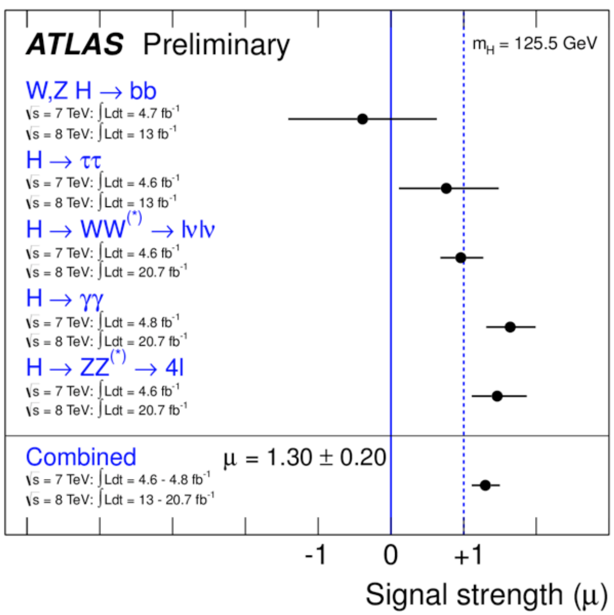
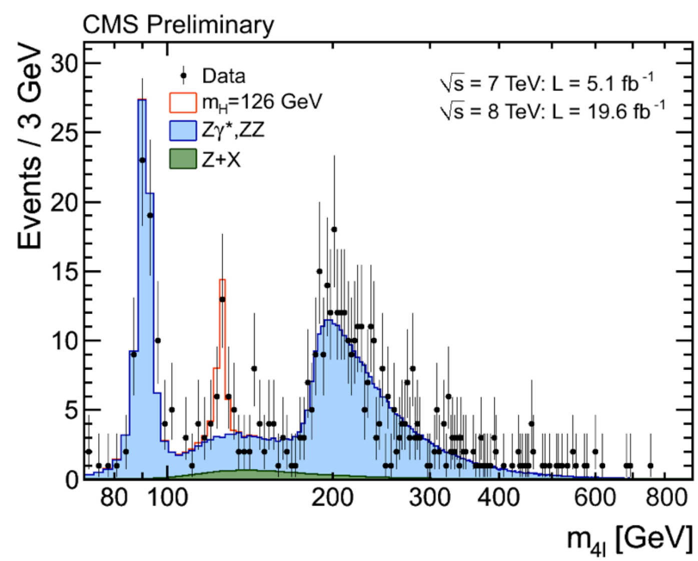
Higgs Physics (I): the discovery

Ian Low
Argonne/ Northwestern
August, 2013 @ SI 2013 Korea





2012 is the Year of the Higgs!

The "Science" magazine picked the Higgs boson as Breakthrough of the Year:

2012 is the Year of the Higgs!

The "Time" magazine picked a particle physicist to be No. 5 on the list of "Person of the Year":

(She leads the ATLAS collaboration at the LHC.)

So what is the Higgs boson?

- The Higgs boson is often "sold" as the *origin of mass*.

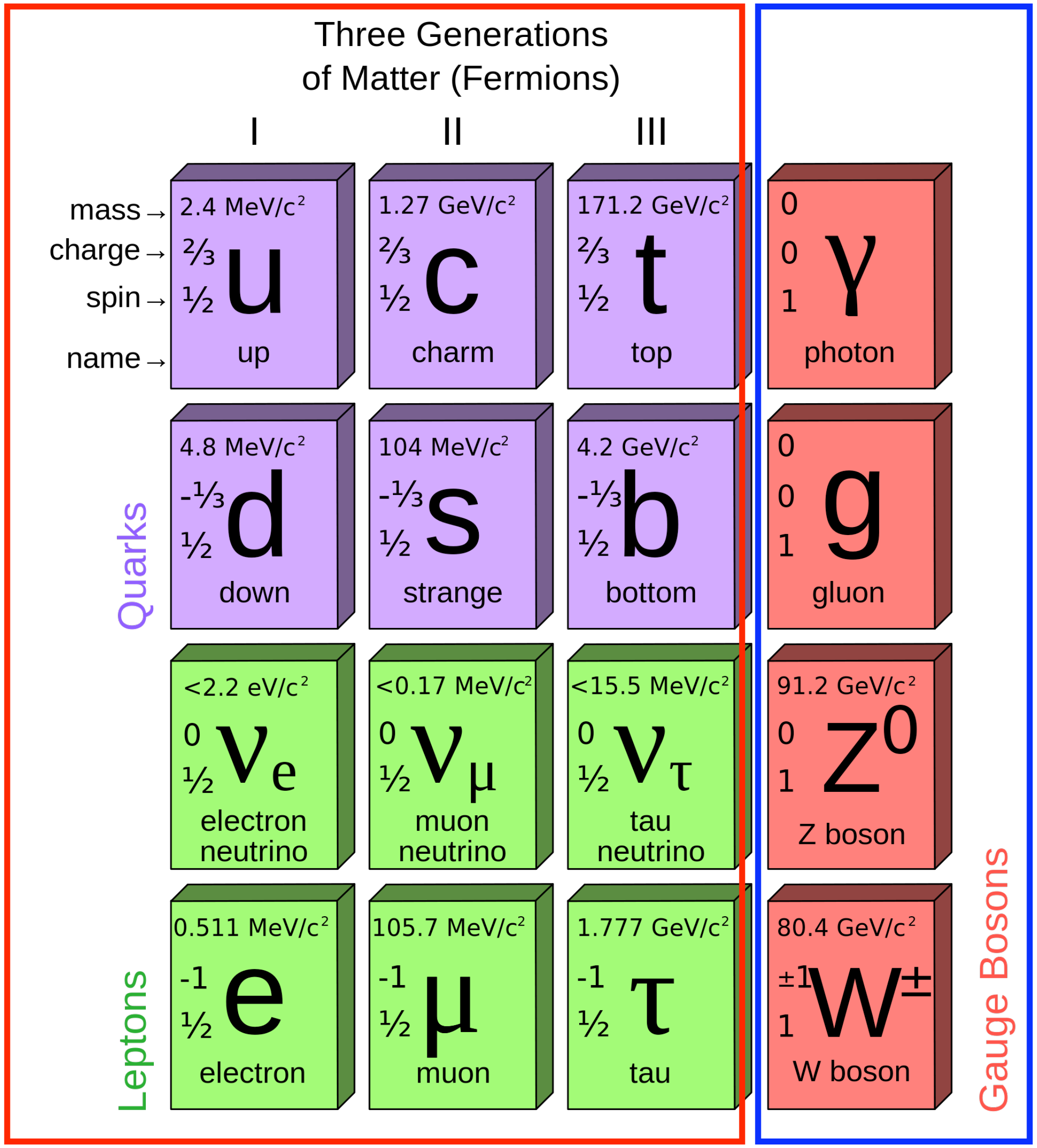
This statement needs qualifications:

1) The majority of the mass in our Universe is carried by "dark matter" --- we do not know whether it has anything to do with Higgs!
2) Even among the visible matter, the majority of the mass is carried by protons and neutrons -- they get their masses from Quantum Chromodynamics (QCD), not from the Higgs!
3) Even among the elementary particles, not all of them get masses from the Higgs -- we do not know whether the neutrino mass comes from the Higgs!

So particle physicists really meant that the Higgs is the origin of mass for *almost* all of elementary particles.

We believe all massive elementary particles, except neutrinos, get their masses from the Higgs boson.

Fermions have half Integer-spin.



Bosons have integer-spin.

For example, an electron does get its mass from the Higgs boson in the standard model of particle physics.

Citation: J. Beringer *et al.* (Particle Data Group), PR **D86**, 010001 (2012) (URL: http://pdg.lbl.gov)

LEPTONS

e

$J = \frac{1}{2}$

Mass $m = (548.57990946 \pm 0.00000022) \times 10^{-6}$ u

Mass $m = 0.510998928 \pm 0.000000011$ MeV

$\left|m_{e^+} - m_{e^-}\right|/m < 8 \times 10^{-9}$, CL = 90%

$\left|q_{e^+} + q_{e^-}\right|/e < 4 \times 10^{-8}$

Magnetic moment anomaly

$(g-2)/2 = (1159.65218076 \pm 0.00000027) \times 10^{-6}$

$(g_{e^+} - g_{e^-}) \,/\, g_{\text{average}} = (-0.5 \pm 2.1) \times 10^{-12}$

Electric dipole moment $d < 10.5 \times 10^{-28}$ $e\,$cm, CL = 90%

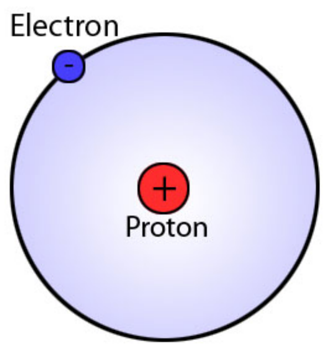
Mean life $\tau > 4.6 \times 10^{26}$ yr, CL = 90% [a]

But why should you care?

For example, an electron does get its mass from the Higgs boson in the standard model of particle physics.

Can you imagine a world with a massless electron??

Let's consider the hydrogen atom:



$$r_n = \frac{n^2 h^2}{4\pi^2 e^2 m_e}$$

So if the electron were massless, the hydrogen atom would not form!

Why do we need the Higgs to give the electron a mass?

It has to do with these two Nobel laureates:

Chen Ning Yang

Tsung-Dao (T.D.) Lee

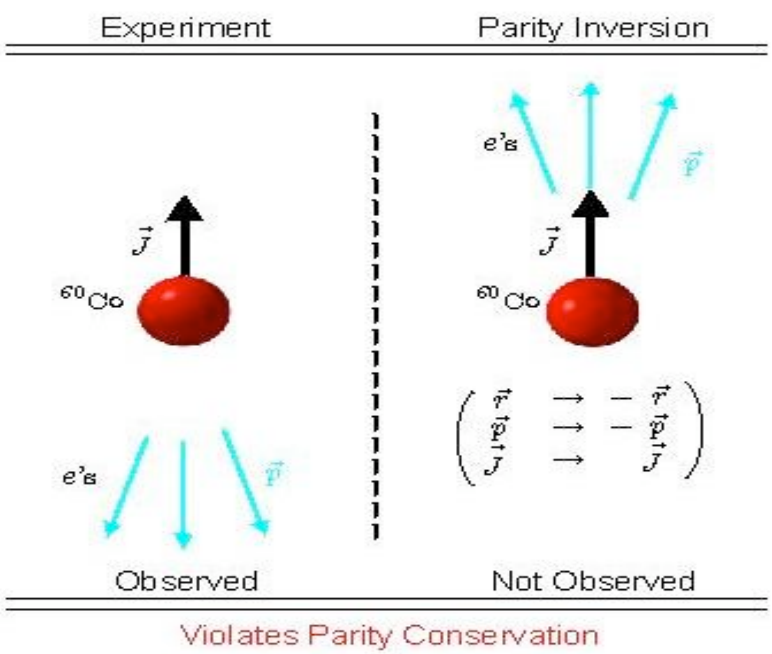
Lee and Yang suggested in 1956 that parity may be violated in weak interactions!

Parity is the operation of space inversion:

$$P : \begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}.$$

$$\begin{aligned} \vec{r} \quad &\rightarrow \quad -\vec{r} \\ \vec{L} = \vec{r} \times \vec{p} \quad &\rightarrow \quad \vec{L} \end{aligned}$$

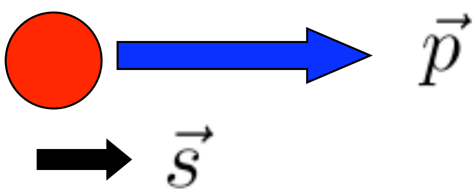
Physicists used to believe that, if an event occurs in nature, the image of that event under parity must also occur….



The fact that parity is broken in nature creates a problem for the mass of the electron….

This is because electron's mass implies invariance under parity!

There is a simple, albeit somewhat naïve, argument:



The fact that parity is broken in nature creates a problem for the mass of the electron….

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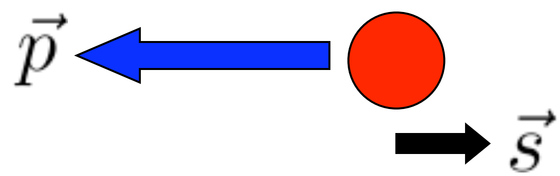
There is a simple, albeit somewhat naïve, argument:

Now perform a Lorentz boost
to a frame where the momentum
is reversed:



The fact that parity is broken in nature creates a problem for the mass of the electron….

This is because electron's mass implies invariance under parity!

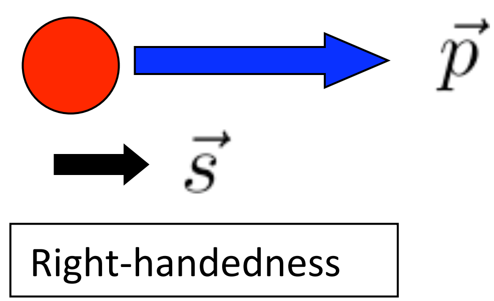
There is a simple, albeit somewhat naïve, argument:

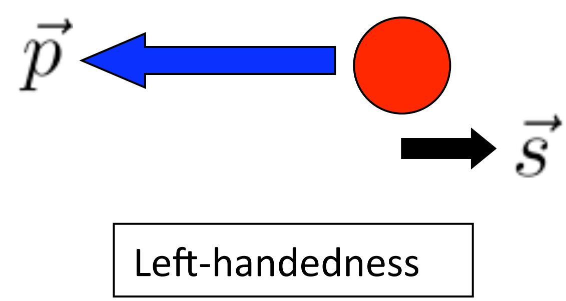
These two states map into each other under parity!

For a massive particle, both handedness must exist!

But if a particle is massless, no Lorentz boost can reverse the direction of the momentum.

In other words, a non-zero mass implies states with different handedness are mixed quantum mechanically!





- This is where the Higgs mechanism and the Higgs boson come to our rescue!

- The Higgs boson is a scalar (spin-0) particle. In fact, it is the only scalar in the standard model.

- In quantum field theory, there is something special about a scalar particle, in that its mass is quadratically sensitive to the scale of new physics:

$$\delta m_h^2 \propto \frac{1}{16\pi^2}\Lambda_{\mathrm{UV}}^2$$

So knowledge of the Higgs mass would give us a rough estimate of the scale of new physics!

- So we have the following expectation on the scale of new physics:

$$m_h \sim \mathcal{O}(100 \text{ GeV}) \;\Rightarrow\; \Lambda_{\text{UV}} \sim \mathcal{O}(1000 \text{ GeV}) = \mathcal{O}(1 \text{ TeV})$$

which would be accessible at the LHC!

An argument like this is what we call the naturalness principle.

If new physics failed to show up at around 1 TeV, the Higgs mass would be "unnatural" or "fine-tuned."

The naturalness principle does not have to hold up here, but it has been very successful in the past!

A classic example: why isn't the mass of an electron infinite?

The electron has, as part of its rest energy, a potential energy of

$$m_e \sim \frac{1}{4\pi\epsilon_0}\frac{e}{r}$$

which is infinite for a point particle.

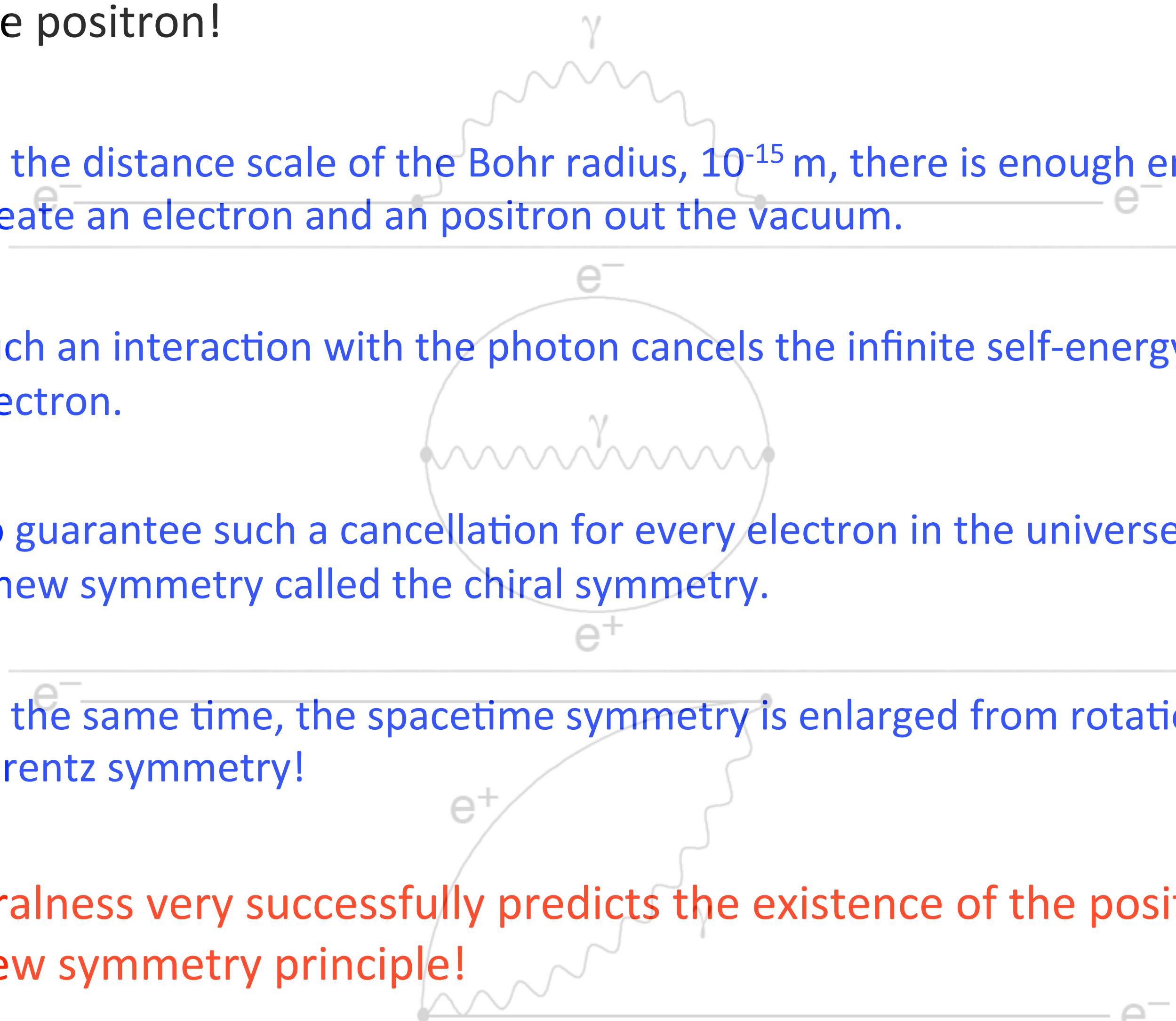
If we use current limit on the size of an electron < 10^{-18} m

$$m_e(r_0) \sim 10 \text{ GeV} \quad \gg \quad m_e^{\text{exp}} = 5 \times 10^{-4} \text{ GeV}$$

So classically, we have a "naturalness problem" for the electron mass!

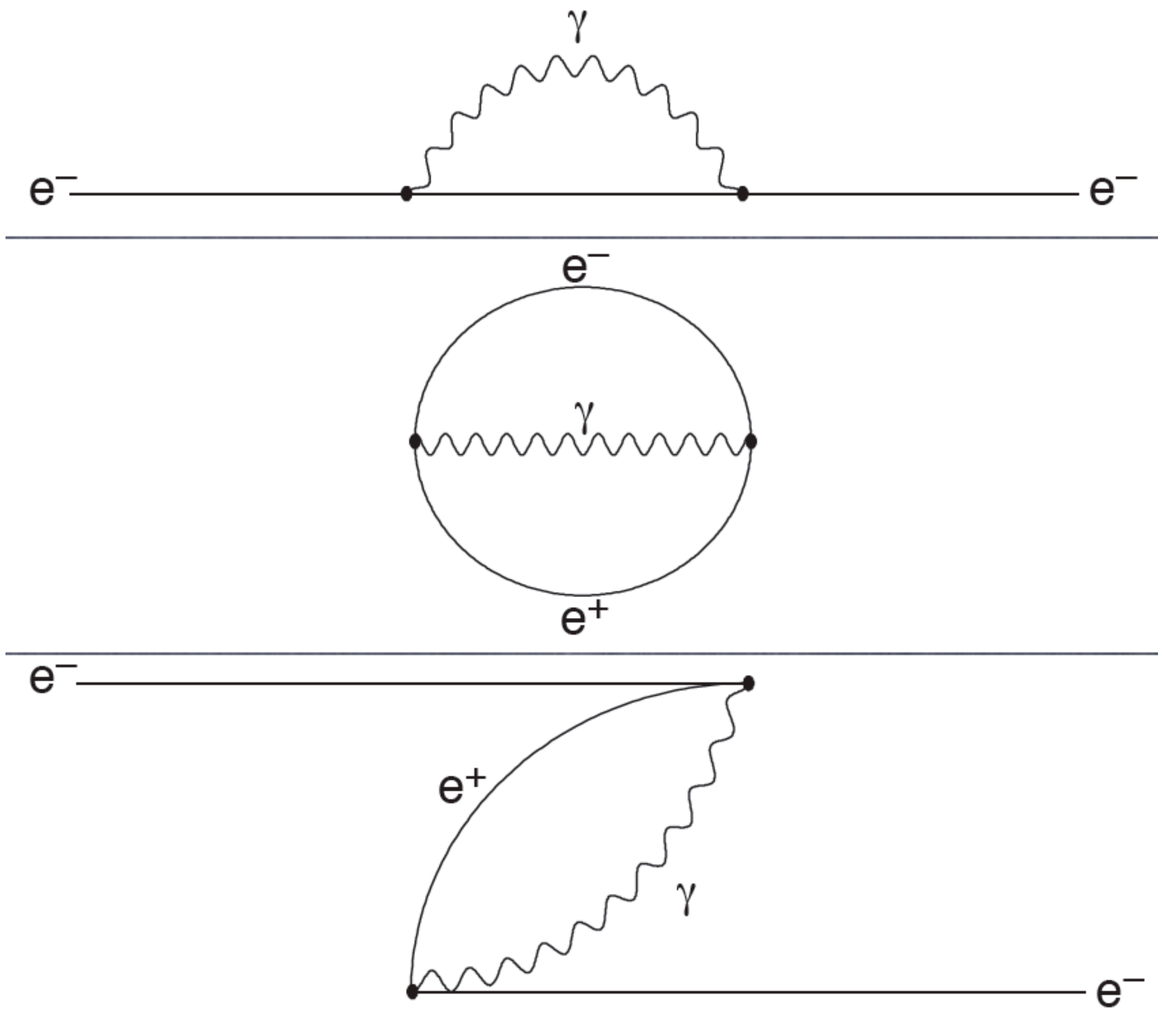
The solution is to introduce new (relative to classical) physics:
the positron!

- At the distance scale of the Bohr radius, 10^{-15} m, there is enough energy to create an electron and an positron out the vacuum.
- Such an interaction with the photon cancels the infinite self-energy for the electron.
- To guarantee such a cancellation for every electron in the universe, we need a new symmetry called the chiral symmetry.
- At the same time, the spacetime symmetry is enlarged from rotation to the Lorentz symmetry!



Naturalness very successfully predicts the existence of the positron and a new symmetry principle!

In the old-fashioned time-ordered perturbation, there are cancellations.



V. Weisskopf

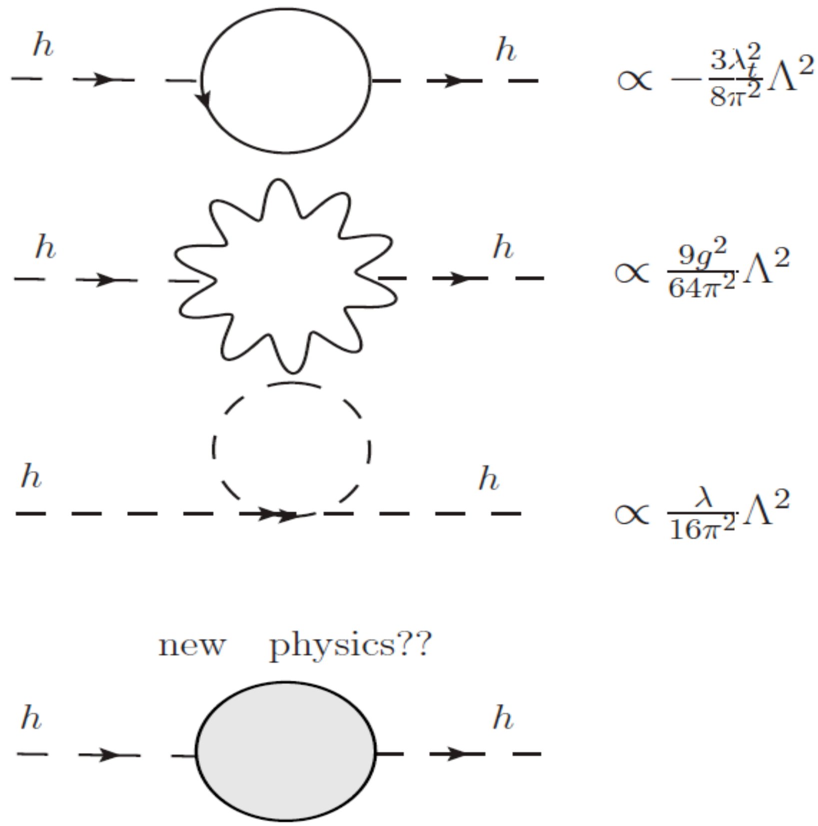
The Higgs boson has a similar naturalness problem:

- Interactions of the Higgs with other standard model particles, such as the top quark and electroweak gauge bosons, create a self-energy that is infinite.

- But now we measure Higgs mass to be at 125 GeV!

- The Higgs mass becomes "unnatural" unless new degrees of freedom and symmetry principles are introduced at the TeV scale, the energy scale of the LHC.

- one-loop quadratic divergences in the higgs mass must be cancelled by “something” at the TeV scale:



- the whole business of naturalness rests on the assumption that things don't cancel without a reason!

- so there should be a symmetry reason why the higgs quadratic divergences cancel.

only two classes of models:

1) bosonic global symmetry ----> higgs as a pseudo Nambu-Goldstone boson. This scenario includes extra-dimensional models by AdS/CFT.

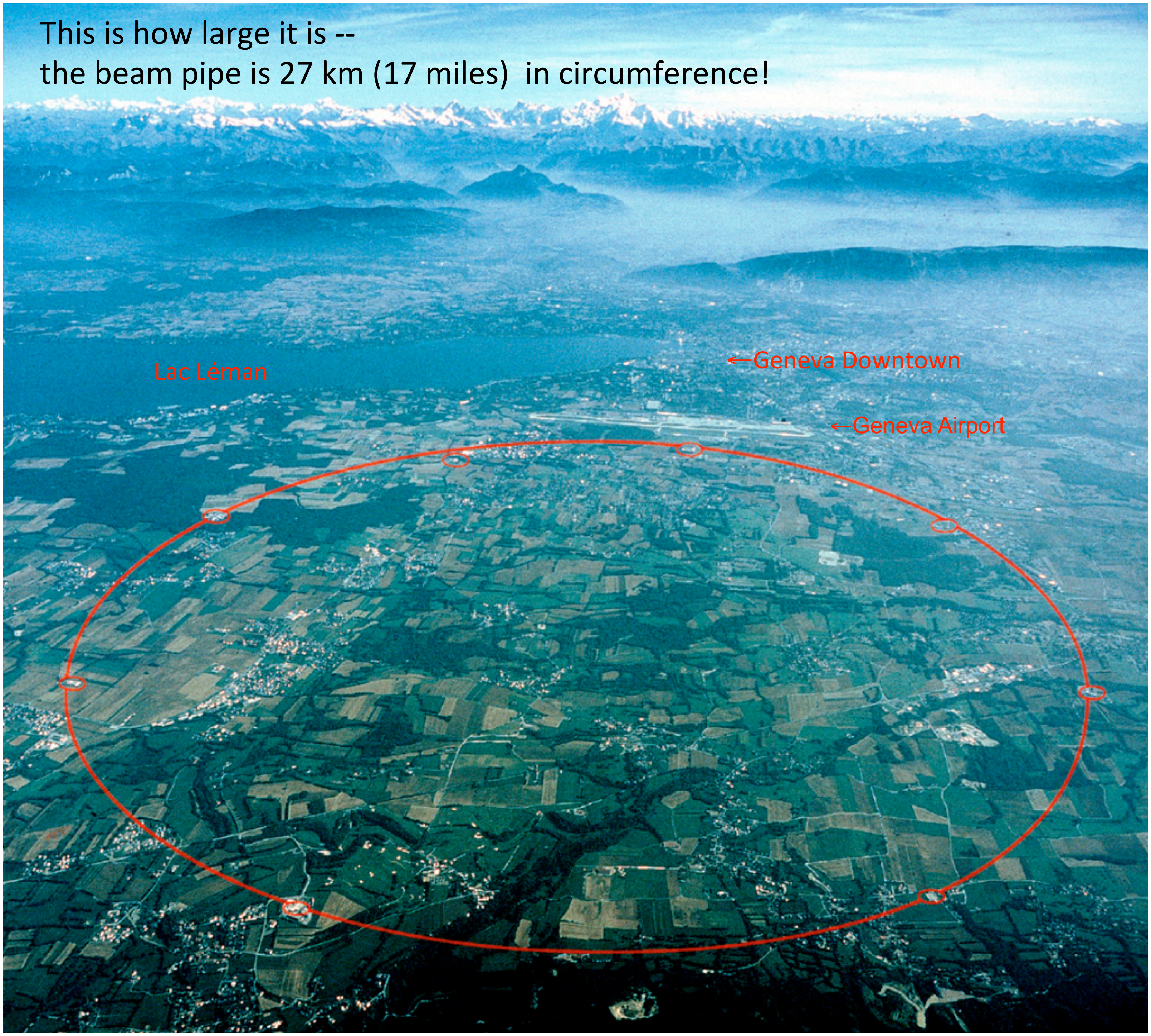
2) fermionic global symmetry -----> supersymmetry

To study such an important question,

Where does the electron mass come from?

several particle accelerators were built over the years:

- LEP at CERN (1989-2000)
- Tevatron at Fermilab (1983-2011)
- LHC at CERN (2009 - ??)


This is how large it is --
the beam pipe is 27 km (17 miles) in circumference!
Lac Léman
←Geneva Downtown
←Geneva Airport

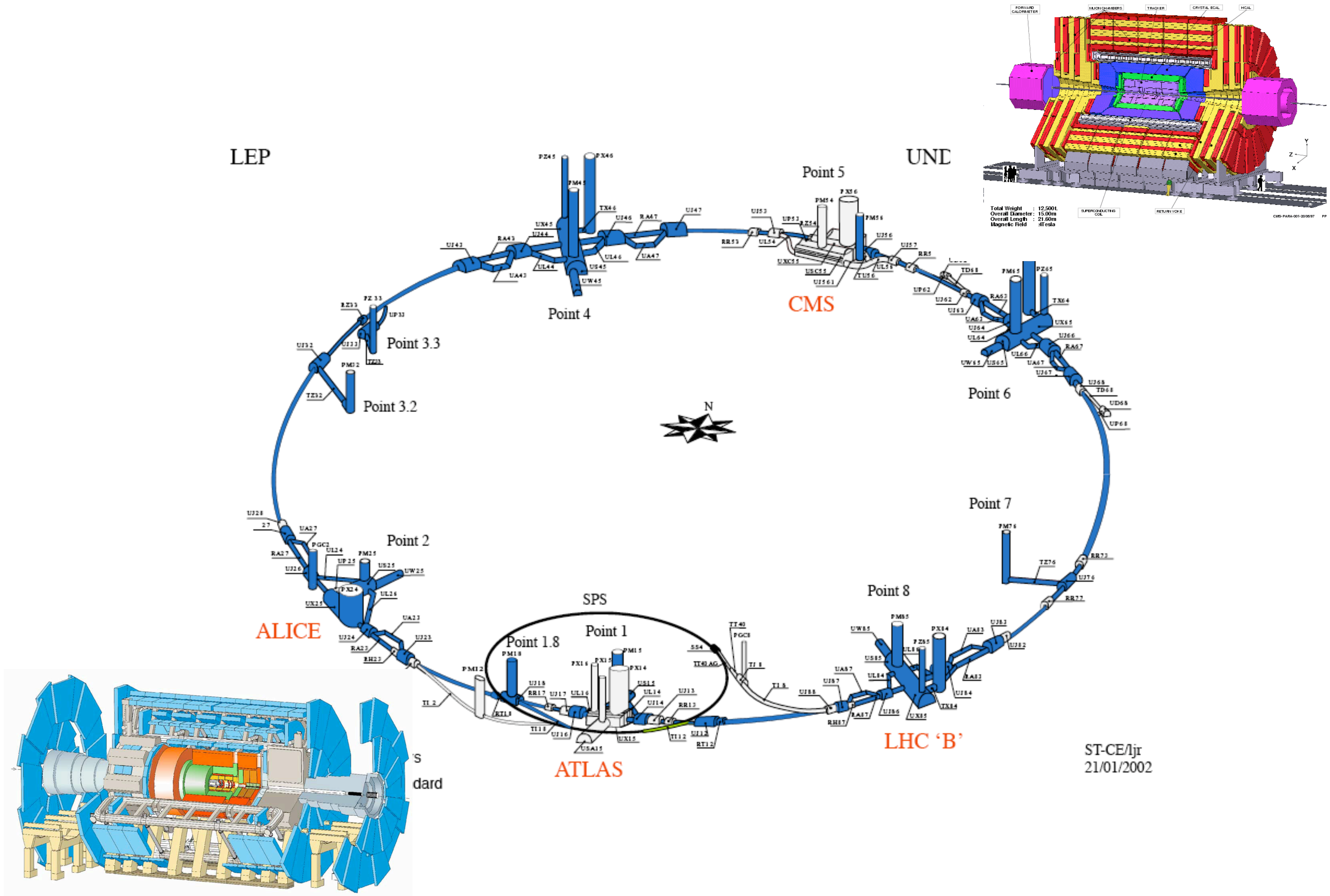
LHC is a proton-proton collider @ center-of-mass energy = 14 TeV by design. It was running at 7 (8) TeV in 2011 (2012).

Some fun facts about the LHC at full design energy:

- At 7 TeV, the proton, which weighs about 0.001 TeV, travels at 0.999999991 times the speed of light!
- Each "beam" will consist of nearly 3000 bunches of particles, and each bunch has nearly 100 billion protons!
- When particle beams "cross," there're only about 20 collisions out of the 200 billion protons.
- But the beam crosses 40 million times per second (bunch crossing has a time-interval of 25 nano sec), producing roughly 800 million collisions per second.

LHC has two general detectors: ATLAS and CMS.

Their main priority is to hunt down the Higgs boson.



AND THEY DID!!

On July 4th of 2012, CERN announced:
"WE HAVE OBSERVED A NEW PARTICLE!"

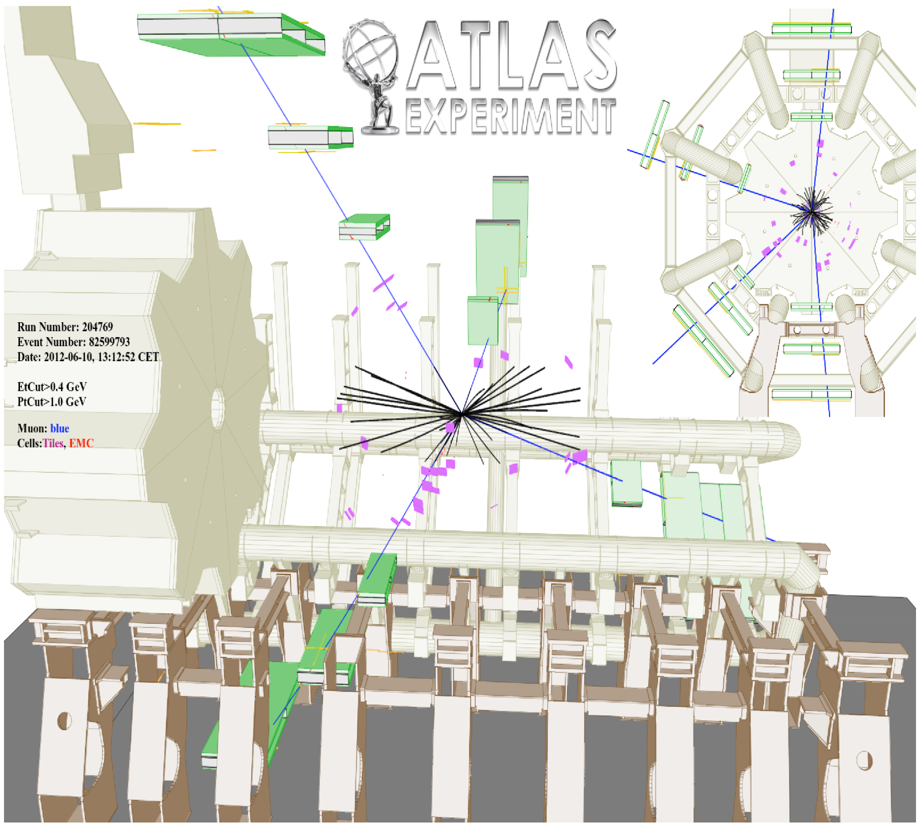
The announcement was made in two seminars delivered by Fabiola Gianotti (ATLAS) and Joe Incandela (CMS):

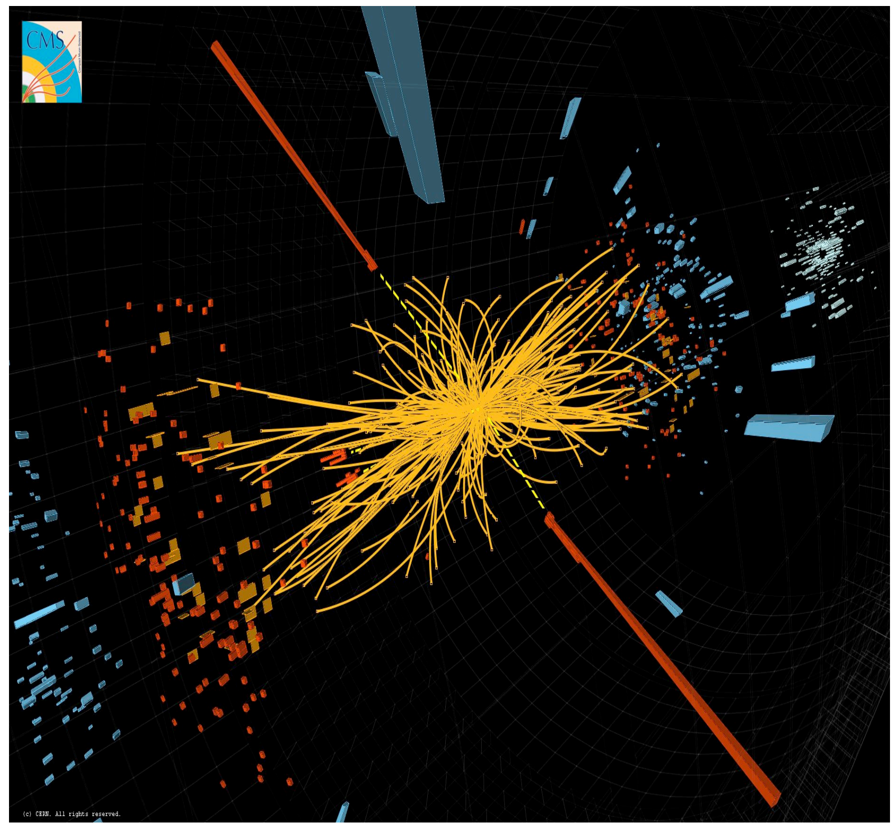
Rolf Heuer famously declared: "***I think we have it!***"

How do you look for a Higgs boson?

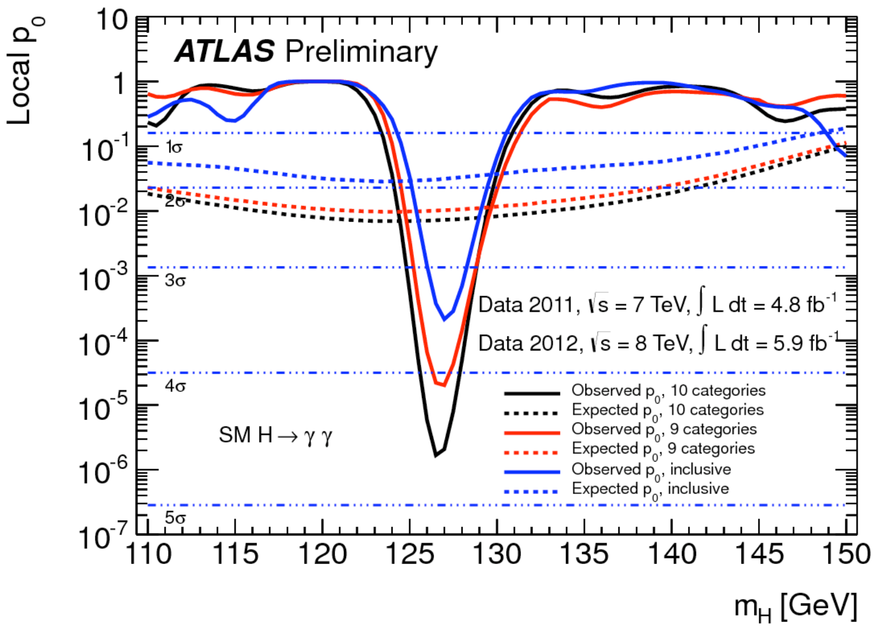
- The Higgs boson is an unstable particle. We can only look for it through its decay products.

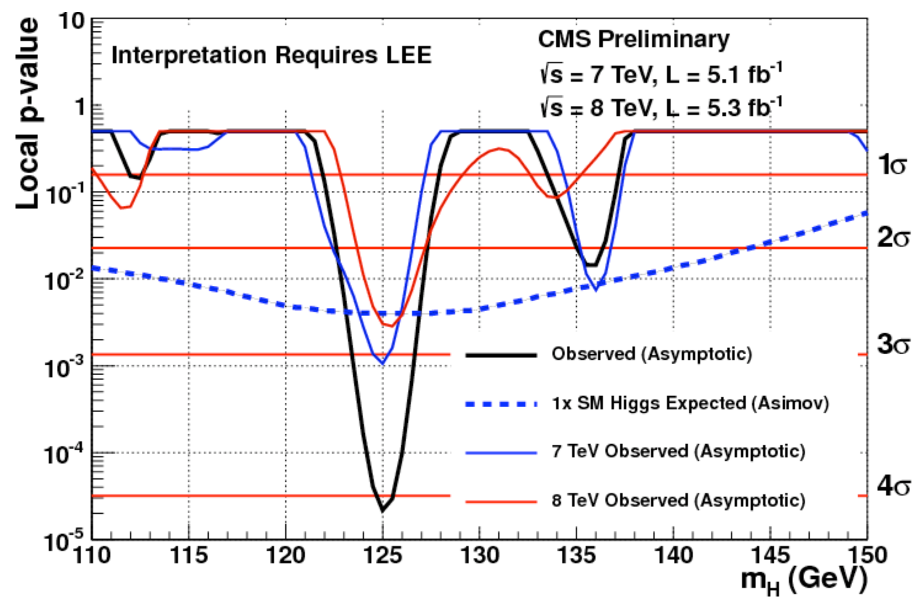
For a 125 GeV Higgs the LHC is most sensitive to WW, ZZ, and diphoton decay channels.





At the time of discovery, ATLAS and CMS both see a “new boson” decaying into two photons, with a mass at around 125 GeV:



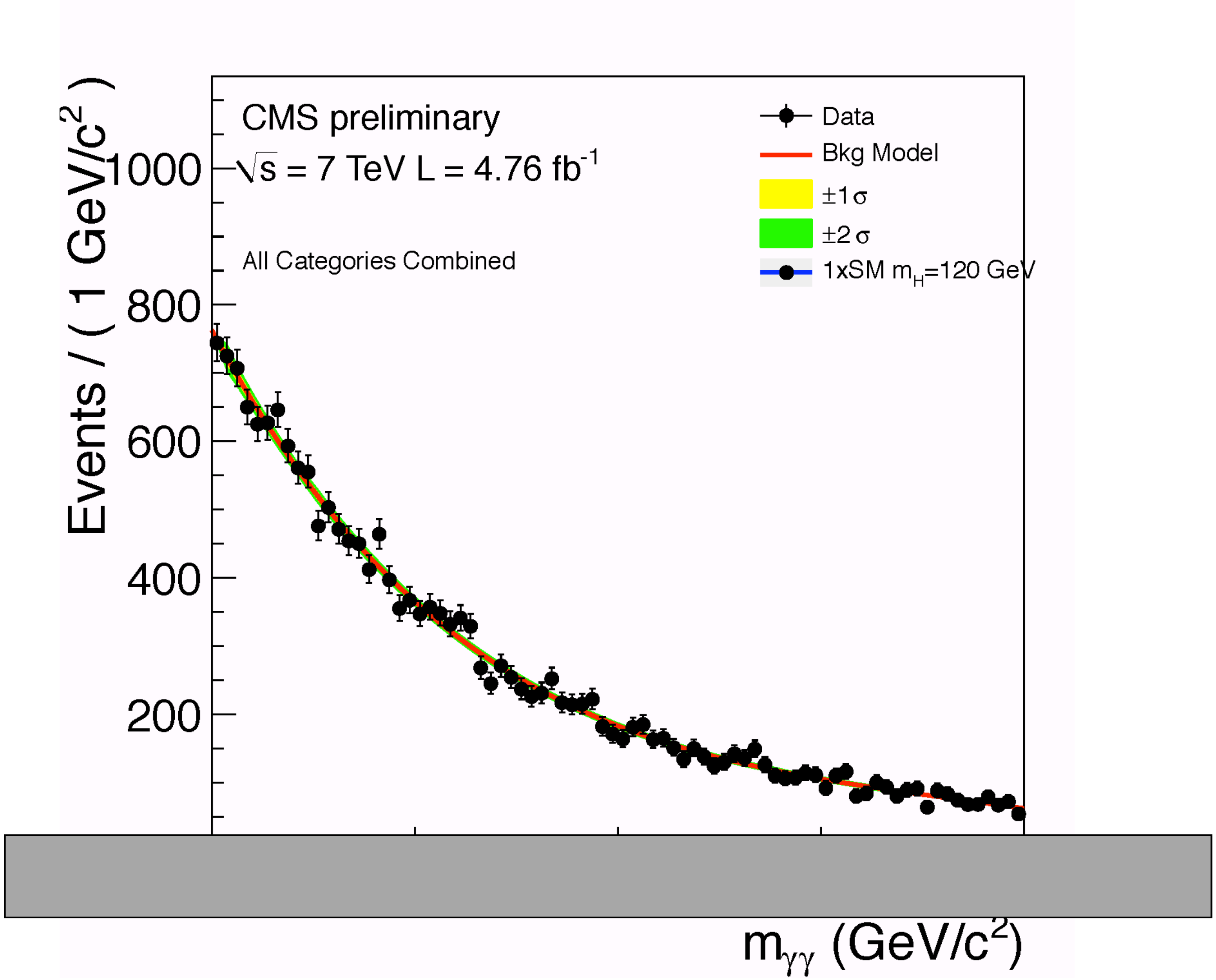


Local p-values are greater than 4sigma for both collaborations.

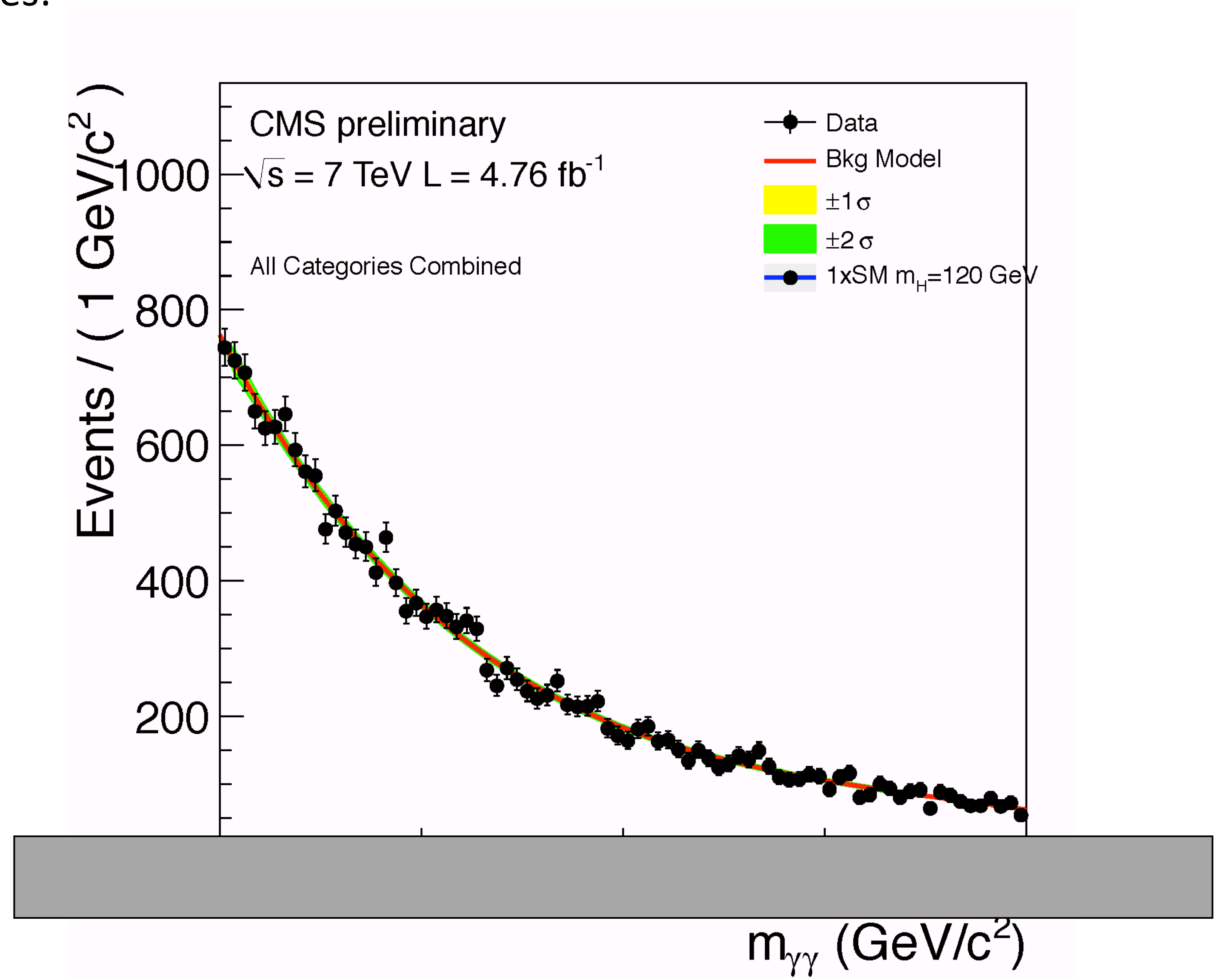
On July 4th both ATLAS and CMS independently claimed 5-sigma discovery, when combining all channels.

5-sigma is the typical benchmark for discovery in particle physics, which means there is only less than 10^{-6} probability that the observed excess is due to statistical fluctuation of background!

To appreciate how far we have come, I like to show the pre-July 4th data from December of 2011:



And I would ask the audience to look for a “bump” with their naked eyes:



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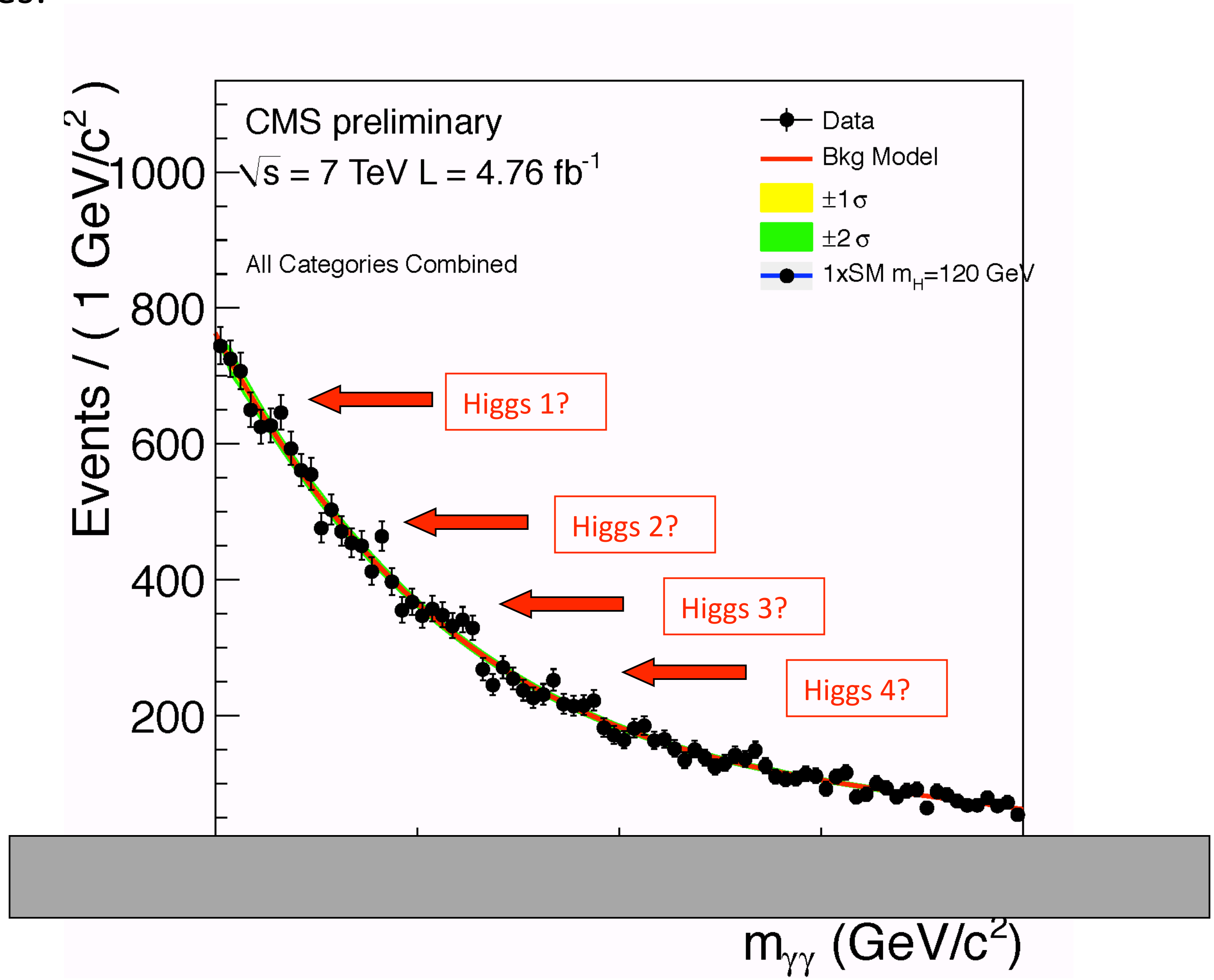

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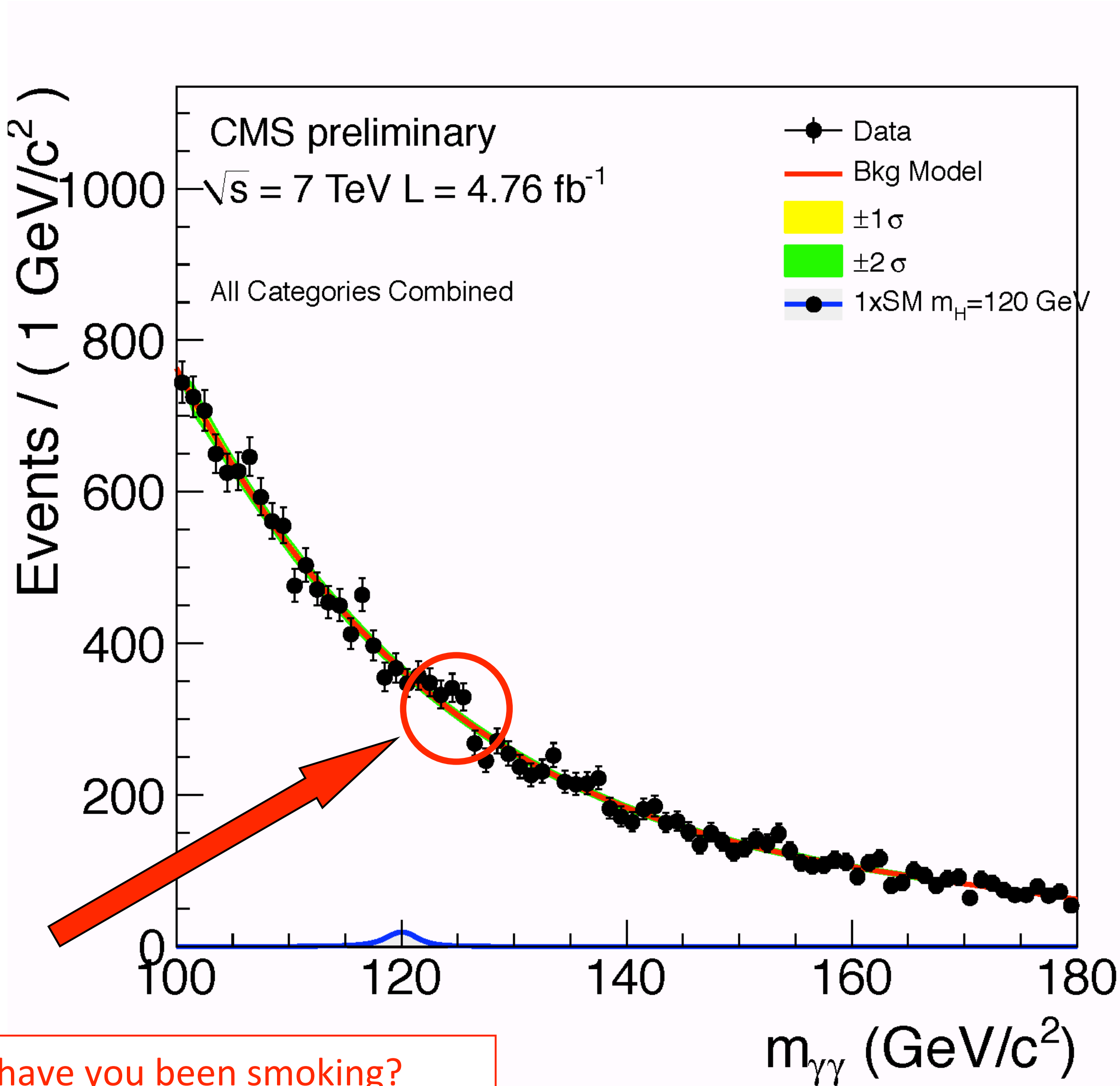
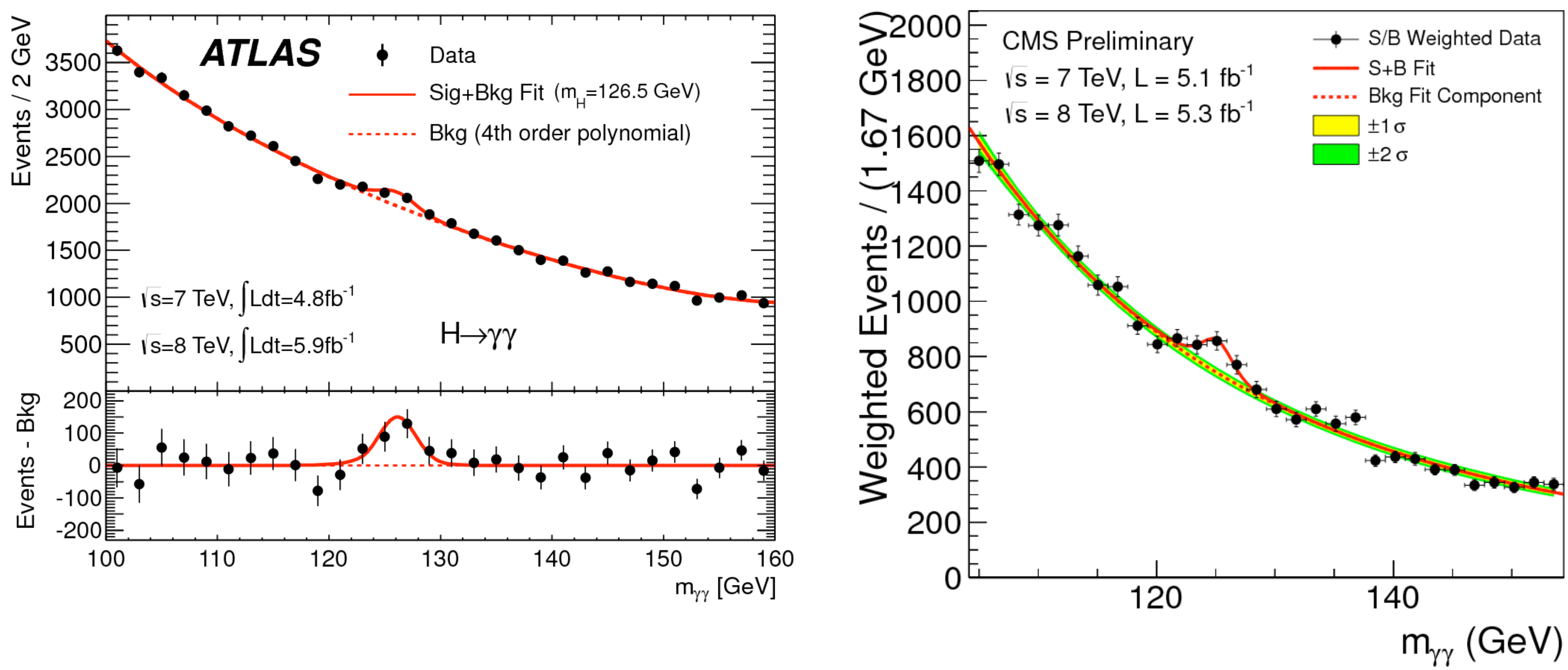
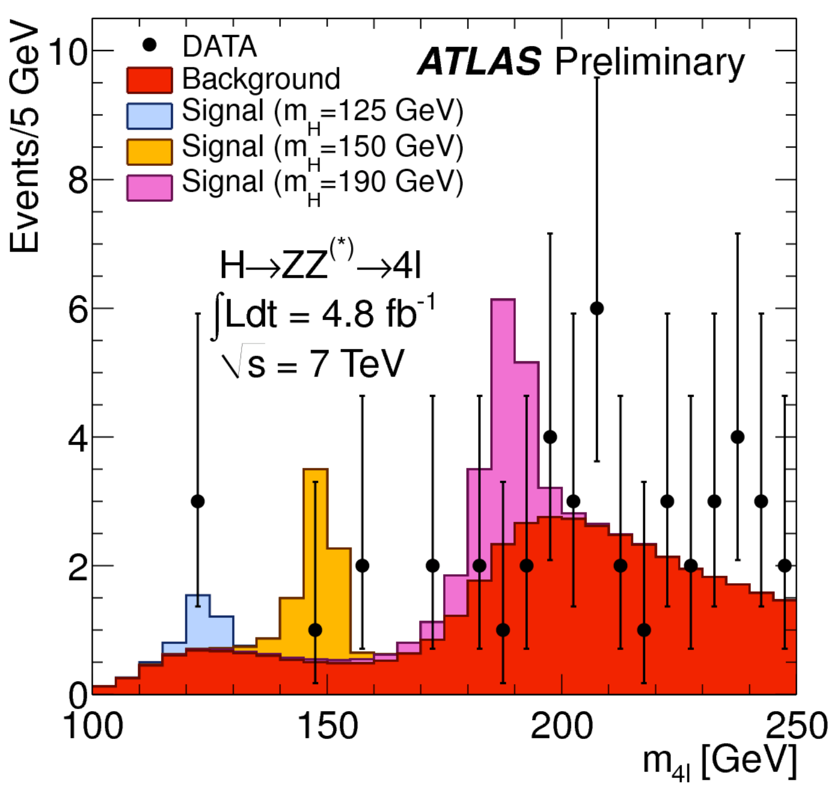


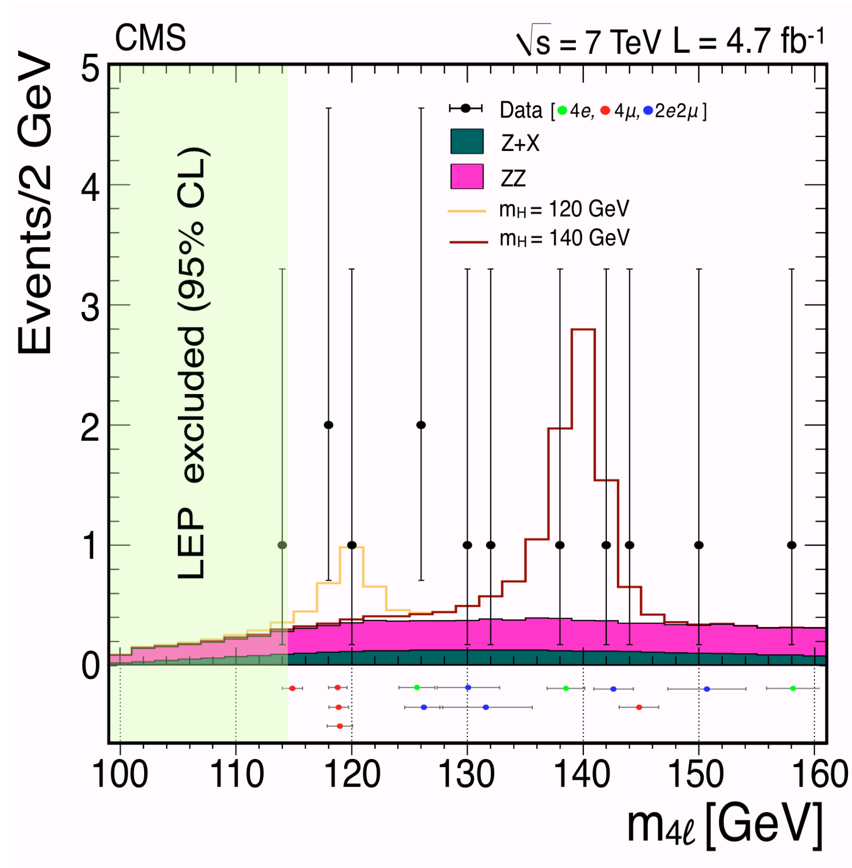
I get asked: what have you been smoking?

In the July 4th, 2012 data, the peak is quite visible:



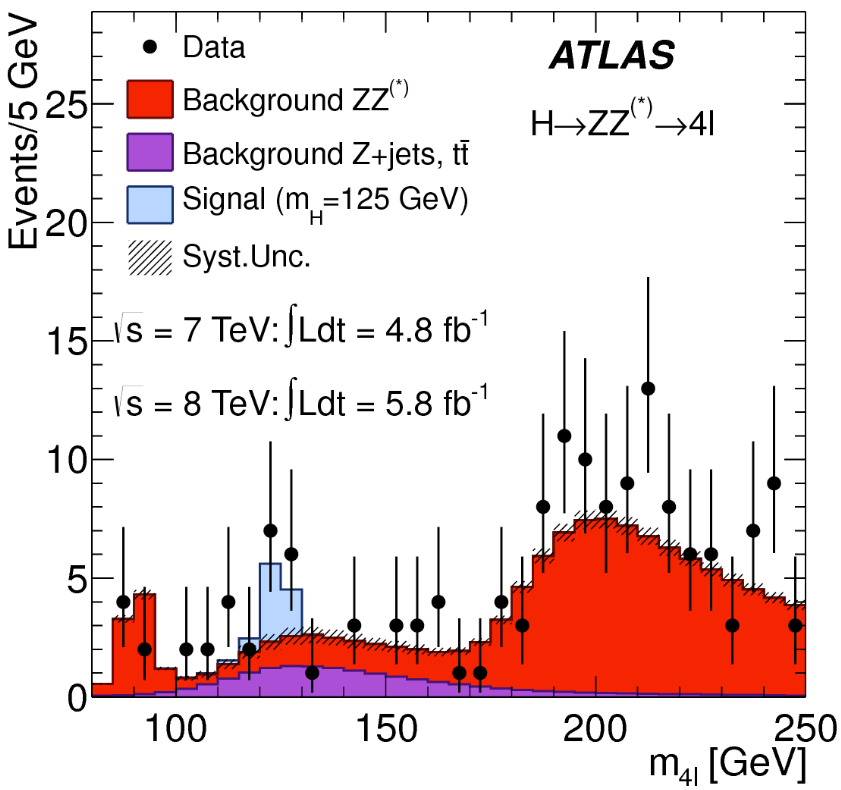
- Its the same in the 4-lepton channel.
  Below are the pre-July 4 plots:

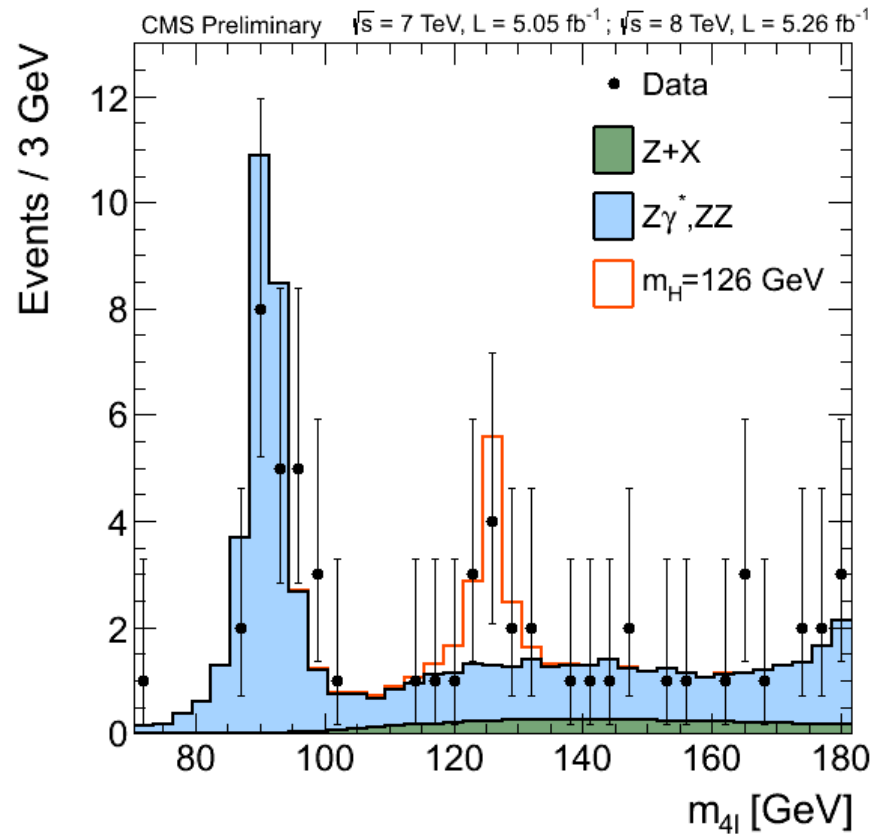




- It's the same in the 4-lepton channel.

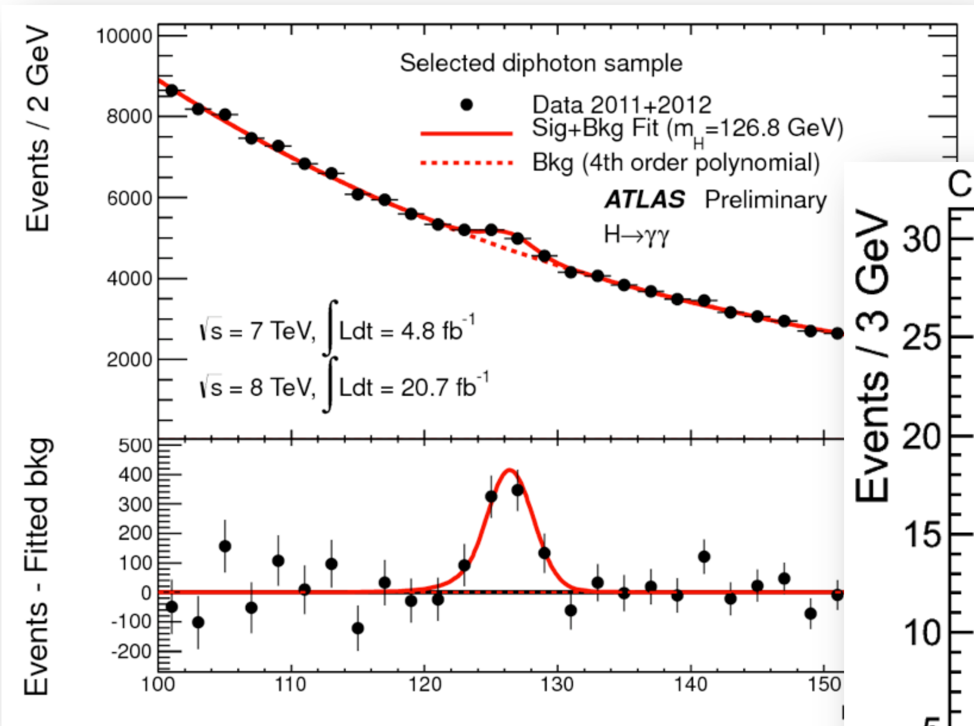
Now the July 4th plots:

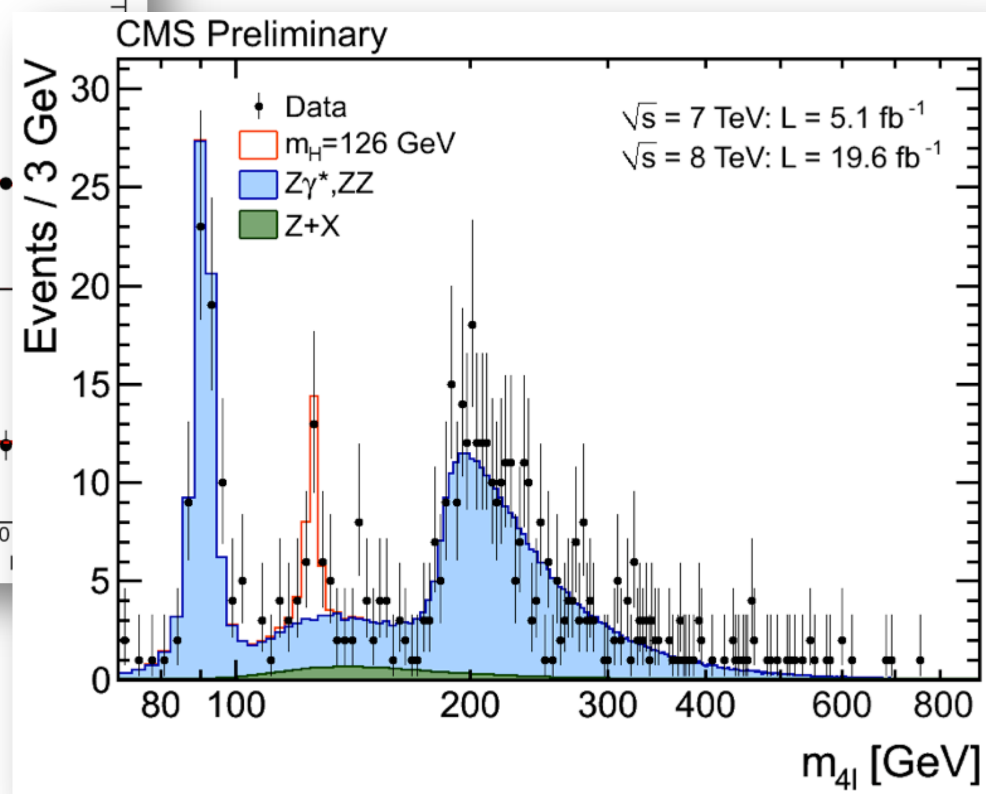




The question since July 4, 2012, and perhaps for many years to come, is "***What exactly do we have?***"

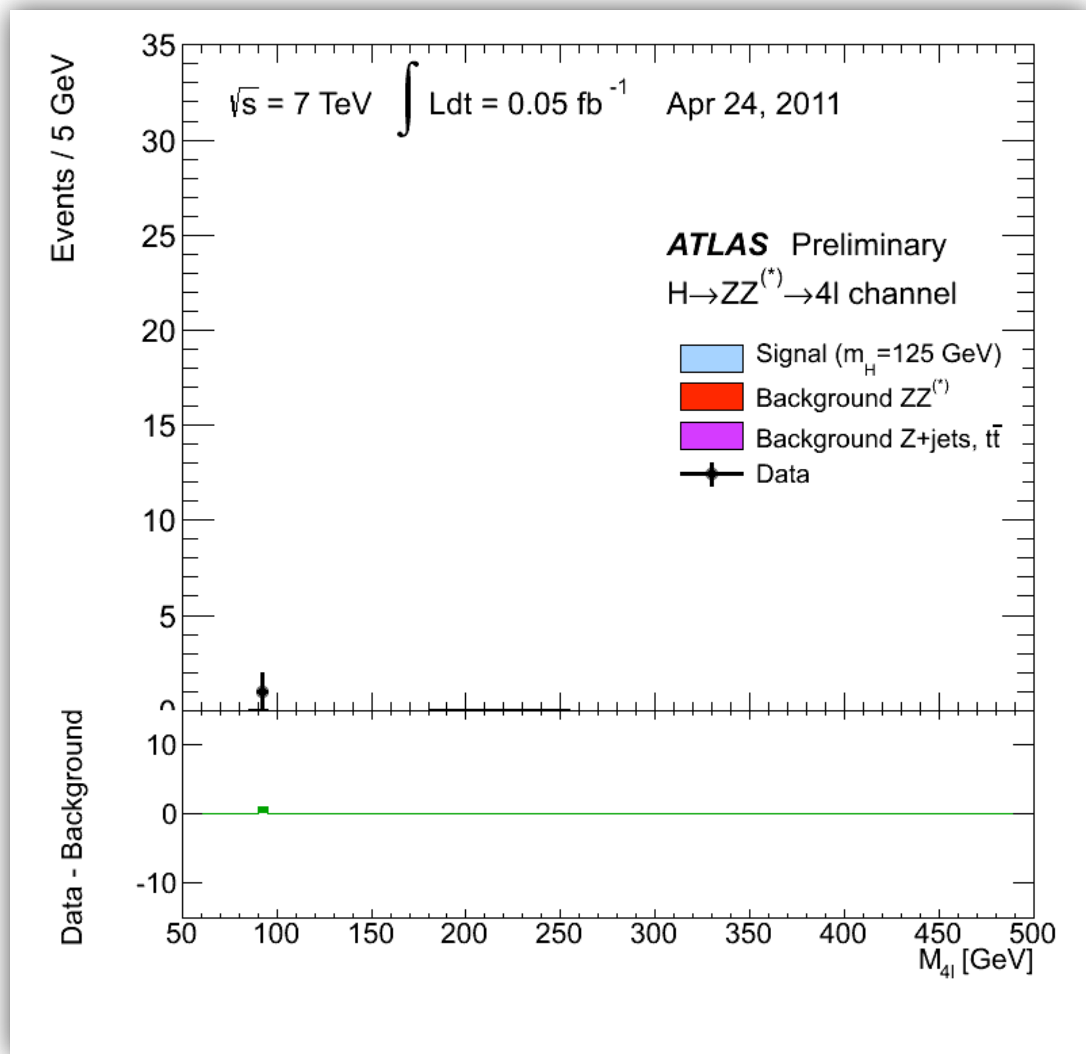
That we have discovered a new particle is without any doubt.





Forget about *p*-values!
Seeing is believing!!

ATLAS has a nice animation of the time-evolution in various channels:



The question since July 4, 2012, and perhaps for many years to come, is "***What exactly do we have?***"

The million dollar question:

Is it the Higgs boson?

A Higgs boson is a particle that is

- Spin-0 (scalar)
- Charge and Parity (CP) even
- The neutral component of an electroweak doublet
- The origin of mass for W/Z bosons as well as the quarks and charged leptons

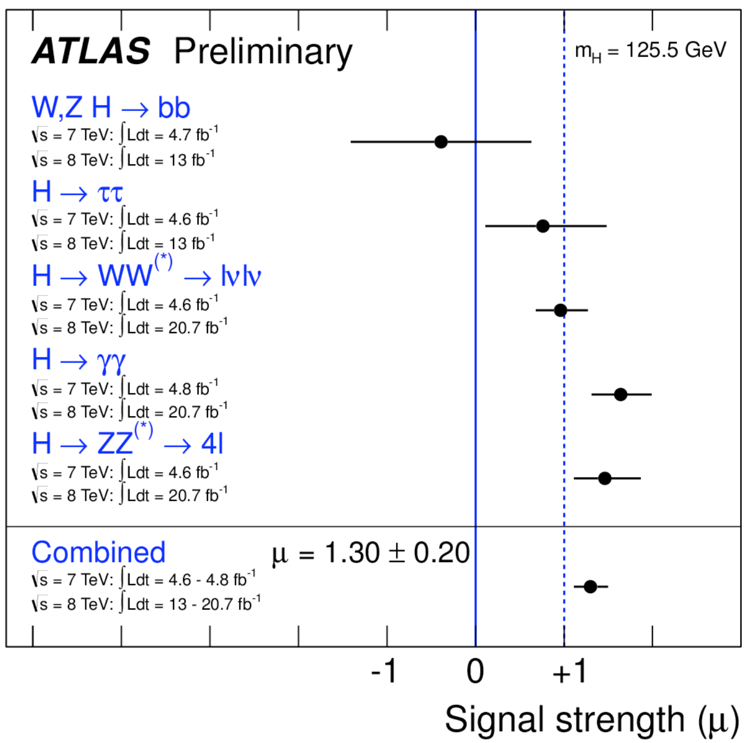
The question since July 4, 2012, and perhaps for many years to come, is "***What exactly do we have?***"

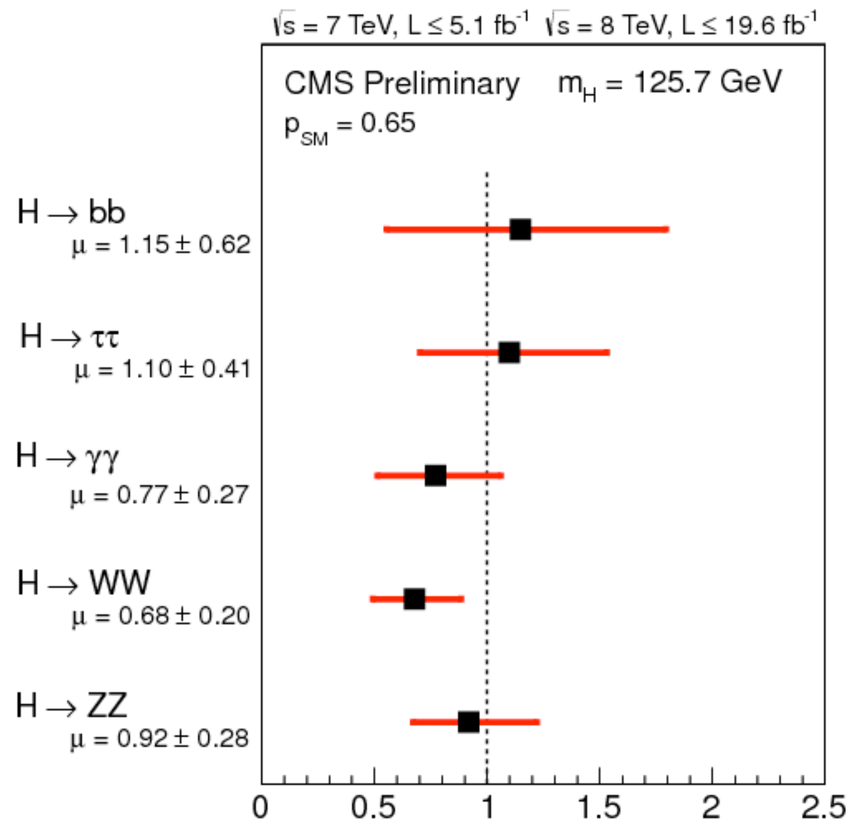
The 10-billion dollar question:

Is it the Standard Model Higgs boson?

Once the mass is known, the coupling of the SM Higgs boson is precisely predicted.

These two plots are worth a thousand words:





Today we can answer the million dollar question definitively:

It is a Higgs boson!

This is such a historic discovery that it is worth pausing for a moment to reflect what has happened….

In 1964 three PRL papers deposited the possibility of the Higgs boson:

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

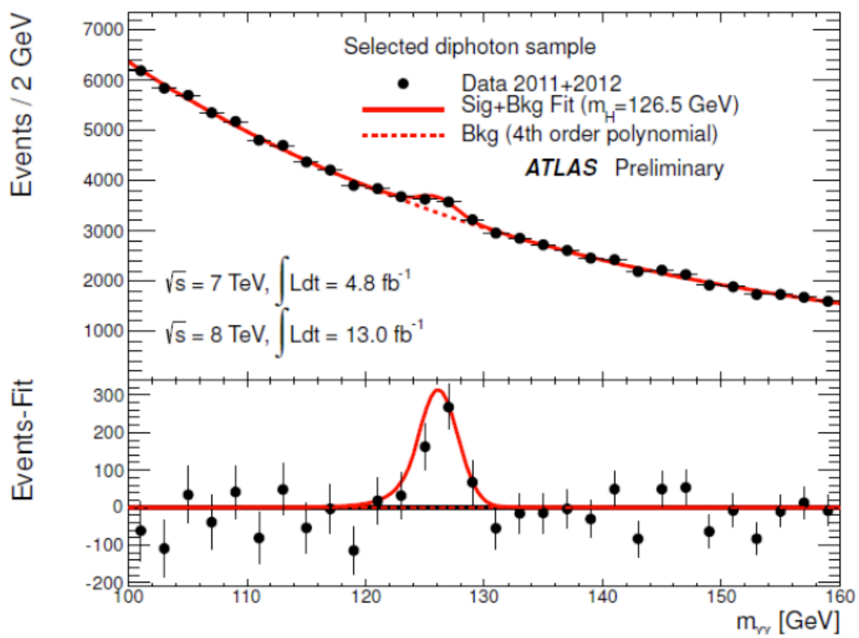
BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

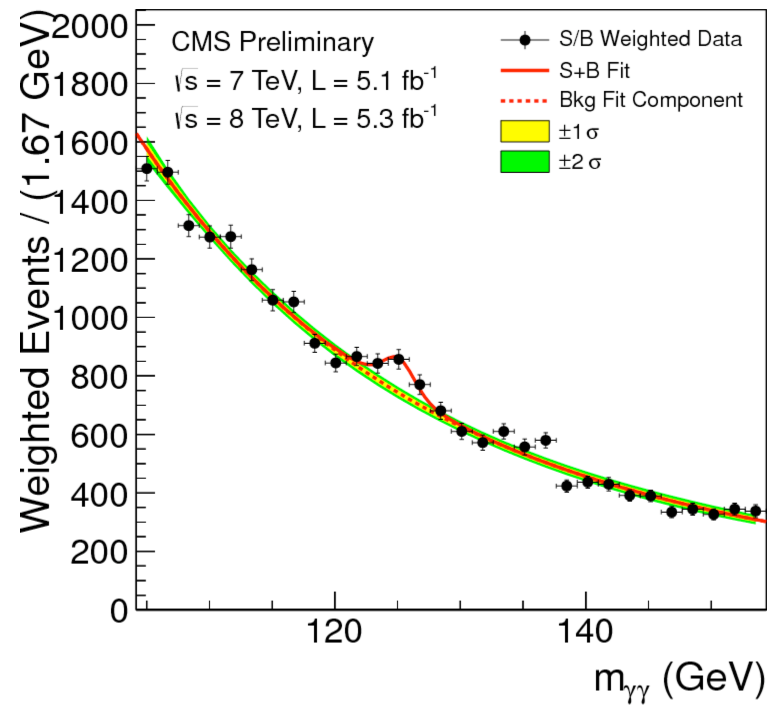
F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

To start from a pure Human thought process, and arrived 48 years later at



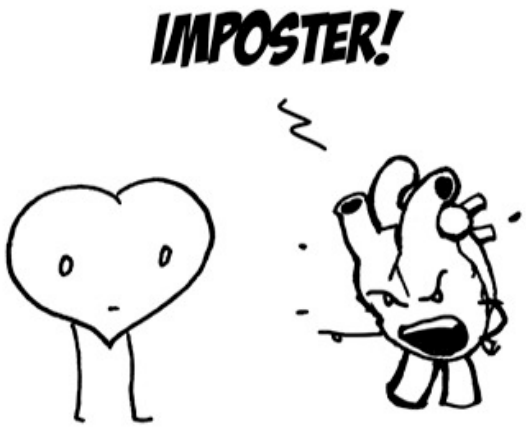


is an extraordinary achievement for both theoretical and experimental physics!

“Extraordinary claims require extraordinary evidence.”

-- Carl Sagan

Let’s review the extraordinary evidence that we have found a Higgs boson, instead of a Higgs imposter.



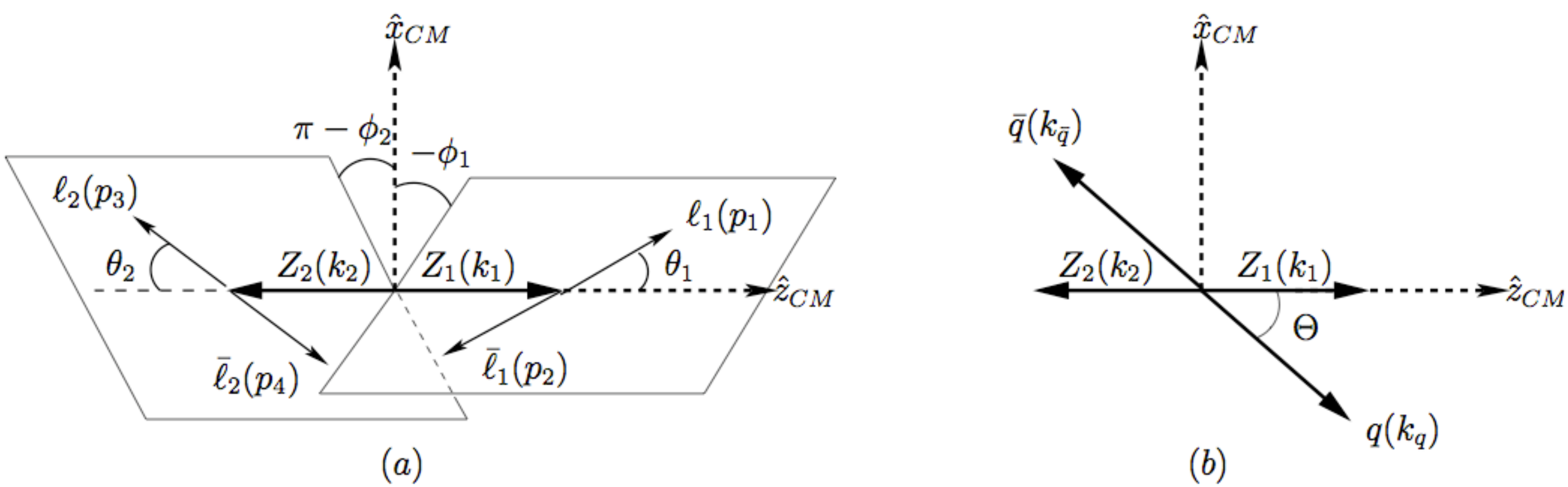
Recall that a Higgs boson is a particle that is

- Spin-0 (scalar).
- Charge and Parity (CP) even.
- The neutral component of an electroweak "doublet."
- The origin of mass for W/Z bosons as well as the quarks and charged leptons.

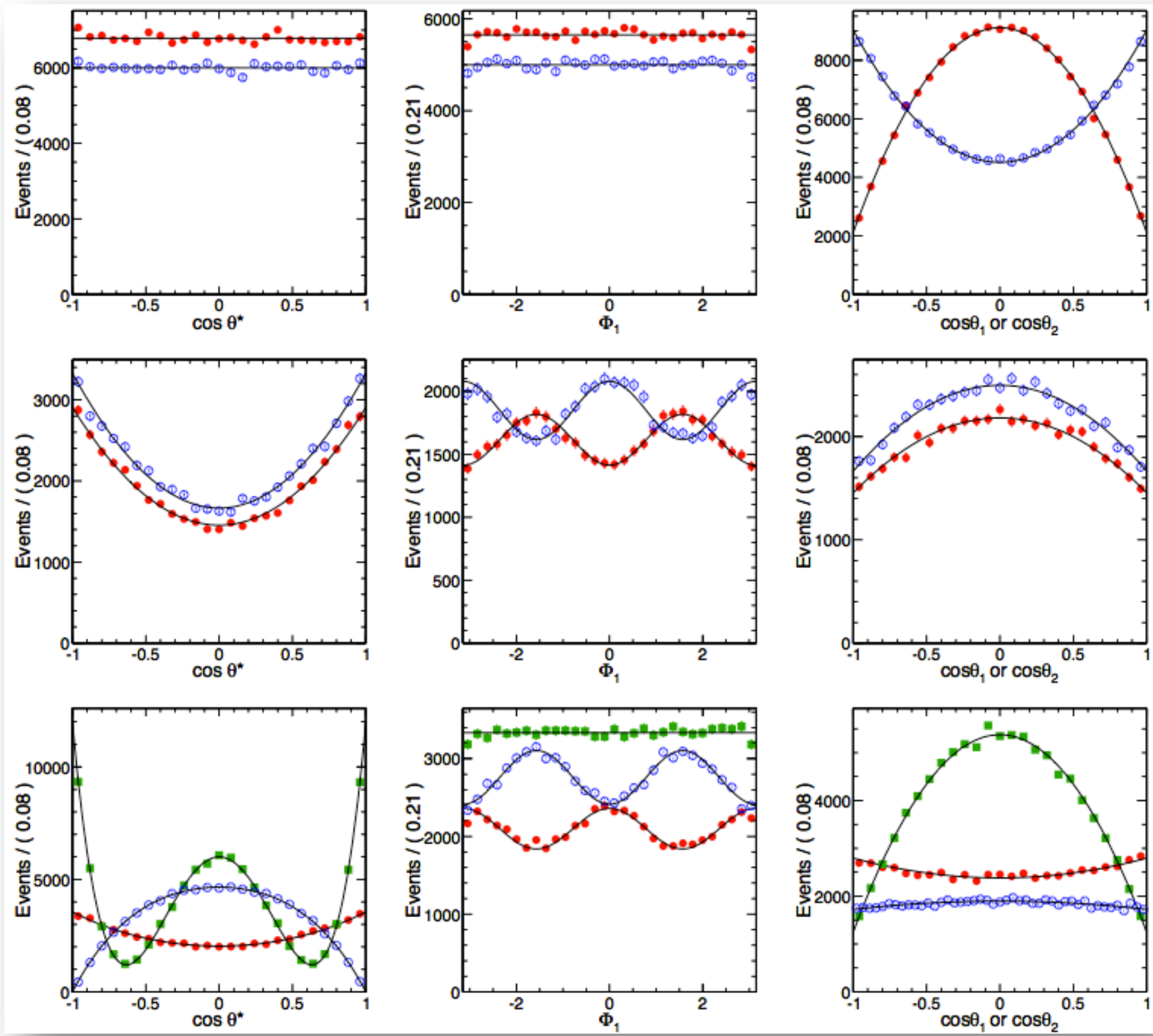
Both spin and CP measurements rely on kinematics of decay products. This is best demonstrated in the golden channel :

$$h \to Z_1 Z_2 \to (\ell_1 \bar{\ell}_1)(\ell_2 \bar{\ell}_2)$$

There are five angles in the decay kinematics:



Different spin/CP of the decaying particle leads to different angular distributions:



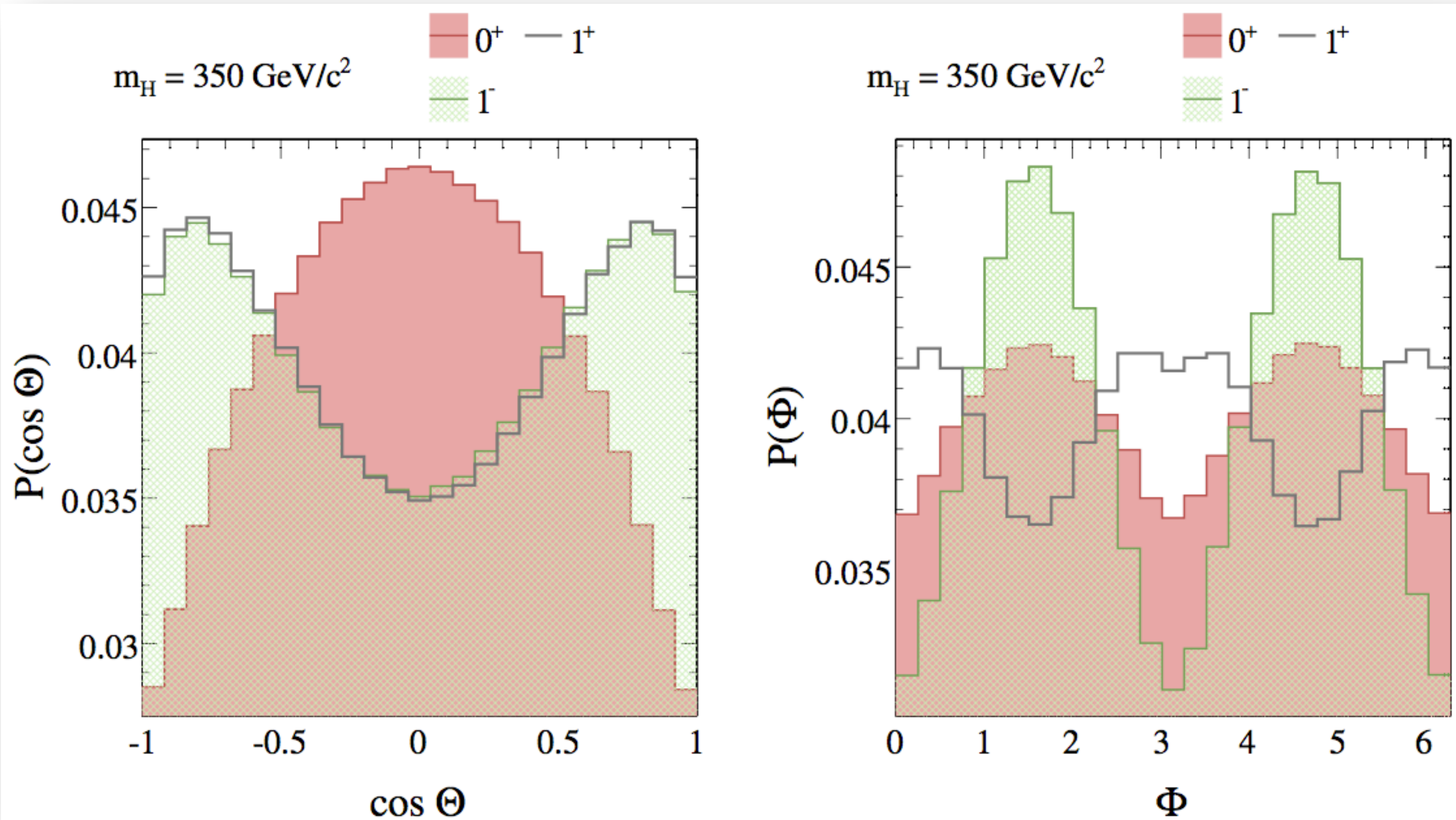
Spin-0

Spin-1

Spin-2

Gao et. al: 1001.3396.

The distributions get distorted by acceptances and detector resolutions, but there are still differences:



De Rujula et al:1001.5300;

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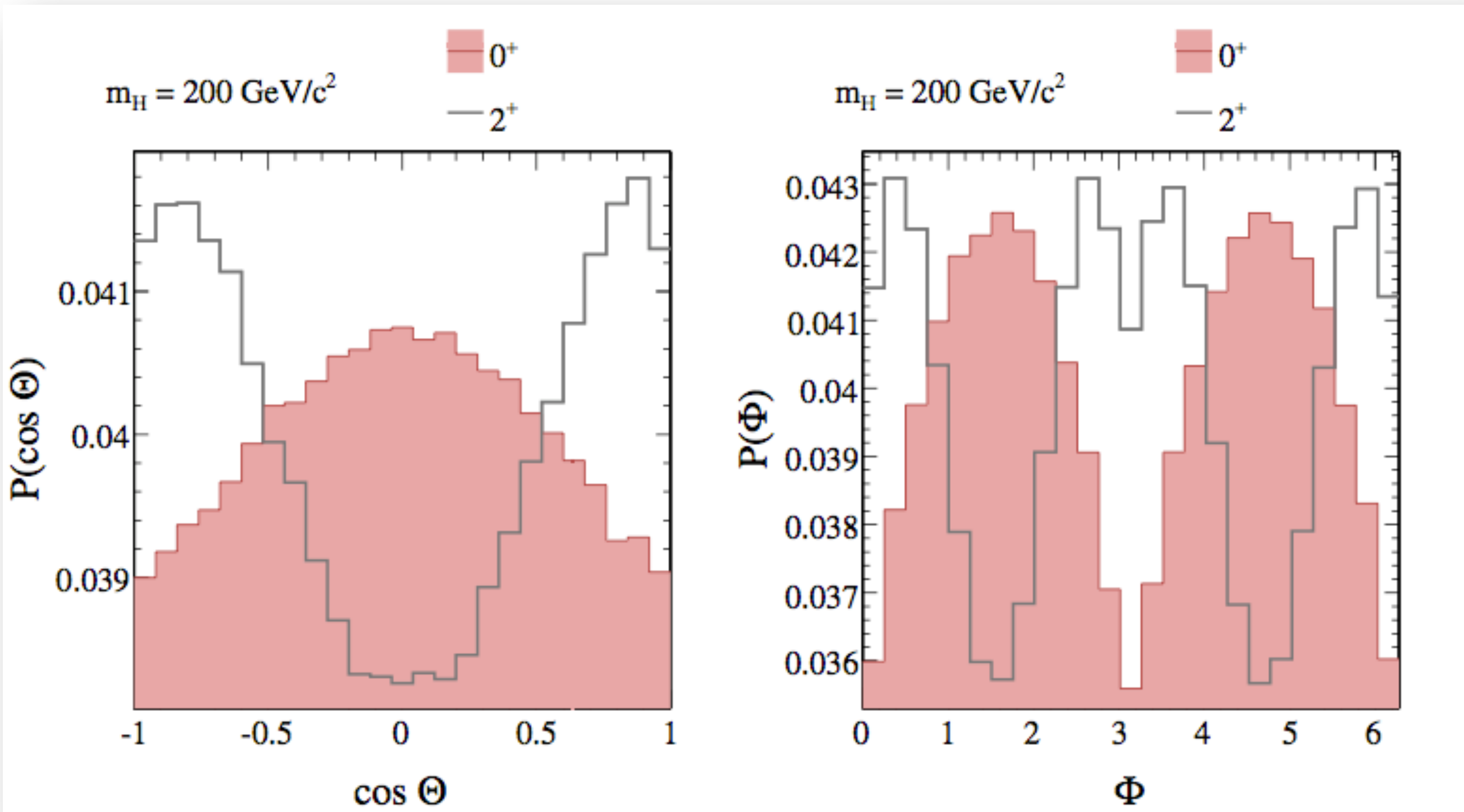
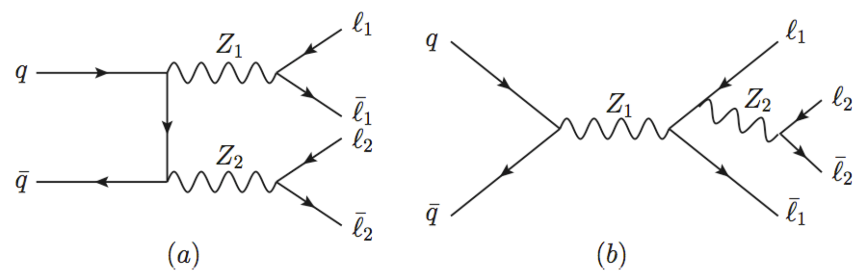
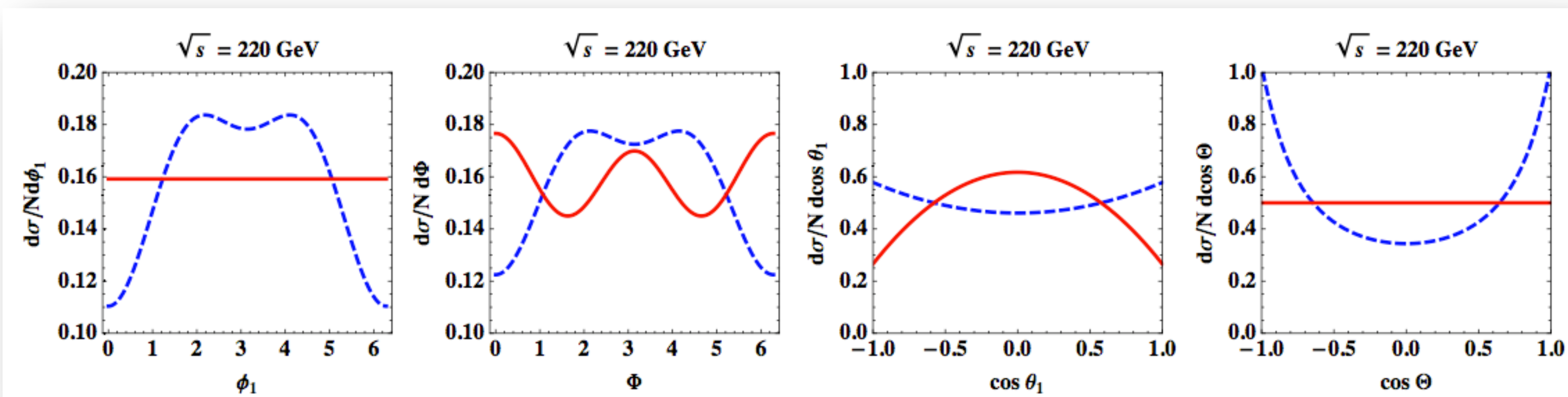


De Rujula et al:1001.5300

The analysis is also complicated by the background,



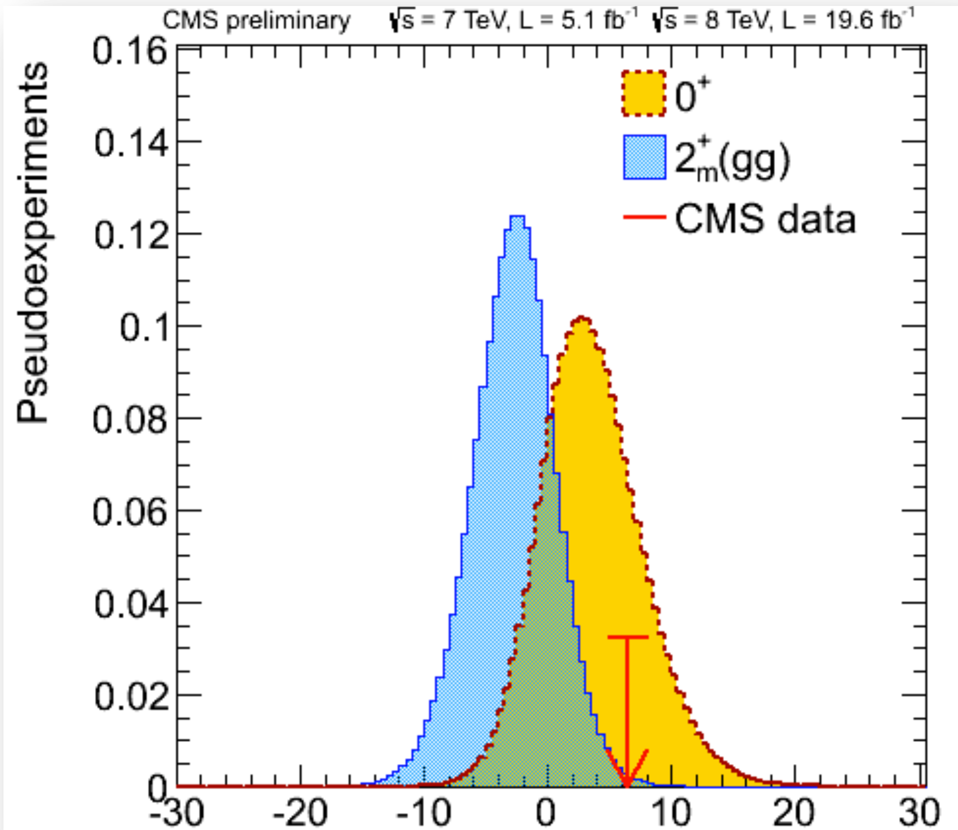
which have yet its own angular distributions



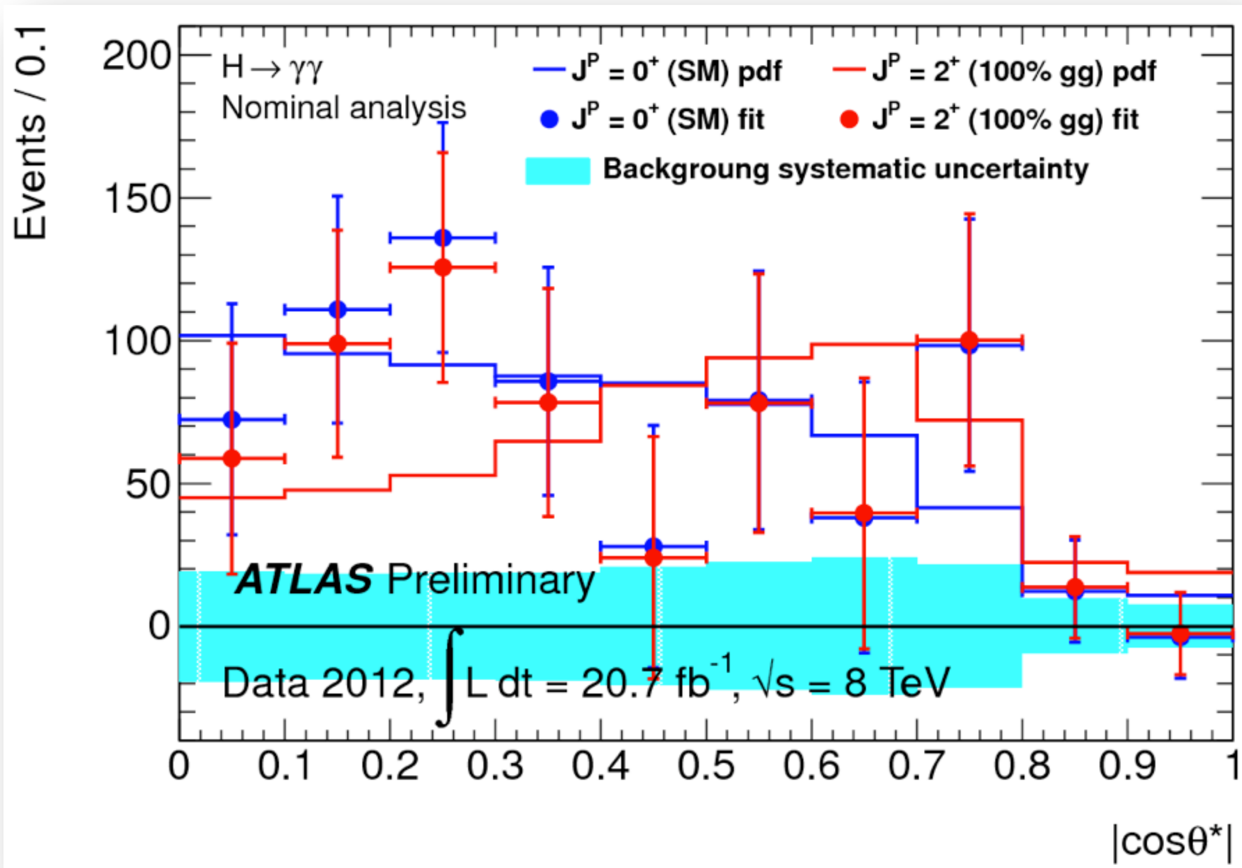
Gainer et al: 1108.2274.

So the actual analysis is quite involved, but it was done nevertheless.

CMS 4-lepton analysis excluded spin-2 (with minimal coupling) at 98.5% C.L.
(ATLAS has similar results.)

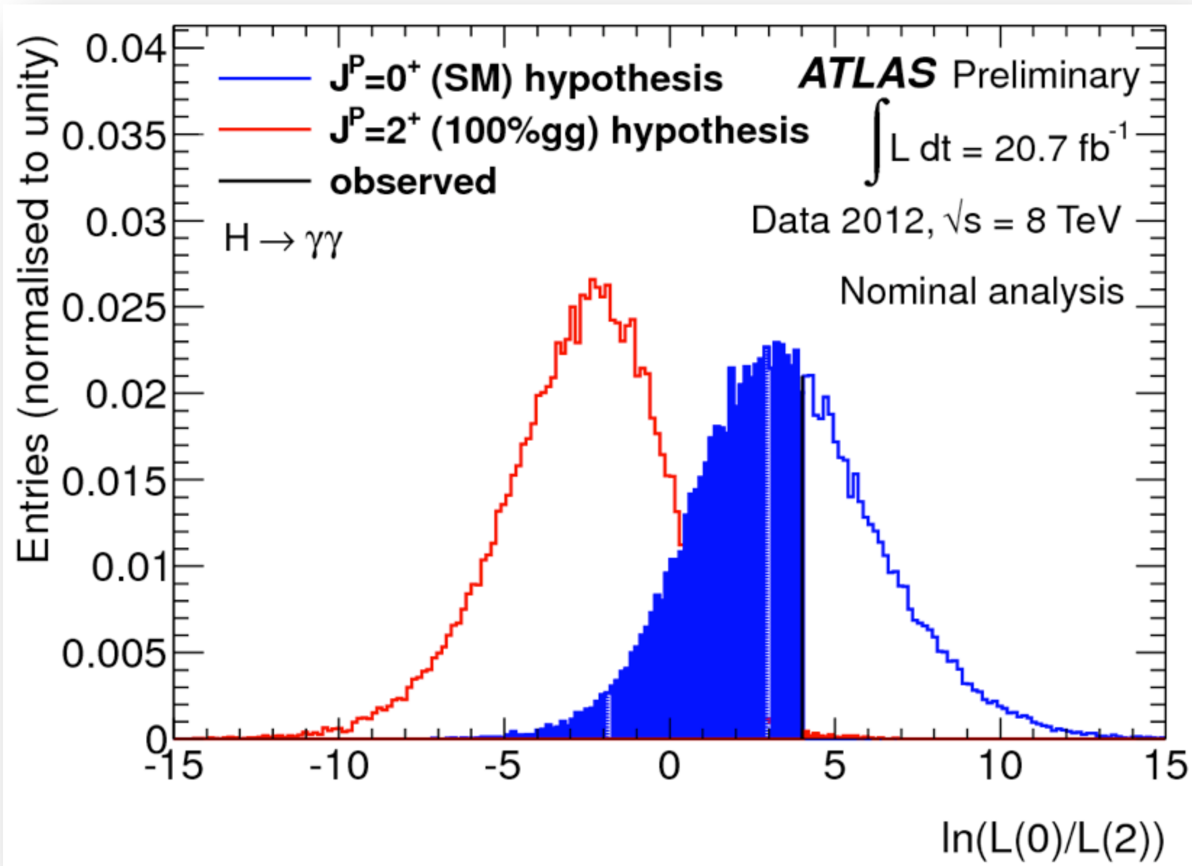


It is also possible to use the production angle in diphoton decays.



It is also possible to use the production angle in diphoton decays.

ATLAS diphoton analysis excluded spin-2 (with minimal coupling) at 99% C.L.

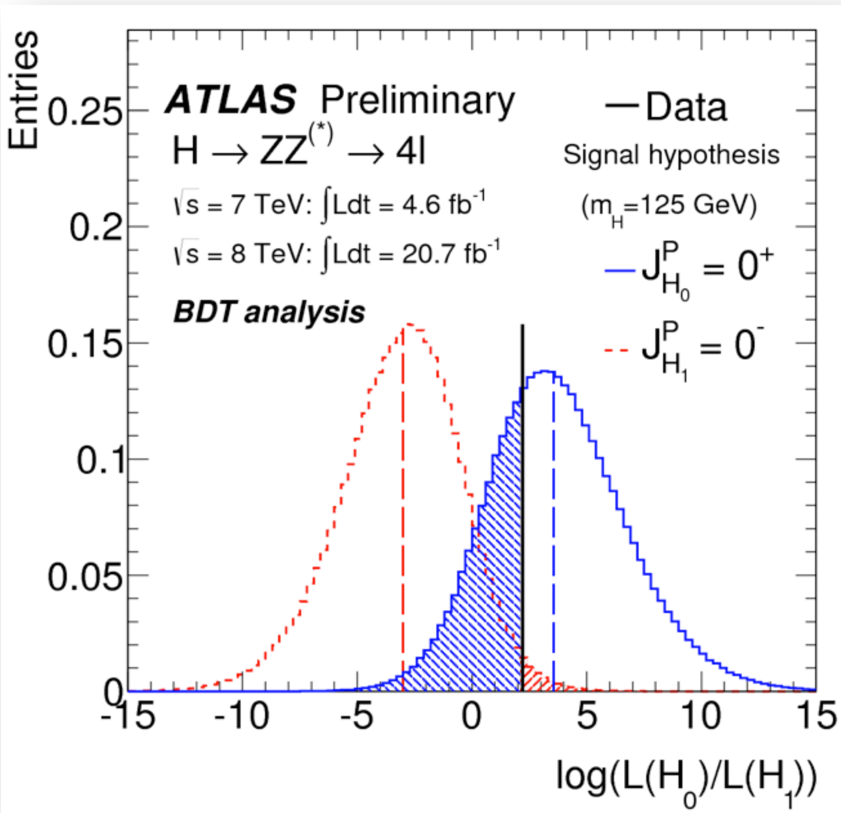


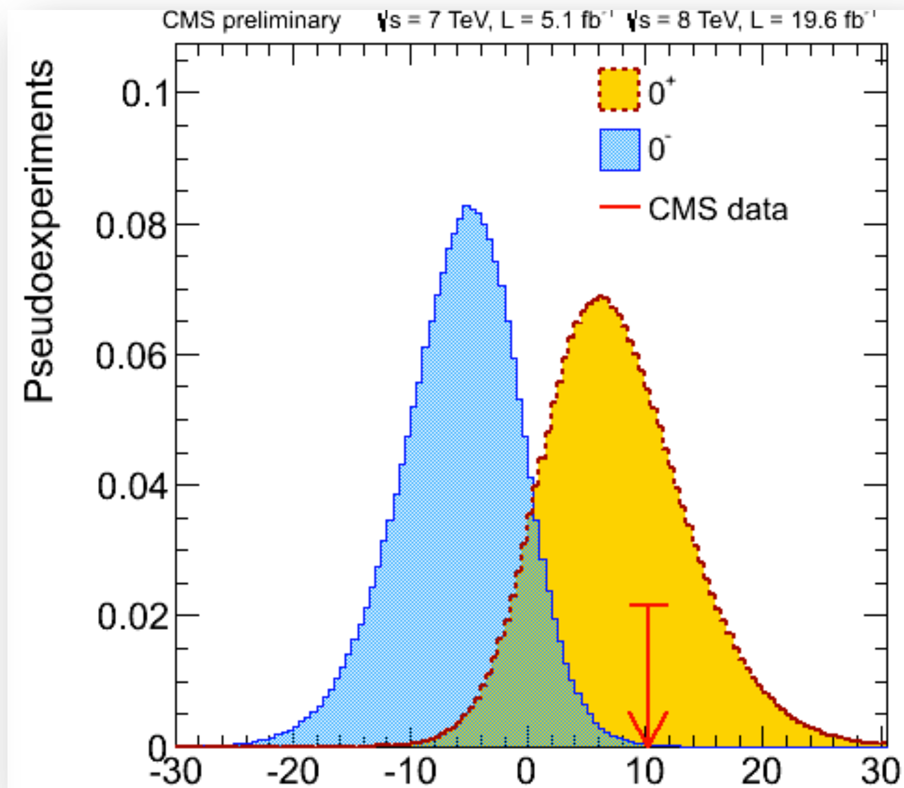
h(125) is

- most likely a spin-0 (scalar) particle. ✔

Along this line, CP property can be measured in 4-lepton final states.
(Diphoton channel does not have enough information to measure CP.)

Both ATLAS and CMS 4-lepton analyses excluded CP-odd scalar :





h(125) is

- most likely a spin-0 (scalar) particle. ✔
- most likely Charge and Parity (CP) even. ✔

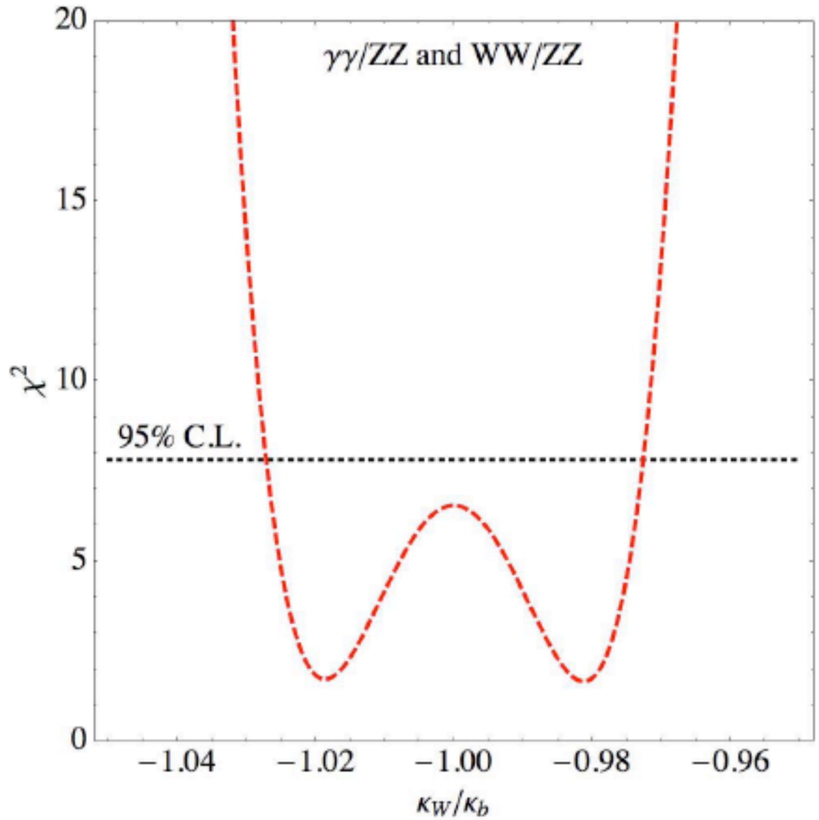
Electroweak quantum number relies on the following reasoning:

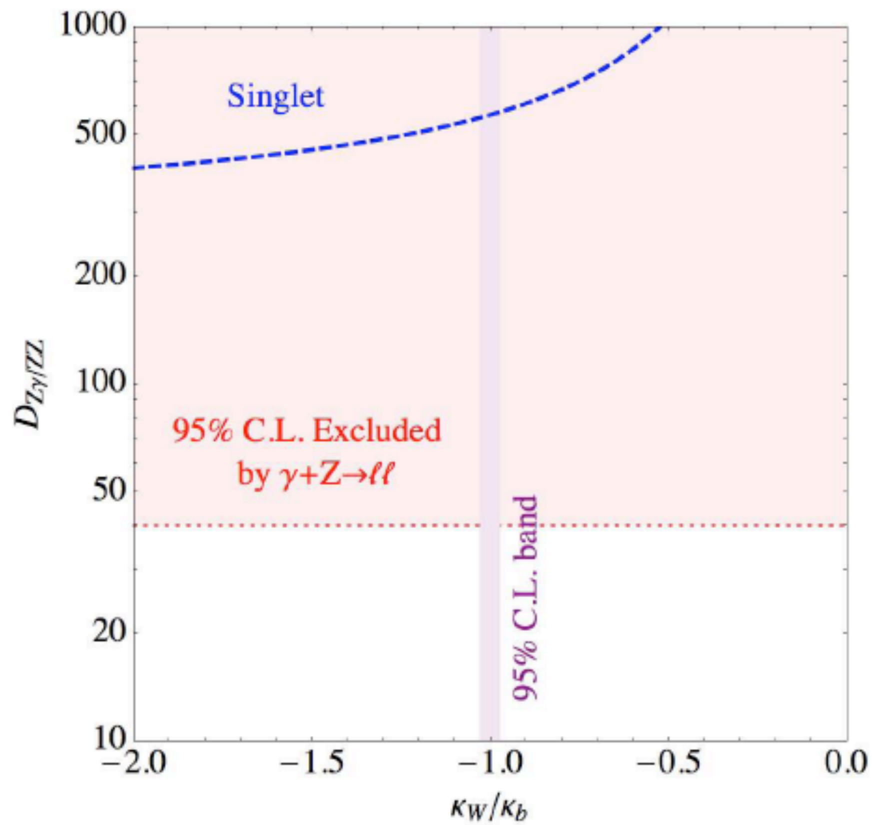
- An electroweak singlet scalar is ubiquitous in BSM theories, whose couplings to pairs of electroweak gauge bosons are controlled by only two parameters at leading order:

$$\kappa_W \frac{\alpha_{em}}{4\pi s_w^2} \frac{S}{4m_S} W^a_{\mu\nu} W^{a\,\mu\nu} + \kappa_B \frac{\alpha_{em}}{4\pi c_w^2} \frac{S}{4m_S} B_{\mu\nu} B^{\mu\nu}$$

Unlike a doublet scalar, the singlet couplings to VV are democratic, without any hierarchy!

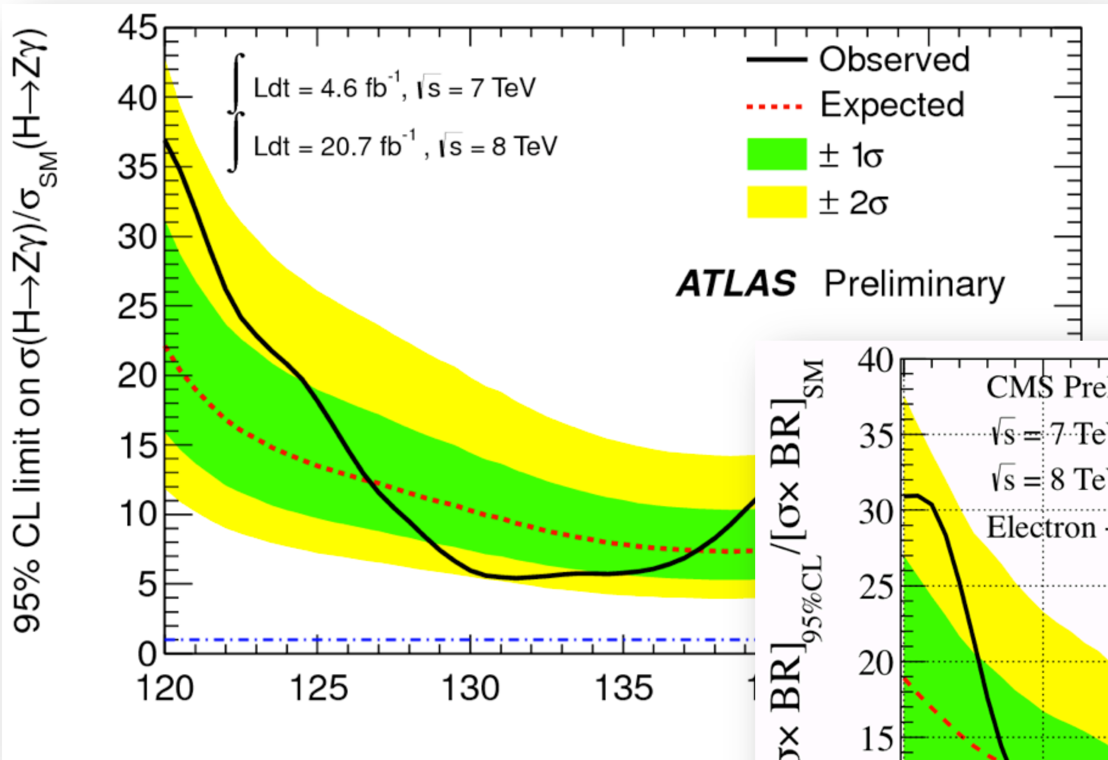
Fitting the electroweak singlet imposter to WW/ZZ and diphoton/ZZ ratios, the predicted Z+Photon rate is 500 times larger than the SM expectation:

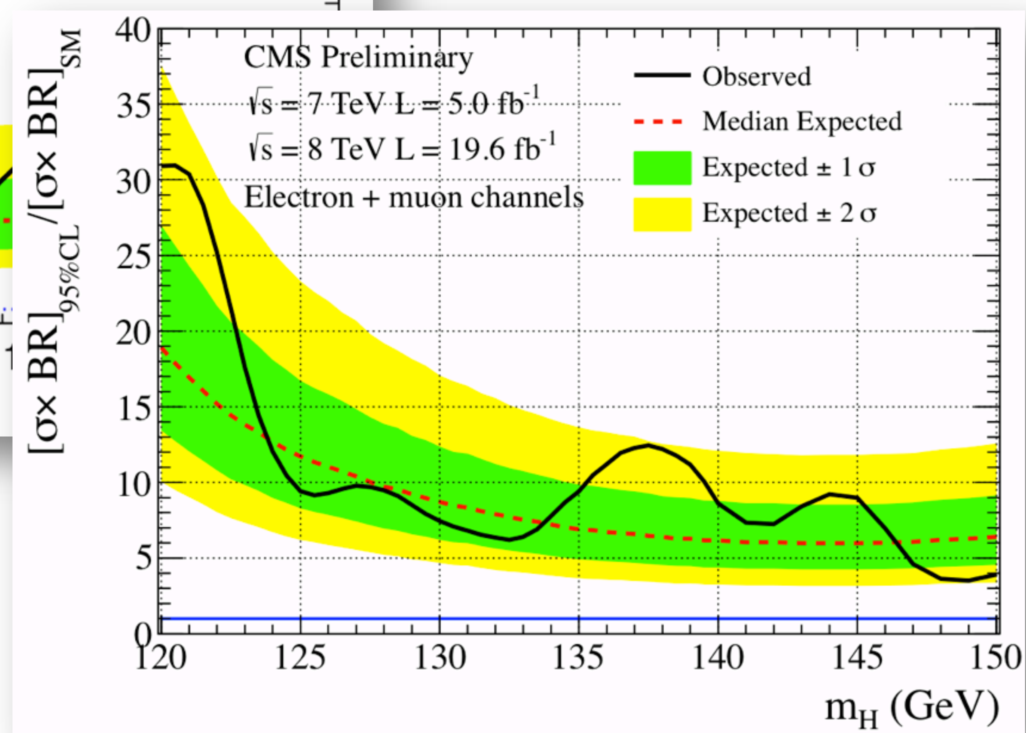




IL and Lykken, 1005.0872
IL, Lykken, and Shaughnessy,1105.4587
IL, Lykken, and Shaughnessy, 1207.1093

ATLAS and CMS finally gave due attention to Z+photon channel:





It is possible to use larger representations of $SU(2)_L$, such as the triplet scalar, as the Higgs imposter.

However, there is very stringent constraint from precision electroweak measurements because the scalar potential of the Higgs in the SM has an accidental global symmetry:

$$V(H) = -\mu^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2$$

is invariant under an SO(4) rotation on

$$\vec{h} = \begin{pmatrix} h^1 \\ h^2 \\ h^3 \\ h^4 \end{pmatrix} \qquad V = -\mu^2 \vec{h}\cdot\vec{h} + \frac{\lambda}{4}\left(\vec{h}\cdot\vec{h}\right)^2$$

After electroweak symmetry breaking,

$$SO(4) \sim SU(2)_L \times SU(2)_R \to SU(2)_C$$

A unique prediction of the "custodial symmetry" is the ratio of couplings to WW and ZZ has only two possible values, depending on the electroweak quantum number:

1. An electroweak doublet (aka Standard Model):

$$g_{hWW/ZZ} = 2\frac{m_{W/Z}^2}{v}\ , \qquad \frac{g_{hWW}}{g_{hZZ}} = \frac{m_W^2}{m_Z^2} = c_w^2\,(1+\mathcal{O}(\%))$$

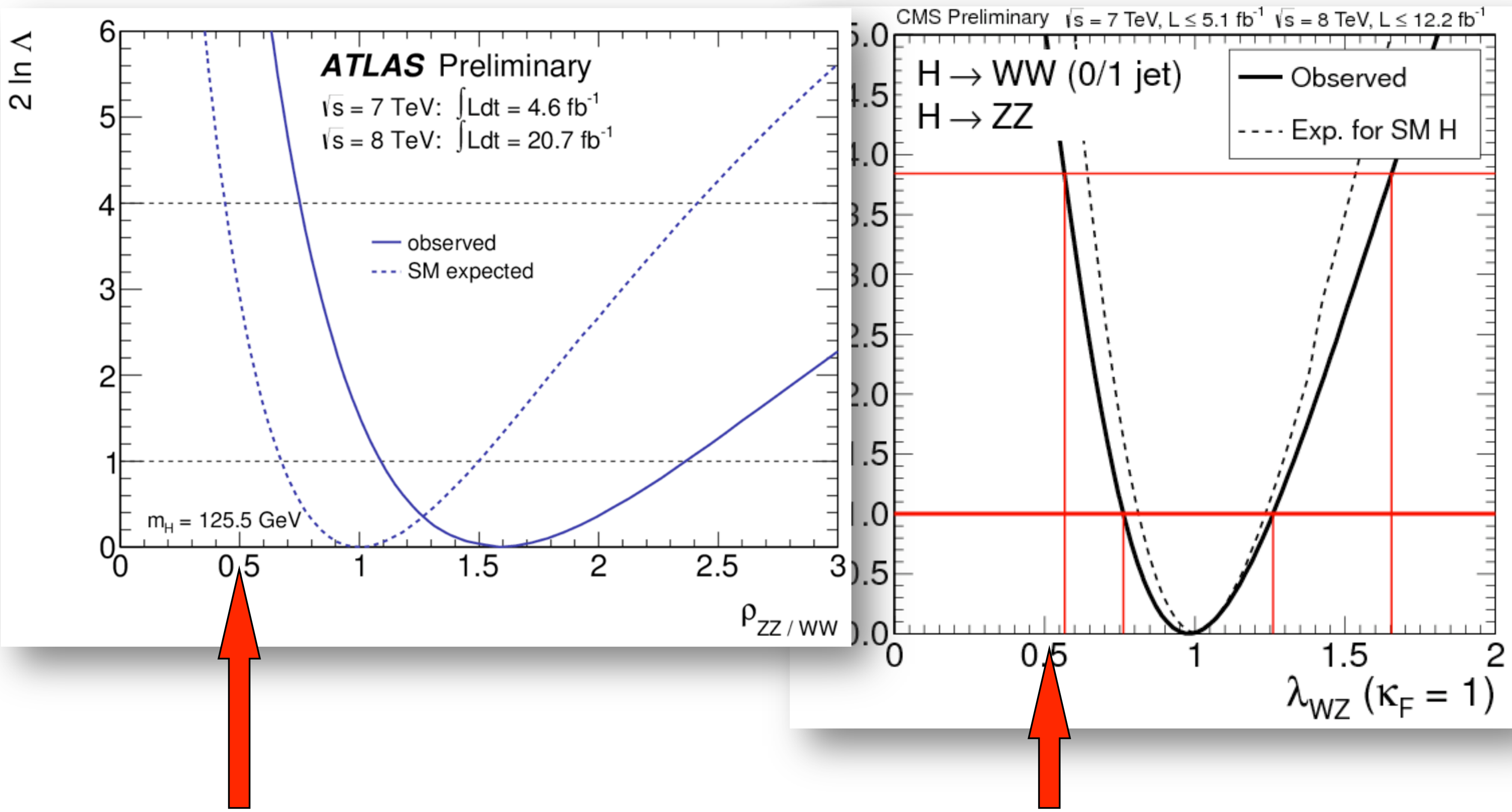
Constrained by precision electroweak measurements of $\Delta\rho \approx 1$!

2. An electroweak triplet imposter:

$$\frac{g_{h_5^0 WW}}{g_{h_5^0 ZZ}} = -\frac{c_w^2}{2}$$

IL and Lykken:1005.0872
See also Georgi and Machacek, NPB (1985)
Gunion, Vega, and Wudka, PRD (1990)

- This ratio has been measured by both ATLAS and CMS:



A triplet scalar is excluded beyond 95% C.L.!

h(125) is

- most likely a spin-0 (scalar) particle. ✔
- most likely Charge and Parity (CP) even. ✔
- most likely the neutral component of an electroweak doublet. ✔

Source of mass for W and Z bosons:

- This is a corollary of the fact that it is an CP-even scalar and an electroweak doublet scalar.

Consider the general couplings of a scalar with two Z bosons:

the other two terms are from electroweak singlet scalars!!

$$\mathcal{L}_{eff} = \frac{1}{2} m_S \, S \left(c_1 Z^{\nu} Z_{\nu} + \frac{1}{2} \frac{c_2}{m_S^2} Z^{\mu\nu} Z_{\mu\nu} + \frac{1}{4} \frac{c_3}{m_S^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

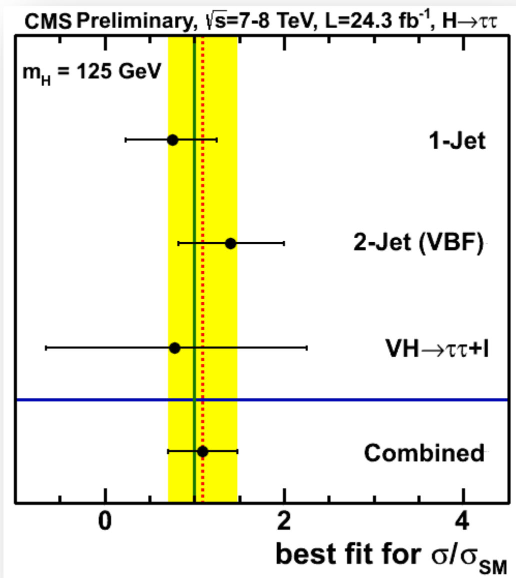
higgs mechanism predicts only this term!

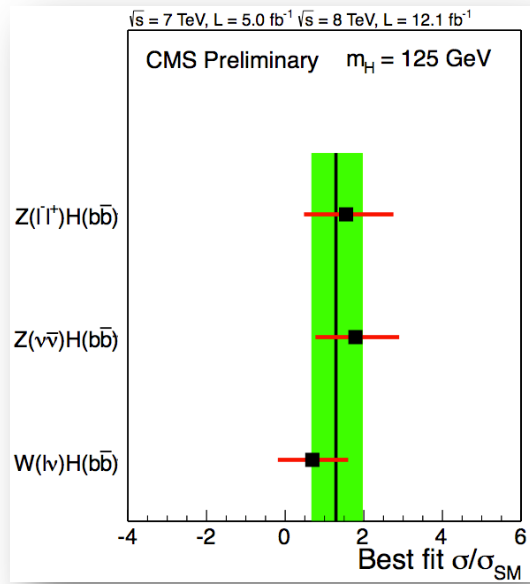
h(125) is

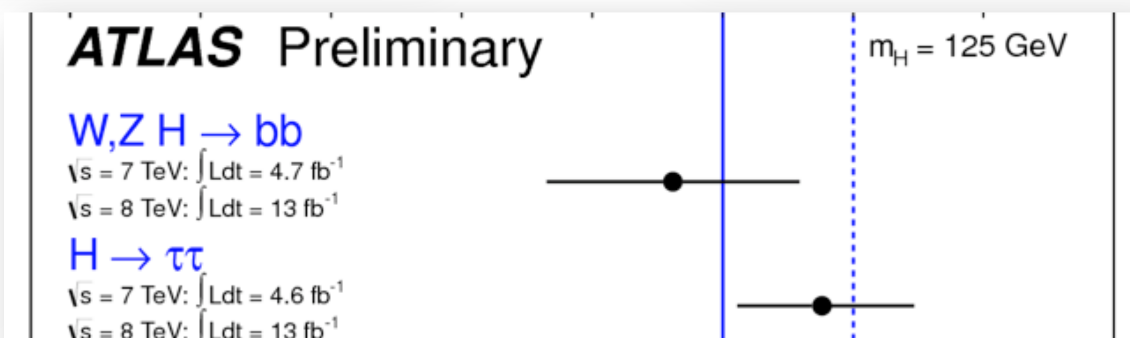
- most likely a spin-0 (scalar) particle. ✔
- most likely Charge and Parity (CP) even. ✔
- most likely the neutral component of an electroweak doublet. ✔
- most likely the origin of mass for W/Z bosons and ✔

Source of mass for quarks and charged leptons:

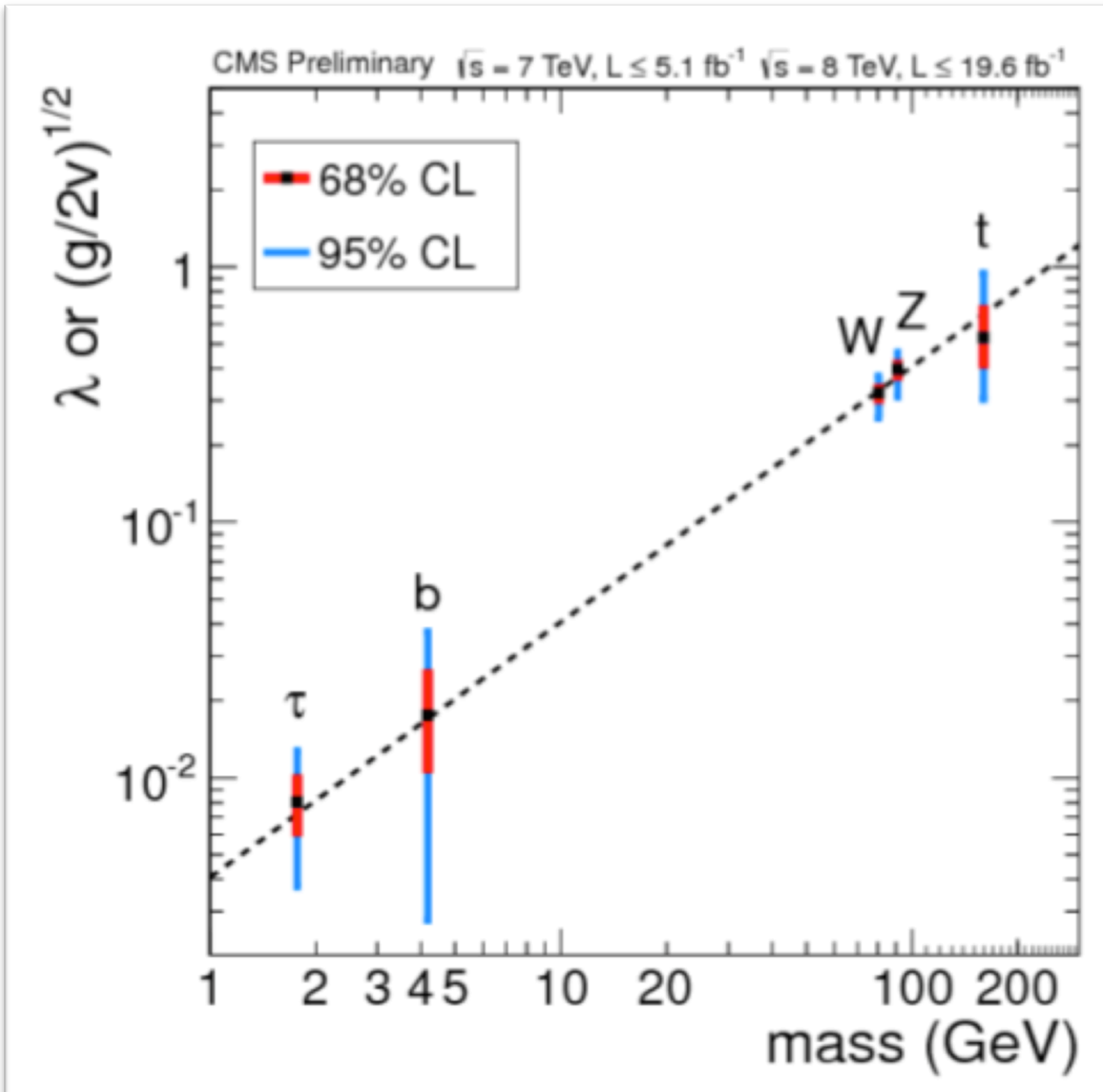
- It does seem to decay to fermions with SM strength:







A very nice figure showing h(125) as the origin of mass:

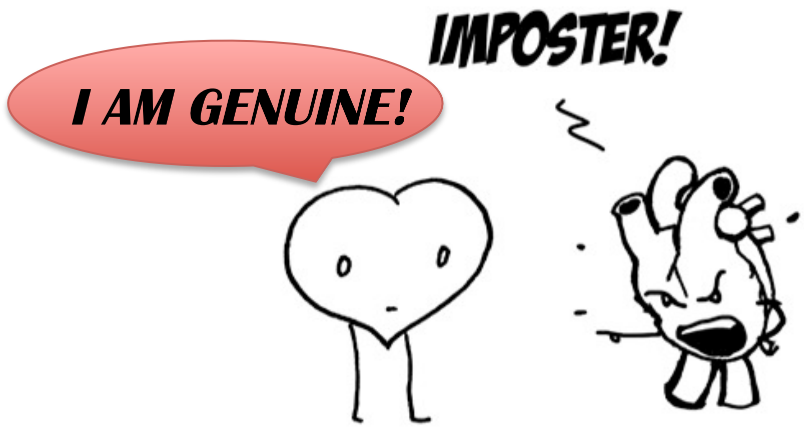


h(125) is

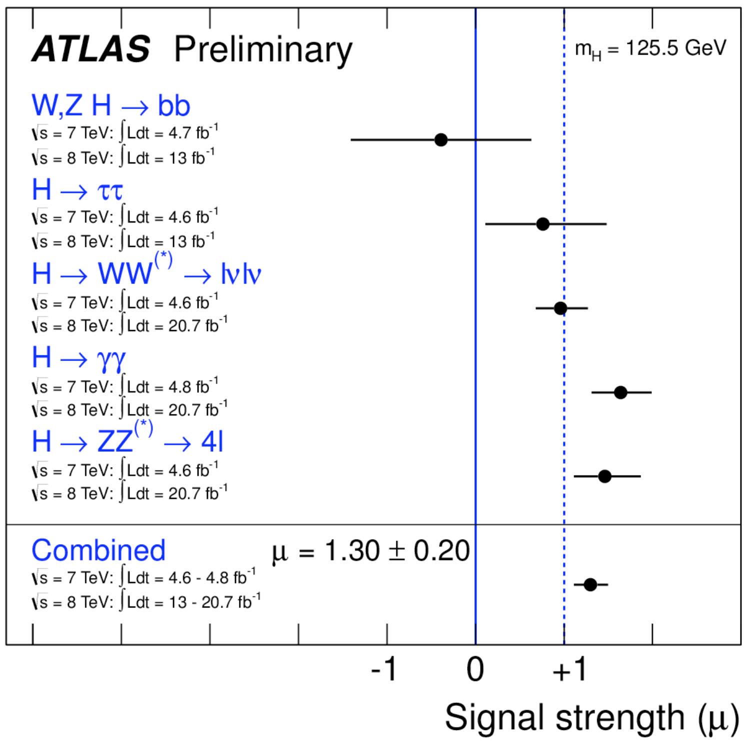
- most likely a spin-0 (scalar) particle. ✔
- most likely Charge and Parity (CP) even. ✔
- most likely the neutral component of an electroweak doublet. ✔
- most likely the origin of mass for W/Z bosons and ✔
- probably the origin of mass for the quarks and charged leptons. ✔

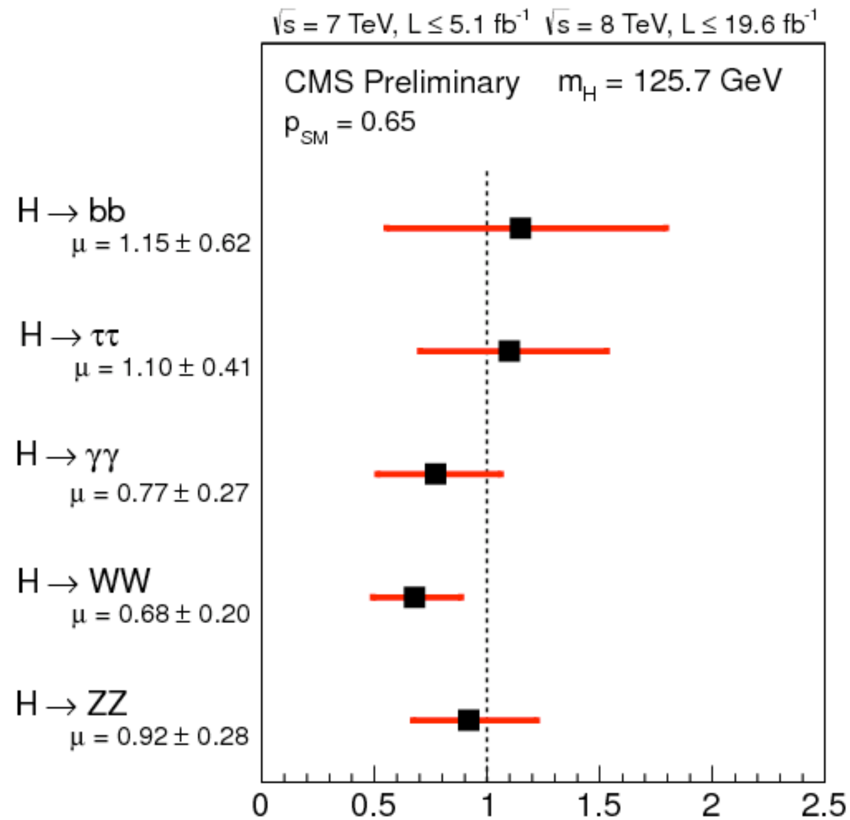
So all the pieces are falling into place:

everything points to a genuine Higgs boson, not an imposter!



The fit for signal strengths in various channels:





So not only do we have a Higgs boson,
we have a Standard Model-like Higgs boson!