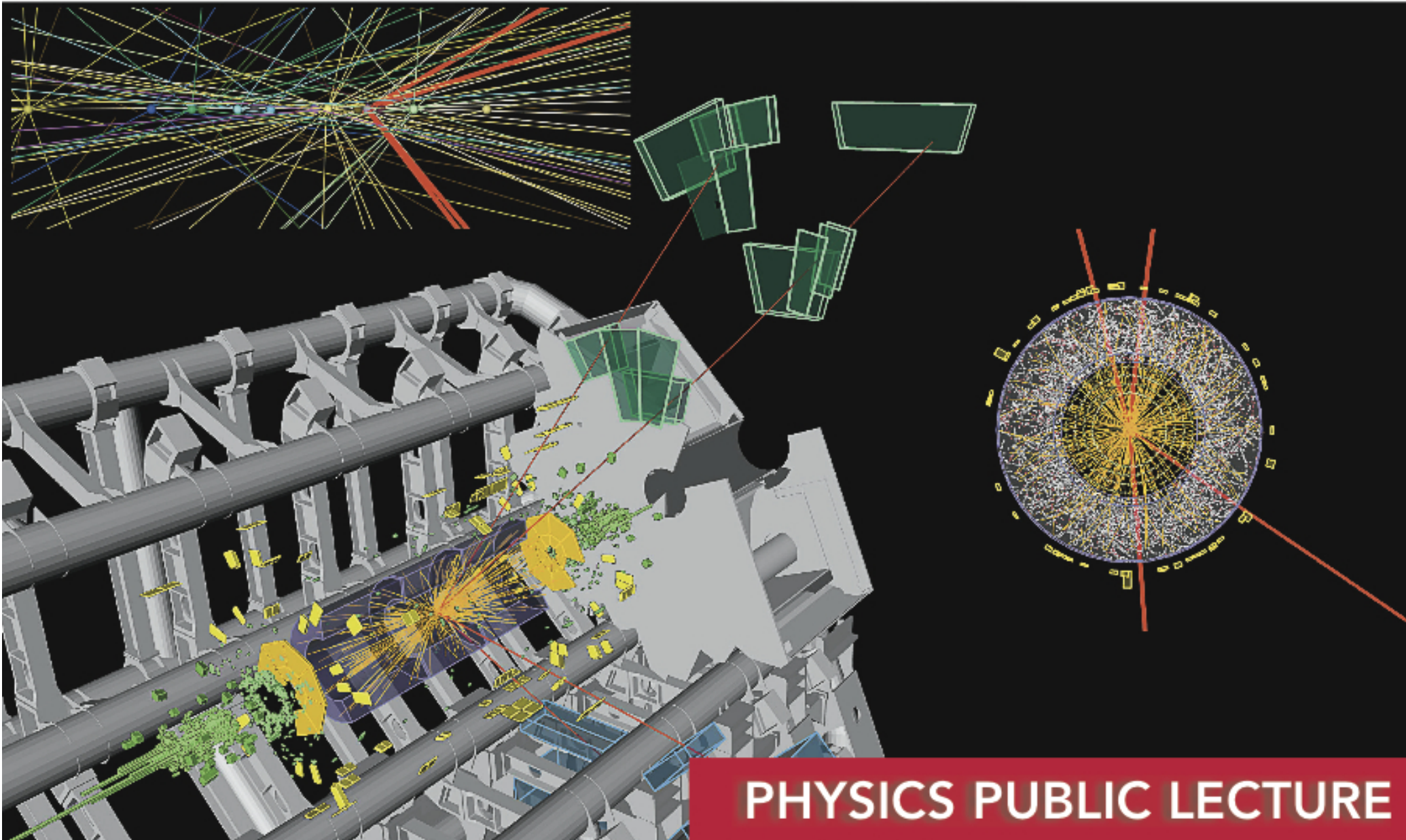


DISCOVERY OF THE HIGGS BOSON

MYSTERY OF MASS REVEALED



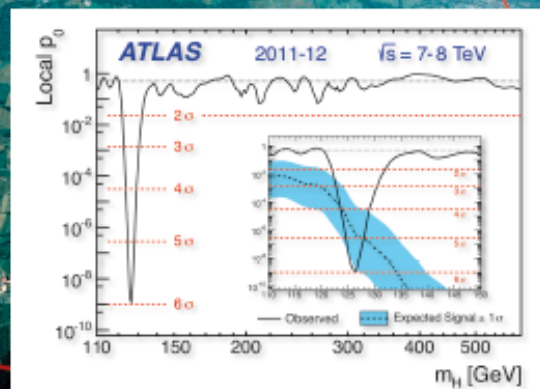
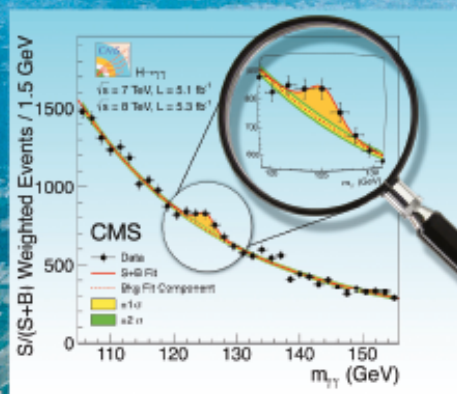
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On July 4 of this year, CERN made a very special announcement.

A new subatomic particle has been discovered.

Its properties are consistent with those of the long-sought Higgs boson.

What does it all mean?

Discovery of the Higgs Boson

Part 1: Theory (Heather Logan)

Part 2: Experiment (Thomas Koffas)

Discovery of the Higgs Boson

Part 1: Theory (Heather Logan)

- Introduction: forces and particles
- The problem of mass
- The Higgs mechanism
- Searching for the Higgs particle

Part 2: Experiment (Thomas Koffas)

Particle physics studies the structure of matter on the smallest scales that we can probe experimentally.

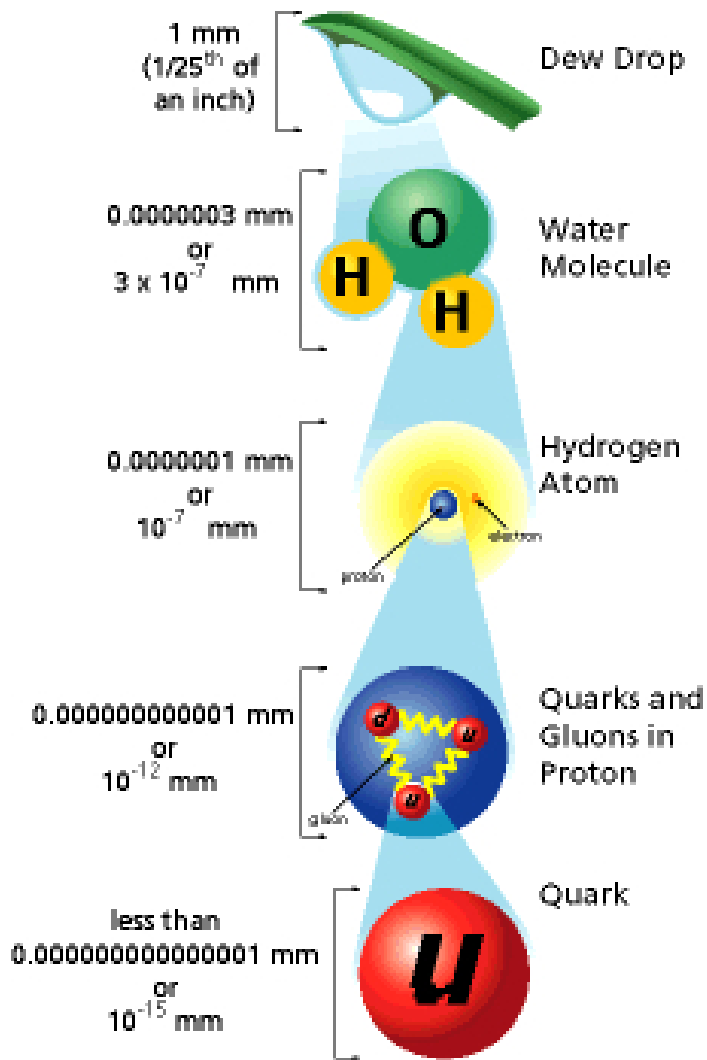


Image: Fermilab

Size of atom = 1/100-million cm
 Size of nucleus = 1/100,000 of atom

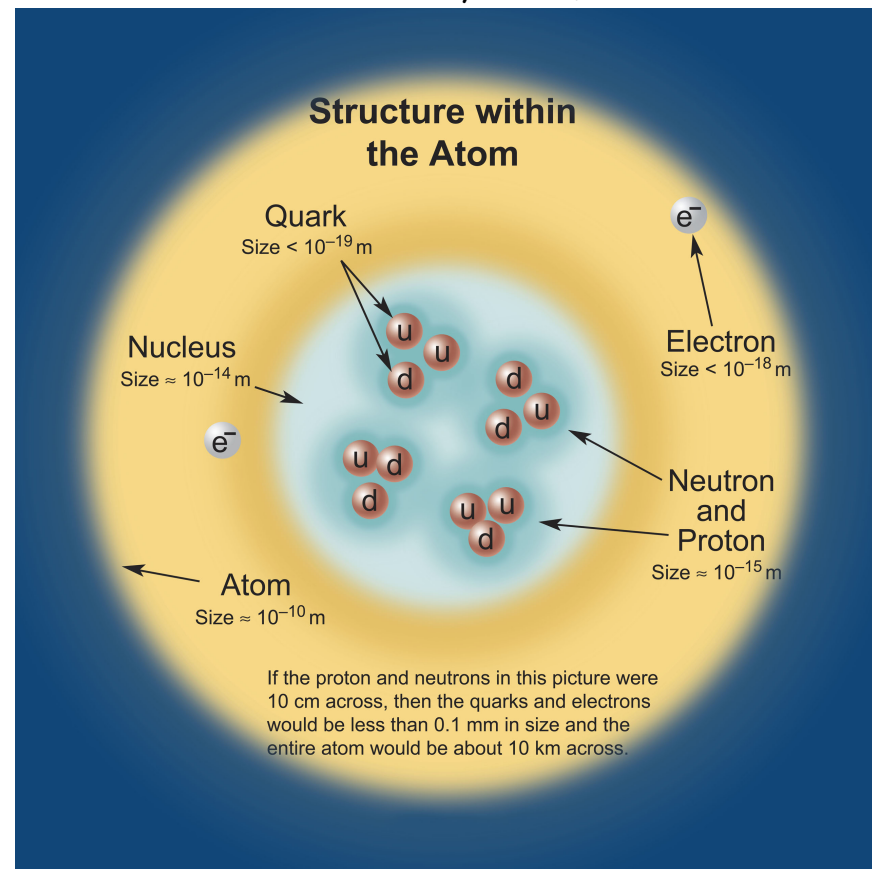


Image: Contemporary Physics Education Project

Matter is made up of **quarks** and **leptons**.

	Quarks		Leptons	
Generation 1 →	<i>d</i>	<i>u</i>	<i>e</i>	ν_e
Generation 2 →	<i>s</i>	<i>c</i>	μ	ν_μ
Generation 3 →	<i>b</i>	<i>t</i>	τ	ν_τ
electric charge:	-1/3	+2/3	-1	0

Atoms:

proton = *u* + *u* + *d* (bound state of 3 quarks)

neutron = *u* + *d* + *d* (bound state of 3 quarks)

electron = e^- (a charged lepton)

Matter particles interact via the four known forces

Gravity

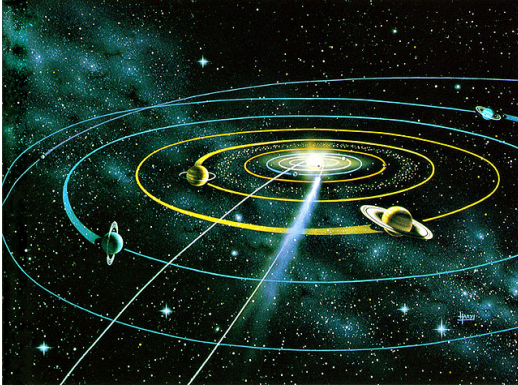


Image: European Southern Obs.

Electromagnetism

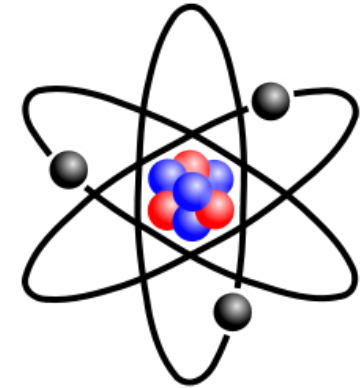


Image: Wikimedia

Strong interaction

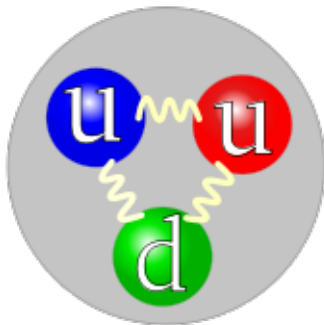


Image: Wikimedia

Weak interaction

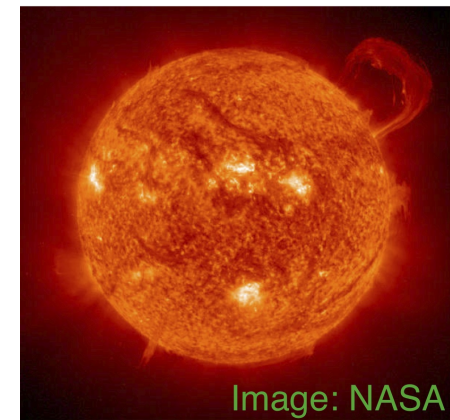
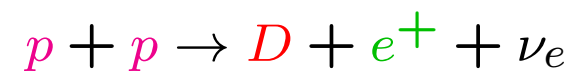


Image: NASA



Each force is carried by a "force carrier"

Gravity

Graviton (never observed; must be massless)

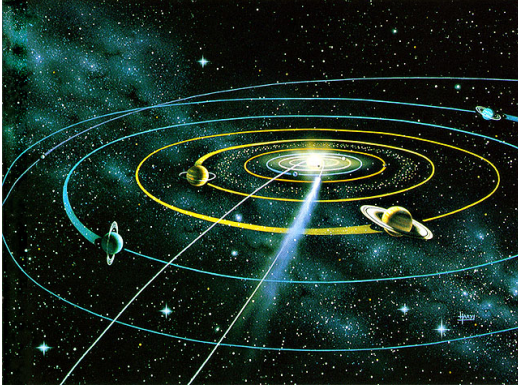


Image: European Southern Obs.

Electromagnetism

Photon (massless)

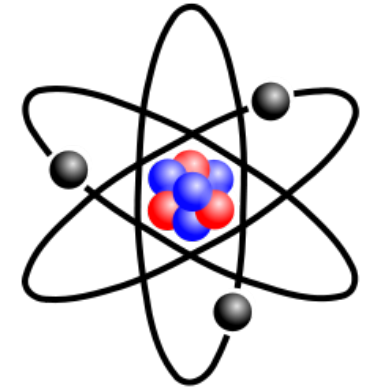


Image: Wikimedia

Strong interaction

Gluon (massless)

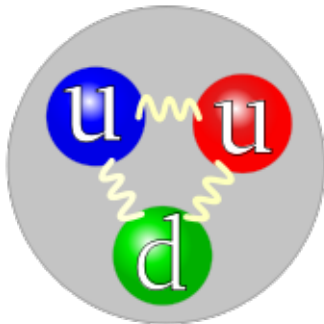


Image: Wikimedia

Weak interaction

W^\pm and Z bosons (NOT massless!)

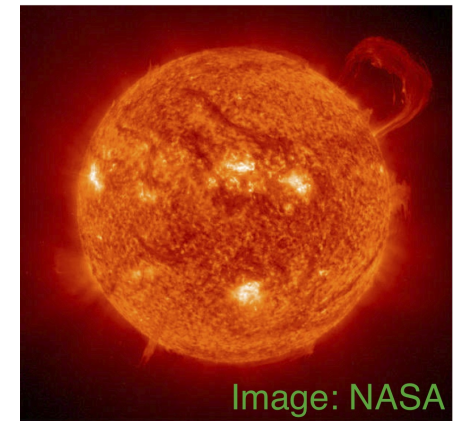
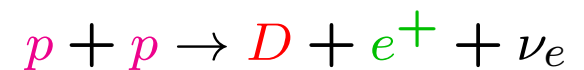


Image: NASA



We have a problem...

The force carriers of the weak interaction are definitely not massless!

BOSONS force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c ²	Electric charge	Name	Mass GeV/c ²	Electric charge
γ photon	0	0	g gluon	0	0
W^-	80.39	-1			
W^+ W bosons	80.39	+1			
Z^0 Z boson	91.188	0			

Image:

Contemporary Physics Education Project

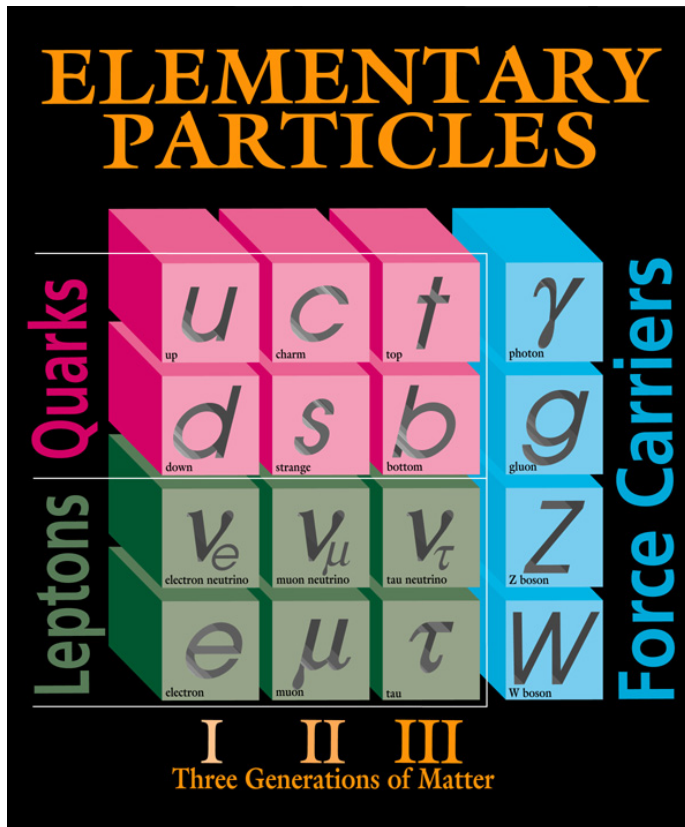
Our quantum-mechanical understanding of forces (via “gauge theories”) requires that the force carriers are massless.

How can this be reconciled with reality?

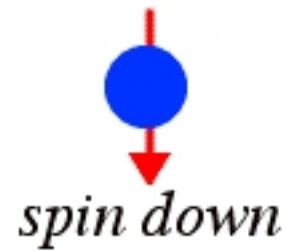
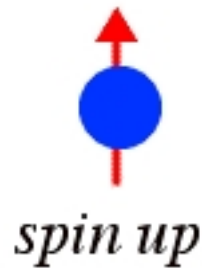
We have another problem...

Quarks and leptons also have a mass problem.

It starts with the **spin** of fermions, and what we know from experiment about how the weak interaction “talks” to them.



Quarks and leptons are **fermions**:
spin 1/2.



For fast-moving particles, it's convenient to quantize spin along the direction of motion: these are called **helicity states**.



If a particle is moving slower than the speed of light, you can “transform” a right-handed particle into a left-handed particle (from your point of view) by running faster than it:



If a particle has no mass, it moves at the speed of light: you can't run faster than that, so the two helicity states are physically distinct.

The problem: Weak interactions treat left-handed and right-handed particles differently!

- W^\pm bosons couple **only** to left-handed fermions.
- Z bosons couple with **different strengths** to left- and right-handed fermions.

This is called **parity violation**.

Discovered 1957 by C.-S. Wu in processes involving weak interactions.

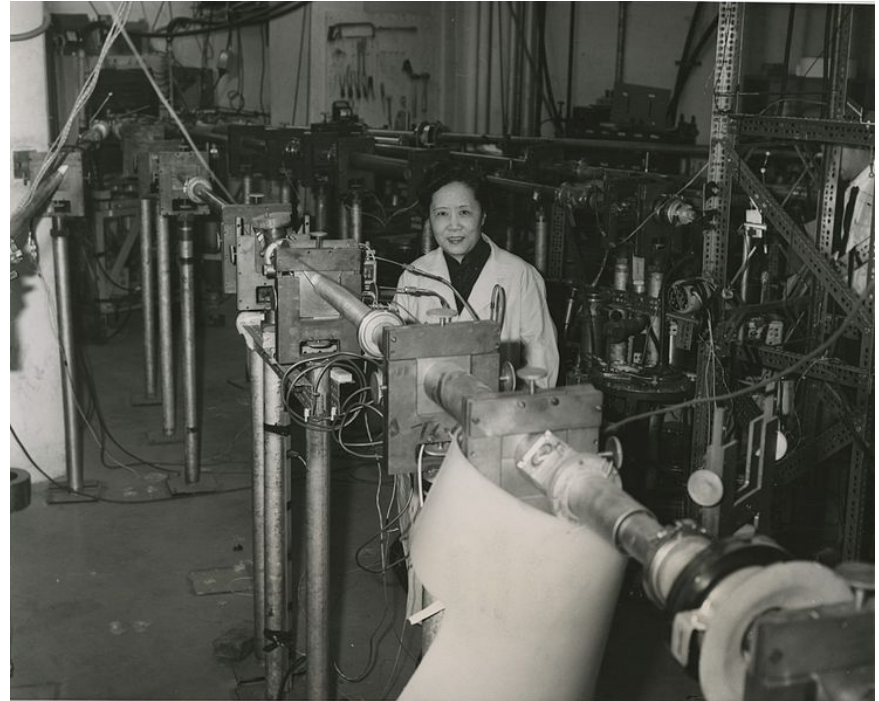


Image: Smithsonian Institution

This would be like the charge of the electron being different depending on which reference frame you look at it from.

Impossible, since electric charge is conserved!

The only sensible solution: **all particles are massless!**

Then they travel at the speed of light, and left- and right-handed states are physically distinct.



The only sensible solution: **all particles are massless!**

Then they travel at the speed of light, and left- and right-handed states are physically distinct.

That is not the world we live in.

The real solution:

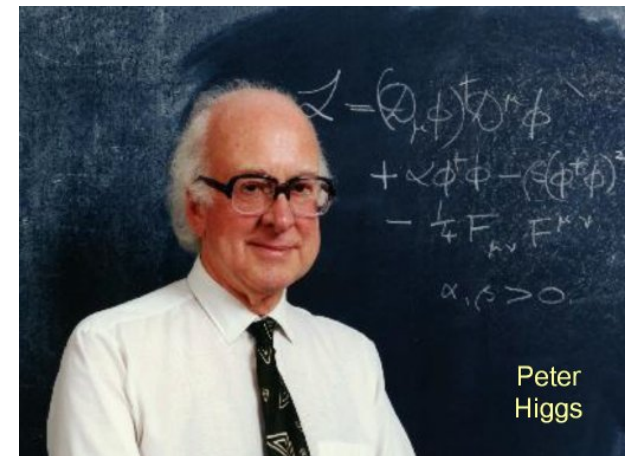
Fill the vacuum with a “sea” of weak-charged stuff.

- Quarks and leptons can pick up the extra weak charge they need to flip helicity.

- Weak-interaction force carriers interact with the “sea”, which gives them an effective mass.

This “sea” is the **Higgs field**:

– like a magnetic field but without a direction.



A quasi-political explanation of the Higgs boson by David Miller (UC London), for the UK Science Minister, 1993: Cartoons: CERN
Imagine a cocktail party of political workers...



These represent the Higgs field filling space.

A Prime Minister enters and crosses the room. Political workers cluster around her, impeding her progress.



The Higgs field interacts with a particle, giving it a mass.

Now imagine that a rumour enters the room...



A particle collision “kicks” the Higgs field, creating a vibration...

The rumour generates a cluster of people, which propagates across the room.



The Higgs boson is a wave or vibration in the Higgs field.

But the universe defaults to the lowest-energy state.

- A magnetic field carries energy: you need a source to produce one.

So how can there be a Higgs field filling the entire universe?

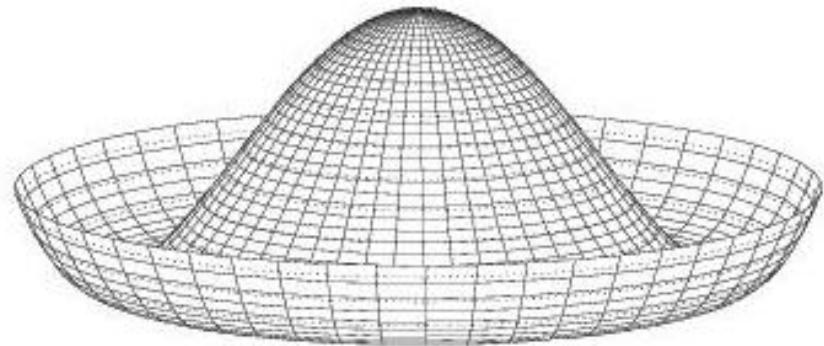
The solution:

- The Higgs field interacts with itself.
- Minimum-energy configuration has nonzero Higgs field!
- **It sucks itself into existence!**

Potential energy function:

$$V = -aH^2 + bH^4$$

Minimum energy configuration is at a nonzero field strength.



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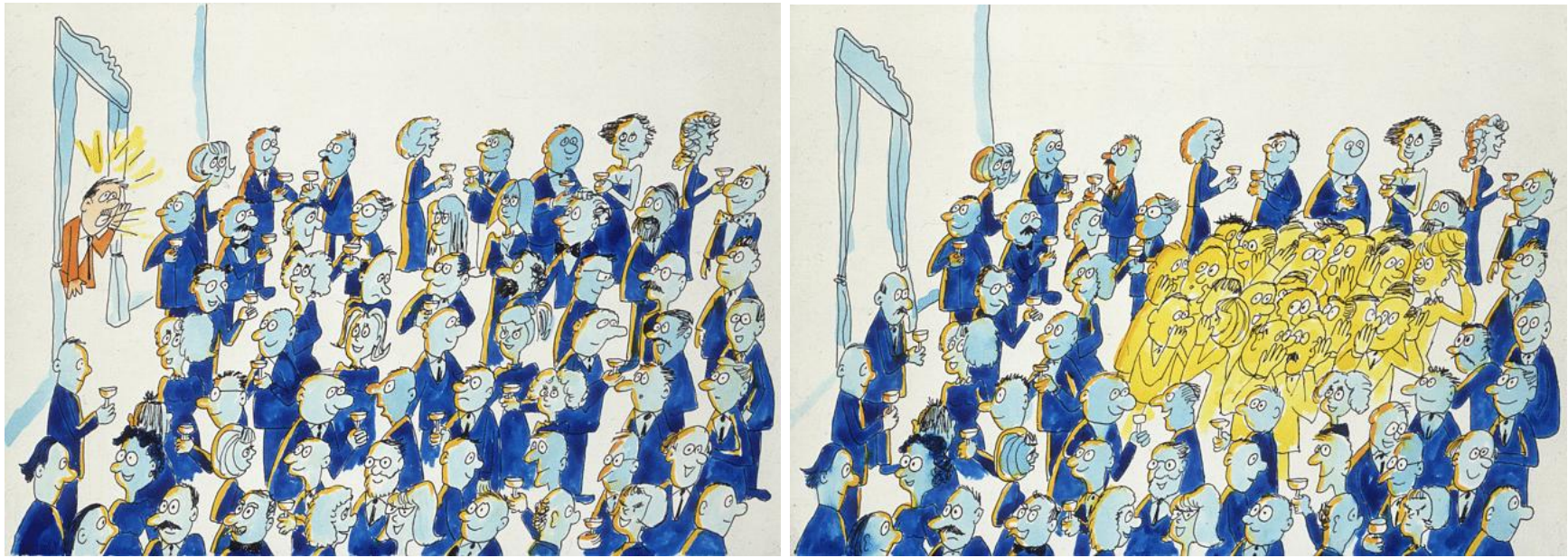
Minimum energy configuration is at a nonzero field strength.

Called the “Mexican hat potential” :)



Image: U.S. National Park Service

A crazy idea... how do we test it?



We need to “kick” the Higgs field and create a vibration. Then we can measure the properties of the vibration.

We can kick up a vibration—a Higgs particle—by colliding ordinary particles.

Kicking up a Higgs vibration requires a minimum “quantum” of energy, related to the Higgs particle mass: $E = mc^2$.

Producing a Higgs boson

To “kick” the Higgs field, you need a “foot” that interacts with the Higgs...

...one with lots of Higgs-field
★star power★.

That means we need to collide very massive particles!



	Quarks		Leptons	
Generation 1 →	<i>d</i>	<i>u</i>	<i>e</i>	ν_e
Generation 2 →	<i>s</i>	<i>c</i>	μ	ν_μ
Generation 3 →	<i>b</i>	<i>t</i>	τ	ν_τ
electric charge:	-1/3	+2/3	-1	0

But ordinary matter is made out of the lowest-mass quarks and leptons.

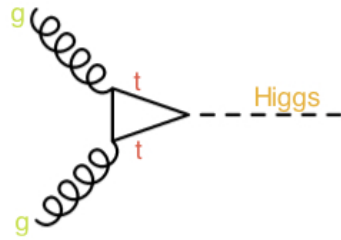
Higgs production is very rare! :(

proton = *u u d*
neutron = *u d d*
electron = e^-

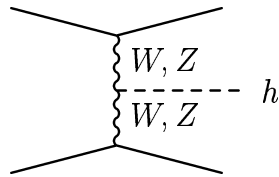
Producing a Higgs particle in collisions of protons:

We actually “kick” the Higgs with a virtual top quark, W^\pm or Z .

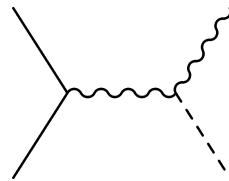
- Gluon fusion, $gg \rightarrow H$



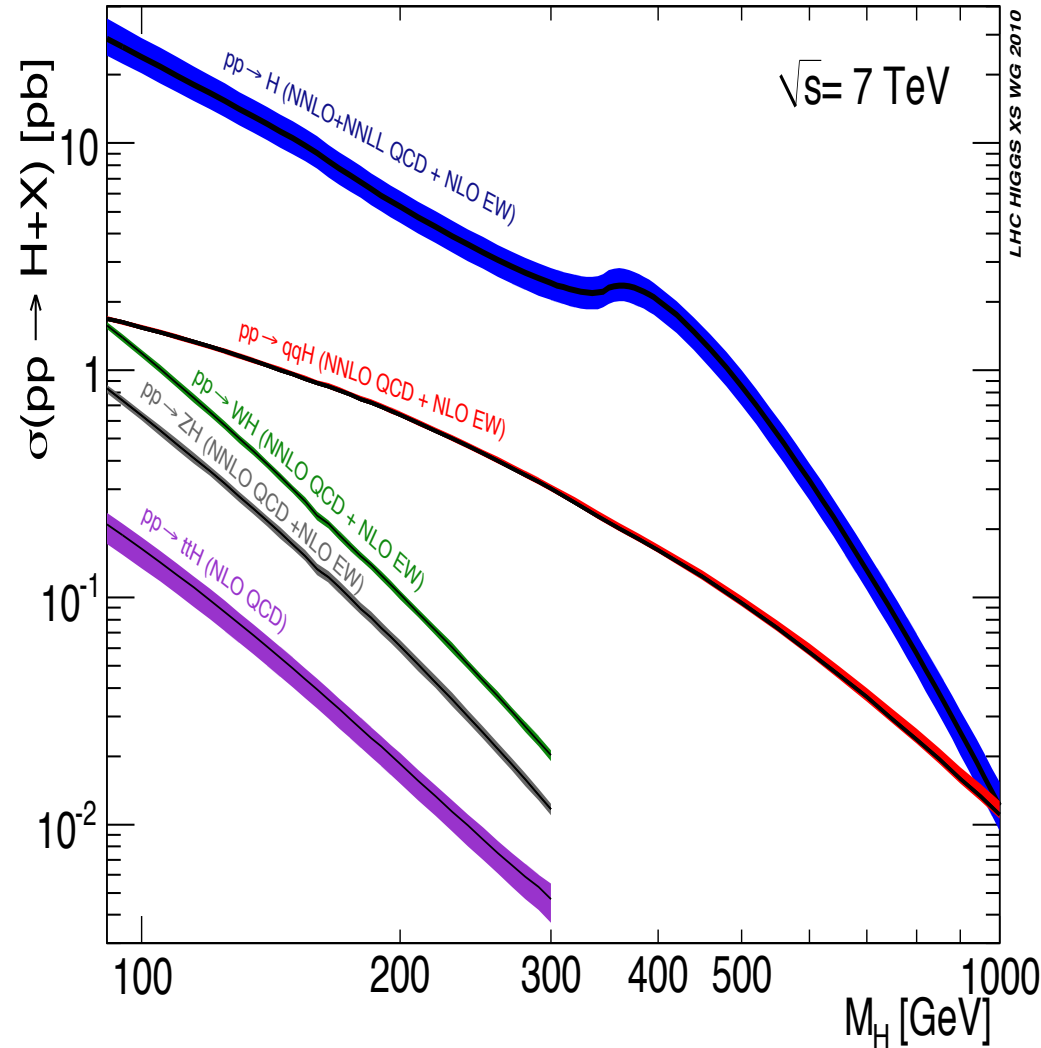
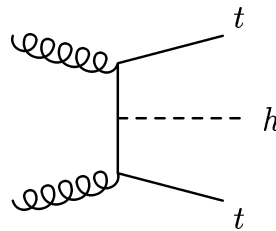
- Weak boson fusion, $qq \rightarrow Hqq$



- WH, ZH associated production

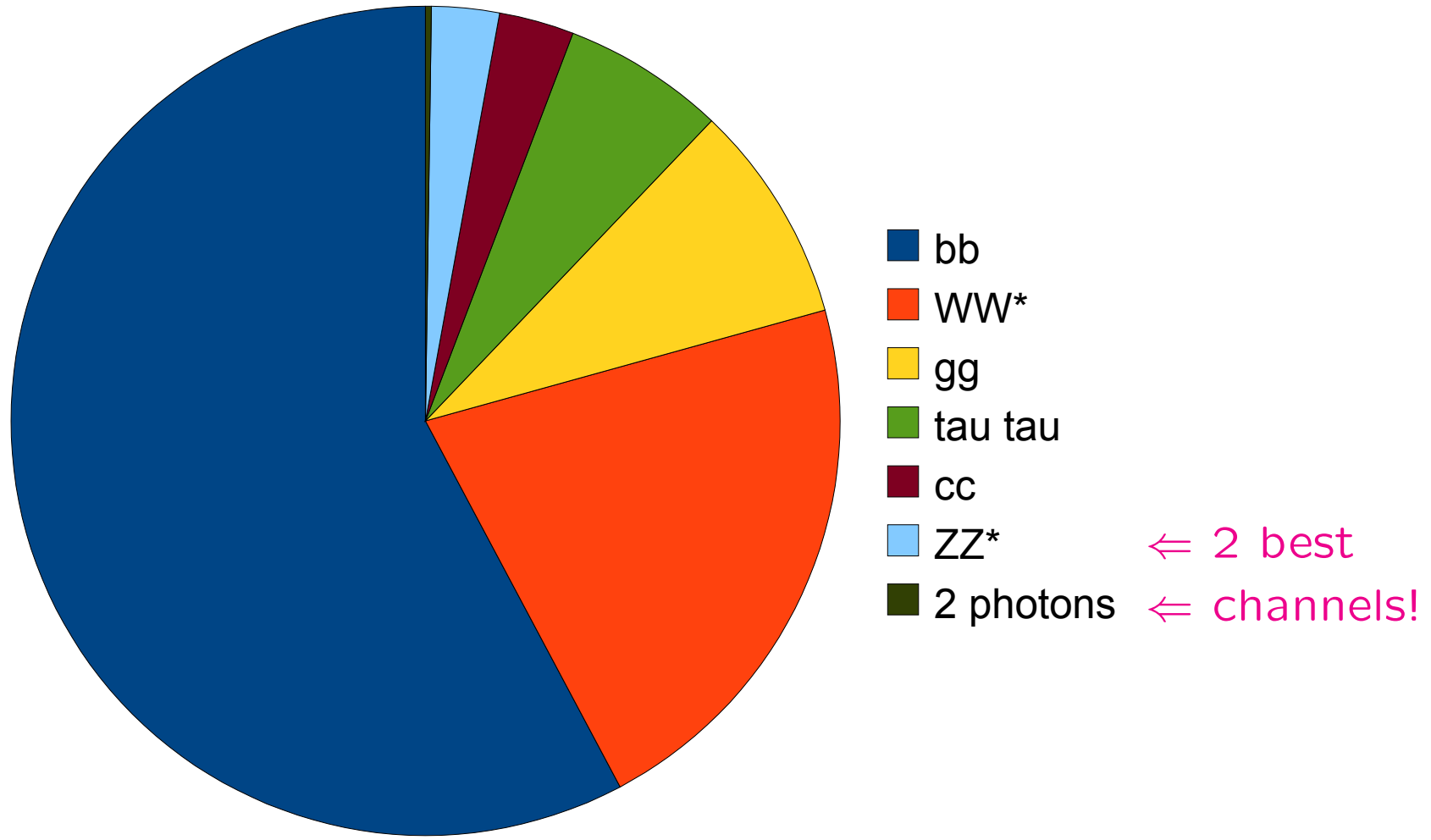


- ttH associated production



Detecting a Higgs particle:

The Higgs boson quickly breaks down (“decays”) into the things it interacts with most strongly.



Hang on, the photon is massless...

How can the Higgs boson decay into photons?

Again, it actually decays via a virtual top quark or W^\pm boson.



PHYSICAL REVIEW D

VOLUME 8, NUMBER 1

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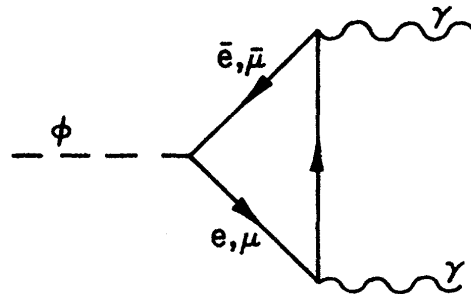
Is There a Light Scalar Boson?

L. Resnick, M. K. Sundaresan, and P. J. S. Watson

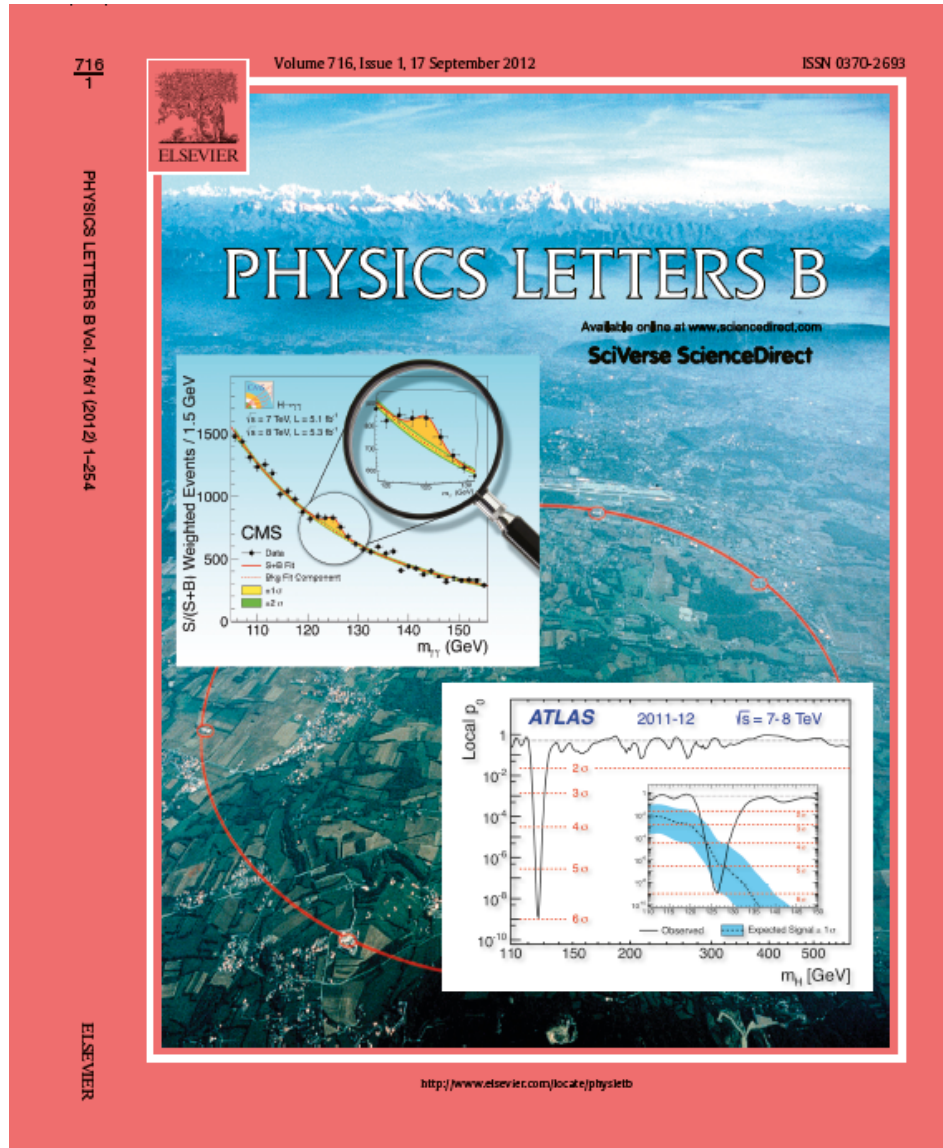
Department of Physics, Carleton University, Ottawa, Canada

(Received 28 July 1972; revised manuscript received 2 January 1973)

In view of recent theoretical interest in the possibility of a light scalar boson ϕ we discuss some of its properties and possible methods for detecting it. Cross sections for its production are typically 10^{-8} of competing processes, with the possible exception of $0^+ \rightarrow 0^+$ transitions in nuclei. We also give a



Enter the Large Hadron Collider...



P. Higgs congratulating ATLAS spokesperson on Higgs boson discovery (or vice versa?)



Picture: Christian Science Monitor

...that part of the talk belongs to my experimentalist colleague.

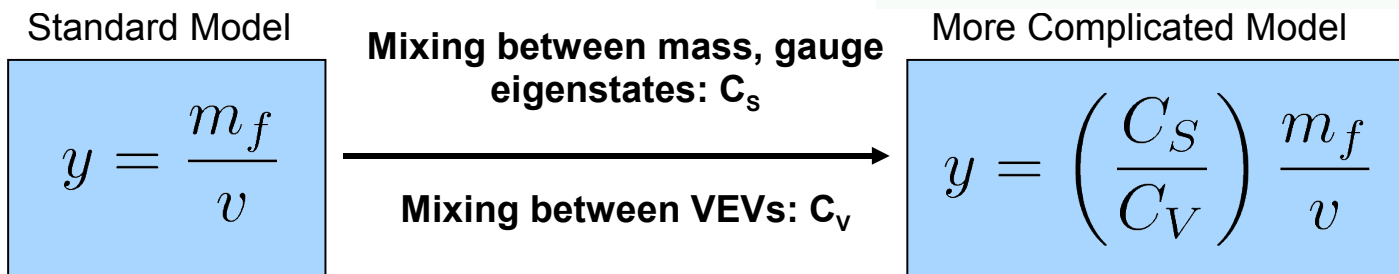
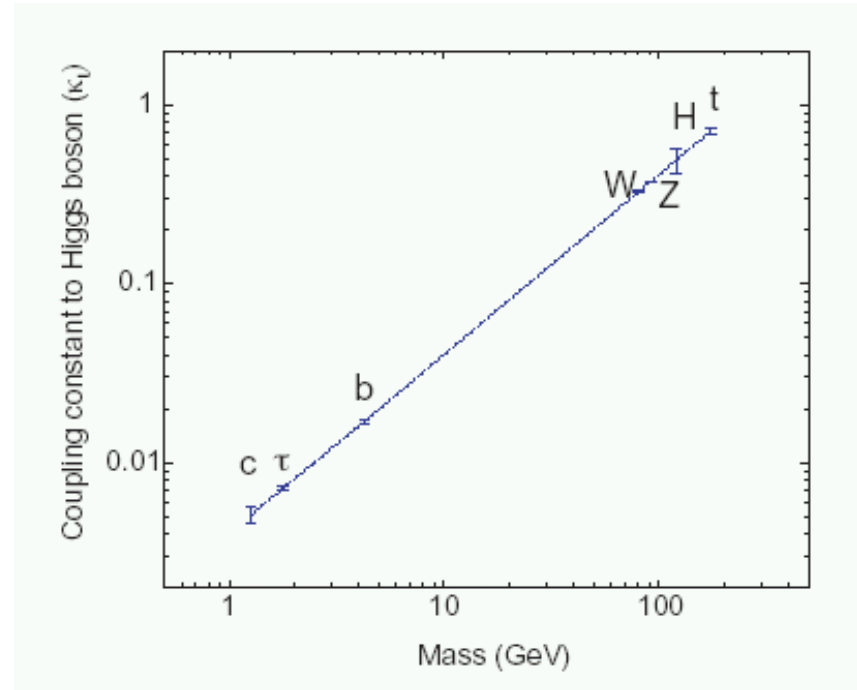
Where next? \Rightarrow Understand the Higgs!

The Standard Model predicts a nice simple relationship between the mass of a particle and its coupling strength to the Higgs.

If that's not the whole story, new effects will show up in the Higgs couplings.

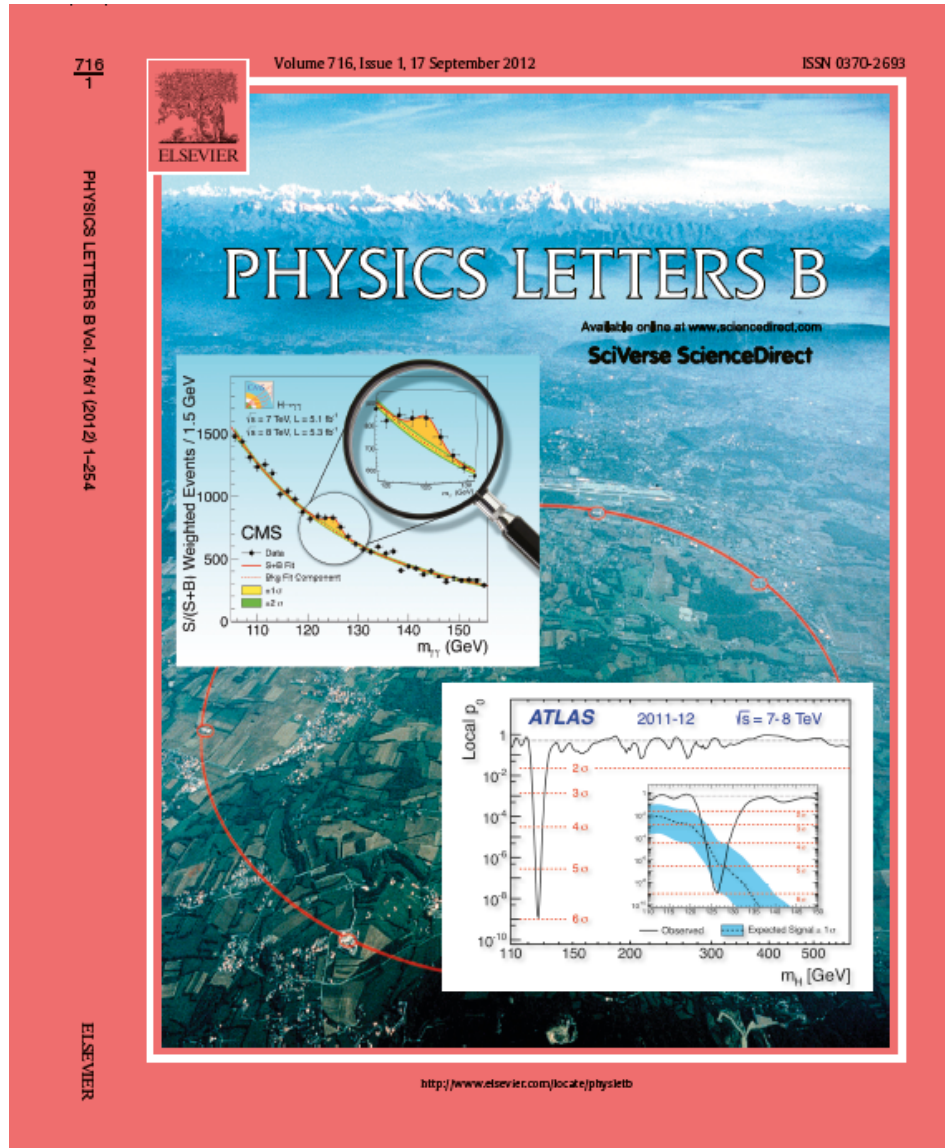
More than one Higgs field?

Different fermions may get masses from different fields.



Theorist's job: figure out what this means for the Higgs theory!

Enter the Large Hadron Collider...



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