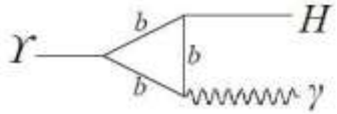
Search and discovery of the Higgs boson

Introduction

In particle physics, there was a little understanding of the masses of the various elementary particles.
For example, even though the masses of the electron and the muon have both been measured to very high accuracy, there is no understanding why the muon is about 200 times heavier than the electron.
As another example, the mass of the top quark was not known even roughly until it was observed in Fermilab in 1995.
It is therefore not surprising that there was no guess on the mass of the Higgs particle even many years after it was proposed theoretically in 1964 [1].

<u>For this reason, the experimental search for this Higgs particle must cover a very large range of mass.</u>

80s search

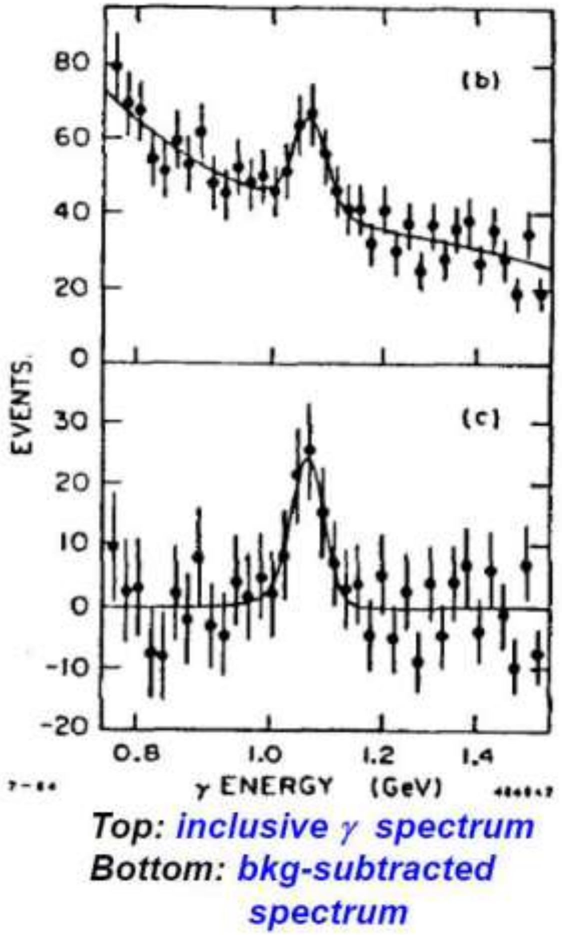


- Crystal Ball Collaboration using the DORIS electron–positron collider at DESY (Germany).
  They studied the decay of the meson $\Upsilon \rightarrow H + \gamma$ and found a peak in the spectrum, corresponding to a Higgs mass of 8.32 GeV/c2 with high statistical significance of 5sigma.[3] (Not confirmed by CESR)

- The SINDRUM Collaboration at the Paul Scherrer Institute (Switzerland) proton cyclotron looked for very low-mass Higgs particle through the decay $\pi^+ \rightarrow e^+ + v_e + H$ with $H \rightarrow e^+ + e^-$, but did not find a signal. [4]

- The CLEO Collaboration at CESR of Cornell University (USA) searched for the Higgs particle in B decay: B -> K + H with $H \rightarrow \mu^+\mu^-$, $\pi^+\pi^-, K^+K^-$; but again did not find any signal, not confirming DESY's results. [5]

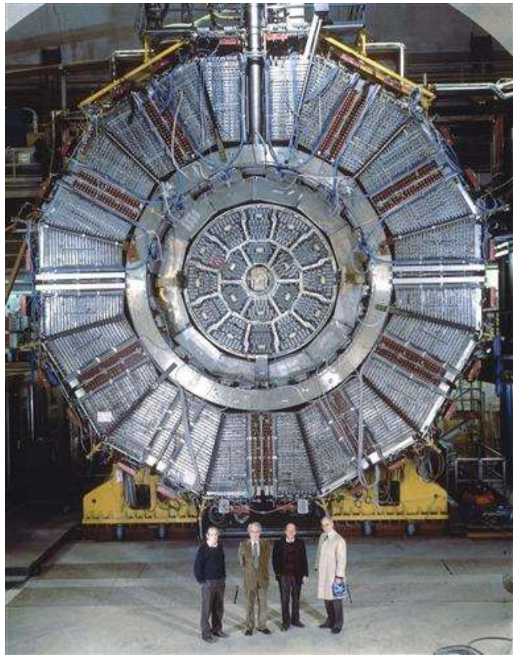
<u>The conclusion from such searches is that the Higgs mass was likely to be larger than 8-9 GeV/c2</u>



Energy spectrum of photons from the Υ decay[2]

LEP (CERN, Switzerland-France)

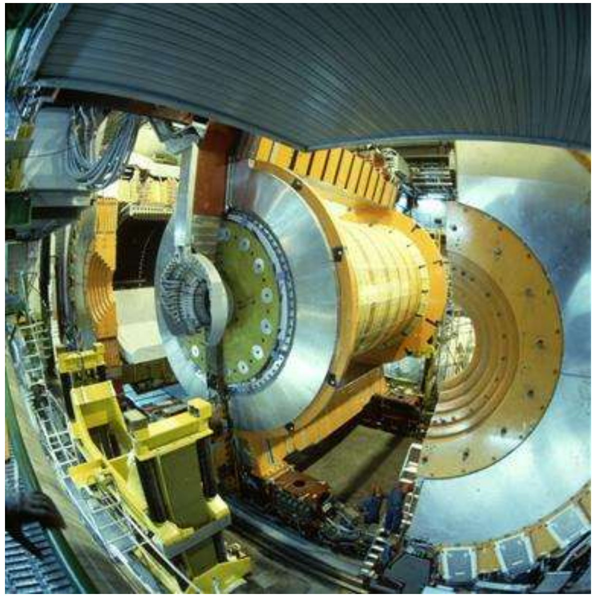
27 km ring electron-positron collider



ALEPH

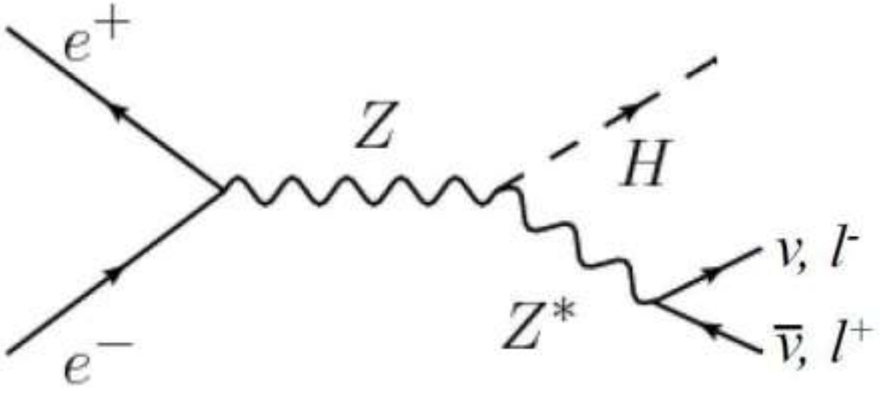
L3

DELPHI



OPAL

LEP 1 (1989-1995)

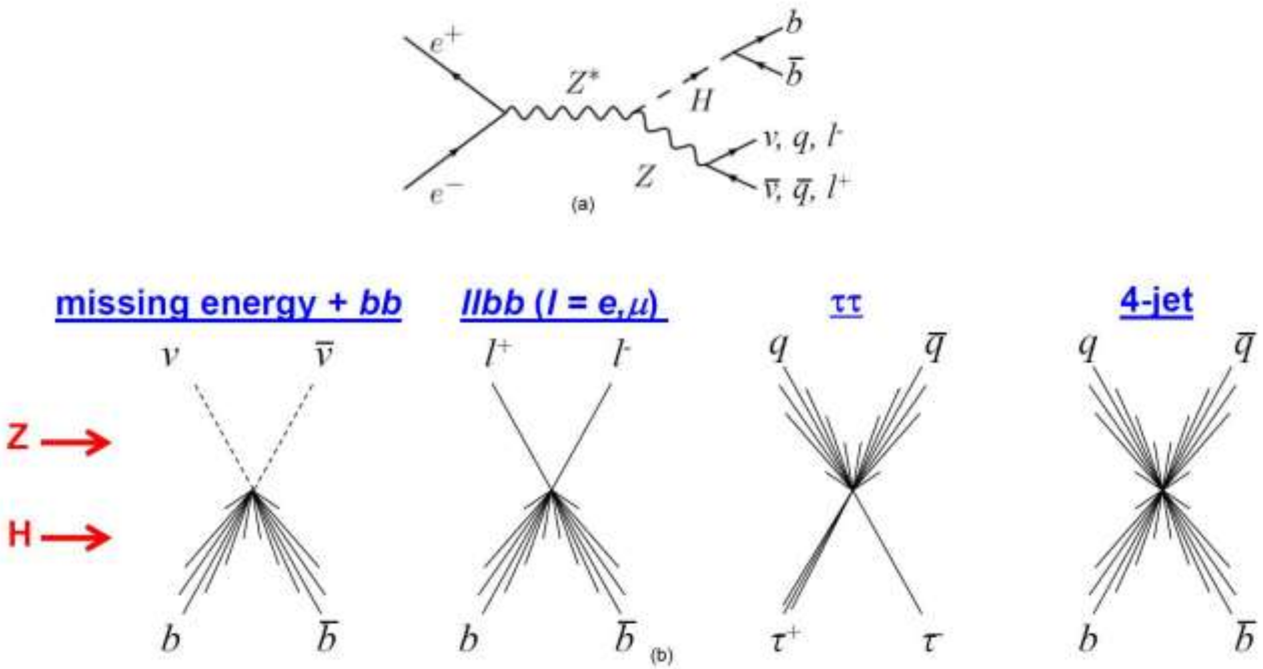


- Center-of-mass energy was 91.18 GeV (Z peak). Since the Z mass is much larger than those of the particles used to search for the Higgs particle, LEP1 provided a significantly larger range for the Higgs mass.
- In the first channel $Z \rightarrow l^+l^- \ (l = e, \mu)$, the observation of the two charged leptons in the decay product gives very clean events. The second channel $Z \ \rightarrow \nu_l \, \bar{\nu}_l$, on the other hand, has the important advantage of a larger branching ratio.

<u>The data from LEP1 excludes the mass of the Higgs particle to be below 65 GeV/c2. [6]</u>

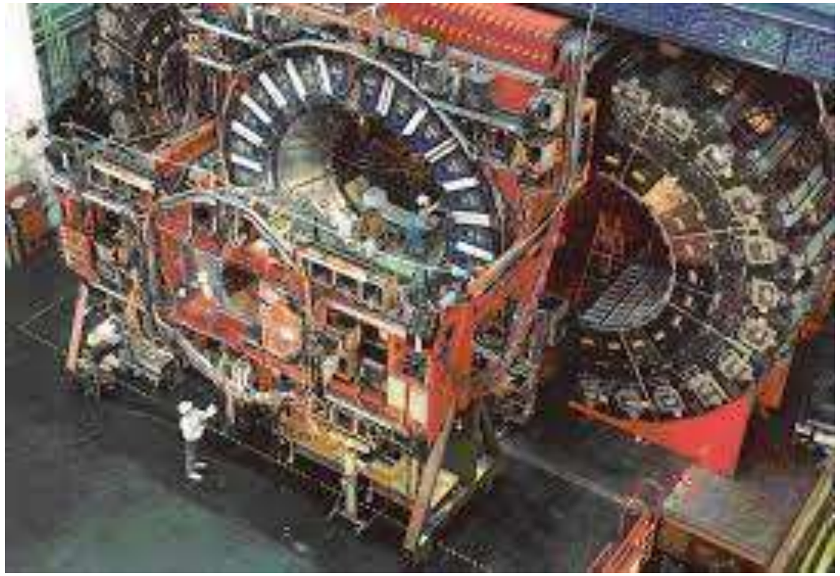
and LEP2 (1995-2000)

- 1995 upgrades.
- Until the year 1999, with LEP running at a center-of-mass energy up to 200 GeV, no indication was found of the production of the Higgs particle. The 95% confidence limit for the lower bound of the Higgs mass was 107.9 GeV/c2. This lower bound is essentially the difference of the LEP energy and the Z mass: 200 – 91,18 = 108,82 .
- After six machine upgrades the center-of-mass energy bumps up to 209GeV, making LEP sensitive in principle to a Higgs mass of 107,9+9=116,9 GeV/c2.
- Until November 2000, ten significant Higgs candidates showed up, found by both cut-based and neural network analyses. None of them proved to be the right one. [7]
- LEP was shut down in the first week of November 2000

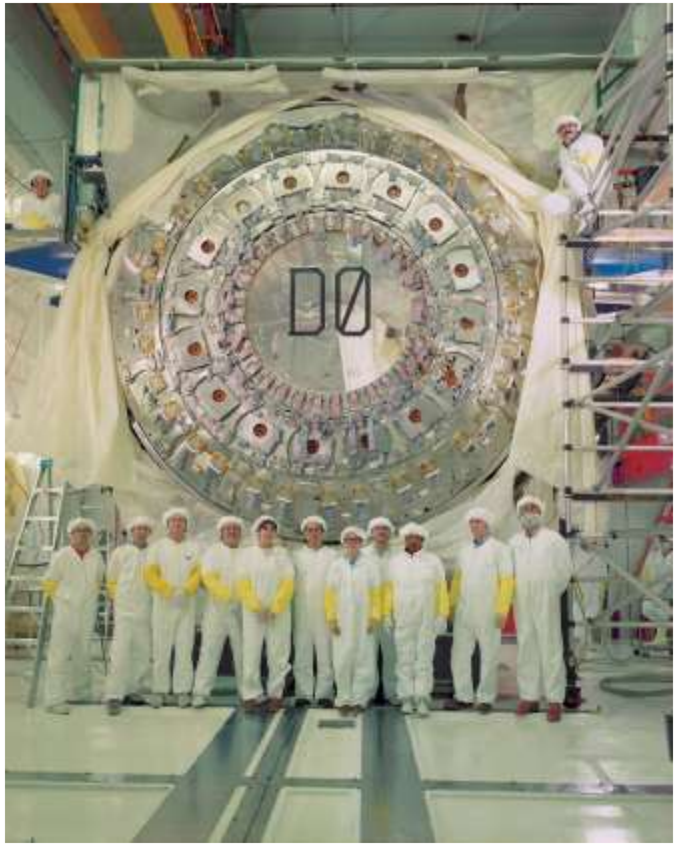


TEVATRON (Fermilab, USA)

1km radius proton-antiproton collider. It discovered the top quark and measured its mass in 1995.



CDF



D0

TEVATRON (Fermilab, USA)

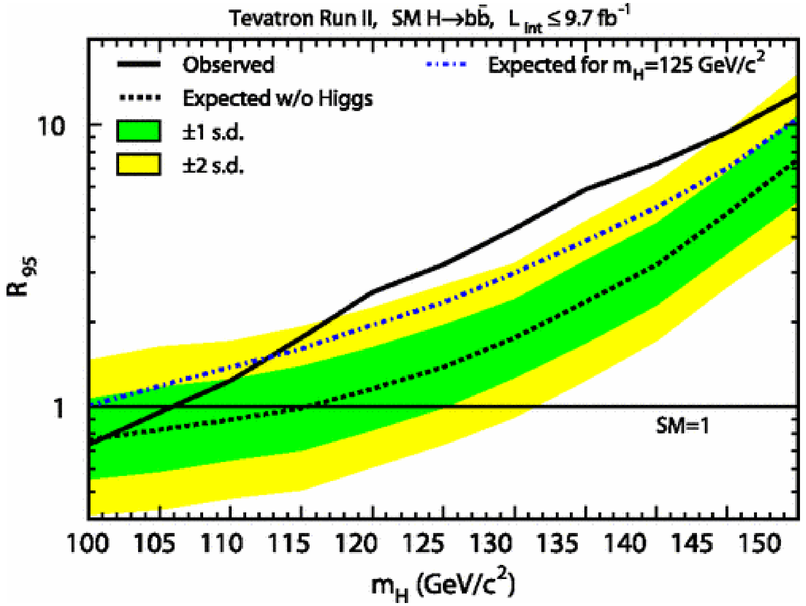
- After LEP was shut down for ten years the Tevatron Collider was the only place to search for the Higgs particle. Unfortunately, during these ten years, it did not manage to discover the Higgs particle; the main reason for this was that it did not produce sufficient amount of integrated luminosity (it did not work as much as it should).
- Its maximum center-of-mass energy was 1.96 TeV, making the it the first collider in TeV energy, hence the name.
- The Tevatron Collider was shut down in 2011 after 24 years of operation.

TEVATRON (Fermilab, Chicago, USA)

In July 2011, with up to L=8.6 fb^-1, the combined Tevatron analysis was able to exclude (at the 95% CL) standard model Higgs boson masses between 156 GeV/c2 and 177 GeV/c2.

In ICHEP (4-11 July) 2012, the Tevatron experiments gave the result of the Higgs search combination with their full dataset (up to L=10 fb^-1). They set a 95% CL exclusion for Higgs boson masses between 100 GeV/c2 and 103 GeV/c2, and between 147 GeV/c2 and 180 GeV/c2.

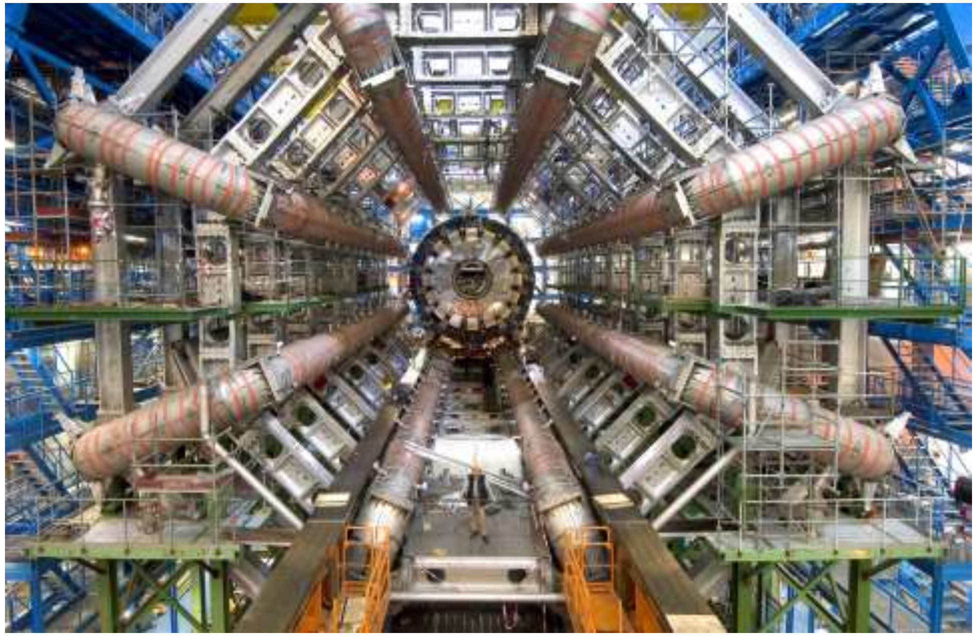
More interestingly, they observed a 3σ excess between 115 GeV/c2 and 140 GeV/c2. The excess was concentrated in the $H \to b\bar{b}$ channel. [8],[9]



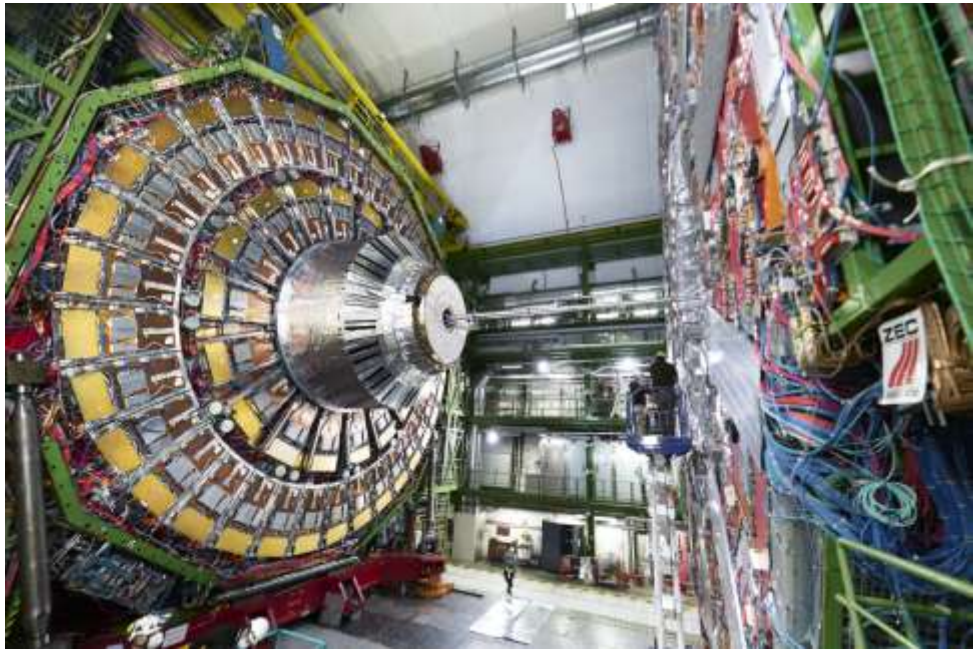
The observed 95% credibility level upper limits on SM Higgs boson production (R95) as a function of Higgs boson mass.

LHC (CERN, Switzerland-France)

27km ring proton-proton collider, design center-of-mass energy 14TeV



ATLAS



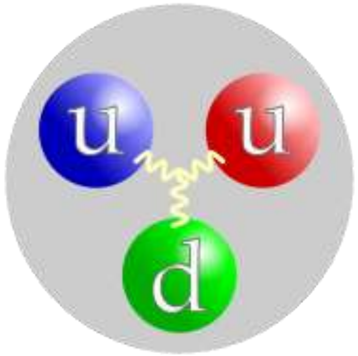
CMS

- Center-of-mass energy: 7TeV in 2010, 8Tev in 2012.
- In both of these two experiments, the mass range of the Higgs particle covered is from 600 GeV/c2 down to about 110 GeV/c2, which is the lower limit of the Higgs mass from LEP.

But also ALICE and LHCb

LHC: PRODUCTION of the HIGGS

- To a good approximation, a proton consists of two u quarks, one d quark, and a number of gluons. Since the coupling of the Higgs particle to an elementary particle is proportional to its mass, there is little coupling between the Higgs particle and these constituents of the proton. Instead, some heavy particle first needs to be produced in a proton-proton collision at the LHC, and then is used to couple to the Higgs. Being the heaviest, the t quark is used to produce the Higgs.
- The top quark can only be produced together with an anti-top quark or an antibottom quark. Since the top quark has a charge of +2/3 and is a color triplet, such pairs can be produced by a photon: $\gamma \rightarrow t\bar{t}$; by a Z: $\mathrm{Z} \rightarrow t\bar{t}$; by a W: $W^{+} \rightarrow t\bar{b}$; or by a gluon: $\mathrm{g} \rightarrow t\bar{t}$.
- There are no photon, Z or W in a proton; the last one is by far the most important production process for the top quark.



LHC: PRODUCTION of the HIGGS

- GLUON-GLUON FUSION

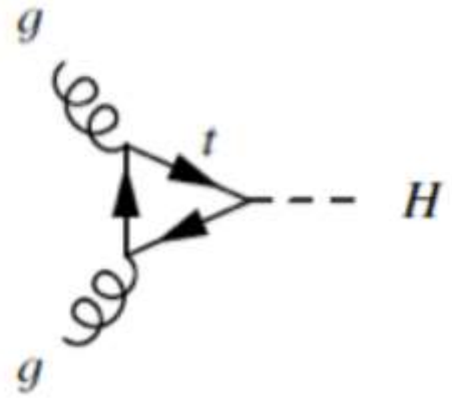
  Because of color conservation – the gluon has color but not the Higgs particle – the top and anti-top pair produced by a gluon cannot annihilate into a Higgs particle. In order for this annihilation into a Higgs particle to occur, it is necessary for the top or the anti-top quark to interact with a second gluon to change its color content. It is therefore necessary to involve two gluons, one each from the protons of the two opposing beams.

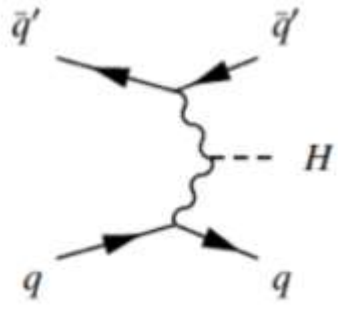
- VECTOR BOSON FUSION

  A quark from one of the incoming protons emits a Z or a W+ while another quark from the other incoming protons provides a Z or a W-. The ZZ pair or the W+W- pair then “fuses” to produce the Higgs particle.

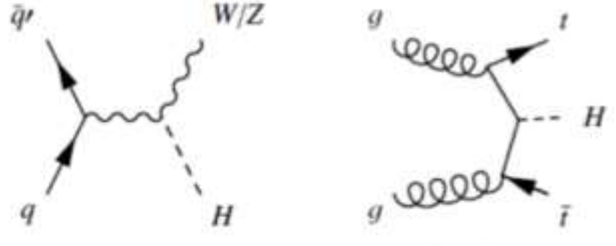
- OTHER PROCESSES

  Higgs production in association with a W or a Z and Higgs production in association with a top-antitop pair.



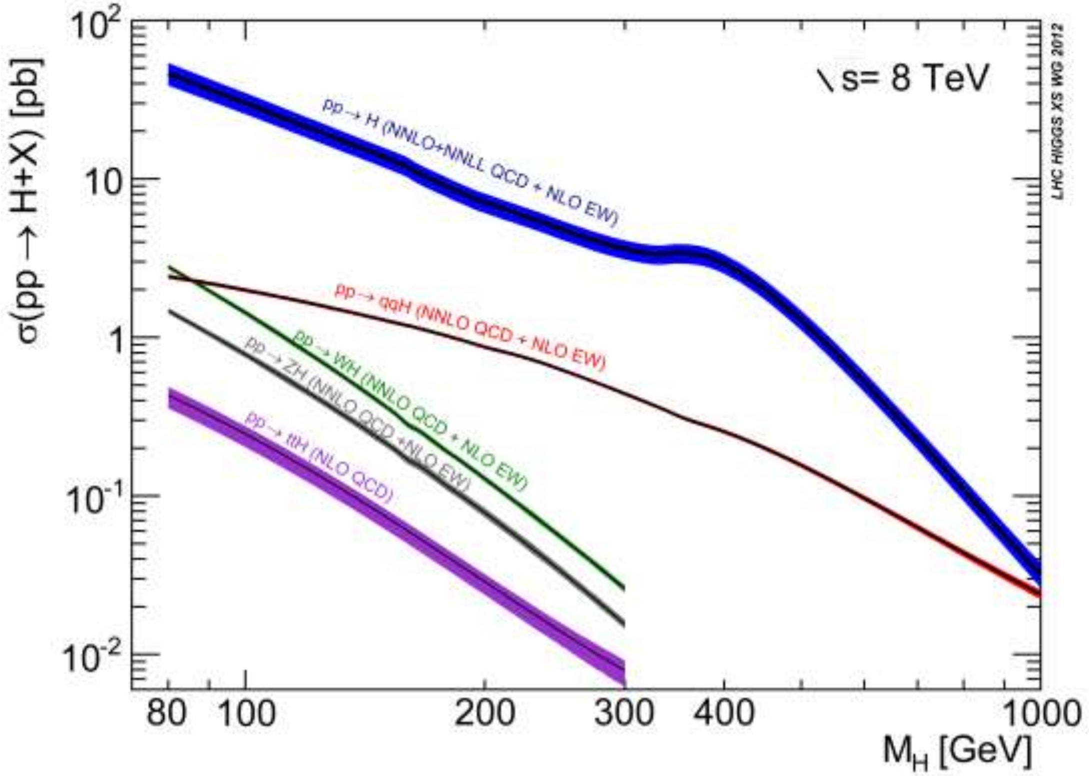


VBF



(a) VH (b) $t\bar{t}H$

LHC: PRODUCTION of the HIGGS



Higgs production cross sections from gluon-gluon fusion (top curve), vector boson fusion (red curve), and three associated production processes at the LHC center-of-mass energy of 8 TeV. (log scale on vertical axis) [10]

It is seen that, for the relatively low (~100Gev) masses of the Higgs particle, VBF cross section is less than 10% of that of gluon-gluon fusion.
Thus, through gluon-gluon fusion, the gluon contributes about 90% of Higgs production at the LHC.
(If there were no gluon, the Higgs particle could not have been discovered for many years!)

LHC: DECAY of the HIGGS

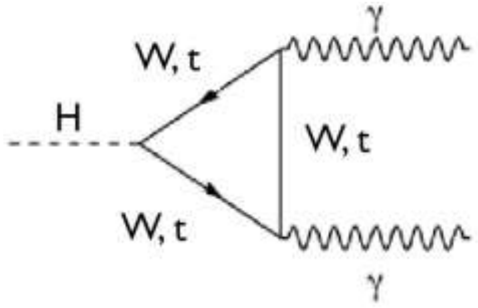
LOW MASS RESOLUTION

- $H \rightarrow W^{+}W^{-}$
  In this decay process there are two possibilities: both W's decay leptonically, or one of the W's decays leptonically while the other decays hadronically. It has not been possible to analyze the channel where both W's decay hadronically, the reason being that the QCD background is too high. When at least one of the two W's decays leptonically as indicated above, there is either one or two neutrinos in the decay product, making it impossible to determine the mass of the Higgs particle event by event. It has a large banching ratio but suffers from these problems.
- $H \rightarrow \tau^{+}\tau^{-}$
  The τ has two different types of decay modes: leptonic and hadronic. For the leptonic decay modes, there are two neutrinos in the final state; for the hadronic modes, there is one. Therefore, for this decay, there are at least two neutrinos, making it impossible to determine the mass of the Higgs particle event by event.
- $H \rightarrow b\bar{b}$
  For Higgs mass below about 135 GeV/c2, the branching fraction for this decay is large. Unfortunately, the signal for this decay is overwhelmed by the QCD production of bottom quarks.

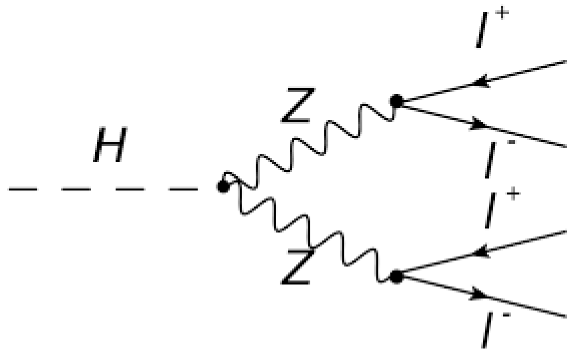
LHC: DECAY of the HIGGS

HIGH MASS RESOLUTION

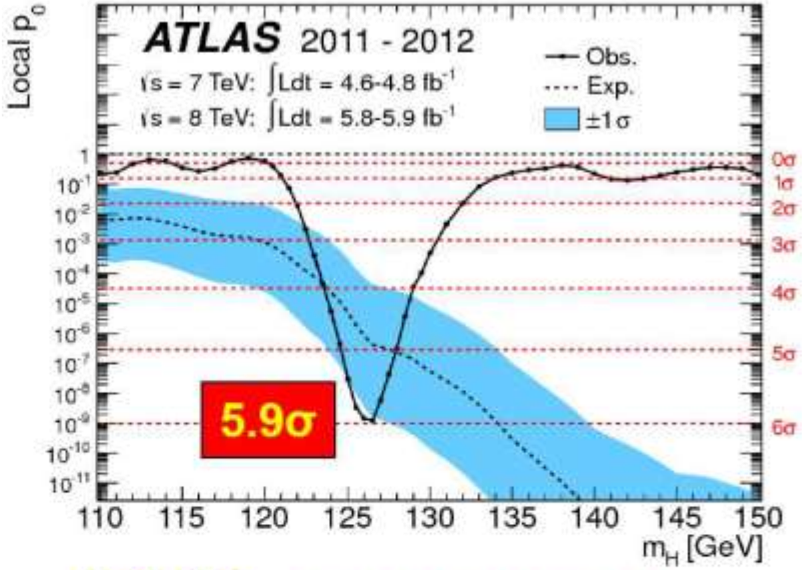
- $H \rightarrow \gamma\gamma$
  Good process to measure since it has clear products (little background) and good photons detectors at ATLAS and CMS.

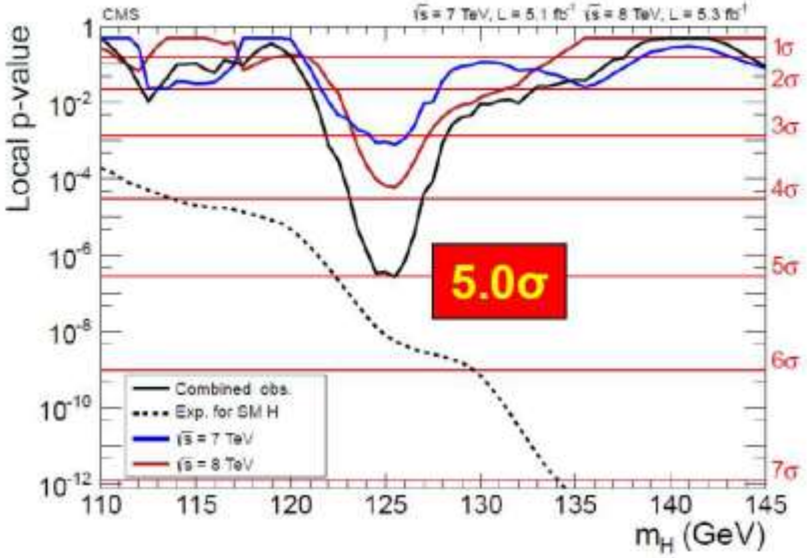


- $H \rightarrow ZZ\ , Z \rightarrow l\bar{l}$
  Being $l = e, \mu$, the final state consists of 4 charged leptons easy to measure (neutrino-antineutrino decay are not measurable at ATLAS and CMS).
  The problem of the so called «golden channel» is the low branching ratio.



DISCOVERY AT LHC IN 2012





ATLAS PLB 716 (2012) 1-29, *Sept 17 (2012)*

Largest local excess:

5.9σ at m_H= 126.5 GeV

H→γγ, bb, ττ, WW(lνlν, lνqq), ZZ(4l, llνν, llqq)

CMS PLB 716 (2012) 30-61, *Sept 17 (2012)*

Largest local excess:

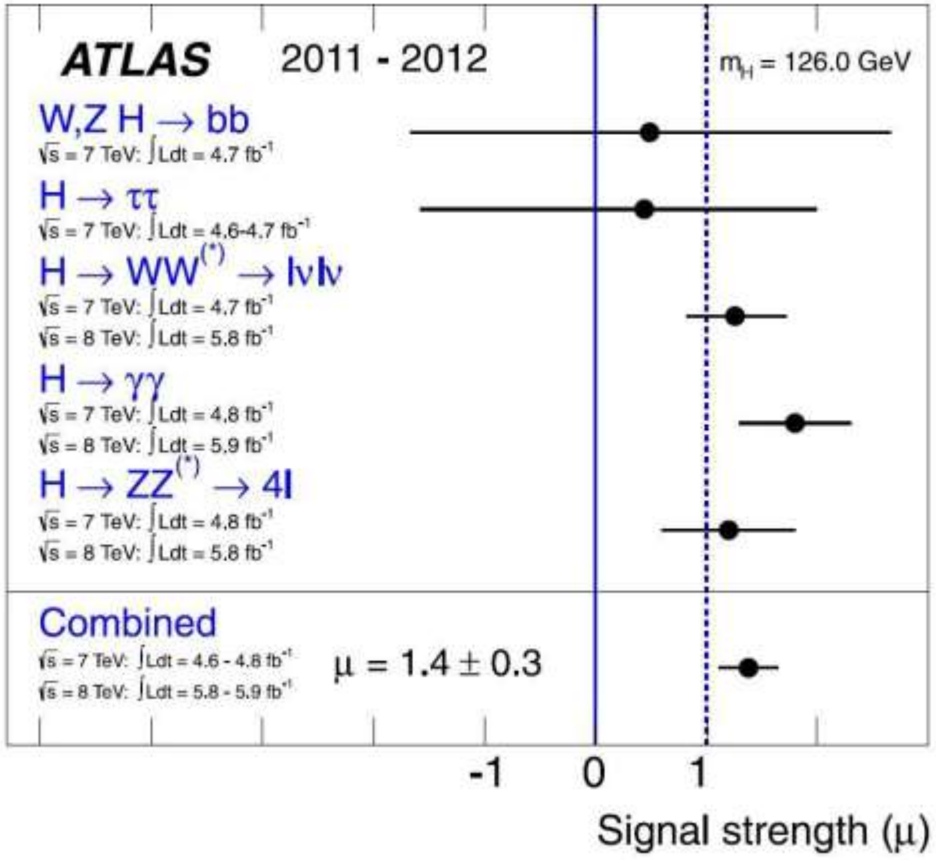
5.0σ at m_H= 125.5 GeV

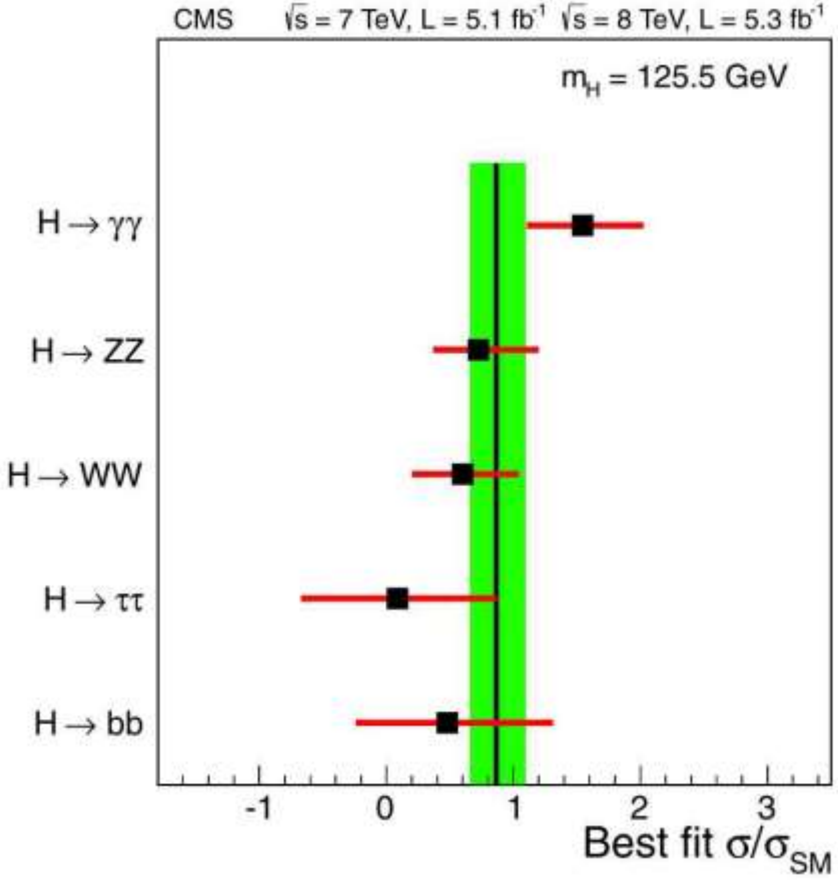
H→γγ, bb, ττ, WW(lνlν), ZZ(4l, llττ, llνν, llqq)

Background fluctuation probability p0 in the Higgs search using the full 2011 datasets and partial 2012 datasets collected by ATLAS (left) and CMS (right), as shown in the discovery publication submitted by the ATLAS and the CMS Collaborations. The results were obtained by combining all available standard model decay channels. The Gaussian significances corresponding to the peak in p0 is 5,9σ for ATLAS and 5σ for CMS. [11],[12]

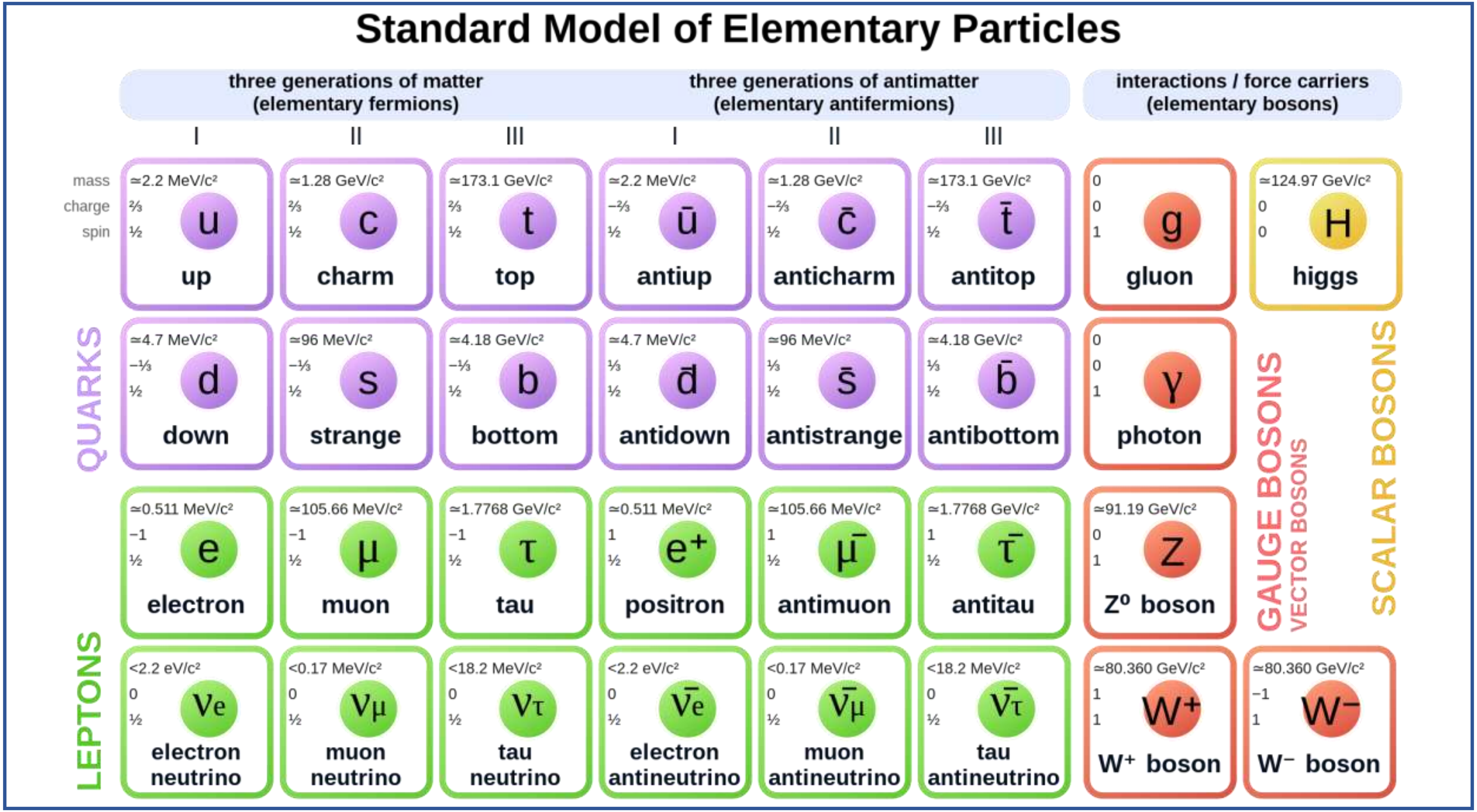
p0 or p-value means the probability that the background fluctuates to the observed data (or higher).

DISCOVERY AT LHC IN 2012





Measurements of the signal strength $\mu = \sigma/\sigma_{SM}$ for the individual channels and their combinations in July 2012 in ATLAS (left) and CMS (right). [11],[12]


Standard Model of Elementary Particles
three generations of matter (elementary fermions)
three generations of antimatter (elementary antifermions)
interactions / force carriers (elementary bosons)
I
II
III
I
II
III
mass
charge
spin
≃2.2 MeV/c² ⅔ ½ u up
≃1.28 GeV/c² ⅔ ½ c charm
≃173.1 GeV/c² ⅔ ½ t top
≃2.2 MeV/c² −⅔ ½ ū antiup
≃1.28 GeV/c² −⅔ ½ c̄ anticharm
≃173.1 GeV/c² −⅔ ½ t̄ antitop
0 0 1 g gluon
≃124.97 GeV/c² 0 0 H higgs
QUARKS
≃4.7 MeV/c² −⅓ ½ d down
≃96 MeV/c² −⅓ ½ s strange
≃4.18 GeV/c² −⅓ ½ b bottom
≃4.7 MeV/c² ⅓ ½ d̄ antidown
≃96 MeV/c² ⅓ ½ s̄ antistrange
≃4.18 GeV/c² ⅓ ½ b̄ antibottom
0 0 1 γ photon
≃0.511 MeV/c² −1 ½ e electron
≃105.66 MeV/c² −1 ½ μ muon
≃1.7768 GeV/c² −1 ½ τ tau
≃0.511 MeV/c² 1 ½ e⁺ positron
≃105.66 MeV/c² 1 ½ μ̄ antimuon
≃1.7768 GeV/c² 1 ½ τ̄ antitau
≃91.19 GeV/c² 0 1 Z Z⁰ boson
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS
LEPTONS
<2.2 eV/c² 0 ½ νe electron neutrino
<0.17 MeV/c² 0 ½ νμ muon neutrino
<18.2 MeV/c² 0 ½ ντ tau neutrino
<2.2 eV/c² 0 ½ ν̄e electron antineutrino
<0.17 MeV/c² 0 ½ ν̄μ muon antineutrino
<18.2 MeV/c² 0 ½ ν̄τ tau antineutrino
≃80.360 GeV/c² 1 1 W⁺ W⁺ boson
≃80.360 GeV/c² −1 1 W⁻ W⁻ boson

NOBEL PRIZE IN 2013

François Englert and Peter W. Higgs are jointly awarded the Nobel Prize

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Thank you