Why do we need a Higgs boson?

Jim Pivarski

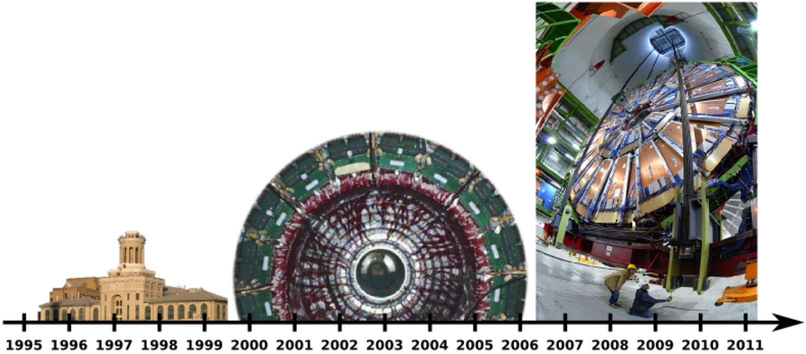
8 December, 2011

My background

CMU physics major, class of '99

Worked with an electron-positron collider at Cornell as a graduate student, measured the Υ wavefunction for a Ph.D. thesis in 2006

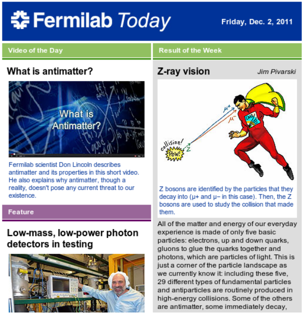
Postdoc at Texas A&M until this year, worked on the CMS experiment at the Large Hadron Collider (LHC); searched for exotic particles in the early data ("muonic jets"— didn't see any)



My background

This year, I've completely changed course:

now I do part-time work in industry
as a statistician/programmer
and use my free time to write popular
physics articles, make outreach
demonstrations and presentations


Fermilab Today
Friday, Dec. 2, 2011

Video of the Day

What is antimatter?

What is Antimatter?

Fermilab scientist Don Lincoln describes antimatter and its properties in this short video. He also explains why antimatter, though a reality, doesn't pose any current threat to our existence.

Feature

Low-mass, low-power photon detectors in testing

Result of the Week

Z-ray vision

Jim Pivarski

Z bosons are identified by the particles that they decay into (μ+ and μ− in this case). Then, the Z bosons are used to study the collision that made them.

All of the matter and energy of our everyday experience is made of only five basic particles: electrons, up and down quarks, gluons to glue the quarks together and photons, which are particles of light. This is just a corner of the particle landscape as we currently know it: including these five, 29 different types of fundamental particles and antiparticles are routinely produced in high-energy collisions. Some of the others are antimatter, some immediately decay,

What is this talk about?

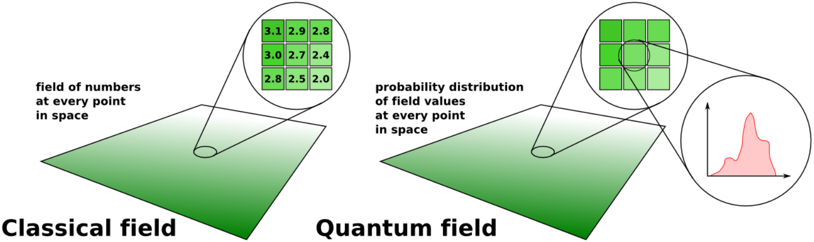
The most difficult thing to explain is the significance of the Higgs boson

- the "origin of mass" story neglects the fact that most mass (protons, dark matter) is not due to the Higgs mechanism
- an explanation of electroweak symmetry breaking requires a more sophisticated audience

In this talk, I'll explain why the Higgs mechanism is important, drawing on your background in intro quantum and intermediate E&M

Cartoon of quantum field theory

Imagine a space-filling field, like the electric field, but instead of having a set of numbers (a vector) at each point in space, we have an amplitude function (whose square is a probability distribution) at each point



- This picture combines the field concept from E&M with the indeterminacy of quantum mechanics
- It provides our current best-understanding of particles and forces

Schrödinger equation for field value ϕ at a space-time point $(t, \vec{x})$:

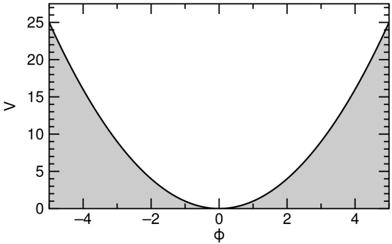
$$i\underbrace{\sqrt{\left(\frac{\partial \Psi}{\partial t}\right)^2 - \nabla^2\Psi}}_{\text{propagation}} = \Bigg(\underbrace{-\frac{1}{2}\frac{\partial^2}{\partial \phi^2}}_{\text{kinetic energy}} + \underbrace{V(\phi)}_{\text{potential energy}}\Bigg)\Psi(\phi; t, \vec{x})$$

where Ψ is the amplitude function over field value ϕ

Particles in quantum field theory

Parabolic potential: $V(\phi) = \dfrac{1}{2}m^2\phi^2$

It costs energy to make field



Solve by separating ϕ dependence from space-time dependence:

$$\Psi(\phi; t, \vec{x}) = \psi(\phi)\varphi(t, \vec{x})$$

$$\frac{i}{\varphi(t, \vec{x})}\sqrt{\left(\frac{\partial \varphi}{\partial t}\right)^2 - \nabla^2\varphi} = -\frac{1}{2\psi(\phi)}\left(\frac{\partial^2}{\partial \phi^2} - m^2\phi^2\psi(\phi)\right) = \text{a constant } M$$

(continued...)

$$\frac{i}{\varphi(t,\vec{x})}\sqrt{\left(\frac{\partial\varphi}{\partial t}\right)^2-\nabla^2\varphi}=-\frac{1}{2\psi(\phi)}\left(\frac{\partial^2}{\partial\phi^2}-m^2\phi^2\psi(\phi)\right)=\text{a constant } M$$

The left-hand side is solved by plane waves:

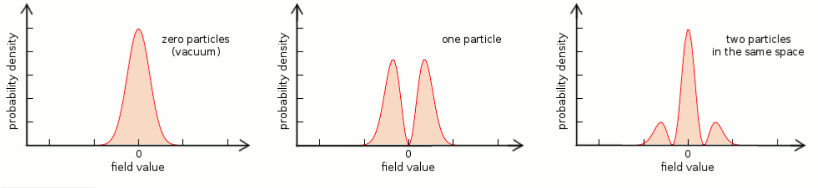
$$\varphi(t,\vec{x})=\text{constant}\times\exp(iEt+i\vec{p}\cdot\vec{x})\text{ with }\sqrt{E^2-|\vec{p}|^2}=M$$

The right-hand side is a hard equation to satisfy:

$$\psi(\phi)=\text{constant}\times\exp(-\tfrac{1}{2}m\phi^2)H_n(\sqrt{m}\phi)$$

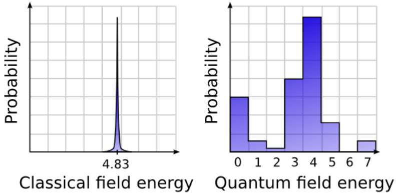
where H_n are Hermite polynomials and $M=(n+\frac{1}{2})m$ for integers $n\geq 0$.

This is why particles are particulate: the rest energy of a field is quantized into a zero-particle solution, a one-particle solution, etc.

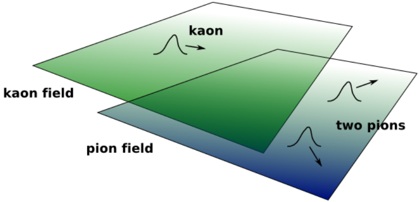


Quantum field theory is both more constrained and less constrained than classical field theory:

- the rest energy is constrained to be a multiple of an integer
- but solutions can superimpose

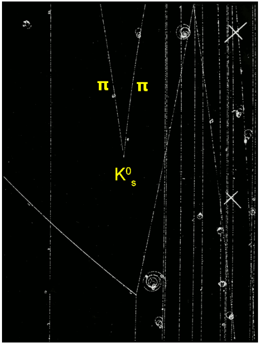


It explains why energy comes in chunks called particles, and it does so in a framework that allows particles to be created and destroyed



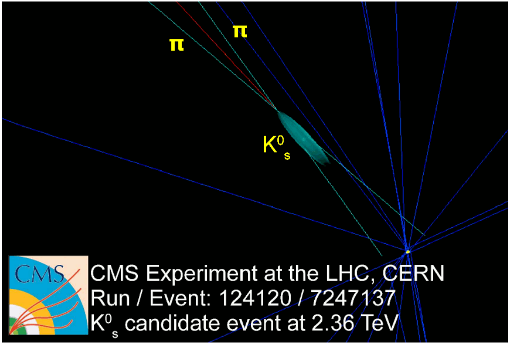
For example, when a kaon decays into two pions, an excitation of the kaon field is transferred to two excitations of the pion field because the kaon field is coupled to the pion field by a $(c\,\phi_K\phi_\pi)$ term in the potential

Bubble chamber photo



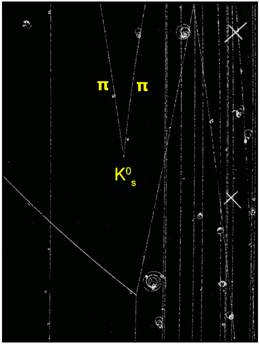
proton beam (upward) on liquid containing protons (stationary)

Reconstructed LHC event



incoming proton beams are perpendicular to this projection, collide at a point and outgoing particles radiate in all directions

Bubble chamber photo



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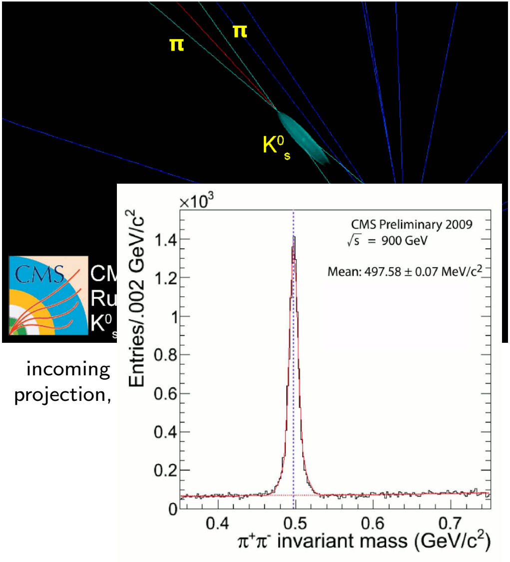


incoming
projection,

$$\sqrt{E^2 - |\vec{p}|^2} = \text{ that constant } M$$

Forces are a consequence of symmetry

If we want a model's Lagrangian (kinetic energy minus potential energy) to be independent of the complex phase of its fields,

$$\phi(t,\vec{x}) \to e^{i\alpha(t,\vec{x})}\phi(t,\vec{x})$$

then we must add another field $A(t,\vec{x})$ to enforce this symmetry

- $\phi(t,\vec{x})$ is the field of any charged particle (e.g. electrons)
- the invariance $\alpha(t,\vec{x})$ is "gauge freedom" from E&M
- and $A(t,\vec{x})$ is the electromagnetic field (a.k.a. photons)

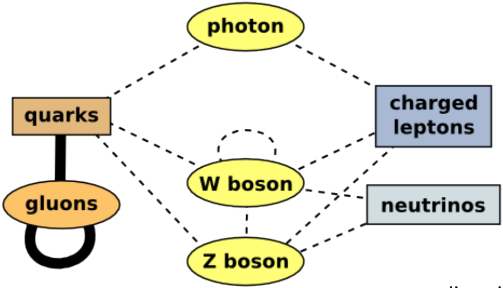
But the photon field cannot have a mass term $\frac{1}{2}{m_\gamma}^2|A|^2$, since that would violate the symmetry

1940/50's: Quantum field theory with phase symmetry *implies* the existence of electromagnetic forces with no photon mass. Light *must* be. Q.E.D.

The Standard Model (except for Higgs)

All known forces except gravity can be described as a single quantum field theory with a (somewhat more complicated) symmetry principle

electromagnetic	photon	massless
strong nuclear holds protons together	gluons (8 kinds)	massless
weak nuclear slow radioactive decays	W^+, W^-, Z	$m_{W^\pm} = 80.40 \pm 0.02$ GeV $m_Z = 91.188 \pm 0.002$ GeV



lines indicate couplings

The Problem

The symmetry principle explains the existence of all of the forces— photon, gluons, $W^{\pm}$ and Z— in one nice package

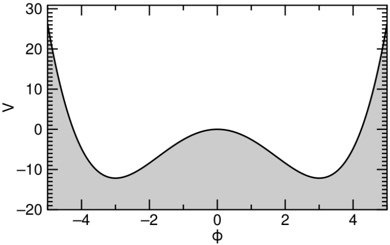
But $W^{\pm}$ and Z are not massless; they violate the symmetry principle!

The Englert-Brout-Higgs-Guralnik-Hagen-Kibble field

1964: Consider adding a field ϕ_H with the following potential:

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

where μ^2 is *negative.*



The ground state solution is peaked at one of the minima, where $\phi_H = \sqrt{-\mu^2/\lambda} = \nu \approx \frac{1}{\sqrt{246\text{ GeV}}}$, rather than at $\phi_H = 0$

- Space would be filled field values near ν: the Higgs condensate
- The particle potentials we observe are perturbations around ν, not the potentials in the fundamental theory
- The Higgs field itself has an approximately parabolic potential around ν: the Higgs boson

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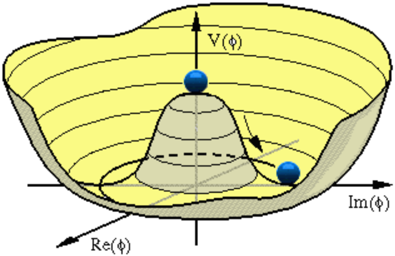

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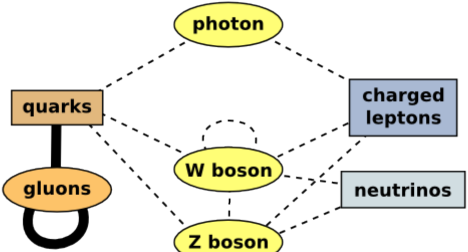
Generating effective masses

fundamental theory	effective theory (expansion around $\phi_H = \nu$)
no explicit W or Z mass terms	
symmetry generates forces	



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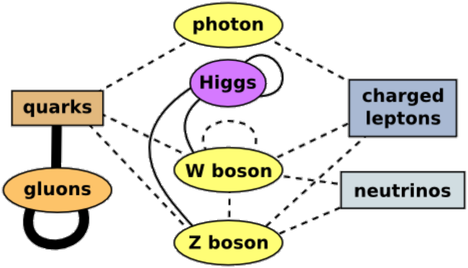
symmetry generates forces	
Higgs-W and Higgs-Z interactions	look like W and Z mass terms



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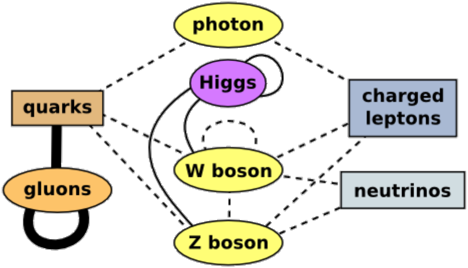
Higgs-W and Higgs-Z interactions e.g. coupling term $ig\phi_W\phi_H$	look like W and Z mass terms becomes $(g\nu)^2|\phi_W|^2$ at $\phi_H = \nu$



Generating effective masses

fundamental theory	effective theory (expansion around $\phi_H = \nu$)
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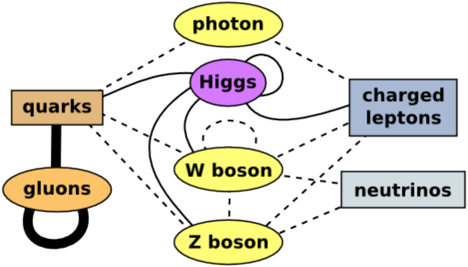
symmetry generates forces	
Higgs-W and Higgs-Z interactions e.g. coupling term $ig\phi_W\phi_H$	look like W and Z mass terms becomes $(g\nu)^2\|\phi_W\|^2$ at $\phi_H = \nu$
Higgs interacts with charged leptons and quarks	also look like mass terms



Introducing the Higgs field makes the Standard Model a consistent theory

But is it true?

Standard Model was formulated around 1972–1976 and has been tested ever since. Example of precision:

	experiment	theory
m_W	80.40 ± 0.02 GeV	80.39 ± 0.02 GeV
m_Z	91.188 ± 0.002 GeV	91.187 ± 0.002 GeV

The only part that hasn't been observed is the Higgs boson, the one-particle excitation of the Higgs field around $\phi_H = \nu$

Popular Mechanics, April 1978

30-mile 'donut' to spin out atomic secrets

World's mightiest atomic accelerator, so huge it will span the border between two European countries, may unlock deep mysteries of the universe—and unleash virtually unlimited supplies of vital electric power.

by Hans Fantel

It will be so big you can see it in its entirety only by looking down from a mountaintop or airplane. A circular tube with a mind-boggling circumference of 30 miles, it's the largest machine ever conceived. It's still in the planning stage, but represents the most ambitious concept yet for building an atomic particle accelerator—popularly known as an atom smasher.

Why the incredible size? Such devices need a long path to accelerate their subatomic particle "bullets" up to the tremendous velocities required to penetrate and break down matter at the atomic level—just as a jumbo jet needs a long runway to get up to flying speed. The longer the path, the greater the acceleration that can be achieved.

Is such a giant merely a paper dream? By no means. The technology for building it exists—the final design, financing, location of construction site, and certain political considerations must still be worked out. But atom smashers have been getting bigger and more powerful all the time—a sign of even more ambitious projects to come. The famed Brookhaven accelerator, half a mile in circumference, is already dwarfed by a similar one with a four-mile girth at Fermilab in Batavia, Ill., currently the biggest atom smasher in the world. And now being planned is another, more modern installation for Brookhaven that will outpower them all—at least until that 30-mile monster goes into operation.

The newly proposed superaccelerator still has no official name. It's just called the VBA—short for Very Big Accelerator, which is an understatement if there ever was one. While the primary objective of the VBA will be to explore the properties of the atom and physical laws governing the universe, its findings may also lead to new ways of mass-producing nuclear energy in safe, economical, commercially usable quantities. If so, such discoveries might well provide virtually unlimited supplies of urgently needed electric power.

Since the VBA will be such a gigantic and costly undertaking, it is unlikely that any one nation could afford to foot the bill by itself. Thus the United States, the Soviet Union and several European countries are expected to chip in, making the project a truly international effort.

While a site has not been definitely chosen, the VBA will probably be built near Geneva, Switzerland (see map at left). To accommodate its immense size—and also to symbolize its international character—it may lie partially in France, straddling the French-Swiss border.

Actually, you won't be able to see the VBA as a whole at all since most of it will be constructed underground, with above-ground service and laboratory facilities stationed along its length. If all goes according to plan, the giant machine will be switched on in the year 2000—a fitting technological milestone to mark the turn of the century.

New twists in technology

All atomic accelerators are basically similar in principle and share the same purpose: to produce an intense beam of subatomic particles, such as protons, that will penetrate

Map below shows one possible site for proposed new 30-mile-long atomic accelerator. If plan is adopted, the mammoth ring would span the boundary between France and Switzerland near Lake Geneva. It would be a joint international venture, built and operated by several countries.

Plan for new Brookhaven accelerator has twin tubes whirling counterrotating proton beams. Future 30-mile atom smasher depicted at left may use same arrangement.

Like an entry ramp to a superhighway, this 500-foot-long linear (straight-line) accelerator at Fermilab pushes protons up to velocities needed to enter high-speed lanes in main circular accelerator. Such "preboosters" will be used in proposed 30-mile atom smasher shown above.

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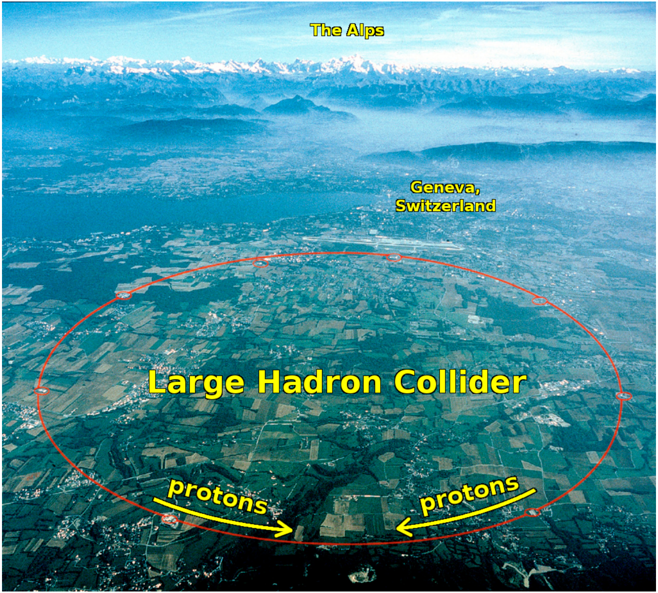
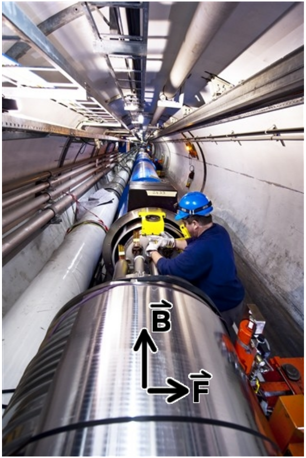
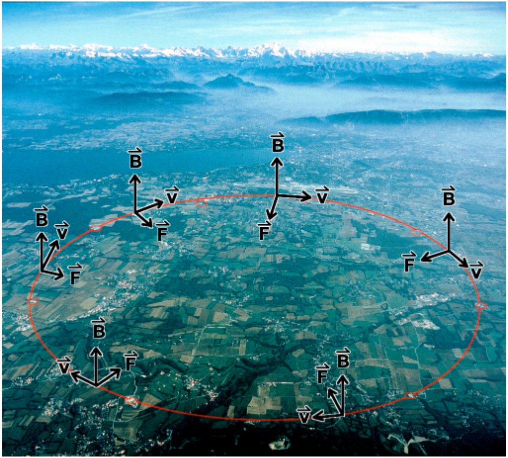
APRIL 1978 97

Searching for the Higgs boson

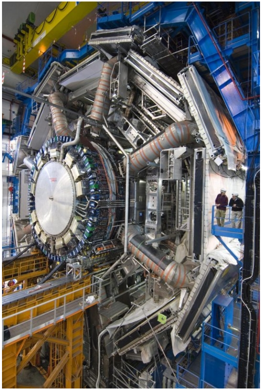


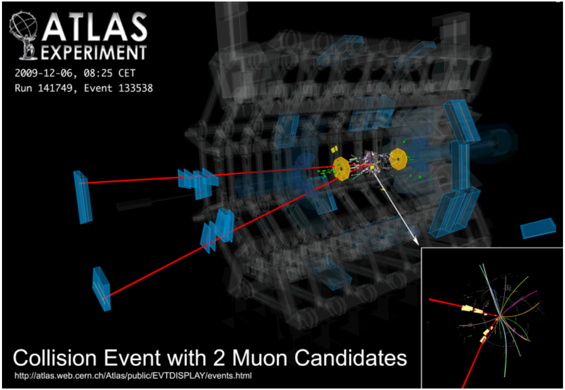




- Protons confined by strong magnetic field ($\vec{F} = q\vec{v} \times \vec{B}$)
  - ultra-high current solenoids made from superconducting wires
- Protons accelerated by oscillating electric fields
  - timed such that bunches of protons enter the field only when they're pointing the right way

ATLAS on the Swiss side of the ring





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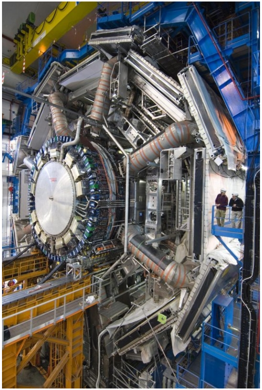
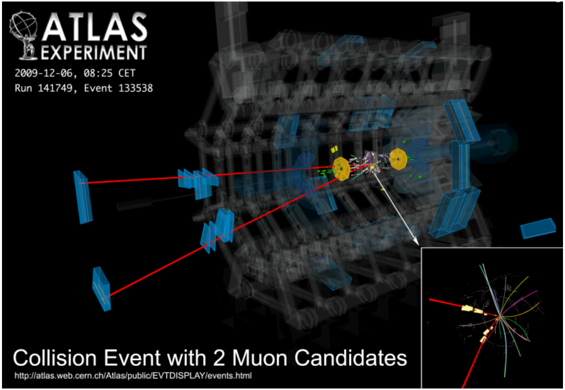
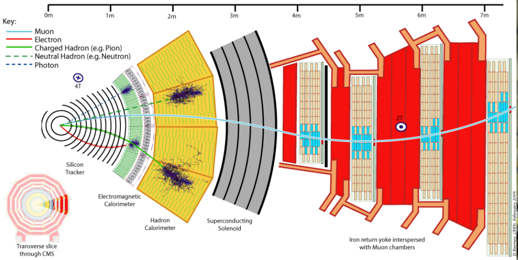
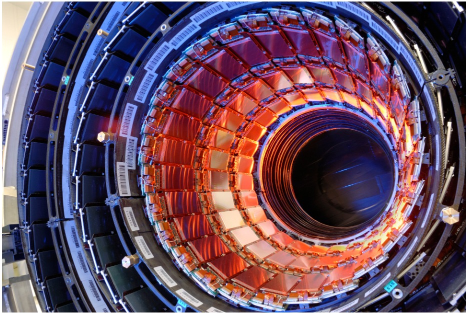
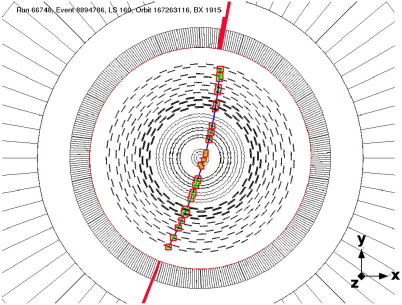




CMS on the French side of the ring

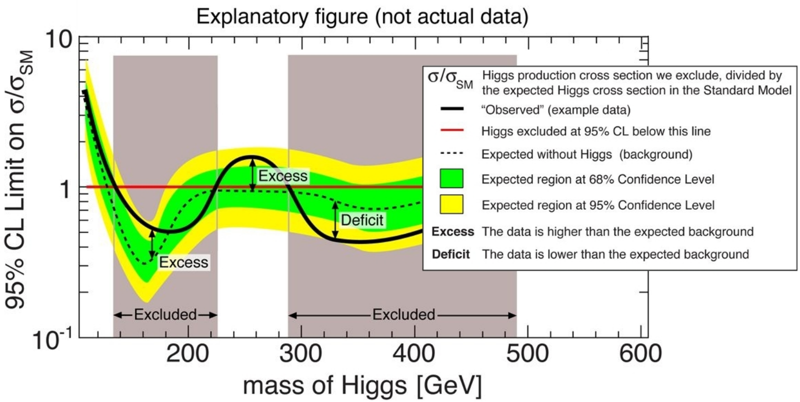




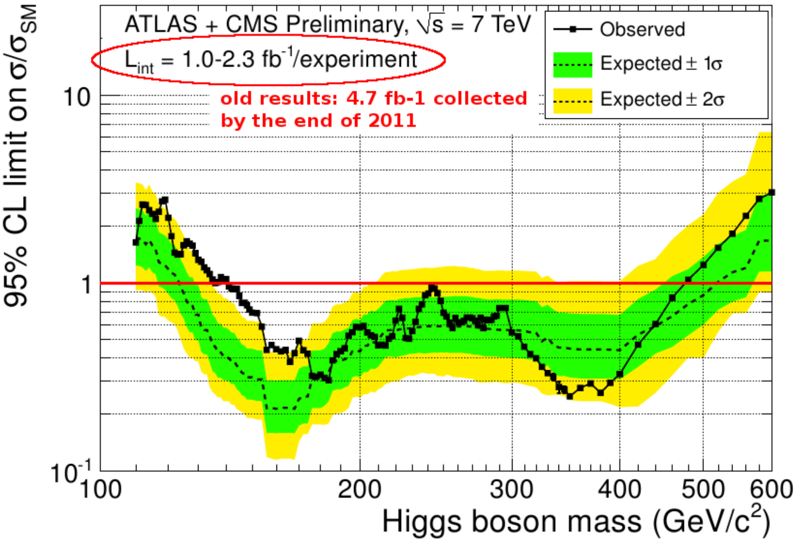


What we know from Higgs searches

- Dozens of different decay signatures, most are hard to distinguish from other Standard Model processes
- To get enough statistical significance, all of these analyses are combined into a single upper-limit plot
- Also (sometimes) combine experiments



ATLAS + CMS combination, not full dataset



Standard Model Higgs boson with 140 < mass < 480 GeV does not exist

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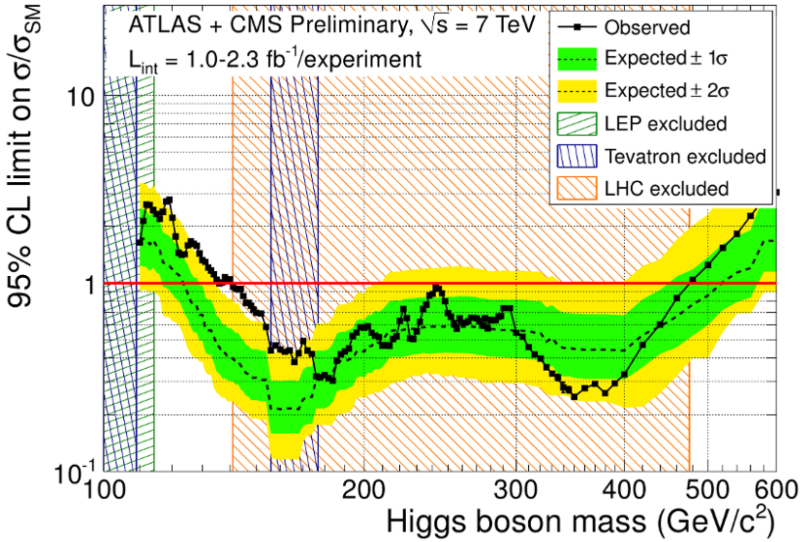

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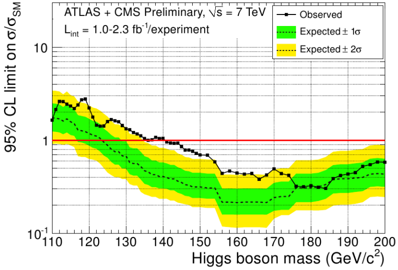
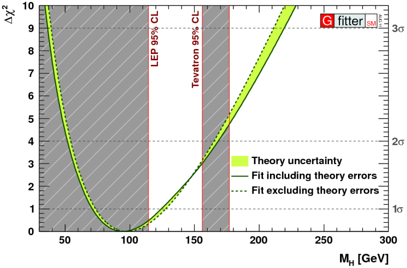
The surviving mass region

LHC direct-search exclusion zoomed into 100–200 GeV



Limits inferred from precision Standard Model measurements (W, Z, top masses, etc.)



- A low-mass Higgs (114–140 GeV) has *not* been excluded
- This region is also considered most likely by precision measurements
- The slight excess of 110–175 GeV events is not statistically compelling, but it is an excess

The Standard Model Higgs, if it exists, has been cornered to a narrow range of masses (finally, after at least 30 years of searches!)

ATLAS and CMS will make their complete 2011 datasets public on Dec 13 at 8 AM EST; four-experiment combination (CDF, D∅, ATLAS, CMS) should be ready by the end of March 2012

LHC expected to produce 2–3 times as much data in 2012 as in 2011—should be enough to fully discover or refute the Standard Model Higgs

- If discovered, its properties are key to understanding the large gap between Standard Model particle masses and the Planck quantum gravity scale (the Hierarchy Problem)
- If not discovered, the cornerstone of the Standard Model will have fallen and we'll *know* that there's some exotic physics happening
  - maybe non-standard Higgses that are hidden somehow
  - maybe something completely different

Conclusions

It will be an exciting year.

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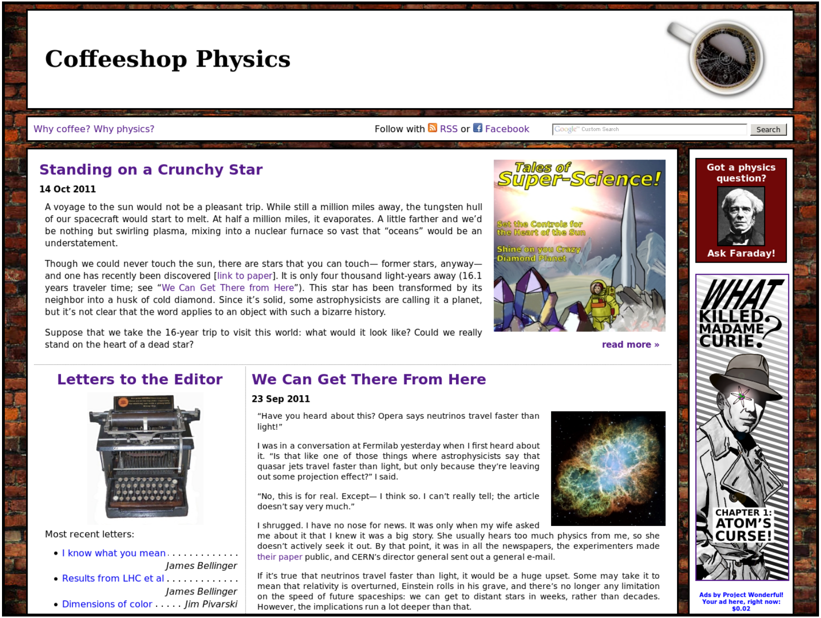

Coffeeshop Physics

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Standing on a Crunchy Star

14 Oct 2011

A voyage to the sun would not be a pleasant trip. While still a million miles away, the tungsten hull of our spacecraft would start to melt. At half a million miles, it evaporates. A little farther and we'd be nothing but swirling plasma, mixing into a nuclear furnace so vast that "oceans" would be an understatement.

Though we could never touch the sun, there are stars that you can touch— former stars, anyway— and one has recently been discovered [link to paper]. It is only four thousand light-years away (16.1 years traveler time; see "We Can Get There from Here"). This star has been transformed by its neighbor into a husk of cold diamond. Since it's solid, some astrophysicists are calling it a planet, but it's not clear that the word applies to an object with such a bizarre history.

Suppose that we take the 16-year trip to visit this world: what would it look like? Could we really stand on the heart of a dead star?

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Letters to the Editor

Most recent letters:

- I know what you mean . . . . *James Bellinger*
- Results from LHC et al . . . . *James Bellinger*
- Dimensions of color . . . . . *Jim Pivarski*

We Can Get There From Here

23 Sep 2011

"Have you heard about this? Opera says neutrinos travel faster than light!"

I was in a conversation at Fermilab yesterday when I first heard about it. "Is that like one of those things where astrophysicists say that quasar jets travel faster than light, but only because they're leaving out some projection effect?" I said.

"No, this is for real. Except— I think so. I can't really tell; the article doesn't say very much."

I shrugged. I have no nose for news. It was only when my wife asked me about it that I knew it was a big story. She usually hears too much physics from me, so she doesn't actively seek it out. By that point, it was in all the newspapers, the experimenters made their paper public, and CERN's director general sent out a general e-mail.

If it's true that neutrinos travel faster than light, it would be a huge upset. Some may take it to mean that relativity is overturned, Einstein rolls in his grave, and there's no longer any limitation on the speed of future spaceships: we can get to distant stars in weeks, rather than decades. However, the implications run a lot deeper than that.

Got a physics question?
Ask Faraday!

WHAT KILLED MADAME CURIE?
CHAPTER 1: ATOM'S CURSE!

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