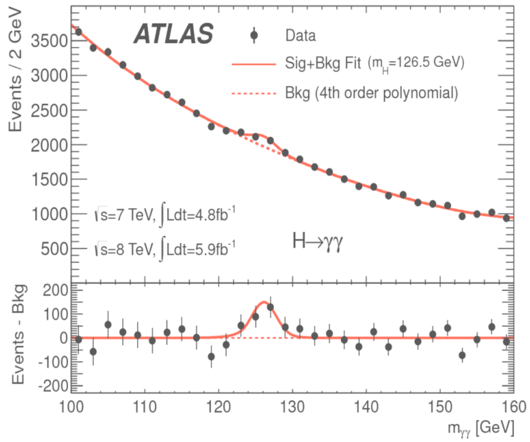
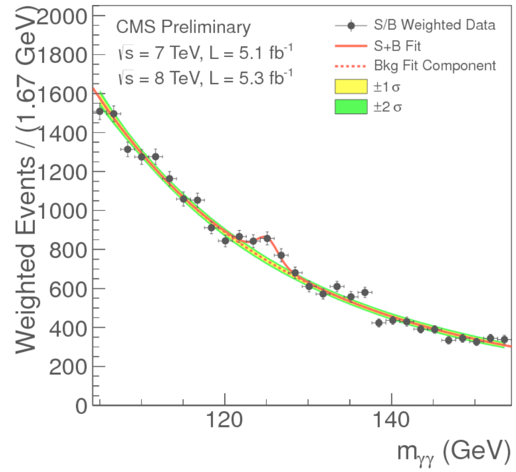
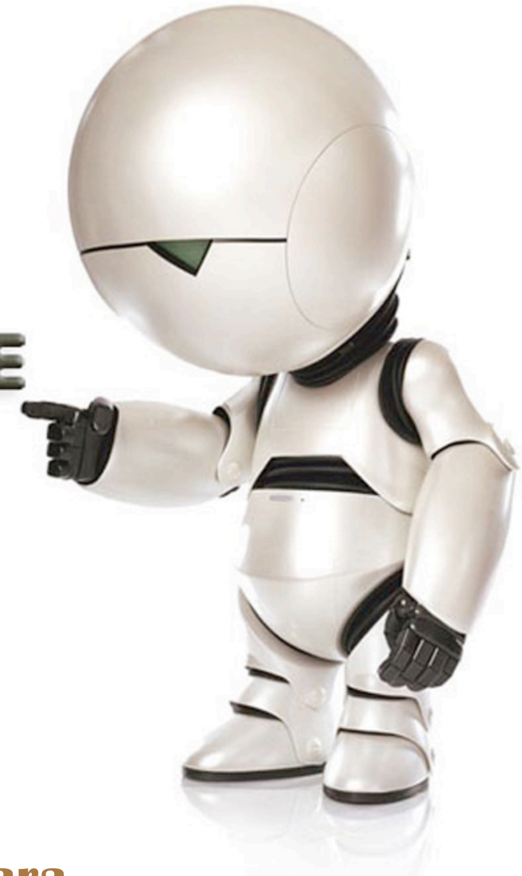




THE HITCHHIKER'S GUIDE TO THE Higgs Boson



Ian Low @ SMU, Sep 6, 2012

Argonne/Northwestern/KITP Santa Barbara

What is a Higgs boson?

- As is often the case, you go on the internet to find out about things. Without thinking too hard, let's go to www.higgsboson.com....

Here is a pop quiz:

If you go to www.higgsboson.com you will find:

(a) A passionate, devoted amateur scientist wanting to find the Higgs boson.

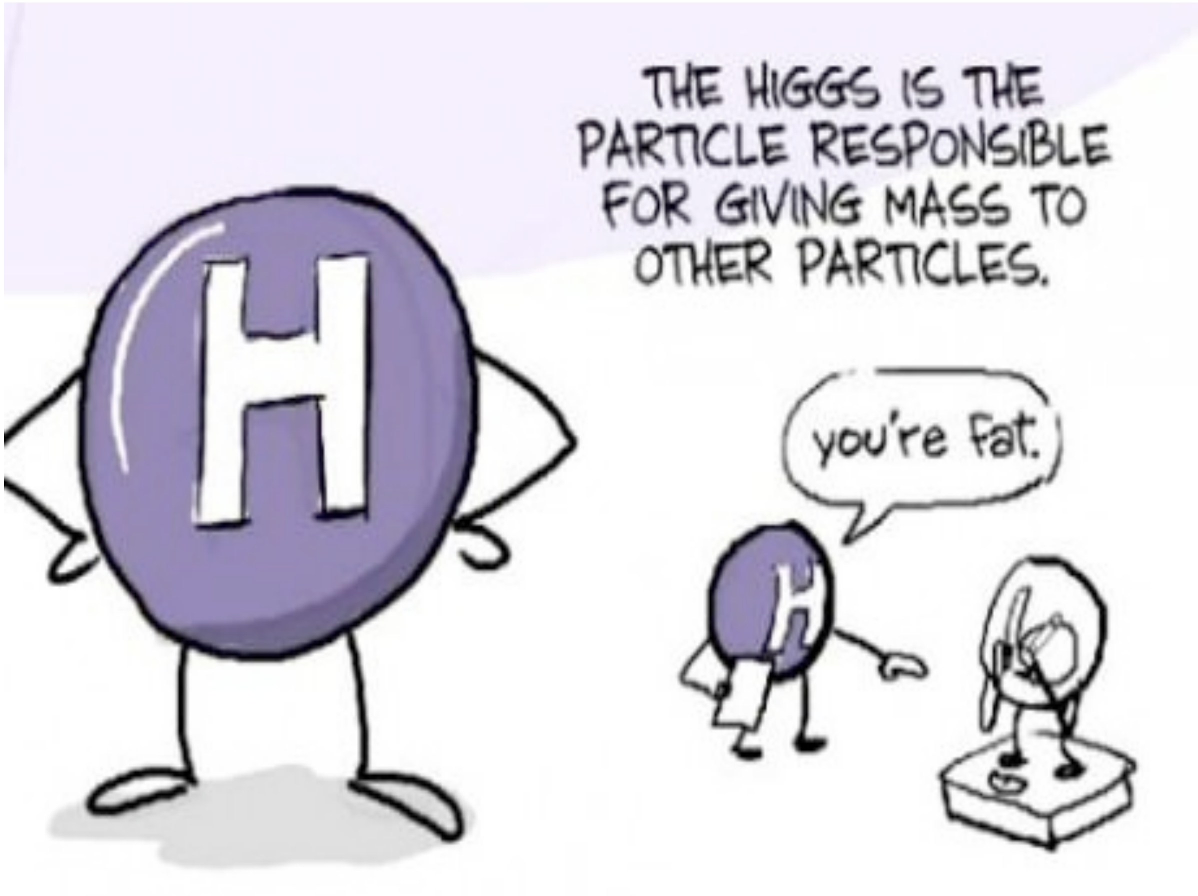
(b) A high-tech startup company commercializing the technology in building accelerators.

(c) An award winning contemporary jazz pianist whose music is inspired by the Higgs boson.

(d) A choir group at CERN consisted of amateur singers.

So, really, what is a Higgs boson?

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



So, really, what is a Higgs boson?

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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!**

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

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??

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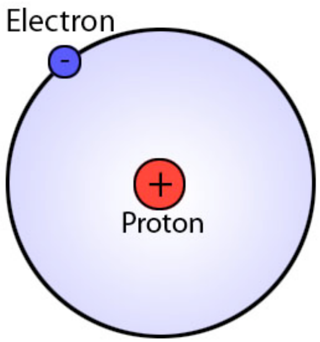
Can you imagine a world with a massless electron??

Let's consider the hydrogen atom:



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

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

Before I tell you how the Higgs boson gives mass to the electron, I need to explain *why* we need the Higgs at all!

It has to do with these two Nobel laureates:

Chen Ning Yang

Tsung-Dao (T.D.) Lee

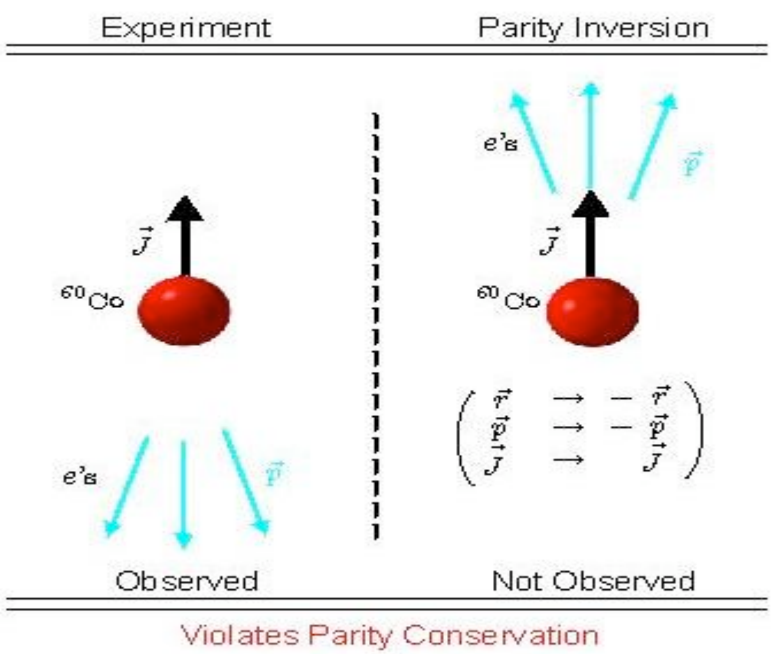
Lee and Yang suggested in 1956 that parity may be violated in weak interactions!

Parity is the operation of space inversion:

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

$$\begin{array}{rcl} \vec{r} & \rightarrow & -\vec{r} \\ \vec{L} = \vec{r} \times \vec{p} & \rightarrow & \vec{L} \end{array}$$

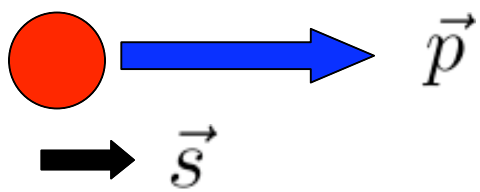
Physicists used to believe that, if an event occurs in nature, the image of that event under parity must also occur….



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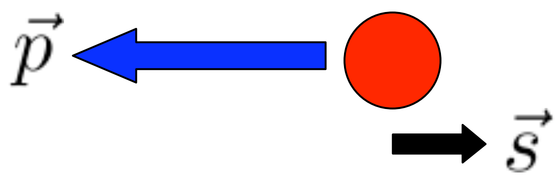
Now perform a Lorentz boost to a frame where the momentum is reversed:



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:

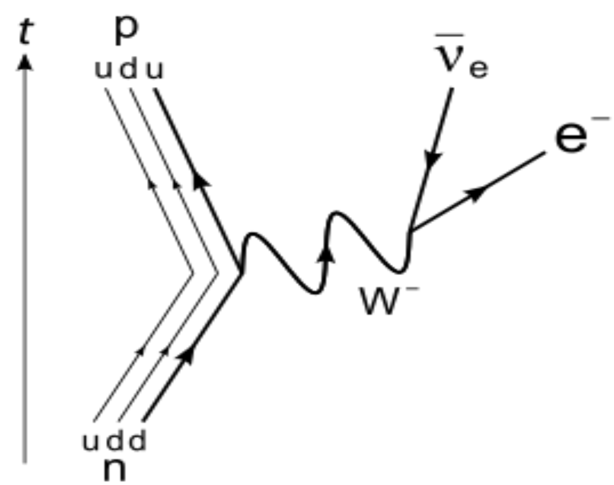
These two states map into each other under parity!

For a massive particle, both handedness must exist!

Buf 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!

- **At around 1968, Glashow, Weinberg, and Salam proposed that weak interactions are mediated by spin-1 particles called the W (charged) and Z (neutral) bosons.**



- **Moreover, they proposed that the weak interaction is unified with the electromagnetic interactions at high energies.**

  --> now called the electroweak interactions, which is based on the symmetry group of SU(2)xU(1)

- **Recall that photon is the force carrier of electromagnetic force and couples electric charge.**

- **Similarly, W and Z bosons couple to an analog of electric charge in the weak interaction, the *weak isospin* charge.**

- **It turned out that parity is <u>maximally</u> violated in weak interactions!**

  (only left-handed state carries weak isospin, but not the right-handed state.)

- **Since states with different handedness carry different quantum number, they cannot mix quantum mechanically.**

  Therefore a mass term is forbidden in the theory of electroweak interactions!

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

There are actually 6+1 persons deserving the credit for the proposal of Higgs mechanism:

6 = Englert, Brout, Higgs, Guralnik, Hagen, and Kibble. They shared the 2010 APS Sakurai Prize

1 = Phil Anderson, but he's not a particle physicist….

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In plain english, the Higgs mechanism is like going to the swimming pool and immersing yourself in the water. Your body moves at a slower speed when using the same strength.

It feels like you pick up a heavier mass in the water!!

We believe the Universe is filled with the condensate of the Higgs boson. When the electron moves through this condensate it picks up a mass!

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A cartoon version:

A room filled with physicists

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Einstein walks into the room

We believe the Universe is filled with the condensate of the Higgs boson. When the electron moves through this condensate it picks up a mass!

A cartoon version:

A room filled with physicists

Einstein walks into the room

He attracts admirers, moves slower, and effectively gains a mass!

Quantum-mechanical excitation of the condensate is the Higgs boson:

If now it's only a rumor enters the room: There's a two-sigma excess for at the LHC!

Quantum-mechanical excitation of the condensate is the Higgs boson:

If now it's only a rumor enters the room: There's a two-sigma excess for at the LHC!

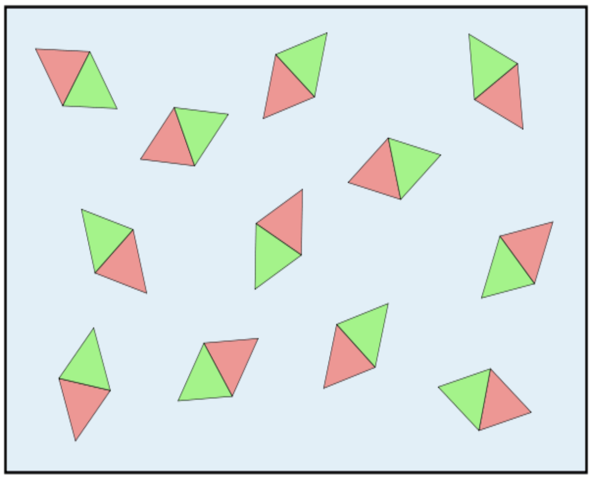
Then all the theorists are excited and got together to discuss: We only have a cluster among the theorists.

The Higgs mechanism is closely related to the notion of spontaneously broken symmetry, for which Nambu won the Nobel prize in 2008:

Yoichiro Nambu
南部 陽一郎

- Spontaneous symmetry breaking refers to the fact that, although the underlying theory may possess a particular symmetry property, the ground state may not.

- This is a phenomenon that is ubiquitous in nature. For example, the theory of ferromagnetism respects rotational invariance:



Above T_C rotational invariance is manifest!

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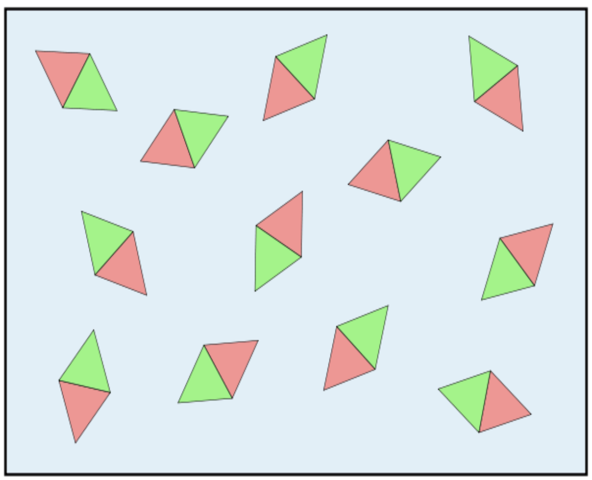

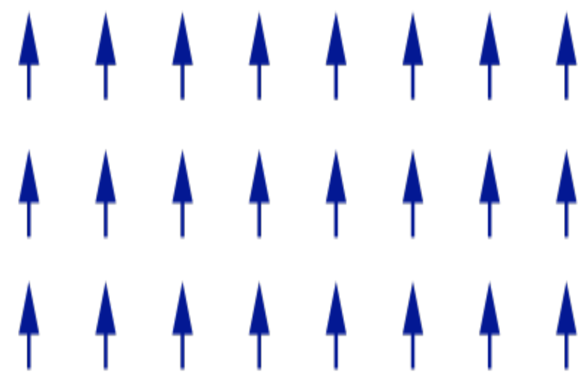

Above T_C rotational invariance is manifest!

Below T_C rotational invariance is spontaneously broken!

- **A more mundane example is a pencil standing on its tip:**

The pencil has no preferred direction to fall --> rotational invariance

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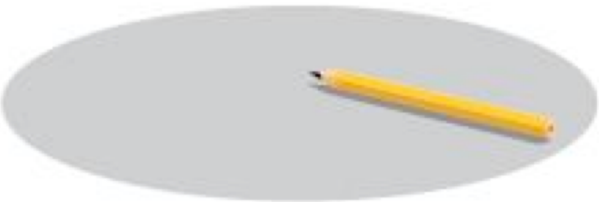
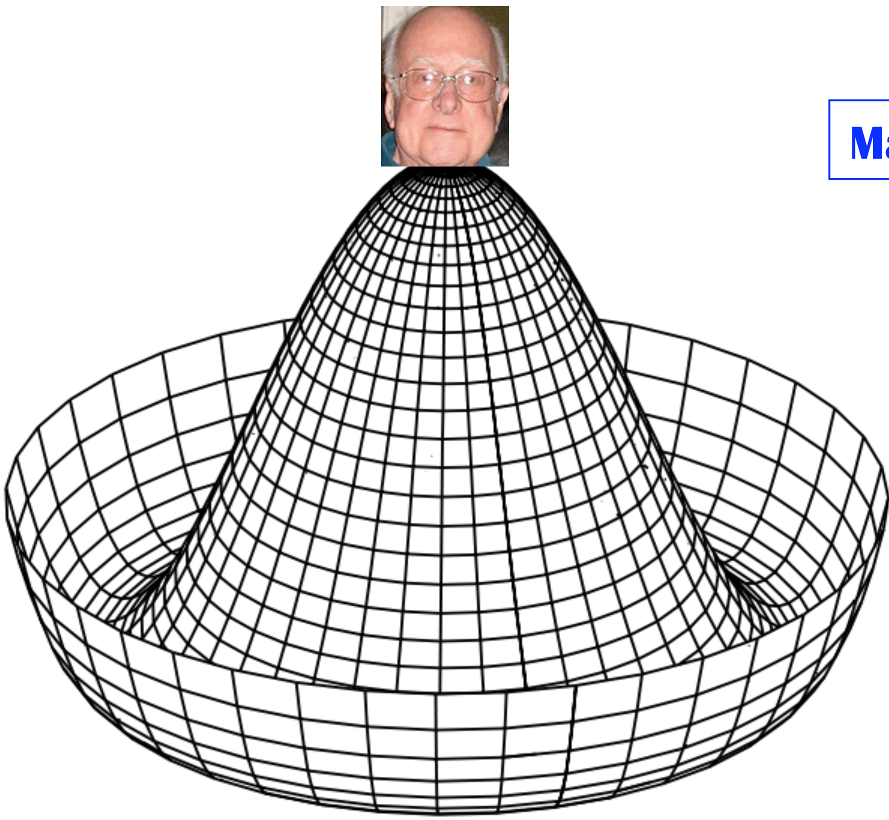


The pencil has no preferred direction to fall --> rotational invariance

The configuration is unstable! Once the pencil falls, rotational invariance is broken.

- **For the Higgs boson, what is being proposed is the following "Mexican hat" potential, which respects the "electroweak symmetry."**



Manifestly symmetric, but unstable!

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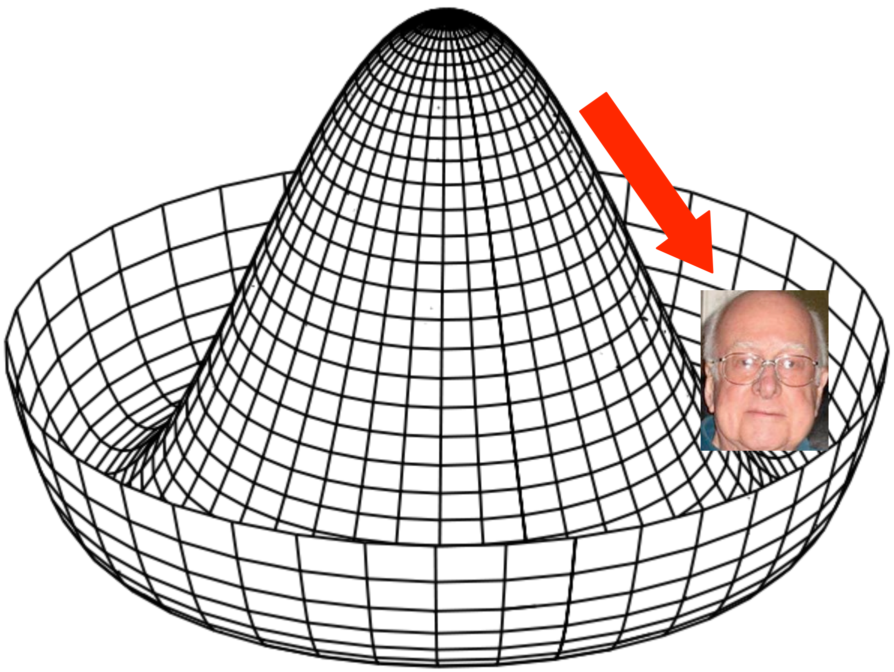
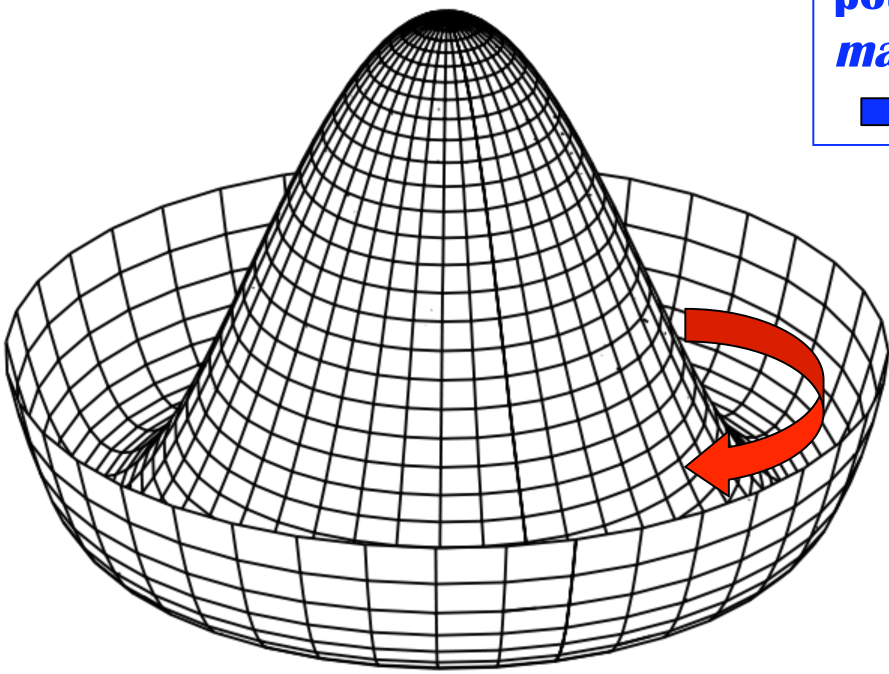


The ground state, but the symmetry is spontaneously broken!

Mathematically, the Higgs receives a VEV (vacuum expectation value):

$$h \rightarrow v + h$$

- **For the Higgs boson, what is being proposed is the following "Mexican hat" potential, which respects the "electroweak symmetry."**



Excitation along the bottom of the potential is "gapless," implying a *massless* particle

➡ the Nambu-Goldstone boson!!

So how does the Higgs mechanism and the Higgs boson resolve the difficult of having an electron mass in the “electroweak theory”, which forbids the mass?

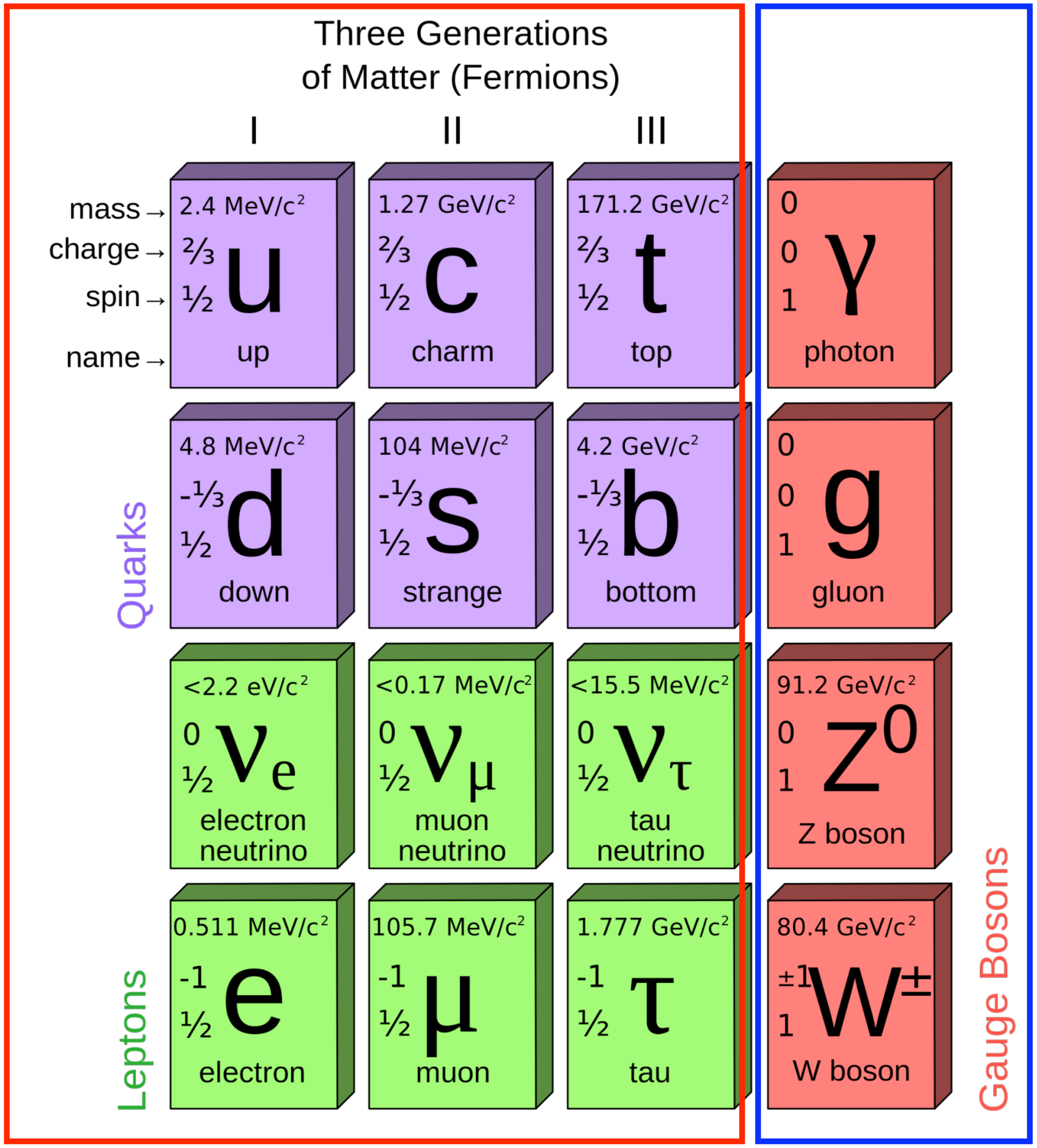
(A mass is forbidden means it does not conserve the electroweak charges, which are analog of the electric charge.)

The way out is the Higgs vacuum expectation value acts like a perfect “dielectric medium.”

It absorbs any non-conserving electroweak charges carried by the mass of the electron.

This is a pictorial summary of the standard model of particle physics, as we know it last year:

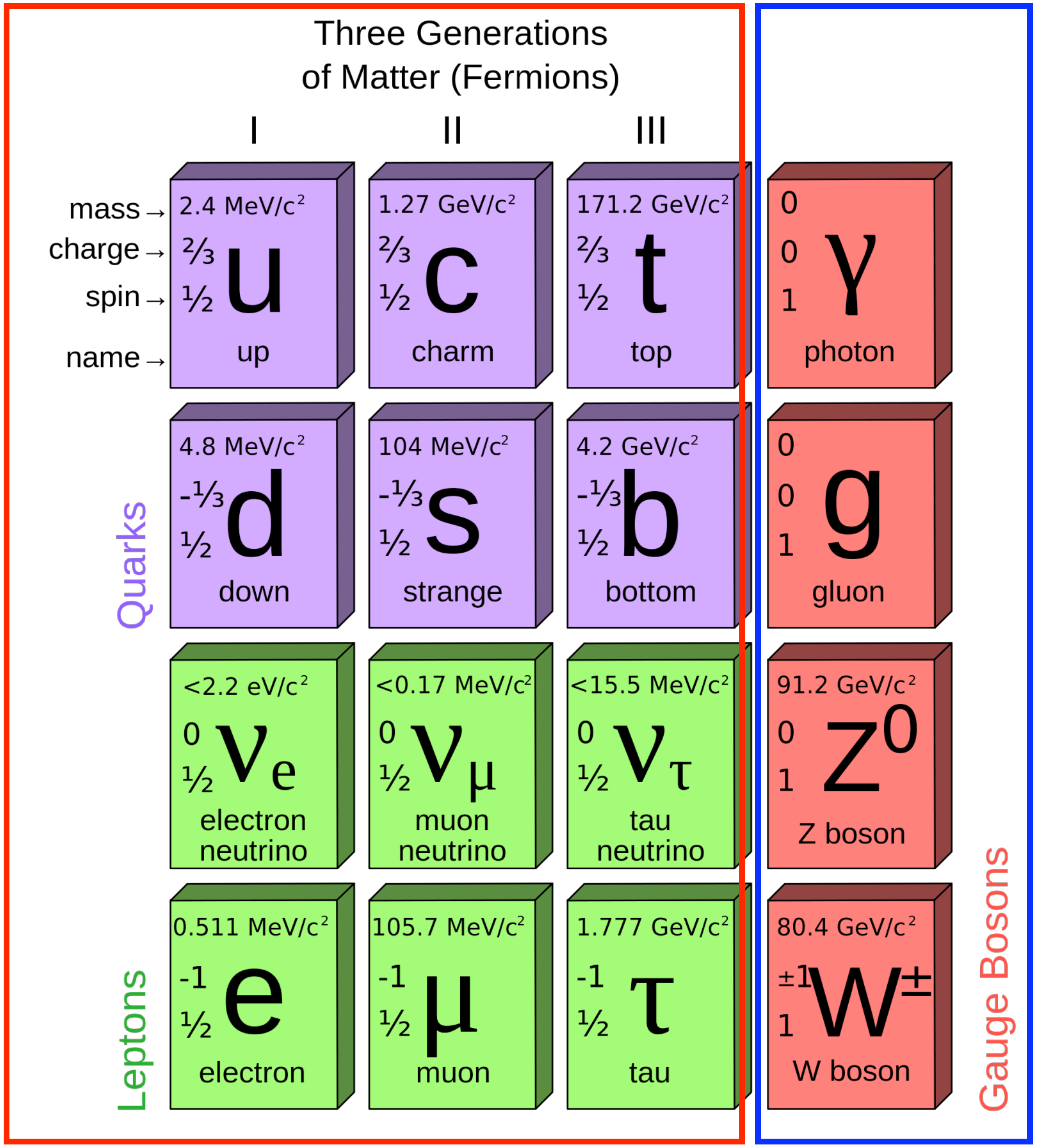
Fermions have half Integer-spin.



Bosons have integer-spin.

We believe all massive particles (except neutrinos) below get their masses from the Higgs boson.

Fermions have half Integer-spin.

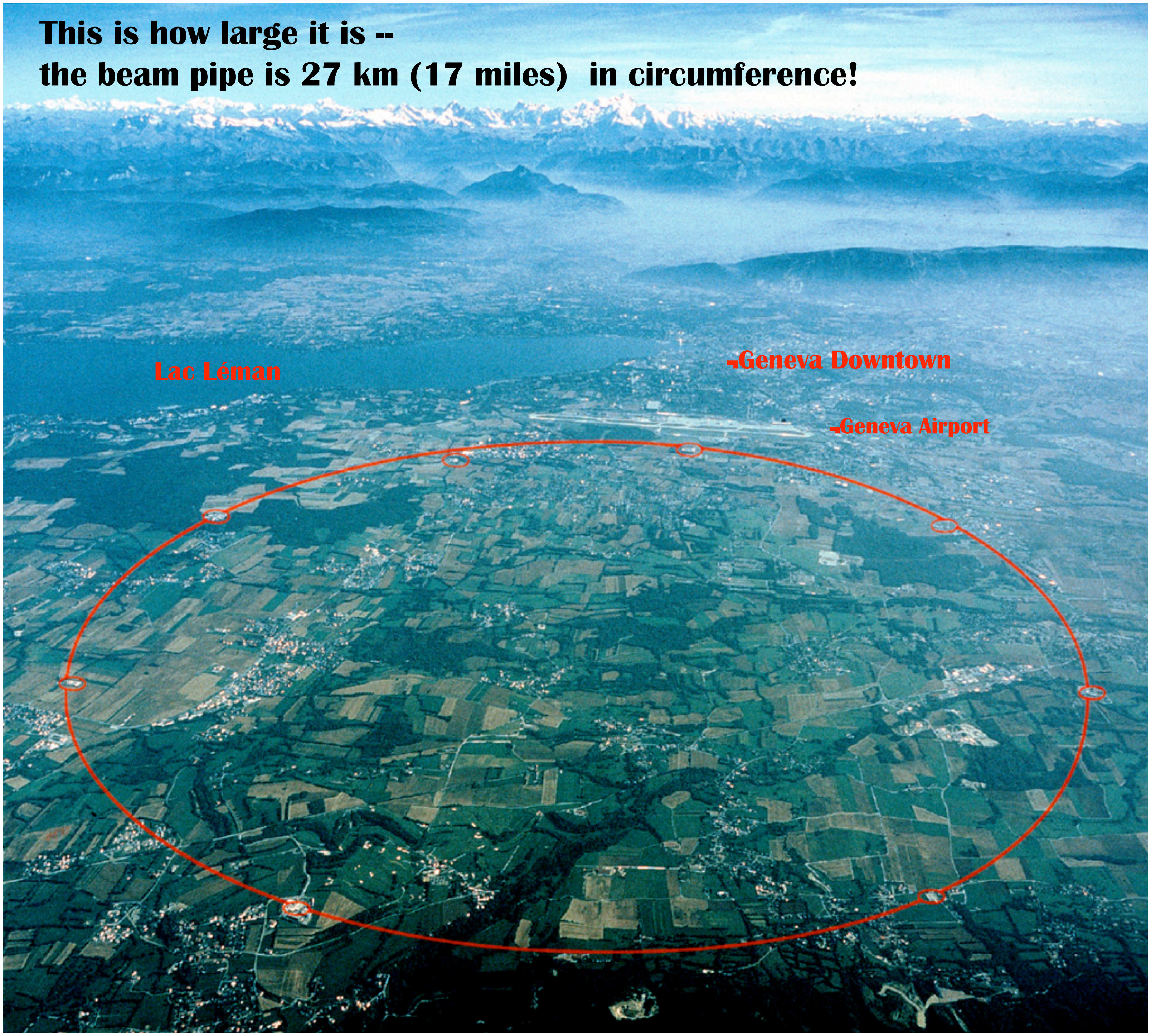


Bosons have integer-spin.

To study such an important question,

Where does the electron mass come from?

$4 billion euro was spent on building the Large Hadron Collider at CERN in Geneva.


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

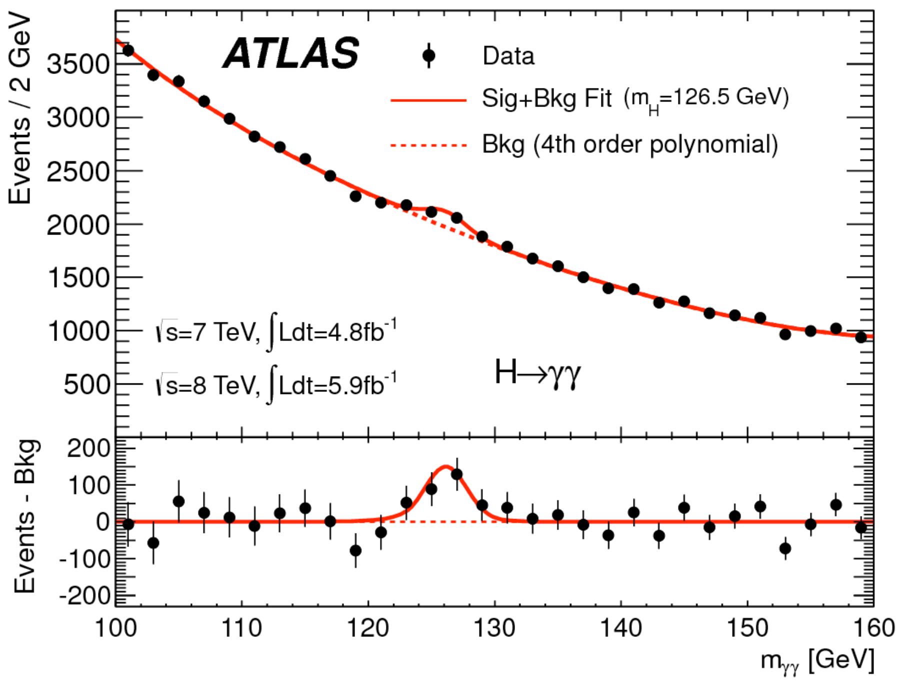
LHC is a proton-proton collider @ center-of-mass energy = 14 TeV by design. Currently running at 7 (8) TeV in 2011 (2012)

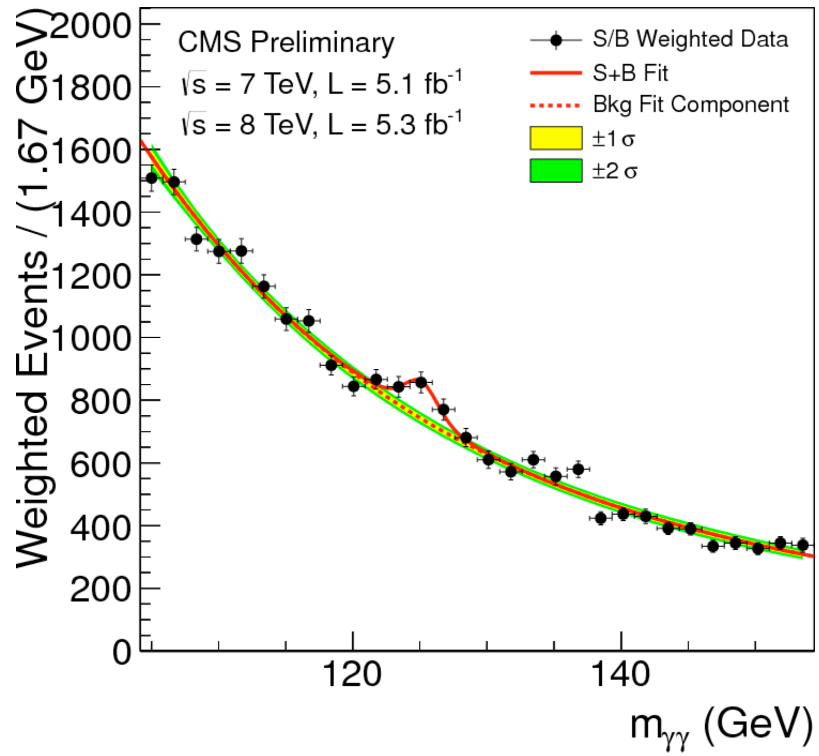
It has two general detectors: ATLAS and CMS. Their main priority is to hunt down the Higgs boson.

AND THEY DID!!

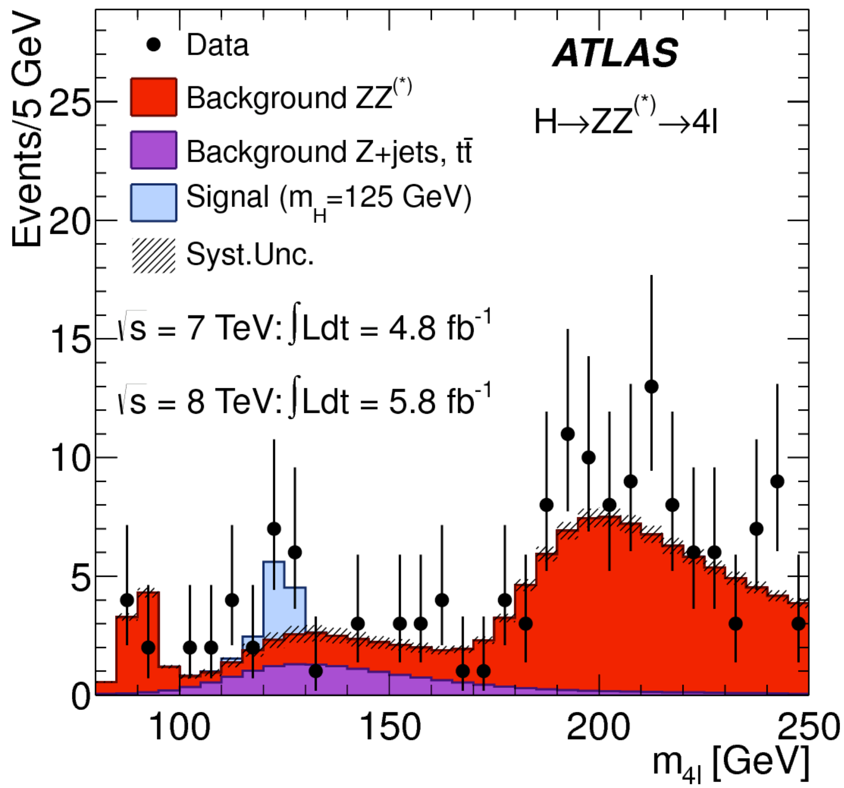
Scenes from the July 4, 2012 announcements:

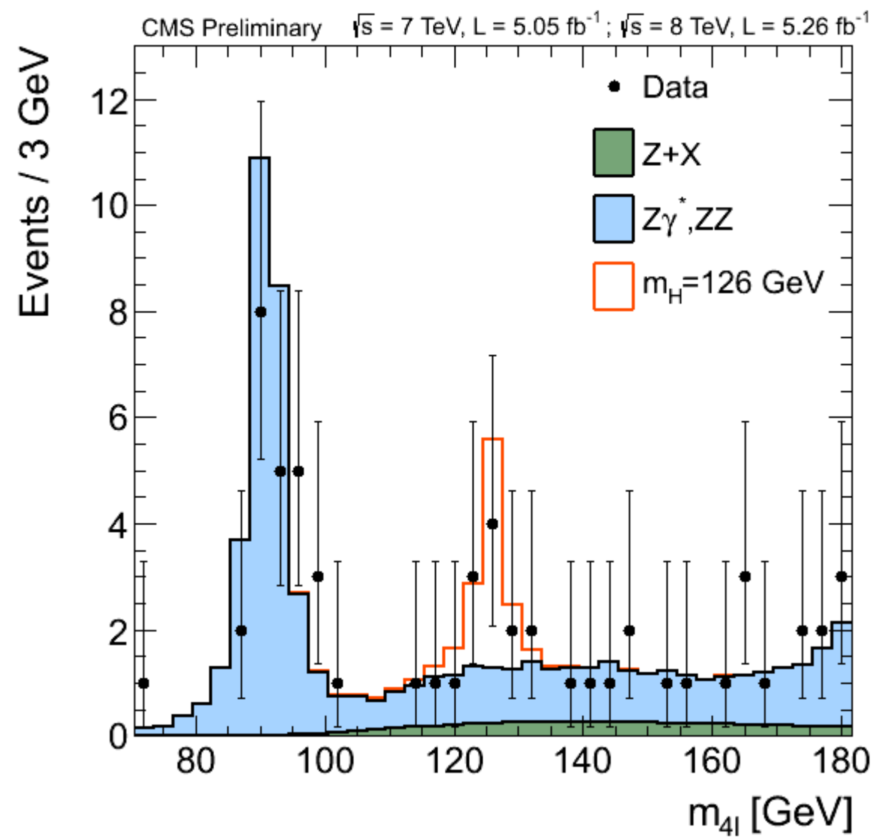
ATLAS and CMS both see a "new boson" decaying into two photons, with a mass at around 126 GeV:



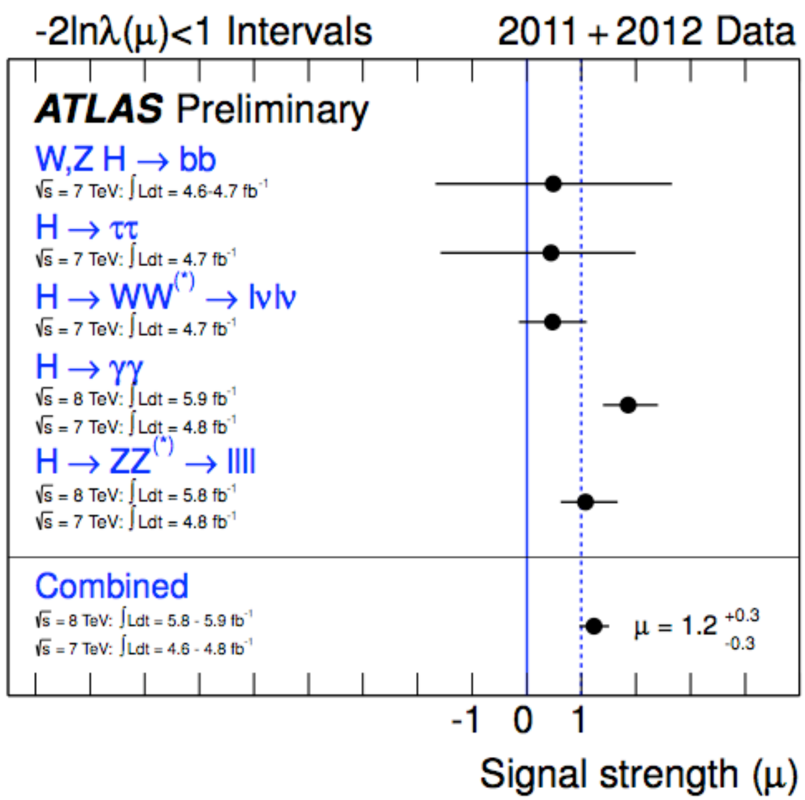


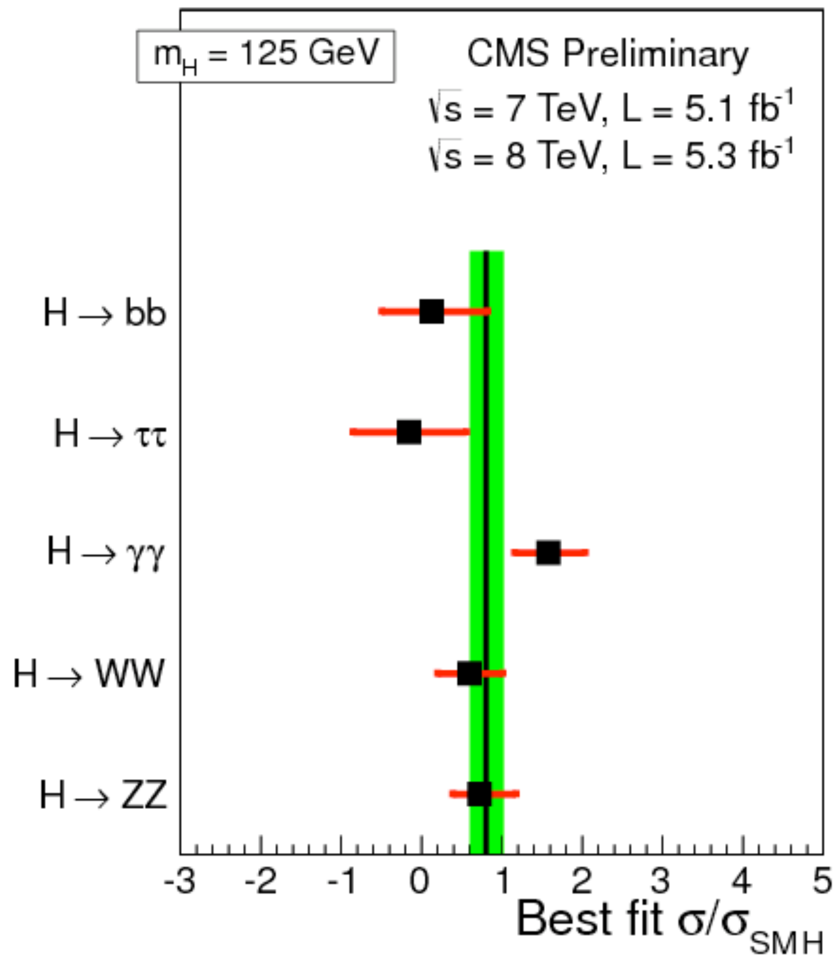
The four-lepton channel also sees a "visual peak":





A summary of current measurements in various channels:





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)

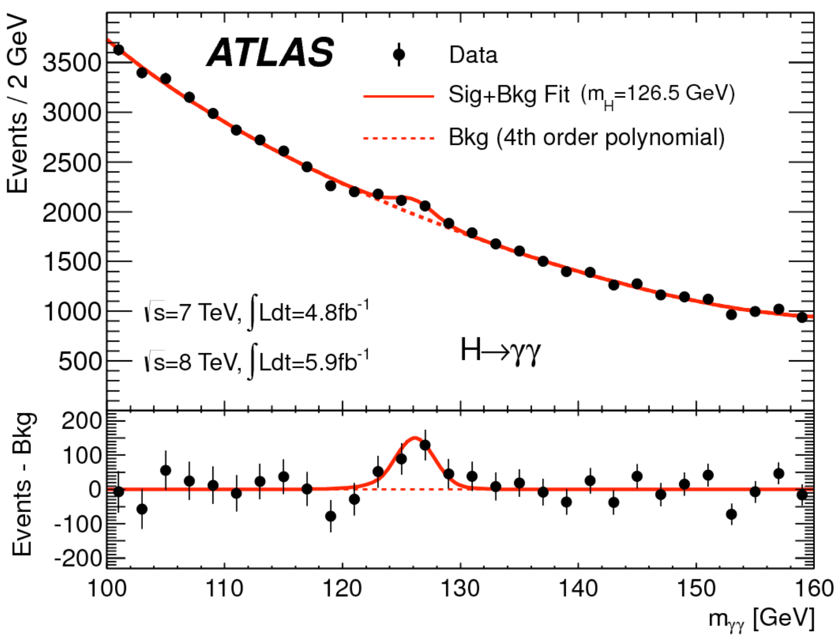
BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

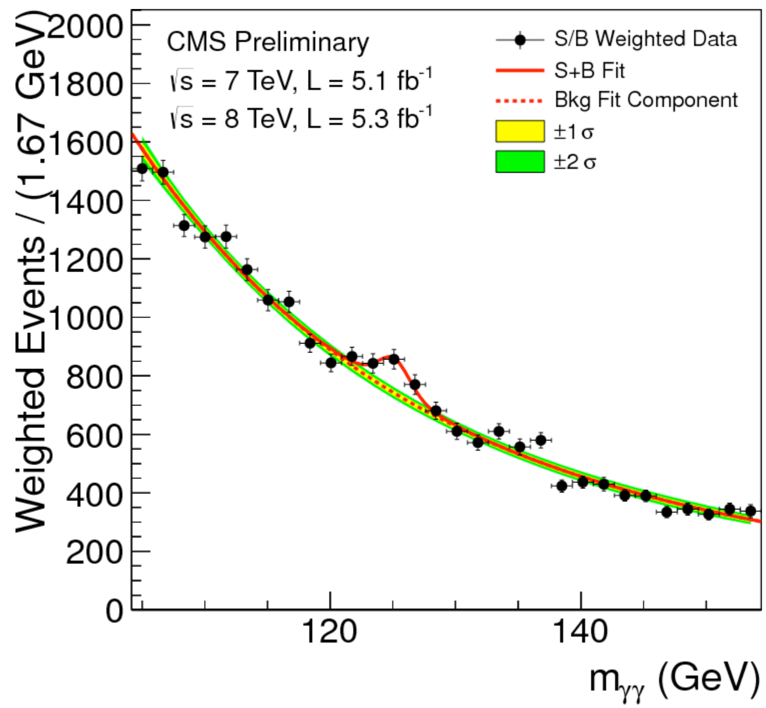
F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

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!

We should all be screaming out loud:

PHYSICS REALLY WORKS!!

But this is also a moment to be prudent….

Recall that CERN only announced the discovery of a *Higgs-like* boson.

After all, extraordinary science requires extraordinary evidence….

We don't want to be fooled into thinking it's the long awaited Higgs boson when it is a Higgs imposter.

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

These specifications imply very specific couplings structure to W/Z bosons, the photon, and the fermions!

So far we have verified none of the above.

This is just the beginning of a challenging program of "Higgs Identification."

In order to confirm the identity of the new particle, we should first establish what it is not.

We can already rule out some Higgs imposters given what we know today.

Some examples of Higgs imposter are

- **An electroweak singlet scalar**
- **A dilaton/radion arising from a nearly conformal sector at high energy scale**
- **An electroweak triplet scalar**

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

Let’s recall what we actually “measure”.

In each channel we measure one number --

the event rate for a particular production mechanism X of the new boson Y, which subsequently decays into Y final states:

$$B\sigma_X(Y) \equiv \sigma(X \to S)\frac{\Gamma(S \to Y)}{\Gamma_{\rm tot}}$$

At the LHC we are most sensitive to

- **two production mechanisms: the gluon fusion (ggh) and the vector-boson fusion (VBF).**
- **Three decay channels: WW, ZZ, and diphoton**

It turns out that ratios of event rates are powerful model-independent discriminators of Higgs imposters!

- **Same production but different decay channels:**

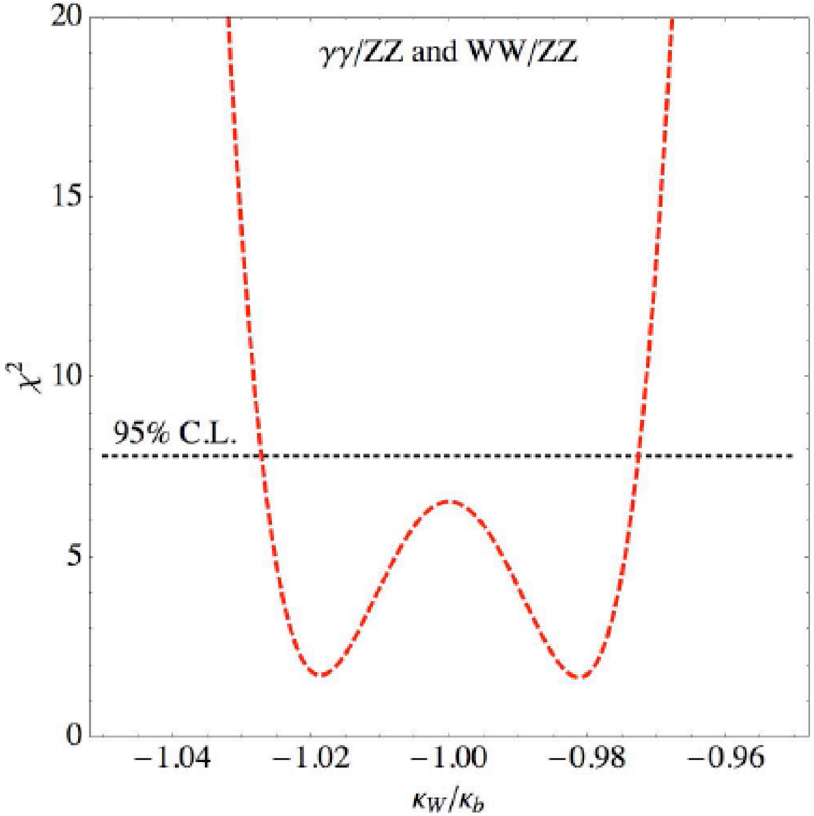
$$D_{W/Z} \equiv \frac{B\sigma_{gg}(WW)}{B\sigma_{gg}(ZZ)} = \frac{\Gamma(S \to WW)}{\Gamma(S \to ZZ)} \ ,$$
$$D_{\gamma/Z} \equiv \frac{B\sigma_{gg}(\gamma\gamma)}{B\sigma_{gg}(ZZ)} = \frac{\Gamma(S \to \gamma\gamma)}{\Gamma(S \to ZZ)} \ ,$$
$$D_{Z\gamma/Z} \equiv \frac{B\sigma_{gg}(Z\gamma)}{B\sigma_{gg}(ZZ)} = \frac{\Gamma(S \to Z\gamma)}{\Gamma(S \to ZZ)} \ .$$

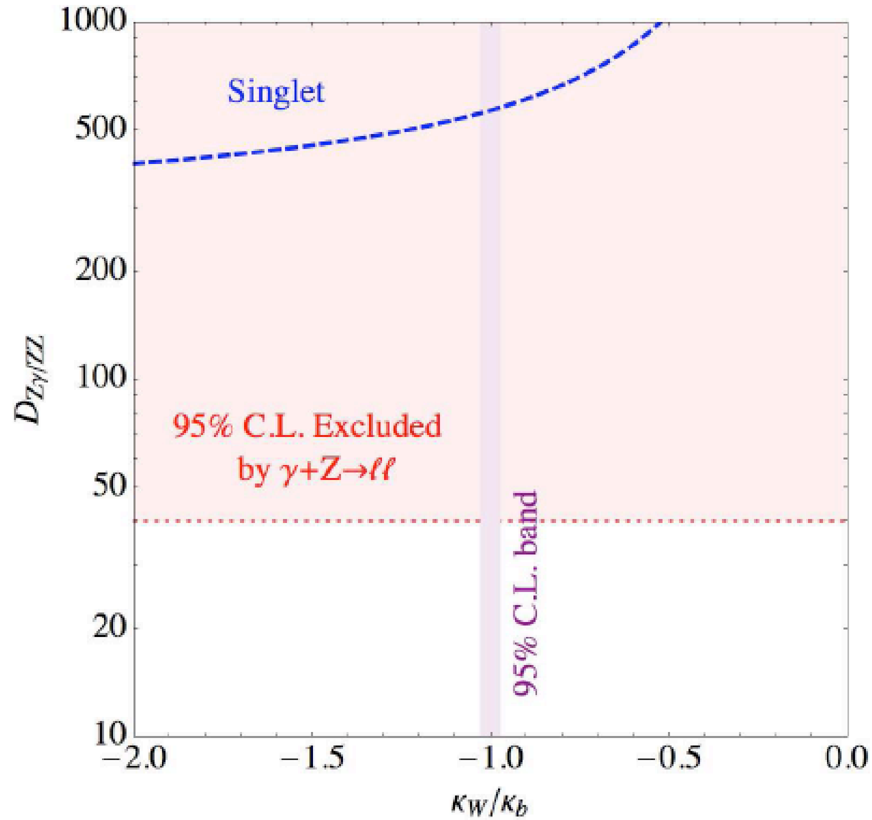
- **Different production but same decay channels:**

$$P_{g/V} \equiv \frac{B\sigma_{gg}(\gamma\gamma)}{B\sigma_{\mathrm{VBF}}(\gamma\gamma)} = \frac{\sigma(gg \to S)}{\sigma(\mathrm{VBF} \to S)}$$

Ratios have the added advantage that common theoretical uncertainties (eg PDF) and systematic uncertainties should cancel.

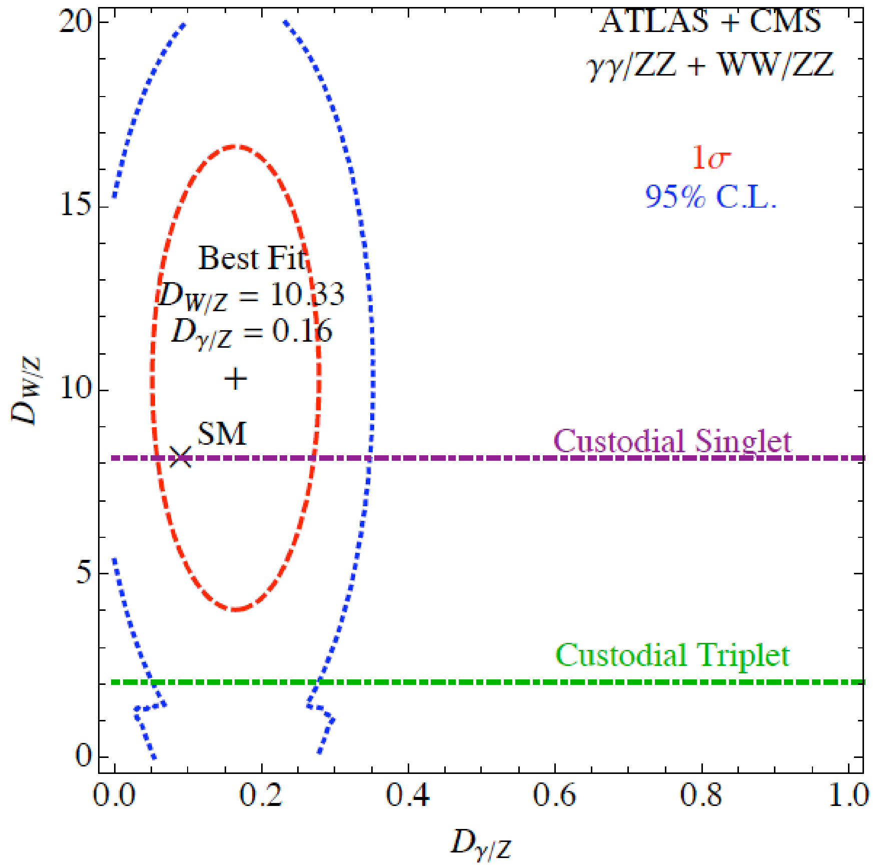
Fitting the electroweak singlet imposter to WW/ZZ and diphoton/ZZ ratios, the predicted Z+Photon rate is so large that it is ruled out by "standard model" Z+Photon measurements!



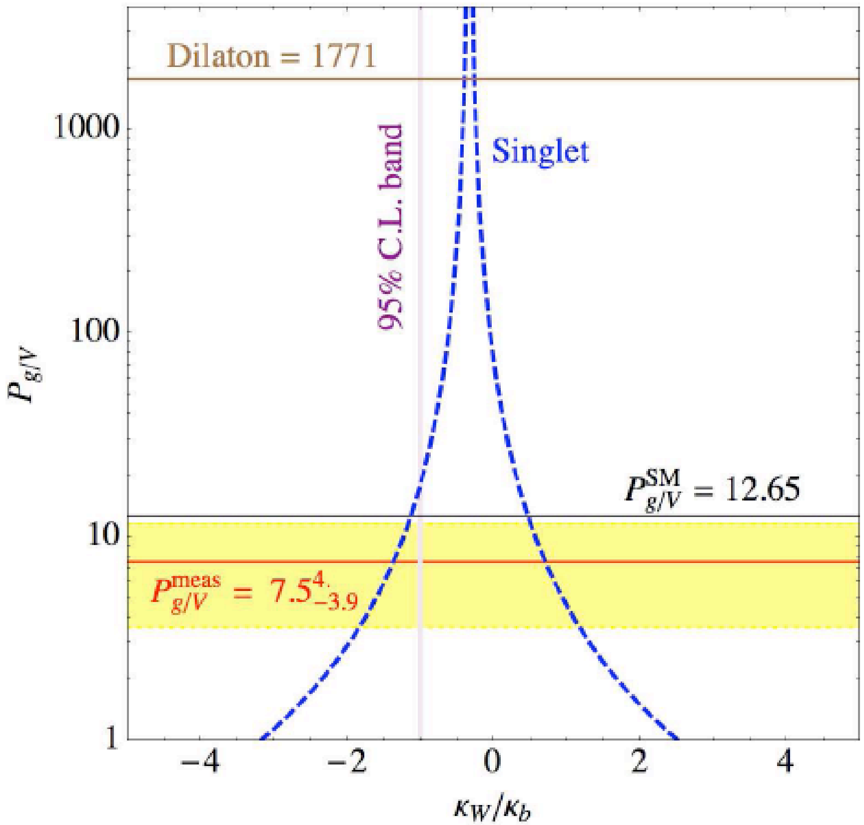


The predicted Z+Photon/ZZ ratio would be 500, while it is <1 for a Higgs boson!

The 2D plot is very useful for discriminating between the Higgs and an electroweak triplet imposter:



The ggh over VBF ratio is a useful discriminator for the dilaton/radion imposter:



$$P^{(D)}_{g/V} = 140 \times P^{(SM)}_{g/V} \sim 1700$$

Basically as soon as one sees a non-zero VBF, the dilaton is dead.

Bu does anyone understand the ratio of gg->h+2j versus VV->h+2j in the VBF-tag bin??

I believe no theorists claim to have a solid understanding of that….

Overall a Standard Model Higgs boson gives an excellent fit!

	χ^2/ν	p-value	c_g	c_V	c_γ	c_b	c_τ
SM Higgs	1.08	0.63	1	1	6.48	1	1
Higgs Boson	0.74	0.27	$0.92^{+0.30}_{-0.19}$	$1.07^{+0.15}_{-0.17}$	$9.7^{+1.9}_{-1.8}$	$1.1^{+0.5}_{-0.4}$	< 0.73
Triplet Imposter	1.34	0.84	$0.37^{+0.08}_{-0.06}$	$0.45^{+0.10}_{-0.09}$	$3.8^{+0.5}_{-0.6}$	–	–

Although a “generic” Higgs doublet gives a slightly better fit, due to the apparent enhancement in the diphoton channel.

Enhancements in the diphoton channel were present in last December in both the ATLAS and CMS data already.

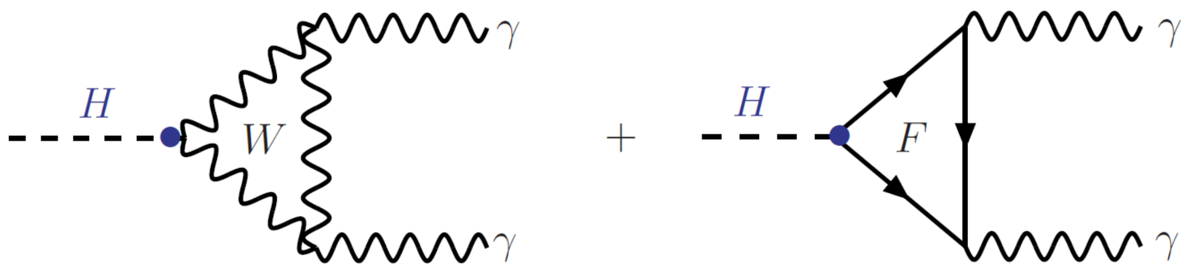
Still there in the July 4, 2012 announcements.

The fact that no enhancement in other channel is seen suggests it's coming from the Higgs to diphoton partial decay width (IF we take it seriously….)

What are the implications of an enhanced Higgs to diphoton decay width??

Carena, IL, and Wagner, 1206.1082

In the standard model Higgs to diphoton width is loop-induced:



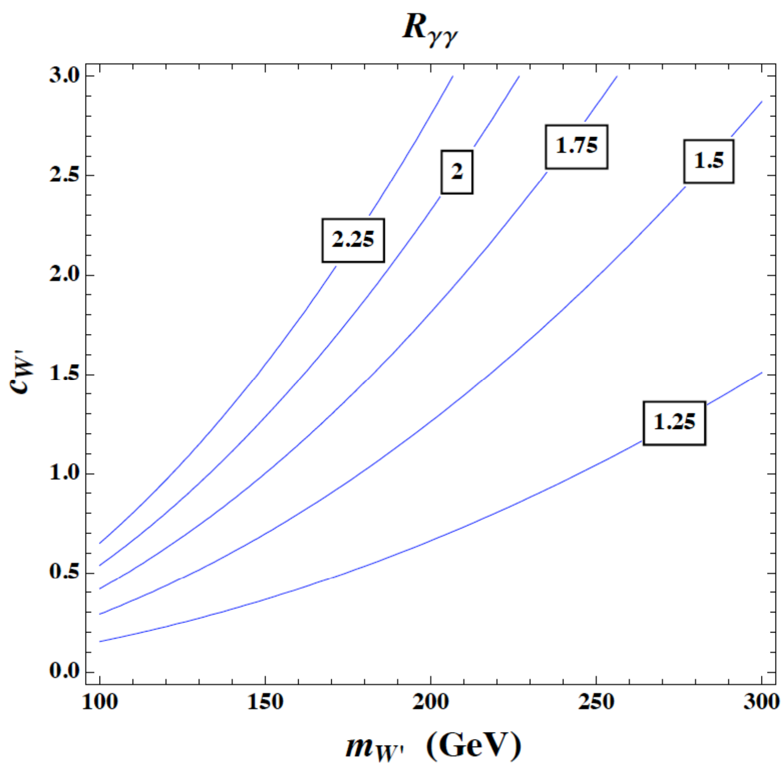
Moreover, SM W-loop is the dominant contribution and has the opposite to the SM top loop.

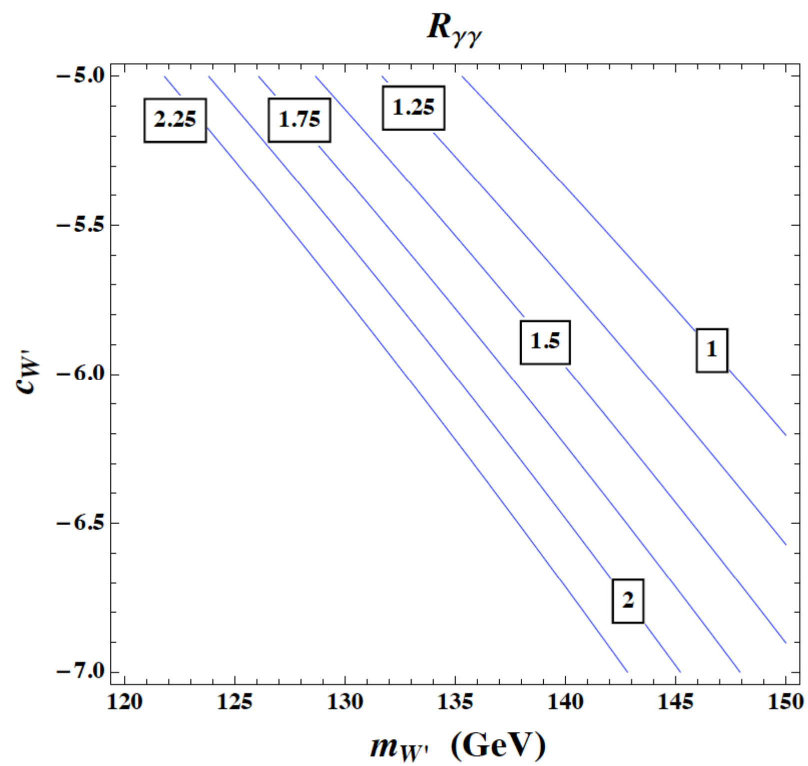
To modify the Higgs to diphoton width, one could add new charged particles with a significant coupling to the Higgs.

- **A new W-prime boson:**

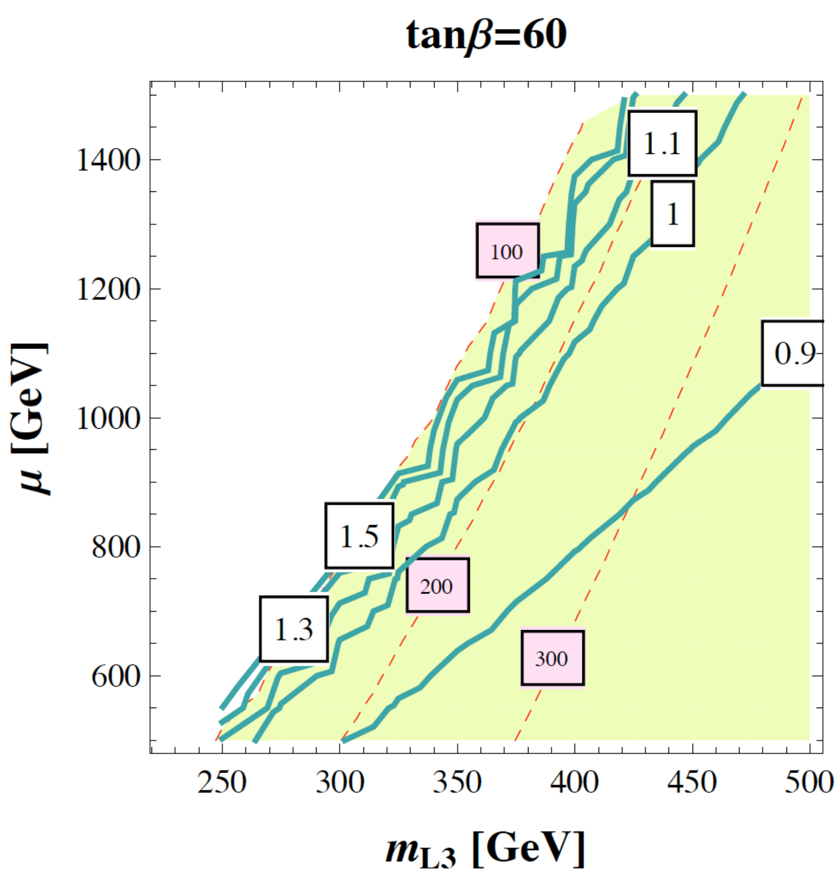
$$m_{W'}(v)^2 = m_{W0}^2 + c_{W'}\, m_W^2$$

$$\mathcal{O}_{W'} = \frac{1}{2} c_{W'} g^2 H^\dagger H\, W'^{+}_{\mu} W'^{-\,\mu}$$



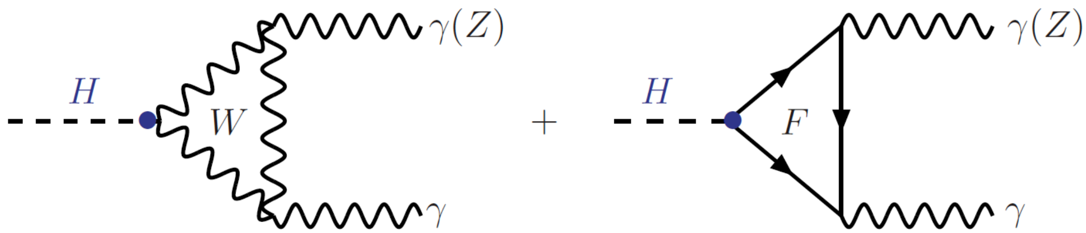


Could play this game with charged scalars and charged fermions as well. For example, in MSSM one could have very light staus, close to the LEP limit of 100 GeV.

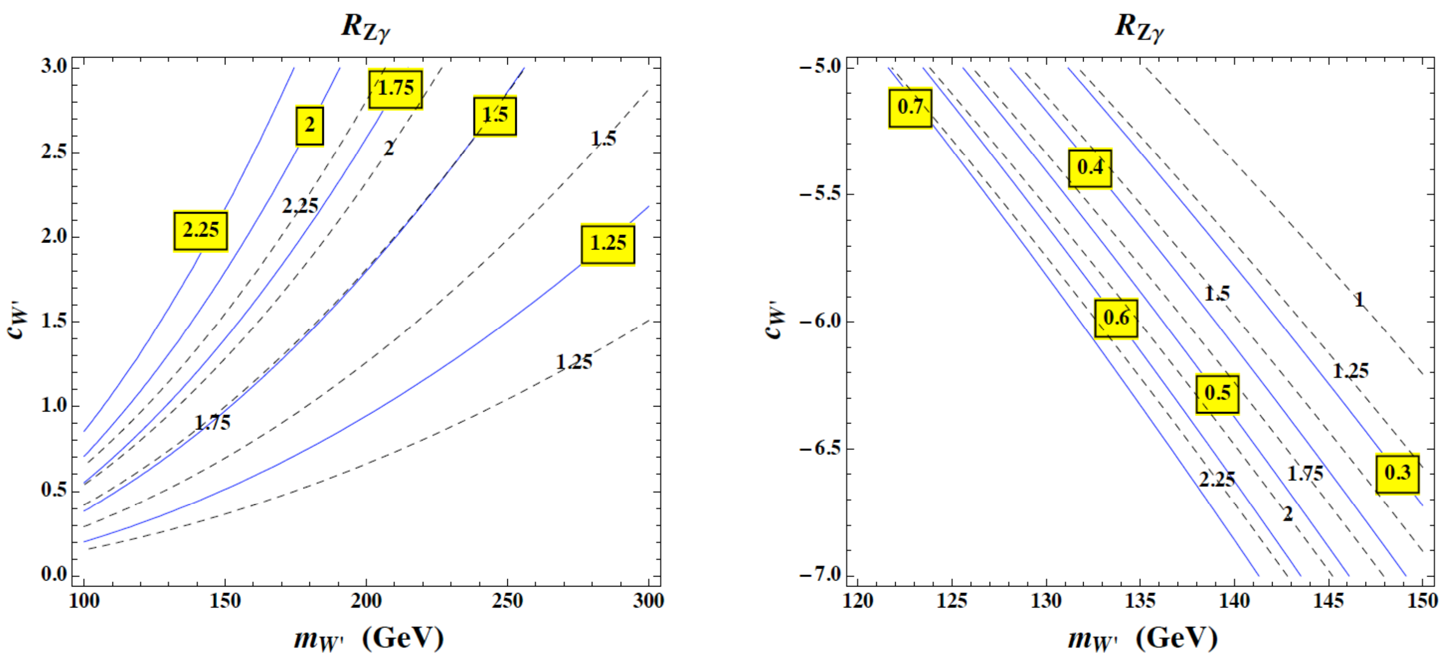


Carena, Gori, Shah, Wagner:1112.3336

Interestingly there're correlations between the h -> $\gamma\gamma$ partial width and h-> Z γ partial width:



W-prime model again:



So where do we go from here?

So where do we go from here?

"Higgs Identification" --

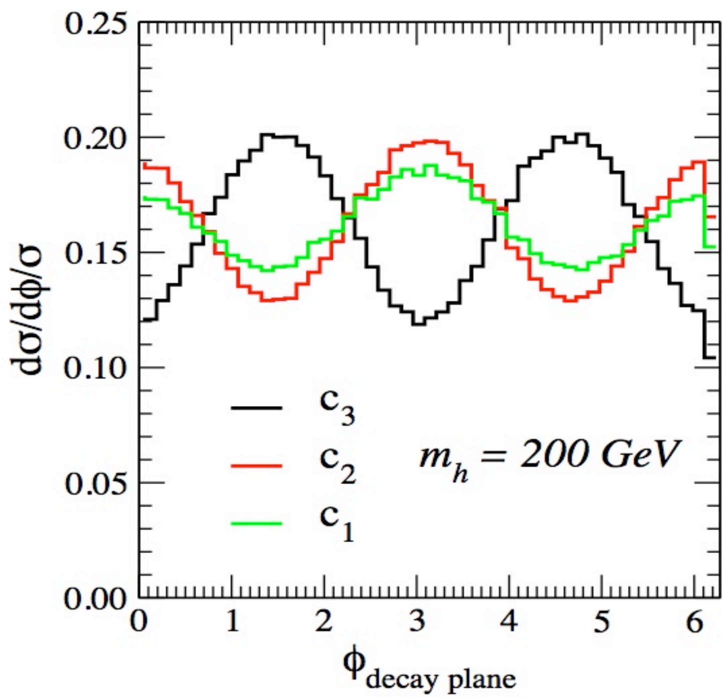
Infrared Identity:

- 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

Ultraviolate Identity:

- Hints of more dynamic and symmetry princples? Supersymmetry? Compositeness?
- Does the naturalness principle work? Do we have to live with Anthropic principle and multiverse?
- Are there more new particles out there? Those enhancing the diphoton width? Those cancelling the Higgs quadratic divergences?

For the IR identity, we need to measure the angular correlations, especially in the four-lepton channel.



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

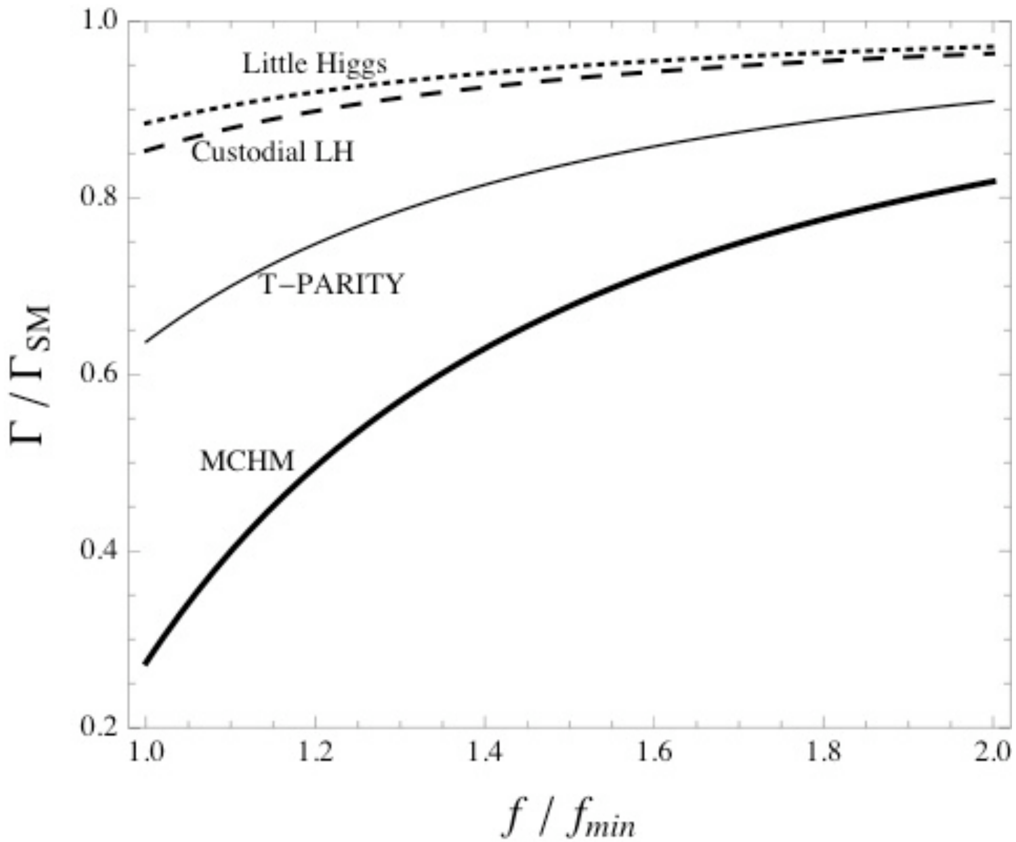
Azimuthal angular correlation between the two decay planes is a particularly useful single-variable observable for spin, CP, and coupling structure.

Cao, Jackson, Keung, IL, Shu:0911.3398

We also need to measure decays into all four pairs of electroweak gauge bosons, including Z+Photon!

Gainer, Keung, IL, Schwaller:1112.1405

For the UV Identity, one particularly useful quantity is the Higgs coupling to two gluons:



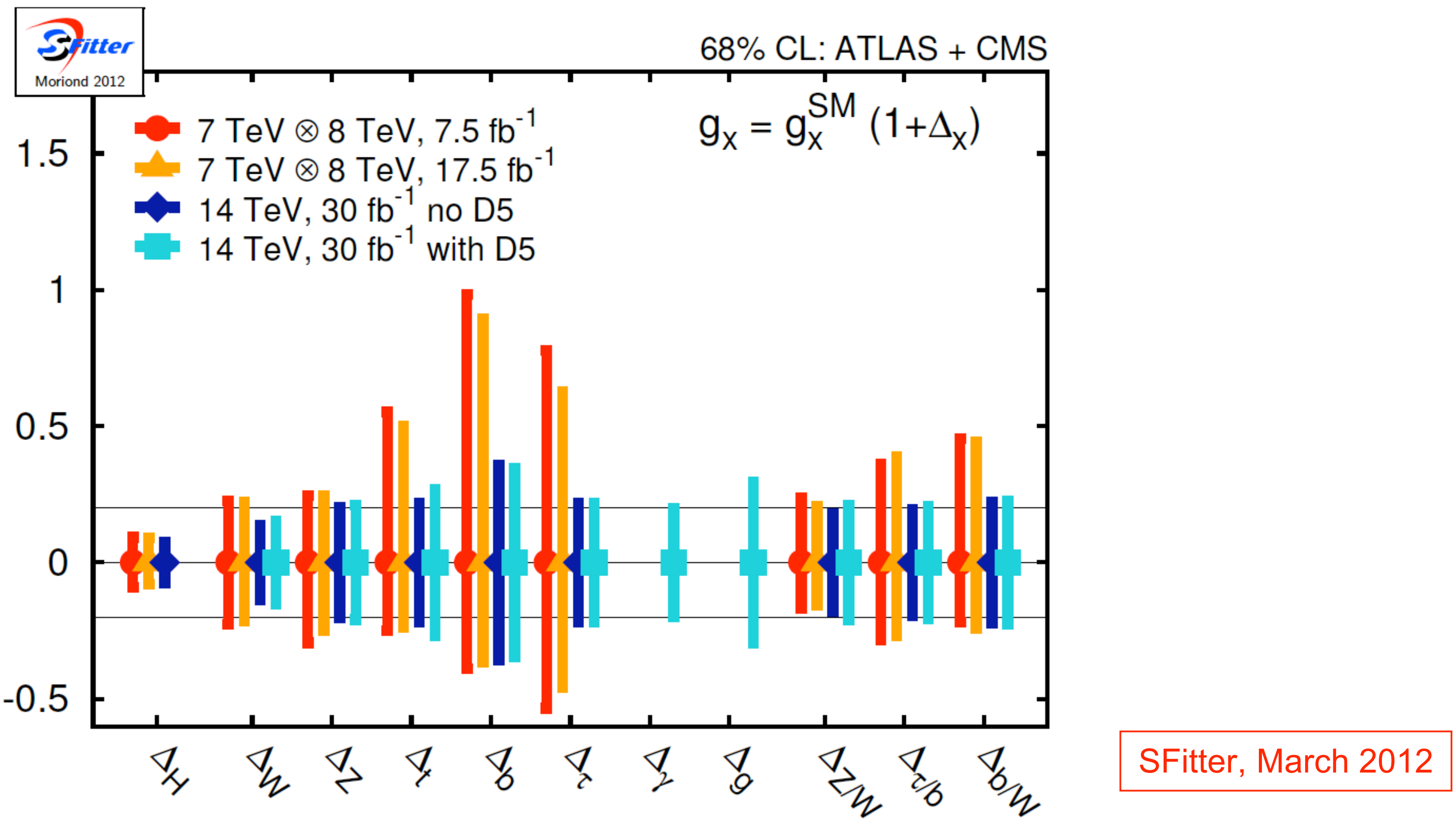
In composite Higgs models this coupling is always suppressed!

IL, Rattazzi, Vichi:0907.5413
IL and Vichi:1010.2753

We also need to look for new particles, in particular those with significant couplings to the Higgs boson.

These searches could tell us whether something is out there “enhancing” the diphoton width or “cancelling” the quadratic divergences in the Higgs mass.

Last but not least: a Higgs factory for precision measurements of Higgs properties!



A hadron mechine is messy: Higgs coupling measurements can be done only with large uncertainties in O(20-50 %)....

A moment of truth:

"The LHC can never claim the discovery a SM Higgs boson; at best the LHC can claim *the discovery of a SM-like Higgs boson*."

--- Quote from Howie Haber at "The Next Stretch of the Higgs Magnificent Mile" workshop

In contrast, it is possible to rule out a SM Higgs boson at the LHC.

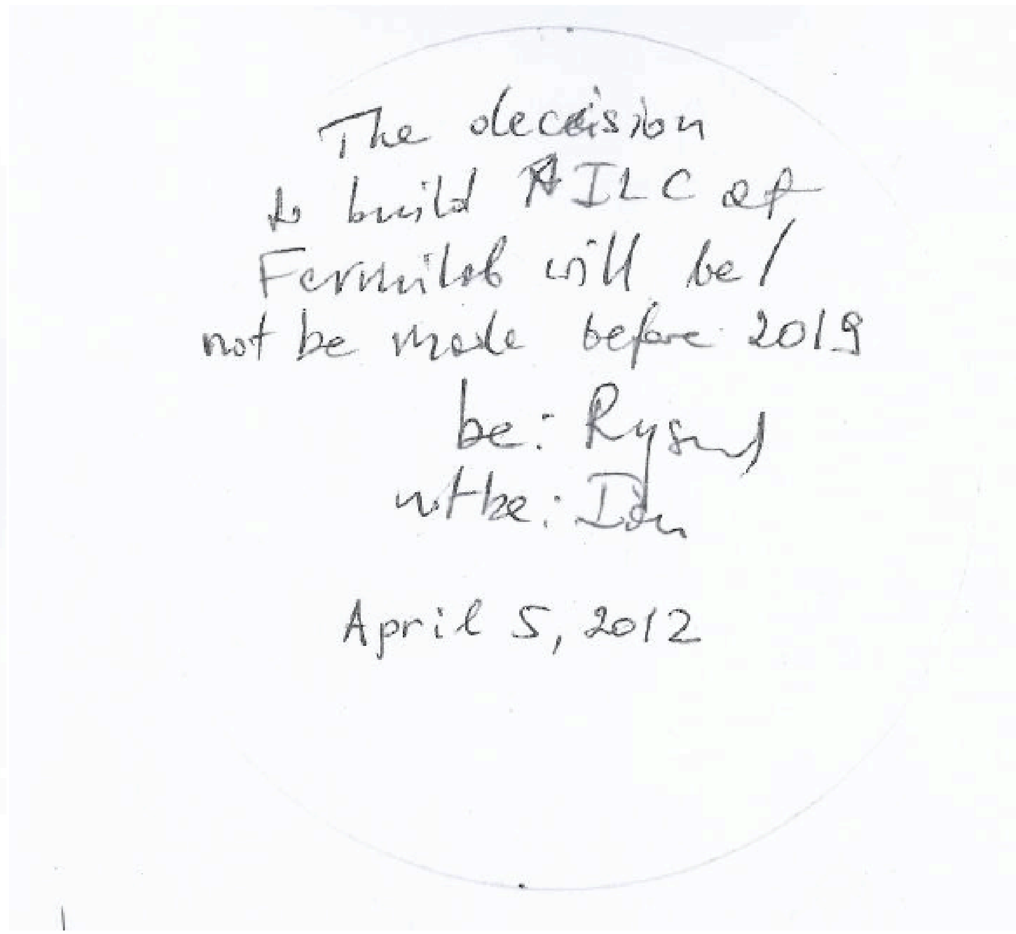
Precision measurements require intensity.

Is a Higgs factory one of the most compelling physics scenarios for intensity frontier?

Higgs Factory Options

- Different energies of interest for Higgs factory
  - Minimum energy (i.e. O(250GeV) for e^+e^-)
  - Some propose to combine top threshold and Higgs run
  - Energies for triple Higgs coupling
- Options discussed are
  - Linear collider (ILC, CLIC)
  - Muon collider
  - Ring-based electron-positron collider
    - LEP3
    - Large electron-positron ring (SuperTristan, DLEP)
  - Gamma-gamma collider (e.g. CLICHE)

The Higgs factory is a very important subject, because I have a bet is with Ryszard:



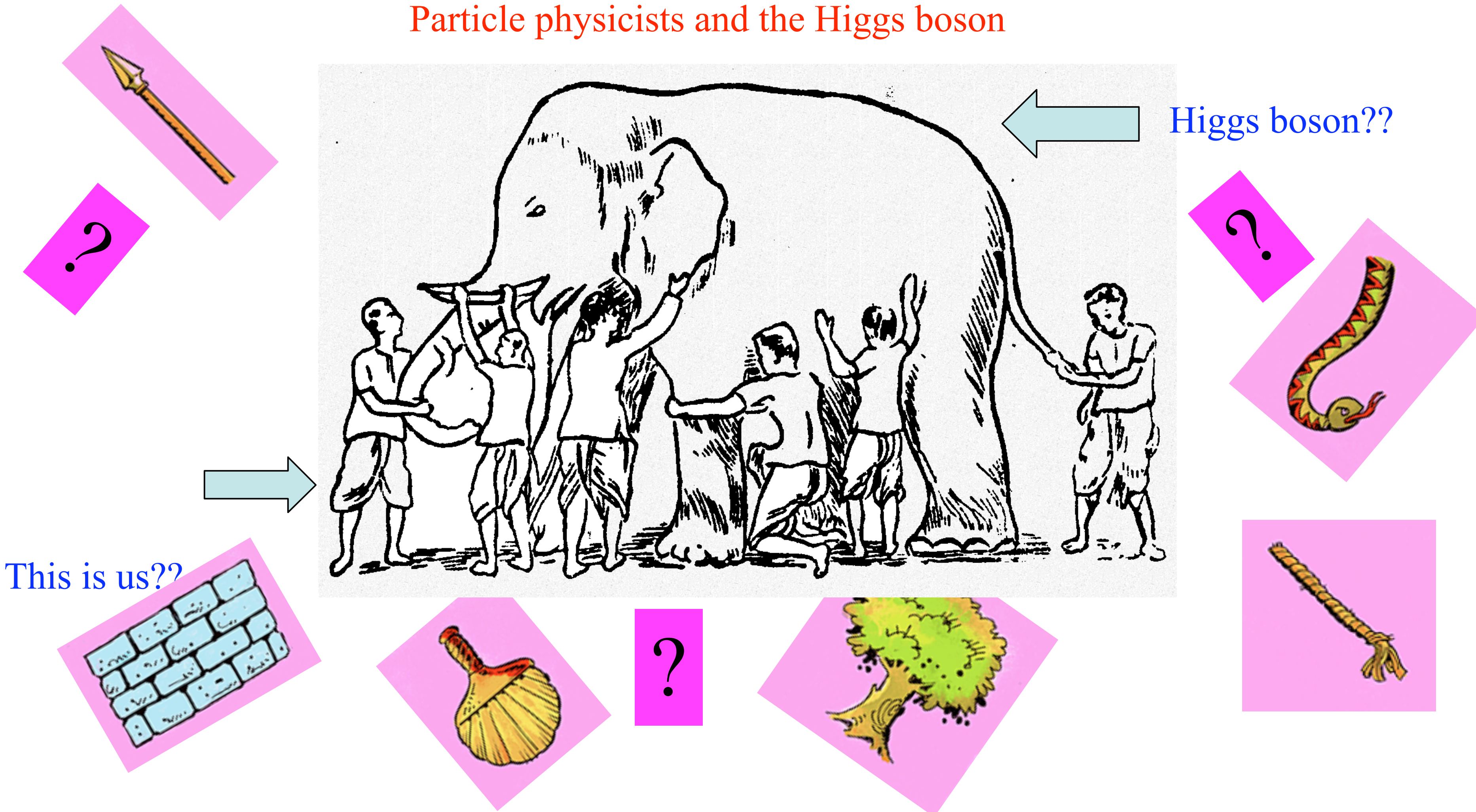
Concluding remarks:

- **The field is at a critical juncture; Higgs physics is the only area of LHC program that shows any remote sign of something going on!**

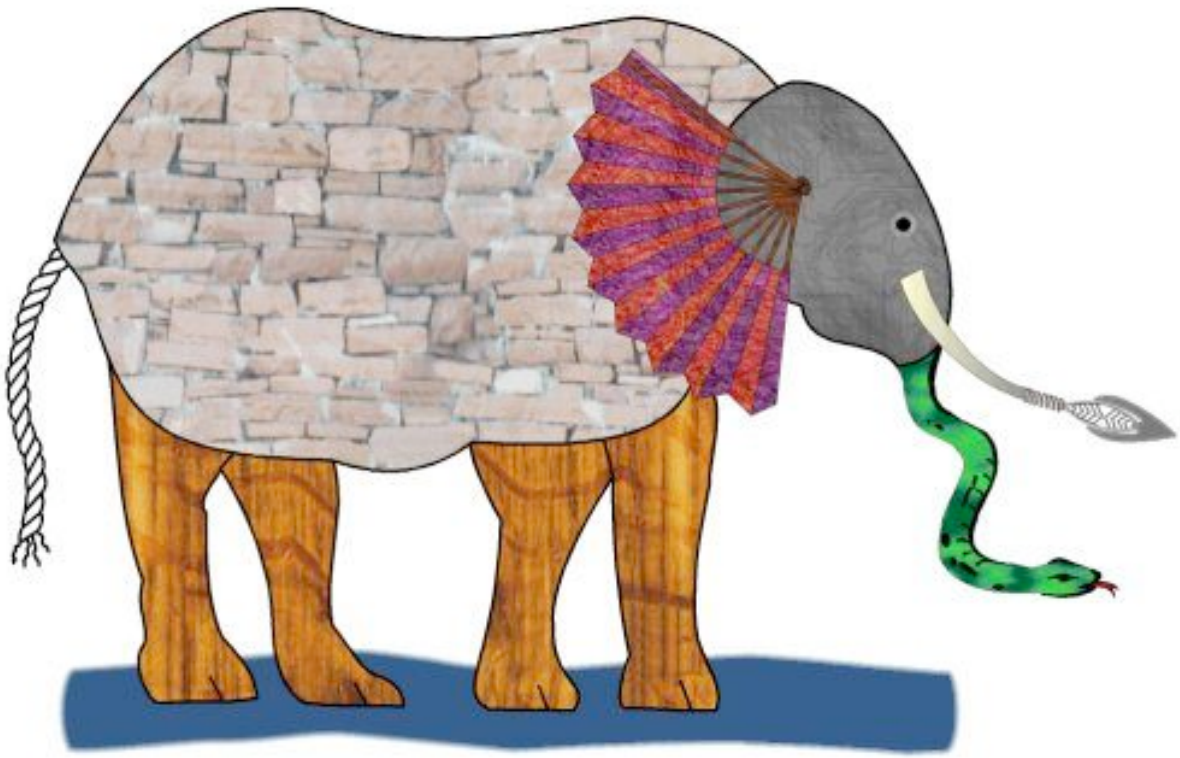
- **We live in a unique moment in history; I gave a very different talk here five months ago!**

- **Higgs boson is our gateway to physics at a higher energy scale. Let's proceed with an open mind; we are the blind men and the Higgs is the elephant….**

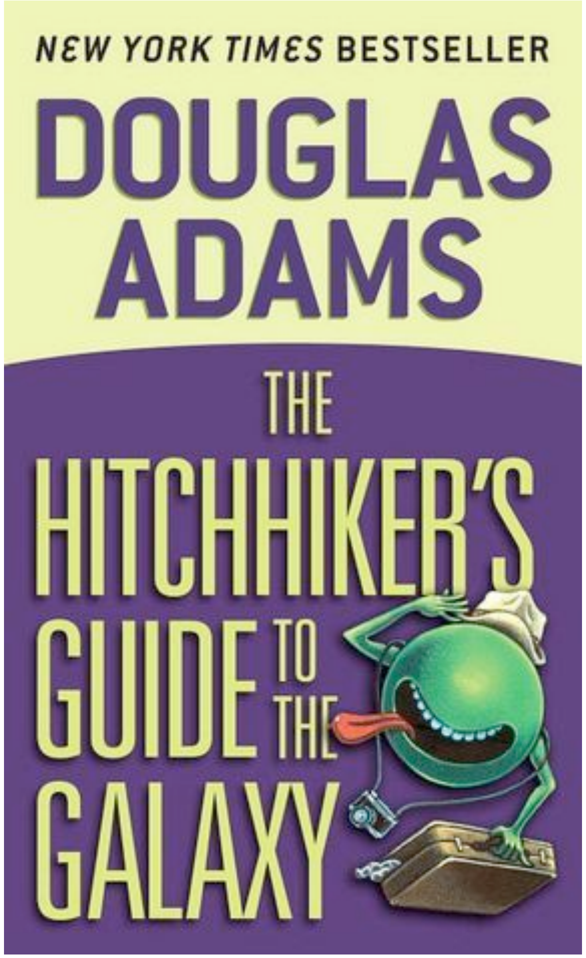
Particle physicists and the Higgs boson



Let’s not discover an elephant like this:



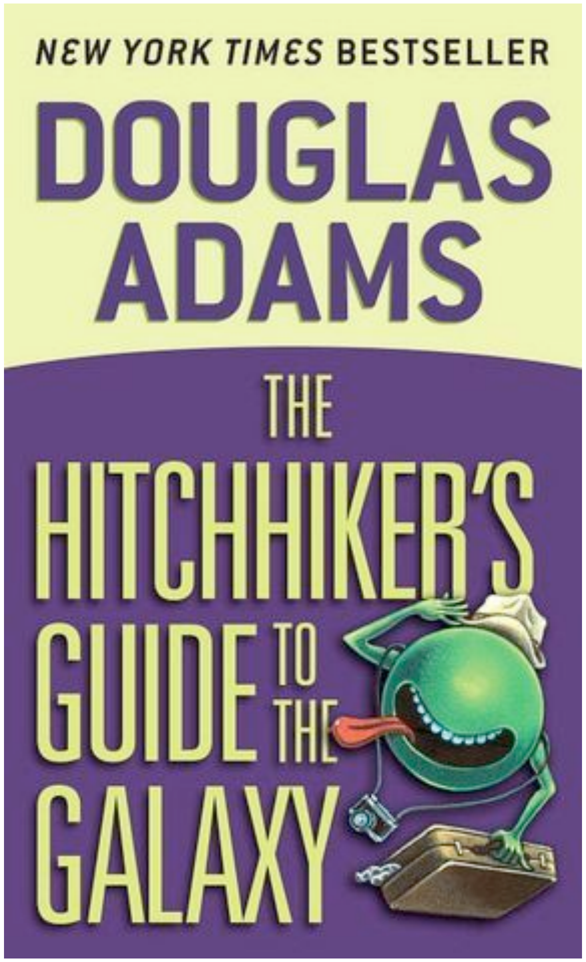
Finally, in the original "the Hitchhiker's Guide to the Galaxy" by Douglas Adams:



There is a computer "Deep Thought" which knows the answer to "Life, the Universe, and Everything" after 7.5 millions years of pondering.

And the answer is.....

Finally, in the original "the Hitchhiker's guide to the galaxy" by Douglas Adams:



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Forty-two is the answer to "Life, the Universe, and Everything"

So is the Higgs boson the answer to "Life, the Universe, and Everything"?

So is the Higgs boson the answer to "Life, the Universe, and Everything"?
a British philosopher came up with this: