Chapter 3

Searches for the Standard Model Higgs Boson at the Tevatron Collider

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During Run II of the Tevatron collider, which took place from 2001 until 2011, the CDF and D0 detectors each collected approximately 10 fb^{-1} of $p\bar{p}$ collision data at a center of mass energy of $\sqrt{s} = 1.96 \text{ TeV}$. This dataset allowed for tests for the presence of the SM Higgs boson in the mass range 90–200 GeV in the production modes $gg \rightarrow H$, W/ZH , vector-boson fusion, and $t\bar{t}H$, with H decay modes $H \rightarrow b\bar{b}$, $H \rightarrow W^+W^-$, $H \rightarrow \tau^+\tau^-$, $H \rightarrow \gamma\gamma$, and $H \rightarrow ZZ$. This chapter summarizes the search methods and the results of the Higgs boson search at the Tevatron. The increased sophistication of the analysis techniques as the collider run progressed is discussed, covering the strategies used over time to improve the sensitivity and breadth of the analyses. Using the full Tevatron data sample for both experiments, the combined Higgs search in all channels observes an excess consistent with the predicted SM Higgs boson signal with mass of 125 GeV, with a significance of 3.0 standard deviations above the background prediction.

1. Introduction

The Tevatron proton-antiproton ($p\bar{p}$) collider was part of a series of particle accelerators at the Fermi National Accelerator Laboratory (FNAL or Fermilab) which is located approximately 60 kilometers west of the city of Chicago. Fermilab hosts a large program of particle physics experiments and has a long history of particle discovery and innovation in high-energy particle accelerators. Following the shutdown of the LEP e^+e^- collider in 2000 (see Chapter 2) and before LHC operations, the Tevatron was the

highest-energy particle collider in the world. A primary goal of the Tevatron physics program was the discovery of the top quark and subsequent measurement of its properties. After the discovery of the top quark at the Tevatron in 1995, the accelerator and its two experiments (CDF and D0) were upgraded for a second running period.

The Tevatron collider and its experiments were not optimized to search for Higgs bosons. However, the upgrades to the Tevatron and the experiments provided an opportunity to expand the Tevatron's physics program to include Higgs boson searches. In the early years of the current millennium there were several studies performed to determine the potential of a Tevatron Higgs boson search.^{1,2} These studies suggested that with integrated luminosities of $10\text{--}20\text{ fb}^{-1}$ per experiment, a search for the Higgs boson could reach sensitivity thresholds of 3-5 standard deviations above background predictions over a Higgs boson mass range of $100 - 200\text{ GeV}$. Sensitivity to beyond-Standard-Model (BSM) Higgs searches was also studied with similar conclusions. With the support of these Higgs boson search sensitivity studies, the CDF and D0 experiments began a Higgs physics program in Run II of Tevatron operations. This program began in 2001 and continued into 2013 beyond the end of Tevatron operations with final studies of Higgs boson properties being finalized at the time of this writing.

2. The Tevatron Collider and Experimental Apparatus

The Tevatron collider operated in two distinct data collection epochs, referred to as Run I and Run II, encompassing the periods of 1992-1996 and 2001-2011, respectively. The Tevatron produced $p\bar{p}$ collisions that were recorded by two multipurpose particle detectors, CDF^{3,4} and D0.⁵⁻⁸ During Run I, the Tevatron operated at a center-of-mass energy of 1.8 TeV and delivered an integrated luminosity of approximately 145 pb^{-1} (110 pb^{-1} recorded by the detectors). For Run II, the detectors were upgraded and the Tevatron's center-of-mass energy was increased to 1.96 TeV, and delivered an integrated luminosity of 11.9 fb^{-1} to each of the two experiments (10.7 fb^{-1} recorded). The search for Higgs bosons at the Tevatron was performed using data from Run II and henceforth this article will solely refer to the period of Run II.

The Tevatron had a circumference of 6.82 kilometers and used 774 niobium-titanium (NbTi) superconducting dipole magnets that produced a field of 4.2 T to maintain the particle orbit. The beam focusing was performed using 240 NbTi quadrupole magnets. The Tevatron's luminous

Fig. 3.1. A schematic representation of the Run-2 D0 detector.⁶ The inner tracking system resides at the center of the detector apparatus and within a 2 T solenoid magnet. The electromagnetic and hadronic calorimeters are located outside the solenoid. The muon system surrounds the calorimetry and incorporates a 1.8 T toroidal magnet.

region was approximately $30 \mu\text{m}$ wide in the directions transverse to the beam axis and 120 cm long. The time between bunch crossings at the Tevatron was 396 ns, with 36 counter-rotating bunches each of protons and antiprotons. The remaining orbit spacing was taken by gaps in the bunch trains to allow time for abort kicker magnets to fire. The Tevatron reached a maximum instantaneous luminosity of $4.31 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$.

The CDF and D0 detectors were solenoidal spectrometers with precise silicon-strip tracking detectors surrounded by a drift chamber (CDF) or a scintillating fiber tracker (D0), inside a magnetic field of strength 1.4 T (CDF) and 2.0 T (D0). Time-of-flight, calorimetry, and muon detectors were located outside of the magnet solenoids, and provided energy measurements and particle identification. For illustration purposes, the organization of detector systems for the D0 detector is shown in schematic format in Figure 3.1 (CDF's construction was highly similar).

For both experiments, the maximum data logging rate was approximately 200 Hz, and so both detectors employed three-level triggering systems to reduce the 2.5 MHz beam collision rate to acceptable levels. The first trigger level operated in dedicated hardware and summed calorime-

ter energies for fast jet/electron identification and E_T^{miss} calculation, and, using separate hardware, identified charged-particle tracks in the trackers. The first-level trigger reduced the event rate to approximately 2-10 kHz. A second-level trigger considered a more complete readout of the detector and operated in specialized hardware and software. At this trigger level, tracks were associated with calorimeter clusters and track segments in the muon detectors in order to form trigger decisions sensitive to the presence of high- p_T leptons. Using tracking information, displaced vertexes could be found at this level of triggering. The trigger rate at this level was approximately 1-2 kHz. A third level of triggering consisted of processing the data with a speed-optimized version of the offline reconstruction software, at which point tighter requirements were made on the missing transverse energy, jet energies, and lepton identification criteria.

3. Data Samples and Monte Carlo Simulation

The data used to perform the Tevatron Higgs search correspond roughly to 10 fb^{-1} per experiment and were recorded over the Run II period of 2001-2011. This represents a subset of the total recorded data and reflects the removal of periods in which the sub-detectors were not operating optimally. These data were used to test for the presence of Higgs bosons by comparing them to predictions of the Higgs boson signal strength yields and those of all known background sources. These predictions require detailed Monte Carlo (MC) simulation of the differential distributions of particles in the final states as well as the detector responses and the trigger and analysis requirements. The MC simulation was typically performed using leading-order (LO) or next-to-leading-order (NLO) event generators. These MC samples were then normalized using the highest-order cross section calculations available for each production process, although for many of the dominant background processes, data-driven techniques were used instead. Predictions of the integral and differential rates require knowledge of the parton momenta inside the proton and the antiproton. The MC simulation used parton distribution functions (PDFs) from CTEQ:^{9,10} CTEQ5L (CDF) and CTEQ6L1 (D0). The cross section calculations also used MSTW¹¹ PDFs in many cases. The parton shower and hadronization were either performed by the generator or via PYTHIA for generators without this functionality. More detail on how these processes were predicted can be found in the specific publications for each data analysis performed.¹²

All MC samples were processed through a GEANT¹³ simulation of the

detector, and reconstructed with the same algorithms used for the data. The effects of instrumental noise and additional $p\bar{p}$ interactions were modeled using MC in the CDF analyses, while recorded data from randomly selected beam crossings with the same instantaneous luminosity profile as data were overlaid on to the MC events in the D0 analyses. Over the entire Run II data sample, the average number of reconstructed primary vertices was approximately 3, including the hard scatter.

In several instances, data control samples were used to predict the rates and differential distributions of backgrounds, as well as to refine the predictions of MC simulations and cross section calculations. The normalization and shape of the instrumental and multijet backgrounds were predicted from subsidiary data samples orthogonal to those used for the Higgs boson search. For the CDF searches, the rate of vector bosons produced in association with heavy-flavor jets was constrained in data samples where the signal-to-background ratio is too small to bias the rate estimation. For the D0 searches, the kinematic distributions of V +jets samples were corrected empirically using data samples which are insensitive to the presence or absence of a Higgs boson signal.

4. Basic Event Selection and Efficiencies

The data and simulated samples were reconstructed using algorithms designed to identify the signatures of particles in the detector. The input to these algorithms are the digitized, calibrated measurements of energy deposition made by particles as they interact with the detector systems. The energy depositions (“hits”) were grouped into basic components such as tracks indicating the paths of charged particles in the tracking detectors, clusters of energy depositions in the calorimeter modules and localized track segments (“stubs”) in the muon systems. These basic components were associated together to identify likely candidates for muons, electrons, taus and parton-initiated jets, based on their respective signatures. The presence of final-state neutrinos was inferred from these measurements by imposing the conservation of momentum in the plane transverse to the beam direction. This “missing transverse energy”, or E_T^{miss} , is indicative of the presence of one or more neutrinos in an event. The algorithms used to reconstruct tracks, calorimeter clusters and muon system hits have an associated inefficiency due to the need to operate the detector digitization well above analog noise levels. There are also inefficiencies and mis-identifications associated with the algorithms themselves in cases where energy depositions

gave rise to ambiguous topologies in the detector.

Electron candidates were identified via the association of charged-particle tracks with clusters of energy in the electromagnetic calorimeter. Muon candidates were identified by matching tracks with hits in the muon detectors. Tau leptons were identified based on the nature of their decay. Leptonic tau decays were typically detected as electrons or muons, provided the decay products satisfied the minimum lepton reconstruction requirements. Hadronic tau decays were identified using charged-particle tracks associated with energy clusters in the calorimeters. For all leptons, an associated quality of the particle identification was generated based on the nature of the contributing energy measurements, which may depend on the location of the candidate particle in the detector, the amount of energy deposited, the degree to which the energy deposition is isolated from other energy depositions, and the number of hits in a detector system. These quality criteria were used to control the relative rates of true or mis-identified leptons, and this property allowed the optimization of Higgs boson searches by analyzing high-quality leptons separately from lower-quality leptons, as described in detail in Sec. 6.

Highly collimated sprays of particles (jets) originating from gluon or quark fragmentation and hadronization were identified by grouping energy clusters in the electromagnetic and hadronic calorimeters using iterative algorithms that associate clusters based on their angular separation. These “cones” of energy can also be combined with charged-particle tracks to improve the identification efficiency, the purity, and the precision of the energy estimation. The transverse energy vector $\vec{E}_T$ of a calorimeter energy deposit is $E \sin \theta \cdot \hat{n}$, where E is the measured energy, θ is the angle with respect to the proton beam axis of a line drawn from the collision point to the energy deposit, and $\hat{n}$ is a unit vector in the plane perpendicular to the beam pointing along that line. The missing transverse energy (E_T^{miss}) is the magnitude of the vector opposite to the sum of the $\vec{E}_T$ vectors measured in the calorimeter, after propagation of all corrections to the calorimetric objects and for identified muons (which deposit only small amounts of energy in the calorimeters).

Jets that originate from bottom or charm quarks were identified by exploiting the relatively long lifetimes and large masses of hadrons containing bottom and charm quarks. These hadrons travel a few hundred microns before decaying into final states with multiple hadrons, often accompanied by charged leptons. By identifying tracks with a significant displacement from the primary $p\bar{p}$ interaction point, these heavy hadron decays were re-

constructed. These "*b-tagging*" algorithms were typically designed to create a selection criterion (or operating point) that allowed a customizable relationship between the efficiency to identify true heavy quark decays and the efficiency to reject light quark jets. These operating points were optimized to allow non-overlapping selections of different Higgs boson signal purity to improve the significance of $H \rightarrow b\bar{b}$ searches. The *b*-tagging algorithms were also able to perform classification of bottom and charm decays based on the difference in their lifetimes, though with a lower efficiency than classification relative to light quarks.

As noted above, these particle identification algorithms were designed to provide flexibility in the design of data analyses. They thus gave rise to adjustable efficiencies in the selection process. The careful optimization of these efficiencies is a large consideration in analysis design. These efficiencies have a strong dependence on the momentum transverse to the beam line (p_T) as well as their angle relative to the beam line (measured as the Lorentz-invariant quantity pseudo-rapidity, or η). Particles with large p_T and large angles relative to the beam line tend to have the highest identification efficiencies. Characteristic selection requirements are $p_T > 20$ GeV and $|\eta| < 2$. Electron, muon and tau selections were categorized into "*tight*" and "*loose*" measurements with typical efficiencies to select real leptons of 82/94% (electrons), 72/89% (muons) and 65/82% (taus) for leptons in the tight/loose categories, respectively. Jets have typical identification efficiencies of 85-95% depending on the region of the detector in which they are detected and their transverse momentum. The efficiency for *b*-tagging algorithms can be described in generic tight and loose categories with bottom/charm/light quark identification of 50/12/0.1% and 70/17/3%, respectively.¹⁴ Finally, there is an inefficiency associated with the hardware and software algorithms used to reduce the data rate in the triggering process. Triggers for single electrons or muons have typical efficiencies of 90% and 75%, respectively. Data analyses commonly use several dedicated triggers in parallel to achieve average triggering efficiencies above 95%.

Further details of the object reconstruction algorithms used in the Tevatron Higgs boson searches can be found in the references for the individual analyses (see Table 3.1).

5. Analysis Channel Summary

The Tevatron Higgs searches were performed in mutually exclusive final states motivated by the Higgs boson production and decay modes kin-

matically accessible at the Tevatron, as discussed below in this section. Lists of the analyses performed at CDF and D0 can be found in Table 3.1. To maximize the sensitivity of the Higgs boson search, the data samples were separated into final state categories defined by the numbers of charged leptons and jets, the amount of missing transverse energy, the number of b -tagged jets, and b -tagging criteria. This subdivision allows, for example, the efficient use of poorly reconstructed leptons, the exploitation of the different signal and backgrounds in each sub-channel, and the reduction of the impact of systematic uncertainties.

The Tevatron Higgs boson searches were focused on the Higgs boson mass range of $90 - 200$ GeV, which was primarily motivated by two considerations. First, the Higgs boson production cross sections above $m_H = 200$ GeV were too small to provide sufficient sensitivity to higher masses. And second, indirect constraints on the Higgs boson mass from top quark and Z and W boson measurements at SLC, LEP and the Tevatron disfavored the regions below $m_H = 90$ GeV above $m_H = 200$ GeV.

5.1. Searches for Higgs Boson Masses Below 135 GeV

For Higgs boson masses below 135 GeV, the dominant Higgs boson decay mode is $H \rightarrow b\bar{b}$. Though the largest production rate is via the fusion of gluons, the signature of two bottom quarks cannot be easily isolated from the continuum production of bottom quark pairs. Thus the associated production modes W/ZH with Higgs boson decays to $b\bar{b}$ provide the largest sensitivity to Higgs boson production for the Tevatron experiments. The leptonic decay of the vector bosons in $W \rightarrow \ell\nu$, $Z \rightarrow \ell^+\ell^-$ and $Z \rightarrow \nu\bar{\nu}$ provide the most distinct signatures relative to the dominant background of jet production. When coupled with a pair of jets with b -tags, these signatures provide a detector topology that can be isolated in a sample of events with an overall purity of 2-3%. This purity is improved to 50% or more for a small subset of events when using multivariate analysis methods (discussed later), typically corresponding to a phase space where the dijet invariant mass is close to the simulated Higgs boson mass. The channels investigated at the Tevatron are $WH \rightarrow \ell\nu b\bar{b}$, $ZH \rightarrow \ell^+\ell^- b\bar{b}$, and $(WH + ZH) \rightarrow E_T^{\text{miss}} b\bar{b}$. The dominant background to these searches is the production of vector bosons in association with jets (W/Z +jets), where the jets may arise from gluons or from light, charm or bottom quarks. The requirement of one or more b -tags also enhances the $t\bar{t}$ background to this final state. Finally, an irreducible background arises from the production

of two vector bosons (WW , WZ and ZZ) with semi-leptonic decays.

Additional sensitivity in this Higgs boson mass search range comes from a channel in which the W boson or the Z boson decays hadronically, resulting in a four-jet final state, which is also sensitive to VBF Higgs boson production. Higgs boson decays to $\tau^+\tau^-$ were sought in analyses that also require an additional one or two jets, which suppresses Drell-Yan background, while focusing on WH , ZH , and VBF production*. Searches for $H \rightarrow \gamma\gamma$ and $t\bar{t}H \rightarrow t\bar{t}b\bar{b}$ also are most sensitive for $m_H < 135$ GeV, but are less sensitive searches due to smaller decay rates and production rates.

5.2. Searches for Higgs Boson Masses Above 135 GeV

For Higgs boson masses between 135 GeV and 200 GeV, the decay $H \rightarrow W^+W^-$ becomes dominant[†]. Leptonic decays of the W bosons provide striking signatures easily separated from hadronic multijet events by requiring the presence of two oppositely-charged leptons and large E_T^{miss} . This allows the $H \rightarrow W^+W^-$ decay to be paired with the gluon fusion production mode to maximize the rate of Higgs production in the search. The most significant backgrounds to these analyses are non-resonant W^+W^- , $t\bar{t}$, and Drell-Yan production. The production of W +jets events in which a jet is misidentified as a lepton is also important and was estimated using data-based techniques. A large sample of W +jets events has been collected by each collaboration, and lepton fake rates measured as functions of the lepton candidate energy and η in inclusive samples of multijet events. These fake rates were applied to the jets in W +jets events in order to estimate the rates and distributions of the background due to mis-identified jets in each of these analyses without relying on Monte Carlo simulations.

The semi-leptonic decays for this mode were also considered ($H \rightarrow W^+W^- \rightarrow \ell\nu q\bar{q}$). While the signal rate is significantly larger, the W/Z +jets background also rises and limits the ultimate sensitivity of this search. The associated production of Higgs and vector bosons was also studied ($VH \rightarrow VVV$, $V = W$ or Z) in both fully leptonic and semi-leptonic final states through specific data analyses. At higher masses, $m_H > 170$ GeV, the $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ search also contributes to the combined search sensitivity. A smaller contribution to the sensitivity comes in at $m_H = 130$ GeV due to the branching ratio dependence on m_H .

*In the case of $H \rightarrow \tau^+\tau^-$ searches, the small signal expected from $gg \rightarrow H$ was also included for completeness

[†]For $H \rightarrow W^+W^-$ decays with $m_H < 2m_W$, at least one W boson must be off mass shell. For simplicity, we do not denote the off-shell W boson in formulas.

Table 3.1. Luminosities, explored mass ranges, and references for the different processes and final states in the Tevatron Higgs search ($\ell = e$ or μ , τ_{had} denotes a hadronic tau decay and $V = W$ or Z).

Experiment	Channel	Luminosity (fb ⁻¹)	m_H range (GeV)	Reference
CDF	$WH \rightarrow \ell \nu b \bar{b}$; 2-jet	9.45	90–150	15
CDF	$WH \rightarrow \ell \nu b \bar{b}$; 3-jet	9.45	90–150	15
D0	$WH \rightarrow \ell \nu b \bar{b}$; 2-jet	9.7	90–150	16
D0	$WH \rightarrow \ell \nu b \bar{b}$; 3-jet	9.7	90–150	16
CDF	$ZH \rightarrow \nu \bar{\nu} b \bar{b}$	9.45	90–150	17,18
D0	$ZH \rightarrow \nu \bar{\nu} b \bar{b}$	9.5	100–150	19
CDF	$ZH \rightarrow \ell^+ \ell^- b \bar{b}$; 2-jet	9.45	90–150	20
CDF	$ZH \rightarrow \ell^+ \ell^- b \bar{b}$; 3-jet	9.45	90–150	20
D0	$ZH \rightarrow \ell^+ \ell^- b \bar{b}$	9.7	90–150	21
CDF	$H \rightarrow W^+ W^- \rightarrow \ell \nu \ell \nu$	9.7	110–200	22
CDF	$H \rightarrow W^+ W^- \rightarrow \ell \nu \tau_{\text{had}} \nu$	9.7	130–200	22
D0	$H \rightarrow W^+ W^- \rightarrow \ell \nu \ell \nu$	9.7	115–200	23
D0	$H \rightarrow W^+ W^- \rightarrow \mu \nu \tau_{\text{had}} \nu$	7.3	115–200	24
D0	$H \rightarrow W^+ W^- \rightarrow \ell \bar{\nu} j j$	9.7	100–200	16
CDF	$WH \rightarrow WW^+ W^-$	9.7	110–200	22
CDF	$ZH \rightarrow ZW^+ W^-$	9.7	110–200	22
D0	$VH \rightarrow e^\pm \mu^\pm + X$	9.7	100–200	25
D0	$VH \rightarrow \ell \ell \ell + X$	9.7	100–200	25
D0	$VH \rightarrow \tau_{\text{had}} \tau_{\text{had}} \mu + X$	8.6	100–150	25
CDF	$H \rightarrow \gamma \gamma$	10.0	100–150	26
D0	$H \rightarrow \gamma \gamma$	9.6	100–150	27
CDF	$H \rightarrow ZZ \rightarrow \ell \ell \ell \ell$	9.7	120–200	28
CDF	$H \rightarrow \tau^+ \tau^-$	6.0	100–150	29
CDF	$WH + ZH \rightarrow j j b \bar{b}$	9.45	100–150	30
CDF	$t \bar{t} H \rightarrow WW b \bar{b} b \bar{b}$	9.45	100–150	31
D0	$H + X \rightarrow \ell^\pm \tau_{\text{had}}^\mp j j$	9.7	105–150	32
D0	$VH \rightarrow \ell \bar{\nu} j j j j$	9.7	100–200	16

The relative search power of each contributing analysis can be visualized in Figure 3.2 wherein the expected upper limit on the Higgs boson production cross section times branching fraction is shown for the major search channels at the CDF experiment.[‡] In this case, the expected upper limits are expressed as a ratio to the SM prediction for the cross section times branching fraction. It is clear from the figure that the dominant search channels are $VH \rightarrow V b \bar{b}$ for masses below 135 GeV and $H \rightarrow WW$ above.

[‡]Details of limit setting and interpretation are discussed in Section 8.

Fig. 3.2. Expected upper limits on the cross section times branching fraction for Higgs bosons as a function of Higgs boson mass in the major search channels at the CDF experiment.³³ The expected upper limits are expressed as a ratio to the SM prediction for the cross section times branching fraction.

6. Analysis Optimization Strategies

Over the years, the searches for the SM Higgs boson at the Tevatron steadily improved in their sensitivity and comprehensiveness. The initial versions of the analyses selected particles consistent with the dominant features of the signal processes, within the ranges the triggers selected. Jet reconstruction and lepton candidate requirements were the same as those used in $t\bar{t}$ cross-section measurements, as were the b -tagging algorithms. Lepton identification requirements included tight cuts on the track/cluster or track/stub matching, track χ^2 , shower shape, hadronic contamination, and other variables, and were restricted to the most central portions of the detector. Lepton transverse momenta were typically required to exceed 20 GeV. These reconstruction and selection requirements were originally optimized to provide a purified sample of $t\bar{t}$ events in analyses with just one sample of selected events, and applied for the Higgs boson search.

The sensitivity to the SM Higgs boson in the low mass range was predicted to be very low with these initial analyses. Calculations indicated that improving the detection efficiency, even at the cost of increased back-

grounds, would improve the search sensitivity. Lowering jet E_T cuts, loosening lepton ID requirements, and including events with just one b -tag instead of two (as well as looser b -tagging criteria) were strategies that improved the signal selection efficiency in the low-mass channels. The triggering also improved over time, especially the E_T^{miss} reconstruction in CDF³⁴ and the use of trigger suites with efficiencies near 95% at D0.

In early data collection periods, the size of the selected search samples was insufficient to constrain the systematic uncertainties in the MC predictions of differential distributions. During this time, the Higgs boson search analyses were designed to isolate regions of kinematic phase space with large signal vs background purity. These analyses used only the total number of selected expected and observed events to test the presence or absence of Higgs boson signal, rather than use the additional information in the final state kinematic distributions. As the dataset size increased, the use of multivariate analysis (MVA) techniques became commonplace. (see Appendix C for more details). The use of MVA methods led to a strategy of separating search selections into orthogonal search samples in which the MVA could be independently optimized. The statistical combination of non-overlapping channels provided the mechanism by which additional samples of events could be included in a way that improved the sensitivity. With a single set of selection requirements, the cuts can be optimized to maximize the predicted sensitivity. Loosening the cuts adds additional data, with both signal and background components. The additional data by itself has a nonzero sensitivity to the Higgs boson, but adding a sample of data with a low signal-to-background ratio (s/b) to a sample of higher s/b can dilute the sensitivity of the latter and reduce the total sensitivity. Placing events selected with a lower s/b selection strategy in a separate channel from those with a higher s/b and combining them with the statistical methods described in Section 8 allows for a broad search program including many additional samples. Existing searches were broken into subsamples. For example, the $H \rightarrow W^+W^-$ searches were broken into separate jet categories: $\ell^+\ell^- + E_T^{\text{miss}} + 0$ jets, +1jet, and +2 or more jets.

The MVA techniques used in the Tevatron Higgs analyses were also studied in depth in the context of the measurements of top quark production, both in pairs and singly via electroweak interactions.^{35,36} Both cases provided a validation of the methods through careful study of the agreement between data and simulation in kinematic regimes and final states shared with Higgs boson searches. Notably, the behavior of MVA techniques in a discovery scenario was scrutinized by both experiments in the Tevatron's

observation of single-top production in 2009.^{37–40} These tests continued in the Higgs boson search *in situ* by using diboson production (WW , WZ , ZZ) as a signal. This is discussed later in this chapter in Section 9.2.1.

7. Systematic Uncertainties

The predictions for the expected signal and background rates in the Tevatron Higgs search depends on three factors used to normalize the MC simulations: selection efficiency, cross-section times branching ratio ($\sigma \times \text{BR}$) and integrated luminosity. Each of these factors was estimated using methods with varying degrees of uncertainty. These uncertainties propagate to the expected signal and background rates, resulting in the potential for over- or under-estimation of rate in the simulation relative to the data. Furthermore, these uncertainties on efficiency and cross-section depend on the kinematics of the process in question. These systematic uncertainties degrade the power of the statistical analysis of the data and their causes and effects must be carefully considered. Systematic uncertainties were evaluated independently for each final state, background, and signal process.

Uncertainties that impact the predicted rates of the signal and the background processes arise from both experimental and theoretical sources. For example, the uncertainty on the identification of electrons was determined using large auxiliary samples of $Z \rightarrow e^+e^-$ decays. This estimation has both statistical uncertainty based on the number of Z decays used and systematic uncertainty associated with the efficiency estimation methodology and its extrapolation to other data samples. These sources of uncertainty were combined in quadrature to describe the total uncertainty on the rate for electron identification. Uncertainties also arose for the theoretical calculations used to determine $\sigma \times \text{BR}$. These uncertainties were estimated from the variations in the factorization and renormalization scales, uncertainties due to PDFs and the dependence on the strong coupling constant, α_s . In addition, in certain instances it is informative to make comparisons with alternative theory calculations. These variations in the parameters of theory calculations sometimes also result in changes in the predicted kinematic distributions for the relevant physics processes, which were considered as described below.

To study uncertainties on the shapes of the probability density functions of the final discriminants, the parameter associated with the uncertainty is varied within one standard deviation (s.d.) of its estimated uncertainty and the full analysis procedure is repeated using the modified distribution. For

example, for the jet energy scale uncertainty, the parameters of the energy scale were varied within one s.d. of their associated uncertainties and the analysis is carried out using the resulting modified jets, which may change the features of each event and its selection efficiency. This process can change the distribution of the final variable and the sample composition. No retraining of MVAs was performed during the propagation of systematic uncertainties to the distributions of the discriminants, as this would introduce a false bias. Correlations between signal and background, across different channels within an experiment and between CDF and D0 were taken into account. Full details on the treatment of the systematic uncertainties in the individual channels can be found in the relevant references, available in Table 3.1.

The largest sources of uncertainty on the predicted signal and background rates arise from the integrated luminosities used to normalize the simulated event yields (6%) and $\sigma \times \text{BR}$. For the luminosity uncertainty, there is a component due to the total inelastic $p\bar{p}$ cross-section of 4% which is considered to be 100% correlated between CDF and D0. The uncertainties on cross-sections vary from the level of 6-7% for diboson and $t\bar{t}$ production to 20-40% for the $V+$ heavy flavor quark, instrumental and multijet backgrounds.

Sources of systematic uncertainty that affect both the normalization and the shape of the final discriminant distribution include jet energy scale (1-4)%, jet energy resolution (1-3)%, trigger efficiencies, and b -tagging. Many of these uncertainties were constrained using auxiliary data samples. For example, the b -tagging efficiencies and rates for falsely tagged light jets were similarly constrained using samples such as inclusive jet data or $t\bar{t}$ events. The uncertainty on the per-jet b -tag efficiency is approximately 4%, and the mistag uncertainties vary between 7% and 15%.

In total, 326 independent sources of systematic uncertainty were evaluated and included in the Tevatron Higgs boson searches. Most of these arose from the independent experimental estimations of selection efficiency and were considered to be uncorrelated between CDF and D0. Uncertainties considered to be correlated between the experiments come from the total inelastic $p\bar{p}$ cross section and the differential and inclusive theoretical predictions for the signal and background rates.

8. Statistical Analysis Methods

After categorizing the data into independent search channels, an estimation of the relative agreement between the data and the MC simulation was made to evaluate the presence or absence of Higgs boson signal. This is facilitated as a hypothesis test in which the data are compared to a hypothesis in which no Higgs boson signal exists (*i.e.*, background-only) and one that includes the known SM backgrounds in addition to the Higgs boson signal (signal-plus-background). The techniques used are described in detail in Appendix B. The Tevatron experiments interpreted their results using two different statistical techniques to provide a robust cross check of the results of each method. The results were calculated using both a Bayesian integration with a uniform prior on the number of signal events and also a modified Frequentist calculation. The results were calculated at each value of m_H studied, every 5 GeV over the range 90 – 200 GeV. The results of the two calculations typically agree very well to within 5% for individual m_H hypotheses and within 1% when averaged over all m_H values tested. These two calculations typically provide different information on the Higgs search and the technique used for each interpretative result was agreed upon *a priori*.

Both statistical techniques are based on the joint likelihood evaluated over each histogram bin in each analysis channel. Of particular importance in the comparison between the two techniques are the methods used to determine the most probable value of the likelihood function. The Bayesian calculation integrates over all values of the systematic uncertainties that result in a non-negative prediction for the signal and background rates in all channels and histogram bins. The modified Frequentist calculation estimates the likelihood maximum by performing a fit to the likelihood function by varying the systematic uncertainties within their priors. Upper limits and measured cross sections are calculated in the Bayesian framework by integrating over the likelihood posterior relative to the observed data. Confidence levels and p -values are evaluated in the modified Frequentist framework by generating large numbers of pseudo-data produced by randomly varying the values of systematic uncertainties and by randomly sampling the Poisson rate of predicted events in each histogram bin. These pseudo-data are evaluated using the log-likelihood ratio (LLR) and the resulting LLR distributions are integrated relative to the observed data to calculate p -values.

9. Results of the Tevatron Higgs Boson Searches

9.1. *The Tevatron Higgs Working Group*

The CDF and D0 collaborations performed their Higgs boson searches independently, with very limited interactions between the two collaborations' teams their on data analysis techniques. Over the many years that the data analyses were performed, there was a healthy competition between the collaborations to present data analyses with more stringent expected limits on Higgs boson production. This competition pushed each collaboration to innovate in data analysis techniques, to work quickly to incorporate the newest data into the searches and to ensure the highest level of understanding for the data itself to avoid mistakes that could slow down progress. Following an intense period from 2001-2006 during which the Higgs boson searches matured significantly, the two collaborations created a formal group to combine the results of the CDF and D0 searches. This provided an independent cross check of each experiments' results, as well as a validation of the combined result. The group's roles also included collecting theoretical predictions and related uncertainties and agreeing on prescriptions for their use within CDF and D0 to facilitate combination, agreeing on statistical procedures and treatment of shared systematic uncertainties, and preparation conference results and publications. The combined results represent the Tevatron's most powerful statement on Higgs boson production and typically improved over the individual experiments by a factor of roughly $\sqrt{2}$ due to the doubling of search statistics. Though the Tevatron experiments each adopted similar analysis strategies, there were many instances in which one experiment could capitalize on detector-specific capabilities that allowed unique search channels to be studied. Furthermore, differences in detection efficiencies often caused common search channels to have different search sensitivities. Thus the full combination had a highly complex improvement relative to each individual experiment as a function of m_H . Though each experiment evaluated their own combination of search channels independently, we present only the Tevatron combined results here. The results from CDF and D0 alone can be found in Refs. 33 and 41 respectively.

9.2. Higgs Boson Search Results

9.2.1. Tests of SM Diboson Production

As a validation procedure to assess the modeling of background processes and the data analysis methods, the experiments performed measurements of SM diboson production in the same final states used for the SM Higgs boson searches. The techniques used in the two largest contributions to the search ($H \rightarrow b\bar{b}$ and $H \rightarrow W^+W^-$) were also able to efficiently isolate diboson production from other processes. The $VH(\rightarrow b\bar{b})$ analysis were able to study $VZ(\rightarrow b\bar{b})$ production, while the $H \rightarrow W^+W^-$ analyses measured $VV' \rightarrow \ell\ell' + X$ cross sections. These studies used the same data sample, reconstruction, background modeling, systematic uncertainties and search methods as the corresponding SM Higgs boson searches. The only differences were in the final discriminants used to classify SM diboson production relative to the remaining background processes. As an example, we consider here the case of $VZ(\rightarrow b\bar{b})$ production. The rate of VZ production with $Z \rightarrow b\bar{b}$ is approximately 6-7 times larger than the analogous $VH(\rightarrow b\bar{b})$ processes for $m_H = 125$ GeV. This larger rate makes VZ production not only important for testing analysis methods, but also provides a crucial means to study the dijet invariant mass spectrum, which is the most important means of discriminating between $H \rightarrow b\bar{b}$ production and its associated backgrounds. By analyzing the distribution of the dijet invariant mass distribution in the data, a comparison can be made with the simulated WZ and ZZ processes. This distribution, for the combined Tevatron data, is shown in Fig. 3.3. In the figure, the predicted VZ signal and backgrounds are fit to the data by varying systematic uncertainties, then the fitted background is subtracted from the data. The resulting data distribution is then compared to the fitted VZ distribution, and the expectation for a SM Higgs boson signal is overlaid for illustration purposes. The measured cross section, using the dijet mass discriminants, for VZ is 4.3 ± 0.7 (stat) ± 0.7 (syst) pb whereas the SM prediction is 4.4 ± 0.3 pb.⁴² The VV' boson cross sections measured by the $H \rightarrow W^+W^-$ analyses also agree well with SM predictions.^{22,23} This result provides a critical validation of the ability to detect and measure a well-known decay of the Z boson, and hence proof of the robustness of the Higgs search method for objects of similar mass and decay mechanisms.

Fig. 3.3. Distribution of background-subtracted data for the reconstructed dijet mass, summed over CDF and D0 measurements of VZ production. The VZ signal and the backgrounds are fit to the data, and the resulting background is subtracted from the data. The fitted VZ and the expected SM Higgs ($m_H = 125$ GeV) contributions are shown as filled histograms. The error bars shown on the data points correspond in each bin to the square root of the sum of the expected signal and background yields. (from Ref. 12).

9.2.2. Search for Higgs Boson Production

The Tevatron Higgs boson search results were obtained by combining results from all contributing channels over the decay modes $H \rightarrow b\bar{b}$, $H \rightarrow W^+W^-$, $H \rightarrow \tau^+\tau^-$, $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$, and in the production modes $gg \rightarrow H$, W/ZH , vector-boson fusion and $t\bar{t}H$ (see Table 3.1). These results were obtained on a grid of hypothesized Higgs boson masses in 5 GeV steps from 90 GeV to 200 GeV. We describe here the final, published results.

Historically, the $H \rightarrow b\bar{b}$ results were ready for combination first, and these were performed in the range $90 \text{ GeV} < m_H < 150 \text{ GeV}$. The combined $H \rightarrow b\bar{b}$ results were published in 2012 for CDF,⁴³ D0,⁴⁴ and the Tevatron.⁴⁵ These results were used to calculate an upper limit on the $WH + ZH$ production cross section times the branching ratio $\text{BR}(H \rightarrow b\bar{b})$ as a function of m_H , and the result is shown in Fig. 3.4. Here the upper limit on $\sigma \times \text{BR}$ at the 95% C.L. is expressed as a ratio to the values predicted by the SM. In the figure, the upper limit evaluated with the observed data is compared to the median upper limit expected if there were no Higgs boson

production. A broad excess is seen in the range $120 \text{ GeV} < m_H < 135 \text{ GeV}$. The significance of this excess is quantified in terms of the p -value $1 - \text{CL}_b$ for the background-only hypothesis[§]. This metric is the probability to find an excess as extreme as that observed in the data, assuming no Higgs boson signal is present. The resulting p -values are shown in Fig. 3.5. At the time of publication, the presence of the Higgs boson had not been established and its mass had not been measured, except for preliminary conference reports, and so the statistical tests were made on the Tevatron’s search region of interest, $115 \text{ GeV} < m_H < 150 \text{ GeV}$, which is determined by the LEP lower bound and the upper end of sensitivity to $H \rightarrow b\bar{b}$. The most significant observed local p -value in this range corresponds to 3.3 standard deviations, and was observed at $m_H = 135 \text{ GeV}$. Because the resolution in the reconstructed mass m_{jj} at CDF and D0 is poor ($\sim 25 \text{ GeV}$), Monte Carlo studies indicated that the Look-Elsewhere Effect (LEE) factor in the mass range $115 \text{ GeV} < m_H < 150 \text{ GeV}$ is approximately 2.0. The resulting LEE-corrected global significance corresponds to 3.1 standard deviations, and was used to claim evidence for the Higgs boson.⁴⁵

The combinations of the results for all channels listed in Table 3.1 were published in 2013 for CDF,³³ D0,⁴¹ and the Tevatron.¹² Between the 2012 publication of combined results and the 2013 round of final publications, the CDF $E_T^{\text{miss}} b\bar{b}$ channel¹⁷ was updated to include the latest neural-network b -tagging algorithm¹⁴ used in the $WH \rightarrow \ell\nu b\bar{b}$ and $ZH \rightarrow \ell^+\ell^- b\bar{b}$ searches, and the result was published in Ref. 18. In the process of updating to the newer b -tagging algorithm, the previous result was repeated and verified, demonstrating consistency of the two results within statistical and systematic uncertainties. Nonetheless, with the more efficient b -tagger, fewer events in the highest-score regions of the neural-network outputs were observed, and the best-fit cross section for $H \rightarrow b\bar{b}$ decreased.

Figure 3.6 shows the observed upper limit on $\sigma \times \text{BR}$ at the 95% C.L., expressed as a ratio to the rates predicted by the SM over the full range $90 \text{ GeV} < m_H < 200 \text{ GeV}$, which is now possible due to the inclusion of the $H \rightarrow W^+W^-$ and $H \rightarrow ZZ$ search channels. The excess of events in the $H \rightarrow b\bar{b}$ channels, noted above, causes the observed limits to be weaker than the expected limits. The shape of this excess is very similar to the excess expected if there were Higgs boson production, shown in dashed blue. To test the agreement of this excess in data with the SM Higgs predictions, the SM Higgs boson signal and background processes are fit to the data with an

[§]See Appendix B for a discussion of p -values.

Fig. 3.4. Observed and median expected (for the background-only hypothesis) 95% C.L. Bayesian upper limits on Higgs boson production expressed as multiples of the SM cross section as a function of Higgs boson mass for the combined CDF and D0 searches in the $H \rightarrow b\bar{b}$ decay mode. The green- and yellow-shaded bands indicate, respectively, the one and two s.d. probability regions in which the limits are expected to fluctuate in the absence of signal. The blue dot-dashed line shows median expected limits assuming the SM Higgs boson is present at $m_H = 125$ GeV. (from Ref. 45).

unconstrained signal rate. The resulting values for the signal rate are shown in Fig. 3.7 along with the expectation for a SM Higgs boson with $m_H = 125$ GeV. The observed signal rate agrees with the prediction for a SM Higgs boson within 1 s.d. with a peak in the rate near $m_H = 125$ GeV where the fit yields $\sigma(\text{Fit})/\sigma(\text{SM}) = 1.44^{+0.49}_{-0.47} (\text{stat})^{+0.33}_{-0.31} (\text{syst}) \pm 0.10 (\text{theory})$.

The significance of the excess in the data over the predicted background is quantified by the background-only p -value, which is shown in Fig. 3.8 as a function of m_H along with the expected p -value assuming a SM Higgs boson signal is present at each tested Higgs mass. The median expected p -values assuming the SM Higgs boson is present with $m_H = 125$ GeV for signal strengths of 1.0 and 1.5 times the SM prediction are also shown. The median expected excess at $m_H = 125$ GeV corresponds to 1.9 standard deviations assuming the SM Higgs boson is present at that mass. The observed local significance at $m_H = 125$ GeV corresponds to 3.0 standard deviations. The maximum observed local significance is at $m_H = 120$ GeV

Fig. 3.5. The solid black line shows the background p -value as a function of m_H for the combined CDF and D0 SM Higgs boson searches in the $H \rightarrow b\bar{b}$ decay mode. The dotted black line shows the median expected values assuming a SM signal is present, evaluated separately at each m_H . The associated green- and yellow-shaded bands indicate the one and two s.d. fluctuations of possible experimental outcomes under this scenario. (from Ref. 45).

and corresponds to 3.1 standard deviations. The width of the dip in the observed p -values from 115 to 140 GeV/c^2 is consistent with the resolution of the combination of the $H \rightarrow b\bar{b}$ and $H \rightarrow W^+W^-$ channels, as illustrated by the injected signal curves. The effective resolution of this search comes from two independent sources of information. The reconstructed candidate masses help constrain m_H , but more importantly, the expected cross sections times the relevant branching ratios for the $H \rightarrow b\bar{b}$ and $H \rightarrow W^+W^-$ channels are strong functions of m_H in the SM. The observed excess in the $H \rightarrow b\bar{b}$ channels and the slight excess in the $H \rightarrow W^+W^-$ channels determine the shape of the observed p -value as a function of m_H .

9.2.3. Studies of Higgs Boson Properties

Higgs Boson Couplings: The Higgs boson is expected to couple more strongly to more massive particles than to less massive ones, and thus may provide sensitivity to non-SM particles whose interactions become more relevant at higher energies. Thus, the CDF and D0 searches are also grouped into combinations by the dominant decay modes: $H \rightarrow b\bar{b}$, $H \rightarrow W^+W^-$,

Fig. 3.6. Observed and median expected (for the background-only hypothesis) 95% C.L. Bayesian upper limits on Higgs boson production expressed as multiples of the SM cross section as a function of Higgs boson mass for the combined CDF and D0 searches. The green- and yellow-shaded bands indicate, respectively, the one and two s.d. probability regions in which the limits are expected to fluctuate in the absence of signal. The blue short-dashed line shows median expected limits assuming the SM Higgs boson is present at $m_H = 125$ GeV. (from Ref. 12).

$H \rightarrow \gamma\gamma$, and $H \rightarrow \tau^+\tau^-$. For each of these four subset combinations the best-fit rate of Higgs boson production is evaluated for $m_H = 125$ GeV and the results are shown in Fig. 3.9. The results for each decay mode are consistent with each other, with the full combination, and with the production of the SM Higgs boson at that mass.

These individual results provide useful insight into the data excess, but their interpretation cannot be directly extended to study potential Higgs boson couplings because the searches mix various couplings in their production and decay modes. Also, each search channel has acceptance to a range of production and decay modes, causing further ambiguity. However, most of the Tevatron's search channels are sensitive to the product of fermionic and bosonic coupling strengths. For example, in the $VH \rightarrow Vb\bar{b}$ searches the production depends on the coupling of the Higgs boson to the weak vector bosons, while the decay is to fermions. Some search channels, such as the trilepton searches for $VH \rightarrow VW^+W^-$ are sensitive only to Higgs boson

Fig. 3.7. The best-fit signal cross section expressed as a ratio to the SM cross section as a function of Higgs boson mass for all CDF and D0 SM Higgs boson searches. The green- and yellow-shaded bands show the one and two s.d. uncertainty ranges on the fitted signal, respectively. Also shown with blue lines are the median fitted cross sections expected for a SM Higgs boson with $m_H = 125$ GeV at signal strengths of 1.0 times (short-dashed) and 1.5 times (long-dashed) the SM prediction. (from Ref. 12).

couplings to vector bosons, while the $t\bar{t}H \rightarrow t\bar{t}b\bar{b}$ searches are sensitive only to the couplings of the Higgs boson to fermions. By introducing multiplicative scaling factors to describe a model with enhanced or suppressed Higgs boson couplings to fermions (κ_f) or to vector bosons (κ_V), the Tevatron data can be tested for deviations from the SM predictions of $\kappa_f = \kappa_V = 1$. To illustrate, the production and decay of Higgs bosons in $VH(H \rightarrow b\bar{b})$ could be expressed as a function of the scaling factors and the SM prediction as $\sigma(VH) \cdot BR(H \rightarrow b\bar{b}) = (\sigma(VH) \cdot BR(H \rightarrow b\bar{b}))^{SM} \times (\frac{\kappa_V^2 \kappa_f^2}{\kappa_H^2})$, where κ_H is introduced to normalize changes to the total rate if individual decays are modified. Assuming that custodial symmetry⁴⁶ holds (*i.e.*, $\kappa_W/\kappa_Z = 1$), the values of κ_V and κ_f can be varied. The results of this test are shown in Fig. 3.10 with the regions preferred at the 68% C.L. and the 95% C.L. in the two-dimensional plane (κ_V, κ_f) . The results are bimodal with a local maximum in both the positive and negative κ_f planes. The asymmetry results from the interference in the diagrams contributing to the $H \rightarrow \gamma\gamma$

Fig. 3.8. The solid black line shows the background p -value as a function of m_H for all of CDF and D0's SM Higgs boson searches in all decay modes combined. The dotted black line shows the median expected values assuming a SM signal is present, evaluated separately at each m_H . The associated green- and yellow-shaded bands indicate the one and two s.d. fluctuations of possible experimental outcomes under this scenario. The blue lines show the median expected p -values assuming the SM Higgs boson is present with $m_H = 125$ GeV at signal strengths of 1.0 times (short-dashed) and 1.5 times (long-dashed) the SM prediction. (from Ref. 12).

decay mode. The maximum in the positive plane agrees with the SM prediction at the level of 1 s.d., providing no evidence for significant deviations from the Higgs couplings predicted by the SM Higgs mechanism.

Higgs Boson Spin and Parity: The Tevatron data have been used to constrain models of the Higgs boson with exotic spin J and parity P , using the $VX \rightarrow Vb\bar{b}$ channels. The kinematics of VX production depend strongly on the spin and parity of the Higgs-like boson X .⁴⁷ Two models are considered: a pseudoscalar, Higgs-like boson with $J^P = 0^-$, and a graviton-like boson with $J^P = 2^+$. For the SM Higgs boson, which has $J^P = 0^+$, the production rate near threshold is proportional to β , where $\beta = 2p/\sqrt{s}$, p is the momentum of the X boson in the VX ($V = W$ or Z) reference frame, and $\sqrt{s}$ is the total energy of the VX system in its rest frame. For the pseudoscalar model, the dependence is proportional to β^3 . For the graviton-like model, the dependence is proportional to β^5 ; however, not all $J^P = 2^+$ models share this β^5 factor.⁴⁷ These powers of β alter the distributions of

Fig. 3.9. Best-fit values of $R = (\sigma \times \mathcal{B})/\text{SM}$ using the Bayesian method for the combinations of CDF and D0 Higgs boson search channels in the $H \rightarrow W^+W^-$, $H \rightarrow b\bar{b}$, $H \rightarrow \gamma\gamma$, and $H \rightarrow \tau^+\tau^-$ decay modes for a Higgs boson mass of 125 GeV. The green shaded band corresponds to the one s.d. uncertainty on the best-fit value of R for all SM Higgs boson decay modes combined. (from Ref. 12).

kinematic variables measured from the decay products of the vector boson and the X boson, most notably the invariant mass of the VX system, which has a higher average value in the $J^P = 0^-$ hypothesis than in the SM 0^+ case, and higher still in the $J^P = 2^+$ hypothesis. These models predict neither the production rates nor the decay branching fractions of the X particles.

Both D0⁴⁸ and CDF⁴⁹ have sought evidence for exotic Higgs-like bosons, taking advantage of the expected differences between the SM Higgs boson and the predictions of the exotic models. The three VH search channels, $WH \rightarrow \ell\nu b\bar{b}$, $ZH \rightarrow \ell^+\ell^- b\bar{b}$, and $ZH \rightarrow \nu\bar{\nu} b\bar{b}$, are combined together using each experiments' results. Because the particle discovered by ATLAS and CMS resembles the SM Higgs boson in all measured ways including its spin

Fig. 3.10. Two-dimensional constraints in the (κ_V, κ_f) plane, for the combined Tevatron searches for a SM-like Higgs boson with mass 125 GeV assuming custodial symmetry ($\lambda_{WZ} = 1$). The points that maximize the local posterior probability densities are marked with dots, and the 68% and 95% C.L. intervals are indicated with the green- and yellow-shaded regions, respectively. The SM prediction for (κ_V, κ_f) is marked with a triangle. (from Ref. 12).

and parity, it is natural that this boson is also present in the Tevatron data. Performing the search in the Tevatron data for exotic Higgs-like bosons however has significant value because the associated production mode with decays of $X \rightarrow b\bar{b}$ may sample an admixture of new particles, if more than one boson were present in the data. CDF and D0 thus sought admixtures of a SM-like Higgs boson and an exotic Higgs boson with the same mass but different spin and parity. The SM Higgs boson search channels were aug-

Fig. 3.11. Two-dimensional constraints in the $(\mu_{\text{SM}}, \mu_{0-})$ (a) and $(\mu_{\text{SM}}, \mu_{2+})$ (b) planes, in the combined Tevatron searches for Higgs bosons with exotic spin and parity. The points that maximize the local posterior probability densities are marked with dots, and the 68% and 95% C.L. intervals are indicated with the green- and yellow-shaded regions, respectively. The SM predictions are marked with red triangles. (from Ref. 50).

mented to use the M_{VX} variable, in order to separate the X boson signals from the SM Higgs boson signal and from the much larger backgrounds. The CDF and D0 results are combined in Ref. 50 using statistical techniques similar to those used to combine the SM Higgs boson search results. Fits for the production rate times the decay branching fraction for the SM Higgs boson and the X boson are shown in Fig. 3.11 for the $J^P = 0^-$ and $J^P = 2^+$ models. Fig. 3.12 shows upper bounds at the 95% C.L. on the fraction of exotic Higgs boson production that may be present alongside a SM-like Higgs boson, as a function of the total production rate. If the total production rate is assumed to be that predicted by the SM and the exotic Higgs boson is assumed to entirely replace the SM Higgs boson, then the exotic Higgs boson models are excluded with significances of 5.0 and 4.9 standard deviations for the $J^P = 0^-$ and $J^P = 2^+$ models, respectively. While the Tevatron results constrain models with exotic Higgs-like bosons, at the time of this writing the LHC experiments have performed measurements of the spin and parity of the Higgs boson in bosonic decay modes. These measurements suggest the particle observed at the LHC does indeed have $J^P = 0^+$ (See sections 7, 6.3, 6.4 and 11).

Fig. 3.12. Observed and expected 95% C.L. upper bounds on the fraction of exotic Higgs boson production as functions of the total assumed Higgs boson production rate, in units of the SM Higgs boson production rate. Curves are shown separately for the 0^- and the graviton-line 2^+ hypotheses. (from Ref. 50).

10. Summary

The Tevatron Higgs boson search represented a broad program that probed the theoretically interesting mass range for the Higgs boson. In addition to providing the first Higgs mass exclusions beyond those set at LEP, the results of the Tevatron Higgs boson search ultimately indicated an excess of data over the expected background processes with no Higgs boson signal present. This excess has a significance of 3.0 standard deviations and can be associated with a Higgs boson production rate at a factor of $1.44^{+0.59}_{-0.56}$ times the SM prediction. This evidence for Higgs boson production is realized through the analysis of four primary final states: $H \rightarrow b\bar{b}$, $H \rightarrow \tau^+\tau^-$, $H \rightarrow W^+W^-$, and $H \rightarrow \gamma\gamma$. The analysis of each of these final states exhibits excesses in data beyond background predictions. While the Tevatron experiments did not discover the Higgs boson, the data collected and analyzed provide significant insight into the nature of the electroweak symmetry breaking mechanism.

The data excess observed at the Tevatron is consistent with the pre-

dictions for the Standard Model Higgs boson, and consistent with the boson discovered by the ATLAS and CMS collaborations.^{51,52} The Tevatron searches results are highly compatible with a Higgs boson mass of $m_H \simeq 125$ GeV (as observed at the LHC), and the apparent couplings of this new boson to the SM particles agree with the SM predictions within measurement uncertainties. The Tevatron Higgs boson search results provided early evidence that the Higgs boson does indeed provide mass for both the gauge bosons and the fermions. This is evidenced by the significant excess of data observed by the Tevatron experiments in the $H \rightarrow b\bar{b}$ search channels. Furthermore, the Tevatron Higgs search data did not show evidence for Higgs bosons with exotic spin and parity and the CDF and D0 collaborations set limits on their production rates.

While searches for the SM Higgs boson at the Tevatron were predicted to be very challenging, the Tevatron Higgs physics program was ultimately very successful in its execution. Because the Higgs boson mass is relatively light, the Tevatron experiments were kinematically capable of studying it, but were ultimately limited by statistics. With a very broad range of search topologies studied and through an extensive effort to optimize and improve the search techniques, the early exclusions and the later measurements of Higgs boson properties will remain major legacies of the Tevatron physics program.

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