Discovery potential at the LHC: channels relevant for SM Higgs

I. Tsukerman on behalf of ATLAS and CMS collaborations
ITEP, Moscow, Russia

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Abstract

The discovery potential of Standard Model Higgs searches at the LHC at 14 TeV center-of-mass energy is reviewed. Decay channels such as $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{\star} \rightarrow 4\ell$, $H \rightarrow WW^{\star}$ and $H \rightarrow \tau\tau$ are considered. Results are based on the most recent full GEANT-based simulations performed by the ATLAS and CMS experiments.

1 Introduction

The primary objective of the Large Hadron Collider (LHC) at CERN is to study the origin of electroweak symmetry breaking. Within the Standard Model (SM), the Higgs mechanism [1] is invoked to explain this breaking and the Higgs boson remains the only particle that has not been discovered so far. The direct search at the $e^{+}e^{-}$ collider LEP has led to a lower bound on its mass of 114.4 GeV at 95% C.L. [2]. In addition, high precision electroweak data constrain the mass of the Higgs boson via their sensitivity to loop corrections. The upper limit is $m(H) \leq 185$ GeV at 95% C.L. provided the LEP result is also used in the determination of this limit [3]. At last, combined preliminary results from the Tevatron experiments CDF and D0 based on 3 fb^{-1} accumulated data at 1.8 TeV lead to a 95% C.L. exclusion of a Higgs boson with $m(H)$=170 GeV [4]. Both ATLAS and CMS experiments at the LHC, scheduled for proton-proton collision data taking in summer 2009, have been designed to search for the Higgs boson over a wide mass range [5]. In these proceedings the sensitivity for each experiment to discover or exclude the SM Higgs boson as well as recent developments that have enhanced this sensitivity are summarized.

2 SM Higgs production at the LHC

Theoretical predictions for NLO SM Higgs production cross-sections at 14 TeV energy as a function of $m(H)$ [6] are shown in Fig.1 (left). The dominant production mechanism, which proceeds via a top-quark loop, is gluon-gluon fusion ($gg \rightarrow H$). It gives rise to 20–40 pb SM Higgs cross section in the mass range between 114 and 185 GeV. The vector-boson fusion (VBF) process ($qq \rightarrow qqH$) has a factor of eight smaller cross section. However, in this case, the Higgs boson is accompanied by two energetic jets going mainly into the forward directions. Usually they have large pseudorapidity gap in-between. In addition, there is no colour flow between these *tagging* jets which allows for use of *a central jet veto* to reduce backgrounds. $q\bar{q} \rightarrow HW$, $q\bar{q} \rightarrow HZ$ and $gg, q\bar{q} \rightarrow t\bar{t}H$ processes have smaller cross sections.

3 SM Higgs discovery final states

The SM Higgs boson is predicted to have many decay channels with branching ratios which strongly depend on its mass (Fig.1 (right)). The evaluation of the search sensitivity of the various channels should take into account the cross-sections of the relevant backgrounds.

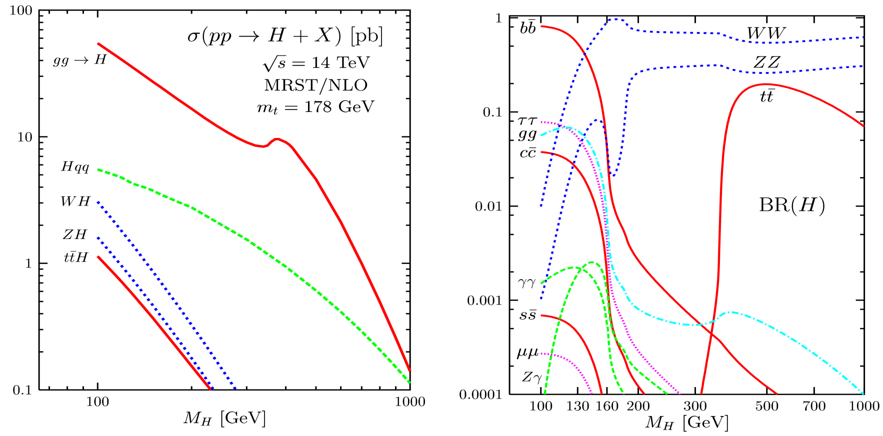

Fig. 1: Left: Theoretical predictions for SM Higgs boson production cross sections at LHC energies. Right: Theoretical predictions for SM Higgs boson decay branching ratios.

At low Higgs mass the dominant decay mode is through $b\bar{b}$. However, due to the enormous QCD backgrounds this channel is not good for the SM Higgs discovery. The $\gamma\gamma$ final state, which appears when the Higgs decays via bottom, top and W-loops, has a small branching fraction. However, excellent diphoton invariant-mass resolution and γ/jet separation can make this mode one of the best discovery channels. $H \to \tau\tau$ has a sizeable rate and should be visible with good purity via the VBF Higgs production mode.

If the Higgs mass is larger, the $H \to WW^\star$ final states are powerful as well as the mode $H \to ZZ^\star \to 4\ell$. In the last case, the resulting branching ratio is small but the signal is easy to trigger on and allows for full reconstruction of the Higgs mass.

Both ATLAS and CMS Collaborations have performed extensive GEANT-based Monte Carlo [7] studies with full simulation and reconstruction to determine the experimental viability of many Higgs decay channels. Results of the recent studies [8] for the most attractive signatures, namely $H \to \gamma\gamma$, $H \to ZZ^\star \to 4\ell$, $H \to WW^\star$ and VBF $H \to \tau\tau$ are summarized below.[1]

3.1 $H \to \gamma\gamma$

Despite a only 0.2% branching ratio in the Higgs mass region 120–140 GeV, $H \to \gamma\gamma$ remains a promising channel as the signal signature is very clean. Irreducible backgrounds come from continuum production of diphotons, $q\bar{q}, gg \to \gamma\gamma$. Reducible backgrounds are mostly due to γ-jet and jet-jet events, where one or more jets are misidentified as photons. Studies performed by both the ATLAS and CMS experiments consider the signal and backgrounds at NLO level. Thanks to a very good electromagnetic energy resolution, with a simple cut-based analysis for an integrated luminosity of 30 fb^{-1} one can obtain a significance above 5σ in the CMS experiment for the mass range 115–140 GeV (Fig.2 (top left)). Having a worse energy resolution, ATLAS nevertheless can reach almost the same significance as the high-granularity electromagnetic calorimeter with longitudinal samplings is capable of determining the primary vertex with

[1]Another summaries of SM Higgs searches were presented at this year conferences, see, e.g. Ref. [9].

great precision. Both experiments have looked beyond a simple cut-based analysis and enhanced the signal significance by 30–50% (Fig.2 (top left)).

3.2 $H \to ZZ^\star \to 4\ell$

The "golden" channels (4μ, $2e2\mu$ and $4e$ final states of $ZZ^\star$ decays) are expected to be good for discovery in a wide mass range (except $m(H) \leq$130 GeV and $m(H) \approx 2m_W$). The dominant background is the $ZZ^\star$-continuum with smaller contributions from $Zb\bar{b}$ and $t\bar{t}$ processes. Through the use of impact parameter and lepton isolation requirements the latter two (which are important only at low $m(H)$) can be significantly reduced. Simulations of the signal and the $q\bar{q} \to ZZ^\star$ backgrounds were made up to the NLO level. An additional 20–30% contribution from the $gg \to ZZ^\star$ process was also taken into account. A 5σ discovery in $H \to ZZ^\star \to 4\ell$ mode is possible in much of the allowed $m(H)$ space with less than 30 fb^{-1} of integrated LHC luminosity (Fig.2 (top right)).

3.3 $H \to WW^\star$

$H \to WW^\star$ is the main search channel in the Higgs mass range $2m_W \leq m(H) \leq 2m(Z)$ due to a very large $H \to WW$ branching ratio (Fig.1 (left)). This mode is also good at lower masses (down to $m(H) \approx$ 130 GeV) and at high $m(H)$. Two different final states are considered: $\ell\nu\ell\nu$ and $\ell\nu qq$. Unlike the $H \to ZZ \to 4\ell$ and $H \to \gamma\gamma$ channels, full mass reconstruction is not possible therefore an accurate background estimate is critical. The dominant background for this analysis is $q\bar{q}, gg \to WW^\star$-production in the case of H + 0 jets signal. This background can be suppressed by exploiting the spin correlation between the two final state leptons. For H + 2 jets, where the contribution from $qq \to qqH$ process is the most important, $t\bar{t}$-production is the main background which can be reduced by the *forward jet tagging* and *central jet veto* requirements. NLO-level studies (with systematics included) have shown that less than 2 fb^{-1} integrated luminosity would be sufficient for a 5σ discovery of the SM Higgs with $m(H)$ =160–170 GeV. Let us note that using the VBF $H \to WW^\star \to e\nu\mu\nu$ mode alone, ATLAS is able to observe this particle with 10 fb^{-1} of integrated luminosity provided 150 GeV $\leq m(H) \leq$ 180 GeV (Fig.2 (bottom left)).

3.4 VBF $H \to \tau\tau$

In gluon-fusion production mode the $H \to \tau\tau$ channel is not promising due to large backgrounds. However, one can consider the $qq \to qqH$ process which helps to reduce contributions coming mainly from the $Z/\gamma^\star \to \tau\tau$ + jets and $t\bar{t}$ processes. Data-driven methods for understanding the dominant backgrounds have been investigated. Three final states of τ decays are considered: lepton-lepton, lepton-hadron and also hadron-hadron. Despite the presence of neutrinos, mass reconstruction can be done via the collinear approximation where τ decay daughters are assumed to go in the same directions as their parents. The resolution on the reconstructed mass ($\sim$ 10 GeV) is mainly affected by the missing transverse energy resolution. Simulations performed by ATLAS and CMS have shown that the combination of the lepton-lepton and lepton-hadron channels should allow for a 5σ measurement with 30 fb^{-1} LHC luminosity in the range 115 GeV $\leq m(H) \leq$ 125 GeV (Fig.2 (bottom right)).

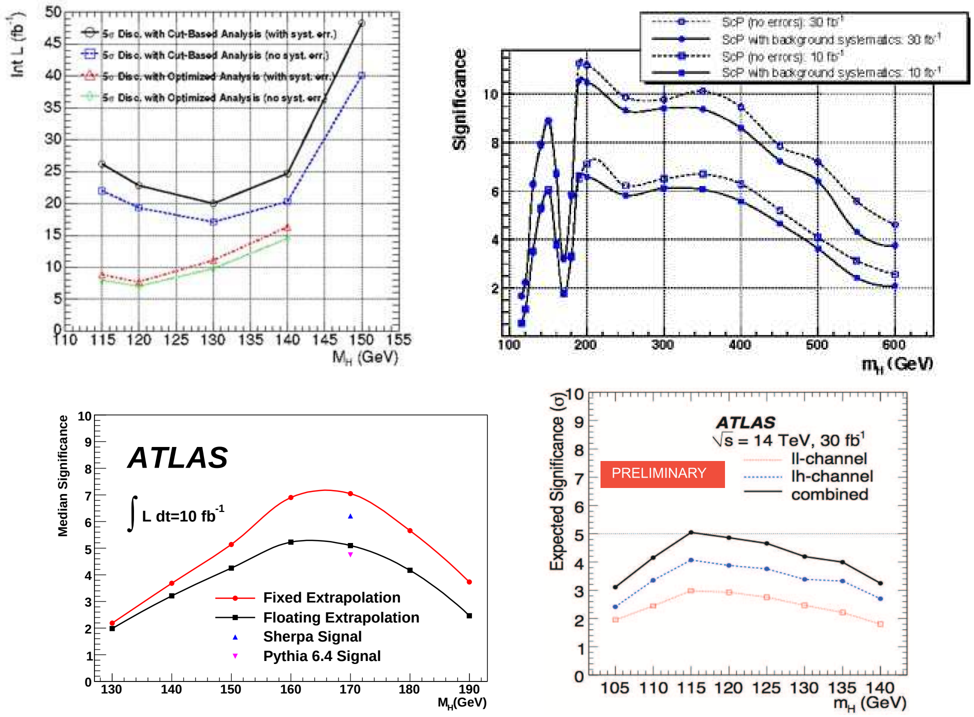

Fig. 2: SM Higgs discovery potential for specific decay modes. Top left: CMS, $H \to \gamma\gamma$. Top right: CMS, $H \to ZZ^\star \to 4\ell$. Bottom left: ATLAS, VBF $H \to WW^\star \to e\nu\mu\nu$. Bottom right: ATLAS, VBF $H \to \tau\tau$.

4 Summary of SM Higgs discovery potential

Figure 3 (left) shows integrated luminosity needed for the 5σ discovery of the inclusive Higgs boson production with the decay modes $H \to \gamma\gamma$, $H \to ZZ^\star \to 4\ell$ and $H \to WW^\star \to \ell\nu\ell\nu$ in the CMS experiment. In the most complicated region below $m(H)$ =130 GeV, less than 10 fb^{-1} would be sufficient while in the range 155 GeV$\leq m(H) \leq$400 GeV only 3 fb^{-1} are required. The signal significance as a function of the Higgs boson mass for 30 fb^{-1} of integrated LHC luminosity for the different Higgs boson production and decay channels is shown in Fig.3 (right). Here $H \to \tau\tau \to \ell\nu j\nu$ and $H \to WW^\star \to \ell\nu jj$ final states are also included. For $m(H)$ between 115 and 500 GeV 10σ discovery can be reached.

In summary, one can conclude that with integrated LHC luminosity of $\sim$5 fb^{-1} it is possible to discover SM Higgs boson provided its mass is above the 114 GeV limit obtained by LEP [10]. It is sufficient to accumulate 1 fb^{-1} for a 95% C.L. exclusion in the full allowed mass range.[2]

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[2] These statements are based on older simulations [11]. However one would not expect major changes when new results will be included.

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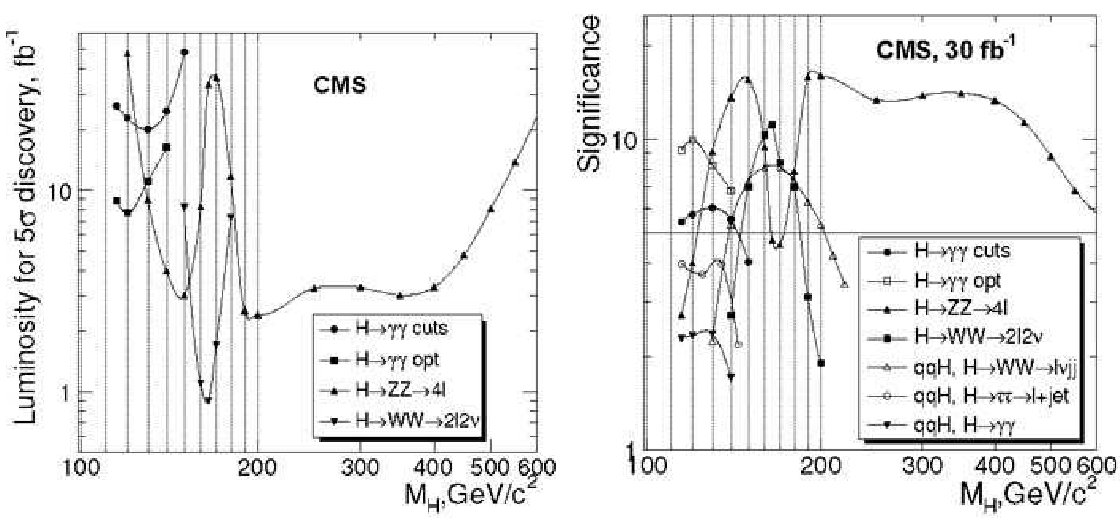

Fig. 3: Left: Integrated luminosity needed for 5σ discovery of the inclusive Higgs boson production pp→ H + X with the Higgs boson decay modes $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{\star} \rightarrow 4\ell$ and $H \rightarrow WW^{\star} \rightarrow \ell\nu\ell\nu$ in the CMS experiment. Right: The signal significance as a function of the Higgs boson mass for 30 fb^{-1} of the integrated luminosity for the different Higgs boson production and decay channels in the CMS experiment.