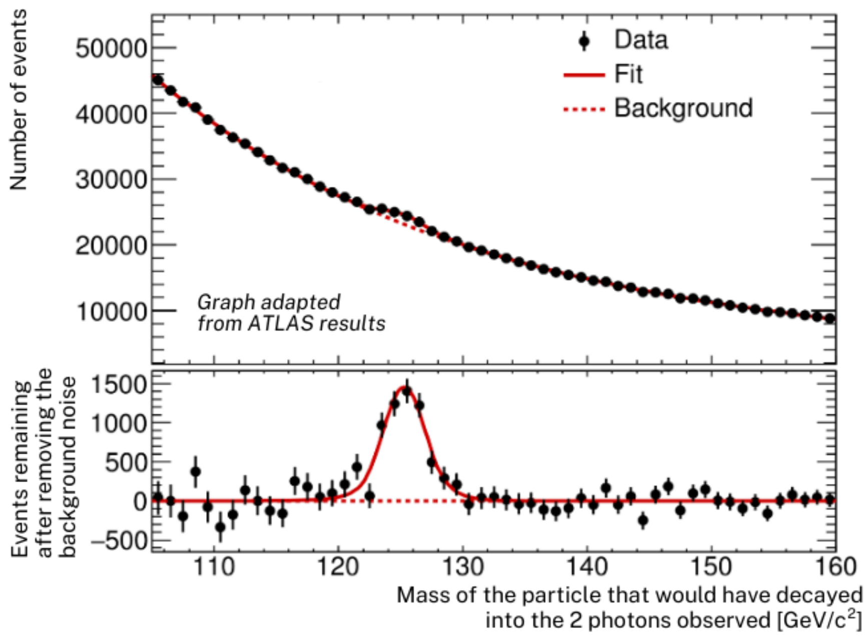
The Higgs Boson

The Higgs boson, the last particle in the Standard Model to have been discovered (in 2012 at the LHC), is of critical importance: the Higgs mechanism gives mass to all particles and is instrumental in unifying electromagnetic and weak interactions.



Credit: CERN

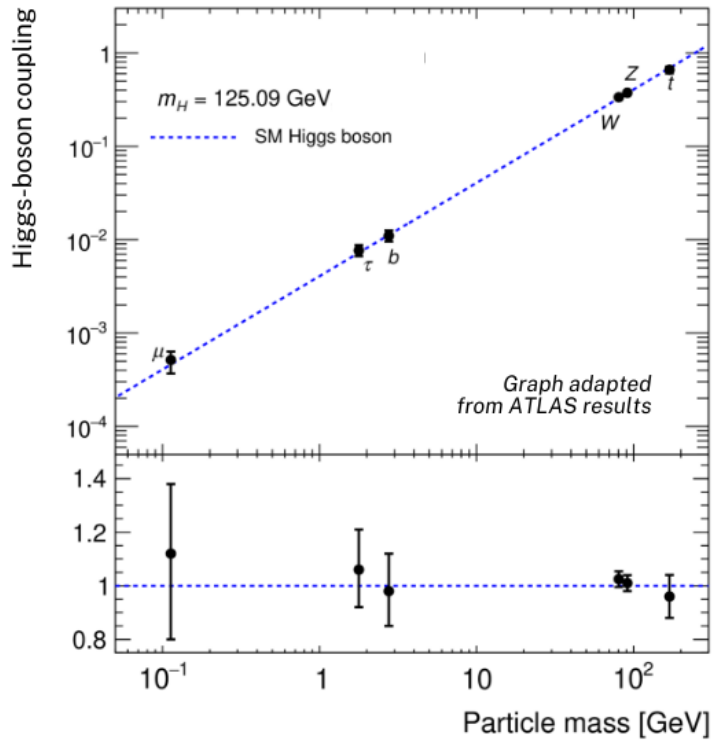
Decay of the Higgs boson into a pair of photons as seen by ATLAS (2019)

To obtain this result, ATLAS began by selecting events involving two photons that could have a common origin. By combining the information provided by the detector, we can calculate the mass of the particle that would have decayed into these two photons. ATLAS then 'counts' the number of such events in different mass intervals and compares the bar chart obtained (black dots) with two mutually exclusive models: the presence (solid red line) or absence (dotted red line) of a Higgs boson. A 'bump', present in the data between 120 and 130 GeV/c^2 range, is clearly visible in the lower graph, which counts the excess of events compared with the 'no Higgs boson' hypothesis – experimental uncertainties being taken into account. The visible structure is sharp enough to indicate the presence of a new particle! Note that it contains barely a few hundred events, compared with the five billion collisions recorded by ATLAS, out of a total of six million billion proton-proton collisions produced at the LHC.

In particle physics, every interaction is carried by one or more particles, whose mass is inversely proportional to the range of the interaction. For example, two electrically charged particles interact by exchanging photons, which have zero mass because the electromagnetic interaction has an infinite range.

The weak interaction is responsible for certain decays of radioactive atomic nuclei. This short-range interaction involves the exchange of very massive particles – nearly 100 times the mass of a proton! – the W^+, W^- and Z^0 bosons.

But during the first half of the 20th century, physicists' calculations produced infinite results when they tried to predict the probability of decay caused by the weak interaction. To avoid these absurd results, they unified the weak and electromagnetic forces into a single interaction. Their equations then became satisfactory, with one slight 'problem': all the particles in the Standard Model had to have zero mass, which was completely unrealistic!



Credit: CERN

In the early 1960s, several theorists, including Peter Higgs, François Englert and Robert Brout, realised that particles could be given masses by adding an extra theoretical ingredient, the 'Higgs field'. All the Standard Model particles are embedded in this field, which fills space. The interactions of the Higgs field with the W^+, W^- and Z^0 bosons and with the photon provide mass to the first three particles, but not to the photon. Similarly, this field 'slows down' quarks and leptons to a greater or lesser extent as they travel, which explains their very different masses: the more intensely a particle interacts with the Higgs field, the more this field 'sticks to it' – the slower the particle moves – and the more massive the particle is.

But how can the existence of this 'Higgs field' be verified? Fortunately, there is a witness, a particle called the 'Higgs boson'. According to the Standard Model, the Higgs boson decays very rapidly into lighter particles. As it is related to the mechanism that seems to confer elementary particles their masses, it is more likely to decay into (heavy) W and Z bosons, or (heavy) quarks such as the bottom quark, than into light particles.

On 4 July 2012, two CERN experiments, ATLAS and CMS, announced the discovery of a new particle that decays in a very similar way to the Standard Model Higgs boson. Its mass – around 125 GeV/c^2 – is only slightly heavier than that suggested by the LEP measurements. Since all the properties measured match predictions, it seems certain that this particle is 'a' Higgs boson, the first representative of a new type of elementary particle. Is it the only one? Time will tell.

Thanks to its properties, the Higgs boson could decay into any new massive particle, such as dark matter. It is also involved in cosmological models, and its study will remain a research priority for several decades.

Higgs-boson coupling

This graph represents the intensity of the Higgs boson's interaction (or coupling) with other Standard Model particles measured by ATLAS. It shows the peculiar affinity of the Higgs boson to mass: the larger the mass of an elementary particle, the stronger its interaction (or coupling) with the Higgs boson.

Translated from 'Le boson de Higgs',* Passeport pour les deux infinis*, IN2P3/Dunod, https://pass2i.ijclab.in2p3.fr/ (French); updated with ICHEP2024 conference (https://ichep2024.org) for IPPOG