Looking Forward: 10 Years After the Higgs Discovery

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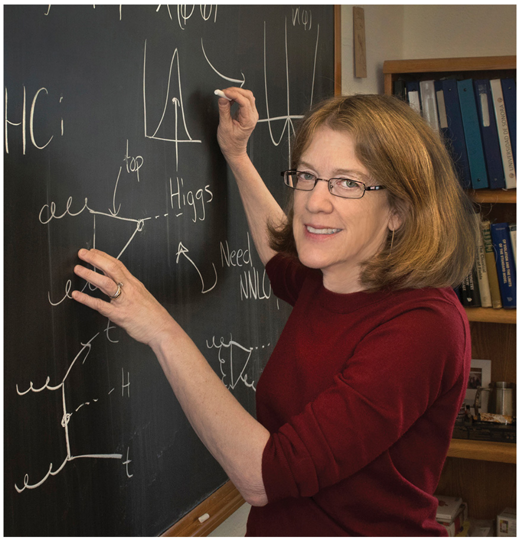


Photo: Roger Stoutenburgh. Courtesy BNL

The Higgs boson has been central to the understanding of particle physics since it was first proposed in 1964. At the time, the weak force was known to be mediated by a massive spin-1 particle, unlike the massless photon of electromagnetism. Understanding the source of this mass came after the Higgs boson, and its corresponding interactions, was proposed. Having a Higgs boson allows us to understand how spin-1 gauge bosons can have mass in a theoretically consistent manner. However, the model (now called the Standard Model) gives no clue as to what the mass of the Higgs boson might be: we only predict the necessity for the existence of the Higgs boson in order for the gauge bosons mediating the weak interactions to be massive. The model is extremely simple and predictive once the Higgs boson mass is specified and the interactions between the Higgs boson and all of the particles of the Standard Model are predicted in terms of particle masses.

In the 1970s, theorists began speculating about how to observe the Higgs boson in processes such as kaon or B meson decays. The first systematic study of the possible mechanisms for observing the Higgs boson was in a seminal paper by Ellis, Gaillard and Nanopoulos [Nucl.Phys.B 106 (1976) 292] with the now infamous quote:

"We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm, and for not being sure of its couplings to other small particles, except that they are probably all very small. For these reasons, we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up."

This advice of course spurred both theorists and experimentalists to get serious about the search for the Higgs boson!

At the same time, the concept of a no-lose theorem was being developed. Following the ground breaking Lee, Quigg and Thacker [Phys.Rev.D 16 (1977) 1519] paper it was realized that there was an upper limit of about 800 GeV on the mass of a weakly interacting Higgs boson. If a Higgs boson did not exist below

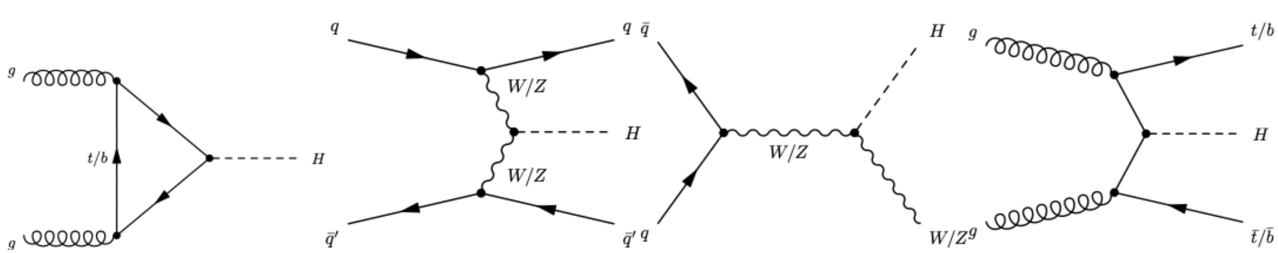


Figure 1: Production mechanisms for the Higgs boson in a hadron collider.

this mass scale, the self-interactions of the gauge bosons would become strongly interacting at an energy scale lower than around 3 TeV, leading to experimentally observable effects. Furthermore, this idea can be used to constrain the possibilities for models with new physics beyond the Standard Model, since any change in the couplings of the Standard Model particles would affect the scale where the gauge bosons become strongly interacting in the absence of a Higgs boson. This notion that the TeV energy scale is special was a strong motivating idea behind both the SSC and the LHC physics programs.

During the 1980s, theorists began exploring mechanisms for producing the Higgs boson at hadron colliders and the important production channels are shown in Fig. 1. Each of these processes is sensitive to a different aspect of the model. The interactions of the gluon with the top quark tests the coupling of the top quark to the Higgs boson. Because the top quark, with a mass of 175 GeV, has the strongest interaction (of all known particles) with the Higgs boson, these processes are of particular interest. The processes where the Higgs boson interacts with a W or Z gauge boson probe the gauge interactions of the Higgs boson. All of these production mechanisms for the Higgs boson have now been observed at the LHC.

The discovery of the Higgs boson gave us the last free parameter in the Standard Model—the Higgs boson mass—allowing the predictions of the model to be tested with great accuracy. We are now in the precision era where Higgs boson measurements challenge our understanding of the Standard Model. The production and decay of the Higgs boson can be predicted in terms of known parameters and the current understanding is summarized in Fig. 2. The widths of the bands in the figures are estimates of the theoretical uncertainties. The observed Higgs boson mass of 125 GeV is particularly fortuitous, as it allows the observation of the Higgs boson in many different decay channels.

Ten years after the Higgs discovery, Higgs couplings are measured with accuracies on the order of 5-10%, as seen in Fig. 3. However, our knowledge is sadly lacking. The interactions with the first generation fermions (up and down quarks and the electron) are unknown, with no realistic prospects for their measurement. Currently, the LHC has roughly 5% of the expected luminosity from future running at the High-Luminosity LHC (HL-LHC). Anticipated measurements at the HL-LHC are expected to give

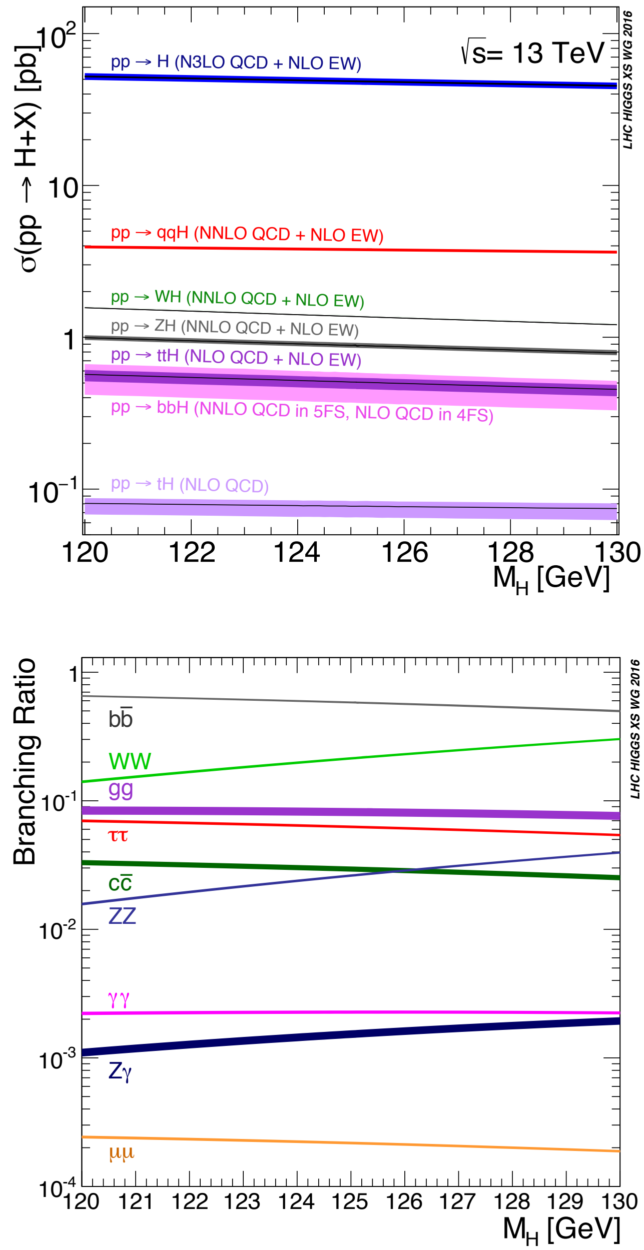
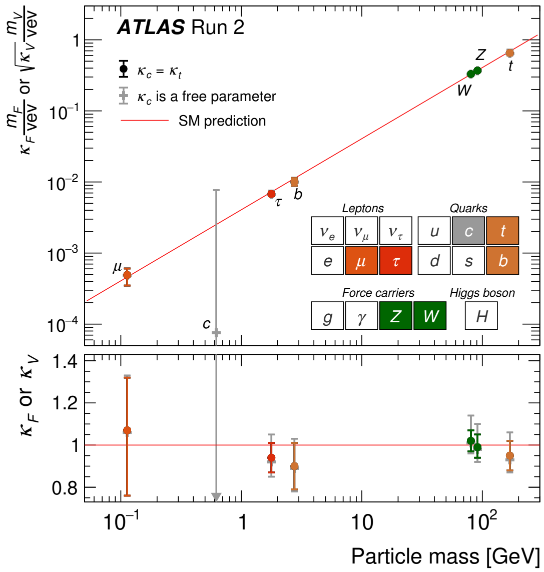
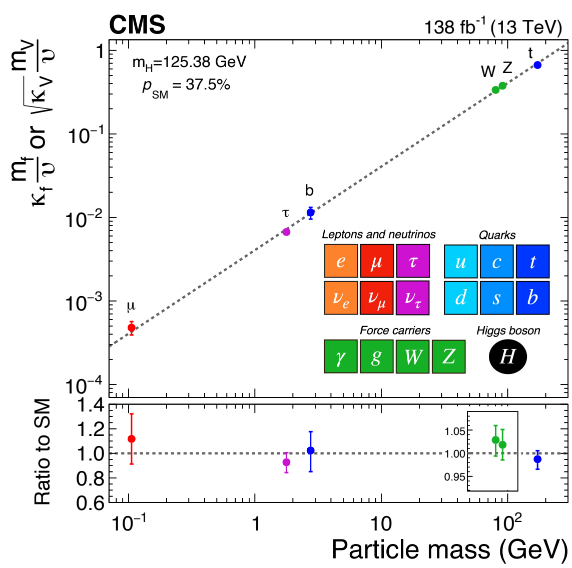


Figure 2: Higgs boson production rates at the LHC (LHS) and Higgs boson branching ratios (RHS) from LHC Higgs cross section working group. https://twiki.cern.ch/twiki/pub/LHCphysics/LHCHWGCrossSectionsFigures >

information (with fairly large uncertainties) about the interactions of the Higgs with the muon and the charm quark.

The predictions for the Higgs production and decay rates represent an impressive success for theoretical physics. The gluon production rate for the Higgs boson can be computed as a power series in the strong coupling constant $\alpha_S \sim .118$, and was first computed at next-to-leading order (NLO) in





Figures 3a and b: Current measurements of Higgs couplings to known particles from the ATLAS experiment at the LHC. Nature, 607, pg 52-57 (2022). CMS, Nature 607, pg 60 2022

perturbative QCD in 1977, with subsequent improvements in the perturbation expansion. The current state of the art includes terms of O(α_S^5), along with various powers of logarithms, α_S log(MH^2), as seen in Fig. 4. With the inclusion of the logarithmic terms (denoted by NNLL, N^3LL, and N^3LL'), the theoretical prediction nicely lines up with the experimental measurement. These calculations represent a triumph of theory, requiring new insights into the structure of the amplitudes and a new understanding of the field theory of the singularity structures.

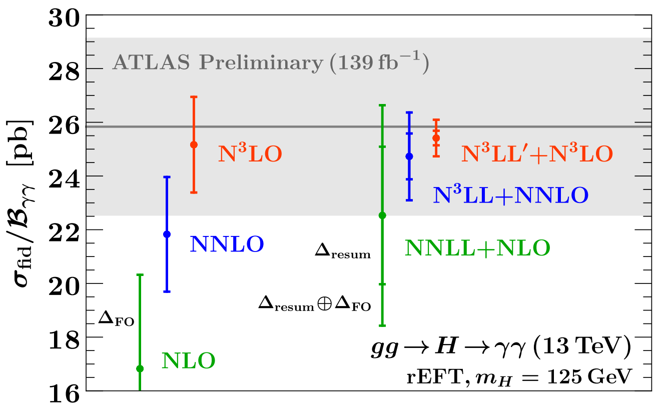


Figure 4: Current state of the art for the calculation of the gluon fusion production of the Higgs boson, along with the Higgs decay to 2 photons. https://arxiv.org/format/2102.08039 >

The challenge for the future is to measure Higgs properties at the percent level. Despite the heroic progress in the calculations of Higgs production rates, our current knowledge is insufficient to meet the needs of future experiments. The expected experimental precision at the end of the HL-LHC era (~2042) will typically be smaller than the theoretical uncertainty, emphasizing the need for future theoretical calculations. Projections for the measurement of Higgs couplings at the HL-LHC are shown in Fig. 5, with the theoretical uncertainty shown in red. The projections are normalized to the Standard Model predictions.

The Standard Model results from an extremely simple structure for the Higgs self-interactions, which depends on only 2 independent parameters: the Higgs vacuum expectation value, v, and the Higgs boson mass. The value of v=246 GeV is inferred from the muon lifetime and so the tri-linear and quartic self-interactions of the Higgs boson are predicted in terms of the Higgs boson mass. There is no experimental evidence supporting this simple picture and one of the major quests of Higgs physicists in the coming decade will be to verify the structure of the Higgs potential. To do this, it is necessary to observe the production of two Higgs bosons simultaneously and then to extract the Higgs self-interactions from the rate. Prospects for the measurement of 2 Higgs bosons are shown in Fig. 6 and the HL-LHC is expected to obtain a measurement of the Higgs tri-linear coupling with roughly 50% accuracy. Models that attempt to explain some of the unanswered questions of particle physics will often predict a value for the Higgs self-coupling that is different from that of the Standard Model, and so the observation and measurement of the self-coupling can give information on new physics at high energy scales.

While the Standard Model is simple and predictive, it gives little information on some basic concepts about the Higgs boson:

- There is no theoretical reason why there should not be more Higgs bosons, leading to a plethora of scenarios. The search for these possibly new Higgs bosons will be greatly extended in the HL-LHC era. In addition, precision measurements of Higgs boson couplings are sensitive to the existence of additional Higgs bosons.
- Roughly 25% of the universe is made of dark matter, and future measurements of Higgs properties could lead to insights into the connection between the Higgs boson and dark matter.
- Is there CP violation in the Higgs sector?
- Can the Higgs boson have flavor violating decays such as H-> μ^+e^- ?

The recently completed Snowmass study [**https://arxiv.org/pdf/2209.07510.pdf**] of the prospects for Higgs physics in the coming years summarizes the many opportunities for expanding our knowledge of the Higgs sector and answering some of the questions listed above. A decade after the discovery of the Higgs boson, the Higgs story is just beginning!

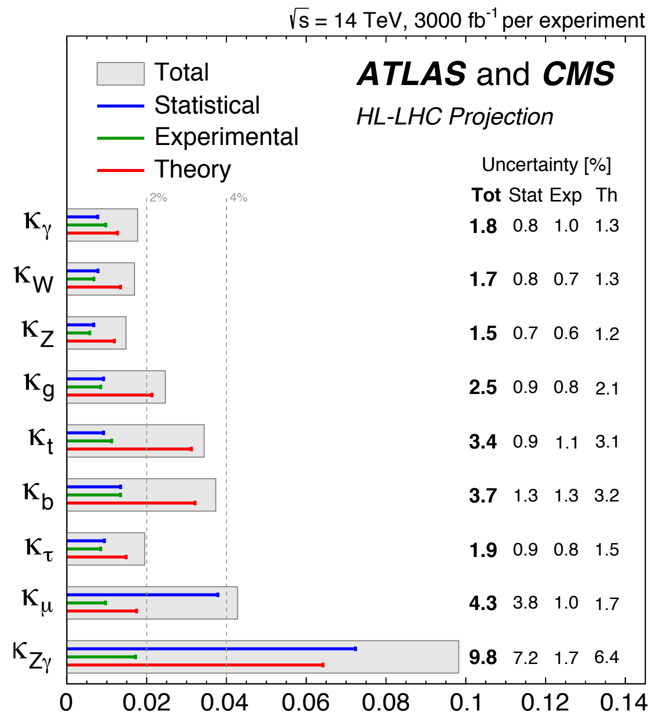


Figure 5: Predictions for the measurements of Higgs couplings to Standard Model particles at the HL-LHC. The rates are normalized to the Standard Model predicitions. ATL-PHYS-PUB-2022-018

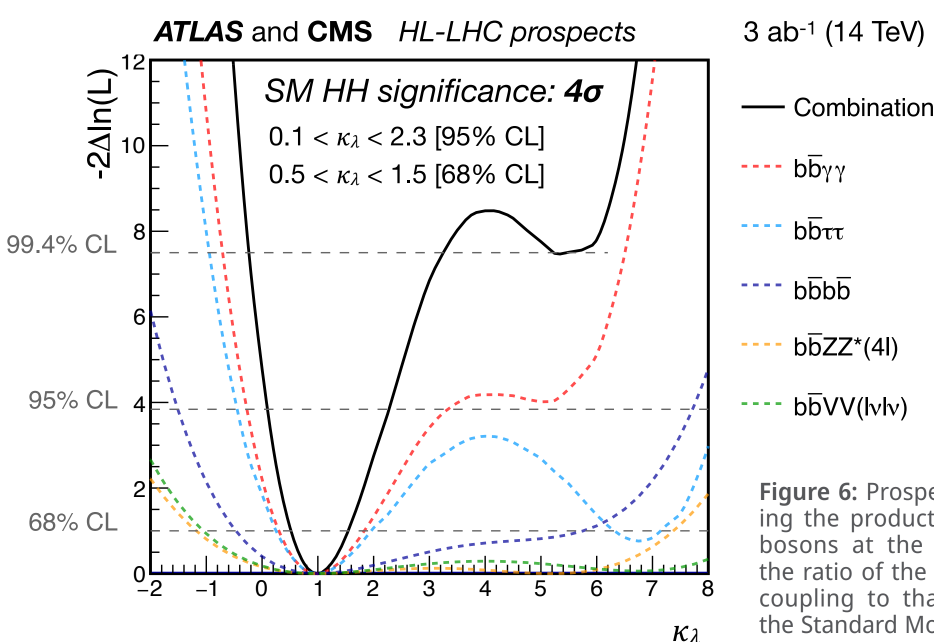


Figure 6: Prospects for observing the production of 2 Higgs bosons at the HL-LHC. $\kappa\lambda$ is the ratio of the Higgs tri-linear coupling to that predicted in the Standard Model. ATL-PHYS-PUB-2022-018