Electroweak Symmetry Breaking

An enduring mystery of the standard model of particle physics and how we hope to solve it

David Schaich

Department of Physics and Center for Computational Science
Boston University

Amherst College Colloquium
1 October 2009

Motivation

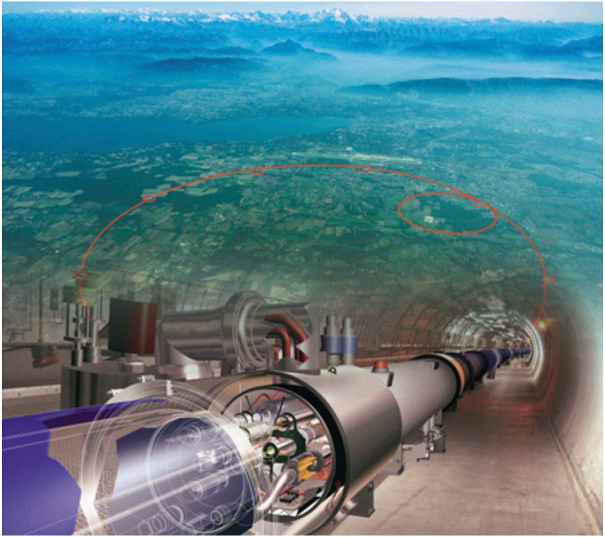


Image credit: CERN

The LHC is coming!

Outline

1. The mystery at the heart of the standard model
   - The standard model of particle physics
   - Electroweak symmetry breaking
2. Decades of detective work
   - The usual suspects: what theory has to say
   - Smoking guns and fingerprints: experiments weigh in
3. Solving the mystery at the Large Hadron Collider

- I am covering a lot of ground, and must do so superficially.
- So *please* interrupt if you have any comments or questions!

Elementary particles: a "tour de force"

The standard model describes
the properties and interactions of elementary particles.

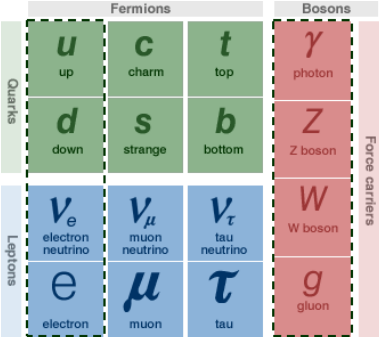


Image credit: AAAS

- Matter made of spin-$\frac{1}{2}$ quarks and leptons
- Forces carried by spin-1 bosons

1. Electromagnetism: photon γ
2. Weak force: Z and $W^\pm$ bosons
3. Strong force: gluons g
4. Gravity not included!

The standard model of particle physics

- The standard model is a relativistic quantum field theory.
- Composed of two interconnected sectors:

QCD

- Quantum chromodynamics, the “color theory”
- Strongly binds quarks into protons, pions, etc.
- No free “colored” particles (quarks and gluons)

Electroweak

- Unifies weak and EM: described by common symmetry principle
- Left- and right-handed particles treated differently

- Both sectors gradually constructed in light of experiments.
- Have been precisely tested by vast array of experiments.

Consequences of electroweak symmetry

- Electroweak symmetry
  unifies weak interaction and quantum electrodynamics.
- Seems surprising at first glance:

Electromagnetism

- Infinite range
- Massless photon
- Conserves parity

Weak interaction

- Extremely short range ($\lesssim 10^{-17}$ m)
- Very massive $W^{\pm}$ and Z ($\sim 90 m_P \sim 175,000 m_e$)
- Violates parity

- Even more surprising:
  apparently requires all elementary particles to be massless.

Consequences of electroweak symmetry

- Electroweak symmetry
  unifies weak interaction and quantum electrodynamics.
- Seems surprising at first glance:

Electromagnetism

- Infinite range
- Massless photon
- Conserves parity

Weak interaction

- Extremely short range
  ($\lesssim 10^{-17}$ m)
- Very massive $W^{\pm}$ and Z
  ($\sim 90 m_P \sim 175,000 m_e$)
- Violates parity

- Even more surprising:
  apparently requires all elementary particles to be massless.

Outline (reminder)

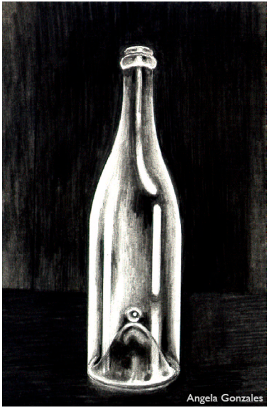
1. The mystery at the heart of the standard model
   - The standard model of particle physics
   - Electroweak symmetry breaking
2. Decades of detective work
   - The usual suspects: what theory has to say
   - Smoking guns and fingerprints: experiments weigh in
3. Solving the mystery at the Large Hadron Collider

Spontaneous symmetry breaking

Observation of particles with nonzero masses

$\Rightarrow$ electroweak symmetry must be "broken".

What does that mean?



Spontaneous symmetry breaking

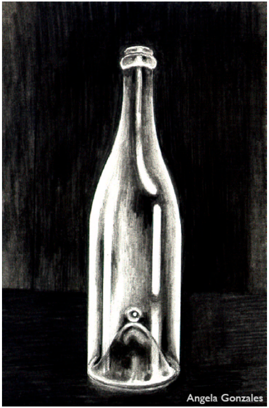
Symmetry remains but is *hidden*

Two different descriptions of the *same physical system*

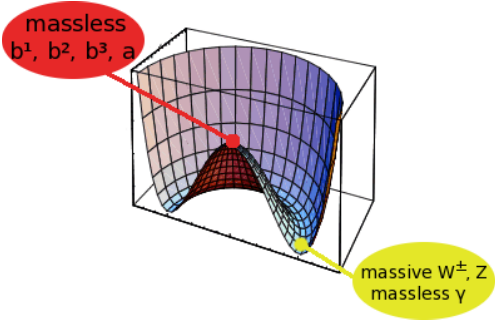
Spontaneous symmetry breaking

Observation of particles with nonzero masses
$\Rightarrow$ electroweak symmetry must be "broken".

What does that mean?



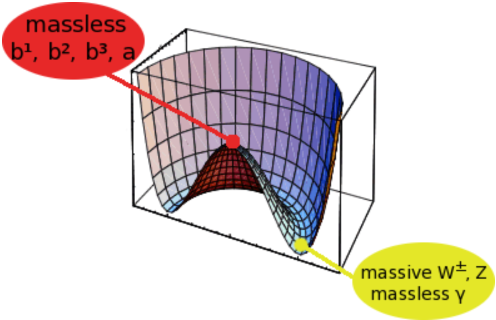
Spontaneous symmetry breaking
Symmetry remains but is *hidden*



Two different descriptions of the
same physical system

Electroweak symmetry breaking (EWSB)

Two different descriptions of the *same physical system*
need the same number of degrees of freedom.



Objection

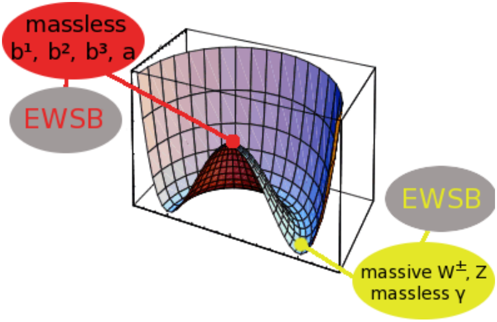
- Massless spin-1: 2 d.o.f.
- Massive spin-1: 3 d.o.f.
- Doesn't add up.

What is EWSB?

That's the mystery.

Electroweak symmetry breaking (EWSB)

Two different descriptions of the *same physical system*
need the same number of degrees of freedom.



Generic solution

- Need to add something to be consistent.
- Three d.o.f. from EWSB "eaten" by $W^{\pm}$, Z.

What is EWSB?

That's the mystery.

History of the mystery

1967 Steven Weinberg publishes “A Model of Leptons”.

1969 Weinberg’s paper cited once.

1970 Weinberg’s paper cited again.

1971 Gerard ’t Hooft puts the work on firmer theoretical foundation.

1973 Discovery of weak neutral current predicted by theory.

1979 Weinberg awarded Nobel Prize for this work (with Glashow and Salam).

1999 ’t Hooft and Veltman awarded Nobel Prize for their contribution.

2009 “A Model of Leptons” most cited paper in high energy physics.

- Weinberg provided a simple model showing how electroweak symmetry *could* be hidden.
- But there are *many* possible mechanisms and we don’t yet know which is realized in nature.

History of the mystery

1967 Steven Weinberg publishes “A Model of Leptons”.

1969 Weinberg’s paper cited once.

1970 Weinberg’s paper cited again.

1971 Gerard ’t Hooft puts the work on firmer theoretical foundation.

1973 Discovery of weak neutral current predicted by theory.

1979 Weinberg awarded Nobel Prize for this work (with Glashow and Salam).

1999 ’t Hooft and Veltman awarded Nobel Prize for their contribution.

2009 “A Model of Leptons” most cited paper in high energy physics.

- Weinberg provided a simple model showing how electroweak symmetry *could* be hidden.
- But there are *many* possible mechanisms and we don’t yet know which is realized in nature.

History of the mystery

1967 Steven Weinberg publishes “A Model of Leptons”.

1969 Weinberg’s paper cited once.

1970 Weinberg’s paper cited again.

1971 Gerard ’t Hooft puts the work on firmer theoretical foundation.

1973 Discovery of weak neutral current predicted by theory.

1979 Weinberg awarded Nobel Prize for this work (with Glashow and Salam).

1999 ’t Hooft and Veltman awarded Nobel Prize for their contribution.

2009 “A Model of Leptons” most cited paper in high energy physics.

- Weinberg provided a simple model showing how electroweak symmetry *could* be hidden.
- But there are *many* possible mechanisms and we don’t yet know which is realized in nature.

Outline (reminder)

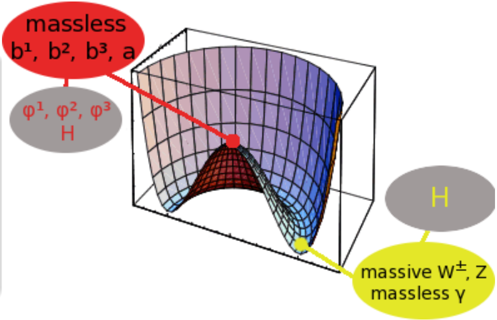
1. The mystery at the heart of the standard model
   - The standard model of particle physics
   - Electroweak symmetry breaking
2. Decades of detective work
   - The usual suspects: what theory has to say
   - Smoking guns and fingerprints: experiments weigh in
3. Solving the mystery at the Large Hadron Collider

Minimal solution: the Higgs boson

Occam's Razor : the simplest solution is often correct.

Simplest EWSB solution

- A single spin-zero field
- A particular potential
- Four degrees of freedom: three eaten by $W^{\pm}$ and Z, fourth is the **Higgs boson**



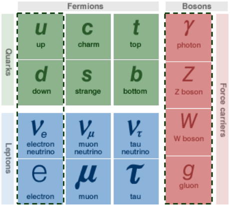
Also provides masses for all the fermions!

Not *required*, but certainly *convenient*.

However, all fermion masses are arbitrary free parameters.

Shortcomings of the minimal theory

- Higgs and its potential
  seem to come out of nowhere
- All masses arbitrary free parameters



We *know* the Higgs can't be the end of the story

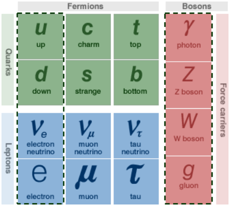
- Short-distance quantum effects make the Higgs disappear!
- Higgs *requires* new physics at short distances.

- Higgs *extremely sensitive* to physics at short distances.
- Properties must be unnaturally "fine-tuned".

None of this *rules out* the Higgs, but does motivate alternatives.

Shortcomings of the minimal theory

- Higgs and its potential
  seem to come out of nowhere
- All masses arbitrary free parameters



We *know* the Higgs can't be the end of the story

- Short-distance quantum effects make the Higgs disappear!
- Higgs *requires* new physics at short distances.

- Higgs *extremely sensitive* to physics at short distances.
- Properties must be unnaturally "fine-tuned".

None of this *rules out* the Higgs, but does motivate alternatives.

A strong, dynamical alternative

Other spontaneous symmetry breaking

1. Superconductivity
2. Chiral symmetry breaking in QCD

Avoid shortcomings of minimal EWSB!

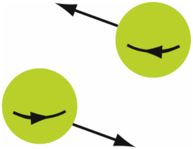


Image credit: Scholarpedia

- Both originally modelled using spin-zero fields.
- Both later explained through the dynamics of spin-$\frac{1}{2}$ fields.

Could the same happen for electroweak symmetry breaking?

- Chiral symmetry breaking in QCD also hides EW symmetry!
- Produces $W^{\pm}$ and Z masses about 2500 times too small...

Technicolor as scaled-up QCD

Technicolor (introduced in late 1970s)

- **Idea:** take QCD and scale it up a couple thousand times to dynamically hide electroweak symmetry.
- *New* strong interactions bind technifermions into technihadrons, the three lightest eaten by $W^{\pm}$ and Z.
- No longer sensitive to short-distance physics.
- Fermion masses *in principle* predictable from extended version of this framework, **but**. . .

It's a **strong** interaction

- Very difficult to work with, no fully realistic model has yet been constructed.
- In particular, the top quark causes difficulties.

Outline (reminder)

Experiments have narrowed the field

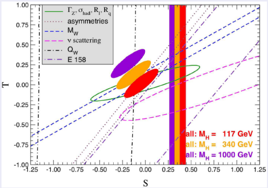
- Decades of experiments have not found the mechanism of EWSB.
- But they have narrowed the field using *indirect* evidence.

Low-energy example: “flavor-changing neutral currents”

- In technicolor, the interactions that produce fermion masses can also change one “flavor” of fermion into another.
- Precise measurements of kaon systems limit such processes.
- Scaled-up QCD flagrantly violates these limits.

High-energy example: “precision electroweak observables”

- Relate high-energy measurements to convenient parameters.
- Scaled-up QCD again has trouble.



Experiments haven't yet solved the mystery

Technicolor disfavored for many years

But now it's back

- Experiments rule out scaled-up QCD
- Technicolor can be completely different

It's a **strong** interaction

- Very difficult to study
  without experimental guidance.
- Need large-scale computations
  to explore most basic features.

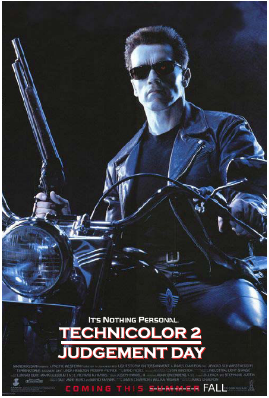


Image credit: Markus Luty

Bottom line: both possibilities (and many more) remain viable,
but not for long...

Outline (reminder)

1. The mystery at the heart of the standard model
   - The standard model of particle physics
   - Electroweak symmetry breaking
2. Decades of detective work
   - The usual suspects: what theory has to say
   - Smoking guns and fingerprints: experiments weigh in
3. Solving the mystery at the Large Hadron Collider

The world's most powerful microscope

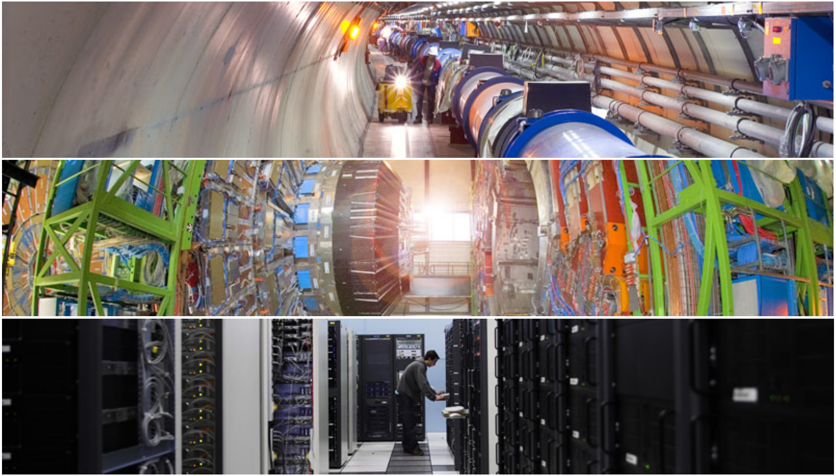
- We have (lots of) *theories* of electroweak symmetry breaking.
- We need *data* to determine which (if any) of them actually describes nature.

> "Faith" is a fine invention
> When Gentlemen can see –
> But *Microscopes* are prudent
> In an Emergency.
> – Emily Dickinson, 1860

The Large Hadron Collider is the world's most powerful microscope, exploring the nanonanoscale, 10^{-18} m.

LHC: Coming soon!

- After delays, scheduled to start up later this fall.
- Planning: 1984; approval: 1994; construction: 2000.



Images credit: CERN

Vital stats

- Located outside Geneva
- 9593 (superconducting) magnets
- Collides protons (and heavy ions)
- Proton energy 7 [3.5] TeV
- Very high *luminosity*
- 600 million collisions per second
- 26,659 m circumference
- Operating at 1.9 K (-271.3° C)
- Collisions every 25 [75] ns
- Proton speed c – 10 km / h
- 15,000 TB of data per year
- cern.ch, twitter.com/cern

Don't expect immediate results

- Will take time to obtain and analyze data.
- May take even longer to understand what the data means.

We expect the LHC to solve this mystery

The minimal Higgs may be running out of places to hide:

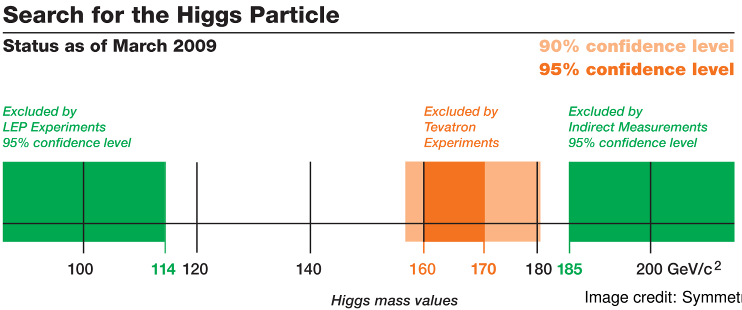


Image credit: Symmetry Magazine

- Similarly, techniparticle zoo expected to appear below 600 GeV.
- More generally, need EWSB mechanism to appear below 1 TeV, or else theories predict apparent nonsense.

Not the end of particle physics

- We're not about to check the last item off our list
  and declare particle physics complete.
- We are about to begin exploration of a brand new scale
  where we expect many interesting things to happen.

Recapitulation

- The standard model relies on electroweak symmetry being hidden
- The specific mechanism that hides electroweak symmetry
  remains a mystery.
- There are many possible suspects, none fully satisfactory.
- Experiments have narrowed the field,
  but we need the LHC to solve this mystery.

Beyond EWSB, many mysteries remain

- What is responsible for the huge range of fermion masses?
  Can fermion masses be predicted from some theory?
- Why is there more matter than antimatter in the universe?
- What are the properties of *quark-gluon plasmas*?
- What are the *dark matter* and *dark energy* that make up most of the universe?
- Is there a *supersymmetry* between bosons and fermions?
  If so, how and at what scale is it broken?
- Does QCD join the electroweak theory in some *Grand Unified Theory?*
- Why is gravity so much weaker than the other three forces?
  Can all four be unified? Is there a quantum theory of gravity?
  Extra dimensions? String theory? . . . ?

Some of these questions are likely related to EWSB

Will the LHC solve these mysteries? Will we get any clues?

Beyond EWSB, many mysteries remain

- What is responsible for the huge range of fermion masses?
  Can fermion masses be predicted from some theory?
- Why is there more matter than antimatter in the universe?
- What are the properties of *quark-gluon plasmas*?
- What are the *dark matter* and *dark energy* that make up most of the universe?
- Is there a *supersymmetry* between bosons and fermions?
  If so, how and at what scale is it broken?
- Does QCD join the electroweak theory in some *Grand Unified Theory?*
- Why is gravity so much weaker than the other three forces?
  Can all four be unified? Is there a quantum theory of gravity?
  Extra dimensions? String theory? . . . ?

Some of these questions are likely related to EWSB

Will the LHC solve these mysteries? Will we get any clues?

We'll find out!

Bonus slides!

Bonus slide: Chiral structure of standard model

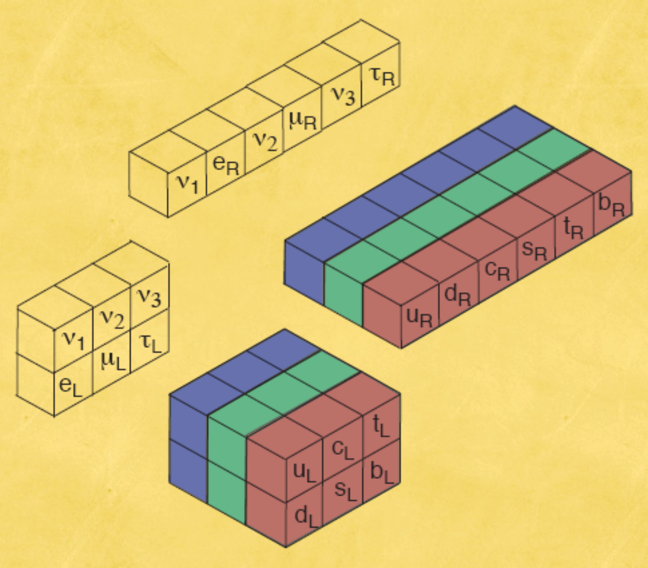


Image credit: Chris Quigg

Bonus slide: Precision tests of electroweak theory

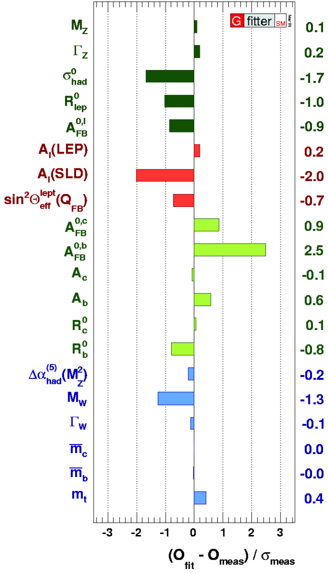
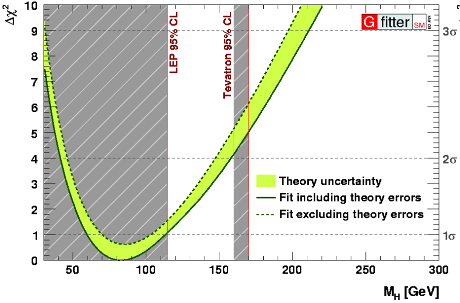


Image credit: Gfitter Group

Bonus slide: Indirect Higgs boson mass bounds



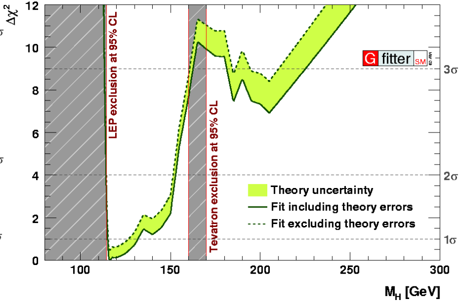


Image credit: Gfitter Group

Bonus slide: Higgs search channels

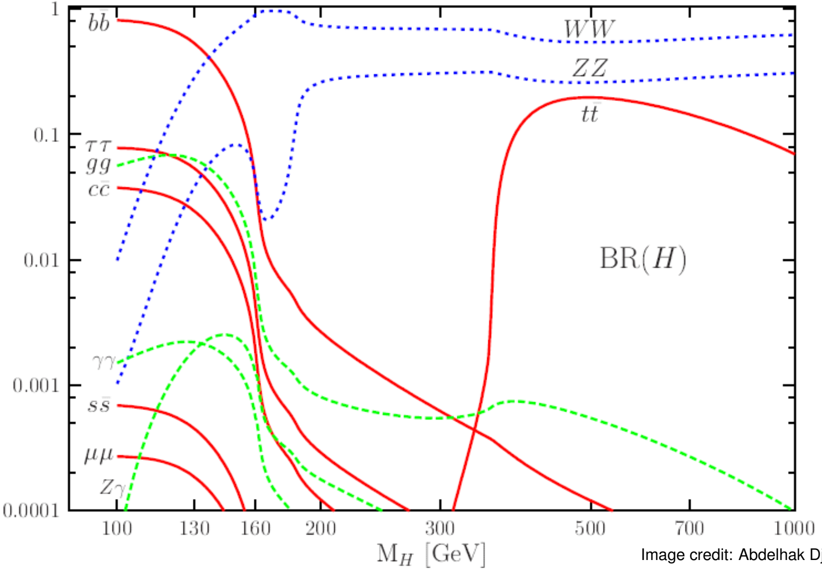
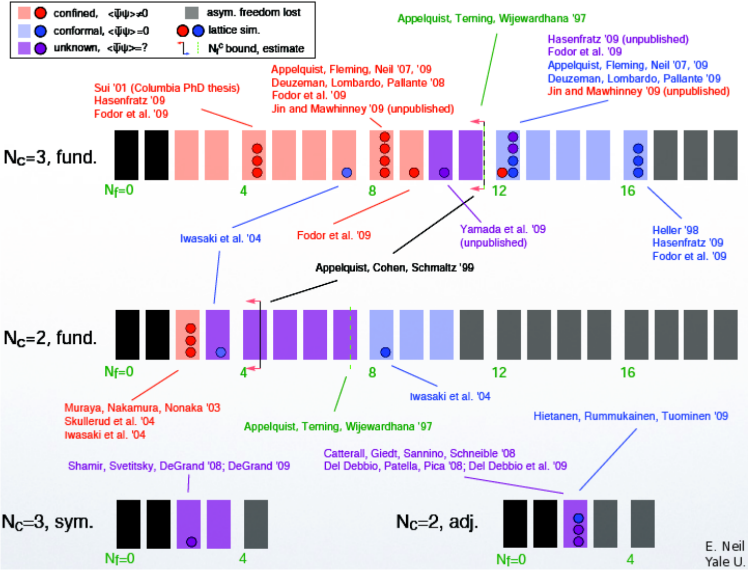


Image credit: Abdelhak Djouadi

Bonus slide: Lattice explorations beyond QCD



Bonus slide: The flavor problem

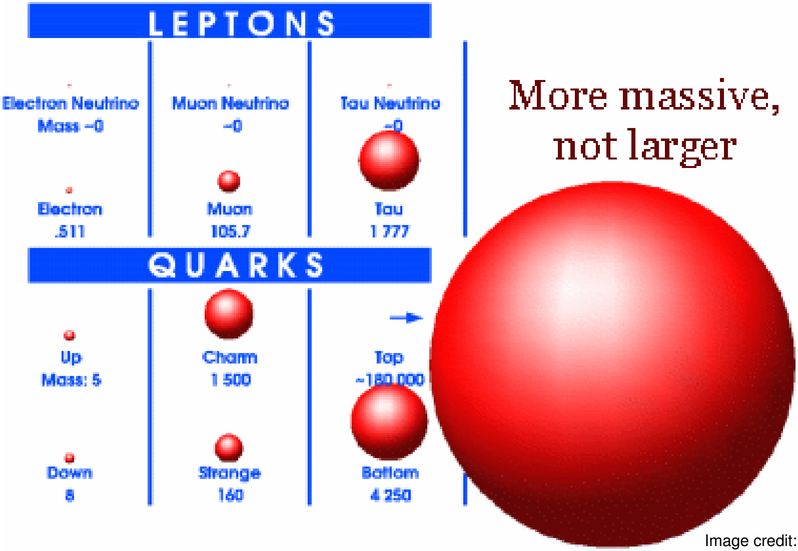


Image credit: Fermilab

Bonus slide: The end of physics?

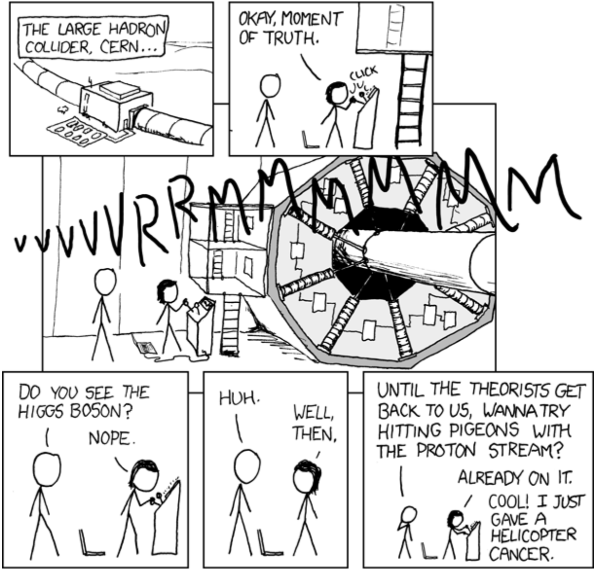


Image credit: xkcd