# Saturday Morning Physics - Accelerators

- Accelerators
- What's Up Now?
- What's Up Next?

- http://tdserver1.fnal.gov/Finley/020406_SMP_ONE.ppt
- http://tdserver1.fnal.gov/Finley/020406_SMP_ONE.pdf

# But First ...

- A little about me …
  - finley@fnal.gov
- A little about you …
  - Linda Spentzouris' Survey ...

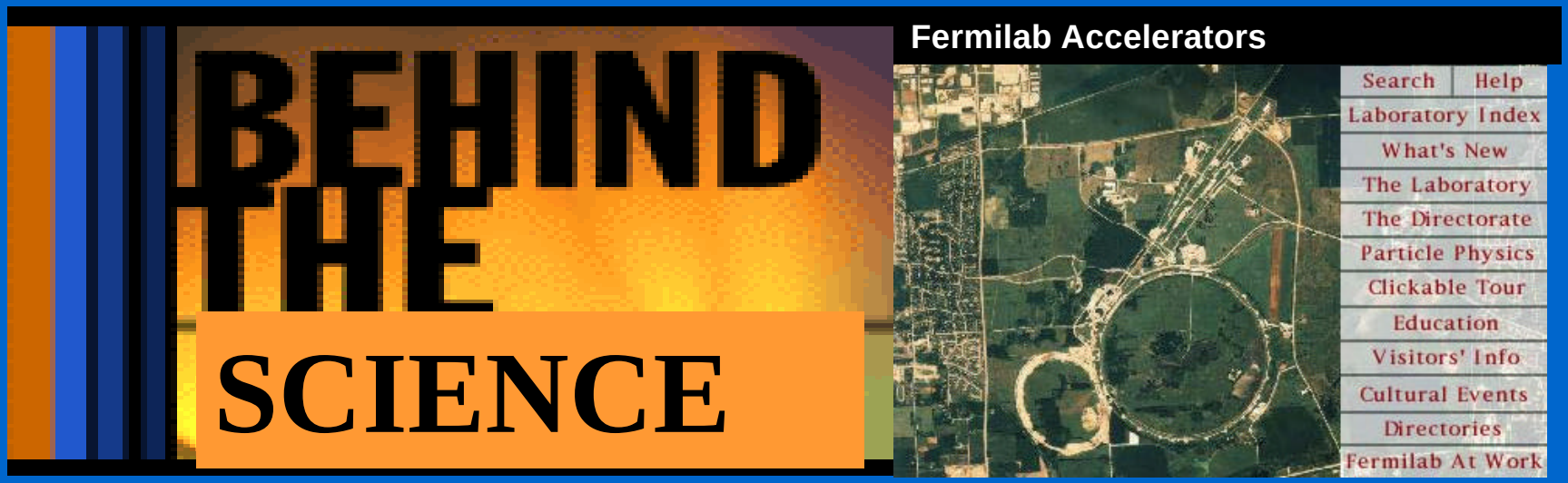
# Behind the ...

www.VH1.com

SHOW AIRS: SUN 1/27 at 11pm ET

# Behind the ...

www.fnal.gov (not likely on www.VH1.com)




SHOW AIRS: SAT 4/6 at 9am CT

Your Host: David Finley

finley@fnal.gov

# Behind the ...

www.fnal.gov (not likely on www.VH1.com)

**Fermilab Accelerators**

SHOW AIRS: SAT 4/6 at 9am CT

Your Host: David Finley

finley@fnal.gov

# A little about me …
# Behind the Scientist

- High School
  - St. Lawrence Seminary
  - Mt. Calvary, Wisconsin
- College: Purdue
  - Physics: BS, MS, PhD
- US Army Officer
  - 72-74 Washington DC
  - Harry Diamond Labs
- Research Associate (PhD)
  - High Energy Physics
  - SUNY Stony Brook NY
- Fermilab (4/1/81 to now)
  - Switchyard Beam Lines
  - Tevatron … Collider
  - Beams Division
  - Future Accelerator R&D
  - 1/20/01 First SMP Lecture

# A little about you …
# Linda Spentzouris' Survey

- Y N: Been to Fermilab (before SMP)?
- Y N: Have studied physics?
- Y N: Have studied chemistry?
- Y N: Have studied biology?
- Y N: Planning a career in physics?
- Last two weeks (or ever)
  - Y N: Hear about particles?
  - Y N: Relativity?
  - Y N: Different Forces?
  - Y N: Know about accelerators?
- Y N: Use the web?
- Y N: Have email?

# Accelerators

- Accelerators (Particle Accelerators)
  - today: particle beams for particle physics research
    - mostly use electrons and protons
    - and antiprotons and positrons, and mesons and neutrinos ...
  - not today: materials, medical, military (aka 3M), etc
- Why do this?
- A “few words about” Acceleration

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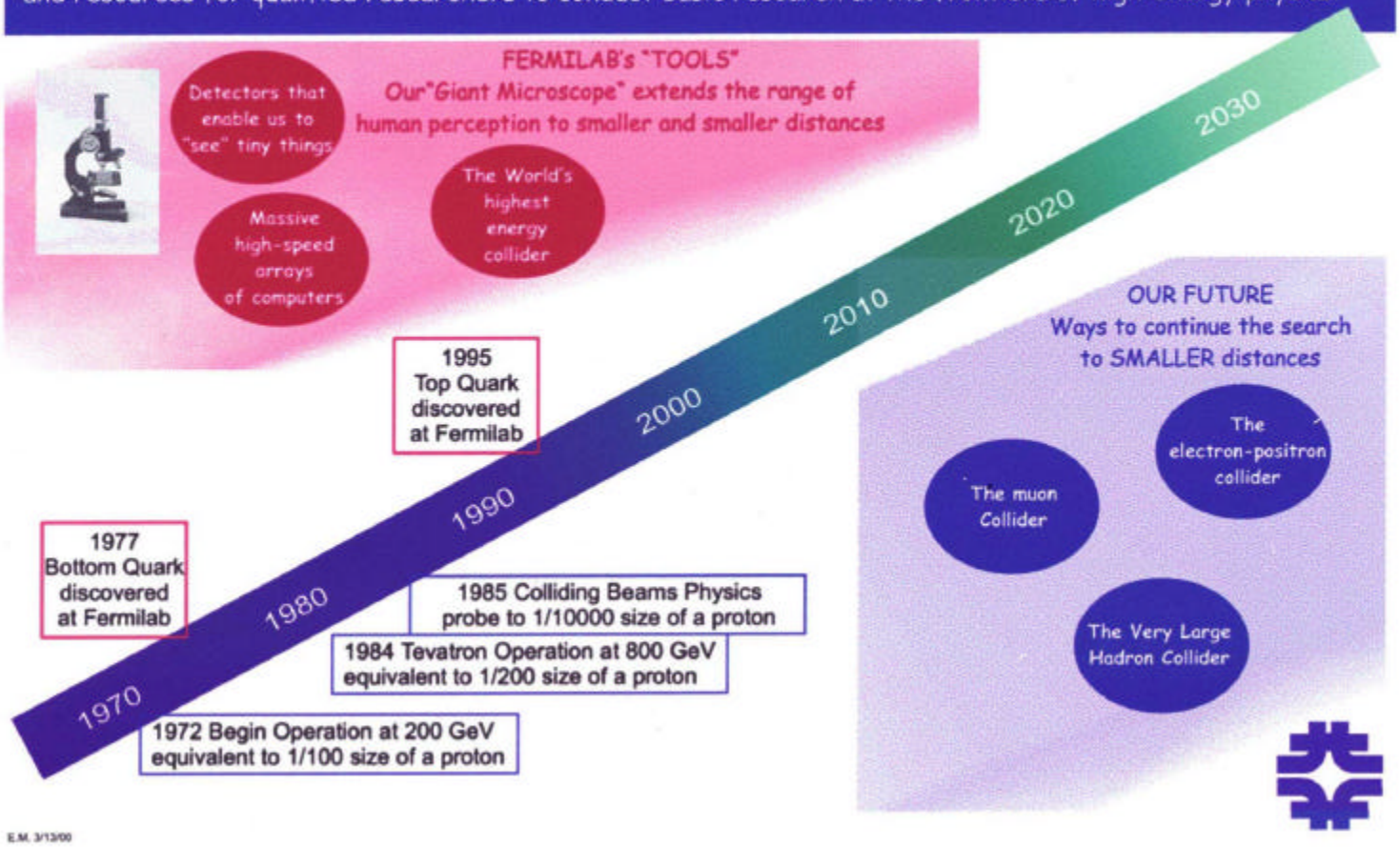
# Science at Fermilab

Fermilab advances the understanding of the fundamental nature of matter and energy by providing leadership and resources for qualified researchers to conduct basic research at the frontiers of high-energy physics




Courtesy E. Malamud malamud@fnal.gov

# References (based on Linda Spentzouris's List)

- David Griffiths

Introduction to Elementary Particles"
ISBN 0-471-60386-4

- Ernie Malamud

www-bd.fnal.gov/public/index.html
malamud@fnal.gov

- David Finley

finley@fnal.gov

- Particle Accelerator

Encyclopedia of Science and Technology
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- Feynman, Leighton, Sands

"The Feynman Lectures on Physics"
ISBN 0-201-02116-1

- Lawrence Berkeley National Lab

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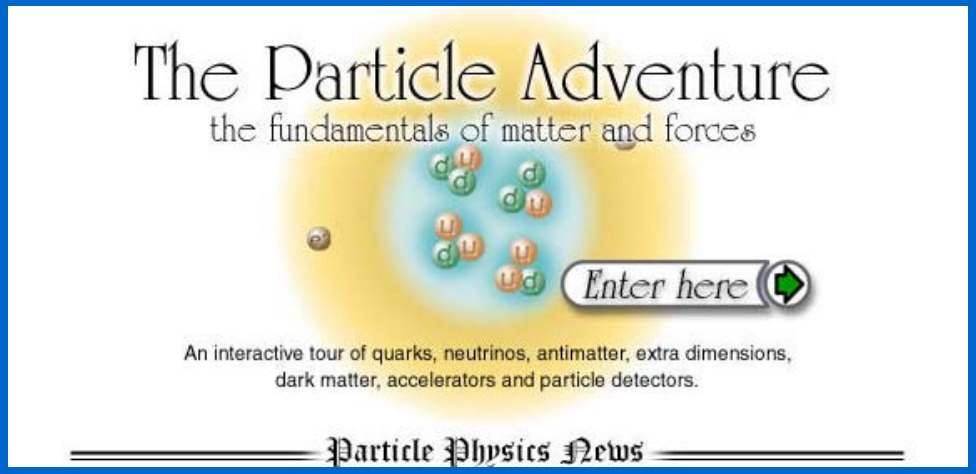

# Accelerators - What are they good for?

- Why do this? This = “particle physics”
  - Q1: What’s it all made of?
  - Q2: How does it all behave?
  - Q3: How do particles come by their mass?
  - Q4: How is it that we see more matter than antimatter?
  - And … Q4++
    - So, how is it all distributed anyway?
    - Etc etc

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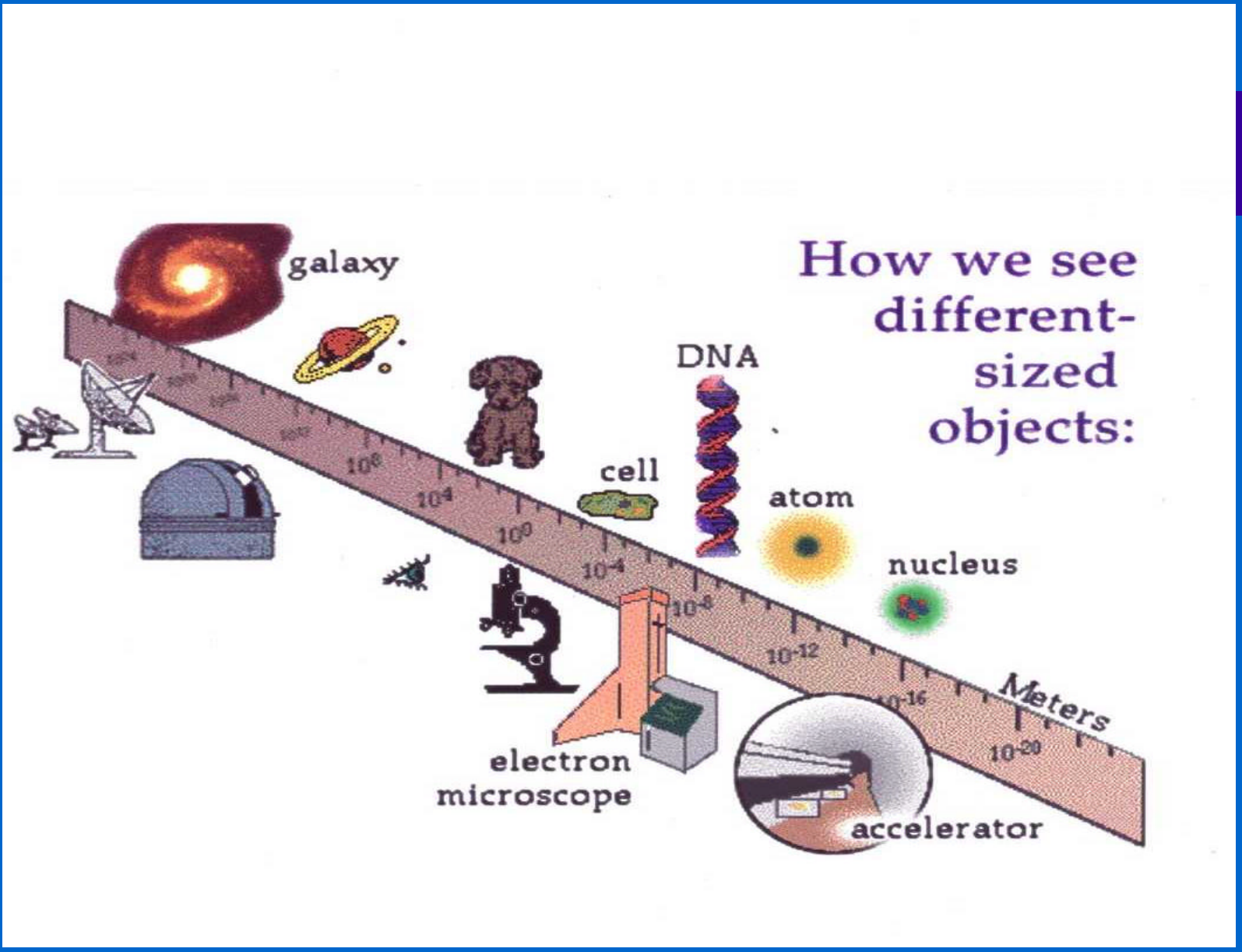


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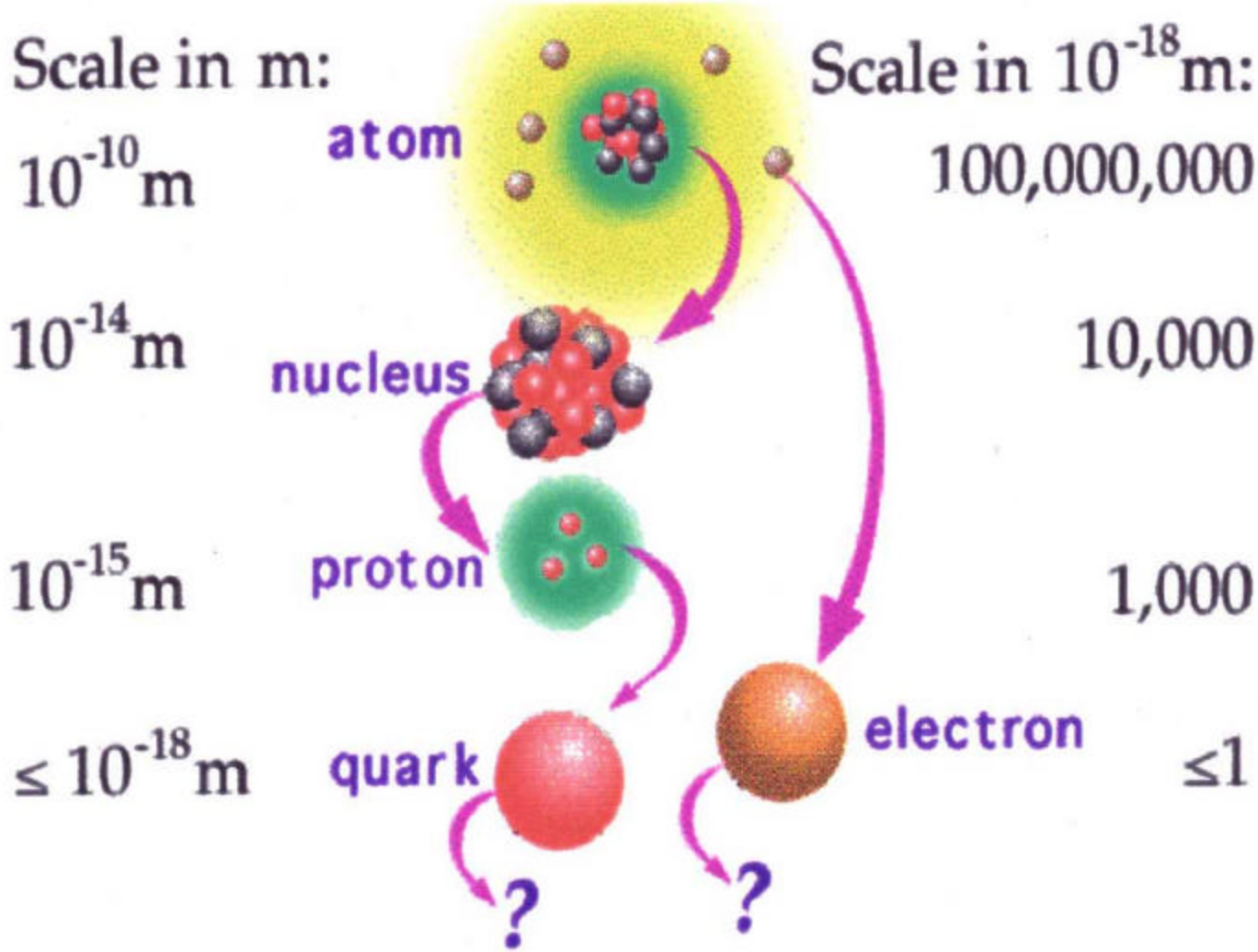
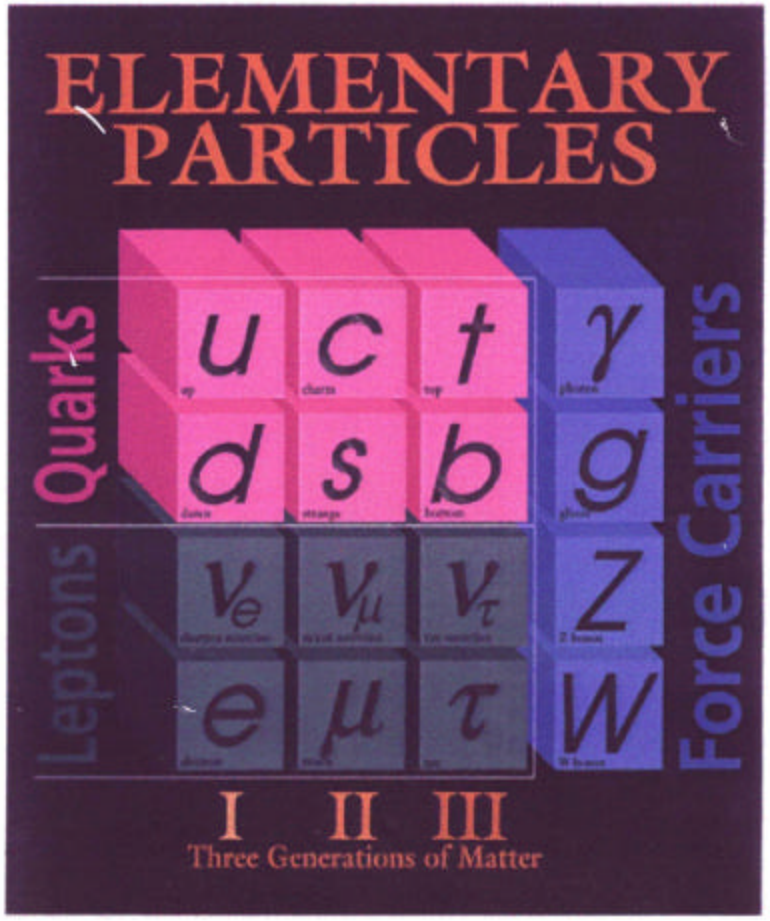
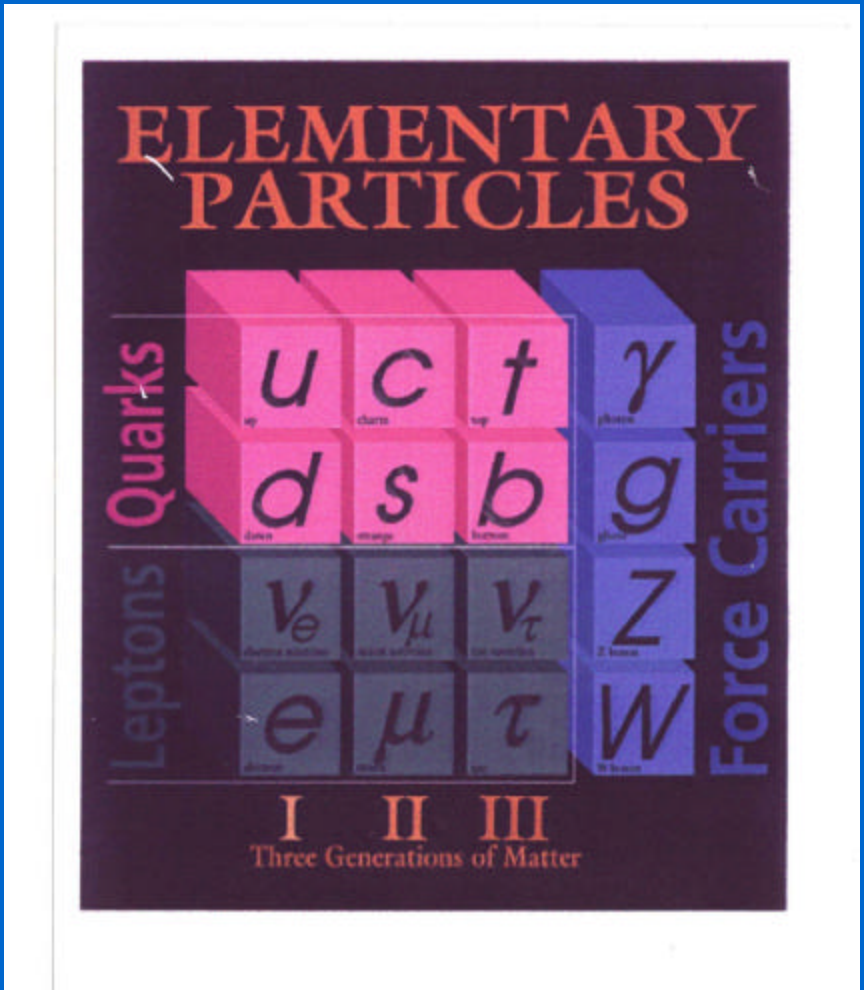



Courtesy E. Malamud malamud@fnal.gov

# The Standard Model



# Fermilab's Role (so far)




Fermilab has aided in the discovery of the:

- bottom quark (1977)
- top quark (1995)
- tau neutrino (2000)

Courtesy L. Spentzouris klamp@fnal.gov

# Accelerators

- Accelerators (Particle Accelerators)
  - today: particle beams for particle physics research
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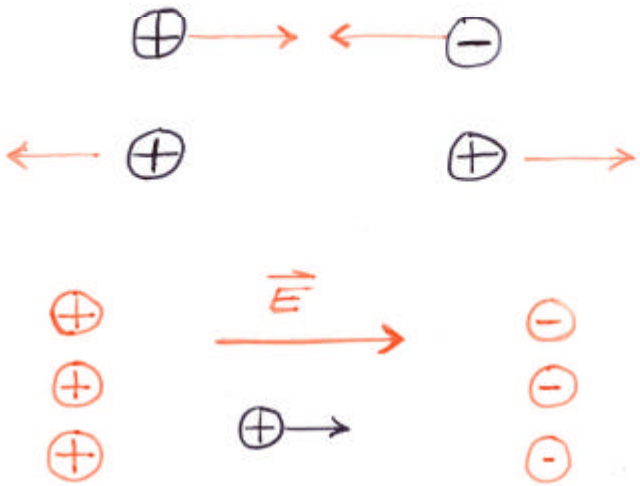
    - and antiprotons and positrons, and mesons and neutrinos ...
  - not today: materials, medical, military (aka 3M), etc
- Why do this?
- Accelerator Basics <<< We Are Here

# Accelerator Basics

- A Little from Maxwell, Newton, Lorentz
  - $\mathbf{F} = e\,\mathbf{E}$ and $\mathbf{F} = q\,(\mathbf{v}/c) \times \mathbf{B}$
  - $\mathbf{F} = d\mathbf{p}/dt$ and $\mathbf{p} = m\,\mathbf{v}$
- A Little Relativity from Einstein
  - $m = m_0 / \mathrm{sqrt}\,(1 - \beta^2)$ with $\beta = v/c$
  - $E = m_0 +$ Kinetic Energy and $E = m\,c^2$
- A Little from Murphy (as in Murphy's Law)

# Electric Force




Force : $\vec{F}$ = (charge) $\vec{E}$ = $e\vec{E}$

Potential : Volts = $-E \times$ (length moved)

Energy : E = (charge)(volt)

1 eV → Energy gained by e when pulled through 1 Volt

Courtesy L. Spentzouris

klamp@fnal.gov

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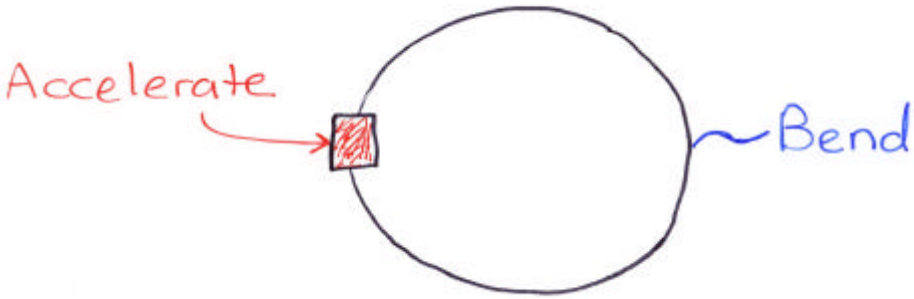
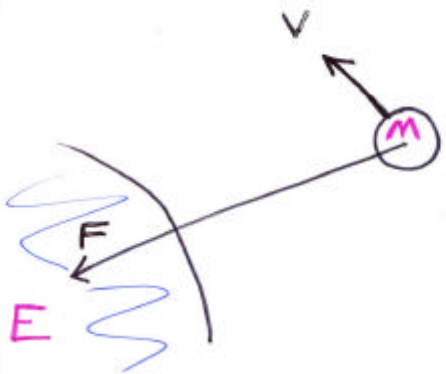
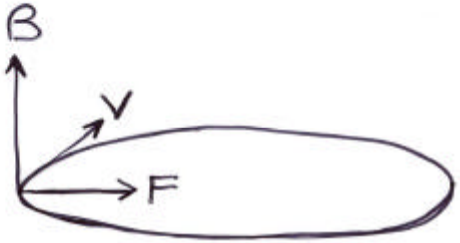
# Magnetic Force




$$F = e(v \times B)$$

Courtesy L. Spentzouris

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# Saturday Morning Physics - Accelerators

- Accelerators
- What’s Up Now? <<< We Are Here.
- What’s Up Next?

# Accelerators - What's Up Now?

- What's Up Now?
  - Concentrate on Fermilab
  - Other Places
  - Equipment Pictures

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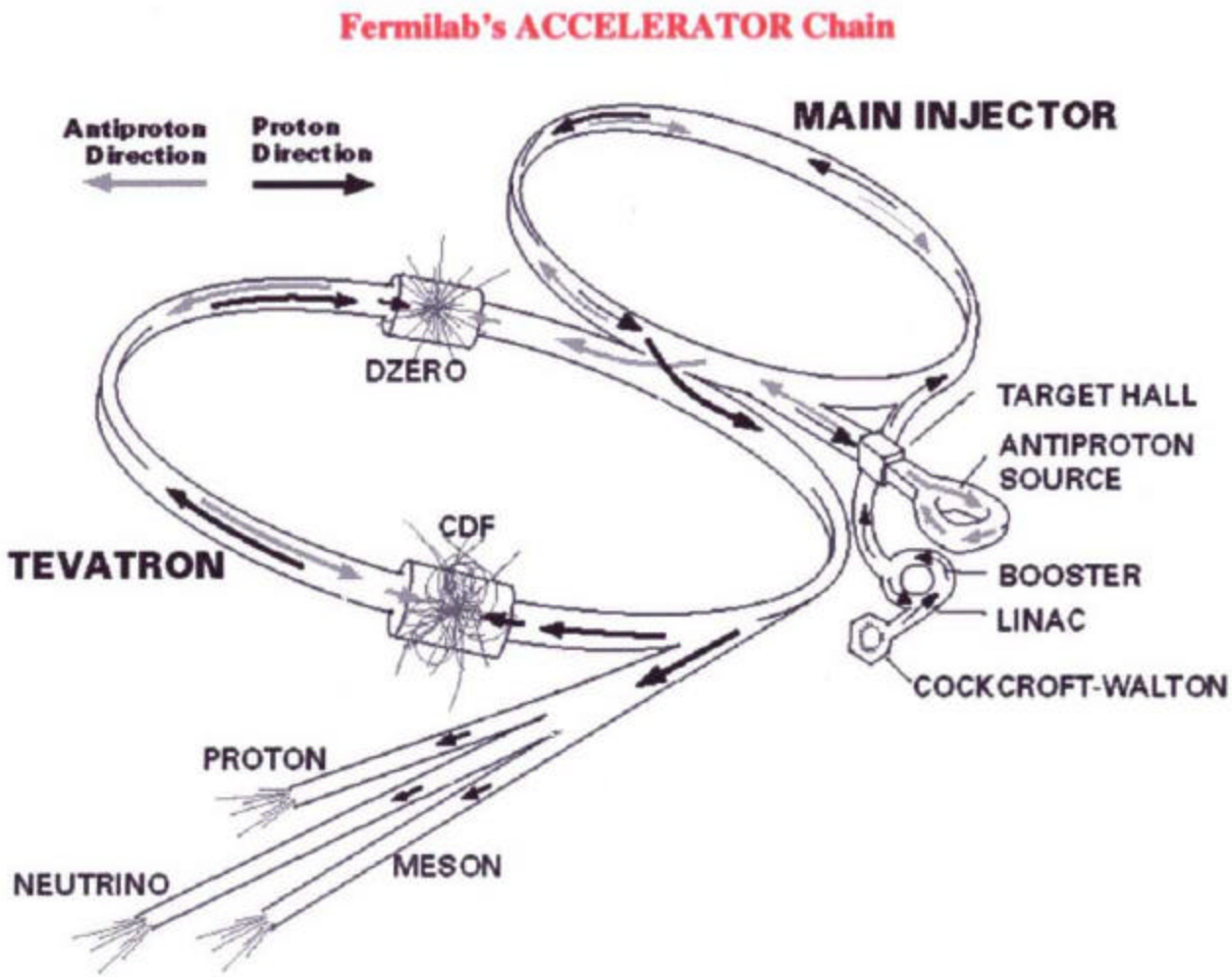


Courtesy E. Malamud malamud@fnal.gov

# HiRise and Tevatron

- Insert 93-683-9 “HiRise and Tevatron” and pretend you are on the 15th floor giving a tour and read the following few slides

# Overheard on the 15th Floor - 1

- So, if you look over there, you see a big orange building. That's where CDF is located. Collider Detector at Fermilab.
- And on a really clear day you can see the Sears Tower in Chicago over there.
- And directly opposite us over there is a blue building where the D-Zero detector is located.
- The Tevatron accelerator is located about 20 feet under the berm you see.
- We send the proton beam around the 6 kilometers of the Tevatron. It's inside a 7 cm diameter beam pipe with all the air removed. Otherwise the air molecules would eat up all the protons.
- The beam pipe goes though about 1000 superconducting magnets. The magnets have two jobs. Some of them keep the protons focussed so they don't wander off the central path. And the others bend the central path around in a circle so the beam keeps passing through the accelerating stations.

# Overheard on the 15th Floor - 2

- Over there to the right is where the accelerating stations are located. They provide electric fields which are carefully timed to push the protons along to a higher energy. We use the same technology that radar is based on. For the rf in the Tevatron, the electric field flips its sign about 53 million times a second. So you have to be pretty careful with the timing.
- The beam goes around the 6 kilometers about 50,000 times a second. (47,713 if you are picky about numbers.) Every second!
- With an energy of about one trillion volts, or 1 TeV.
- That's the highest energy particle beam in the world. And will be until about 2006 when CERN starts up the LHC with its 7 TeV proton beams.
- In the Tevatron, a bunch of protons is about 40 microns in diameter at CDF or D-Zero. That's about the diameter of your hair.
- And a meter or so long. Like really long, really thin needles.

# Overheard on the 15th Floor - 3

- There are about 100 billion protons in a bunch.
- And we collide it with an antiproton bunch going the opposite direction. About 50,000 times a second.
- An antiproton bunch looks pretty much the same as the proton bunch, but there are fewer antiprotons.
- So we collide these things that are about the size of your hair, and they are going at about the speed of light. You'll have to trust me.
- Antiprotons are antimatter. But, unlike Star Trek, we don't just talk about it, we actually make antimatter and use it. For particle physics research.
- When the bunches pass though one another, a few of the protons and antiprotons interact with one another. These matter / antimatter interactions convert some of the energy to mass.
- Remember $E=mc^2$? That's what really happens. Right over there and there.

# Overheard on the 15th Floor - 4

- And sometimes, not very often, an interaction converts the energy to mass in the form of a top quark. And an anti-top quark. Made right here at Fermilab in the Tevatron. And detected right over there in those orange and blue buildings.
- But we really use 36 bunches distributed around the Tevatron. But as we increase the performance of the Tevatron, we will have to start using about 100 bunches in each beam.
- That way we can have more collisions per second, but not many more interactions per bunch crossing. Too many interactions per crossing makes it hard on CDF and D-Zero.
- And it really works.
- And when you get this complex running, you run it 24/7. And pretty much 365. For several years.
- I've been here for about 27 years, and it still amazes me.

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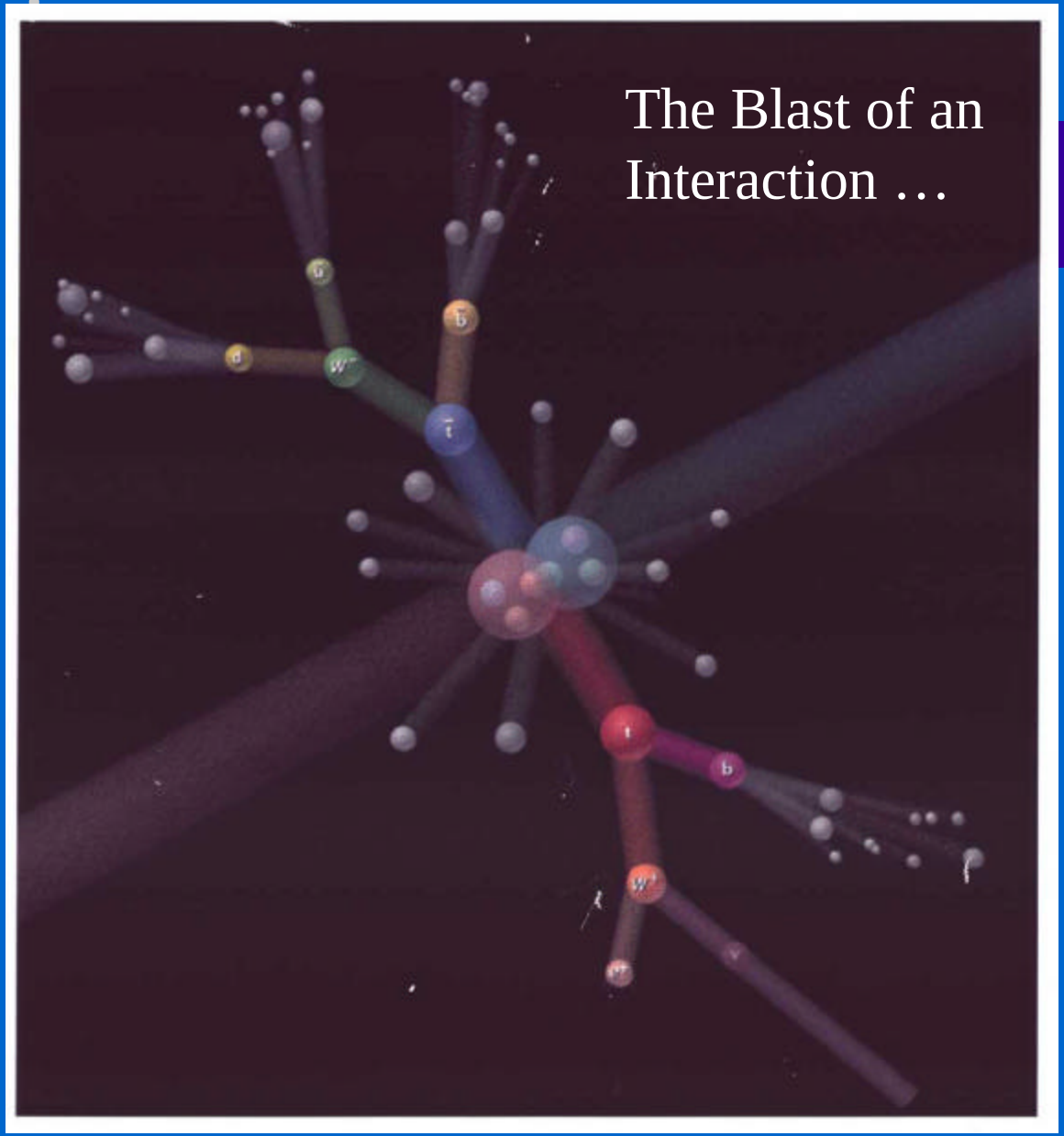
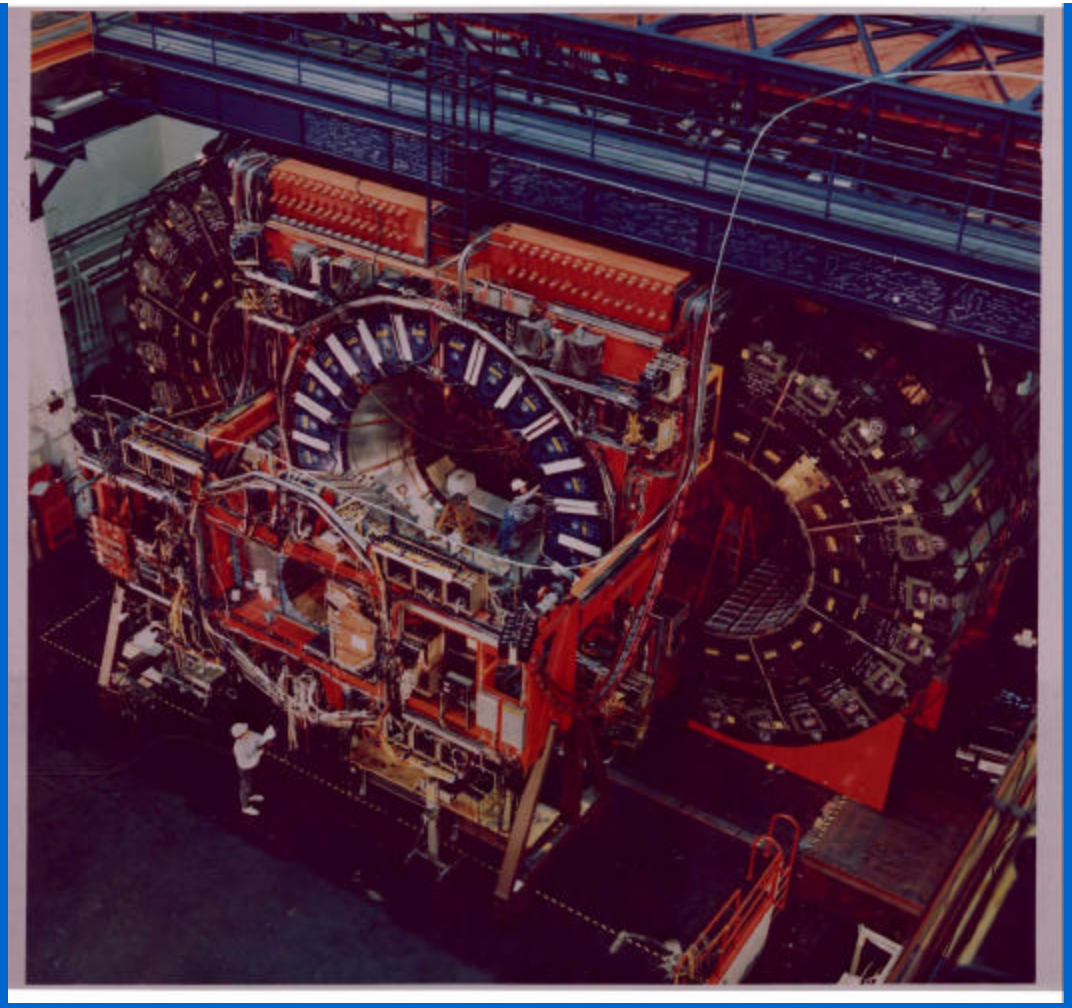



Courtesy E. Malamud malamud@fnal.gov

- Protons and antiprotons (really quarks, antiquarks, gluons, sea) come in with kinetic energy …
- $E = mc^2$ … and …
- Lots and lots of new particles come out …
- And the standard model rules! (So far.)

# CDF (Collider Detector at Fermilab)



# Low Energy Links in Accelerator Chain

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| Machine | Cycle Time | Final Energy | $\beta$ |
|---|---|---|---|
| Pre-accel. | 20 μs | 750 keV | .04 |
| Linac | Pulse ~200 μs<br>Beam 20 μs | 400 MeV | .71306 |
| Booster | 66 ms | 8 GeV | .99448 |
| Main Ring | $\bar{p}$ production 2-3 sec | 120 GeV | .9999699 |
| | TeV injection 5 sec | 150 GeV | .9999807 |
| Tevatron | Fixed Target 60 sec | 800 GeV | .999999313 |
| | Collider 200 sec.... | 900 GeV (980) | .999999457 |

Courtesy L. Spentzouris

klamp@fnal.gov

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## How fast are the protons traveling?
## How relativistic are they?

| ACCELERATOR | Kinetic Energy at "business end" | $\beta=v/c$ | $1-\beta$ | $\gamma=1/(1-\beta^2)^{1/2}$ |
|---|---|---|---|---|
| Hydrogen Atoms in the "Bottle" | ~ 0.04 eV (room Temperature) | $9.1 \times 10^{-8}$ (6100 miles/hour) | | |
| $H^-$ ion source | 25 KeV | 0.0073 (1,358 miles/second) | | 1.0000266 |
| Cockroft-Walton | 750 KeV | 0.04 | | 1.0008 |
| Linac section of original - 1971 | 116 MeV | 0.456 | | 1.1236 |
| Linac new 805 MHz, 1993 | 400 MeV | 0.713 | | 1.426 |
| Booster, Debuncher, Accumulator, Recycler | 8 GeV | 0.9945 | | 9.53 |
| Main Injector | 150 GeV | | $1.93 \times 10^{-5}$ | 160.9 |
| Tevatron | 1000 GeV = 1 TeV | | $4.39 \times 10^{-7}$ | 1067 |
| *Electrons at CERN* | *100 GeV* | | *$1.30 \times 10^{-11}$* | *195,695* |
| VLHC Injector | 3 TeV | | $4.89 \times 10^{-8}$ | 3197 |
| VLHC | 50 TeV | | $1.76 \times 10^{-10}$ | 53,290 |



Courtesy E. Malamud malamud@fnal.gov

# Accelerators - What's Up Now?

- What's Up Now?
  - Concentrate on Fermilab
  - Other Places <<< We Are Here
  - What does some of the equipment look like?

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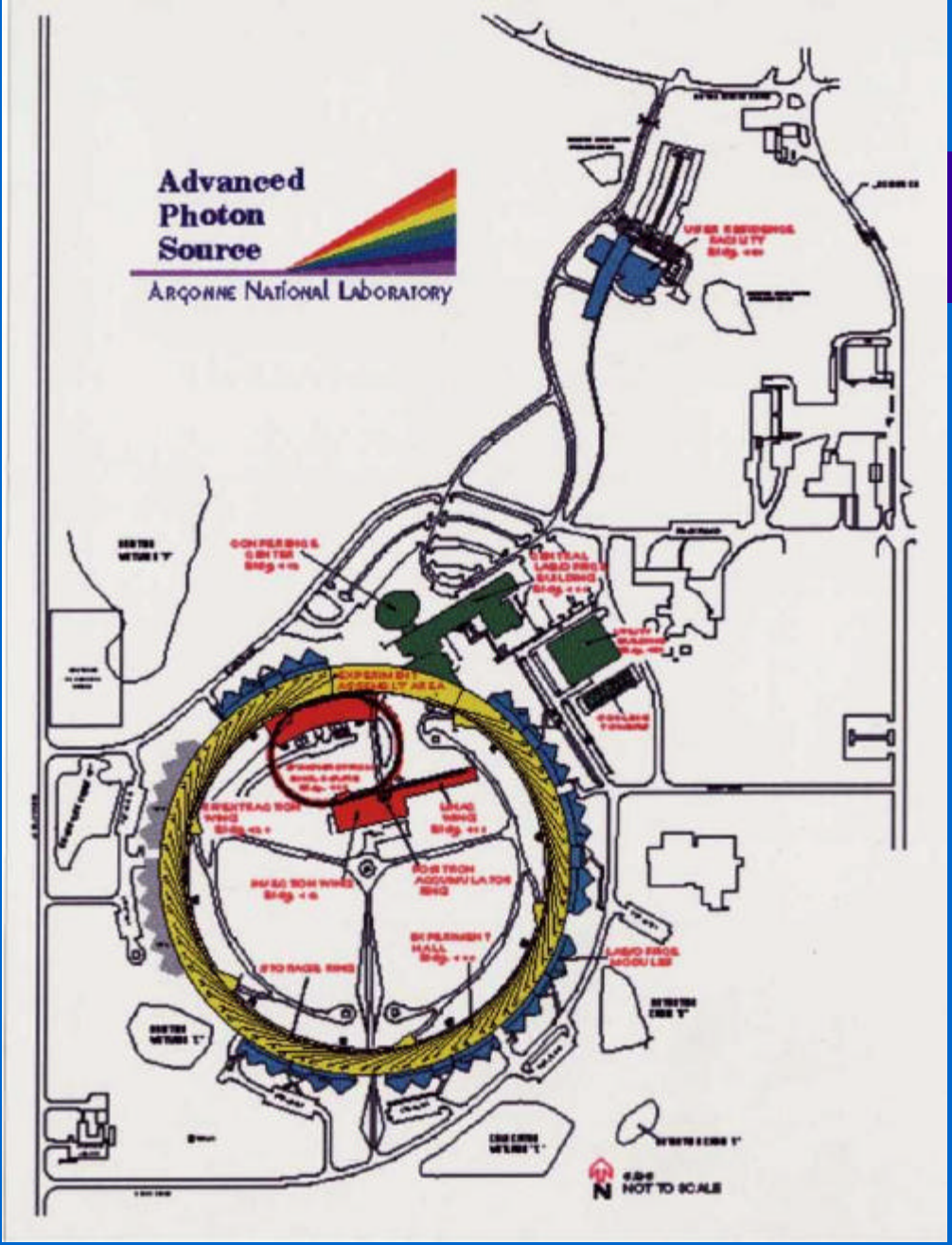


- The Advanced Photon Source (APS) at Argonne

Right down the road from here..

Electrons and photons

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RHIC

Daily Status Report for June 13

Success!

Last night two experiments (STAR and PHOBOS) measured beam-beam collisions at gamma=30.

We will continue to work on steering at the IP's with colliding beams.

## June 13, 2000 PRESS RELEASE

**Relativistic Heavy Ion Collider (RHIC) Begins Smashing Atoms**

***Experiments will yield insights into the structure of matter and how the universe evolved***

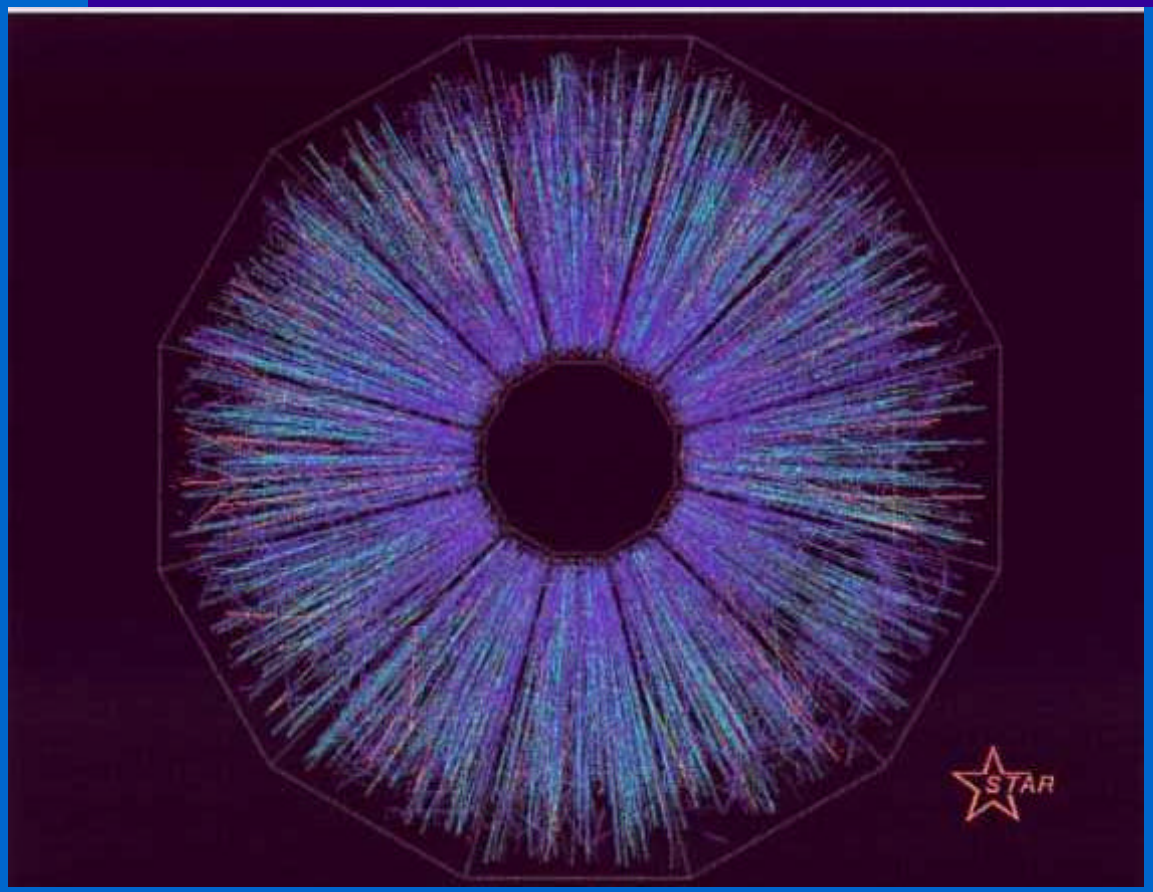
**UPTON, NY - Scientists at the U.S. Department of Energy's Brookhaven National Laboratory have begun detecting head-on collisions between gold nuclei in the Relativistic Heavy Ion Collider (RHIC), the world's newest and biggest particle accelerator for studies in nuclear physics. While the beams have been in collision mode since the weekend of June 10, the first spectacular images of particles streaming from a collision point -the definitive evidence the scientists were waiting for - were produced by the STAR detector last night at 9 p.m. High-energy collisions were also seen by the PHOBOS detector early this morning.**

*Last updated 6/13/00 by Public Affairs*

- RHIC is on Long Island in New York.

Ions … nuclei … GOLD no less!

# End view of STAR at RHIC



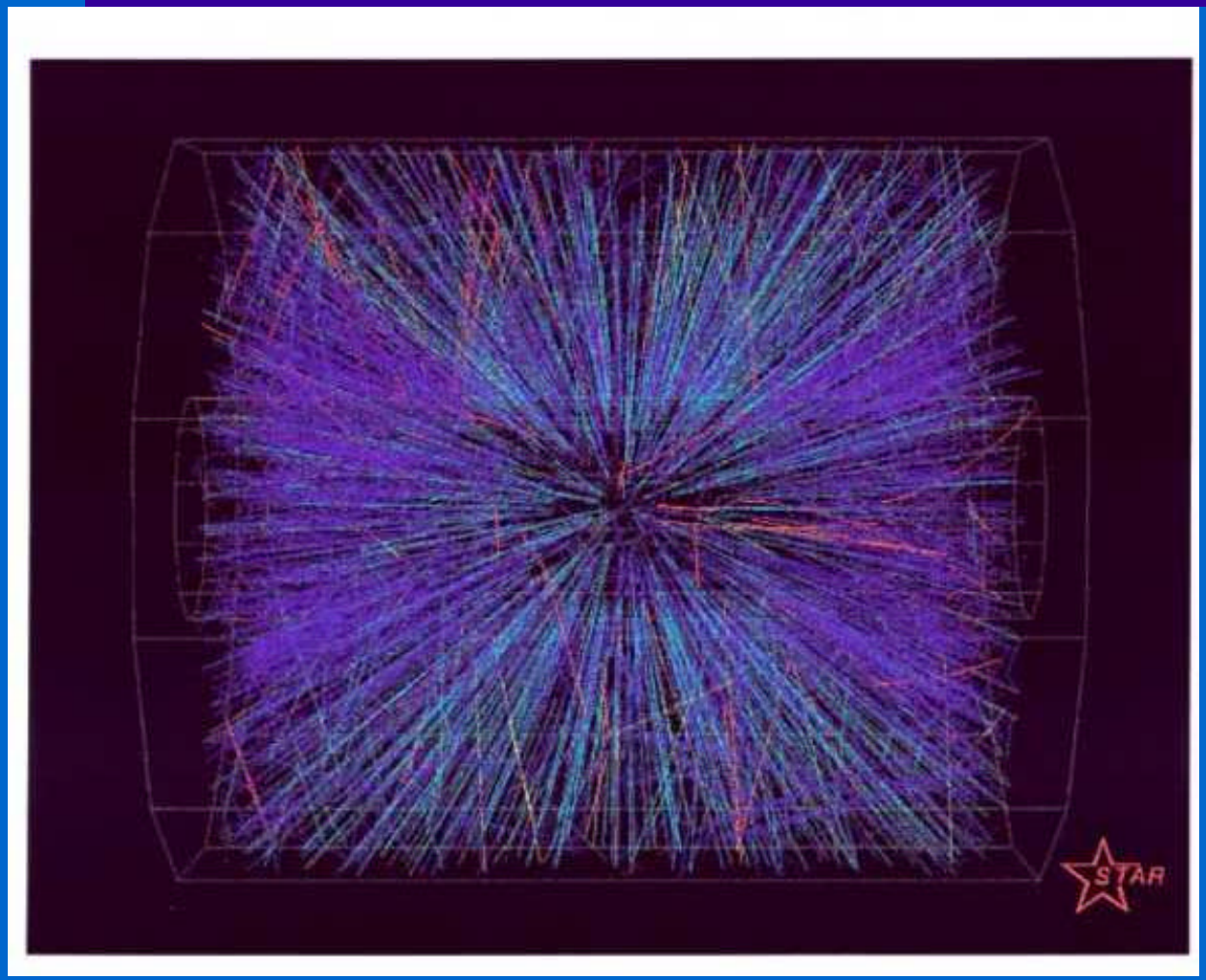

This is the view along the beam line

RHIC collides beams made of gold atoms

The fuzz represents the tracks of the particles created from the kinetic energy of the gold beams

$E = m c^2$ lives!

# Side View of STAR at RHIC




Same as previous slide but seen from the side

Try to figure out what's going on here!

Remember the detector talk?

# CERN

The CERN accelerator is 26 kilometers in circumference

Near Geneva on the Swiss / French Border

LEP (Large Electron Positron collider) turned off in 2000 with a “hint of a Higgs” … no discovery.

The LHC will collide a pair of 7 TeV proton beams starting in about 2006 or so

# DESY (Deutches Elektronen-Synchrotron)

The HERA accelerator is about 6.2 km in circumference

Partly under the town of Hamburg, Germany

HERA's superconducting magnets are very similar to those in the Tevatron

HERA collides electron beams with proton beams

# f SLAC (Stanford Linear Accelerator Center)

The SLAC linac is about 4 km long.

Goes under I-280 outside Palo Alto, California.

50 GeV electrons.

“linear collider” demonstration

B quark factory.

“Partons”, Charm quark, Tau lepton

# Accelerators - What's Up Now?

- What's Up Now?
  - Concentrate on Fermilab
  - Other Places
  - Equipment Pictures <<< We Are Here

# Main Injector Dipole Magnet

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- This is the lower half of a Main Injector Dipole.
- The racetrack-shaped copper coil wraps around the iron pole and inside the return yoke.

- This is the Tevatron tunnel (pre Main Injector) era)

# Three Magnets … Three Purposes

Quadrupole Dipole Sextupole

Dipole deflects all particles the same onto the closed orbit.

Quadrupole focuses particles towards the closed orbit in one plane … and defocuses in the other plane.

Sextupole is used to focus off-energy particles harder than on-energy particles.

# Now for a Break ...
# And Time To Ask Questions

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**Your Host: David Finley**
**finley@fnal.gov**

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