Why We Believe In Quarks

What Is Everything Made of?

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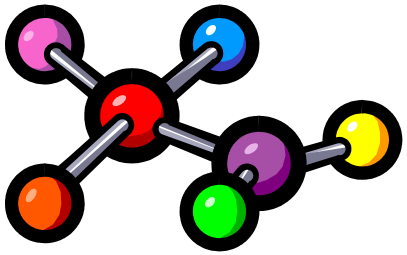
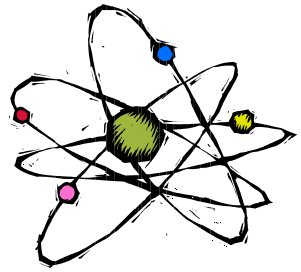
The Picture as of Today from the top down…

- **Things.**
  - Stars, planets, trees, buildings, people, cats…
    - **When? Forever.**

Old picture:
Fire, Water, Earth Air…

- **Molecules.**
  - Water, lactose, fructose….
    - **When? 1800-1900.**



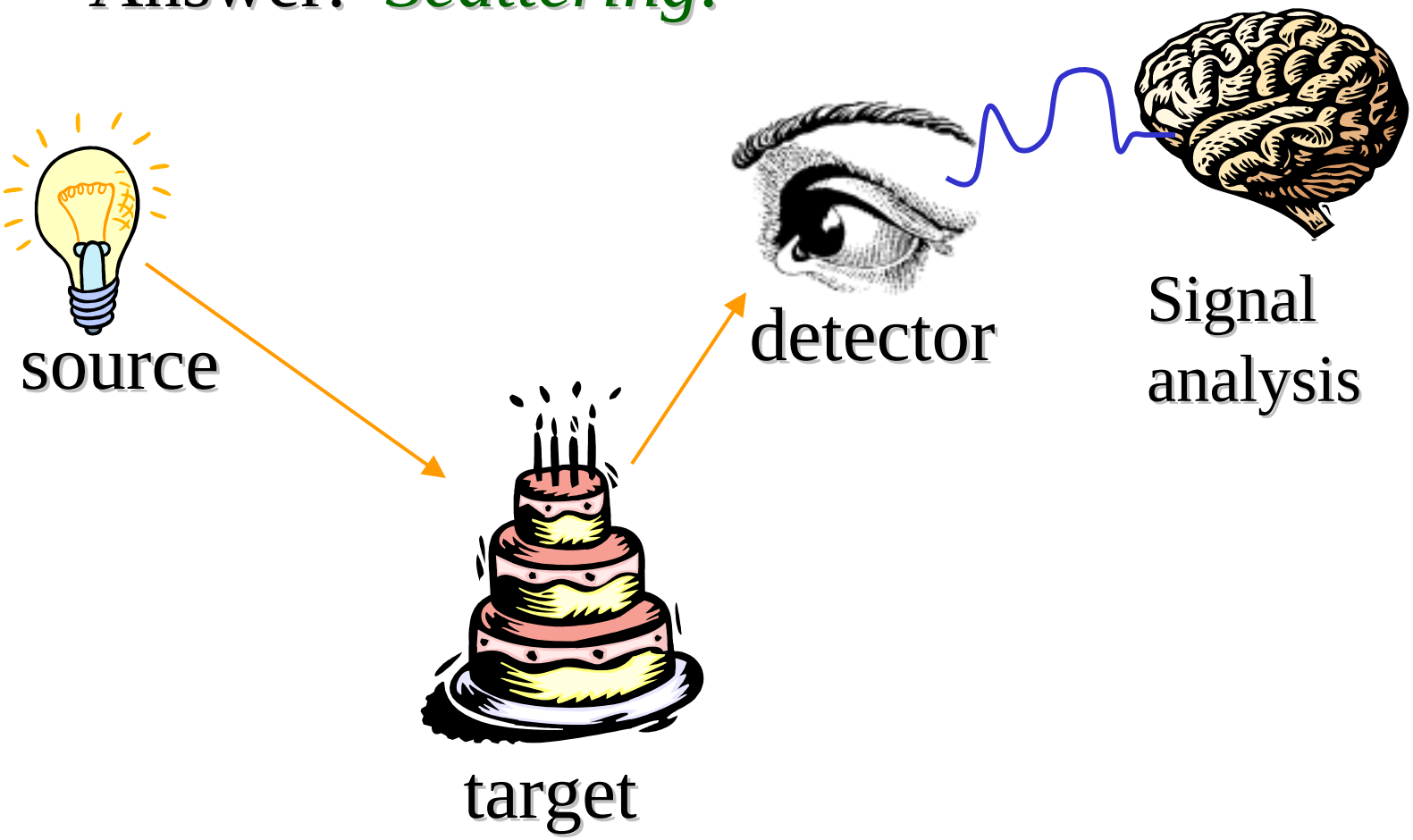


- **Atoms.**
  - Hydrogen, Helium….Iron…Gold… Uranium…
    - **When? 1869.**
- **Nuclei** and **Electrons.**
  - **When? 1897 (electron).**
  - **When? 1911 (nucleus).**

- **Protons** and **Neutrons.**
  - **When? 1932 (neutron).**
- **Quarks.**
  - **When? 1970.**

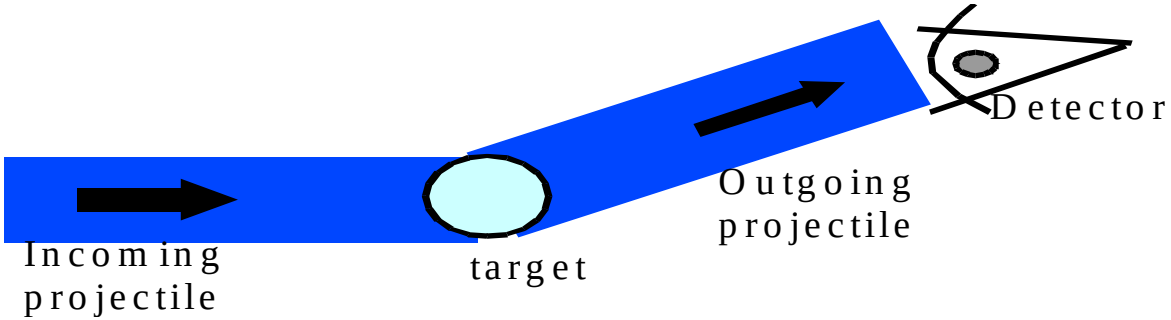
How do you see what something is made of?

Answer: *Scattering.*



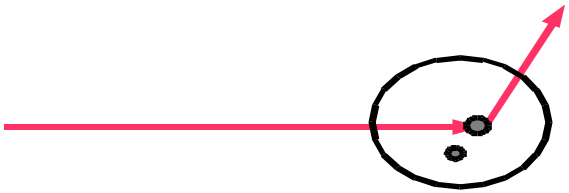
Scattering Diagram.

Low Resolution



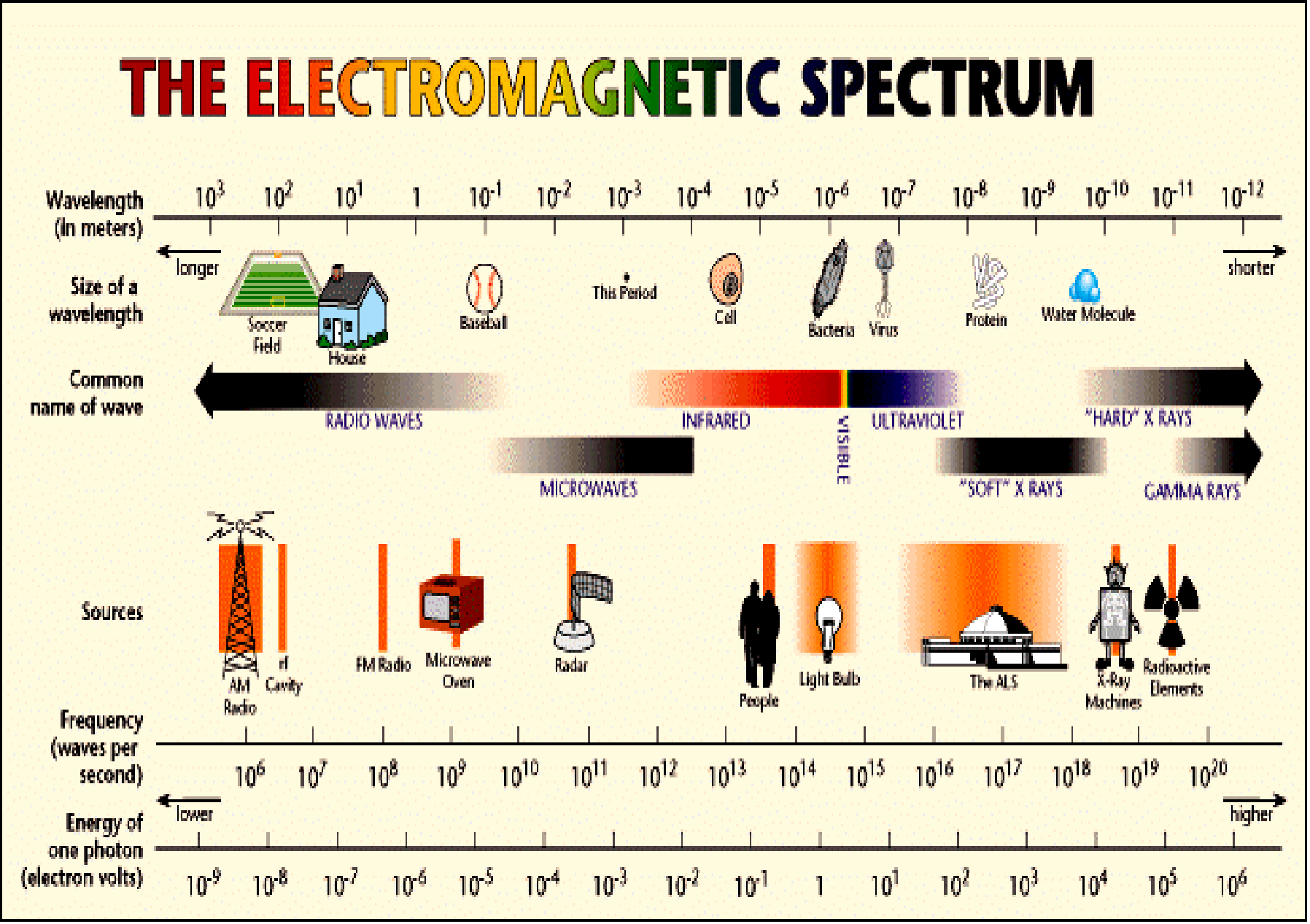
Large wavelength, low energy, target looks like a big blob.

High resolution



Small wavelength, high energy, constituents of targets become visible

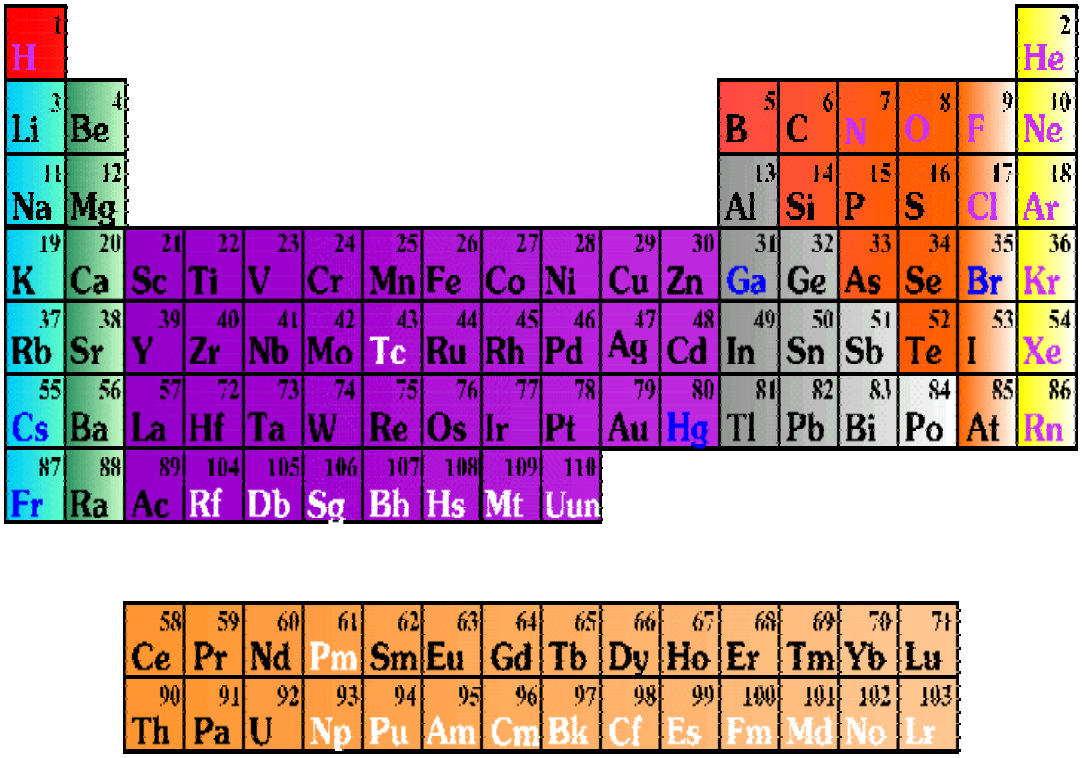
What's *wavelength?*



Visible light is a tiny, tiny part of the electromagnetic spectrum.
But only recently have we become aware of that.

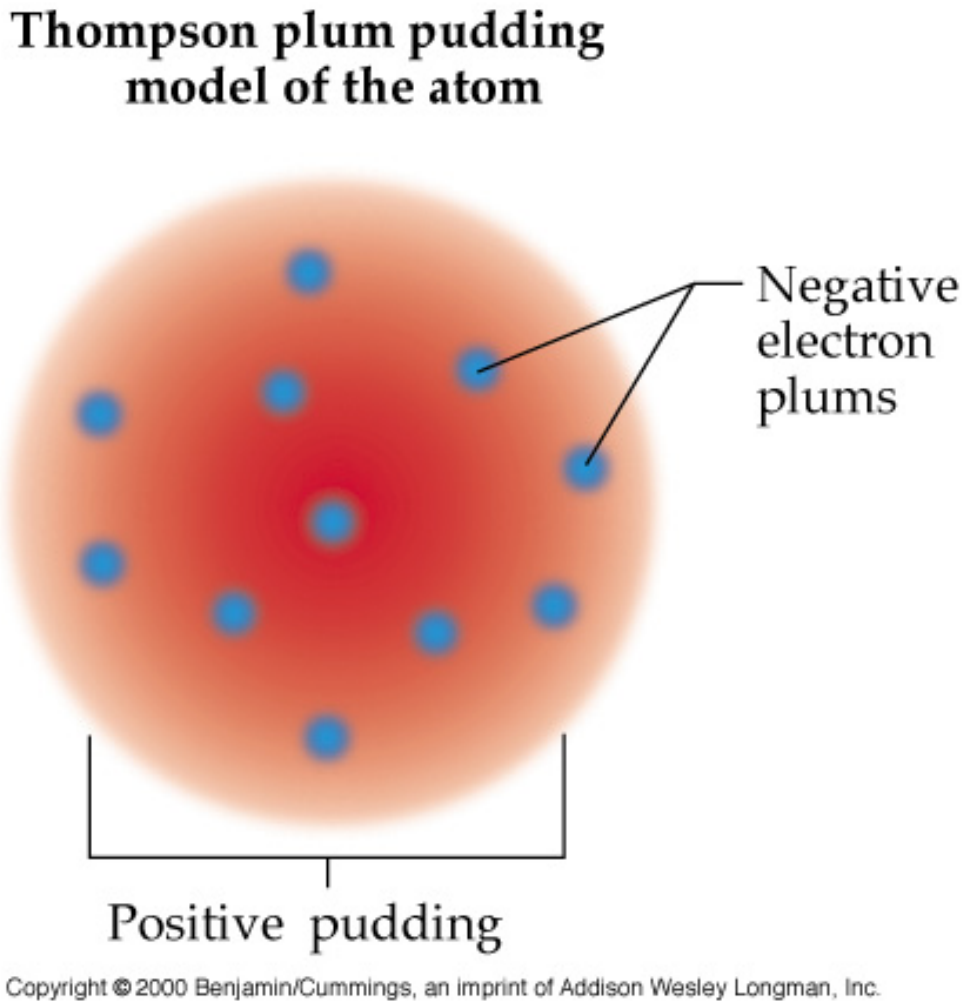
What are things made of ~1900

- **Dmitrii Mendeleev:** Periodic Table of Elements.
  - Everything is made up of mixtures of pure elements (*ATOMS*).
- **JJ Thompson:** electron.
  - ATOMS can eject these small, negatively charged bits that are also the carrier of electric current.

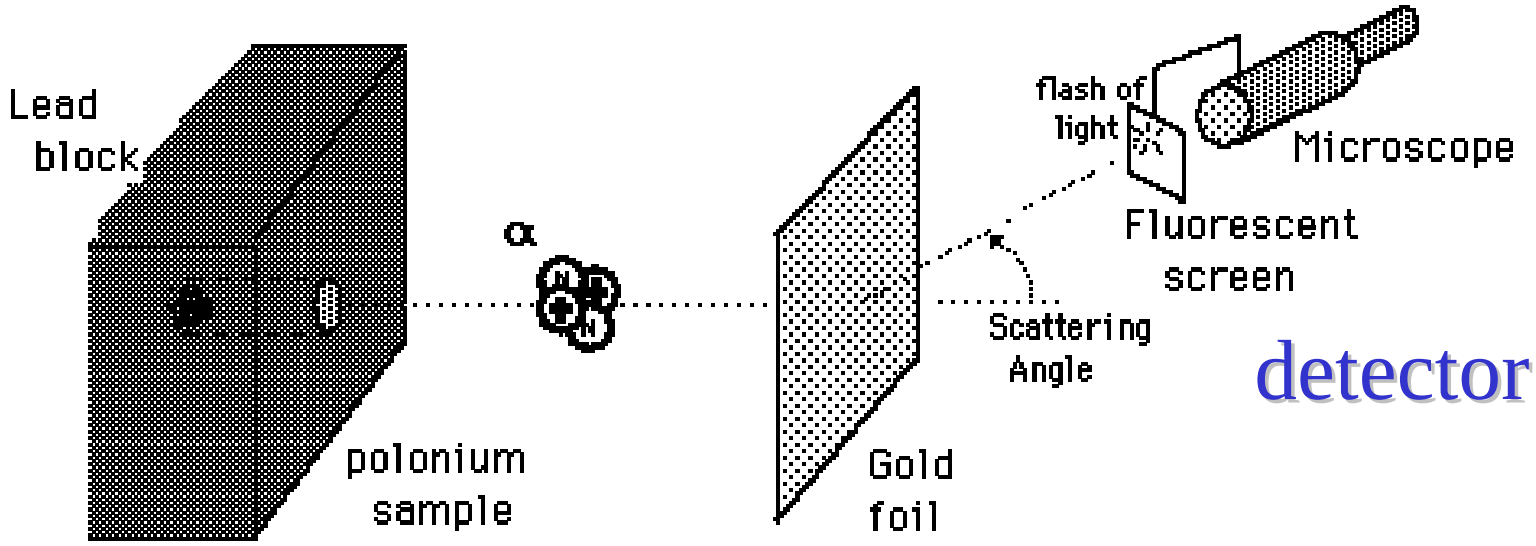


But why is helium 4 times heavier than hydrogen?

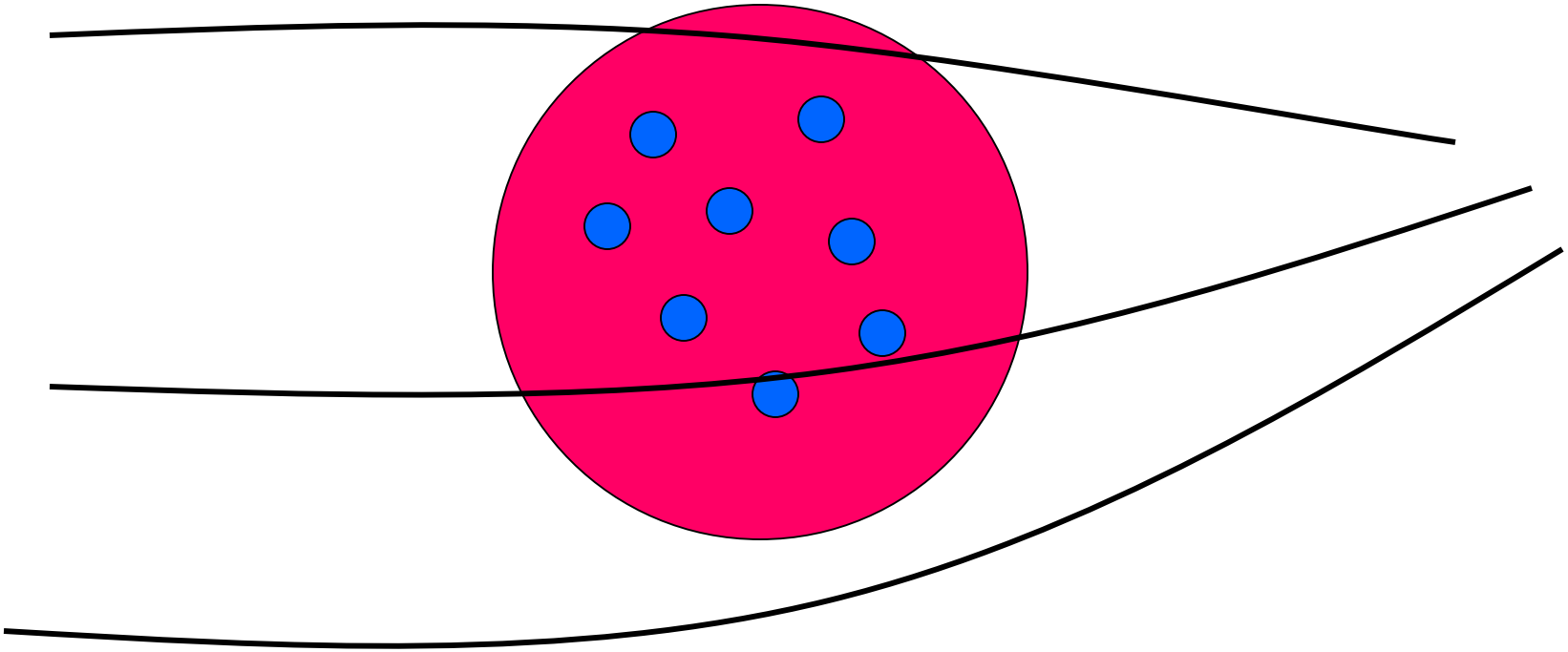
Picture of the Atom ~1900



Rutherford Destroys the Plum Pudding Model

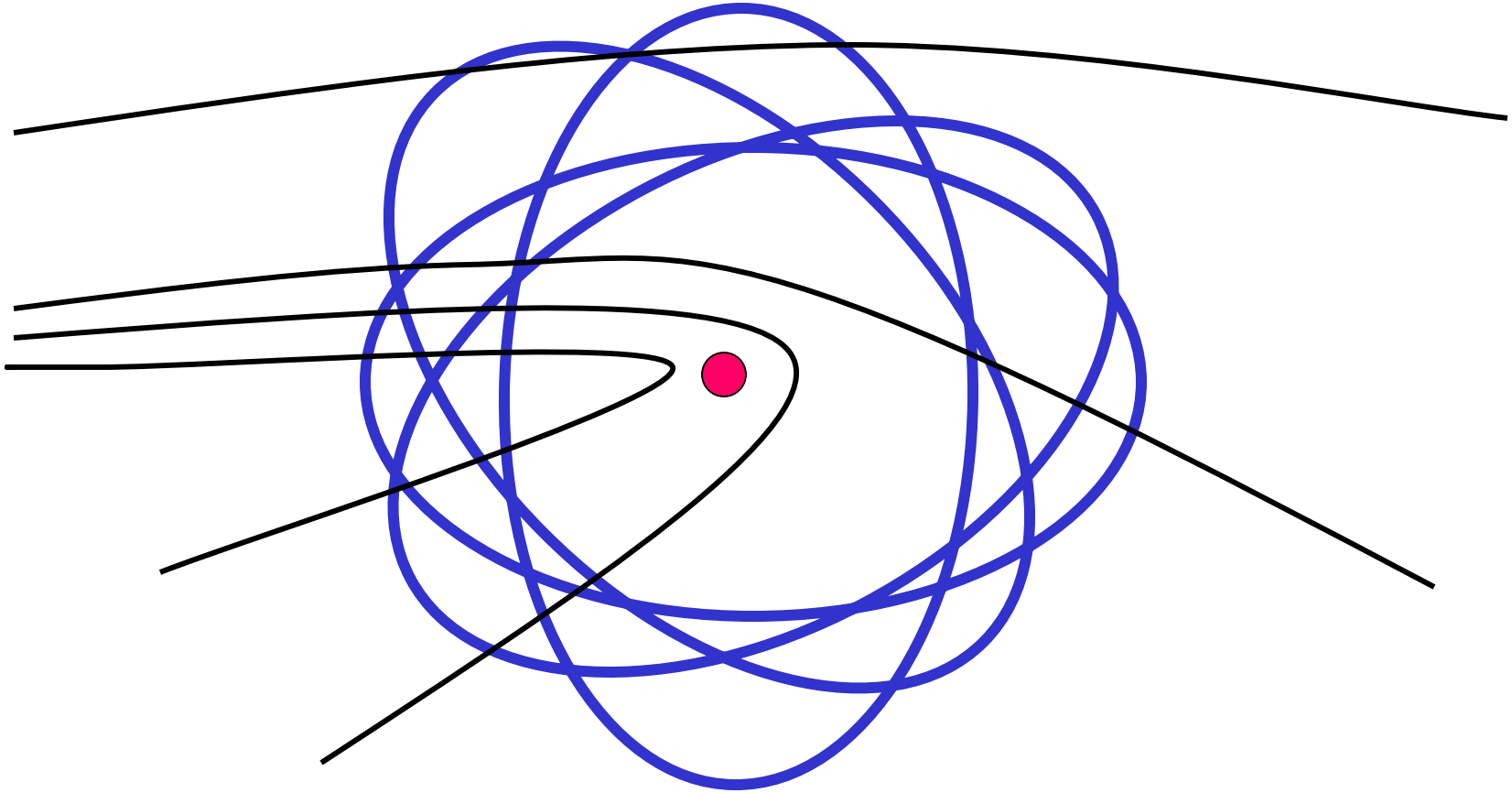


What Rutherford Expected



Projectiles (very fast He nuclei called *alpha particles*) will be slightly deflected by gold atoms

What Rutherford Saw



Occasionally (rarely) the projectile scattered at huge angles. *What did this mean*?

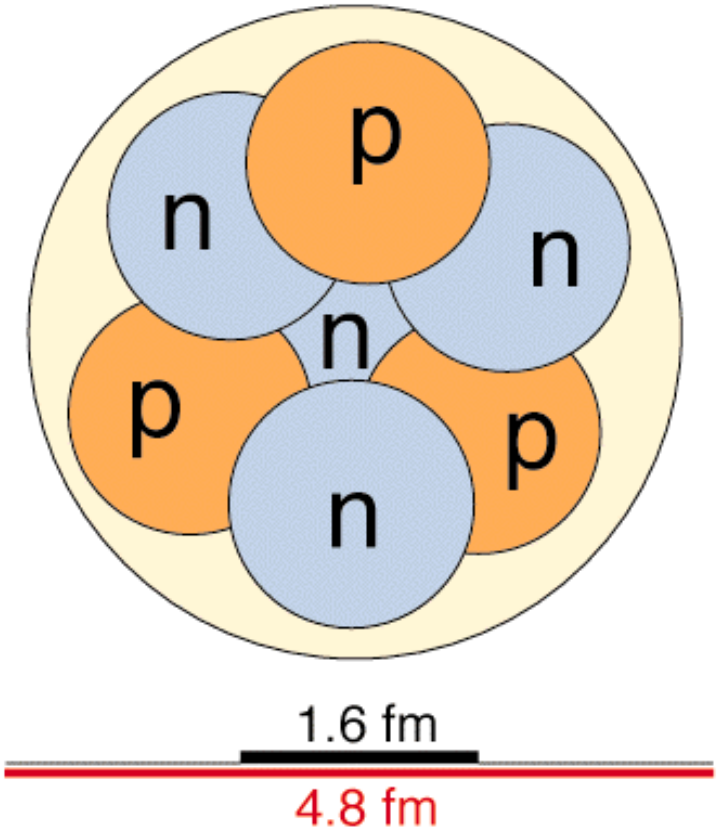
The Early 20th Century Atom

…like firing a 16" shell at a piece of tissue paper and seeing it bounce back.
- E Rutherford.

- An atom's mass must be concentrated in a **small positively charged nucleus** as only a very small number of alpha particles either deflected or rebounded off the foil.
  - Atom:Yankee Stadium :: Nucleus:grain of sand.
- Most of the atom must be **empty space**. This space must contain the electrons.
  - The electrons orbit the nucleus like planets around the sun.
- Nucleus found to be made of *protons* and *neutrons* .
  - Chadwick, 1932.
  - Fixes Mendeleev's problem of masses of elements!

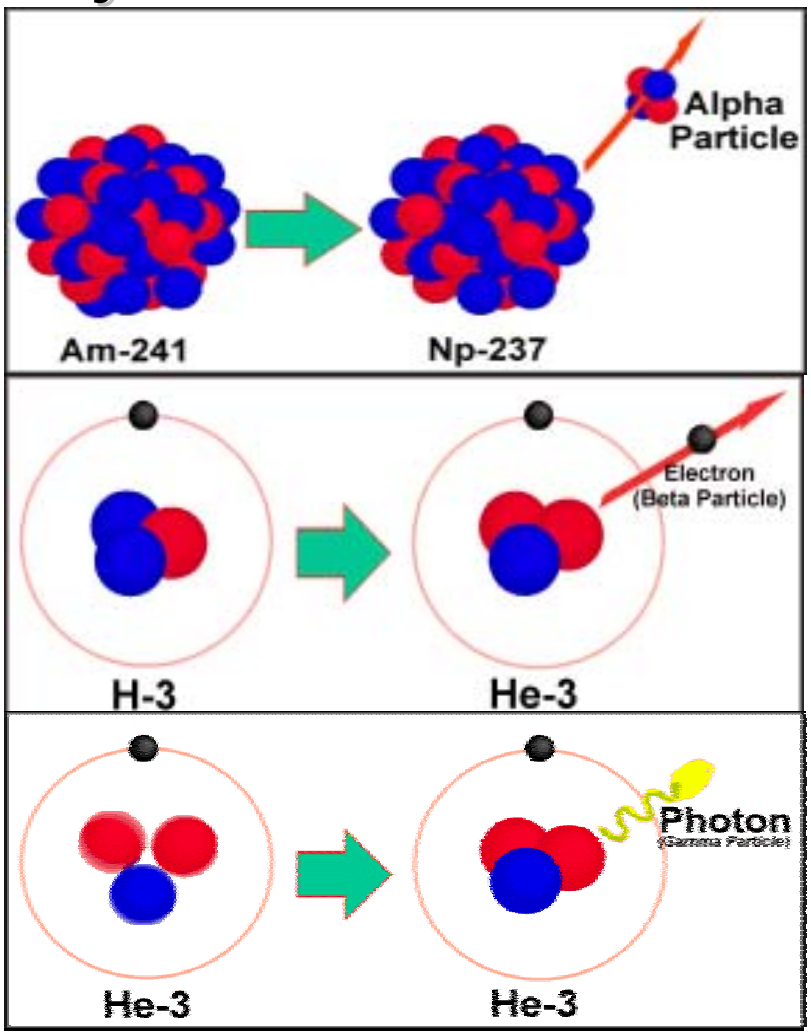
The Mid-20th Century Nucleus

- The nucleus is very small: 1fm = 10^{-15} m!
- What keeps the protons from flying apart?
  - **The STRONG force.**
- Some combinations of neutrons+protons are happy (*stable*)…but some are not (*unstable*).
  - Radioactivity!
- Some disintegrations of unstable nuclei can cause their unstable neighbors to disintegrate.
  - Fission, **chain reaction**.

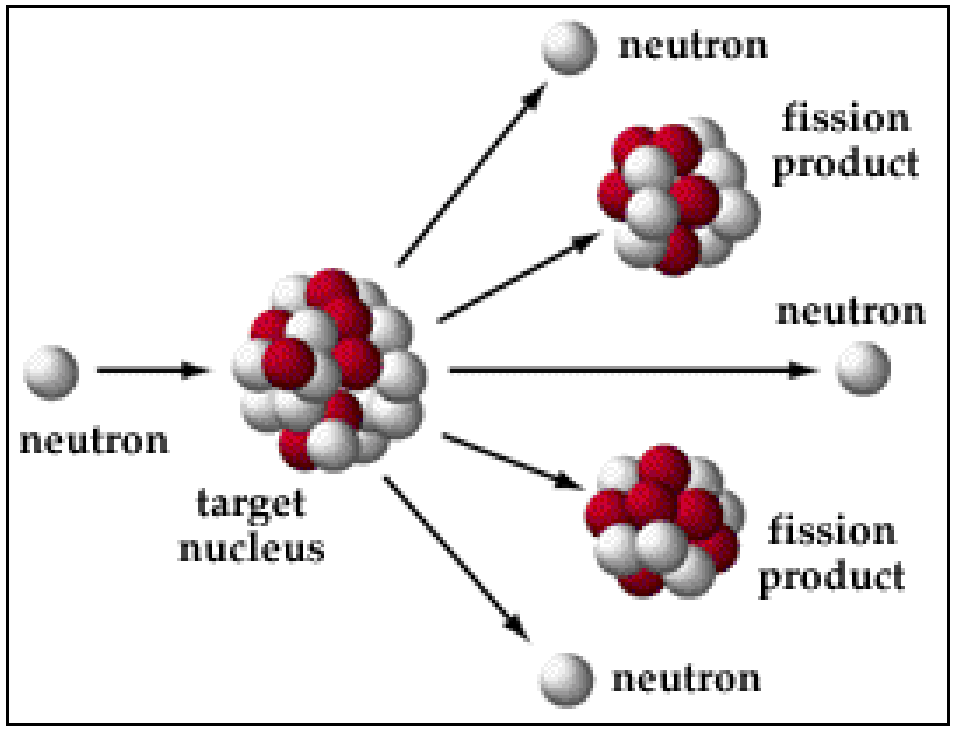


All happy nuclei are alike; every unhappy nucleus is unhappy in its own way

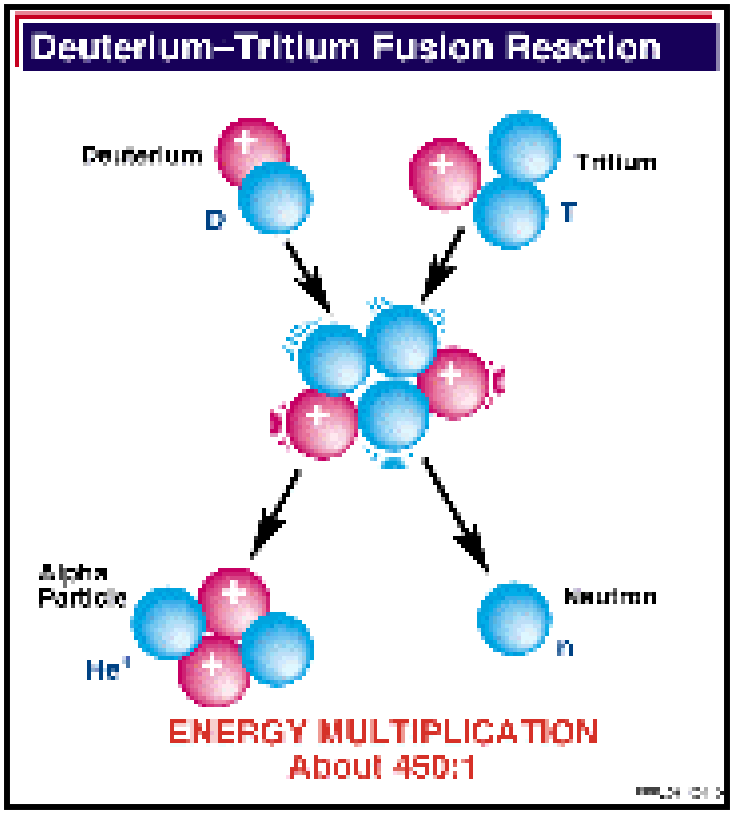
- Alpha Decay.
  - An unstable nucleus spits off a [nnpp] (alpha particle).
  - Light nuclei can't do this.
- Beta Decay.
  - A neutron inside nucleus changes to a proton, giving off an electron (aka beta particle) and neutrino.
- Gamma Decay.
  - A photon (like visible light,
  - Only more energetic).



Fission and Fusion



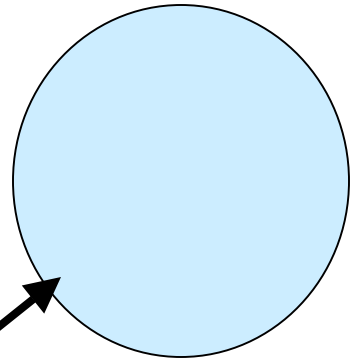
Semi-stable nuclei like ^{235}U can be induced to break up.



Smaller nuclei can combine to make a larger, more stable nucleus.
This is what powers the sun and stars.

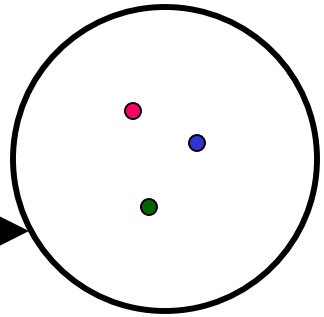
But What's Inside a Proton or Neutron?

- Protons, neutrons making up the nucleus with orbiting electrons completed the atom.
  - *But are these particles the final layer of matter?*
- Two competing theories:
  - **Proton is fundamental.**
  - **Constituents within proton.**
- Electron is fundamental as far as we know.



"snowball" of charge?

OR



Tiny particles surrounded by empty space?

Why is this so hard to answer?

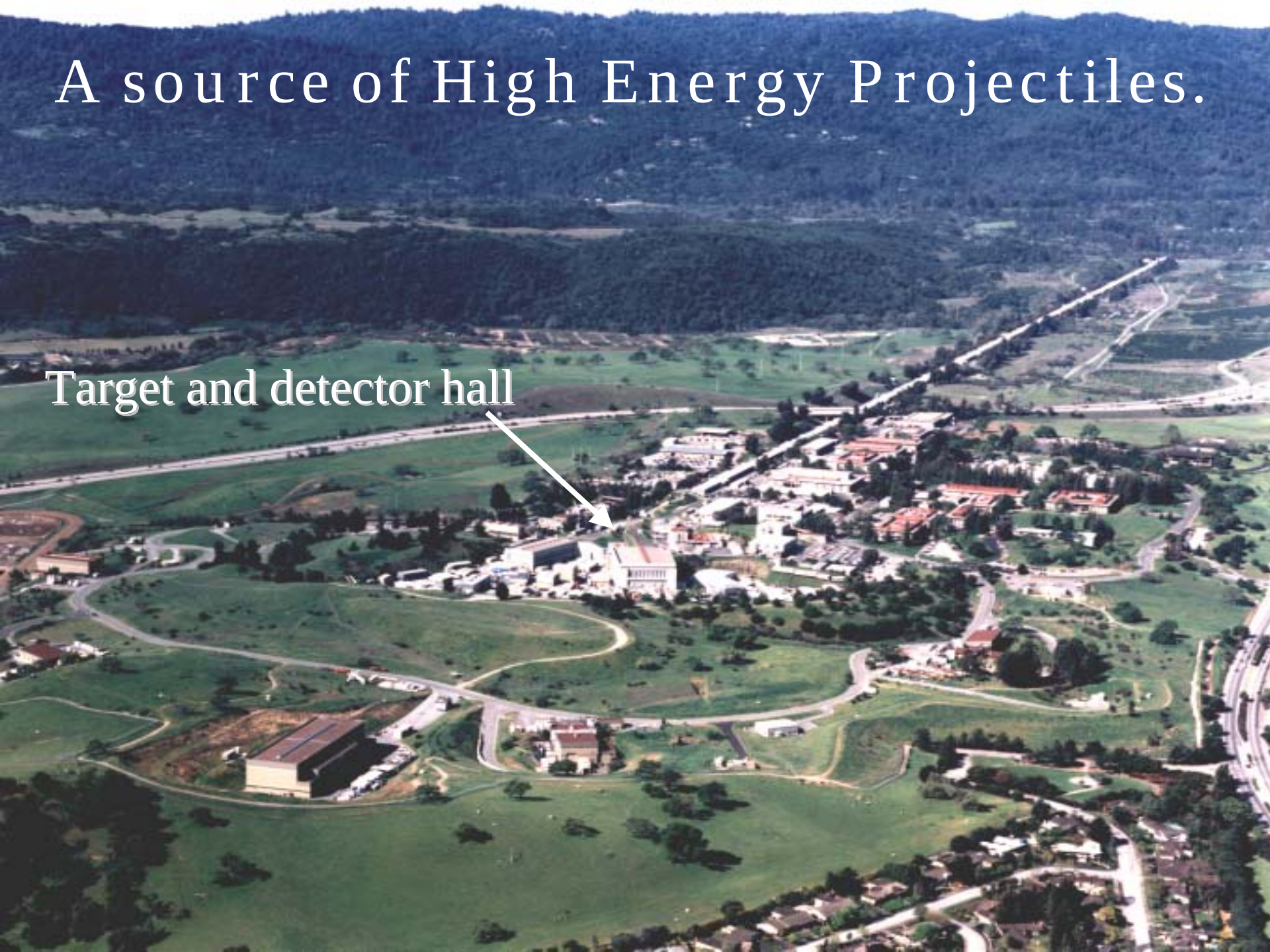
- Rutherford: looked inside atom.
  - Needed energy equivalent to an electron ~10 million volts.
  - He saw nucleus.

  Less than 10^{-8} m, or 0.0000004 inches.
- Kendall, Friedman, Taylor: looked inside proton.
  - Energy needed was ~**10 billion volts.**

  Less than 10^{-15} m, or 0.00000000000004 inches.
- By contrast:
  - A TV accelerates electrons by ~10 volts.
  - X-ray tubes by ~1000 volts.

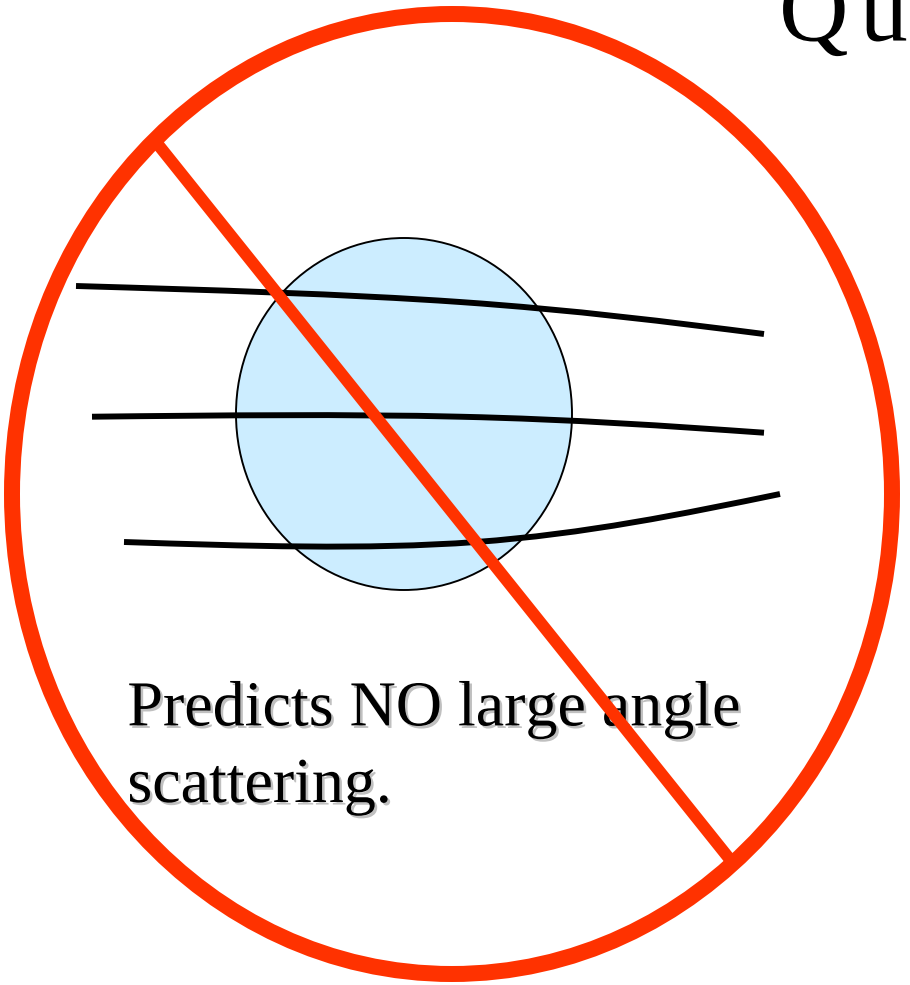
Visible light microscope limit is ~0.0001 inches

A source of High Energy Projectiles.

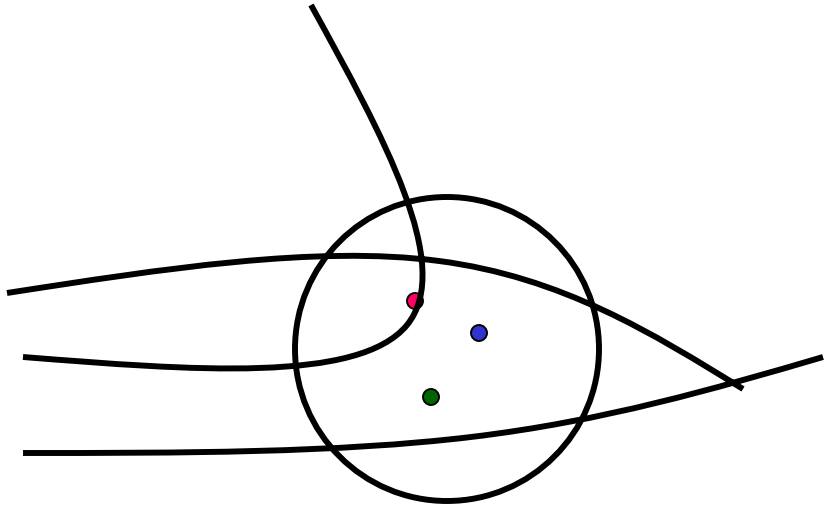



Target and Detector for the Scattered Projectiles

Quarks!



Predicts NO large angle scattering.

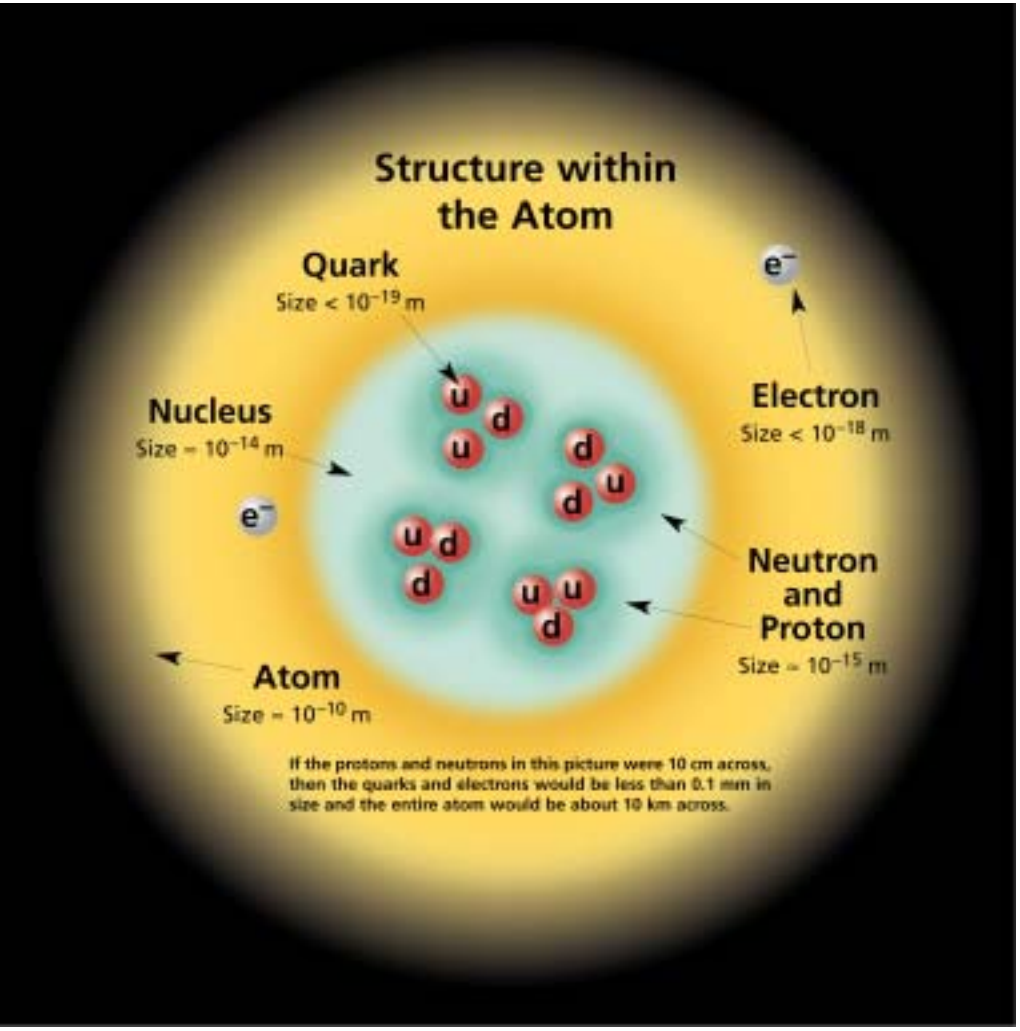


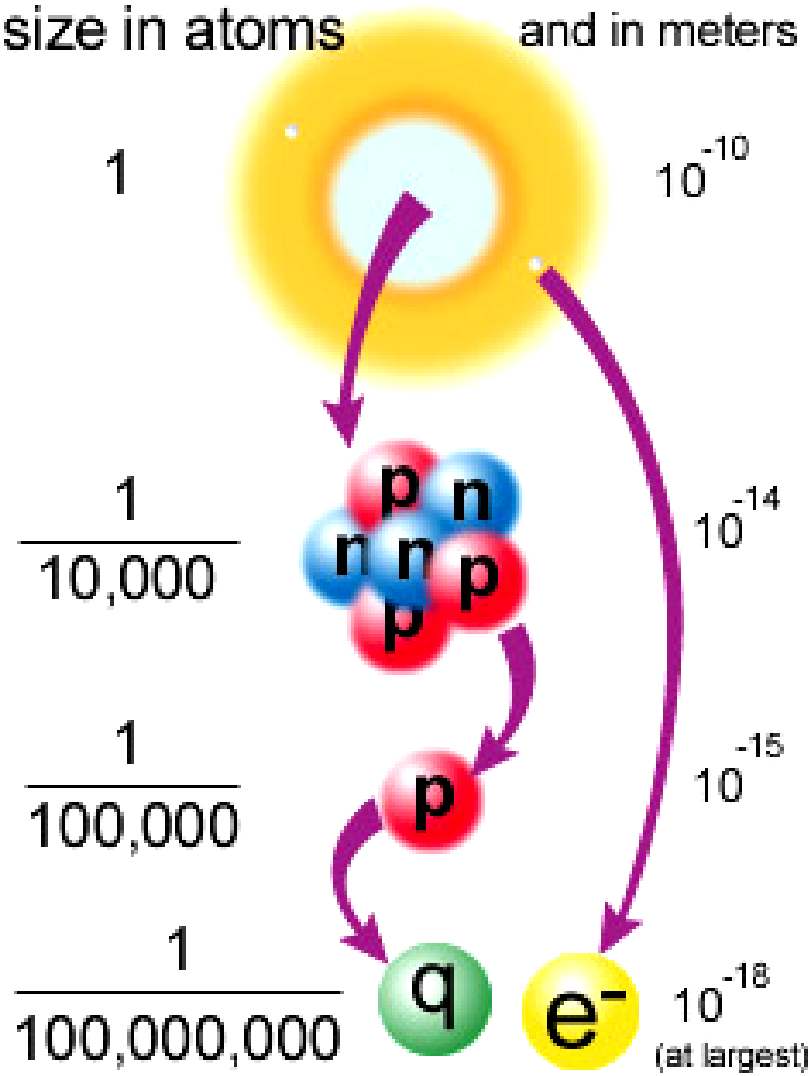
Large angle scattering can happen.

And did!

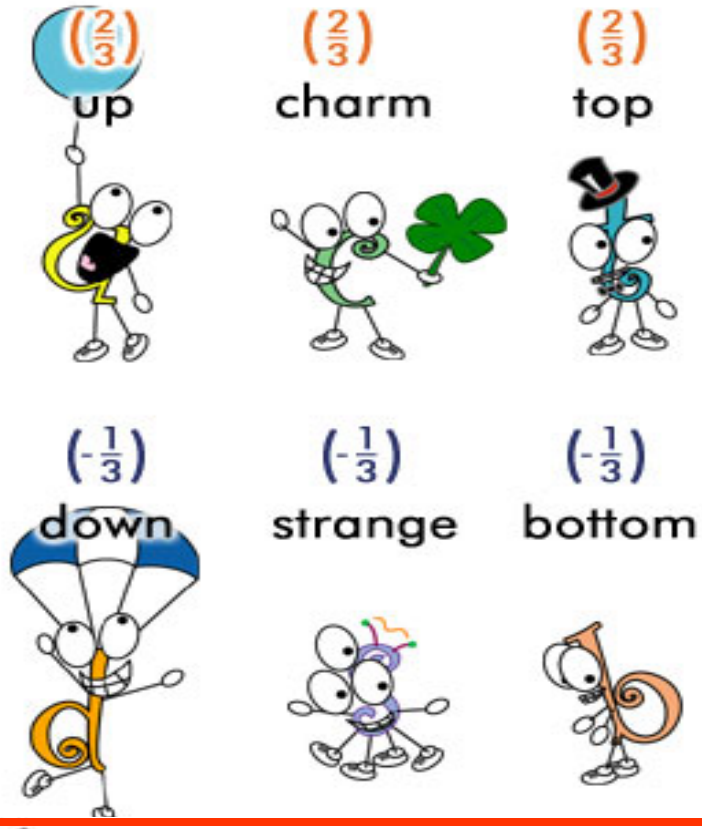
The 1990 Nobel Prize

Structure of Matter

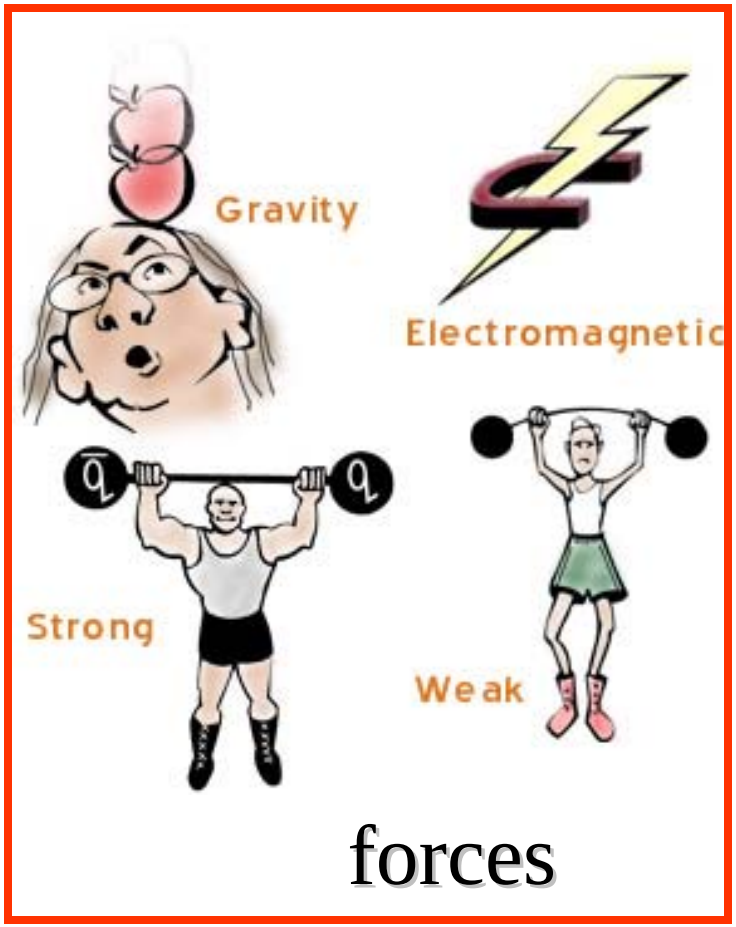




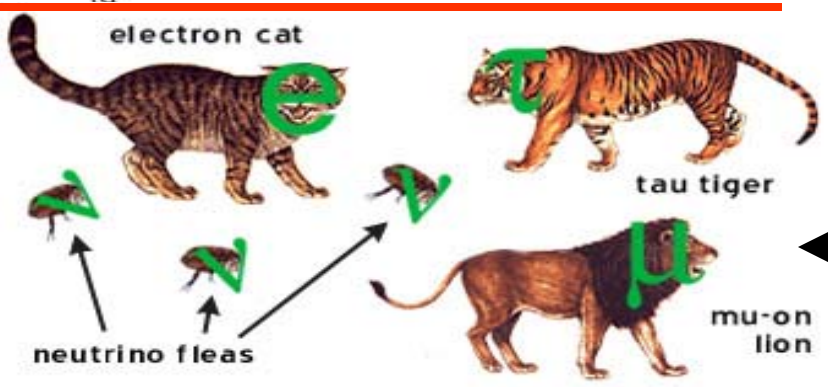
The Early 21st Century: Standard Model



quarks



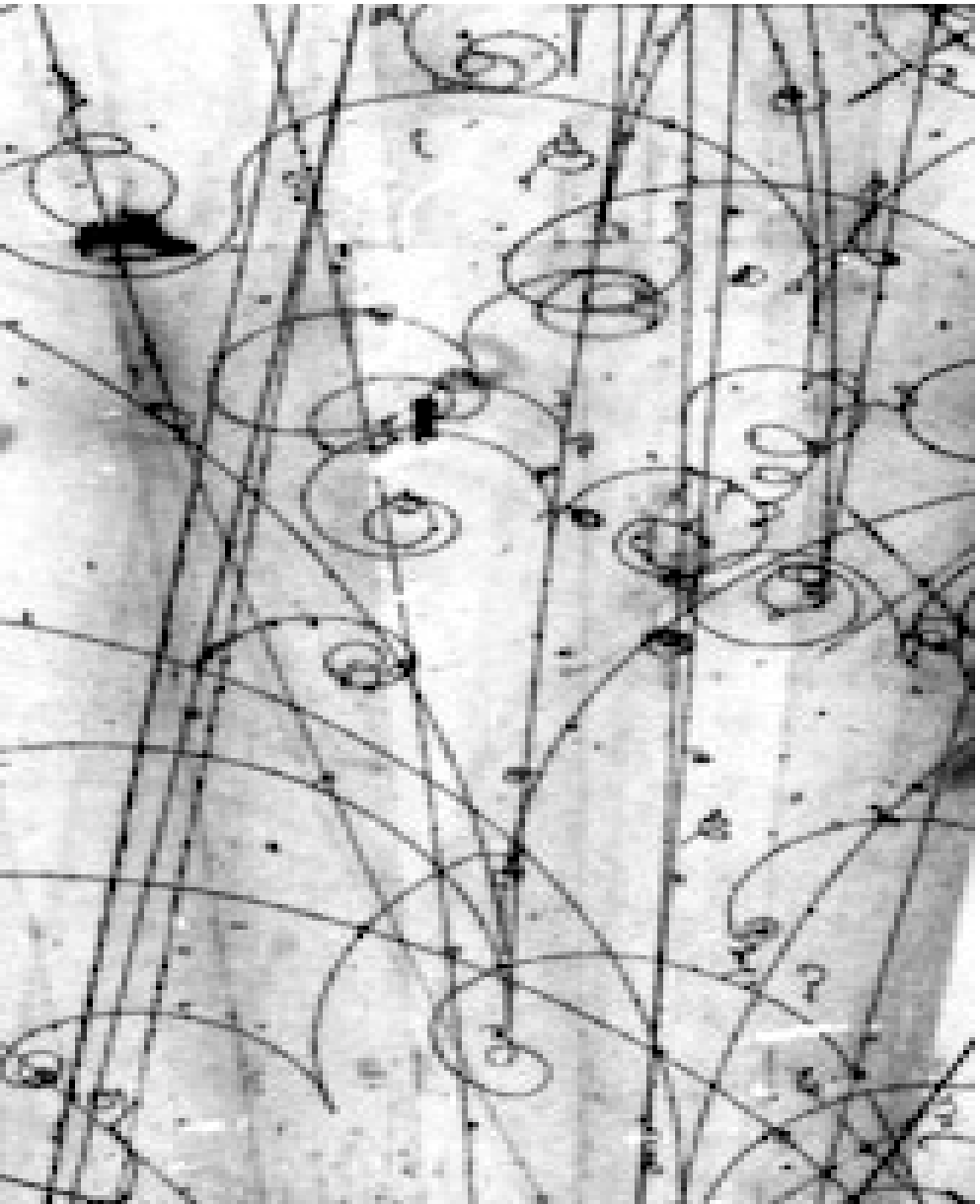
forces



leptons

Busy, ain't it?

But Wait, there's Antimatter



- Predicted in 1930's.
  - P.A.M Dirac.
- Every particle has antimatter "partner."
  - Proton : Antiproton.
  - Electron : Positron.
  - Quark : Antiquark.
- Cannot create matter without equal amount of antimatter.
- So where is all the antimatter from when the universe was created?
  - Umm… good question…

A Few Questions

- So how many "fundamental" particles are there now?
  - 6 quarks.
  - Electron, muon and tau leptons.
  - Their three neutrinos.
- Total of 12 fundamental particles.
  - Plus their antiparticles.

- Isn't that a bit much?
  - Wasn't it easier with just proton, neutron and electron?
- All stable particles are made of up, down quarks and electrons.
  - All the other quarks, leptons quickly decay to these three.

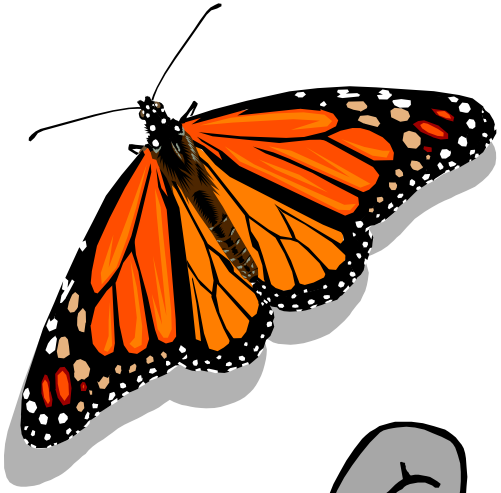
Making Things from Quarks

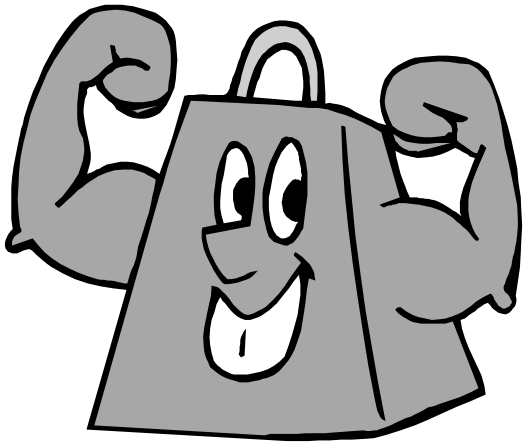
Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ Baryons are fermionic hadrons. There are about 120 types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Notice masses!

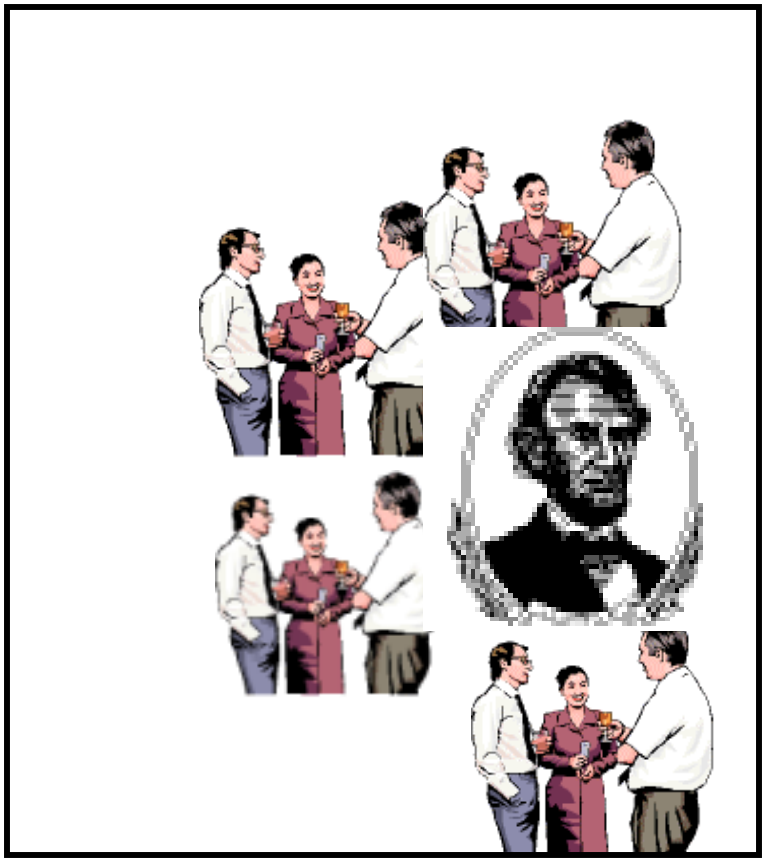
The Mystery of Mass

- Masses can be given in terms of energy.
  - Einstein said: $E=mc^{2.}$
- Neutrinos have m=0.
- Electron is very light.
  - M_e = 0.511 Million $eV/c^{2.}$
- Top quark is very heavy.
  - M_t = 175 Billion $eV/c^{2.}$





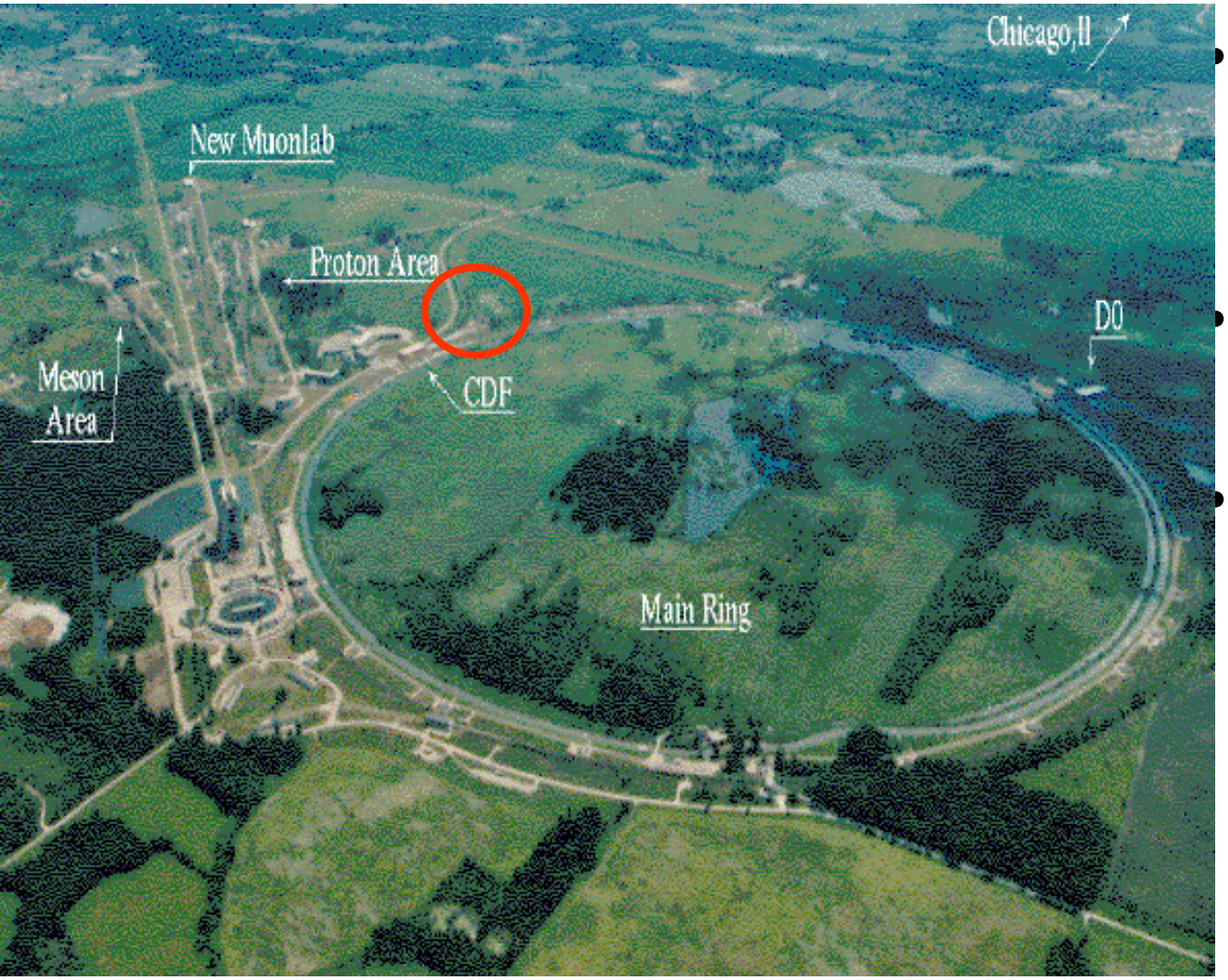
One Idea: Higgs



Popular person enters a crowded room. People cluster. The person has a difficult time getting across the room. **HEAVY**

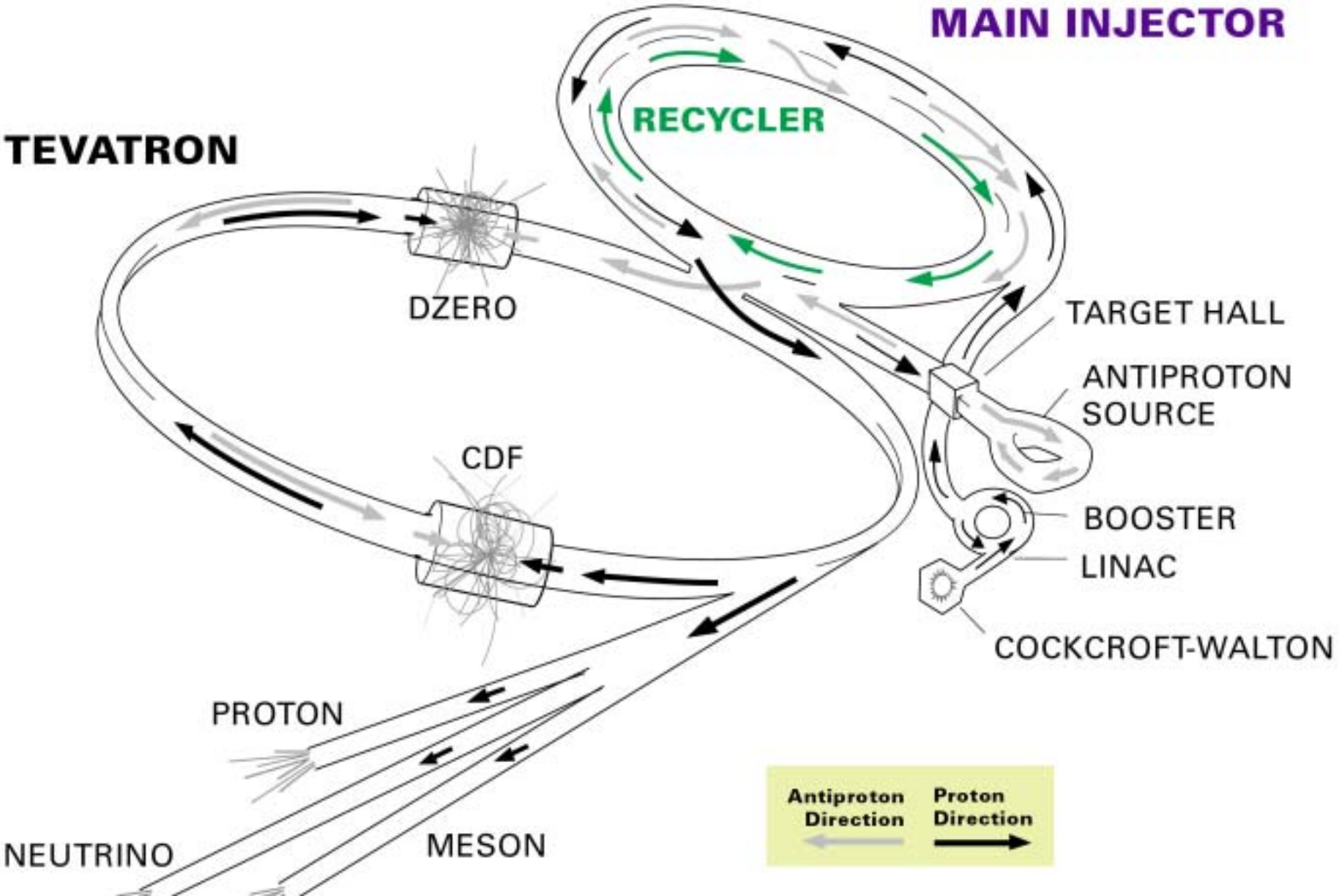
Unknown person enters a crowded room. No one notices. The person has no problem getting across the room. LIGHT

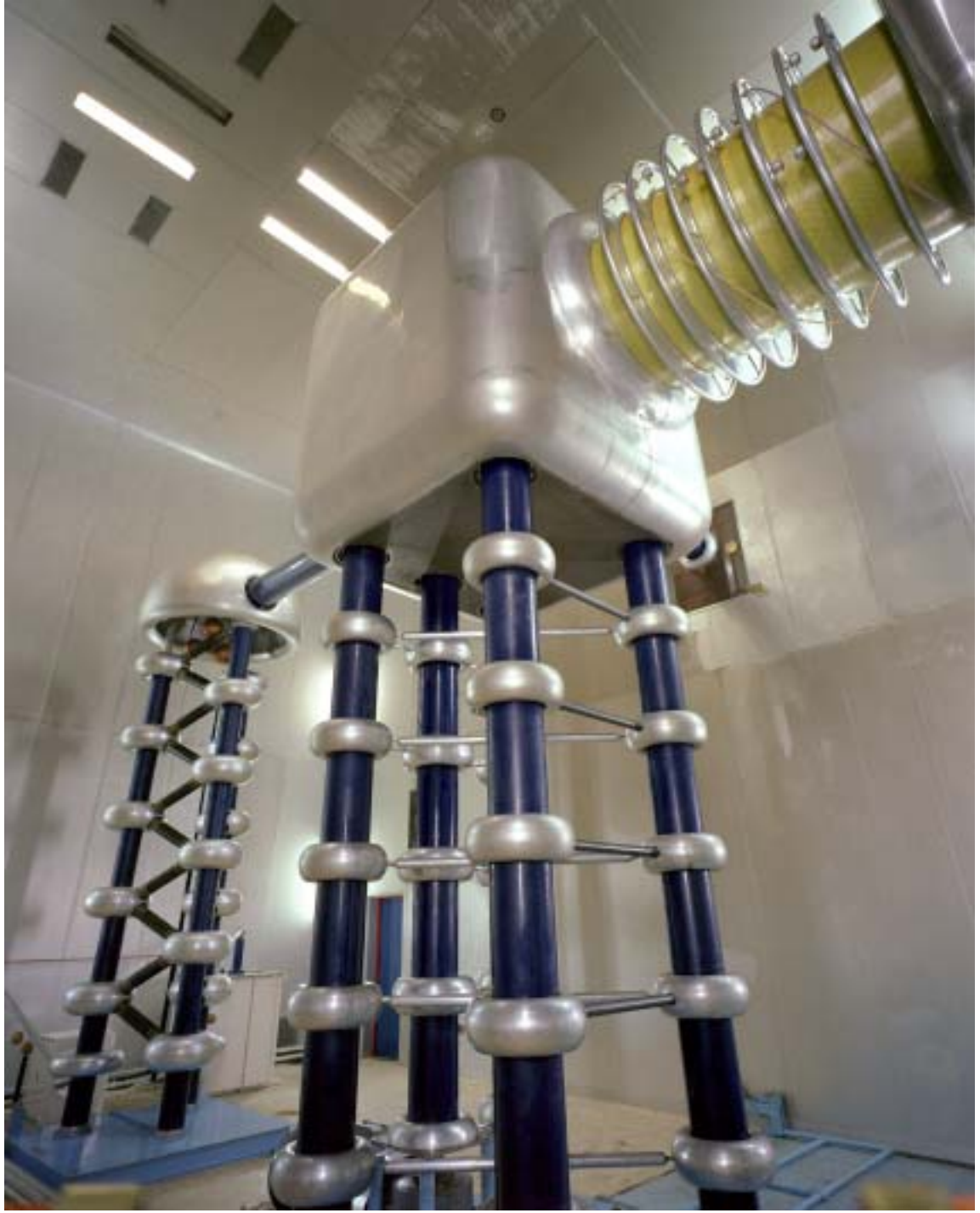
How to make the Higgs



- 4 mile ring with superconducting magnets.
- Collides protons with antiprotons.
- Energies up to 2 TRILLION eV achieved.

FERMILAB'S ACCELERATOR CHAIN

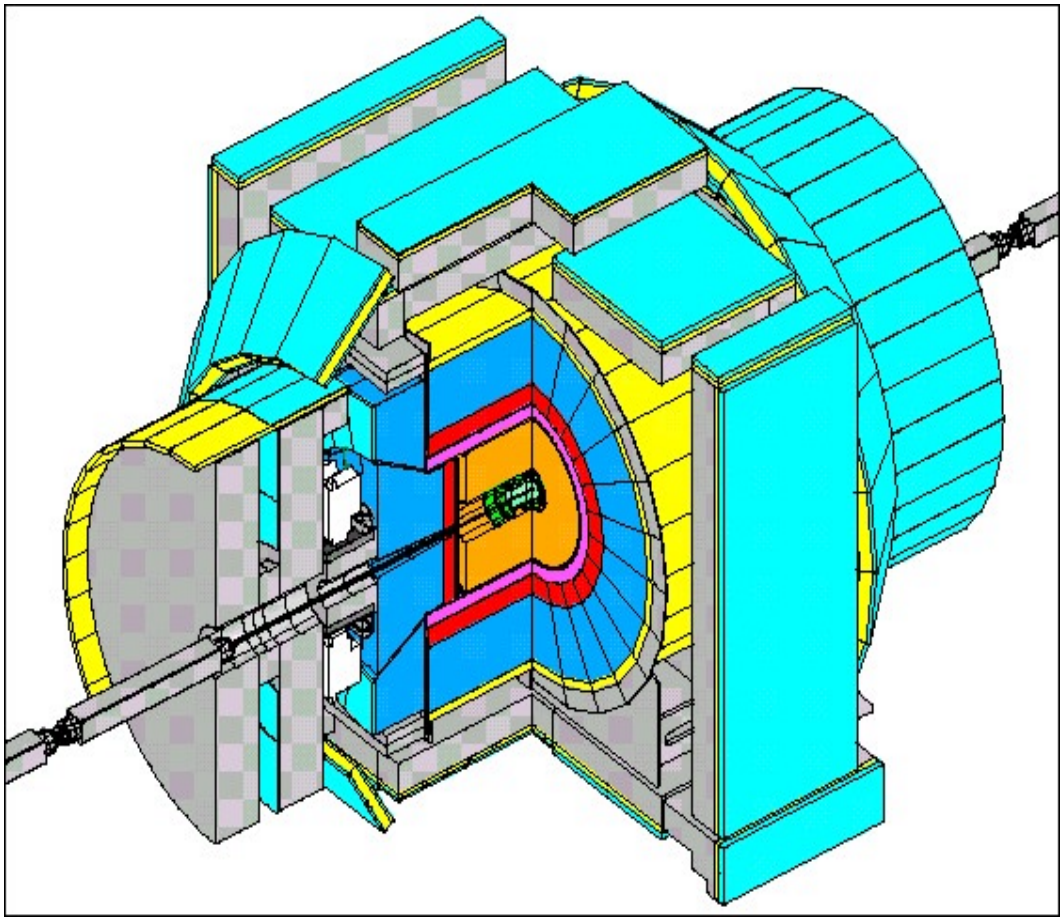




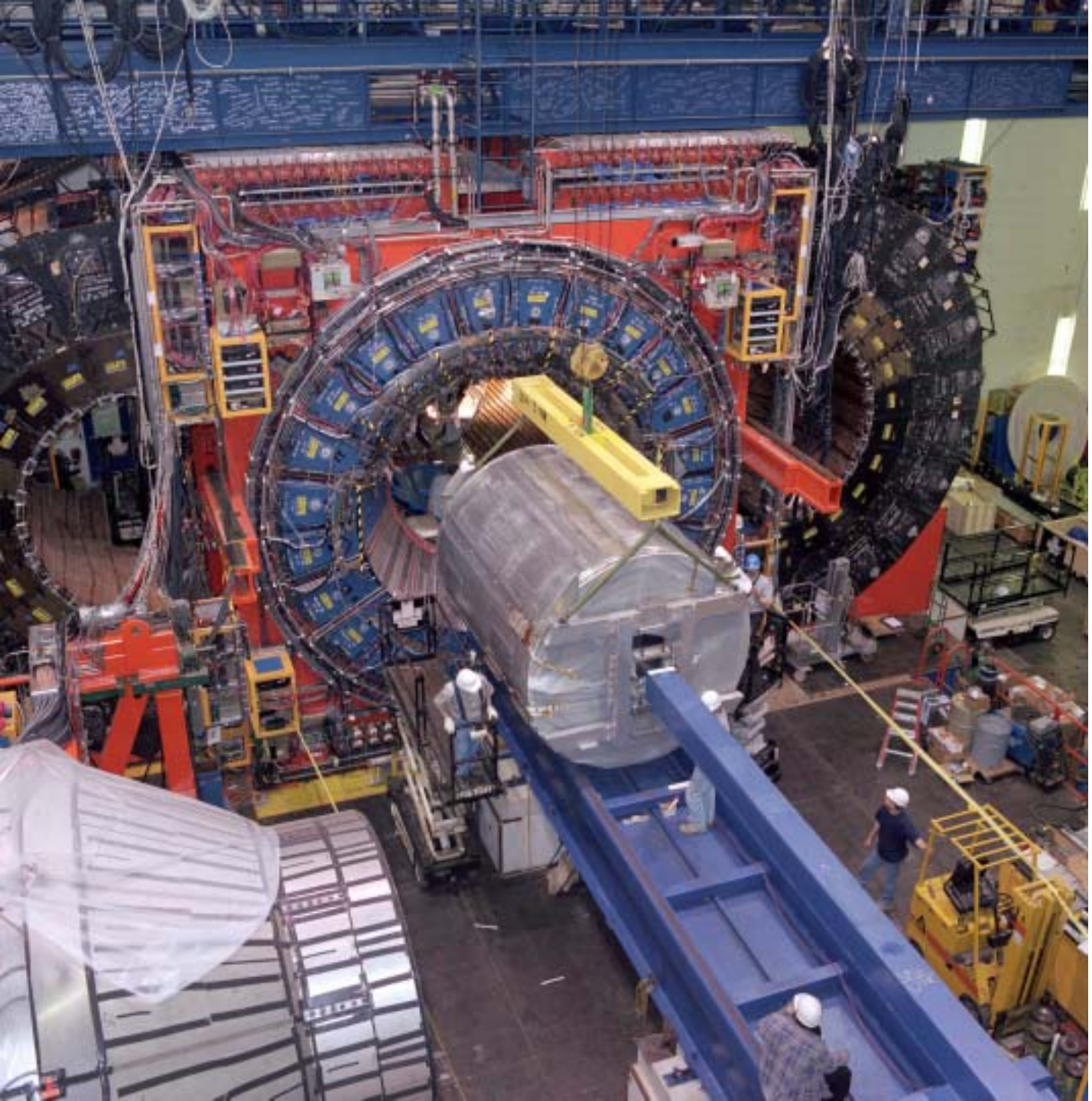
The Cockroft-Walton.

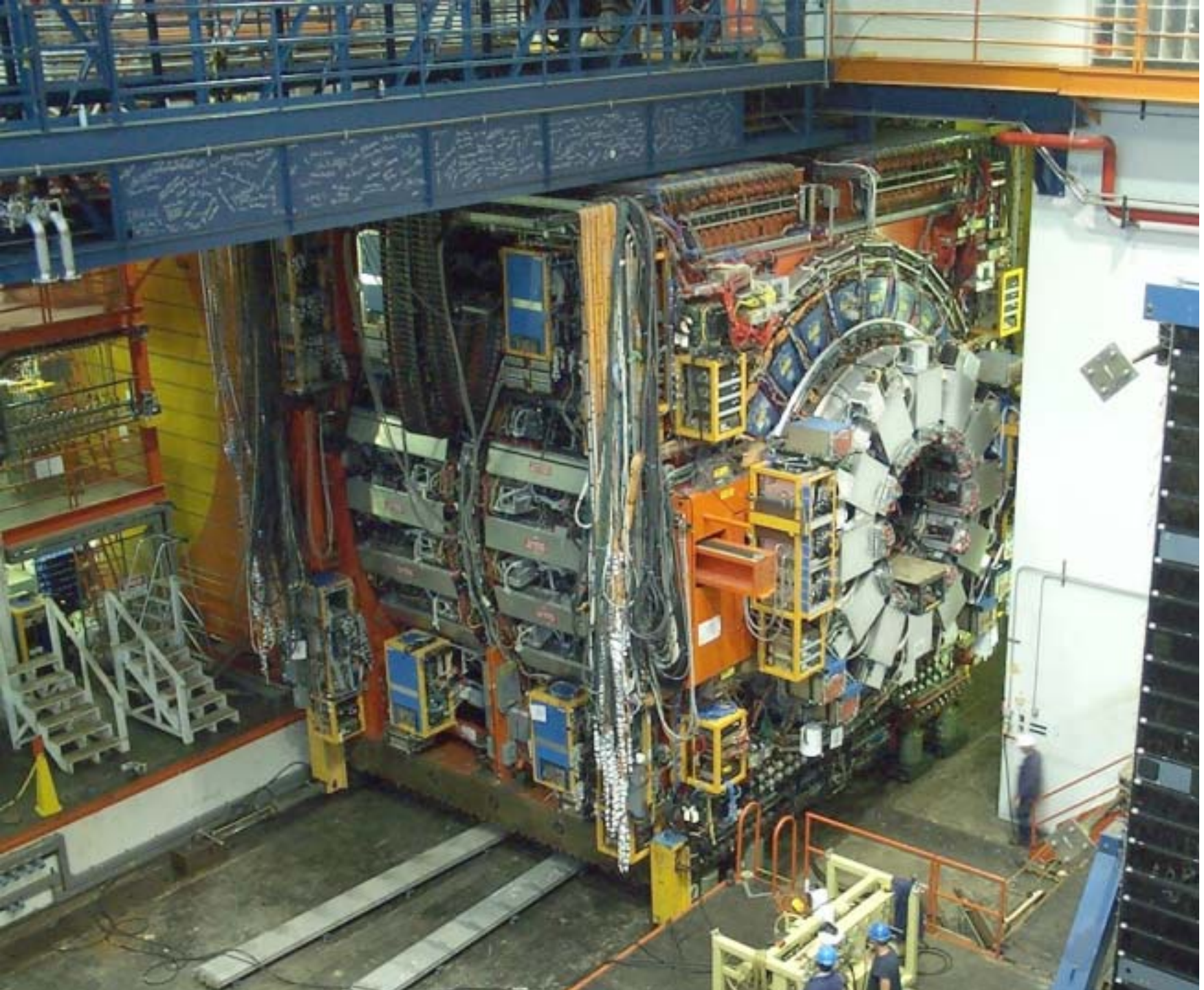
This is where the protons start out

How to find the Higgs

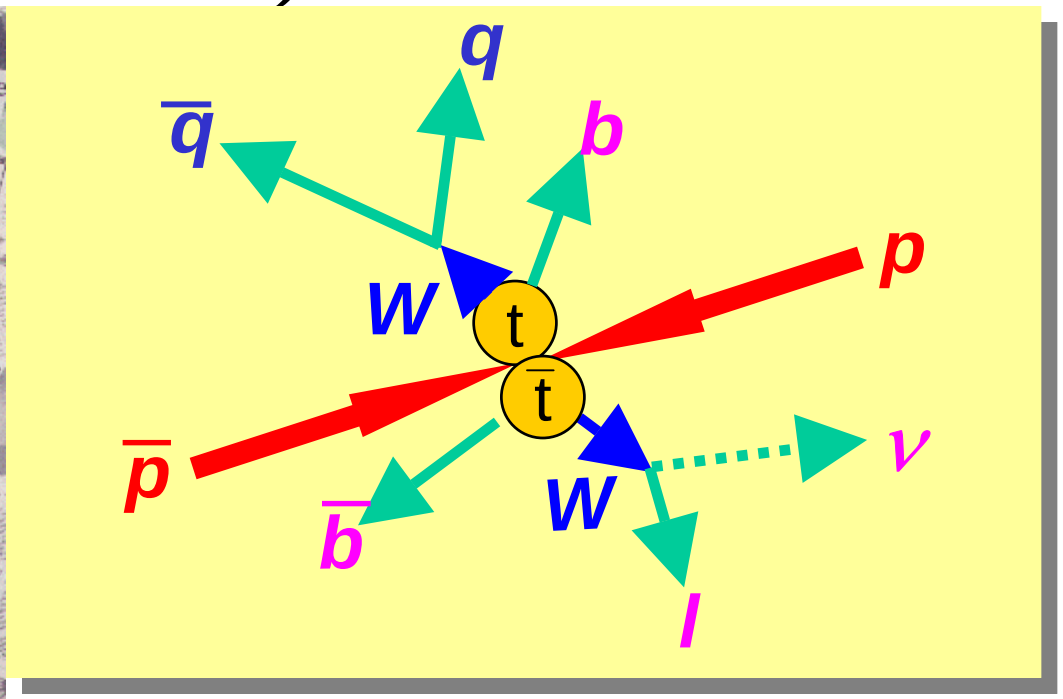


- Big Detectors.
  - Measure **momentum** and **energy** of things that are created when proton-antiproton collide.
- High Energy final particles
  - When heavy things (like the Higgs) are created, they can produce very high energy electrons, photons, etc.
  - Also b-quarks.
  - Plain vanilla collisions don’t often do that.





The top quark Discovery (1995)



Top quark is very heavy.
Decays right away to bottom quarks.
Can we find bottom quarks?

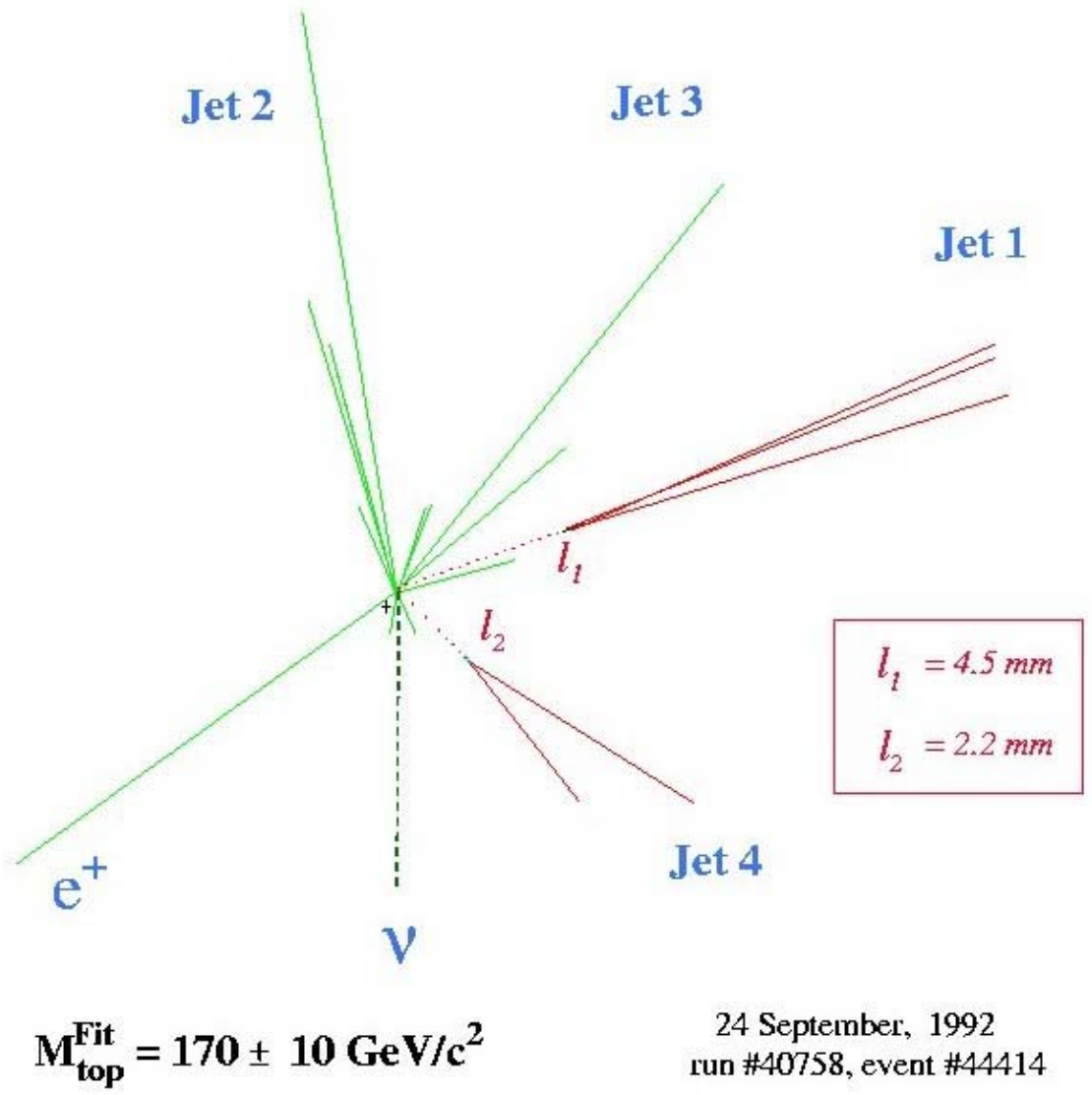
A top quark event

***Look at* top** event (CDF)

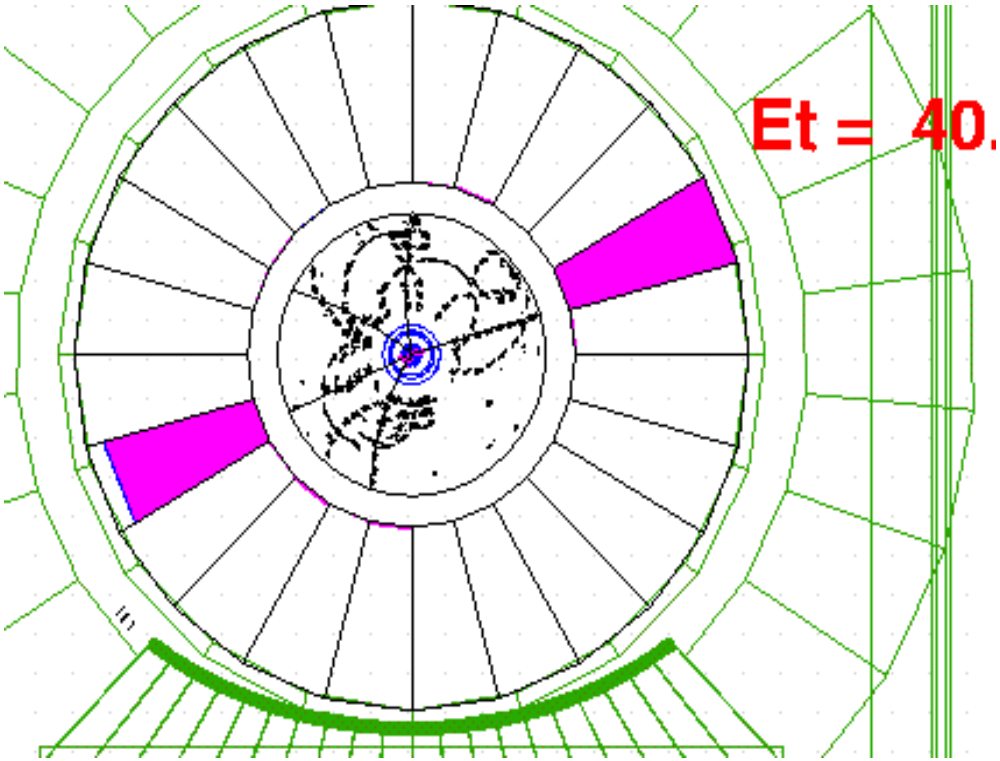
What happened?

$p\bar{p} \rightarrow t\bar{t}$

- b $W \rightarrow e\,\nu$
- b $W \rightarrow q\,q'$ *(jets)*

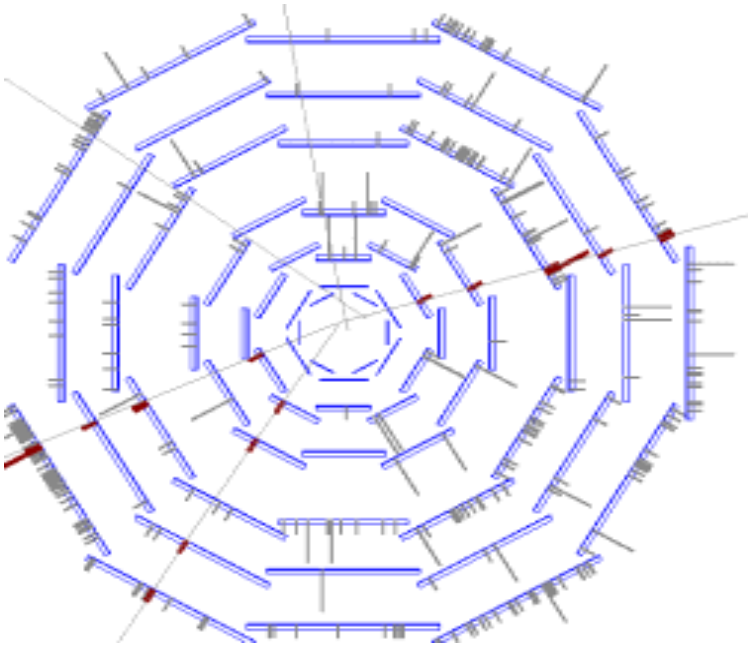


Some Recent Events from CDF

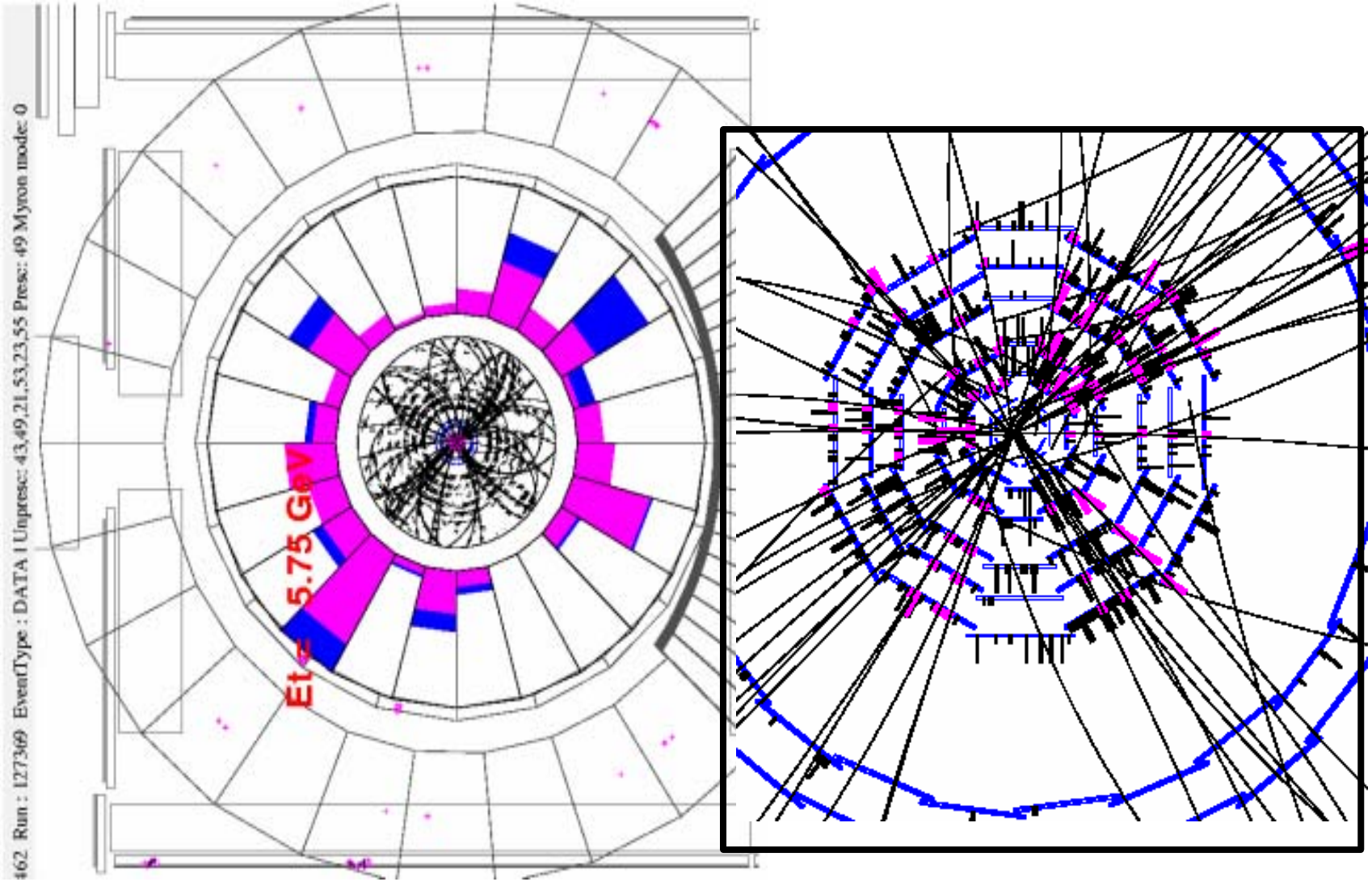


Full Picture

Zoomed in

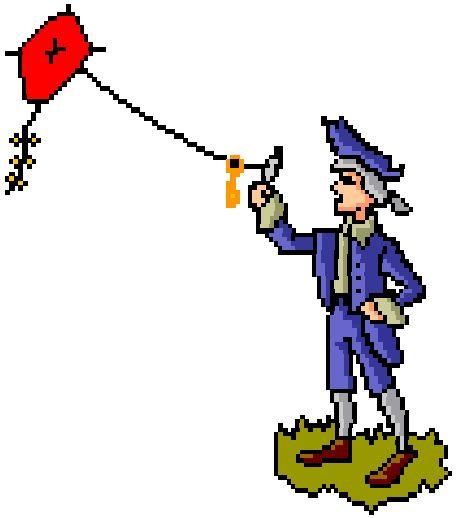


Not always so pretty



Jpsi to mu mu event. M = 3.0859

Where do you fit in?



- We are on the verge of astounding discoveries:
  - Why mass?
  - Why no antimatter?
  - What's all this "dark matter"?
- **Higgs. Supersymmetry. String Theory. Extra Dimensions**…

  We need bright, motivated young people.
  - A golden age of discovery (particle physics, astrophysics, cosmology) is starting.
  - **Major in physics when you get to college.**