Search of the Higgs boson decaying into tau-leptons at ATLAS

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The search for the Higgs boson is one of the main goals of the Large Hadron Collider experiments. Both in the Standard Model (SM) and in its minimal supersymmetric extensions (MSSM), one or several new bosons are expected as manifestations of the Higgs field. The tau lepton will be essential for Higgs(es) discovery. In fact, both in SM and in the MSSM, the Higgs boson(s) decaying into tau-pairs is one of the favourite discovery channels, especially at low masses. The discovery potential of the ATLAS experiment for neutral Higgs bosons decaying into tau-pairs is shown both in the SM and the MSSM. For the latter, the results on the charged Higgs boson decaying into tau lepton plus neutrino are also discussed.

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1. STANDARD MODEL HIGGS

1.1. Experimental limits

The Higgs boson mass cannot be theoretically predicted. The most tight limits come from the LEP experiments. The four LEP Collaborations (ALEPH, DELPHI, L3 and OPAL) have collected a total of 2461 pb^{-1} of integrated luminosity in e^+e^- collisions at centre of mass energies between 189 and 209 GeV. The results of the four collaborations have been combined in a likelihood ratio analysis [1] to provide the final result. The conclusion of the LEP analysis provides an experimental lower bound for the Higgs boson obtained by direct search: a Higgs boson with $m_H < 114.4$ GeV has been excluded at 95% C.L..

Within the SM, the mass of the Higgs boson can be constrained indirectly since it enters in the calculation of higher order corrections of SM parameters. The LEP Electroweak Working group has performed a global fit to a large number of measurements sensitive to SM parameters [2]. Using recent results from TeVatron top mass, the preferred value for the Higgs boson mass is $m_H = 84^{+34}_{-26}$ GeV, with an upper limit at 154 GeV at the 95% C.L.. This limit increases to 185 GeV when including LEP-2 direct search limit of 114 GeV [3]. Thus, although internal consistency conditions of the SM allow a theoretical upper bound $m_H < 1$ TeV [4], the experimental data prefer a light Higgs boson.

1.2. Vector Boson Fusion H$\rightarrow \tau\tau$

Although the largest cross section for the Higgs boson at a pp collider with $\sqrt{s} = 14$ TeV is that of the $gg \rightarrow H$ production over the whole mass range, it is often convenient to consider associated production channels. The associated production with two light quarks via Vector Boson Fusion (VBF production) is the next to leading process for the Higgs boson production, with a cross section of 5-3 pb for a Higgs boson in the mass range 105-170 GeV. The peculiar final state [5] with two jets with large transverse momentum in the forward and backward region of the detector (coming from the fragmentation of the two quarks after the vector boson radiation) provides a distinctive signature that can be efficiently used to disentangle the signal from the background.
For a low mass Higgs boson, the most important decay channel is $H \rightarrow b\bar{b}$. Because of the huge QCD background ($\sigma_{b\bar{b}} \simeq$ 100 μb), the most important contribution for the Higgs boson discovery in this mass region comes from the $H \rightarrow \tau\tau$ decay [6], which is the second favourite Higgs boson decay channel. The missing transverse energy (E_T^{miss}) due to the neutrinos from the tau lepton decays provides a further handle to extract the signal from the background.
In the VBF associated production, all the three possible decay modes of the tau-pair have been

studied: lepton-lepton, lepton-hadron, hadron-hadron [7]. Cross-sections calculated to next to leading order (NLO) have been used for the signal and for the backgrounds. A full GEANT-based detector simulation has been used and current trigger and reconstruction algorithms have been applied.

For the ll- and lh-channels single lepton triggers (electron or muon trigger) have been employed, while for the hh-channel tau triggers in association with E_T^{miss} triggers have been used. The analysis cuts exploit the peculiar topology of the VBF process: two high p_T jets are required in the opposite hemispheres of the detector, with a large separation in pseudorapidity and large invariant mass. A reduced hadronic activity between them is expected because of the lack of colour exchange between quarks in the initial state. This characteristic is used by applying a veto to jets in the central region ($|\eta|$ <3.2). A cut on the reconstructed E_T^{miss} is also applied and the selection criteria for electron, muon and hadronic tau identifications are chosen to optimize the efficiency and the fake rate. Very good detector performances in the reconstruction of the jets in the forward region, in the identification of the hadronic tau lepton, in the measurement of the E_T^{miss} are essential to extract the signal and to have a good tau-pair invariant mass resolution. In fact, although there are several neutrinos in the event, it is possible to reconstruct the $\tau^+\tau^-$ invariant mass by making the approximation that the decay products of the τ are collinear with the τ in the laboratory frame [8]. Other quantities, calculated from E_T^{miss}, leptons and jet momenta, have been used in the selection to discriminate signal from background [7] for the three decay channels. To calculate the final significance, signal and background events in a mass window around the nominal Higgs boson mass value are considered.

The most important irreducible backgrounds to these channels come from the QCD $Z+jets$ production and electroweak (ELWK) $Z+jets$ production via vector boson fusion, with Z decaying into a tau-pair. Sources of reducible background as $t\bar{t}$, $W+jets$, $WW/ZZ/WZ+jets$, $Z(\rightarrow ll)+jets$, where l represents electron and muon, have also been considered. The results in terms of signal efficiency and background rejection are similar for the three channels. For the hh-channel, however, only a rough evaluation of the background coming from the QCD multijets has been given: having a cross section of several mb, a reliable estimate of this background, and therefore of the sensitivity for this channel, can only be done once data are available.

Figure 1 shows the expected signal significance for 30 fb^{-1} of collected data at different mass points for the ll-channel (dotted red line), lh-channels (dashed blue line), and combining the two (solid black line). These results do not include the effects of pileup (i.e. other soft $p-p$ collisions in the same bunch crossing or in neighboring bunch crossings). A significance of about 5-σ can be obtained for 115 GeV< m_H <125 GeV.

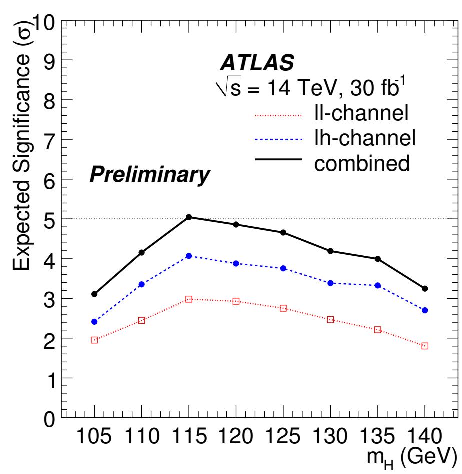

Figure 1. Expected signal significance for different Higgs boson masses. The results do not include the impact of pileup.

2. MSSM HIGGS

In order to provide the spontaneous symmetry breaking in a supersymmetric model two scalar complex doublets have to be introduced, leading to 8 more degrees of freedom, i.e., 5 new bosons: two CP-even (usually named h, H), one CP-odd (A) and two charged (H^+, H^-) particles [4].

To evaluate the potential for the Higgs boson discovery in the MSSM sector with the ATLAS detector, a constrained model of the MSSM with seven free parameters has been considered. The parameters are: M_{SUSY} (the energy scale for the soft SUSY–breaking parameters in the sfermion sector), M_2 (the $SU(2)$ gaugino mass parameter at the electroweak scale), μ (the supersymmetric Higgs boson mass parameter), A_t (the trilinear Higgs–squark coupling parameter), the gluino mass $m_{\tilde{g}}$, $\tan\beta$ (the ratio between the vacuum expectation values of the two Higgs doublets) and M_A (the mass of the CP-odd Higgs). Each choice of the values of five parameters among the seven provides a different scenario [9].

At the tree level the model depends only on two parameters (usually chosen to be M_A and $\tan\beta$). Moreover, it provides some predictions on the masses of the Higgs bosons: $M_h < M_Z, M_A < M_H$ for the neutral bosons, $M_W < M_{H^\pm}$ for the charged ones. The radiative corrections (which depend mainly on the mixing in the stop sector, the top and stop quark masses and the SUSY mass scale M_{SUSY}) modify the tree level predictions allowing (for example) a h mass up to 135 GeV [10] in the $m_h - max$ scenario where $M_{SUSY} = 1$ TeV, $m_{\tilde{g}} = 800$ GeV, $M_2 = 200$ GeV, $\mu = 200$ GeV and $X_t := A_t - \mu\cot\beta = 2$ TeV.

The couplings to SM fermions and bosons are also modified at the tree level by factors that depend on β. In particular, at high values of $\tan\beta$, the couplings to down–type fermions are enhanced with respect to the SM, leading to enhanced branching ratios into $b\bar{b}$ for A and H, as well as to enriched $b\bar{b}A$ and $b\bar{b}H$ associated productions.

Direct searches at LEP have given lower bounds of 92.9 GeV and 93.4 GeV on the masses of the lightest CP-even Higgs boson h and the CP-odd Higgs boson A within the $m_h - max$ scenario [11]. At the Tevatron, no excess of events has been observed looking to the tau-pair and b-pair production, using an integrated luminosity of 1.8 fb^{-1} [12][13]. For the charged Higgs bosons, direct searches have been carried out at LEP, yielding a lower bound of 78.6 GeV on $m_{H^\pm}$ [14]. At the Tevatron, the CDF and D0 experiments have performed direct and indirect searches. These searches have excluded the small and large $\tan\beta$ regions for $H^\pm$ masses up to about 160 GeV [15].

2.1. h/A/H→ $\tau\tau$

At the LHC the two main production mechanisms for the neutral Higgs bosons are the gluon fusion $gg \rightarrow h/H/A$ and the associated production $gg \rightarrow h/H/A\ b\bar{b}$ [7]. The first dominates for low and moderate $\tan\beta$ values, the latter for large $\tan\beta$ due to enhanced bottom couplings.

If the supersymmetric partner particles are not accessible, the main decay channels of the neutral Higgs bosons are $b\bar{b}$ and $\tau\tau$. The $b\bar{b}$ decay channel is difficult to exploit without an additional distinguishing signature. The most promising channel over a wide mass range is $h/H/A \rightarrow \tau\tau$. All final states (lepton-lepton, lepton-hadron, hadron-hadron) have been investigated in ATLAS.

For the ll-channel, a new analysis has been performed using the full simulation of the detector and the most recent generators. The $b\bar{b}$ associated production has been considered.
This channel relies on single lepton triggers [7]. The basic backgrounds are $t\bar{t}$, $W + jets$, $Z + jets$, $b\bar{b}Z$. To extract the signal, the selection requires less than three jets in the event, with at least one b-jet; an upper p_T bound is required for the leading b-jet; the invariant mass of the two leptons is required to be below the Z mass; cuts on the tau lepton visible energy fraction and on the angle between the two leptons are applied in order to reconstruct the di-tau invariant mass using the collinear approximation procedure. Bounds are also set for the p_T of the leading lepton and of the di-lepton system. Neutrinos in the final state allow also to cut on E_T^{miss}. Events in the mass window around the nominal Higgs boson mass are used to calculate the final signal significance.

For low m_A, the dominant background is due to $Z \rightarrow \tau\tau + jets$, while for high values of m_A the most significant background contribution comes from $t\bar{t}$.

This study shows that the dominant systematic uncertainties are due to the jet energy scale and resolution, and to the b-tagging efficiency.

Figure 2 shows the five sigma discovery contour as a function of m_A and $\tan\beta$ for an integrated luminosity of 30 fb^{-1}. The solid line takes into account the experimental systematic uncertainties; the dotted line includes an additional systematic uncertainty on the cross-section of the $t\bar{t}$ background. In both cases the bands indicate the systematic uncertainty on the signal cross section.

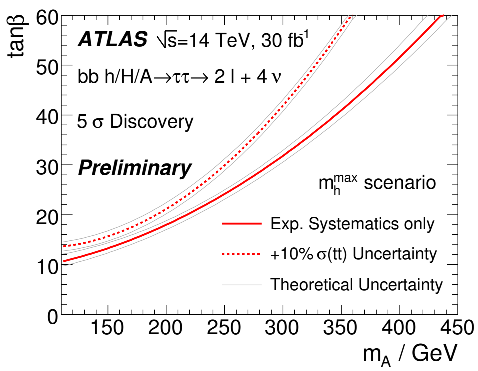

Figure 2. 5-σ discovery contour for ll-channel of $b\bar{b}\ h/H/A \rightarrow \tau\tau$ as a function of m_A and $\tan\beta$ for an integrated luminosity of 30 fb^{-1}.

For the lh and hh-channels, studies with full simulation are still ongoing. Analyses performed with the fast simulation of the ATLAS detector, ATLFAST [16], using cross-sections for signal and background calculated to leading order (LO), show that a wide mass range can be covered in the Maximal Mixing scenario of MSSM [17][18].

The hh-channel has been studied in the mass range between 450 GeV and 800 GeV. Multijet and tau or jet plus E_T^{miss} triggers can be used to select signal events. Events with less than five jets are selected in this case, with one b-jet, two tau lepton candidates and no lepton. The other cuts are similar to those ones of the ll-channel. In this case the additional background from QCD jets

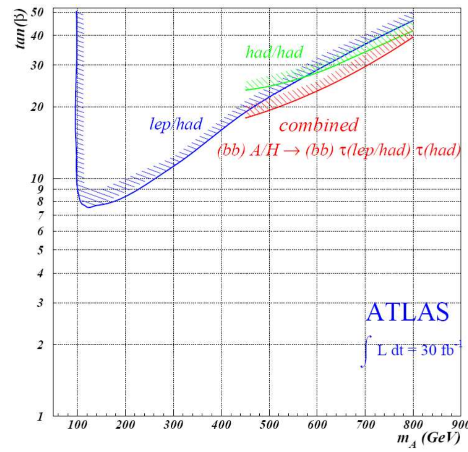

Figure 3. 5-σ discovery contour for the ll and lh-channels of $b\bar{b}$ H/A$\rightarrow \tau\tau$ as a function of m_A and $\tan\beta$ for an integrated luminosity of 30 fb^{-1}. Results have been obtained with ATLAS fast simulation.

has been considered. A signal significance above 5-σ is achieved in the region of $\tan\beta > 25$ with 30 fb^{-1} of data. The most important sources of systematic uncertainty for this channel come from the tau-tagging and the b-tagging efficiencies.

The lh-channel relies on single lepton triggers. For this decay channel also the direct production mechanism has been considered to improve the signal significance at low masses. The studied mass range is from 150 GeV to 800 GeV. Two uncorrelated analyses are performed requiring zero or at least one b-jet, rispectively. The results are then combined to calculate the final significance.

Figure 3 shows the five sigma discovery contour for the lh and hh-channels as a function of m_A and $\tan\beta$ for an integrated luminosity of 30 fb^{-1}.

2.2. $\mathbf{H^\pm \rightarrow \tau^\pm\nu}$

The search strategies for charged Higgs bosons depend on their hypothesized mass, which dictates both the production rate and the available decay modes. Below the top quark mass, the main production mode is through top quark decays, $t \rightarrow H^+b$, and in this range the $H^+ \rightarrow$

$\tau\nu$ decay mode is dominant[1]. Above the top quark threshold, the production mainly takes place through $gb \to tH^+$ and $gg \to btH^+$, and the decay into a top quark and a b quark dominates, $H^+ \to tb$. The second dominant decay is again $H^+ \to \tau\nu$.

Several final states have been studied with the full simulation of the ATLAS detector to assess the potential for discovering a charged Higgs boson. In the following two of them are discussed, $t\bar{t} \to bH^+bW \to b\tau_{had}\nu bqq$ in case of a light Higgs boson and $gg/gb \to t[b]H^+ \to bqq[b]\tau_{had}\nu$ for the heavy one [7]. For both these fully hadronic channels, tau trigger in combination with E_T^{miss} or tau plus jets plus E_T^{miss} triggers are used.

The analysis of the first channel requires exactly one tau-jet, two b-jets, at least two light jets and no isolated lepton. A cut on the E_T^{miss} is also applied to reduce QCD events. After this selection the W is reconstructed from the pair of light jets with invariant mass m_{jj} closest to the nominal W mass. The parent top quark is then found by pairing the reconstructed W with the b quark which leads to mass m_{jjb} closest to the nominal value of the top mass. The top quark decaying into H^+b cannot be fully reconstructed due to the presence of the neutrino from the H^+ decay.

The W + $jets$, single top, QCD jets backgrounds have been found to be negligible. The main background remaining after the previous selection is $t\bar{t}$, in particular those events in which one W decays hadronically and the other to a tau lepton and a neutrino. To discriminate between this background and the signal a likelihood discriminant is built that exploits the heavier mass of the H^+ with respect to the W mass. After a cut on the likelihood, the transverse mass of H^+ is calculated for the retained events. A final cut is then applied to this reconstructed transverse mass of the H^+ candidate. The cut values have been selected to optimize the significance considering both systematic and statistical uncertainties.

Figure 4 shows the discovery contour in the $(\tan\beta,\ m_{H^+})$ plane for an integrated luminosity of 1, 10 and 30 fb^{-1}. It can be seen that additional integrated luminosity does not give any further H^+ sensitivity after a few fb^{-1} have been recorded. The reason is the statistical error from the small $t\bar{t}$ Monte Carlo sample which is equivalent to about 1 fb^{-1} and makes extrapolation to higher luminosities difficult.

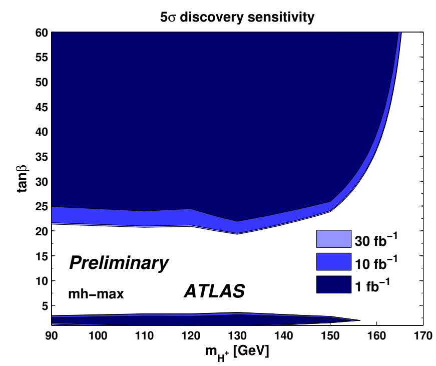

Figure 4. Discovery contour in the $m_h - max$ scenario for $t\bar{t} \to bH^+bW \to b\tau_{had}\nu bqq$. Systematic and statistical uncertainties are included. The systematic uncertainty is assumed to be 10% for the background, and 24% for the signal. The lines indicate a 5σ significance for the discovery.

The selection for the heavy charged Higgs boson is very similar. Exactly one tau jet with high quality cuts is required, with at least three jets with exactly one b-jet among them. Also for this channel $t\bar{t}$ events are the main background and a likelihood approach is chosen to reduce it. The charged Higgs boson transverse mass of the remaining events is used as the final discriminating observable to extract the significance of the H^+ signal. The resulting discovery contours are presented in Figure 5. In 30 fb^{-1} the region at large $\tan\beta$ and $m_{H^+} < 350$ GeV can be experimentally covered.

[1]In the following, the charged Higgs boson will be denoted H^+, but H^- is always implicitly included.

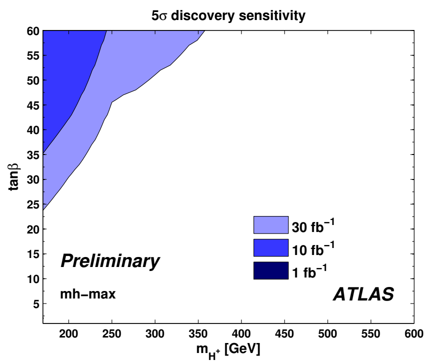

Figure 5. Discovery contour in the $m_h - max$ scenario for $gg/gb \rightarrow t[b]H^+ \rightarrow bqq[b]\tau_{had}\nu$. Systematic and statistical uncertainties are included. The systematic uncertainty is assumed to be 10% for the background, and 44% for the signal. The lines indicate a 5σ significance for the discovery.

3. CONCLUSIONS

The tau lepton decay mode is fundamental for many searches for Higgs bosons both in the Standard Model and in the Minimal Supersymmetric Standard Model at LHC.

The ATLAS collaboration has developed algorithms that allow to trigger and to reconstruct efficiently also the hadronic final state of the tau lepton, keeping a very good rejection against the ordinary jets. This allows to exploit all the possible final states of the tau lepton for the Higgs searches.

Standard Model $H \rightarrow \tau\tau$ produced via Vector Boson Fusion has been studied with detailed detector simulation and the latest theoretical developments in the three possible final states lepton-lepton, lepton-hadron, hadron-hadron: with an integrated luminosity of 30 fb^{-1} Higgs can be discovered with a 5-σ significance in the mass interval 115 – 125 GeV.

Also the MSSM Higgs bosons, neutral and charged, can be discovered with the ATLAS detector in a significant fraction of $m_A - \tan\beta$ parameter space already with 10 fb^{-1}, exploiting all the tau lepton final states.

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