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Spinning the Higgs. Spin and Parity Measurement of the Discovered Higgs-Like Boson in the H→WW→lvlv Decay Mode

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Figure 1: *The elementary particles collected in the Standard Model of Particle Physics. The quarks and leptons are referred to as matter particles. The gauge bosons are the propagators of three fundamental forces: the strong, electromagnetic and weak force. The Higgs boson is responsible for the masses of the elementary particles. Picture taken from Wikipedia.*

Nevertheless, to *prove* that the Higgs mechanism indeed describes physics in a correct way, it needs experimental verification. This can be achieved by detection of a manifestation of the Higgs field: the Higgs boson.

The search for the Higgs boson has been one of the primary motivations to build the Large Hadron Collider (LHC) at CERN, the European Organisation for Nuclear Research. The LHC is a circular particle accelerator that collides a certain type of particles, called protons, at record breaking energies of up to 8 TeV in 2012; energies sufficient to produce a Higgs boson, if it exists. In the proton collisions heavy new particles are created - possibly Higgs bosons - that almost immediately decay into the known elementary particles. The Higgs boson itself can therefore not be observed, but it can be recognised by the observable decay particles. At the four points along the LHC where the proton beams are collided, detectors are positioned to measure the traces that are left by the decay particles. By evaluation of these traces, which are based on electrical signals that are caused by the traversing particles, the original particles can be identified. Two of the detectors, ATLAS and CMS, have had the objective to discover the Higgs boson; both succeeded in doing so.

On the 4th of July 2012 - forty years after the realisation that the SM should include a Higgs boson - the discovery of a Higgs-like boson was announced. Both the ATLAS and CMS experiments claimed the discovery of a new particle with a mass of around 125 GeV and properties that are in agreement with the predictions for a Higgs boson. To allow for this discovery each experiment analysed approximately a quadrillion (10^{15}) proton-proton collisions. The observed excess of collision events in which presumably a Higgs boson has been produced was reported to have a significance of 5σ. This means that the probability for the observed excess to be a statistical fluctuation instead of the result of a Higgs-like boson, is a mere one in 3.5 million. A firm statement that a new particle was found.

One could naively think of this discovery as the completion of the SM and that no more research on this topic has to be done. However, more research is required in order to characterise the discovered boson. We do not yet know if the observed particle really is the Higgs boson as it is predicted by the SM. The discovered particle may be called a Higgs-like boson, because its roughly measured properties match with the predictions for a SM Higgs boson: its mass falls within the allowed range, its production rate in the various different sets of decay particles is as expected, and the particle can be identified as an electrically neutral particle with an integer spin value; the latter indicating that it is a boson. However, this does not yet prove that the particle is the SM Higgs boson. There are many more properties that have to be determined and only when all of these are precisely measured and found to be in agreement with the predictions of the SM, it can be excluded that the observed signal is not that of a Higgs boson 'look-alike' with slightly different properties. Therefore, the experimental research currently focusses on analysing the properties of the Higgs-like boson.

Two of the properties of the Higgs boson that can be measured with the current amount of data are its spin and parity. Spin and parity are quantum mechanical properties. Classically, spin can be seen as the rotation of a particle around its axis, but quantum mechanically it has no intuitive explanation. Every particle has a fixed spin value. It can be an integer value (0,1,2,...) or half-integer ($\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, ...). All known elementary particles have a non-zero spin, but the Higgs boson is the only particle that is predicted to have zero spin. This property is inherent to a field that generates mass for elementary particles. Consequently, if the Higgs-like boson turns out to have a non-zero spin it cannot be a manifestation of the Higgs field. Parity can be understood as a symmetry property. Are the properties of a particle the same or opposite if you would measure it via a mirror? If the properties are the same the particle has even parity, while if the properties are exactly the opposite the parity

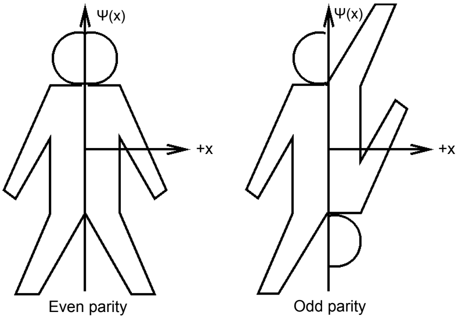


Figure 2: *Illustration of even and odd parity.*

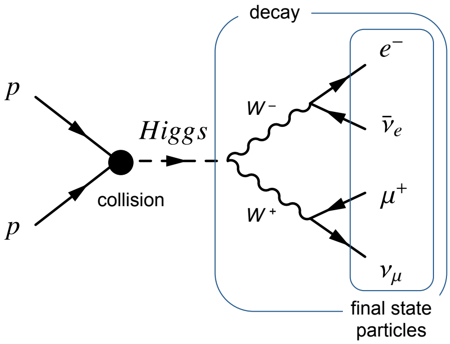


Figure 3: *Schematic overview of the studied Higgs production and decay.*

is odd, as is depicted in figure 2. The SM Higgs boson is predicted to have even parity. There are however theoretical extensions of the SM that predict more than one Higgs boson, where one of the additional Higgs bosons has odd parity. Thus, the measurement of the spin and parity of the Higgs-like boson will already give a clear indication of its nature.

In the analysis presented in this thesis, the spin and parity of the Higgs-like boson are measured, using the data of the ATLAS detector. To do this measurement alternative hypotheses for the observed boson are formulated. The SM hypothesis corresponds to a Higgs boson with spin-0 and even parity, denoted as: $J^P = 0^+$. The four studied alternative hypotheses include other possible spin and parity combinations: $J^P = 0^-, 2^+, 1^+$ and 1^-. Then, the total dataset of collision data that are collected in 2012 is compared to the SM hypothesis and each of the alternative hypotheses. In this way a statement can be made about the spin and parity of the observed Higgs-like boson. Are the data more compatible with the SM hypothesis or one of the alternatives? Is it possible to exclude the other spin and parity hypotheses?

To evaluate the spin and parity of the Higgs-like boson, the particles into which the Higgs boson decays, referred to as final state particles, are studied. The Higgs boson can decay into different sets of final state particles. The specific decay that has been studied in this thesis, the so-called WW channel, is shown in figure 3. The final state consists of an electron (e), a muon (μ) and two neutrinos (ν); which are elementary stable particles. The properties of these particles give information about the spin and

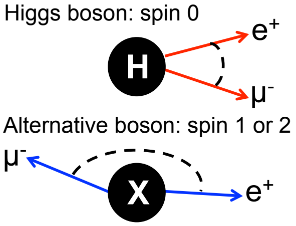


Figure 4: *Illustration of the effect of the spin of the original particle on the angle between the muon and electron.*

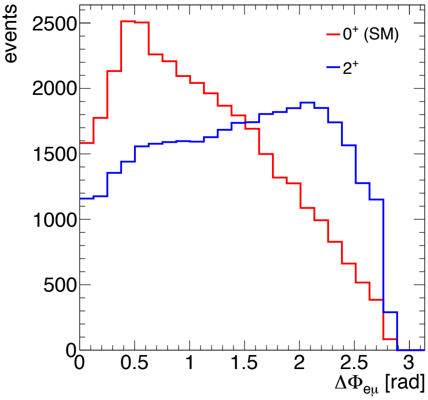


Figure 5: *Distributions of the angle between the electron and the muon ($\Delta\phi_{e\mu}$), simulated for a SM Higgs boson in red and a hypothetical spin-2 boson in blue.*

parity of the original particle. Hence, by studying the properties of the final state particles, the spin and parity of the original particle can be determined.

One property of the final state that is particularly sensitive to the spin and parity of the Higgs-like boson is the angle between the electron and the muon, denoted as $\Delta\phi_{e\mu}$. If the Higgs-like boson is indeed a spin-0 particle, this angle will be small, while the angle will be much larger (wider) if the Higgs-like boson has spin-1 or spin-2, as depicted in figure 4. This angle can be calculated for simulations of collision events in which either a 0^+ or a 2^+ boson is produced. Figure 5 shows distributions of $\Delta\phi_{e\mu}$ for the simulated SM Higgs boson in red and a hypothetical 2^+ boson in blue. Clearly, the distributions are different for the two hypotheses. This makes it possible to compare the collision data with the two simulated hypotheses and determine which hypothesis fits best with the data.

In figure 5, only simulations of the signal hypotheses, i.e. a SM Higgs boson or a 2^+ boson, are taken into account. However, the collision data consist mostly of background events, which are events in which no Higgs boson is produced. Only in one in ten billion collisions a Higgs boson is created. Thus, to allow for a sensitive comparison between data and the simulated hypotheses, the number of background events in the dataset has to be reduced. This is done by applying selections to the

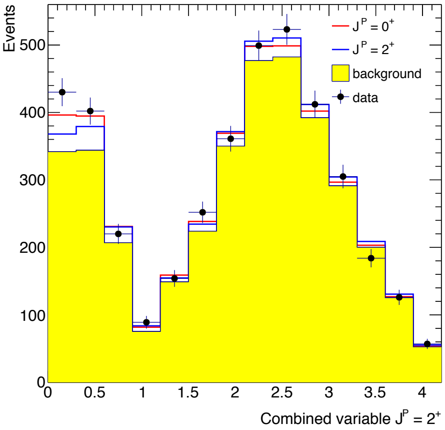
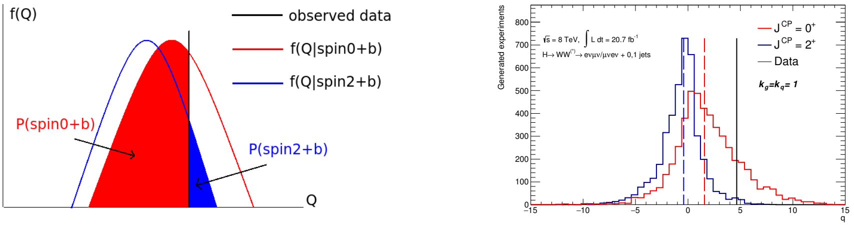


Figure 6: *The simulated separating variable for the* 2^+ *hypothesis, distributed for the SM Higgs boson in red and a hypothetical spin-2 boson in blue, on top of the irreducible background that is shown in yellow. The data are indicated as black dots.*

dataset that remove as much background as possible, while preserving most of the signal, i.e. Higgs events. After these selections we are left with approximately 200 signal events and 4000 background events.

The background cannot be further reduced without substantially reducing the signal. Therefore the different hypotheses have to be distinguished on top of this irreducible background. Consequently, only using $\Delta\phi_{e\mu}$ to separate the different hypotheses is not sufficient. More final state properties that are sensitive to the spin and parity of the Higgs-like boson need to be utilised in order to obtain the required separation power between the two hypotheses. This is done by analytically combining the sensitive properties into an ultimately separating variable. For each alternative hypothesis such a combined variable is made. Figure 6 shows the combined variable - after background rejecting selections - that has been determined for the 2^+ hypothesis. The distribution of the variable is shown for the simulations of the SM hypothesis in red and for the 2^+ hypothesis in blue, on top of the simulated irreducible background that is indicated in yellow. In this combined variable also the momenta of the final state particles are exploited. The separation between the two hypotheses is small, but large enough to evaluate if the data are more compatible with one or the other hypothesis. The black dots show the actual collision data after applying the background rejecting selections.



(a)

(b)

Figure 7: *Example (a) and real result (b) for the probability distributions used to quantify the compatibility of the data (indicated as a black vertical line) with the two hypotheses: the SM Higgs boson (red) and the* 2^+ *boson (blue). The shaded red area in (a) represents the compatibility of the SM hypothesis with the data, while the blue area indicates the compatibility with the alternative hypothesis.*

By eye it is hard to see with which hypothesis the data are more compatible, therefore the compatibility is quantified using a *statistical analysis*.

In the statistical analysis, the combined variable is fitted in such a way that the compatibility of the data with the different hypotheses can be quantified with a variable q. Figure 7a shows a fictive example of the q distributions. The red distribution is made of the sum of the simulated SM hypothesis events and irreducible background and the blue distribution of the simulated 2^+ hypothesis plus background. The black vertical line represents the actual data. The red area indicates the compatibility of the data with the SM hypothesis, and the blue area with the 2^+ hypothesis. The larger the area, the more compatible the data with the corresponding hypothesis. From these areas the degree of compatibility with the data can be calculated. Figure 7b shows the real result for the comparison of the data with the SM and 2^+ hypotheses. Clearly, the data are more compatible with the SM hypothesis. By calculating the area of the blue distribution to the right of the data line, can be concluded that the probability that the 2^+ hypothesis is correctly rejected in favour of the SM Higgs boson is 98.5%. These q distributions have also been evaluated for the other alternative hypotheses, $J^P = 0^-, 1^+$ and 1^-, and show that the data favour the SM Higgs boson. The probability that the alternative hypothesis is correctly rejected in favour of the SM Higgs boson is more than 92.2% for any of these hypotheses.

This measurement is one of the early stage properties analyses of the discovered Higgs-like boson and contributes to the characterisation of the new boson. It shows that it is possible to perform a spin and parity measurement for the WW Higgs decay, something that did not seem feasible at the time of the discovery in 2012. The results are however not conclusive yet. Although the alternative hypotheses seem unlikely, one cannot yet be sure that the spin of the observed boson is zero and the parity even. In order to be able to make a firmer statement about the spin and parity of the observed boson, further analysis is required. Various optimisations of the analysis are possible to improve the sensitivity. One example is to make a more precise combination of the spin and parity sensitive properties of the final state particles. Furthermore, analysis of more data will result in an increased sensitivity. From May 2015, after a shutdown of two years in which the LHC and the detectors have been upgraded, the LHC has started delivering new data. This allows for an update of the measurement with more statistics.

The next generation of spin and parity analyses of the Higgs-like boson will study more complex hypotheses and do a more precise measurement. Ultimately, all the properties of the new boson have to be measured and compared to the SM predictions. Only then can be concluded if the observed Higgs-like boson is the SM Higgs boson, or if the discovered particle does not belong to the SM and reveals new physics. The analysis that has been presented in this thesis is a first step in the characterisation of the new Higgs-like boson and suggests that the discovered boson is the Standard Model Higgs boson.