# PHYS 3446 – Lecture #18

*Tuesday April 21, 2015*
*Dr. **Brandt***

- Cherenkov
- Silicon
- Calorimeter
- Dzero Upgrade
- Accelerator

# Projects

1 UA1 Higgs (non) discovery/Carlo Rubbia Nick Stadler, John Havens, Paul T.

2 Top Discovery CDF/Dzero John Crouch, Matthew Gartman, **Bernard Nuar**

3 J/$\Psi$ (Charm quark) Michael Davenport, Charles Knight, Richard Humphries

4 Top Quark at LHC: Kathleen Brackney, David Soward, Kevin Strehl

5 Charged Higgs1 search/discovery: Ashley Herbst, Anthony Rich, **Garrett Leavitt**?

6 Charged Higgs2: Kelly Claunch, Robert Mathews, Charles Jay

7 Higgs Discovery (ATLAS/CMS): Raul Dominguez, Peter Hamel, Kennedy

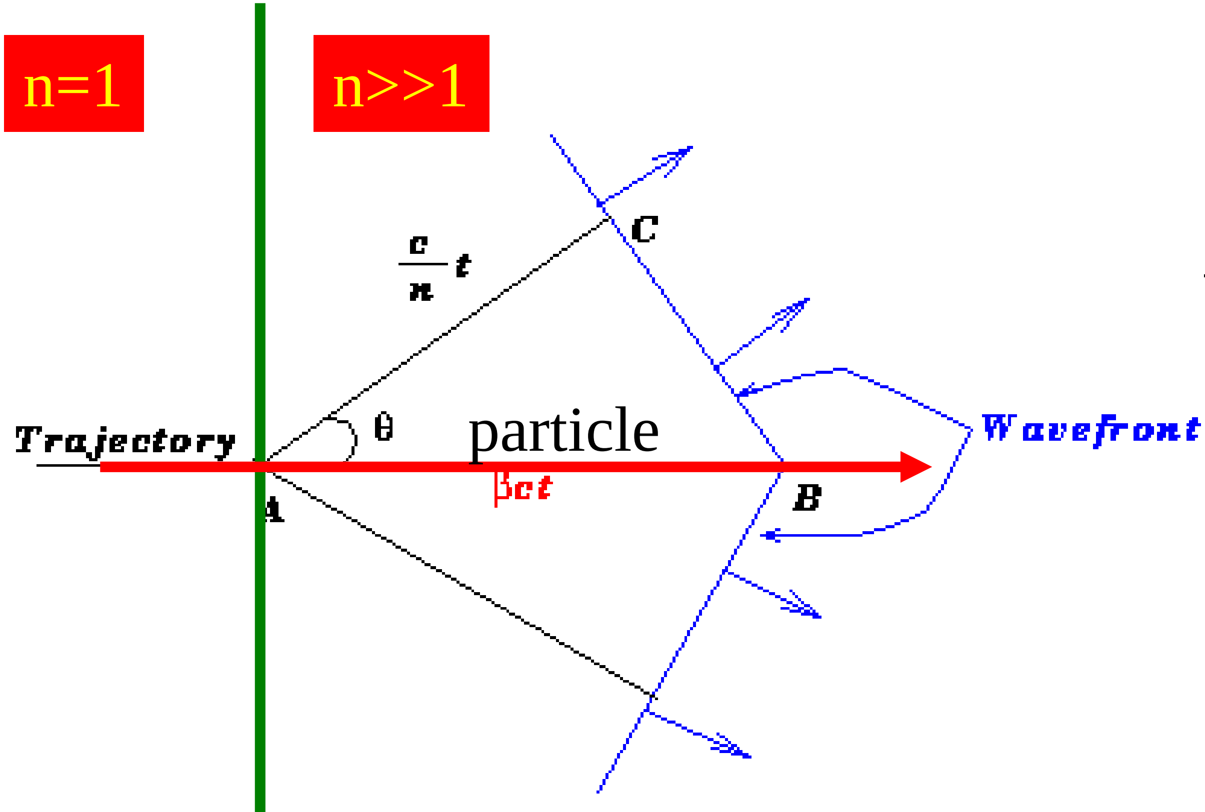
X8 B quark Discovery: Rajendra Paudel?

1) Intro/Theory-what are you looking for and what is it's signature and background: how do you know if you find it
2) Detector-how is detector optimized for the task at hand, trigger/data collection
3) Analysis-operate on the data to accomplish the goals/Conclusion
4) Grading will include intermediate milestones, due is a "developed outline" today
5) Rough draft next tuesday

# Cerenkov Detectors

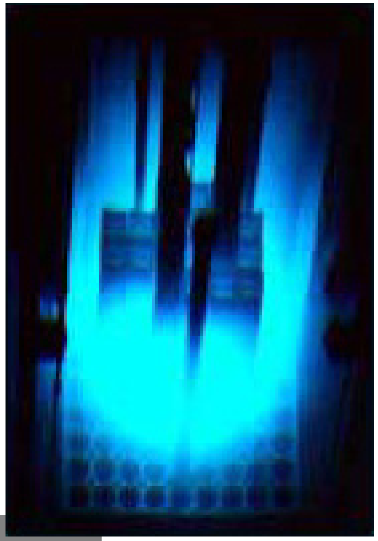
- What is Cerenkov radiation?
  - Emission of coherent radiation from the excitation of atoms and molecules
- When does this occur?
  - If a charged particle enters a dielectric medium with a speed faster than light in the medium
  - How is this possible?
    - Since the speed of light is c/n in a medium with index of refraction n, if the particle's $\beta>1/n$, its speed is larger than the local speed of light
- Cerenkov light has various frequencies but blue and ultraviolet band are most interesting
  - Blue can be directly detected w/ standard PMTs
  - Ultraviolet can be converted to electrons using photosensitive molecules mixed with some gas in an ionization chamber

# Cerenkov Effect




$\beta c$ = speed of particle

$\frac{c}{n}$ = speed of radiation



Use this property of prompt radiation to develop a fast timing counter

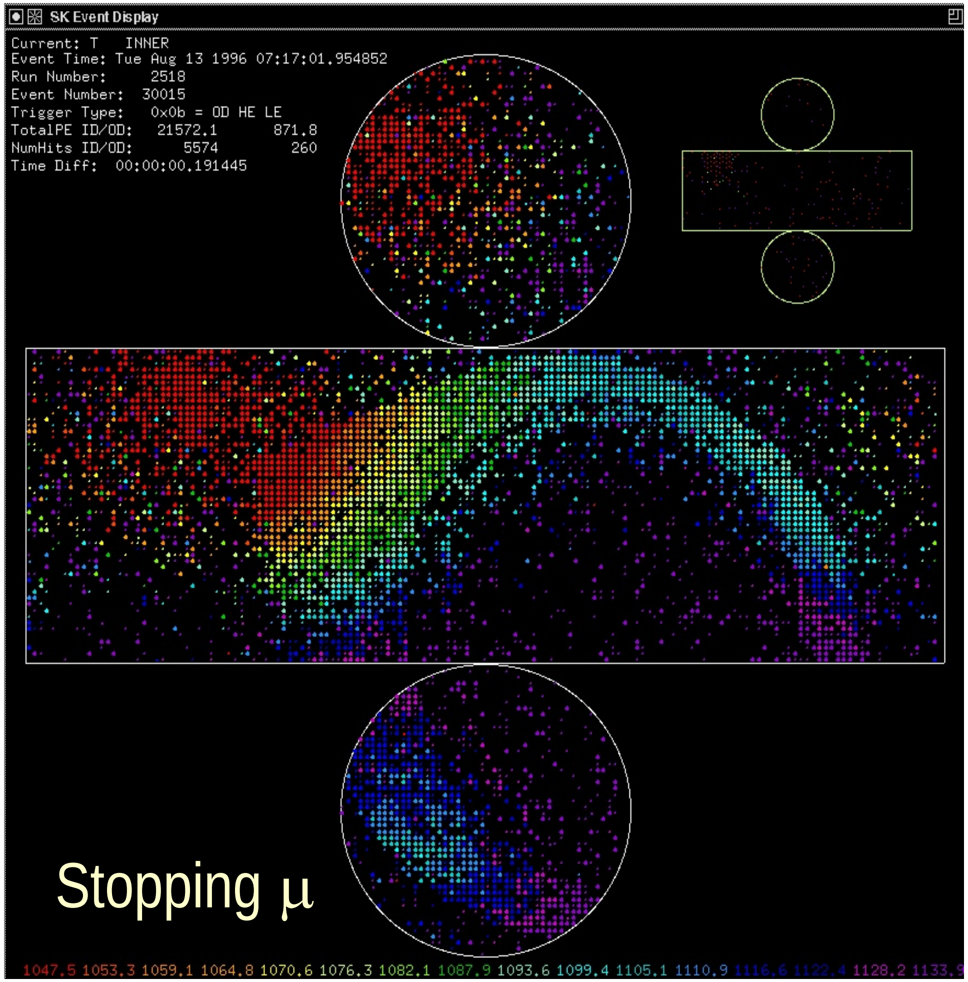
# Cerenkov Detectors

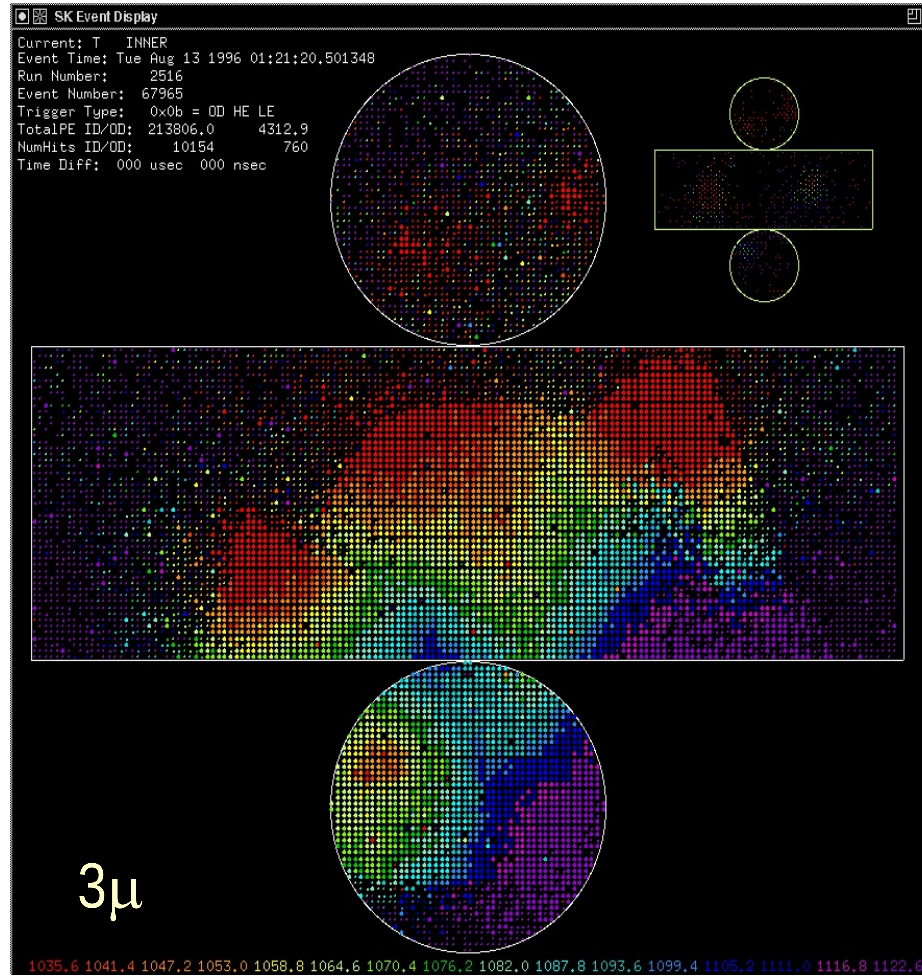
- The angle of emission is given by $\cos\theta_c = \frac{1}{\beta n}$
- The intensity of the produced radiation per unit length of the radiator is proportional to $\sin^2\theta_c$.
- For $\beta n>1$, light (Cerenkov Radiation) will be emitted while for $\beta n<1$, no light is observed.
- One can use multiple chambers of various indices of refraction to detect Cerenkov radiation from particles of different mass but with the same momentum

# Cerenkov Detectors

- Threshold counters
  - Particles with the same momentum but with different mass will start emitting Cerenkov light when the index of refraction is above a certain threshold
  - These counters have one type of gas but could vary the pressure in the chamber to change the index of refraction to distinguish particles
  - Large proton decay experiments use Cerenkov detector to detect the final state particles, such as $p \rightarrow e^+\pi^0$
- Differential counters
  - Measure the angle of emission for the given index of refraction since the emission angle for lighter particles will be larger than heavier ones

# Super-K Event Displays



# Cerenkov Detectors

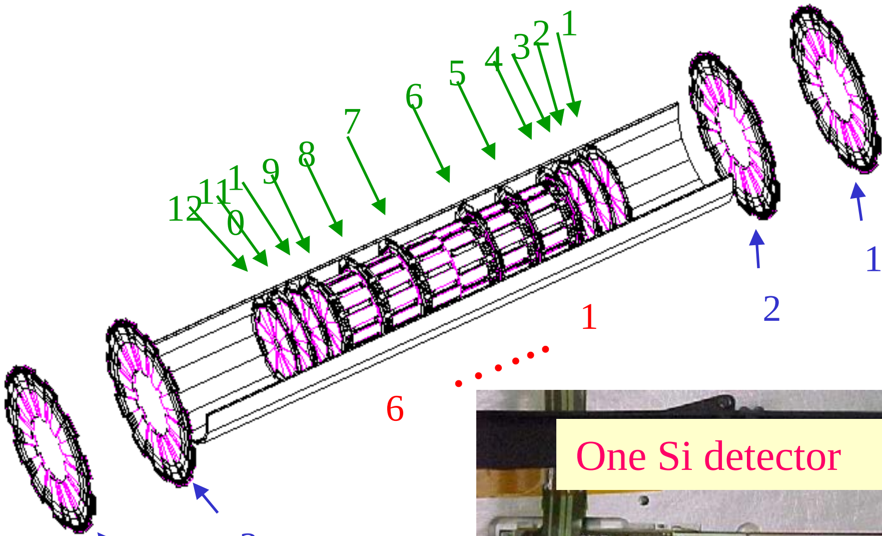
- Ring-imaging Cerenkov Counters (RICH)
  - Use UV emissions
  - An energetic charged particle can produce multiple UV photons distributed about the direction of the particle
  - These UV photons can then be put through a photo-sensitive medium creating a ring of electrons
  - These electrons then can be detected in an ionization chamber yielding a ring shaped pattern in the detector, the details of which can be used for particle ID
  - The Babar experiment at SLAC used this type of detector

# Semiconductor Detectors

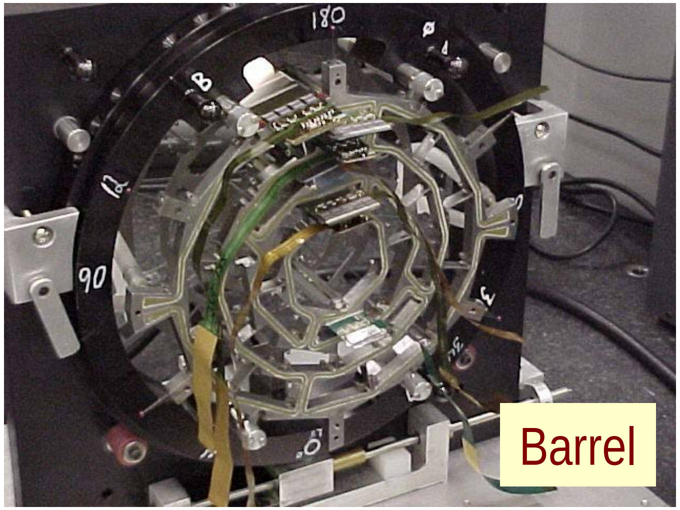
- Semiconductors can produce large signals (electron-hole pairs) for relatively small energy deposit (~3 eV)
  - Advantageous in measuring low energy at high resolution
- Silicon strip and pixel detectors are widely used for high precision position measurements (solid state MWPC)
  - Due to large electron-hole pair production, thin layers (200 – 300 $\mu$m) of wafers sufficient for measurements
  - Output signal proportional to the ionization loss
  - Low bias voltages sufficient to operate (avoid recombination)
  - Can be deposited in thin stripes (20 – 50 $\mu$m) on thin electrode
  - High position resolution achievable
  - Can be used to distinguish particles in multiple detector configurations
- So what is the catch?
  - Very expensive → On the order of $30k/m$^2$

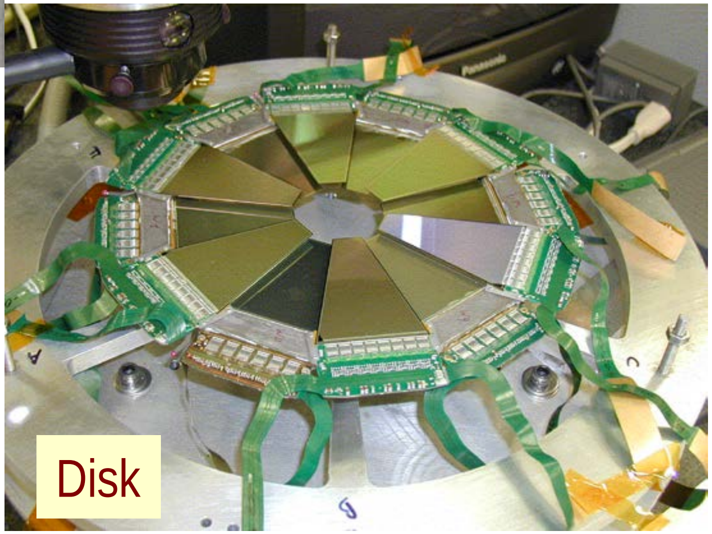
# DØ Silicon Vertex Detector

| | Barrels | F-Disks | H-Disks |
|---|---|---|---|
| Channels | 387120 | 258048 | 147456 |
| Modules | 432 | 144 | 96 |
| Inner R | 2.7 cm | 2.6 cm | 9.5 cm |
| Outer R | 9.4 cm | 10.5 cm | 26 cm |







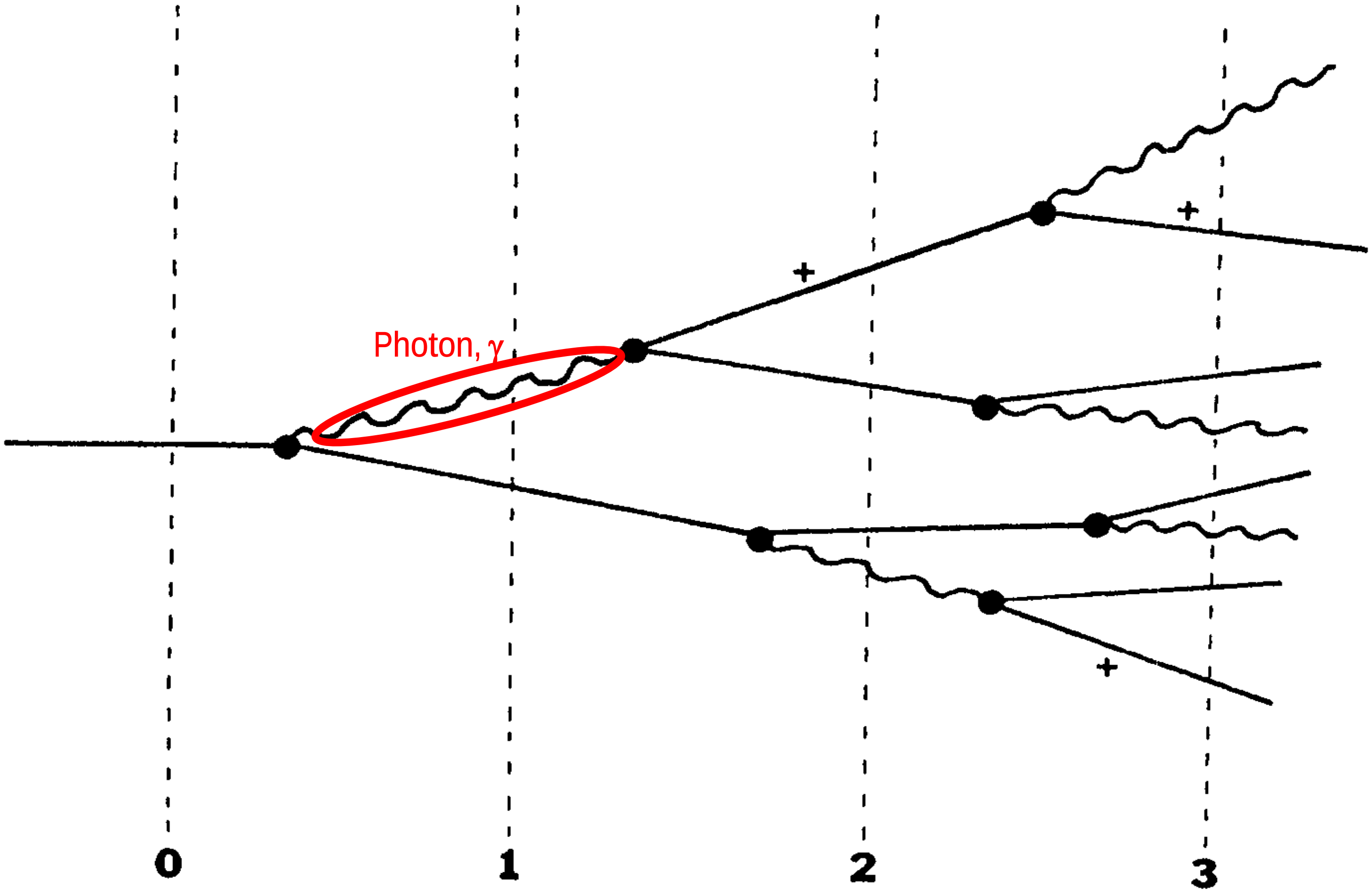
# Calorimeters

- Magnetic measurement of momentum is not sufficient for physics, why?
  - The precision for angular measurements gets worse as particles' momenta increases
  - Increasing magnetic field or increasing precision of the tracking device will help but will be expensive
  - Cannot measure neutral particle momenta
- How do we solve this problem?
  - Use a device that measures kinetic energies of particles
- Calorimeter
  - A device that absorbs full kinetic energy of a particle
  - Provides signal proportional to deposited energy

# Calorimeters

- Large scale calorimeter were developed during 1960s
  - For energetic cosmic rays
  - For particles produced in accelerator experiments
- How do high energy EM (photons and electrons) and Hadronic particles deposit their energies?
  - Electrons: via bremsstrahlung
  - Photons: via electron-positron pair production, followed by bremsstrahlung of electrons and positrons
  - electron and photon interactions result in an electromagnetic shower that continues until all the initial energy is deposited

# Electron Shower Process

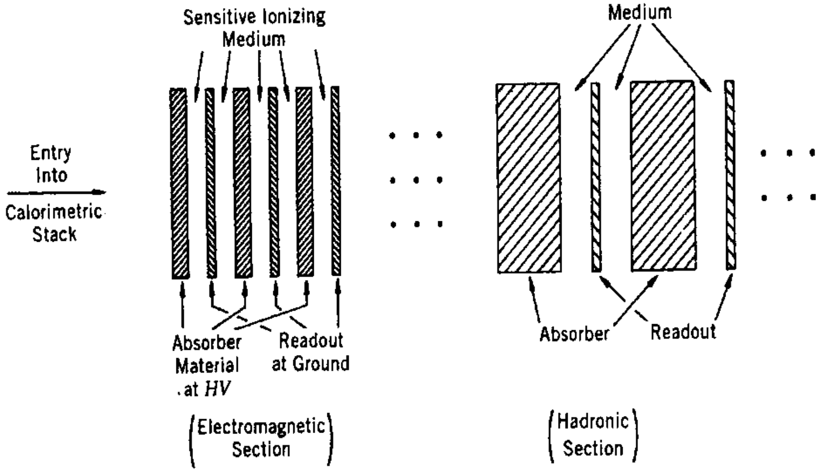


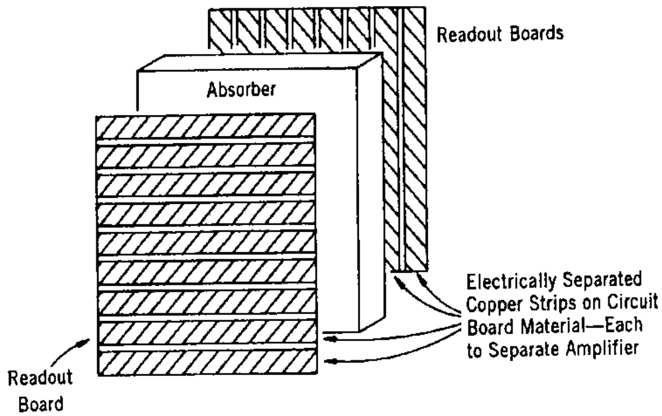
# Calorimeters

- Hadrons are massive thus their energy deposit via brem is small
- They lose their energies through multiple nuclear collisions
- Incident hadron produces multiple pions and other secondary hadrons in the first collision
- The secondary hadrons then successively undergo nuclear collisions
- Mean free path for nuclear collisions is called the <u>nuclear interaction length</u> and is substantially larger than that of EM particles
- Hadronic shower processes are therefore more extended and erratic than EM shower processes (also may produce neutrinos, so Hadronic energy resolution worse than EM)

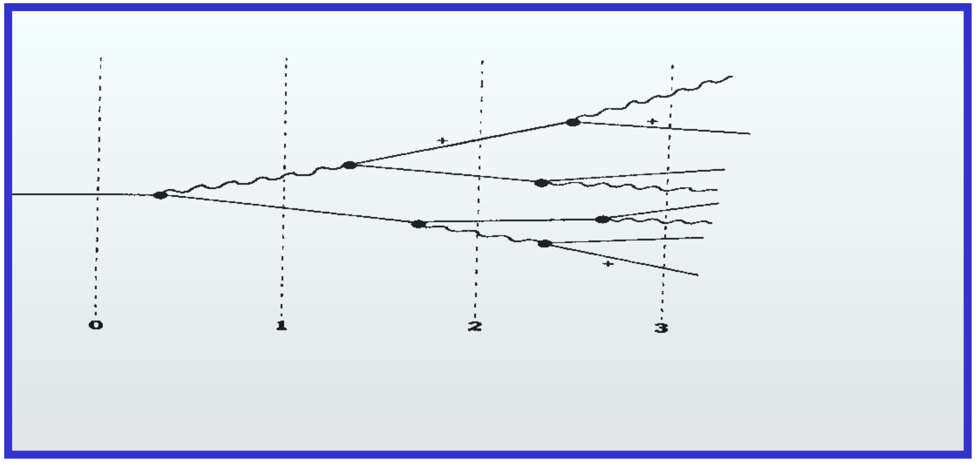
# Sampling Calorimeters

- High energy particles require large calorimeters to absorb all of their energies and measure them fully in the device (called total absorption calorimeters)
- Since the number of shower particles is proportional to the energy of the incident particles…
- One can deduce the total energy of the particle by measuring only a fraction of their energy, as long as the fraction is known ➔ Called sampling calorimeters
  - Most the high energy experiments use sampling calorimeters

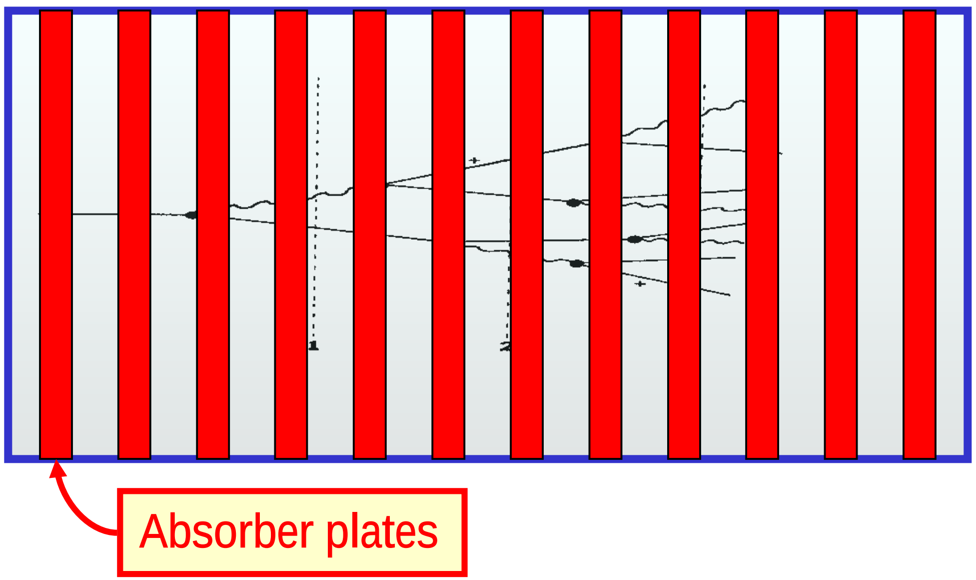


# Principles of Calorimeters




Total absorption calorimeter: See the entire shower energy

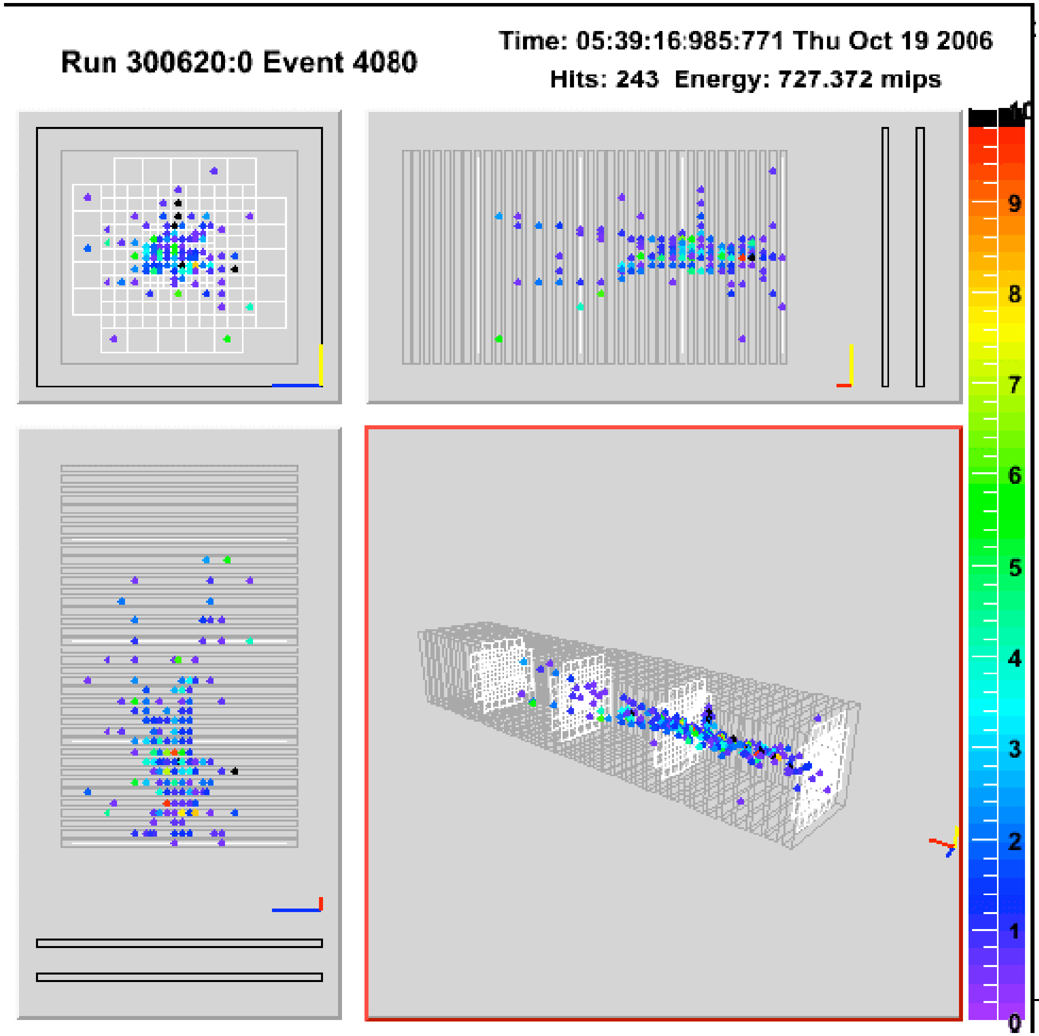


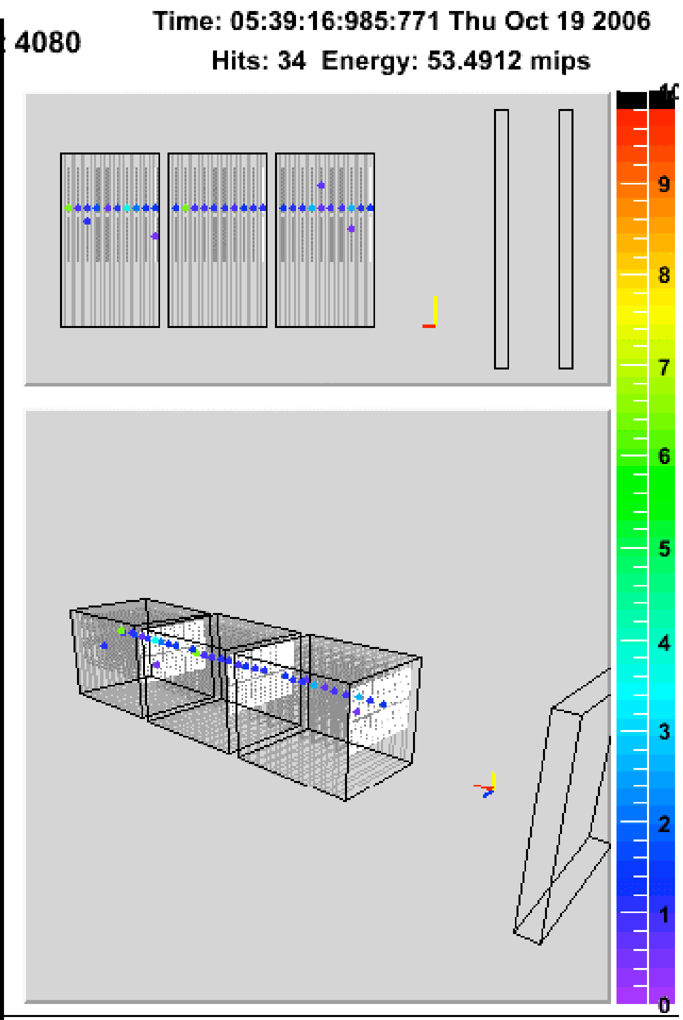

Sampling calorimeter: See only some fraction of shower energy

For EM $E = fE_{vis} = \frac{X_0^{vis}}{X_0^{abs} + X_0^{vis}} E_{vis}$

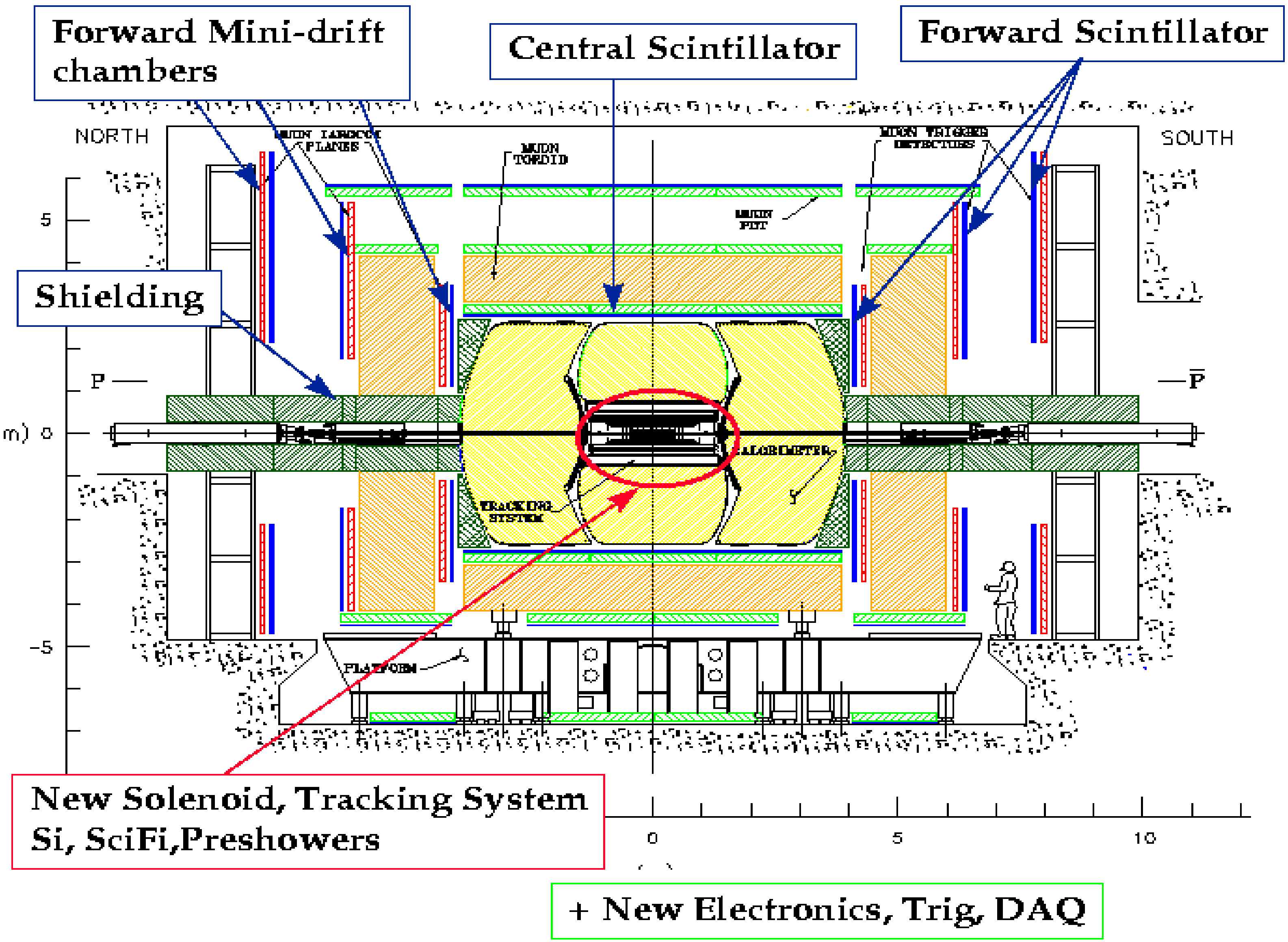
For HAD $E = fE_{vis} = \frac{\lambda_0^{vis}}{\lambda_0^{abs} + \lambda_0^{vis}} E_{vis}$

# Example: Hadronic Shower (20GeV)



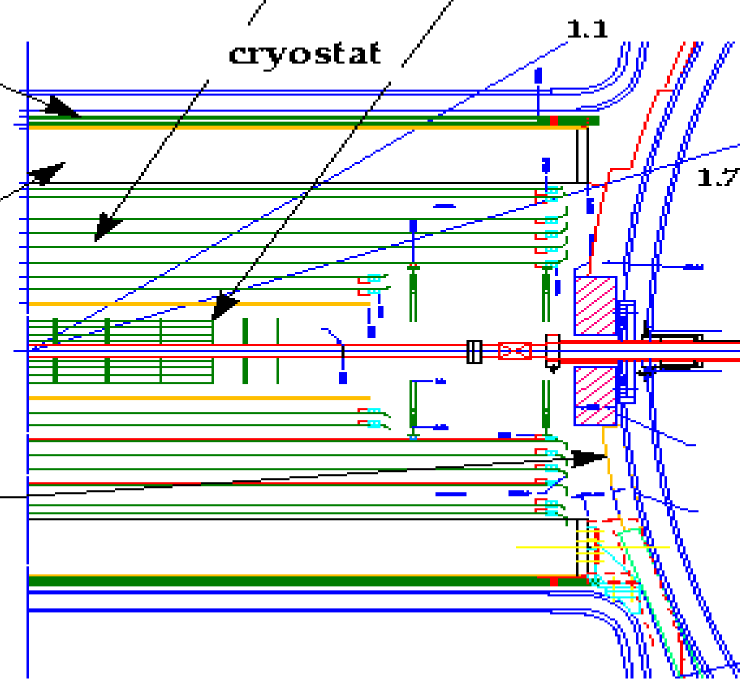
# Run II DØ Detector



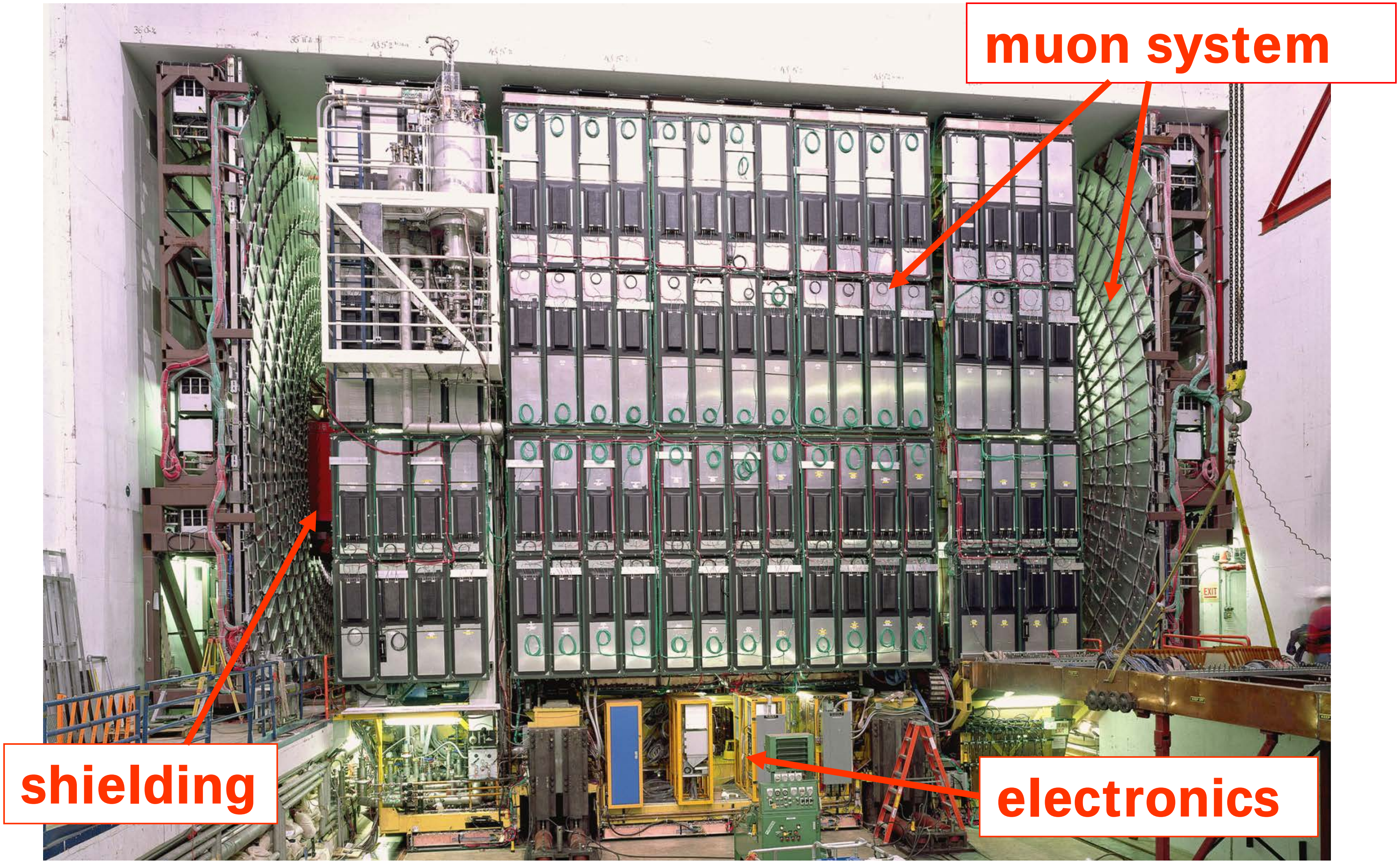
# The DØ Upgrade Tracking System

- Silicon Tracker
  - Four layer barrels (double/single sided)
  - Interspersed double sided disks
  - 840,00 channels
- Fiber Tracker
  - Eight layers sci-fi ribbon doublets (z-u-v, or z)
  - 74,000 830um fibers w/ VLPC readout
- Central Preshower
  - Scintillator strips, WLS fiber readout
  - 6,000 channels
- Solenoid
  - 2T superconducting
- Forward Preshower
  - Scintillator strips, stereo, WLS readout
  - 16,000 channels

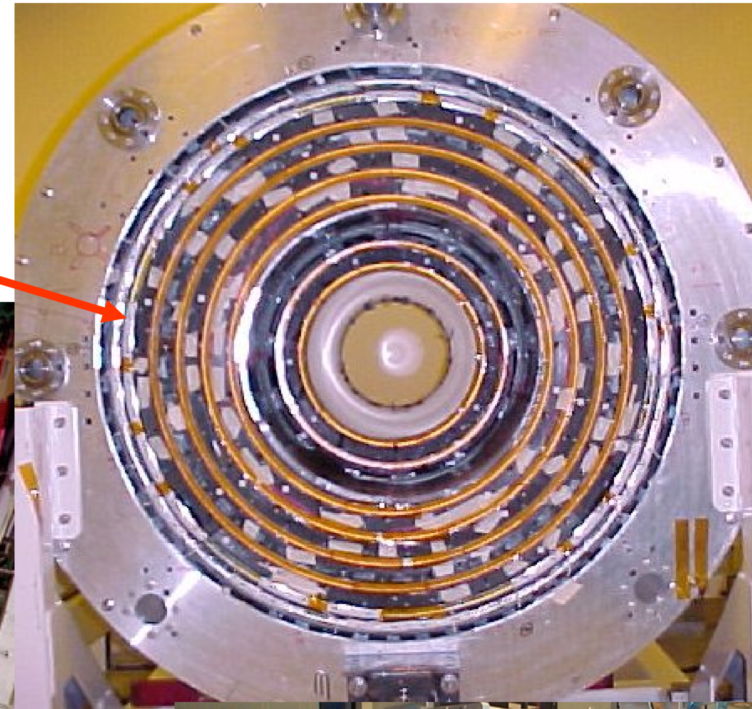
**Charged Particle Momentum Resolution**
**$\Delta p_T/p_T \sim 5\%$ @ $p_T$ = 10 GeV/c**



# DØ Detector

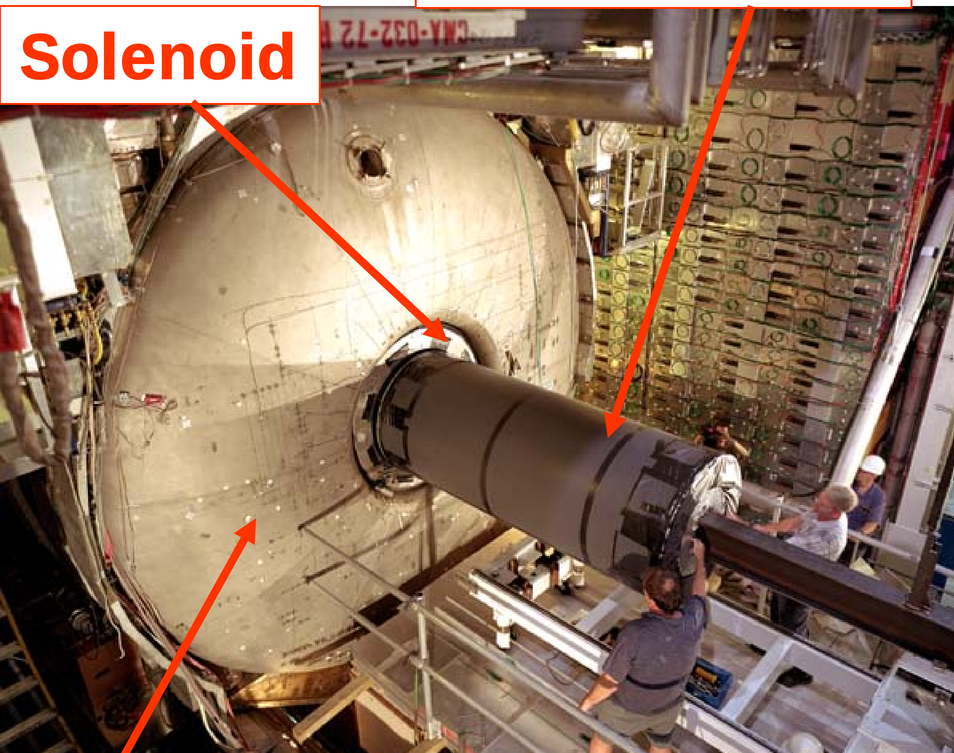


# DØ Detector

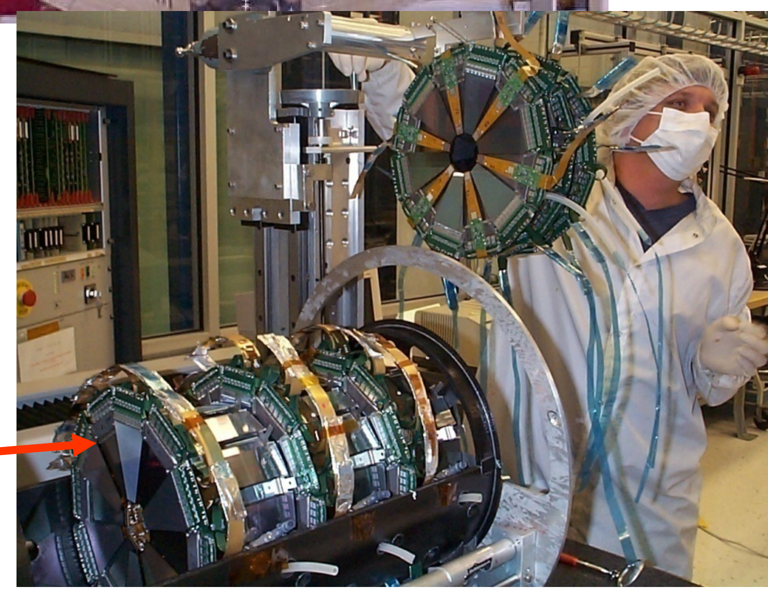


Fiber Tracker

Solenoid



Central Calorimeter



Silicon

# New forward components of the D0 detector

# Particle Accelerators

- How can one obtain high energy particles?
  - Cosmic ray → Sometimes we observe 1000 TeV cosmic rays
    - Low flux and cannot control energies too well
- To probe the fundamental constituents with full control of particle energies and fluxes
  - Particle accelerators
- Accelerators need not only to accelerate particles but also to
  - Maneuver them
  - Constrain their motions to the order of 1$\mu$m
  - Must correct particle paths and momenta to increase fluxes and control momenta

# Particle Accelerators

- Fixed target experiments: Probe the nature of the nucleons → Structure functions
  - Results also can be used for producing secondary particles for further accelerations → Tevatron anti-proton production
- Colliders: Probes the interactions between fundamental constituents
  - Hadron colliders: Wide kinematic ranges and high discovery potential
    - Proton-anti-proton: TeVatron at Fermilab
    - Proton-Proton: Large Hadron Collider at CERN
  - Lepton colliders: Very narrow kinematic range, typically used for precision measurements
    - Electron-positron: LEP at CERN
    - ILC in the med-range future
    - Muon-anti-muon: Conceptual accelerator in the far future
  - Lepton-hadron colliders: HERA at DESY (ep)

X

# Electrostatic Accelerators: Cockcroft-Walton

- Cockcroft-Walton Accelerator
  - Pass ions through sets of aligned DC electrodes at successively increasing fixed potentials
  - Consists of ion source (hydrogen gas) and a target with the electrodes arranged in between
  - Acceleration Procedure
    - Electrons are either added or striped off of an atom
    - Ions of charge q then get accelerated through series of electrodes, gaining kinetic energy of T=qV through every set of electrodes
- Limited to about 1MeV acceleration due to voltage breakdown and discharge
- Available commercially and also used as the first step high current injector (to ~1mA).

X

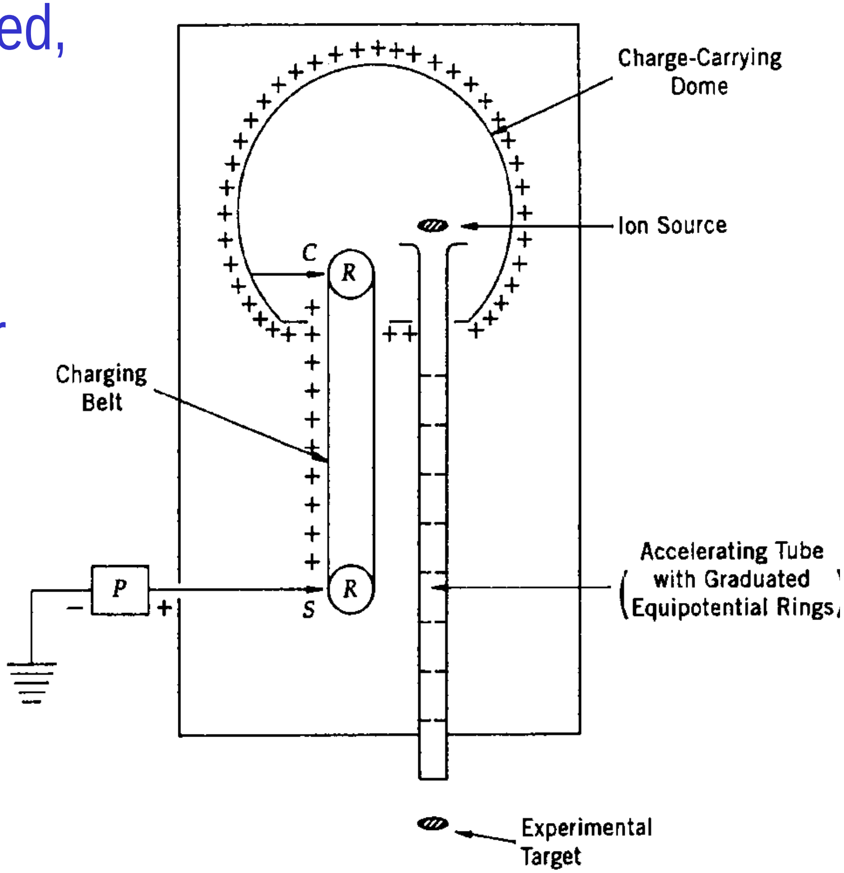
# Electrostatic Accelerators: Van de Graaff

- Energies of particles through DC accelerators are proportional to the applied voltage
- Robert Van de Graaff developed a clever mechanism to increase HV, based on the following known facts
  - The charge on any conductor resides on its outermost surface
  - If a conductor carrying additional charge touches another conductor that surrounds it, all of its charge will transfer to the outer conductor increasing the charge on the outer conductor and consequently the HV

X

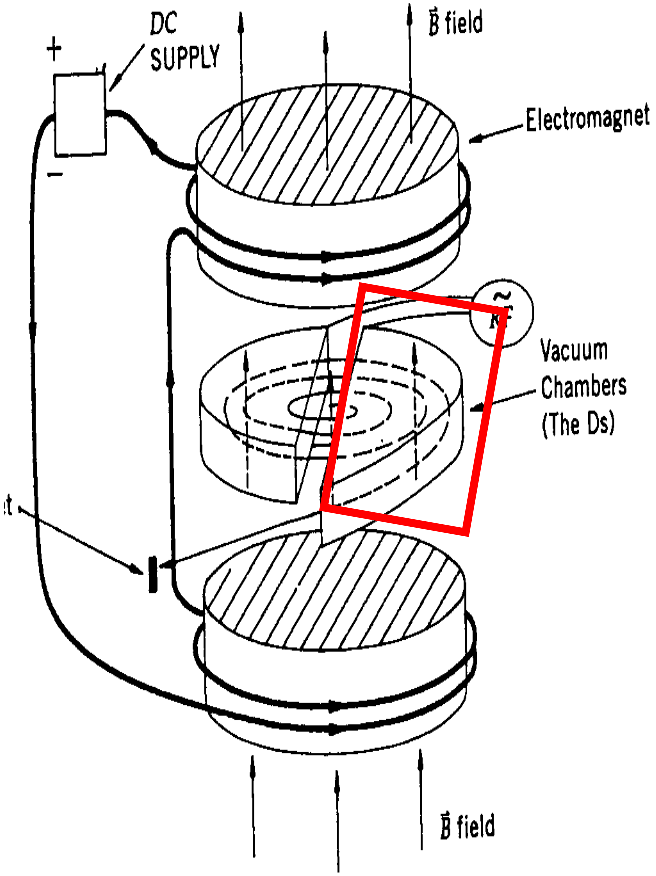
# Electrostatic Accelerators: Van de Graaff

- High voltage ionizes gas, ions are collected, transferred to dome, thus increasing HV
- “Sprayer” (S) adds positive charge to the conveyor belt (“electrons go to P”)
- Charge is carried on a conveyor belt over motorized rollers (R)
- The charges get transferred to the dome via the collector (C)
- The ions in the source then get accelerated to about 12MeV
- This acceleration normally occurs in high pressure gas that has very high breakdown voltage



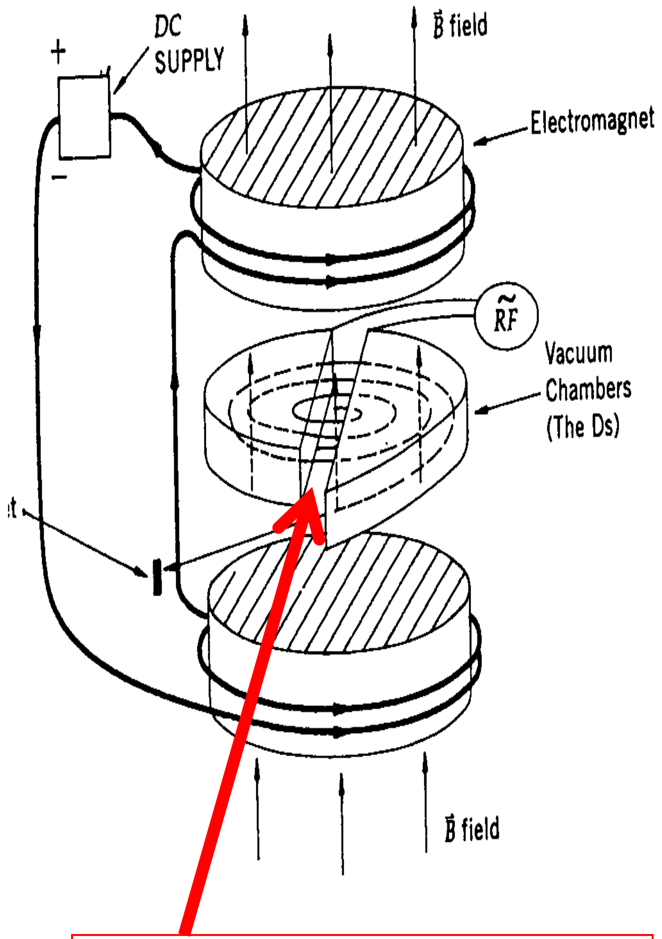
# Resonance Accelerators: Cyclotron

- Fixed voltage machines have intrinsic limitations in their energy due to breakdown
- Machines using resonance principles can accelerate particles to higher energies
- Cyclotron developed by E. Lawrence is the simplest one
- Accelerator consists of
  - Two hollow D shaped metal chambers connected to alternating HV source
  - The entire system is placed under a strong magnetic field



# Resonance Accelerators: Cyclotron

- Because of shielding of the metal D's, there is no electric field inside them
- Strong electric field exists only in the gap between the D's
- An ion source is placed in the gap
- The path is circular due to the perpendicular magnetic field
- Ion does not feel any acceleration inside a D but gets bent due to magnetic field
- When the particle exits a D, the direction of voltage can be changed and the ion gets accelerated before entering into the D on the other side
- If the frequency of the alternating voltage is just right, the charged particle gets accelerated continuously until it is extracted




Gap between D's

# Resonance Accelerators: Cyclotron

- For non-relativistic motion, the frequency appropriate for alternating voltage can be calculated from the fact that the magnetic force provides centripetal acceleration for a circular orbit

$$m\frac{v^2}{r} = q\frac{vB}{c} \quad \Rightarrow \quad \frac{v}{r} = \frac{qB}{mc} = \omega$$

- For a constant angular speed, ω=v/r. The frequency of the motion is

$$f = \frac{\varpi}{2\pi} = \frac{qB}{2\pi mc} = \frac{1}{2\pi}\left(\frac{q}{m}\right)\frac{B}{c}$$

- Thus, to continue to accelerate the particle, the electric field should alternate at this frequency, the cyclotron resonance frequency (and the velocity and radius will increase at same rate)
- The maximum kinetic energy achievable for an cyclotron with radius R is

$$T_{\max} = \frac{1}{2}mv_{\max}^2 = \frac{1}{2}m\varpi^2R^2 = \frac{(qBR)^2}{mc^2}$$

X

With this sense of the magnetic field defined, the force that arises when a charge moves through this field is given by

$$\vec{F} = q\frac{\vec{v}}{c} \times \vec{B} \ ,$$

where $c$ is the speed of light. The appearance of $c$ in this force law is a hint that special relativity plays an important role in these discussions.

If we have both electric and magnetic fields, the *total* force that acts on a charge is of course given by

$$\vec{F} = q\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right) \ .$$

This combined force law is known as the Lorentz force.

Where did the c come from?

### 10.1.1 Units

The magnetic force law we've given is of course in cgs units, in keeping with Purcell's system. The magnetic force equation itself takes a slightly different form in SI units: we do not include the factor of $1/c$, instead writing the force

$$\vec{F} = q\vec{v} \times \vec{B} \ .$$

This is a very important difference! It makes comparing magnetic effects between SI and cgs units slightly nasty.

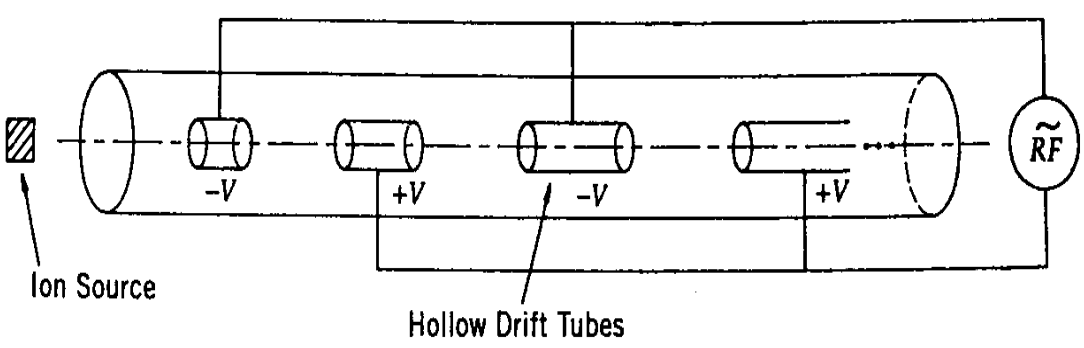
Notice that, in cgs units, the magnetic field has the same overall dimension as the electric field: $\vec{v}$ and $c$ are in the same units, so $\vec{B}$ must be force/charge. For historical reasons, this combination is given a special name: 1 dyne/esu equals 1 Gauss (1 G) when the force in question is magnetic. (There is no special name for this combination when the force is electric.)

In SI units, the magnetic field does *not* have the same dimension as the electric field: $\vec{B}$ must be force/(velocity $\times$ charge). The SI unit of magnetic field is called the Tesla (T): the Tesla equals a Newton/(coulomb $\times$ meter/sec).

To convert: $1\,\mathrm{T} = 10^4\,\mathrm{G}$.

# Resonance Accelerators: Linear Accelerator

- Accelerates particles along a linear path using resonance principle
- A series of metal tubes are located in a vacuum vessel and connected successively to alternating terminals of radio frequency oscillator
- The directions of the electric fields changes before the particles exits the given tube
- The tube length needs to get longer as the particle gets accelerated to keep up with the phase
- These accelerators are used for accelerating light particles to very high energies




# Synchroton Accelerators

- For very energetic particles, relativistic effects must be taken into account
- For relativistic energies, the equation of motion of a charge q under magnetic field B is*

$$m\gamma\frac{d\vec{v}}{dt} = m\gamma\vec{v}\times\vec{\varpi} = q\frac{\vec{v}\times\vec{B}}{c} \Rightarrow \omega = \frac{qB}{\gamma mc}$$

- For v ~ c, the resonance frequency (ν or f) becomes

$$f = \nu = \frac{\varpi}{2\pi} = \frac{1}{2\pi}\left(\frac{q}{m}\right)\frac{1}{\gamma}\frac{B}{c}$$

- Thus for high energies, either B or ν should increase
- Machines with constant B but variable ν are called synchro-cyclotrons
- Machines with variable B independent of the change of ν are called synchrotrons

# Synchroton Accelerators

- Electron synchrotrons, B varies while $\nu$ is held constant
- Proton synchrotrons, both B and $\nu$ vary
- For v ~ c, the frequency of motion can be expressed

$$f = \frac{1}{2\pi}\frac{v}{R} \approx \frac{c}{2\pi R} = \frac{1}{2\pi}\left(\frac{q}{m}\right)\frac{1}{\gamma}\frac{B}{c}$$

- with p=$\gamma$mc and q=e

$$R(m) = \frac{pc}{qB} \approx \frac{p(GeV/c)}{0.3B(Tesla)}$$

- For magnetic field strength of 2 Tesla, one needs a radius of 50 m to accelerate an electron to 30 GeV/c.