Why is there Mass in the Universe?

Bob Kehoe
Michigan State University
Feb 18, 2003

¬ Elemental Physics

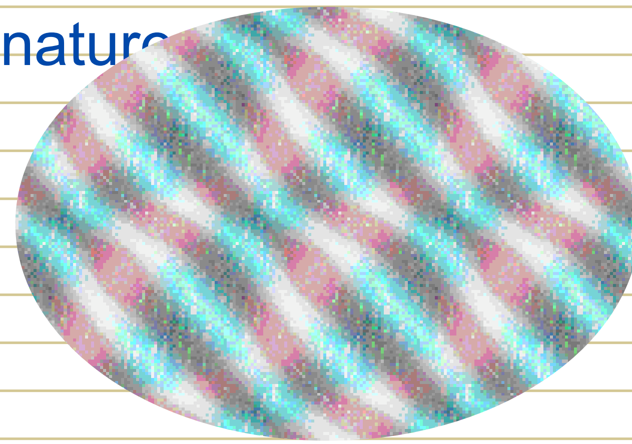
¬ Experimental Strategy

¬ Discovery

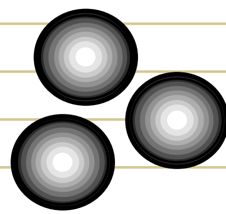
Elemental Physics

¬ human attention to nature's order

forces of nature



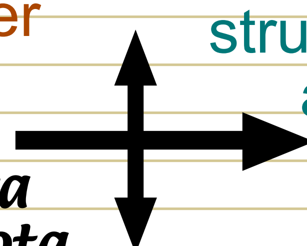
Greece (atomism)
India (vaisesika)
China



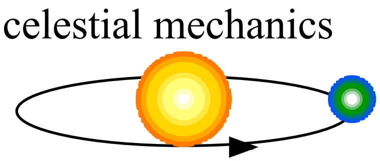
Zulu (amandala)
Yoruba

building blocks of matter

structure of time
and space

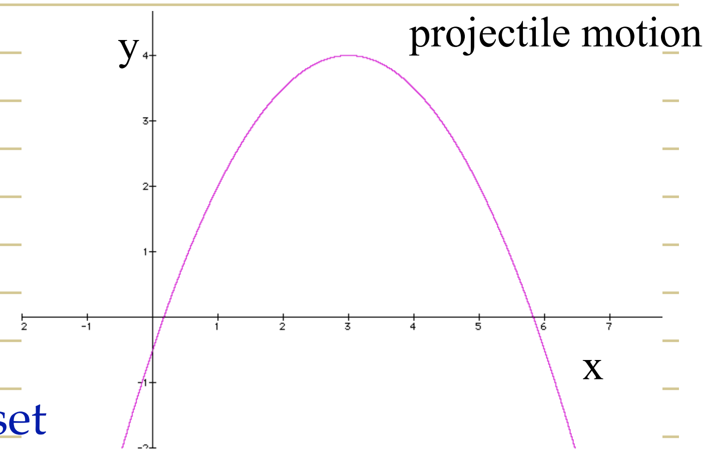


Maya
Lakota
Hopi



Classical Physics

- **arose out of work of Galileo, Newton**
  - motions of material objects
    - **F = ma**
  - atomistic view
    - fundamental particles
    - deterministic operation
    - the cosmos is a clockwork
    - once the hands of the clock are set
      - evolution of the system completely determined



- **unification of forces**
  - celestial and terrestrial mechanics → **gravity**
  - electricity and magnetism → **electromagnetism**
- **a prominent difficulty**
  - what is light? a particle ('photon') or a wave?

Breakdown

- **radioactivity**
  - atoms not at most fundamental level
  - first direct hint of nuclear forces
- **no ether for light to propagate thru**
  - speed of light constant regardless of frame of reference
    - special relativity: **$E=mc^2$**
- **photon energies 'quantized'**
  - leads to uncertainty principle: **$\Delta p \Delta x > h/2$, $\Delta E \Delta t > h/2$**
    - can't obtain position and momentum perfectly, simultaneously
      - multiple measurements give multiple values
      - NOT measurement error: **measurement alters system**
- **cosmic rays observed: new unusual particles**
- **birth of particle physics**

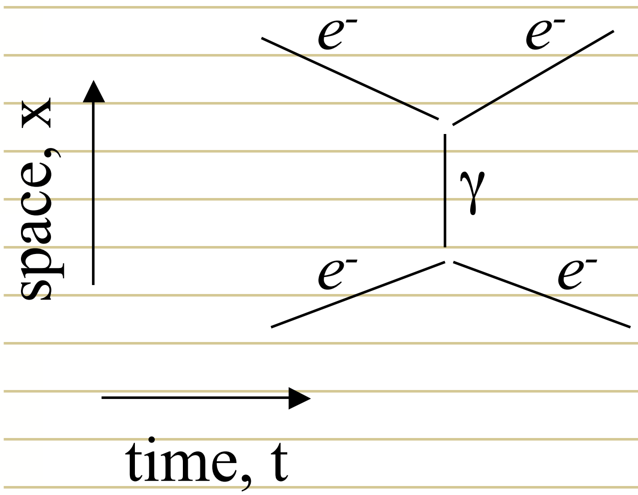
Four Fundamental Forces

- **nuclear forces discovered**
  - strong, responsible for holding atomic nucleus together
  - weak, responsible mainly for particle decay

force	coupling	range (cm)	strength
strong	color	10^{-18}	1
electromagnetic	charge	∞	0.01
weak	flavor	10^{-15}	10^{-5}
gravity	mass	∞	10^{-38}

Interactions as Momentum Exchange

- **conservation of momentum**
- **think of forces as interactions**
  - two particles interact by exchanging a messenger particle
    - eg. electronmagnetism uses the photon

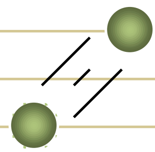


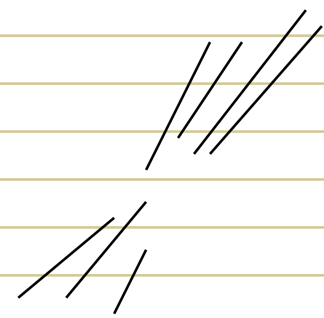
Think of two skaters
- one throws heavy ball to another
- thrower looses momentum
- receiver gains momentum

- exchanged particle
  - transfers momentum from one interacting particle to another

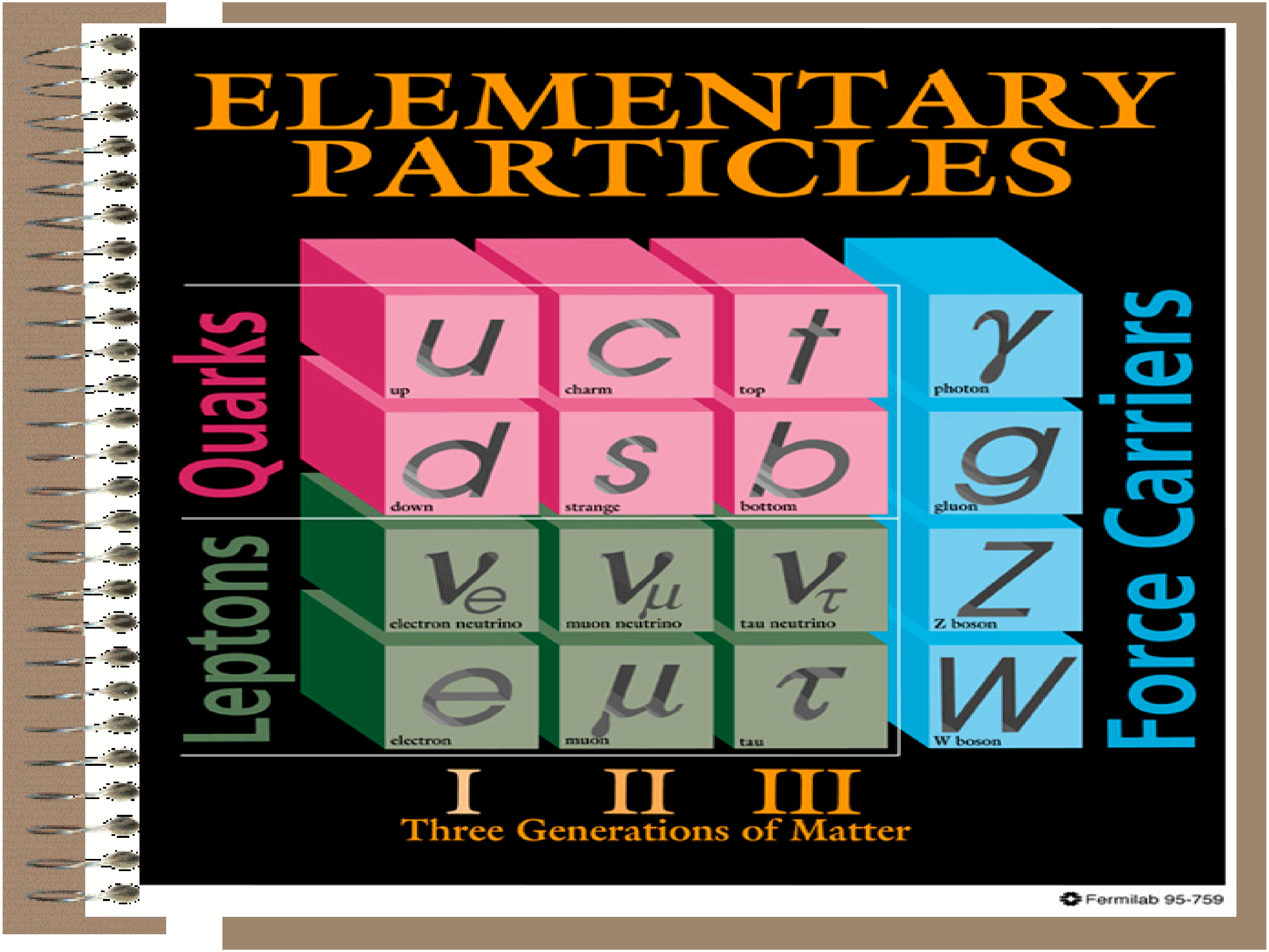
Example: Jet Production

- **strength of strong interaction**
  - increases with increasing distance
    - opposite to gravity and electromagnetism





- **when have to colored particles interacting**
  - nature does not permit 'naked' color
  - energy in strong interaction
    - grows as particles move apart
  - when energy greater than masses of fundamental particles
    - a 'jet' of particles 'pulled' out of the virtual sea or vacuum
    - extremely messy and poorly understood process


ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u
up
c
charm
t
top
γ
photon
d
down
s
strange
b
bottom
g
gluon
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Z
Z boson
e
electron
μ
muon
τ
tau
W
W boson
I
II
III
Three Generations of Matter
Fermilab 95-759

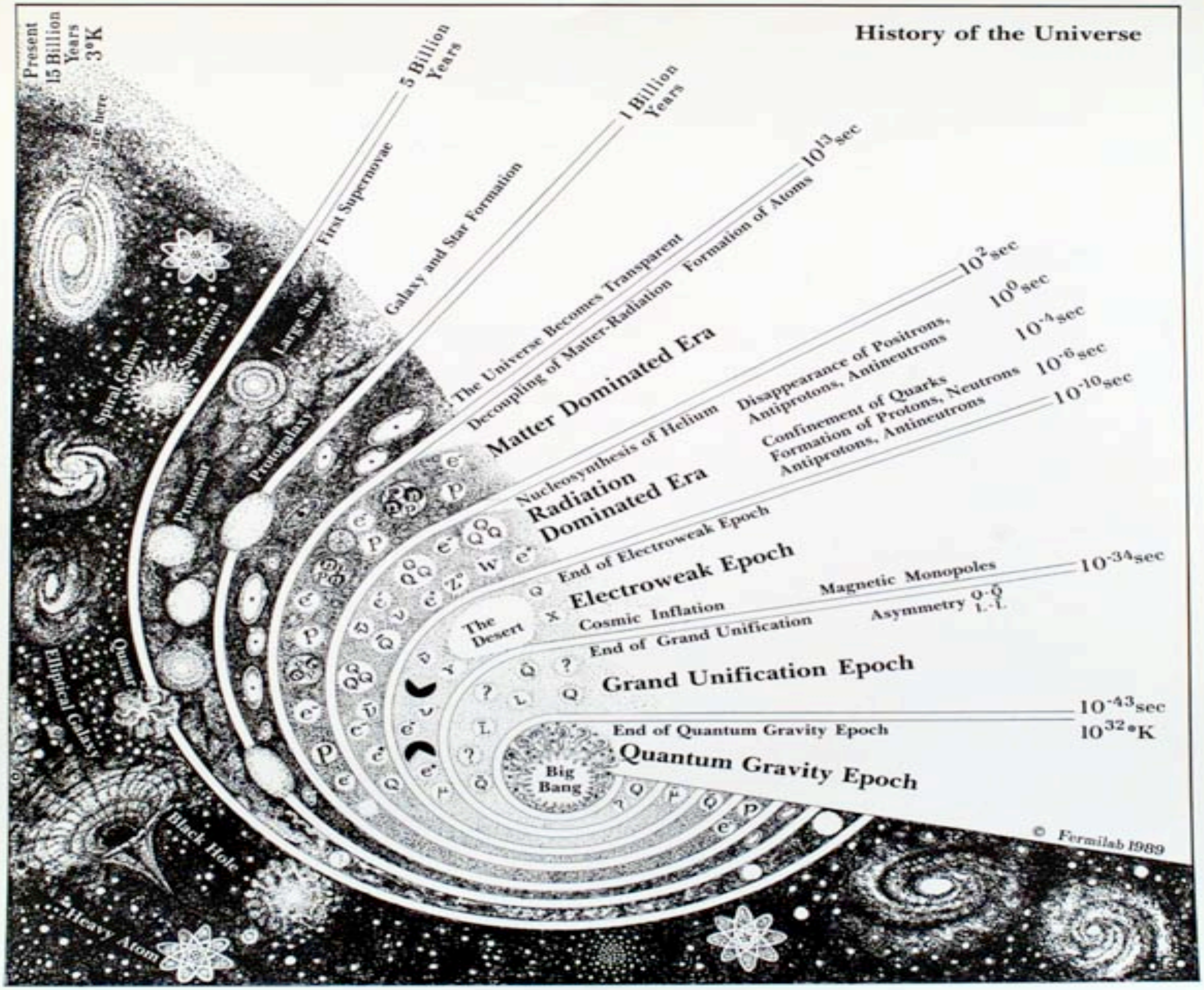
Electroweak Unification

- **electromagnetic and weak interactions**
  - different manifestations of same, more fundamental force
  - why so different in strength?
    - due to mass of exchange particle (W and Z)
      - restricts distance over which weak interactions can occur
    - only different in strength at low energies
      - at higher energies, W and Z massless
- **so how do the W and Z acquire mass?** ➡ **the Higgs**
  - analogy: iron atoms will align themselves at low temperatures
    - despite no direction preferred in interaction between atoms
    - therefore atoms acquire a certain energy
      - ie. must add heat to break the alignment
  - lowest energy state of universe
    - nonzero Higgs field
    - generates mass for W and Z

'Grand' Unification

- **is there evidence nature unifies more forces?**
  - yes
  - maybe we can understand:
    - electroweak+strong tried

  - different models give different predictions for what the Higgs is
  - inherent prediction
    - protons will decay (ie. all matter inherently unstable)
    - looked for in experiment in Cleveland salt mine
      - no decay in longer than predicted lifetime (10^{32} yrs)
      - all models not yet ruled out



History of the Universe
Present 15 Billion Years 3°K
5 Billion Years
1 Billion Years
10^{13} sec
10^{2} sec
10^{0} sec
10^{-4} sec
10^{-6} sec
10^{-10} sec
10^{-34} sec
10^{-43} sec
10^{32} °K
we are here
First Supernovae
Galaxy and Star Formation
The Universe Becomes Transparent
Decoupling of Matter-Radiation
Formation of Atoms
Matter Dominated Era
Disappearance of Positrons, Antiprotons, Antineutrons
Confinement of Quarks
Formation of Protons, Neutrons
Antiprotons, Antineutrons
Nucleosynthesis of Helium
Radiation Dominated Era
End of Electroweak Epoch
Electroweak Epoch
The Desert
Cosmic Inflation
Magnetic Monopoles
Asymmetry
End of Grand Unification
Grand Unification Epoch
End of Quantum Gravity Epoch
Quantum Gravity Epoch
Big Bang
Spiral Galaxy
Supernova
Large Star
Protogalaxy
Protostar
Quasar
Elliptical Galaxy
Black Hole
Heavy Atom
© Fermilab 1989

The Fermilab Tevatron

- **strategy**
  - higher energy allows
    - more energy to produce massive particles
      - like W, Z, top, Higgs
    - increases probability that colliding particles will interact
- **1 mile wide ring**
  - counterrotating beams of protons, and antiprotons
  - special superconducting magnets (quadrupoles)
    - bring beams to focus
    - two interaction regions -- ‘DZERO’ detector at one of them
  - highest energy particle accelerator in the world (since 1985)
  - 7.6 million collisions per second!
- **current run began in 2001**
  - goes until end of this decade

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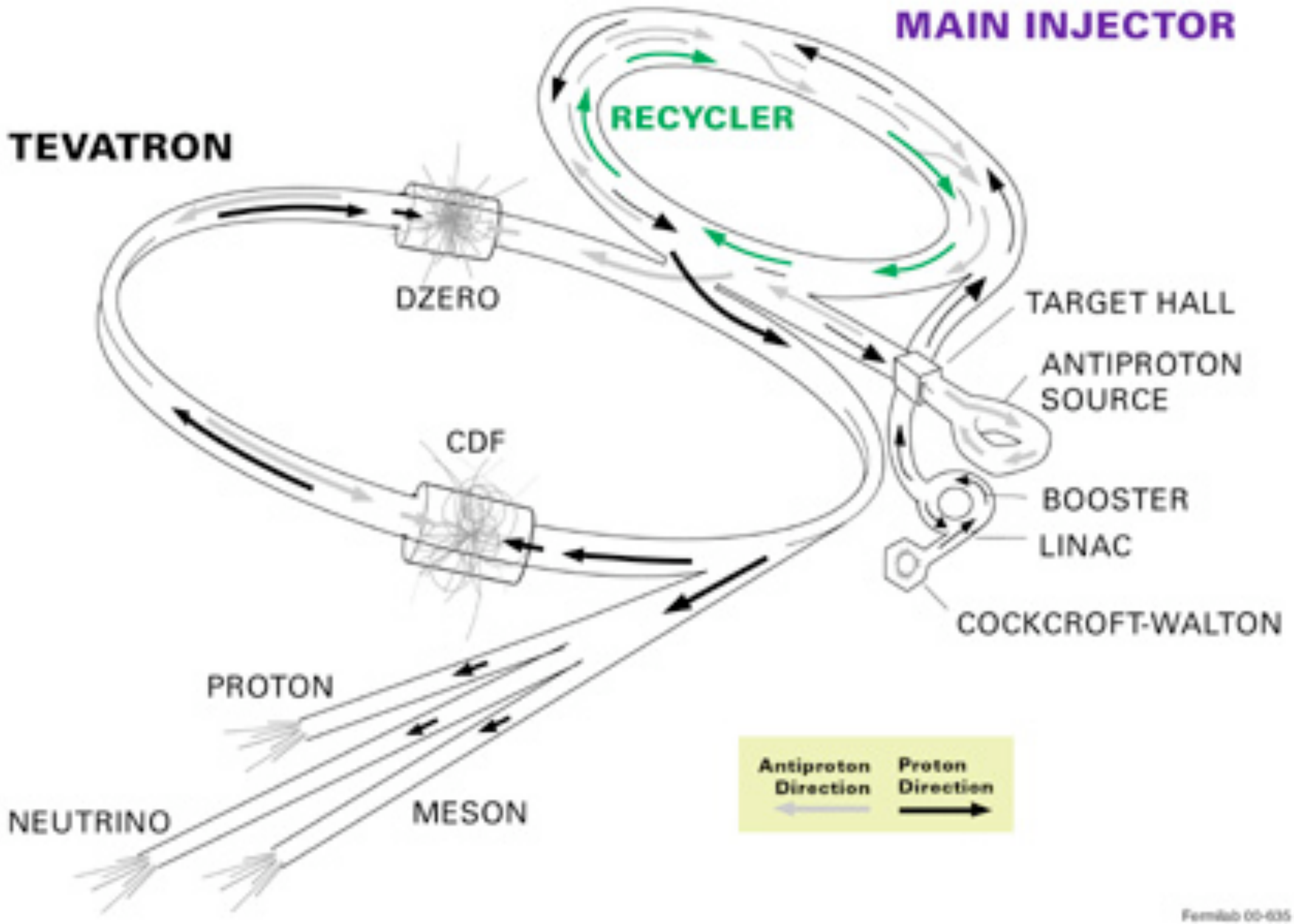
FERMILAB'S ACCELERATOR CHAIN



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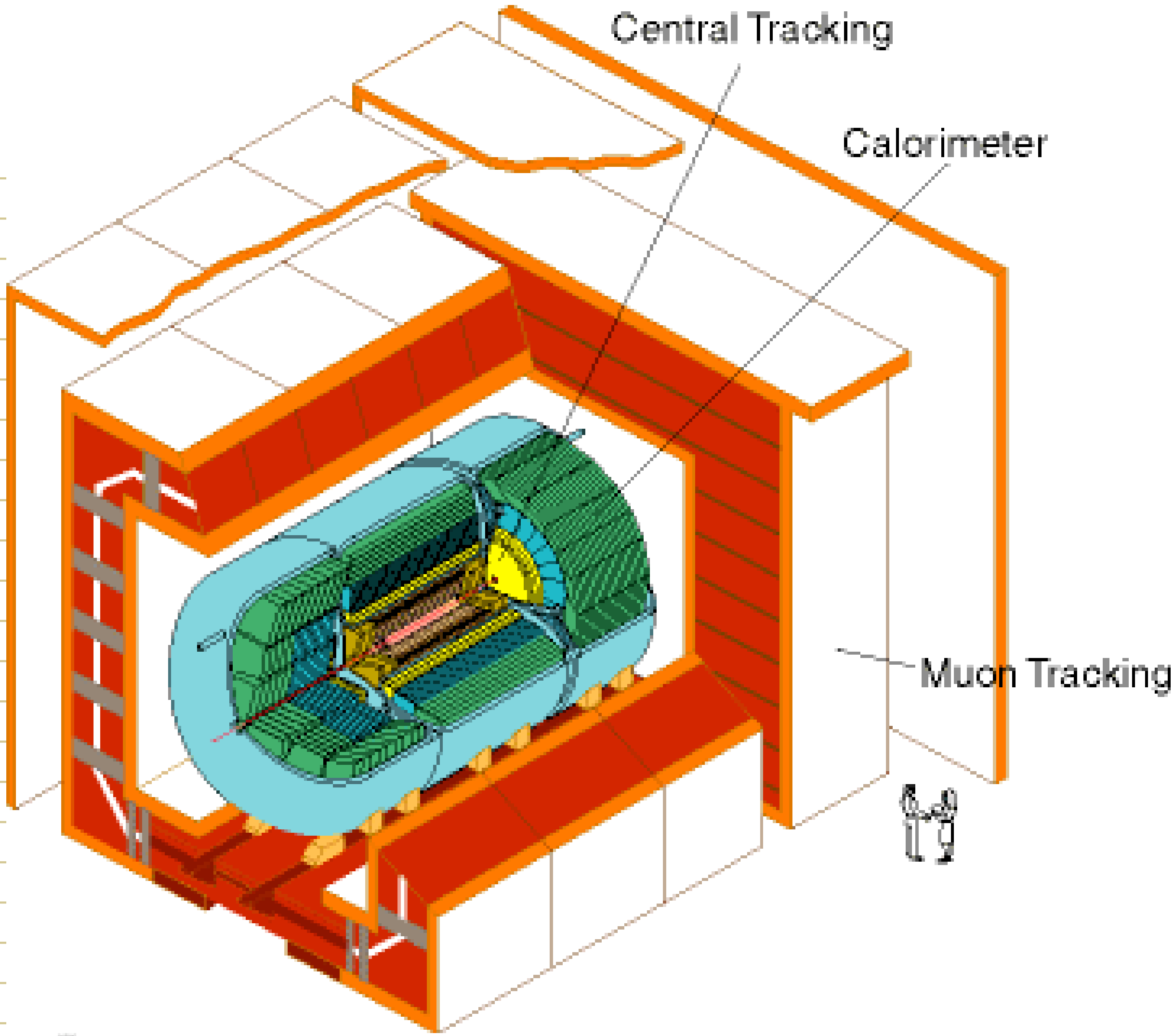
The DØ Detector

- **a collider detector**
  - approx. 1 million detector elements
    - centered on a point along beamline where collisions occur
  - approximately 4 stories tall, and half a football field long
- **3 main regions/components**
  - \`Tracking': closest to beampipe
    - observe 'tracks' left by charged particles from collisions
  - \`Calorimeter': next outward from beam
    - measure main energy depositions in event
  - outer region dedicated to identifying muons
    - muons can penetrate calorimeter
      - because don't interact strongly


Central Tracking
Calorimeter
Muon Tracking

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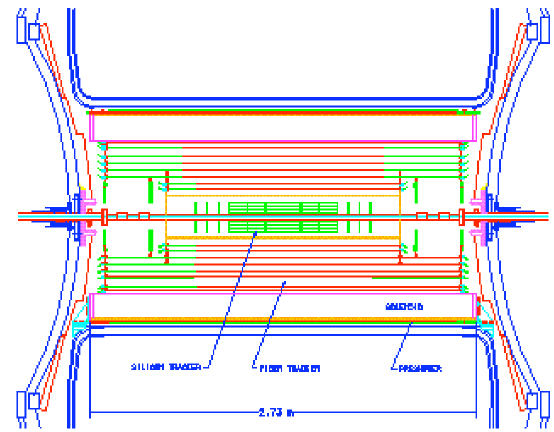
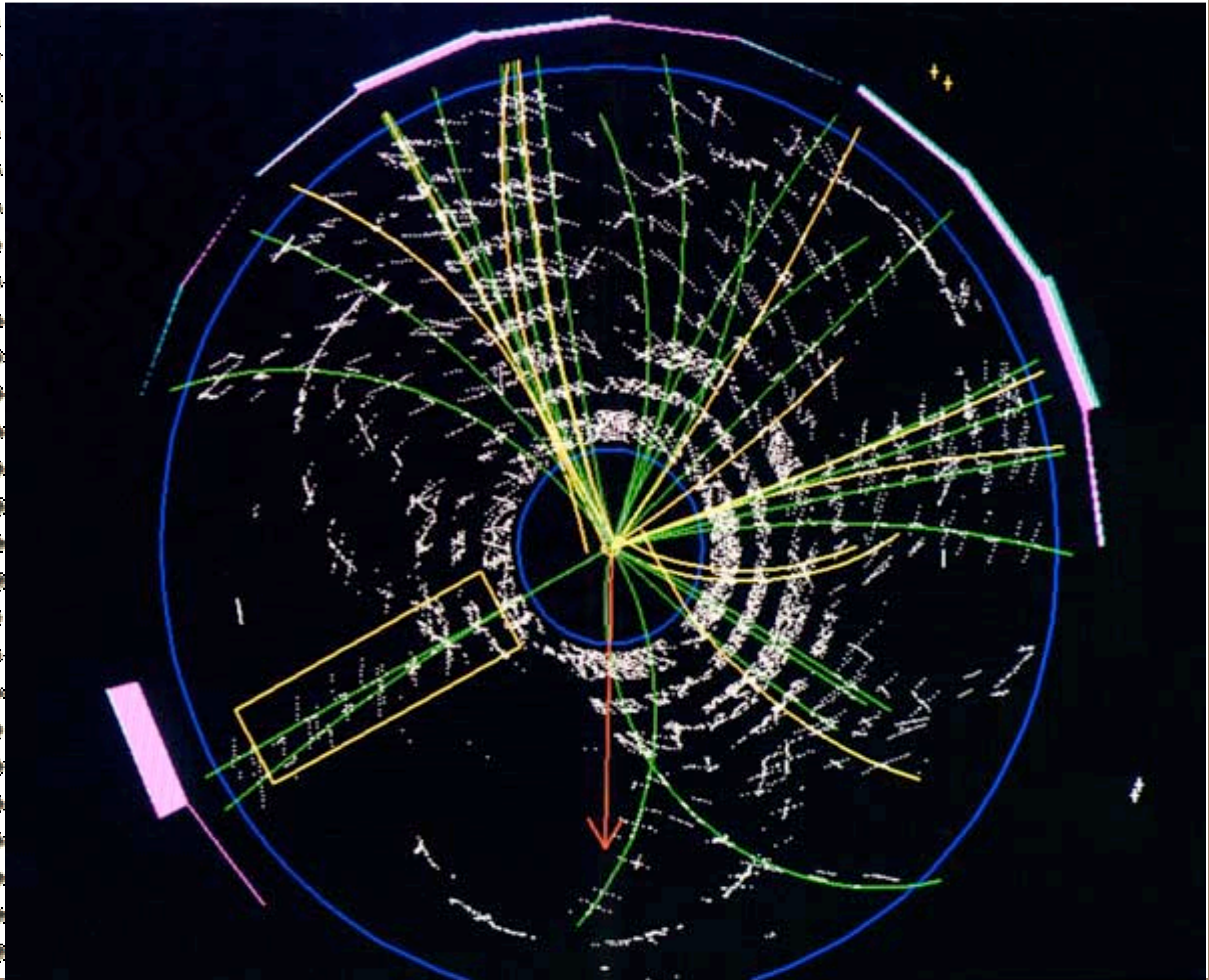
Tracking

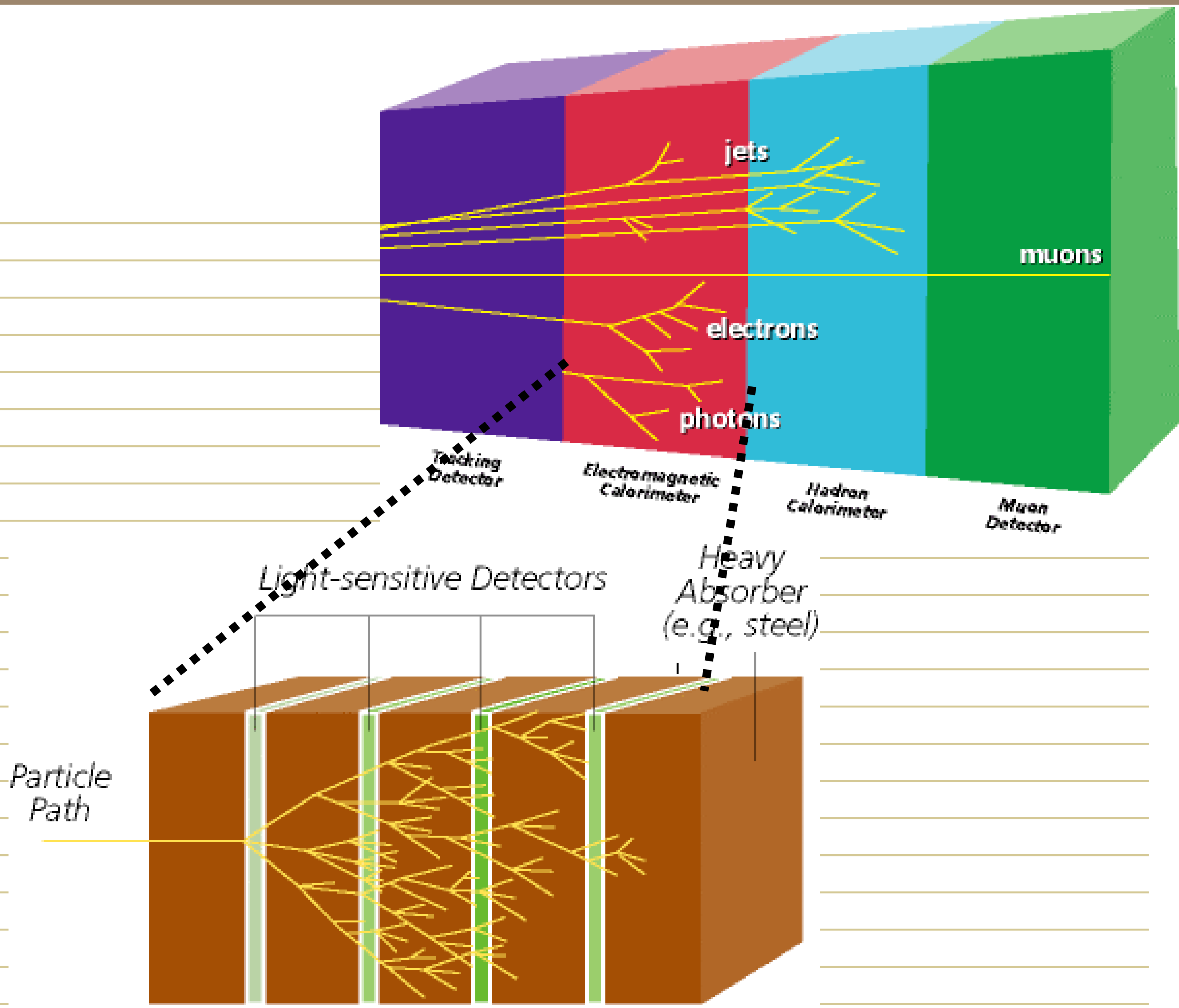
- **measure particles’ momentum vector**
  - rely on their interactions with detector material via electromagnetism
- **main component: ‘fiber’ tracker**
  - similar to fiber optics used in phone lines
  - particle travels thru fiber
    - causes light to be produced
  - light travels down fiber to a detector at its end
- **magnetic field**
  - allows momentum of particle to be measured (F=qvxB)





Calorimetry

- **particle interactions with matter**
  - leptons and photons interact only via electromagnetic interaction
  - jets interact via both strong and electromagnetic
  - when a particle collides with a block of matter
    - energy of particle goes into producing a ‘shower’ of electrons
      - ie. a current
    - total charge related to energy of original particle lost in absorber
- **sampling calorimeter**
  - calorimeter
    - put enough material to absorbe ALL of particle’s energy
  - not necessary to detect all of charge produced
    - ‘sample’ the shower
      - use to estimate what happened in total shower
      - use high voltage to bring charge to a conductor where can measure current

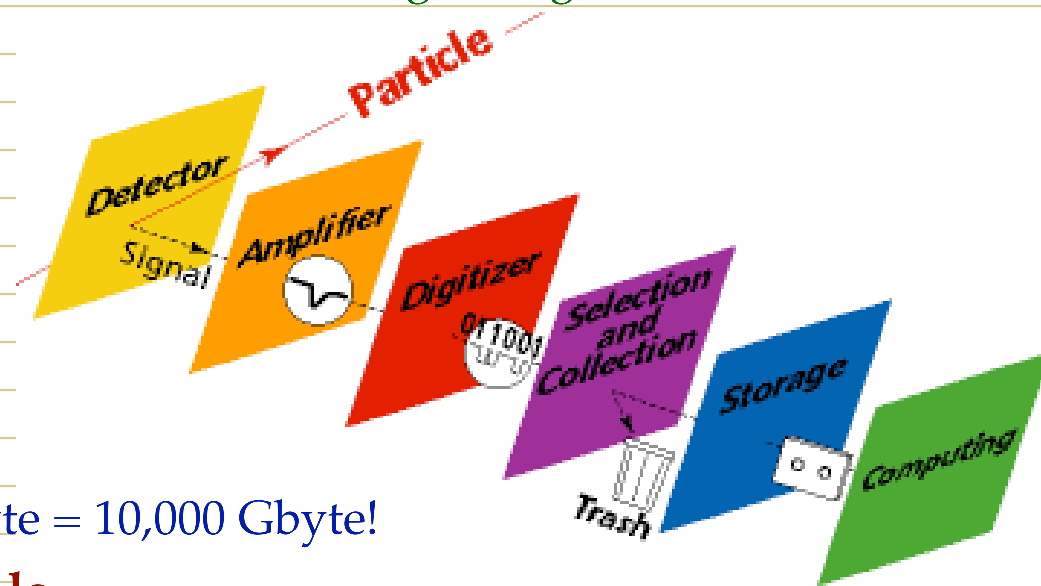

jets
muons
electrons
photons
Tracking Detector
Electromagnetic Calorimeter
Hadron Calorimeter
Muon Detector
Light-sensitive Detectors
Heavy Absorber (e.g., steel)
Particle Path

Particle Identification

- **electrons**
  - shower in first layers of calorimeter
  - inner track pointing to calorimeter energy
- **jets**
  - interact with calorimeter by strong interaction
  - energy deposited in all layers of calorimeter
- **muons**
  - inner track plus track in outer muon system
  - no significant calorimeter energy observed
- **neutrinos: major problem**
  - no color, no charge, so don't interact with detectors
  - identify by conservation of momentum
    - incoming proton and antiproton
      - only have momentum along z-axis
      - no momentum in the plane transverse to beam axis
      - if net 'transverse energy' observed, we infer a neutrino

Running DZERO

- **approximately 1 million detection elements**
  - value at each must be 'buffered' EVERY beam crossing
  - hold until a trigger decision is available
  - approximate amount of analog data generated and buffered per second
    - 10 Tbyte = 10,000 Gbyte!



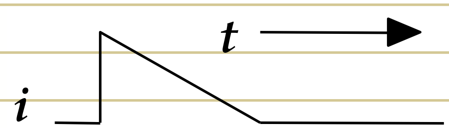
- **control signals**
  - control readout timing and coordination between detectors and data acquisition system
  - 128 Gbit ethernet links → approximately 10 Gbyte per second!

Triggering

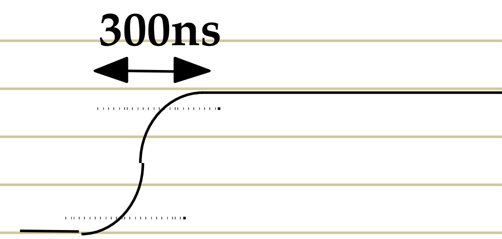
- **8 million interactions per second**
- **but, we can only write about 50 to tape!**
- **How do we choose which 50?**
  - first level hardware trigger
    - electrons move really fast!
    - if setup electronics properly
      - can deliver information allowing quick decisions
    - usually loose some quality of the full information out of the detector
  - final software trigger level
    - much slower, but can use full information
    - performs refined measurements for final decision

Example: Hardware Calorimeter Trigger

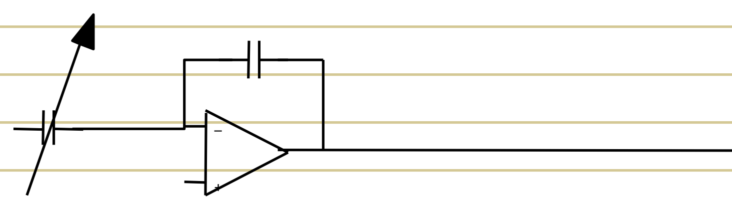
- **current comes from detector**
  - amplified and converted to a voltage
    - rise time around 300 ns (> 132 ns intercollision time)
      - still too slow for trigger



current from shower



voltage (O(~1 v)) from preamp - gain of 10^7

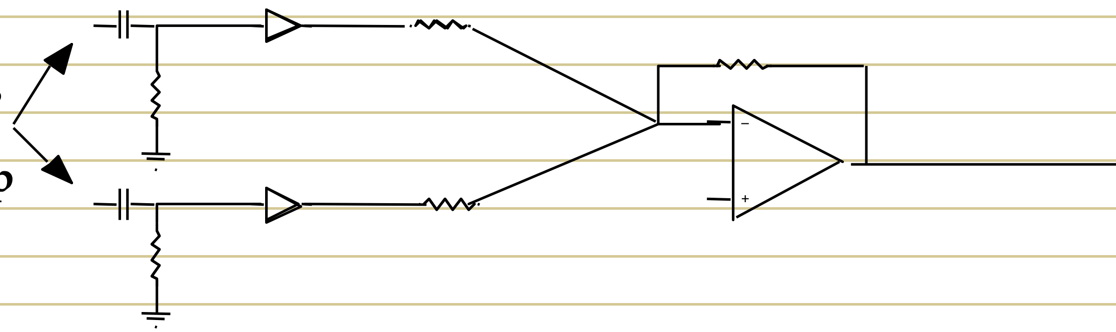


particle thru detector cell

Trigger Signals

- don't have time to let all charge arrive
  - take derivative of signals for each calorimeter cell
  - sum up nearby cells
    - if alot of energy grouped together, then trigger event

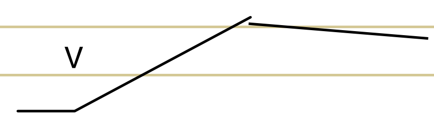
signals
from
preamp



Differentiation Stage:

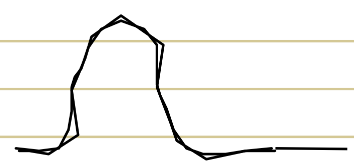
Summation Stage:

incoming
voltage



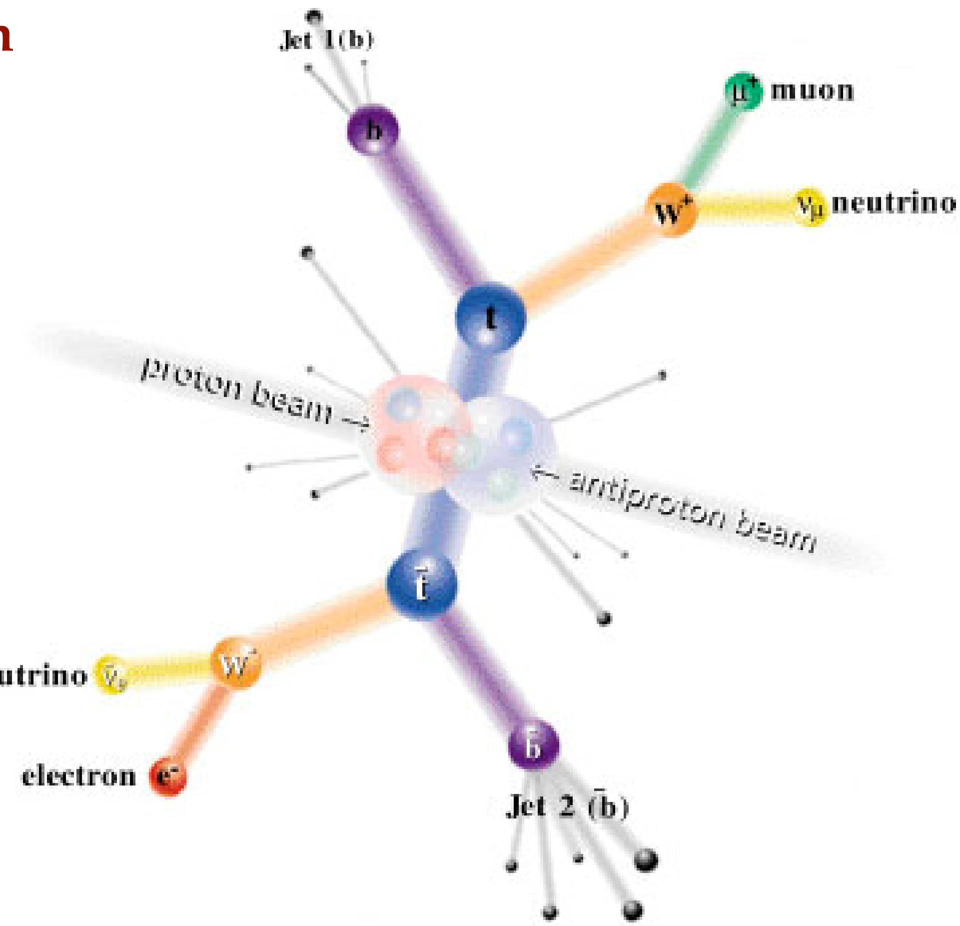
- outgoing pulse sum
of incoming pulses

differentiated
signal for
triggering



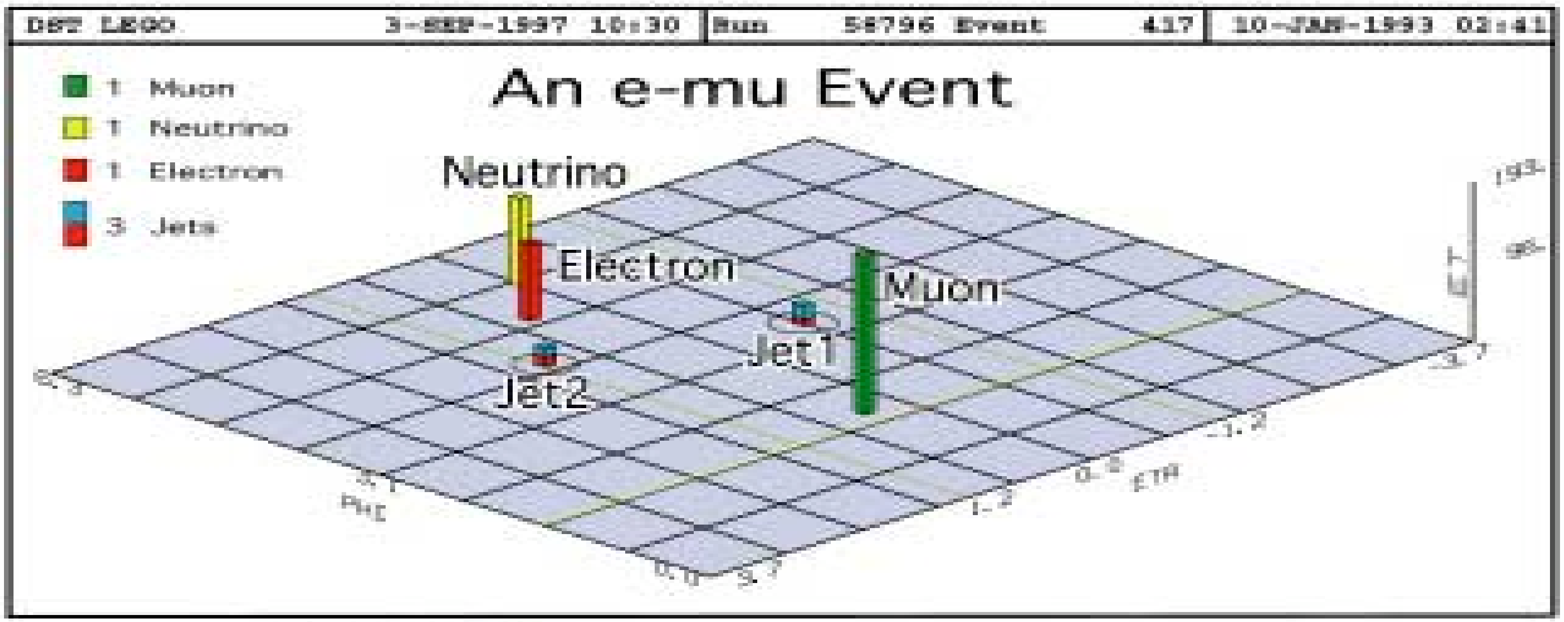
Top Quark

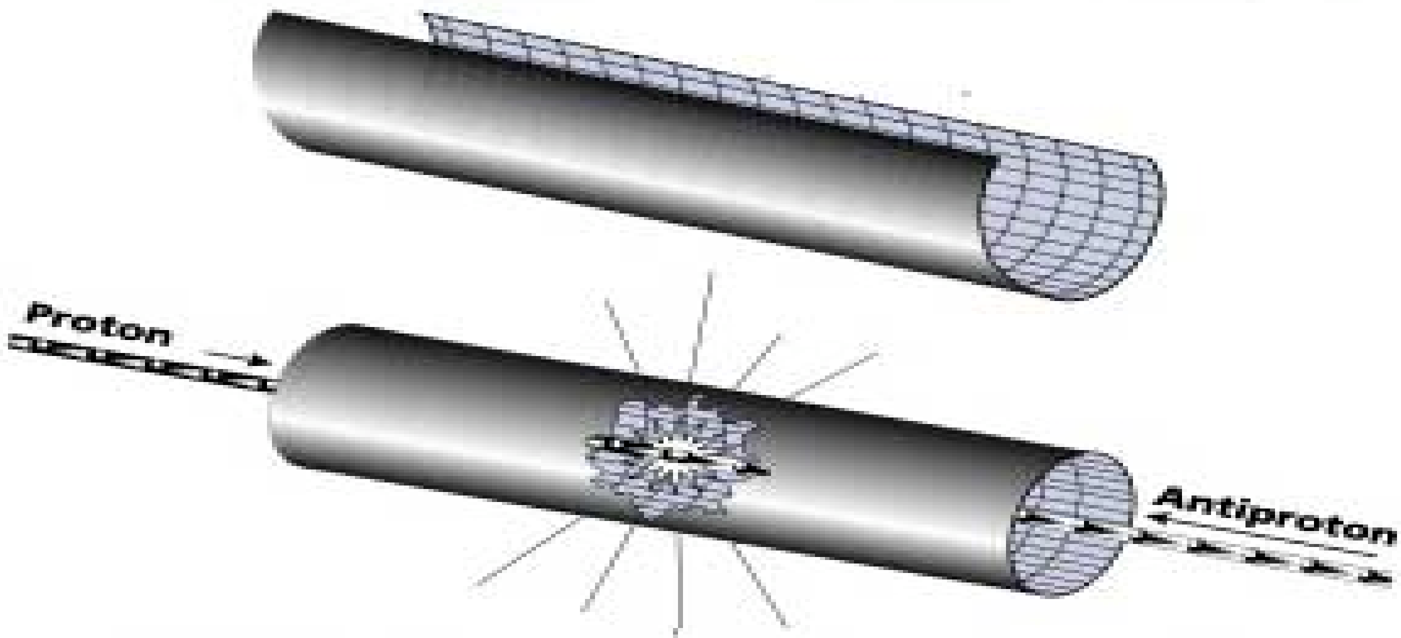
- **crucial test of the electroweak model**
  - since there is a b-quark, there must be a partner, the top quark
  - also required in most extensions of the electroweak model
- **produced at the Tevatron**
  - top and antitop pairs
  - very rare
- **each top quark**
  - decays to a W particle
  - W decays to
    - quark-antiquark
    - OR lepton-neutrino



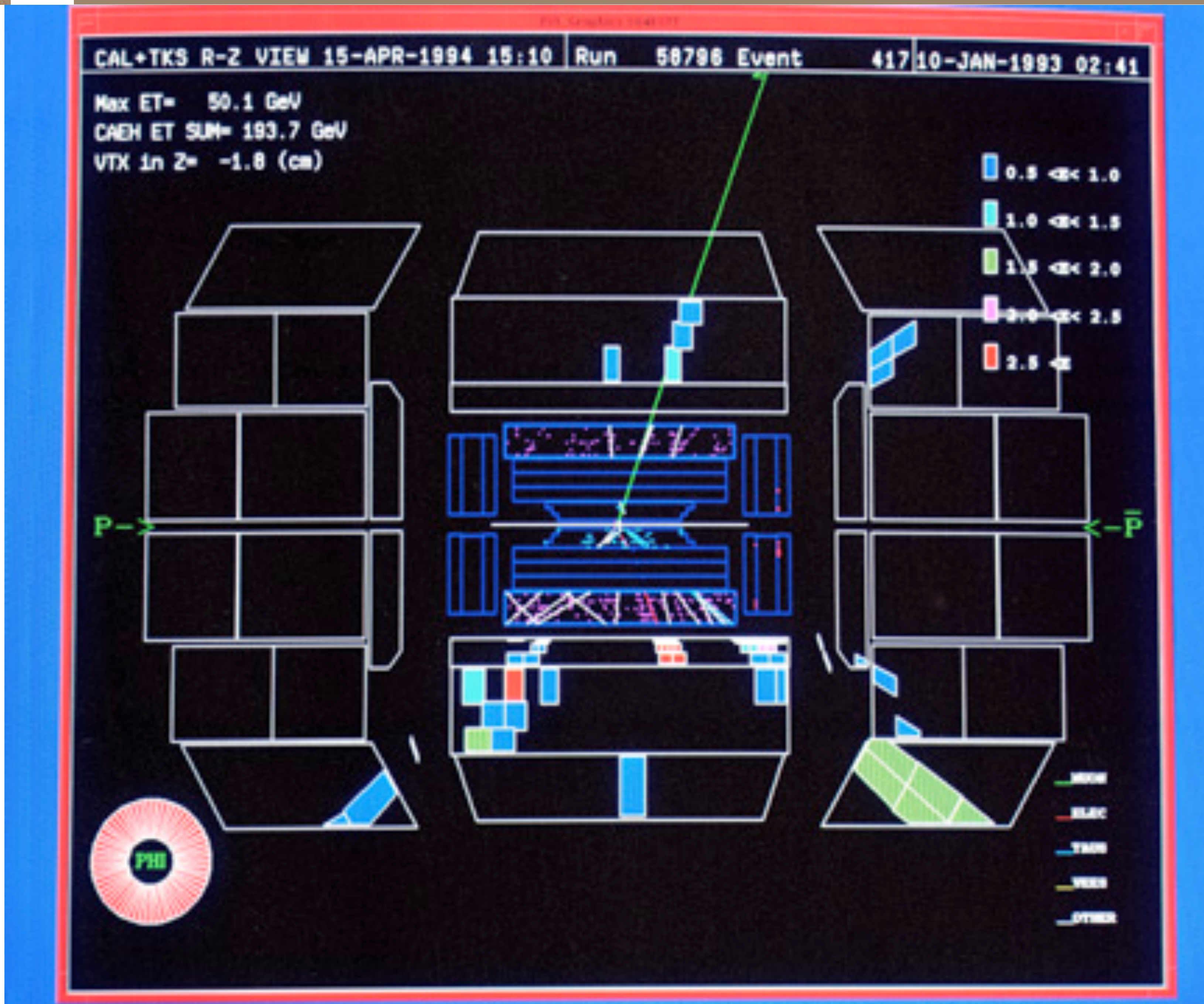
Example: ‘Dilepton events’

- **both W’s decay to lepton/neutrino pairs**
- **detectable final states**
  - dielectron, dimuon, and electron-muon, plus two neutrinos
  - each state also has two jets from b-quarks
- **backgrounds inherently low**
  - very few real physics process can make significant #s of high energy lepton pairs
    - most common of these does not produce neutrinos
  - leptons can be faked by detector imperfections
    - also very rare
    - due to noise, or similarities of photon and electron showers
    - important in any detector:
      - minimize noise
      - maximize descrimination power against background

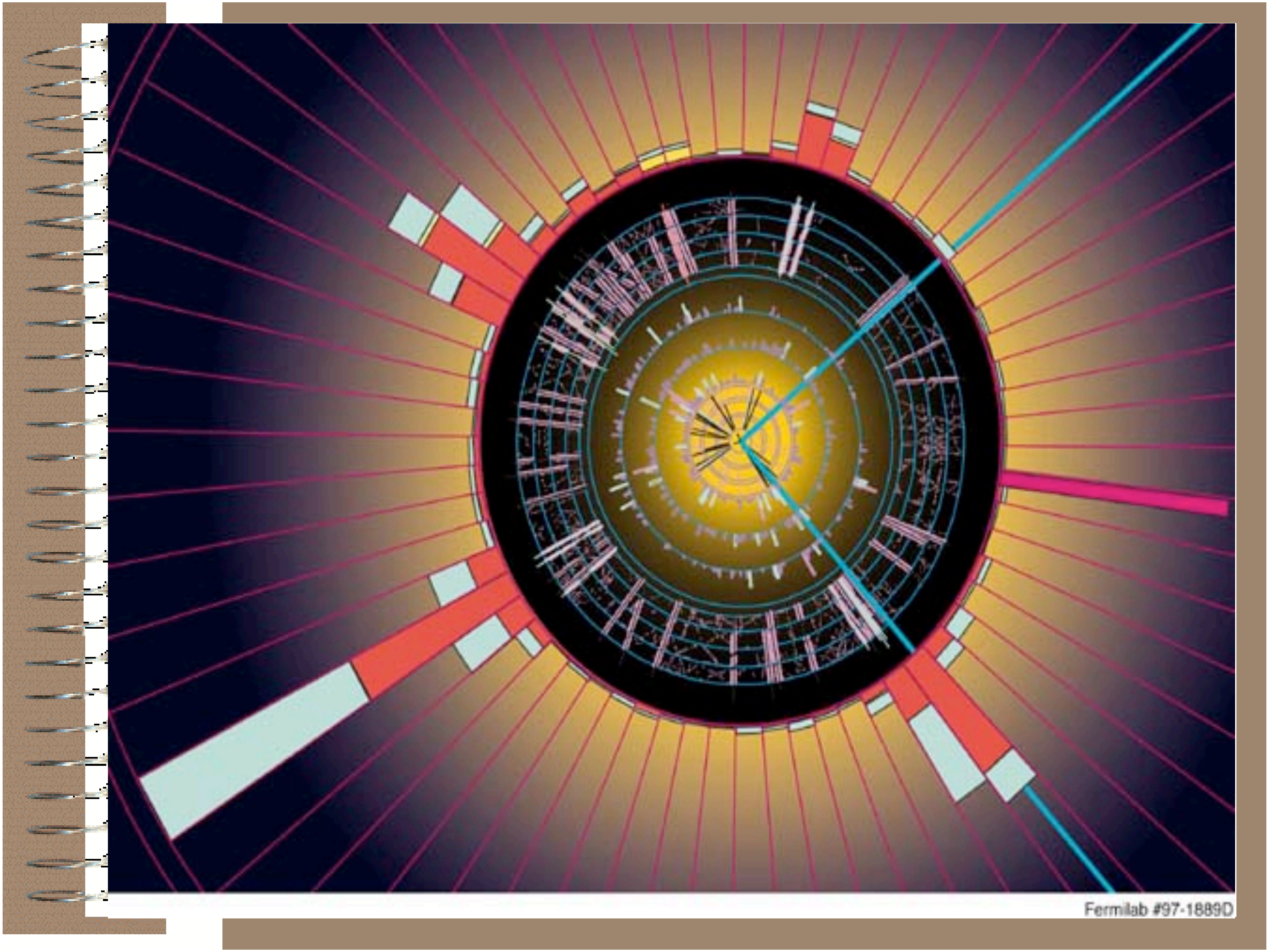




Collision in Calorimeter



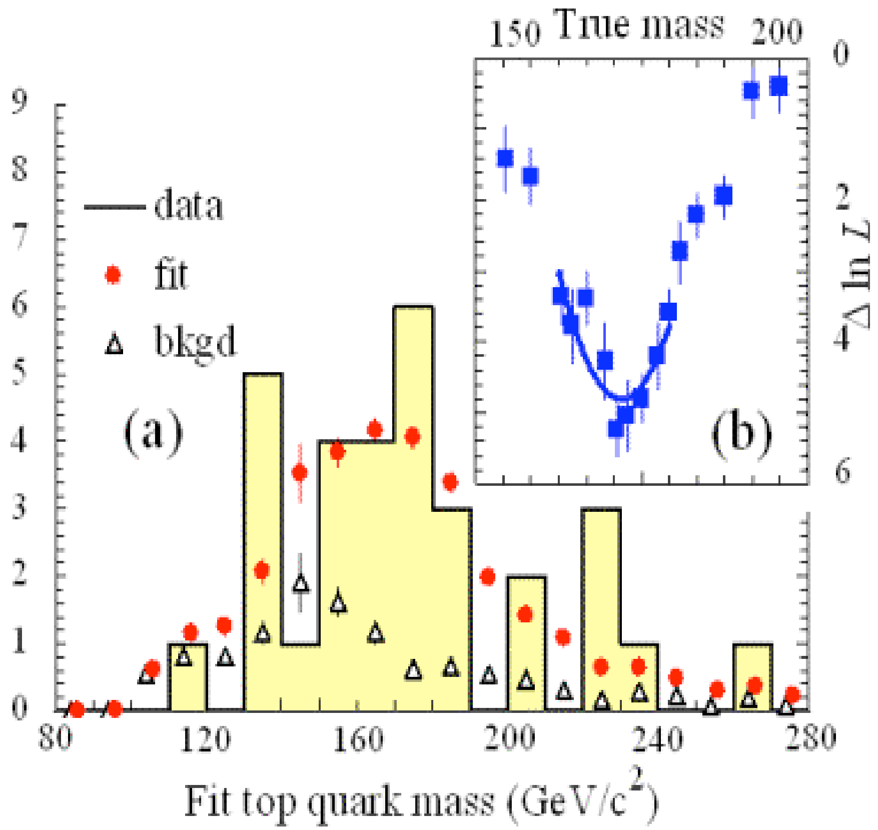
CAL+TKS R-Z VIEW 15-APR-1994 15:10
Run 58796 Event 417
10-JAN-1993 02:41
Max ET= 50.1 GeV
CAEH ET SUM= 193.7 GeV
VTX in Z= -1.8 (cm)
0.5 <E< 1.0
1.0 <E< 1.5
1.5 <E< 2.0
2.0 <E< 2.5
2.5 <E
P->
<-P̄
PHI
OTHER



Fermilab #97-1889D

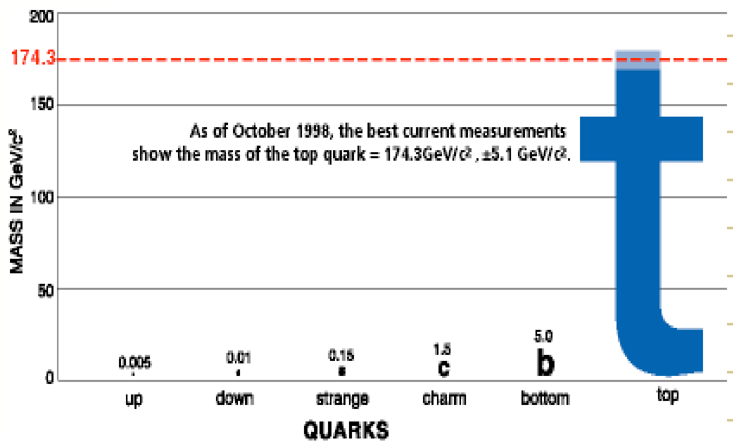
What We Know About Top So Far

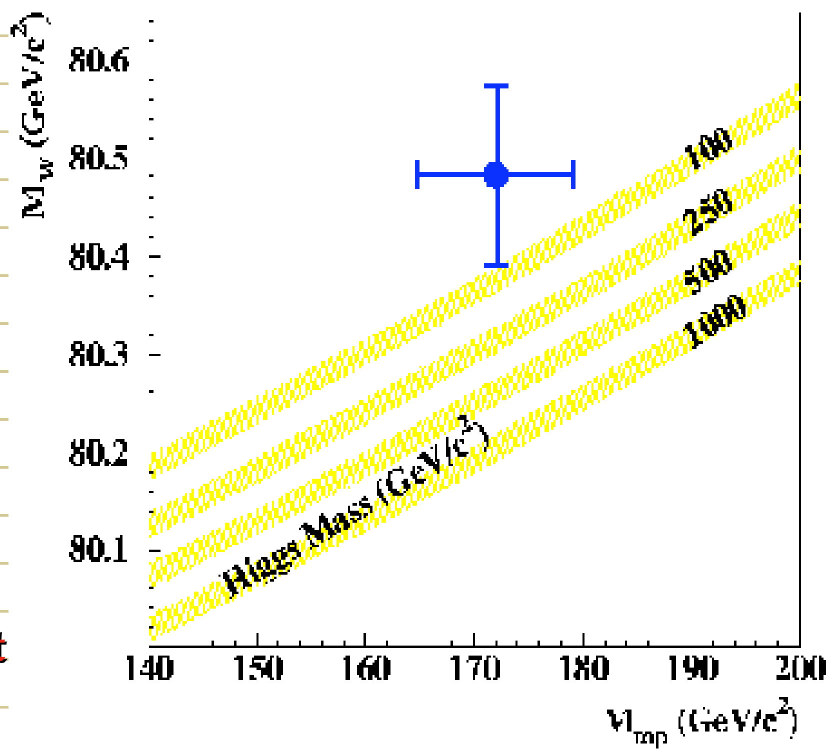
- **discovered in 1995**
- **first measurement of production probability**
  - agrees well with theory
- **important to studies of underlying physics:**
  - early relative rates of decay modes
    - as predicted
  - first top mass measurement
    - where electroweak model expects it



The Hunt for the Higgs

- top mass strangely high: Why?





- top and W masses together
  - point to Higgs being light
  - **means Tevatron has real shot at finding it**
    - **so Stay Tuned!!**