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Higgs Boson Searches with ATLAS based on 2010 Data

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The results of Higgs Boson searches with the ATLAS detector based on 2010 proton proton collision data corresponding to integrated luminosities of up to 39 pb^{-1} are presented. Searches for $H \to \gamma\gamma$, $H \to WW \to \ell^+\nu\ell^-\bar{\nu}$ and $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}/\ell^+\ell^- q\bar{q}$ in the context of the Standard Model (SM), for $H \to \tau\tau$ in the context of the Minimal Supersymmetric Extension of the Standard Model (MSSM) and for a generic scalar at low mass in the vicinity of the Υ resonance decaying to a pair of muons are discussed. All observations are in agreement with the expectations from the background-only hypothesis. Hence exclusion limits at 95% confidence level are derived.

1 Introduction

Unraveling the mechanism responsible for electroweak symmetry breaking and the generation of elementary particle masses is one of the great scientific quests of high energy physics today. The Standard Model (SM) and its supersymmetric extensions address this question by the Higgs-Englert-Brout-Gurnalik-Hagen-Kibble mechanism. The first manifestation of this mechanism is represented by the existence of at least one Higgs boson. This motivates the large experimental effort for the Higgs boson search in the past, presence and future. During the year 2010 the Large Hadron Collider (LHC) delivered proton proton collisions at a center of mass energy of 7 TeV corresponding to an integrated luminosity of 48 pb^{-1} to the ATLAS experiment [1]. These data have been used to search for Higgs bosons in the SM and its supersymmetric extensions in a variety of final states. For the signal rates, their central values and the estimation of the associated systematic uncertainties, which arise from variations in the renormalization and factorization scales, the choice of the value of the strong coupling constant and the choice of the parton distribution functions of the proton, the recommendations from the LHC Higgs cross-section working group have been used [2]. As no hints for the production of Higgs bosons are observed in data, exclusion limits at the 95% confidence level are derived. In order to do so the profile likelihood method [3] is used as the test statistic, which allows systematic errors to be incorporated in the signal and background predictions as nuisance parameters. As the main result power constrained exclusion limits [4] to the signal+background hypothesis are derived (PCL_{S+B}). The power constraint requires that the confidence level for the background-only hypothesis is at least 16% ($CL_B > 0.16$). Hence, if the observed CL_{S+B} is smaller than the expected median CL_{S+B} minus one standard deviation, the observed limit quoted is replaced by $CL_{S+B}^{expected} - 1\sigma$. For comparisons with other experiments the exclusion limits obtained from $CL_S = CL_{S+B}/CL_B$ [5] are also given in [6,7,8,9,10], in which also details of the individual analyses discussed below can be found.

2 Searches for the Higgs Boson of the SM

2.1 $H \to \gamma\gamma$ with 38 pb^{-1}

In the mass range from 100 GeV to 140 GeV the decay of the SM Higgs boson into two photons provides a very good sensitivity to observe Higgs boson production. The signal topology is characterized by two isolated photons with large transverse momentum ($p_{\mathrm{T}}^{1(2)} > 40(25)$ GeV). The reducible background arises from photon plus jet(s) and multijet production. These backgrounds are suppressed by the excellent capabilities of the ATLAS detector to discriminate photons from jets. The irreducible background stems from di-photon production which can be separated from the signal by excellent reconstruction of the invariant mass of the di-photon system. The contributions from the different background classes have been estimated from data using an iterative double sideband method by comparing event yields of loosely and tightly identified photon candidates which are isolated or non-isolated. The events yields extracted via this method are in good agreement with the prediction from simulations (see Fig. 1 (left)). The invariant di-photon mass spectrum after all selection cuts applied is shown in Fig. 1 (middle). No significant resonance structure is observed. The background is parametrized via an exponential shape with two nuisance parameters (normalization and slope) and no use is made of the MC prediction. The signal shape is described by the sum of a Crystal Ball function [11] plus a Gaussian with a full width at half maximum of 4.4 GeV. The uncertainties on the signal yield are dominated by the uncertainty on the inclusive signal cross-section (20%) and the one on the photon identification and isolation (10% each). The width of the hypothetical signal is known to a level of 13% from the energy scale and resolution uncertainties for photons. The expected limits are at the level of 20 times the SM predicted rate (Fig. 1 (right)), and the observed exclusion limits lie in the range between 8 and 38 times the SM cross-section in the mass range between 110 and 140 GeV.

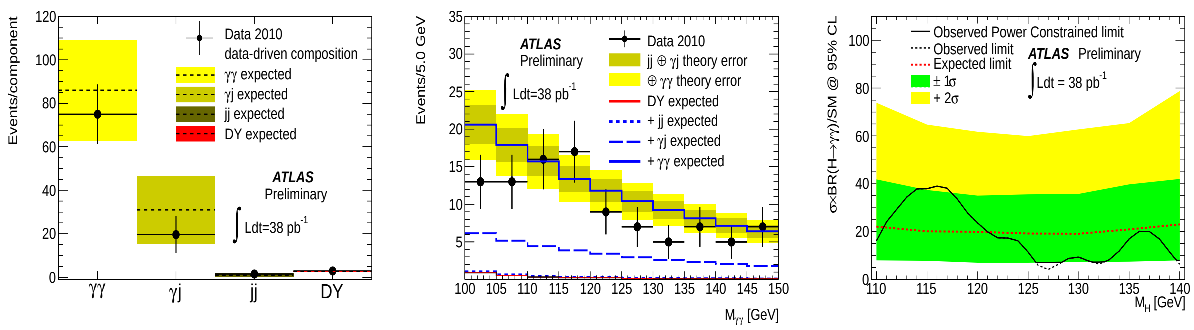

Figure 1: $H \to \gamma\gamma$: comparison of background prediction from simulation with the results from the data-driven technique (left), observed invariant di-photon mass spectrum with the one predicted from simulation (middle), and excluded signal cross-section with respect to the SM prediction (right).

2.2 $H \to WW \to \ell^+\nu\ell^-\bar{\nu}$ with 35 pb^{-1}

The decay of Higgs bosons into a pair of W bosons yields the highest sensitivity for an early discovery of a Higgs boson at the LHC especially in the mass range around 170 GeV. The decay of each W boson to an electron or muon and the corresponding neutrino, which is produced in gluon fusion or weak vector boson fusion, is considered. The preselection exploits the basic signature of two leptons, which due to spin correlations are close in phase space, and significant transverse missing energy (MET) arising from the two undetected neutrinos. In order to maximize the sensitivity the analysis is split into a zero, one and two jet selection, where different additional topological cuts are applied in each branch. The uncertainty on the fraction of signal events in each jet topology is determined by varying renormalization, factorization scales, parton density functions, and strong coupling constant in a NNLO+NNLL calculation for Higgs production in gluon fusion. Finally a cut on the transverse mass M_{T} derived from from the lepton momenta and the MET is applied, which depends on the Higgs boson mass hypothesis ($0.75{\cdot}M_H < M_{\mathrm{T}} < M_H$). The distribution of the transverse mass after all cuts for the zero and one jet analyses is shown in Fig. 2 (left and middle). The individual background contributions are derived from signal-free control regions in data, which are defined by inverting and omitting selection criteria or applying additional requirements to enhance a specific contribution. The extrapolation factors from control regions to signal regions as well from one control region to another control region are derived from MC simulated event samples. The extrapolation factors are subject to a variety of systematic uncertainties: experimental ones from lepton and MET energy scale and resolution uncertainties and theoretical ones from variation of QCD scales etc. (details can be found in [7]). As no deviatons from the background only hypothesis are observed, exclusion limits on the Higgs boson production cross-section are derived (see Fig. 2 (right)). Higgs boson production for a mass of 160 GeV with a rate larger than 1.2 times the SM rate can already be excluded.

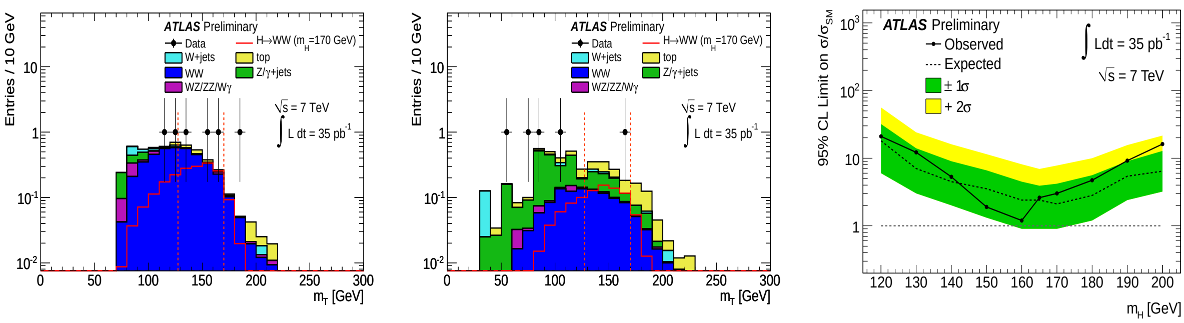

Figure 2: $H \to W^+W^-$: observed transverse mass spectrum compared to the background prediction for zero and one jet analyses (left and middle), and excluded signal cross-section with respect to the SM prediction (right).

2.3 $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}/\ell^+\ell^-q\bar{q}$ with 35 pb^{-1}

Higgs boson decays into $ZZ \to \ell^-\ell^+q\bar{q}$ and $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ in the mass range between 200 and 600 GeV have been searched for. The signal is characterised by one pair of same flavour, oppositely charged leptons with invariant mass consistent with the Z boson and either a pair of jets whose invariant mass is also consistent with the Z boson mass or large MET due to the two neutrinos in the final state. Additional kinematical cuts are applied to suppress the backgrounds. The shape and normalisation of the expected backgrounds have been confirmed by comparing MC simulated event samples with the observed event yield in data e.g. in sideband regions of $M_{\ell^+\ell^-}$ and $M_{q\bar{q}}$ and other control regions. No deviation from the SM expectation without a Higgs boson are observed in the final mass distributions (shown in Fig. 3 (left) and (middle)) and hence exclusion limits with repect to the SM production rate are set. Those are in the range of 3.5 to 39 times the SM prediction and are currently the most stringent exclusion limits for Higgs boson mass hypotheses beyond 300 GeV.

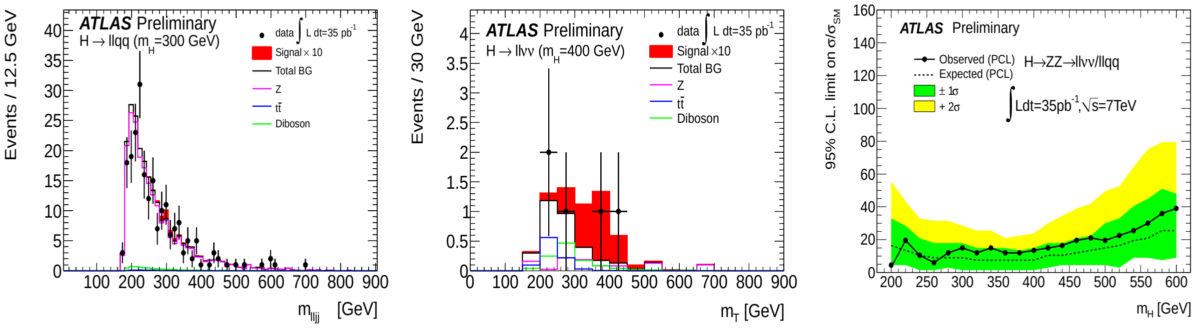

Figure 3: $H \to ZZ$: observed mass spectrum compared to the background prediction for the $\ell\ell qq$ final state (left), observed transverse mass spectrum compared to the background prediction for the $\ell\ell\nu\nu qq$ final state (middle), and excluded signal cross-section with respect to the SM prediction (right).

3 Search for $H \to \tau\tau$ in the MSSM with 36 pb^{-1}

The most promising channel for the observation of Higgs bosons in the context of the MSSM is the decay into a pair of tau leptons. Production in gluon fusion and in association with b-quarks have been considered. One tau lepton is assumed to decay hadronically, the other one leptonically. The inclusive selection exploits the signal characteristics by requiring one electron and muon, an oppositely charged hadronically decaying tau candidate and significant MET and applies an upper cut on the transverse mass of the lepton and MET system in order to suppress background from W boson production. The final discriminant is the invariant mass of the visible tau decay products. The prediction of the mass shape for the irreducible $Z \to \tau\tau$ background in MC simulated events has been confirmed in data, by selecting $Z \to \mu\mu$ collision events and replacing the muons by tau lepton decays from simulation with the same kinematic properties (see Fig. 4 (left)). The backgrounds with fake tau candidates dominated by $W + jet$ production has been estimated mostly from data by using the observed mass shape of signal free events with same charge sign of electron or muon and tau candidate and determining the ratio of same sign to opposite sign events for $W + jet$ and multijet production in control regions in data. The normalization of $Z \to \tau\tau$ background and the normalization and shape of other small backgrounds are obtained from MC simulated event samples. The dominant systematic uncertainties on shape and normalization of the $\tau\tau$ event yield from Z and H boson production arise from the uncertainty in the tau lepton energy scale and the jet energy scale its influence on the MET scale and to a lesser extent in the tau lepton identification efficiency. The final visible mass distribution (see Fig. 4 (middle)) with data-driven background predictions compared to the data shows no hint for Higgs boson production. Hence parameter regions in the M_A-vs.-$\tan\beta$ plane of the MHMAX benchmark scenario ($\mu > 0$) of the MSSM [12] can be excluded (see Fig. 4 (right)). At $M_A = 130$ GeV $\tan\beta$ values above 22 can be excluded. These findings extend those published previously by the LEP and Tevatron experiments [13,14].

4 Searches for $\phi \to \mu^+\mu^-$ at low mass with 39 pb^{-1}

In extensions of the MSSM either via additional singlets as in the NMSSM (see e.g. [15]) or via allowing for complex parameters in the MSSM, yielding additional sources of CP-violation, the existence of a low mass Higgs boson in the vicinity and below the masses of the Υ resonances is not completely excluded. A search for a generic scalar ϕ in the mass range from 6 to 9 and

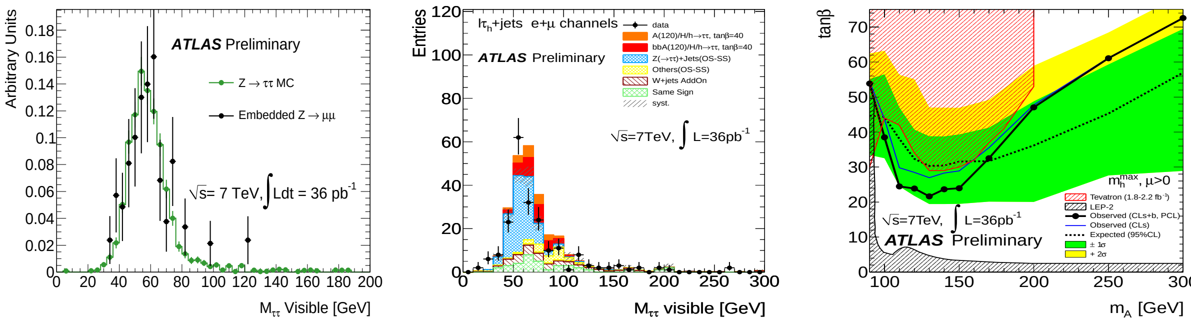

Figure 4: $H \to \tau\tau$: comparison of the visible mass shape of embedded $Z \to \mu\mu$ collision events with simulated $Z \to \tau\tau$ events (left), comparison of the visible mass distribution of event selected in data with the prediction for all background processes and a hypothetical signal (middle), and excluded parameter space in the MHMAX benchmark scenario of the MSSM (right).

11.0 to 12.5 decaying to a pair of muons produced in gluon fusion has been performed. After selecting events with two muons with a transverse momentum exceeding 4 GeV a likelihood ratio selection is applied. The probability density functions of the input variables for the signal and background hypothesis are derived from data itself by selecting events outside the search region: i.e. 9 to 11 GeV for the signal hypothesis, which has been confirmed to be kinematically identical to Υ production, and for the background hypothesis from events with $M_{\mu\mu}$ below 6 and above 11.5 GeV. The final mass distribution after applying a cut on the likehood ratio is shown in Fig. 5 (left). The uncertainty on the expected signal yield is estimated to be 70% for a signal mass of 6 GeV and 28% for a signal mass of 11 GeV, which is dominated by the uncertainty on the kinematical acceptance. The continuum background is parametrised by a forth order polynomial, where all parameters are nuisance parameters. The signal and the Υ resonances are modelled by a double Gaussian probability density function, where the masses are fixed to the hypothetical signal mass and the world averages for Υ masses, respectively. The width and fraction of the two Gaussians for the $\Upsilon(1S)$ resonance are nuisance parameters. For the other Υ resonances and the signal resonance the widths and fractions are obtained using a linear dependence of the mass resolution on the resonance mass. All normalisations are left floating in the fits. The cross-section times branching ratio limit is shown in Fig 5 (right). Production rates down to 200 pb can be excluded.

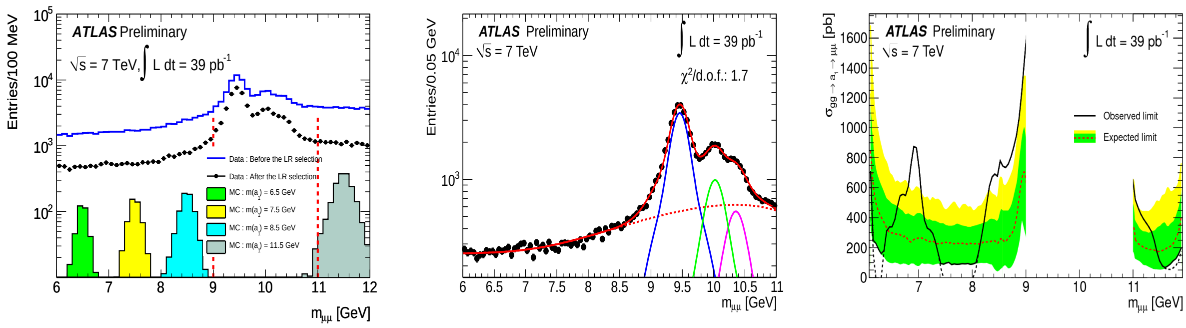

Figure 5: $\phi \to \mu\mu$: observed invariant di-muon mass spectrum (left), result of the background-only hypothesis fit to the invariant di-muon mass spectrum (middle), and cross-section times braching ratio limit(right).

5 Conclusions

LHC and ATLAS performed very well during their operation in 2010. However searches in a data sample corresponding to an integrated luminosity of up to 39 pb^{-1} have not revealed any hint for Higgs boson production at LHC yet. So far mostly simple cut based selections have been performed and the major backgrounds in most analyses have been estimated or at least being confirmed using data-driven methods. In the search for $H \to \gamma\gamma$ a sensitivity of 20 times the SM Higgs boson production rate has been achieved. The $H \to WW$ search allows to exclude already a production rate of 1.2 times the SM rate at a mass of 160 GeV. The search for $H \to ZZ$ decays yield the world's best limits for a Higgs boson mass above 300 GeV up to now. The sensitivity of the search for neutral Higgs bosons of the MSSM via decays to a pair of tau leptons already supercedes the findings obtained at the Tevatron. Collecting a data set corresponding to 4 fb^{-1} at LHC at a center of mass energy of 7 TeV will allow to exclude Higgs boson mass hypotheses in the SM down to the LEP limit of 114.4 GeV [16] assuming that no deviation from the background-only hypothesis is observed [17]. Higgs boson hunters in all experiments hope that a different scenario is realised in nature.

References

1. G. Aad *et al.* [ATLAS Collaboration], JINST **3** (2008) S08003.
2. LHC Higgs Cross-Section Working Group (S. Dittmaier *et al.*), *Handbook of LHC Higgs Cross-Sections: 1. Inclusive Observables*, CERN-2011-002, arXiv:1101.0593.
3. G. Cowan, K. Cranmer, E. Gross, O. Vitells, Eur. Phys. J. **C 71** (2011) 1554.
4. G. Cowan, K. Cranmer, E. Gross, O. Vitells, *Power-Constrained Limits*, arXiv:1105.3166.
5. A. L. Read, J. Phys. **G 28** (2002) 2693-2704; A. L. Read, CERN-OPEN-2000-205.
6. ATLAS Collaboration, *Search for the Higgs boson in the diphoton final state in 38 pb^{-1} of data recorded with the ATLAS detector at $\sqrt{s}$=7 TeV*, ATLAS-CONF-2011-025.
7. ATLAS Collaboration, *Higgs Boson Searches using the $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ Decay Mode with the ATLAS Detector at 7 TeV*, ATLAS-CONF-2011-005.
8. ATLAS Collaboration, *Search for a Standard Model Higgs Boson in the Mass Range 200-600 GeV in the Channels $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ and $H \to ZZ \to \ell^+\ell^-q\bar{q}$ with the ATLAS Detector*, ATLAS-CONF-2011-026.
9. ATLAS Collaboration, *Search for neutral MSSM Higgs bosons decaying to $\tau^+\tau^-$ pairs in proton-proton collisions at $\sqrt{s}$ =7 TeV with the ATLAS Experiment*, ATLAS-CONF-2011-024.
10. ATLAS Collaboration, *Search for NMSSM light CP-odd Higgs a1 with $\mu^+\mu^-$ final states with pp collisions at $\sqrt{s}$ =7 TeV in ATLAS*, ATLAS-CONF-2011-020.
11. M. J. Oreglia, *A Study of the Reactions $\Psi' \to \gamma\gamma\Psi$*, Ph.D. Thesis, SLAC-R-236 (1980).
12. M. S. Carena, S. Heinemeyer, C. E. M. Wagner, G. Weiglein, Eur. Phys. J. **C 26** (2003) 601.
13. S. Schael *et al.* [ALEPH, DELPHI, L3 and OPAL Collaborations and LEP Working Group for Higgs Boson Searches], Eur. Phys. J. **C 47** (2006) 547-587.
14. D. Benjamin *et al.* [Tevatron New Phenomena & Higgs Working Group, CDF and D0 Collaborations], *Combined CDF and D0 upper limits on MSSM Higgs boson production in tau-tau final states with up to 2.2 fb-1*, arXiv:1003.3363.
15. M. Maniatis, Int. J. Mod. Phys. **A25** (2010) 3505-3602.
16. R. Barate *et al.*[ALEPH and DELPHI and L3 and OPAL Collaborations and LEP Working Group for Higgs boson searches], Phys. Lett. **B565** (2003) 61-75.
17. ATLAS Collaboration, *Further investigations of ATLAS Sensitivity to Higgs Boson Production in different assumed LHC scenarios*, ATL-PHYS-PUB-2011-001.