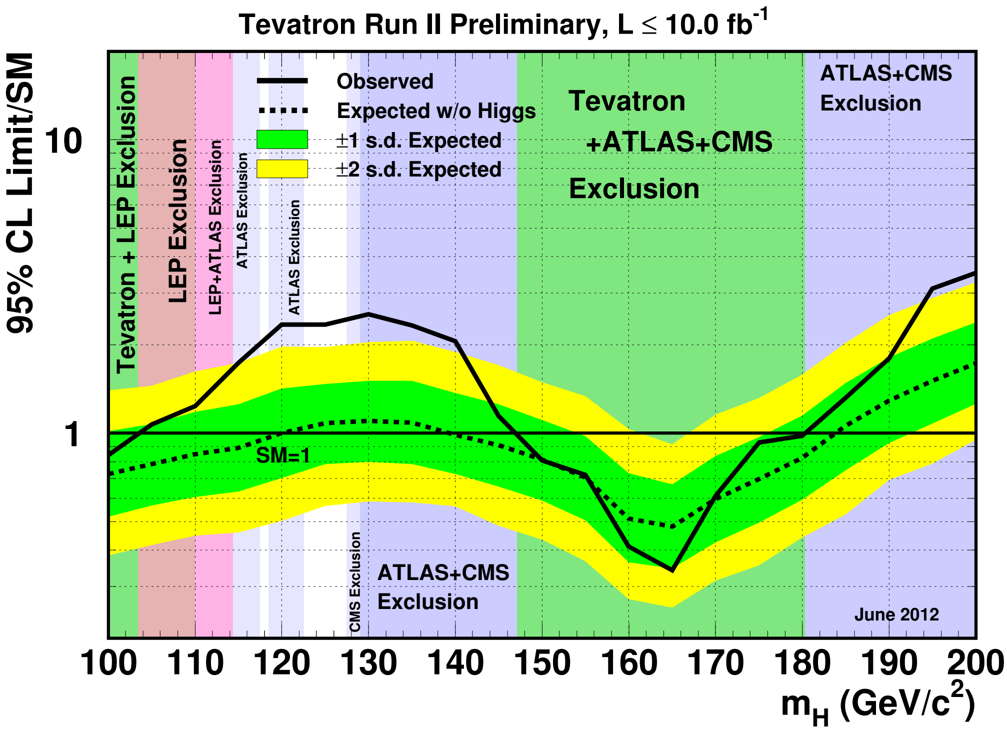

Figure 1: The Bayesian observed and median-expected 95% CL upper limits on the SM Higgs boson production rate, presented as a function of the Higgs boson mass (in steps of 5 GeV/c^2), as obtained from the combination of all Tevatron search channels. The green (yellow) band indicates the 68% (95%) probability regions about the median expected upper limits.

We perform separate combinations of all Tevatron $H \to b\bar{b}$ and $H \to WW$ searches. The 95% CL upper limits extracted in the $H \to b\bar{b}$ and $H \to WW$ combinations are displayed in figures 2 and 3 respectively. We find the Tevatron excess to be concentrated in the $H \to b\bar{b}$ search channels, in which a minimum p-value occurs at a value of $m_H = 135$ GeV/c^2 corresponding to a local significance of 3.2 standard deviations. This represents a global significance of roughly 2.9 standard deviations after accounting for the look-elsewhere effect.

4. Conclusions

In summary, we have presented the result of the combination of Tevatron searches for the standard model Higgs boson. We have summarized the key features of the main channels contributing to the combined sensitivity to the Higgs boson. In the combination of all search channels, a broad excess is observed at lower values of m_H. An excess of events observed in the combined $H \to b\bar{b}$ searches is the primary source of the overall excess.

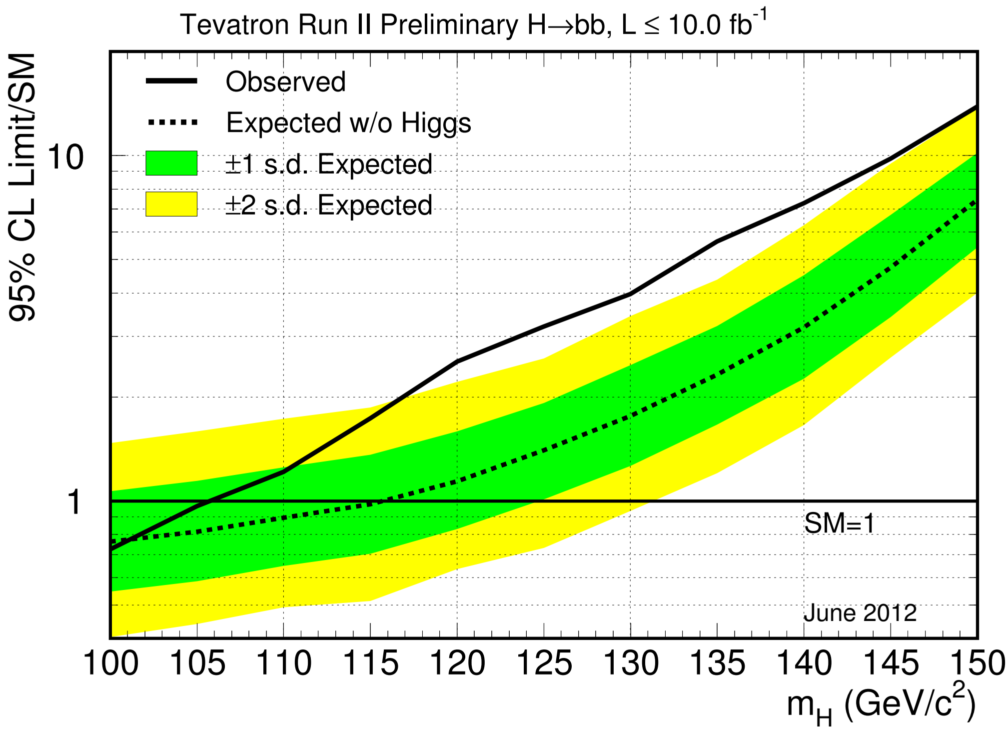

Figure 2: The Bayesian observed and median-expected 95% CL upper limits on the SM Higgs boson production rate in $H \to b\bar{b}$, presented as a function of the Higgs boson mass (in steps of 5 GeV/c^2), as obtained from the combination of all Tevatron $H \to b\bar{b}$ search channels. The green (yellow) band indicates the 68% (95%) probability regions about the median expected upper limits.

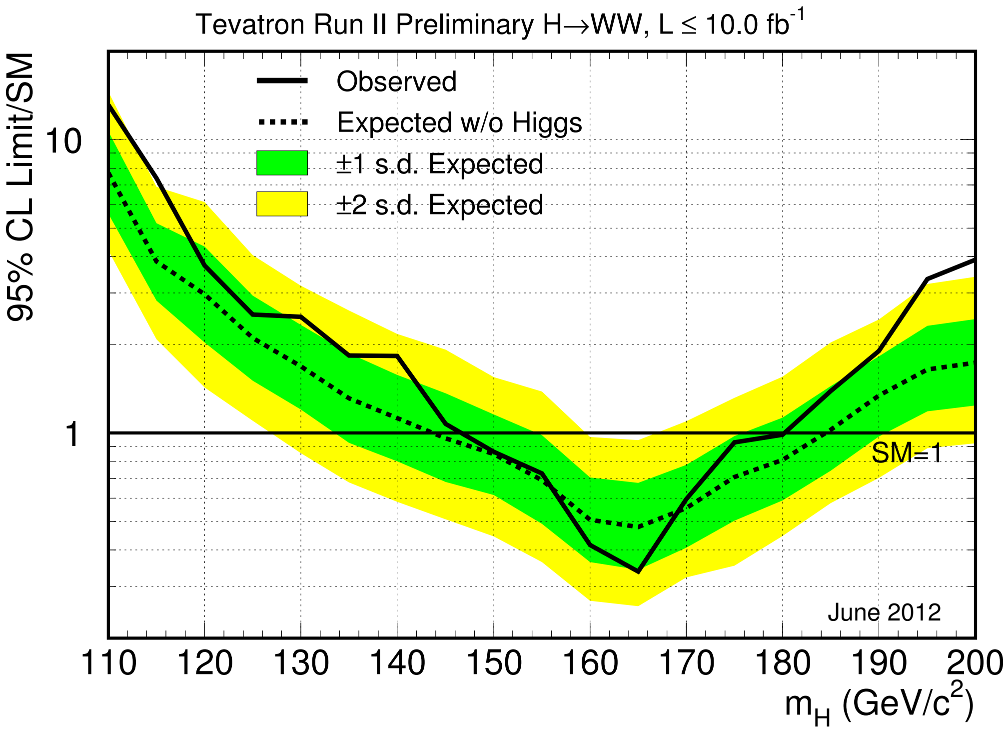

Figure 3: The Bayesian observed and median-expected 95% CL upper limits on the SM Higgs boson production rate in $H \to WW$, presented as a function of the Higgs boson mass (in steps of 5 GeV/c^2), as obtained from the combination of all Tevatron $H \to WW$ search channels. The green (yellow) band indicates the 68% (95%) probability regions about the median expected upper limits.

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