The search strategy for the Standard Model Higgs boson at the Large Hadron Collider is reviewed, with a particular emphasis on its potential observation by the ATLAS and CMS detectors in the $\gamma\gamma$, $\tau^+\tau^-$, $ZZ^*$ and $WW^*$ final states. The combined Higgs discovery potential of ATLAS and CMS is discussed, as well as the expected exclusion limits on the production rate times the branching ratio as a function of the Higgs mass and the collected luminosity.

1 Introduction

The main goal of the Large Hadron Collider (LHC) is to shed light on the mechanism responsible for the electroweak symmetry breaking. In the context of the Standard Model (SM) this is ensured by the Brout-Englert-Higgs mechanism that, by assuming the existence of one doublet of scalar fields, gives also rise to an additional scalar particle known as the Higgs boson. The mass of the Higgs boson $m_H$ is not predicted by the theory, but direct experimental searches have set a lower limit to $m_H > 114.4 \text{ GeV}/c^2$, and have recently excluded the range between 160 and 170 $\text{ GeV}/c^2$ at the 95\% confidence level (CL).

The global fit of precision electroweak data including the LEP–2 data indicates a preferred mass of $m_H = 116^{+15}_{-13} \text{ GeV}/c^2$ with an upper bound of 191 $\text{ GeV}/c^2$, if the Tevatron direct limits are not included.

The two LHC general-purpose detectors ATLAS and CMS are designed to search for the SM Higgs boson over a wide mass range, from the LEP exclusion limit up to several hundreds of $\text{ GeV}/c^2$. An overview of the the search strategies over the whole mass range is presented here, as well as the sensitivities of the detectors with different integrated luminosities at $\sqrt{s} = 14 \text{ TeV}$, the nominal LHC center-of-mass energy for the proton–proton collisions.

2 The Standard Model Higgs boson at the LHC

The dominant production mechanism of the SM Higgs boson in the proton–proton collisions provided by the LHC is the gluon fusion (Fig. 1), where at leading order the production is mediated by an heavy quark loop. The next-to-leading (NLO) order cross section for this process accounts to about 37.6 pb for $m_H = 120 \text{ GeV}/c^2$. The following production mechanism is trough Vector Boson Fusion (VBF), despite being approximately one order of magnitude smaller – the NLO cross section for this process accounts to about 3.19 pb for $m_H = 120 \text{ GeV}/c^2$ – this mechanism is nevertheless interesting for the particular topologies of its final states.

The productions of the Higgs boson in association with a $Z$ or $W$ vector boson or with a $t\bar{t}$ pair have much smaller cross sections: they are used by ATLAS and CMS to improve their sensitivity further more, or to study very specific final states, but they will not be discussed here.
In the mass region the Higgs is strongly disfavored because of the very high QCD background and the small pT provides instead a clear signature of high decay rates in that mass range.

Figure 1: SM Higgs production cross-sections at the LHC for \(\sqrt{s} = 14\,\text{TeV}\) as a function of the Higgs mass.

Figure 2: Branching ratios for SM Higgs decays as a function of the Higgs mass.

3 Higgs discovery final states

The most promising Higgs decay modes to search for the particle in a given mass range are selected both by the Higgs branching ratios \(^4\) (see Fig. 2) and by the relative level of background for those particular decays in that mass range.

In the low mass region \((m_H \lesssim 135\,\text{GeV}/c^2)\) the \(b\bar{b}\) final state accounts for about 81% of the decays, but it is strongly disfavored because of the very high QCD background and the small pT of the decay particles. In this mass region the \(H \rightarrow \gamma\gamma\) decay, despite the tiny branching ratio (~0.2% for \(m_H = 120\,\text{GeV}/c^2\)), provides instead a clear signature of high pT photons, and represents the most promising search channel (see Sec. 3.1). The decay in \(\tau^+\tau^-\) pairs accounts only for about 8% of the decays at low mass, and potentially suffers of limitations similar to the ones affecting the \(b\bar{b}\) decay mode; on the other hand the use of the particular final state topology provided by the VBF production mode promotes this decay channel to be an important support to increase the sensitivity in the low mass region (see Sec. 3.2).

For larger masses \((m_H \gtrsim 130\,\text{GeV}/c^2)\) the decay in a pair of \(Z\) or \(W\) bosons becomes accessible, with at least one of them on-shell. Thanks to its kinematics providing a very clear signature, the decay of the Higgs boson into four leptons mediated by two \(Z\) bosons \((H \rightarrow ZZ^{(*)} \rightarrow 4l)\) represents the search golden channel in this mass range (see Sec. 3.3), except for the region around \(m_H \approx 2m_W\) where the decay in two \(W\) bosons account for about 95% of the branching ratio, and the search for \(H \rightarrow WW^{(*)} \rightarrow l\nu l\nu\) becomes the most significant one (see Sec. 3.4).

3.1 \(H \rightarrow \gamma\gamma\)

Two high pT photons represent the clean signature of this final state: the kinematic of the event can be fully reconstructed, and the existence of the Higgs boson would manifest itself as a bump in the di-photon invariant mass spectrum, sitting on top of the irreducible background spectrum constituted by genuine photon pairs from \(q\bar{q} \rightarrow \gamma\gamma\), \(gg \rightarrow \gamma\gamma\) and quark bremsstrahlung (Fig. 3).

Jet–jet and \(\gamma\)-jet events where the jets are misidentified as photons make up the reducible background, that has to be kept as low as possible with an excellent jet rejection. In order to achieve the higher sensitivity possible the best invariant mass resolution is needed: this implies guaranteeing an optimal electromagnetic calorimetric resolution, an excellent measurement of the interaction primary vertex, and a good control of the photon conversions.

Both ATLAS and CMS have studied this signal and its background at NLO, have extended their cut–based analysis’s to more statistical–aggressive approaches, and have reached similar signal sensitivities in this channel. With an integrated luminosity of 10 (30) fb\(^{-1}\) their discovery significance is about 4\(\sigma\) (8\(\sigma\)) for \(m_H = 130\,\text{GeV}/c^2\).

3.2 \(H \rightarrow \tau^+\tau^-\)

The search of low mass \((m_H \lesssim 140\,\text{GeV}/c^2)\) the Higgs boson decaying in a \(\tau^+\tau^-\) pair can be performed exploiting the particular topology of the events where the Higgs is produces through VBF. When the Higgs is produced by this mechanism the products of the \(\tau\) decays are accompanied by the presence of
two high \( p_T \) jets, that can be used to distinguish the signal. The absence of color flow between these tag jets introduces a rapidity gap between them: a central jet veto suppresses then the background.

Because of the small \( \tau \) mass with respect to the Higgs mass, the products of the \( \tau \) leptonic or hadronic decays can be considered approximately collinear: despite the presence of neutrinos in the final states, the Higgs invariant mass can be fully reconstructed using the two components of the measured missing transverse energy, if the Higgs boson has some transverse momentum. The Higgs mass peak would be partly superimposed to the transverse energy, if the Higgs boson has some transverse momentum. The Higgs mass peak would be fully reconstructed using the two components of the measured missing transverse energy, if the Higgs boson has some transverse momentum. The Higgs mass peak would be fully superimposed to the \( Z \rightarrow \tau^+\tau^- \) peak in the di-\( \tau \) invariant mass spectrum. In order to evaluate this contribution, the similarities between the \( Z \rightarrow \mu^+\mu^- \) and \( Z \rightarrow \tau^+\tau^- \) processes are used: the measure of the latter helps to estimate all the detector effects from data, that are then transposed to the former replacing the measured \( \mu \)'s with simulated \( \tau \)'s.

A 5\( \sigma \) discovery with this channel alone will require about 30 fb\(^{-1} \) (60 fb\(^{-1} \)) for \( m_H = 115 \text{ GeV}/c^2 \) (140 GeV/\( c^2 \)) \(^{11}\)\(^{14}\).

3.3  \( H \rightarrow ZZ^{(*)} \rightarrow 4l \)

The Higgs boson with \( m_H \gtrsim 130 \text{ GeV}/c^2 \) decaying in \( ZZ^{(*)} \) is sought for in the \( e^+e^-e^+e^- \), \( \mu^+\mu^-\mu^+\mu^- \) and \( e^+e^-\mu^+\mu^- \) channels, taking advantage of the excellent energy reconstruction of electrons and muons of both the ATLAS and CMS detectors. Since four leptons are present in all final states, the reconstruction efficiency plays a crucial role.

The main reducible backgrounds for this channel are \( Zbb, \, t\bar{t} \) and fakes, that can be strongly reduced requiring lepton isolation and imposing selections on the impact parameter; requiring that at least one \( Z \) is on-shell helps reducing the background further more.

Since the full kinematics of the event can be reconstructed, the Higgs boson would manifest itself as a clear mass peak of the four leptons invariant mass sitting on top of a smooth continuum due to the irreducible background of \( ZZ^{(*)} \) (Fig. \(^{14}\)), for Higgs masses ranging from 130 to 600 GeV/\( c^2 \).

This channel would guarantees 5\( \sigma \) discovery significance over this mass range with about 30 fb\(^{-1} \), except in the region around 2 \( m_W \) \(^{11}\)\(^{15}\). Already with the 1 fb\(^{-1} \) this channel could disprove the existence of an Higgs boson with \( m_H > 185 \text{ GeV}/c^2 \) at 95\% CI \(^{16}\).

3.4  \( H \rightarrow WW^{(*)} \rightarrow ll\nu\nu \)

Unlike the other channels described above, the Higgs mass peak cannot be reconstructed in the \( H \rightarrow WW^{(*)} \rightarrow ll\nu\nu \) decays, because of the presence of neutrinos in the final state and the large \( W \) mass. The discovery of the Higgs boson in this channel reduces to a counting experiment, in which the estimate of the background level from data is therefore crucial. The background is dominated by \( WW \) and \( tt \) production, followed by \( Wt, \, WZ, \, ZZ, \, \text{Drell–Yan and fakes} \).

The decay leptons from the \( W \)’s originating from the Higgs boson would be preferentially emitted in the same direction in the Higgs rest frame: this introduces a kinematical correlation that can be used to separate the signal from the background, and especially to build signal–depleted samples to measure the background level with.
This powerful decay channel would already allow to exclude the existence of an Higgs boson between 150 and 180\,GeV/c$^2$ at 95\% CL with the first few fb$^{-1}$, while with 10 fb$^{-1}$ a 5\,$\sigma$ discovery could be claimed\cite{ATLAS, CMS}.

### 4 Higgs discovery and exclusion potentials

The SM Higgs boson discovery reach combining the various final states described above for an integrated luminosity of 30 fb$^{-1}$ is presented in Fig. 5 as a function of the Higgs mass for the CMS experiment\cite{CMS} ATLAS has similar performances\cite{ATLAS}. Both experiments exceed a 5\,$\sigma$ significance over the whole mass range with 30 fb$^{-1}$ provided by LHC at $\sqrt{s} = 14$\,TeV.

The combined SM Higgs boson exclusion limits are presented in Fig. 6 as a function of the Higgs mass and the integrated luminosity for the ATLAS experiments\cite{ATLAS}. CMS has similar performances\cite{CMS}. Both experiments will be able to exclude a SM Higgs boson at 95\% CL over the whole mass range with the first few fb$^{-1}$ provided by LHC at $\sqrt{s} = 14$\,TeV.

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