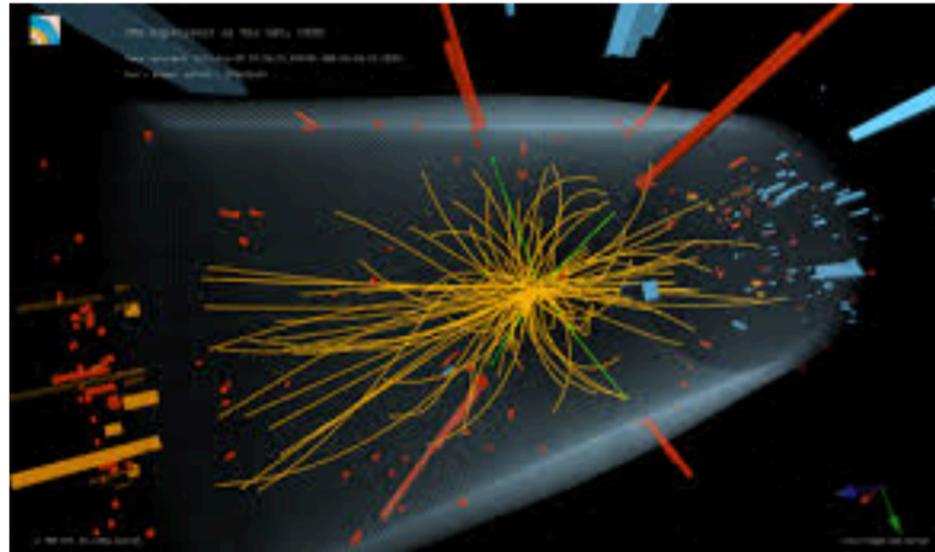


A theory of *almost* everything:

The Standard Model of Particle Physics

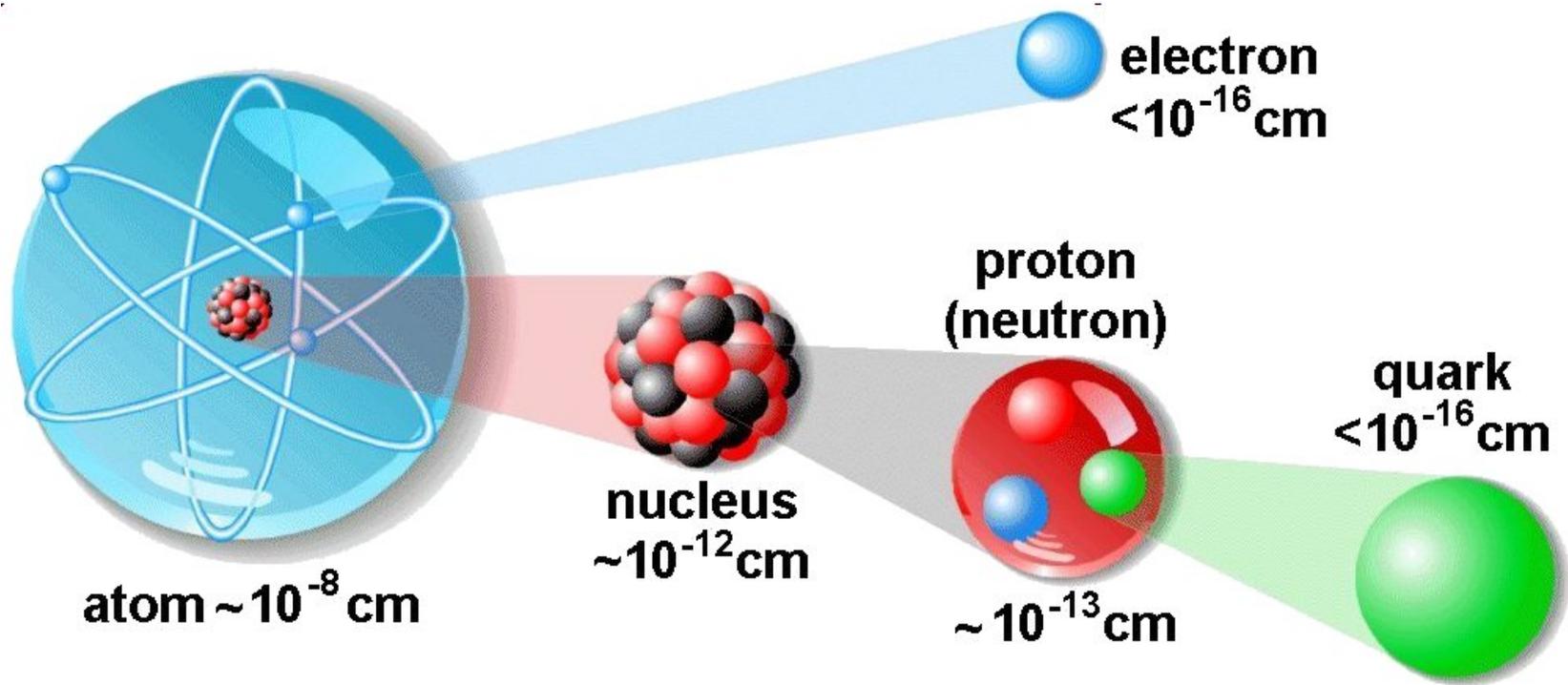
Bogdan Dobrescu

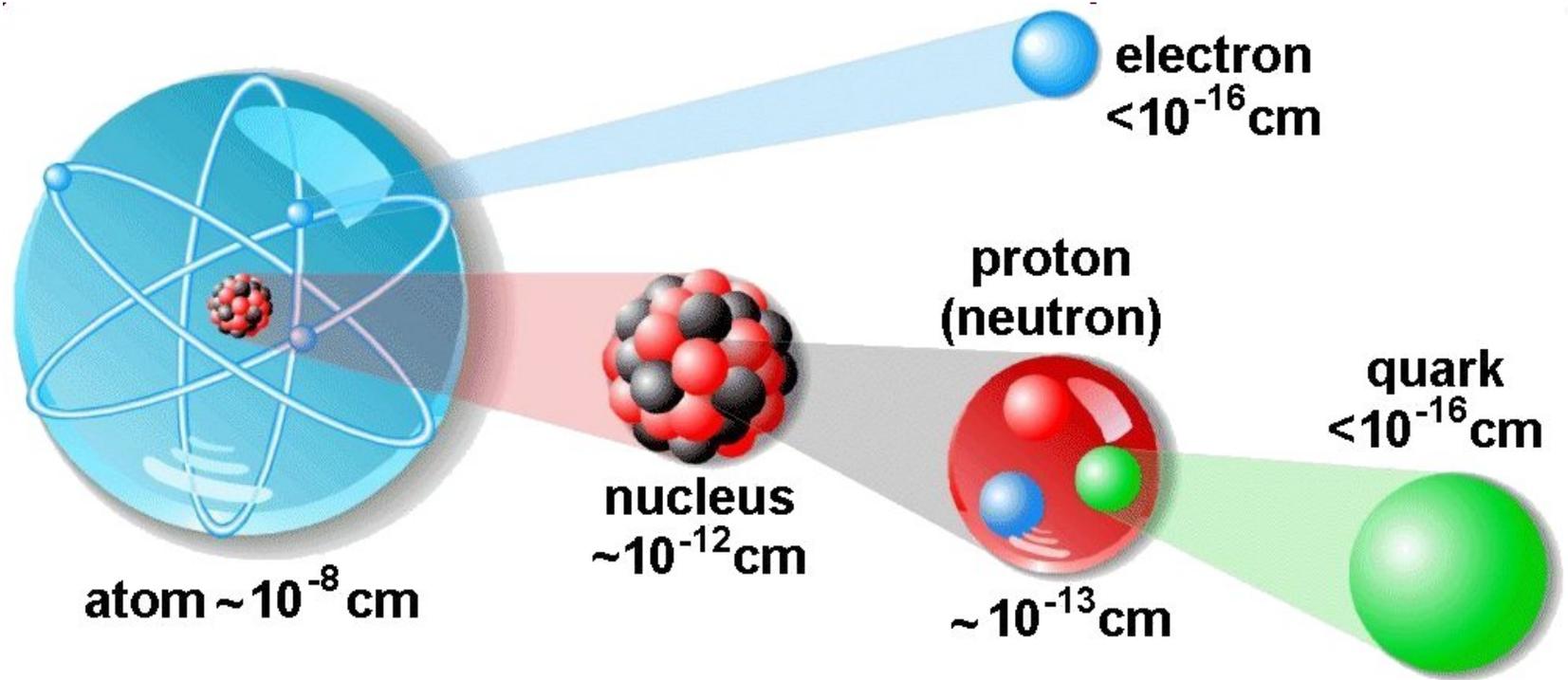
Fermilab, Theoretical Physics Department



Higgs boson event at the LHC

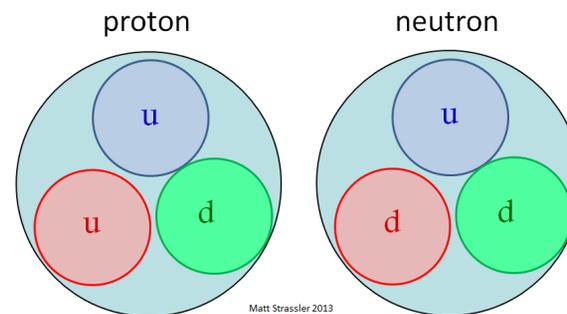
September 9, 2018 - Public Lecture





“Everything” around—and in—us is built of three types of particles:

up and *down* quarks,
and electrons.



Classical mechanics

- objects much bigger than atoms
- objects much slower than light

Quantum mechanics

- **any** size objects
- objects much slower than light

Special relativity

- objects much bigger than atoms
- **any** speed $\leq c$

Quantum field theory

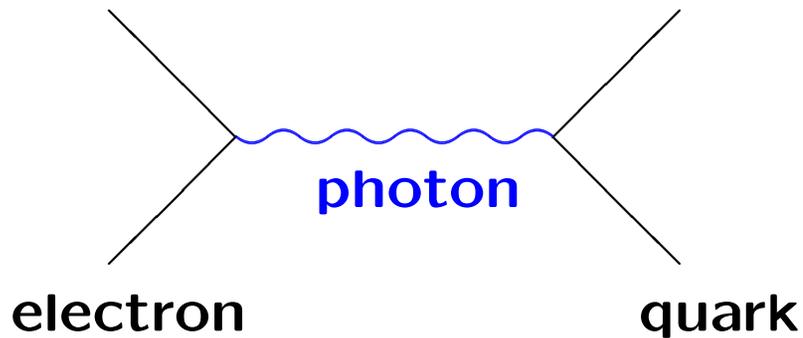
- **any** size objects
- **any** speed $\leq c$

Elementary particles are manifestations of quantum fields.

Interactions at a distance are mediated by particle exchange.

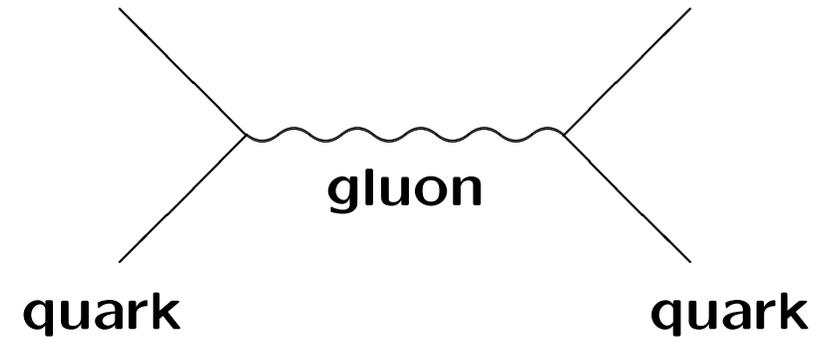
The particle of the electromagnetic field is called *the photon*.

The force between electric charges is due to photon exchange:

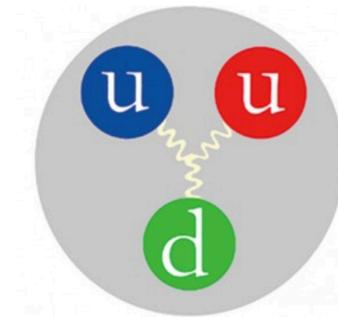


The Strong force between quarks

- ★ is due to *gluon* exchange:



- ★ it keeps the quarks inside protons and neutrons.

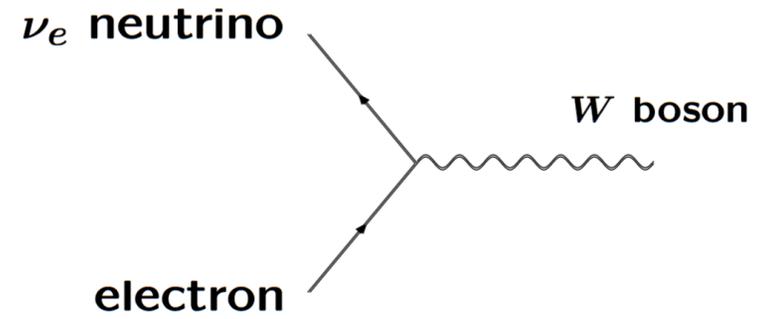
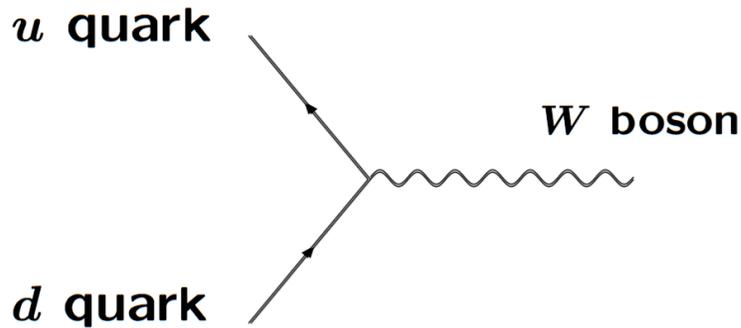


- ★ it keeps the protons and neutrons inside the atomic nucleus.

“Weak” interaction

This is mediated by heavy particles: the W and Z bosons.

The W boson changes an up quark into a down quark,
or an electron into a neutrino:



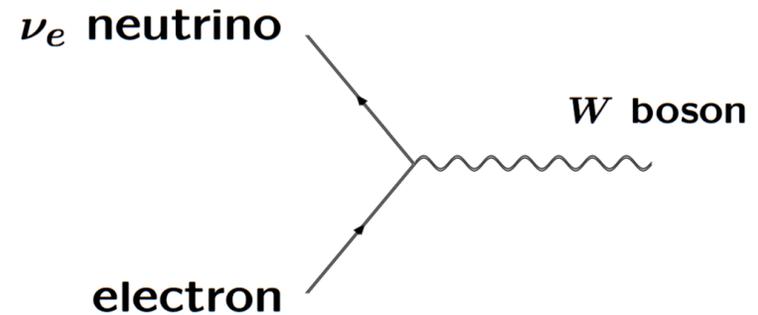
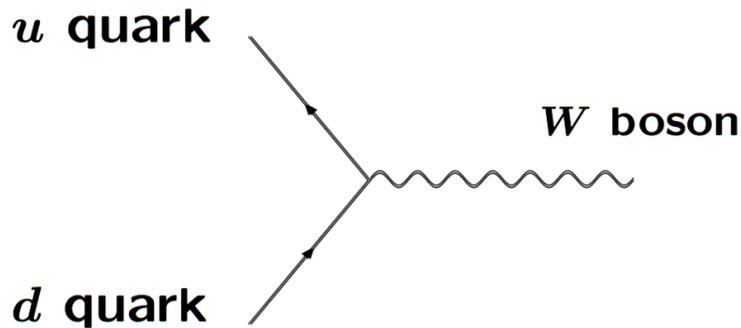
This allows the radioactive decay of atomic nuclei.



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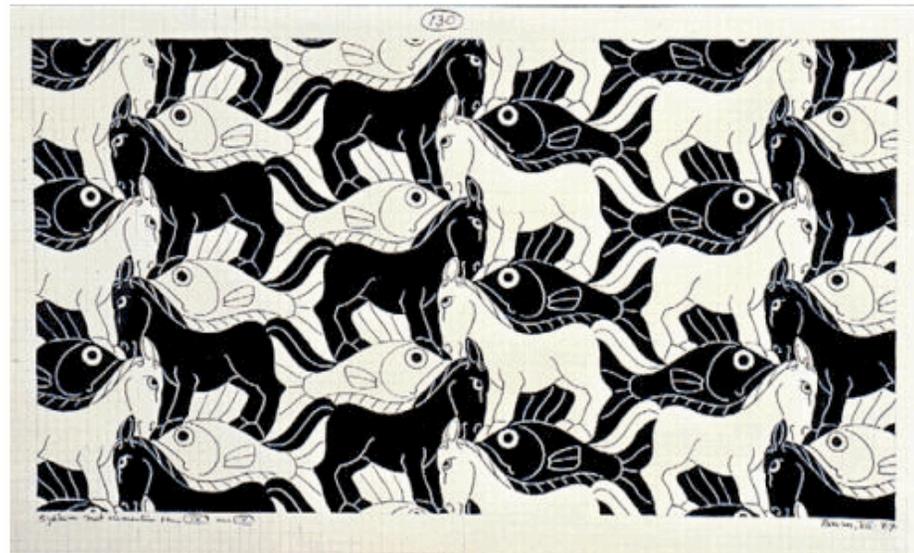
*powers the motion
of tectonic plates*



The photon and the gluon are massless particles (*they move at the speed of light*).

This is a consequence of the symmetries of the equations that describe the electromagnetic and strong interactions.

W and Z bosons are heavy → Their symmetry must be broken...



What is the origin of electroweak symmetry breaking?

Vacuum = lowest energy state of a quantum field theory.

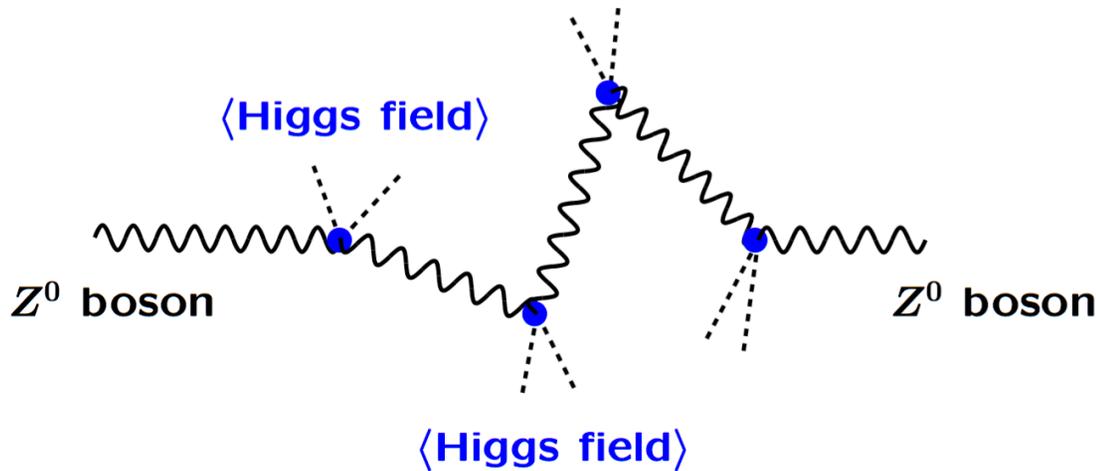
**Laws of nature have an electroweak symmetry,
vacuum has only an electromagnetic symmetry.**

*Need something to
populate the vacuum ...*

FloridaMemory.com

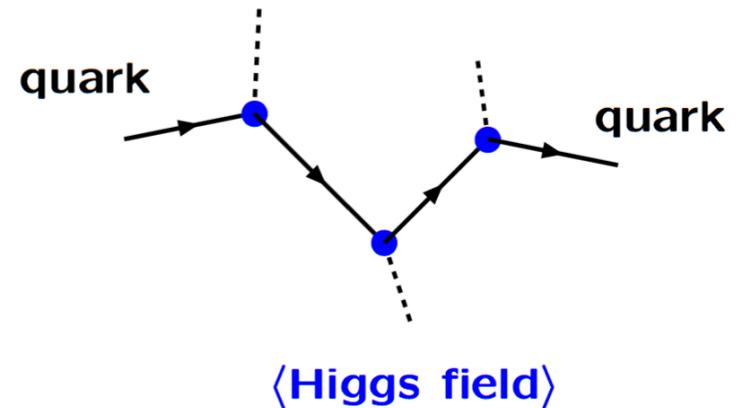


Higgs field 'condenses'



Z^0 acquires a mass!

Quark masses also arise due to the Higgs field:



Higgs field implies the existence of a particle which interacts with the other particles proportional to their mass:

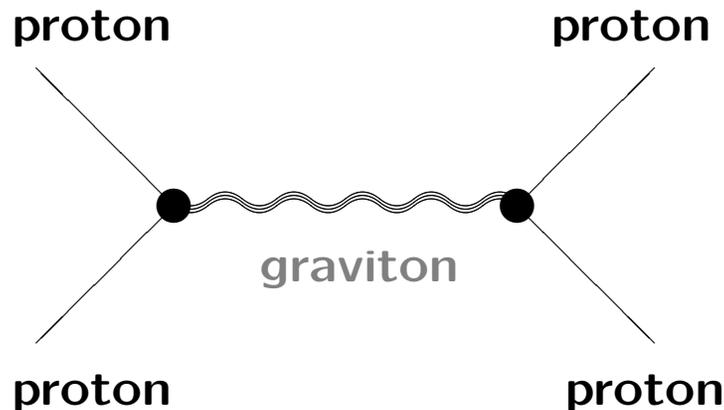
Higgs boson discovered in 2012 at the Large Hadron Collider

Gravitational interaction

Mediated by a massless particle, the “*graviton*”.

Classical limit is identical to General Relativity.

Consequence at low speeds – Newton’s law: $Force \sim \frac{1}{distance^2}$



Theory is valid up to energies of 10^{18} GeV

→ *much beyond what can be currently probed in experiments,
(LHC probes the laws of physics at energies up to 10^4 GeV).*

Standard Model of Particle Physics

a set of equations that describe the interactions and other properties of the following particles:

$$\begin{pmatrix} \nu^e \text{ neutrino} \\ \text{electron} \end{pmatrix} \quad \begin{pmatrix} \nu^\mu \\ \text{muon} \end{pmatrix} \quad \begin{pmatrix} \nu^\tau \\ \text{tau} \end{pmatrix}$$

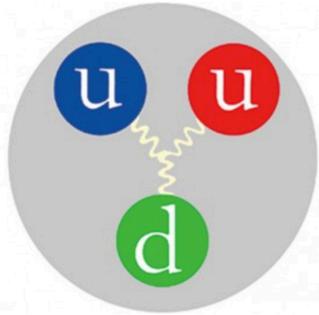
$$\text{quarks} \left\{ \begin{pmatrix} \text{up} \\ \text{down} \end{pmatrix} \quad \begin{pmatrix} \text{charm} \\ \text{strange} \end{pmatrix} \quad \begin{pmatrix} \text{top} \\ \text{bottom} \end{pmatrix} \right.$$

$$\text{photon} + \text{gluon} + W^\pm, Z^0$$

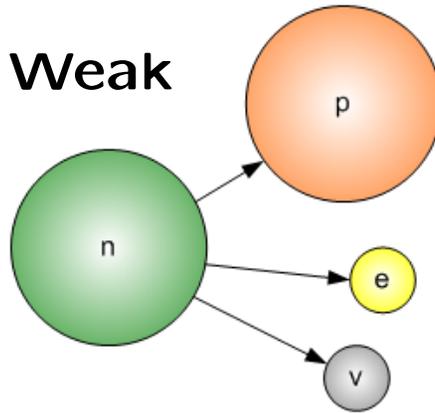
Higgs boson

graviton

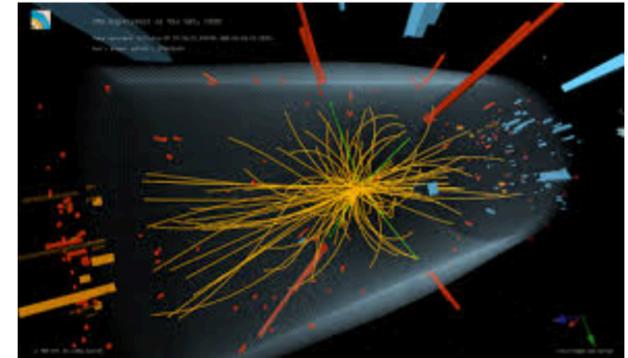
Strong



Weak



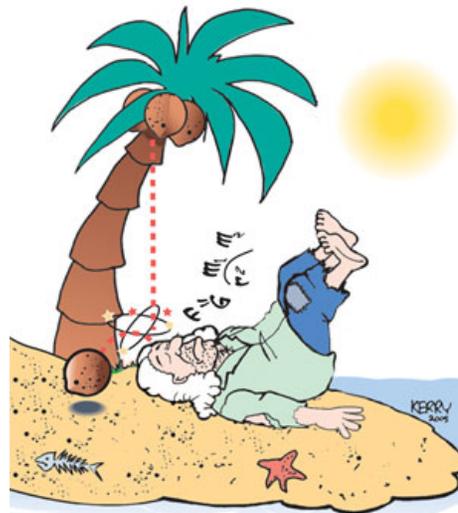
Higgs interactions



Electromagnetic



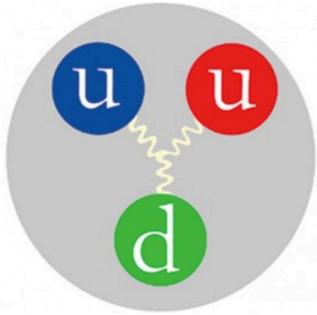
Gravity



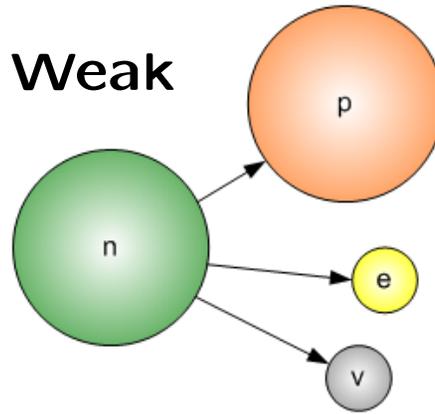
Why gravity was not discovered in Tahiti.

Based on an idea submitted by Zachary H. Levine and Ellen S. Levine

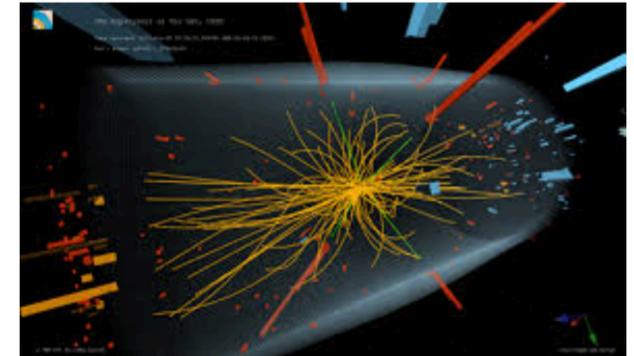
Strong



Weak



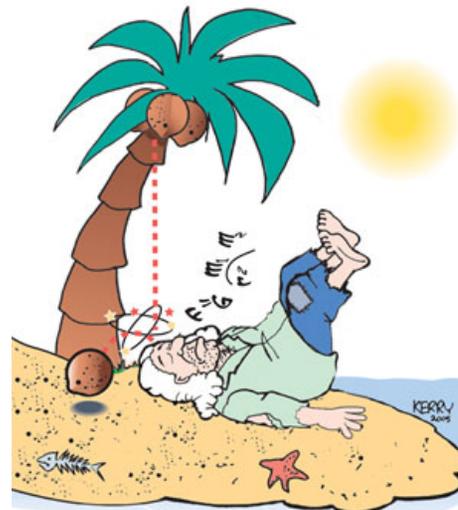
Higgs interactions



Electromagnetic



Gravity



Why gravity was not discovered in Tahiti.

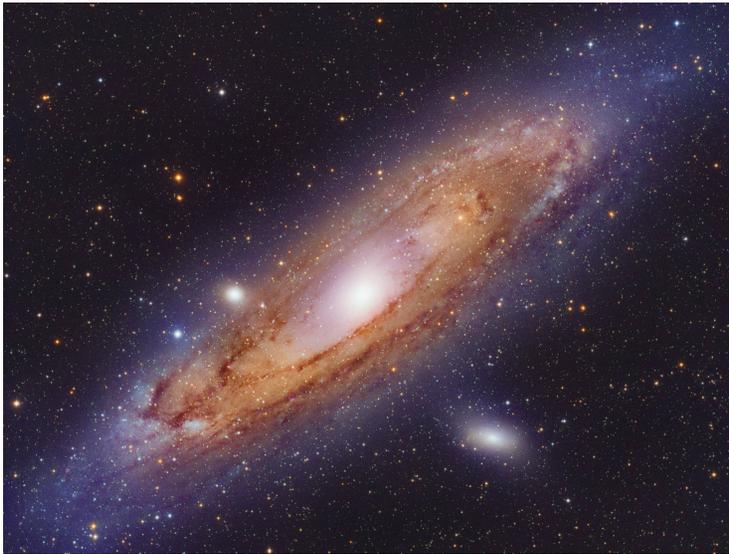
Based on an idea submitted by Zachary H. Levine and Ellen S. Levine

Could there exist additional interactions?

Yes, if new particles are sufficiently heavy, or very weakly coupled.

Dark Matter requires particle(s) beyond the Standard Model

Motion of stars within galaxies and several other astronomical and cosmological observations provide evidence for Dark Matter.



Perhaps a single new type of particle forms Dark Matter, or there could be lots of new particles with intricate interactions.

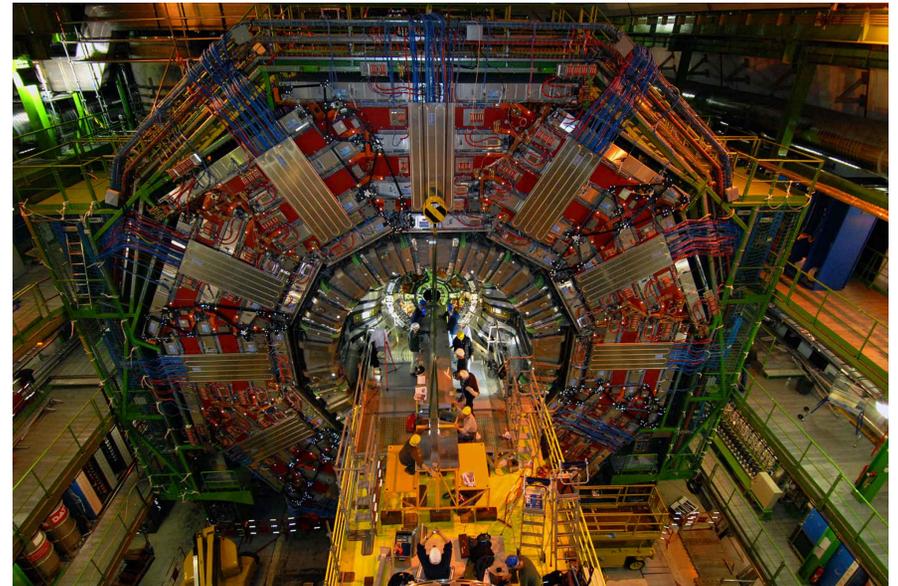
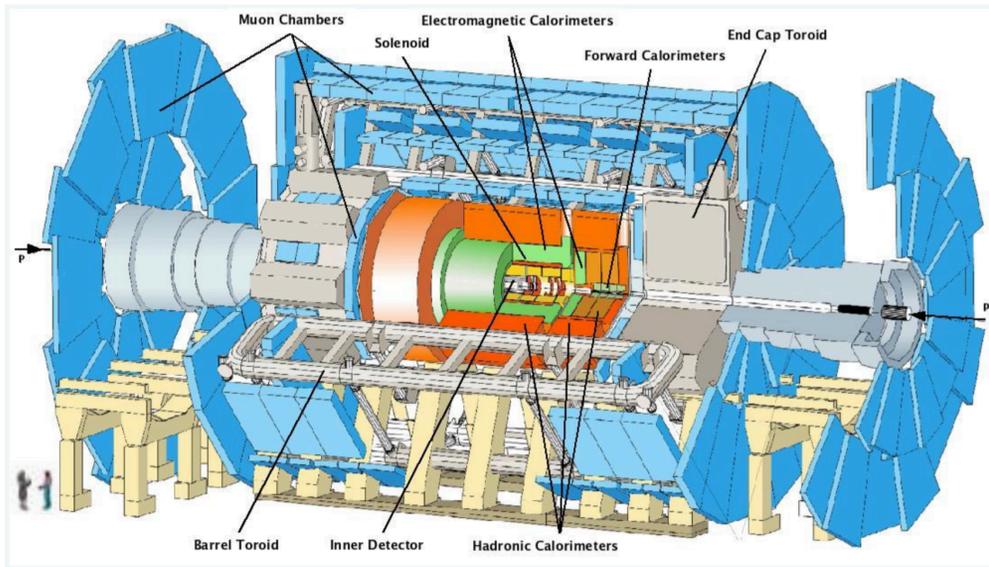
Either way, the Standard Model must be extended ...

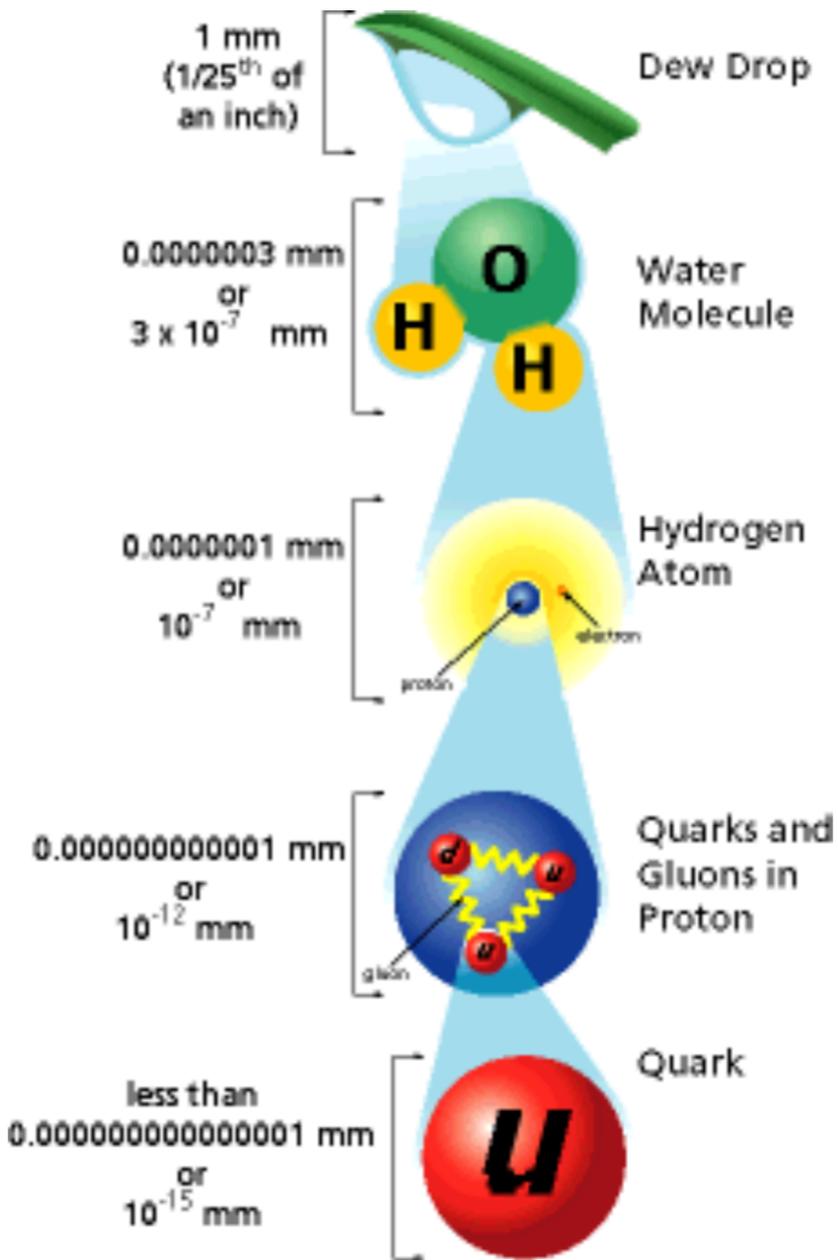
Scientific method: formulate a hypothesis, perform an experiment, check whether the data confirms the hypothesis.

The hypothesis that electrons interact with photons as in the Standard Model has been confirmed with an accuracy of 10^{-13} .

Measurements of the Higgs boson interactions have confirmed the Standard Model predictions with an accuracy of 10%.

The ATLAS and CMS detectors at the LHC:





The equations of the Standard Model allow us to compute the properties of simple systems (e.g., the color of the sky, or the conductivity of metals), but it is too difficult to do it for complicated systems (e.g., a butterfly).

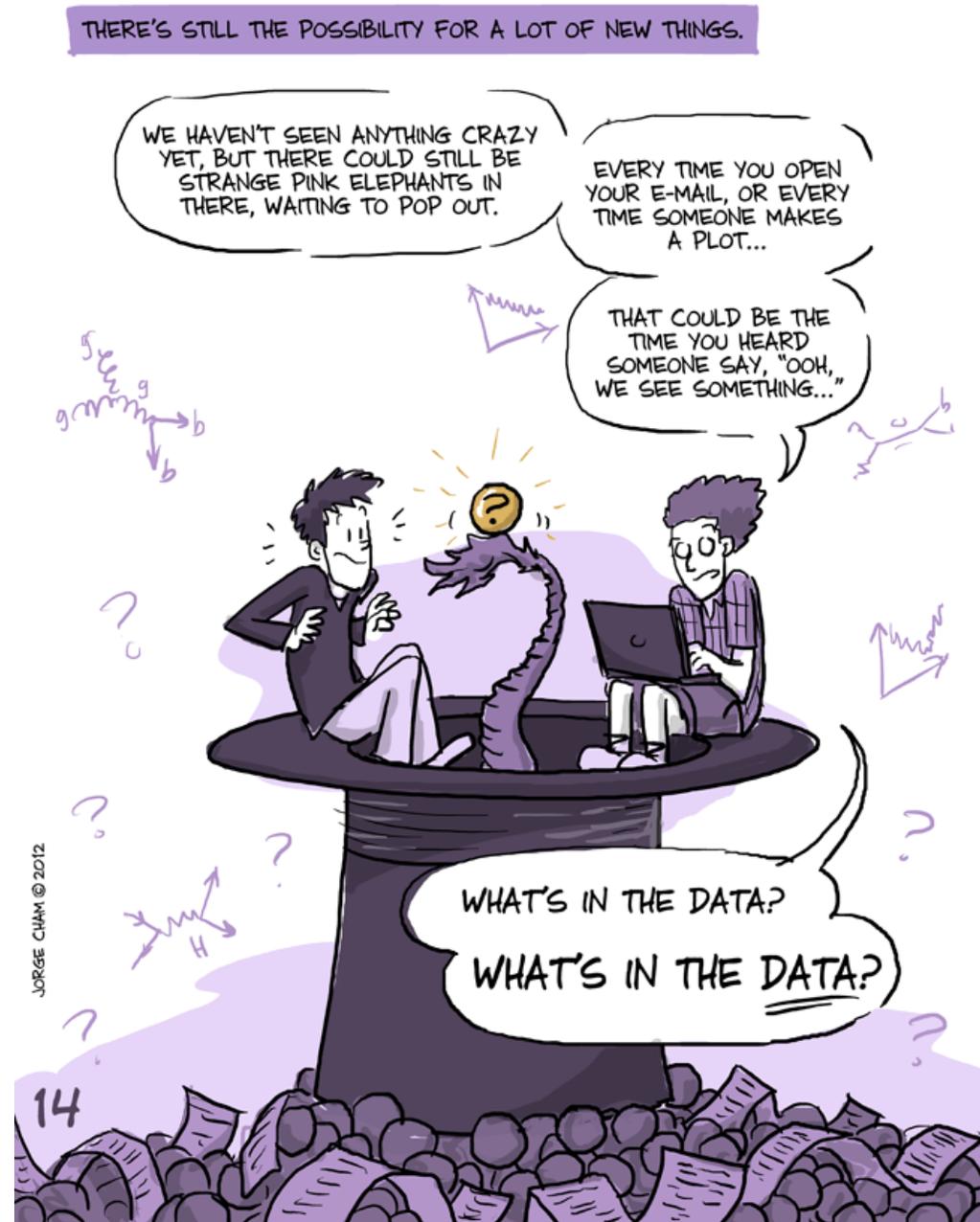


However, the laws of nature described by the Standard Model (plus graviton and dark matter) can in principle explain everything we see.

Conclusions

- 5 known interactions:
 - electromagnetic; gravitational
 - strong; weak; Higgs
- 3 families of matter particles; each contains two quarks, an electron-like particle, and a neutrino.
- All known phenomena can in principle be explained by the “Standard Model”

Bogdan Dobrescu (Fermilab)



phdcomics.com/higgs