The Discovery of the Higgs

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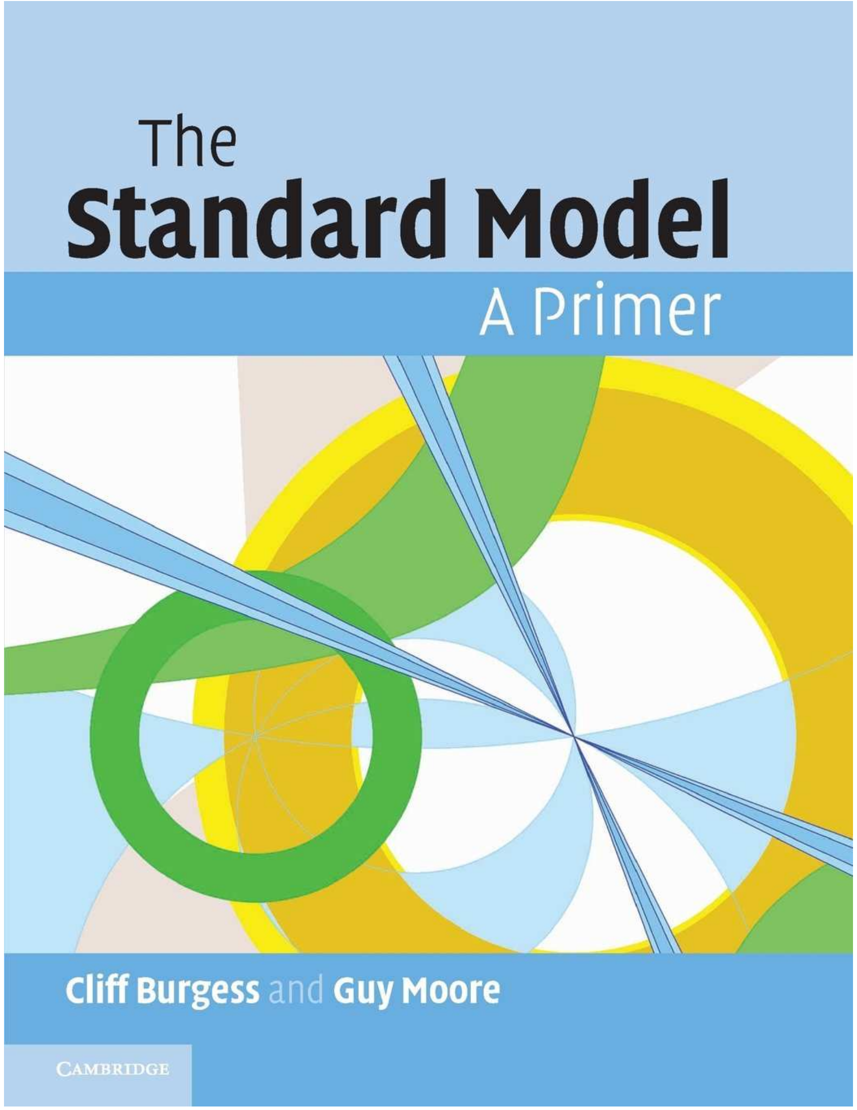


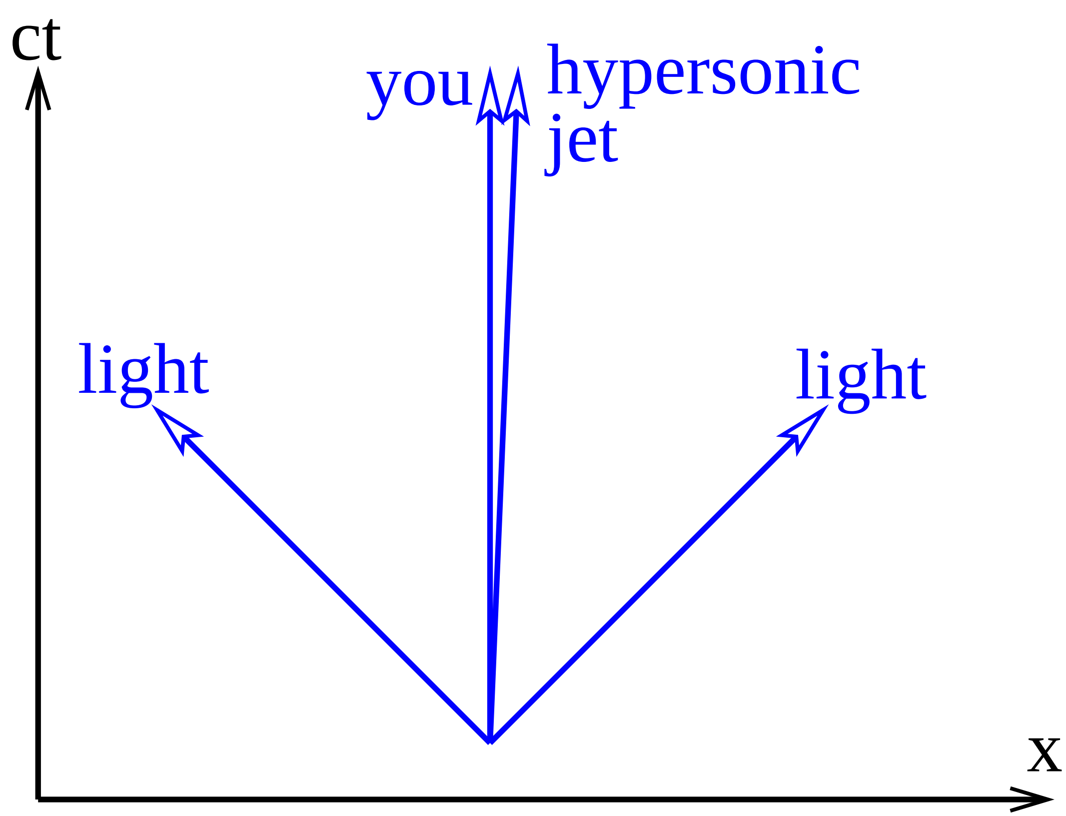
The Discovery of the Higgs

- What is the Higgs?
  - Massless vs Massive States
  - Nature of (fermionic) mass
  - Handedness, Charge balance
- How did we discover it?
  - How the Higgs boson interacts
  - How we looked for it

Space-time diagrams

Most things we deal with move at velocities $v \ll c$.

Light is an exception.

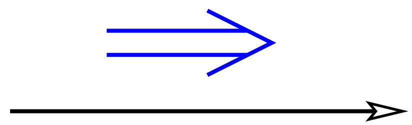
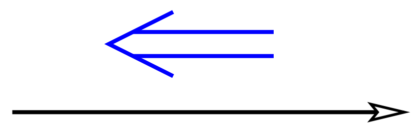


Spin 1/2 particles

Matter is built from spin-$\frac{1}{2}$ particles electron, proton, neutron, . . .

Particle has 3 properties: *Energy* E*, Momentum* P*, Spin* S*.*

Particle physics naturally built from two kinds of spin-$\frac{1}{2}$ particles called different *chiralities*:

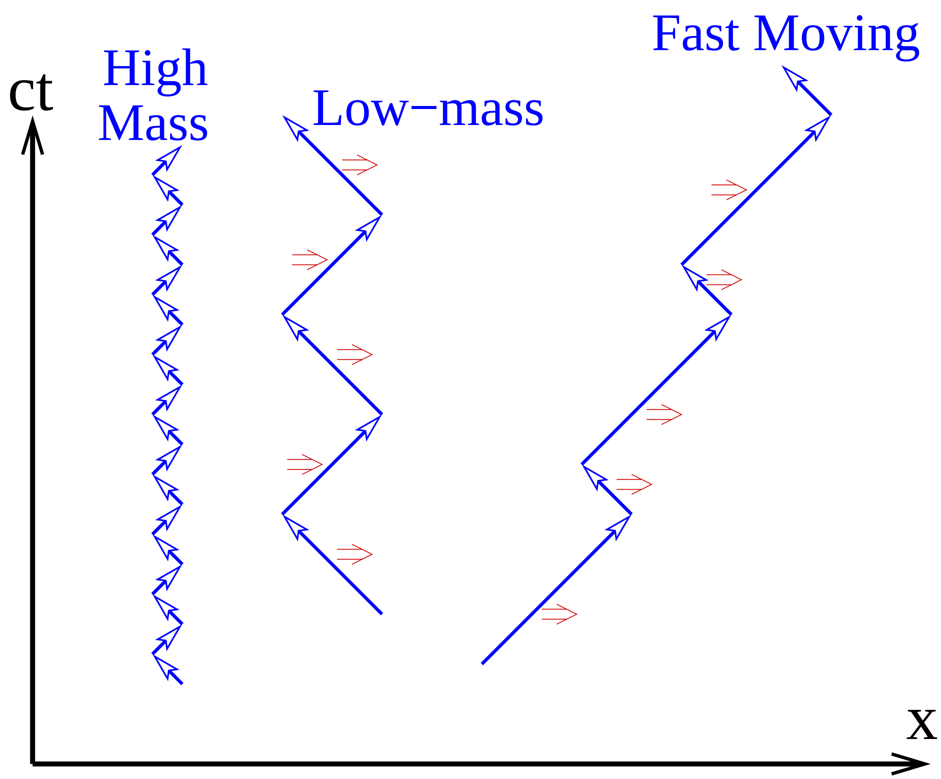
- $E = P$ and $S \parallel P$:  (R-handed)
- $E = P$ and S opposite P:  (L-handed)

These are the two types of particles which naturally show up. Each is *massless* and moves at *light-speed*.

Mass for Spin-$\frac{1}{2}$ Particles

Mass is an *interaction* between these two types.

It preserves spin but switches direction:



At-rest: zig-zags of equal size

Moving: longer zigs than zags

Heavy: frequent zig-zags

Spin stays the same.

Size: Compton length $\hbar/mc$

Quantum conceals zig-zags

(but see *Zitterbewegung*)

Electric charge

Right-handed and Left-handed versions are best considered distinct particles. But they must have some things in common.

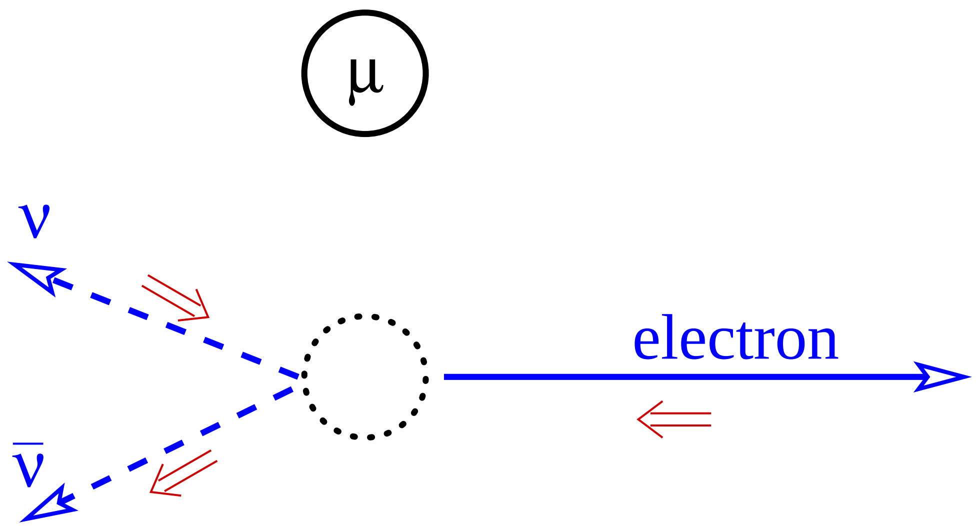
Electric charge is conserved.
Electric charge of e_R and of e_L must be the same.

Masses are only possible when the R- and L- versions have the same properties (charge, electron number, baryon number)

Which is where the puzzle begins.

Weak processes

Some things happen very slowly as the interaction is *weak.*
An example is the decay of e^-'s heavy cousin μ^-:



The escaping e^- moves at around $.999c$ and has about 99.9% chance to have its spin and motion *anti-alligned*.

Decay of μ^- is due to some kind of charge, called the *weak charge*. Preponderance of L-handed e^- coming out means that only the L-handed e^- carries *weak charge*.

As e^- moves along, it switches back and forth between R- and L-handed. To do so, it has to alternately drop off and pick up *weak charge*.

That is strange. "Mass" couples things of different charge. What about *weak charge* conservation? Where does that charge go when the electron switches direction?

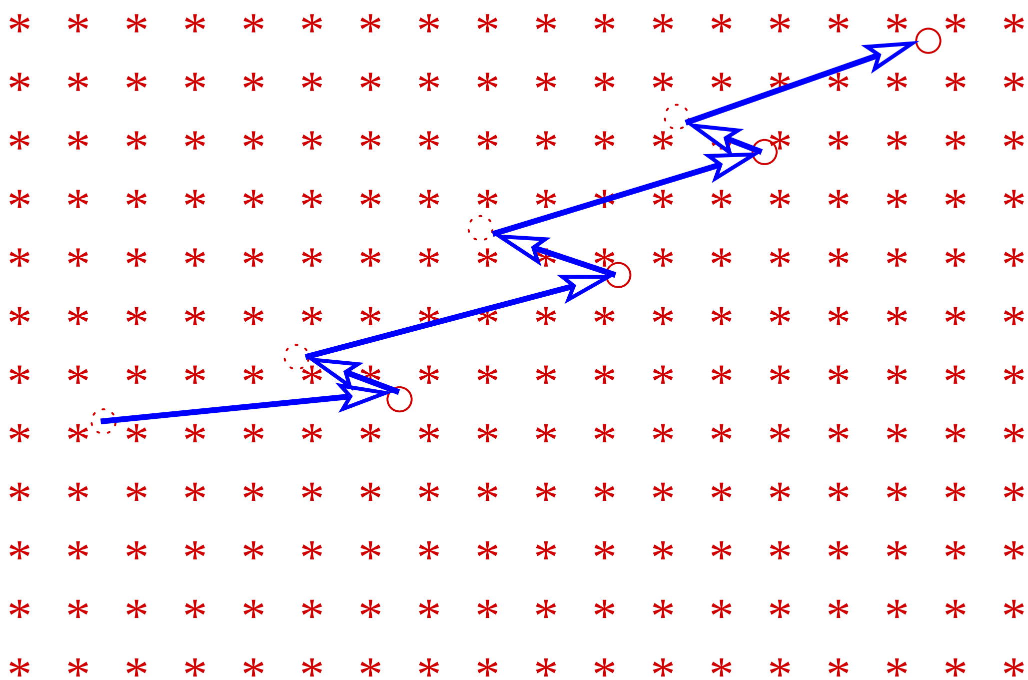
The Higgs Mechanism

Weinberg, Salam explained this using an idea due to *Higgs*

(and Anderson, Brout, Englert, Kibble, Guralnik, Hagen).

A field (the Higgs field) pervades space.

It can carry *weak charge*, can collect or donate it as needed.

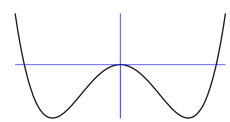


Higgs Field, Higgs Boson

A Scalar field is a *number* at each point in space. (ϕ)
Higgs' field ability to give/take charge depends on size of this number. Larger the number $\Rightarrow$ heavier the particles.

Higgs field **must** be actual, dynamical degrees of freedom. Size of field is determined by some physics:

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

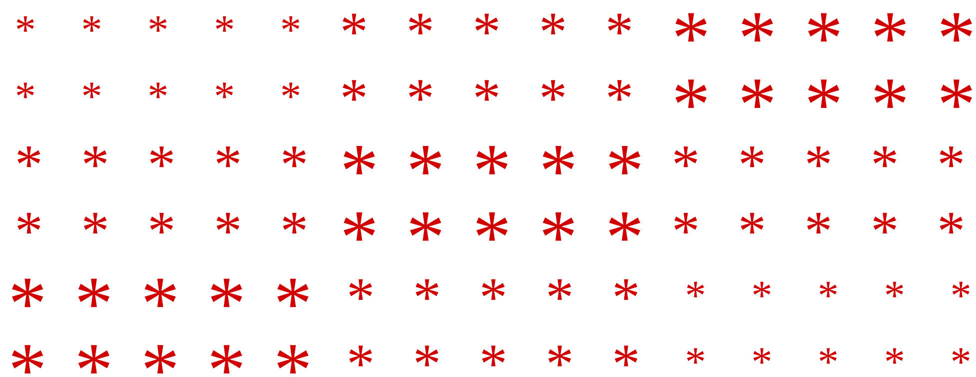


where $V(\phi)$ is the energy-density associated with field ϕ.
The $-$ sign means that ϕ prefers to be non-zero.

If ϕ is dynamical, why can't it fluctuate? It can!

Higgs boson

There can be fluctuations in the value of this Higgs field ϕ



Where field is large, particle masses are large.

Where field is small, particle masses are small.

Fluctuations *oscillate* at frequency $\omega_{_H}$ set by μ^2, λ.

Unfortunately, *not* predicted by the theory.

Higgs boson particle

This is quantum mechanics. Fluctuations are **quantized** with the quantum called a **Higgs boson**. $M_H c^2 = \hbar\omega_H$

In the wave-packet of a Higgs boson, other particles' masses oscillate between being larger, smaller than normal.

This can *spontaneously* create pairs of any particle lighter than half the Higgs boson's mass (which is 126 GeV or 2.25×10^{-22} grams)
That means a Higgs boson will *decay* into such pairs.

Likelihood to make a particle is in proportion to m^2.

List of known (fundamental) particles:

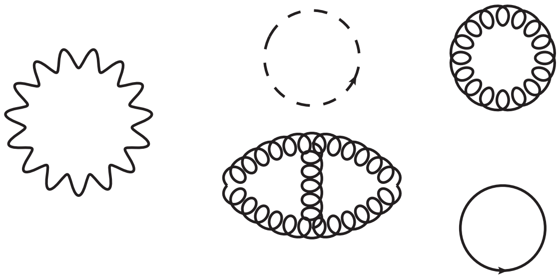
Particle	Mass (GeV)	Particle	Mass (GeV)
top quark	173	μ-lepton	0.105
Higgs boson	126	down quark	0.005
Z-boson	91	up quark	0.002
W-boson	80	electron	0.0005
bottom quark	4.3	neutrino	0
τ-lepton	1.8	gluon	0
charm quark	1.4	photon	0
strange quark	0.15		

Higgs bosons should mostly decay into bottom quarks

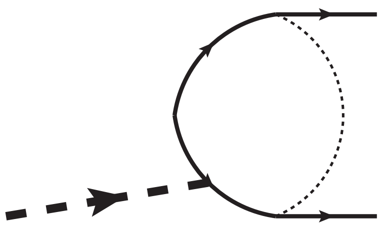
At LHC, this signal buried under other bottom-quark sources

Virtual particles

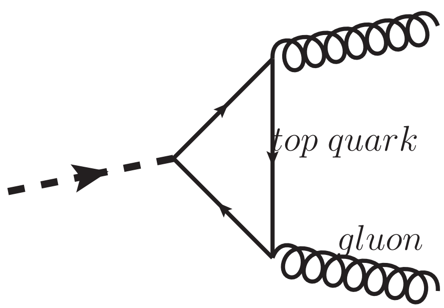
Quantum Field Theory (Quantum Mechanics for particle physics) says that empty space is full of fluctuations.



Simple Higgs decay: Higgs stimulates particle (bottom-quark) fluct. to become real particles.



Complicated Higgs decay: the Higgs stimulates heavy particle (top-quark) fluctuation, which stimulates a light field fluct. to be real particles.

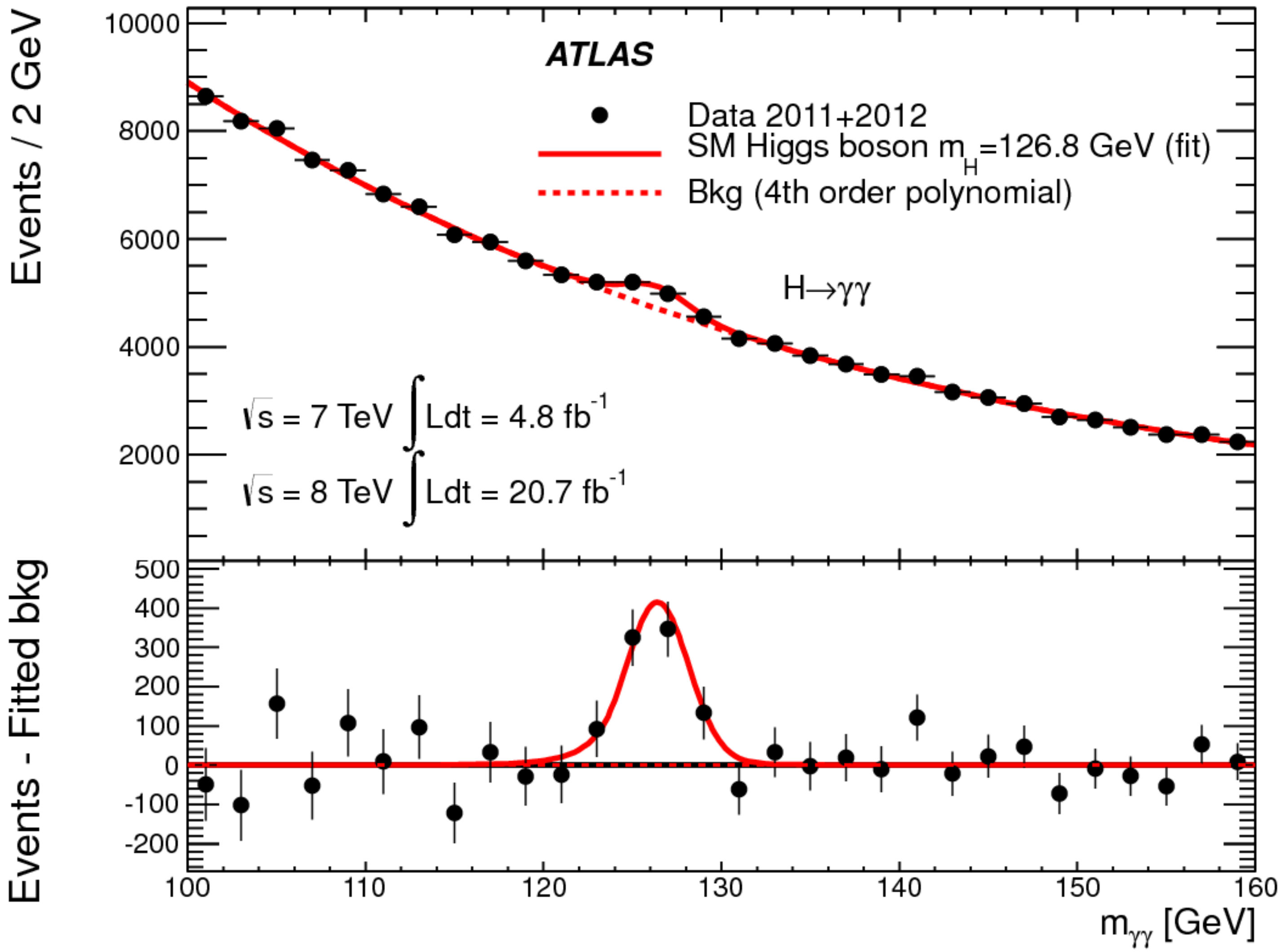


Higgs production and decay

This “double virtual” process explains:

- production: proton contains *gluons*, which produce the Higgs via top-quark fluctuations
- decay: Higgs produces top-quark fluctuations. Top quark is electrically charged, radiates photons.

Photons are a small fraction of the decay products of top quarks. But they are distinctive, and many fewer are produced by other processes. So they can be detected . . .



The money plot

Summary

- Mass is the zig-zagging in space.
  Length of zig-zag $=$ Compton length $\hbar/mc$.
- L- and R- handed particles have different *weak charge*.
- There needs to be a charge-accepting background – the Higgs field – for them to have a mass.
- Higgs: (quantum) fluctuations in this background.
- The Higgs boson has been detected,
  with the expected properties (so far)