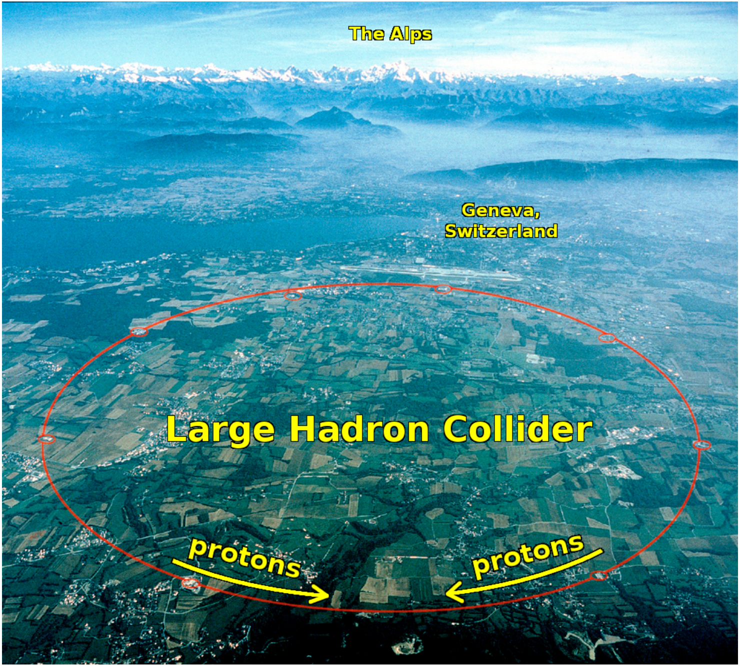
The Role of the Large Hadron Collider (LHC) in the Quest to Understand Matter

Jim Pivarski

Texas A&M University

and a member of the CMS Collaboration (experiment at the LHC)

25 February, 2009


The Alps
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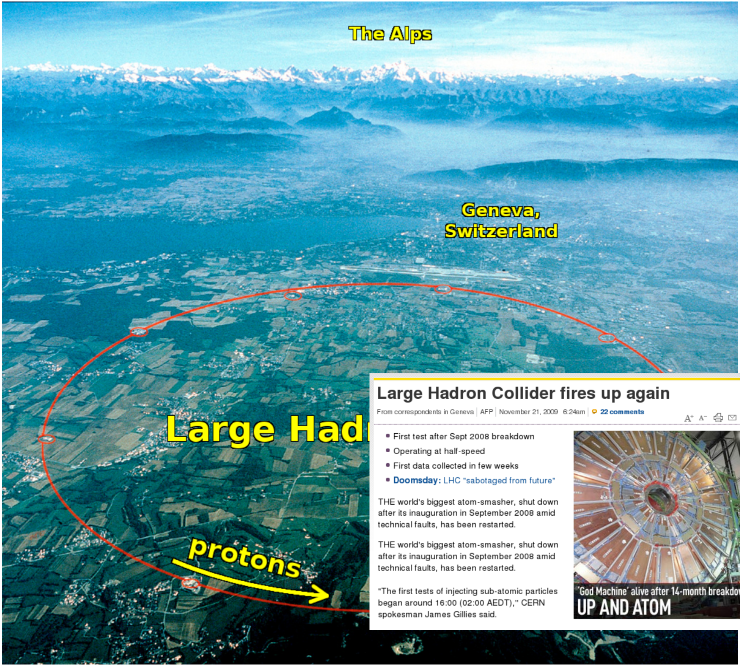
Large Hadron Collider
protons
protons



Large Hadron Collider fires up again

From correspondents in Geneva | AFP | November 21, 2009 6:24am | 22 comments

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- First test after Sept 2008 breakdown
- Operating at half-speed
- First data collected in few weeks
- **Doomsday:** LHC "sabotaged from future"

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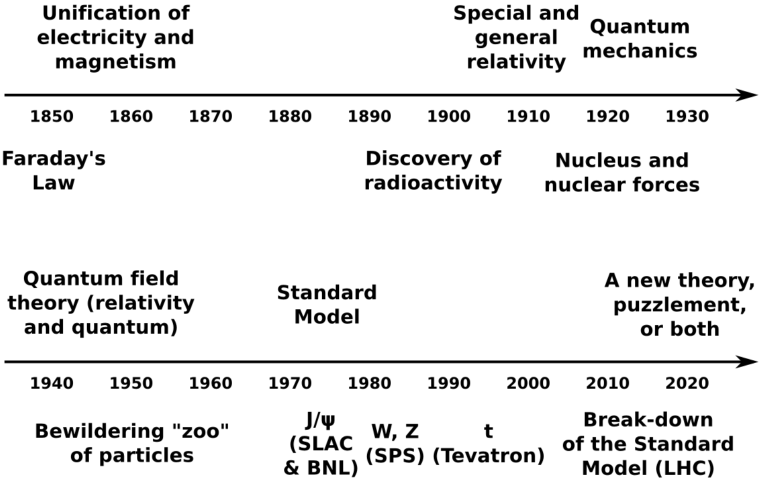
"The first tests of injecting sub-atomic particles began around 16:00 (02:00 AEDT)," CERN spokesman James Gillies said.

'God Machine' alive after 14-month breakdown
UP AND ATOM

What's the big deal?

- Highest-energy collisions ever made by humans in a laboratory
  - on December 18, 2009: 2.36 TeV
  - previous record: 1.96 TeV (Fermilab Tevatron, 1987–now)
  - sometime next month: 7 TeV
  - after 2011 upgrade: 14 TeV
- World's largest scientific experiment (not counting moon landing)
  - accelerators became too large for a single college campus in the mid-20^{th} century
  - this is the first that is too large for a single nation: the first "world's accelerator"
- Long-anticipated: plans began in the mid-1970's
- Why do we need such high-energy collisions?
  What can we learn from them?

The LHC in context



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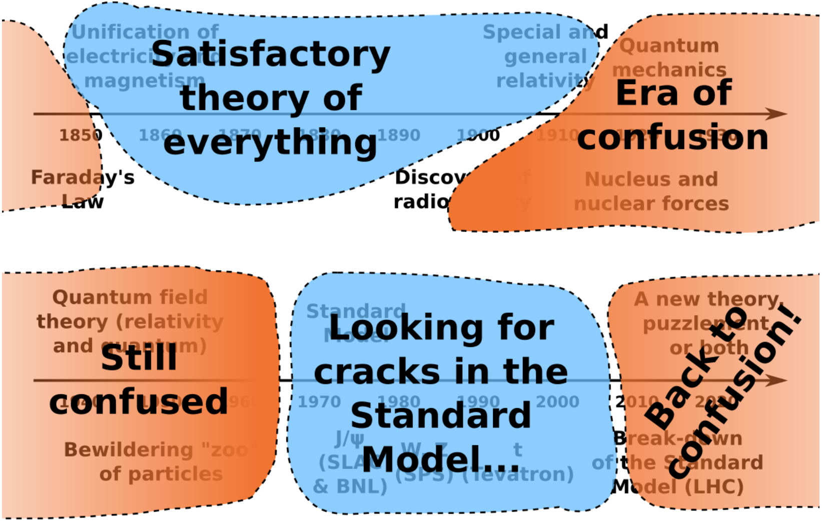

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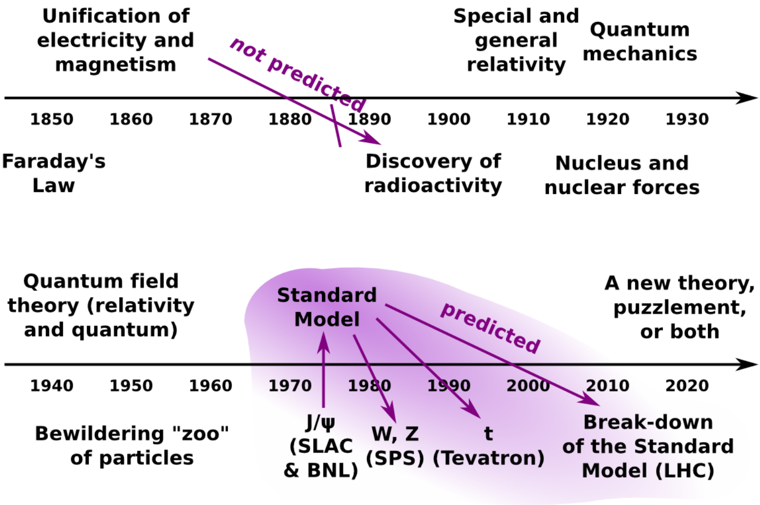
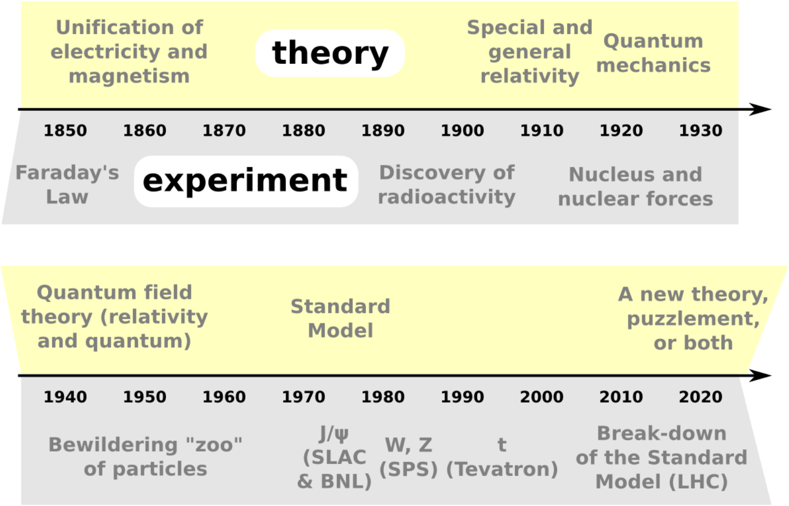


Color scheme for this talk

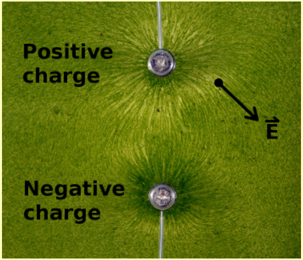


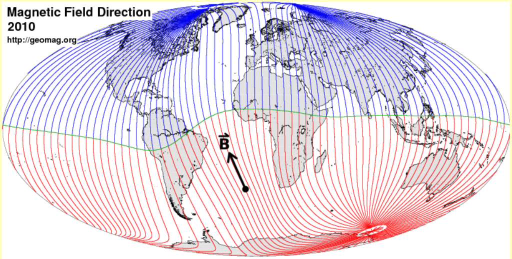
Electricity and magnetism

- Field concept: every point in space (and time) has associated with it an electric field $\vec{E}$ (a vector; three numbers) and magnetic field $\vec{B}$
- These numbers describe the local conditions at that position in terms of the force felt by a bit of matter with charge q, velocity v

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

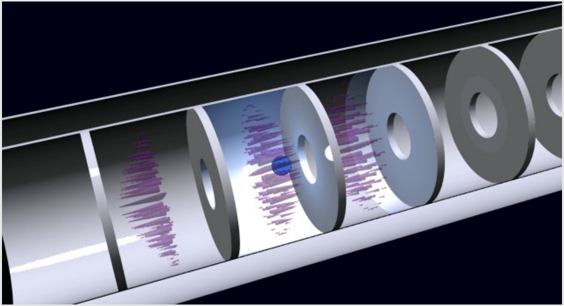
- The field obeys certain transformation rules when changing coordinate systems and is the solution to a set of equations





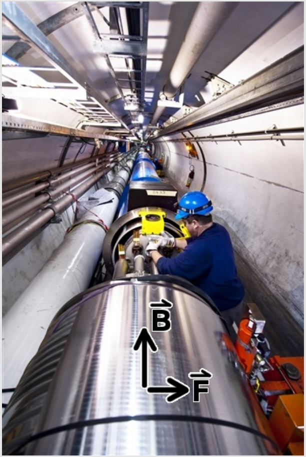
How the LHC accelerates protons

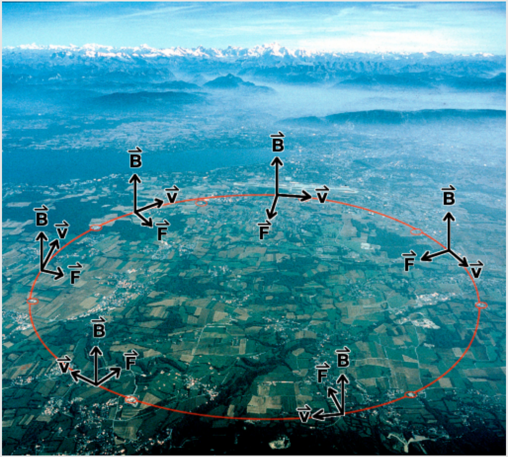
- A postively-charged proton feels a force $\vec{F} = q\vec{E}$ in a strong electric field $\vec{E}$ and undergoes acceleration $\vec{a} = \vec{F}/m$ ($m =$ proton mass)
- Technical challenge: creating strong fields $\vec{E}$
- Solution: strong *oscillating* fields can be produced with radar towers and piped into resonating cavities. A pulsed beam is timed to enter each cavity exactly when the field is pointing in the right direction to accelerate it, rather than decelerate it.



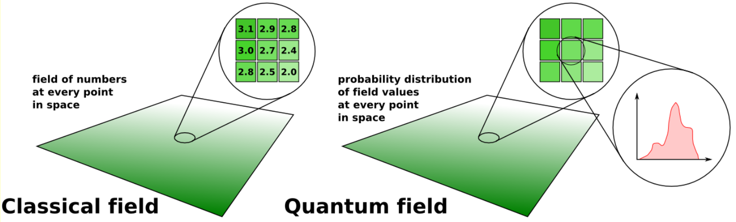
How the LHC contains proton beams

- Constant magnetic field $\vec{B}$ yields $\vec{F} = q\vec{v} \times \vec{B}$ ("right-hand rule")
- Challenge: strong $\vec{B}$. Solution: ultra-high current electromagnets made from superconducting wires (no losses due to resistance)

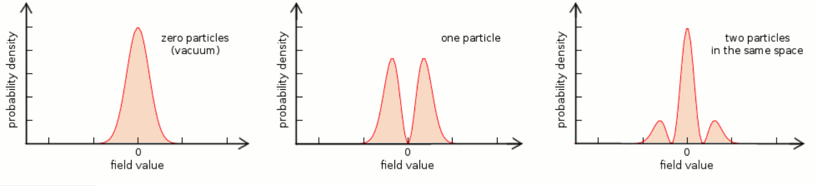




Quantum field theory



- No distinction between fields and matter: everything's a field
- Quantum field: *probability distribution* of values at each point in space-time, with correlations between neighboring points
- Consequence: energy of field configuration is *quantized* into integers— zero particles, one particle, two particles...



Quantum field theory

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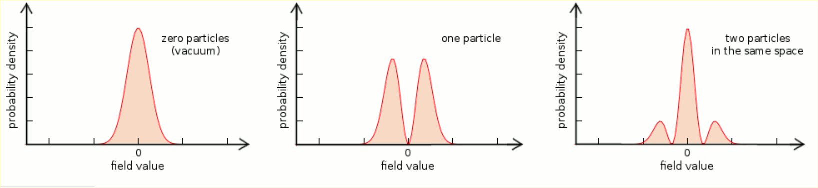

- What we call "empty space" is the minimum-energy fluctuation of the field; what we call "a particle" is the first excitation
- For each fundamental type of particle, there is a distinct field; what we call a photon is a single excitation of the photon field, an electron is an excitation of the electron field, etc.

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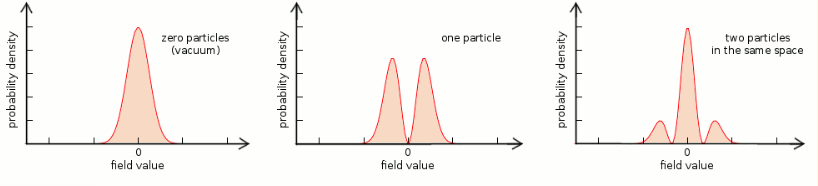

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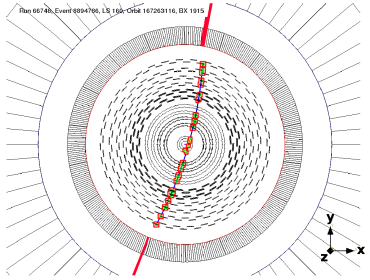
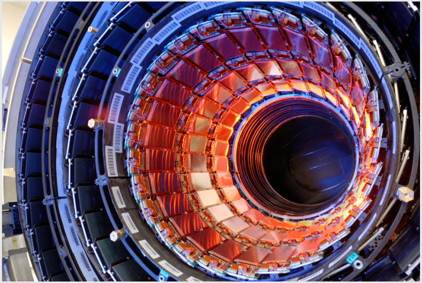
- Why quantized? $i\sqrt{-\left(\frac{\partial\Psi}{\partial x}\right)^2+\left(\frac{\partial\Psi}{\partial t}\right)^2}=\left(-\frac{1}{2}\frac{\partial^2}{\partial\phi^2}+m^2\phi^2\right)\Psi$ is a seperable equation where $|\Psi(\phi;x,t)|^2$ is the probability density of field values ϕ at space-time points x, t

Detecting individual particles at the LHC

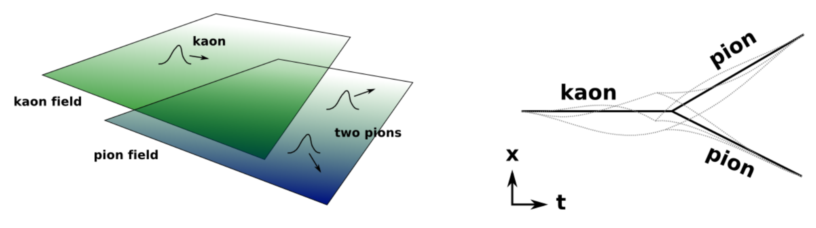
- A single high-energy charged particle pulls the electrons off of neutral atoms as it passes by; this released charge is collected onto wires and read into a computer
- Pattern of observed hits line up as a track, indicating the trajectory of the original high-energy particle
- Below: a muon from space passing through the CMS silicon tracker, with a strong magnetic field in the $\hat{z}$ direction (see the curvature?)





Creating and destroying particles

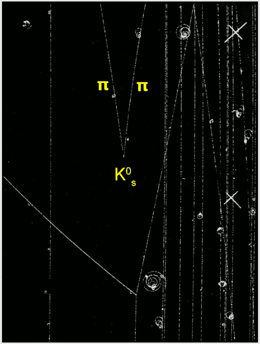
- Fields are *coupled* to each other, allowing energy to flow from one field into another
- Massive particles can decay into lighter particles, converting the leftover mass into kinetic energy of the decay products
- The probability of decay depends on the strength of the coupling



- It also works in reverse: colliding two protons at 14 TeV allows anything to be created that satisfies all conservation rules— any new particle with mass at most 14 TeV/c^2, or several particles

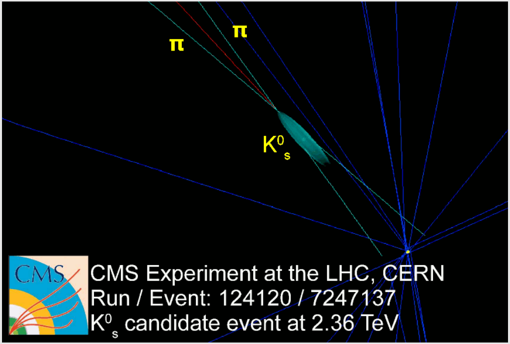
Creating particles in proton collisions

Photo from an old bubble chamber, identified by hand



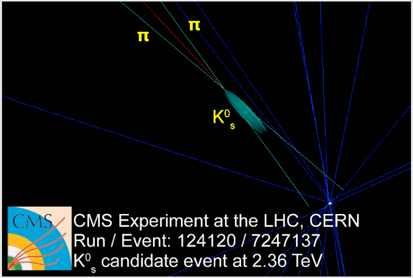
Proton beam (upward) on liquid containing protons (stationary)

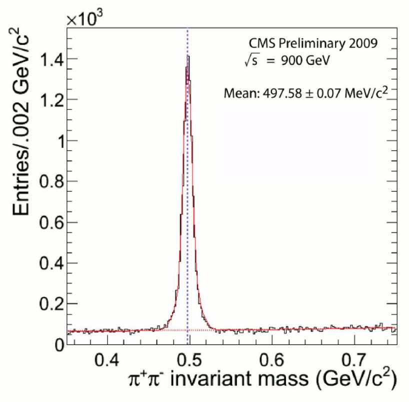
Reconstructed LHC event, December 18, 2009



Proton beams are perpendicular to this projection before collision; newly-created particles go everywhere

Identifying particles by their decays





- Neutral kaon leaves no track
- Energy E and momentum $\vec{p}$ are conserved in the decay

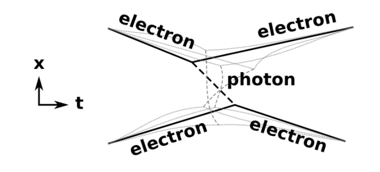
$$(E)^2 = (mc^2)^2 + |\vec{p}|^2 c^2$$

- Add up the energies and momenta of the pion pairs and solve for m, for all pairs of observed tracks
  - in the statistical distribution, true kaons peak at m, the kaon mass
  - false combinations, *or background*, are more uniformly distributed

Forces in quantum field theory

- Quantum field theory explains how particles are created from kinetic energy and how they can decay into other types of particles

- Also describes forces, e.g. repulsion of two electrons:



Two electrons are initially approaching each other, one of them creates a photon and recoils because of the momentum it gave to the photon, then the photon is absorbed by the other electron, which recoils when it accepts that momentum.

- Goal of particle physics: to discover and understand all of the matter fields (like electrons) and all of the force fields (like photons) in a unified framework

- How many forces are there, anyway?

The fundamental forces

- Electromagnetism: fundamental cause of all attributes of matter known before 1896 (stickiness, repulsion, sparks, chemical properties, light, color, etc.), other than gravity

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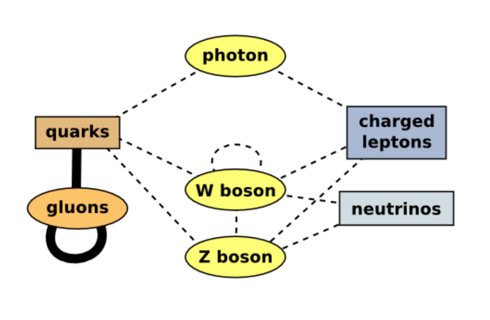
- Gravity: has more to do with space-time itself than field values at space-time points. Because the gravitational force between microscopic particles is so small, the quantum nature of gravity can't be experimentally studied in particle collisions.

The Standard Model

All known fields and their couplings:



- Electromagnetic is the photon part of the diagram
- Electroweak is photon, W boson, and Z boson
- Strong nuclear force is the quark/gluon part

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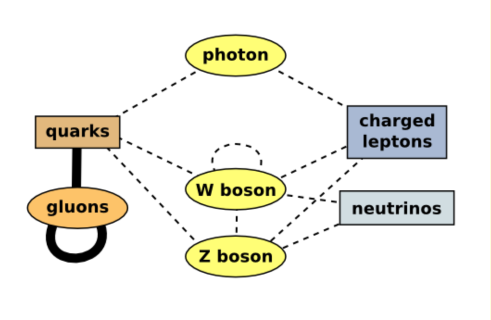

- Electroweak couplings are approximately equal, but electromagnetic interactions are far more common in everyday life than weak ones.
- Standard Model explanation: W and Z mass is a trillion times higher than room-temperature energy, and the probability to create an intermediate W/Z is correspondingly small

The Standard Model

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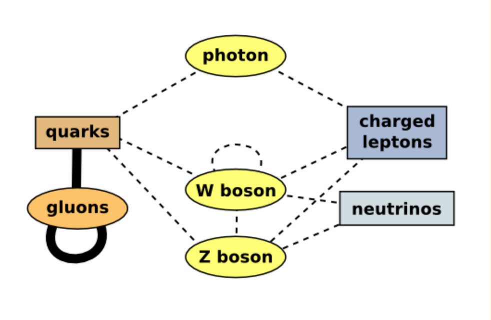
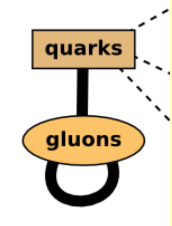
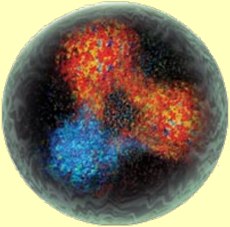


- Technical problem: in quantum field theory, mass of matter fields (boxes) can simply be part of the equations describing the fields

  but force fields (ellipses), must have zero mass in the wave equation!
- Solution: take a hint from the strong nuclear force...

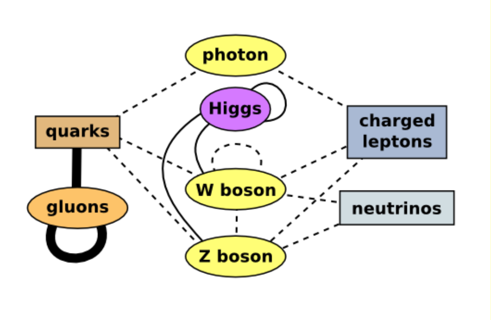
Masses in the strong nuclear force





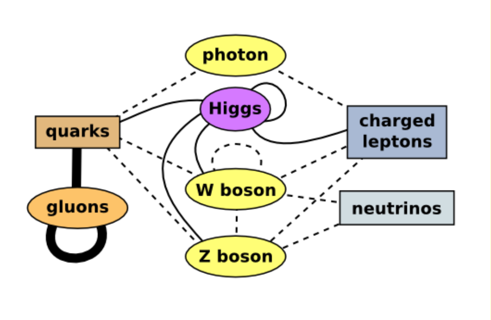
- Nuclear force has a large coupling and a self-coupling
- Intermediate gluons spawn more gluons and more gluons...
- Mass of three quarks in a proton is about 1% of the proton mass
- 99% of the mass of protons, neutrons— and therefore us— is the potential energy of the attraction of the quarks to each other through gluons and the attraction of gluons to gluons
- We are made of potential energy!

Using this trick



- Don't give W and Z masses by hand, but let them be dynamically generated by interactions
- Need to introduce a new particle to do it, a Englert-Brout-Higgs-Guralnik-Hagen-Kibble boson ("Higgs" for short)
- Now it's consistent

Using this trick



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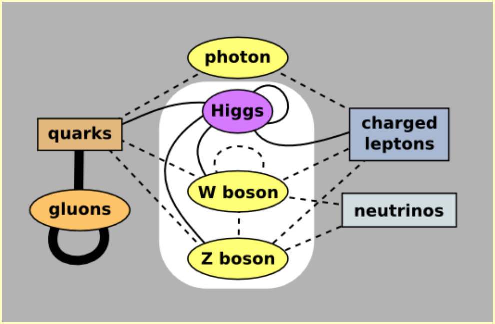
- Variant: explain all quark and charged lepton masses the same way

Standard Model: a falsifiable hypothesis



- When the Standard Model was proposed, the W, Z, and Higgs had not been observed as particles
- The model predicts their properties (e.g. production rate in proton collisions and what they decay into)
- If they are not discovered by a collider/detector which is sensitive to them, the model is wrong. If they are discovered with the right properties, that's great evidence for the model.

Long-term dreams: “tens of TeV” collisions are ideal

Popular Mechanics, April 1978: early plans for LHC

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.

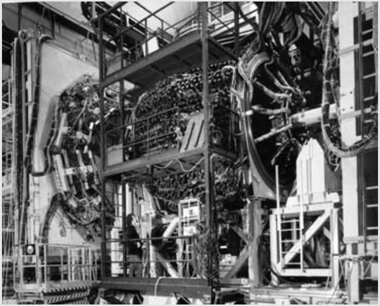
Plan for new Brookhaven accelerator has twin tubes whirling counterrotating proton beams. Future 30-mile atom smasher depicted at left may use same arrangement.

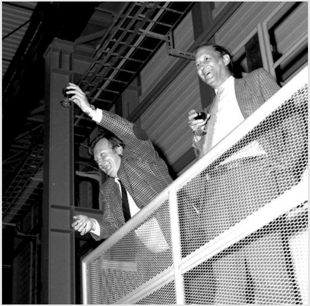
Like an entry ramp to a superhighway, this 500-foot-long linear (straight-line) accelerator at Fermilab pushes protons up to velocities needed to enter high-speed lanes in main circular accelerator. Such "preboosters" will be used in proposed 30-mile atom smasher shown above.

APRIL 1978 97

1980's: Super Proton Synchrotron at CERN

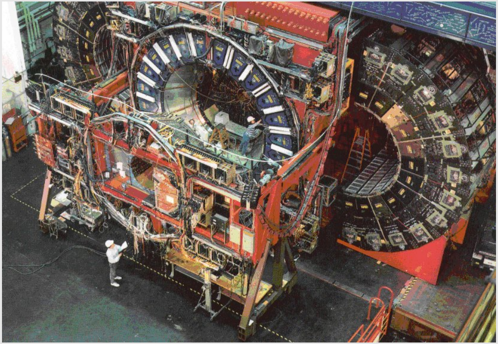
- Collided protons and anti-protons at 0.9 TeV
- Discovered W and Z bosons in 1983!
- Now used to pre-accelerate protons into the LHC





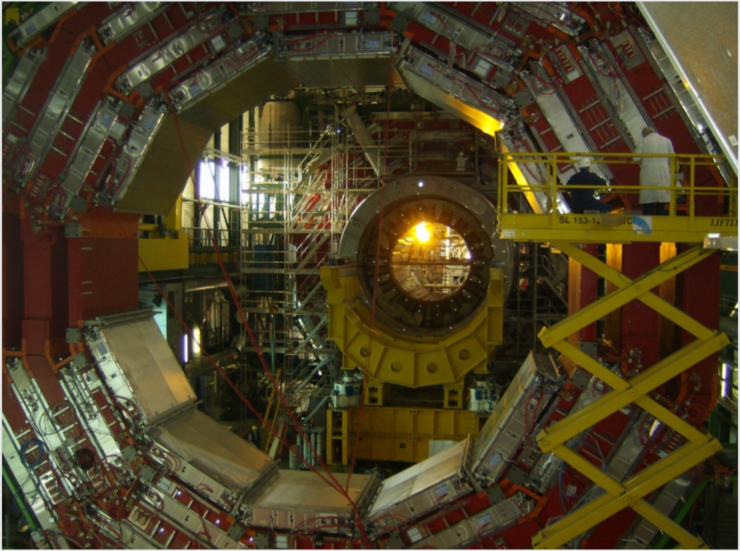
1990's: Tevatron at Fermilab (near Chicago)

- Colliding protons and anti-protons at 1.96 TeV
- Discovered *t* quark in 1995
- Two detectors on the same beamline; provides independent cross-checks when only one accelerator of this scale can be constructed

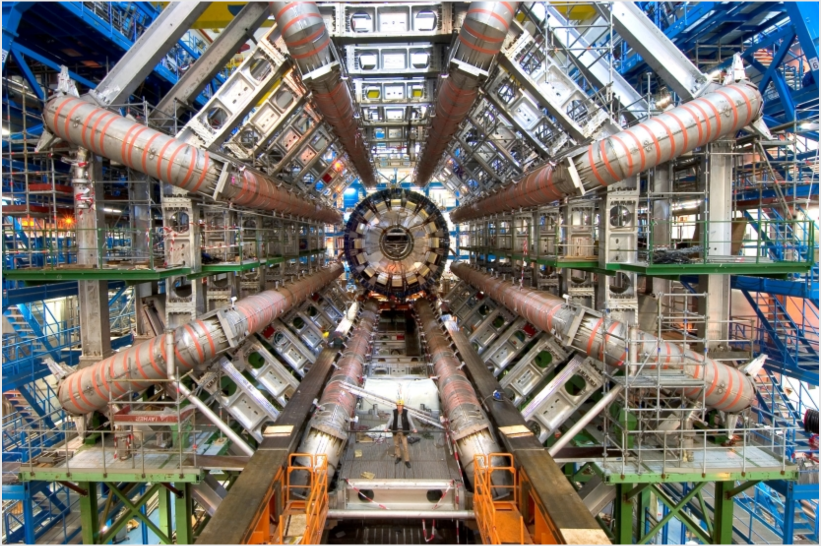


2010's: LHC at CERN

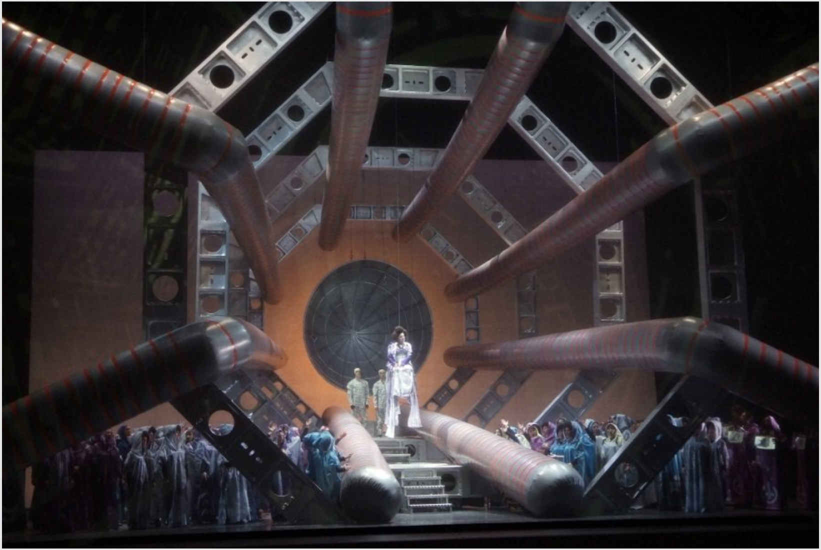
- Four detectors along the beamline; two are general-purpose



2010's: LHC at CERN



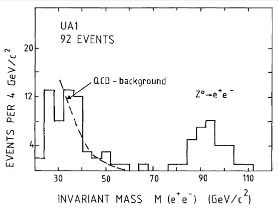
Berlioz's *Les Troyens*

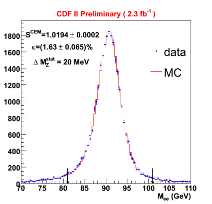


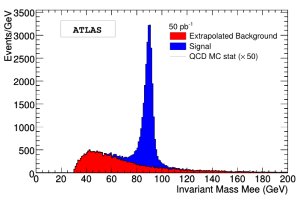
What the Z boson looks like

Statistical mass distributions of $Z \to e^+e^-$ (with backgrounds):

Discovery	Today (Tevatron)	Future (few months LHC)



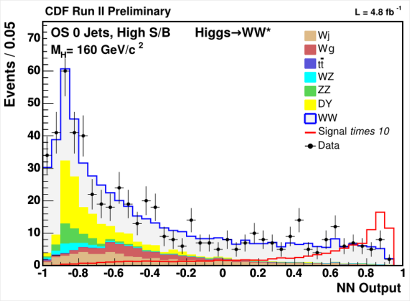




- Discovery of massive W and Z with the right properties confirmed the Standard Model
- High-precision studies in the 1990's makes the Standard Model one of the most precisely tested theories in physics
- But… no Higgs…

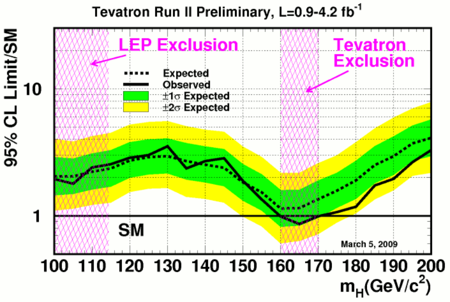
Why Higgs searches are hard

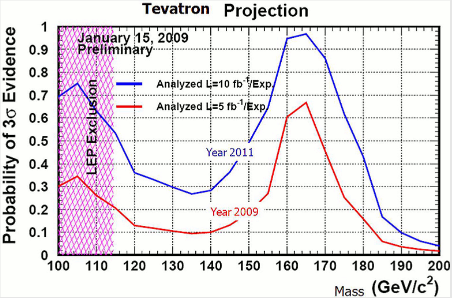
- A Higgs boson is probably created once every few days at the Tevatron, but it's hidden under backgrounds
- Many different types of backgrounds
- Applying artificial intelligence algorithms (neural nets, etc.) to distinguish signal from background using many variables simultaneously, the way a human would



- Example plot (one of the more promising modes): signal is multiplied by 10

What can the Tevatron say about the Higgs?



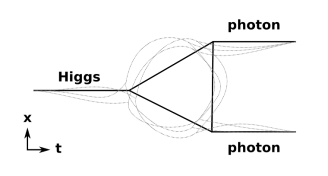


- Top: which Higgs masses have been ruled out
- Bottom: probability of obtaining marginal evidence for a discovery, as a function of Higgs mass

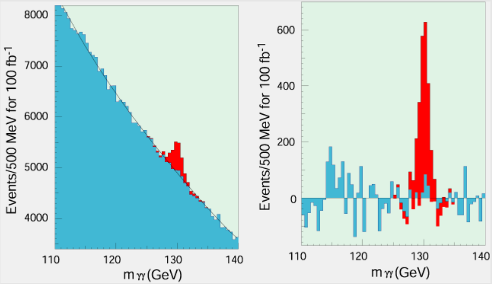
LHC needed to definitively discover/rule out Higgs

Example signature only at LHC: Higgs decaying into two photons

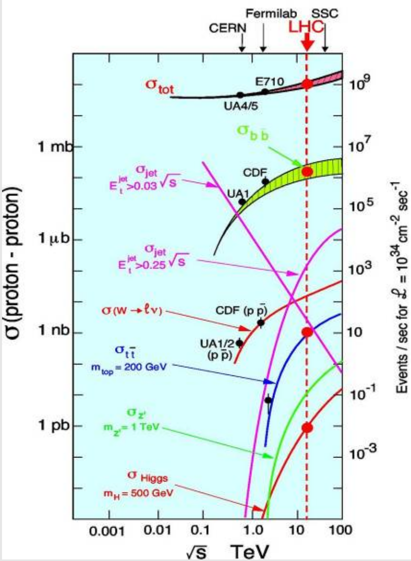
- Higgs does not couple to photons, so it must get there through a loop of another particle
- The rate for this kind of decay is correspondingly low



- The LHC projection below assumes 20$\times$ as much data as Tevatron, several years of running the LHC



Why do we need such high-energy collisions?



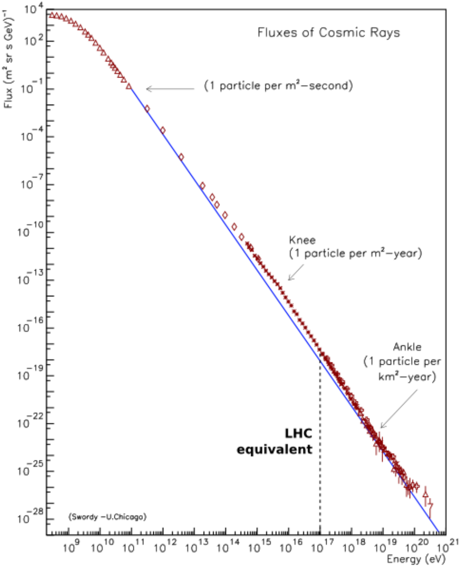
- Plot of rates of various types of processes versus proton collision energy
- Note that the vertical axis is a log scale: every tick-mark is a factor of 10
- Also notice that Higgs is on the bottom, but rises quickly with proton collision energy
- High energy dramatically increases the signal-to-background ratio

The Higgs isn't the whole story

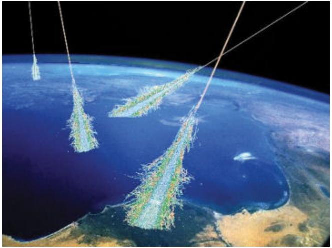
- Theorists have had 35 years to think about the Standard Model; it is incomplete
- The Higgs boson's *own* mass needs to be explained
- "Physics as we know it breaks down at energy scales of several TeV. At that point, something new takes the place of the Standard Model."
- We provide the 14 TeV collisions, nature will do what it will do, and we have general-purpose detectors to analyze whatever that turns out to be
- For the first time in a generation of physicists, we are stepping into the unknown. . .

Backup Slides

We're not doomed

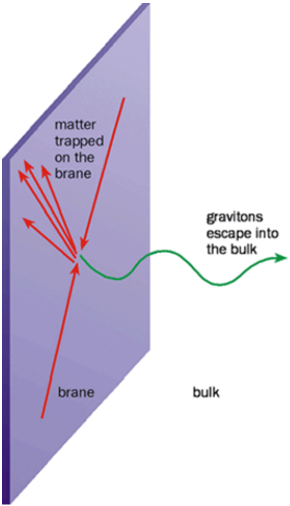


- The universe is raining 16 LHC-like proton collisions down on the Earth every millisecond



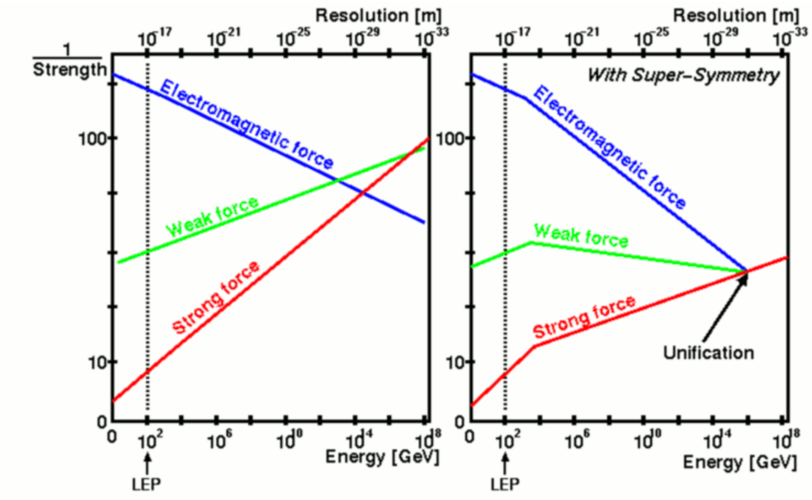
- And it has been for 4 billion years
- At full luminosity, the LHC would need to run for 65,000 years to contribute significantly

Extra dimensions

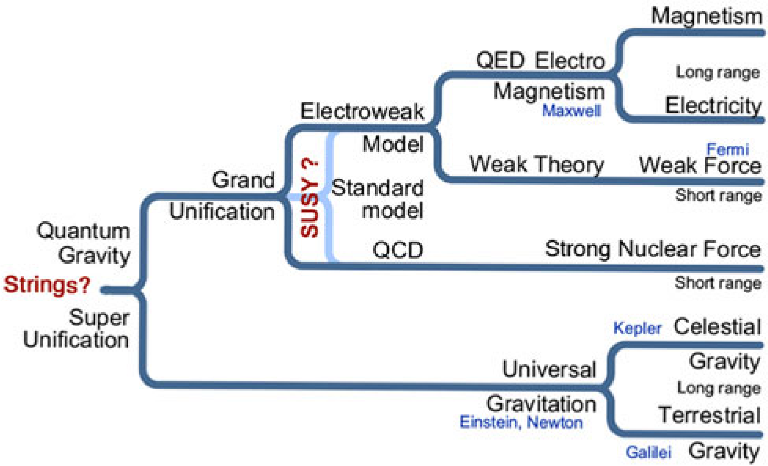


?

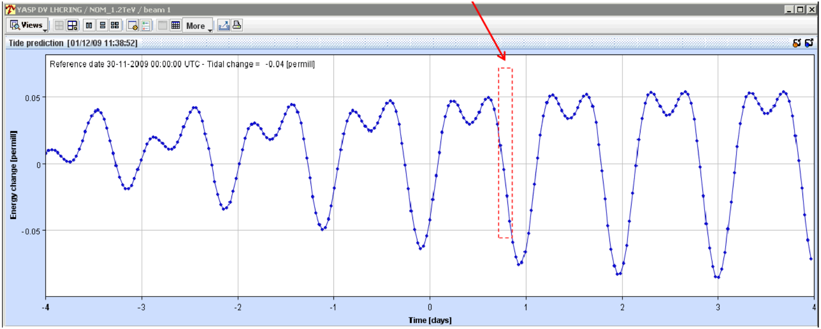
Supersymmetry



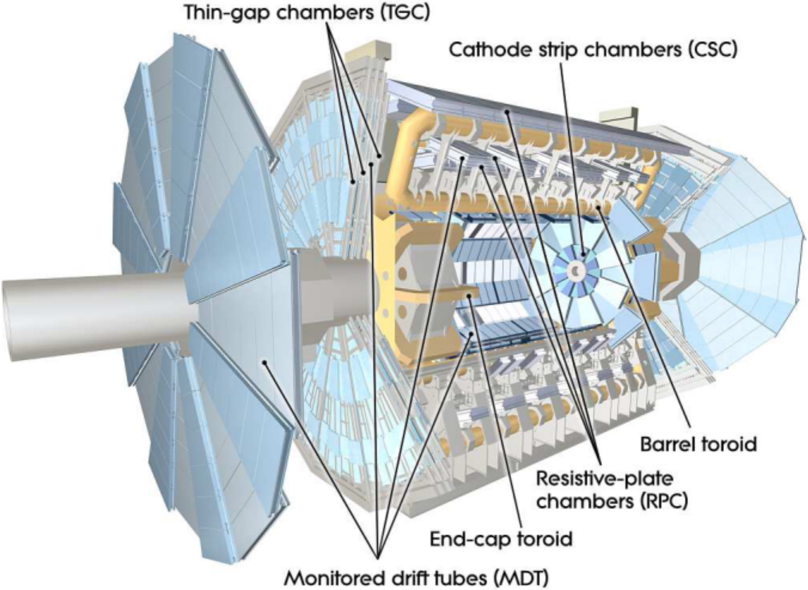
Unification



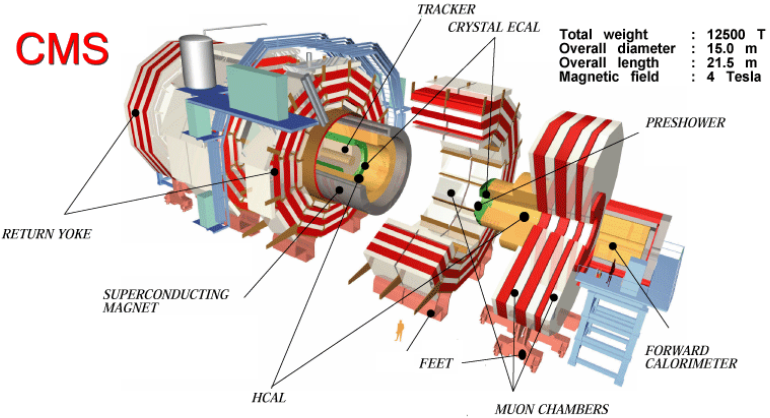
LHC tides



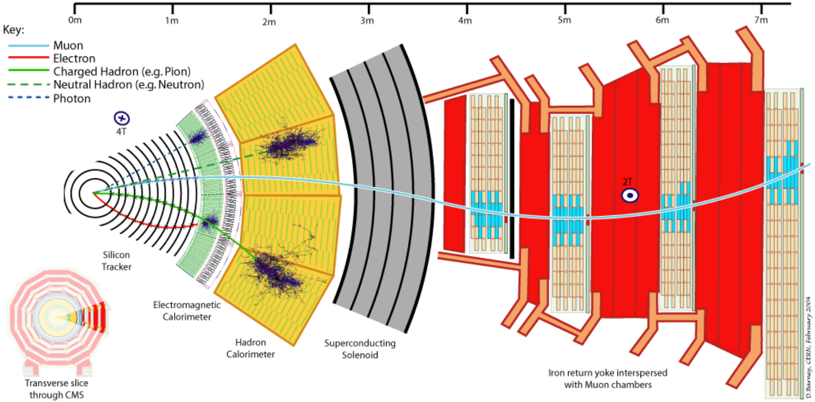
- The tides have an already-observable effect on the LHC
- When the size of the ring stretches, the protons' orbit is perturbed
- Corrections are necessary


Thin-gap chambers (TGC)
Cathode strip chambers (CSC)
Barrel toroid
Resistive-plate chambers (RPC)
End-cap toroid
Monitored drift tubes (MDT)

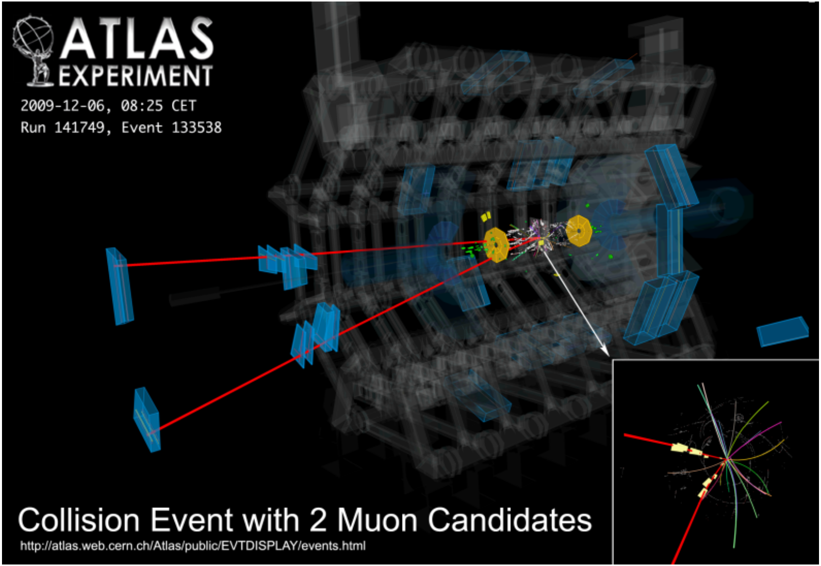
CMS


CMS
TRACKER
CRYSTAL ECAL
Total weight : 12500 T
Overall diameter : 15.0 m
Overall length : 21.5 m
Magnetic field : 4 Tesla
PRESHOWER
RETURN YOKE
SUPERCONDUCTING MAGNET
FORWARD CALORIMETER
FEET
HCAL
MUON CHAMBERS

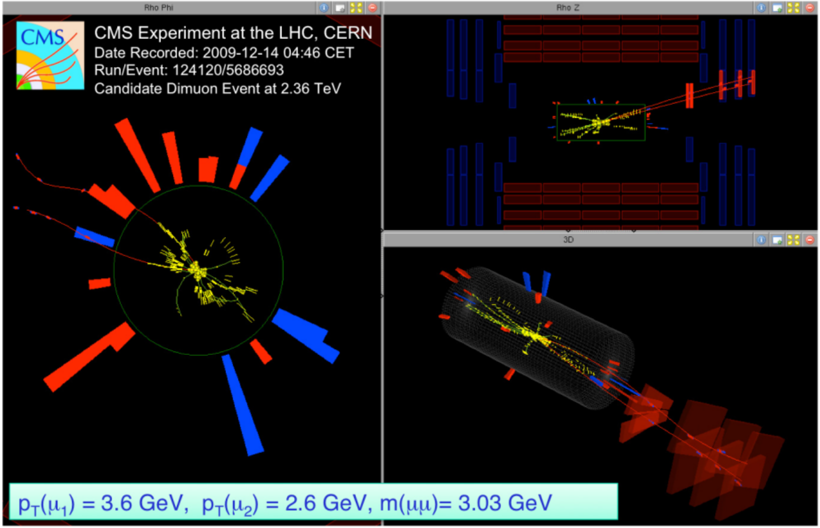
CMS


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

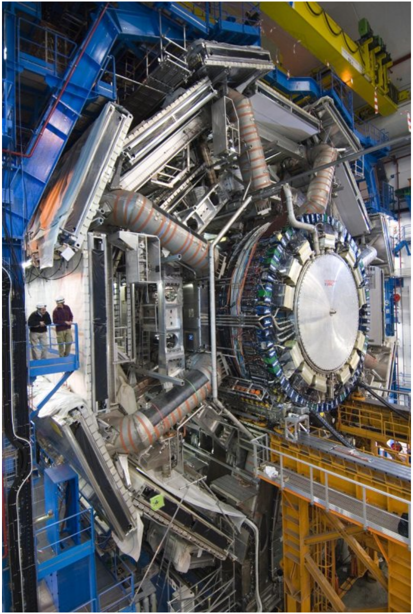
ATLAS two-muon event



CMS two-muon event



ATLAS



ATLAS