HERTHA-SPONER-PREIS

To be put through its paces

Precise and fine-grained measurements of the Higgs boson are continuously improved.

Adinda de Wit

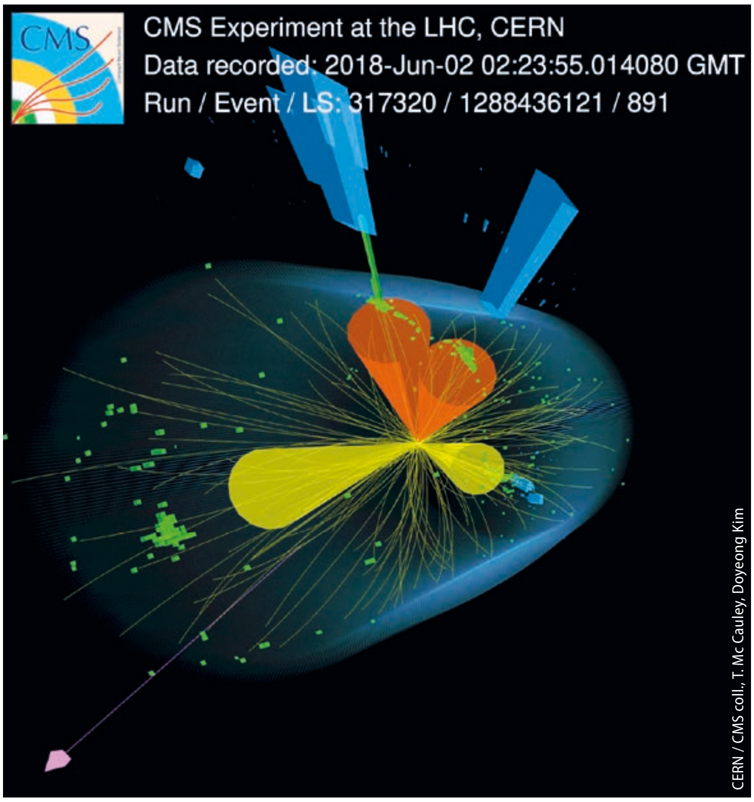
The Large Hadron Collider is a 27 km-long circular particle collider which has been in operation since 2010 at CERN. At the Large Hadron Collider, protons collide at a record-breaking centre-of-mass energy of up to 13.6 TeV. Four large experiments are placed around the ring at the intersection points of the proton beams: ATLAS, CMS, LHCb, and ALICE detect the products of the resulting collisions. The study of these data helps to improve our understanding of the universe.

In July 2012, the ATLAS and CMS collaborations announced the discovery of a new particle with a mass of around 125 GeV/c^2 [1 – 3]: the Higgs boson, a particle predicted in the 1960s which is responsible for generating the masses of other elementary particles. The Standard Model of particle physics describes the building blocks of everything around us. Matter consists of fermions: quarks and leptons which exist in three generations. The interactions between these particles are mediated by ‚force carriers': the bosons. The discovery of the Higgs boson completed a major missing piece of the Standard Model.

One of the reasons, it took nearly half a century to find the Higgs boson is that its mass was not predicted by the Standard Model. Therefore, physicists had to search a wide range of masses. Furthermore, the Higgs boson can decay to a range of other elementary particles – and the rate of a particular decay channel depends on the mass of the Higgs boson. Thus, many different final states had to be investigated. With a mass of 125 GeV/c^2, the Higgs boson might decay into pairs of bosons (WW, ZZ, γγ) or pairs of fermions such as bottom quarks and tau leptons. In addition to a range of decay channels, there are several ways to produce the Higgs boson at the Large Hadron Collider (LHC): the dominant production mechanism with 87 % is the fusion of two gluons, followed by the fusion of vector bosons (W or Z boson), the production in association with a vector boson, and with a pair of top quarks.

The CMS and ATLAS collaborations studied different production modes and decay channels with the data collected during the first run of the LHC which lasted until the end of 2012. Using the data, they established the couplings between the Higgs boson and vector bosons as well as the effective coupling to photons. In addition, they determined the production cross sections per production process and decay channel combining data from ATLAS and CMS.

However, these investigations marked only the beginning of the story of the Higgs boson. Using the data



The collision of two protons with an energy of 13 TeV might produce a Higgs boson decaying into a pair of tau leptons. Two forward pointing jets (yellow) in the opposite endcaps of the CMS detector are characteristical for such an event. The jets of the tau leptons (orange) are identified by energy deposits in the electromagnetic (green) and hadronic (blue) calorimeter systems. Some transverse energy is missing (pink arrow).

collected from 2015 to 2018 during the second run of the LHC, both experiments were able to confirm the couplings between the Higgs boson and third generation fermions: the top quark, the bottom quark, and the tau lepton. It is important to understand these couplings in detail because the mechanism of mass generation differs for fermions and bosons and the Standard Model predicts that the coupling between the Higgs boson and other particles is proportional to their mass. As the third-generation fermions are heavier than their first- and second-generation counterparts, their couplings are weaker and more difficult to access. However, during the second run, significant progress was made when evidence for the decay of the Higgs boson into pairs of muons was found. The probability that the observed signal was just a statistical blip is less than half

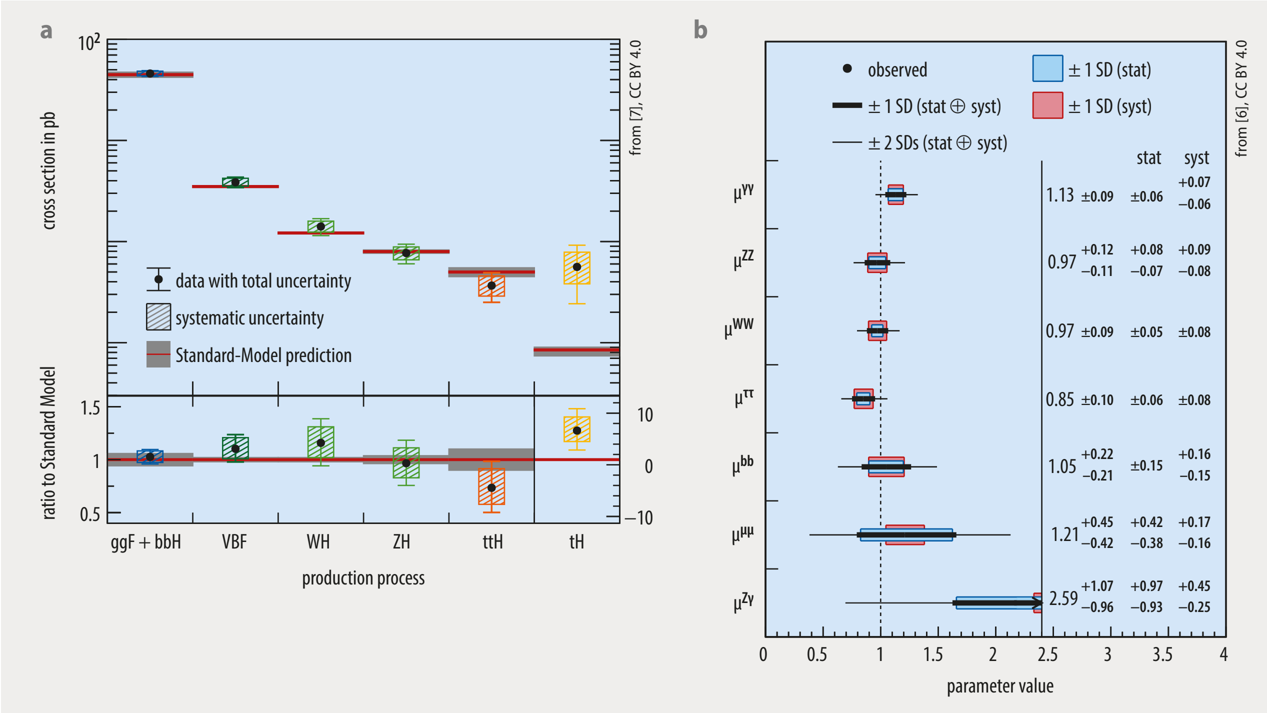


Abb. 1 The cross sections for different production mechanisms of the Higgs boson measured by the ATLAS collaboration (a, top) are compared to the value expected by the Standard Model (bottom). The CMS collaboration derived the decay rates of the Higgs boson for various decay channels relative to the prediction of the Standard Model (b).

a percent. Moreover, both experiments have made strides in studying the coupling between the Higgs boson and the charm quark. Upper limits on the decay $H \rightarrow c\bar{c}$ now reach the order of ten times the expectation set by the Standard Model. Thus, the decay of a Higgs boson to charm quarks was not observed yet, but we are starting to get closer [4, 5] – a particularly remarkable achievement. Ten years ago, this decay channel was not considered to be within reach at the LHC.

Precise measurements

Having established many of the major Higgs boson production modes and decay channels, the data collected during the second run now serves to perform precise measurements of the Higgs boson. But what are we measuring in that case? Studying a particular decay channel of the Higgs boson – for example, the Higgs boson decaying to a pair of tau leptons – always involves looking at one or more different production mechanisms – for example vector boson fusion. Hence, it is not possible to isolate the decay channel, or conversely the production mode, using a single measurement. In consequence, a single measurement does not reveal whether the production rate, the decay rate or both of them deviate from the Standard Model, if the observed combined rate does not match the predictions. Fortunately, a combined measurement is able to overcome this limitation. A combined measurement takes into account all available production modes and decay channels, thus, providing a complete picture of the couplings of the Higgs boson and its production and decay rates, with the best possible precision on those measurements reached [6, 7].

Using the data collected during the second run, ATLAS and CMS were both able to measure the cross section for gluon-gluon fusion, which is the dominant production mechanism, with a precision better than ten percent. This precision enables learning more about physics beyond the Standard Model from these measurements. Uncertainties of the other major production modes, i. e. vector boson fusion as well as W-associated, Z-associated, and top-quark-pair-associated production, are in the range of ten to twenty percent for the ATLAS experiment (**Fig. 1a**). For the first time, both collaborations were able to measure the production of a Higgs boson in association with a single top quark – although the uncertainty of the measured value is still very large (50 %). The data being collected in the current third run and in future will further improve this precision. The CMS experiment measured the decay rates of the Higgs boson with a precision similar to the one of the production cross-sections (**Fig. 1b**): If the Higgs boson decays to bosons, i. e. pairs of W, Z, or γ, the precision is around ten percent; rarer decay channels, such as pairs of muons, suffer from a limited precision.

Fine-grained measurements

The increasing precision of these measurements stems from the large data sets as well as the continuous improvement of the analysis methods. Both enable progress and allow not only considering Higgs-boson production cross-sections inclusively but also performing more fine-grained measurements. There are two approaches for the Higgs boson: simplified template cross sections (STXS) and fiducial differential cross-section measurements. In both cases, different slices of the parameter space called bins are defined to measure the Higgs-boson production cross-sections within. Examples for a binning include the transverse momentum of the Higgs boson, the number of particle jets in the event, and many other variables. The two approaches differ in various points; most importantly, the bins of the STXS approach are defined using multiple different variables at the same time. In addition, the number of variables changes with the position in the parameter space. Therefore, the binning occurs ad-hoc compared with the one used in ‚standard' differential cross-section measurements. The ATLAS and CMS collaborations agreed on the STXS bins while consulting theoretical colleagues. This simplifies the comparison between the results of ATLAS and CMS and eventually allows combining their data to increase the precision of the measurements.

Beyond the Standard Model

The aim of achieving more precise results for cross sections and decay rates corresponds to one of the main goals of the LHC: to find physics beyond the Standard Model. One hint for such physics is the mass of the Higgs boson of around 125 GeV/c^2: if there are no further particles than the ones already observed, this mass would be too low. Many theories beyond the Standard Model address this problem. Some of them predict deviations in the couplings of the Higgs boson at the percent level. Therefore, a comparable precision of the measurements is mandatory to decide whether such deviations exist and which of the new models might be correct.

Another aspect relates more to the STXS and differential measurements. The presence of physics beyond the Standard Model might affect the couplings of the Higgs boson not only inclusively but also differentially. For instance, a new particle might exist which is too heavy to be produced directly at the LHC whose collision energy is limited to 14 TeV for protons. Although such a particle is not directly observable, it would still affect the production cross-sections of particles in the Standard Model like the Higgs boson. For example, this new, heavy particle might modify the cross section of the Higgs boson at high transverse momentum (**Fig. 2a**). An inclusive measurement of the cross section would yield results compatible with the prediction of the Standard Model as the overall effect is negligible. However, measuring the production cross-sections in bins of transverse momentum, the deviation might become significant in some of the last bins of the distribution (**Fig. 2b**).

If different distributions show deviations from the predictions, a consistent interpretation of the data is needed. In so-called effective field theories the Standard-Model Lagrangian is extended by taking into account higher-order operators that describe the effects of new physics. A rather old example is the Fermi theory of beta decay: it described successfully the decay of a neutron to a proton, an electron, and an electron antineutrino – half a century before the W boson which mediates the interaction was discovered. Similarly, ATLAS and CMS have both already used STXS and differential measurements to constrain effects in an effective field theory which describes the Higgs sector. In addition, an extensive measurement programme trying to identify anomalous contributions to the interactions of the Higgs boson with other particles is under way – for example, to understand the charge-parity structure of the various couplings.

Future perspectives

The third run of the LHC is currently under way and will last for the next years. Its data set should more than double the data available after the second run. Afterwards, the collider will be upgraded to operate at higher instantaneous luminosity. This high-luminosity LHC (HL-LHC) will increase the amount of data enormously: twenty times more than analysed so far. Although decades are needed to collect these data, not to mention the time for analysis, it is already worth exploring the precision to be expected for the measurements related to the Higgs boson. To derive this precision, it is possible to scale up the performed measurements such that the data collected so far matches the data set assumed from the HL-LHC. This procedure relies on several assumptions: for example, the efficiency for the reconstruction of particles in the detector has to persist. On top of that, it is necessary to assume the uncertainties

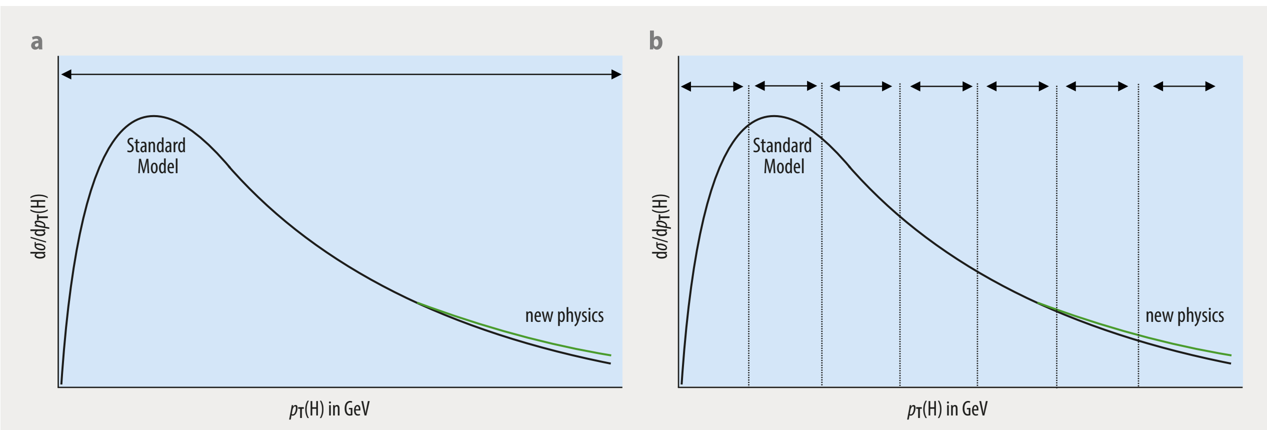


Abb. 2 In an inclusive measurement, the measured cross section (a, green) appears to agree with the prediction of the Standard Model (black). Precise measurements allow a more granular investigation: More granular kinetic information reveals even small deviations (b).

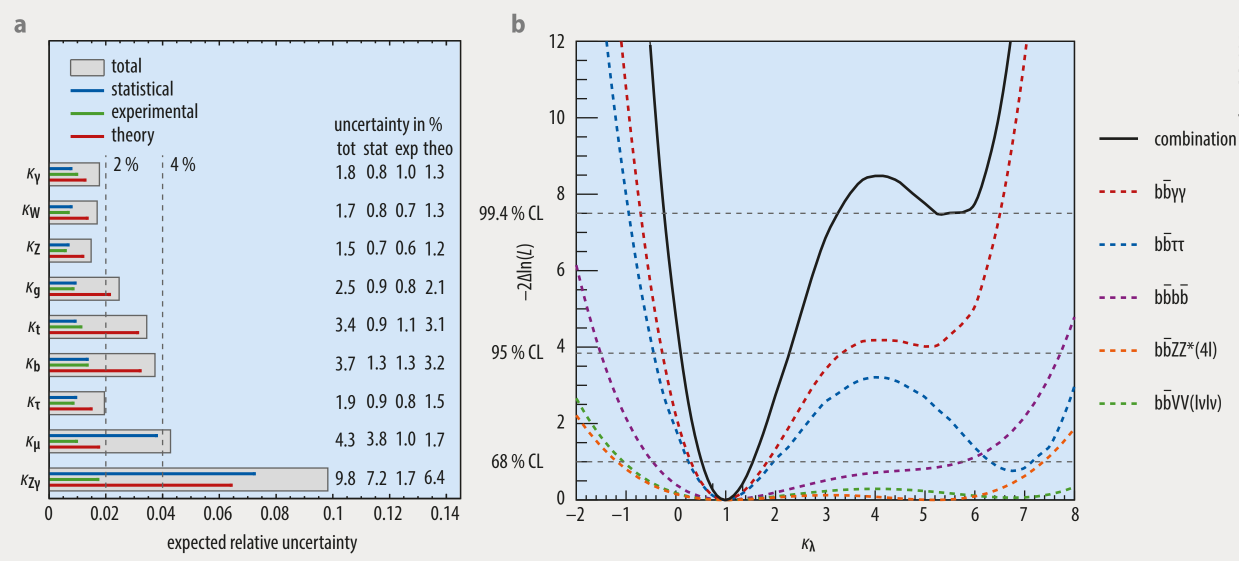


Abb. 3 The HL-LHC will give the opportunity to measure most of the couplings of the Higgs boson to other particles (a) to the percent level with theoretical uncertainties being the limiting factor in the precision. In addition, the precision of the measured Higgs-boson self-coupling (b) will be around 50 percent.

entering in the measurements: for example, the theoretical uncertainties in the predictions of the Higgs-boson production cross-sections could be halved while experimental uncertainties, like the ones stemming from the calibration of the luminosity measurement, are expected to reduce with the square root of the increase in luminosity.

Using these assumptions, most of the couplings of the Higgs boson will be obtained with a precision on the percent level when combining the entire data set collected at the HL-LHC by ATLAS and CMS (**Fig. 3a**). At that point, the precision is limited by theoretical uncertainties. Thus, a further improvement of the measurements relies on the precision of the theoretical calculations.

Another goal of the HL-LHC is a significant progress for rarer Higgs-boson couplings, for example the interaction which provides the self-coupling of Higgs bosons – a property with a significant lack of experimental information today. Measurements of the production of a pair of Higgs bosons determine this coupling, however, this process occurs only once per thousand productions of one Higgs boson. As a matter of fact, neither of the detectors at the LHC has observed the production of a Higgs-boson pair yet, but the data of the HL-LHC should confirm this rare process. In addition, the precision of the measured strength of the Higgs-boson self-interaction is predicted in the range of fifty percent (**Fig. 3b**) – with this value representing a conservative estimate: the analysis methods improve continuously, thus, the expected precisions for the HL-LHC are not yet based on the most sensitive possible analyses.

Summary

The eleven years after the discovery of the Higgs boson have provided a lot of progress in establishing the properties of this particle, and the measurements of its production cross-sections and decay rates continue to improve. Increasingly fine slices of kinematic variables allow the search for new physics using the production cross-sections. Even though a large data set is already available, physicists will continue to collect more data during the next decades aiming for a data set twenty times larger than the one already analysed. Therefore, there are many more precise Higgs-boson measurements to come.

Literature

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Adinda de Wit studied physics at Utrecht University, Netherlands, and at Imperial College London, UK. There, she obtained her PhD on searches for additional Higgs bosons in 2017. As a postdoc, she has worked at DESY and at the University of Zurich, Switzerland. Currently, she holds a postdoc position at Laboratoire Leprince-Ringuet, Palaiseau, France. Her research focuses on Higgs-boson physics using the CMS experiment at the Large Hadron Collider.

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