Early Higgs search with the ATLAS data

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Abstract. A search for the Higgs boson at the Large Hadron Collider (LHC) running at a center-of-mass energy of 7 TeV is reported, based on an early data collected by the ATLAS detector. For the Standard Model Higgs boson search, several decay channels are used: $H \rightarrow \gamma\gamma$, $H \rightarrow WW^{(*)}$, $H \rightarrow ZZ^{(*)}$, $H \rightarrow WW \rightarrow l\nu qq$, $H \rightarrow ZZ \rightarrow llvv$, $H \rightarrow ZZ \rightarrow llqq$ ($l$ is $e, \mu$). After obtaining the search results for the individual channels, the combined exclusion limits on the Higgs boson production are determined in a mass range from 110 GeV to 600 GeV. A search for the Higgs boson generated by the extended models of the Standard Model is also performed. The exclusion limits for the MSSM $A/H/h \rightarrow \tau\tau$ and the NMSSM $a_1 \rightarrow \mu\mu$ are presented.

1. Introduction
Discovering the mechanism responsible for the electroweak symmetry breaking and the origin of mass for elementary particles is one of the key aims of the Large Hadron Collider (LHC) at CERN [1]. In the Standard Model (SM) this mechanism requires the existence of a scalar particle, the Higgs boson [2, 3, 4, 5, 6]. Prior to the LHC, the best direct information is a lower limit of 114.4 GeV, set using the combined results of the four LEP experiments [7], and an excluded band of 158 GeV to 175 GeV from the combined Tevatron experiments [8, 9]. There are also extended models of the Standard Model providing the mechanism of giving masses to all the particles. In the Minimal SuperSymmetric Standard Model (MSSM) [10, 11], two Higgs doublets of opposite hypercharge are required, resulting in five observable Higgs bosons, where three of the bosons are neutral ($h$, $H$ and $A$) while two are charged ($H^\pm$). In the Next-to MSSM (NMSSM) [12], where the Higgs sector is expanded to generate a total of three CP-even scalars ($h_1$, $h_2$, $h_3$), two CP-odd scalars ($a_1$, $a_2$) and two charged scalars ($H^\pm$), the existence of the light CP-odd Higgs boson $a_1$ is predicted.

In this note, a search for the Higgs boson at the Large Hadron Collider (LHC) is reported, based on early data at the ATLAS experiment. The search for the Standard Model Higgs boson is described in Section 3. In this section, the results for individual Higgs boson decay channels $H \rightarrow \gamma\gamma$, $H \rightarrow WW^{(*)}$, $H \rightarrow ZZ^{(*)}$ are outlined, and the combined result in a mass range from 110 GeV to 600 GeV is also presented. A search for the Higgs boson in the extended model is also performed : MSSM $H \rightarrow \tau\tau$ and NMSSM $a_1 \rightarrow \mu\mu$, and their results are presented in Section 4. The conclusions are given in Section 5, where the prospect for the SM Higgs boson search is also discussed.

1 On behalf of the ATLAS Collaboration
2. Limit extraction procedure
In the statistical interpretation, the profile-likelihood ratio is used as test-statistic. Exclusion limits are obtained using the power-constrained profile likelihood method which is known as the Power Constrained Limit, PCL [13, 14, 15]. This method is preferred to the more familiar CL$_s$ technique [16] because the constraint is more transparently defined and it has reduced overcoverage resulting in a more precise meaning of the quoted confidence level. In some analysis channels, the limits from the CL$_s$ method are also presented for the comparison with the results from other experiments using only CL$_s$.

3. Search for the Standard Model Higgs boson
At the LHC, the Standard Model Higgs boson is produced mainly from the following four production processes: gluon fusion (ggF, $gg \rightarrow H$), vector boson fusion (VBF, $qq' \rightarrow qq'H$), associated production with a vector boson ($q\bar{q}/gg \rightarrow WH/ZH$) and associated production with a top-quark pair ($q\bar{q}/gg \rightarrow t\bar{t}H$). Their cross-sections have been gathered and summarized in Ref. [17]. The Higgs boson decay branching ratios used take into account the higher order QCD and EW corrections in each of Higgs boson decay channels [17, 18]. The cross section in $pp$ collisions at $\sqrt{s} = 7$ TeV and the branching ratio for each final state are shown in figure 1 as a function of the Higgs boson mass.

![Image](image-url)

(a) The production cross section  
(b) The branching ratio

**Figure 1.** The cross section and decay branching ratios for the Standard Model Higgs boson in $pp$ collisions at a 7 TeV center-of-mass energy as a function of mass [17]: In (a), the cross section is shown for each of the main production processes: gluon fusion ($ggF$, $gg \rightarrow H$), vector boson fusion (VBF, $qq' \rightarrow qq'H$), associated production with a vector boson ($q\bar{q}/gg \rightarrow WH/ZH$) and associated production with a top-quark pair ($q\bar{q}/gg \rightarrow t\bar{t}H$). In (b), the branching fraction for each final state is shown.

In this section, the Standard Model Higgs boson is searched by using the six final states: $H \rightarrow \gamma\gamma$, $H \rightarrow WW^{(*)} \rightarrow ll\nu\nu$, $H \rightarrow WW \rightarrow lvqq$, $H \rightarrow ZZ^{(*)} \rightarrow llll$, $H \rightarrow ZZ \rightarrow ll\nu\nu$ and $H \rightarrow ZZ \rightarrow llqq$. The search regions for the Higgs boson mass are summarized in table 1. In the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow ll\nu\nu$ and $H \rightarrow ZZ \rightarrow llqq$, the exclusion limit is extracted from a fit of signal plus background contributions to the observed Higgs boson candidate mass distributions. In all other channels, limits are extracted from a comparison of the numbers of observed events to the numbers of estimated background events.
Table 1. The search region for the Higgs boson mass in each of the analysis channels.

| Mode                  | Mass range (GeV) |
|-----------------------|------------------|
| $H \rightarrow \gamma\gamma$ | 110-140          |
| $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ | 120-200          |
| $H \rightarrow WW \rightarrow l\nu q\bar{q}$ | 220-600          |
| $H \rightarrow ZZ^{(*)} \rightarrow llll$ | 120-600          |
| $H \rightarrow ZZ \rightarrow l\nu l\nu$ | 200-600          |
| $H \rightarrow ZZ \rightarrow llqq$ | 200-600          |

3.1. Search for $H \rightarrow \gamma\gamma$

The search for the Higgs boson using the decay channel $H \rightarrow \gamma\gamma$ is performed using a dataset corresponding to an integrated luminosity of 209 pb$^{-1}$. Events are selected by requiring the presence of at least two identified and isolated photons [19]. The leading photon is required to have $p_T > 40$ GeV while the subleading photon is required to have $p_T > 25$ GeV. The main background processes in this analysis are the irreducible prompt diphoton production ($\gamma\gamma$), the reducible photon-jet process ($\gamma$-jet), the dijet (jet-jet) process with one or more fake photons from jets fragmenting mainly into $\pi^0$ or $\eta$ meson. The abundance of these background contributions is estimated from sideband control samples of the data. The background from Drell-Yan events, where both electrons are misidentified as photons, is estimated using $Z$ decays to electrons where one electron is misreconstructed as a photon.

The di-photon invariant mass distribution after the full event selection is shown in figure 2. The background in the di-photon mass range between 100 and 150 GeV is modelled by fitting an exponential function to the data. The signal peak is modelled by the sum of a Crystal Ball function (for the bulk) and a Gaussian (for the tails) by using the Monte Carlo. The relative uncertainty on the resolution of the signal peak is ±13%, where the dominant contributions come from those on the constant term of the cluster energy resolution (±11%), the photon energy calibration (±6%) and so on. The systematic uncertainty on the signal yield is also considered (±15% in total), which mainly arises from the uncertainty on photon identification and photon isolation efficiencies. The signal search is performed in the Higgs boson mass range of $110 \leq m_H \leq 140$ GeV, and no significant evidence for an excess is found. The extracted limits by using PCL method is shown in figure 3.

3.2. Search for $H \rightarrow WW^{(*)}$

The search using the decay $H \rightarrow WW^{(*)}$, while either one of the $W$ bosons may be off the mass shell ($W^{(*)}$), offers strong sensitivity in the mass range of $m_H \geq 120$ GeV. Two different decay modes of the $W$ bosons are considered: the search for $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu (l = e, \mu)$ is performed in the range between 120 and 200 GeV, and that for $H \rightarrow WW \rightarrow l\nu q\bar{q}$ channel is performed in the range from 220 to 600 GeV.

3.2.1. $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$

The search for $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ is performed by using a dataset corresponding to an integrated luminosity of 35 pb$^{-1}$. Events are selected requiring exactly two isolated leptons with opposite charge, where the leading lepton is needed to have $p_T > 20$ GeV and the subleading lepton is required to have $p_T > 15$ GeV. The large missing transverse energy in the event is also imposed to suppress the backgrounds ($E_T^{miss} > 30$ GeV).

Events are classified into $3 \times 3 = 9$ channels by depending on: (i) the lepton flavours ($ee, e\mu$...
Figure 2. Di-photon invariant mass distribution after applying the full event selection in $H \to \gamma\gamma$ analysis: Distribution for data is presented with black plots. The cumulative predictions of the Drell Yan (red solid), di-jet (blue dotted), photon-jet (blue dashed) and diphoton (blue solid) are also shown. The light yellow band indicates the overall uncertainty on the expected total yield, while the dark yellow one is the uncertainty due to the reducible background contribution.

or $\mu\mu$) : (ii) the number of jets of $p_T > 25$ GeV and $|\eta| < 4.5$ in the event (0/1/2-jet channels). In each channel, kinematic requirements are applied using the azimuthal opening angle between the two leptons ($\Delta \phi_{ll}$), the invariant mass of the two leptons ($m_{ll}$) and the transverse mass ($m_T$), where the transverse mass is defined as [20] :

$$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - (\mathbf{P}_T^{ll} + \mathbf{P}_T^{miss})^2}.$$ 

$E_T^{ll} = \sqrt{\mathbf{P}_T^{ll}^2 + m_{ll}^2}$, $|\mathbf{P}_T^{miss}| = E_T^{miss}$ and $\mathbf{P}_T^{ll}$ is the transverse momentum of the dilepton system. Cut value for each selection is optimized depending on the Higgs boson mass hypothesis in order to increase the sensitivity as much as possible.

The major backgrounds come from $WW$, top quark ($t\bar{t}$ and single top) and $W$+jets events. Their contributions into the signal region are estimated by using dedicated control regions in data, while the expected contributions from other smaller backgrounds are estimated by using the Monte Carlo. The observed and expected $m_T$ distributions for the combined $e\mu$, $ee$ and $\mu\mu$ channels are shown in figure 4, which are obtained after all the selections except for the transverse mass cut. For masses of $120 < m_H < 200$ GeV, no evidence for an excess is observed in any of the analysis channels.

The obtained exclusion limits are shown in figure 5. By using the PCL method, a SM-like Higgs boson with a production rate of 1.2 times the SM value is excluded at 95% C.L. for $m_H = 160$ GeV. In the figure, the Tevatron results are overlaid. As their results were calculated using the CL$_{s}$ method, the ATLAS results with CL$_{s}$ are also shown.

3.2.2. $H \to WW \to l\nu qq$

For the $H \to WW \to l\nu qq$, a dataset corresponding to an integrated luminosity of 35 pb$^{-1}$ is used. Events with exactly one high-$p_T$ lepton ($p_T > 30$ GeV), and large missing transverse
(a) The 0jet channel

Figure 4. Distributions of the transverse mass $m_T$ for the combined $e\mu$, $ee$ and $\mu\mu$ channels for the $H \to WW(\gamma^*) \to l\nu l\nu$ search: (a) the 0-jet channel; (b) the 1-jet channel. The distributions are obtained after all the selections except for the transverse mass cut. The data plots are compared with the background expectation and an added hypothetical signal, where the Higgs boson mass is assumed as $m_H = 170$ GeV. The cut values for the transverse mass are indicated by the vertical dotted lines.

(b) The 1jet channel

Figure 5. The 95% C.L. exclusion limits on the production cross section relative to the Standard Model cross section for the $H \to WW(\gamma^*) \to l\nu l\nu$, for an integrated luminosity of 35 pb$^{-1}$ at $\sqrt{s} = 7$ TeV: The ATLAS limit using the PCL method is compared with the Tevatron limits. Since the Tevatron results were calculated using the CL$_s$ method, the ATLAS results with CL$_s$ are also shown.

energy ($E_T^{\text{miss}} > 30$ GeV) are selected. The number of jets in the event is required to be 2 or 3, and the selected events are separated into two channels depending on the jet multiplicity. The two jets with the invariant mass closest to the mass of the $W$ boson are required to satisfy $71 < m_{jj} < 91$ GeV. The final discriminant is the invariant mass of the Higgs boson candidate, $m_{l\nu jj}$, which is reconstructed with a $W$ boson mass constraint on the lepton-neutrino system, giving rise to a quadratic equation. If there are two solutions, the one with the lower longitudinal momentum is chosen. And if a complex solution is obtained, the real part is used. The major backgrounds come from $W/Z+jets$ and multijet events. Their background levels are determined.
using a fit to the $E_T^{miss}$ distribution, while other small contributions from the top and diboson events are estimated by using the Monte Carlo.

The $m_{\ell\nu jj}$ distributions are shown in figure 6. The background spectrum is modelled with a single exponential function. By using the fit result, the limit extraction is made in a mass range of $200 < m_H < 600$ GeV. The result is shown in figure 7, where the Higgs boson with a production rate of 11.2 times the Standard Model prediction is excluded at 95% C.L. for $m_H = 400$ GeV.

![Figure 6](image_url)

**Figure 6.** Distributions of the invariant mass $m_{\ell\nu jj}$ for the $H \to WW \to l\nu qq$ search after applying all selection criteria. The plots are summed over lepton flavour. In (a), no extra jets are allowed and in (b), one additional jet is required. The data plots are compared with the background expectation and an added hypothetical signal, where the Higgs boson mass is assumed as $m_H = 400$ GeV. The expected signal yield is scaled up by a factor of 30 for illustration purposes.

**3.3. Search for $H \to ZZ^{(*)}$**

For searching $H \to ZZ^{(*)}$, three final states are analyzed: $H \to ZZ^{(*)} \to llll$, $H \to ZZ \to l\nu\nu$ and $H \to ZZ \to l\ell qq$.

**3.3.1. $H \to ZZ^{(*)} \to llll$**

A dataset with an integrated luminosity of 40 pb$^{-1}$ is used for the $H \to ZZ^{(*)} \to llll$ search. Events are required to have two same-flavour and opposite-charge pairs of leptons. All leptons must be well separated and isolated. The cut values for $p_T$ are 7 GeV and 15 GeV for muons and electrons, respectively. And at least two out of the four leptons are required to have $p_T > 20$ GeV. The invariant mass needs to be close to the $Z$ boson mass for at least one lepton pair, while the requirement on the invariant mass of the other lepton pair varies depending on the Higgs boson candidate mass ($m_{llll}$).

The main backgrounds come from the irreducible component $ZZ^{(*)} \to llll$ and from the reducible ones, $Z + jets$ and $t\bar{t}$ events. But after applying all the selection criteria, no candidate events remain in data at any Higgs boson mass, that is consistent with the expectation of very small background level.
Figure 7. The 95% C.L. exclusion limits on the production cross section relative to the Standard Model cross section for the $H \to WW \to l\nu qq$, for an integrated luminosity of 35 pb$^{-1}$ at $\sqrt{s} = 7$ TeV. The exclusion limit on a four-generation Standard Model (SM4) which assumes that the masses of the fourth-generation quarks are infinite [29] is also shown.

3.3.2. $H \to ZZ \to llqq$

Events with exactly two same-flavour leptons are selected, where the invariant mass of the lepton pair must be close to the $Z$ mass ($76 < m_{ll} < 106$ GeV). The missing transverse energy is required to be less than 50 GeV to reduce background from top events. The leading and subleading jets also need to have an invariant mass near the $Z$ mass ($70 < m_{jj} < 105$ GeV). In the case of searching for high mass Higgs boson, further kinematics cuts are applied by using the azimuthal opening angles between the two jets ($\Delta \phi_{jj}$), the two leptons ($\Delta \phi_{ll}$) and so on, where the cut values are optimized depending on the Higgs mass.

The dominant background comes from $Z$+jets, and other backgrounds are $t\bar{t}$, QCD and $ZZ/WZ$ production. The contribution from each of $Z$+jets, $t\bar{t}$ and QCD events is well understood by using the side-band region in data, and that from $ZZ/WZ$ is estimated using the Monte Carlo. The distribution of the Higgs boson candidate mass ($m_{lljj}$) for the events passing the full selection is shown in figure 8.

3.3.3. $H \to ZZ \to l\nu\nu$

Events with exactly two leptons of the same flavour and with large $E_T^{miss}$ are selected. The lepton pair must have an invariant mass near the $Z$ mass, and in order to reject top background, events with jets that have been identified as coming from $b$-quarks are rejected. Kinematic requirements on $\Delta \phi_{ll}$, $\Delta \phi_{l\nu}$ and so on are also applied, where the cut values are optimized depending on the Higgs mass.

The major background comes from $Z$+jets, $t\bar{t}$ and $ZZ/WZ$ and QCD production. As in the $H \to ZZ \to llqq$ analysis, the contribution from each of $Z$+jets, $t\bar{t}$ and QCD events is well understood by using the side-band region of data, and that from $ZZ/WZ$ is estimated using the Monte Carlo. The dilepton transverse mass distribution after applying all selection criteria for $m_H = 400$ GeV is shown in figure 9.

3.3.4. Exclusion limit

The exclusion limits from the $H \to ZZ^{(*)} \to llll$ channel is shown in figure 10, where a SM-like
Figure 8. Distribution of the invariant mass $m_{lljj}$ for the $H \rightarrow ZZ \rightarrow llqq$ search after applying all selection criteria. Data plots are compared with the background expectation (black histogram) and an added hypothetical signal (red filled histogram) where the Higgs boson mass is assumed as 300 GeV. The contribution from each background component is shown with pink ($Z$), blue ($t\bar{t}$) and green (Diboson) histograms. The plots are summed over lepton flavour.

Figure 9. The dilepton transverse mass distribution for the $H \rightarrow ZZ \rightarrow ll\nu\nu$ search after all selection cuts. Data plots are compared with the background expectation (black histogram) and an added hypothetical signal (red filled histogram) where the Higgs boson mass is assumed to be 400 GeV. The contribution from each background component is shown with pink ($Z$), blue ($t\bar{t}$) and green (Diboson) histograms. The plots are summed over lepton flavour.

Figure 10. The 95% C.L. exclusion limits on the production cross section relative to the Standard Model cross section for the $H \rightarrow ZZ \rightarrow llll$, for an integrated luminosity of 40 pb$^{-1}$ at $\sqrt{s} = 7$ TeV.

Figure 11. The 95% C.L. exclusion limits on the production cross section relative to the Standard Model cross section obtained from the combined $H \rightarrow ZZ \rightarrow llqq$ and $ll\nu\nu$ channels for an integrated luminosity of 35 pb$^{-1}$ at $\sqrt{s} = 7$ TeV.

A SM-like Higgs boson with a production rate of 3.5 to 39 times the SM value is excluded at 95% C.L in the mass region of $200 < m_H < 600$ GeV.
3.4. Combined result for the exclusion limits on the Standard Model Higgs boson

The combined exclusion limits on the Standard Model Higgs boson, using the results for $H \rightarrow \gamma\gamma$, $H \rightarrow WW^{(*)}$ and $H \rightarrow ZZ^{(*)}$ channels, are extracted. As for $H \rightarrow \gamma\gamma$ channel, the result for 2010 data (an integrated luminosity of 38 pb$^{-1}$) is used in the combination, while the result for 2011 data (an integrated luminosity of 209 pb$^{-1}$) is shown in Section 3.1. The exclusion limits for the individual channels are shown in figure 12, where the step with which the limit is investigated is 5-10 GeV. The combined limits, obtained using PCL, are shown in figure 13, where the limits with the CL$_{s}$ method are also shown for comparison purposes. Further details of the combination method are well described in Ref. [21].
4. Search for the Higgs boson in the extended models of the Standard Model

The search for the Higgs boson generated by the extended models of the Standard Model is also performed, which is described in this section.

4.1. Search for neutral MSSM Higgs bosons decaying to \(\tau\tau\)

The search for neutral MSSM Higgs bosons in the decay mode \(A/H/h \rightarrow \tau\tau\) is performed. As explained in Section 1, there are five observable Higgs bosons in the MSSM. At the tree level their properties such as masses, widths and branching ratios are described in terms of only two parameters: the mass of the CP-odd Higgs boson (\(m_A\)) and the ratio of the vacuum expectation values of the two Higgs doublets (\(\tan\beta\)). The Higgs boson is produced mainly via gluon fusion (\(gg \rightarrow \phi\)) or in association with \(b\) quarks (\(bb \rightarrow b\phi\)), where \(\phi\) denotes a neutral Higgs boson, and the latter process becomes important especially for large \(\tan\beta\).

The decay into a \(\tau\tau\) pair is a promising channel since the coupling of the Higgs bosons to third-generation fermions is strongly enhanced for a wide region in the MSSM parameter space.

The search is performed by using two different final states: \(A/H/h \rightarrow \tau\tau \rightarrow l\tau\hbar\bar{\nu}\) and \(e\mu4\nu\).

4.1.1. \(A/H/h \rightarrow \tau\tau \rightarrow l\tau\hbar\bar{\nu}\)

Events with one isolated lepton (\(e\) or \(\mu\)) and one \(\tau\) decaying hadronically (\(\tau_{\hbar\bar{\nu}}\)) are selected. Exactly one electron or muon with \(p_T^{\ell} > 20\) GeV or \(p_T^{\mu} > 15\) GeV and one oppositely-charged \(\tau\) candidate with \(p_T^{\tau_{\rm vis}} > 20\) GeV are required in the event. In order to enhance the sensitivity, the large missing transverse energy \((E_T^{\rm miss} > 20\) GeV), and small transverse mass of the \(e/\mu-E_T^{\rm miss}\) system \((m_T < 30\) GeV) are required.

In order to perform the signal search, the normalization and shape of the \(m_{\tau\tau}^{\rm visible}\) distribution need to be determined. The main backgrounds in this analysis come from \(Z \rightarrow \tau\tau\) (irreducible), QCD and \(W +\)jets. The \(m_{\tau\tau}^{\rm visible}\) distribution for the total background is estimated by using events with same-sign charges of the electron/muon and the \(\tau_{\hbar\bar{\nu}}\) candidate, assuming that the distribution shape is the same between opposite-sign (OS) and same-sign (SS) events; an assumption that has been verified with simulated events. When extrapolating from the SS to the OS regions, corrections are needed to compensate for the difference of the number of events between the two regions. Correction factor to be taken is well understood with data for \(W +\)jets and QCD events, while that for \(Z \rightarrow \tau\tau\) is predicted from the Monte Carlo. Figure 14 shows the \(m_{\tau\tau}^{\rm visible}\) distribution for the estimated background compared with data.

4.1.2. \(A/H/h \rightarrow \tau\tau \rightarrow e\mu4\nu\)

Events with one isolated electron and one isolated muon are selected. Exactly one electron with \(p_T^e > 20\) GeV and one muon with \(p_T^\mu > 10\) GeV with opposite charge are needed in the event. To reduce background events, the scalar sum of the transverse momentum of the electron, that of the muon and \(E_T^{\rm miss}\) is required to be smaller than 120 GeV, and the cut on the azimuthal opening angle between the electron and muon is also applied (\(\Delta\phi_{e\mu} > 2.0\) rad.). The effective mass \((m_{\tau\tau}^{\rm effective})\) is used as a final discriminant to search for a potential Higgs boson signal, where \(m_{\tau\tau}^{\rm effective}\) is defined as the invariant mass of the electron, muon and \(E_T^{\rm miss}\) system:

\[
m_{\tau\tau}^{\rm effective} = \sqrt{(p_e + p_\mu + p_{\rm miss})^2}
\]

where \(p_e\) and \(p_\mu\) are the four-vectors of the electron and muon, while the missing energy four-vector is defined by \(p_{\rm miss} = (E_T^{\rm miss}, E_{x}^{\rm miss}, E_{y}^{\rm miss}, 0)\). Major backgrounds come from \(Z \rightarrow \tau\tau\) and QCD events. QCD contribution is estimated from the control data sample, while the contribution of the irreducible component is obtained from the simulation. The effective mass distribution after applying all selection criteria is shown in figure 14, where data and the estimated background are compared.
Figure 14. (left) : Distribution of visible mass $m_{\tau\tau}^{\text{visible}}$ after applying all selection criteria for the $A/H/h \rightarrow \tau\tau \rightarrow l\tau_{\text{had}}3\nu$ search. (right) : Distribution of effective mass $m_{\tau\tau}^{\text{effective}}$ after all selection criteria for the $A/H/h \rightarrow \tau\tau \rightarrow e\mu4\nu$ search. The data plots are compared with the background expectation and an added hypothetical signal.

4.1.3. Exclusion limits

Figure 15 shows the obtained exclusion limits. The cross section limit is evaluated for signal acceptances of two different production processes ($gg \rightarrow \phi$ and $bb \rightarrow bb\phi$). The limits on the Higgs boson production cross-section times branching ratio into a pair of $\tau$ leptons is in the range between approximately 300 pb for a Higgs boson mass of 90 GeV and approximately 10 pb for a mass of 300 GeV. The limit in the $\tan\beta$-$m_A$ plane is obtained by using the $m_h^\text{max}$ scenario and Higgsino mass parameter $\mu > 0$. Limits from previous experiments at LEP [22] and the Tevatron [23] are shown for comparison.

Figure 15. (left) : The 95% C.L. exclusion limits on the production cross section for the MSSM $A/H/h \rightarrow \tau\tau$ search for an integrated luminosity of 36 pb$^{-1}$. For comparison, the Standard Model cross section is also shown. (right) : The 95% C.L. exclusion limits in the $m_A$-$\tan\beta$ plane. The limits from LEP and Tevatron are also overlaid. For a direct comparison with the Tevatron limit, the observed limit based on CL$_s$ is shown in addition to the one based on CL$_{s+b}$. 
4.2. Search for a light CP-odd Higgs boson decaying to $\mu\mu$

The next-to-minimal SSM (NMSSM) solves the $\mu$-term problem by introducing a complex singlet scalar field $S$. This generates the $\mu$-term as the vacuum expectation value of $S$ through spontaneous symmetry breaking, allowing it naturally to reach the electroweak scale without the fine-tuning required in the MSSM [12]. As a result of introducing a new scalar field, the Higgs sector of the NMSSM expands to a total of three CP-even scalars ($h_1$, $h_2$, $h_3$), two CP-odd scalars ($a_1$, $a_2$) and two charged scalars ($H^\pm$). If the mass of CP-odd Higgs boson $a_1$ is around 10 GeV, the NMSSM can account for the anomalous muon magnetic moment [24], and it also explains the discrepancy in the ratio of $\Upsilon$ widths $\Gamma(\Upsilon \to \tau\tau)/\Gamma(\Upsilon \to \mu\mu)$ between the value measured by the BaBar experiment and the value expected in the SM [25, 26, 27, 28].

Based on these facts, a direct search for the $a_1$ boson, produced via gluon fusion ($gg \to a_1$) and decaying to muon pair ($a_1 \to \mu\mu$) is performed in the mass regions 6-9 GeV and 11-12 GeV. Dimuon masses around the $\Upsilon$ resonances (9-11 GeV) are not included because uncertainties in the expected rate of $\Upsilon$ production make it difficult to distinguish an additional resonance in this mass range. Event selection for this search is quite simple. Events with two muons having opposite charge are selected. Each event is required to pass a trigger requiring two muons with $p_T > 4$ GeV. As for muon identification, likelihood ratio-based selection is performed. The mass spectrum of the selected dimuon candidates is shown in figure 16. The signal search is performed by fitting the mass spectrum in the region of 6-12 GeV. The continuum background spectrum is modeled by using sidebands, while the spectrum shapes for signal and $\Upsilon(1/2/3s)$ are modeled by double-gaussian. No evidence for an excess is observed, and the obtained exclusion limits on the Higgs boson production are shown in figure 17.

5. Conclusions

A search for the Higgs boson at the Large Hadron Collider (LHC) running at a center-of-mass energy of 7 TeV is reported, based on early data collected by the ATLAS detector. For the Standard Model (SM) Higgs boson, the decay channels of $H \to \gamma\gamma$, $H \to WW^{(*)}$ and $H \to ZZ^{(*)}$ are analyzed, where the search for $H \to \gamma\gamma$ is performed by using a dataset with an integrated luminosity of 209 pb$^{-1}$, while $H \to WW^{(*)}$ and $H \to ZZ^{(*)}$ are searched by using
Figure 18. The luminosity required to give exclusion, evidence or discovery sensitivity for the Standard Model Higgs boson with data at $\sqrt{s} = 7$ or $8$ TeV, where the sensitivity is expected based on the simulation.

35-40 pb$^{-1}$. From the $H \to \gamma \gamma$ channel, the observed exclusion limits at 95% C.L. between 4.2 and 15.8 times the SM cross section are achieved in the Higgs boson mass range between 110 GeV and 140 GeV. With the $H \to WW^{(*)} \to l\nu l\nu$ channel, the Higgs boson in the mass range of $120 \leq m_H \leq 200$ GeV is searched, where the obtained limit of 1.2 times SM prediction is obtained at $m_H = 160$ GeV, coming closer to Tevatron limit and also the SM cross section. By using $H \to WW \to l\nu qq$, $H \to ZZ \to llll, ll\nu\nu$ and $llqq$, Higgs boson in the high mass region ($200 \leq m_H \leq 600$ GeV) is also searched, where the observed limits on the production rate over the SM prediction are 11.2 at $m_H = 400$ GeV ($H \to WW \to l\nu qq$), 24.0 at $m_H = 200$ GeV ($H \to ZZ \to llll$) and 3.5 at $m_H = 200$ GeV ($H \to ZZ \to ll\nu\nu/llqq$). A search for the Higgs boson in the extended models of the Standard Model is also performed. Neutral MSSM Higgs bosons are searched in the channel $A/H/h \to \tau^+\tau^-$, where the obtained exclusion limit supersedes the ones from previous experiments. By using the $a_1 \to \mu\mu$ channel, a light CP-odd Higgs boson generated by the next-to MSSM (NMSSM) model is searched, where the useful exclusion limits are obtained in the mass range of 6-9 GeV and 11-12 GeV.

The prospects for the Standard Model Higgs boson search at $\sqrt{s} = 7$ TeV are finally considered in figure 18, where the projected sensitivity as a function of the Higgs boson mass is calculated based on the simulation. For the exclusion, it is predicted that the ATLAS result reaches the LEP limit with 4fb$^{-1}$. For the discovery of the signal events, 3σ observation and 5σ discovery are expected in a mass range of $m_H > 120$ GeV and $m_H > 135$ GeV with 10fb$^{-1}$, respectively.

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