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The Higgs Boson. An experimental overview

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This presentation covers the discovery of the Higgs boson from an experimental point of view. We will review the search for the Higgs boson and the most up-to-date results on the properties of this particle that was announced by the LHC experiments ATLAS and CMS in 2012.

I. INTRODUCTION

This introduction is entirely inspired on Gavin Salam's talk at the *Sixth Annual Conference on Hadron Collider Physics (LHCP2018)* [1].

The Standard Model of Particle Physics [2–4] describes the building blocks of matter, the elementary particles and their interactions. The strong interaction is mediated by the gluon (that is massless), the electromagnetic interaction is mediated by the massless photon whilst the weak force is mediated by the $W^{\pm}$ and Z^0 vector bosons which have masses of 80 GeV and 91 GeV, respectively. The electromagnetic and weak interactions are unified in the electroweak theory.

The mechanism that explains the generation of mass of the weak mediators [5–10] was proposed nearly fifty years ago by Peter Higgs, François Englert, Robert Brout and others. According to this theory the spontaneous symmetry breaking in gauge theories could be achieved by the introduction of a scalar field. By applying this mechanism to the electroweak theory through a complex doublet field, the masses of the W and Z bosons are explained. Along with the scalar field, comes the existence of its quantum which is the only scalar boson of the SM, the Higgs boson.

The SM interactions can be summarized in the compact form of:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi + h.c. + \bar{\psi}_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi) \quad (1)$$

The first term of (1), $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi$ is known as the gauge sector and has been established by numerous experiments over the last decades. The term $i\bar{\psi}D\psi$ relates to gauge-matter interactions and corresponds to processes such as $ee\gamma$, $e\nu\gamma$, qqg and qqZ in e^+e^-, *Deep Inelastic Scattering* (DIS) and hadron collider experiments and the term $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$ is known as the triple-gauge sector and is responsible for the gauge-gauge interactions, with processes such as ggg and ZWW.

The remaining terms of the Lagrangian in (1) describes the Higgs sector of the Standard Model. The term $|D_\mu\phi|^2$ is yet another gauge interaction and entails processes such as HWW and HZZ. These processes had a big role in the Higgs boson discovery and made possible measurements of the properties of the boson, such as spin-parity tests [11].

The term $\bar{\psi}_i y_{ij}\psi_j\phi$ accounts for the interaction of the Higgs field with the fundamental fermions via the Yukawa coupling, generating mass to all quarks and leptons. This coupling had never been probed until the discovery of the Higgs boson.

The Higgs potencial term, $V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$ generates interactions like the Higgs self-coupling HHH, also known as triple Higgs coupling. The energy and luminosity to start probing these interactions will only be possible at the next generation of colliders, such as the *High Luminosity LHC* (HL-LHC) [12] and the *International Linear Collider* (ILC) [13].

The discovery of the Higgs boson was the last missing piece of a long-sought puzzle and it opens the doors to a variety of new possibilities. It is well-known that the Standard Model is an incomplete theory, as for instance it does not take gravitation into account. So we need complementary theories to the Standard Model, the so-

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called *Beyond the Standard Model* theories, for which Supersymmetry is one of the most well-known candidates. A question that might arise is how do these BSM theories influence the SM measurements? Could we see the effect of a BSM process by measuring, say, a Higgs coupling? Part of the answer to this question will come from a series of high precision measurements that are not possible to achieve at the Large Hadron Collider (LHC) [14].

In this presentation, an overview of the Higgs boson results are shown, from the discovery until the latest experimental results.

II. THE HIGGS BOSON SEARCH

Since the theorized Higgs boson is not a stable particle, the Higgs production cross section and the branching ratios need to be taken into account.

A. Higgs boson production modes

According to theoretical calculations [15–17], the main production mechanisms and their cross-sections at the LHC are shown in figure 1. Since the Higgs mass is a free parameter in the theory, the searches for the Higgs had to assume all possible masses that had not been excluded by previous experiments. The calculations were done by a group of theoreticians and experimentalists that worked together to produce the most precise cross-section calculations. They reported the results in the famous "CERN Yellow Reports".

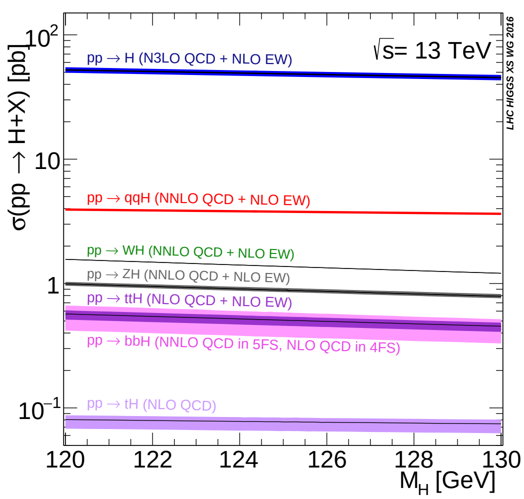

FIG. 1: Higgs dominant production modes at the LHC at $\sqrt{s} = 13$ TeV

The dominant modes are listed below in order of decreasing cross-sections at $\sqrt{s} = 7$ TeV [18]:

- gluon fusion production $gg \to H$;
- vector boson fusion production $qq \to qqH$;
- associated production with a W boson, $qq \to WH$;
- associated production with a Z boson, $qq \to ZH$ and $gg \to ZH$;
- associated production with a pair of top (b) quarks via $qq/gg \to tt(bb)H$;

B. Higgs boson decay channels

Each decay mode of the Higgs boson defines an experimental channel. The search strategy for the Higgs depends on its decay products. Thus each decay channel probes a region with a higher or lower possible mass. The Higgs decay branching fractions computed by the *LHC Higgs Cross Section Working Group* for a center of mass energy of $\sqrt{s} = 13$ TeV are shown in figure 2.

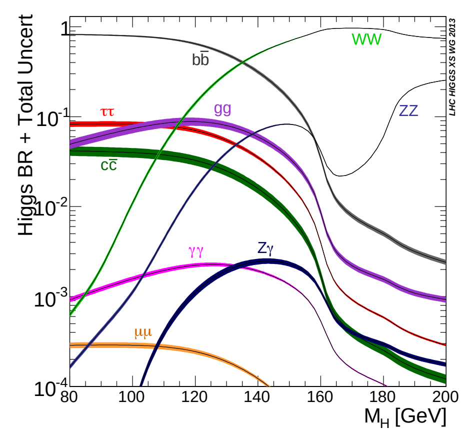

FIG. 2: Higgs branching ratio at the LHC at $\sqrt{s} = 13$ TeV as a function of the Higgs mass [30, 31, 32]. The width of the lines represents the total theoretical uncertainty in the cross section and in the branching fractions.

The channel in which the Higgs decays to W or Z vector bosons (that occur via a tree-level process, shown in figure 3), are examples of channels that probe the highest mass value whereas the one where the Higgs decays to a pair of photons (mediated by heavy quarks or the W boson, as shown in figure 4) is optimal in the region of lower masses.

In the hunt for the Higgs boson, all possible channels were searched by reconstructing the invariant-mass of the system formed by the Higgs decay products and looking for a peak. The most promising ones, due to aspects of theoretical cross-sections, branching ratios and experimental sensitivity were searched.

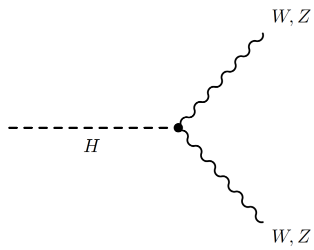

FIG. 3: Example of leading-order Feynman diagram for Higgs decays into a W or a Z boson.

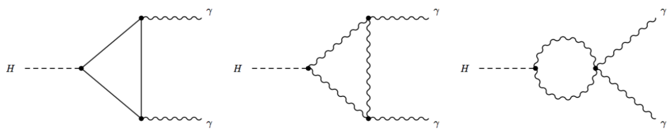

FIG. 4: Examples of leading-order Feynman diagrams of Higgs boson decay into a pair of photons.

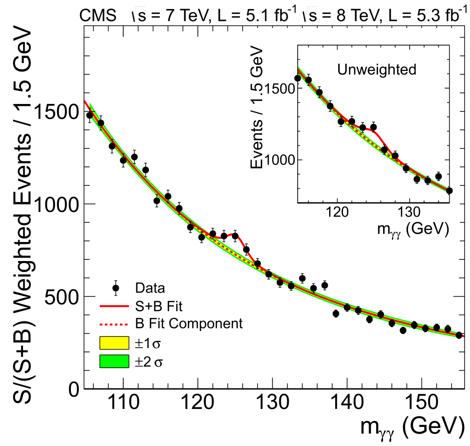

FIG. 5: The diphoton invariant-mass distribution for the 7 and 8 TeV data sets (points). The light and dark bands represent the ±1 and ±2 standard deviation uncertainties respectively on the background estimate [21].

III. THE HIGGS BOSON DISCOVERY

On July 4th 2012 at CERN, the collaborations of the LHC, ATLAS [19] and CMS [20], announced the observation of a new boson. At that time, the newly discovered particle was found by combining the data of a few of the Higgs decay channels.

At CMS, a fit to the invariant mass of the two high resolution channels, $H \to \gamma\gamma$ and $ZZ \to 4\ leptons$, gave a mass estimate of $125.3 \pm 0.4\ (stat.) \pm 0.5\ (syst.)$ GeV [21].

One of the most famous Higgs physics results is the 'bump' in the invariant-mass of the $\gamma\gamma$ channel that is shown in figure 5. In that figure, the diphoton invariant-mass distribution for the 7 and 8 TeV data sets (points) are shown and the Higgs resonance is clearly seen at around 125 GeV.

With the measurements done in 2012 it was possible to probe the interaction of the Higgs field with leptons and vector bosons as well as a measurement of the couplings, although without enough statistics to make any conclusive statements.

A combination of both CMS and ATLAS Run 1 data [22] resulted in the world's most precise estimate of the Higgs boson mass up to this date: $125.09 \pm 0.21(stat) \pm 0.11(syst)$ GeV.

After establishing the existence of the Higgs boson, Peter W. Higgs and François Englert, two of the theoreticians that idealized the spontaneous symmetry breaking mechanism, were awarded with the Nobel Prize in Physics 2013 "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."[23].

IV. MEASUREMENTS OF THE HIGGS BOSON PROPERTIES

With the discovery a new era has begun in particle physics and the measurements of the Higgs properties and its couplings, branching ratios and cross-sections have just started. Verifying that the newly discovered boson is indeed the SM Higgs boson requires to measure its properties.

Some of the SM Higgs boson properties are:

- Scalar boson: has spin zero
- Electrically neutral: has zero electrical charge
- Couples to the fundamental fermions
- Couples to the $W^{\pm}$ and Z^0 vector bosons
- Couples to itself: self-coupling.

In this review, the statistical approach used to define significance and for the combination of data between experiments will not be covered. For that the reader is referred to this note on the procedure for the Higgs mass combination: [24].

A. Higgs boson spin

The spin-parity quantum number of the Higgs boson can be probed by inferring on the angular distributions of its decay products. It is expected that a spin zero particle does not show any dependence on its kinematical variables whereas a non zero spin particle would show non-trivial correlations. The measurements [11] show consistency of the discovered particle with the Standard Model Higgs boson within 3σ.

B. Higgs boson couplings

It is known from the theory that the Higgs coupling should be proportional to the fermion mass. Figure 6 shows the measured couplings and proves it indeed [25]. The couplings are multiplied by a coupling modifier that would take into account a possible BSM effect. It is amazing to see that the couplings increase with the particle masses, as predicted by the Standard Model, taking into account the statistics available. The caveat of this plot is that it assumes there exists no other particles besides the ones from the SM and that there are no BSM decays. But it does show that the Higgs couples to the vector bosons and to the fundamental fermions. Therefore the importance of measuring these couplings, with as much precision as possible.

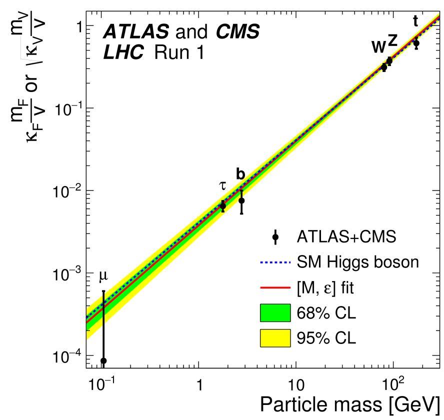

FIG. 6: Measured "couplings" of the Higgs boson [25].

One of the windows that was open with the Higgs discovery is the possibility of probing a new type of coupling that has no prior tests: the Yukawa coupling. For this reason the last updates from ATLAS and CMS that show the observation of the coupling of the Higgs to tau leptons, bottom and top quarks is of great importance as it sets the ground on studies of this kind of coupling.

1. $H \to \tau\tau$

The first observation of a Higgs boson decay to τ leptons by a single experiment was published by CMS in April 2018 [26]. The combination of data collected by the CMS experiment at the LHC in 2016 at a center-of-mass energy of $\sqrt{s} = 13\ TeV$ with proton-proton collision data at center-of-mass energies of 7 and 8 TeV led to the observation of $H \to \tau\tau$ events with a significance of 5.9 σ.

The production mechanisms for this type of signal are via gluon fusion and vector boson fusion. All τ decays were considered, except for the ones where the τ decays to muons or electrons because of the high background rate.

Figure 7 shows the Higgs peak in the mass distribution of a combination of some of the channels used in the data analysis. The red line represents the signal while the other colors describe the contributions from background processes like $Z \to \tau\tau$ or QCD multijets that can mimic the signal.

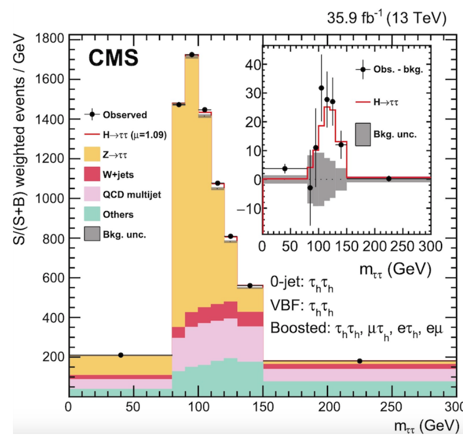

FIG. 7: Predicted and measured invariant mass of the final $\tau\tau$ system, $m_{\tau\tau}$.

The probing of the direct coupling of the Higgs to fermions, like the τ is necessary for establishing these particles' mass generation mechanism. In this sense, such a result is groundbreaking.

2. Higgs in associated production with top quark pairs, $t\bar{t}H$

The top quark is the heaviest fundamental particle and as the Higgs coupling is dependent on the mass of the particle it couples to, it is expected to have the strongest coupling. The Higgs boson is either produced through radiation from a top quark or in the fusion of a top quark-antiquark pair.

The associated production of the Higgs boson with a top quark pair is a direct probe of the top-Higgs coupling, therefore the importance of this measurement. The CMS experiment searched for this type of production [27] where the Higgs boson decays into a pair of vector bosons ($W^{\pm}$ or Z^0), a pair of τ leptons, in diphotons and $b\bar{b}$. The result of the different channels was combined and an excess of events was observed, with a significance of 5.2 σ.

This was a first measurement of its kind and establishes the tree-level coupling of the Higgs boson to the top quark, paving the way to understanding the coupling of the Higgs to fermions.

3. $H \to b\bar{b}$

The largest branching ratio of the Higgs boson is the one where it decays to a pair of bottom quarks, as can be seen in figure 2. But this Higgs decay channel is also the one with the most challenging background rates and for this reason the most sensitive production mode for probing the Higgs coupling to b-quarks is the one where the Higgs is produced in association with a $W^{\pm}$ or Z^0 vector boson.

The CMS experiment published a measurement [28] where it probes the coupling of the Higgs to a bottom quark using data with center-of-mass energies of $\sqrt{s} =$ 7, 8 and 13 TeV. It considered the production modes where the Higgs is produced in association with the vector bosons, a pair of top quark-antiquark and the direct production of Higgs boson via gluon fusion and vector boson fusion. In all the production modes the Higgs decays directly into a pair of b quarks.

The Higgs coupling to bottom quark was observed by the CMS collaboration with a significance of 5.6 σ by combining all the production channels. The measurement is consistent with the SM prediction within uncertainties.

V. CONCLUSION

In 2012, the long-sought boson that establishes the mechanism by which the $W^{\pm}$, Z^0 vector bosons and the fundamental fermions acquire their masses was discovered. It was the last missing piece of the Standard Model of Elementary Particles, one of the most successful physics theories.

It is though misleading to think that this chapter of physics is closed. On the contrary, the Higgs discovery opened a new era where a new kind of coupling that was never before probed can now be tested.

All the measurements done so far by the LHC experiments cover a broad list of the Higgs properties, like its spin and parity, its coupling to vector bosons and to the fundamental fermions. But these measurements have still a limited precision (of the order of 20%) while we do not know how the influence of processes from beyond the standard model would impact the current measurements. Could it be in 5% or 10% order?

A better precision on the measurements is needed. That only comes with more data, meaning more time collecting the data from the LHC proton-proton collisions, increasing its center-of-mass energy or colliding particles other than protons (for instance e^+e^- with the International Linear Collider).

The High-Luminosity LHC will be an upgrade of the LHC that is predicted to start in 2026 and intends to increase the amount of data to up to ten times.

At the HL-LHC and at the ILC it will also be possible to probe the Higgs self-coupling.

We have, thankfully, a long road ahead of us.

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