PROCEEDINGS OF SCIENCE

Search for the Standard Model Higgs boson through the $H \to ZZ$ decay channels with the ATLAS detector

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The search for the Standard Model Higgs boson via its decays into two Z bosons is presented, based on the $1.04-1.21\,\mathrm{fb}^{-1}$ of ATLAS data collected in the first half of 2011. The results obtained in the fully leptonic "golden" decay channel cover a wide range of Higgs boson mass hypotheses, between 110 and 600 GeV. For Higgs boson masses above 200 GeV, the sensitivity is substantially enhanced by using channels in which one of the Z bosons decays into neutrinos or quarks. With the current integrated luminosity, the mass range of 340 GeV to 450 GeV is excluded at the 95% confidence level by the neutrino channel alone, while for the other two channels the cross section upper limit is approaching the Standard Model Higgs boson cross section expectation.

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1. Introduction

The search for the Standard Model (SM) Higgs boson [1 – 3] is a major aspect of the Large Hadron Collider (LHC) physics programme. Direct searches at the CERN LEP e^+e^- collider led to a lower limit on the Higgs boson mass, m_H, of 114.4 GeV at 95% confidence level (CL) [4]. The searches at the Fermilab Tevatron $p\bar{p}$ collider have excluded the region 156 GeV $< m_H <$ 177 GeV at 95% CL [5]. Results from the 2010 LHC run extended the search in the region 200 GeV $< m_H <$ 600 GeV by excluding at 95% CL a Higgs boson with cross section larger than 5 – 20 times the SM prediction [6, 7].

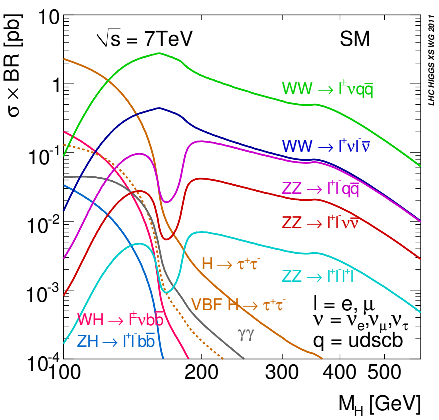


Figure 1: Standard Model Higgs boson production cross section times branching ratio [8].

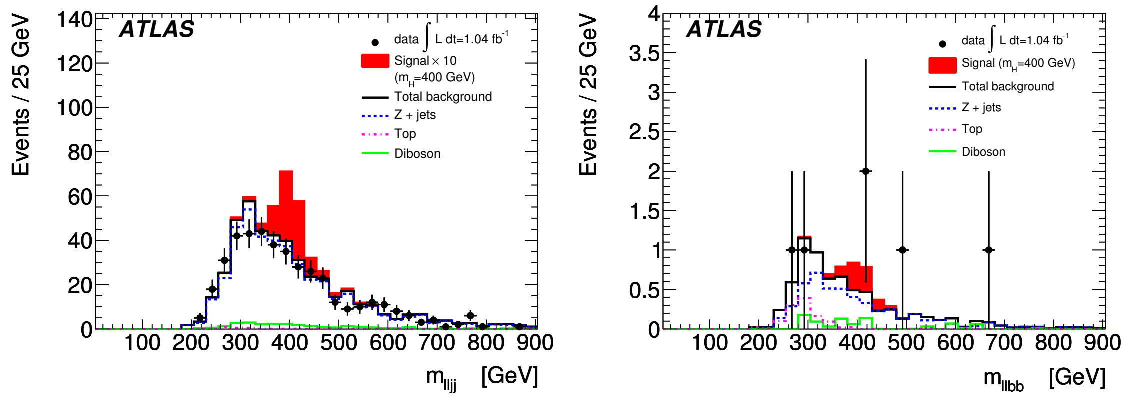
The production cross sections of the SM Higgs boson have been estimated up to next-to-next-leading orders for all the major production mechanisms in pp collisions at centre-of-mass energy ($\sqrt{s}$) of 7 TeV [8]. The gluon fusion mechanism dominates the Higgs production at LHC, followed by the vector-boson fusion mechanism. The associated Higgs boson production with a vector-boson, contributes for $m_H <$ 300 GeV. The decay channels of the Higgs boson vary as a function of its mass. For $m_H <$ 130 GeV the Higgs boson decays preferentially to a pair of b-quarks, while for higher masses the decays to a pair of vector-bosons dominate. In Fig. 1 the production cross section times branching ratio for several Higgs boson decay channels are presented. The $H \to ZZ$ decays have a sizeable contribution, especially in the high mass region. Furthermore, the presence of at least one on-shell Z boson in the final state leads to better signal-to-background ratio with respect to other Higgs boson decay channels.

In the following, the search for the SM Higgs boson are presented in three different decay channels of $H \to ZZ$; $\ell\ell qq$ (section 2), $\ell\ell\nu\nu$ (section 3) and $\ell\ell\ell\ell$ (section 4) using $1.04 - 1.21\,\text{fb}^{-1}$ of data at $\sqrt{s} = 7\,\text{TeV}$. The 95% CL upper limits on the Higgs boson production cross section are extracted with the CL_s technique [10] using the profile likelihood ratio [11] as the test statistic.

2. $H \to ZZ \to \ell^+\ell^-q\bar{q}$

The search for $H \to ZZ \to \ell^+\ell^-q\bar{q}$ [9] is performed in the Higgs boson mass range between 200 and 600 GeV using $1.04\,\text{fb}^{-1}$ of data. The event selection requires exactly one pair of same-flavour leptons ($\ell = e,\mu$) and a pair of jets. The leptons are required to have a transverse momentum, p_{T}, greater than 20 GeV and a pseudorapidity, η, satisfying $|\eta| < 2.5$ (2.47 for electrons), while for the jets $p_T > 15$ GeV and $|\eta| < 2.5$ are required. The invariant mass of the lepton pair must lie within the range 76 GeV $< m_{\ell\ell} <$ 106 GeV, while the invariant mass of the dijet within the range 70 GeV $< m_{jj} <$ 105 GeV. The magnitude of the missing transverse momentum (MET) is required to be less than 50 GeV, to suppress top production. The analysis is divided into a "tagged" subchannel, containing events with two b-tags, and an "untagged" subchannel, containing events with less than two b-tags. Events with more than two b-tags are rejected. This event selection defines the "low-m_H" selection.

For larger Higgs boson masses, the kinematic characteristics of the boosted Z boson is useful to further suppress the backgrounds. The jet p_T threshold is increased to 45 GeV and additional requirements on the azimuthal separation of the decay products of the Z bosons are applied: $\Delta\phi_{\ell\ell} < \pi/2$ and $\Delta\phi_{jj} < \pi/2$. This "high-m_H" selection is applied for $m_H \geq 300$ GeV. The final discriminant variable is the invariant mass of the $lljj$ system, where the dijet mass is constrained to the nominal Z boson mass, m_Z.



(a) (b)

Figure 2: The invariant mass of the $lljj$ system for both the untagged (a) and tagged (b) channels, for the high-m_H selection. The expected Higgs boson signal for $m_H = 400$ GeV is also shown; in the untagged plot, the signal has been scaled up by a factor of 10 to improve visibility.

The dominant background is the Z+jets production, which is normalized from data using the side-band of the m_{jj} distribution. The corresponding systematic uncertainty is less than 10% and 20% for the untagged and tagged samples, respectively. The top background normalisation is taken from the simulation with a 9% theory uncertainty, and it is validated in the control region defined by the $m_{\ell\ell}$ sidebands. The diboson production - ZZ, WW and WZ - is estimated directly from the simulation, with an 11% theory normalization uncertainty. Contribution from QCD multi-jet production, where leptons are faked by high-p_{T} jets, is shown to be small using a template fit method in the dielectron channel, and a two dimensional sideband method in the $m_{\ell\ell}$-lepton isolation plane in the dimuon channel.

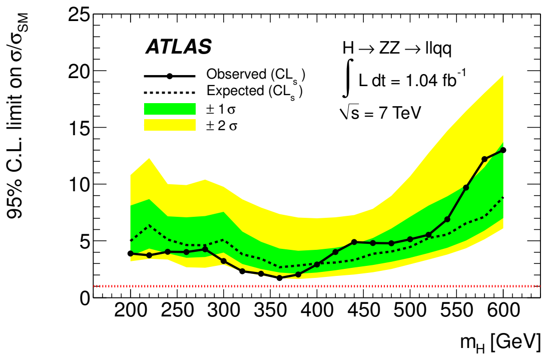


Figure 3: The expected (dashed) and observed (solid line) 95% CL upper limits on the Higgs boson production cross section as a function of the Higgs boson mass, divided by the expected SM Higgs boson cross section. The green and yellow bands indicate the expected sensitivity with $\pm1\sigma$ and $\pm2\sigma$ fluctuations in the absence of signal, respectively. The horizontal line indicates the SM value of unity.

The invariant mass of the events surviving the "high-m_H" selection is shown in Fig. 2(a) and (b) for the untagged and tagged selections, respectively. The obtained 95% CL upper limits are shown in Fig. 3, expressed as a ratio to the SM expectation. In the range between 200 and 600 GeV the expected exclusion limit varies from 2.7 to 9 times the SM cross section. For a Higgs boson with a mass of 360 GeV, where the sensitivity is maximal, the observed and expected cross section upper limits are 1.7 and 2.7 times the SM prediction, respectively.

3. $H \to ZZ \to \ell\ell\nu\nu$

The search for $H \to ZZ \to \ell\ell\nu\nu$ [12] is performed for Higgs boson masses between 200 and 600 GeV using 1.04 fb^{-1} of data at $\sqrt{s} = 7$ TeV. The event selection requires exactly one same-flavour and opposite-sign pair of isolated high-p_{T} leptons with an invariant mass within 15 GeV from m_Z, as shown in Fig. 4(a). Events with additional leptons are discarded. Since the kinematics of the leptons and the MET depend on m_H, the search is separated in a "low-m_H", $m_H < 280$ GeV, and a "high-m_H" selection. The leptons of the Z boson must fullfill requirement on their azimuthal separation: $1 < \Delta\phi_{\ell\ell} < 2.64$ for "low-m_H" and $\Delta\phi_{\ell\ell} < 2.25$ for "high-m_H". Subsequently, a large reconstructed MET, larger than 66 GeV and 82 GeV for the "low-m_H" and "high-m_H" respectively, is required as shown in Fig. 4(b). To suppress contributions from Z+heavy flavour and top backgrounds events are discarded if they contain a b-jet, while to reject events with misreconstructed MET a requirement is used on the azimuthal separation of the direction of the missing momentum and the direction of the most energetic jet in the event: $\Delta\phi_{MET,jet} > 0.3$. For the "high-$m_H$" selection the direction of the missing transverse momentum is required to be "back-to-back" with respect to the momentum of the dilepton in the transverse plane: $\Delta\phi(MET, Z) > 1$. The final discriminant variable is the transverse mass

$$m_{\mathrm{T}}^2 \equiv \left[\sqrt{m_{\mathrm{Z}}^2 + |\vec{p}_{\mathrm{T}}^{\,\ell\ell}|^2} + \sqrt{m_{\mathrm{Z}}^2 + |\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}|^2}\right]^2 - \left[\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}\right]^2,$$

where $\vec{p}_{\mathrm{T}}^{\,\ell\ell}$ denotes the transverse momentum vector of the dilepton and $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ denotes the vector of the missing momentum which is assumed to arise from the decay of a Z boson.

The major background in this search, the SM diboson production: ZZ, WW and WZ, is normalized from simulation assigning a theory systematic uncertainty of 11%. The background from inclusive Z boson production is derived from simulation, after checking that the simulation describes the data well in samples samples selected by requiring the presence of a lepton pair. The top production is taken from simulation, but is verified using data in two independent control samples: in the first at least one b-tag is required, while in the second the dilepton is required to be an electron-muon pair. A 9% systematic uncertainty is assigned to the top normalization, estimated from the data-driven measurement. The W+jets contribution is extracted from the data using same-sign lepton pairs. Contribution from QCD multi-jet production is shown to be small, following strategies similar to that of the $\ell\ell qq$ search.

The transverse mass of the events surviving all the "high-mass" analysis selection criteria are shown in Fig. 5(a). The obtained 95% CL upper limits are shown in Fig. 5(b), expressed as a ratio to the SM expectation. The most sensitive point of this search is at $m_H = 380$ GeV where the expected upper limit is 1.1 times the SM Higgs boson cross section. A SM Higgs boson in the range 340 GeV $< m_H <$ 450 GeV is excluded at the 95% CL.

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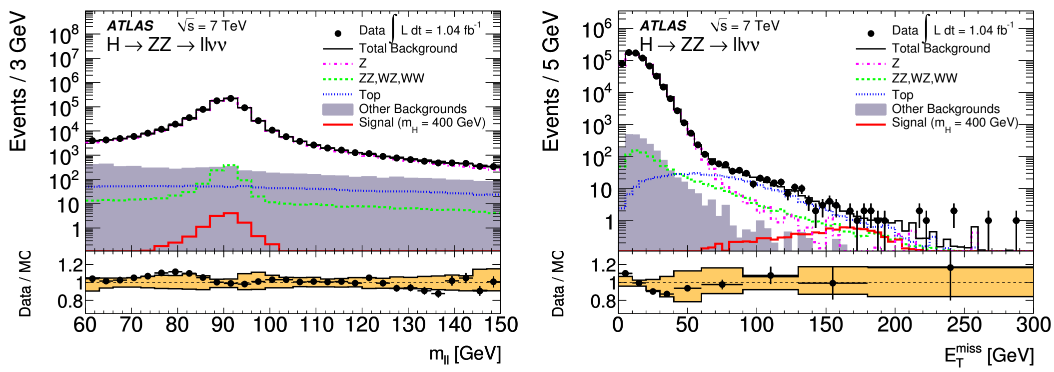
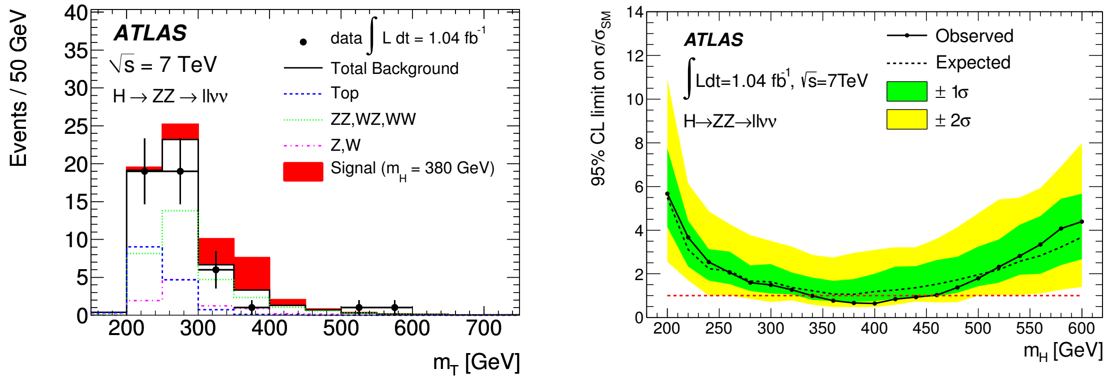


(a) (b)

Figure 4: (a) The dilepton invariant mass distribution for events with exactly two oppositely charged electrons or muons. (b) The $E_{\rm T}^{\rm miss}$ distribution for events with exactly two oppositely charged electrons or muons inside the Z mass window. The insets at the bottom of the figures show the ratio between the data and the combined background expectations as well as a band corresponding to the combined systematic uncertainties of the analysis.



(a) (b)

Figure 5: (a) The transverse mass distribution of $H \to ZZ \to \ell\ell\nu\nu$ candidates in the "high-mass" search for the data (dots), the expected backgrounds (histograms) and a Higgs boson of mass 380 GeV (filled histogram). The electron and muon channels are combined. (b) Observed and expected 95% confidence level upper limits on the Higgs boson production cross section divided by the SM prediction. For the interpretation of the lines and bands see caption of Fig. 3.

4. $H \to ZZ \to \ell\ell\ell\ell$

The search for $H \to ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$, where $\ell, \ell' = e, \mu$ [13] is performed in the mass range from 110 to 600 GeV. Three distinct final states, $\mu\mu\mu\mu$ (4μ), $ee\mu\mu$ ($2e2\mu$), and $eeee$ ($4e$), are selected. The integrated luminosity used in this search is 1.21 fb^{-1}, 1.07 fb^{-1} and 1.07 fb^{-1} for the 4μ, $2e2\mu$ and $4e$ final states, respectively.

Higgs boson candidates are searched by selecting two same-flavour, opposite-sign isolated lepton pairs in an event. Each lepton must satisfy $p_{\rm T} > 7$ GeV and be measured in the pseudorapidity range $|\eta| < 2.47$ for electrons and $|\eta| < 2.5$ for muons. The electron $p_{\rm T}$ threshold is increased to

15 GeV in the transition region between the barrel and end-cap calorimeters ($1.37 < |\eta| < 1.52$). At least two leptons must have $p_{\rm T} > 20$ GeV. The leptons are required to be well separated from each other with $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} > 0.1$. The invariant mass of the lepton pair closest to m_Z is denoted by m_{12} and it is required that $|m_Z - m_{12}| < 15$ GeV. The invariant mass of the remaining lepton pair, m_{34}, is required to be lower than 115 GeV and greater than a threshold depending on the reconstructed four lepton mass, $m_{4\ell}$. For $m_{4\ell} < 190$ GeV, a requirement on the ratio of the transverse impact parameter to its uncertainty of the two lowest $p_{\rm T}$ leptons is added. The final discriminating variable is $m_{4\ell}$, where the Higgs boson production would appear as a clustering of events.

The dominant $ZZ^{(*)}$ background is estimated using simulation, and a 15% systematic uncertainty is applied. The $t\bar{t}$ background is also estimated using simulation. Comparison of data to MC predictions, in a control sample of events with opposite sign electron-muon pairs consistent with the Z boson mass and with one or two additional charged leptons, are used to verify that the $t\bar{t}$ background is small with respect to the dominant $ZZ^{(*)}$ process and in agreement with expectation. The $Z+$jets background is normalized using data. The control sample is formed by selecting events with a pair of same-flavour, opposite-sign isolated leptons consistent with the Z boson mass, $|m_Z - m_{12}| < 15$ GeV, and a second same-flavour, opposite-sign lepton pair where only kinematic, but no isolation or impact parameter, requirements are applied. At this stage, the dominant background source depends on the flavour of the second lepton pair: Z+light flavour jets dominates in the final states with a second electron pair, while $Zb\bar{b}$ production dominates in the final states with a second muon pair after the contributions from $t\bar{t}$, $ZZ^{(*)}$, and muons from in-flight π and K decays which correspond to 44% of the event yield are subtracted. The observed background, which is found to be in good agreement with expectation, is extrapolated to the signal region by means of the MC simulation.

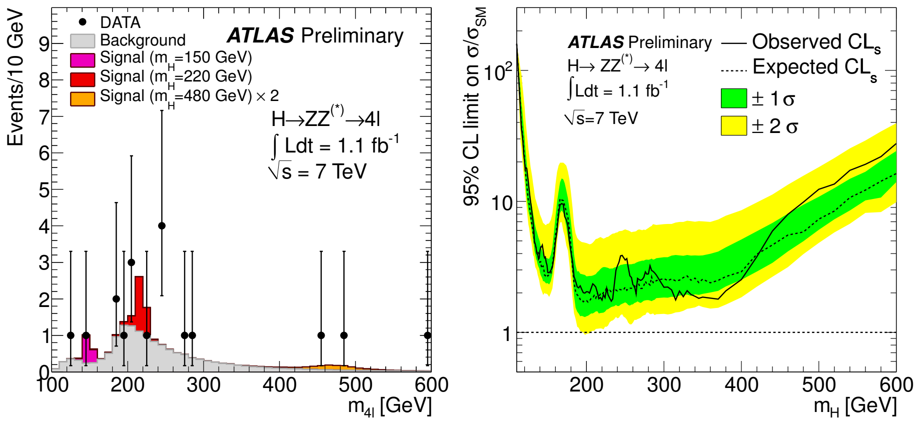
In Fig. 6(a) the $m_{4\ell}$ distribution for the selected event is presented along with the expected background and the expected signal for several m_H hypotheses, while Fig. 6(b) shows the expected and observed exclusions as a function of m_H. The consistency with the background-only hypothesis is quantified using the p-value, the probability that a background-only experiment will fluctuate more than a given observation. The most significant deviation from the background-only hypothesis is observed at $m_H = 246$ GeV with a p-value of 3%.

5. Summary

With more than 1 fb^{-1} available for physics analysis, the $H \to ZZ$ searches are well under way in ATLAS dominating the sensitivity for $m_H \geq 200$ GeV and contributing substantially - through the $H \to ZZ \to 4\ell$ channel - in the low mass region. The searches are already sensitive to Standard Model Higgs boson production cross sections, and in particular the $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ channel already excludes at the 95% confidence level the Higgs boson mass hypotheses 340 GeV $< m_H <$ 450 GeV.

References

[1] F. Englert and R. Brout, “Broken Symmetry and the Mass of Gauge Vector Mesons,” Phys. Rev. Lett. **13** (1964) 321.



(a) (b)

Figure 6: (a) $m_{4\ell}$ distribution of the selected candidates, compared to the background expectation. Error bars represent 68.3% central confidence intervals.The signal expectation for three m_H hypotheses is also shown. (b) Observed and expected 95% confidence level upper limits on the Higgs boson production cross section divided by the SM prediction. For the interpretation of the lines and bands see caption of Fig. 3.

[2] P. W. Higgs, “Broken symmetries, massless particles and gauge fields,” Phys. Lett. **12**, 132 (1964).

[3] G. S. Guralnik, C. R. Hagen and T. W. B. Kibble, “Global Conservation Laws and Massless Particles,” Phys. Rev. Lett. **13**, 585 (1964).

[4] LEP Working Group for Higgs boson searches, “Search for the standard model Higgs boson at LEP,” Phys. Lett. B **565**, 61 (2003) [arXiv:hep-ex/0306033].

[5] CDF and D0 Collaborations, “Combined CDF and D0 Upper Limits on Standard Model Higgs Boson Production with up to 8.6 fb^{-1} of Data,” arXiv:1107.5518 [hep-ex].

[6] ATLAS Collaboration, “Limits on the production of the Standard Model Higgs Boson in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector,” Eur. Phys. J. C **71** (2011) 1728 [arXiv:1106.2748 [hep-ex]].

[7] CMS Collaboration, “Measurement of W^+W^- Production and Search for the Higgs Boson in pp Collisions at $\sqrt{s} = 7$ TeV,” Phys. Lett. B **699**, 25 (2011) [arXiv:1102.5429 [hep-ex]].

[8] LHC Higgs Cross Section Working Group, S. Dittmaier, C. Mariotti, G. Passarino, and R. Tanaka (Eds.), *Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables*, CERN-2011-002 (CERN, Geneva, 2011), `arXiv:1101.0593 [hep-ph]`.

[9] ATLAS Collaboration, *Search for a heavy Standard Model Higgs boson in the channel $H \to ZZ \to \ell\ell qq$ using the ATLAS detector*, `arXiv:1108.5064 [hep-ex]`.

[10] A. L. Read, “Presentation of search results: The CL(s) technique,” J. Phys. G **28** (2002) 2693.

[11] G. Cowan, K. Cranmer, E. Gross and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics,” Eur. Phys. J. C **71**, 1554 (2011) [arXiv:1007.1727 [physics.data-an]].

[12] ATLAS Collaboration, *Search for a Standard Model Higgs boson in the $H \to ZZ \to \ell\ell\nu\nu$ decay channel with the ATLAS detector*, `arXiv:1109.3357 [hep-ex]`.

[13] ATLAS Collaboration, *Search for the Standard Model Higgs boson in the decay channel $H \to ZZ \to \ell\ell\ell\ell$ with the ATLAS detector*, ATLAS-CONF-2011-13.