Higgs searches
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Abstract
We present the status and prospects of Higgs searches at the Tevatron and the LHC. Results from the Tevatron are using up to 5 fb\(^{-1}\) of data collected with the CDF and D0 detectors. The major contributing processes include associated production (\(WH \rightarrow l\nu b\bar{b}\), \(ZH \rightarrow \nu\nu b\bar{b}\), \(ZH \rightarrow llb\bar{b}\)) and gluon fusion (\(gg \rightarrow H \rightarrow WW^{(*)}\)). Improvements across the full mass range resulting from the larger data sets, improved analyses techniques and increased signal acceptance are discussed. Recent results exclude the SM Higgs boson in a mass range of 160 < \(m_H\) < 170 GeV. Searches for the neutral MSSM Higgs boson in the region 90 < \(m_A\) < 200 GeV exclude tan\(\beta\) values down to 30 for several benchmark scenarios.

1. Introduction
In the Standard Model (SM) the fermions and vector bosons acquire their masses through the Higgs mechanism. It predicts the existence of a heavy scalar boson, the Higgs boson, with a mass that cannot be predicted by the SM. The Higgs particle has been searched for for decades but it is the only particle of the Standard Model which has yet to be directly observed.

Such searches have been performed at the LEP experiments where the principal production channel is Higgs production associated with a Z boson. The kinematic limit for these searches was the collider energy modulo the Z mass which gives approximately 115 GeV. The combined searches of the four LEP experiments resulted in an exclusion of SM Higgs bosons with a mass lower than 114.4 GeV at the 95% confidence level (C.L.) \(^{11}\). This is still the lower bound for the mass of the SM Higgs boson from direct searches up to date.

An upper bound on the Higgs mass can be obtained by global electroweak fits. The \(\Delta\chi^2\) with respect to the minimum of these fits is displayed in Fig. 1. Here the W mass and the top quark mass play an important role because they are directly related to the Higgs mass by radiative corrections. New precision measurements of the W mass \(^{2}\) and the top mass \(^{3}\) from the Tevatron favor a light SM Higgs boson and yield an upper value of 157 GeV at 95% C.L. (or 186 GeV if the LEP2 limit is included) \(^{4}\).

The results from direct searches at LEP and from the global electroweak fits indicate that if the SM is correct the Higgs mass is likely to be somewhere between 100 and 200 GeV. This region is within reach of the Tevatron and LHC colliders, thus searching for the Higgs is of highest priority in their physics program.

Several theories beyond the SM predict the existence of one or more than one Higgs boson as well. The Minimal Supersymmetric Standard Model (MSSM) predicts two Higgs doublets leading to five physical Higgs bosons. Constraints from the combined result of the four LEP experiments to the MSSM parameter space \(^{5}\) are being extended by the Tevatron experiments with increasing integrated luminosities.

2. Experimental environment
Higgs searches at the Tevatron depend crucially on the performance of the accelerator and detectors. Both, CDF and D0 detectors are currently performing close to their optimal design values, taking data with an efficiency of about 90%. The present Tevatron performance is matching the design values in terms of the current weekly integrated and peak luminosity. As of today, more than 7 fb\(^{-1}\) have been delivered to both of the experiments, while the weakly integrated luminosity is above 50 pb\(^{-1}\) on average. If the accelerator keeps following the designed luminosity evolution, an integrated luminosity of about 12 fb\(^{-1}\) will be achieved by the end of 2011, which increases the potential for a Higgs discovery at the Tevatron significantly.

The two general purpose experiments at the LHC, ATLAS and CMS, have been optimised for the discovery of a Higgs mass up to 1 TeV. An integrated luminosity of around 10 fb\(^{-1}\) will be required to cover this entire mass range and data taking is expected to start end of 2009.

3. Higgs searches at the Tevatron

Standard Model Higgs searches
Production cross sections for the SM Higgs boson at the Tevatron are rather small. They depend on the Higgs mass and are about 0.1 – 1 pb in the mass range of 100 – 200 GeV. The largest production cross section comes from gluon fusion, where the Higgs is produced via a quark loop. The second largest cross section, almost an order of magnitude smaller, is the associated production with vector bosons. At the mass range covered by the Tevatron, below 135 GeV the highest branching ratio is given by the decay to \(bb\) pairs and for masses above 135 GeV the Higgs boson decays mainly to \(WW\) pairs.

These production and decay properties lead to the following search strategy at the Tevatron:

- For masses below 135 GeV the main search channels...
3.1. Searches for a low mass Higgs

Search channels of associated production with vector bosons can be grouped into three final states. These are:

- no isolated lepton, missing E_T and two b jets
- two isolated leptons and two b jets

Each of these final states has its advantages and disadvantages. The signal for the final state with one isolated lepton comes mainly from associated production of a W boson which has the largest signal production cross-section among these processes. The final state with the lowest background contribution is the one with two isolated leptons. It also has the advantage that it is fully constrained, both, the Higgs and Z boson resonances can be reconstructed. The final state without any isolated leptons has the highest signal contribution. The Z boson branching fraction into neutrinos is three times higher than into electrons and muons, in addition, half of the signal contribution comes from associated production with a W boson where the lepton from the W decay escapes detection. This final state has, however, most common large instrumental backgrounds which are difficult to handle.

The main backgrounds to these production modes arise from two sources, physics and instrumental backgrounds. Physics backgrounds are estimated from Monte Carlo (MC) and are mainly from W/Z plus jets, diboson, top anti-top and single top production. Instrumental backgrounds are due to multijet events with mismeasured missing E_T or jets faking leptons. It is challenging to model these backgrounds with MCs and they are estimated from data sideband regions.

Searches in all three final states can be described as a three step approach. The first step is to select events consistent with W/Z and 2 jets. As an example, Fig. 2 shows the mass of the Z plus two leptons system after the basic selection in the \( \ell \ell b \) analysis [6]. As can be seen, the background at this stage of the selection is completely dominated by Z plus light flavor jets events, and the signal to background ratio is still very small, (the signal contribution is scaled by 1500 in this plot).

The second step is to tag b jets which takes advantage of the large Higgs to \( b \bar{b} \) branching fraction. b jet tagging exploits B meson lifetime, mass, fragmentation and decay modes to separate b from light-quark jets. Both experiments use neural networks for optimal combination of tagging information. Typically the events are separated in two orthogonal categories with either two loosely tagged jets and one tightly tagged jet. Where loose tag jets are tagged with an efficiency of 75%, and tight tag jets with an efficiency of 50%. The corresponding mistag rates, i.e., the probabilities to wrongly tag u, d, s, g jets, are 5% and 0.5%, respectively. These values apply to jets with \( p_T > 30 \) GeV and \( |\eta| < 0.8 \) at D0, with similar tagging efficiencies at CDF.

b tagging reduces the backgrounds in the basic selection by almost two orders of magnitude. Fig. 3 shows the di-jet invariant mass of the \( \ell \ell b \) final state. This is the same selection as in Fig. 2 but after requiring two b jets. After b jet selection the background composition changes significantly and is now dominated by W/Z + bb, diboson and top anti-top production. At this stage the signal over background ratio is still very small, (the signal contribution is scaled by 1500 in this plot).

The separation power can be further optimized with the use of multivariate discrimination. Most common in Higgs searches at the Tevatron are techniques of Neural Network, Decision Tree and Matrix Element Likelihood. The basic idea for all of these is to exploit information from several final state variables and correlations among them. Fig. 4 shows the output of a Neural Network for the \( \ell \ell b \) final state where the signal was trained against

![CDF Run II Preliminary (4.1 fb⁻¹)](image)

**Fig. 2.** Mass of the Z+jj system in the \( \ell \ell b \) final state at CDF prior to b tagging.

![CDF Run II Preliminary (4.1 fb⁻¹)](image)

**Fig. 3.** Di-jet mass in the \( \ell \ell b \) final state at CDF after requiring two b tagged jets. The signal is plotted before (blue) and after (red) corrections from the kinematic fit.

![CDF Run II Preliminary (4.1 fb⁻¹)](image)

**Fig. 4.** Projection of a two dimensional NN output, with a cut made (NNy< 0.1) to highlight the most signal like region in the \( \ell \ell b \) final state after requiring two b tagged jets.

are the associated productions with vector bosons where the Higgs decays into \( b \bar{b} \) pairs. In order to isolate the main background processes to these channels, an efficient b-tagging algorithm and a good di-jet mass resolution are essential. The same final state produced via the gluon fusion process leads to a higher cross section but is overwhelmed by the huge multijet QCD background at a hadron collider.

- For masses above 135 GeV the search is mainly focused on the gluon fusion production process where the Higgs decays into WW pairs.
the $Z + b\bar{b}$ background.

Both Tevatron experiments make large efforts to improve in all areas of these analyses, from the selection to the final discrimination step. An example to increase signal acceptance is the use of looser lepton identification criteria. Both, D0 and CDF use in the $t\bar{t}b\bar{b}$ final state events with isolated tracks, electrons from less well instrumented regions of the calorimeter or minimal ionizing particles that escaped detection in the muon chambers. In addition, leptonic final states now also include hadronic $\tau$ decays of vector bosons.

Similar efforts are underway for a better signal to background discrimination at the final selection stage. Both experiments are developing further algorithms after heavy flavor tagging to discriminate $b$ and $c$ quark jets and to discriminate a single $b$ jet against two merged $b$ jets. Since the most discriminating quantity is the di-jet mass resolution, there are a lot of efforts to improve the di-jet mass resolution at both experiments. The $t\bar{t}b\bar{b}$ final state is ideal in this respect since it is fully reconstructed and has no intrinsic missing $E_T$ in the decay. These constants can be effectively used to improve the di-jet mass resolution, since the detector resolution to the high $p_T$ leptons is significantly better compared to the jet resolution. Fig. 3 shows the signal mass peak before (blue) and after (red) this resolution improvement. This correction improved the sensitivity by 10% of this analysis. In addition, multivariate techniques for the final discrimination can be combined to increase the sensitivity further. This can be for example a matrix element likelihood as input into a final decision tree, or the separate training against different dominant backgrounds. The $t\bar{t}b\bar{b}$ final state presented in Fig. 4 used a two dimensions neural network which is trained separately against the two major backgrounds, $Z + b\bar{b}$ and top anti-top pair production. Fig. 4 shows a slice from the output on the 2D network.

With an integrated luminosity of up to 5 fb$^{-1}$, cross section limits from individual channels are a factor 4-8 larger than the SM prediction at Higgs masses around 115 GeV and the combination of all contributing channels crucial. The systematic uncertainties for these searches are typically a total of 15% for the signal where the main contributing uncertainties are theory uncertainties for the cross section calculations, $b$-tagging and object identification efficiencies. The total background uncertainty is up to twice as large (25-30%) and is mainly due to normalisation of the $W/Z$ plus jets heavy flavor samples, modeling of multijet and $W/Z$ plus jets background and $b$-tagging. At high discriminant values signal over background ratios are typically 1/10 - 1/20 for the most sensitive low mass channels.

### 3.2. Searches for a high mass Higgs

Above a Higgs mass of 135 GeV the dominant decay mode is to a pair of $W$ bosons. With the clean environment of the subsequent leptonic decay modes of the vector bosons one can take advantage of the dominant production mode from gluon fusion. However, there is also important signal contribution from vector boson fusion and associated production with vector bosons. For this reason the most sensitive search channel for a high mass Higgs boson considers all sources of opposite sign dilepton plus missing $E_T$.

The main backgrounds to this final state are Drell-Yan production, diboson, top anti-top pair production, $W$ plus jets and multijet production. Whereas SM $W$ pair production is an irreducible background. Upper Fig. 5 shows the dilepton invariant mass distribution after the basic selection. The dominant background at this stage is Drell-Yan production, which can be reduced with cuts on missing $E_T$ and missing $E_T$ significance variables which take into account that the missing $E_T$ can be caused by mismeasurement of leptons or jets. As an example lower Fig. 5 shows the missing $E_T$ distribution from D0’s di-electron final state, which is plotted before the missing $E_T$ cut of 20 GeV.

Spin correlation gives the main discrimination against the irreducible background from non-resonant SM $W$ pair production. In contrary to this process, in the Higgs decay the $WW$ comes from a spin zero particle and the leptons prefer to point in the same direction. This feature is exploited with the use of the distribution of the di-lepton opening angle in the azimuthal plane.

To increase sensitivity the D0 analysis splits the samples according to lepton flavor. A Neural Network with 11 kinematic and topological input variables is trained against the sum of all backgrounds at each hypothetical Higgs mass value in bins of 5 GeV. Such a combined evaluation of many kinematic variables in the Neural Network became increasingly important as the additional signal contributions to the gluon fusion are contributing as well. The Neural Network output of the D0 analysis is plotted in Fig. 6 where the signal contribution is drawn without any additional enhancement factor.

The CDF analysis splits the samples into jet multiplicity and lepton identification criteria. In particular the separation of the sample into different jet multiplicity bins with different signal and background compositions makes the final discrimination with the Neural Network effective. In addition, events with tight $b$-tagged jets are vetoed to reduce the $t\bar{t}$ background and in the Neural Network the output of a Matrix Element Likelihood is used in the 0-jet case.

Main systematic uncertainties for the high mass Higgs
searches are from theoretical cross sections, lepton identification and trigger for the signal and yield about a 10% error in total. For the backgrounds the total uncertainty is about 15%, coming from theory uncertainties for the cross section calculations, jet to lepton fake rate, jet identification/resolution/calibration. Variations due to these systematic uncertainties are propagated through the entire analysis such that these effect also the shape of the final discriminant. Fig. 7 compares the SM signal expectation (red) with the data after background subtraction. The constrained total systematic uncertainty is shown in blue. The expected 165 GeV SM Higgs signal would be visible over the background uncertainty. The exclusion limits per experiment are around 12 – 1.4 for the most sensitive mass region which is at 165 GeV. At high Neural Network values signal over background ratios are close to 1. With additional luminosity and improvements (e.g. additional channels) single experiment exclusion around Higgs masses of 165 ± 5 GeV can be expected in the near future.

3.3. Combined Standard Model Higgs limits

In order to reach the highest sensitivity a full combination of all channels from CDF and D0 is performed. In such a Tevatron combination 75 different orthogonal channels are considered with more than 50 different systematic uncertainties taking into account correlations between channels and across experiments. Both a bayesian and a modified frequentist approach have been used for the combination, and results have been shown to agree within 10%.

Fig. 8 shows the combined cross section limit relative to the SM expectation. The limits are expressed as a multiple of the SM prediction for test masses (every 5 GeV) for which both experiments have performed dedicated searches in different channels. The points are joined by straight lines for better readability. The bands indicate the 68% and 95% probability regions where the limits can fluctuate, in the absence of signal. The limits displayed in this figure are obtained with the Bayesian calculation. This result is based on an effective luminosity of 2.6 fb⁻¹ around masses of 115 GeV and 3.8 fb⁻¹ at masses around 160 GeV. Observed and expected limits agree within one standard deviation and no indication of a Higgs boson signal has been observed. A mass range of 160 to 170 GeV has been excluded at the 95% C.L. This is the first direct exclusion of a SM Higgs in a mass range above the LEP limits.

The Tevatron collider is expected to deliver an integrated luminosity of 12 fb⁻¹ per experiment by the end of
2011. This corresponds to a final dataset of 10 fb$^{-1}$ per experiment after accounting for data taking efficiencies. Fig. 9 shows the probability of seeing a $3\sigma$ excess as a function of the Higgs mass for analyzed integrated luminosities of 5 fb$^{-1}$ and 10 fb$^{-1}$ per experiment, assuming CDF and D0 perform the same [9]. Two scenarios are shown, in which channels have the same performance as for the Winter 2009 combination (solid lines), and for the case with another factor of 1.5 increase in sensitivity (dashed lines). With expected future improvements in the analyses there can be a 50% chance to find evidence for a 115 GeV Higgs boson should it exist.

MSSM Higgs searches

The Minimal Supersymmetric Standard Model (MSSM) predicts two Higgs doublets leading to five Higgs bosons: a pair of charged Higgs boson ($H^{\pm}$); two neutral CP-even Higgs bosons ($h, H$) and a CP-odd Higgs boson ($A$). At tree level, the Higgs sector of the MSSM is fully described by two parameters, which are chosen to be the mass of the CP-odd Higgs, $m_A$, and $\tan \beta$, the ratio of the vacuum expectation values of the two Higgs doublets. The Higgs production cross-section is enhanced in the region of low $m_A$ and high $\tan \beta$ due to the enhanced Higgs coupling to down-type fermions. This leads to a significant increase in production cross section of neutral Higgs bosons $\phi$ in gluon-fusion (via a $b$ quark loop) as well as in associated production with $b$ quarks. This makes it possible to search in the MSSM for the inclusive productions: $\phi \rightarrow \tau \tau$, $b\phi \rightarrow b\tau \tau$, $b\phi \rightarrow bbb$, which would be very challenging in the SM due to the smallness of the cross section and the large irreducible backgrounds of $Z \rightarrow \tau \tau$ and multijet production. In the low $m_A$, high $\tan \beta$ region of the parameter space, Tevatron searches can therefore probe several MSSM benchmark scenarios extending the search regions covered by LEP [10].

Both collaborations analyzed these channels, searching for a resonance in the di-$\tau$ or di-$b$-jet mass spectrum. Fig. 10 shows the invariant mass distribution for the 3 jets channel in the $b\phi \rightarrow bbb$ search. No significant excess has been observed in any of the channels, allowing to set limits on production of neutral Higgs bosons.

The results on these three search channels at D0 were combined to obtain upper limits on $\tan \beta$ as a function of $m_A$ [10]. Radiative corrections to the Higgs couplings introduce a dependence on other model parameters of the MSSM so the combined result is provided within various benchmark models using the same combination technique as has been employed for the combination of SM Higgs boson searches. Fig. 11 shows the region excluded in the $(m_A$, $\tan \beta)$-plane at 95% C.L. within the $m_A$-max scenario, based on an integrated luminosity of $1.0 - 2.6$ fb$^{-1}$. A similar combination across the two experiments was done for the $\phi \rightarrow \tau \tau$ results from CDF and D0, which has a similar exclusion region in the parameter space [11]. It is expected that with the full Run II dataset and the combination of all MSSM channels across the two experiments sensitivity down to $\tan \beta$ values of 20 can be reached in the different benchmark scenarios.

4. Higgs searches at the LHC

With a centre of mass energy of 14 TeV and a high design luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ the LHC offers the best opportunity to make a direct observation of the Higgs boson, and both general purpose experiments, ATLAS and CMS will search for its existence.

Higgs production cross sections at the LHC are roughly two orders of magnitude larger than at the Tevatron and the dominant production channel is gluon fusion. This is followed by vector boson fusion which plays at the LHC an important contribution. From Tevatron to LHC energies the relevant backgrounds, like top anti-top pair production, rise often faster then the signal. The main handle against the huge multijet backgrounds at the LHC will be mainly to search in the leptonic decay modes.

The main discovery channels at the LHC are the inclusive searches $H \rightarrow \gamma \gamma$ and $H \rightarrow WW$ or $H \rightarrow ZZ$. For a low mass Higgs discovery, $H \rightarrow \gamma \gamma$ is one of the most promising channels. It has a small branching ratio, thus it needs good calorimeter resolution to observe a narrow mass peak in the prompt $\gamma \gamma$ continuum. The inclusive search for $H \rightarrow WW$ is similar to the same search at the Tevatron and has it highest sensitivity in the same mass region around 160 GeV. $H \rightarrow ZZ$ with the decay into four leptons is called the “gold plated decay channel” due to the very little background contribution especially for Higgs masses where one of the $Z$ bosons has to be off-shell.

These channels will be complemented with more exclusive searches. In particular, the vector boson fusion
5. Outlook

With Tevatron’s excellent performance matching the designed delivered weekly luminosities, a significant amount of sensitivity will be gained with an increase of the luminosity by the end of 2011. This will make it possible to use four times more data than was used in the presented results, to search for the Higgs at lower masses, with the possibility of a 3σ discovery of a light SM Higgs boson. The reach of sensitivity around 165 GeV will be significantly expanded as well with the final dataset. To improve the di-jet mass resolution, b-tagging, multivariate techniques and to increase the signal acceptance are the most important challenges for future Higgs searches at the Tevatron.

The LHC will offer the best possibility to search for a SM or beyond-SM Higgs bosons and with a data collected after a few years of running discovery is guaranteed if the Higgs boson exists and has a mass below 1 TeV.

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