A superconducting proton collider

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July 31, 2008

What is particle physics?

Particle physics is the ultimate *reductionist* science and seeks to answer just two questions:

What are the fundamental building blocks (particles) in nature?

and

What is the nature of the forces acting between the particles?

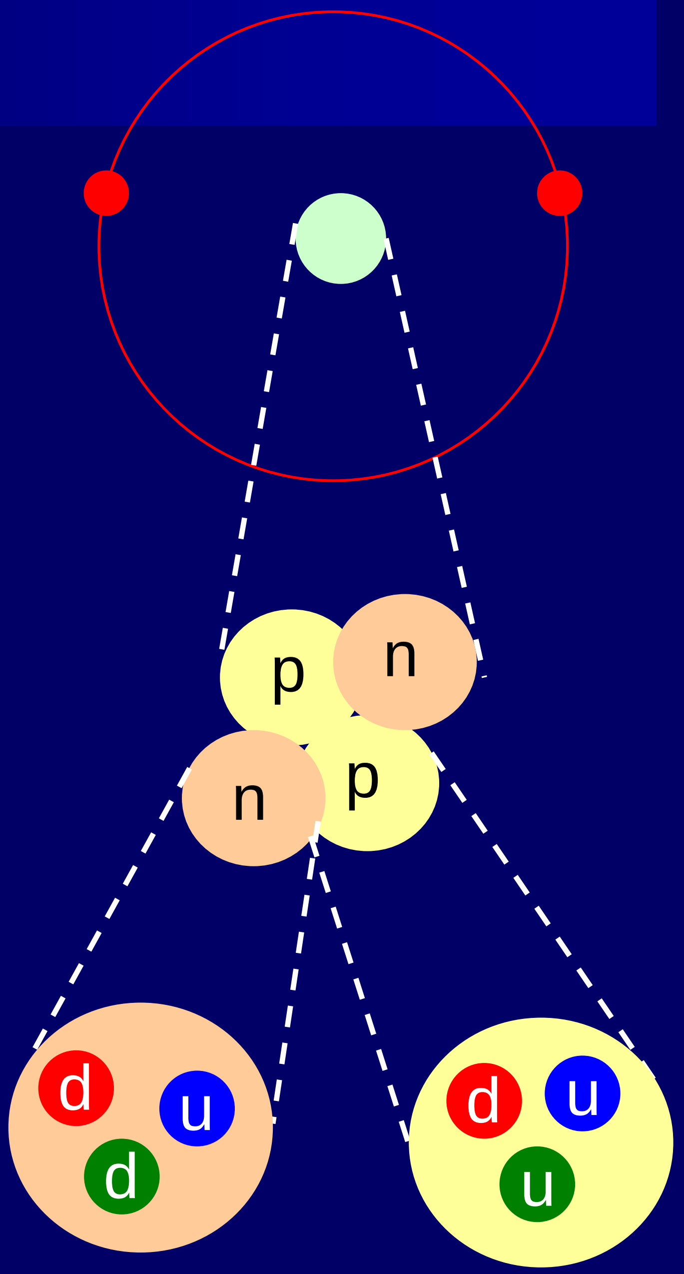
First I will tell you what we know, starting with the fundamental particles…

Inside a helium atom

Atoms are made up of a nucleus surrounded by electrons. Neutral helium has 2 electrons.

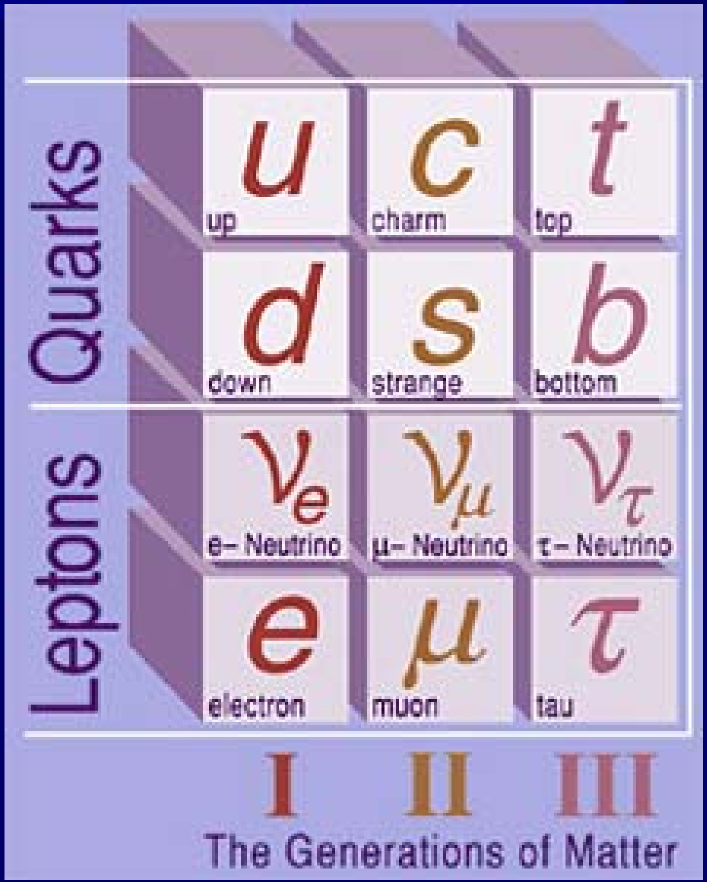
The nucleus contains protons and neutrons. (Helium has 2 protons).

The protons and neutrons are composed of *up* and *down* quarks.



The Fundamental Particles

Although only 2 quarks (*up* and *down*) are needed to make up normal matter, there are two other pairs for a total of 6. (Nobody knows why this is so.)



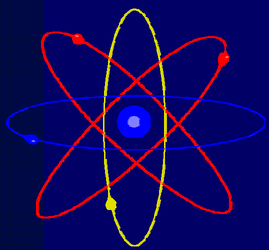
This 3 family structure extends to particles like electrons. There are 2 particles like the electron plus a set of 3 neutrinos

The 2nd and 3rd generation particles have more mass and are "unstable" which means they decay into 1st generation particles. This happens in a tiny fraction of a second.

Fundamental forces

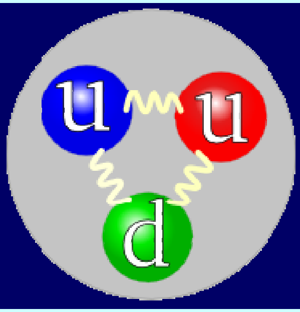
The second part of particle physics is figuring out the interactions (forces between particles). We know of 4:

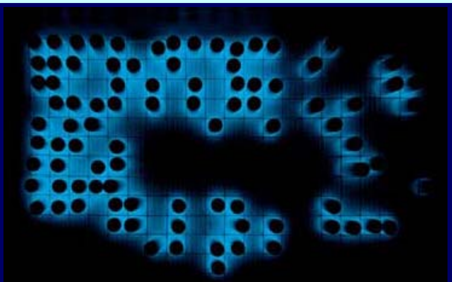
Gravity – important for big objects and long distances (keeps Earth from escaping the Sun); negligible in particle physics



Electromagnetism – causes opposite charges to attract (keeps negative electrons from escaping the positive nucleus). Causes lightning and compass behavior.

Strong force – causes quarks to attract, keeps quarks inside proton and neutron and keeps protons and neutrons inside the nucleus.

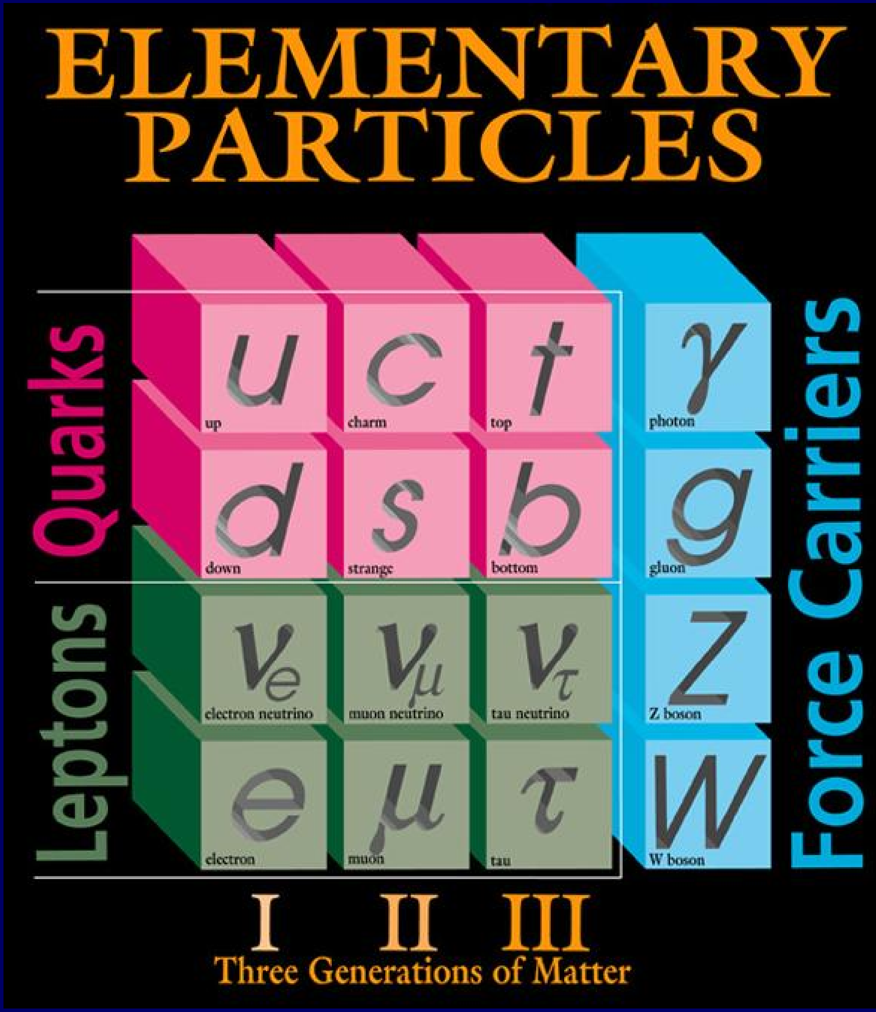




Weak force – Causes radioactive decay; for example of the radon inside your basement.

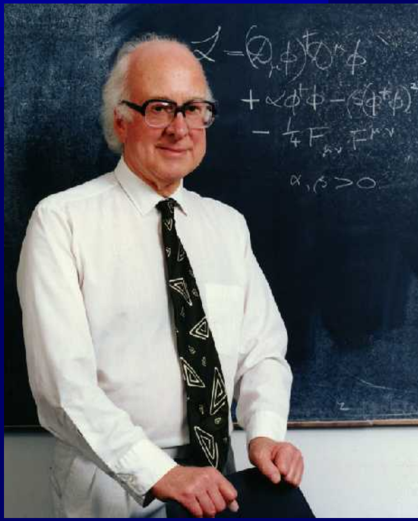
The *Standard Model* of particle physics

- Matter is made up of 3 families of quarks & leptons
- In quantum physics there is a force particle (carrier) that communicates the force between particles.
- 3 forces with force carriers
  - Electromagnetism carried by photons
  - Weak force carried by W & Z
  - Strong force carried by gluons



All of these particles have been detected by particle physicists

The Higgs Particle



The Standard Model has been around for 40 years.

Only 1 particle of the Standard Model is left to be found. It is called the Higgs particle (after Peter Higgs who came up with the idea in 1964).

The Standard Model supposes that a Higgs field exists throughout the universe and is what gives fundamental particles their mass.

There should also be a Higgs particle associated with the Higgs field. This is one of the things we are looking for.

If the Higgs particle (or something like it) does not exist the whole Standard Model will fall apart.

How does Higgs give mass to particles?

In the normal world, more mass corresponds to more protons and neutrons.

2 gallons of water is twice as massive as 1 gallon of water because there are twice as many water molecules so twice as many protons and neutrons.

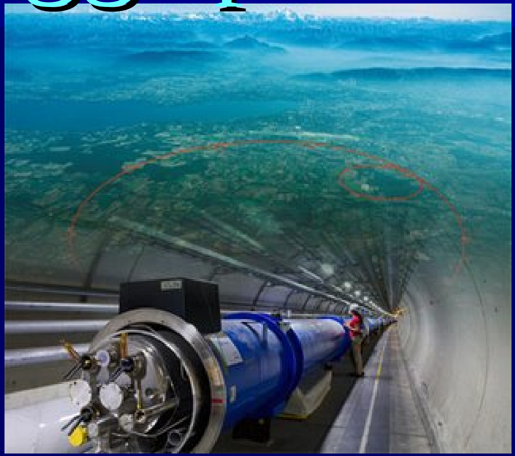
But quarks aren't made up of anything else. So where do they get their mass from?

Each quark is connected to the Higgs field. The stronger the connection, the greater the mass. So really the mass is just the strength of the connection to the Higgs field.

This mass behaves just like normal mass.

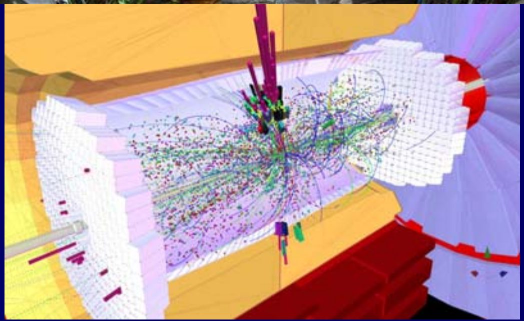
How do we find the Higgs particle?

- Need a high energy accelerator to produce the interesting particles



- Need detectors to record what happens when the particles decay

- Need to separate the interesting stuff from the background



The particle accelerator

The Higgs particle is unstable and so it decays into other particles immediately after being created. This means we need to make our own Higgs particles.

The most famous formula in physics gives us the prescription.

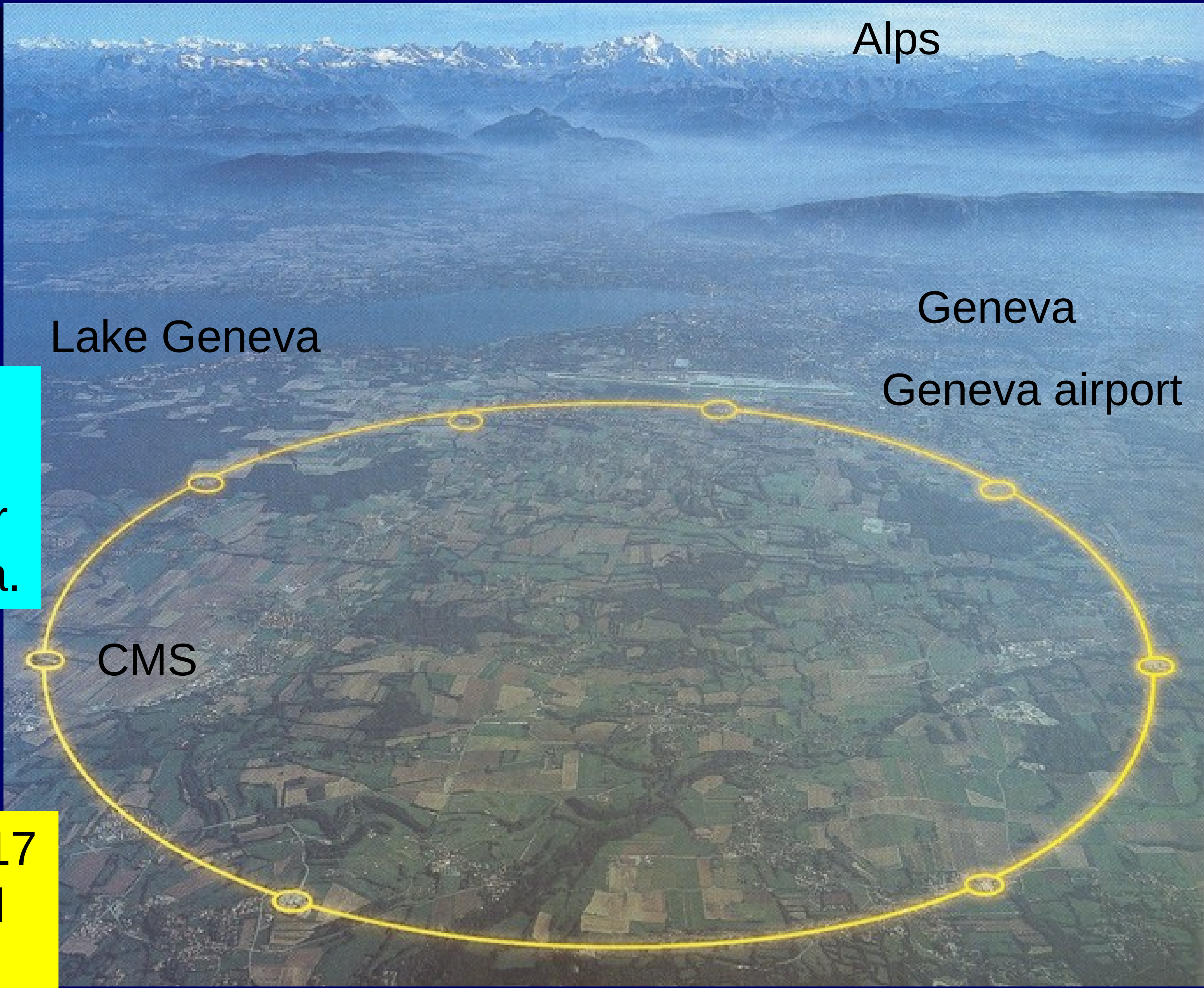
$E=mc^2$ tells us that mass and energy are equivalent.

An atomic bomb converts a small amount of mass into energy.

We do the opposite. With enough energy, you can create mass such as a Higgs particle.

The name of the accelerator is the Large Hadron Collider (LHC) and is located at CERN (European Center for Nuclear Research).

LHC



CERN is on the French-Swiss border near Geneva.

The LHC is 17 miles around and located 100-500 feet underground

How the LHC works

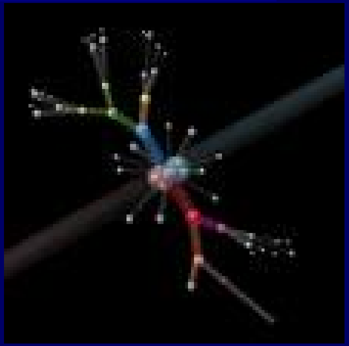
Accelerate protons to a very high speed (99.999999% of the speed of light)

The proton energy is 7000 times greater than at rest.

Natural tendency of moving particles is to move in a straight line.

Use powerful superconducting magnets to bend protons so they go in a circle. The reason the accelerator is so large is because we cannot make stronger magnets.

We actually accelerate protons in both directions and at 4 places we steer the protons into each other to collide.

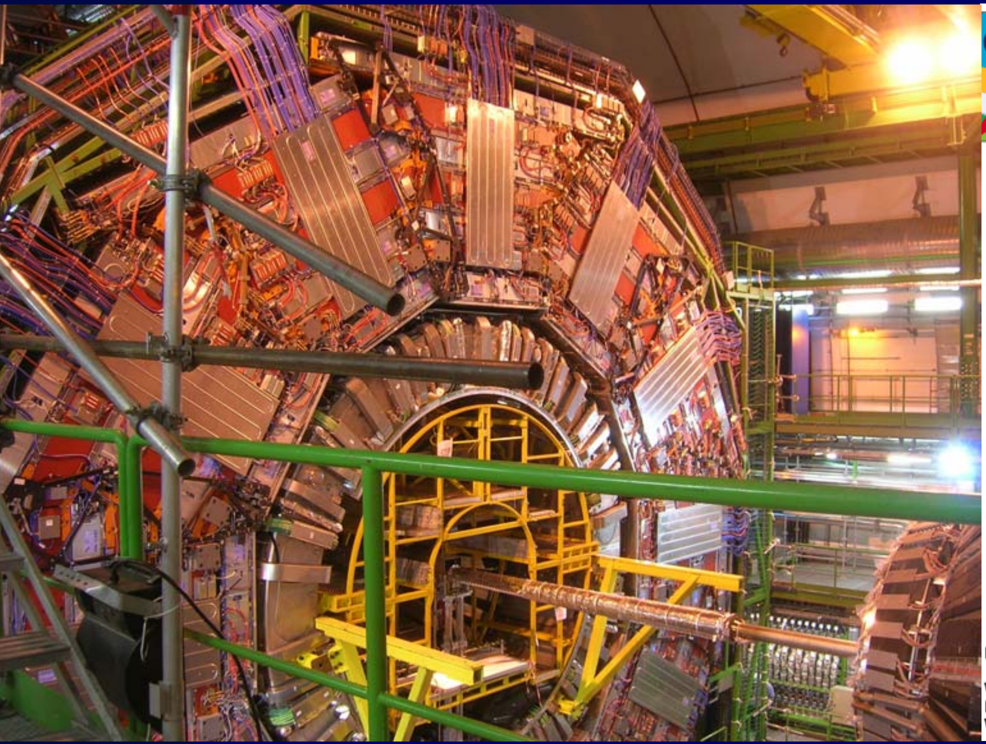


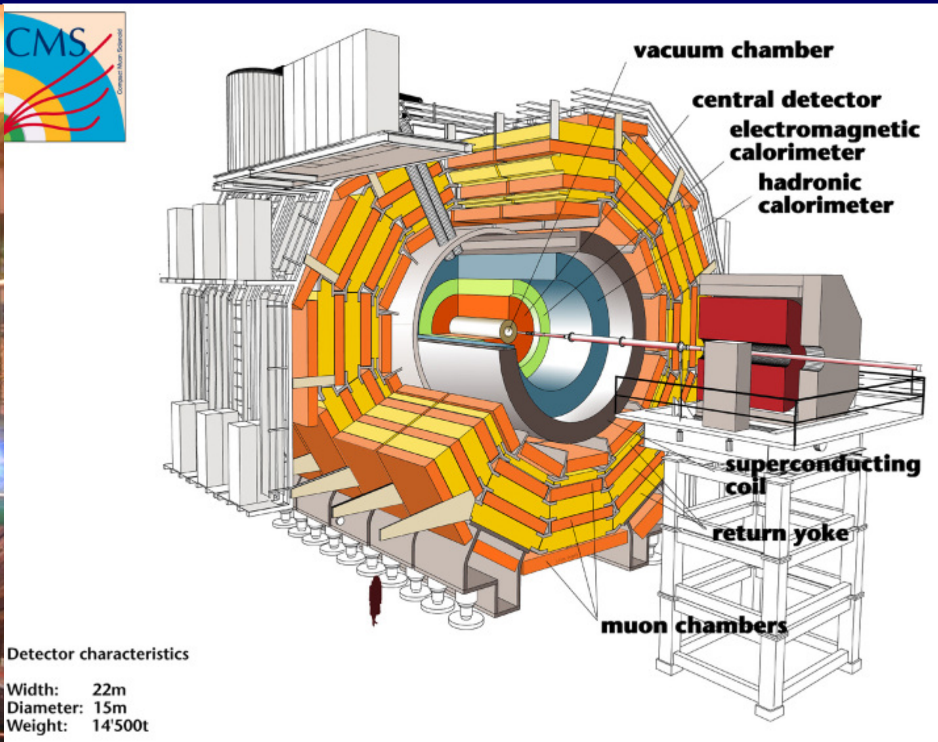
Detecting the particles

So we collide two protons at very high energy to create a Higgs particle. But the Higgs particle immediately decays into other particles.

We need to detect these particles to reconstruct what happened.

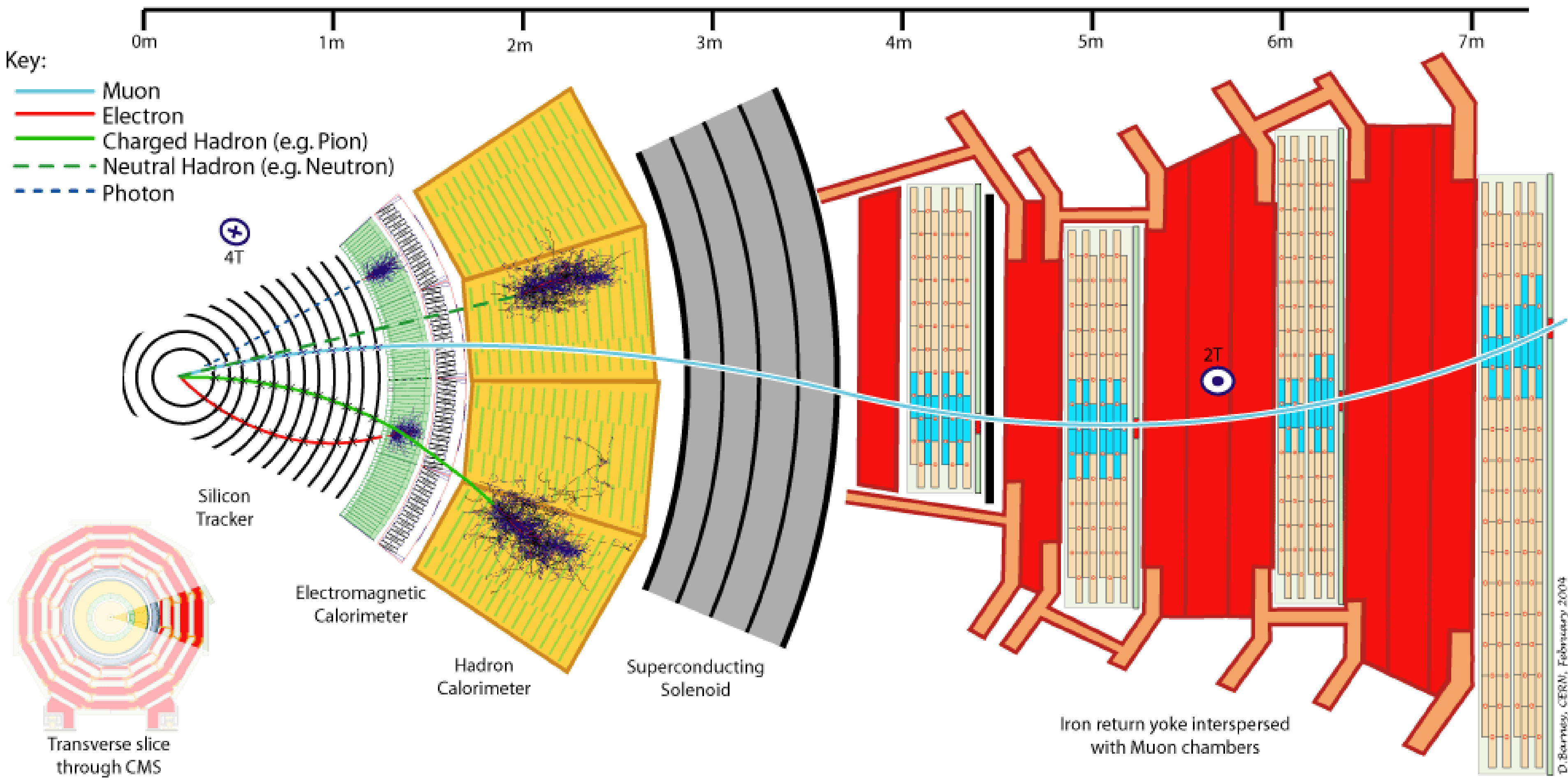
The CMS detector is in an excavated cavern 300 feet underground.

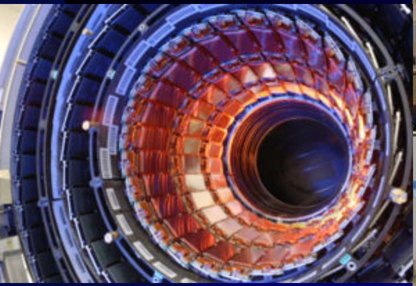


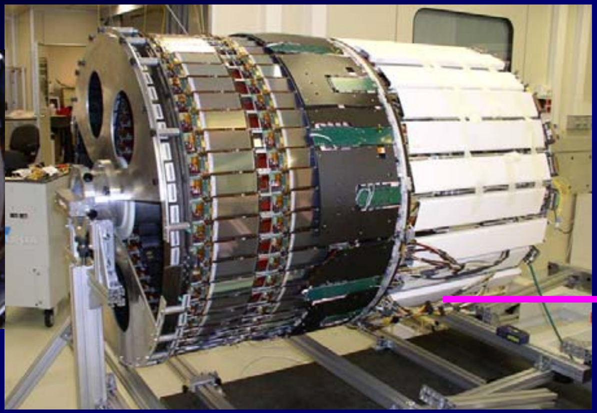


CMS Slice

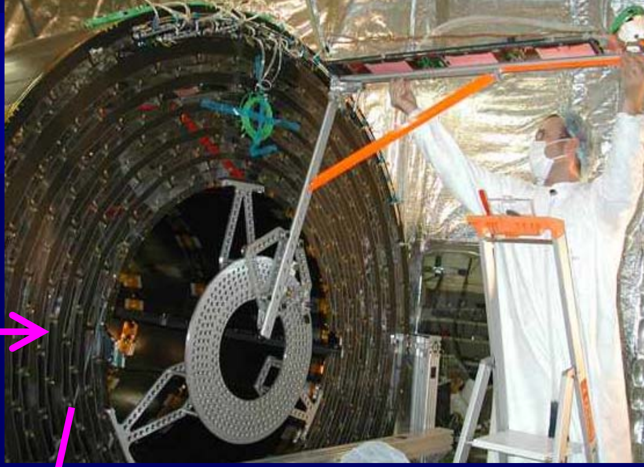
Different particles behave differently as they pass through the detector. This allows us to identify them and measure their energy.



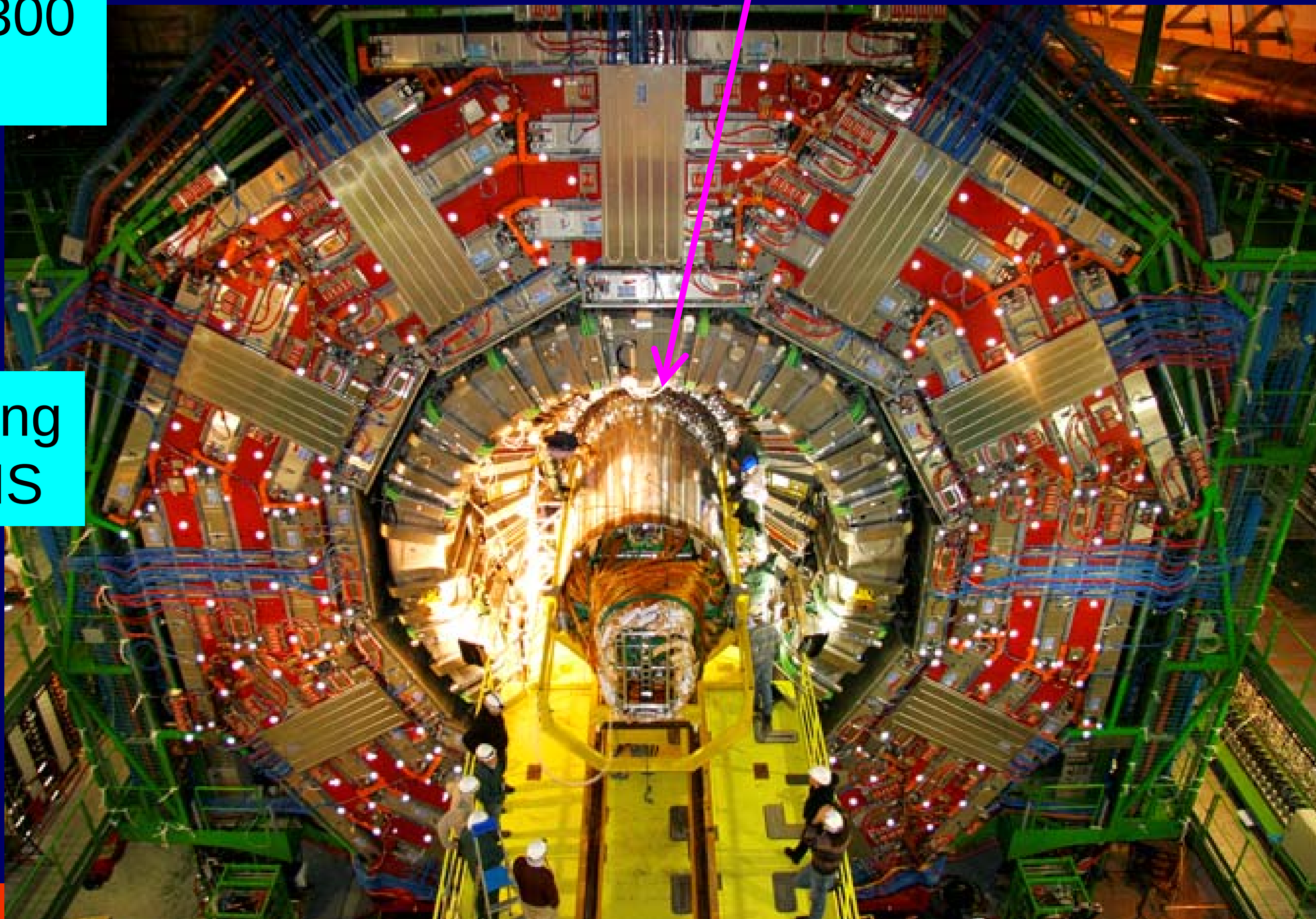




Goes inside



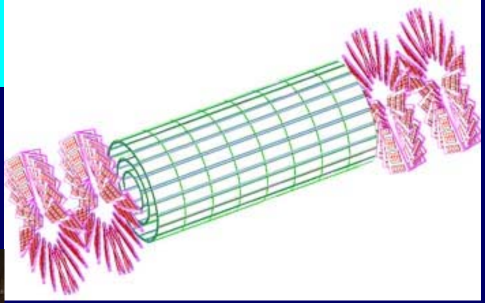
CMS tracker uses 2300 square feet of silicon

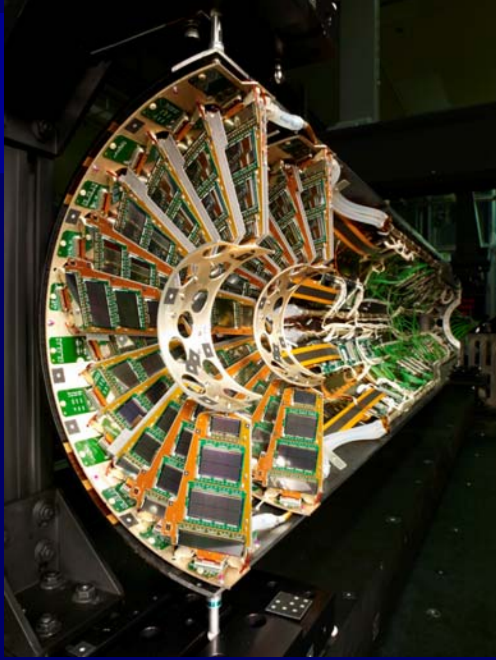


CMS tracker being inserted into CMS

CMS silicon pixel detector

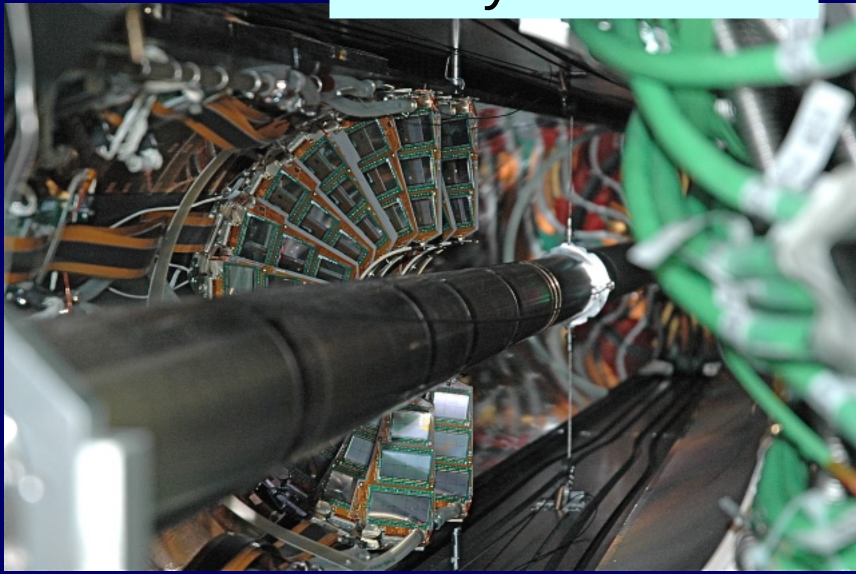
Smallest detector but the most channels. There are 65 million pixels, each 4/1000 of an inch by 6/1000 of an inch.





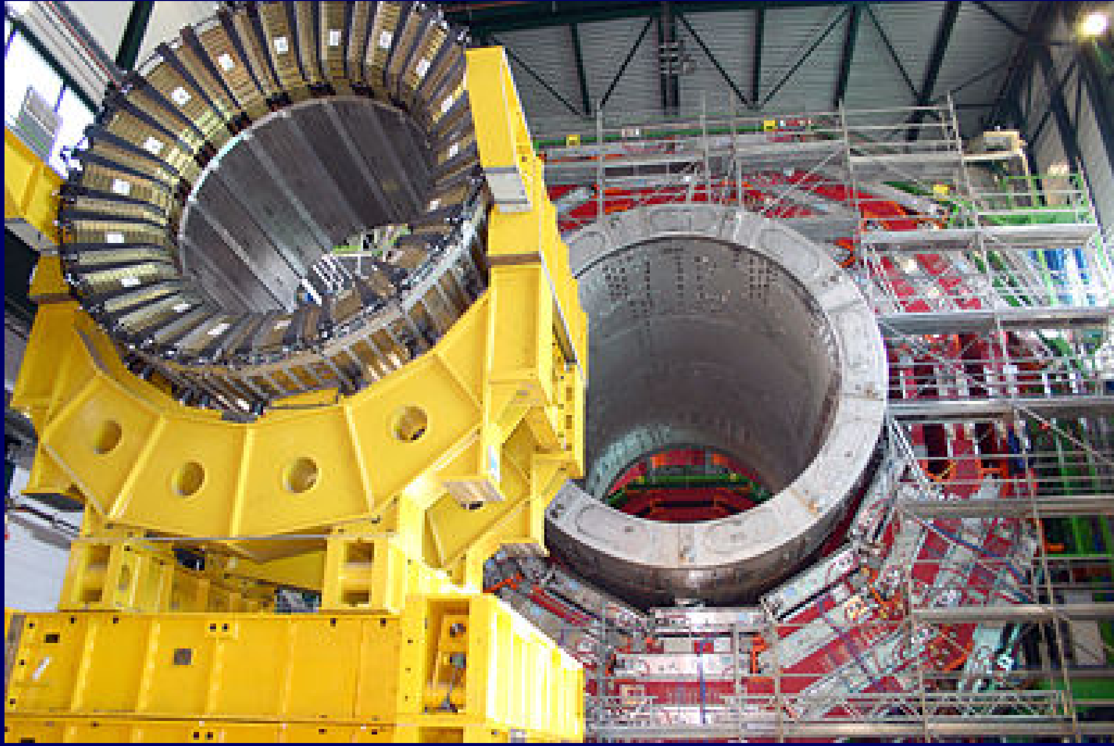
Last weeks insertion

Today's insertion

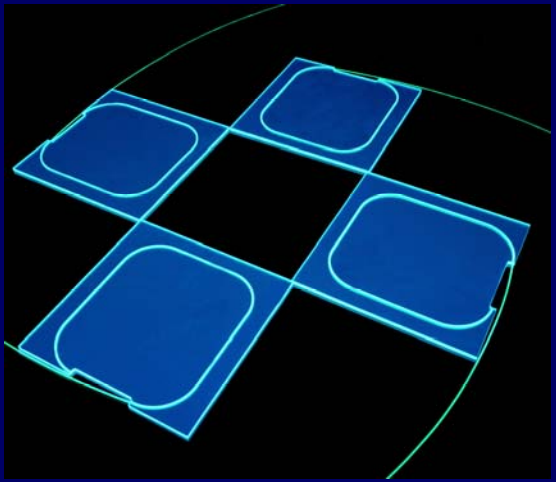


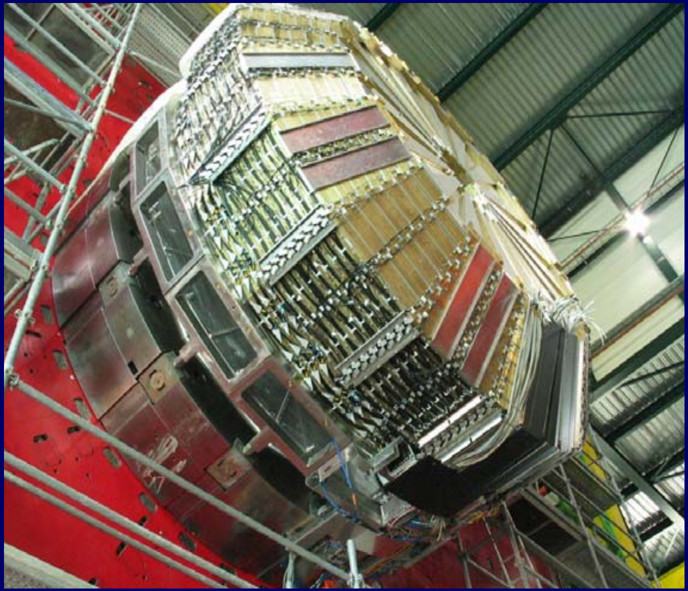
CMS HCAL

- Shown here ready to be inserted.
- Measures energy of particles.
- Brass absorber from Russian artillery shells is what the particles hit.



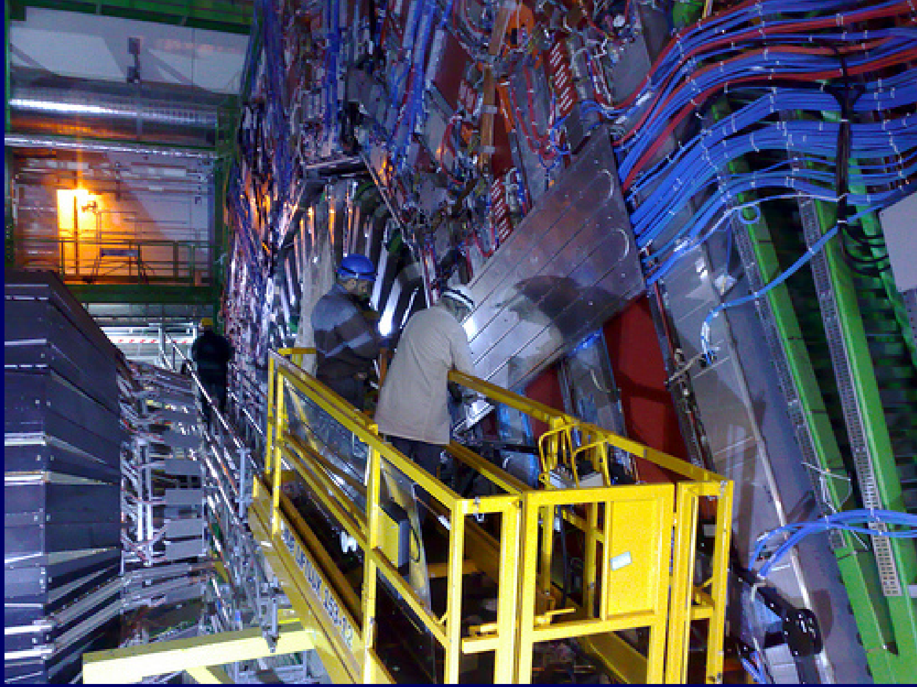
- Scintillating tiles with wavelength shifting fiber between the brass layers are used to measure the energy.

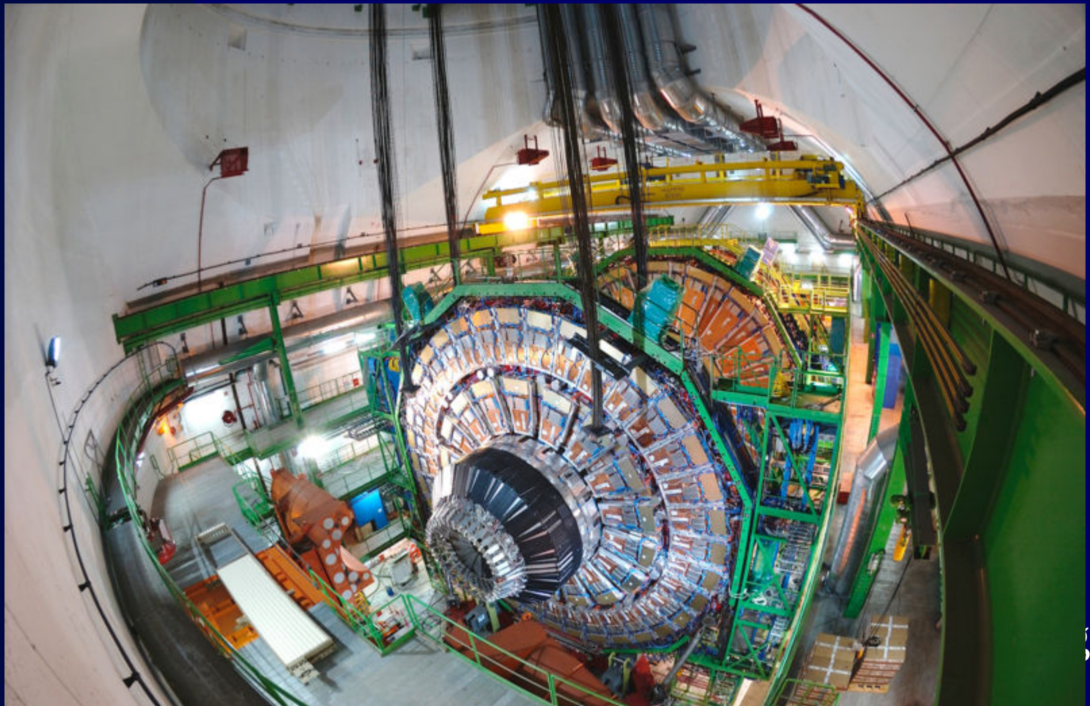


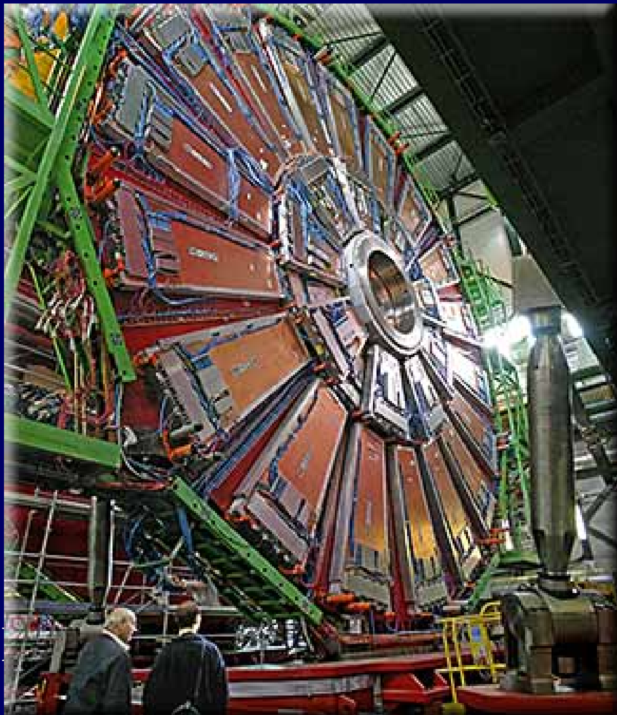


Muon detector

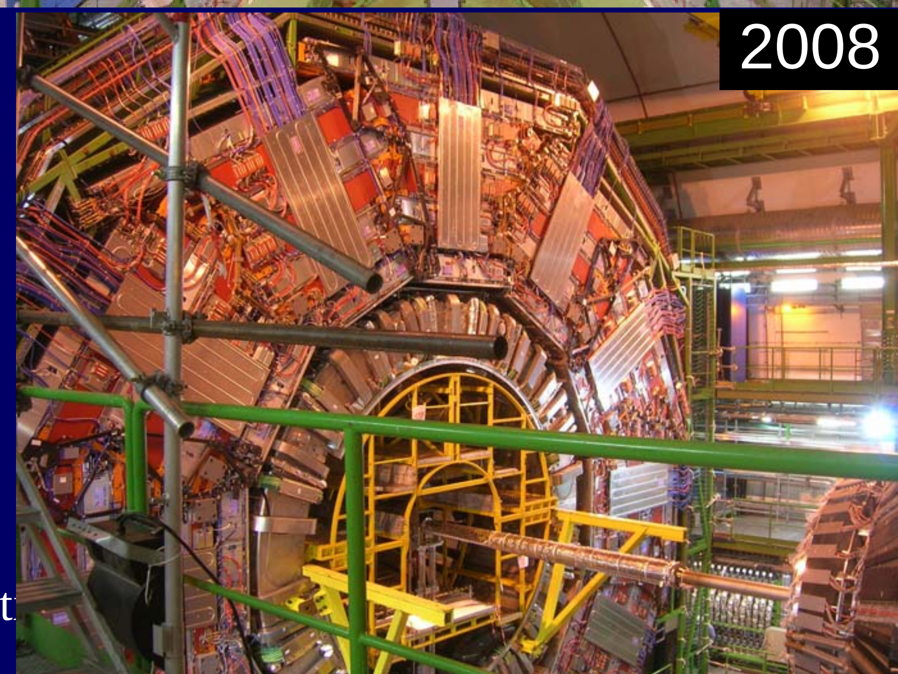
- Muons interact less than other charged particles
- Place detectors after lots of steel and whatever comes through is a muon
- We use 12000 tons of steel.







CMS assembly



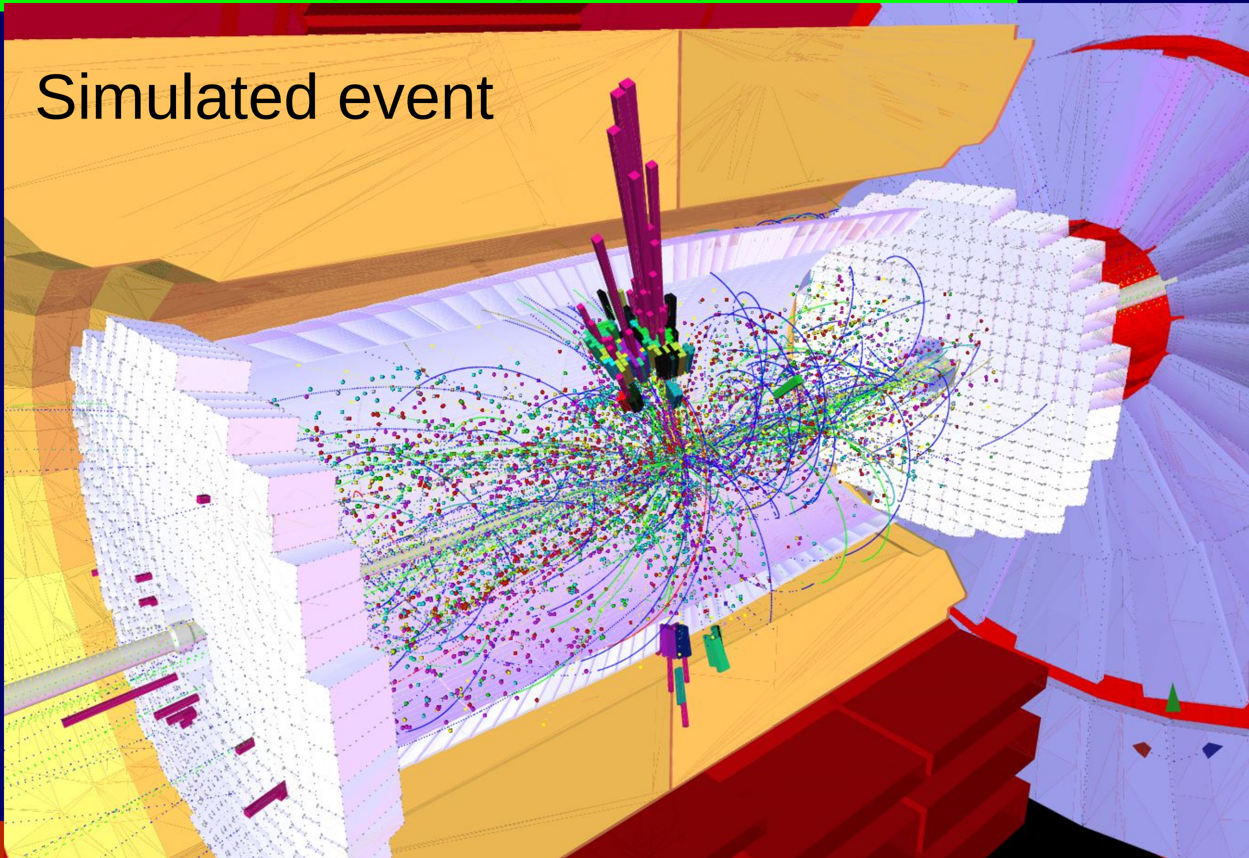
Last step: finding the Higgs

Protons collide 40 million times a second, generating 1 Megabyte of data each time. This is 40 Terabytes/second (40 disk drives per second)

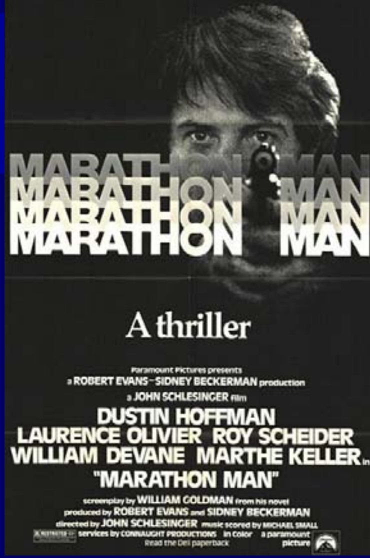
Only 1 in a trillion of these will have a Higgs particle we can find.

Some of the other 1 trillion events may *look* like a Higgs but are not (this is background). The challenge is separating the two.

We reject 99.9998% of events immediately and save the rest. This is about 10 Terabytes/day or 1 Petabyte/year. Thousands of computers around the world process the data.



Is it safe?



Recently the LHC received publicity regarding the safety of the Earth when the particles start colliding.

There was even a lawsuit filed to stop operation.

A safety study initially performed in 2003 was updated and released last month confirming that it is safe.

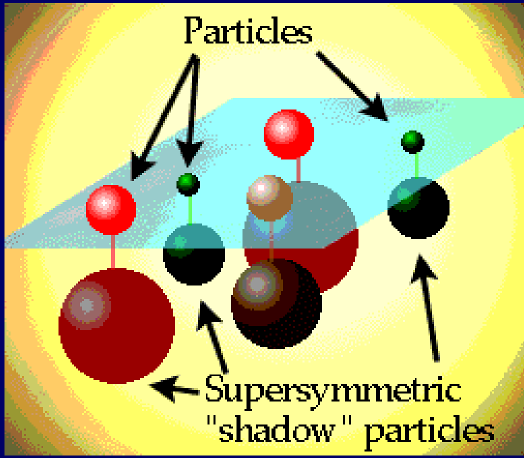
The universe has natural particle accelerators which create cosmic rays at *much* higher energy than the LHC can produce.

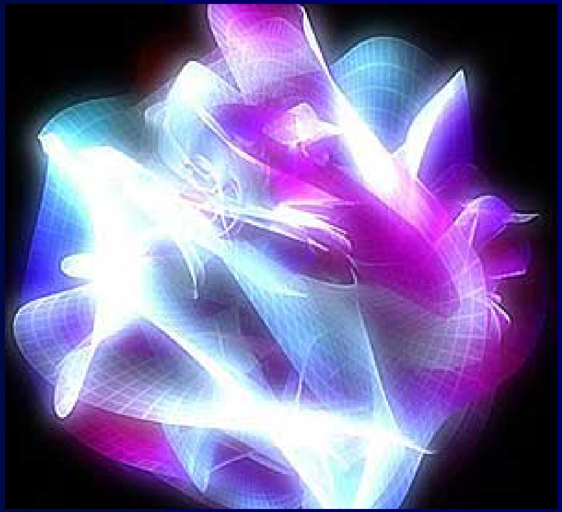
These cosmic rays have been hitting the Earth and other planets, stars, etc. for billions of years with no ill effects so there is no reason to expect problems from LHC operation.

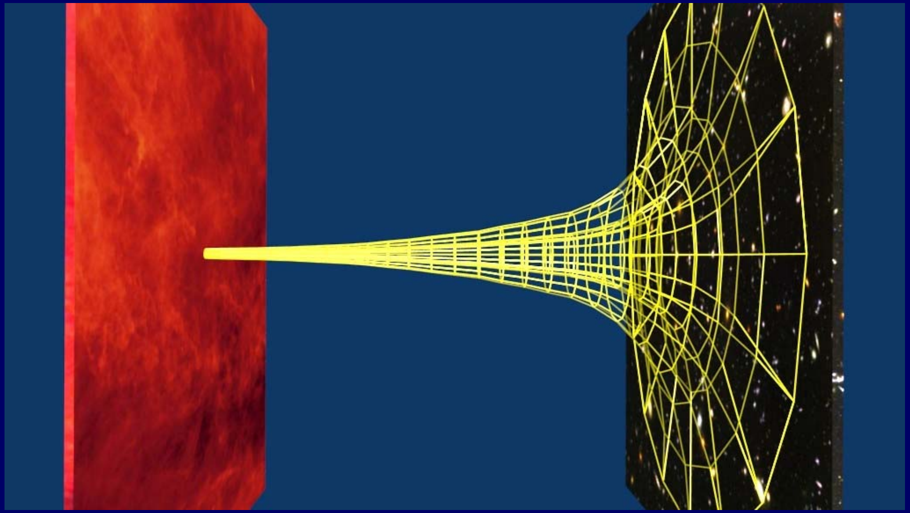
This also agrees with our understanding of the physics. Microscopic black holes created by the LHC would evaporate immediately.

What is beyond the Higgs?

- From other evidence, we know that there is a theory beyond what we understand so we will be looking for signs of that. This could be:
  - Supersymmetry
  - Warped extra dimensions
  - Extra particles
  - Signs of string theory







Connections to cosmology

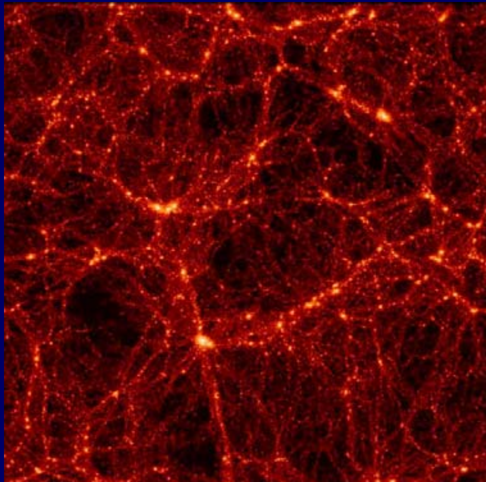
Particle physics seeks to find the fundamental theory of the universe as a goal in and of itself.

However, particle physics also has several direct connections to our understanding of the universe.

The LHC energy is like the universe just 1 picosecond (10^{-12} seconds) after the Big Bang when the universe was basketball sized. So we are really probing the origins of the universe.

Also, 95% of the universe is made up of *dark matter* & *dark energy*.

We might find the source of dark matter at the LHC if we find the right type of supersymmetry.



Particle physics should also be able to explain the dark energy but so far the calculations are way off.

Take home message

- After 15 years and several billion dollars, the program at the Large Hadron Collider will start this fall.
- What we learn at the LHC in the next few years will have a profound impact on our understanding of the fundamental theory of the universe including the origin of mass.
- We will be exploring an unknown energy range and so we will likely encounter some interesting surprises.