Discovery Potential of the Standard Model (SM) Higgs at ATLAS

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March 27, 1998

Abstract

The discovery of the Higgs boson is a key issue to prove the Standard Model (SM) or to extend it. Here firstly the properties of SM Higgs will be briefly reviewed. Secondly the discovery potential at ATLAS will be discussed based on the productions and the decay properties of the SM Higgs.

1 Introduction

The Standard Model (SM) is the most successful theory which can account for the experimental observations without apparent contradictions so far. In the frame work of SM, particles are classified into following two types;

- fermions with spin-1/2, i.e. leptons and quarks
- gauge bosons with spin-1, which cause interactions between fermions and also self interaction between themselves.

Interactions between the massless fermions are caused by requiring a local gauge invariance which is equivalent to creations of the gauge bosons. However, the real particles are massive, therefore we have to introduce a new Lagrangian by which fermions and weak gauge bosons can obtain their correct masses keeping the gauge invariance. A simple mind is to add mass terms into the massless Lagrangian by hand, but those mass terms break the local gauge invariance. To solve this problem, a scalar potential term is introduced in the SM Lagrangian, which conserves the local gauge invariance, but by requiring the spontaneously broken symmetry of the potential, weak gauge bosons can have their masses and a new boson, Higgs boson must emerge as the consequence. If such boson exists, quarks and leptons can also have their masses via the interaction with the Higgs boson. Therefore it is a key issue to discover the SM Higgs boson experimentally in order to prove the scenario of SM or to extend it. Although the Higgs boson can give masses, the SM scenario can not predict the absolute values including Higgs boson mass itself. Therefore the Higgs mass must be determined by the experimental observation. So far the experimental lower limit on the SM Higgs mass is 77 GeV from the LEP2 experiment[1]. Future projects like hadron collider and e^+e^- liner collider experiments would give abundant information on this key issue.

In this talk, firstly the properties of the SM Higgs will be briefly reviewed. Secondly the discovery potential at Large Hadron Collider (LHC) experiment will be discussed based on the studies dedicated for the ATLAS detector [2].

2 Properties of the SM Higgs

2.1 Theoretical Limit on the SM Higgs mass

Although SM can not predict the Higgs mass principally, the mass can be constrained by the consideration on the validity of the perturbative treatment and the vacuum stability of the Higgs potential up to a cut-off scale Λ. The Higgs potential in SM takes the following form;

$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2, \tag{1}$$

where ϕ is a Higgs doublet, μ^2 satisfies $\mu^2 < 0$ and the self-coupling λ is related with μ^2 via the vacuum expectation value of $v = \sqrt{-\mu^2/\lambda}$. The upper bound on Higgs mass

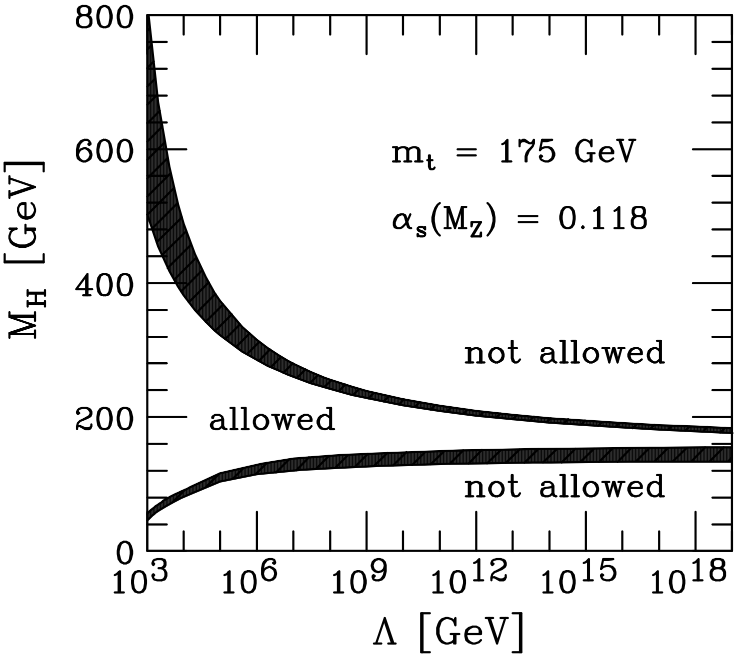

Figure 1: Allowed mass region of the SM Higgs as a function of the scale Λ taken from [4].

can be obtained by requiring that λ does not increase too rapidly up to a certain scale Λ, which guarantees that perturbative theory is valid up to the scale. The lower bound can be obtained by requiring that λ does not take negative value so that the minimum of the vacuum remains absolute minimum in the loop corrected effective Higgs potential [3]. Since currently top quark mass is known as $M_t = 175 \pm 6$ GeV experimentally, the Higgs mass can be expressed as a function of Λ for $M_t = 175$ GeV. Figure 1 shows the allowed SM Higgs mass region with respect to the scale Λ, which conclude that upper bound on the Higgs mass is $M_H < 180 \pm 4 \pm 5$ GeV for $M_t = 175$ GeV, if the SM renormalization-group behavior is perturbative and well-behaved up to the Plank scale $\Lambda = 10^{19}$ GeV [4].

2.2 Decay mode

Figure 2 shows the mass dependence of the total decay width and the branching ratios of the SM Higgs. The key points to evaluate properties of the SM Higgs is in the strength of its couplings to fermions $g_f = g_2 M_f / 2M_W$ and to gauge bosons $g_w = g_2 M_W$, where g_2 is the weak coupling constant, M_f is a mass of a fermion and M_W is a mass of a weak gauge boson. From those couplings the decay width to fermion pair $\Gamma_{f\bar{f}}$, to gauge bosons $\Gamma_{WW/ZZ}$, and to gluons Γ_{gg} can be expressed as follows;

$$\Gamma_{f\bar{f}} \propto M_f^2 M_H \tag{2}$$

$$\Gamma_{WW/ZZ} \propto M_H^3 \tag{3}$$

$$\Gamma gg \propto \alpha_s^2 M_H^3. \tag{4}$$

It is clear from those relations that the decay modes heavily depend on the Higgs mass M_H. While M_H is below the weak boson mass, the factor M_f^2 dominates M_H, therefore the dominant decay modes become $H \to f\bar{f}$ out of which the main decay mode is $H \to b\bar{b}$. Once M_H exceeds the weak boson masses, $H \to WW^*/ZZ^*$ and $H \to WW/ZZ$ dominate $H \to f\bar{f}$, since the decay width depends on M_H^3. For the top-loop mediated decay into gluons, the decay is suppressed by the factor of α_s^2. Thus the turning point of the SM Higgs searches is in $M_H \sim 130$ GeV, which corresponds to the mass threshold where a weak boson and a virtual weak boson pair can be created.

The total decay width in the lower mass region below ~ 130 GeV is less than 10 MeV. On the other hand the width increases rapidly above ~ 130 GeV and reaches 1 GeV at around ZZ threshold.

3 SM Higgs search at LHC

Large Hadron Collider (LHC) can achieve the center of mass energy of 14 TeV and the design peak luminosity is 10^{34} cm^{-2}s^{-1}. The expected integrated luminosity over one year is 10^4 pb^{-1} for the initial low luminosity and 10^5 pb^{-1} for the design luminosity. By LHC the SM Higgs search can be made from ~ 100 GeV to ~ 1 TeV for the Higgs mass.

3.1 Production of the SM Higgs at LHC

The expected production modes of the SM Higgs boson at LHC are following;

- $gg \to H$
- $qq \to Hqq$
- $q\bar{q} \to W/Z + H$
- $gg, q\bar{q} \to t\bar{t}/b\bar{b} + H$.

Figure 3 shows the production cross sections for the decay modes above. The dominant production mode is $gg \to H$ over the wide range of the Higgs mass. However, in low mass range $70 < M_H < 130$ GeV where $H \to b\bar{b}$ is the dominant decay mode, $q\bar{q} \to HW$ and $gg, q\bar{q} \to Ht\bar{t}$ might be also available, since W and $t\bar{t}$ could be a signal to reduce the background. For the high mass range 600 GeV $< M_H <$ 1 TeV, $qq \to Hqq$ would be more useful rather than $gg \to H$, since qq in the final state could be a signal to reduce the background.

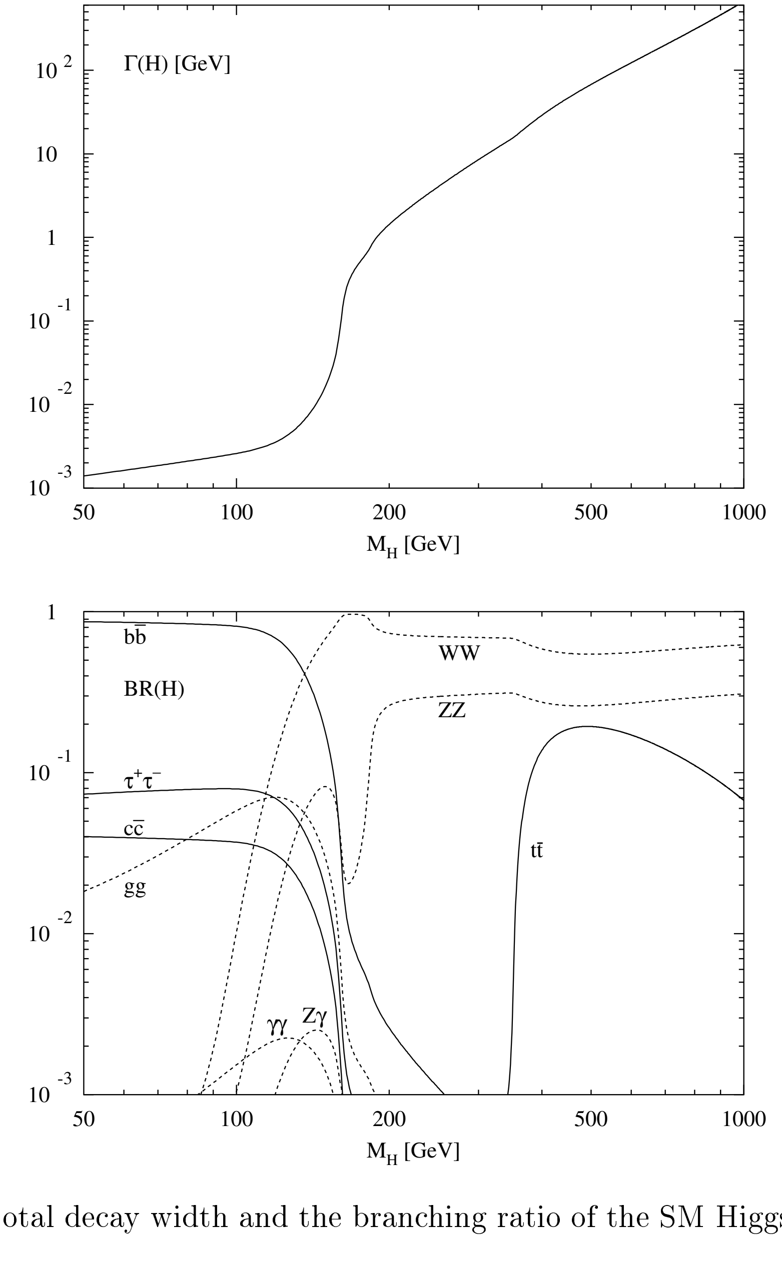

Figure 2: The total decay width and the branching ratio of the SM Higgs taken from [5].

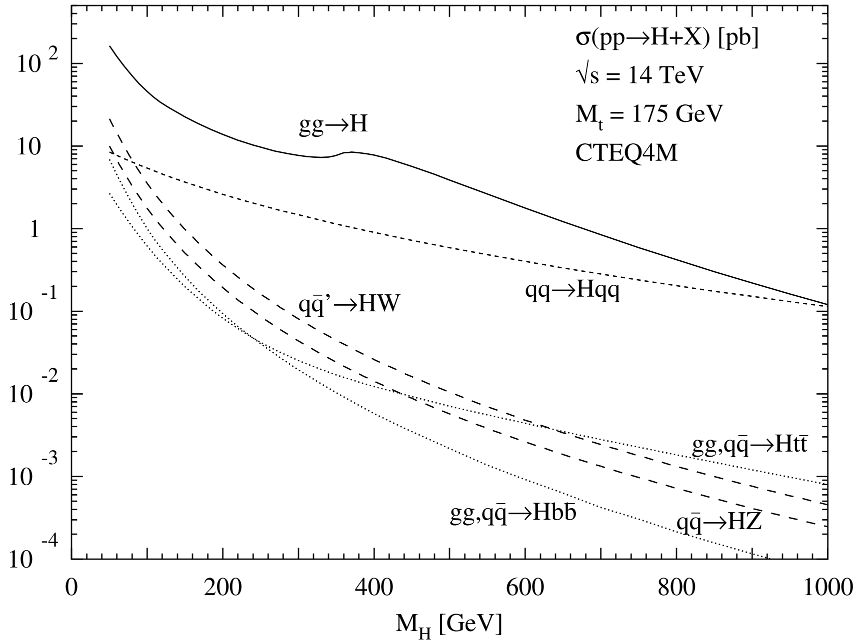

Figure 3: The production cross sections at LHC taken from [6].

3.2 Search in 70 $< M_H <$ 130 GeV

The most promising decay mode in this mass region is the top-loop mediated decay into phones, $H \to \gamma\gamma$. Although the branching ratio is order of 10^{-3}, the signal of $\gamma\gamma$ is much cleaner compared to the signal from $H \to b\bar{b}$ in the production $q\bar{q} \to HW$ or $gg, q\bar{q} \to Ht\bar{t}$. The reducible backgrounds for $H \to \gamma\gamma$ are $jet - jet$, $jet - \gamma$ and $Z \to e^+e^-$. The irreducible backgrounds are $qq \to \gamma\gamma$, $gg \to \gamma\gamma$ and quark bremsstrahlung $qg \to \gamma + jet - \gamma$, which make $\gamma - \gamma$ continuum. In order to get a reasonable S/N, the reducible background must be suppressed within 20% of the irreducible $\gamma - \gamma$ continuum. To achieve this background level, π^0/γ separation must be refined by pre-shower counter with finer granularity in the calorimetry.

Figure 4 shows the expected $H \to \gamma\gamma$ signal for $M_H = 120$ GeV combined with the $\gamma - \gamma$ continuum background with the integrated luminosity of 10^5 pb^{-1}.

3.3 Search in 130 $< M_H <$ 600 GeV

In this mass range the most promising decay mode is $H \to ZZ \to l^+l^-l^+l^-$ where l is electron or muon. This event is called Gold-Plate event, since this is the most beautiful signal from the experimental point of view. The reducible backgrounds are cascade decays from $t\bar{t}$ and $Zb\bar{b}$. The irreducible background is $qq \to ZZ/ZZ^*/Z\gamma^*$. The required reducible background level is less than 10% of the irreducible continuum.

The main cuts to get the signal well above the backgrounds are following;

- P_T cut on leptons

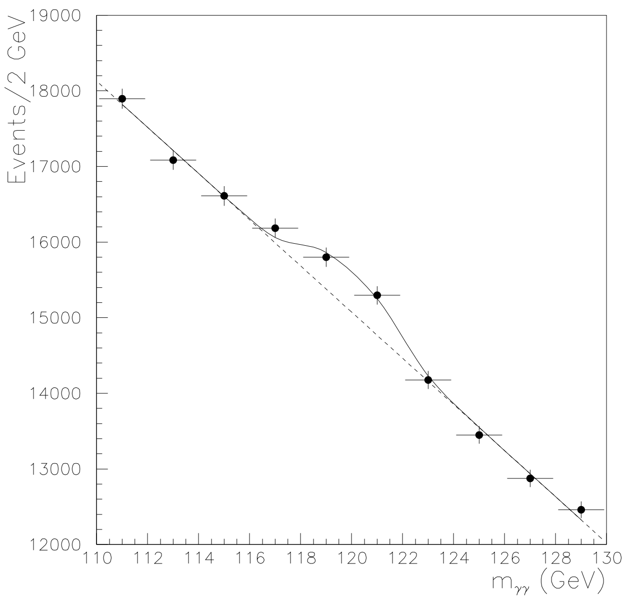

Figure 4: The reconstructed Higgs mass from $H \to \gamma\gamma$ signal for $M_H = 120$ GeV combined with the $\gamma - \gamma$ continuum background with the integrated luminosity of 10^5 pb^{-1}.

- M_Z reconstruction
- isolation around leptons to reduce leptons from semileptonic decay
- small transverse impact parameter
- small missing P_T.

Figure 5 shows reconstructed four charged lepton masses above the backgrounds for $M_H = 130$, 150 and 170 GeV with the integrated luminosity of 3×10^4 pb^{-1}. (a) depicts the expected average numbers of events and (b) is the same events, but results obtained by randomizing statistics in each mass bin.

3.4 Search in $600 < M_H < 1$ TeV

For larger mass range, $H \to WW/ZZ \to l\nu jj/lljj$ in the production mode of $qq \to Hqq$, would be available, since the branching ratio is expected to be larger than $H \to ZZ \to 4l$ and the qq in the final state would be useful to reduce the background. In this mass range the reducible backgrounds dominate the irreducible ones. The reducible backgrounds are from $W/Z + multi - jets$ and $t\bar{t} \to l\nu jjb\bar{b}$.

The main cuts to obtain the signal well above the backgrounds are following;

- $M_{W/Z}$ reconstruction from two jets in a big cone
- P_T cut on l and ν

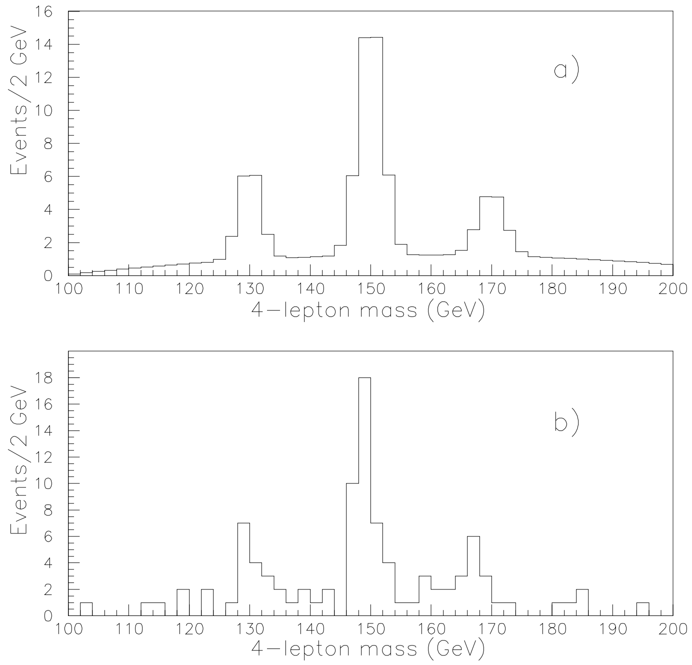

Figure 5: Reconstructed four charged lepton masses above the backgrounds for M_H = 130, 150 and 170 GeV with the integrated luminosity of 3×10^4 pb^{-1}. (a) depicts the expected average numbers of events and (b) is the same events, but results obtained by randomizing statistics in each mass bin.

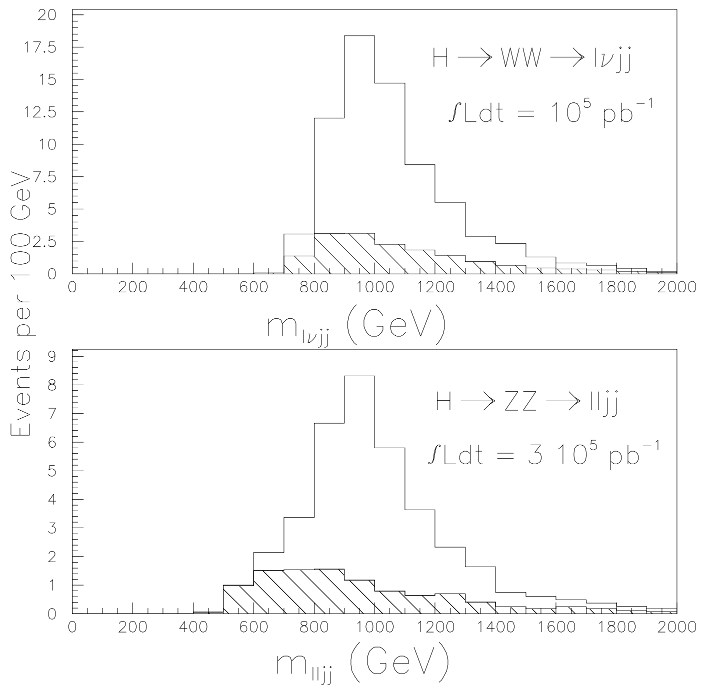

Figure 6: Reconstructed Higgs masses where backgrounds are depicted as shaded. The upper plot is the case of $H \to WW \to l\nu jj$ with integrated luminosity of 10^5 pb^{-1} and the lower plot is the case of $H \to ZZ \to lljj$ with integrated luminosity of 3×10^5 pb^{-1}.

- P_T cut on jets from W/Z to veto $t\bar{t}$ backgrounds
- forward jet tagging by requiring large jet energy.

Figure 6 shows reconstructed Higgs masses where backgrounds are depicted as shaded areas. The upper plot is the case of $H \to WW \to l\nu jj$ with integrated luminosity of 10^5 pb^{-1} and the lower plot is the case of $H \to ZZ \to lljj$ with integrated luminosity of 3×10^5 pb^{-1}.

4 Summary

As a summary of the discovery potential of the SM Higgs at ATLAS, a naive estimator $S/\sqrt{B}$ where S is the number of signals and B is the number of background events, are plotted with respect to the Higgs mass. Apparently the Gold-Plate event, $H \to ZZ \to 4l$ is the most promising channel, however the other channels are also well above the background with 5σ beyond the backgrounds. Therefore we can expect to be able to observe the SM Higgs by ATLAS detector in 70 GeV $< M_H <$ 1 TeV.

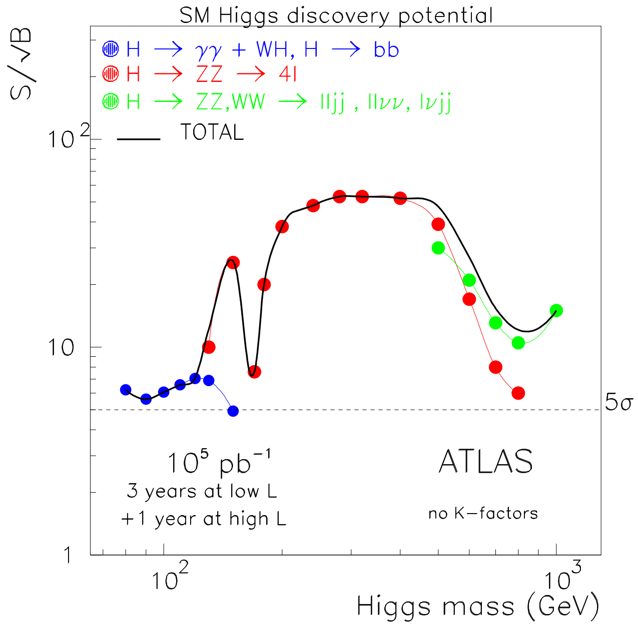

Figure 7: An estimator $S/\sqrt{B}$ where S is the number of signals and B is the number of background events, are plotted with respect to the Higgs mass.

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