Fermilab's Accelerators

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

Peter H. Garbincius – Fermilab – since 1976

Ask-a-Scientist – July 13, 2008

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?

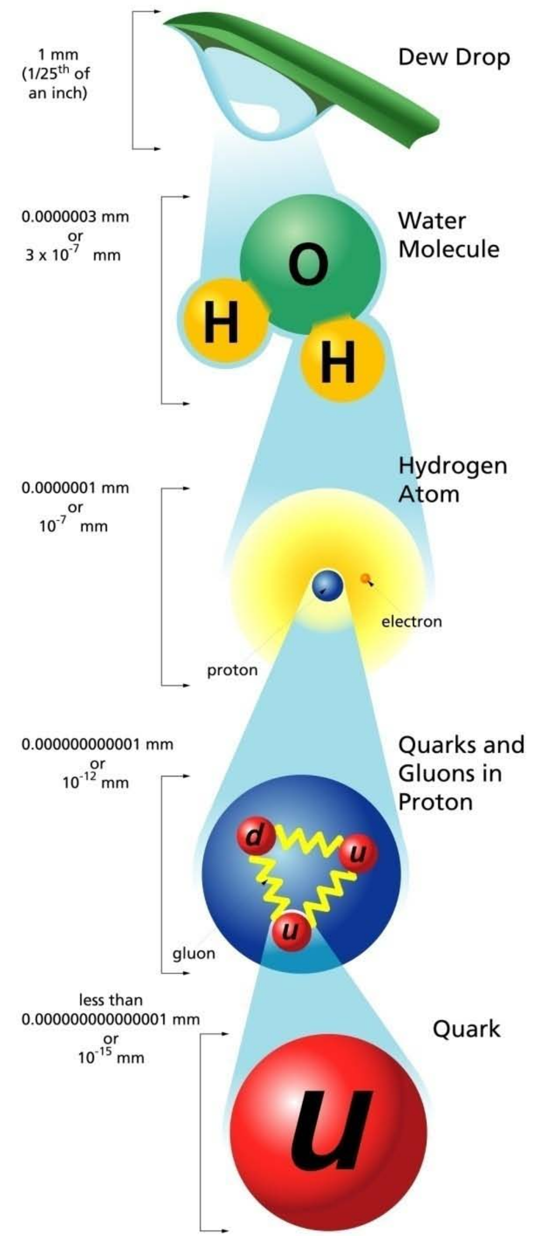
. . . .

Questions of

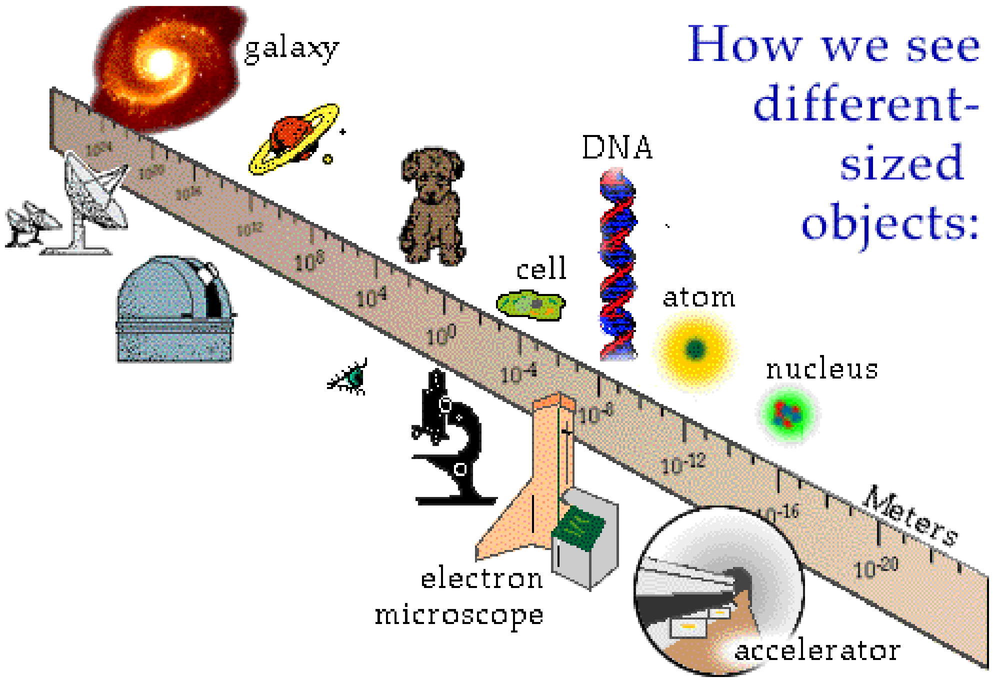
little children →

ancient Greeks (atoms) →

today's physicists

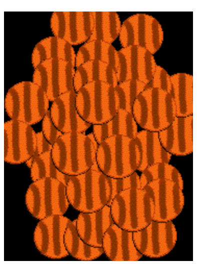


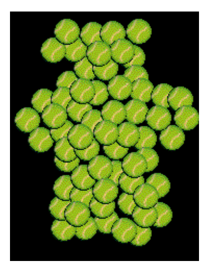
Wave-Particle Duality of Nature

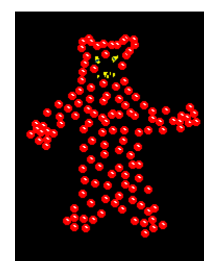


DeBroglie said moving particles have an equivalent wavelength,

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







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

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

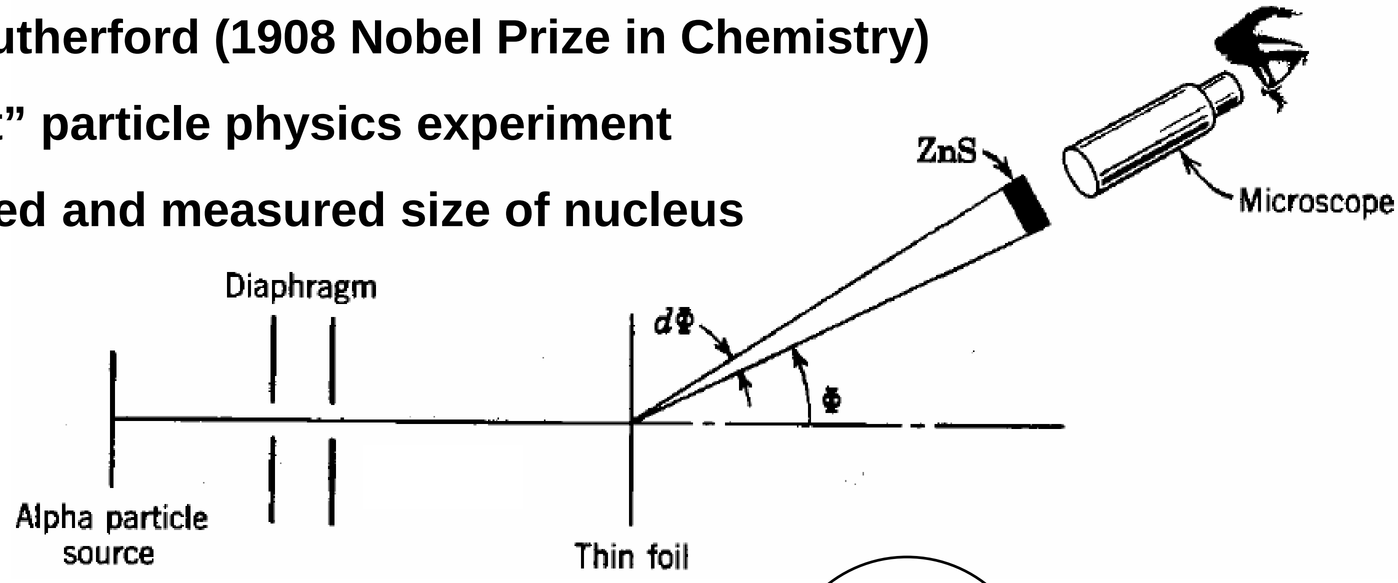
How do we measure the very small?

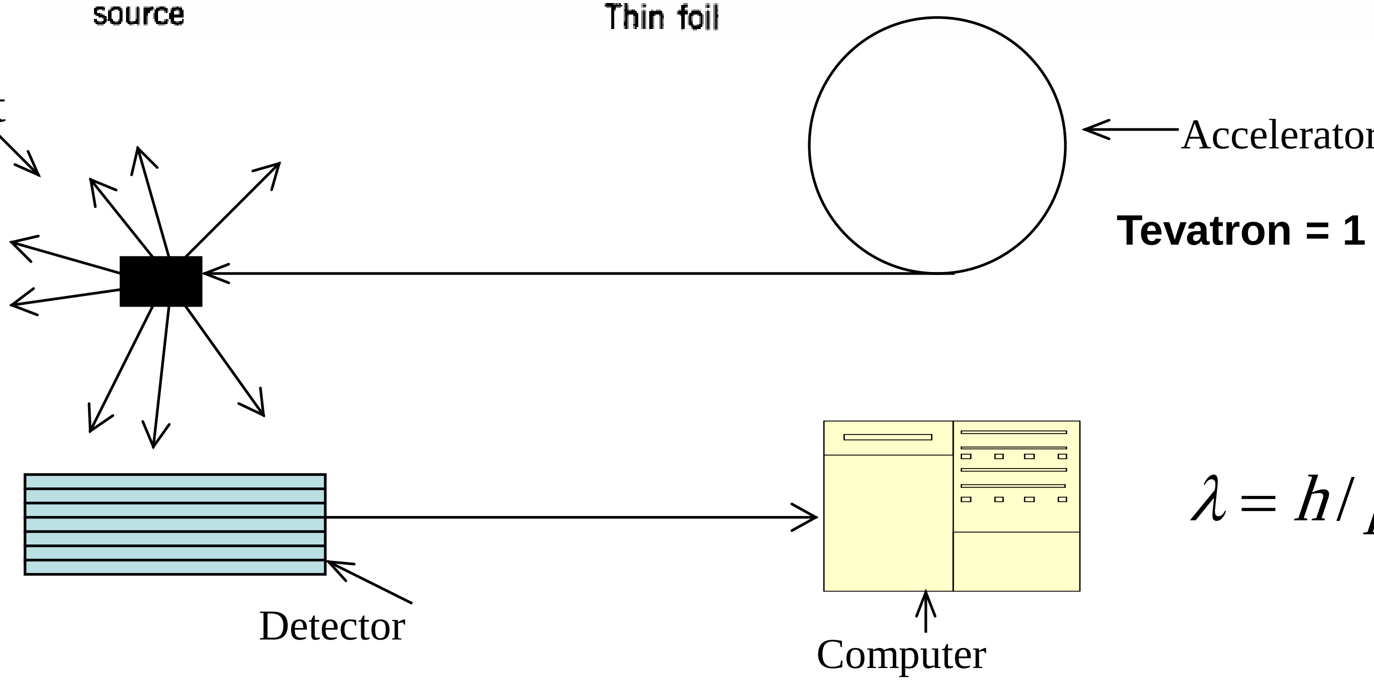
Ernest Rutherford (1908 Nobel Prize in Chemistry)

The “first” particle physics experiment

Discovered and measured size of nucleus

radioactive source a few MeV

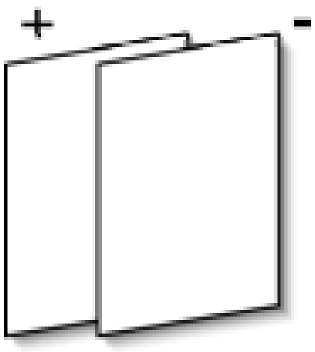




Tevatron = 1 TeV

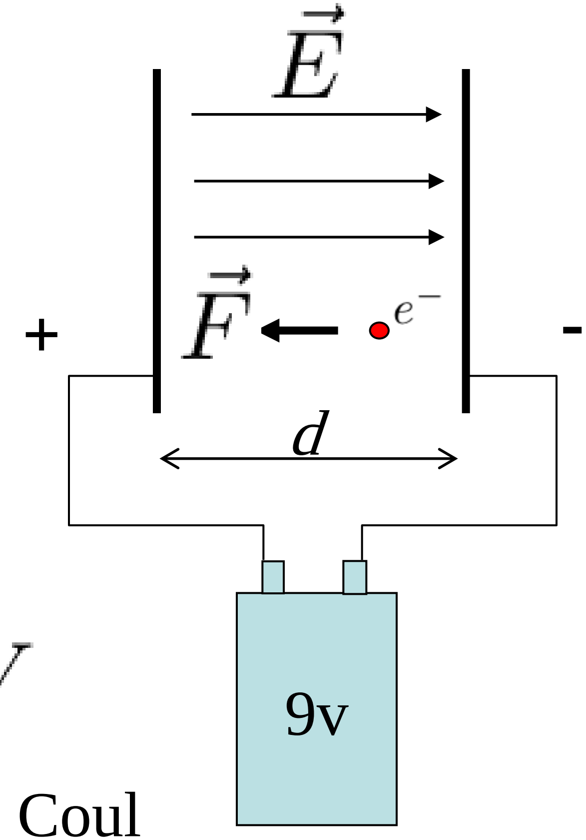
$$\lambda = h / p$$

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 $q = -e = -1.6 \times 10^{-19}$ Coul

(on a proton, $+1.6 \times 10^{-19}$ 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**) $(= 1.6 \times 10^{-19}$ J)

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

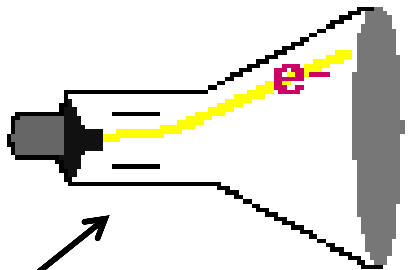
Lets have a show of hands:

How many of you have a particle accelerator at home?

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

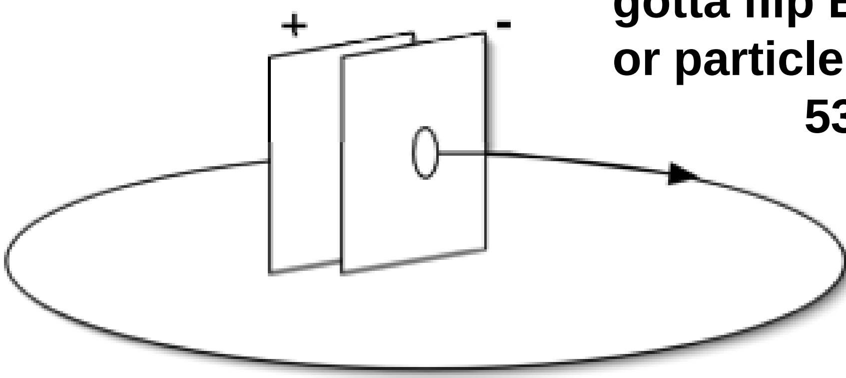
electromagentic fields to *accelerate* and steer the electron beam (ray)

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!



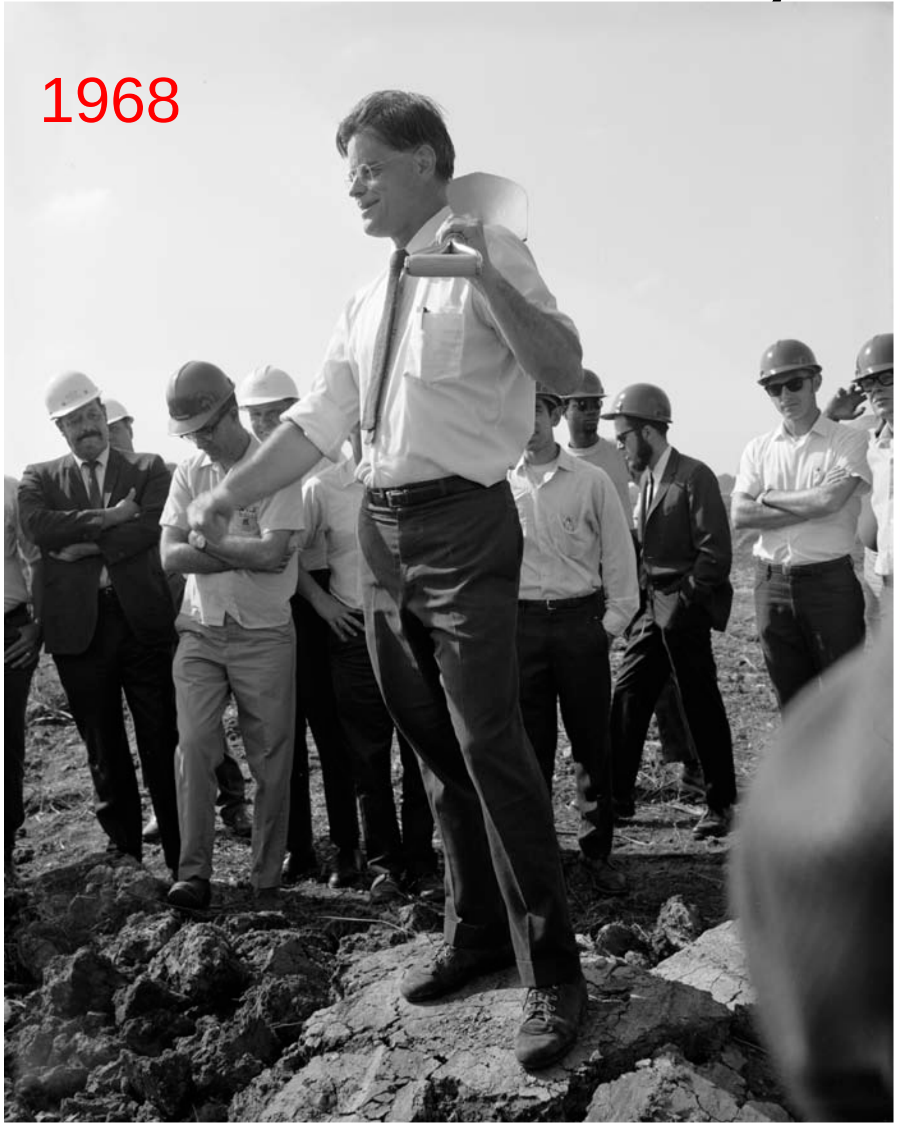
gotta flip E-field when particle outside of plates or particle will be decelerated – RF voltages

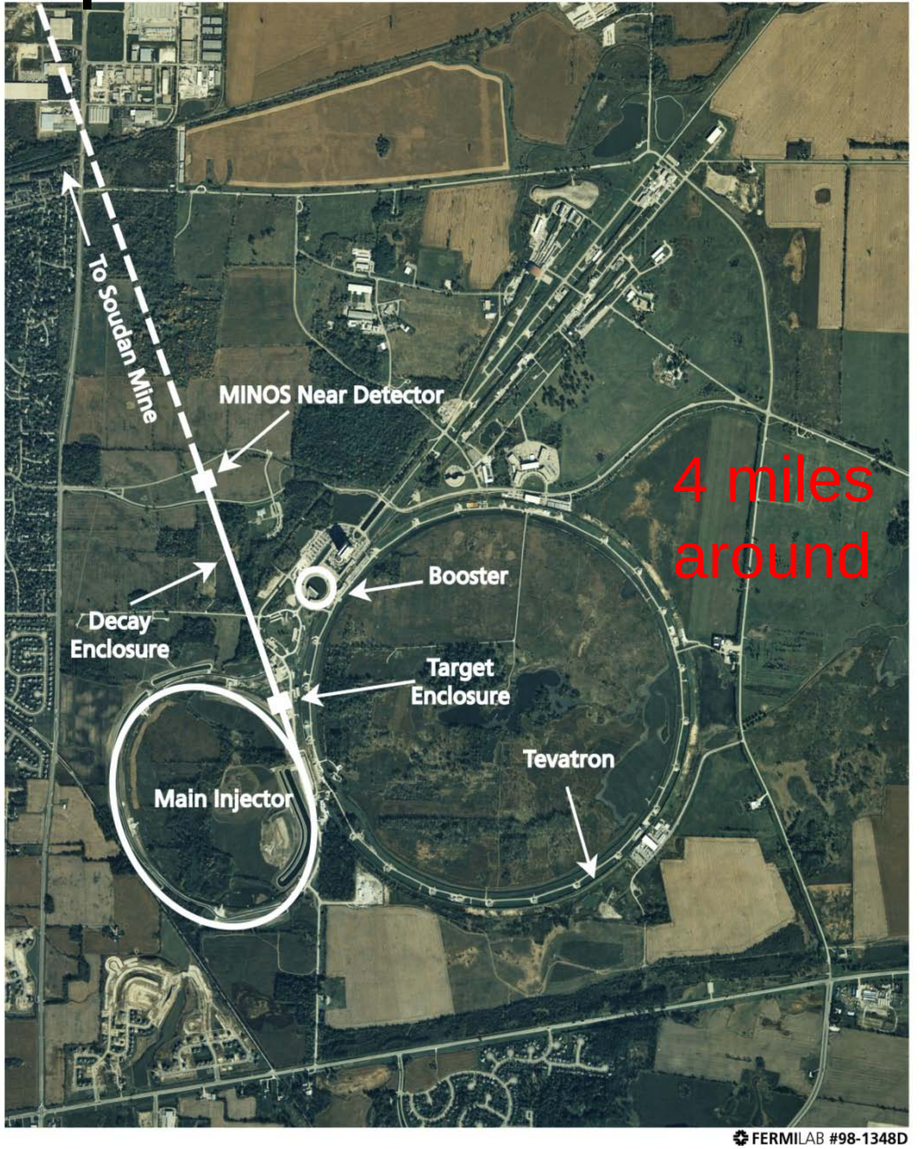
53 MHz = TV Ch2

bend particles with magnetic field

The First Cyclotron, Berkeley -- 1930’s

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





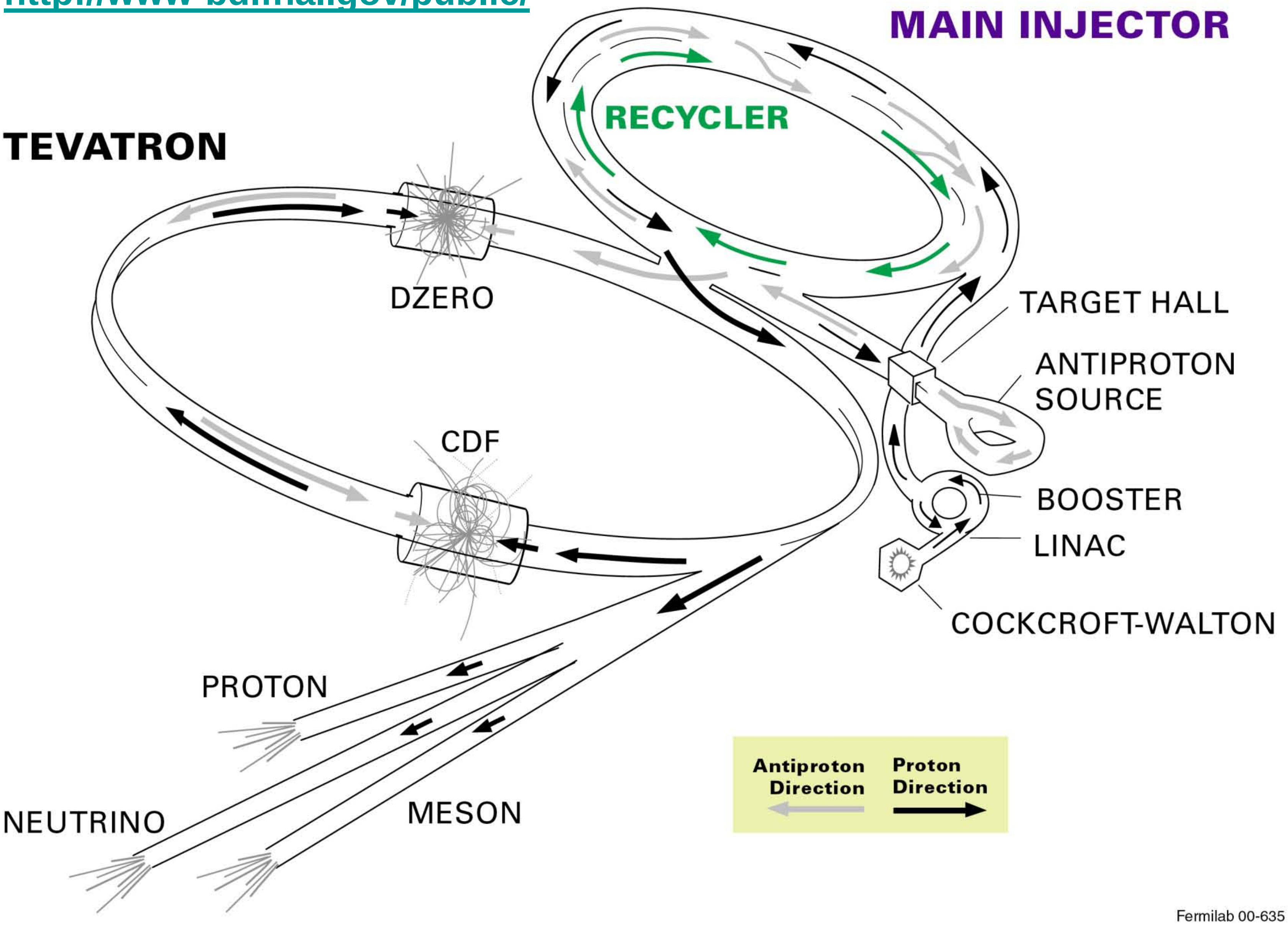
FERMILAB #98-1348D

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/



Cockcroft-Walton 750 KeV | **LINAC 400 MeV** | **Booster 8 GeV**

velocity = 0 → *0.04 c* → *0.71 c* → *0.994 c*

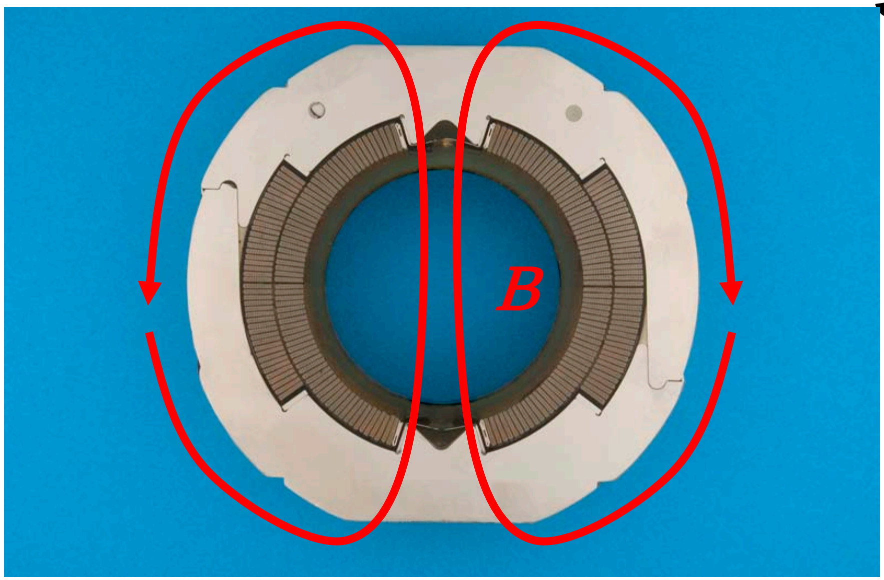
Main Injector 150 GeV | **Antiproton “Bottle”** | **Tevatron 1000 GeV = 1 TeV**

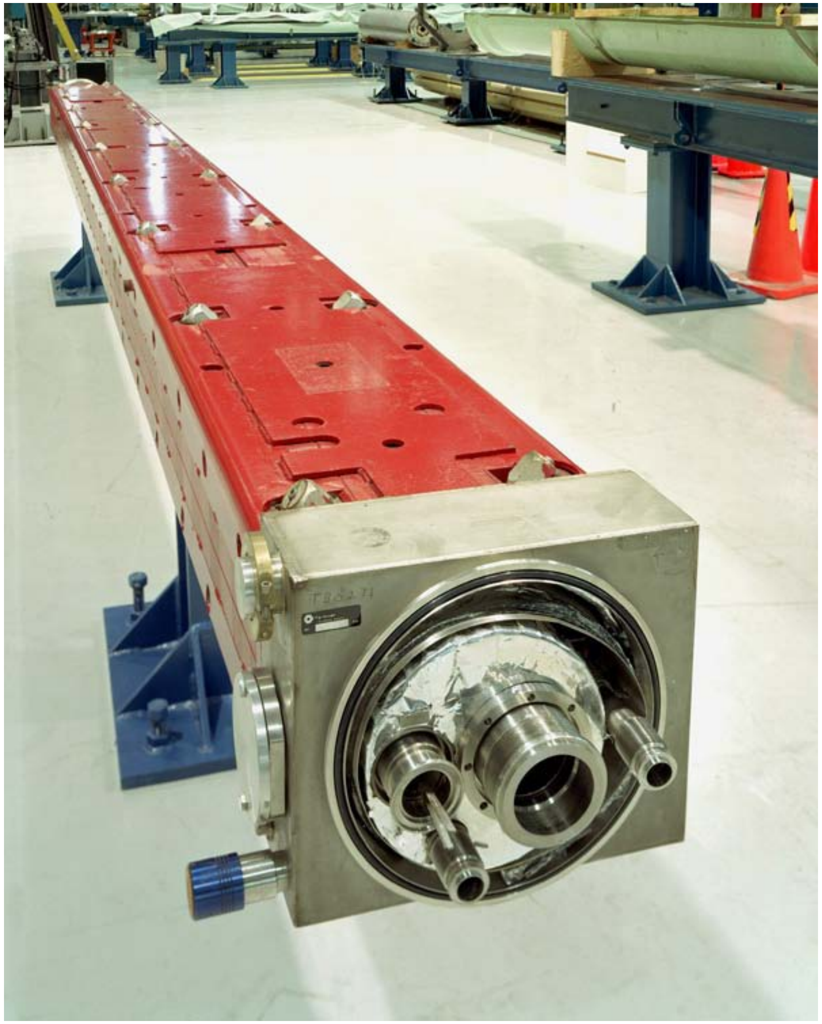
0.994 c → *0.99998 c*

@ 8 GeV

0.99998 c → *0.9999995 c*

Superconducting Tevatron Magnet





- Outside is at room temperature; inside is at 4ºK = - 452ºF!
- 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

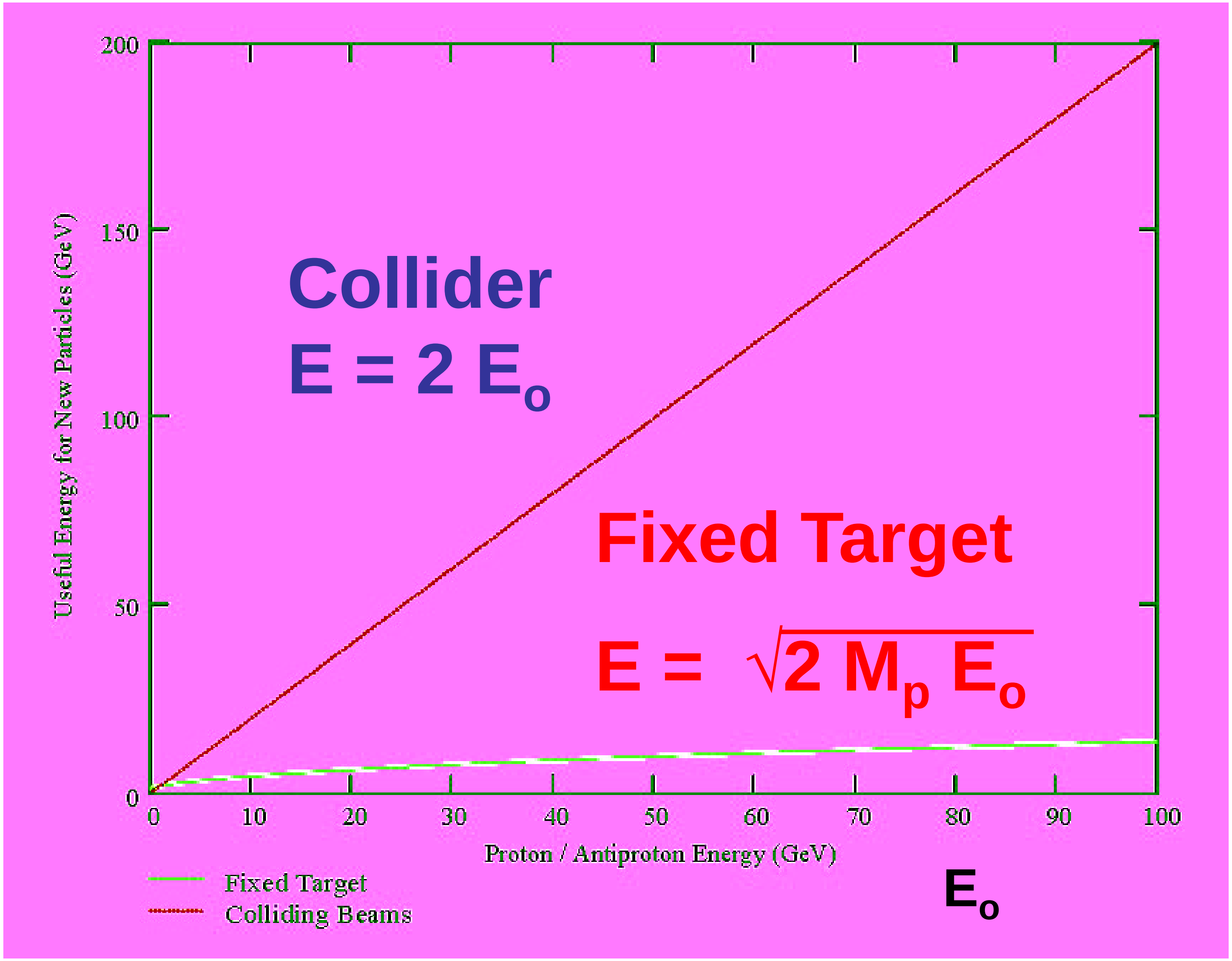
around the clock operation, 24/7 all year

shut down periods occur, for maintenance

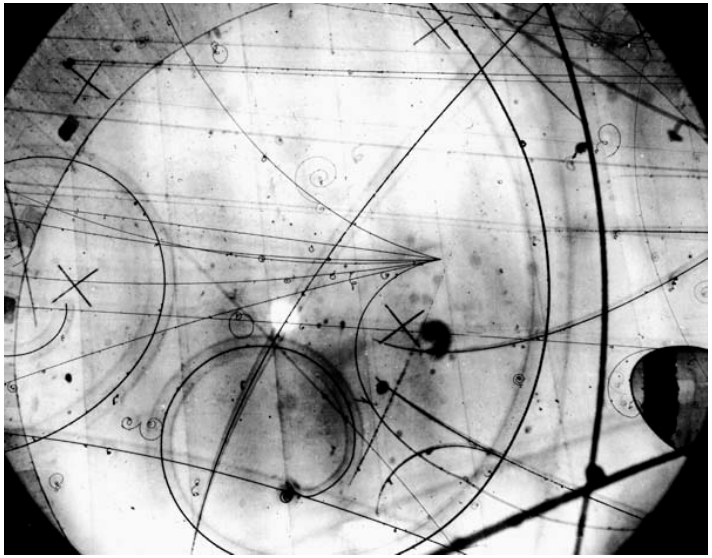
-- *now, for instance!*

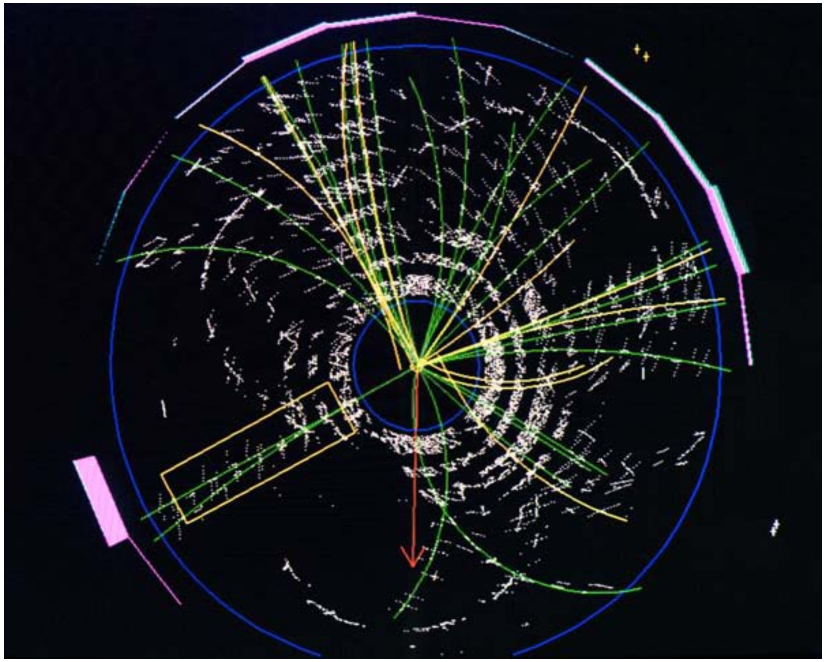
crews of 5-6 Accelerator Operators and Crew Chief

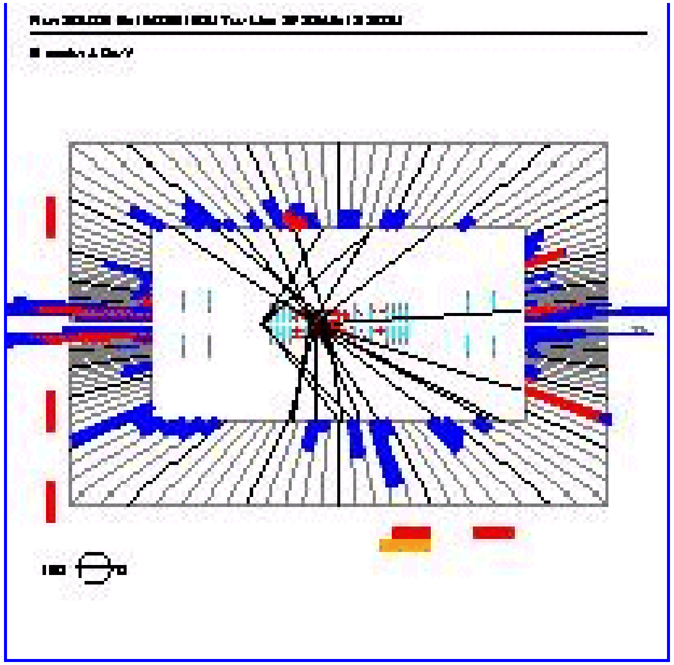
Energy Available for Particle Production



Seeing particles - indirectly

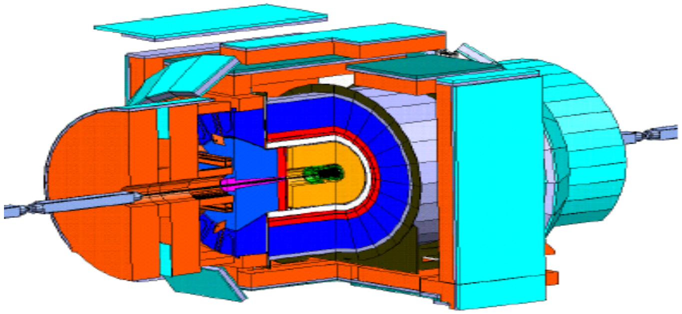




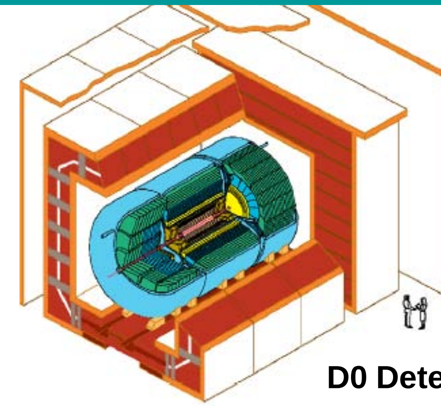


CDF & D-Zero Experiments

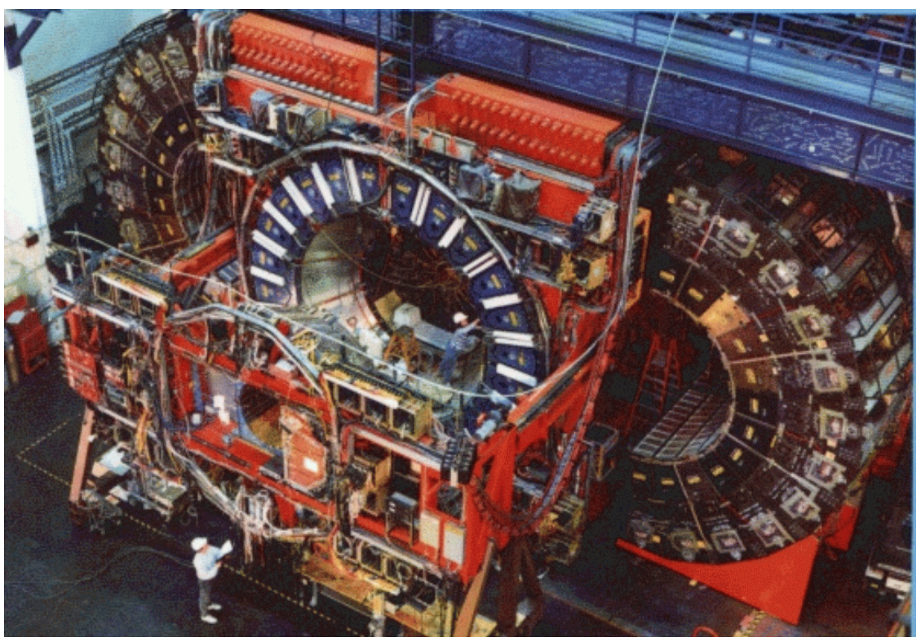
http://www.fnal.gov/pub/now/live_events/index.html

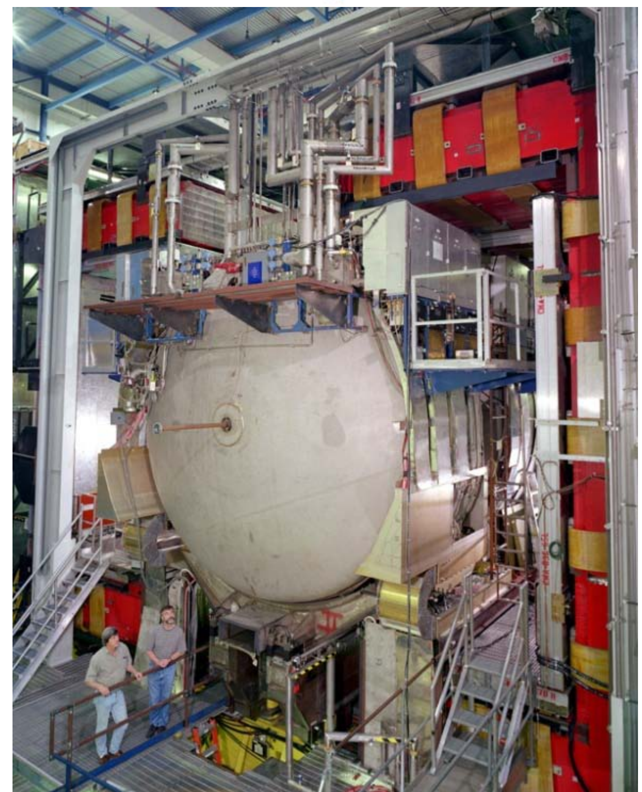


CDF Detector



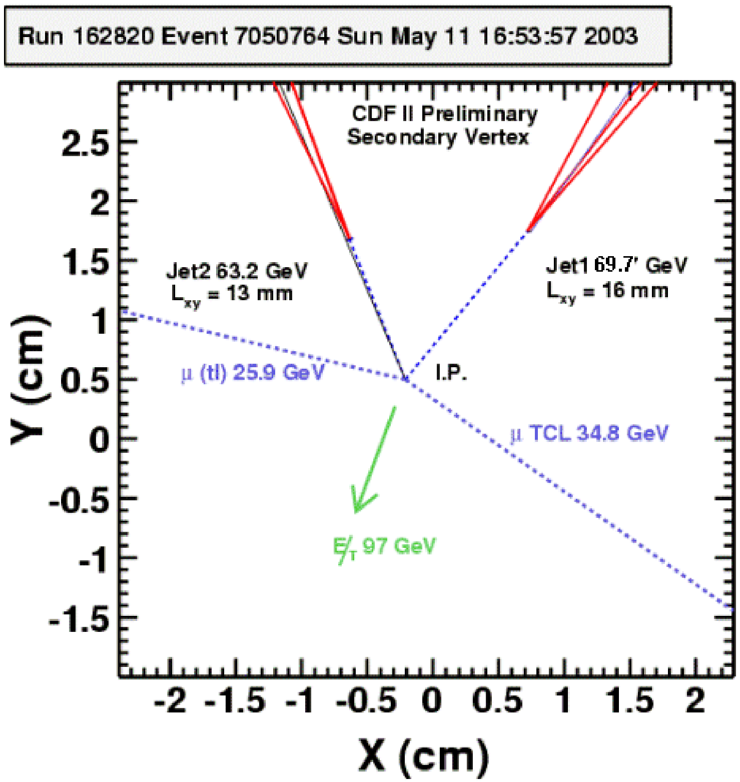
D0 Detector

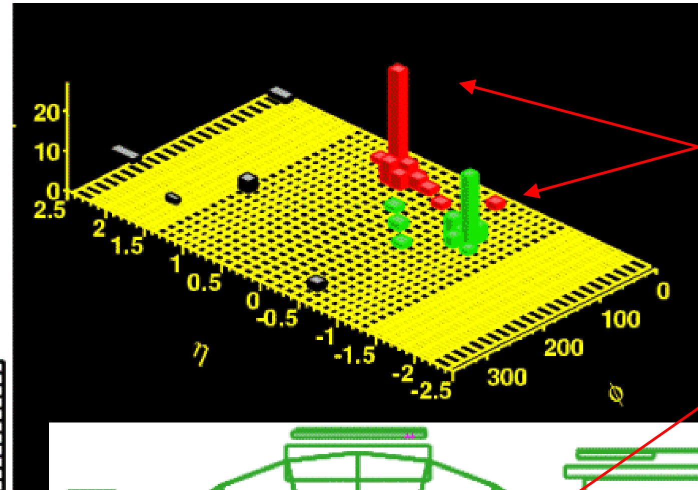


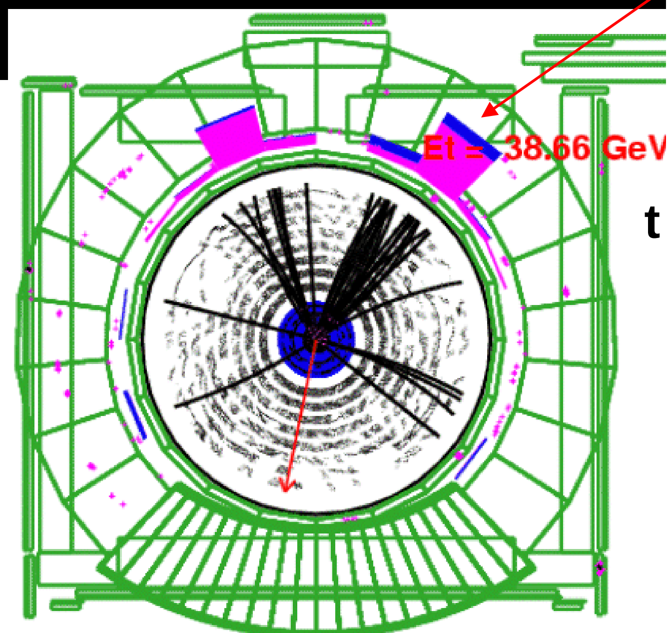


Observation of top-quark pair production at Fermilab

Double b-tagged dilepton event @ CDF







$E = mc^2$

Jets or sprays of particles from bottom quarks

$t \rightarrow W + b$

$W \downarrow \nu + \mu \downarrow$ missing energy

$b \downarrow$ jet $\downarrow$ multi-particles

similar for decay for **t-bar**

ZOOM IN : silicon microstrip detector

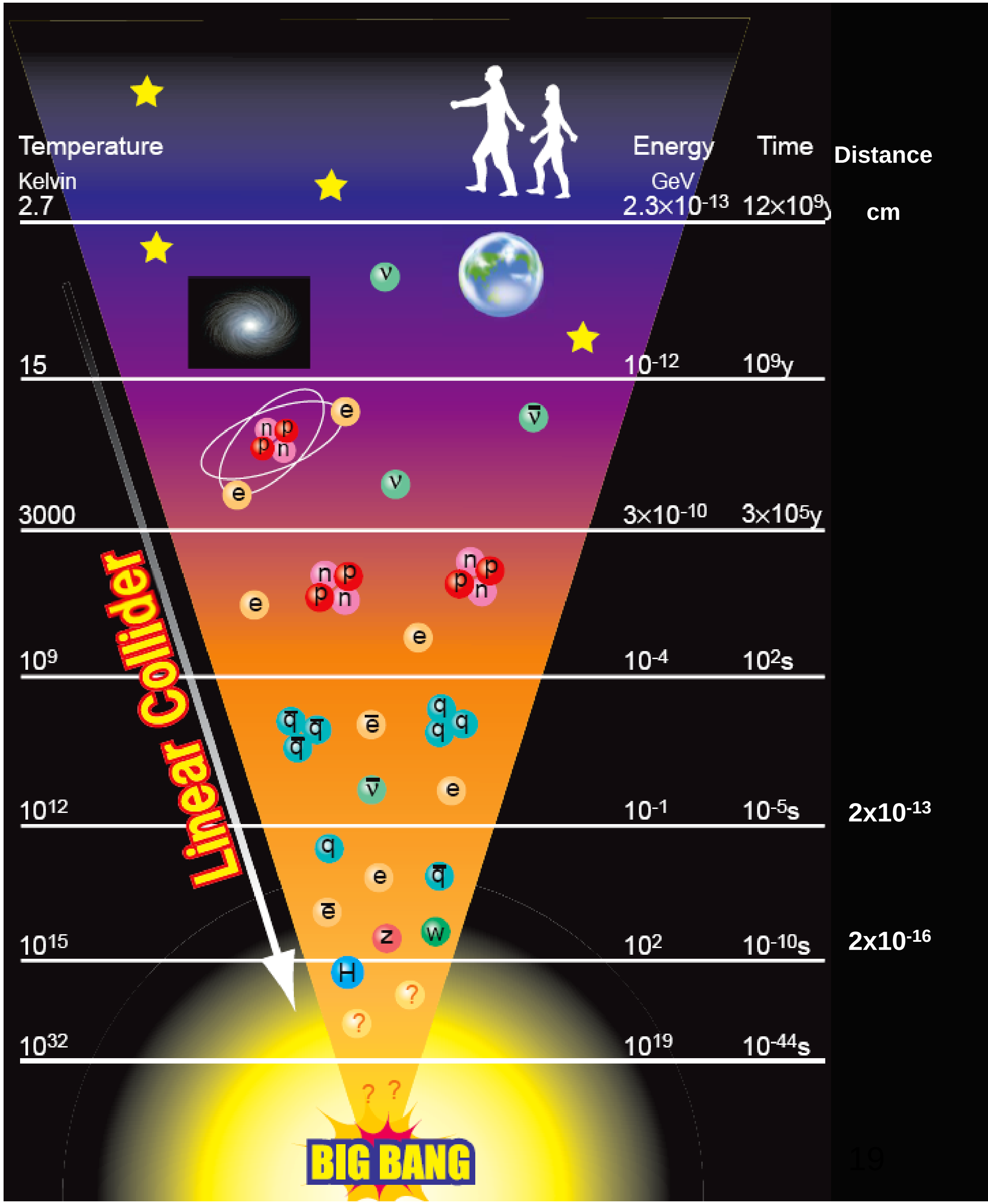
Accelerators are like ***microscopes:***

Energy => 1/distance

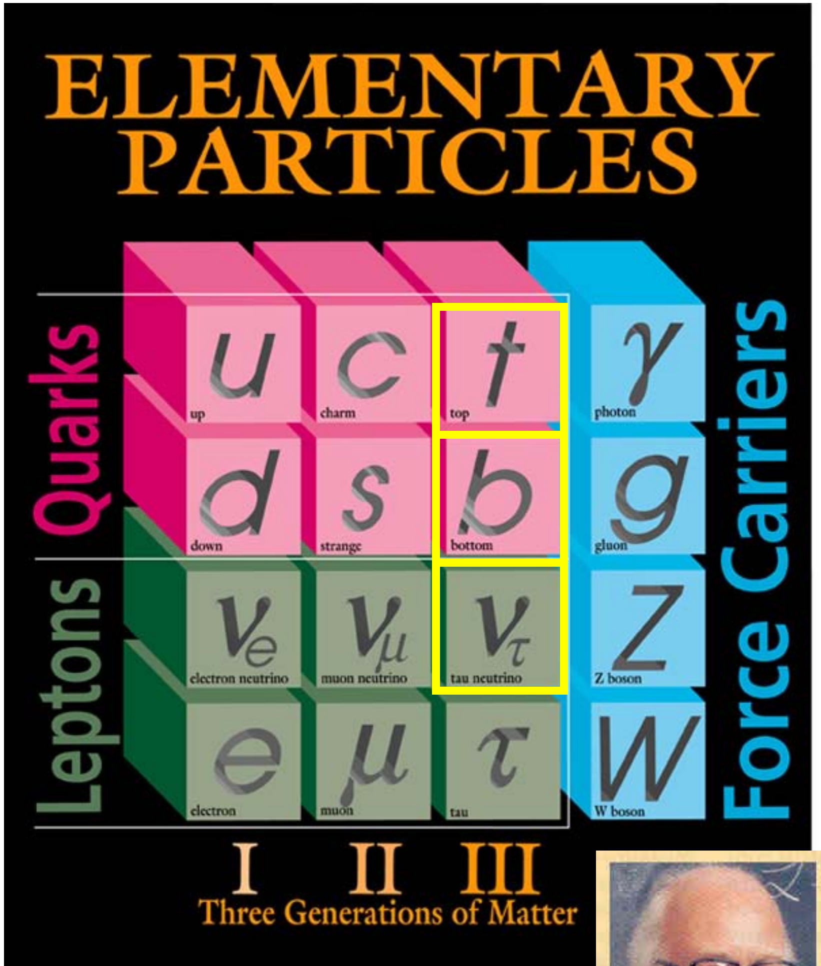
and like ***time machines:***

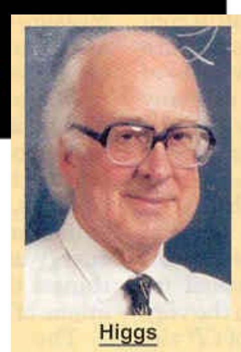
Energy => 1/time

also Energy => ***Temperature***



Our "Periodic Table"





Quarks, Leptons, & Forces

b, t, ν_τ 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:

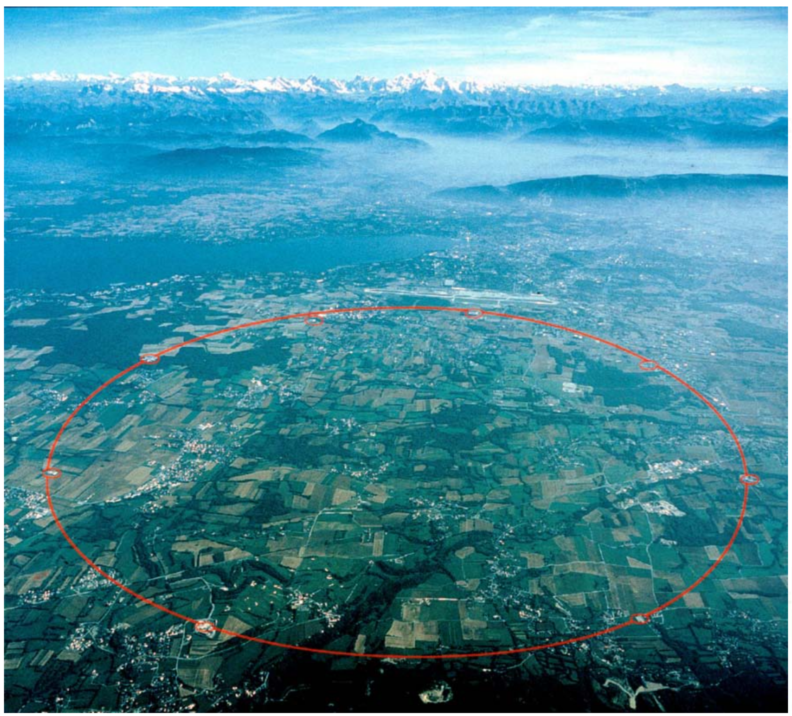
What causes *mass*? Is it the *Higgs boson*?
Why are there different types of quarks & leptons?
Very curious *neutrinos*! (weak force)
Why does the universe seem to be "*matter*",
rather than a balance of matter and anti-matter?
Is there anything *inside* quarks & leptons?
Are there any *other types* 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

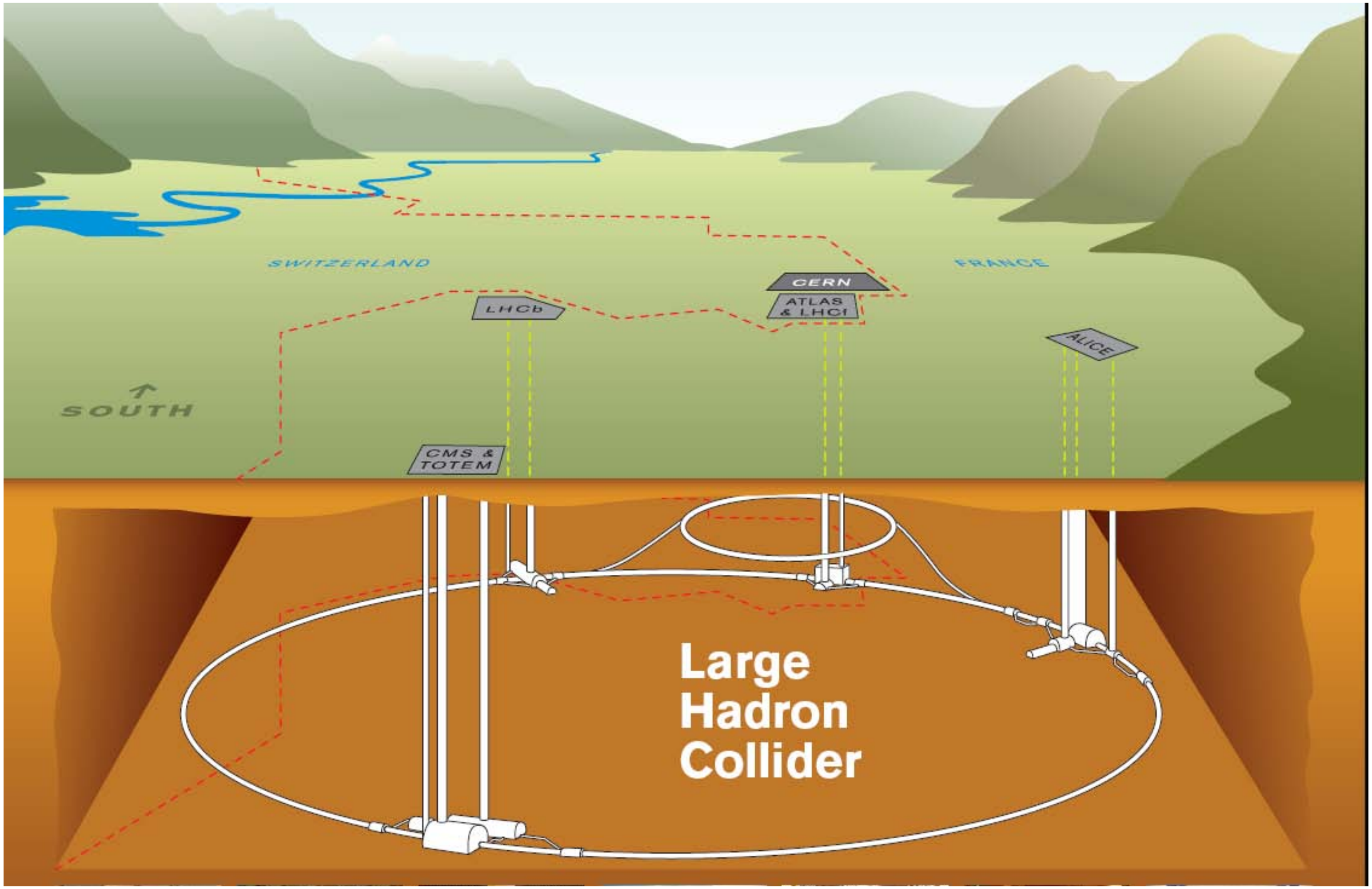
Chicago Tribune Web Edition

September 5, 2007

CERN ACCELERATOR (France and Switzerland)

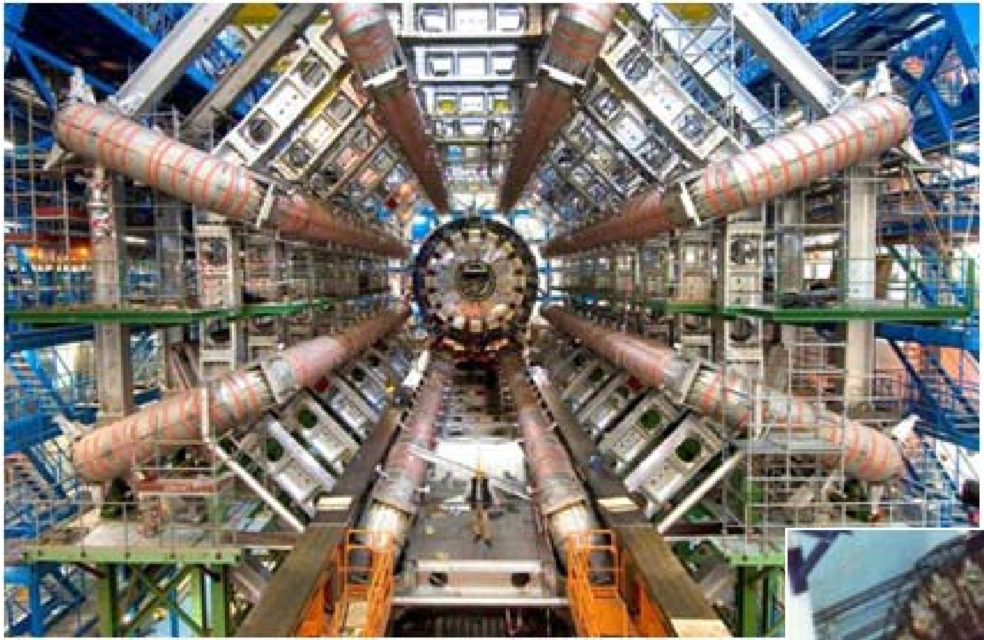
FERMILAB ACCELERATOR (Batavia, Illinois)

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

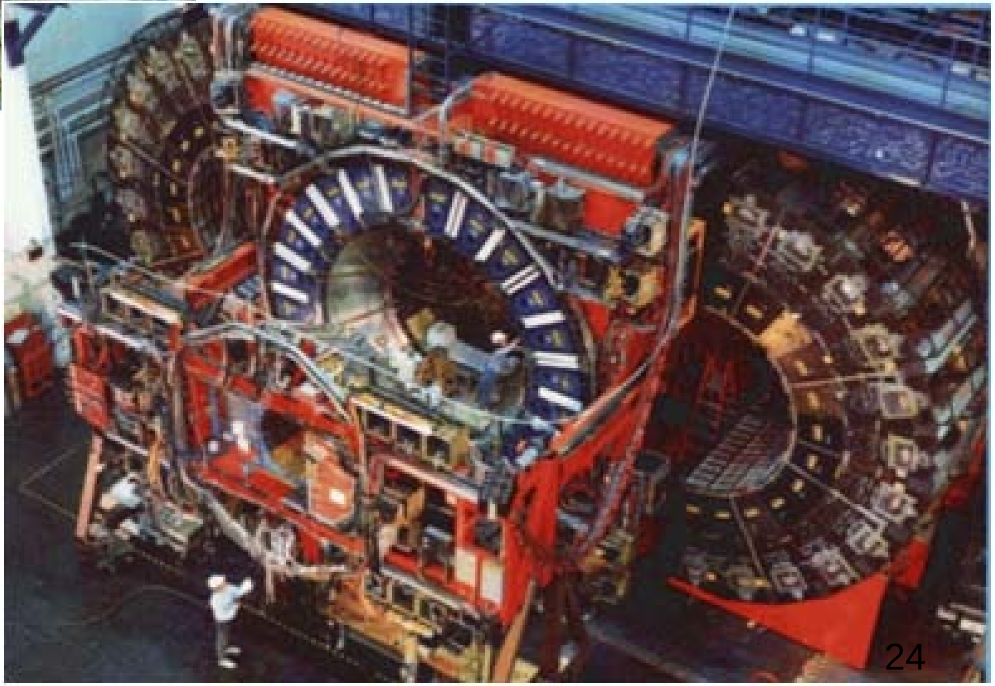


CERN’s LHC will have
4.25 x circumference, 1.65 x stronger magnets,
7 x more energy, and 33 x event rate,
than Fermilab’s Tevatron Collider

And Much Bigger Experiments!

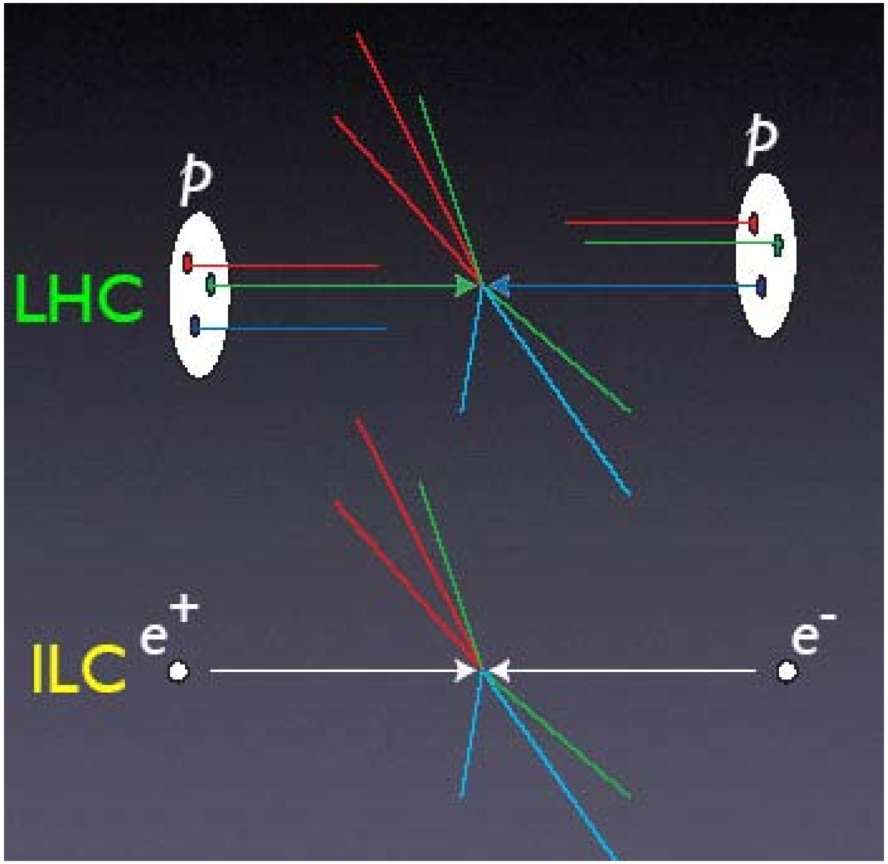


ATLAS at CERN



CDF at Fermilab

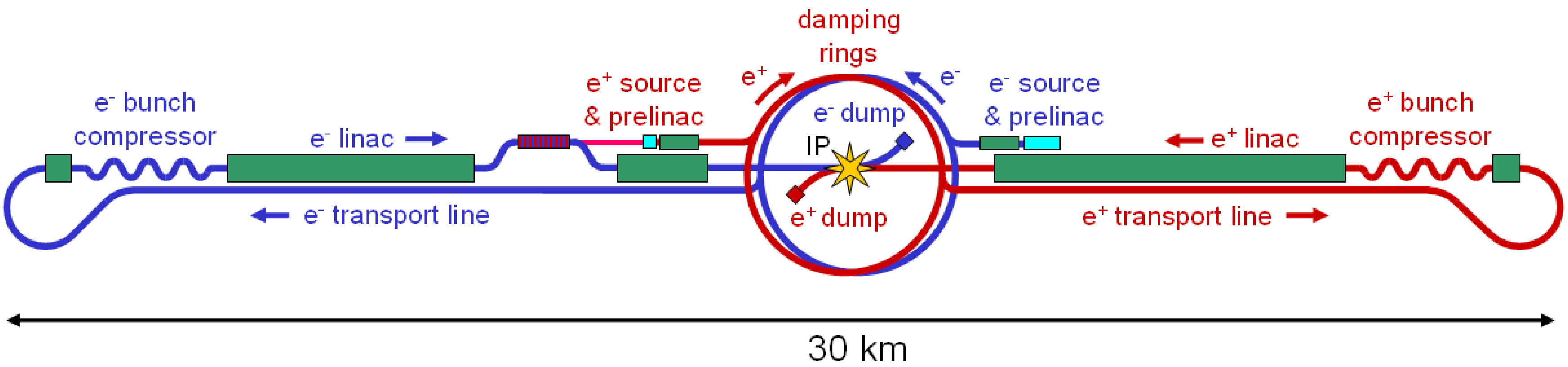
500-1000 GeV e^+e^- Linear Collider is under consideration by Europe, Japan, and U.S./Canada initially 250x250 GeV, with possible upgade to 500x500 GeV



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!

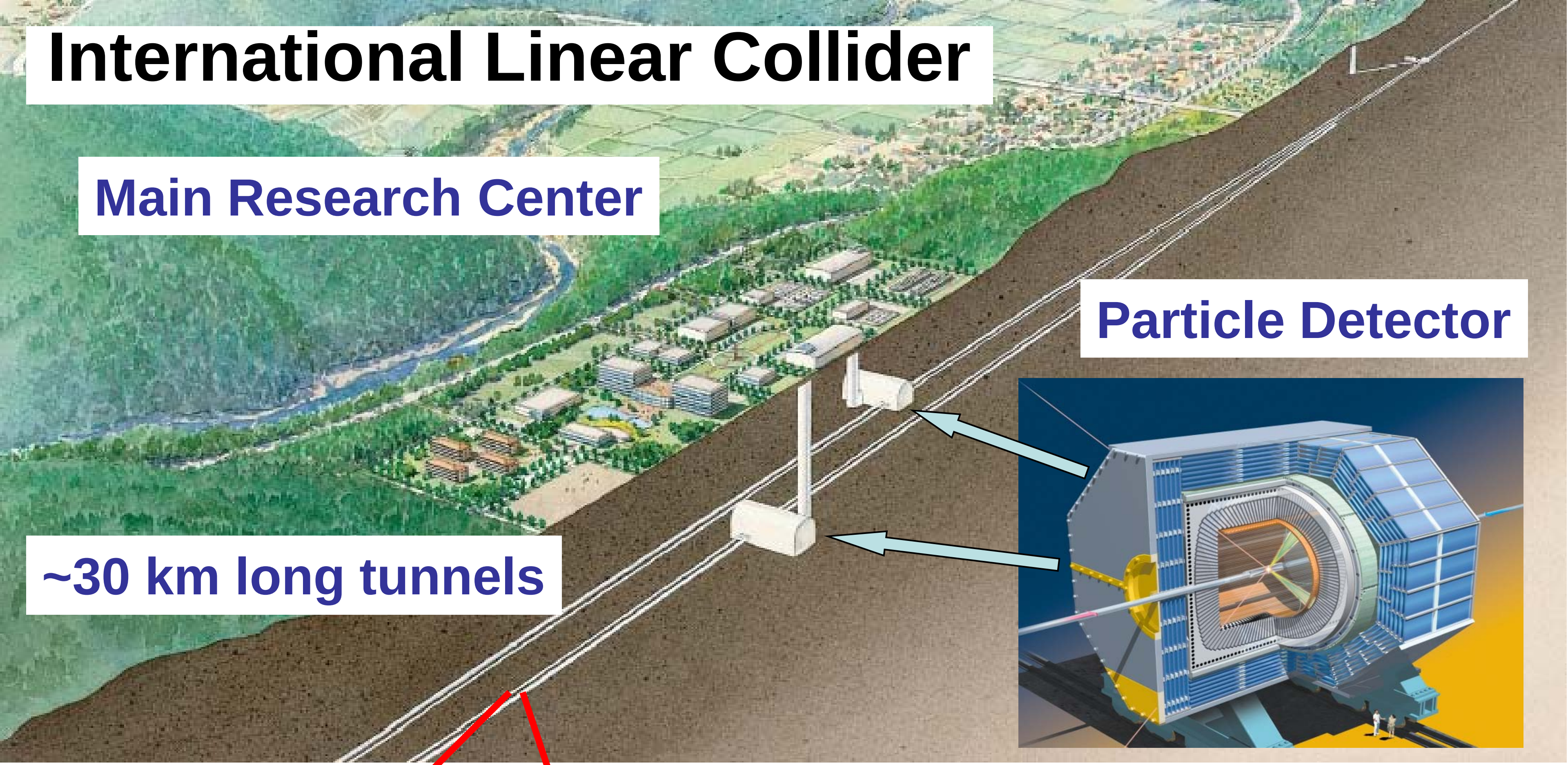
The Reference Design Report (RDR) for the ILC including cost and labor estimates was released in August, 2007

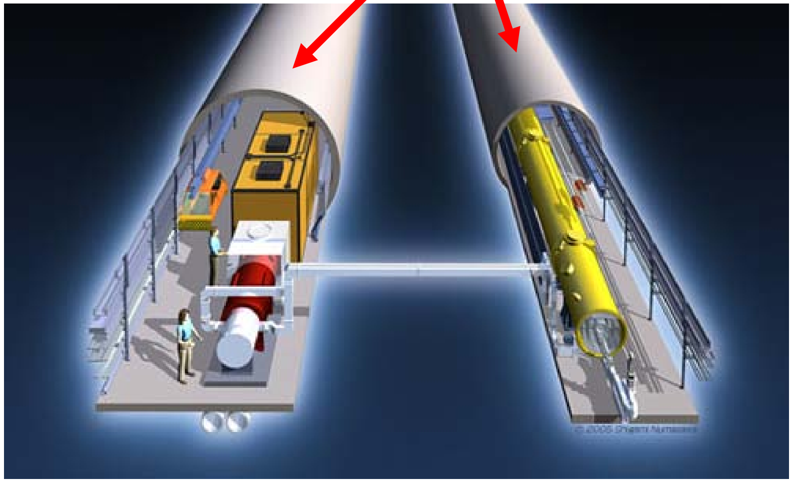
International Linear Collider

Main Research Center

Particle Detector

~30 km long tunnels





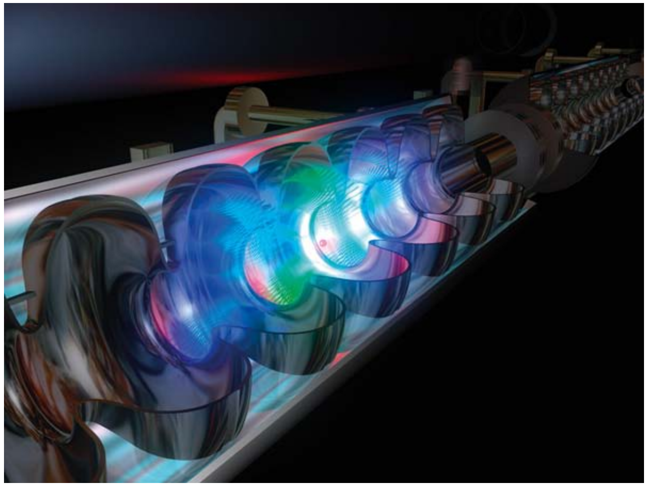
Two tunnels

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

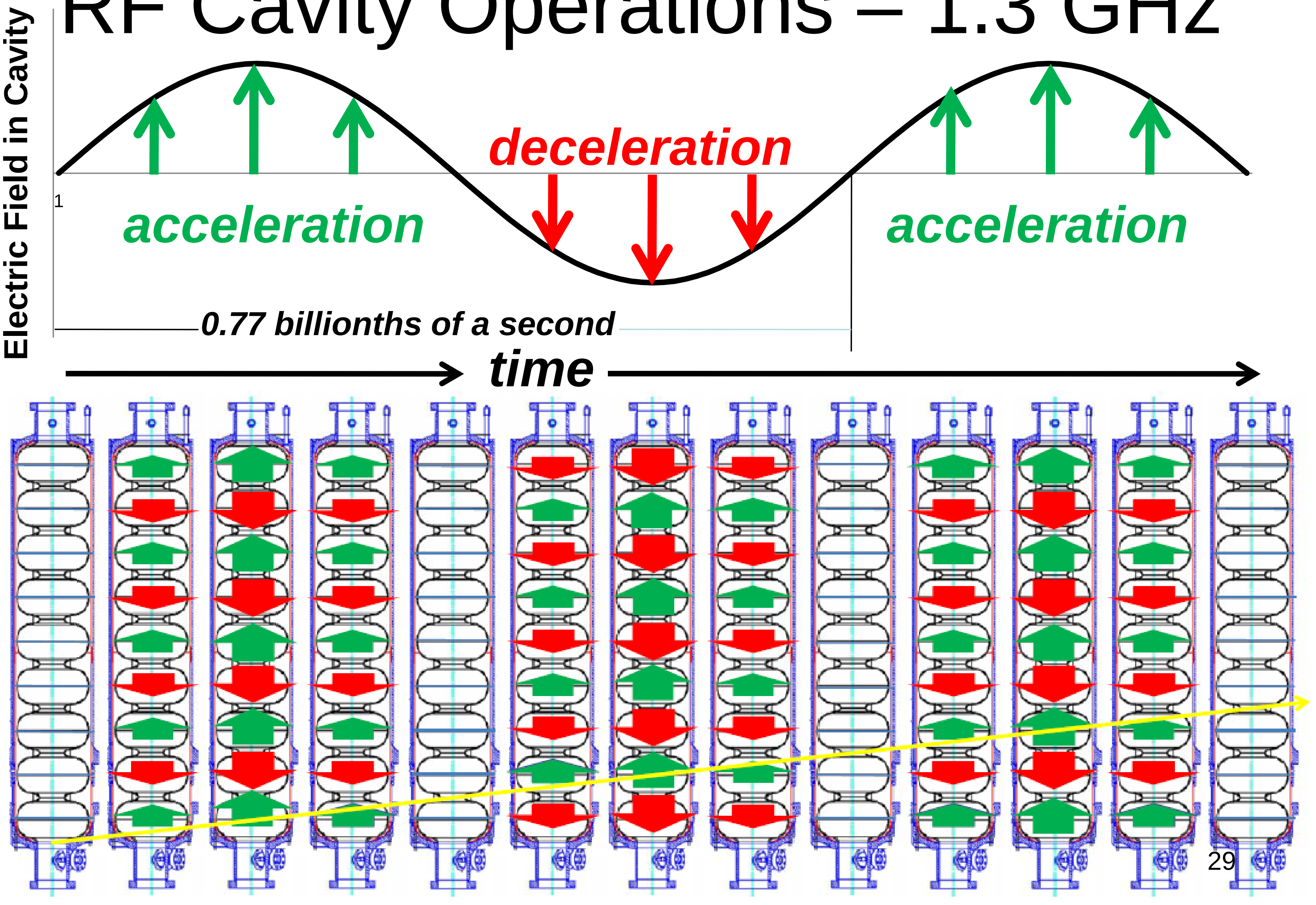
~ 16,000 SC RF cavities

below is first Fermilab Cryomodule

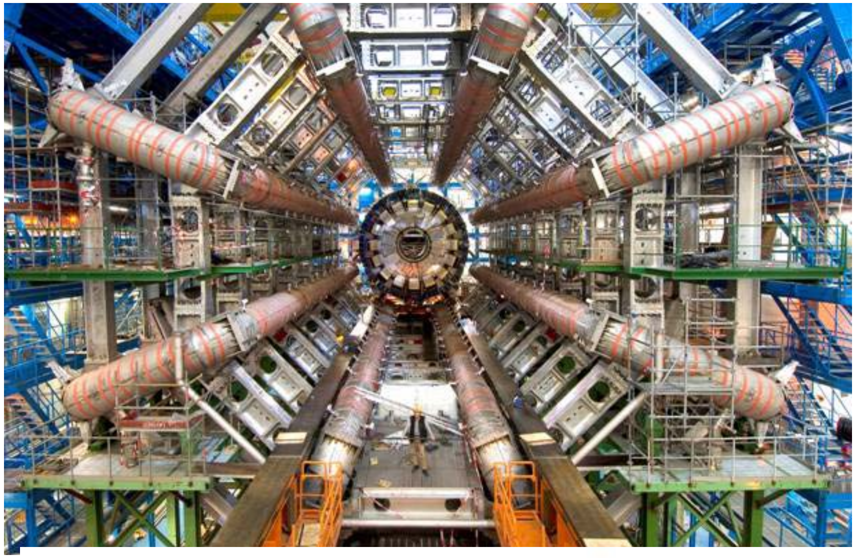
8 cavities, 12 m long x 1 m dia.

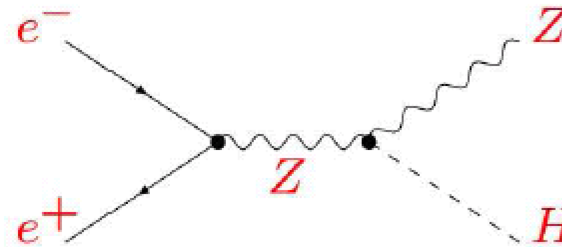


RF Cavity Operations – 1.3 GHz

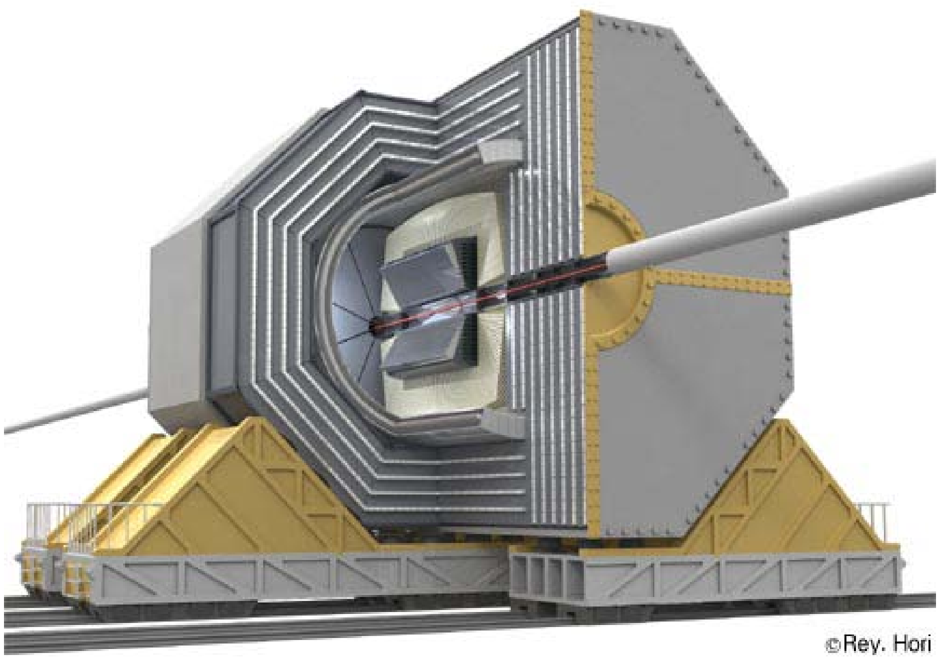


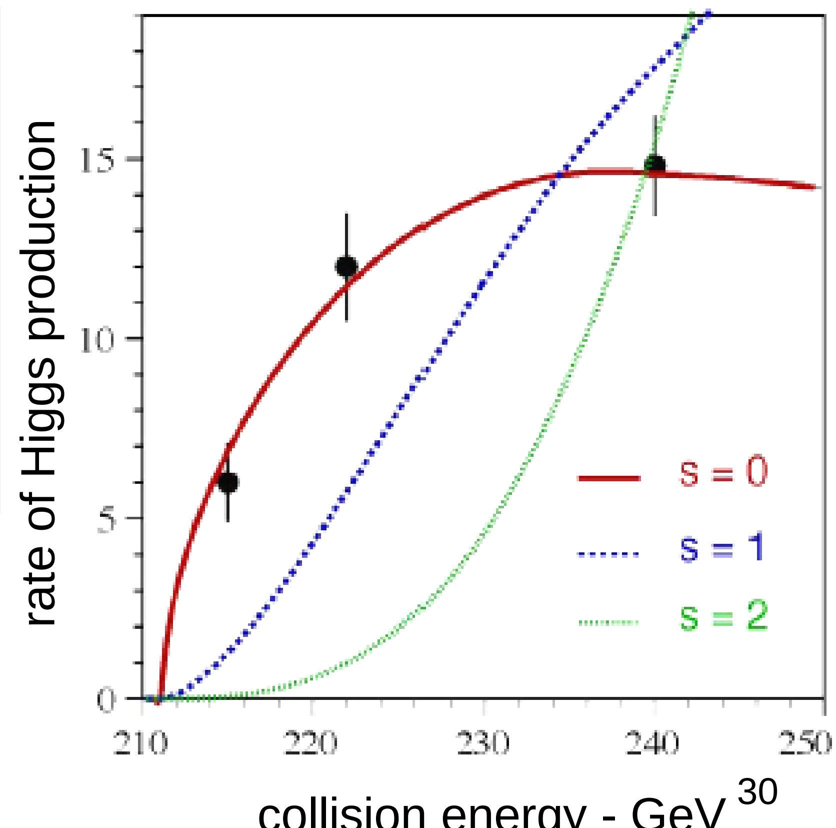
Complementarity of LHC and ILC

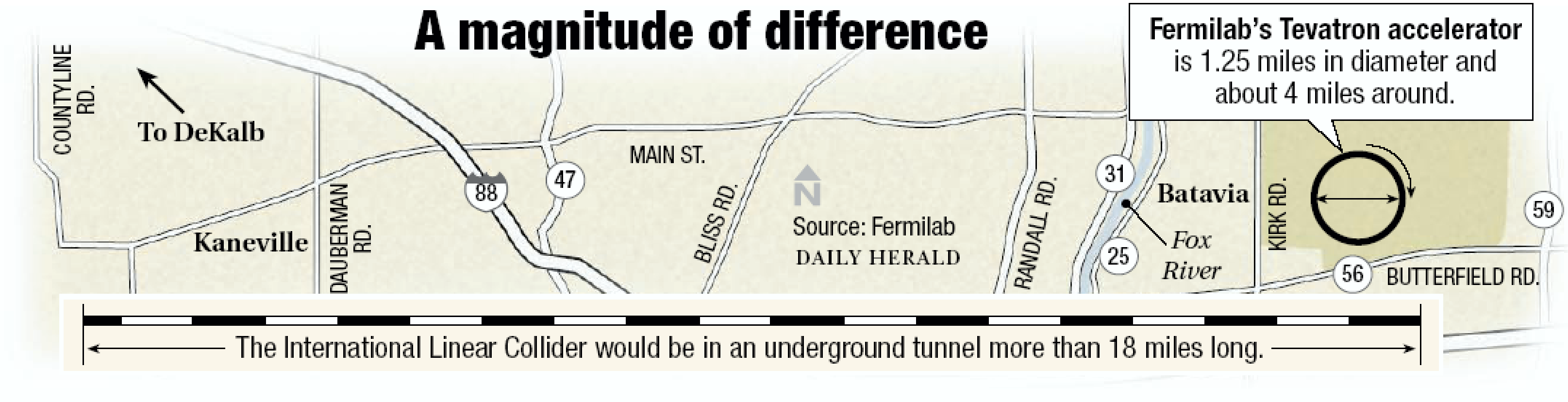




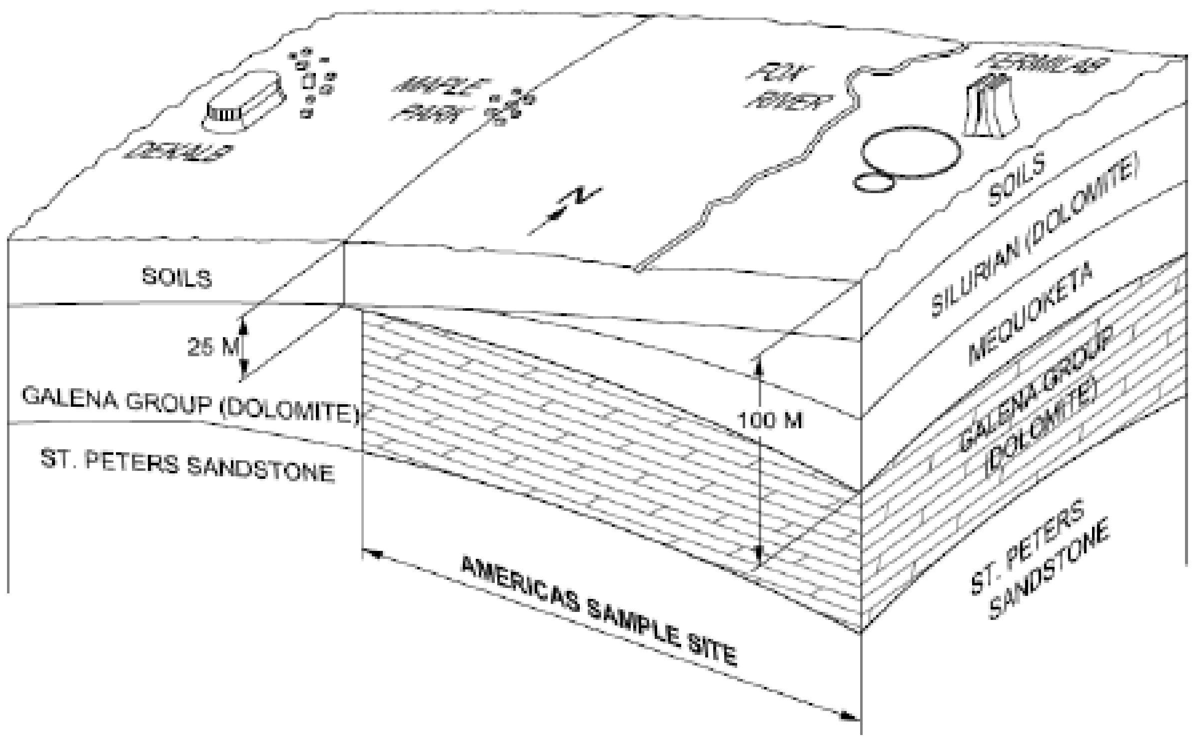
Does Spin of Higgs = 0 ?





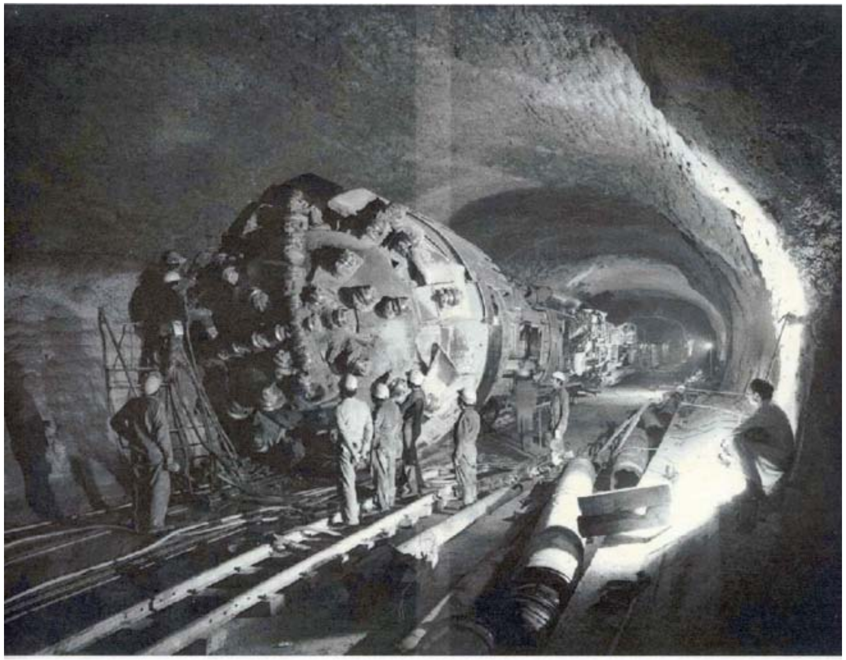


Americas Sample Plan / Section



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

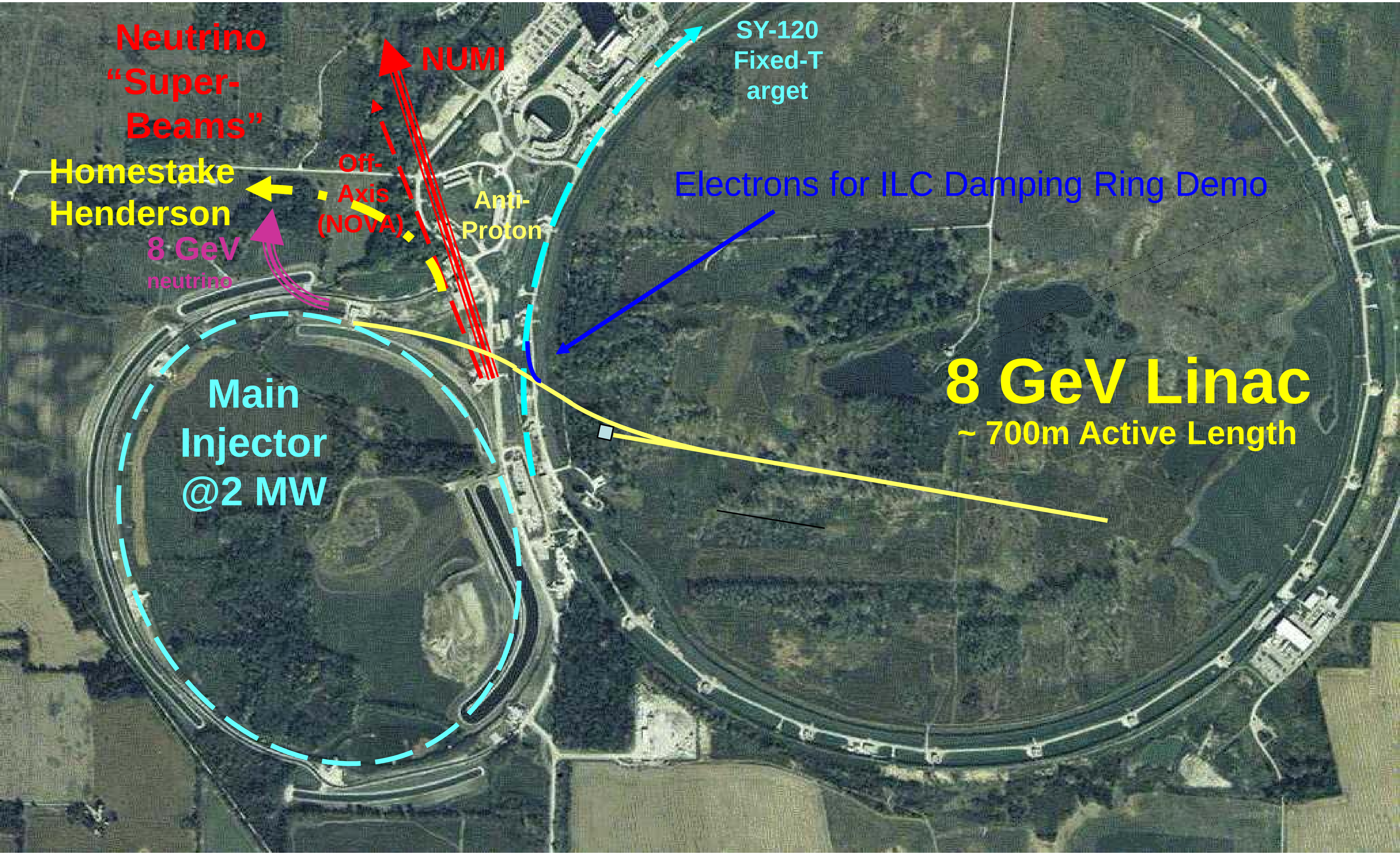
then 7 years construction – I'll be > 75 years old!

We are hoping that Fermilab will be the site,

also investigated sites in Switzerland & Japan.

This will be a big international decision!

Fermilab is proposing an **interim** Project X



uses same RF technology as ILC, can serve as a proof-of-principle test

Accelerator Uses

- **Fundamental Research into Nature** } **~ 100 accelerators**
  - **Particle Physics and Nuclear Physics**
- **Light sources**
  - **Condensed Matter Physics**
  - **Chemistry**
  - **Biology**
  - **Archeology**
- **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/

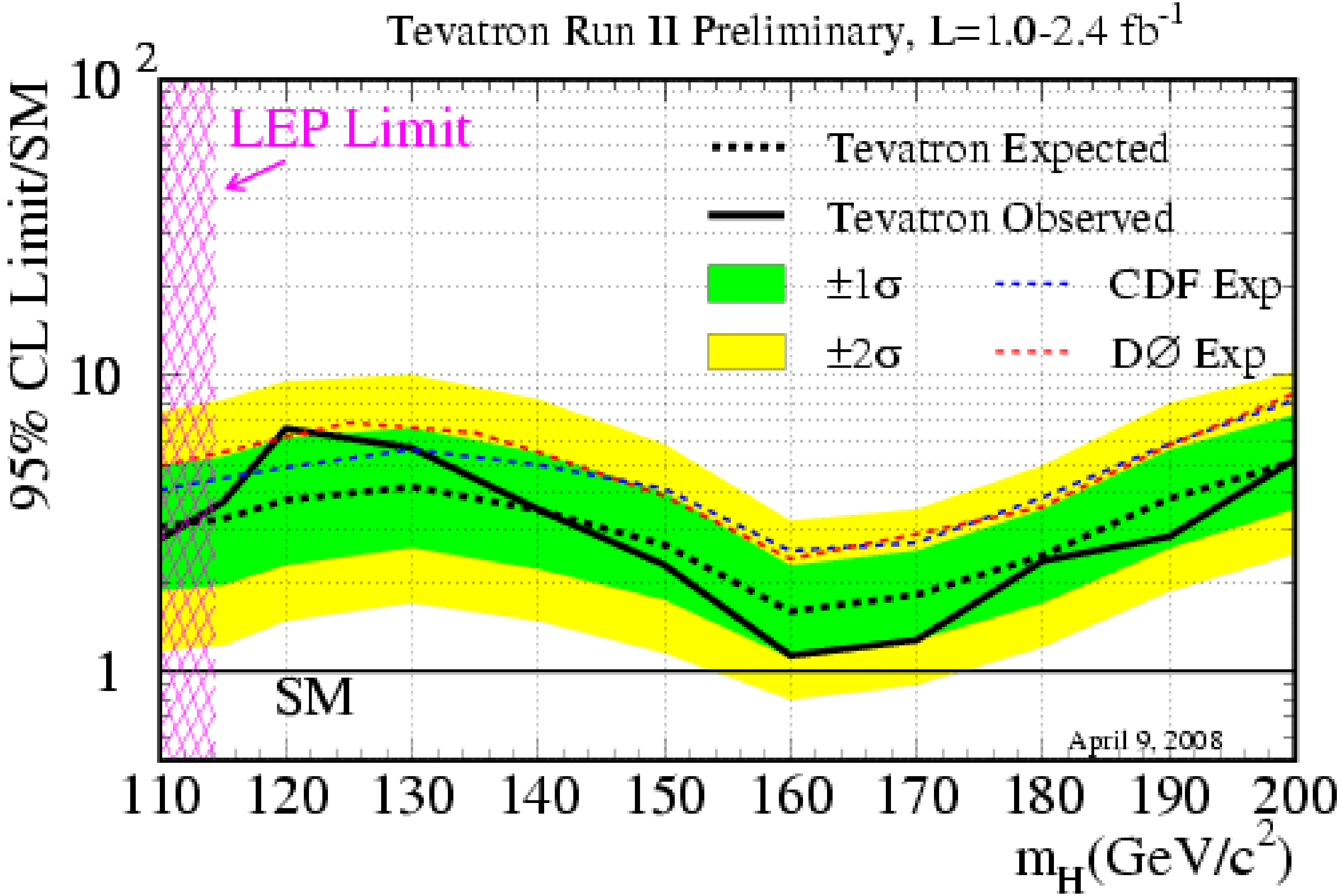
http://www.linearcollider.org

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**

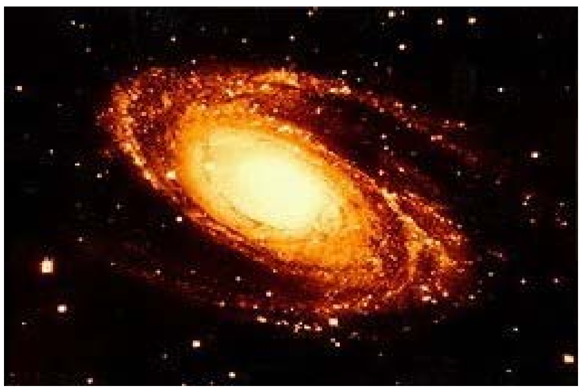


Tevatron Run II Preliminary, L=1.0-2.4 fb-1
95% CL Limit/SM
10 2
10
1
LEP Limit
Tevatron Expected
Tevatron Observed
±1σ
±2σ
CDF Exp
DØ Exp
SM
April 9, 2008
110
120
130
140
150
160
170
180
190
200
mH(GeV/c2)

The mass-energy of Universe consists of 25 % dark matter & 70% dark energy "dark" => doesn't emit or absorb starlight

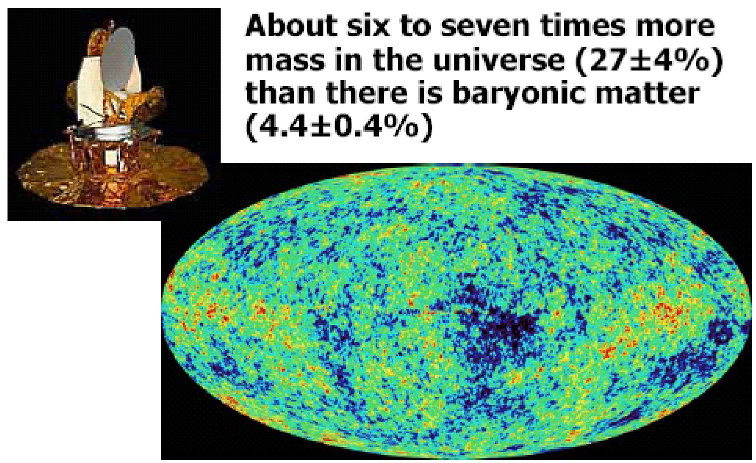
Rotational speed of galaxies

Clumpiness of cosmic microwave background radiation

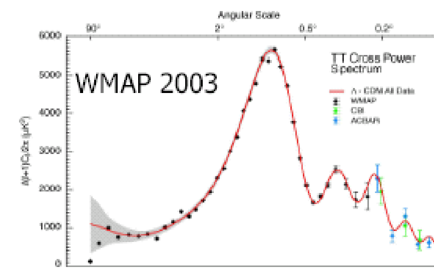


M81 galaxy &

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!*

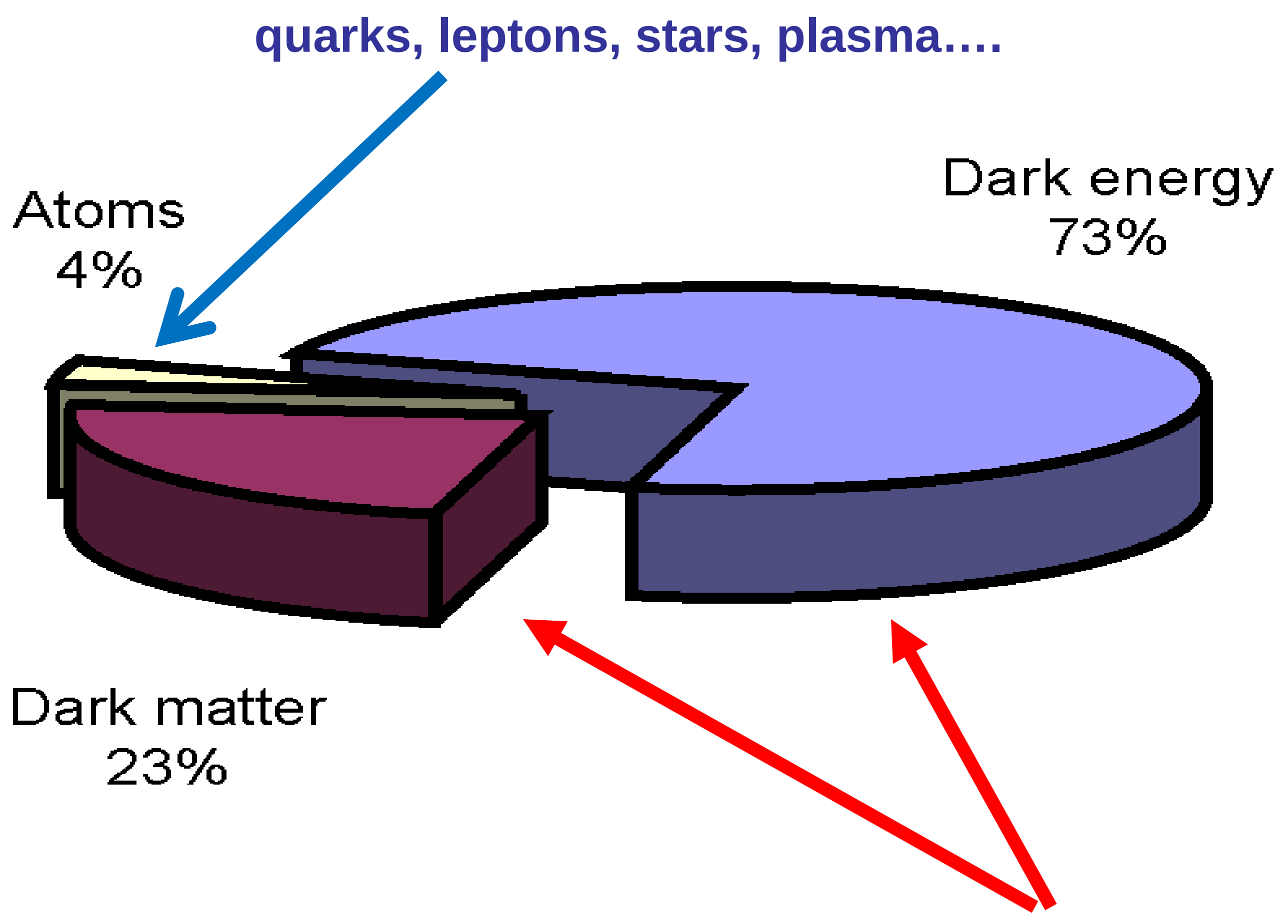
Much more mass-energy than (known) quarks & leptons!

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



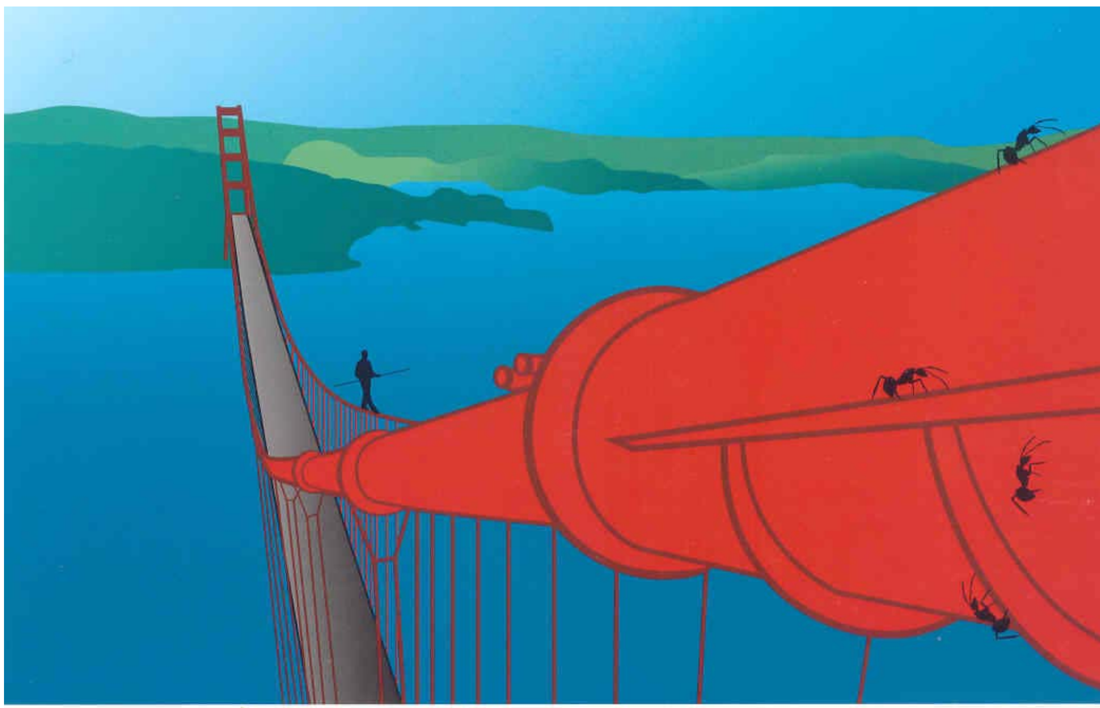
So what is all of this "stuff"?

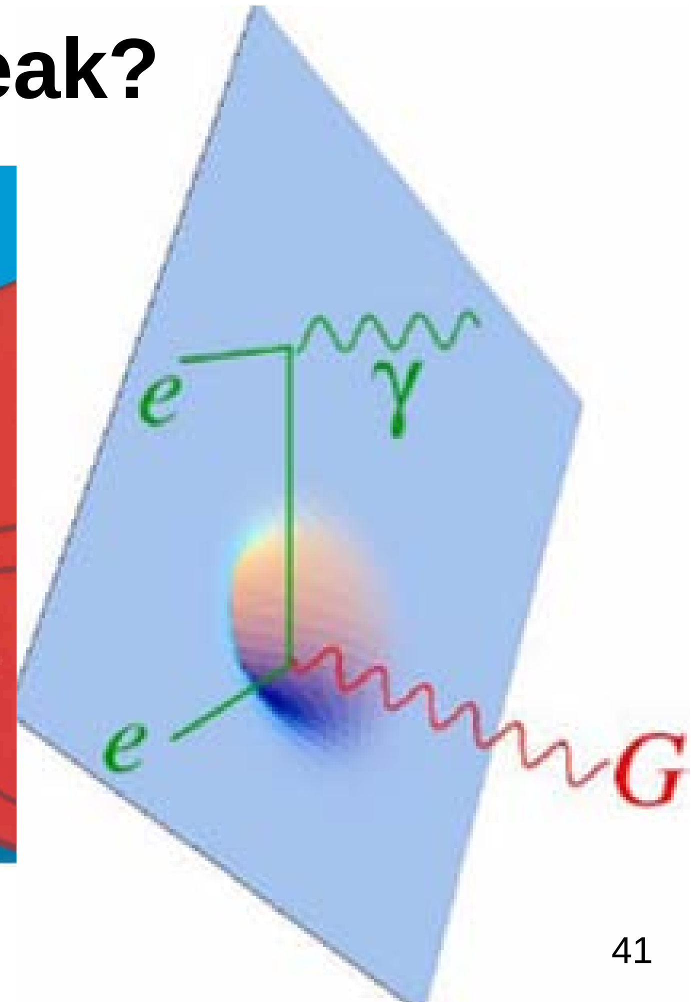
I thought we knew
what the universe is all about!

Example of a curled-up (invisible) extra dimension

How can we observe it?

Is that why gravity is so weak?





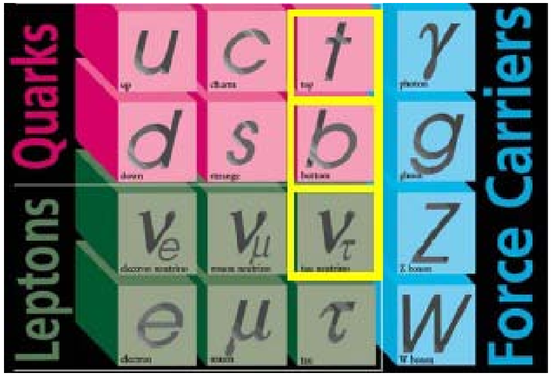
Is There a New Symmetry in Nature?

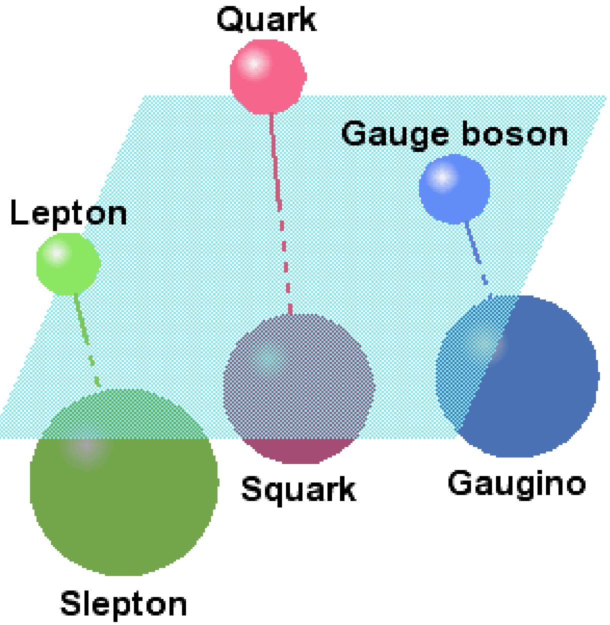
Supersymmetry

Bosons ⟷ Fermions

Particles

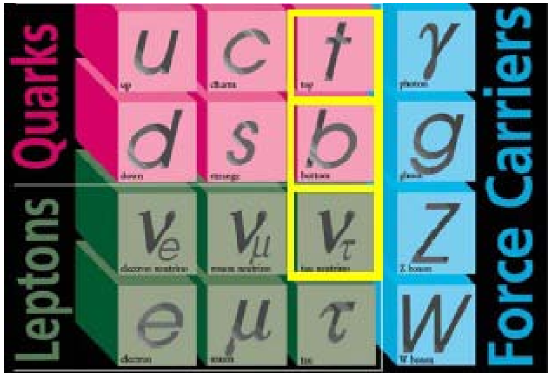
S = ½   S = 1





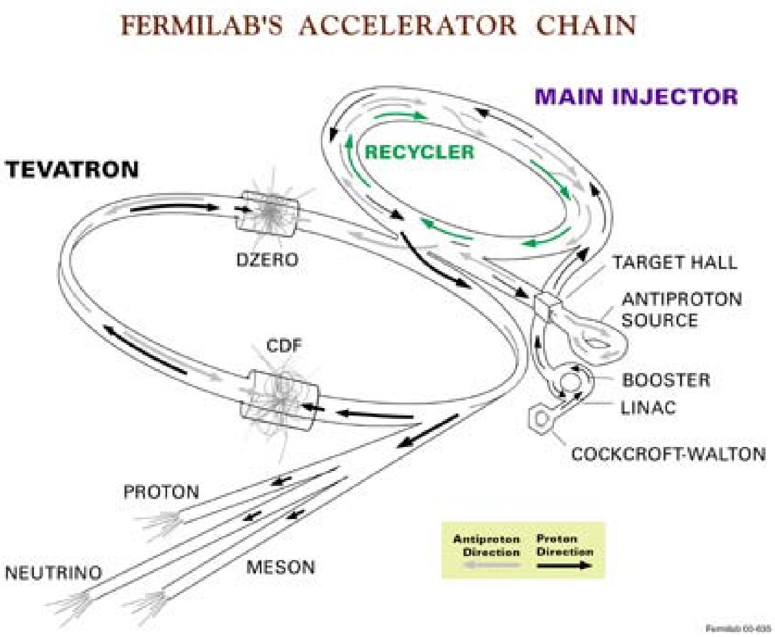
SUSY Sparticles

S = 0,1   S = 1/2



Fermilab Accelerator Complex

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



You need big machines to study small particles!

Toward the ILC
International Linear Collider

Technology: Copper – SLAC or SC – DESY

2004 – Choice => **Super Conducting RF**

2005 – Baseline Configuration Design

2007 – Reference Design Report and
initial Cost Estimate (**multi-$B range**)

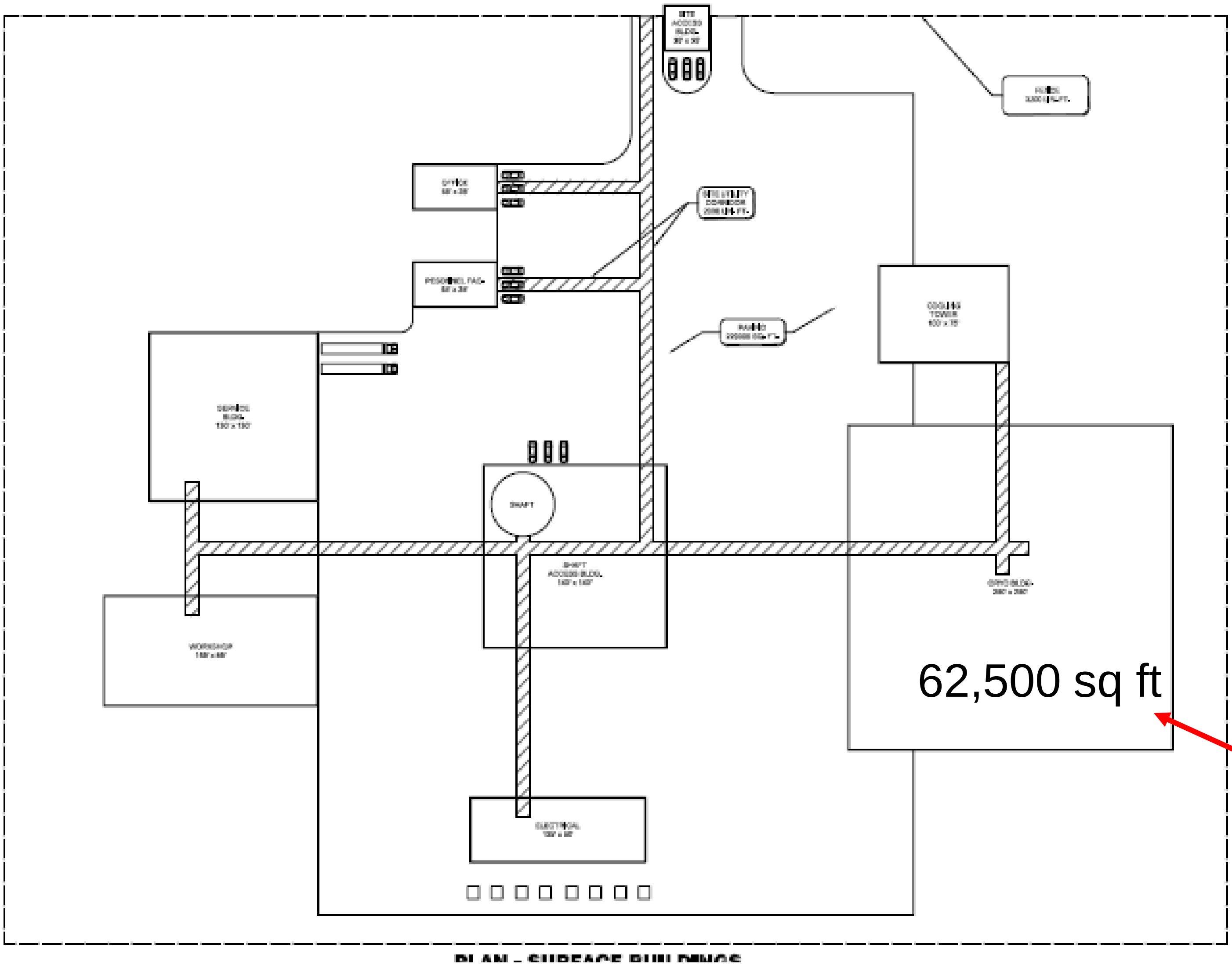
~ 2012 – R&D => affordable & reliable

~ 2012-18 – site selection and approval???

then at least a 7 year construction period

(for the next generation - **I'll be > 75 years old!**)

off-Fermilab sites (4 @ 500 GeV)



early functional concept

~ 14.5 acres

~ size of the Jewel in Batavia

Citizens Task Force to Provide Input to Fermilab's Bid to Host the International Linear Collider in Illinois

Mission of the ILC Citizens Task Force

The ILC Task Force will provide guidance and advice to Fermilab to ensure that community concerns and ideas are included in all public aspects of ILC design to include:

- Orientation of the ILC
  - o Location of the underground tunnel
  - o Community issues related to locating an underground tunnel
- Surface Structures located off the Fermilab property
  - o Locations
  - o Aesthetic issues
  - o Features that could be included to benefit communities
- Construction of the ILC
  - o Timing of activities
  - o Safety
  - o Mitigating noise, traffic, and other disruptions
- Fermilab-Community Relationships
  - o Maximizing economic benefits to the region
  - o Communicating and working with neighbors
  - o Building effective relationships with local government and communities
  - o Strengthening the community role in the long term mission of Fermilab

Who?

- Residents throughout the region
- Immediate Fermilab neighbors
- Political jurisdictions
- Local business, industry, and real estate
- School districts
- Building trades
- Environment
- Agriculture
- Civic organizations
- Faith-based organizations
- Youth organizations
- Fermilab employees

Benefits of Fermilab Research

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

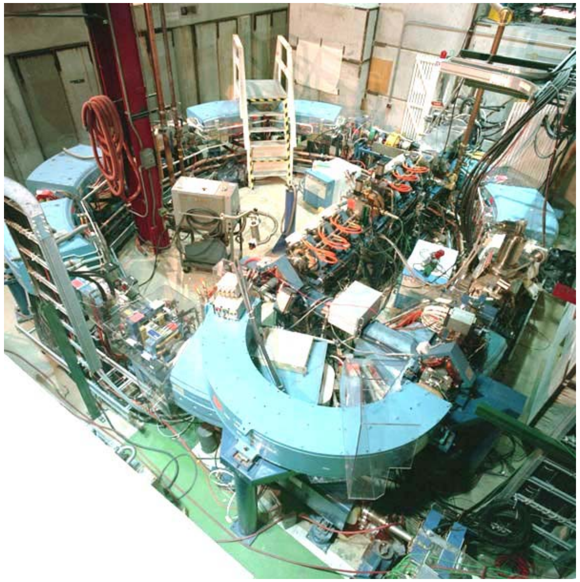
- **technological spin-offs – often far in future much of today's economy based on research in the late 1800's – early 1900's**

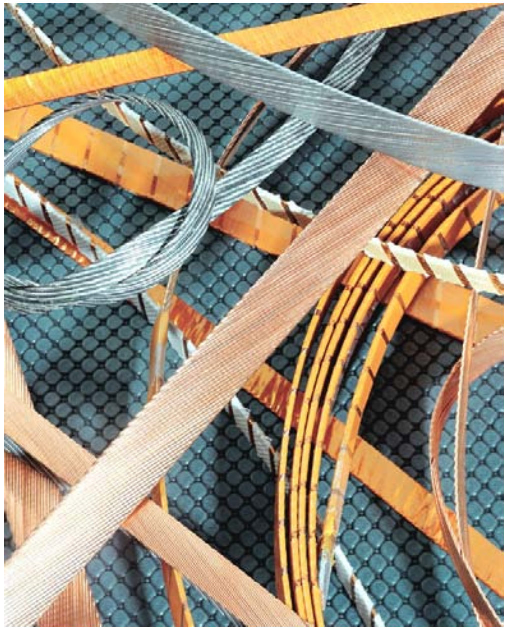
electron → TV (accelerator) & communications

- **some examples from Fermilab & HEP**

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

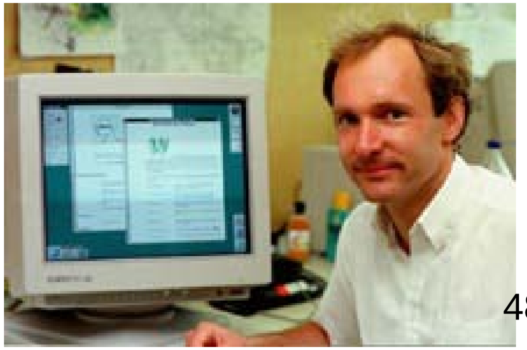
Proton Accelerators for Medicine – Loma Linda & PET

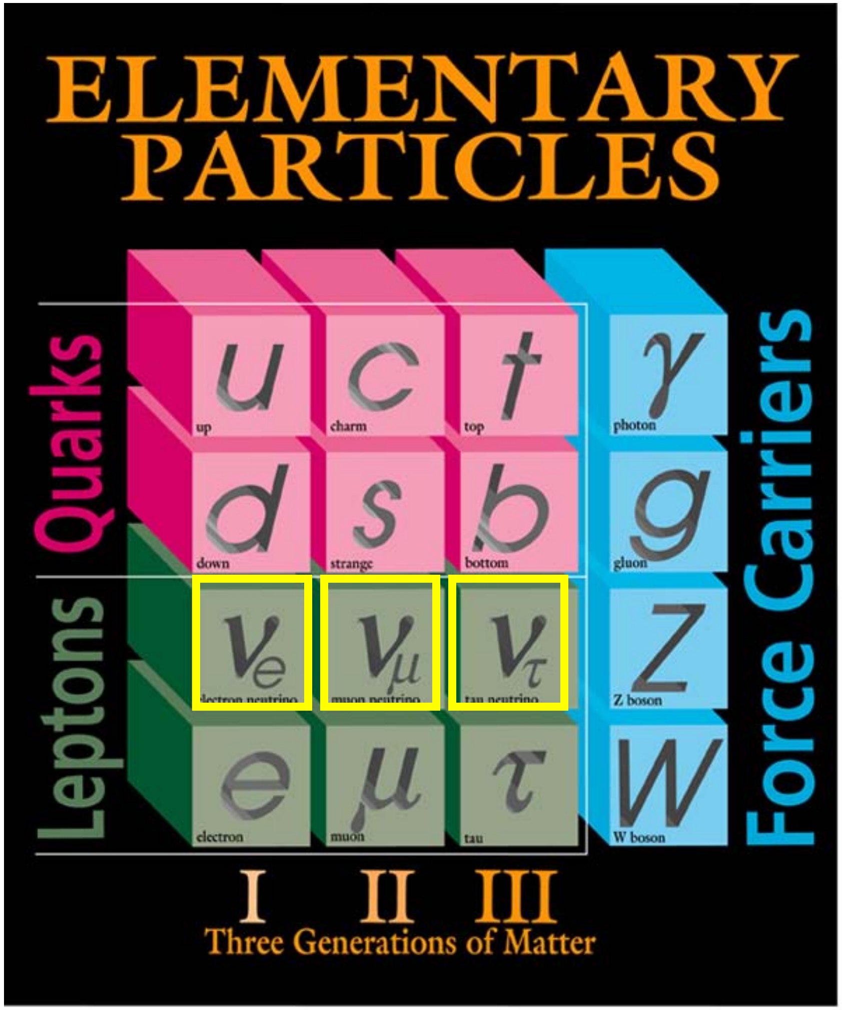




SC wire – Tevatron → practical MRI (medical diagnostic)

WWW – invented @ CERN by Tim Berners-Lee





Fermilab 95-759

***Curious neutrinos*!**

only *Weak* force

do ν have any *mass*?

if so, one kind of ν

could change

into another

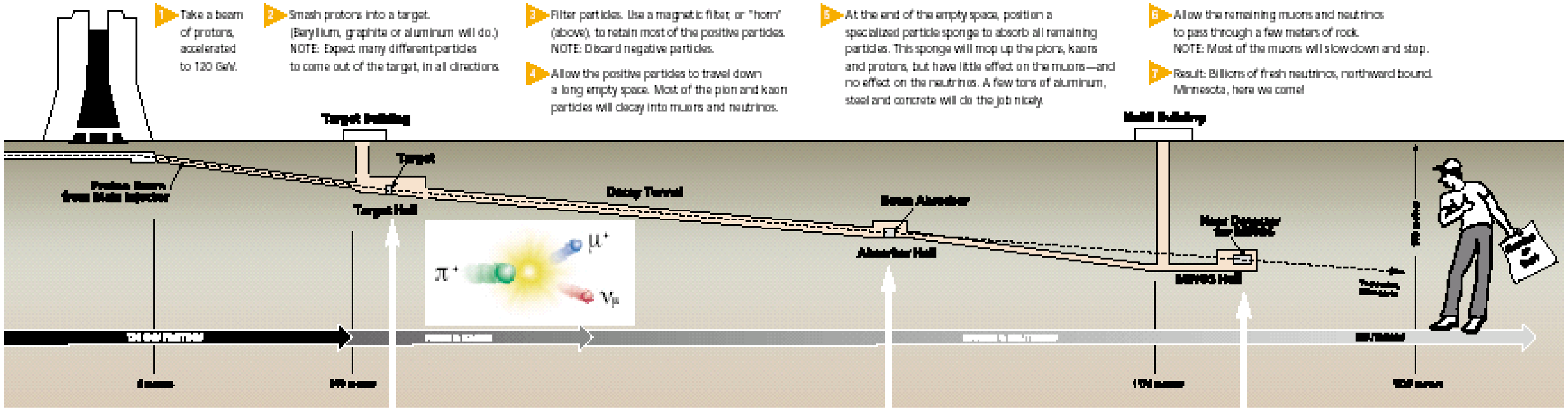
kind of ν and

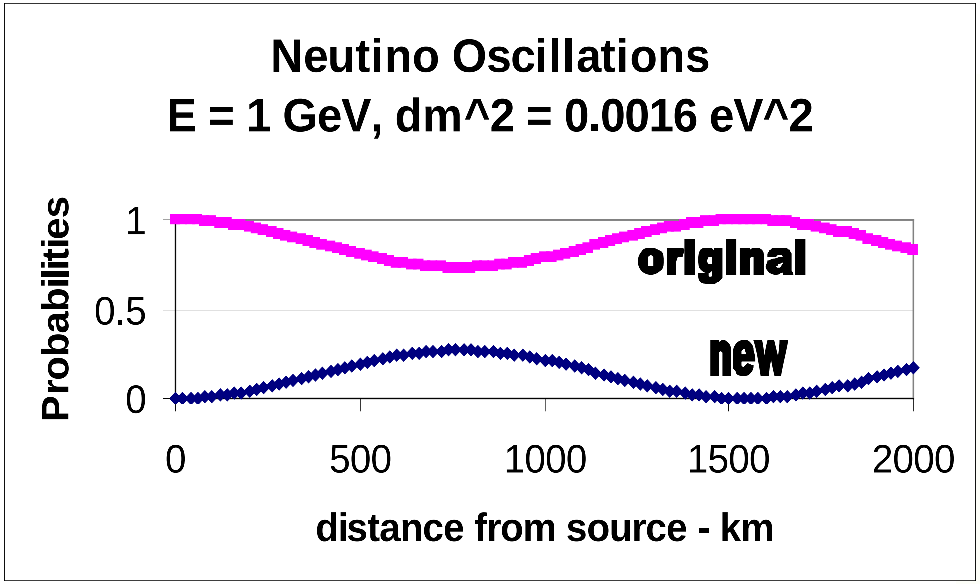
back again!

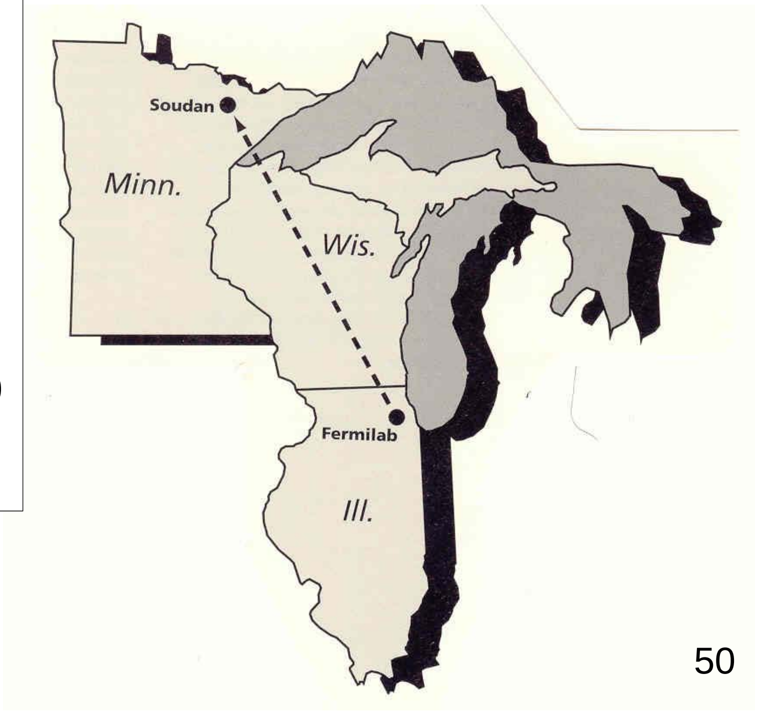
oscillations…

$\nu_e <-> \nu_\mu <-> \nu_\tau$

NUMI – Neutrinos at the Main Injector







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

Neutrino Interactions

- ν's interact very weakly (the weak force!)
- total νp cross section (interaction probability)

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

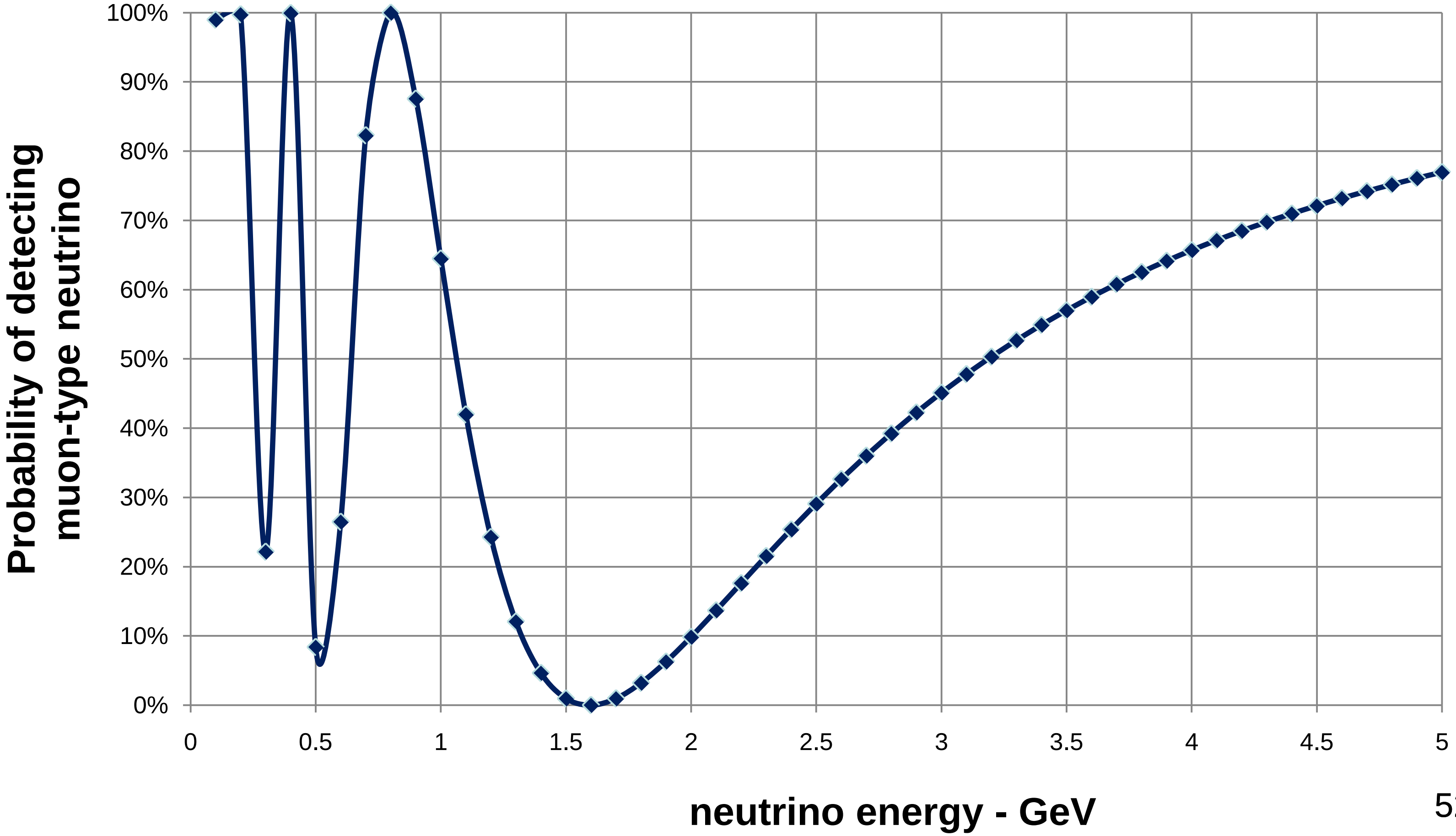
  $\sigma(pp) = 2.2 \times 10^{-26}$ cm^2 (strong force)

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

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

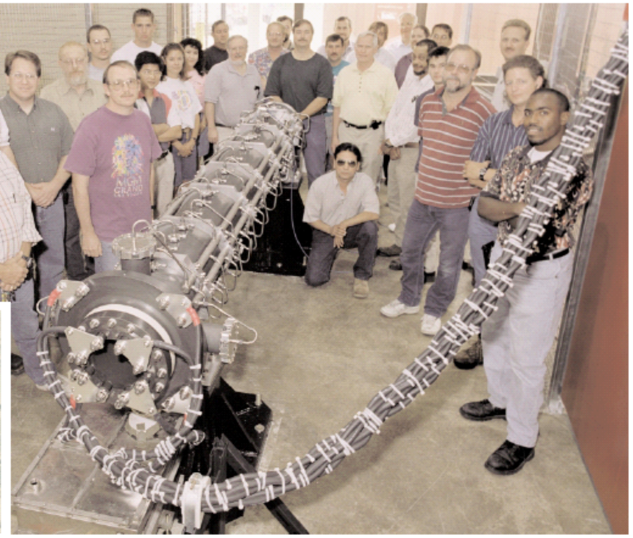
Oscillation function – disappearance

L = 730 km δm^2 = 0.0027 eV^2 $\sin^2(2\theta)$ = 1.0



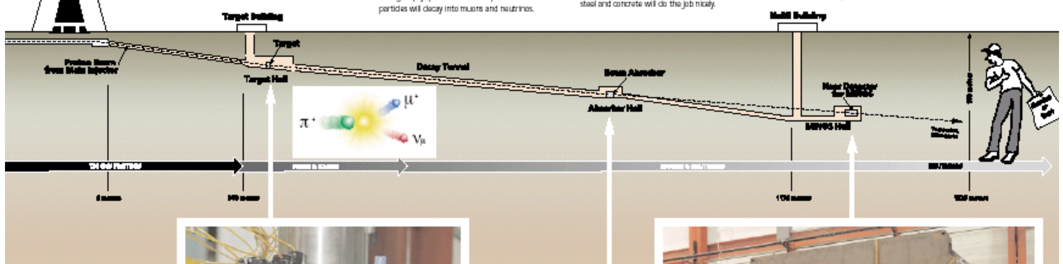
How to MAKE a Neutrino Beam

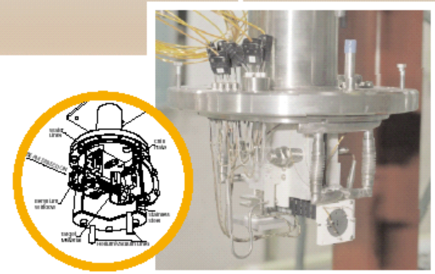
TAKE A BEAM OF PROTONS...



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.

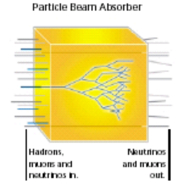
1. Take a beam of protons, accelerated to 120 GeV.
2. Smash protons into a target. (Beryllium, graphite or aluminum will do.) NOTE: Expect many different particles to come out of the target, in all directions.
3. Filter particles. Use a magnetic filter, or "horn" (above), to retain most of the positive 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!

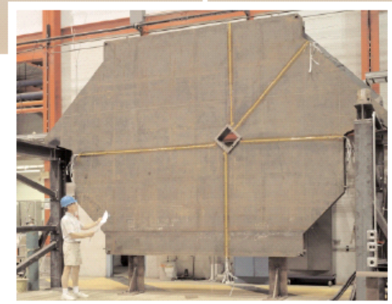




A prototype of the MINOS target. 4 x 10^{13} protons, accelerated to 120 GeV, will strike the black graphite fins of the target every 1.9 seconds. Water cooling keeps the target from melting.

Particle Beam Absorber





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

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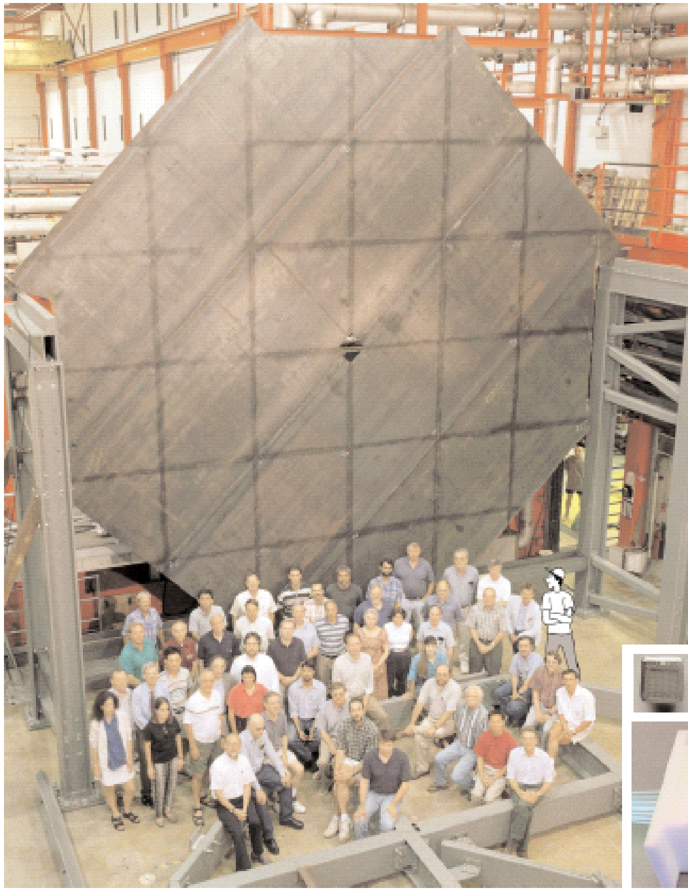
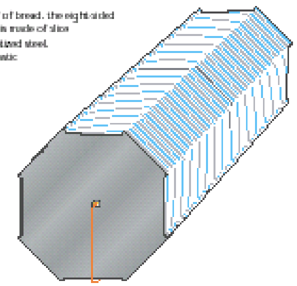
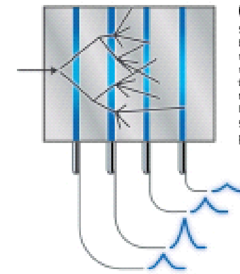
How to DETECT a Neutrino



The MINOS collaboration poses for a photo in front of a steel plane of the MINOS detector. Eventually the detector will be 90 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.

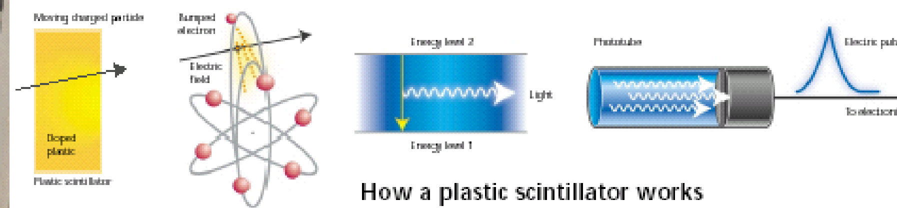
Like a 5000-ton loaf of bread, the eight-sided MINOS far detector is made of slice after slice of magnetized steel, sandwiched with plastic scintillator. When a neutrino collides with an iron nucleus, it produces a splash of particles. Charged particles passing through the scintillator produce light,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



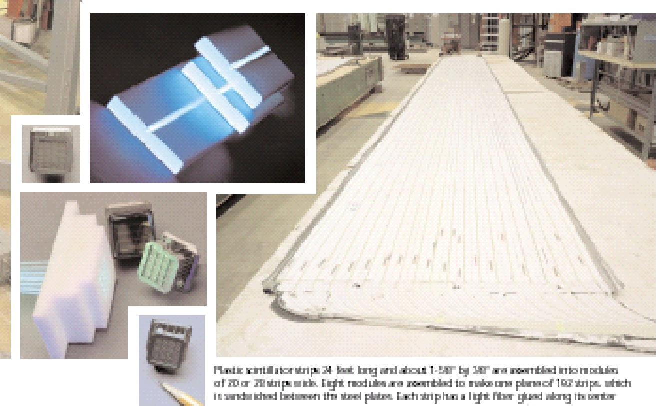


Calorimeter Sandwich Detector

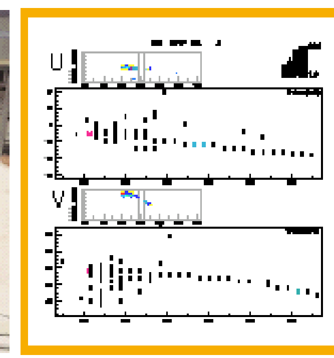
Sheets of plastic scintillator are placed between the steel plates. The particle splash is quickly absorbed in the calorimeter sandwich. Each charged particle passing through the scintillator creates light. The more particles, the more light. The more light the bigger the electronic signal.
So we can 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 1-5/8" 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.

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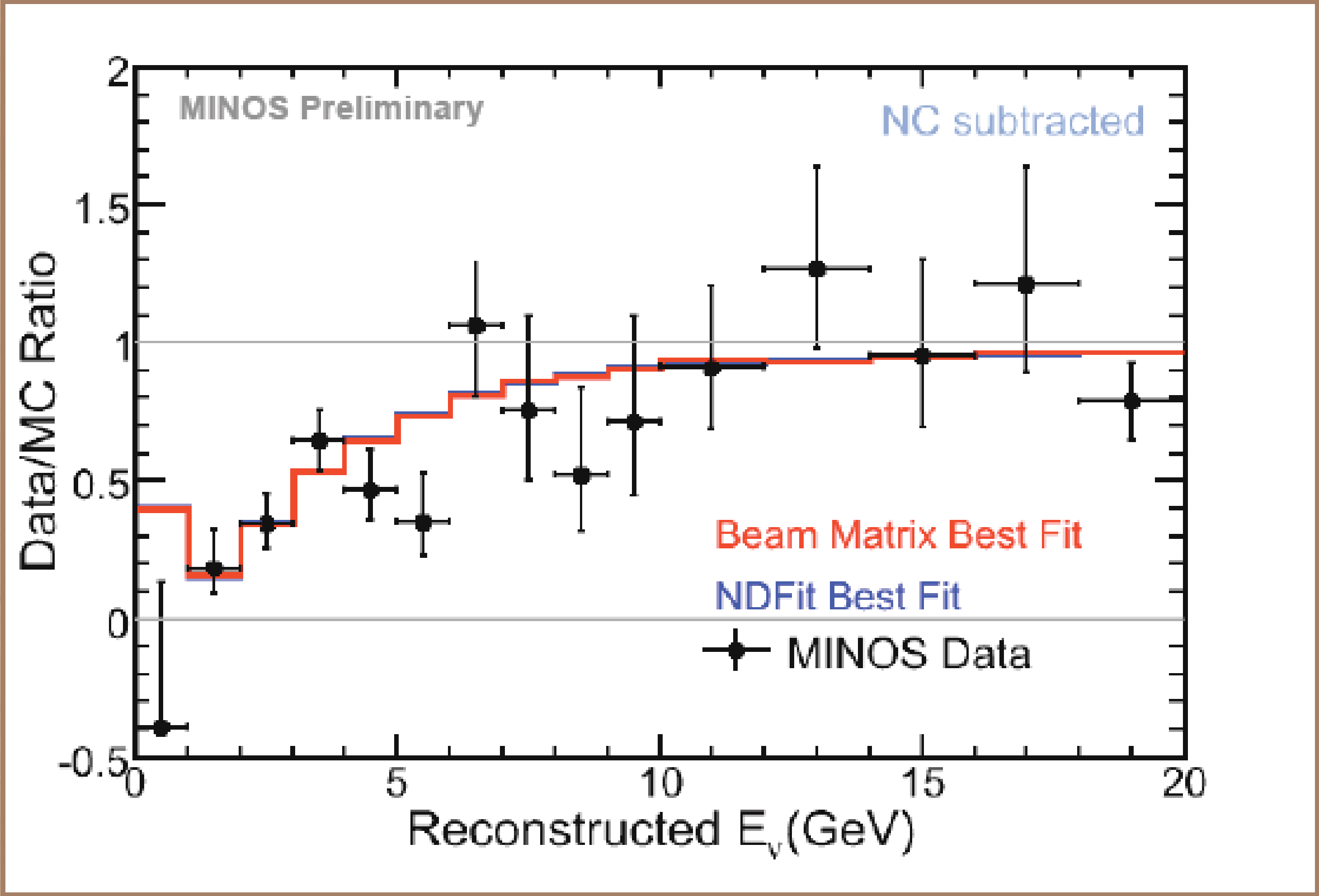
NuMI installation in Minnesota mine

first NuMI results – July 31, 2006



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

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