Search for the Standard Model Higgs boson at the LHC

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Abstract

A corner stone of the Standard Model (SM) is the Higgs mechanism, which predicts the existence of one scalar Higgs boson. The hunt for the Higgs boson at the Large Hadron Collider (LHC) is a crucial endeavor for establishing the formulation of the SM electroweak theory. In this presentation, the channels most susceptible to lead to a discovery of the Higgs boson at the LHC are outlined.

Presented at DIS2008, April 7-11, 2008, London, U.K.
Search for the Standard Model Higgs Boson at the LHC

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A cornerstone of the Standard Model (SM) is the Higgs mechanism, which predicts the existence of one scalar Higgs boson. The hunt for the Higgs boson at the Large Hadron Collider (LHC) is a crucial endeavor for establishing the formulation of the SM electroweak theory. In this presentation, the channels most susceptible to lead to a discovery of the Higgs boson at the LHC are outlined.

1 Introduction

The breaking of the electroweak symmetry is provided by the Higgs mechanism. Interactions between gauge bosons or fermions with the Higgs field generate the masses of these particles. One scalar field component is not absorbed in this process, manifesting itself as the physical Higgs particle. The mass of the Higgs boson ($m_H$) is the only unknown parameter as all of the couplings are fixed by the masses of the particles. Nevertheless, stringent bounds on $m_H$ can be determined based on vacuum stability and Higgs self-coupling. If the SM is valid up to the Planck scale, then the mass of the Higgs boson is confined to a window between 130-190 GeV/$c^2$ [2]. Direct experimental searches at the Large Electron Positron Collider have set a lower bound of $m_H > 114.4$ GeV/$c^2$ at the 95% confidence level [3].

The LHC offers the possibility of discovering the Higgs boson over a wide mass range. Three factors must be taken into account: the Higgs production cross section, the subsequent decay branching ratios, and the backgrounds. These factors vary with $m_H$ and as such various channels must be considered. Gluon fusion (GF) is the dominant production mechanism at the LHC in the entire relevant $m_H$ range up to about 1 TeV/$c^2$. The second most important production mode is vector-boson fusion (VBF). Although an order of magnitude less than GF at 100 GeV/$c^2$, VBF is important as the two forward jets provide a distinctive signature. Associated processes also provide a clear signature but have smaller cross sections. The Higgs boson decay branching ratio as a function of $m_H$ is displayed in Fig. 1. Three regions can be identified in this figure. For $m_H < 140$ GeV/$c^2$, the dominant decay is via $b\bar{b}$, but QCD background is huge ($\sigma_{b\bar{b}} \sim 55$ mb), such that discovery is unlikely using this channel [5]. Similarly, the $H \rightarrow \tau\tau$ mode suffers from QCD backgrounds and observation of the Higgs in this channel will require a significant amount of luminosity [5]. Instead, $H \rightarrow \gamma\gamma$ is the most promising channel for low $m_H$. For $m_H > 140$ GeV/$c^2$, the Higgs boson predominantly decays into $W$ pairs, but because of backgrounds, the channel offering the best discovery potential is $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$, except for a narrow region near 160 GeV/$c^2$ where $H \rightarrow WW^{(*)} \rightarrow 2\ell 2\nu$ dominates.

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2 The $H \rightarrow \gamma\gamma$ channel

The $\gamma\gamma$ final state is produced via $W$ and heavy quark loops. Although rare, it is a clean signature with two isolated high $E_T$ photons and a narrow peak in the di-photon invariant mass, as the width of the Higgs is of order 10 MeV at 120 GeV/$c^2$. The ATLAS and CMS detectors have excellent electromagnetic calorimetry (ECAL) with $\sigma_E/\sqrt{E} < 1\%$, which allows the observation of this narrow peak. Inclusive studies have been performed: GF, VGF and Higgs produced in association with $W$, $Z$ and $t\bar{t}$ were simulated, resulting in a total cross section for $H \rightarrow \gamma\gamma$ of $\sim 0.1$ pb at 120 GeV/$c^2$. In comparison, background cross sections computed at NLO are several orders of magnitude more important and include the following processes: $pp \rightarrow jets$ ($2.8 \times 10^7$ pb), $pp \rightarrow \gamma + jets$ ($8.6 \times 10^4$ pb), $pp \rightarrow \gamma\gamma$ (216 pb). Thus, excellent photon separation from jets is needed.

Because of the significant amount of material between the beam pipe and the electromagnetic calorimeters, conversion photons must also be recovered to maximize signal efficiency. The photon reconstruction efficiency was evaluated to be 99% within the fiducial volume of the ECAL. Tracker and calorimetry based isolation was applied to suppress backgrounds from fakes such as jets or charged hadrons detected in the tracker, and charged particles undetected in the tracker, neutrons or $K_L^0$. Photons were categorized in terms of lateral shower shape and pseudorapidity. Two complimentary approaches were then used: cut based and optimized neural network analyses.

In the latter approach, events were split into categories depending on photon properties, jet multiplicity and energy ratios. Figure 2 displays the $m_{\gamma\gamma}$ distribution in the CMS barrel ECAL for a neural net output greater than 0.85. Signal simulation with $m_H = 120$ GeV/$c^2$ used. Events were normalized to $L = 7.7$ fb$^{-1}$, and the signal was scaled by a factor 10. The dominant systematic uncertainty is due to signal simulation (15% theory) and affects the exclusion limits but not the discovery potential. Other significant systematic uncertainties in this study come from luminosity measurement (5%), trigger efficiency (1%) and tracker material thickness (1%). As shown in Fig 5, less than 10 fb$^{-1}$ of integrated luminosity is necessary to discover the Higgs boson if $m_H < 130$ GeV/$c^2$.

3 The $H \rightarrow WW^{(*)} \rightarrow 2\ell’ 2\nu$ channel

The $H \rightarrow WW^{(*)} \rightarrow 2\ell’ 2\nu$ channel, where $\ell’ = e$ or $\mu$, is characterized by two isolated leptons of opposite charge in the final state, missing energy and no jet. Because of the invisible neutrinos, $m_H$ cannot be reconstructed. Instead, a search for an excess of events in the di-

$^a$These cross sections have uncertainties at the 20-30% level.
lepton mass spectrum is performed. This requires precise background estimates. Simulations were performed using PYTHIA and reweighted to the MC@NLO predictions leading to an inclusive cross section of about $2.3 \text{ pb}$ for $m_H = 160 \text{ GeV}/c^2$. Several backgrounds were considered in this study. Top production $t \bar{t}$ ($840 \text{ pb}$) and $tWb$ ($33.4 \text{ pb}$) were generated using TopRex at NLO. Continuum VBF backgrounds were generated using PYTHIA at NLO for $ZZ$ ($16 \text{ pb}$), $WZ$ ($50 \text{ pb}$), and $WW$ ($114 \text{ pb}$).

Criteria on the leptons $p_T^l$ were first applied to remove some of the soft QCD backgrounds. In order to suppress leptons produced in jets, tracker and calorimeter isolation were imposed for electron and muon selection. A cut on the impact parameter significance in the transverse plane further reduced contributions from $b\bar{b}$. Backgrounds from top were suppressed using a central jet veto. The separation between forward jets from VBF Higgs production is large. Hence, a $\Delta\eta$ cut between the two forward jets was also used to reduce top backgrounds. Preliminary studies at CMS have shown that the latter two requirements reject over 90% of top background while retaining more than half the signal [6]. Spin correlations can be exploited to suppress WW backgrounds. In fact, the angular separation in the transverse plane between leptons from $H \rightarrow WW^{(*)} \rightarrow 2\ell 2\nu$ decays, $\Delta\phi_{\ell\ell}$, tends to be less than for WW backgrounds as shown in Fig. 3, and an upper threshold was then set on $\Delta\phi_{\ell\ell}$. Early discovery can be achieved very rapidly in the $H \rightarrow WW^{(*)} \rightarrow 2\ell 2\nu$ channel as can been seen in Fig. 5. But this will require the understanding of the detector, in particular for missing energy reconstruction, and backgrounds will need to be evaluated as they are the dominant source of uncertainties, about 20% for 1 $\text{ fb}^{-1}$ of integrated luminosity.

4 The $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ channel

The $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ channel, where $\ell = e$ or $\mu$, has a very clean signature with relatively small backgrounds and is therefore an important discovery channel for the Higgs boson over a wide range of masses. Since the resolution on the lepton $p_T$ is excellent for both ATLAS and CMS, this is also an important channel for the measurement of the mass and width of the Higgs boson. Signal events were simulated at NLO using GF and VBF. Three backgrounds which yield four leptons in the final state were considered: $t \bar{t}$ ($1500 \text{ fb}$), $Zb\bar{b}$ ($800 \text{ fb}$) and $ZZ^{(*)}/\gamma^*$ ($80 \text{ fb}$). The first two backgrounds were simulated using GF and VBF, whereas only $t$-channel VBF was used for $ZZ^{(*)}/\gamma^*$. In order to account for contributions from all NLO and GF at NNLO, events were reweighted.
with a \( m_{4\ell} \) dependent K-factor using MCFM. As a reference, signal to background ratio is about 1:200 for \( m_H = 200 \text{ GeV/c}^2 \). Charge and lepton flavor balance was required and lepton \( Z_T \) thresholds were used to remove QCD backgrounds and fakes. Constraints were imposed on the \( Z \) and \( Z^{(*)} \) masses. Isolation was used to suppress leptons from \( b \) jets. An upper cut was also applied on the impact parameter significance to further suppress leptons from \( b \) decay. These requirements were very effective against \( t\bar{t} \) and \( Zb\bar{b} \), but were powerless against the irreducible \( ZZ^{(*)}/\gamma^* \) background.

The \( ZZ^{(*)}/\gamma^* \) background can only be cut away at the final stage of the analysis by selecting a narrow window in \( m_{4\ell} \), as shown in Fig. 4. In this figure, the top plots display signal and background \( m_{4\ell} \) distribution for \( m_H \) of 140 (left) and 200 GeV/c^2 (right), whereas the bottom plot show the same distribution after applying the full selection. Note that the requirements were optimized for maximum significance as a function of \( m_H \). Systematic uncertainties vary with \( m_H \) and come from background simulation (5-30%), and PDF uncertainties in \( ZZ^{(*)}/\gamma^* \) (1-5%). As shown in Fig. 5, the \( H \rightarrow ZZ^{(*)} \rightarrow 4\ell \) channel can lead to a Higgs discovery with less than 10 fb\(^{-1}\) for most of the \( 130 < m_H < 500 \text{ GeV/c}^2 \) range.

5 Conclusion

The LHC has excellent potential for discovering the Higgs boson. The experiments will first try to exclude the Higgs boson near the \( WW \) mass with only a few 100’s of pb\(^{-1}\). As shown in Fig. 5, discovery can then be achieved with as little as 1 fb\(^{-1}\), and with 30 fb\(^{-1}\), the Higgs boson should be discovered if \( m_H < 600 \text{ GeV/c}^2 \). Combining channels and results from ATLAS and CMS, discovery is expected with 5 fb\(^{-1}\) up to \( m_H < 1 \text{ TeV/c}^2 \).

6 Acknowledgments

Thanks to my ATLAS and CMS colleagues for providing me with material for this talk.

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