# Fermilab's Accelerators

***for now,*** ***Tevatron*** **is the world's highest energy accelerator**

**Peter H. Garbincius – Fermilab – since 1976**

**video-Ask-a-Scientist – SC2009 – Nov 18, 2009**

**What are accelerators?**
**Fermilab's accelerators**
**What do we use them for?**
**What we've learned**
**What we don't know**
**What we are planning**

**general particle physics reference:**
http://www.particleadventure.org
http://www.fnal.gov
http://www.linearcollider.org
http://www-ilcdcb.fnal.gov/Ask_accelerators_13july08.pdf

**What is the universe made of and how does it work?**

**What is this made of, Daddy?**

**What's inside of that?**

**What's that made of?**

**What inside of that?**

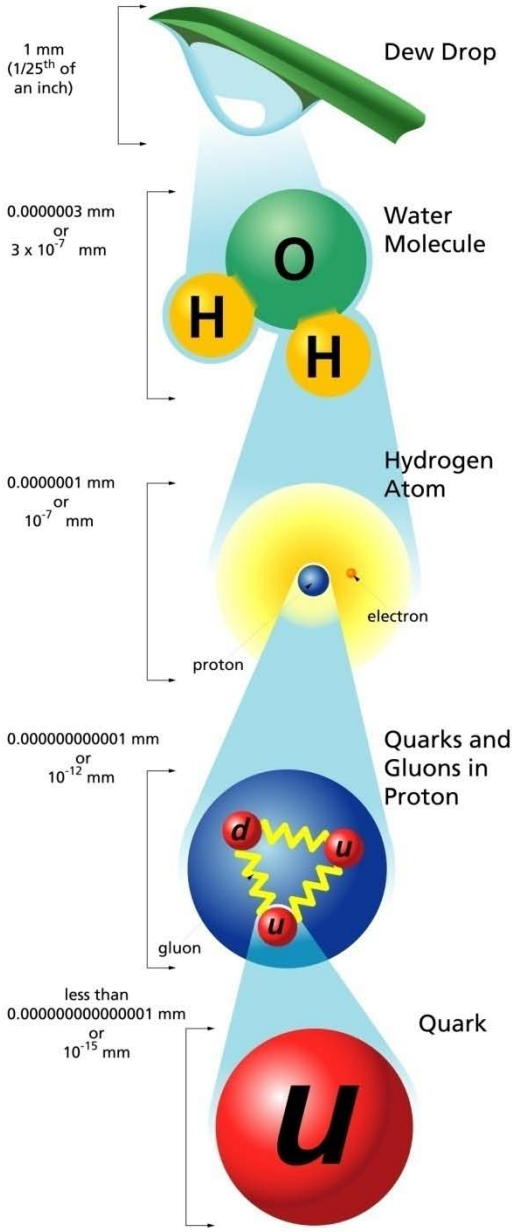
**. . . .**

**Questions of**

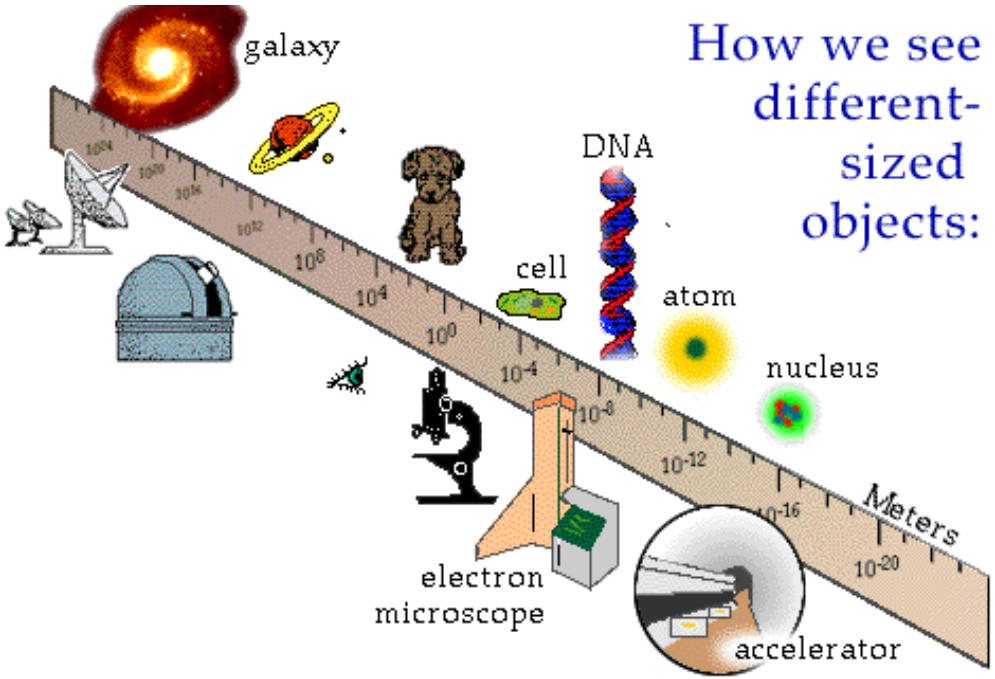
**little children →**

**ancient Greeks (atoms) →**

**today's physicists**

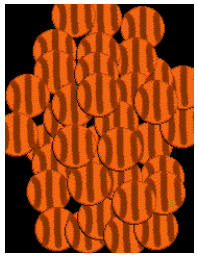


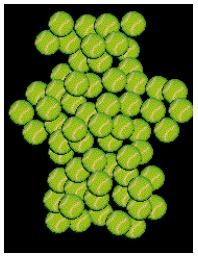
# Wave-Particle Duality of Nature

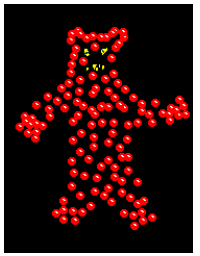



DeBroglie said moving particles have an equivalent wavelength,

$$\lambda \propto \frac{1}{p}$$







**as size of probe decreases (energy goes up) => resolution improves**

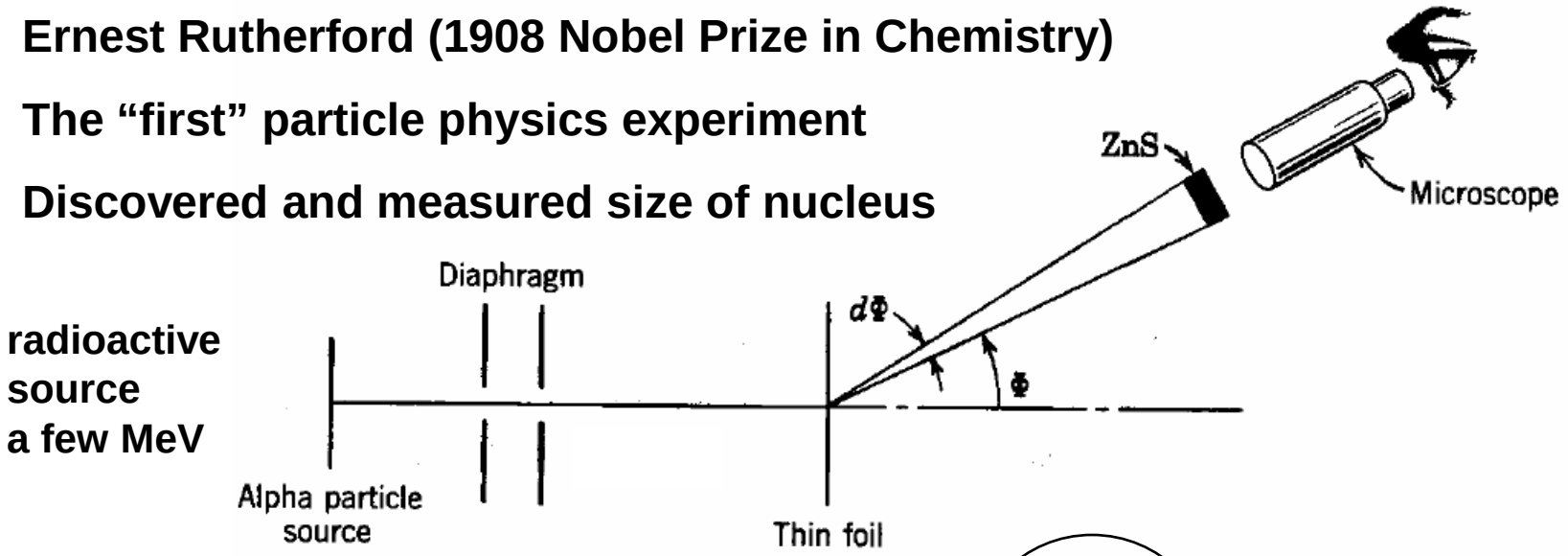
**basketball** **tennis ball** **pea**

# How do we measure the very small?

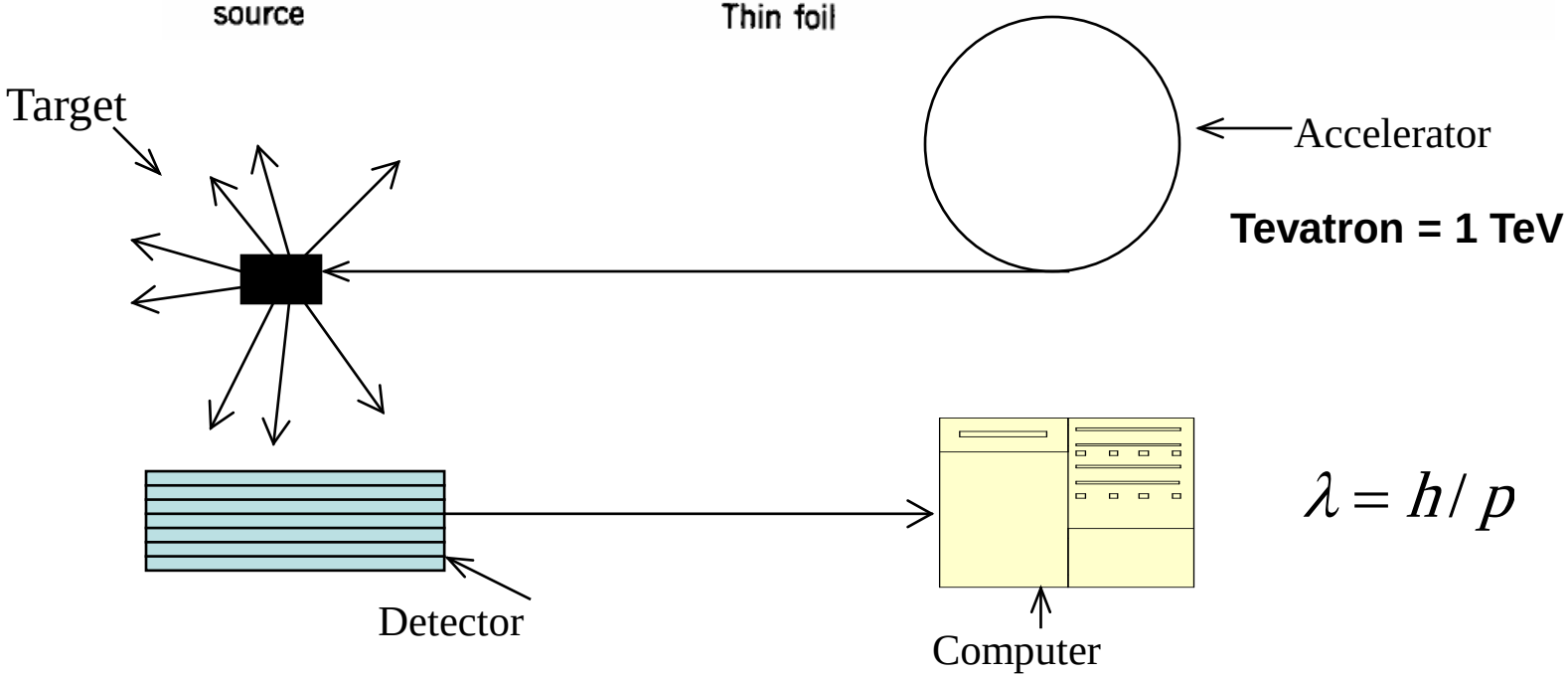
**Ernest Rutherford (1908 Nobel Prize in Chemistry)**

**The "first" particle physics experiment**

**Discovered and measured size of nucleus**



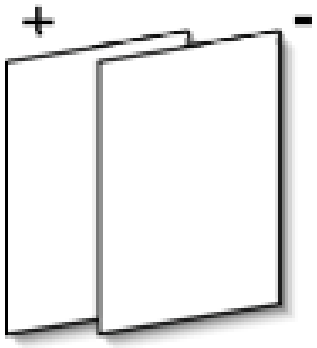

**radioactive source a few MeV**




**Tevatron = 1 TeV**

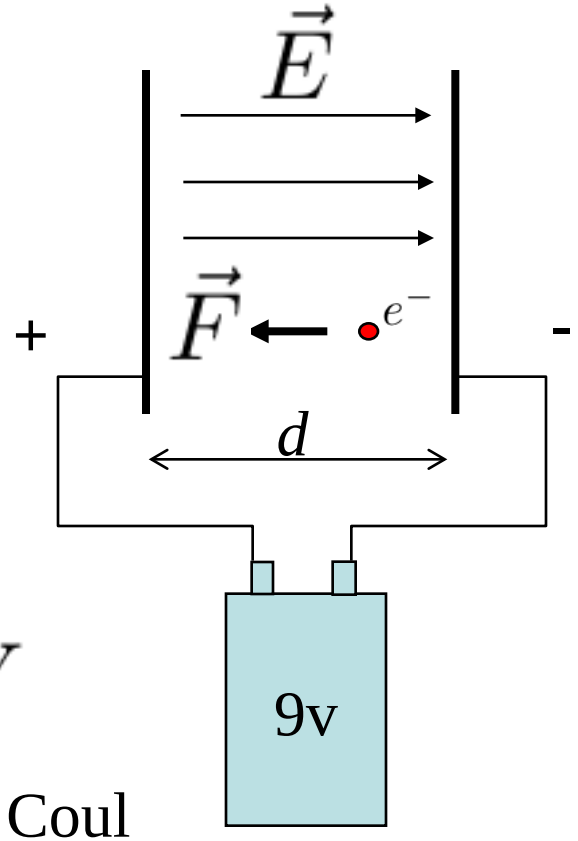
$$\lambda = h / p$$

# How to Accelerate Charged Particles




$$|\vec{E}| = V/d$$

$$|\vec{F}| = q|\vec{E}| = qV/d$$




As the electron accelerates from the right hand plate to the left, the change in energy is the work done,

different *E*!

$$\Delta E = F \times d = qV$$

The charge on an electron is $q = -e =$ -1.6 x $10^{-19}$ Coul

(on a proton, +1.6 x $10^{-19}$ Coul = $+e$)

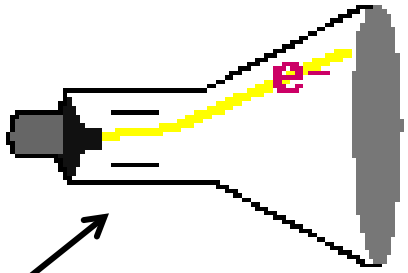
So, we say that an electron/proton accelerated through 1 volt gains an amount of energy $\Delta E$ = 1 eV (1 **electron volt**) (= 1.6 x $10^{-19}$ J)

In example above, the electron would gain energy of amount 9 eV.

# the “classic” cathode ray tube television is

## **both an accelerator and detector!**

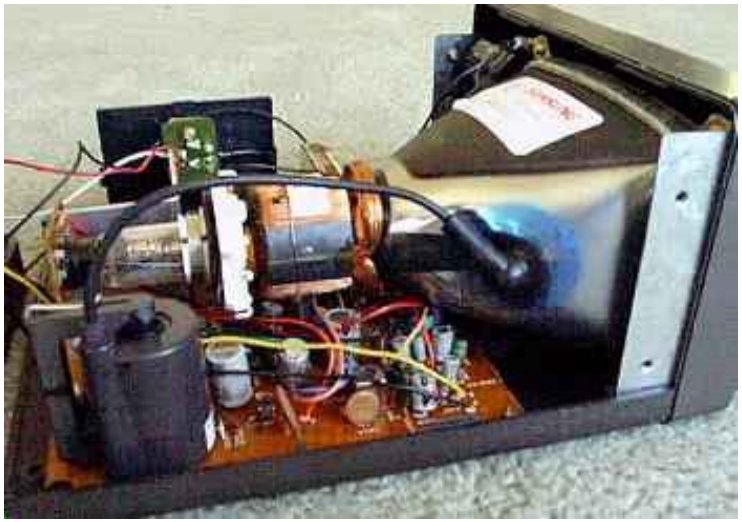
heated *filament*, electron source (cathode)




phosphorescent screen which lights up when struck by $e^-$’s

electromagentic fields to ***accelerate*** and steer the electron beam (ray)

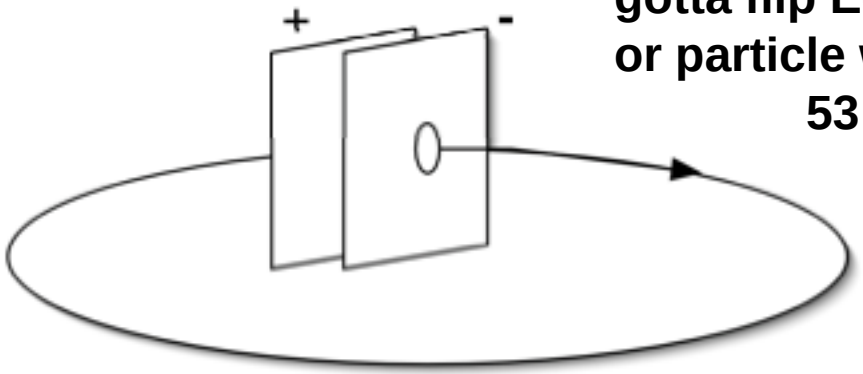
evacuated glass container (tube)



OK, so it’s a *little* more than that…
but not much! *Really*!

Note: voltages encountered are a few tens of thousands of volts, therefore particle energies of about **10 keV**, say!

# Let's re-use (recycle) the E-field!



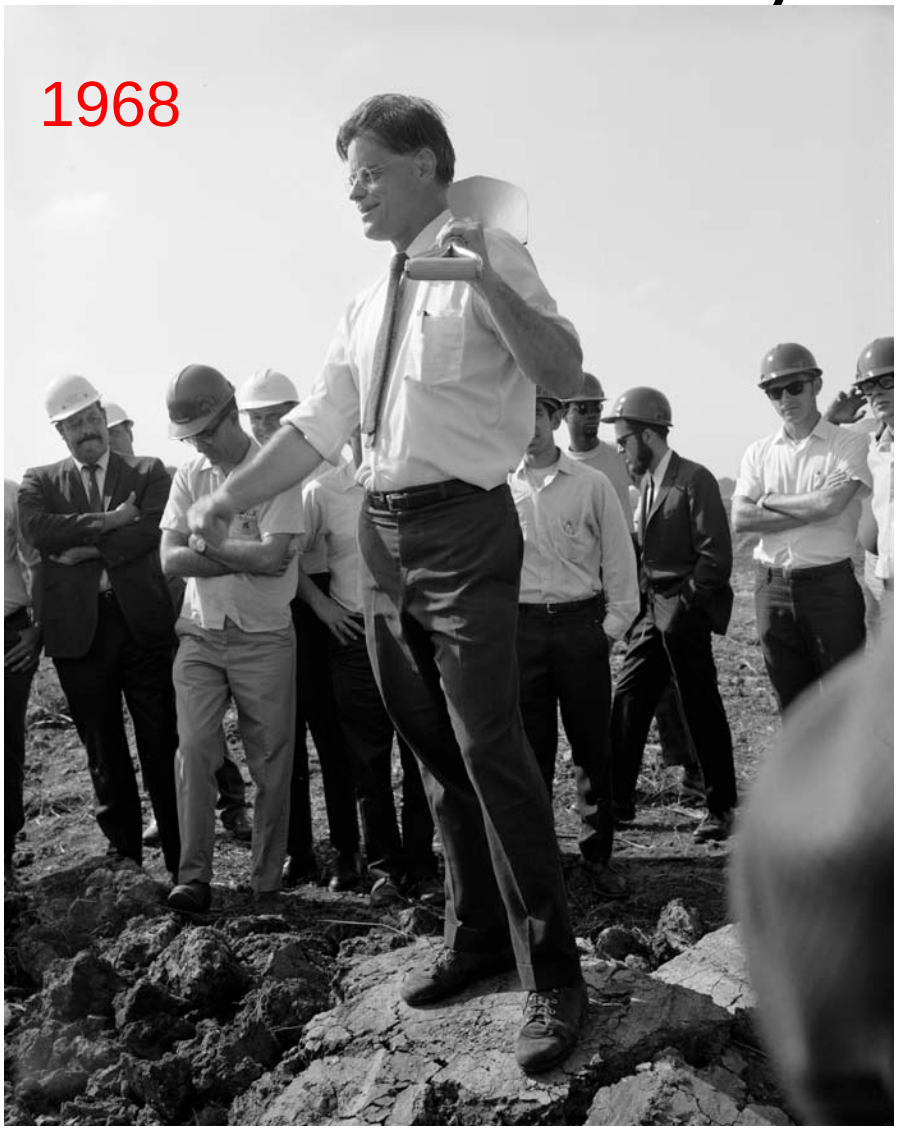

**gotta flip E-field when particle outside of plates or particle will be decelerated – RF voltages**

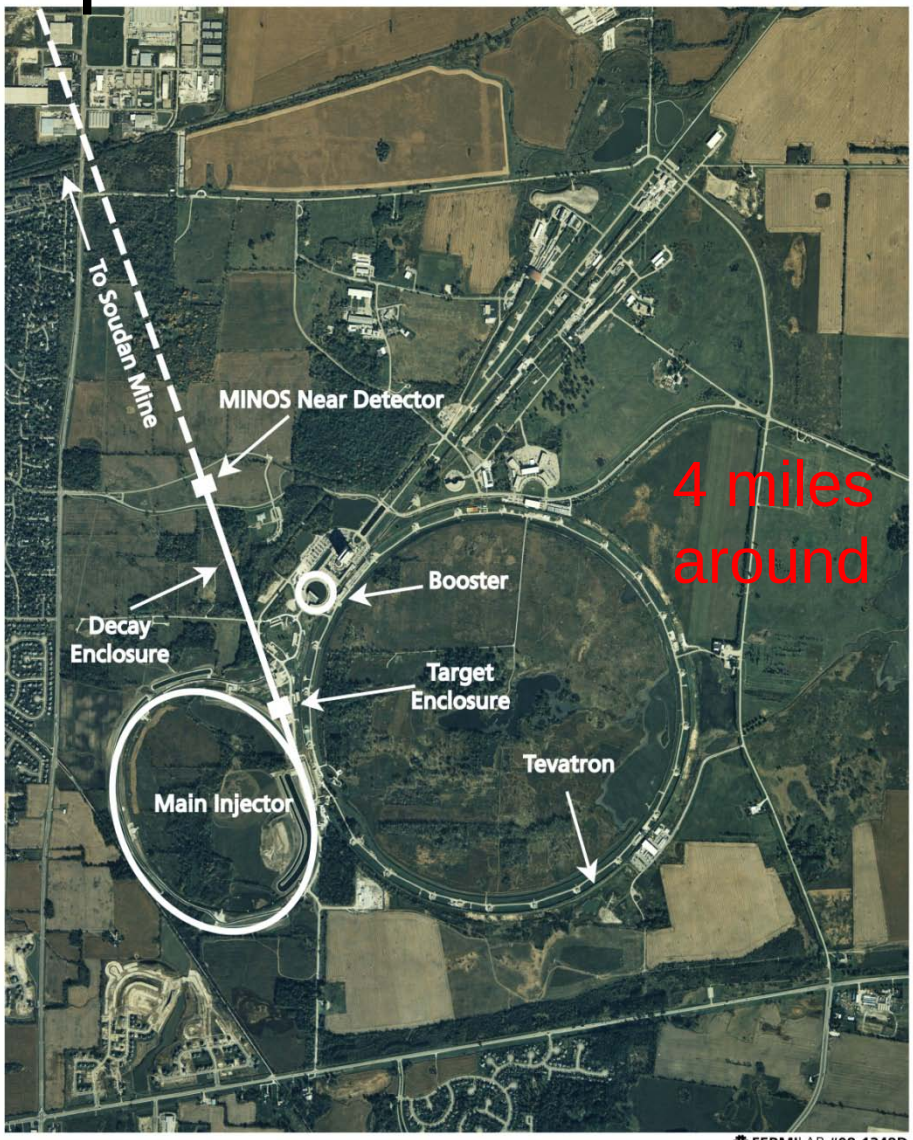
**53 MHz = TV Ch2**

**bend particles with magnetic field**

The First Cyclotron, Berkeley -- 1930's

# You need *big* machines to study *small* particles!



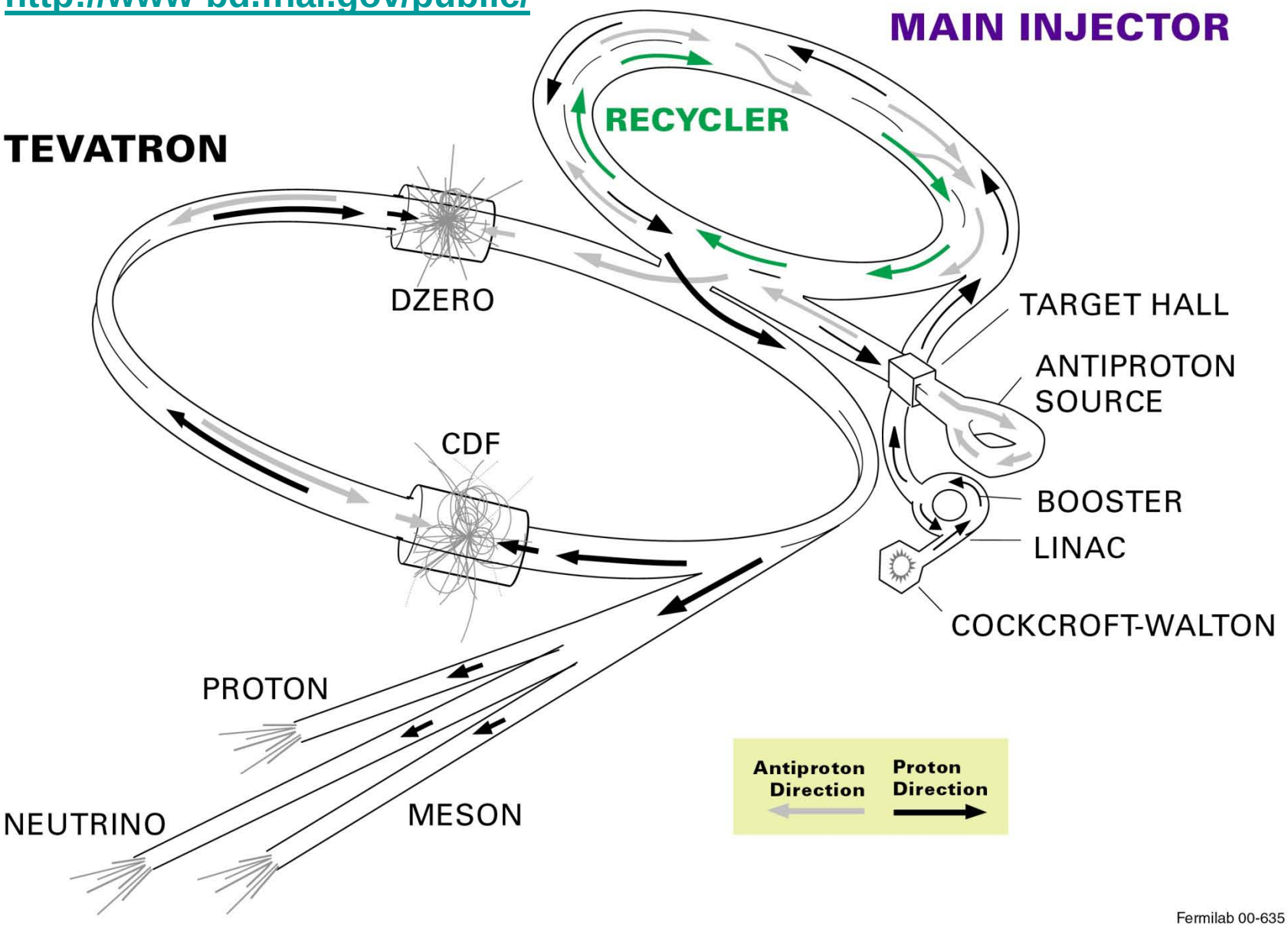



# Fermilab Accelerator Complex

- **Complex Accelerator Systems**
  - **Fermilab-- 11 separate machines**
    - **Cockcroft- Walton (2)**
    - **Linac**
    - **Booster**
    - **Main Injector**
    - **Recyler**
    - **Pelletron**
    - **Debuncher**
    - **Accumulator**
    - **Tevatron**
    - **Fermilab NICADD Photo Injector Laboratory (FNPL)**

# FERMILAB'S ACCELERATOR CHAIN

http://www-bd.fnal.gov/public/




Fermilab 00-635

**Cockcroft-Walton 750 KeV** — ***velocity = 0*** → ***0.04 c***

**LINAC 400 MeV** — ***0.71 c*** →

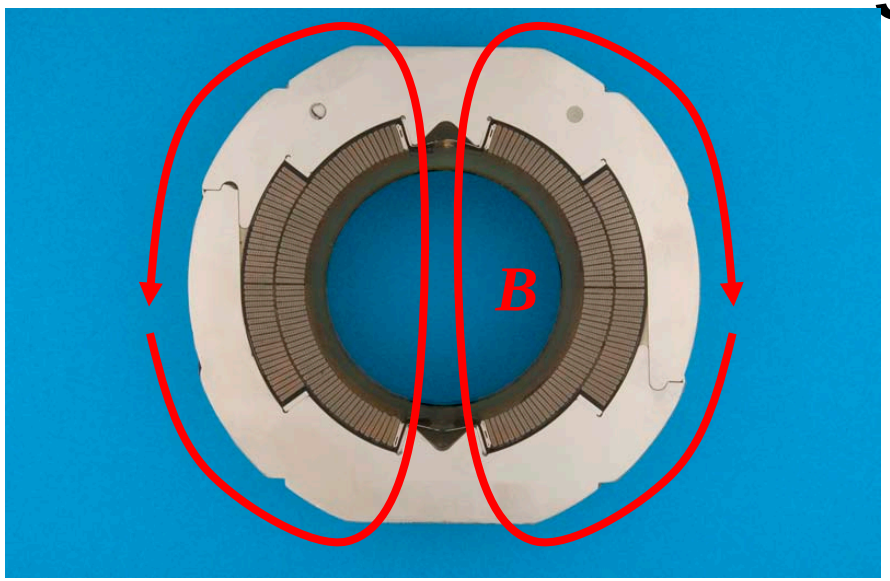
**Booster 8 GeV** — ***0.994 c***

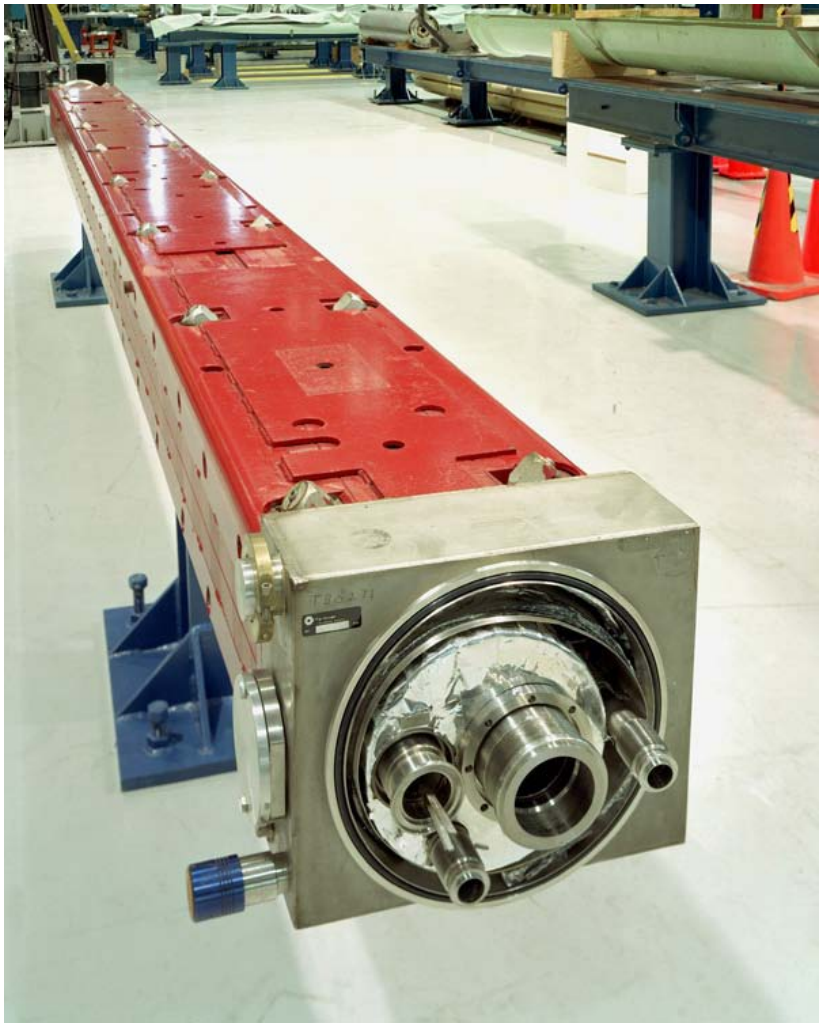
**Main Injector 150 GeV** — ***0.994 c*** → ***0.99998 c***

**Antiproton "Bottle"** — ***@ 8 GeV***

**Tevatron 1000 GeV = 1 TeV** — ***0.99998 c*** → ***0.9999995 c***

# Superconducting Tevatron Magnet



- Outside is at room temperature; inside is at 4°K = - 452°F!
- Field is 4.4 Tesla @ ~4,000 A
- Each magnet is ~20 ft long, and weighs about 4 tons
- ~1000 magnets in the Tevatron (~800 dipoles, ~200 quadrupoles)

# Fermilab Main Control Room

From here, control and monitor properties of all accelerators

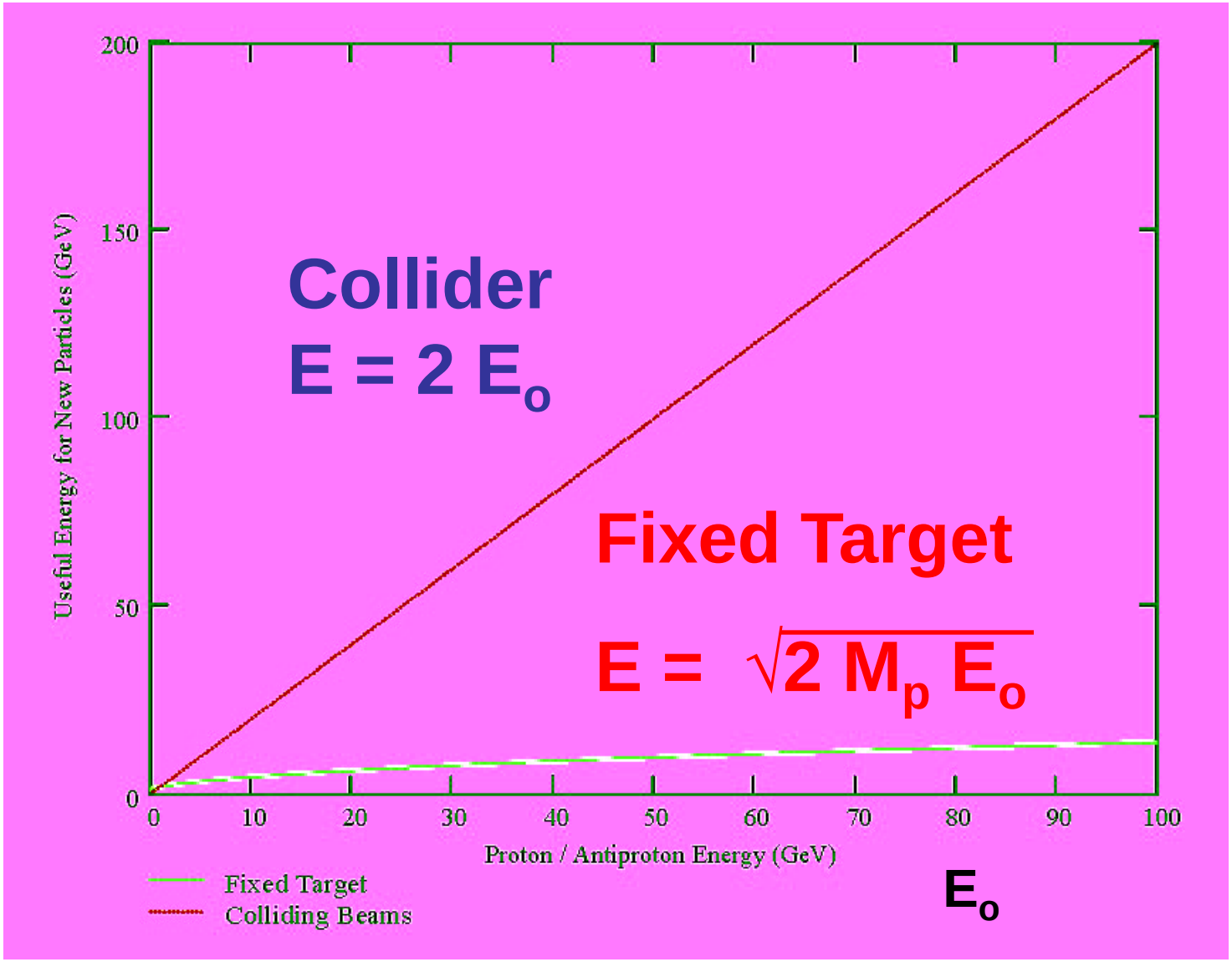
around the clock operation, 24/7 all year

shut down periods occur, for maintenance

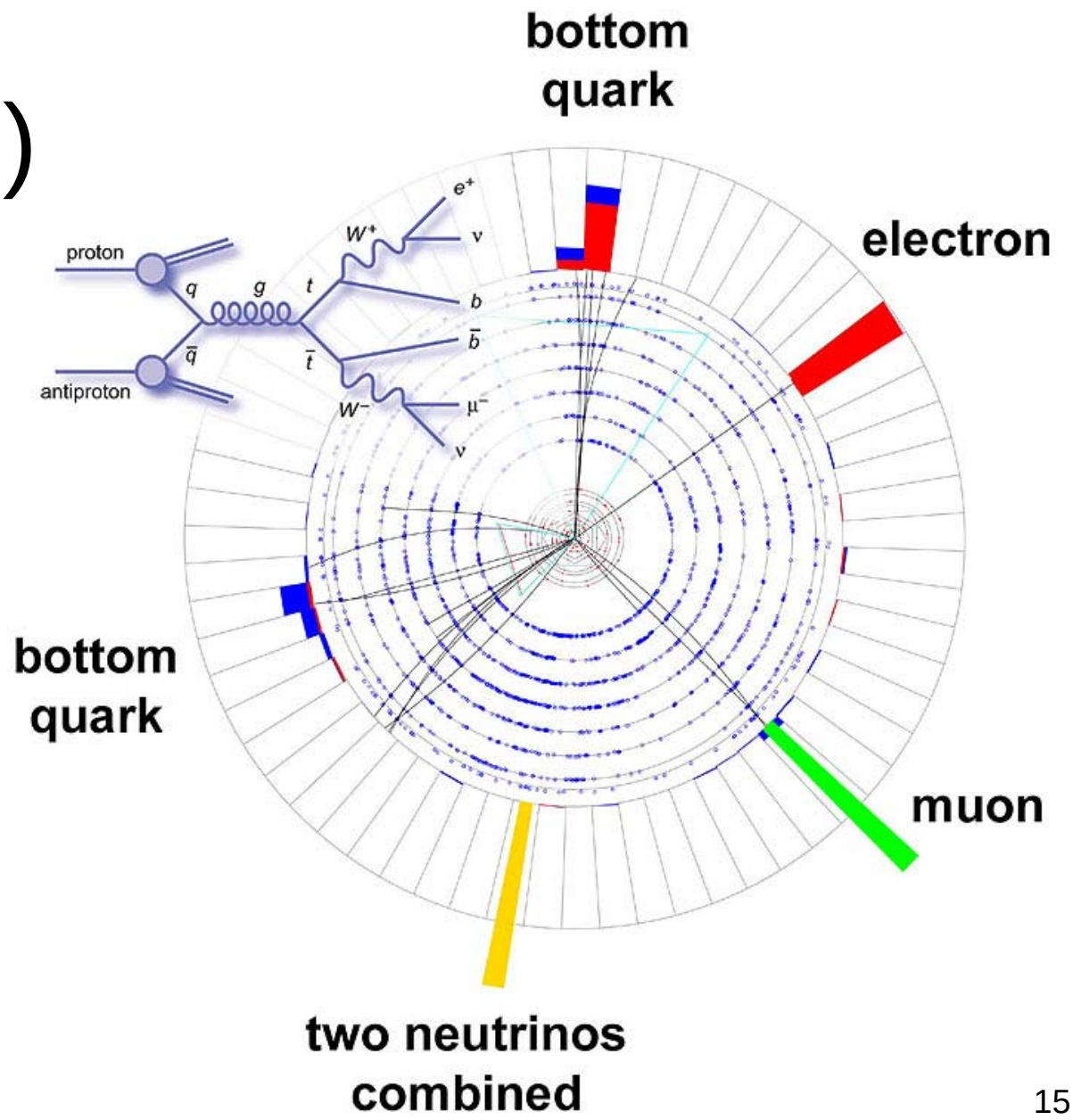
-- *now, for instance!*

crews of 5-6 Accelerator Operators and Crew Chief

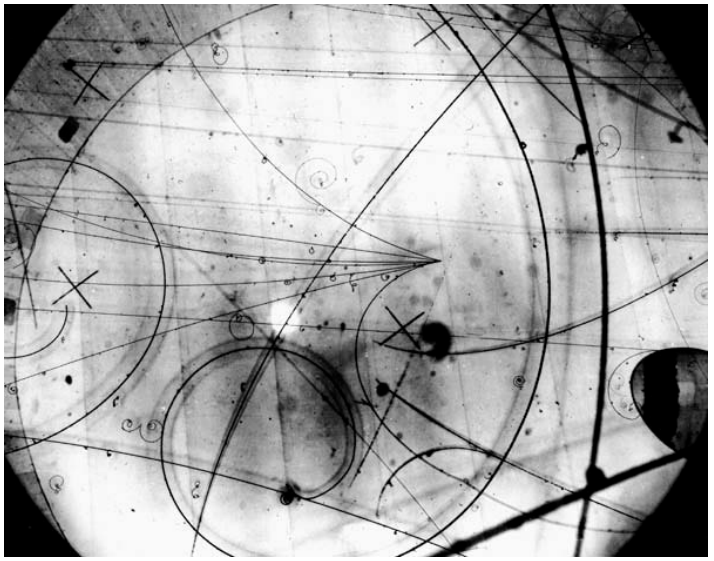
# Energy Available for Particle Production

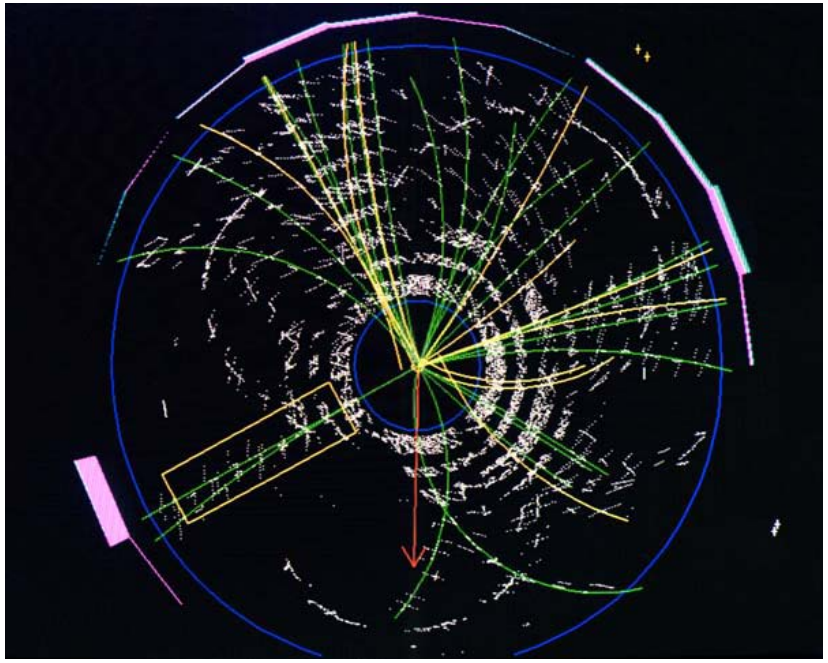


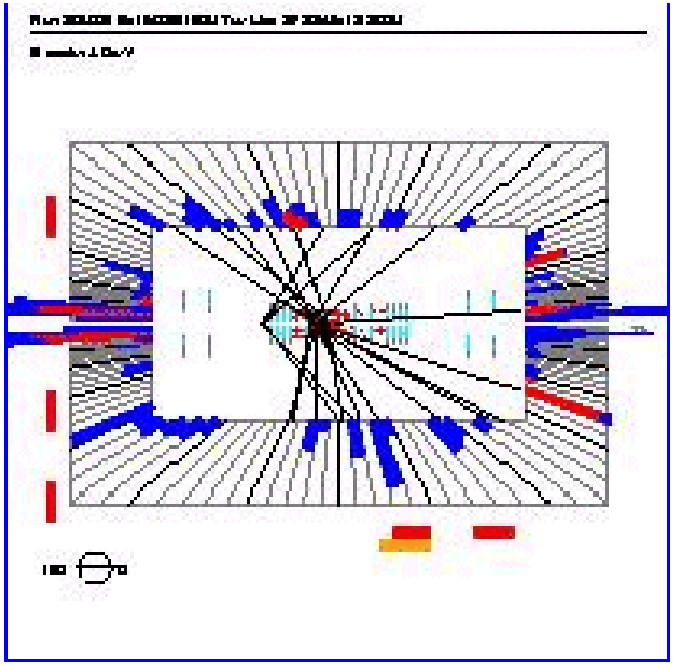
# A typical (interesting) “event”



# Seeing particles - indirectly

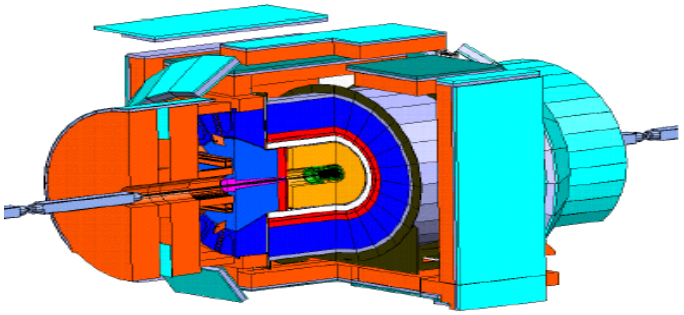




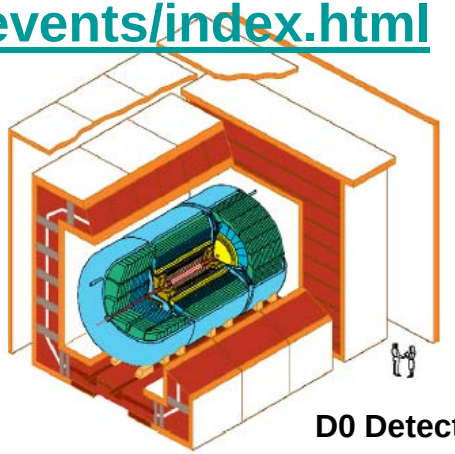


# CDF & D-Zero Experiments

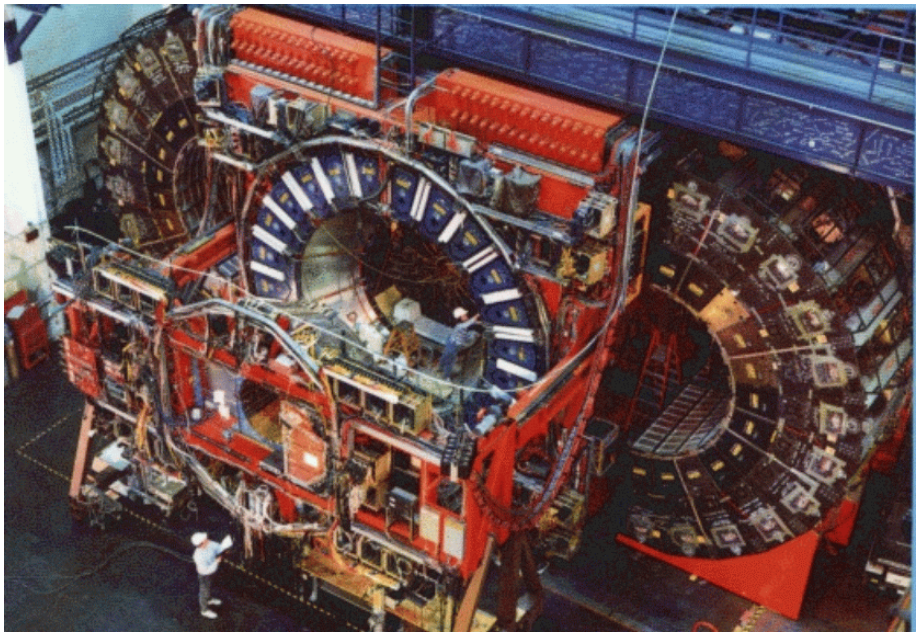
http://www.fnal.gov/pub/now/live_events/index.html



CDF Detector

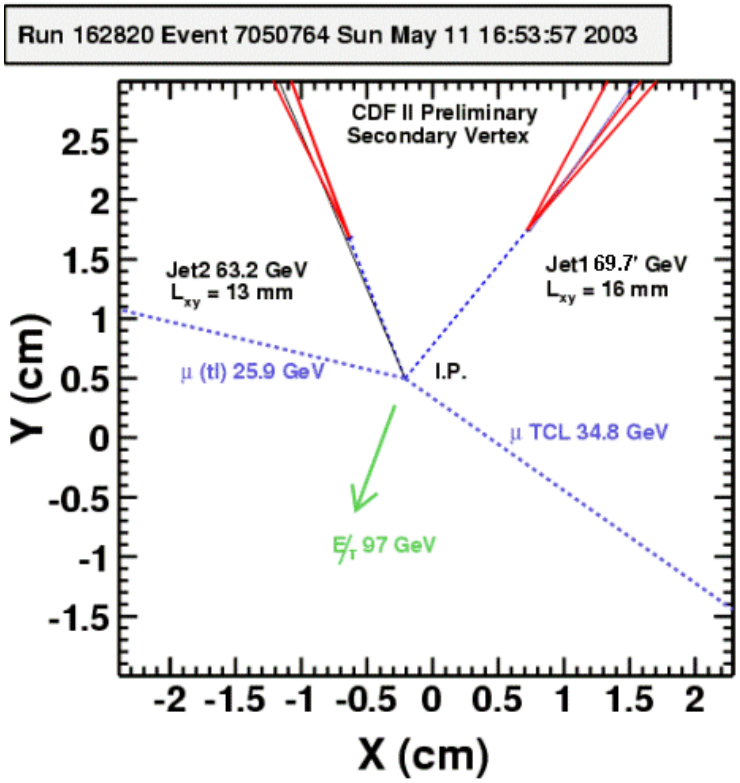


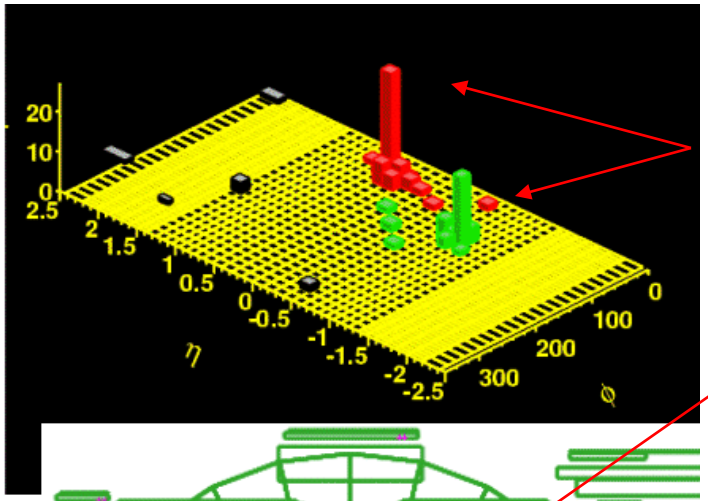
D0 Detector

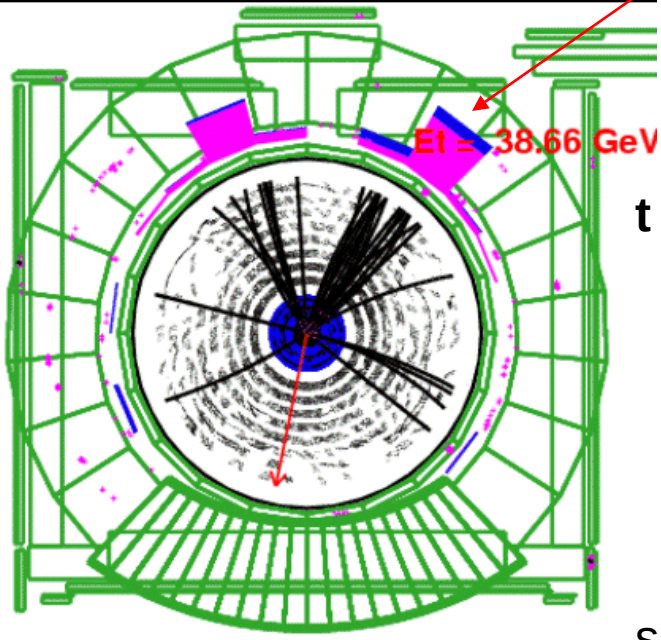


# Observation of top-quark pair production at Fermilab

**Double b-tagged dilepton event @ CDF**




$E = mc^2$

**Jets or sprays of particles from bottom quarks**

$t \rightarrow W + b$

$\downarrow \quad \downarrow$

$\nu + \mu \quad$ **jet**

$\downarrow \quad \downarrow$

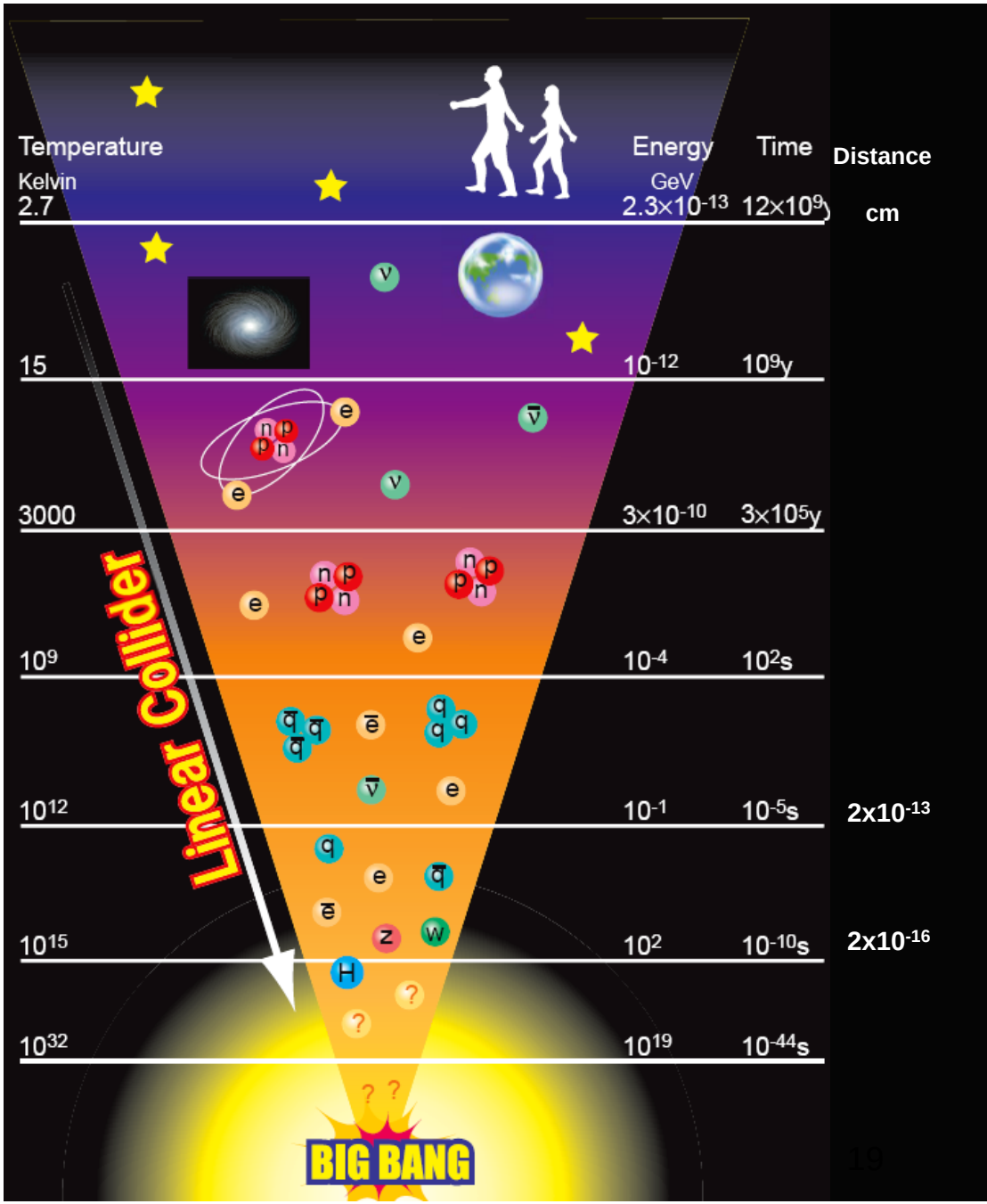
missing energy — multi-particles

similar for decay for **t-bar**

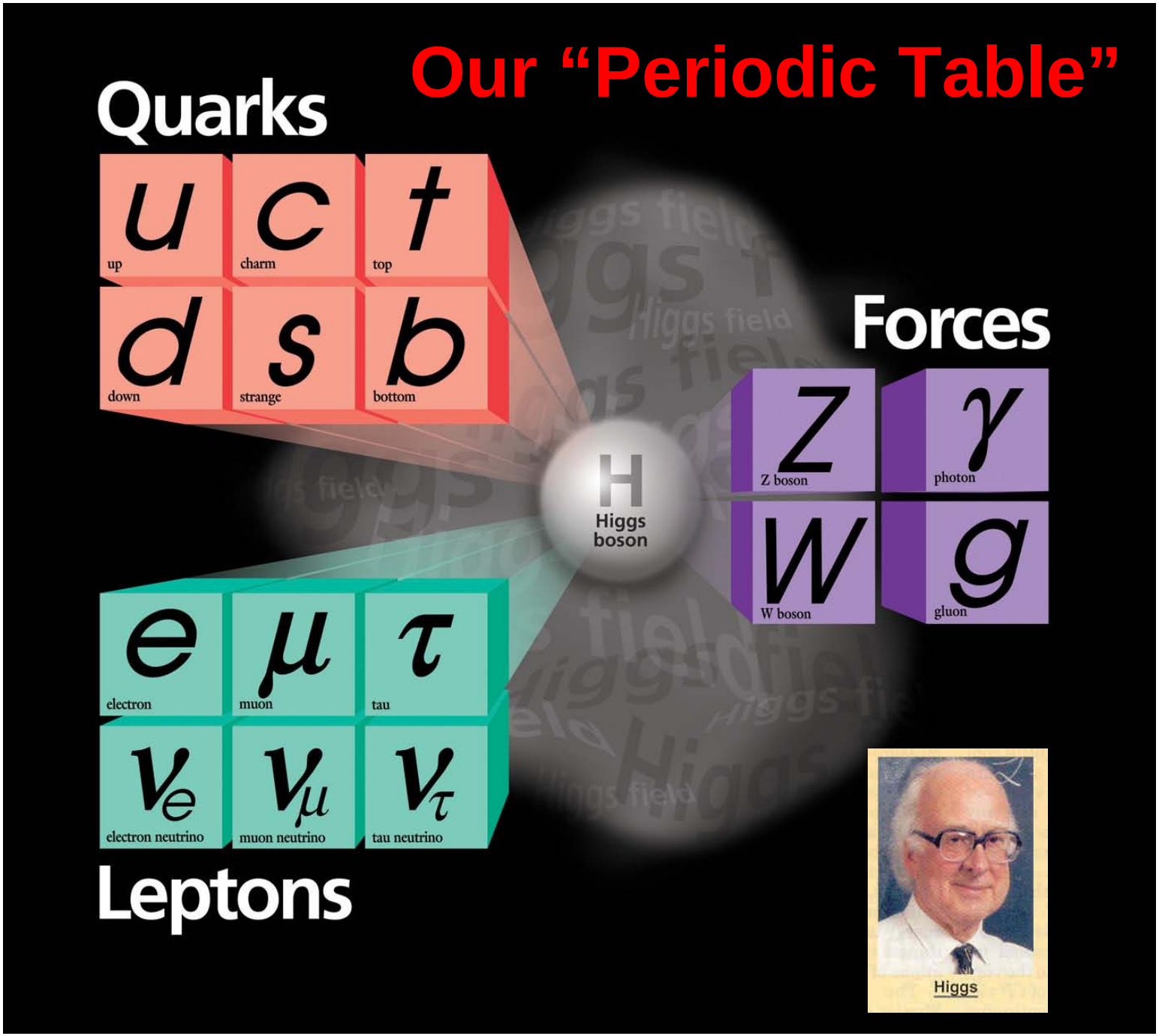
**ZOOM IN : silicon microstrip detector**

Accelerators are like ***microscopes:*** Energy => 1/distance and like ***time machines:*** Energy => 1/time

also Energy => ***Temperature***



# Our "Periodic Table"



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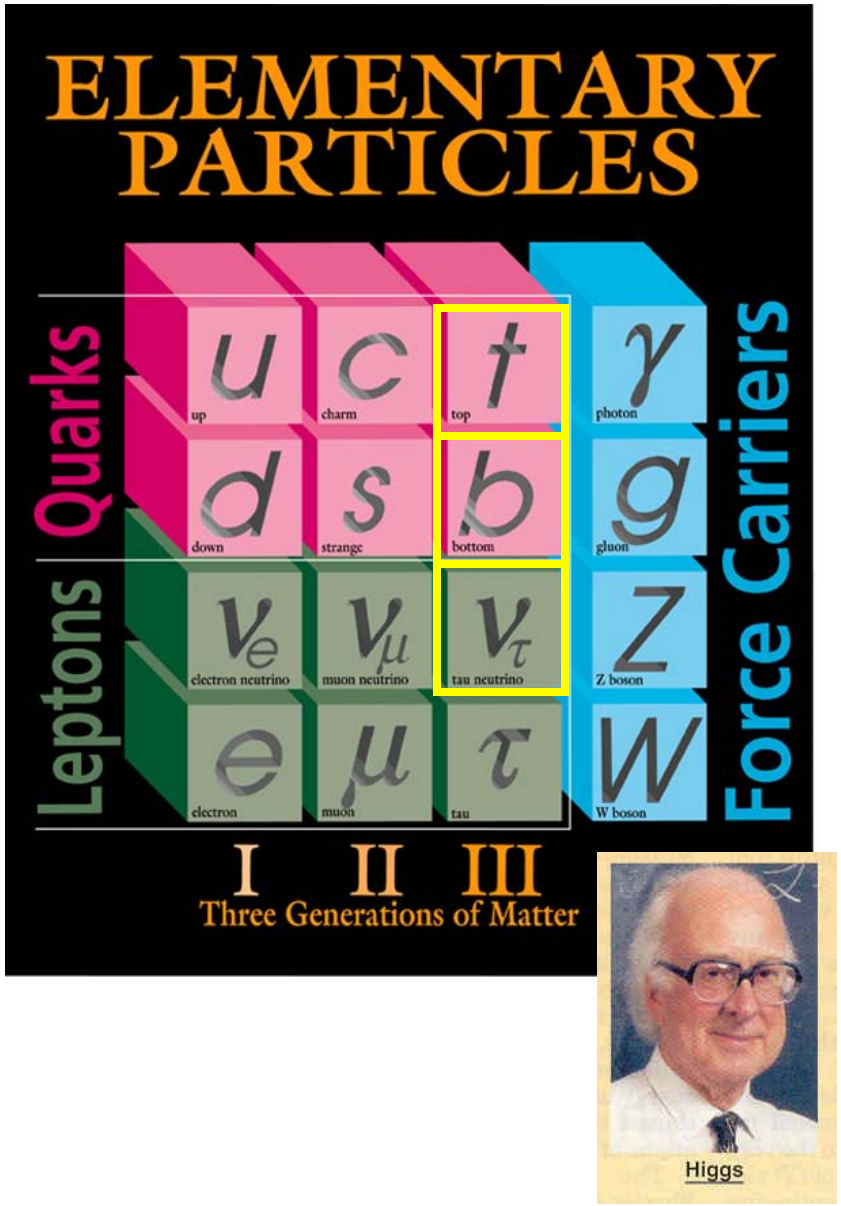






**Quarks, Leptons, & Forces**

**b, t, $\nu_\tau$ discovered at FNAL**

**Electromagnetism**
**Strong Nuclear Force**
**Weak Nuclear Force**
**(radioactive decay)**
**Gravity is too weak**
**for Fermilab to study**

**fundamental particles**
**no size – without parts**
**can't break them apart**
**(at least with today's accelerators)**

**Looking for the Higgs boson at Tevatron today!**

**Gives all the other particles their mass**

# Some of today's *hot* physics topics:

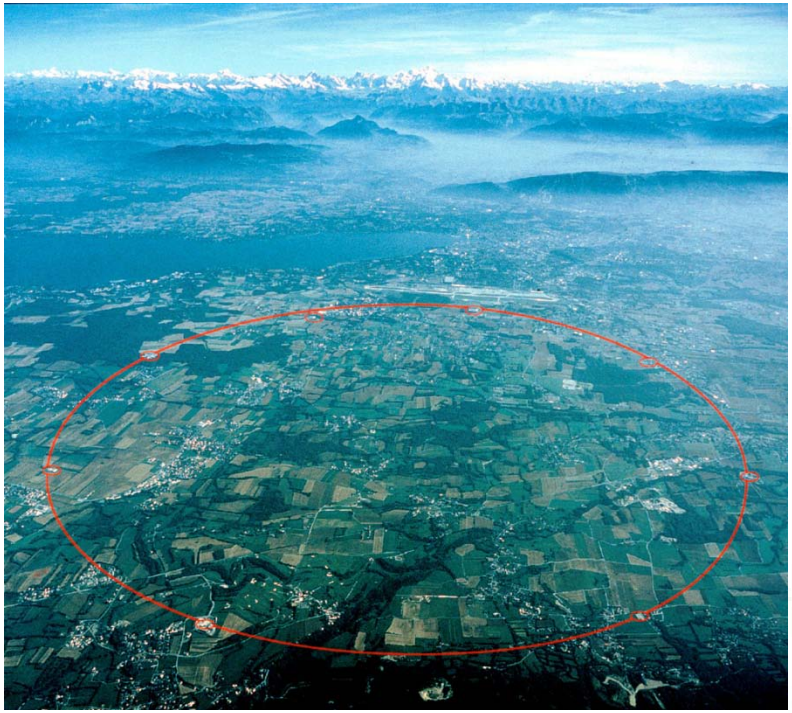
**What causes *mass*? Is it the *Higgs boson*?**
**Why are there different types of quarks & leptons?**
**Very curious *neutrinos*! (weak force)**
**Why does the universe seem to be "*matter*",**
**rather than a balance of matter and anti-matter?**
**Is there anything *inside* quarks & leptons?**
**Are there any *other types* of particles or forces?**
**Are there more than 4 *dimensions* (x, y, z, t)?**
**How does *gravity* fit in to the picture?**
**What is "*dark matter*" and "*dark energy*"?**
**not just high energy or particle physics,**
**but also *experimental astrophysics* questions**

# Fermilab: 2 TeV proton-antiproton collider

## 6 km circumference, 4.4 Tesla magnets, ~20 yrs old

# CERN is now building a 14 TeV p-p collider

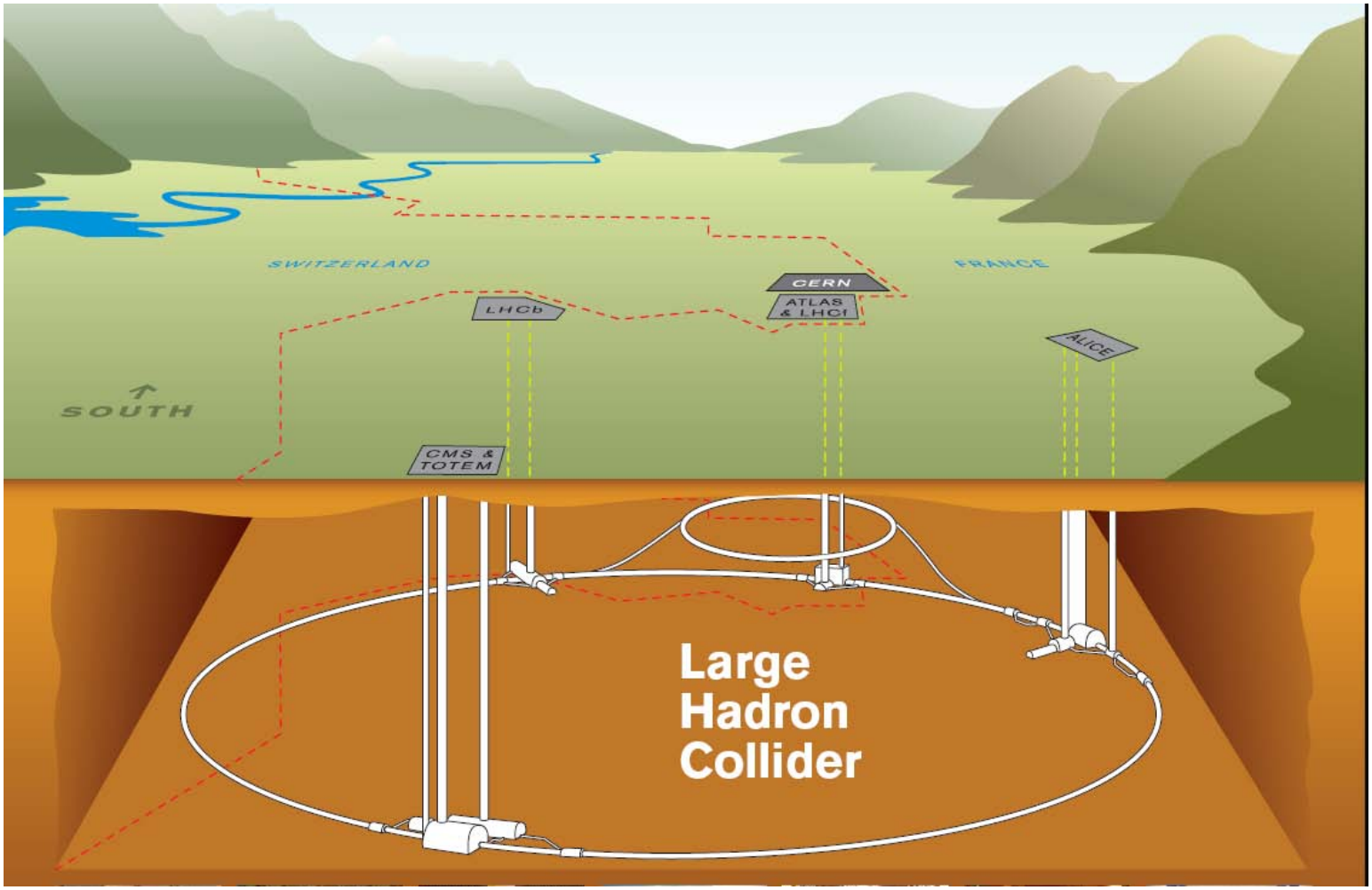
## in a 27 km tunnel, 8 Tesla magnets, start-up ~2008



chicagotribune.com
Chicago Tribune Web Edition

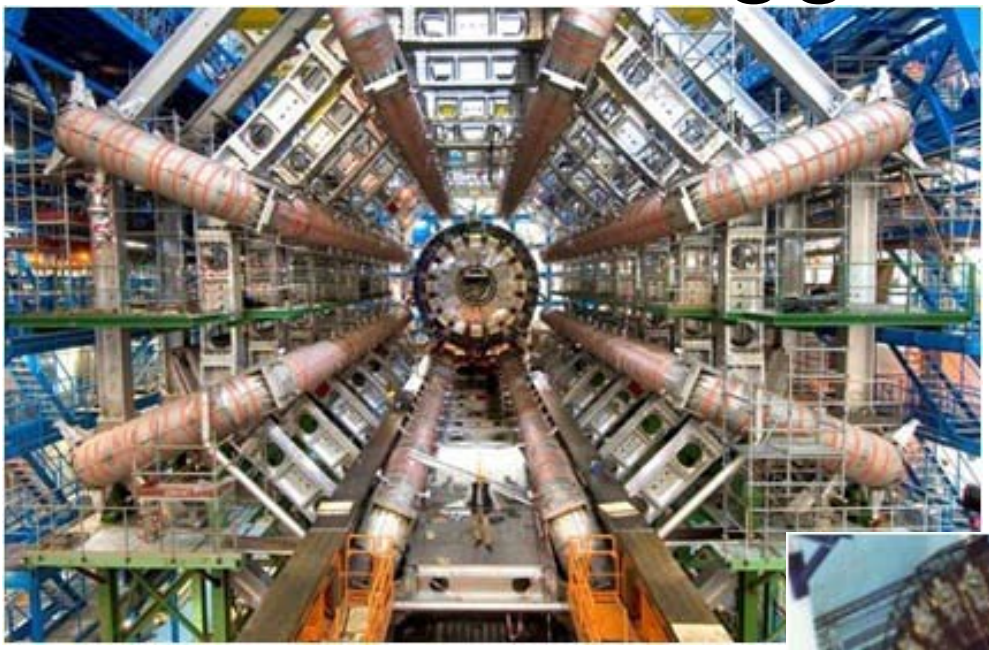
September 5, 2007

**We've been on top for 20 years, what do we do next?**

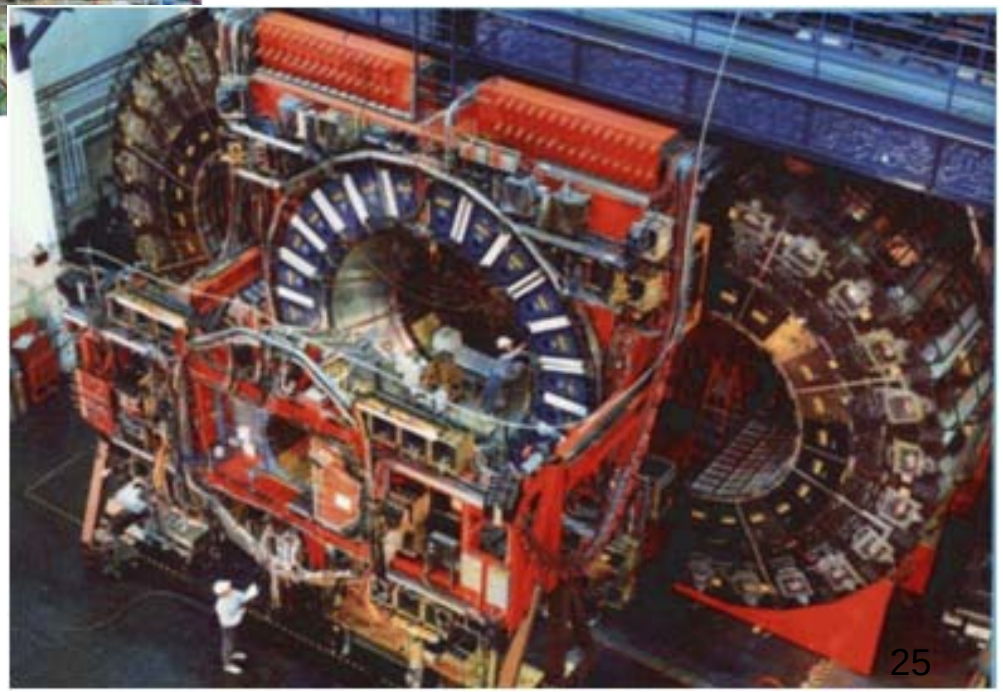



CERN's LHC will have
4.25 x circumference, 1.65 x stronger magnets,
7 x more energy, and 33 x event rate,
than Fermilab's Tevatron Collider

# And Much Bigger Experiments!



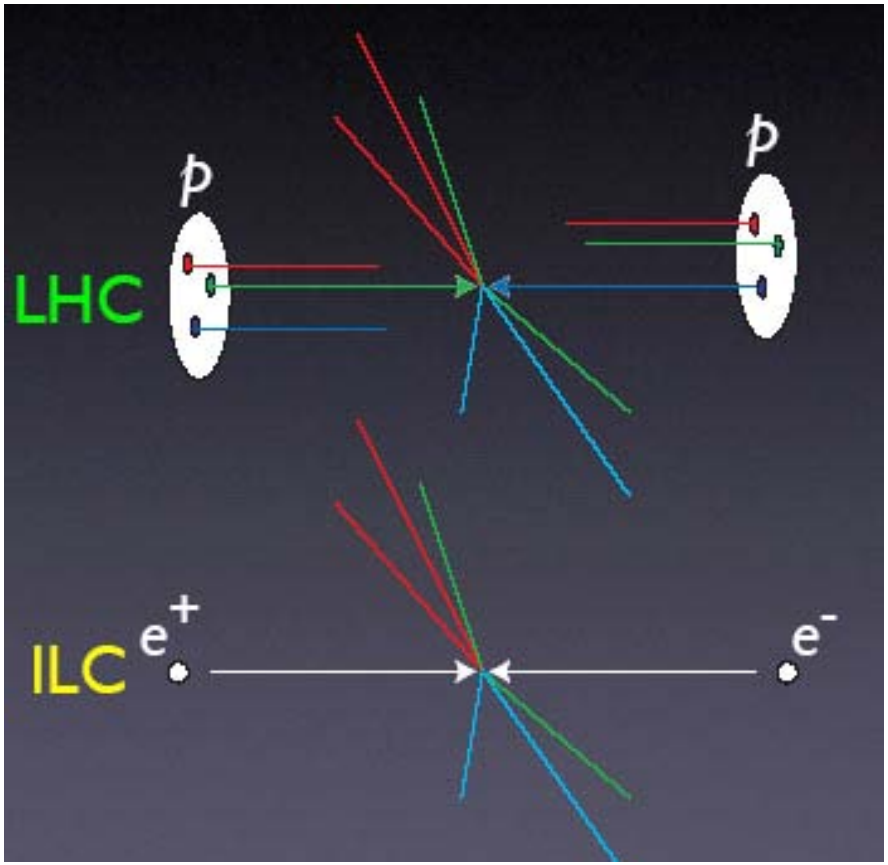
**ATLAS at CERN**



**CDF at Fermilab**

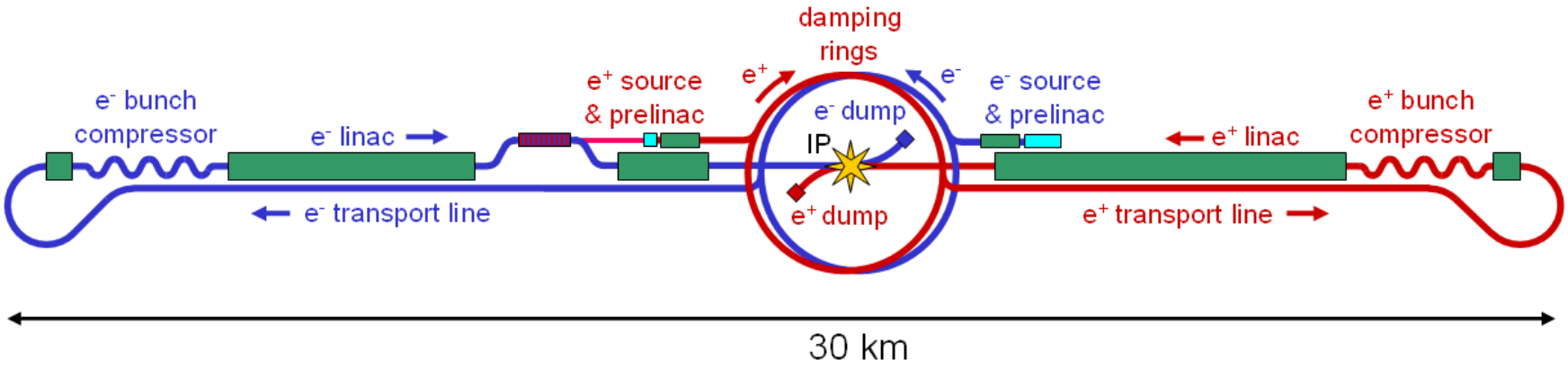
# 500-1000 GeV $e^+e^-$ Linear Collider is under consideration by Europe, Japan, and U.S./Canada initially 250x250 GeV, with possible upgade to 500x500 GeV

proton-(anti-)proton colliders
are like a blunt objects,
colliding bags of quarks & gluons
statistically share total energy
higher raw energy for discovery




electron-positron colliders are
tools for precision measurement
collide fundamental particles
without internal structure
full energy available
simple, understood, and variable initial state
e.g. can tune the energy and polarizations

# The International Linear Collider




**a 250 GeV x 250 GeV $e^+e^-$ collider**

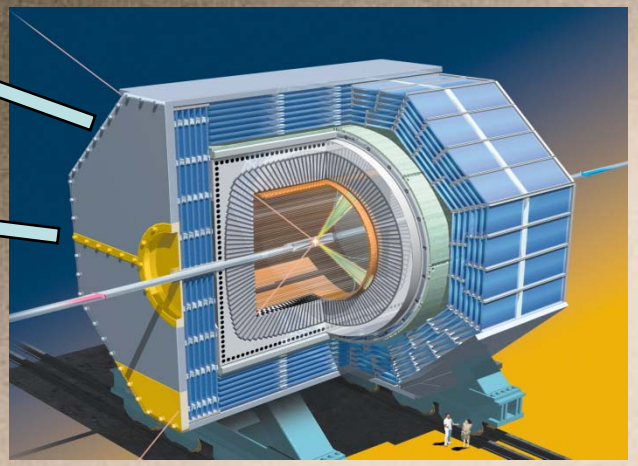
**~ 31 km long!**

The Reference Design Report (RDR) for the ILC
including cost and labor estimates
was released in August, 2007

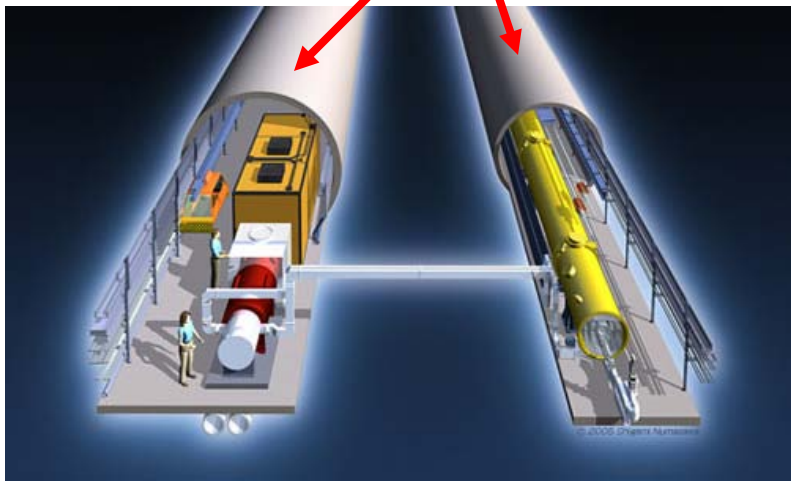
# International Linear Collider

Main Research Center

Particle Detector



~30 km long tunnels



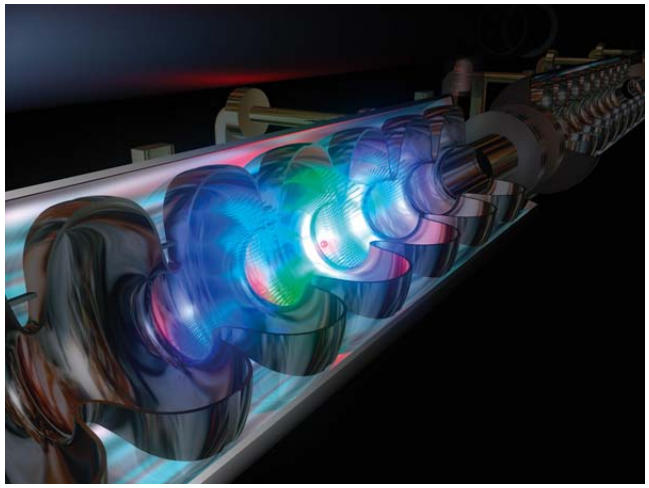
## Two tunnels

- one housing accelerator units
- other for services - RF power

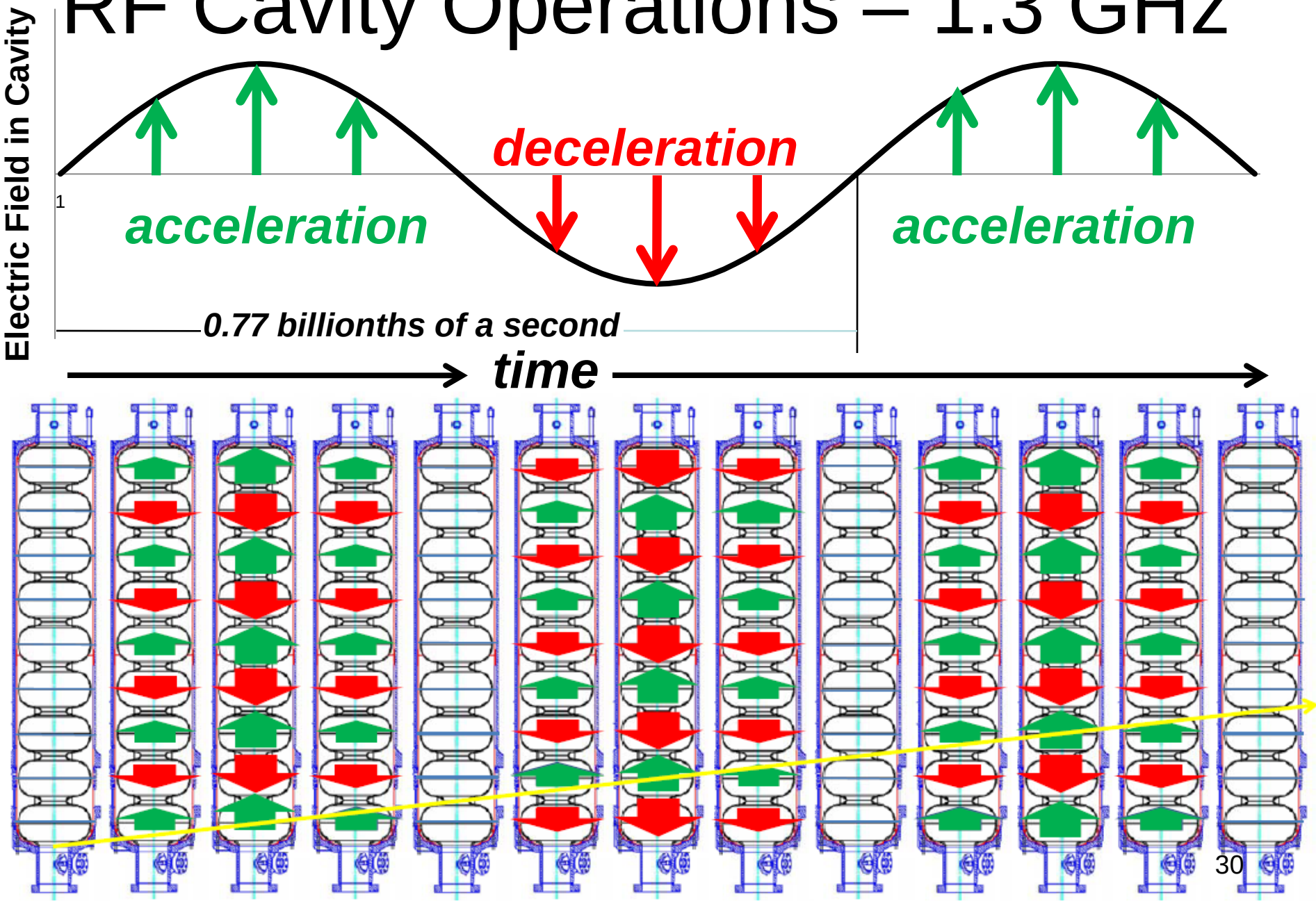
# ~ 16,000 SC RF cavities

## below is first Fermilab Cryomodule

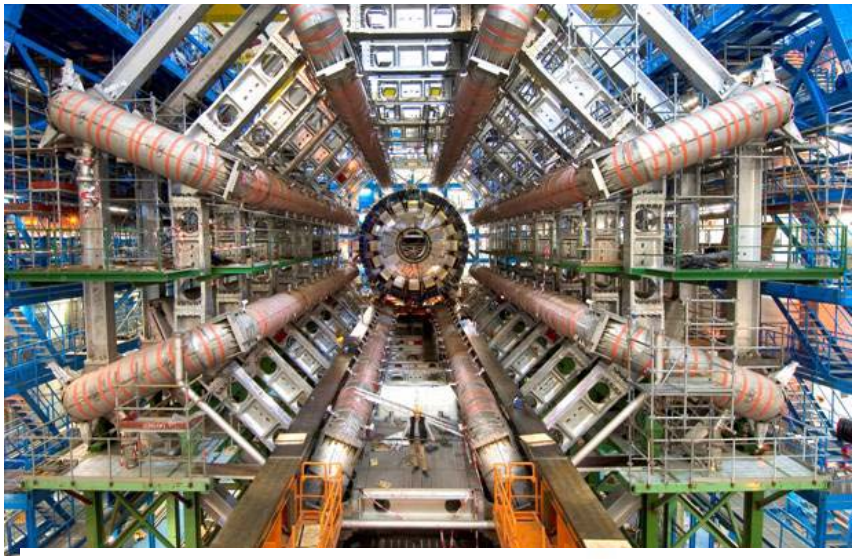
## 8 cavities, 12 m long x 1 m dia.

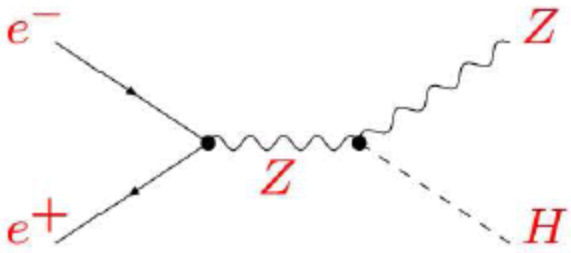


# RF Cavity Operations – 1.3 GHz

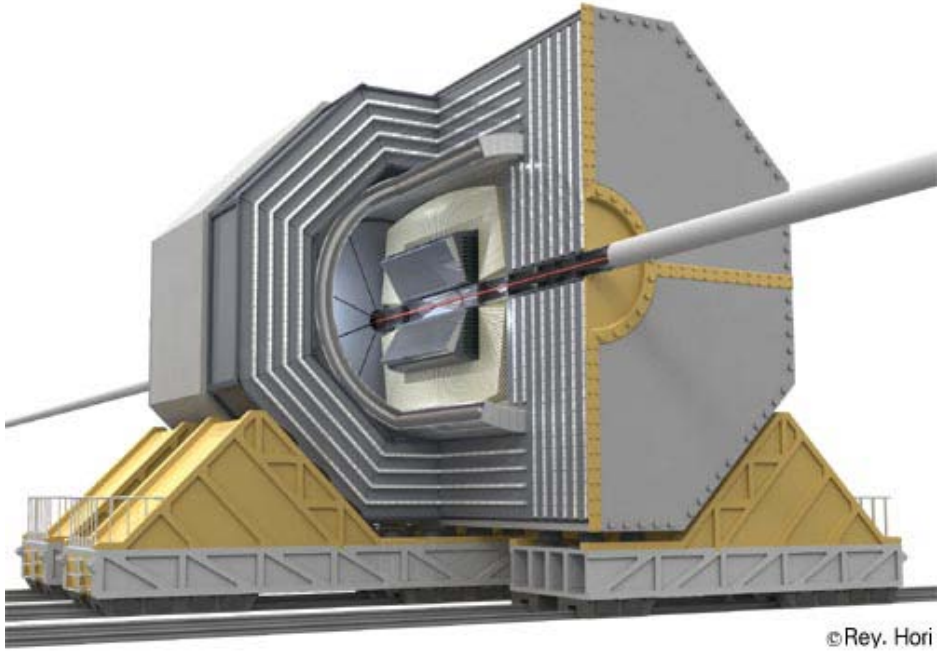


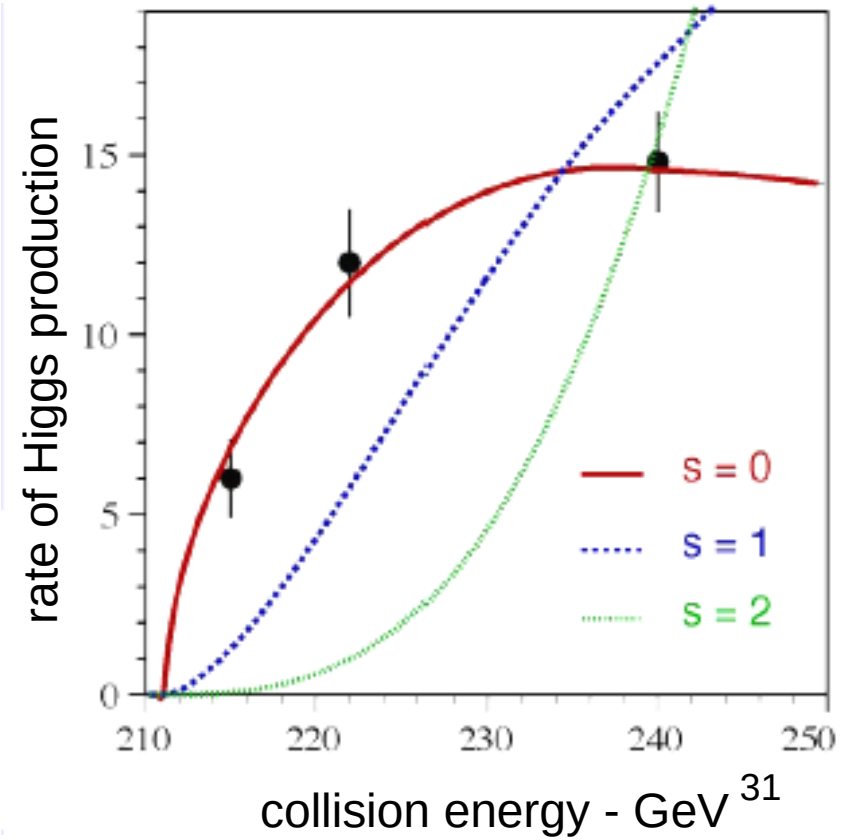
# Complementarity of LHC and ILC

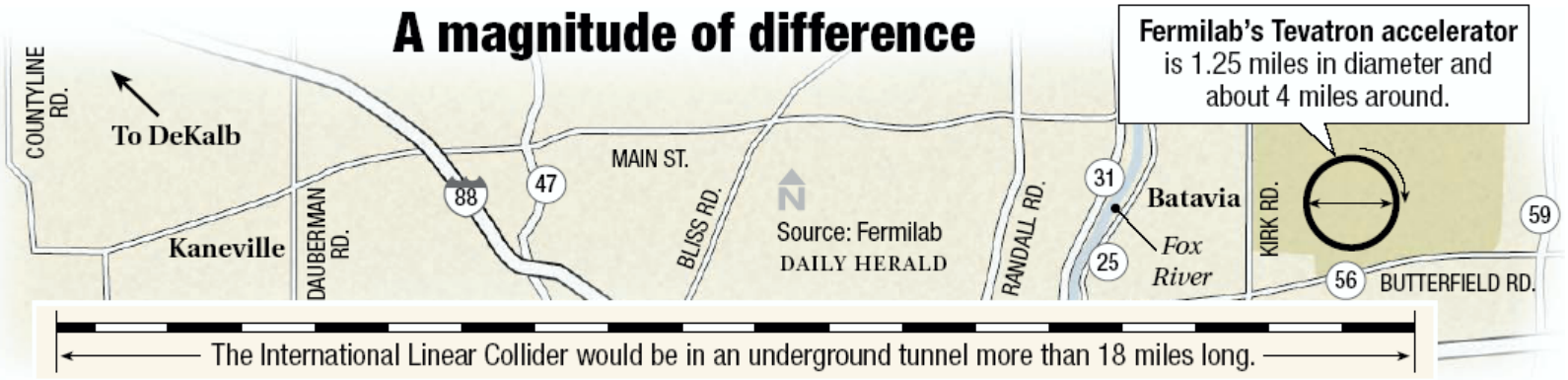




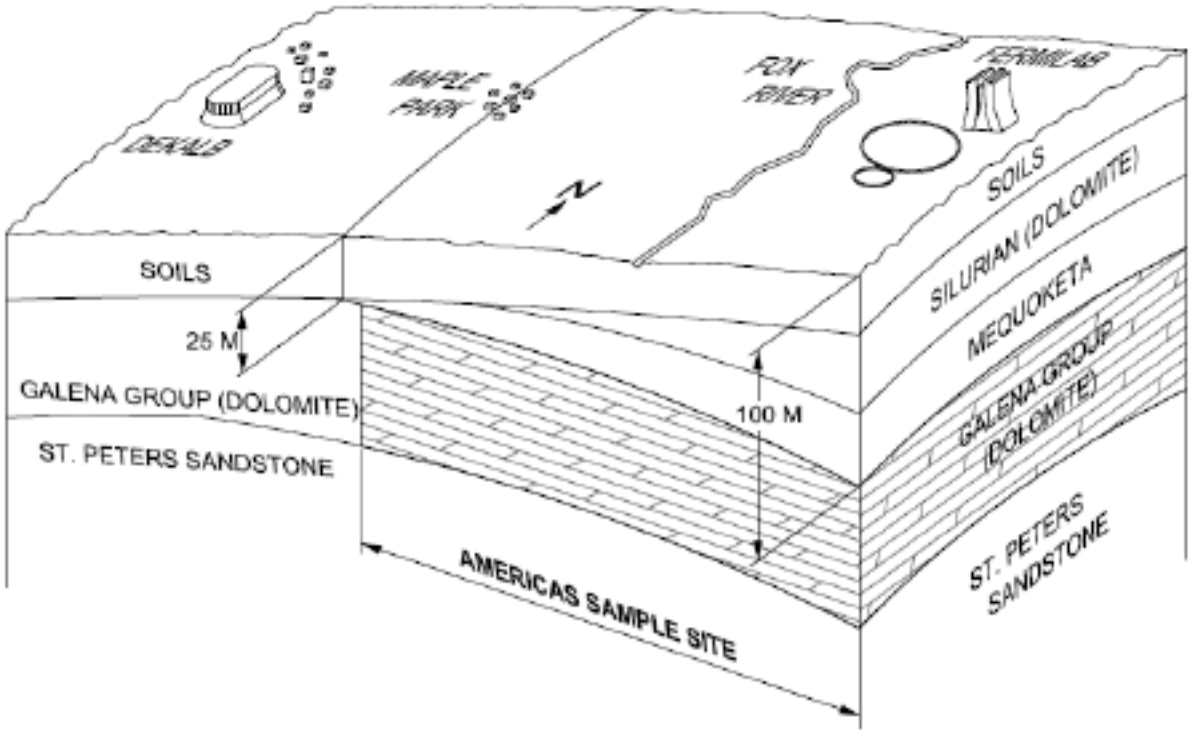

Does Spin of Higgs = 0 ?



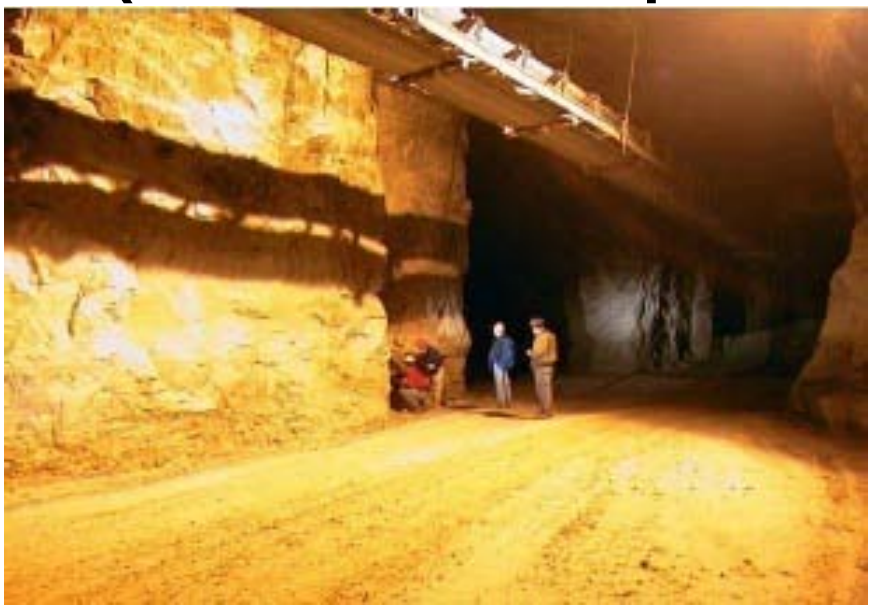



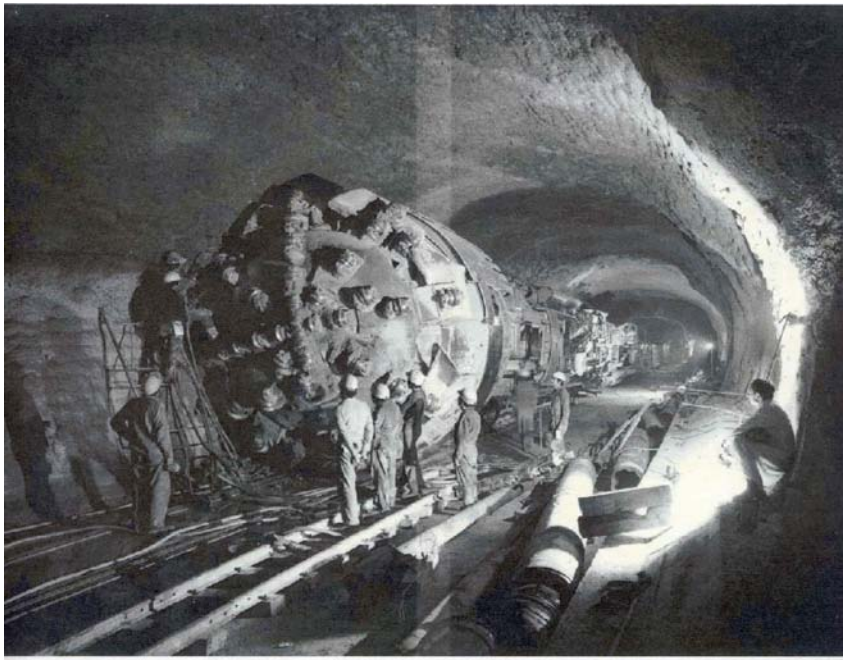



# *Americas Sample Plan / Section*



# North Aurora mine & CERN TBM (also TARP = Deep Tunnel)





# What, $, When, Where?

**500 GeV $e^+e^-$ collider (250 GeV x 250 GeV),**

**but include sizing to enable upgrade to 1 TeV,**

**e.g. beam stops, BDS tunnels, identify land**

**Cost ~ $ 6.7 B (2007$) (~ same for 3 regions sites)**

**plus 13,000 person-years laboratory labor**

**plus escalation (inflation) and contingency**

**Start construction ~2018 at the earliest**

**then 7 years construction – I'll be > 75 years old!**

**We are hoping that Fermilab will be the site,**

**also investigated sites in Switzerland & Japan.**

**This will be a big international decision!**

# Accelerator Uses

- **Fundamental Research into Nature**
  - **Particle Physics and Nuclear Physics**
- **Light sources**
  - **Condensed Matter Physics**
  - **Chemistry**
  - **Biology**
  - **Archeology**

} **~ 100 accelerators**

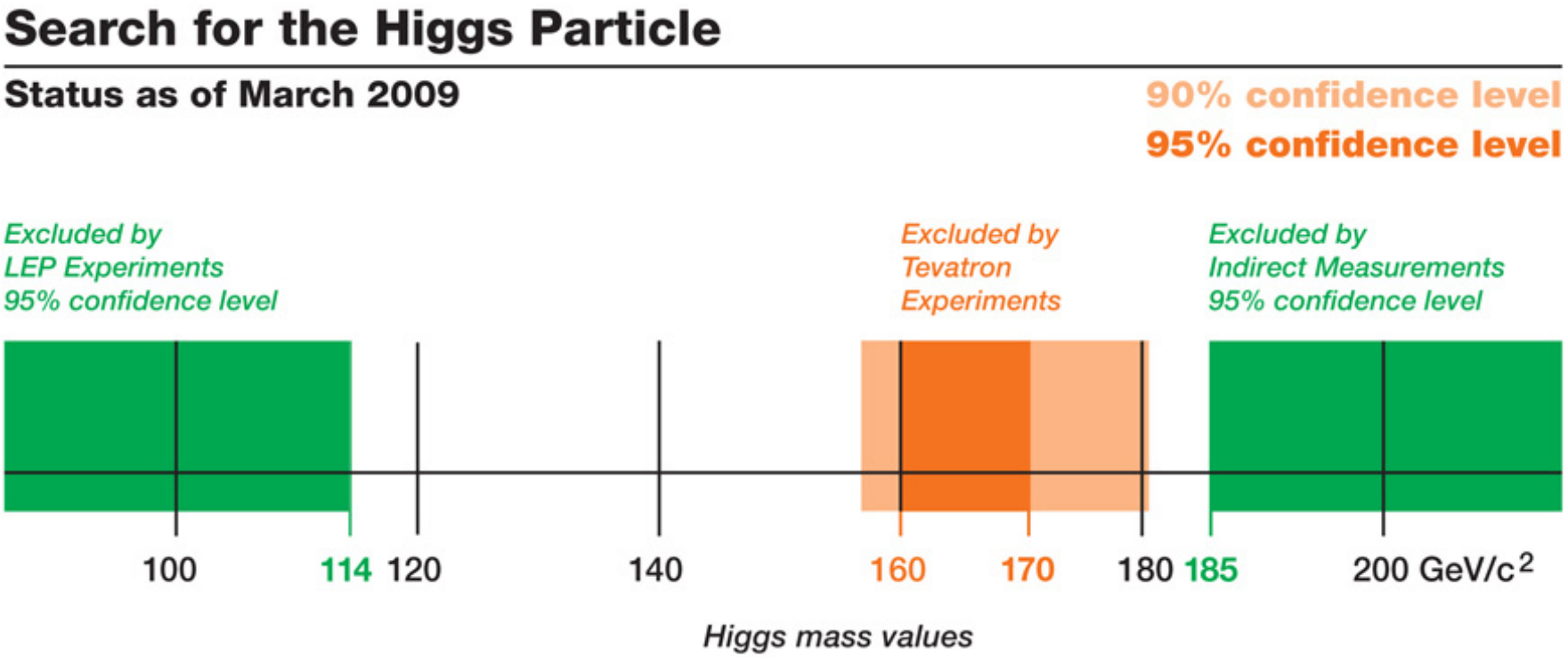
- **Medicine (~ 5000 accelerators)**
  - **X-rays**
  - **Direct Treatment of Tumors**
  - **Production of Radioactive Sources, e.g. PET**
- **Industrial Applications (~ 4900 accelerators)**
  - **Semiconductor Fabrication**
  - **Electron Beam Welding and Furnaces**
- **(old-fashioned) Televisions!**

# End of my Presentation
# Thank you for coming!

http://www.fnal.gov
http://www.fnal.gov/pub/today/
http://www.linearcollider.org
http://www.symmetrymagazine.org
http://www.particleadventure.org
http://www-ilcdcb.fnal.gov/Ask_accelerators_13july08.pdf

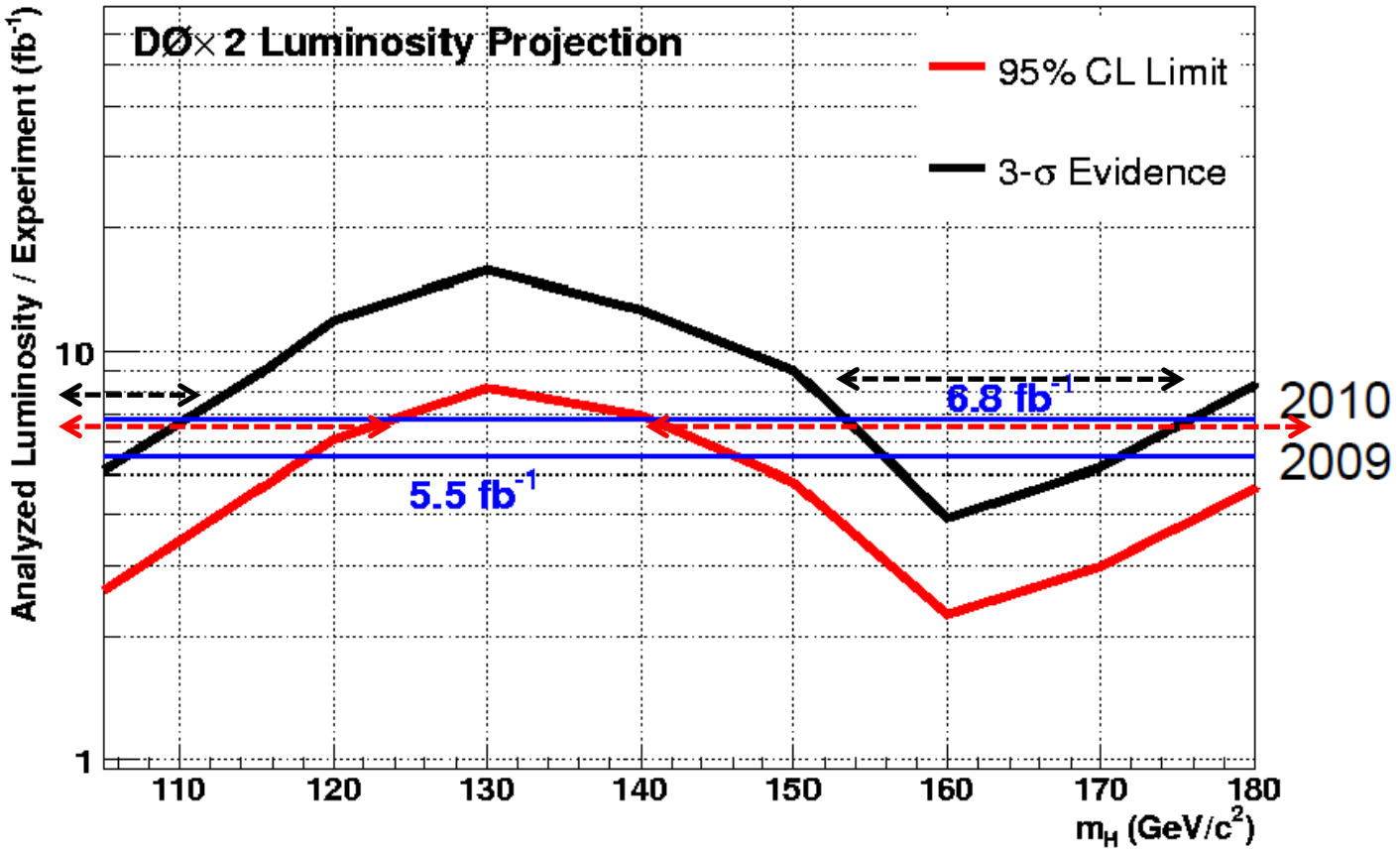
- **I'll be happy to continue discussion:**
  - **More on ILC**
  - **Benefits of Research at Fermilab**
  - **NuMI update (beam to Minnesota)**
  - **More on what we don't know about nature**

# We think we know everything about the Higgs boson via SM, except its ***MASS***



# SM Higgs Limit Projections

**D0x2 = assumes combining all channels for D0 + CDF**

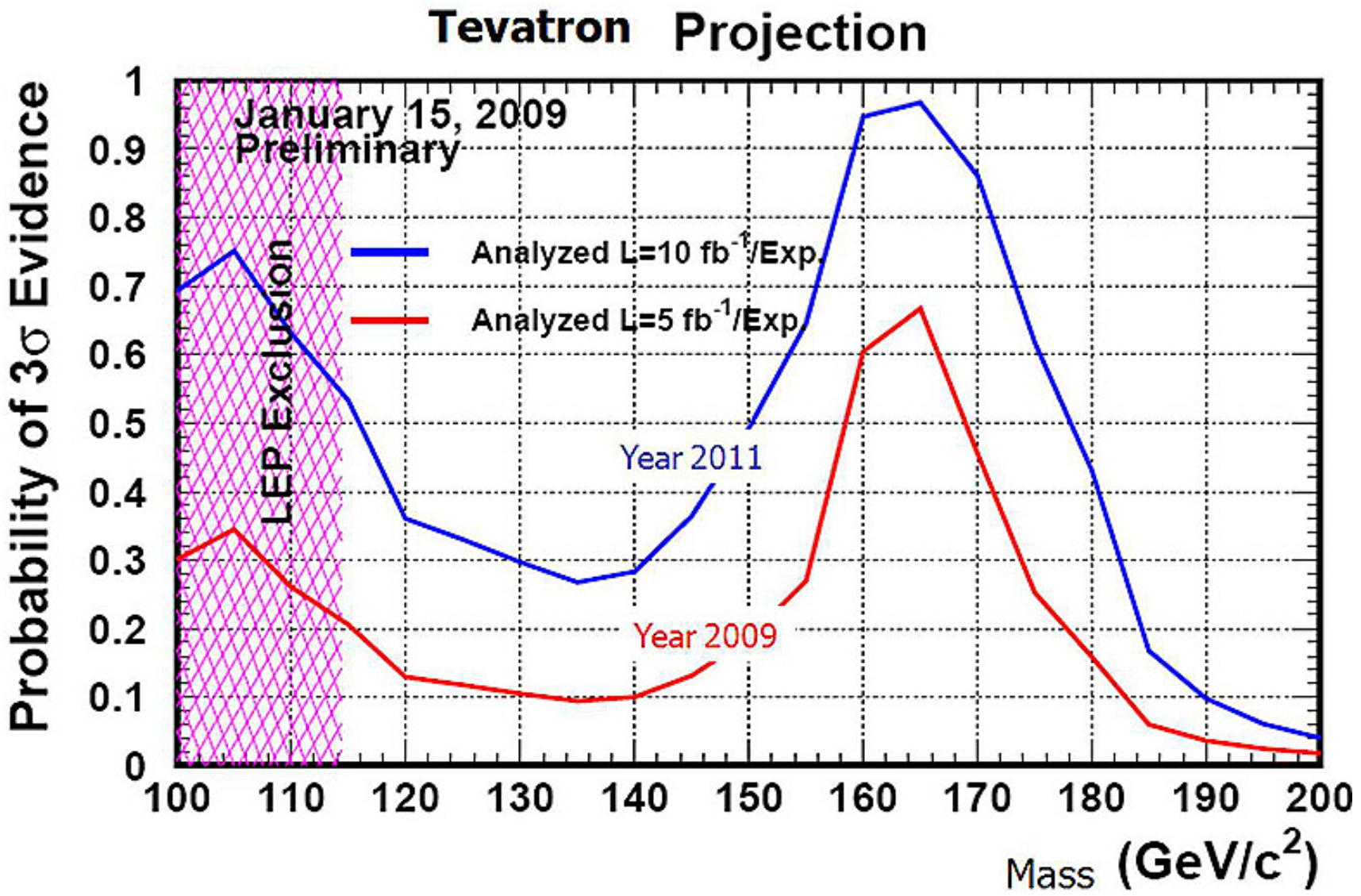



**Can exclude SM Higgs at this mass if nothing seen**

**Expect a 3 σ observation if SM Higgs exists at this mass**

D0-plusCDF_Higgs_limits_10nov08.ppt – from Darien Woods

http://d0server1.fnal.gov/projects/spokes/financialcommittee/DzeroIFC_10nov08_dw_v2.pdf


Tevatron Projection
January 15, 2009
Preliminary
LEP Exclusion
Analyzed L=10 fb-1/Exp.
Analyzed L=5 fb-1/Exp.
Year 2011
Year 2009
Probability of 3σ Evidence
Mass (GeV/c2)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
100
110
120
130
140
150
160
170
180
190
200

# The mass-energy of Universe consists of 25 % dark matter & 70% dark energy

# "dark" => doesn't emit or absorb starlight

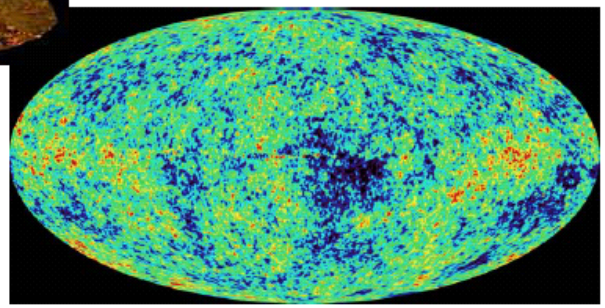
**Rotational speed of galaxies**

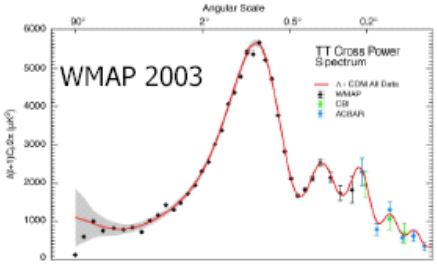
**Clumpiness of cosmic microwave background radiation**

**M81 galaxy &**

**WMAP satellite**

**About six to seven times more mass in the universe (27±4%) than there is baryonic matter (4.4±0.4%)**






**What is this stuff? How can we get a firmer understanding of it?**

**Accelerators**

**The rate of expansion of universe seems to be *increasing!***

**Much more mass-energy than (known) quarks & leptons!**

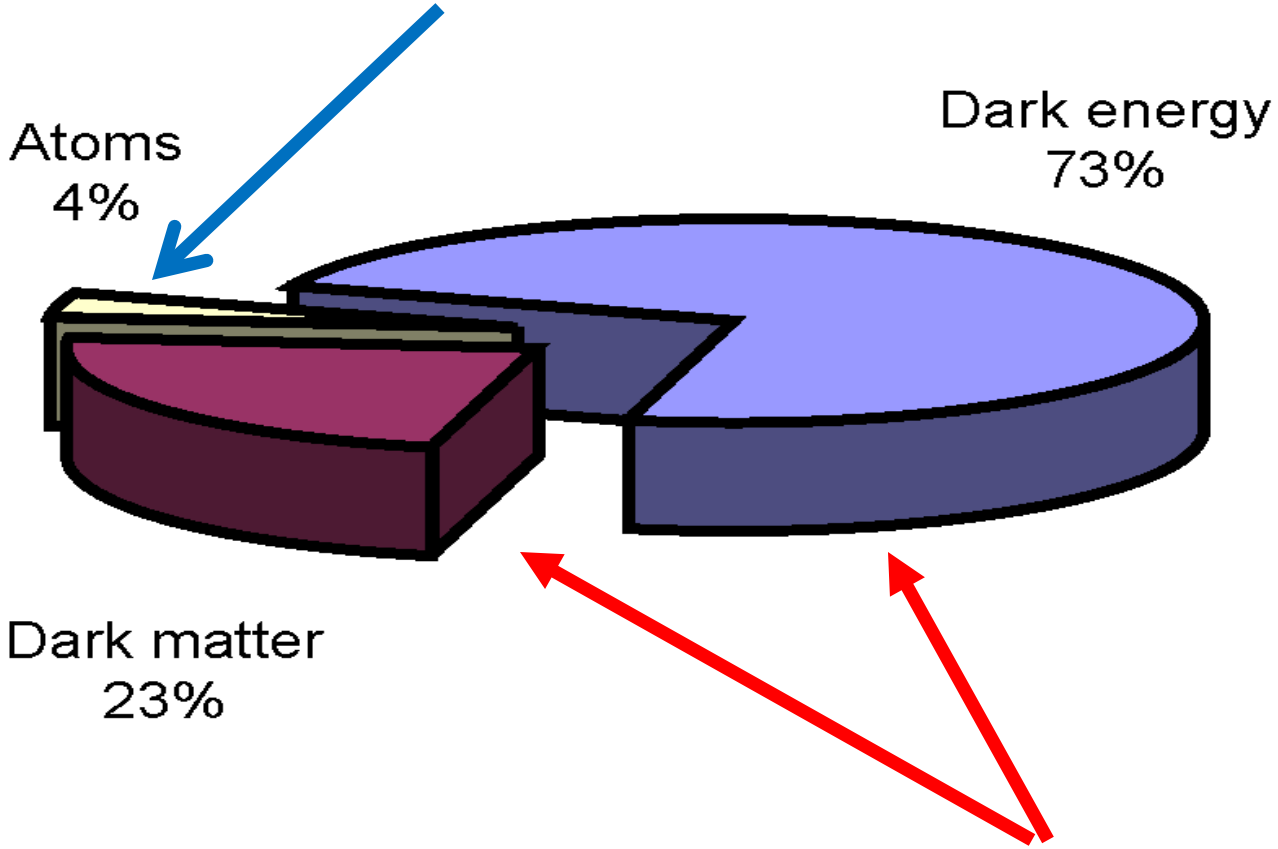
**We only know (understand?) ~ 5% of the universe!!!**

# Colliding galaxy clusters 1E0757-558

**Luminous normal matter (pink): hot gas - Chandra X-rays**

**Total mass (blue): optical (gravitation lensing) – Hubble**

quarks, leptons, stars, plasma….



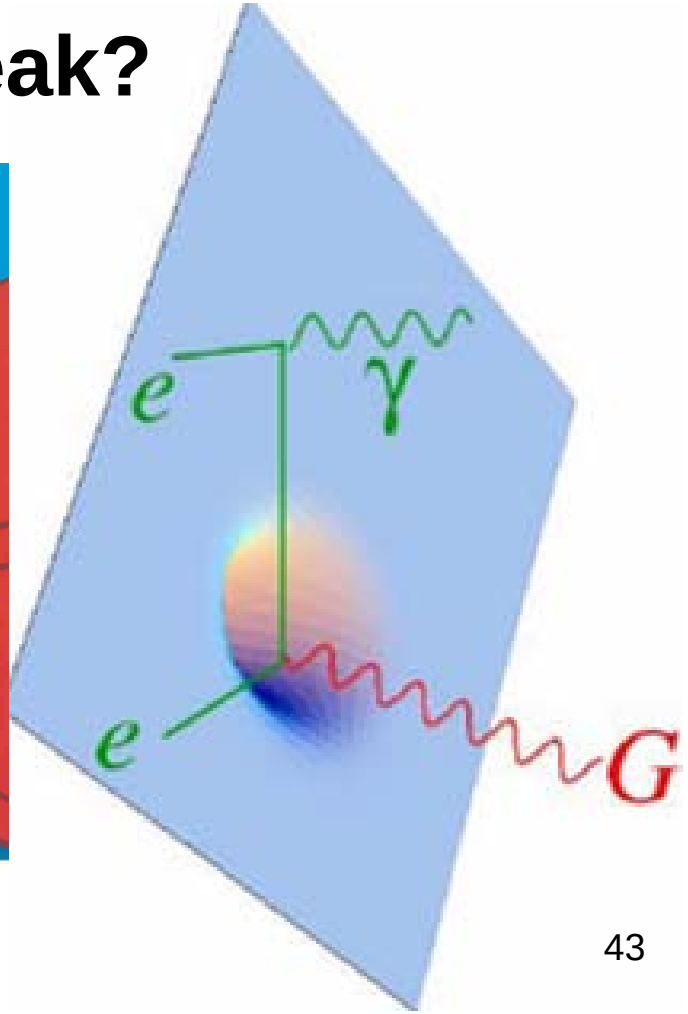

**So what is all of this "stuff"?**

**I thought we knew**
**what the universe is all about!**

# Example of a curled-up (invisible) extra dimension

## How can we observe it?

## Is that why gravity is so weak?



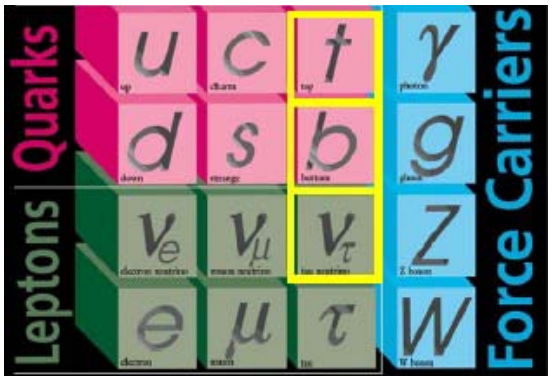
# Is There a New Symmetry in Nature?

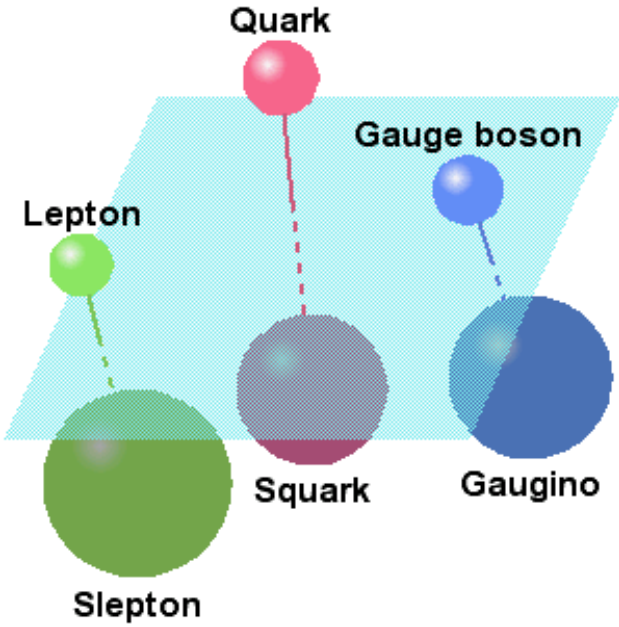
## *Supersymmetry*

**Bosons** ⟷ **Fermions**

**Particles**

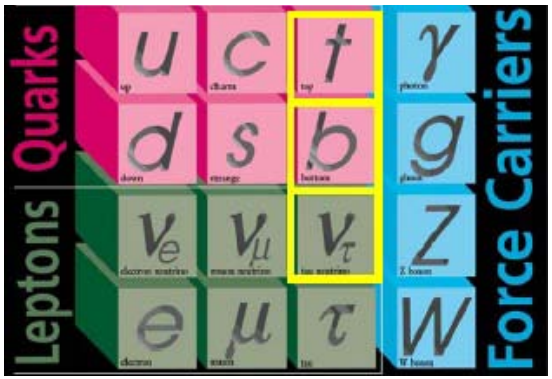
**S = ½  S = 1**



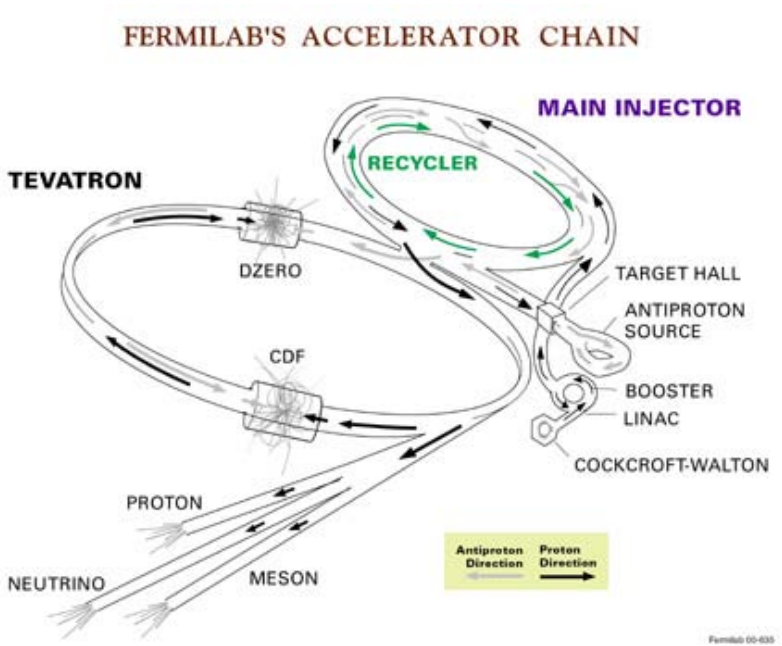

**SUSY Sparticles**

**S = 0,1  S = 1/2**



# Fermilab Accelerator Complex

http://www-bd.fnal.gov/public/



**You need big machines to study small particles!**

# Benefits of Fermilab Research

- **increase our understanding of nature and how it works – just part of being human**

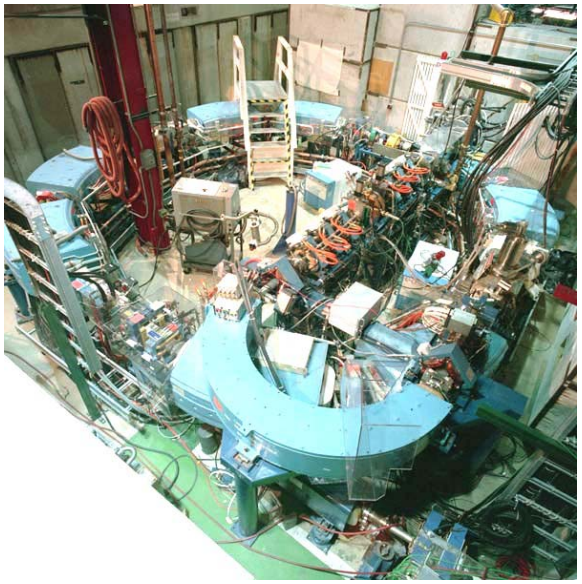
- **technological spin-offs – often far in future**
  **much of today's economy based on research in the late 1800's – early 1900's**

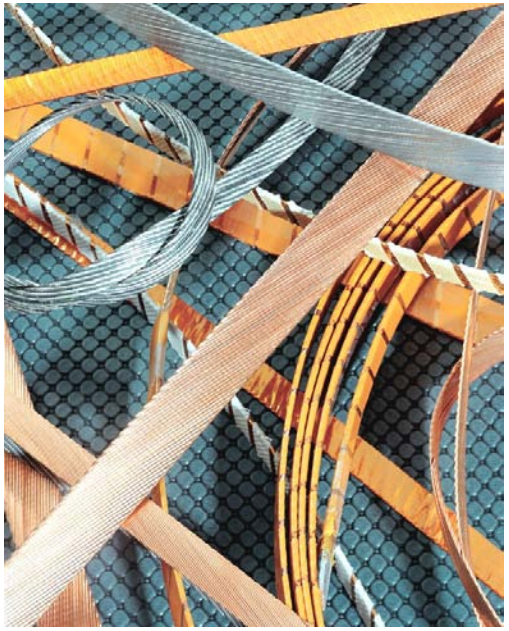
**electron → TV (accelerator) & communications**

- **some examples from Fermilab & HEP**

# Neutron Therapy Facility (with NIU) – R. R. Wilson

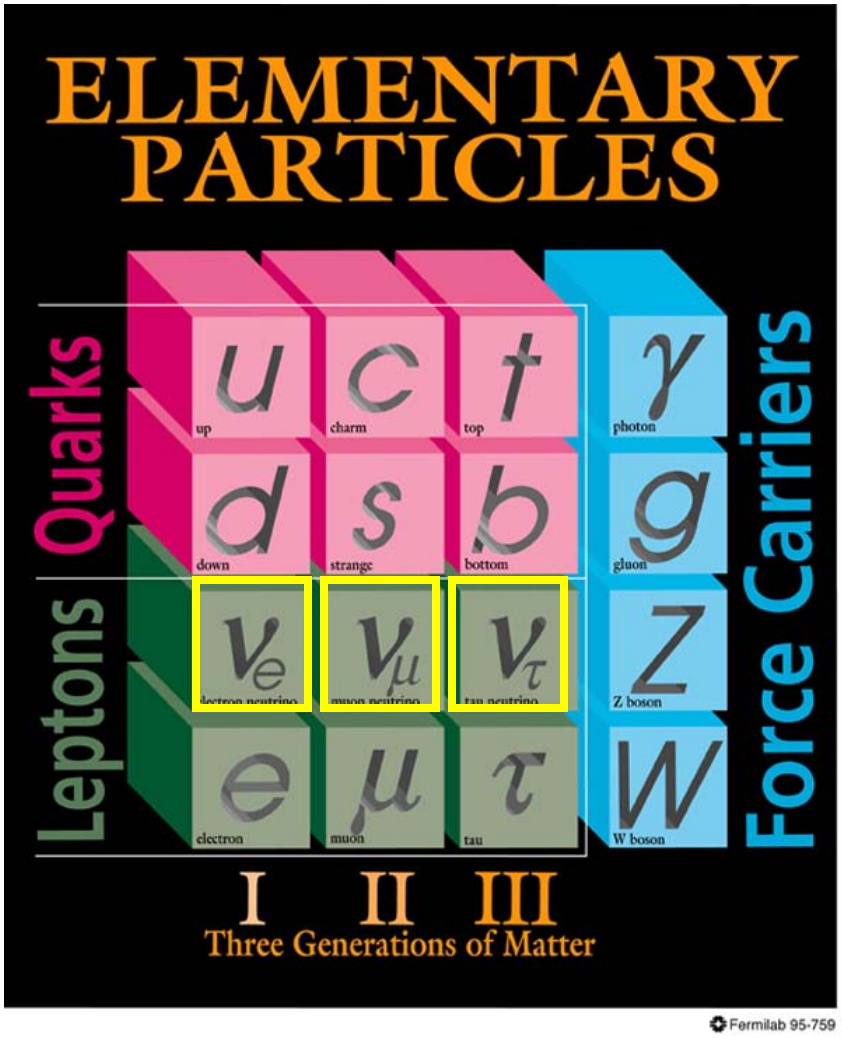
## Proton Accelerators for Medicine – Loma Linda & PET





## SC wire – Tevatron → practical MRI (medical diagnostic)

## WWW – invented @ CERN by Tim Berners-Lee




***Curious neutrinos*!**

**only *Weak* force**

**do $\nu$ have any *mass*?**

**if so, one kind of $\nu$**

**could change**

**into another**

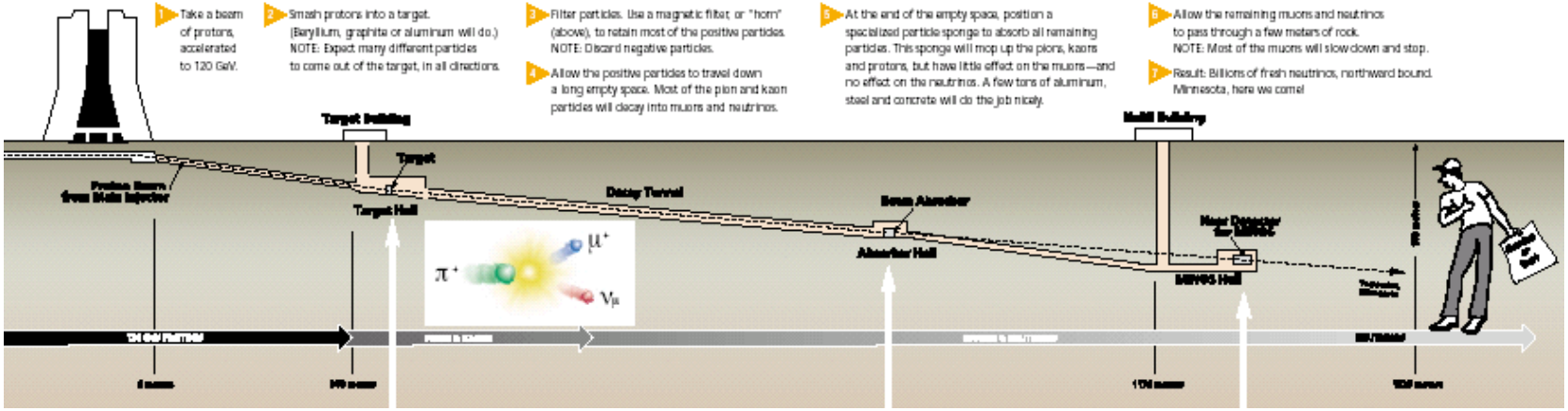
**kind of ν and**

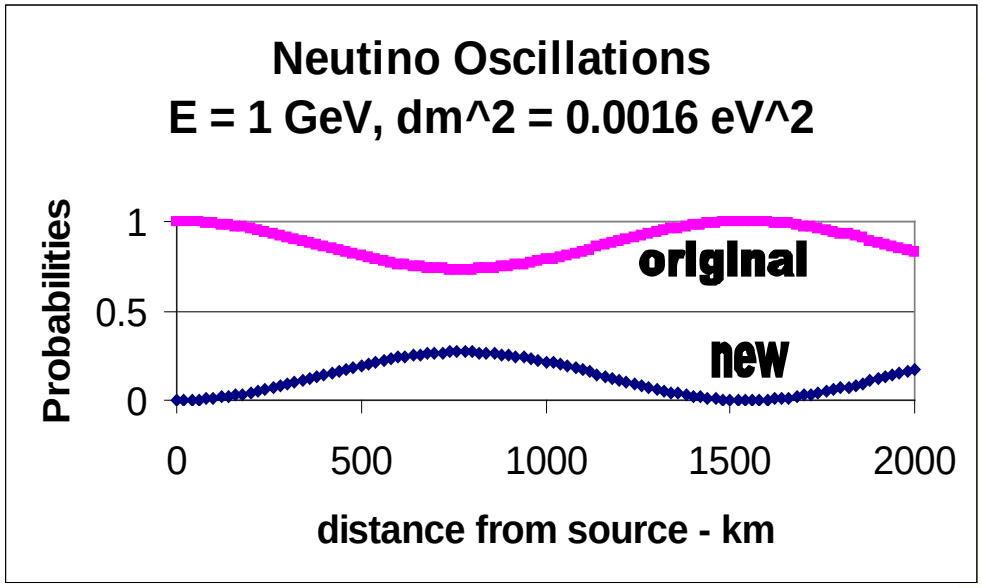
**back again!**

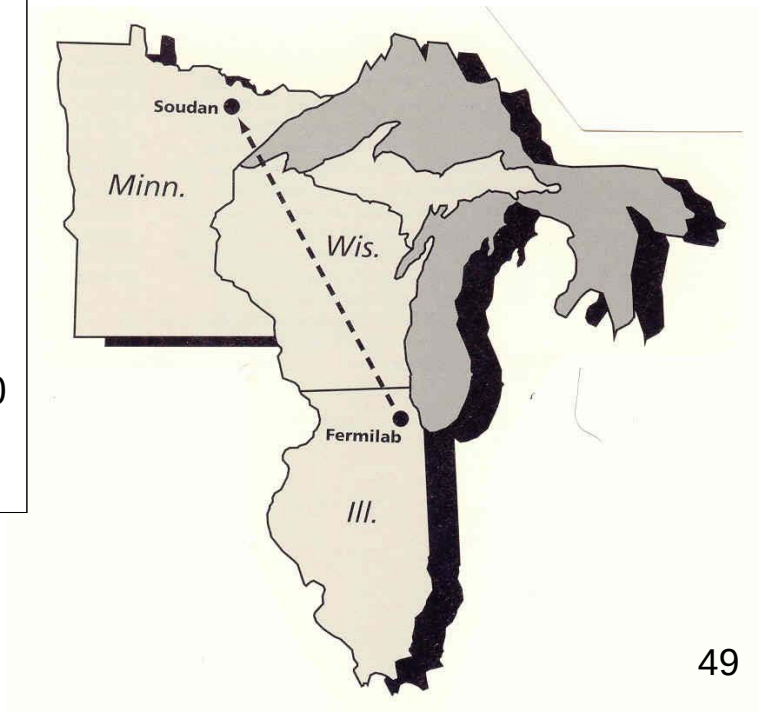
**oscillations…**

$\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$

# NUMI – Neutrinos at the Main Injector




a 735 km long beam, right thru the earth! 10 km deep

# Neutrino Interactions

- $\nu$'s interact very weakly (the weak force!)
- total $\nu$p cross section (interaction probability)

  $\sigma(\nu p) = 6.7 \times 10^{-39}$ cm$^2$ at 1 GeV

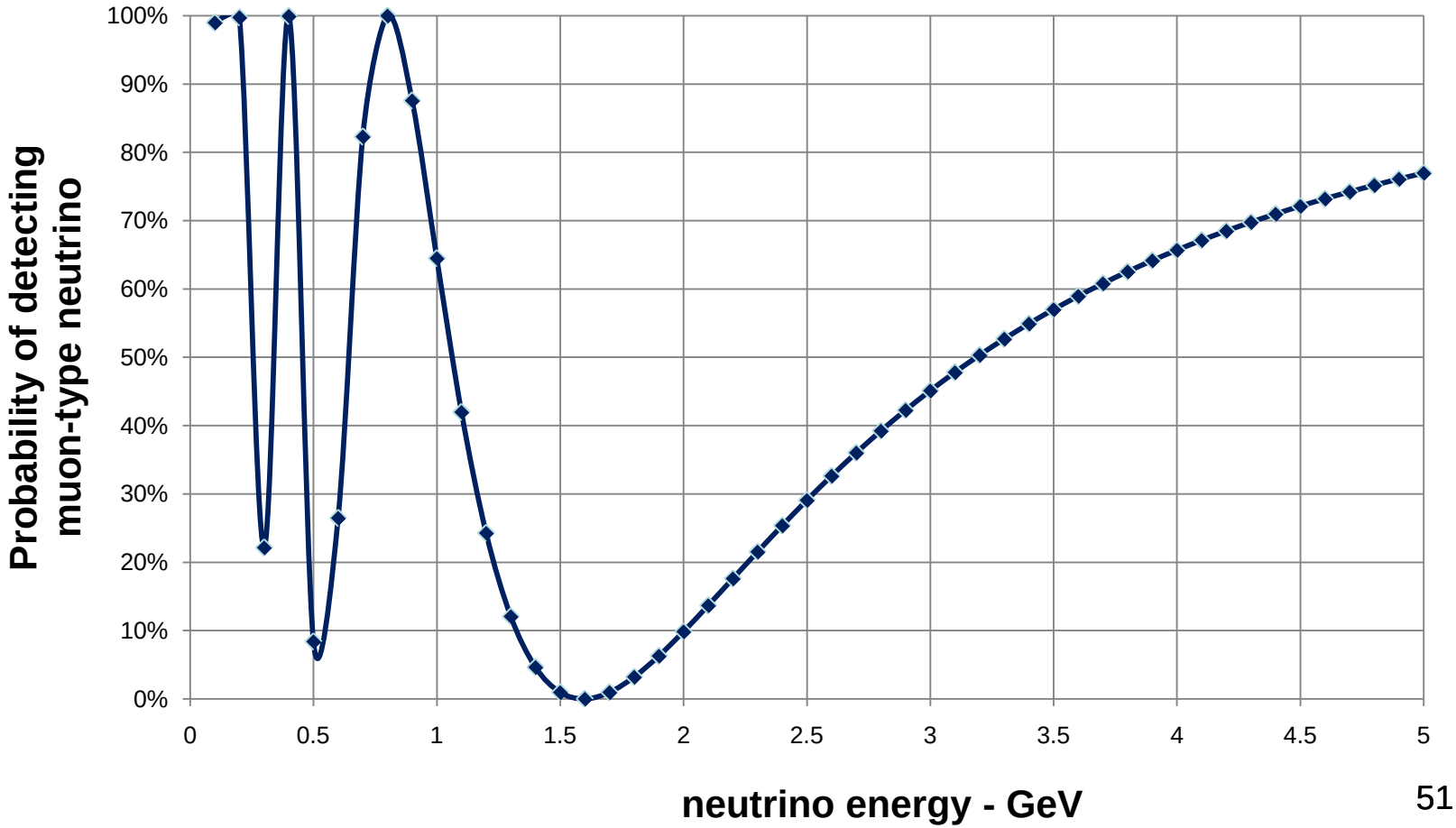
  $\sigma(pp) = 2.2 \times 10^{-26}$ cm$^2$ (strong force)

  $\sigma(\gamma p) = 2 \times 10^{-28}$ cm$^2$ (E.M. force - photons)
- EM force/Gravitation $\approx 10^{36}$ between 2 protons
- only 650 out of 1 billion $\nu$'s interact before reaching Soudan (735 km earth)
- only 40 out of 1 trillion $\nu$'s interact in detector

# Neutrino Oscillation $\nu_\mu \Rightarrow \nu_x$

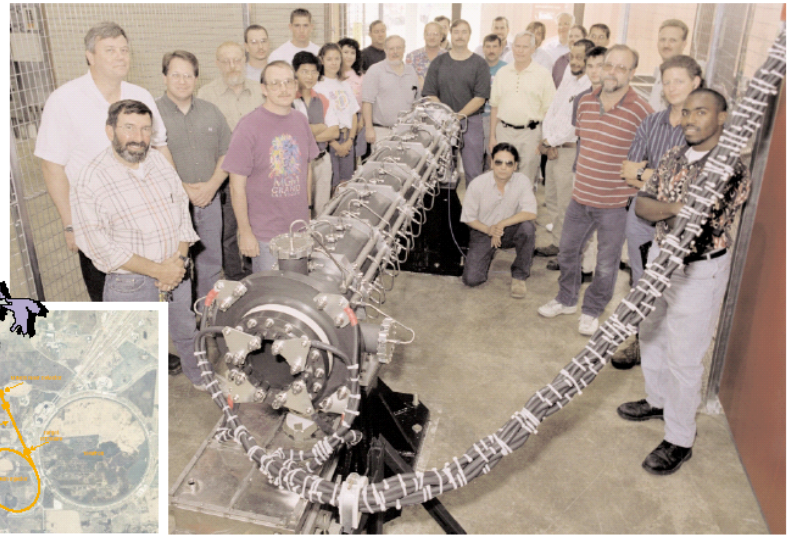
**Oscillation function – disappearance**

**L = 730 km  $\delta m^2 = 0.0027\ eV^2$  $\sin^2(2\theta) = 1.0$**



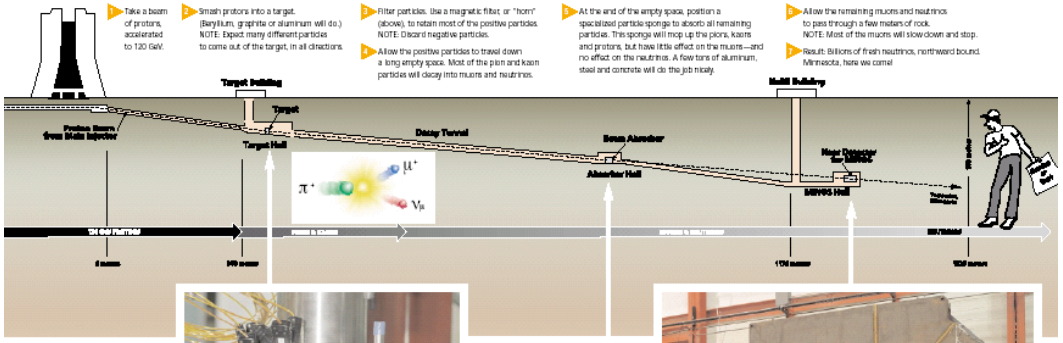
# How to MAKE a Neutrino Beam

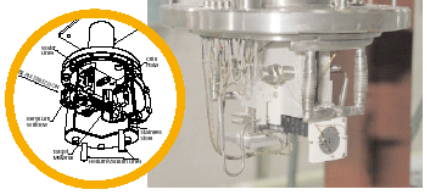
*TAKE A BEAM OF PROTONS...*



The first of two horns (magnetic filters) that align the positively charged particles produced in the target, posed with the team that built it. Current pulses of 200,000 amps are applied to the horn for a thousandth of a second at the same time as the proton beam strikes the target.

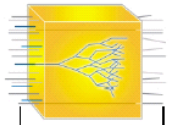
1. Take a beam of protons, accelerated to 120 GeV.
2. Smash protons into a target. (Beryllium, graphite or aluminum will do.) NOTE: Expect many different particles to come out of the target, in all directions.
3. Filter particles. Use a magnetic filter, or "horn" (above), to retain most of the positive particles. NOTE: Discard negative particles.
4. Allow the positive particles to travel down a long empty space. Most of the pion and kaon particles will decay into muons and neutrinos.
5. At the end of the empty space, position a specialized particle sponge to absorb all remaining particles. This sponge will mop up the pions, kaons and protons, but have little effect on the muons—and no effect on the neutrinos. A few tons of aluminum, steel and concrete will do the job nicely.
6. Allow the remaining muons and neutrinos to pass through a few meters of rock. NOTE: Most of the muons will slow down and stop.
7. Result: Billions of fresh neutrinos, northward bound. Minnesota, here we come!



A prototype of the MINOS target. 4 x $10^{13}$ protons, accelerated to 120 GeV, will strike the black graphite fins of the target every 1.9 seconds. Water cooling keeps the target from melting.

Particle Beam Absorber



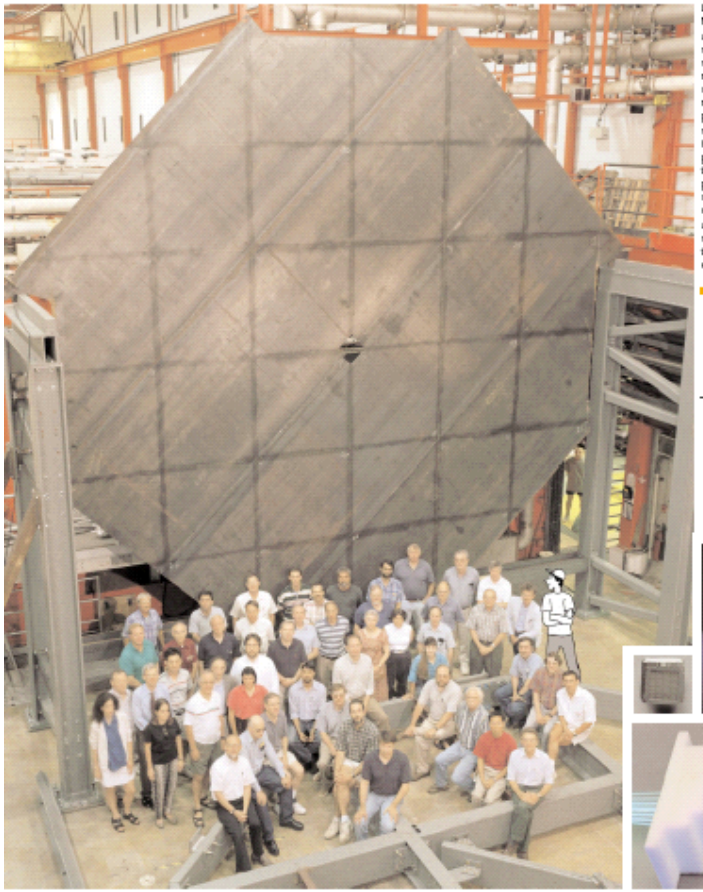
Hadrons, muons and neutrinos in.

Neutrinos and muons out.

The near detector, located at Fermilab, is a smaller version of the main MINOS detector at Soudan, Minnesota. The near detector is used to verify the flavor of the neutrino beam at the source. The detector is smaller because the neutrino beam hasn't yet spread out very much.

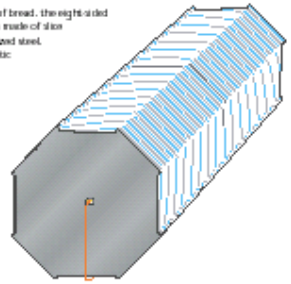
Neutrinos@FERMILAB
A U.S. DEPARTMENT OF ENERGY NATIONAL LABORATORY

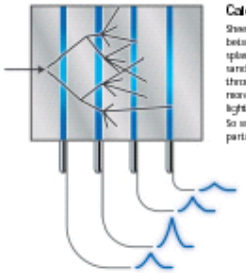
# How to DETECT a Neutrino



The MINOS collaboration poses for a photo in front of a steel plane of the MINOS detector. Eventually the detector will be 60 feet long and 24 feet in diameter, made of 486 layers of these eight-sided steel plates. Even with 5,000 tons of steel, only a few in 10 billion neutrinos coming from Fermilab will interact in the MINOS detector.

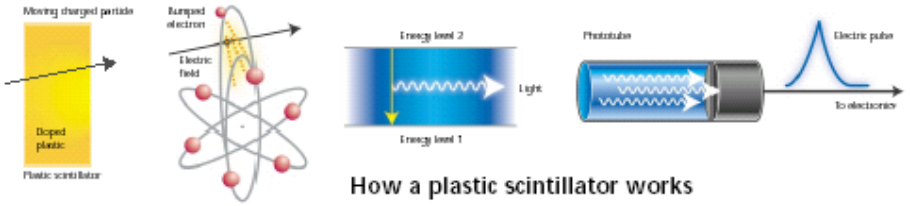
Like a 5000-ton loaf of bread, the eight-sided MINOS far detector is made of slice after slice of magnetized steel, sandwiched with plastic scintillator. When a neutrino collides with an iron nucleus, it produces a splash of particles. Charged particles passing through the scintillator produce light, which is then converted to an electronic signal for the watching experimenters.



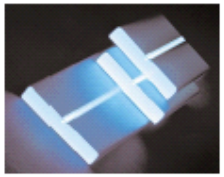


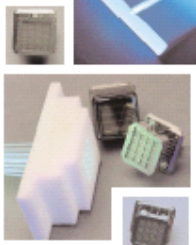
**Calorimeter Sandwich Detector**

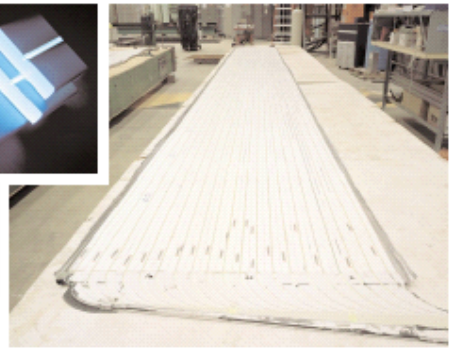
Sheets of plastic scintillator are placed between the steel plates. The particle splash is quickly absorbed in the calorimeter sandwich. Each charged particle passing through the scintillator creates light. The more particles, the more light. The more light the bigger the electronic signal. So we can measure the energy of the particles by adding up the electronic signals.



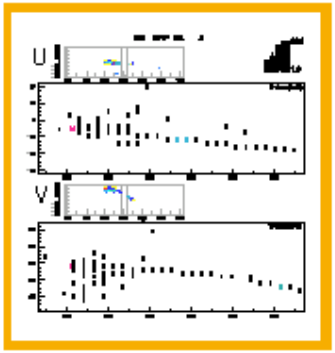

**How a plastic scintillator works**







Plastic scintillator strips 24 feet long and about 1-7/8" by 3/8" are assembled into modules of 20 or 28 strips wide. Eight modules are assembled to make one plane of 192 strips, which is sandwiched between the steel plates. Each strip has a light fiber glued along its center to bring the light to a phototube. Each phototube receives the light from 128 fibers.



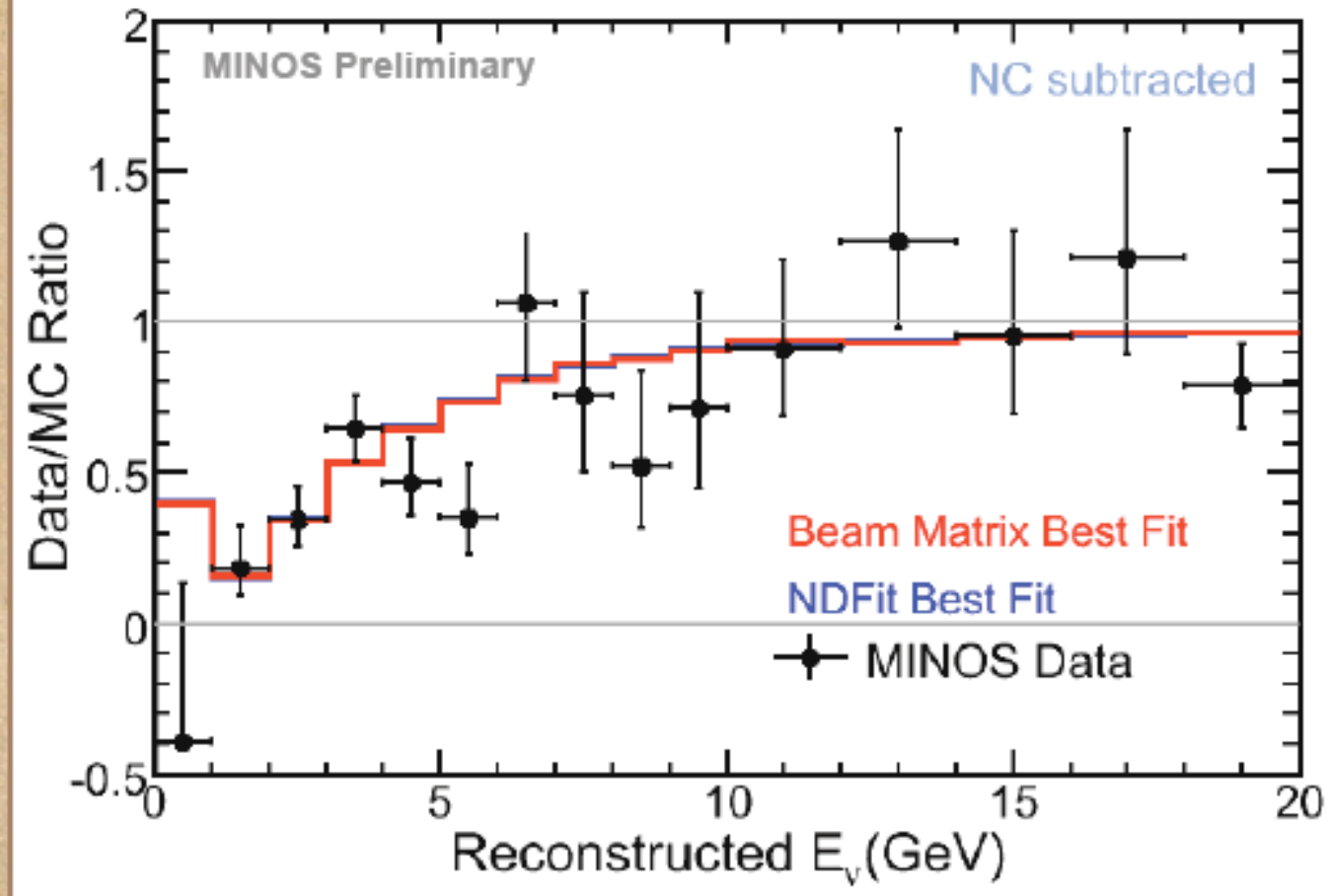

A picture of a typical interaction of a muon-flavor neutrino. The muon produced in the interaction (the long track in the picture) is gradually losing energy as it goes through the steel plates. The magnetic field present in the steel causes the muon to bend. The amount of bending gives a measurement of the muon energy.

Neutrinos @ FERMILAB

A U.S. DEPARTMENT OF ENERGY NATIONAL LABORATORY

# NuMI installation in Minnesota mine

# first NuMI results – July 31, 2006




$$|\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26}(stat + syst) \times 10^{-3} eV^2$$

$$sin^2(2\theta_{23}) = 1.00_{-0.13}(stat + syst)$$