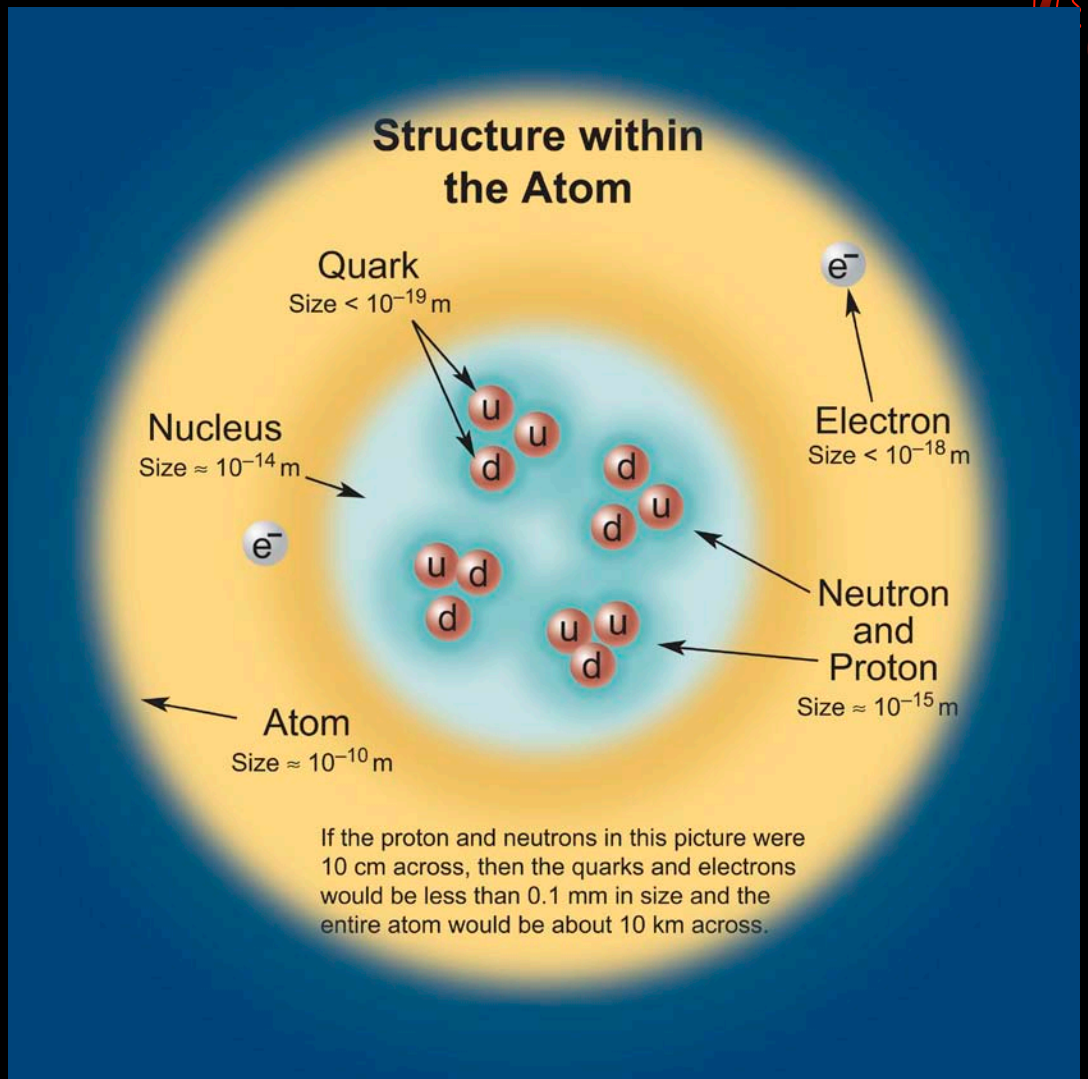
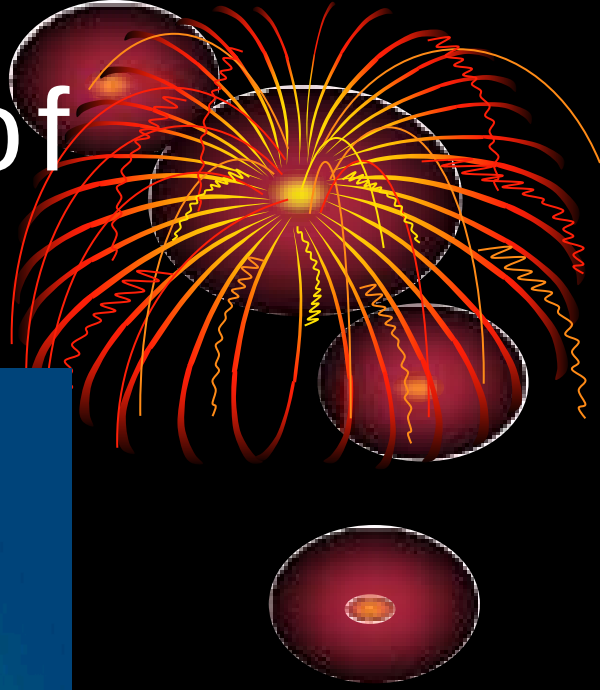
Building Blocks of Nature





History of the Universe

Now
(15 billion years)

Stars form
(1 billion years)

Atoms form
(300,000 years)

Nuclei form
(180 seconds)

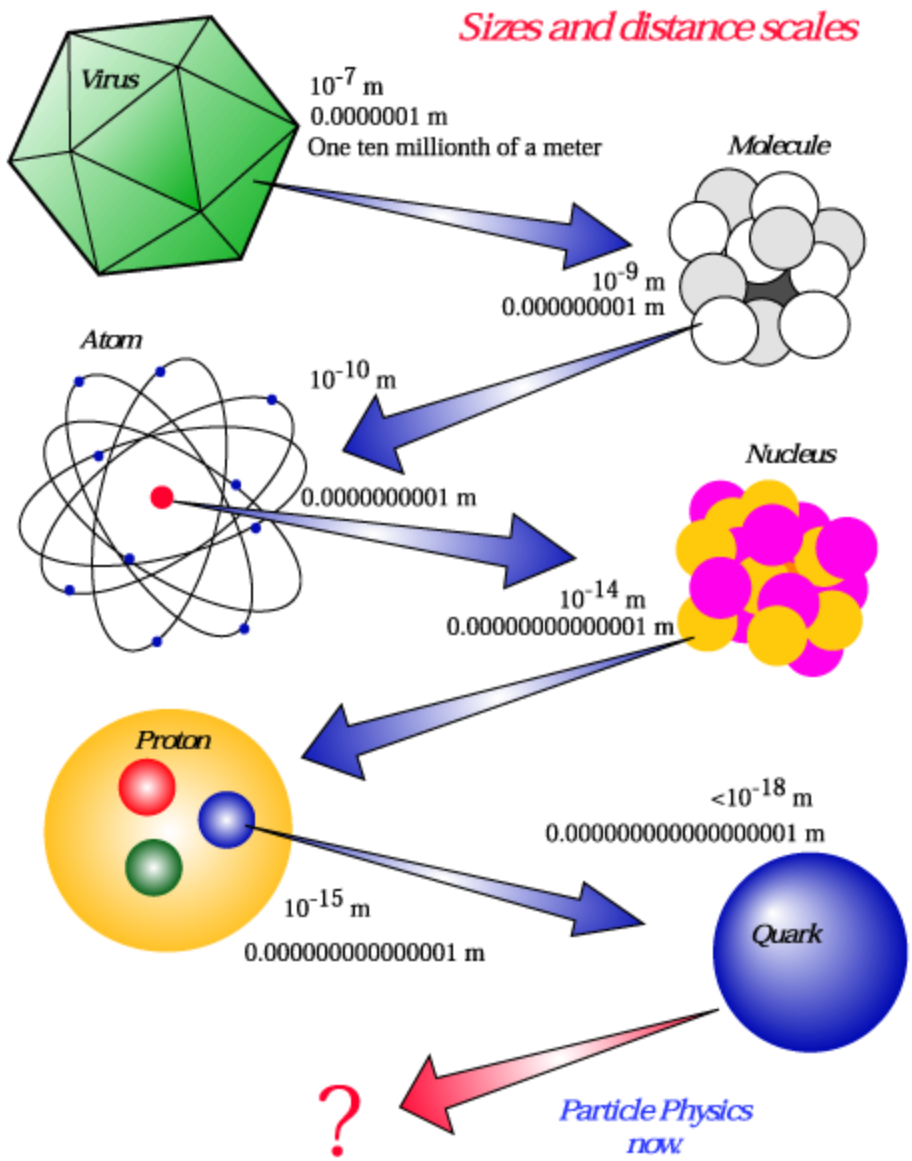
Nucleons form
(10^{-10} seconds)

Fermilab

4×10^{-12}
Seconds
$.004 \times 10^{-9}$

Quarks differentiate
(10^{-34} seconds?)

??? (Before that)



What's the Point?

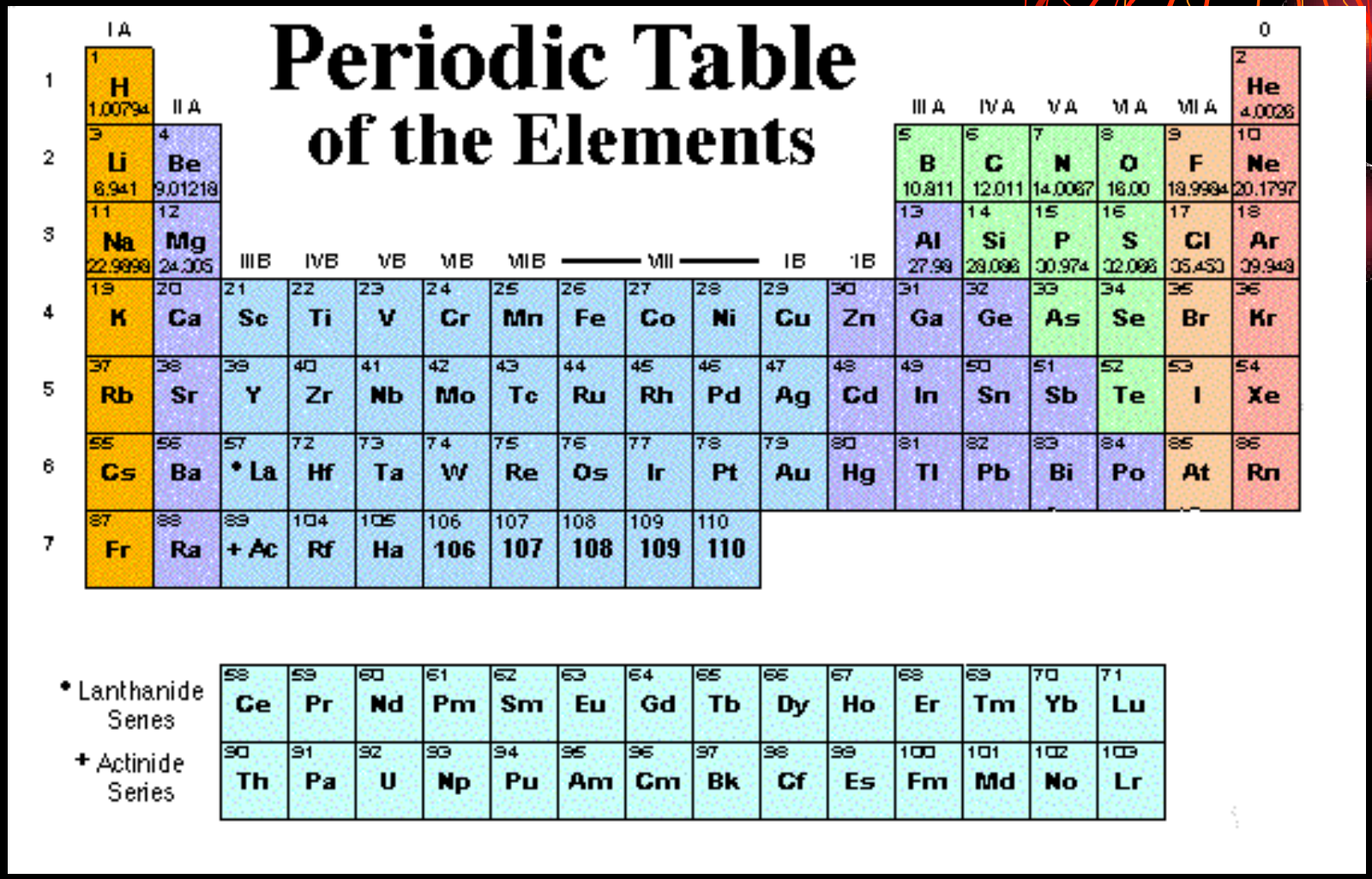
High Energy Particle Physics is a study of the smallest pieces of matter.

It investigates (among other things) the nature of the universe immediately after the Big Bang.

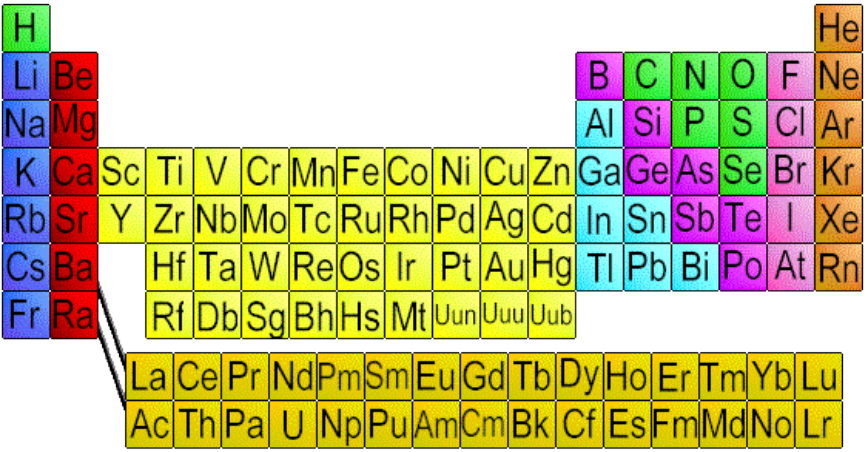
It also explores physics at temperatures not common for the past 15 billion years (or so).

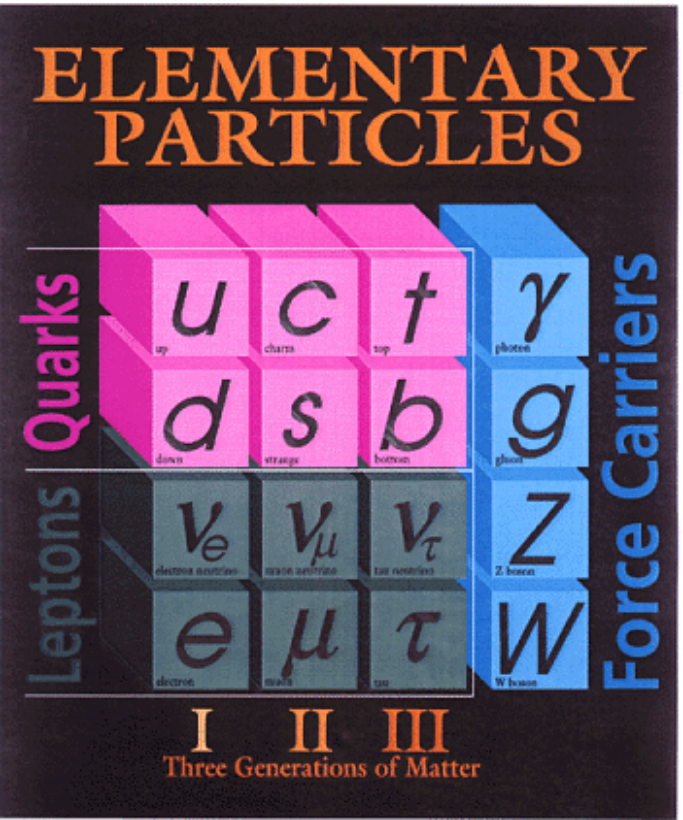
It's a lot of fun.

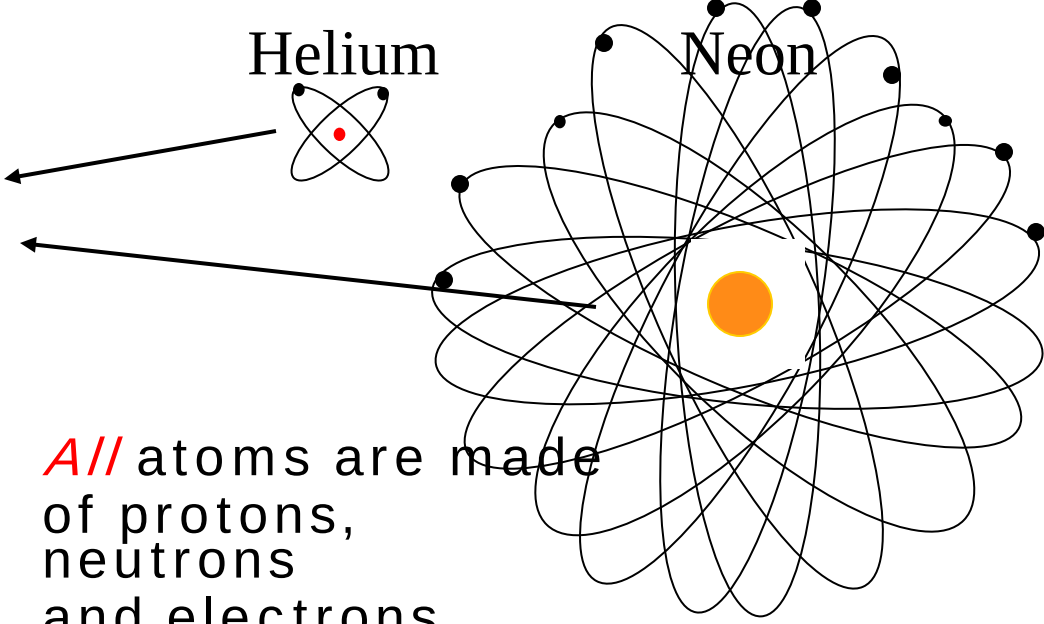
Periodic Table



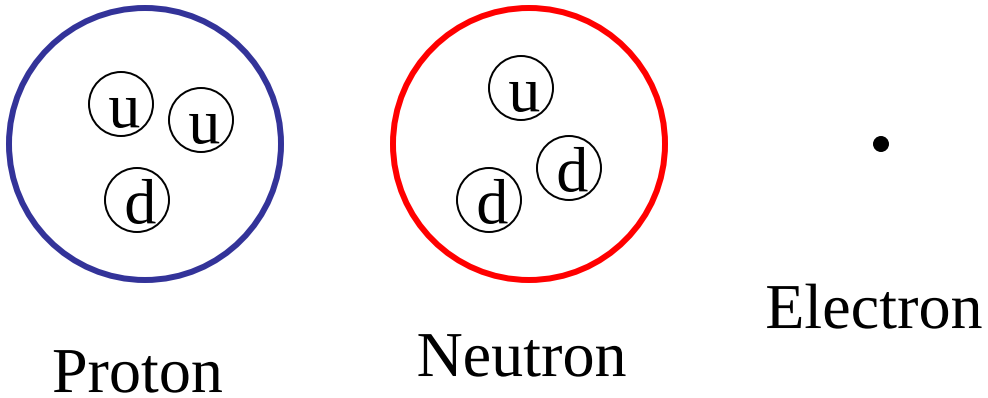
Periodic Table





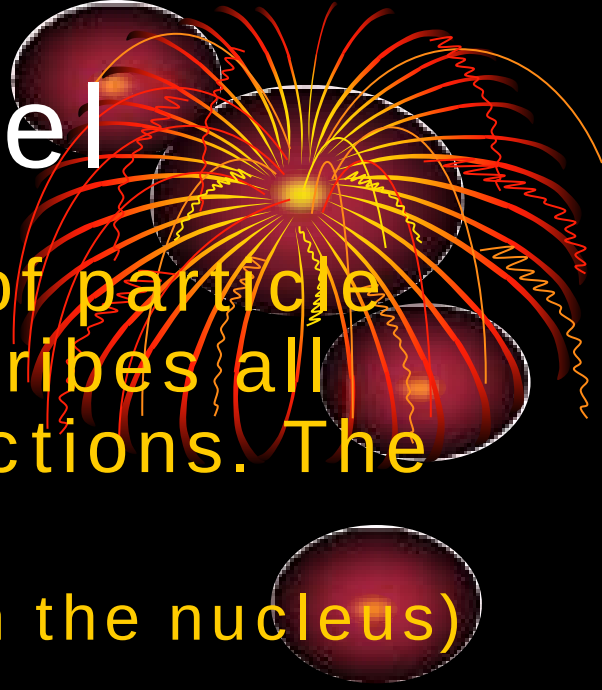


All atoms are made of protons, neutrons and electrons



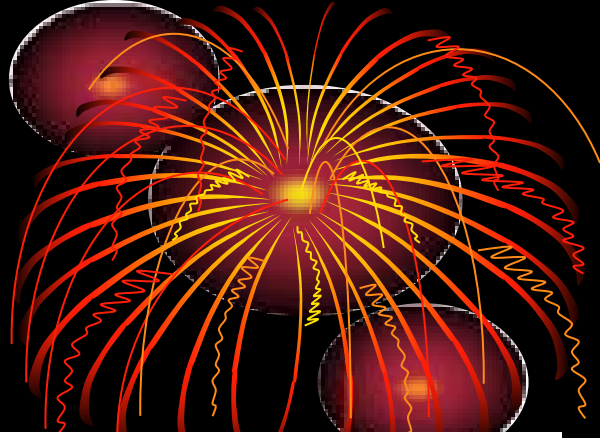
Gluons hold quarks together
Photons hold atoms together

The Standard Model

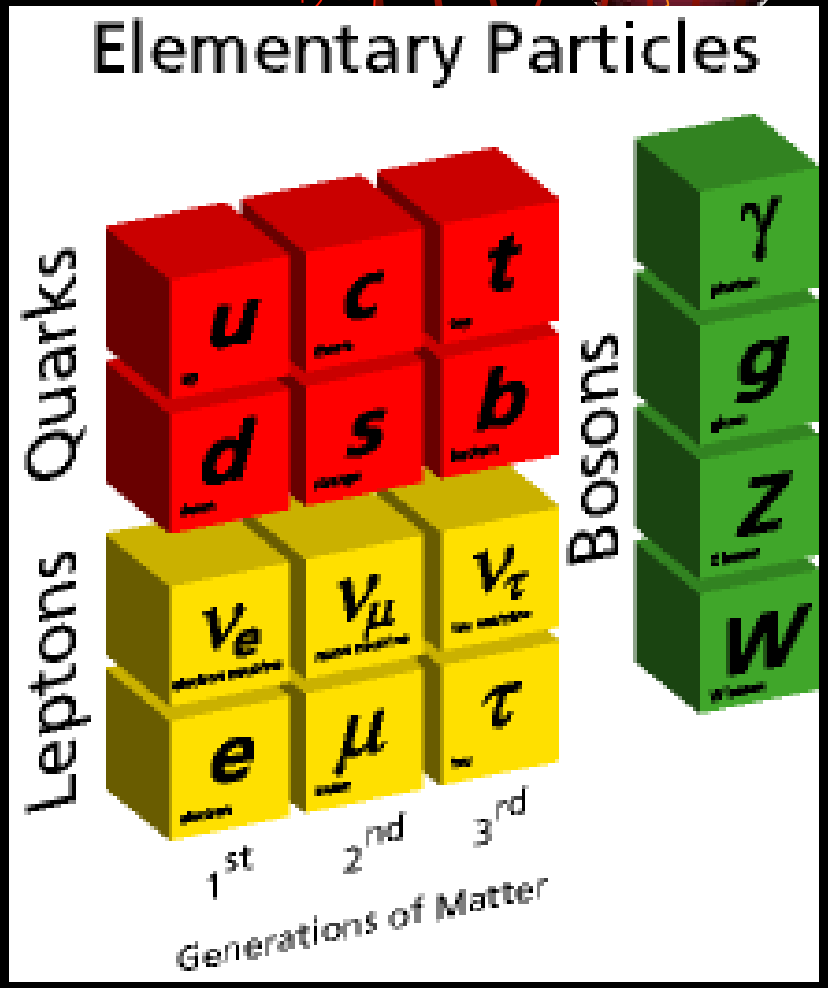


- The crowning achievement of particle physics is a model that describes all particles and particle interactions. The model includes:
  - 6 quarks (those little fellows in the nucleus) and their antiparticles.
  - 6 leptons (of which the electron is an example) and their antiparticles
  - 4 force carrier particles (of which the photon is an example)
- **All known matter is composed of composites of quarks and leptons which interact by exchanging force carriers.**

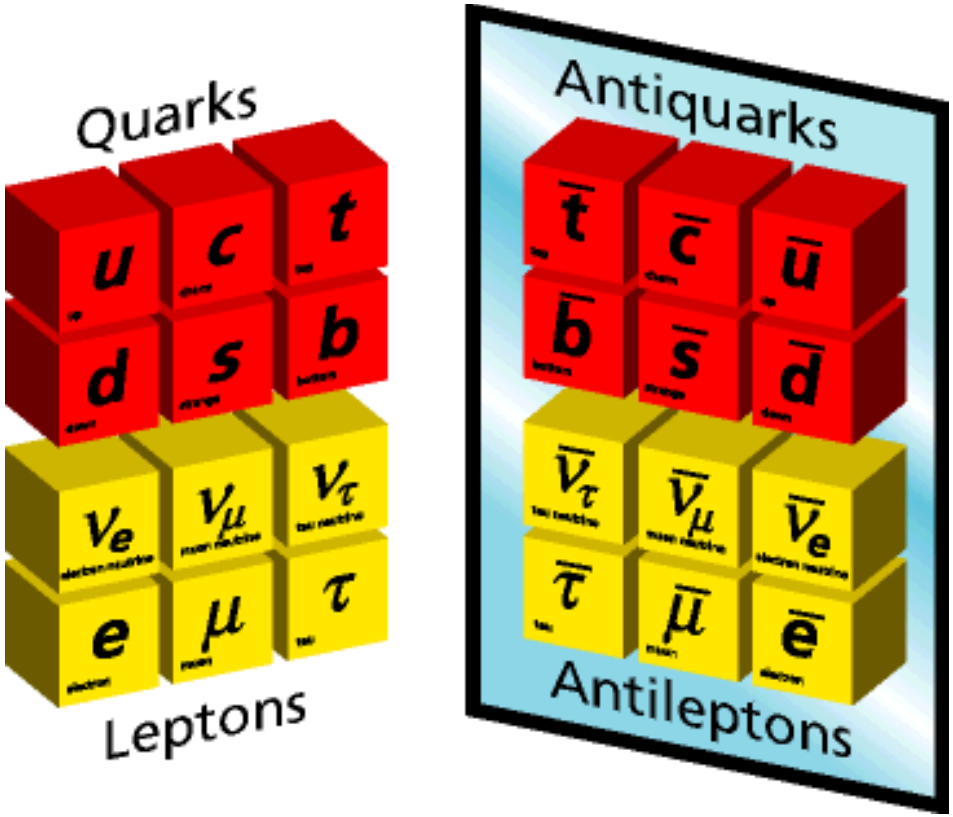
Quarks, Leptons, and Bosons



- Physicists currently believe there are three types of basic building blocks of matter: quarks, leptons, and bosons.
- Quarks and leptons make up everyday matter, which is held together by bosons.
- Each boson is associated with a force.
- The photon, the unit of the electromagnetic force, holds the electron to the nucleus in the atom.
- The way these particles combine dictates the structure of matter.



Anti-Matter



- All particles have 'anti-particles', which have similar properties, but opposite electrical charge

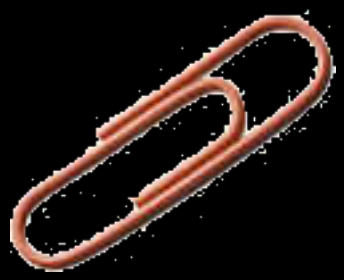
→ Particles
- u,c,t +2/3
- d,s,b -1/3
- e,μ,τ -1

→ Anti-particles
- u,c,t -2/3
- d,s,b +1/3
- e,μ,τ +1

So what's the deal on antimatter?

Fiction?

How much energy?



+

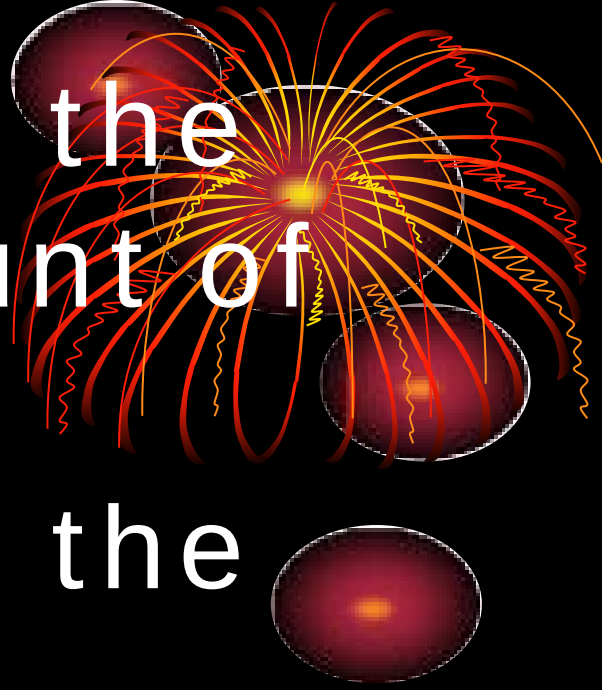
=

1 gram of matter

1 gram of antimatter

Energy release equivalent to Hiroshima explosion

FACT: Fermilab has the largest amount of antimatter anywhere on the planet.



Question:
What would happen if you took all of the antimatter ever made at Fermilab and combined it with an equal amount of matter?

Answer:
Enough energy to raise your 20 oz coffee from room to drinkable temperature

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.

These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{\mathbf{p}}$	antiproton	$\bar{\mathbf{u}}\bar{\mathbf{u}}\bar{\mathbf{d}}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons

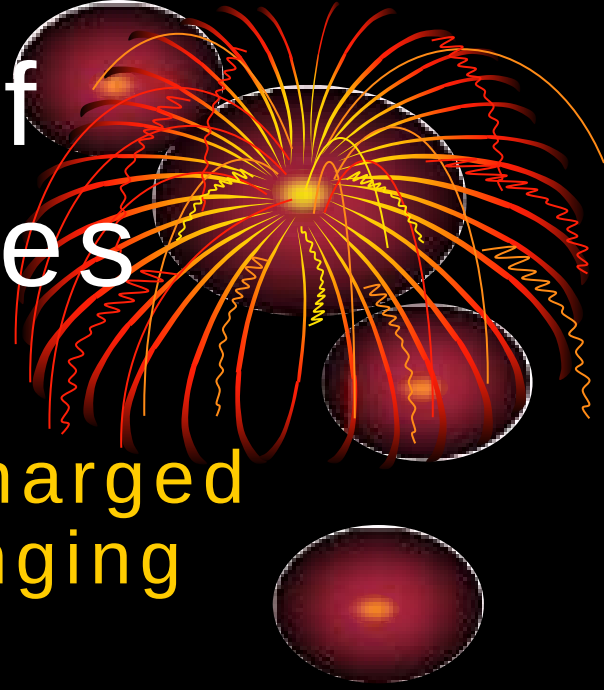
These are a few of the many types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$\mathbf{u\bar{d}}$	+1	0.140	0
$\mathbf{K^-}$	kaon	$\mathbf{s\bar{u}}$	–1	0.494	0
ρ^+	rho	$\mathbf{u\bar{d}}$	+1	0.776	1
B^0	B-zero	$\mathbf{d\bar{b}}$	0	5.279	0
η_c	eta-c	$\mathbf{c\bar{c}}$	0	2.980	0

Forces of Nature

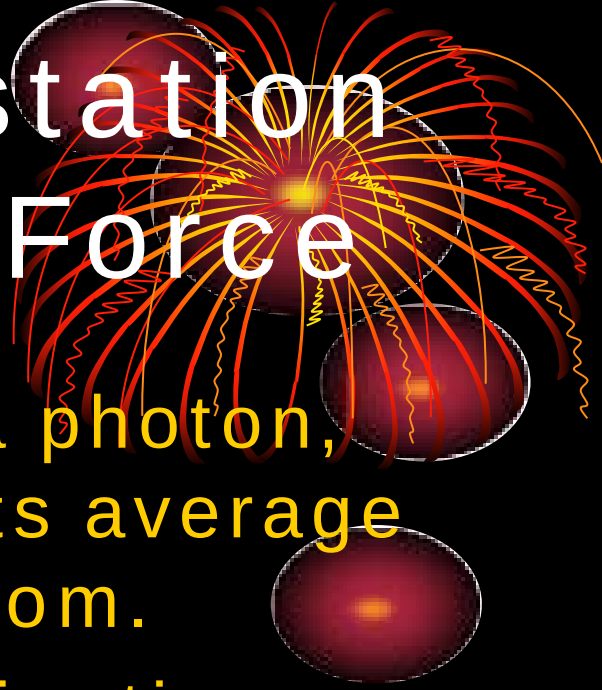
- Electromagnetic
  - The *electromagnetic force* causes electric and magnetic effects such as the repulsion between like electrical charges or the interaction of bar magnets. It is long-ranged, but much weaker than the strong force. It can be attractive or repulsive, and acts only between pieces of matter carrying electrical charge.
- Weak
  - The *weak force* is responsible for radioactive decay and neutrino interactions. It has a very short range and, as its name indicates, it is very weak.
- Strong
  - The *strong interaction* is very strong, but very short-ranged. It acts only over ranges of order 10-13 centimeters and is responsible for holding the nuclei of atoms together. It is basically attractive, but can be effectively repulsive in some circumstances.
- Gravity
  - The *gravitational force* is weak, but very long ranged. Furthermore, it is always attractive, and acts between any two pieces of matter in the Universe since mass is its source.

A Characteristic of Fundamental Forces



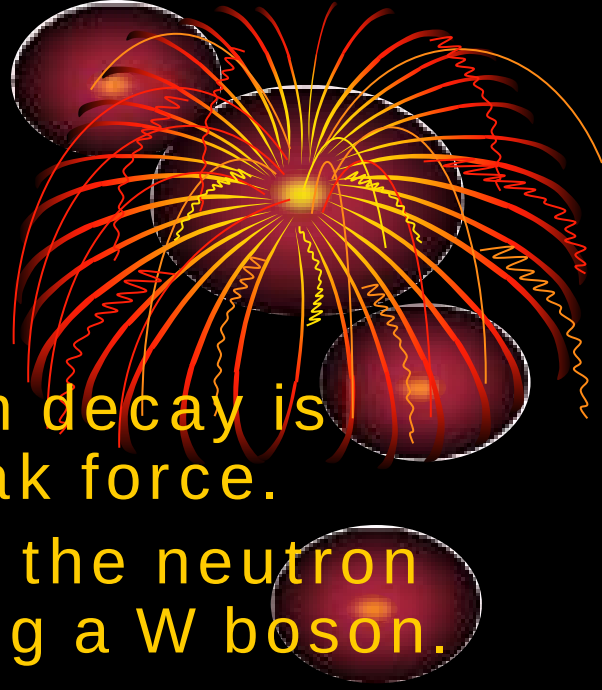
- As the light bulb hinted, charged objects interact by exchanging photons.
- In the atom the electron and nucleus are held together by exchanging photons.
- <u>In fact all fundamental forces involve the exchange of a fundamental particle.</u>

Light as a Manifestation of a Fundamental Force

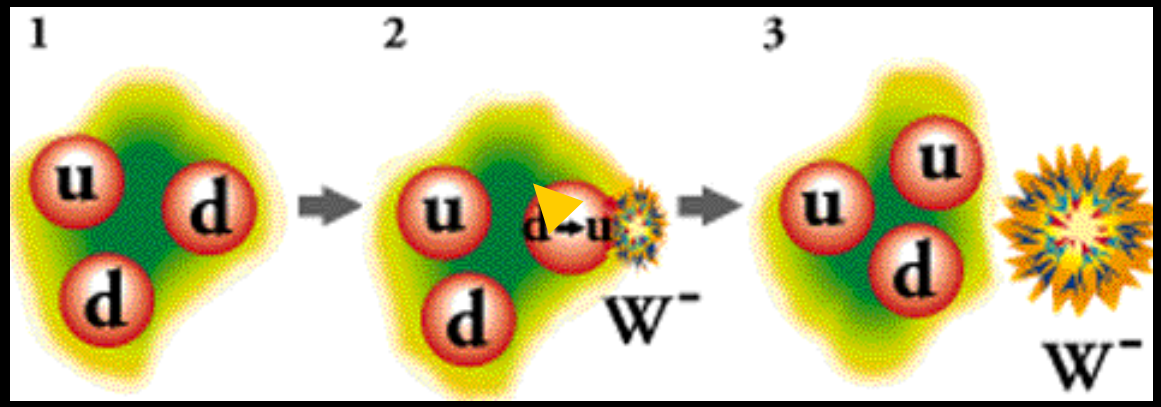


- By emitting or absorbing a photon, the electron can change its average position or energy in an atom.
- In every day life, the illumination from your light bulb is just a very great number of photons emitted from the excited filament atoms.
- This is a <u>classic electromagnetic interaction</u> and our first <u>manifestation of a fundamental force</u>!

The Weak Force

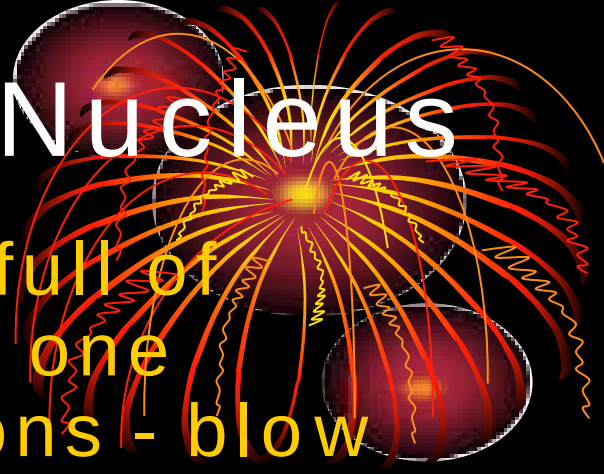


- Radioactivity, in particular, neutron decay is actually a manifestation of the weak force.
- At the quark level, a down quark in the neutron decays into an up quark, by emitting a W boson.
- $n \rightarrow p + e + \bar{\nu}$

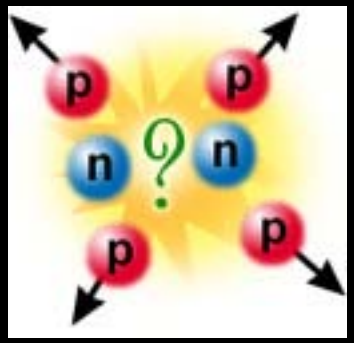


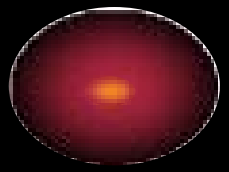
- <u>The heavy W boson is the carrier of the weak force.</u>

The Problem of the Nucleus



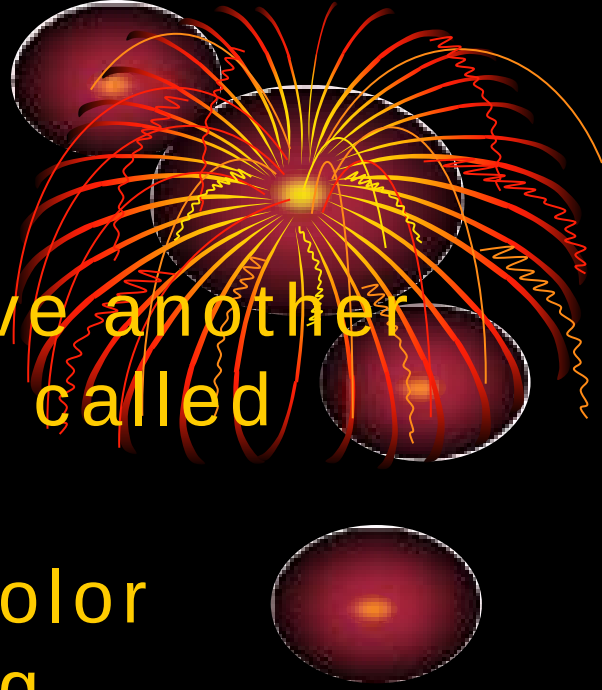
- Why doesn't the nucleus - full of positive protons that repel one another and neutral neutrons - blow itself apart?





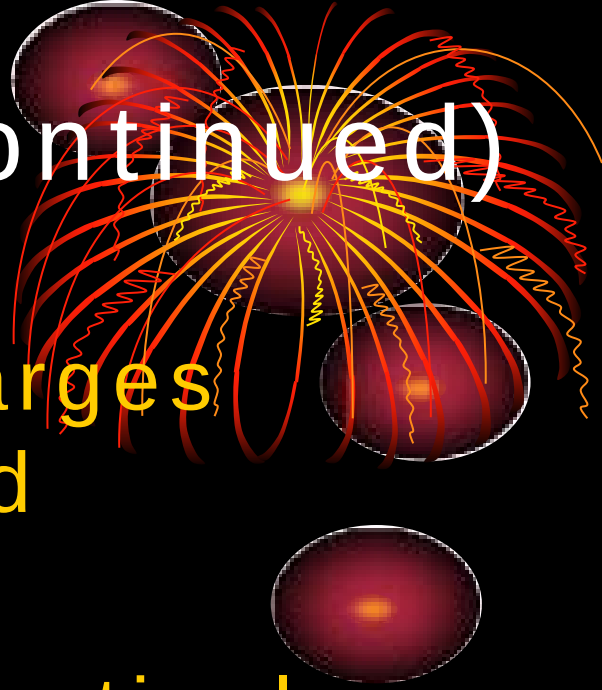
- Gravity doesn't work since it's much too weak compared to electromagnetism.
- There must be yet another force around!

The Color Charge

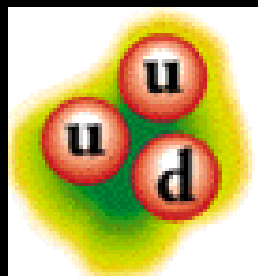


- Well it turns out quarks have another quantum number or charge called "color charge".
- The force between these color charges is extremely strong.
- Two quarks interact by exchanging the strong carrier dubbed the "gluon"
- Gluons themselves have color charges

The Color Charge (continued)

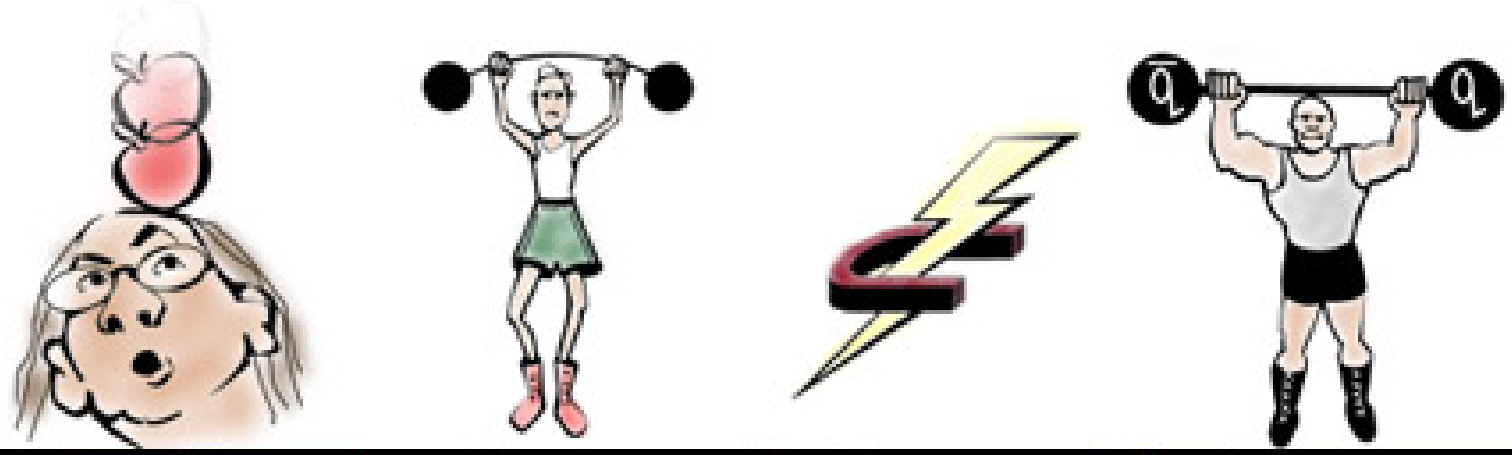


- There are three color charges named: “red”, “green” and “blue”.
- These names are mathematical identifiers and have nothing to do with visible colors.
- Quarks are bound in a particle, like the proton, by madly exchanging gluons and forming a binding color field:



Gravity

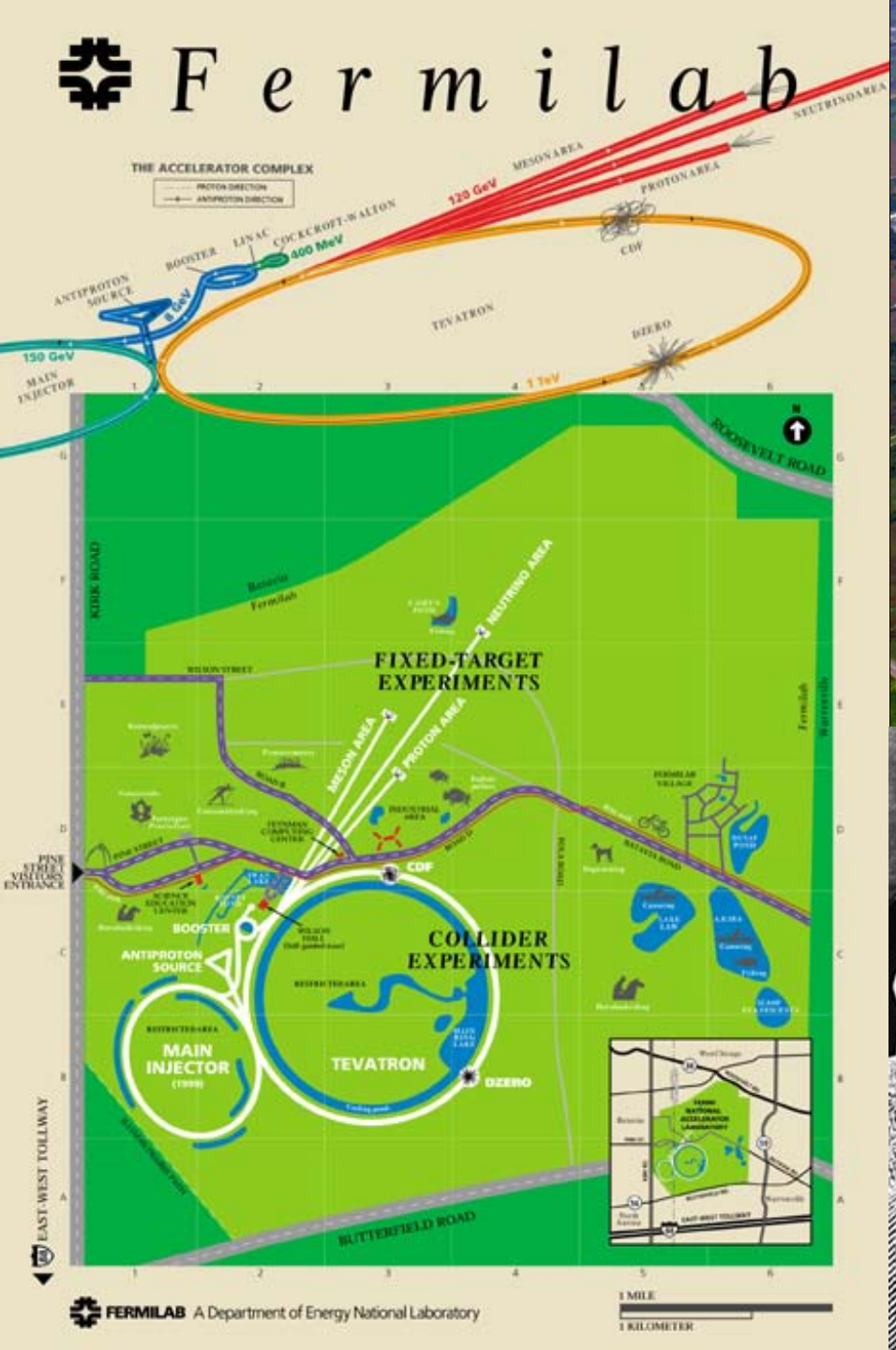
- Although a deep understanding of gravity has been around the longest it is not understood at the carrier level.
- The graviton has not been discovered.
- Still since this is a very weak force the Standard Model works very well in the absence of a full description

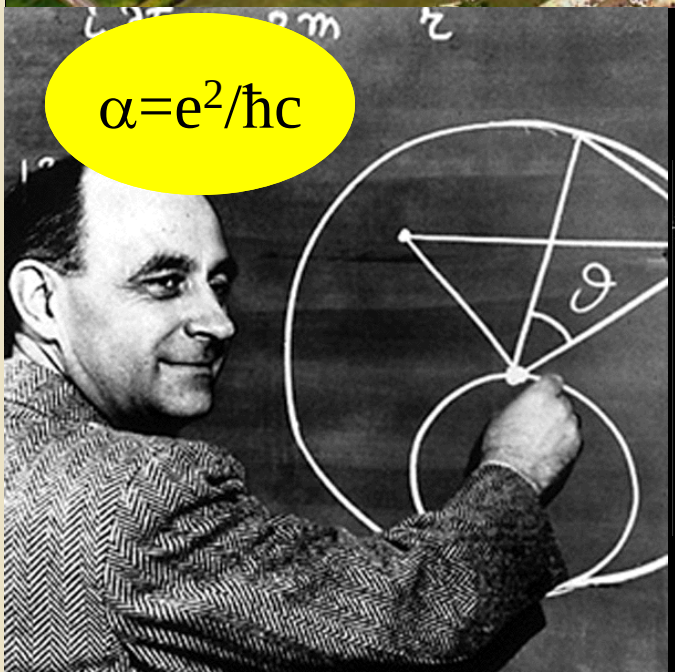


	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

10^{-37} weaker than EM

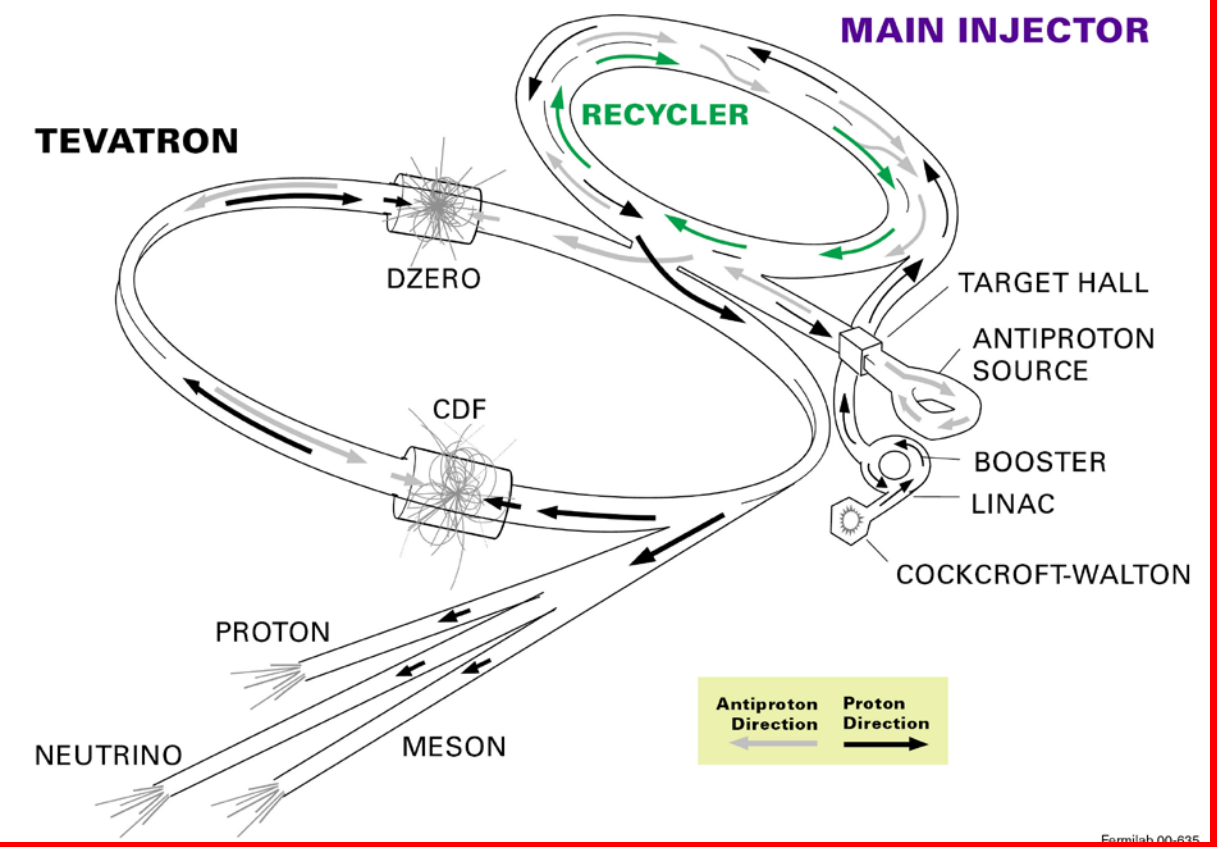
Explained by complete theory

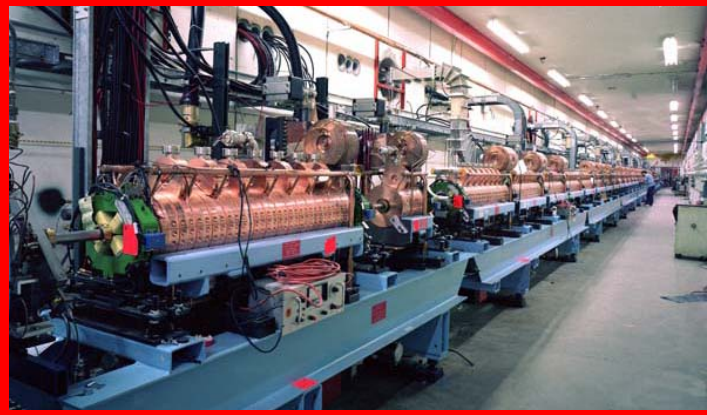

Fermilab
THE ACCELERATOR COMPLEX
PROTON DIRECTION
ANTIPROTON DIRECTION
120 GeV
MESON AREA
NEUTRINO AREA
PROTON AREA
400 MeV
COCKCROFT-WALTON
LINAC
BOOSTER
ANTIPROTON SOURCE
8 GeV
150 GeV
MAIN INJECTOR
TEVATRON
1 TeV
CDF
DZERO
ROOSEVELT ROAD
KIRK ROAD
FIXED-TARGET EXPERIMENTS
NEUTRINO AREA
MESON AREA
PROTON AREA
CDF
BOOSTER
ANTIPROTON SOURCE
COLLIDER EXPERIMENTS
MAIN INJECTOR
TEVATRON
DZERO
PINE STREET VISITORS ENTRANCE
EAST-WEST TOLLWAY
BUTTERFIELD ROAD
FERMILAB A Department of Energy National Laboratory
1 MILE
1 KILOMETER


$\alpha = e^2/\hbar c$

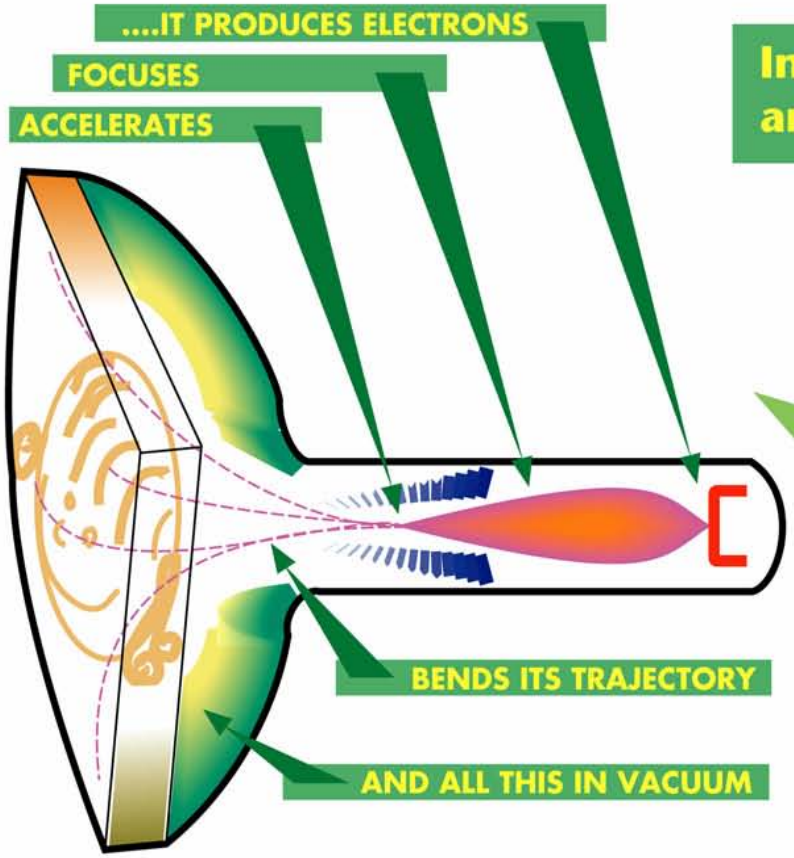
USA Enrico 33 Fermi

FERMILAB'S ACCELERATOR CHAIN



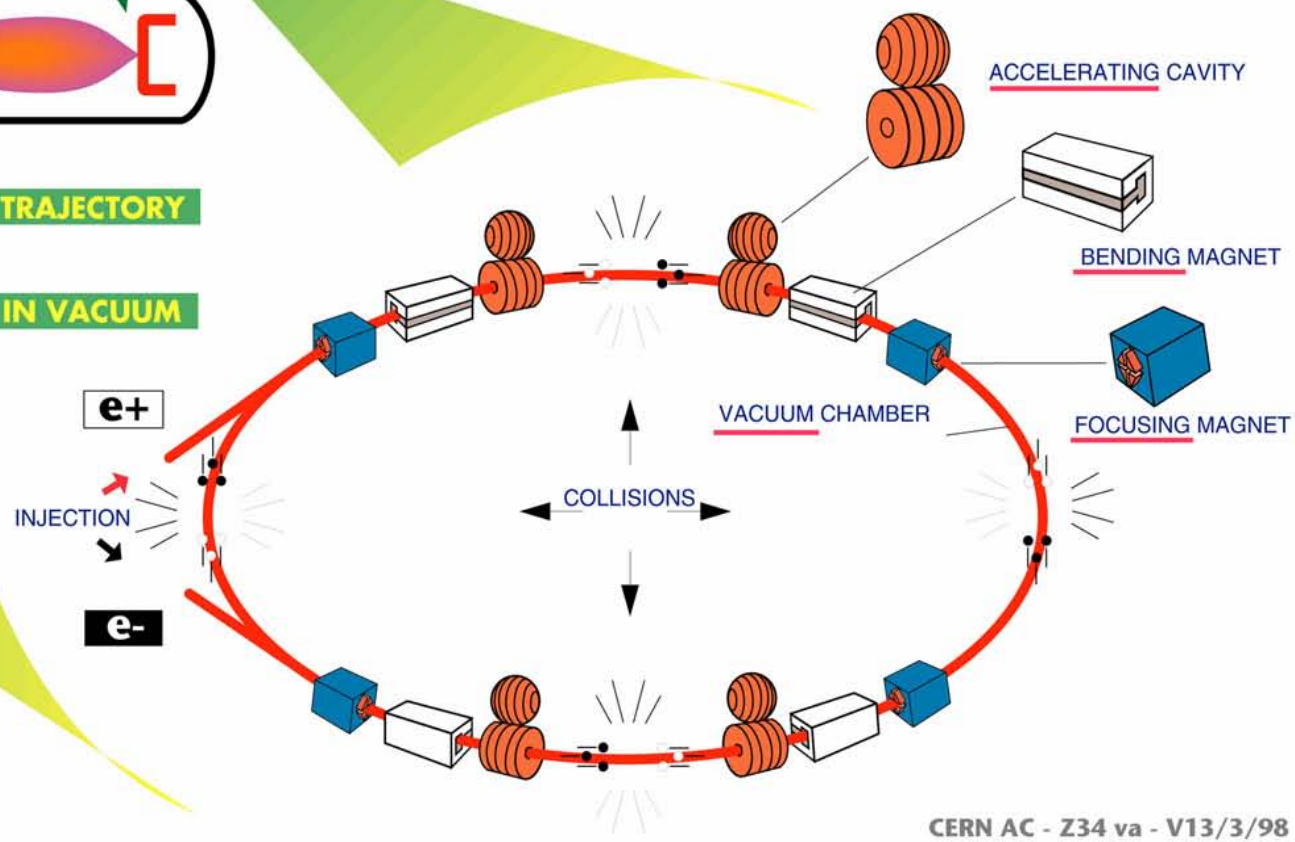


DID YOU KNOW YOUR TELEVISION SET IS AN ACCELERATOR ?



In your TV set, the electrons are accelerated to 20000 volts.

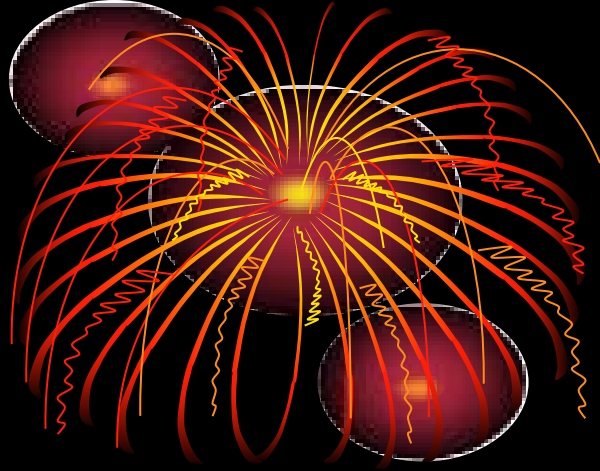
In LEP, they are accelerated to 100 000 000 000 volts.

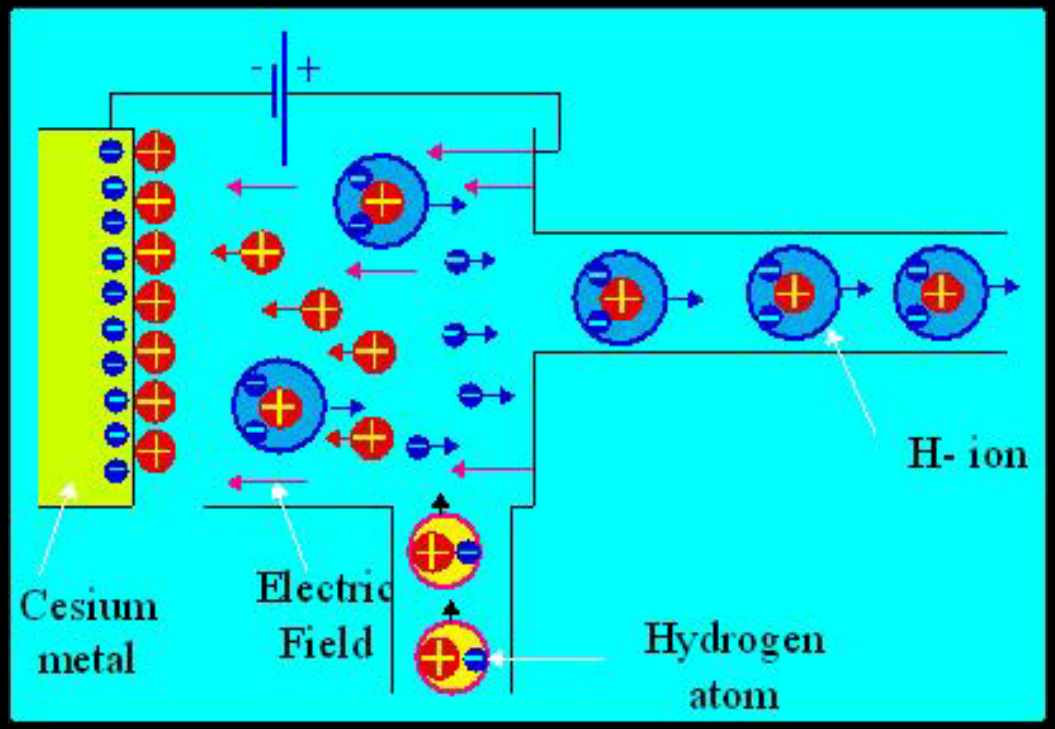


Fermilab Facts

- Named after Enrico Fermi, the famous Italian physicist who worked on the Manhattan Project.
- Current Director: Pier Oddone
- Fermilab encompasses 6800 acres, much of it used for prairie restoration and preserving open space in the western suburbs.
- Employees about 2000 people.
- Original cost $250,000,000. Approximately the same amount in upgrades over the last 30 years.
- Electric bill between $10,000,000 and $20,000,000
- NO classified work is done here, ask all the questions and take all the pictures you want.

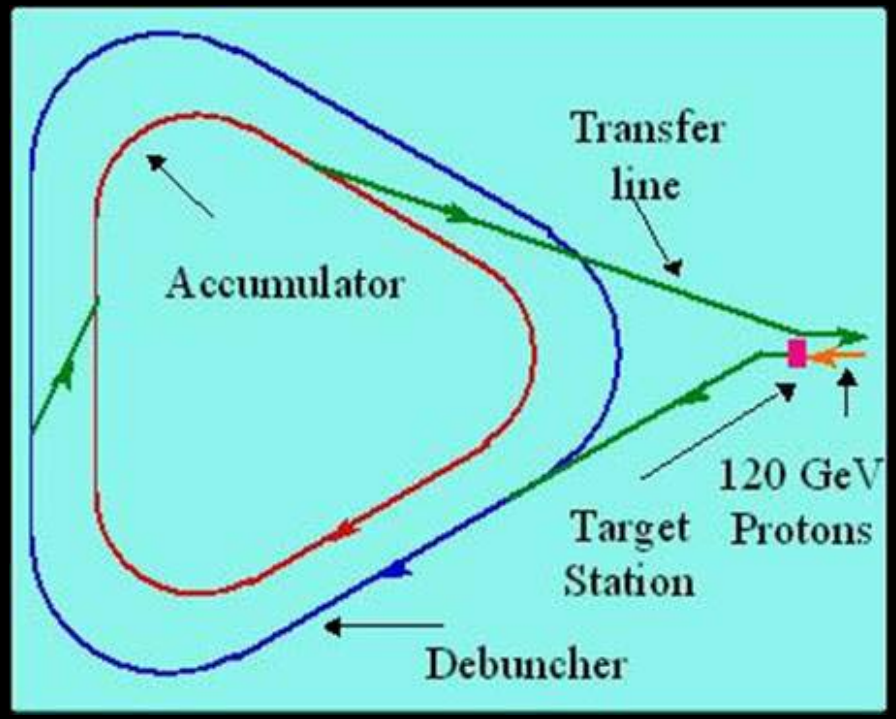
Proton Source





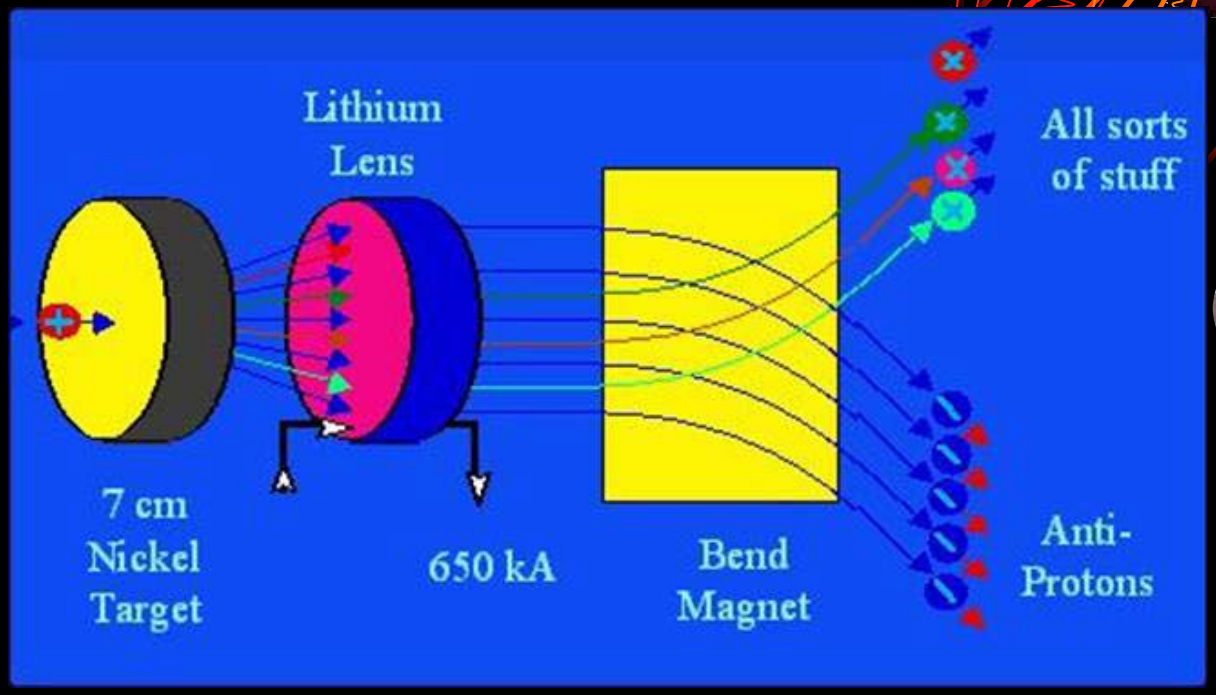
- Place H atom in an E field - strip away the e.
- p congregate on metal surface w/ cesium.
- Free e from metal/cesium combine with p.
- Incoming p smacks a H^- ion off the metal plate.
- H^- ion moves away from negative surface.
- Ions pass through a thin carbon foil to remove electrons.

P-bar Source



- 120 GeV p from MI smash into a Nickel target.
- For every 1 million p that hit the target, only ~ 20 8 GeV pbars survive to the Accumulator.

Lithium Lens



- Anti-protons (p-bars) pass through a Lithium Lens where they are focused.
- Bending magnets bend all anti-protons in one direction.

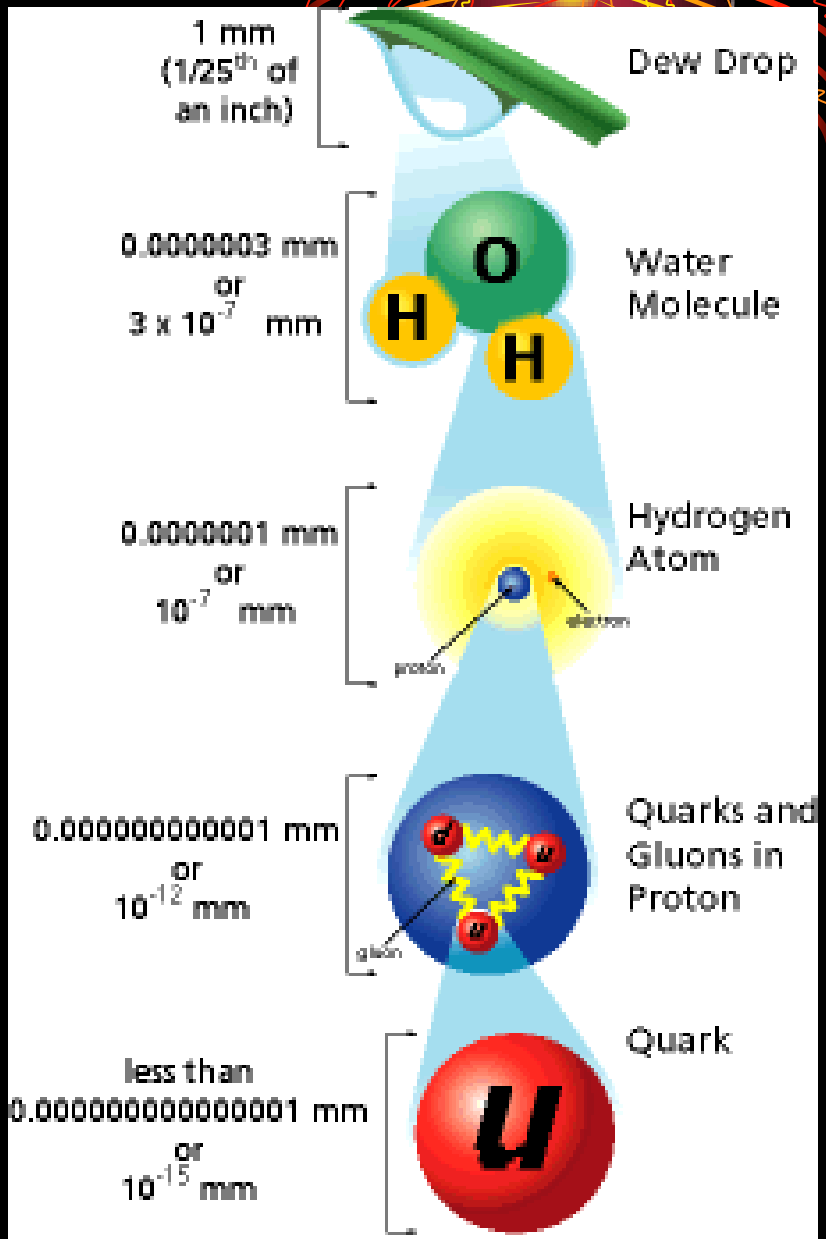
How Do You Detect Collisions?

- Use one of two large multi-purpose particle detectors at Fermilab (DØ and CDF).
- They're designed to record collisions of protons colliding with antiprotons at nearly the speed of light.
- They're basically cameras.

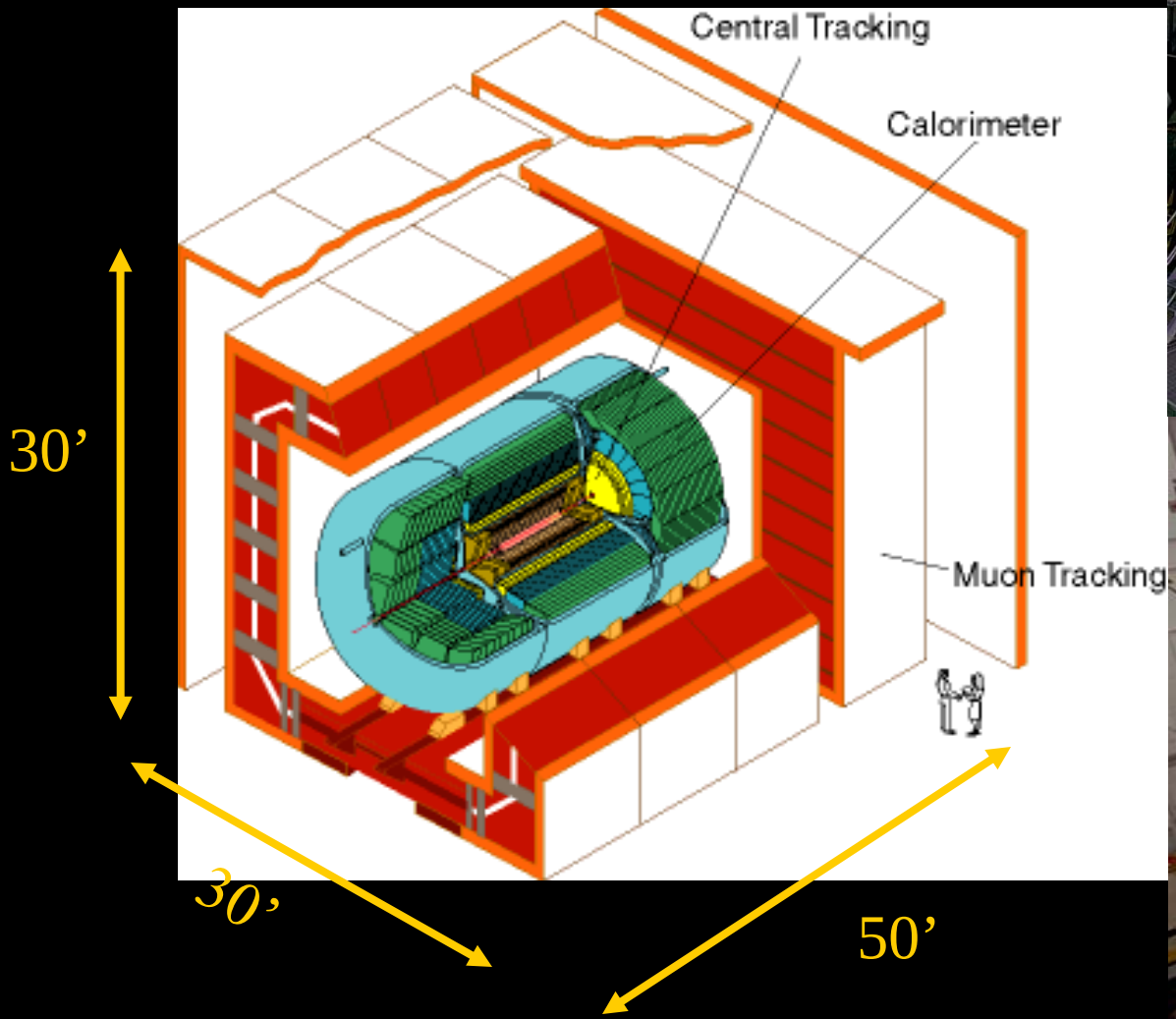
Main Control Room

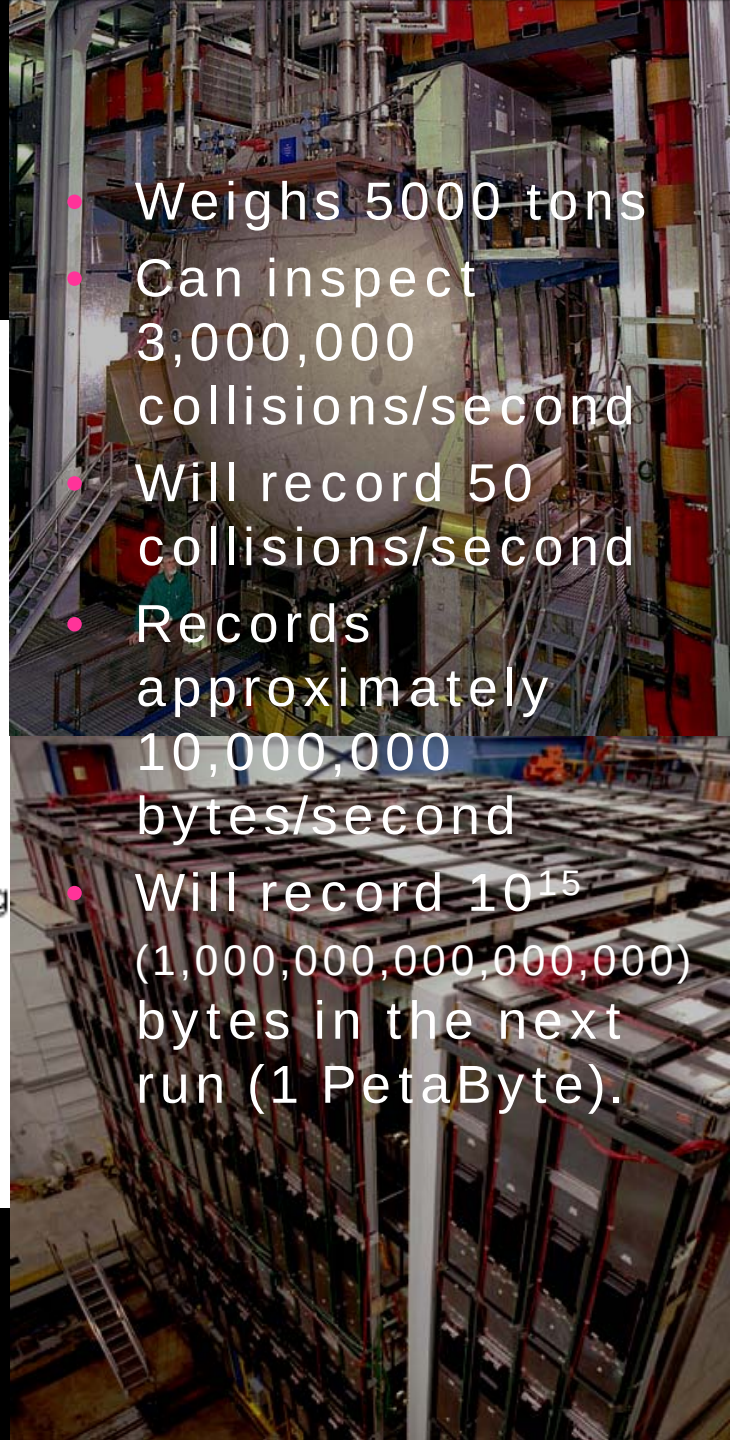
Building Blocks of a Dew Drop

- A dew drop is made up of many molecules of water (10^{21} or a billion trillion).
- Each molecule is made of an oxygen atom and two hydrogen atoms (H2O). At the start of the 20th century, atoms were the smallest known building blocks of matter.
- Each atom consists of a nucleus surrounded by electrons. Electrons are leptons that are bound to the nucleus by photons, which are bosons. The nucleus of a hydrogen atom is just a single proton.
- Protons consist of three quarks. In the proton, gluons hold the quarks together just as photons hold the electron to the nucleus in the atom.

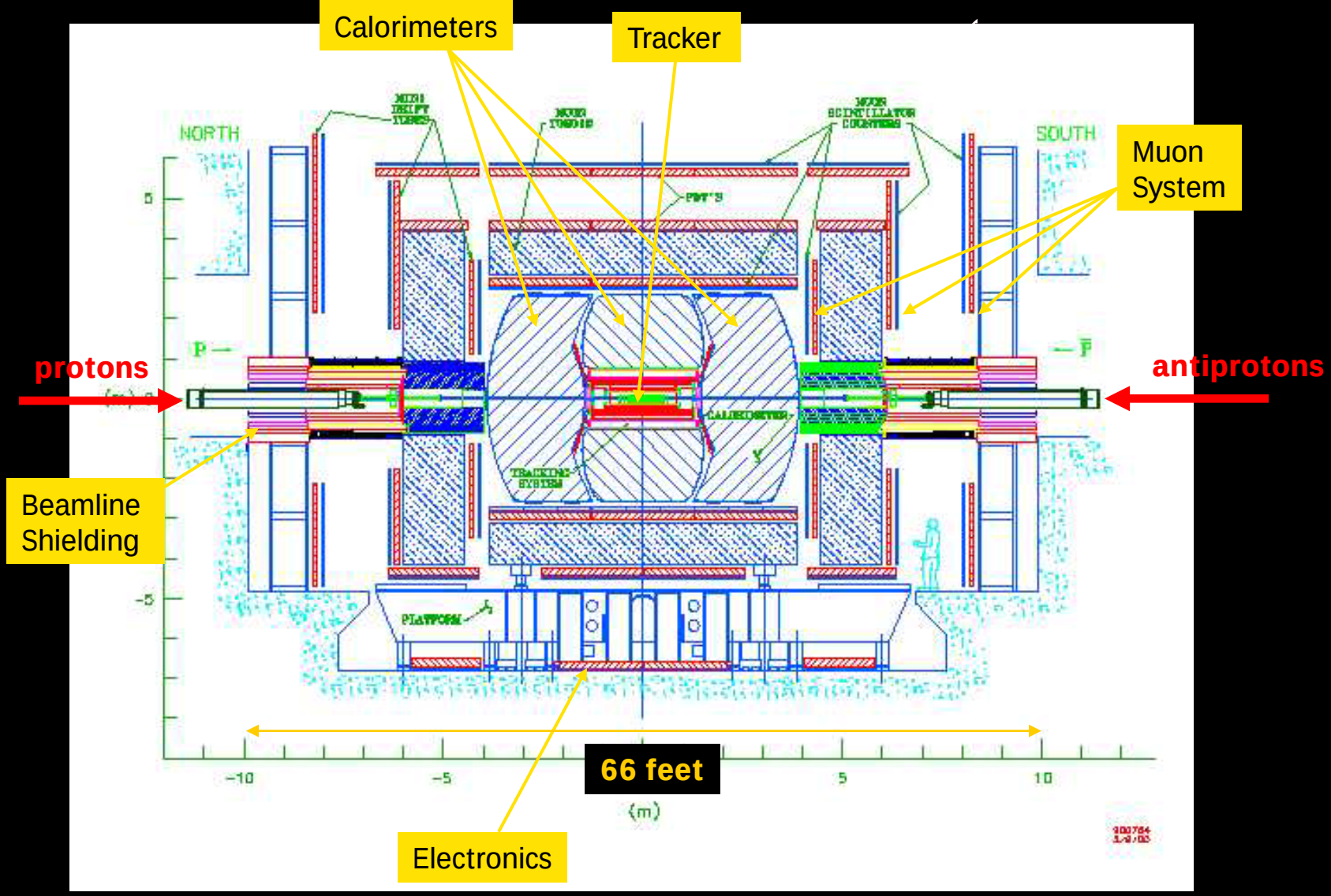


DØ Detector: Run II





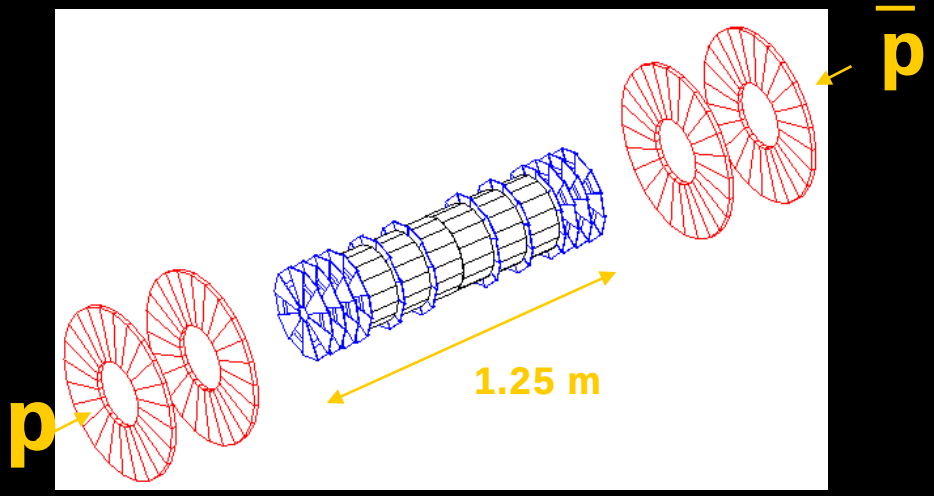
- Weighs 5000 tons
- Can inspect 3,000,000 collisions/second
- Will record 50 collisions/second
- Records approximately 10,000,000 bytes/second
- Will record 10^{15} (1,000,000,000,000,000) bytes in the next run (1 PetaByte).

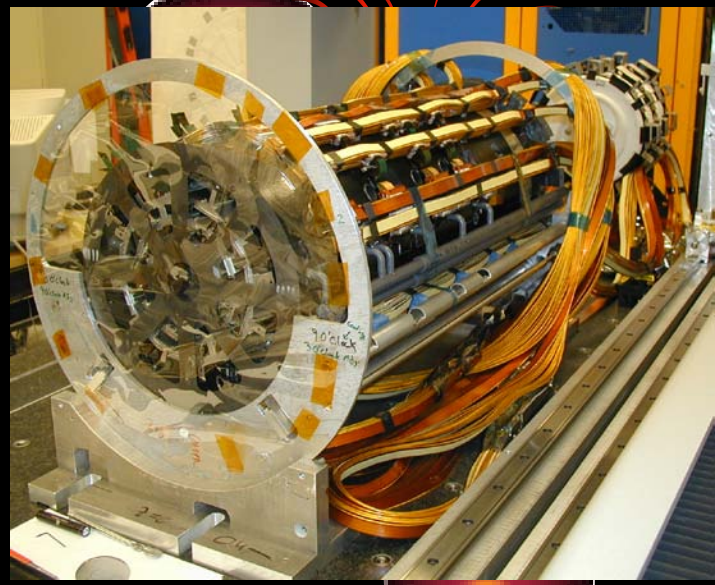


In Run II (March 1, 2001), the Fermilab Tevatron will deliver 10-20 times as many collisions per second as Run I.

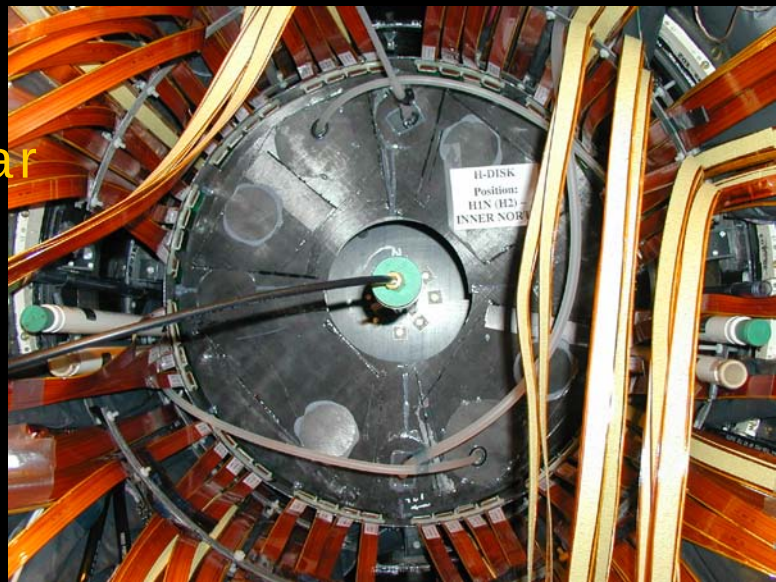
The DØ detector required an overhaul in order to cope.

DØ Silicon Tracker



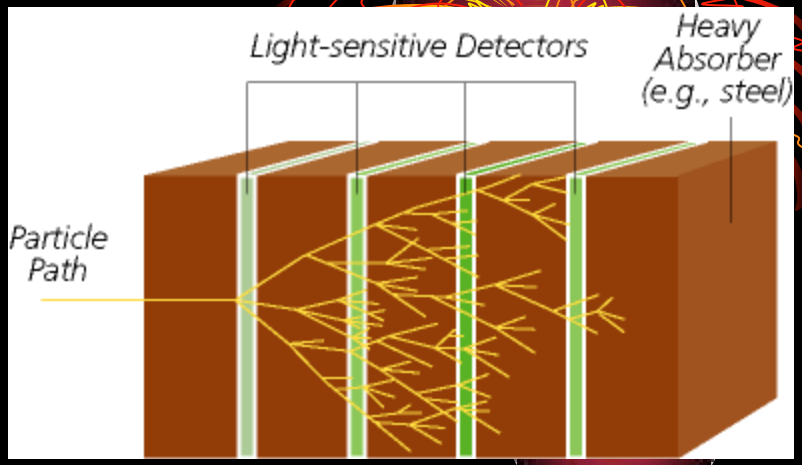


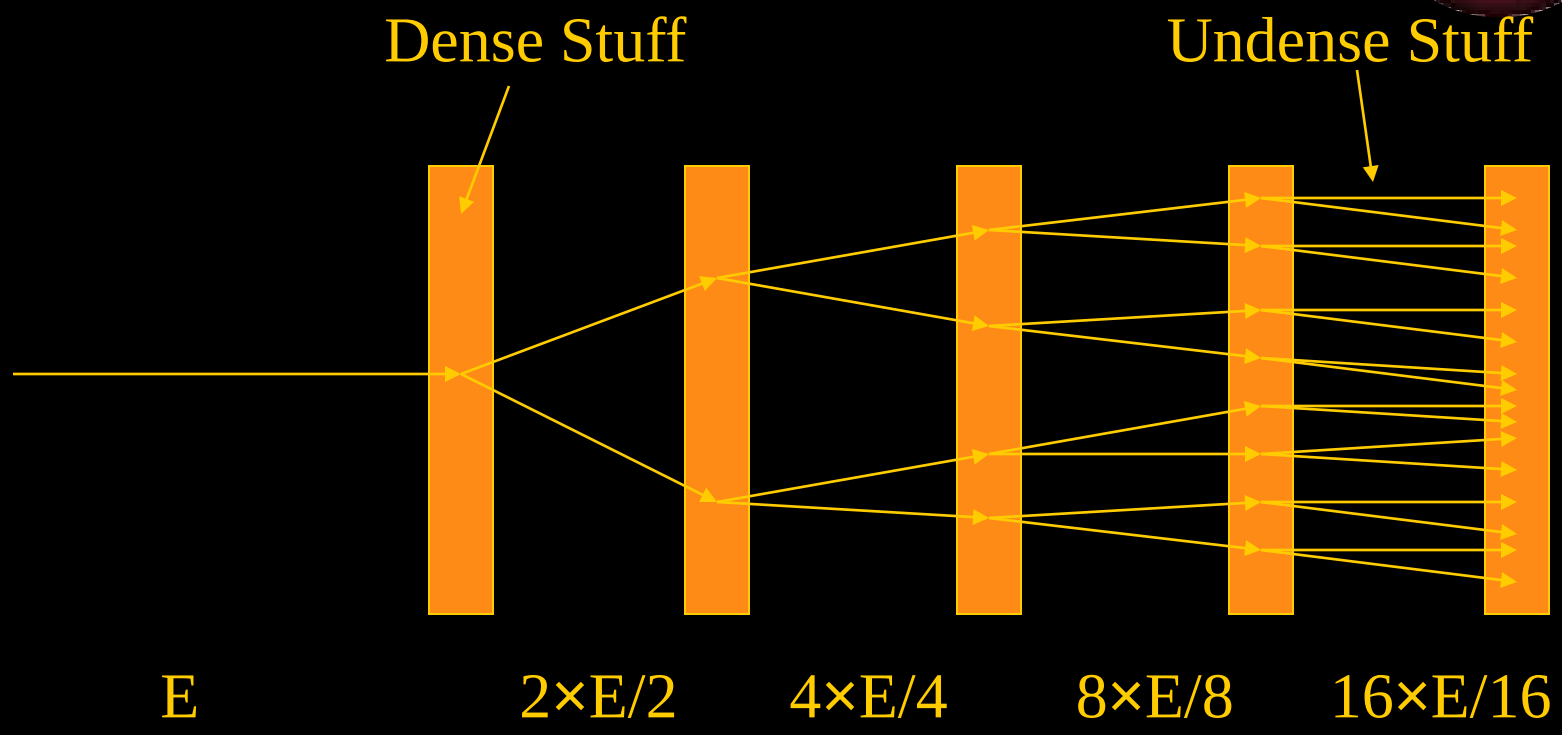
- 800,000 distinct detector elements.
- Very complex (fragile)
- Absolutely crucial for viewing the details of how particles behave near the collision.
- Particles that don't come from the collision point serve as 'flags' of interesting physics.



Calorimetry: Measuring Energy

A particle hits some dense stuff (like metal) and creates more particles, each of which have less energy. In the undense material you count particles. The number of particles is proportional to the energy.





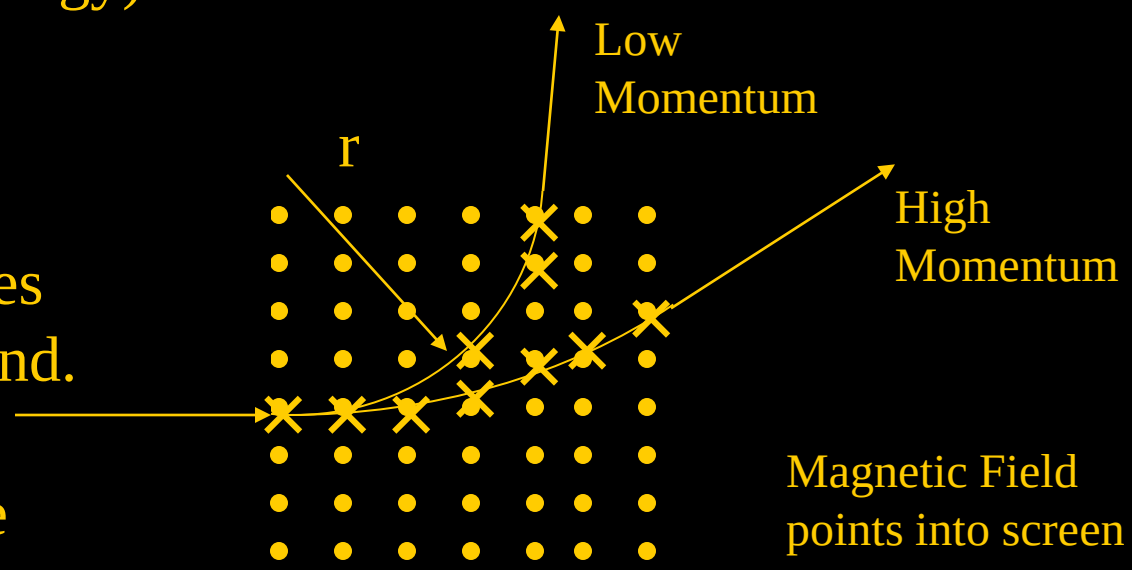
Measuring Momentum

$$F = qvB$$

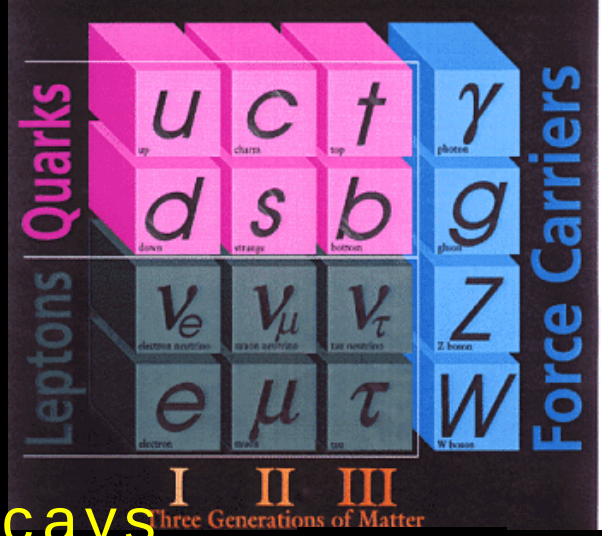
$$r = p/(qB)$$

F=force
v = velocity
r = radius of curvature
p (mv) = momentum (~energy)
q = electrical charge
B = magnetic field

The use of a magnet makes the path of the particle bend. Thus we can measure the momentum (related to the velocity)



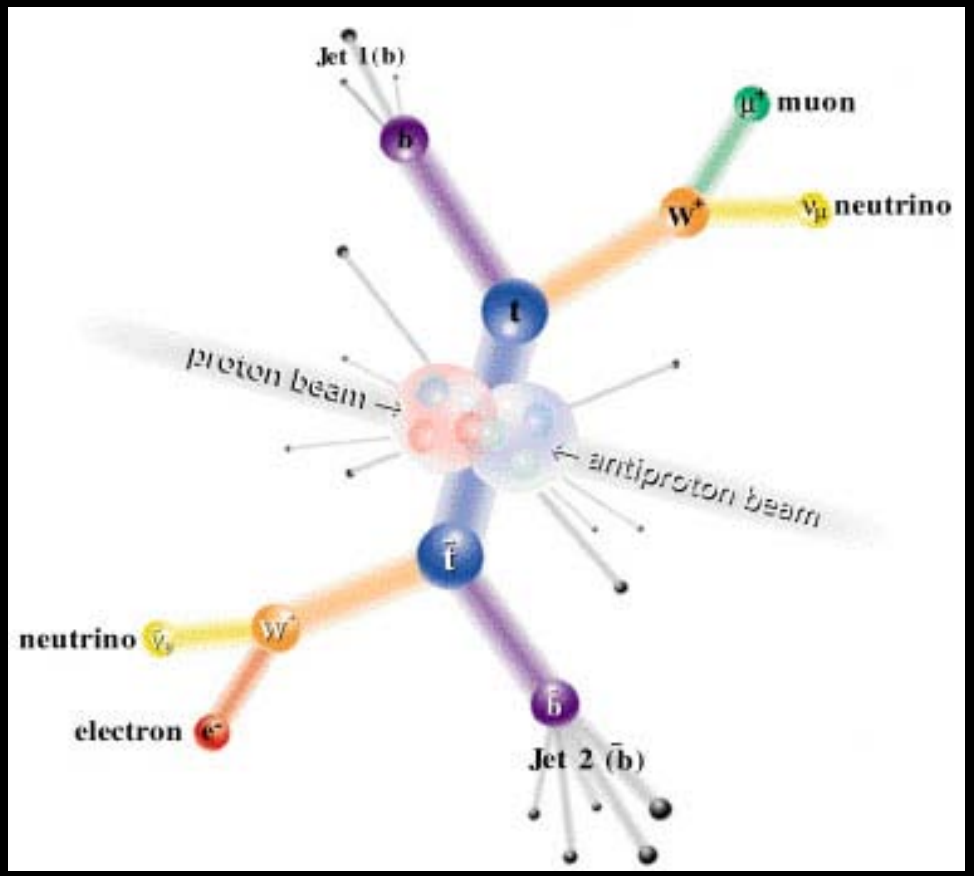
Top Facts

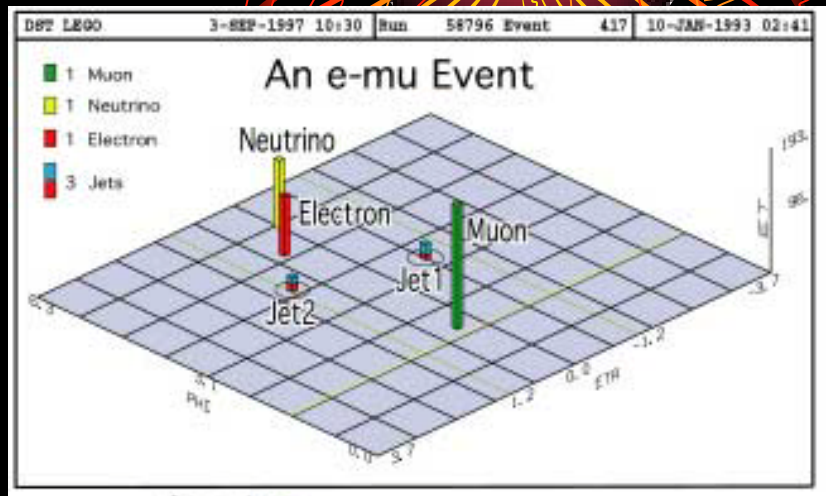


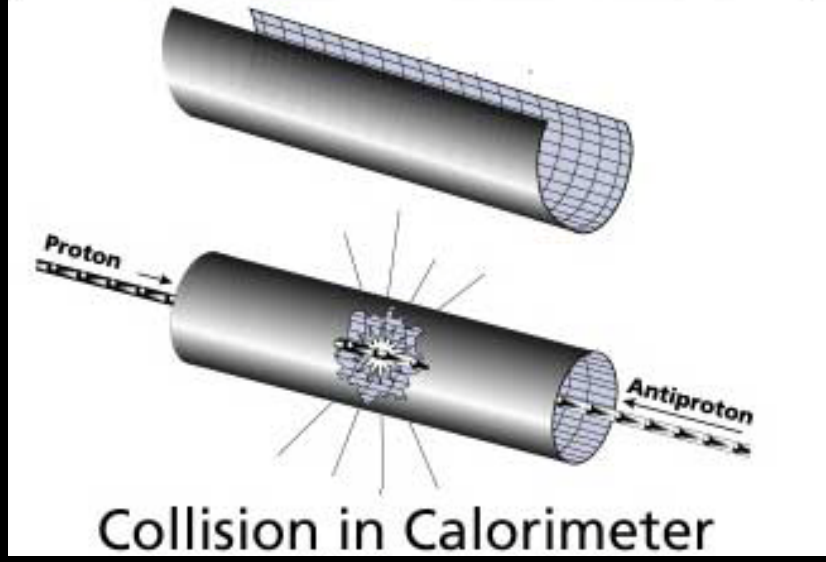
- In each event, a top and anti-top quark is created.
- ~100% of the time, a top quark decays into a bottom quark and a W boson.
- A W boson can decay into two quarks or into a charged lepton and a neutrino.

- So, an event in which top quarks are produced should have:
  - 6 quarks
  - 4 quarks, a charged lepton and a neutrino
  - 2 quarks, 2 charged leptons and 2 neutrinos

What Do Top Quarks Look Like?



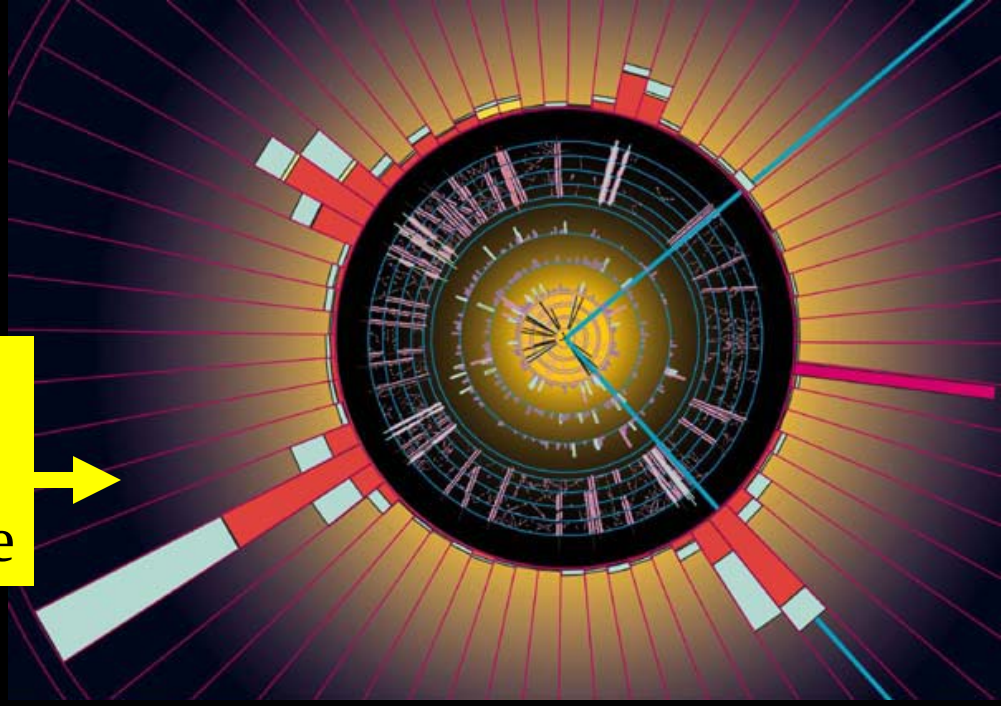


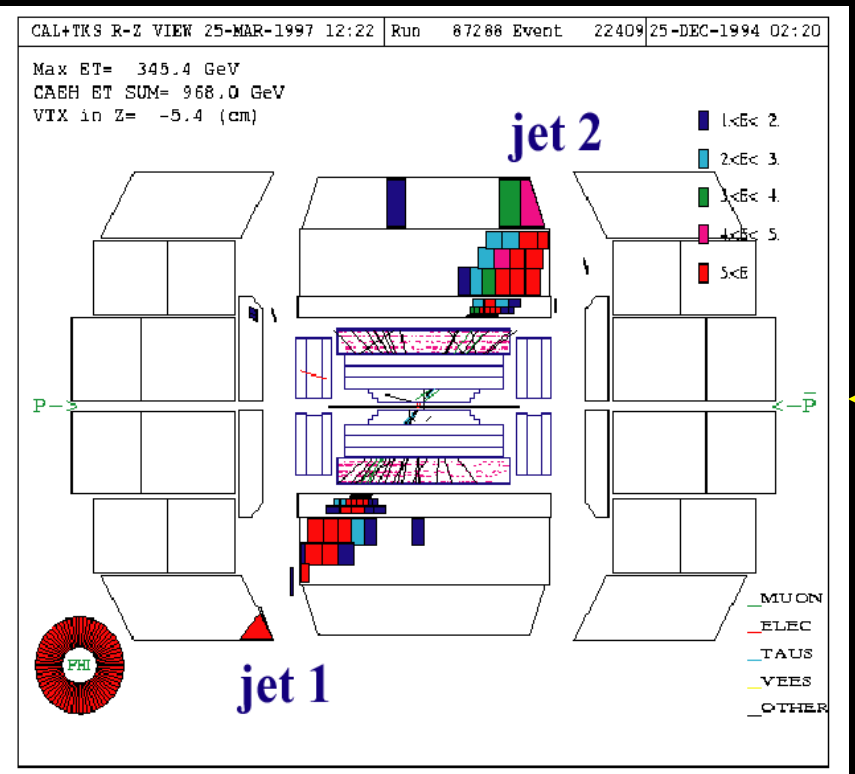


Top quarks are the heaviest particle known. Each one has the mass of an entire gold atom (while remaining among the smallest objects known).

Top Event

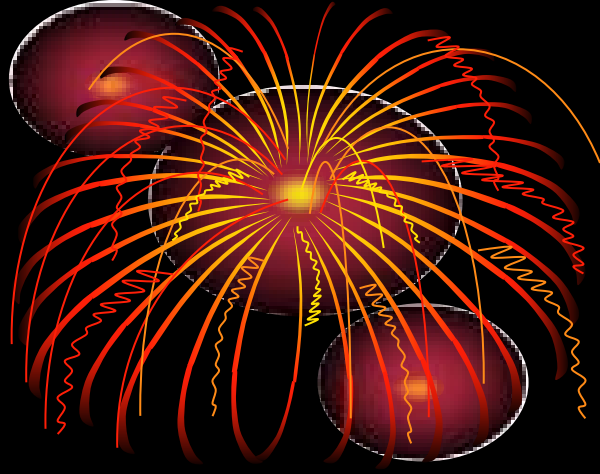
In this collision, a top and anti-top quark were created, helping establish their existence



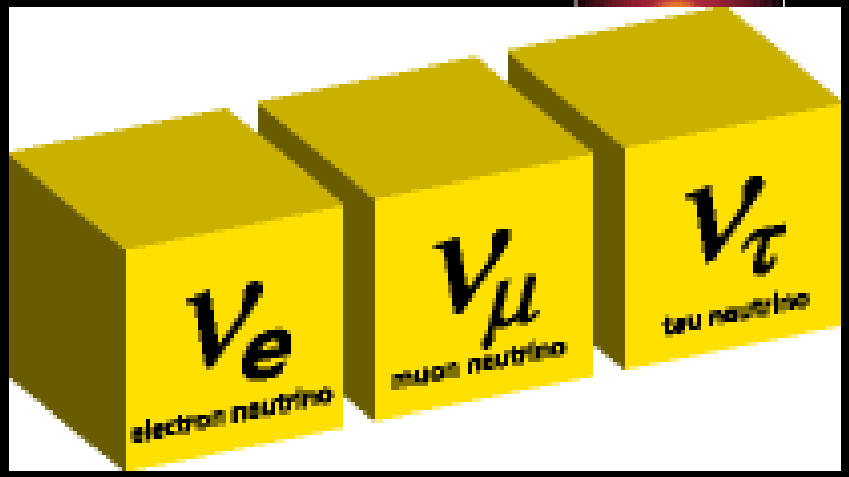


This collision is the most violent ever recorded (and fully understood). It required that particles hit within 10^{-19} m or 1/10,000 the size of a proton

Do neutrinos have mass?



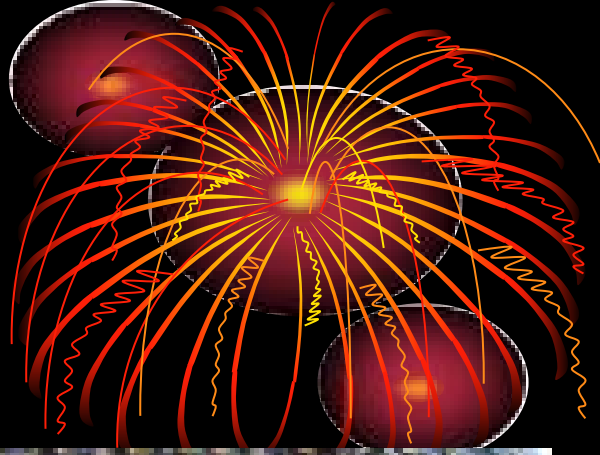
- Neutrinos are curious particles; they interact so weakly that 20 trillion of them come from the sun and pass through this room every second without any change whatsoever to either themselves or anything in this room.
- If neutrinos have mass, they might change from one type into another, an effect called oscillations.
- At Fermilab, physicists have two experiments, NuMI and MiniBooNE to see if muon neutrinos can change into electron neutrinos or tau neutrinos



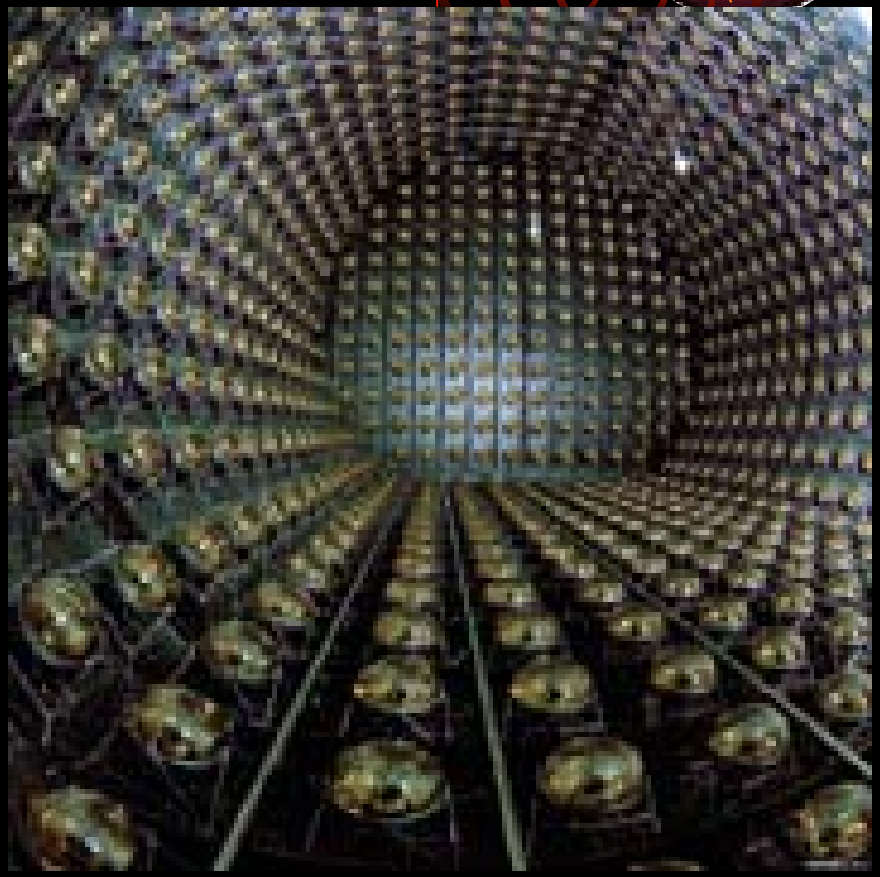
Neutrino Oscillations

- The NuMI experiment gives neutrinos more time to change, they will travel some 450 miles to a new detector in the old Soudan Mine in Minnesota.

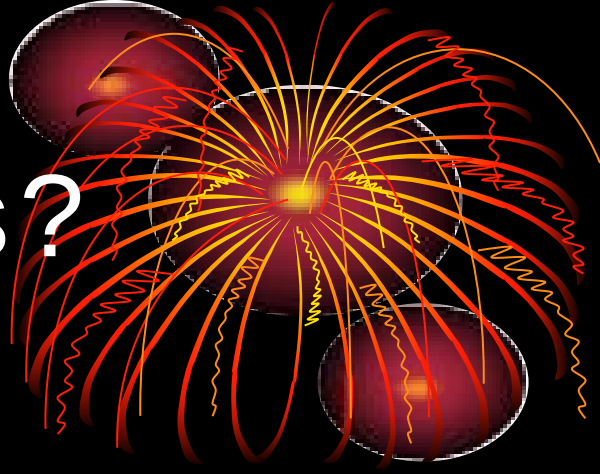
MiniBooNE



- The MiniBooNE experiment on the left will use the Fermilab Booster to improve the sensitivity of an experiment conducted at Los Alamos National Laboratory.
- It aims to prove or disprove a controversial signal in the liquid scintillation neutrino detector in which physicists believe they have seen a signal for oscillations.



Why is there mass?



- Stars, people, and insects all have mass because the particles they are made of have mass. But, not all types of particles have mass.
- Why do some have mass and others don't?
- Why does a top quark have about 40 times as much mass as a bottom quark?
- One theory for mass requires a new heavy boson, called the Higgs, which has yet to be discovered.

In 1993, William Waldegrave, the British Science Minister, Announced a contest, the prize for which was none other than a bottle of very good champagne.

The contest? Explain how the Higgs mechanism works in simple terms.

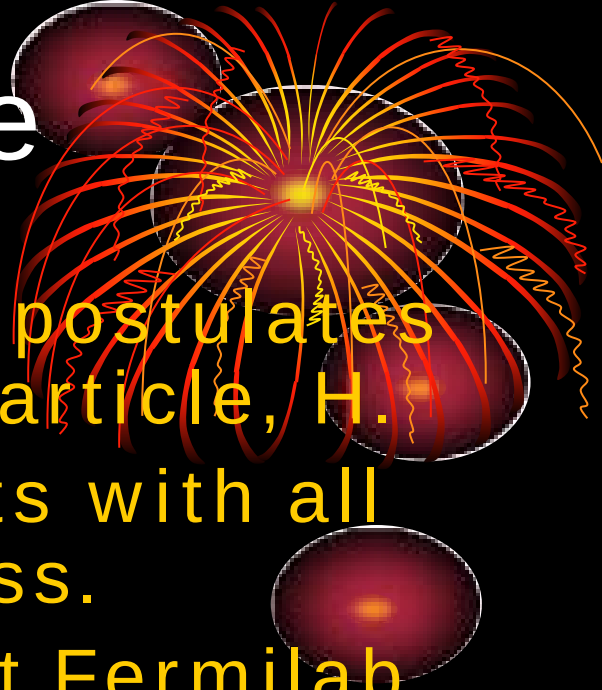
The winner:

David Miller

Particle gains mass

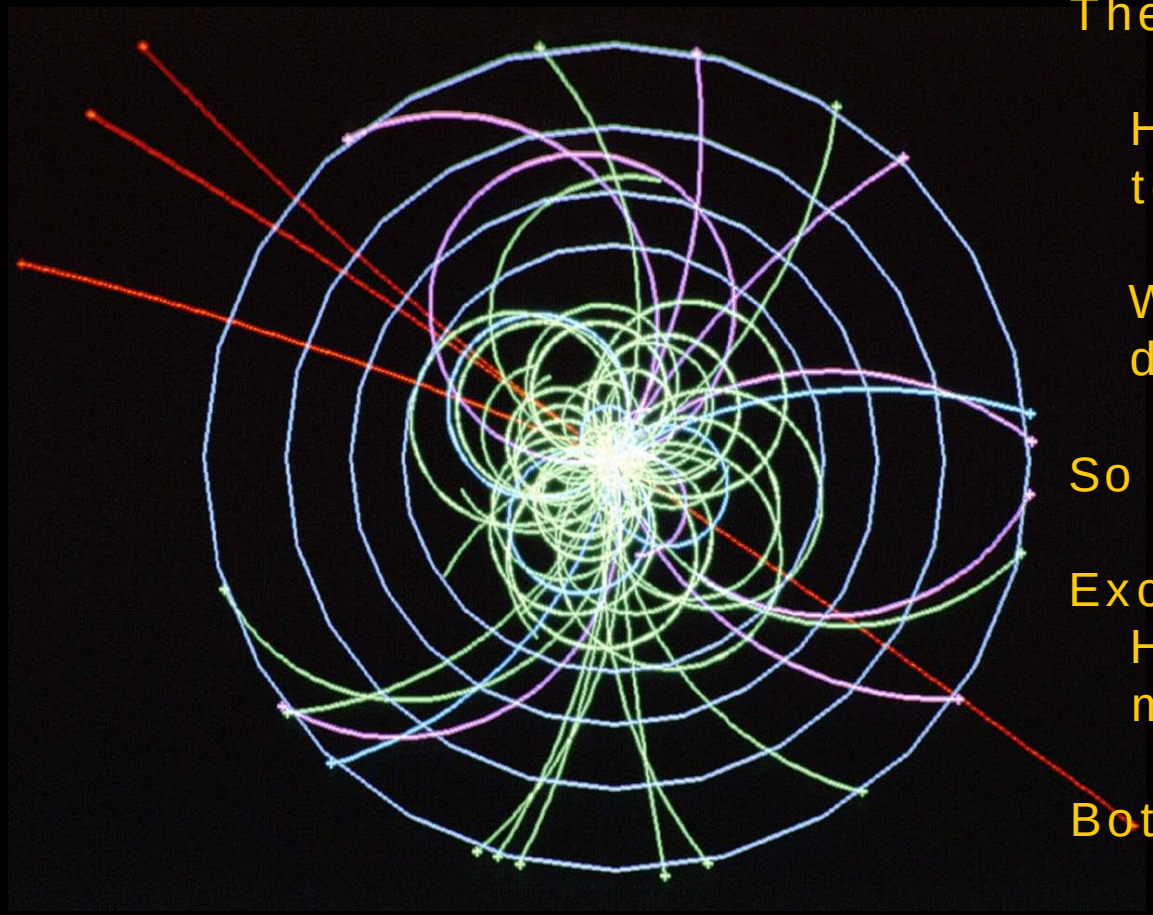
Higgs boson manifests

The Higgs Particle



- The electroweak unification postulates the existence of the Higgs Particle, H.
- This particle or field interacts with all other particles to impart mass.
- The experimental program at Fermilab in Illinois and the Large Hadron Collider in Europe are dedicated to the search for this particle.
- It's discovery would be an achievement of the highest order – reaching an understanding of the origins of mass!

How do you find a Higgs Boson?



The Challenge:

Higgs is ×10 rarer than the top quark was.

We will have ×10 times more data to look through.

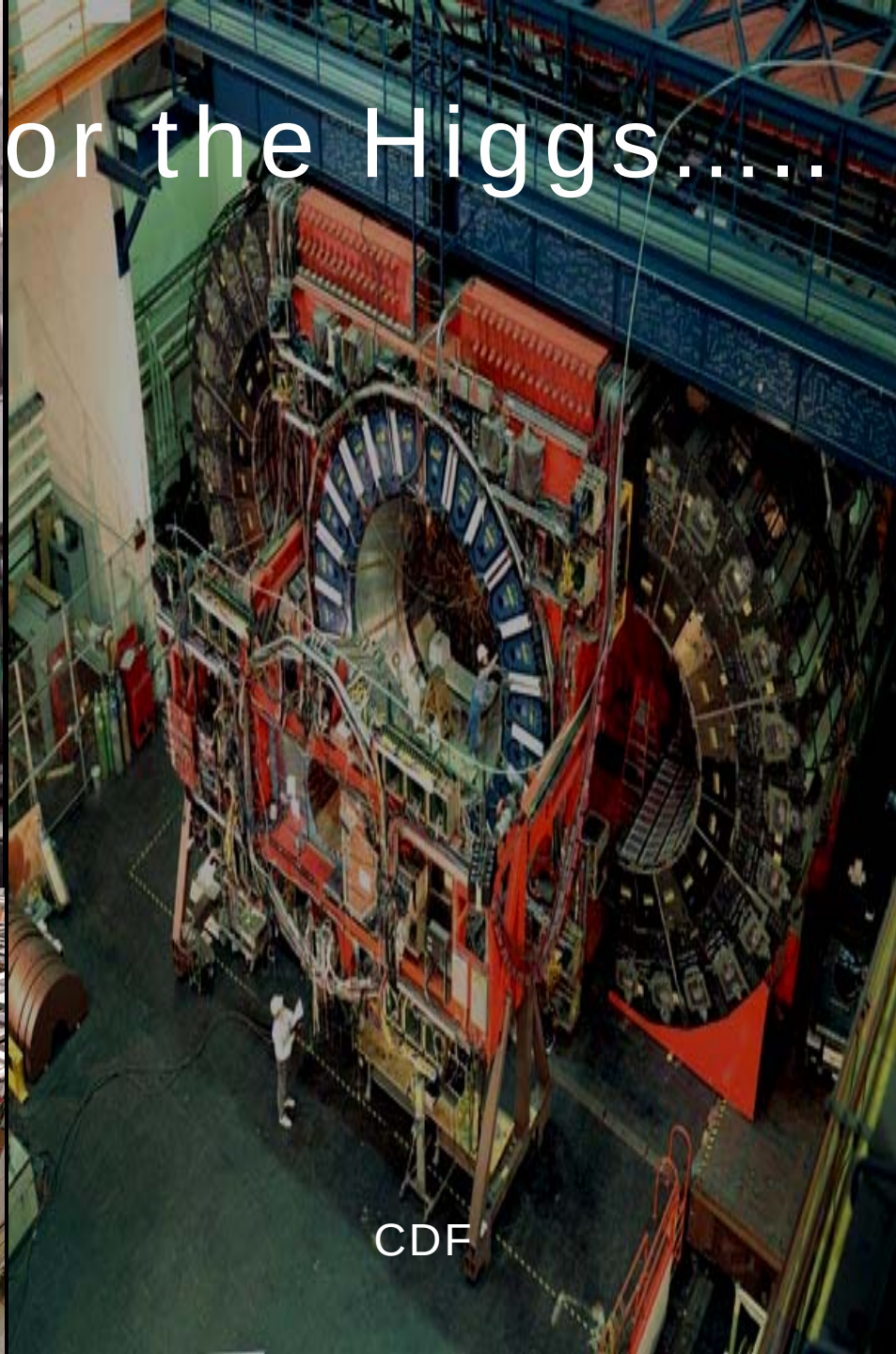
So it's a wash....

Except...things that look like a Higgs Boson, but aren't are much more common.

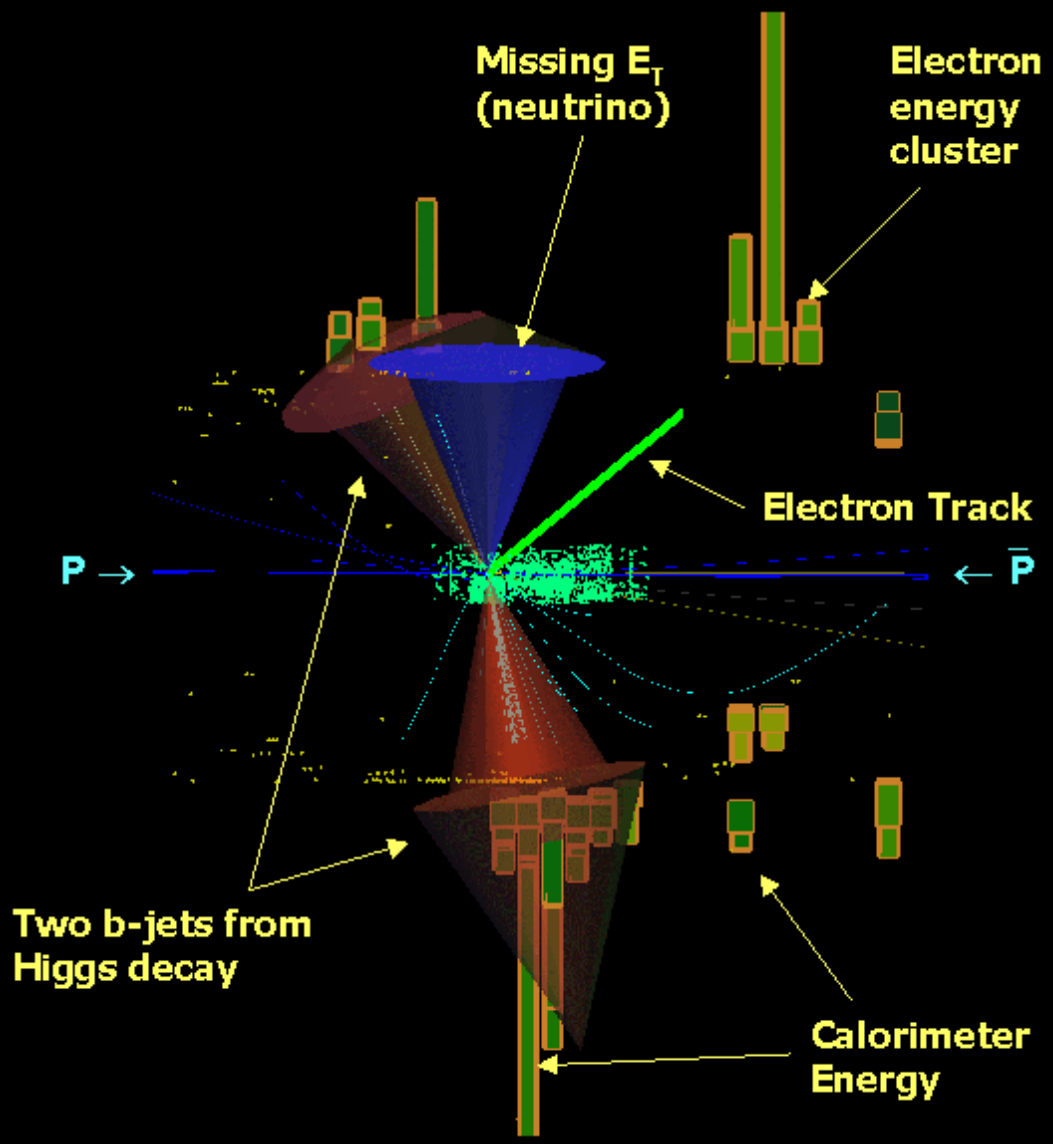
Bottom line

It's going to be hard!

Who’s looking for the Higgs.....



Higgs Event


Missing E_T
(neutrino)
Electron
energy
cluster
Electron Track
P →
← $\bar{P}$
Two b-jets from
Higgs decay
Calorimeter
Energy

CERN

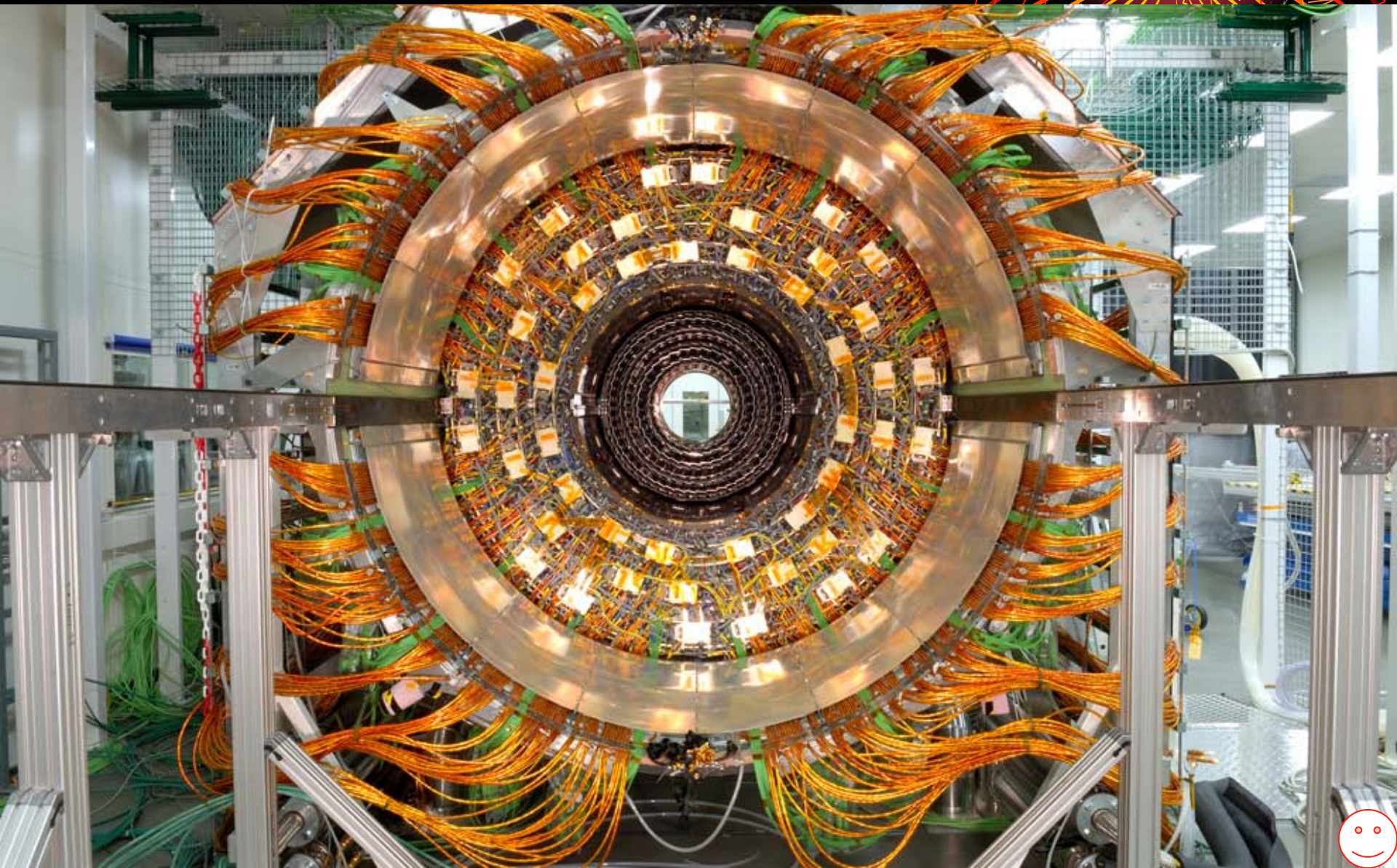
The Globe @ CERN

ROUTE A. EINSTEIN
CERN

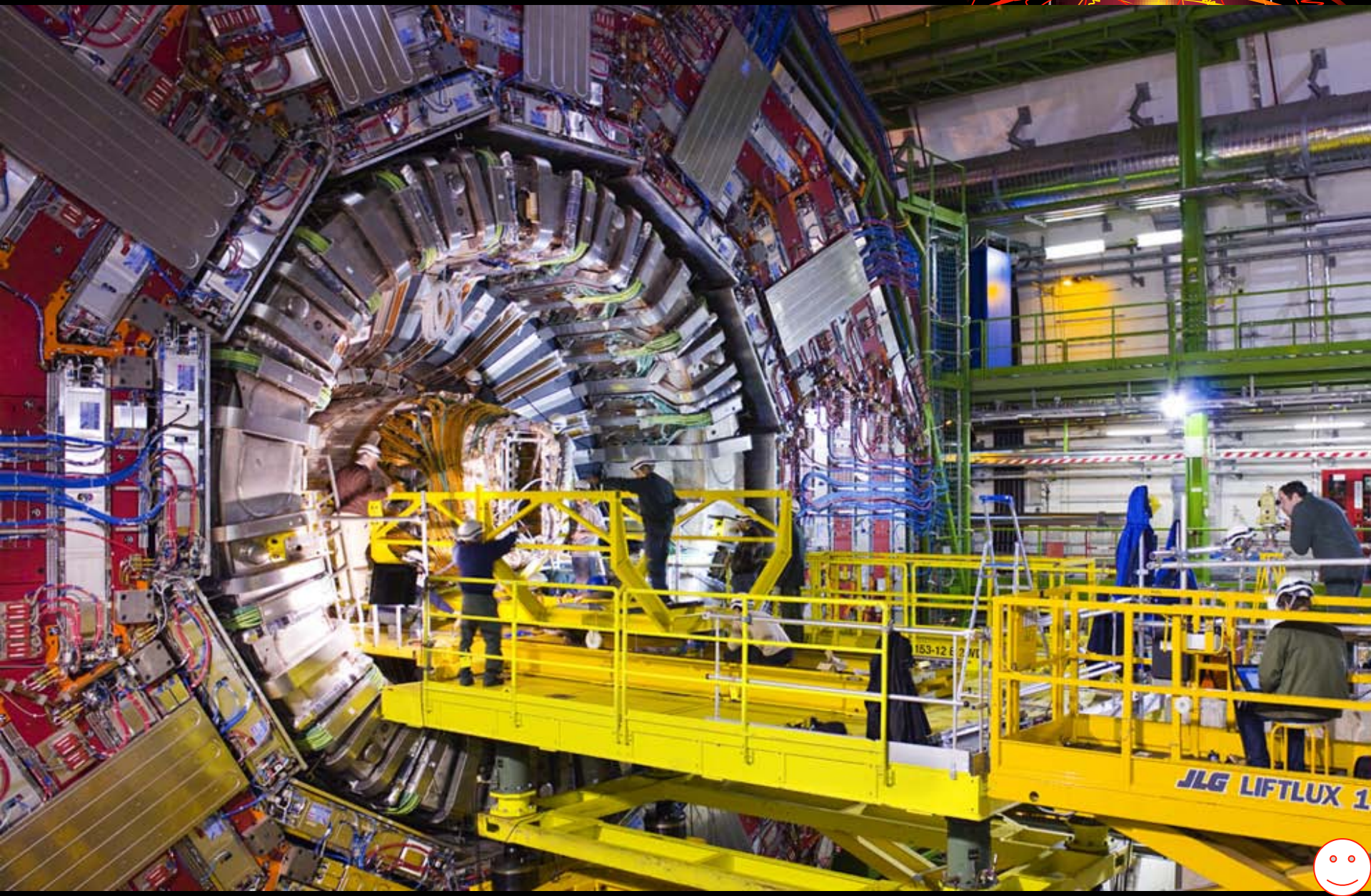
Pierre AUGER

124
124

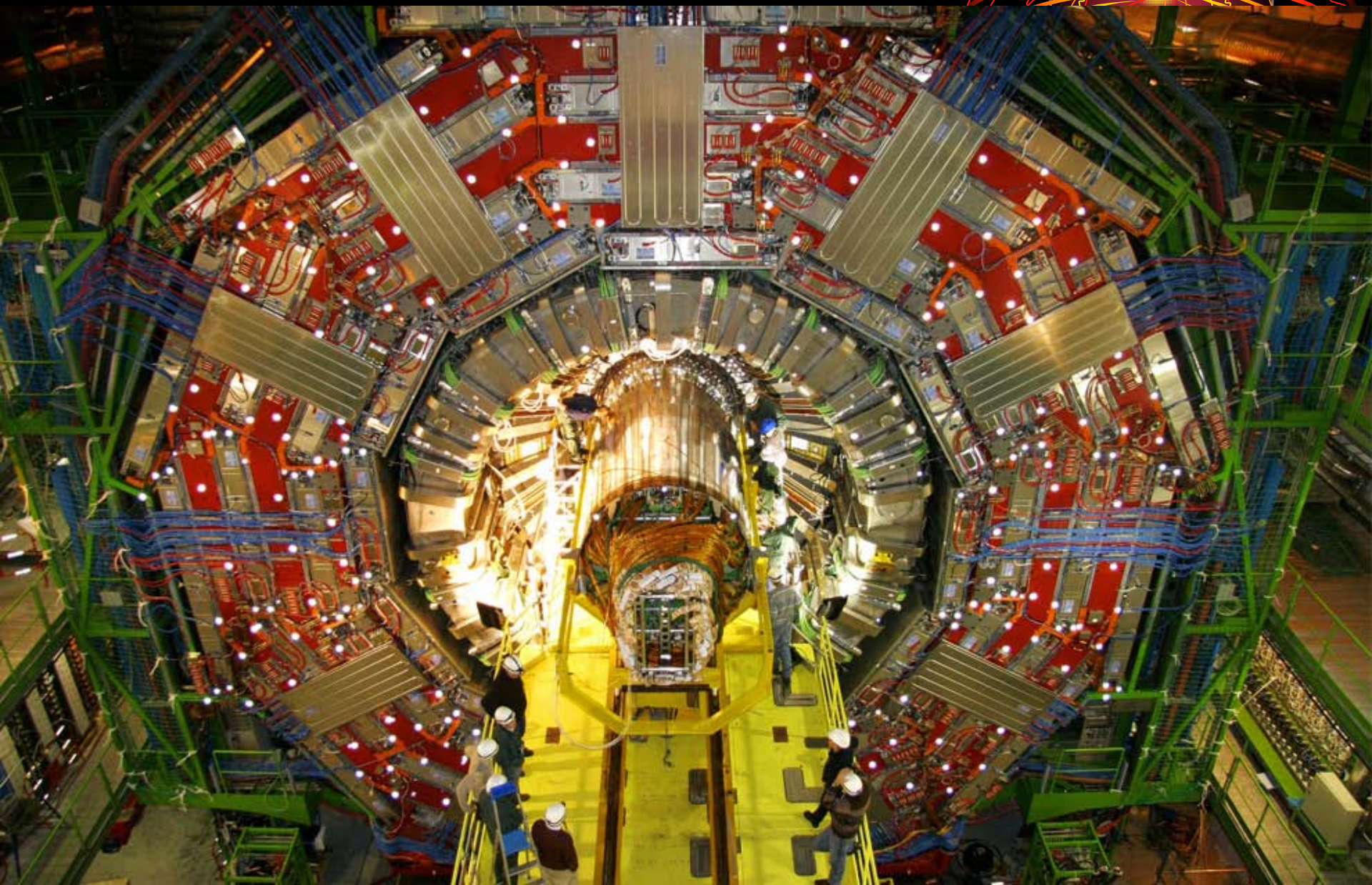
Outer Barrel @ the TIF



CMS: Compact Muon Solenoid



Inserting the Silicon Tracker



LHC: Large Hadron Collider Tunnel

A Few of the Unsolved Questions

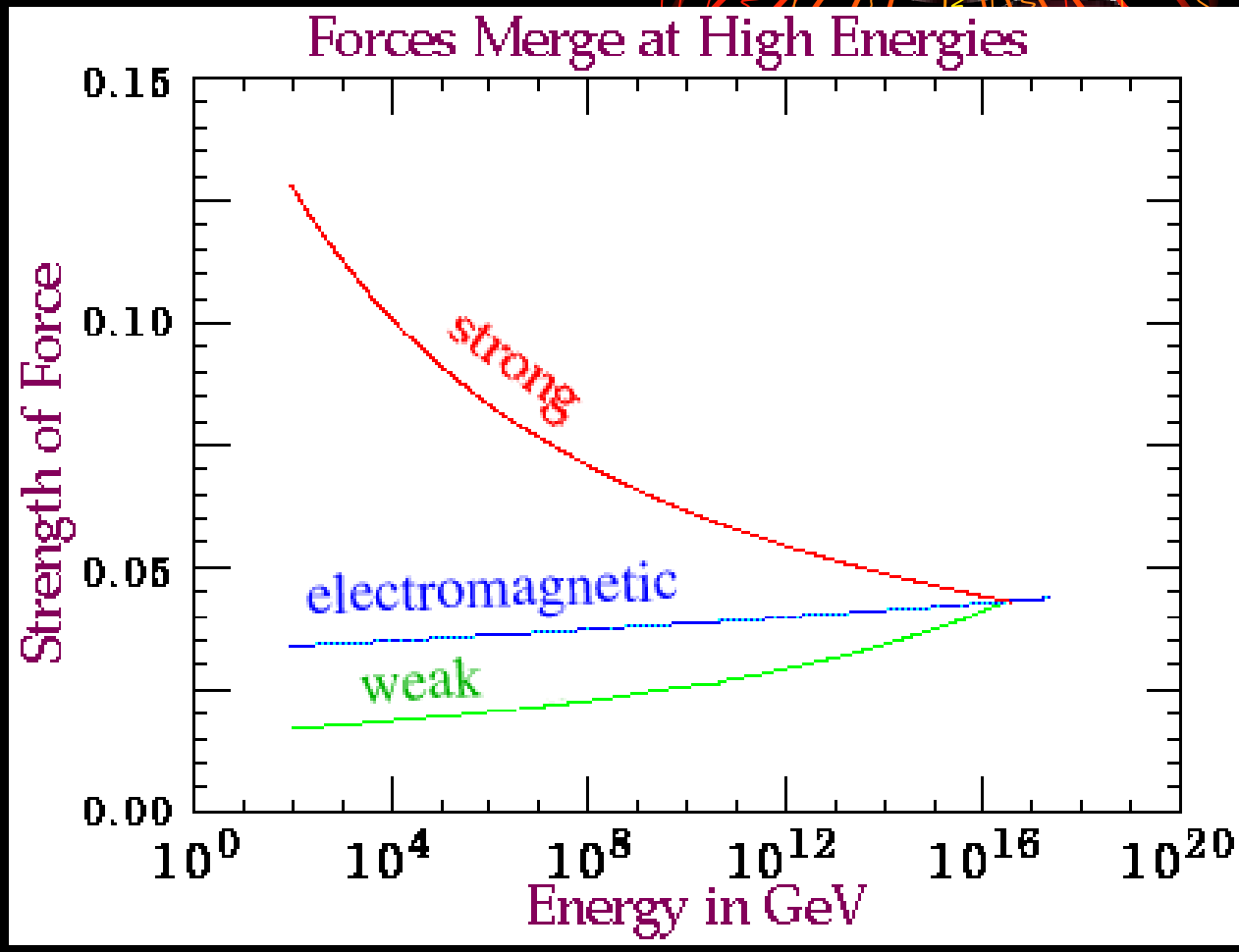
- Can the forces be fully unified?
- How do particles get mass?
- How does gravity fit into all of this?

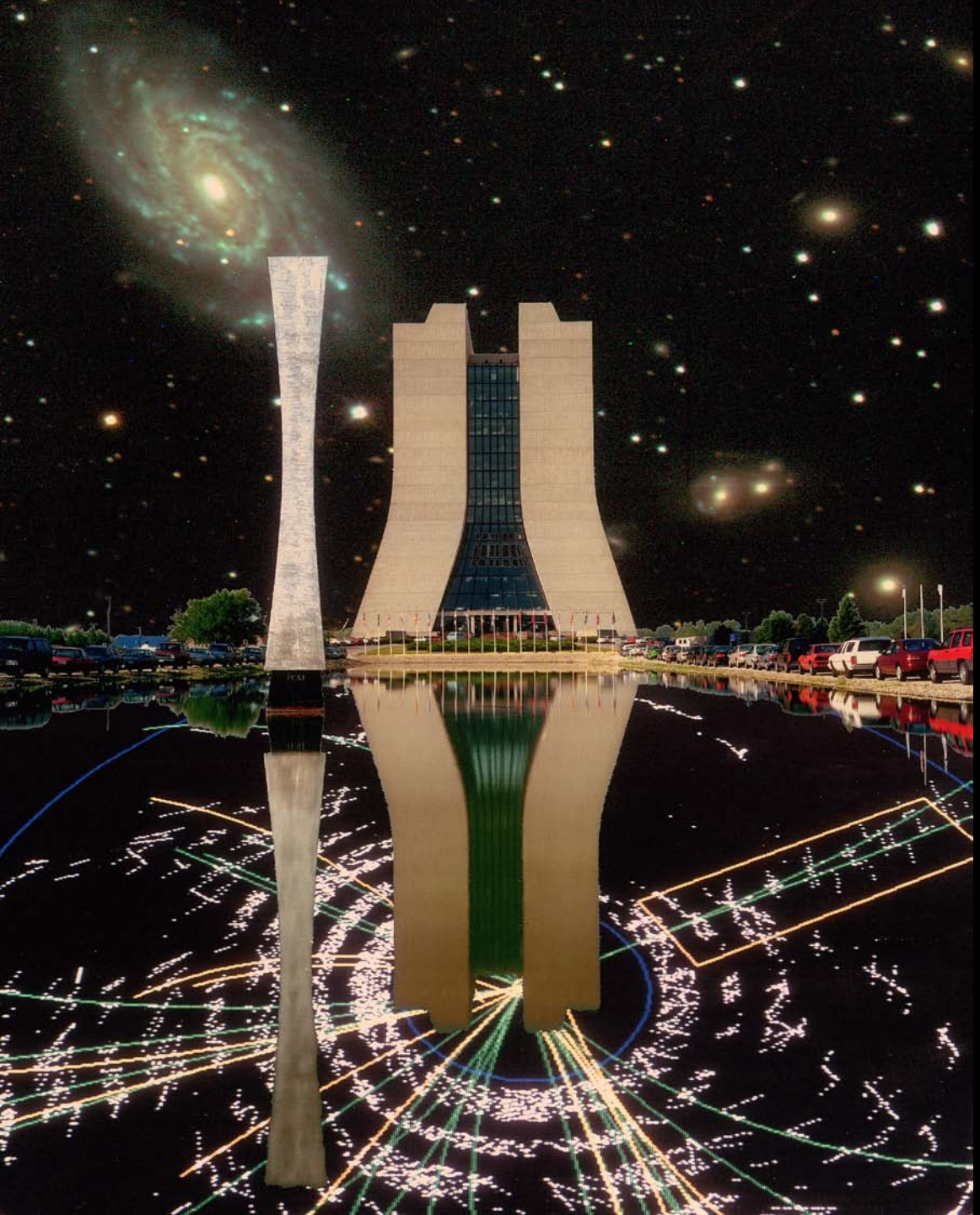
Extra Dimensions

- Amazingly enough an 11 dimensional world (time, 3-D, 7 very small less than 1mm in size) can accommodate a fully unified theory!
- Only gravity can communicate to the other dimensions and so it's "strength" is diluted in ours. That is, the graviton can spread it's influence among all 10 spatial dimensions.
- Experiments are underway searching for signals of these dimensions.

Grand Unified Theories(GUTs)

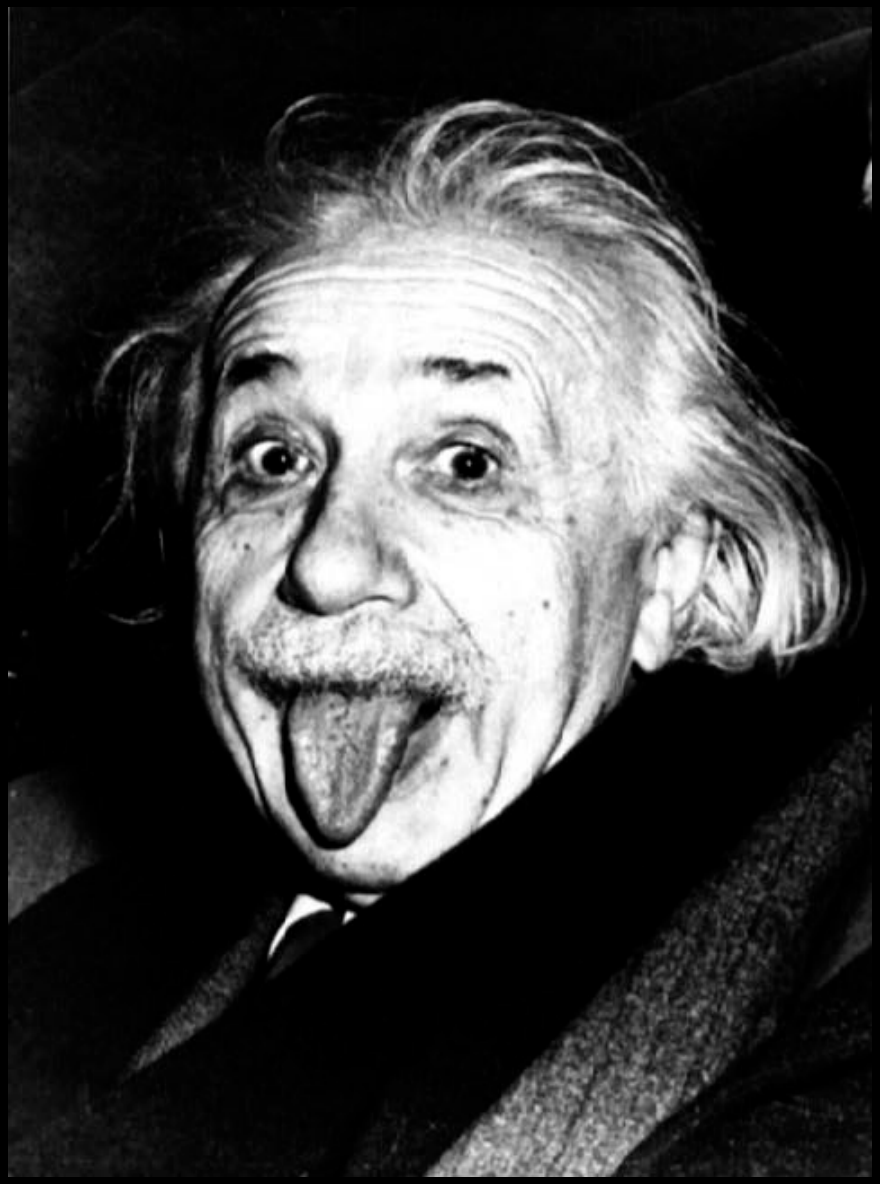
At very high energies all interactions merge to a single force.





"The most exciting phrase to hear in science, the one that heralds new discoveries, is not 'Eureka!' (I found it!), but 'That's funny...' "

-- Isaac Asimov



$E = m c^2$

Energy is Matter
Matter is Energy

Lots of energy makes lots of matter

and vice versa!!!!!!

Looking for particles is like .....