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Measuring the Higgs Boson Mass Using Event-By-Event Uncertainties

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Summary

This thesis presents the results of my research on the measurement of the Higgs boson mass and signal strength in the four leptons decay channel. The measurement is based on the data collected by the ATLAS detector during the first run of the Large Hadron Collider (LHC) operations, in 2011 and 2012.

The production of a Higgs boson is a very rare process. To generate such a particle, the LHC was designed to collide protons at the unprecedented center of mass energy of 14 TeV. The dataset analyzed in this thesis was collected at a center of mass energy of 7 TeV (18%) and 8 TeV (82%). A these energies a Higgs boson is produced roughly once every $2 \cdot 10^{11}$ collisions.

The Higgs boson is a neutral and extremely short-lived particle. The only possibility to reveal it is to reconstruct the invariant mass of its decay products. Since the Higgs boson couples to all massive Standard Model[1] particles there is a large variety of decay modes. The choice of the decay mode to analyze is driven by the probability of the decay to happen (the so-called branching ratio) and the amount of background expected for that particular final state. The Higgs boson decay analyzed in this thesis is the one into four leptons[2]

$$H \to ZZ^* \to \ell^+\ell^-\ell'^+\ell'^- \quad \text{with} \quad \ell, \ell' = e, \mu.$$

In this process the Higgs particle decays into two neutral weak bosons (one of them can be virtual) and each of them subsequently decays into a pair of opposite charge and same flavor leptons: e^+e^- or $\mu^+\mu^-$. This decay has a probability to occur of only $\sim 10^{-4}$ but the Standard Model processes generating the same final state also extremely rare. As a consequence with an appropriate selection of the events it is possible to achieve a signal to background ratio larger than one.

Since there are no strongly-interacting particles (hadrons) involved in the decay, the four final state leptons can be easily distinguished from the large amount of objects produced by the LHC proton-proton collision. These are mostly hadrons originated by the fragmentation of the proton components. Because of the difficulty to separate an hadronic signal from the background associated to every collision, the decays of the Z boson into a $\tau^+\tau^-$ pair have not been considered in this analysis. The τ lepton, in fact, decays 75% of the times into strongly-interacting particles.

The electrons and muons produced in the Higgs boson decay are reconstructed by the ATLAS detector. The ATLAS detector is one of the four particle detectors placed at the four interaction points of the LHC beams. To maximize the acceptance ATLAS has a nearly hermetic cylindrical shape surrounding the LHC beam pipe. It is divided into three main sub-detectors placed at increasing distances from the interaction point: the inner detector (or tracker), the electromagnetic and the hadronic calorimeter and

[1] The Standard Model is the theoretical model currently used to describe the interactions among elementary particles.

[2] A lepton is a particle interacting only through the electromagnetic and the weak force.

the muon spectrometer. The reconstruction of electrons and muons exploits the informations provided by all sub-detectors. ATLAS is equipped with two different type of magnets. The first one is a solenoidal magnet in which the inner detector is placed. The momentum of electrons and muons is measured in the inner detector from the bending of the reconstructed trajectory induced on the transverse plane by the solenoidal magnetic field. This measurement is combined with the energy measurement provided by the calorimeter (for the electrons) and with the momentum measurement provided by the muon spectrometer (for the muons). The muon spectrometer is incapsulated between the coils of a toroidal magnet which provide another field bending particle trajectories on the longitudinal plane.

A Higgs boson candidate event must have in the final state two pairs of electrons or muons with opposite charge. The pair of leptons with an invariant mass closest to the nominal Z boson mass is identified as the leading lepton pair. If the Higgs boson mass m_H is smaller than twice the Z boson mass, $m_Z \simeq 91$ GeV,one of the two Z boson is produced off-shell with a mass of roughly $m_H - m_Z$. These features and the expected distribution of the momentum of the leptons produced in the decay of the Z boson are used to suppress the contribution of other Standard Model processes generating the same final state.

Apart from those, there are also processes that can be wrongly reconstructed by the detector as four-lepton events. These processes are characterized by the presence of hadrons which can decay into muons or mimic the experimental signature of an electron. The contribution of these events is suppressed by requiring the final state leptons to be isolated and their trajectory to be originated close to the primary vertex of the collision.

If an event fulfills all the selection criteria the invariant mass of the four leptons, called $m_{4\ell}$, is stored. Analyzing all the events delivered by the LHC and collected by the ATLAS detector the distribution shown in Figure S.1 is obtained. An excess of events on top of the Standard Model background is observed in the region around 125 GeV, as summarized in Table S.1. The probability for this excess to be compatible with the background only hypothesis is smaller than 10^{-13}, corresponding to a Gaussian significance of 8 standard deviations.

Table S.1: List of the observed and expected events from the signal and background processes in the mass window $120 < m_{4\ell} < 130$ GeV.

Signal expectation	16.2
Background expectation	10.4
Total expectation	26.6
Observation	37

In this thesis I use the selected events to extract the mass, the signal strength and the decay width of the Higgs boson assuming that the excess of events is generated by the $H \to ZZ^* \to 4\ell$ process. The best estimate for these parameters is obtained through an unbinned maximum likelihood fit to the data. A measurement from the same dataset has been already published in [1] and [2]. In this thesis I propose to improve these results exploiting the information provided by the uncertainty, called $m_{4\ell}^{err}$, measured on the four-lepton invariant mass event by event.

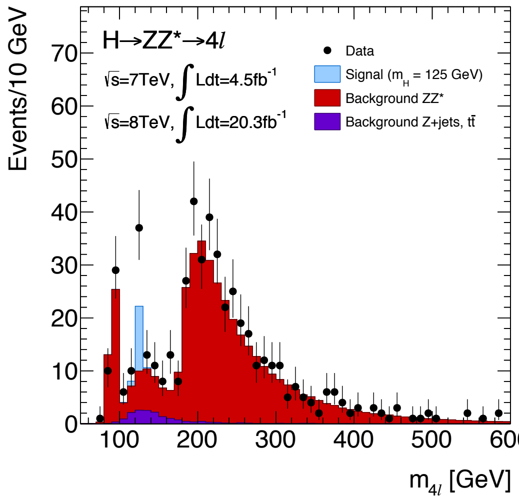

Figure S.1: Distribution of the four-lepton invariant mass of the $H \to ZZ^* \to 4\ell$ candidates passing all the selection criteria.

The signal model used in the publications is composed of Monte Carlo templates of the $m_{4\ell}$ distribution. To improve the separation between the signal and the background, four different templates are used according to the value of the output of a multivariate discriminant (*Boosted Decision Tree*).

The strategy presented in this thesis also exploits the information from the multivariate discriminant, but instead of Monte Carlo templates, analytic probability density functions (PDFs) are used. The PDFs in each multivariate discriminant bin are described by a sum of analytic functions defined by the convolution of Exponential and Gaussian distributions. The most probable value of the Exponentials in the convolution represents the estimator for the Higgs boson mass. The use of an analytic function allows to insert in the model the $m_{4\ell}^{err}$ variable

The width of the signal PDF relative to a specific event is proportional to the uncertainty on the four-lepton invariant mass measured for that event. As a consequence events with a large uncertainty enters in the likelihood with a lower weight with respect to the ones with a more precise measurement of $m_{4\ell}$. The shape of the model is optimized on large statistic datasets obtained simulating the $H \to ZZ^* \to 4\ell$ process and the detector resolution. Separate models have been built for every final state, for every Higgs boson production mechanism and for the two center of mass energies of the collisions ($\sqrt{s} = 7$ and 8 TeV) delivered by the LHC during 2011 and 2012. The probability density function used for the background has been obtained by smoothing simulated templates as it has been done in the most recent publications.

The distribution of the data plotted with the best fit probability density function is shown in Figure S.2. The results on the Higgs boson quantum number are reported in Table S.2. Using the model proposed in this thesis the uncertainty on the Higgs boson mass and signal strength measurement is improved by approximately 6% with respect to the most recent publication. The model allows also to set an upper limit on the Higgs boson decay width Γ_H which is smaller than 3.4 GeV at 95% confidence level. The limit on Γ_H is extracted with the so-called CL_s method after performing a convolution of the signal PDF with a Breit-Wigner model used to describe the theoretical distribution of the Higgs boson mass.

The per-event-uncertainty model represents a valid alternative to the one used in the recent publications, providing a more precise and robust estimation of the parameters under study. The measurement strategy followed so far by the ATLAS experiment collaboration is insensitive to the uncertainty associated to the four-lepton invariant mass measurements. Nevertheless it is known that the $m_{4\ell}^{err}$ quantity has an asymmetric distribution with a non negligible spread of $\mathcal{O}(1\text{ GeV})$ around its mean value. From simulation it is possible to check that larger $m_{4\ell}^{err}$ values correspond to wider $m_{4\ell}$ distributions. As a consequence events measured with a large uncertainty represents a less precise estimation of the Higgs boson mass and this should be taken into account in the fit.

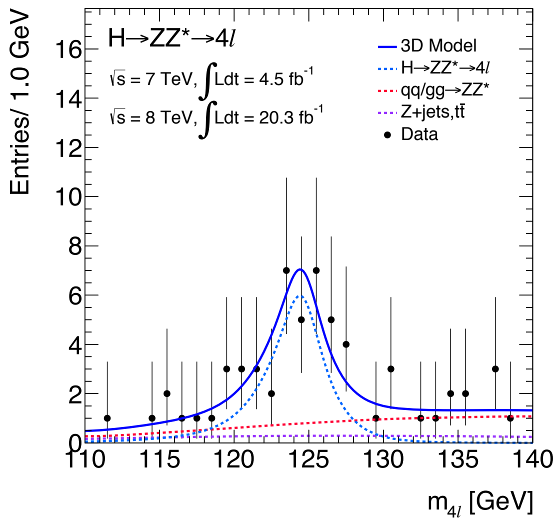

Figure S.2: Best fit PDF (solid blue curve) superimposed on the four-lepton invariant mass distribution from the data. Signal and background components are also plotted (dashed colored curves).

The method presented in this thesis allows to capture all the variation of $m_{4\ell}$ as a function of $m_{4\ell}^{err}$ and the difference in the uncertainty distributions among the various Higgs boson production modes and among the Higgs boson signal and the background processes. Moreover the fit performed with per-event-uncertainties is much less affected by problem connected with event simulation. The shape of the signal PDF, in fact, is still tuned using Monte Carlo templates but it changes smoothly as a function of the measured uncertainty. This allows to absorb an eventual discrepancy between the observed data and the distributions predicted by simulation.

The event-by-event uncertainty method is ready to be used during the second run of the LHC when there will be more Higgs boson events to analyze. A similar technique has been already sucsessfully used in the $H \to ZZ^* \to 4\ell$ analysis provided by the CMS experiment collaboration, as described in [3]. The larger amount of data to analyze will not represent a computational problem since the complexity of the model with three observables is compensated by the analiticity of the signal PDF, which remains extremely fast to evaluate.

Table S.2: Summary of the results on the Higgs boson quantum numbers obtained by analyzing the $H \to ZZ^* \to 4\ell$ candidate events with the model presented in this thesis. The value corresponding to the Higgs boson total width represent the upper limit at 95% confidence level. The number between parenthesis is the expected limit assuming a Standard Model Higgs boson signal.

Mass [GeV]	124.55 ± 0.49
Signal strength	$1.67^{+0.42}_{-0.36}$
Decay width [GeV]	$\leqslant 3.4$ (3.4)

References

[1] G. Aad et al. ATLAS Collaboration. “Measurement of the Higgs boson mass from the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels with the ATLAS detector using 25 fb^{-1} of pp collision data”. *Phys. Rev. D* **90** (Sept. 2014), p. 052004. arXiv: 1406.3827 [hep-ex].

[2] G. Aad et al. ATLAS Collaboration. “Measurements of Higgs boson production and couplings in the four-lepton channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector”. *Phys. Rev. D* **91** (Jan. 2015), p. 012006. arXiv: 1408.5191 [hep-ex].

[3] S. Chatrchyan et al. CMS Collaboration. “Measurement of the properties of a Higgs boson in the four-lepton final state”. *Phys. Rev. D* **89** (May 2014), p. 092007. arXiv: 1312.5353 [hep-ex].