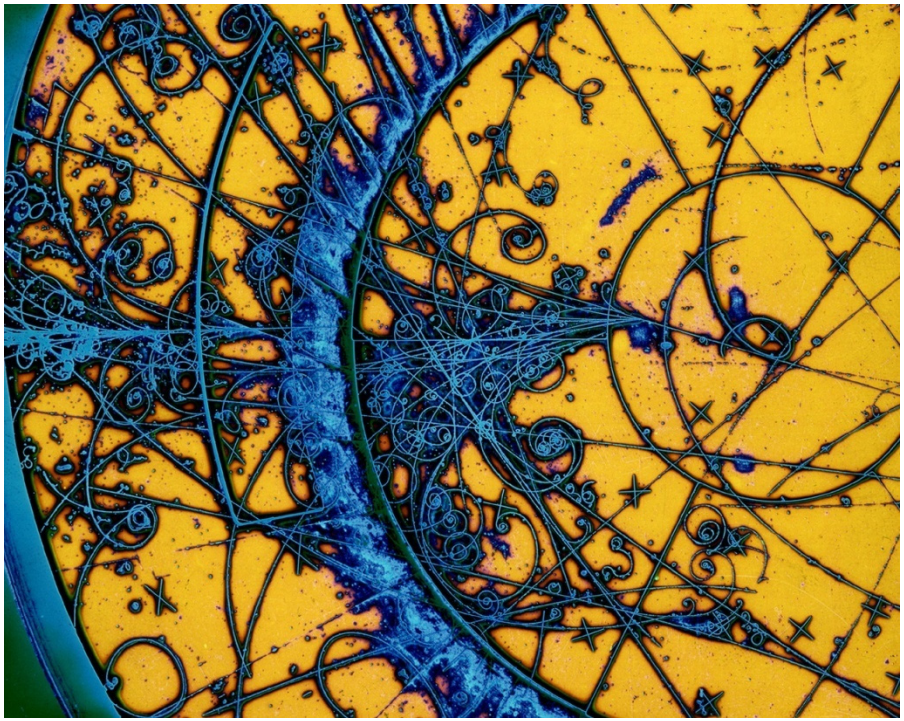
DETECTORS



Summer Lecture Series
SIST, 2009

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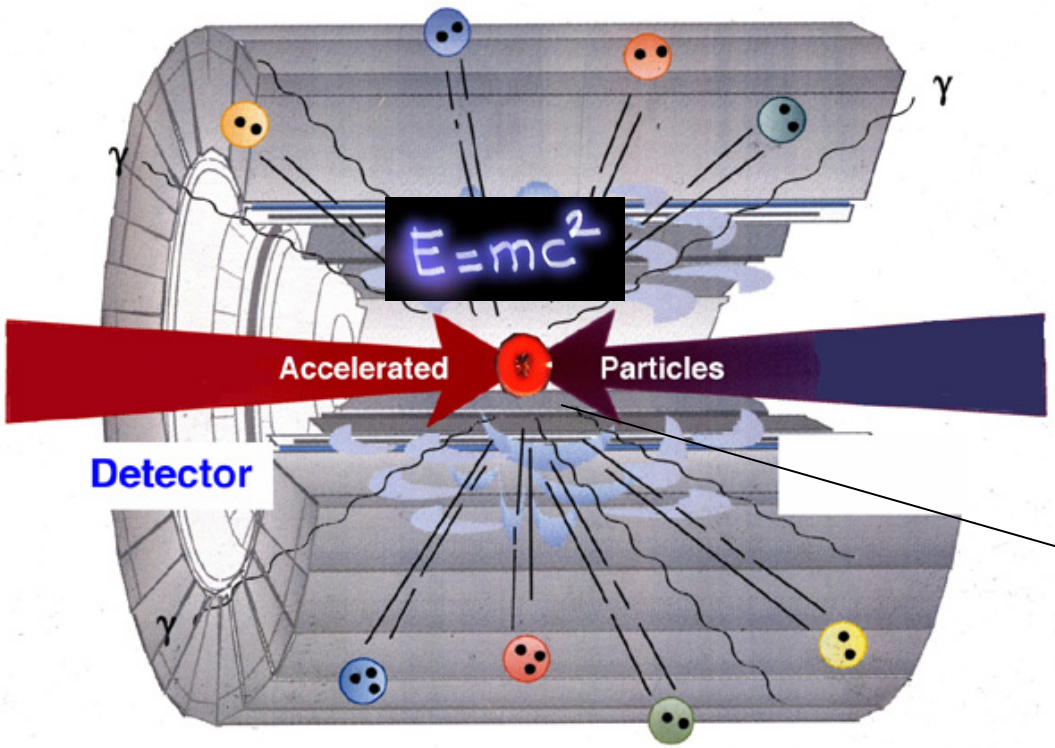
Particle Physics Division
Fermilab

July 20, 2009

This Lecture is about …

- March 23, 2007 issue of Science magazine
  - Picture of the CMS Detector under construction at the LHC at CERN
    - "Part of the cylindrical Compact Muon Solenoid particle detector descends to a hall 100 meters underground at the European particle physics laboratory CERN. The detector will capture the hail of particles produced when CERN's Large Hadron Collider smashes protons at unprecedented energies."
- Outline
  - Particles and their Interactions
  - Particle Detectors

Methods of Particle Physics



1) Concentrate energy on particles (**accelerator**)

2) **Collide** particles (recreate conditions after Big Bang)
- Collide two particle beams head on
- Collide particle beam with stationary target

3) Identify created particles in **Detector** (search for new clues)

- Generally two types of detectors:
  - Collider detectors for colliding beam experiments
  - Fixed target experiments for
    - Particle beams from accelerator on stationary target
    - Natural sources of particles: cosmic rays, neutrinos from the sun, …

What is a Particle Detector ?

- Oxford Dictionary
  - Particle:
    - a very small piece of matter, such as an electron or proton, that is part of an atom
  - Detector
    - piece of equipment for discovering the presence of something, such as metal, smoke, explosives or changes in pressure or temperature

- Particle detectors are extensions of our senses: make particles visible to human senses

- However, this definition of particle detector has limited emphasis

Tracks

- Particles leave tracks, just as animals leave tracks, from which we deduce their presence
- But, what more can we learn ?

- Which track is the deer mouse and which is the gray fox
- What more do the tracks tell us ?
  - how heavy was the animal ?
  - was the animal running ?
  - being hunted ?
  - tired ?
  - well fed ?
  - Did it have a tail ?

Measurement of Particle Properties

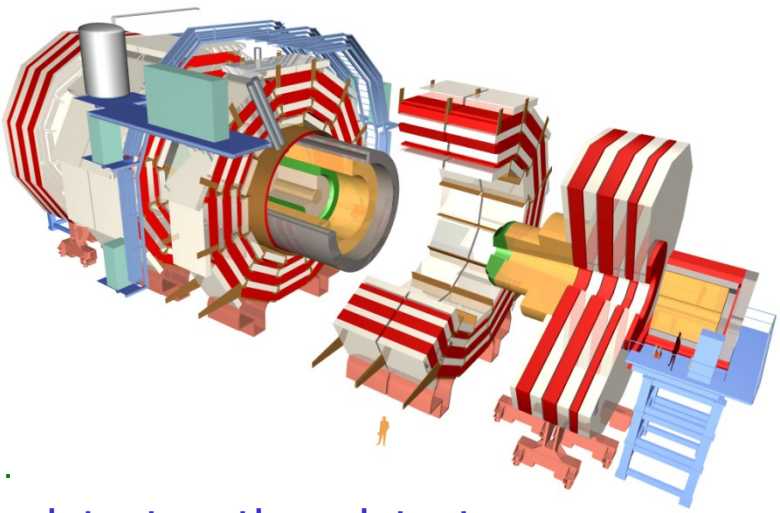
- The purpose of particle detectors is to fully reconstruct a recorded event
  - Identify the particles from the interaction
    - Electron, muon, quark, neutrino, pion, …
  - Measure as many (all) properties of the particles as possible
    - Mass, charge, momentum, spin, energy, lifetime, …
  - Reconstruct fundamental reaction mechanism
    - Weak decay, strong interaction, …
    - Often, we can only 'see' the end products of the reaction, but not the reaction itself, for example, when particles decay rapidly
- End result is the validation or falsification of a theory

- Purpose is to measure as many properties of all particles as possible

- Particles are detected through their interaction with matter
  - Many different physical processes involved mainly of electromagnetic nature
  - Ultimately, we will always observe ionization and excitation of matter

Detector Systems

- The 'ideal' particle detector should provide…
  - Coverage of full solid angle (no cracks, fine segmentation)
  - Measurement of momentum and/or energy
  - Detect, track and identify all particles (mass, charge, spin, …)
  - Fast response, no dead time, no noise
  - Satisfy all practical limitations
    - technology, accelerator, space, budget, safety, …



- Normally this cannot be achieved with a single detector; thus detectors are integrated into detector systems
- Integration depends on physics strategy
  - Fundamental properties of particles may dictate integration strategy
    - For example, short lifetimes of particles
  - Physics priorities
    - What are the most relevant parameters ?

- Particles are detected through their interaction with matter

Review Particles and Interactions

Matter Particles

Quarks

Electric Charge

Bottom	-1/3	2/3	Top
Strange	-1/3	2/3	Charm
Down	-1/3	2/3	Up

each quark: R, B, G 3 colours

Leptons

Electric Charge

Tau	-1	0	Tau Neutrino
Muon	-1	0	Muon Neutrino
Electron	-1	0	Electron Neutrino

Matter Particles and Interactions

Quarks

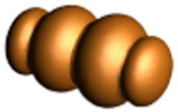
Electric Charge

Bottom	-1/3	2/3	Top
Strange	-1/3	2/3	Charm
Down	-1/3	2/3	Up

each quark: R, B, G 3 colours

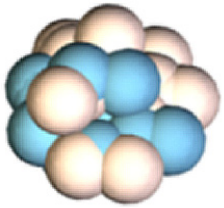
Strong

Gluons (8)



Quarks

Mesons
Baryons



Nuclei

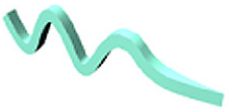
Leptons

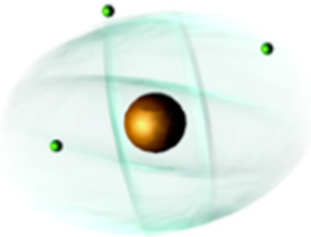
Electric Charge

Tau	-1	0	Tau Neutrino
Muon	-1	0	Muon Neutrino
Electron	-1	0	Electron Neutrino

Electromagnetic

Photon

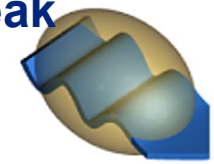


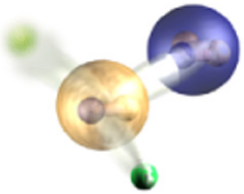


Atoms
Light
Chemistry
Electronics

Weak

Bosons (W,Z)

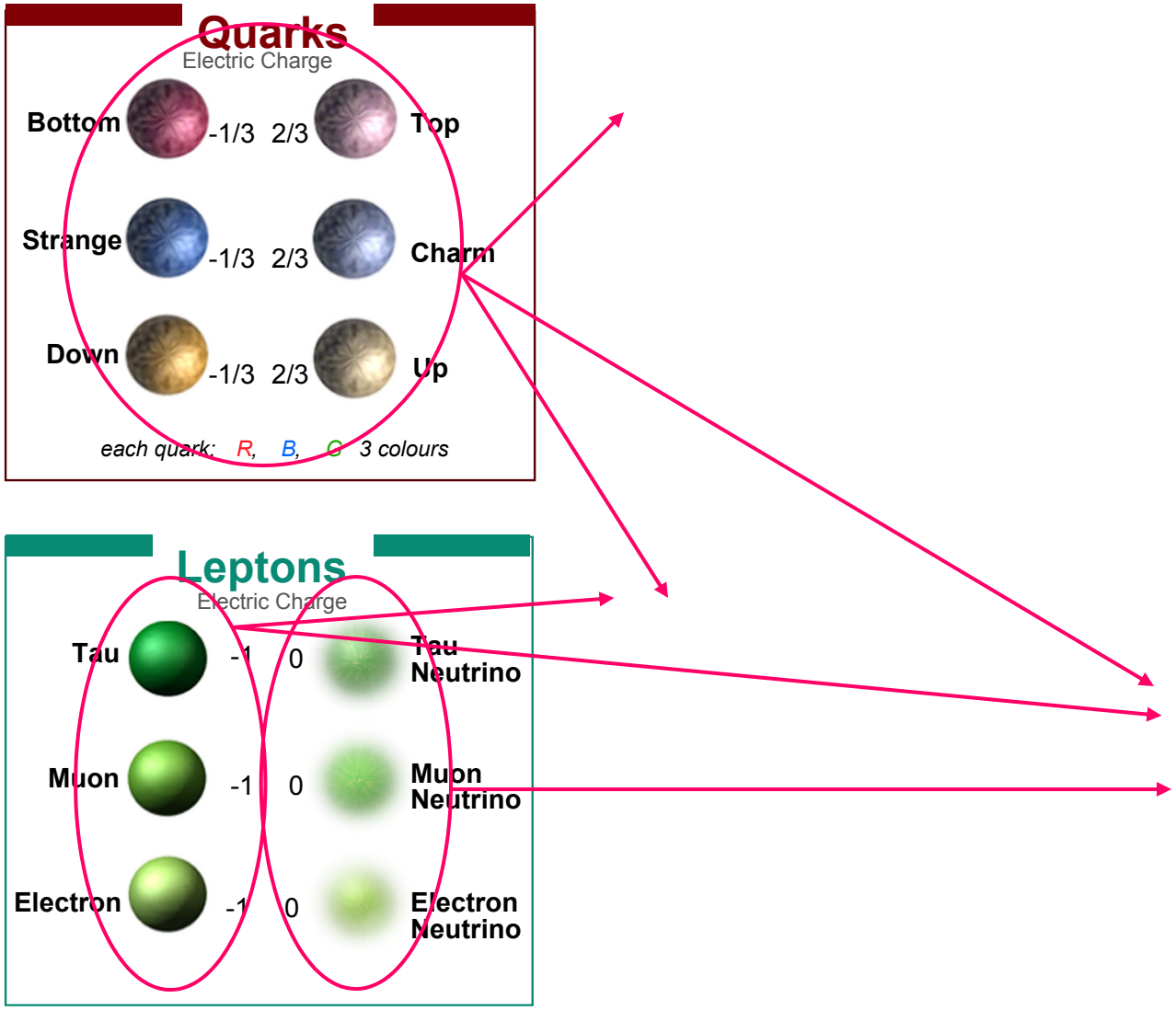




Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun

The particle drawings are simple artistic representations

Matter Particles and Interactions



Principles of Particle Detection and Detection Techniques

Some Definitions

- Einstein Equation

$$E = m\,c^2 = \gamma\, m_0\, c^2; \quad E^2 = p^2 c^2 + m_0^2 c^4$$

c: *speed of light in vacuum*
E: *Energy*
m_0: *rest mass*

- Relativistic factors

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \quad (1 \le \gamma \le \infty) \qquad \beta = \frac{v}{c} \quad (0 \le \beta \le 1)$$

- Units
  - Energy and mass normally expressed in eV: energy an electron gains when passing a potential difference of 1 Volt: 1 eV=1.6 10^{-19} Joule
  - Speed of light often set to 1
  - Example: proton has total energy equal to twice its rest mass: $\gamma = 2$

$$\gamma = \frac{E}{m_0} \qquad \beta = \sqrt{1-\frac{1}{\gamma^2}}$$

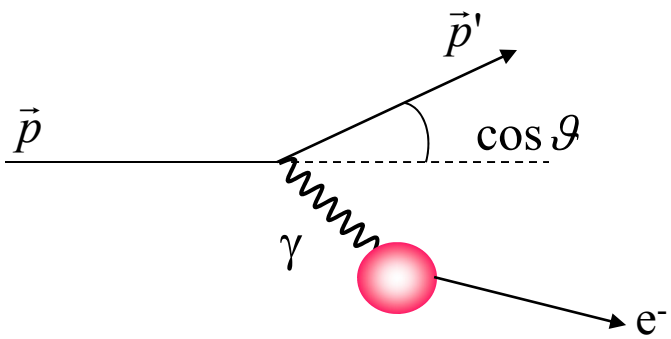
β = 0.87: 87% of the speed of light

- Momentum

$$p = m\,v = \gamma\, m_0\, \beta\, c = E\,\beta / c \qquad \Rightarrow \quad \beta = \frac{p\,c}{E}$$

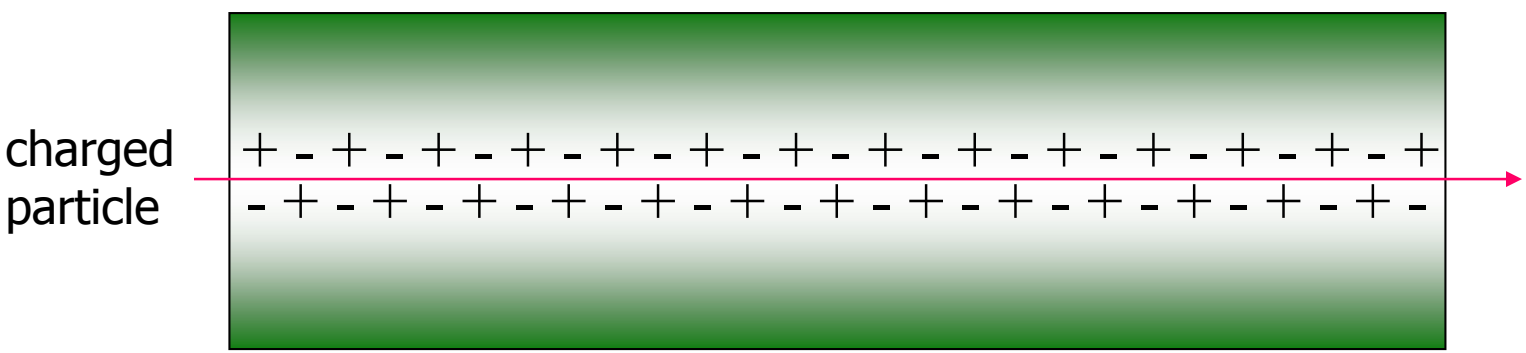
Interactions of Heavy Charged Particles

- Incoming charged particle with charge *z* interacts elastically with a target with charge Z and scatter, cf. Rutherford scattering
  - Does not lead to significant energy loss
- Charged particle loses energy through discrete collisions with the atomic electrons of the target
  - Ionization: pass through material and knock electrons off atoms
- Leaves positive ions and free electrons



$$\left\langle \frac{dE}{dx} \right\rangle = -\int_0^\infty N\,E\,\frac{d\sigma}{dE}\,\hbar\,d\omega$$

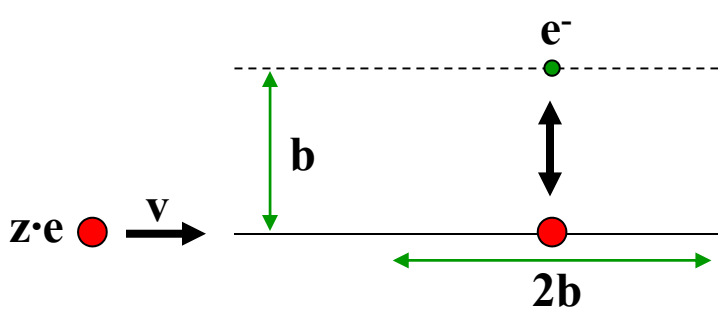
N : *electron density*



- determine amount of energy lost per unit distance traveled

Appoximation of Average Energy Loss

- Approximate "derivation" of average energy loss
- Determine energy loss for single encounter with an electron



$$F_c = \frac{ze^2}{b^2} \qquad \Delta t = \frac{2b}{v} \qquad \Delta p_e = F_c\ \Delta t$$

$$\Delta E_e = \frac{(\Delta p_e)^2}{2m_e} = \frac{2z^2e^4}{b^2v^2m_e} = \frac{2r_e^2 m_e c^2 z^2}{b^2} \cdot \frac{1}{\beta^2}$$

$$with\ \ r_e = \frac{e^2}{m_e c^2}$$ classical electron radius

Number of encounters proportional to the electron density in the medium:

$$N_e \propto \frac{Z}{A} N_A \cdot \rho$$

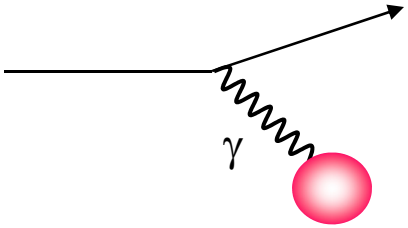
Z=atomic number, A=atomic mass,
N_A = Avogadro's number, ρ=density

Multiply factors:

$$\left\langle \frac{dE}{dx} \right\rangle = r_e^2 m_e c^2 z^2 N_A \frac{Z}{A} \frac{1}{\beta^2} \cdot \cancel{\frac{2b}{b^2}} \cdot 4\pi \left[\ln \frac{2m_e c^2 \beta^2 \gamma^2}{I} - \beta^2 - \frac{\delta}{2} \right]$$

Average Energy Loss: Bethe-Bloch

- Energy loss by heavy charged particle ($M > m_\mu$)
  - primarily by ionization and atomic excitation
  - mean rate of energy loss given by Bethe-Bloch equation



$$\left\langle \frac{dE}{dx} \right\rangle = -K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{2 m_e c^2 \beta^2 \gamma^2}{I} - \beta^2 - \frac{\delta}{2} \right]$$

$$K = 4\pi N_A r_e^2 m_e c^2$$

$$Z = Atomic\ number\ of\ Absorber$$

$$A = Atomic\ mass\ of\ Absorber$$

$$I = Mean\ excitation\ energy$$

$$\delta = density\ effect\ correction$$

- dE/dx in units of MeV g^{-1} cm^2; multiply by density to get energy loss
- dE/dx depends only on β, independent of M
- $I \approx I_0 Z$, with $I_0 \approx 10$ eV
- Z/A does not differ much for most elements, except for hydrogen

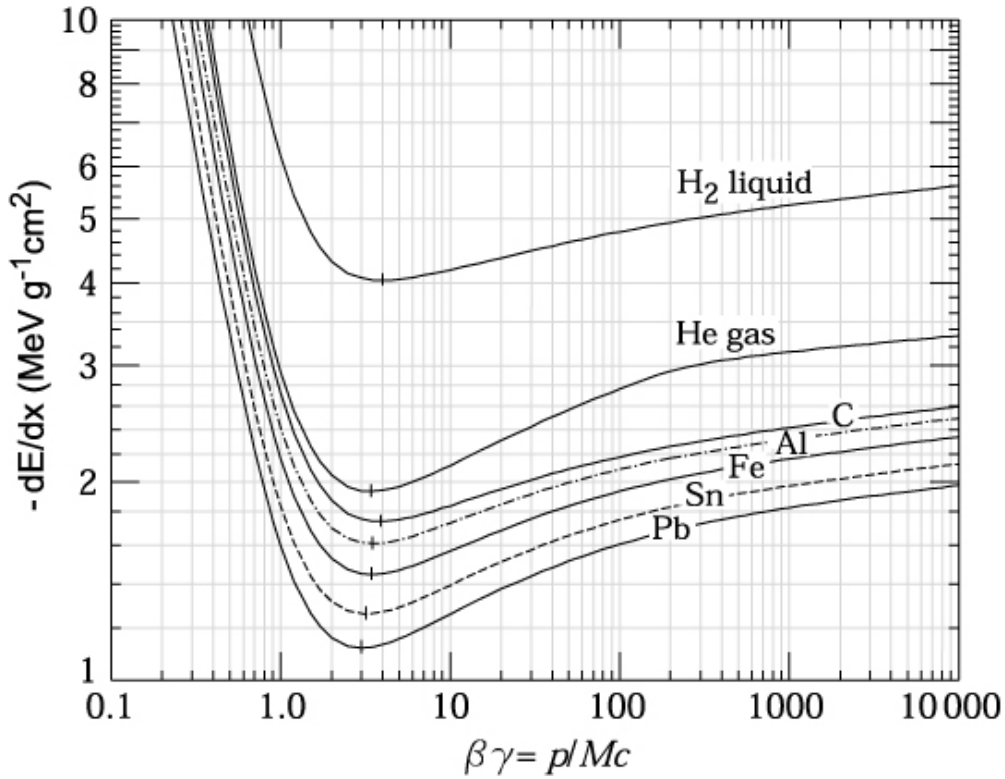
Bethe-Bloch

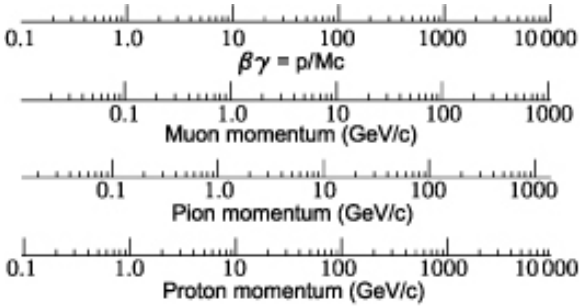
$$\left\langle \frac{dE}{dx} \right\rangle = -K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{2 m_e c^2 \beta^2 \gamma^2}{I} - \beta^2 - \frac{\delta}{2} \right]$$

- dE/dx first falls ~ $1/\beta^2$
- dE/dx minimum at 3.0 – 3.5
- dE/dx minimum of 1 – 2 MeV g^{-1} cm^2 Minimum Ionizing Particle (MIP)
- At high $\beta\gamma$ relativistic rise due to ln $\gamma^2\beta^2$, attributed to relativistic expansion of EM-field: contribution from more distant collisions
- Relativistic rise cancelled by density effects, δ

- Striking uniformity for all elements !

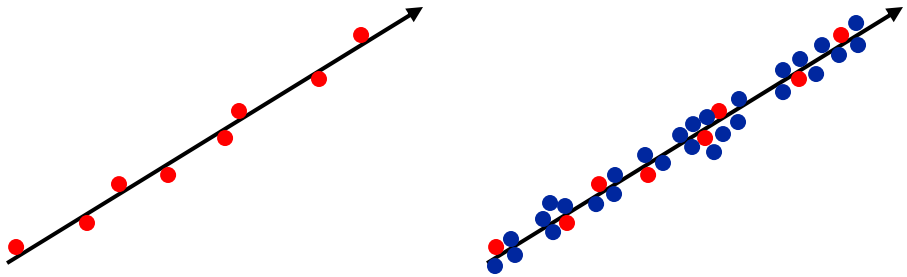
- Measure energy loss and momentum: particle identification !





Ionization Chambers

Ionization



- Use chambers filled with active medium (gas, liquid)
- Traversing fast charged particle will ionize the medium

- Often resulting primary electron will have enough kinetic energy to ionize other atoms

$$n_{total} = \frac{\Delta E}{W_i} = \frac{\frac{dE}{dx}\Delta x}{W_i}$$

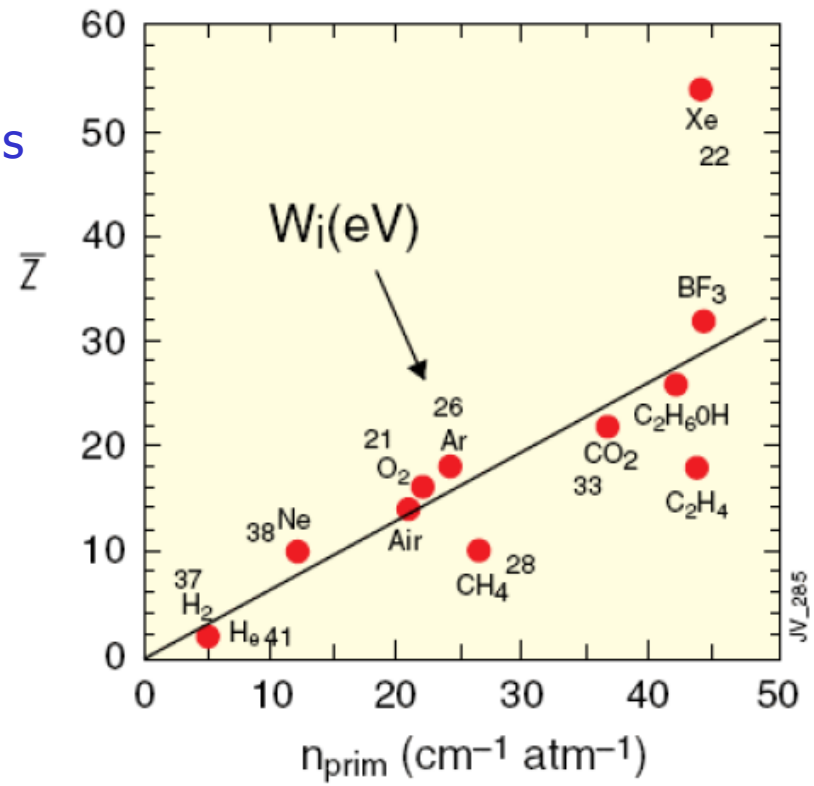
$$n_{total} = 3 \ldots 4 \cdot n_{primary}$$

n_{total} = number of created e^--ion pairs

ΔE = total energy loss

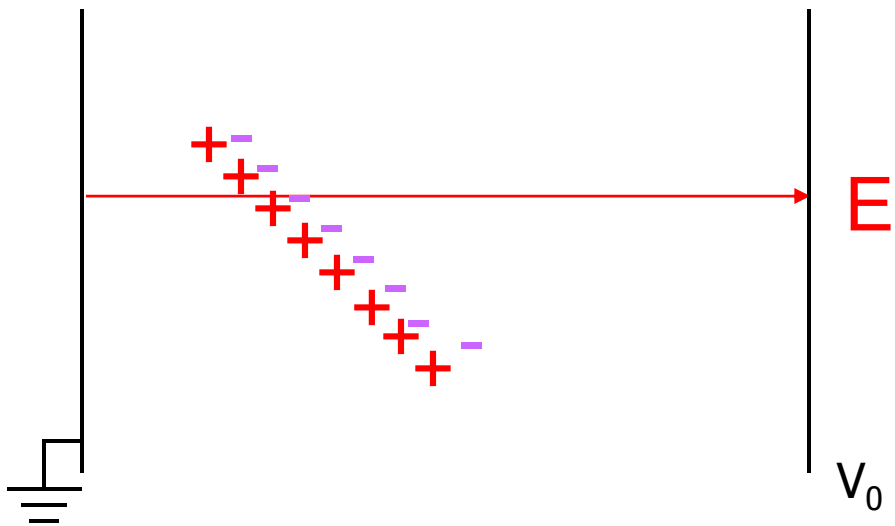
W_i = effective average energy loss /pair

- N_{prim} for different gases as function of Z, with W_i (eV)



Ionization and Gas Amplification

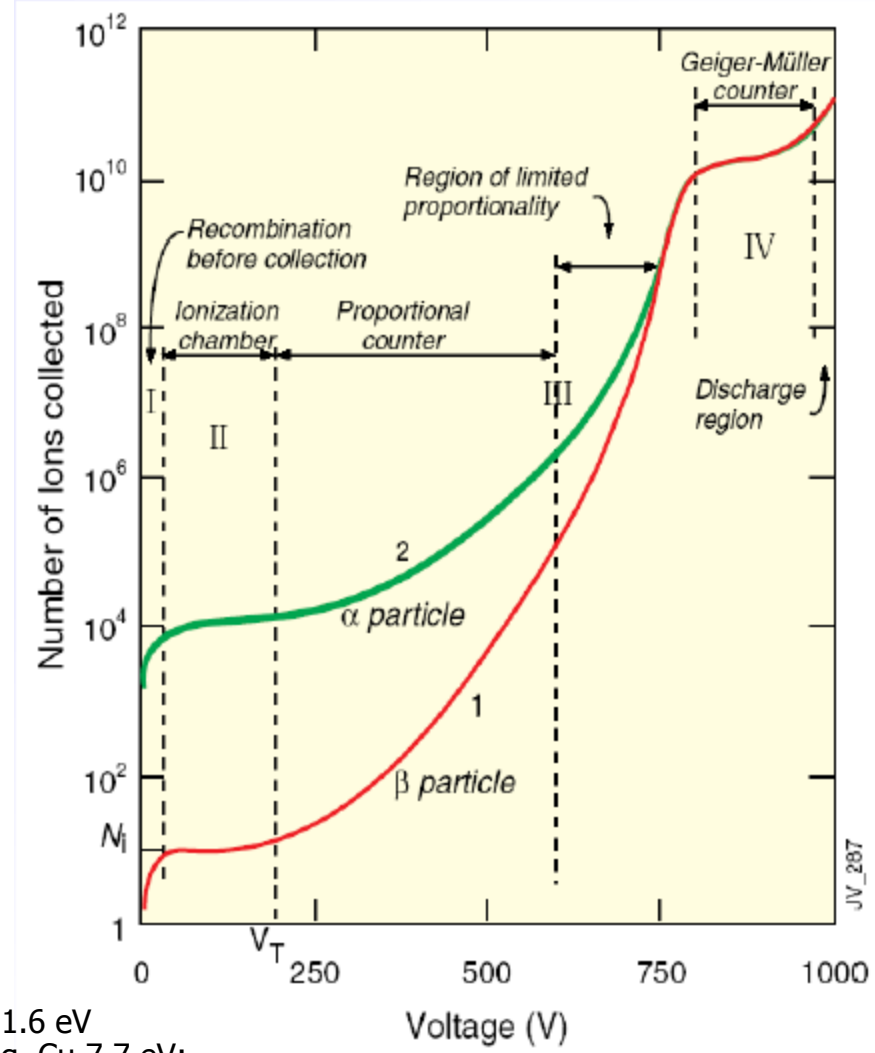
- Collect the charge using drift in electric field; apply voltage across electrodes
- Traversing charged particle will ionize the medium
  - In low fields the electrons eventually recombine with the ions: recombination
  - Under higher fields it is possible to separate the charges and collect the signal
  - Primary signals are small; generally need some for of amplification



- Note: electrons and ions generally move at very different rate (mobility)

Operating Modes

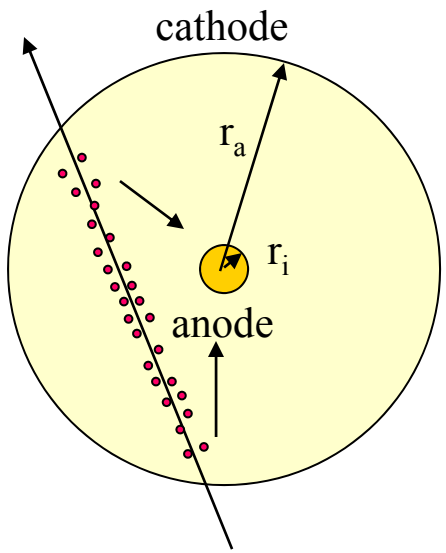
- Recombination mode
  - No charge collection
- Ionization mode
  - Full charge collection, but no charge multiplication; gain ~ 1
- Proportional mode
  - Multiplication of ionization; detected signal proportional to original ionization → possible energy measurement (dE/dx); secondary avalanches have to be quenched; gain ~ 10^4 – 10^5
- Limited proport. mode (saturated, streamer)
  - Strong photoemission; secondary avalanches merging with original avalanche; requires strong quenchers or pulsed HV; large signals → simple electronics; gain ~ 10^{10}
- Geiger mode
  - Massive photoemission; discharge stopped by HV cut; strong quenchers needed as well

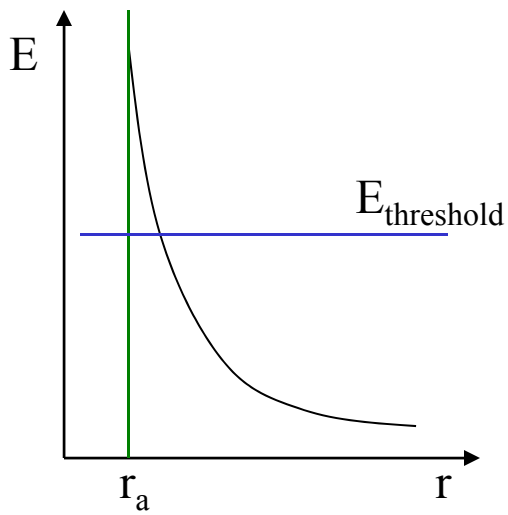


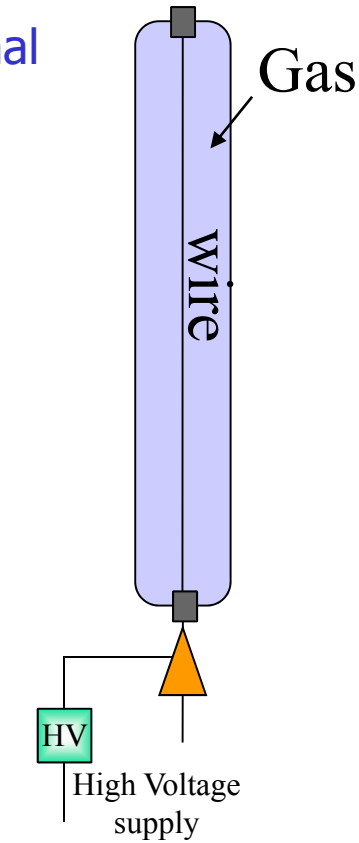
- Quenching
  - De-excitation of gases via emission of photons; e.g. 11.6 eV for Ar. This is above ionization threshold of metals; e.g. Cu 7.7 eV: permanent discharge
  - Solution: addition of polyatomic gas as a quencher: Absorption of photons in a large energy range

Proportional Counter

- small signals are difficult to detect. Intrinsic amplification of signal







$$V(r) = V_0 \frac{\ln r/r_a}{\ln r_i/r_a}$$

$$\vec{E}(r) = -\frac{V_0}{\ln r_a/r_i}\frac{1}{r}$$

- Electrons drift towards anode wire
- Close to the anode wire the field is sufficiently high that e^- gain enough energy for further ionization
  - Exponential increase in the number e^--ion pairs: gas amplification

Geiger – Müller Counter

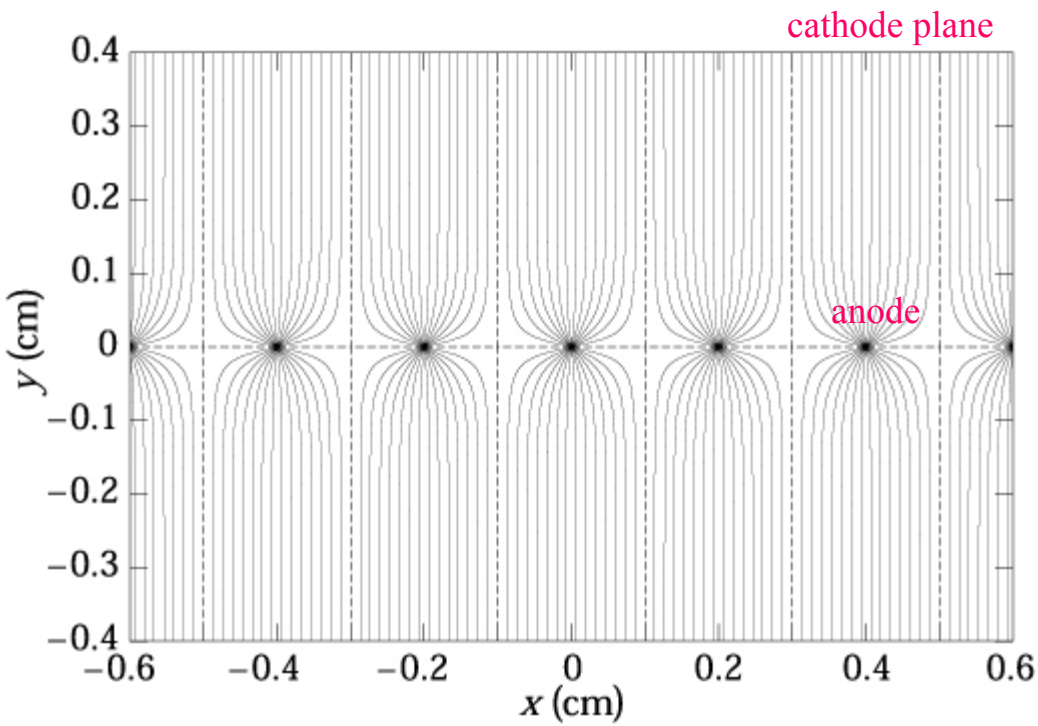
- Particles pass through gas filled tube
- Avalanche: total charge independent of initial ionization
- Current causes counter to chirp
- One particle one chirp
- Used to verify if there is radioactive material present

- Summary modes of operation:
  - (Recombination)
  - Ionization mode
  - Proportional mode
  - Geiger mode

Gaseous Tracking Chambers

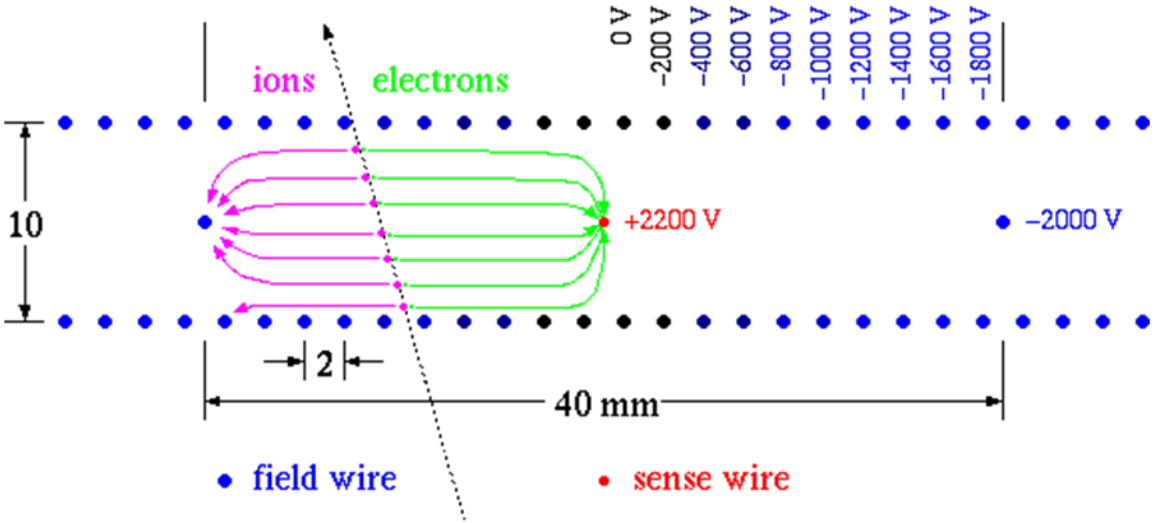
Multi Wire Proportional Chamber (MWPC)

- Invented by George Charpak, 1962 (Nobel Prize 1992)
- Ultimate goal is complete 3-d track reconstruction over large area
  - with high resolution
  - high repetition rate (fast)
  - high occupancy: many particles at the same time
- Employ large chamber with many wires, each wire acts as separate detector



- Field configuration
  - anode pitch = 2 mm
  - anode wire diameter = 10 μm
    - spatial resolution of ~ 0.5 mm
    - Timing resolution of ~ 30ns
- Drawback: need lots of wires

Drift Chamber

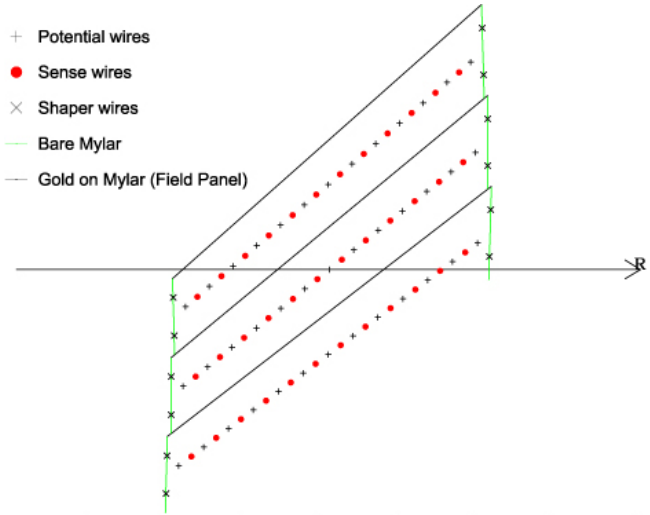


measure arrival time of electrons on sense wire relative to a reference time t_0

$$x = v_D \cdot t_D$$

typical drift velocity
$v_D = 5$ cm/μs

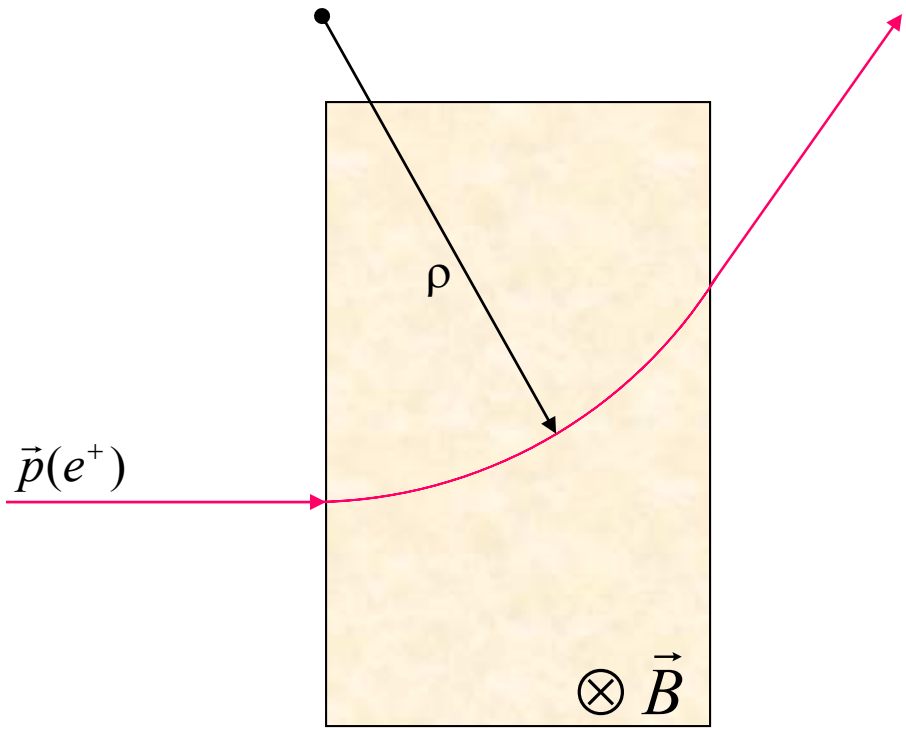
- Fewer wires, less electronics, less support structure than MWPC
- Using field shaping wires, electrical field can be shaped is any desired configuration
- With the advance of fast readout electronics, measurement of drift time possible



Momentum Measurement

- Charged particle moving in magnetic field will experience Lorentz force

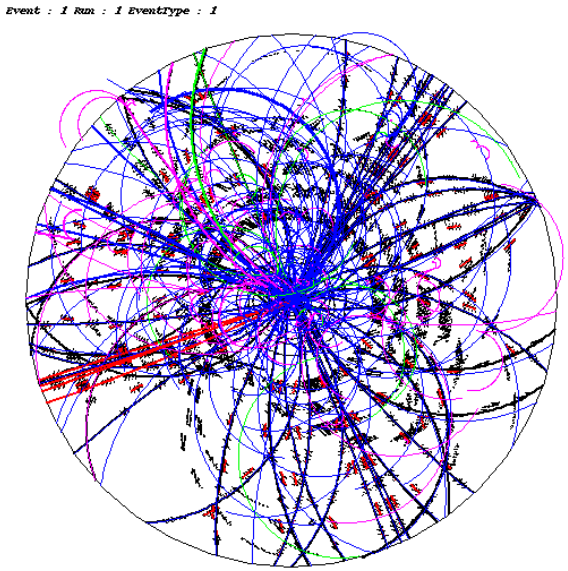
$F_L = q\ \vec{v} \times \vec{B}$ which equals centrifugal force $F = \dfrac{m v^2}{\rho}$



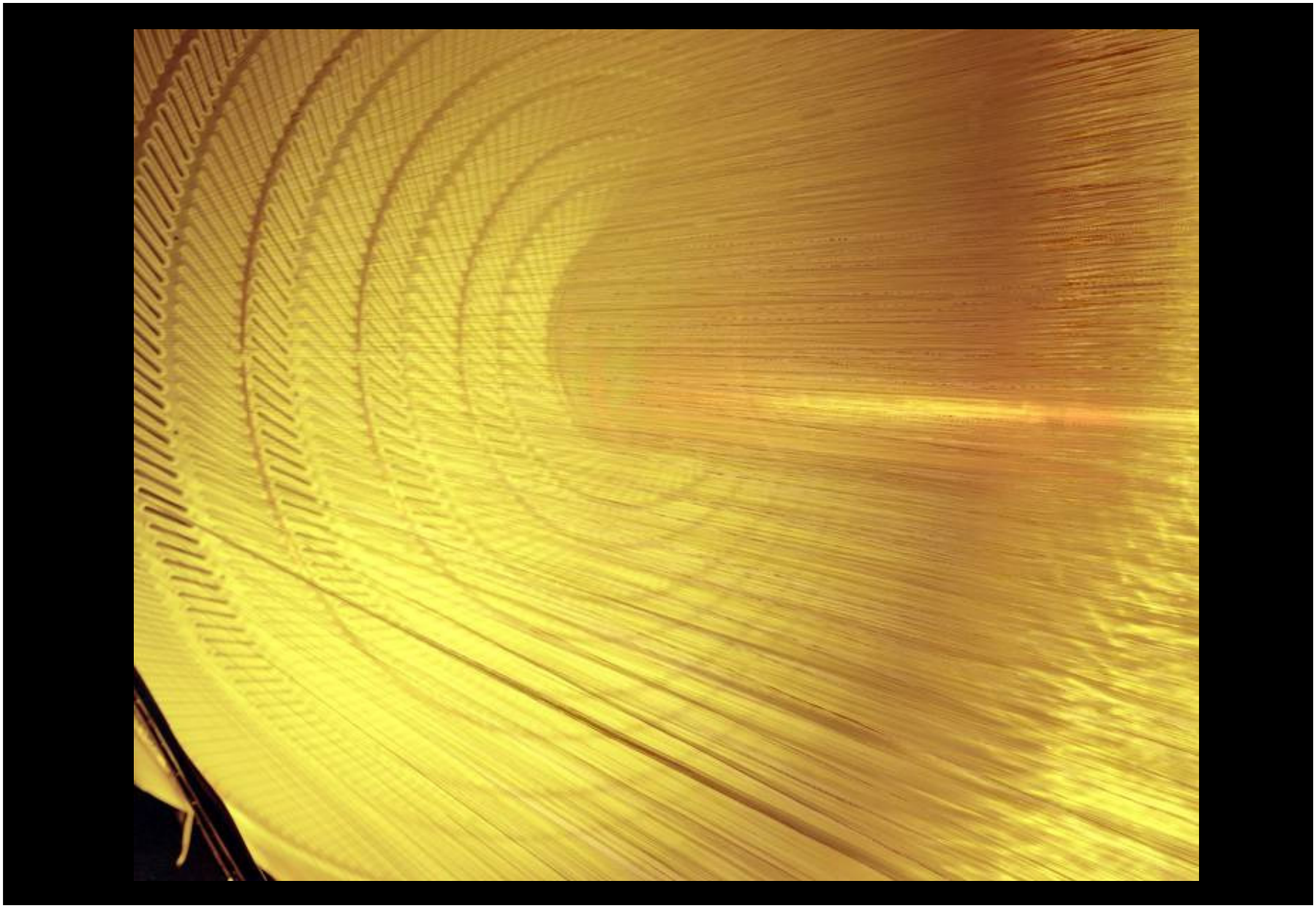
- If particle moves perpendicular to magnetic field: $p = q\,B\,\rho$
- The faster the particle goes, the more magnetic field is needed for the same deflection

CDF: Outer Tracking System

- CDF: Drift chamber
  - Eight planes of axial and stereo sense wires

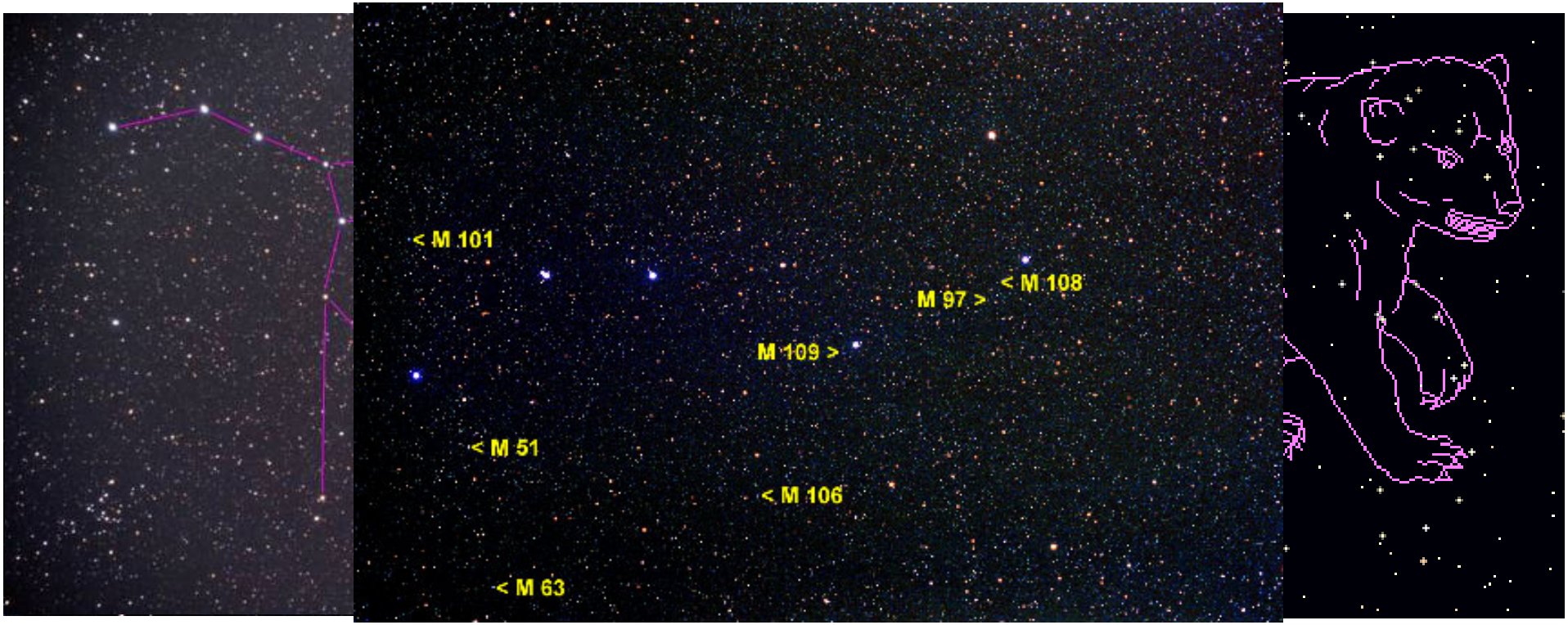


CDF Central Outer Tracker



Pattern Recognition

- Spotting constellations and galaxies



Ursa Major (Big Bear) is the third largest constellation in the skies, seen at northern sky in evening of spring. The constellation has no first magnitude stars, but the Big Dipper that forms the bear's tail is a rough guide on the clarity of the evening's sky.

Picture taken March 25, 2000, Japan

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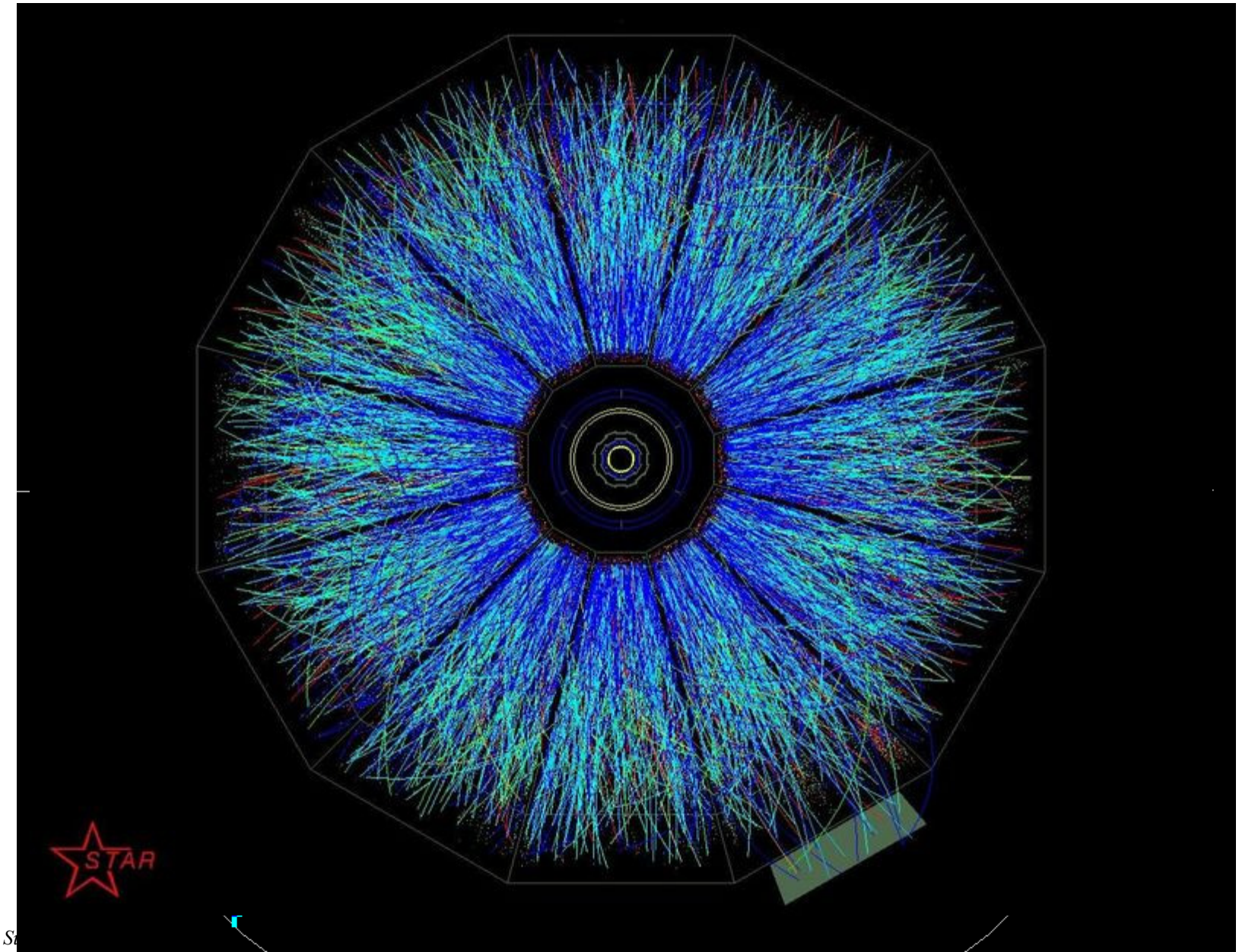
http://www.ne.jp/asahi/stellar/scenes/english/seiza.htm
from O. Ullaland

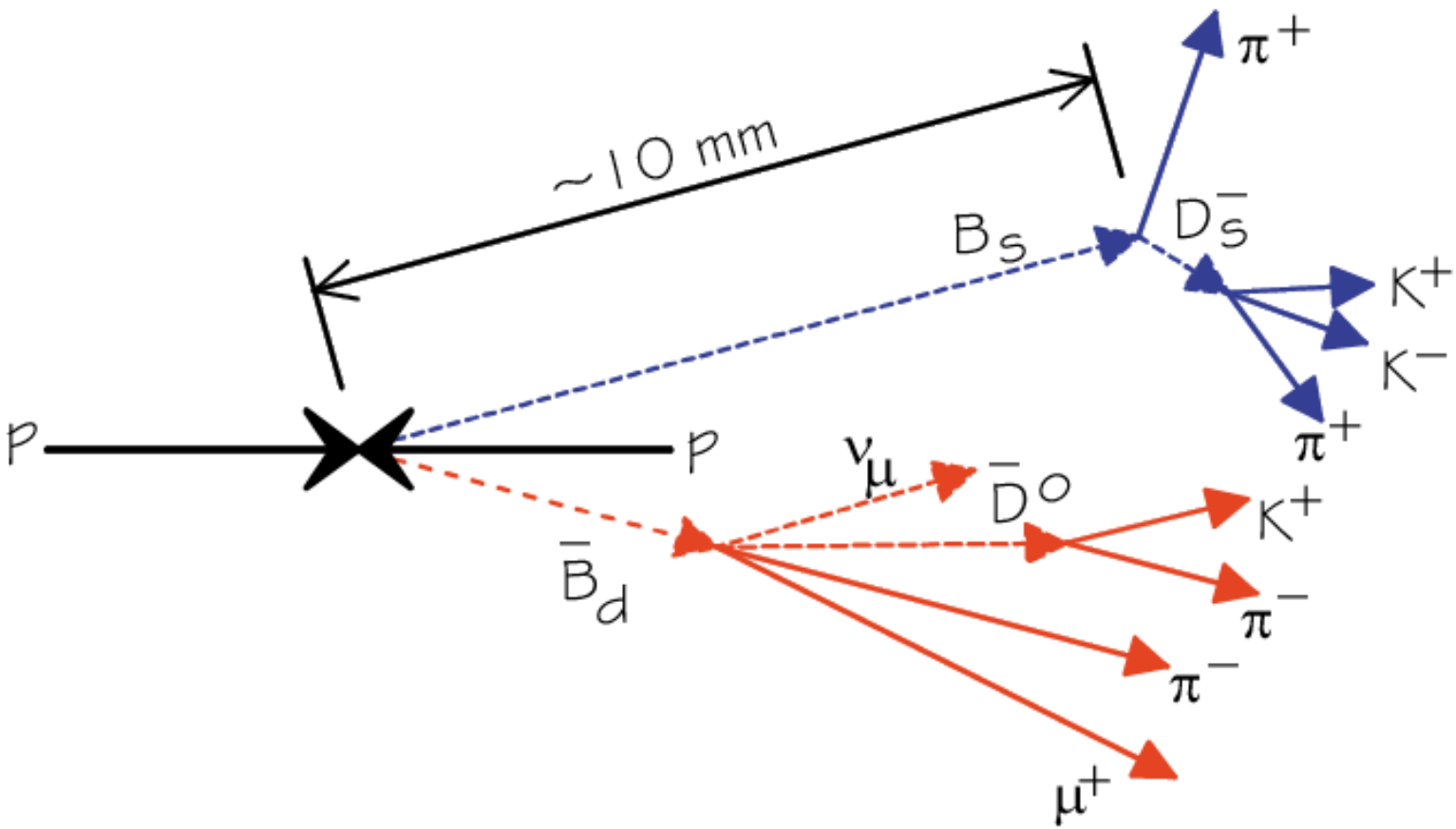
Pattern Recognition



Solid State Tracking

'Ultimate' Precision

- What do you do if you want to measure not only the primary interaction point, but also secondary decay vertices?
- Lifetime of particles of order 10^{-12} s, decay length of order cm

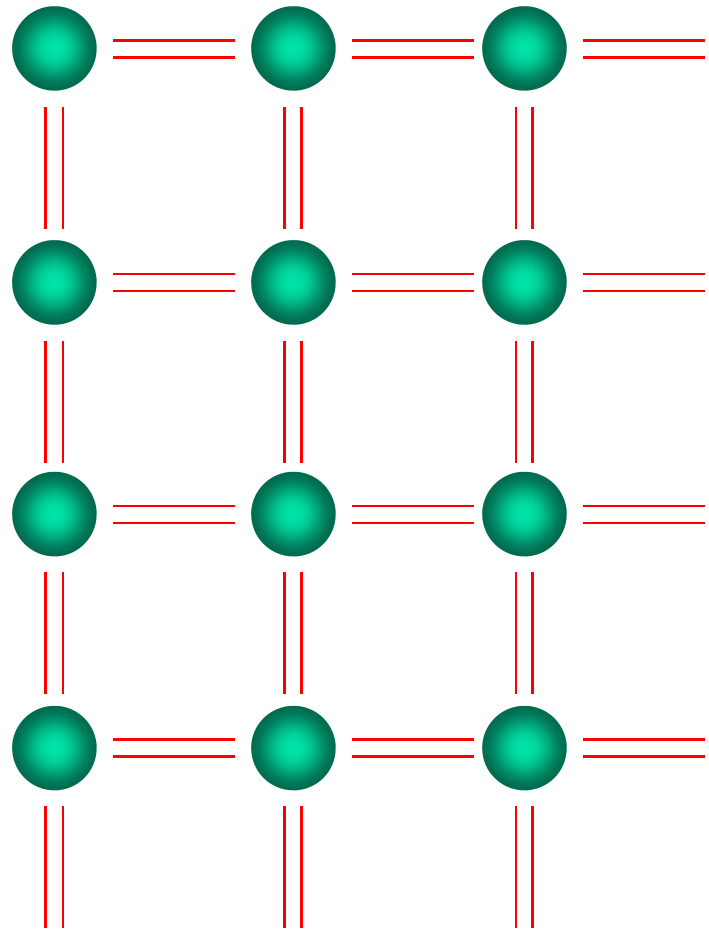


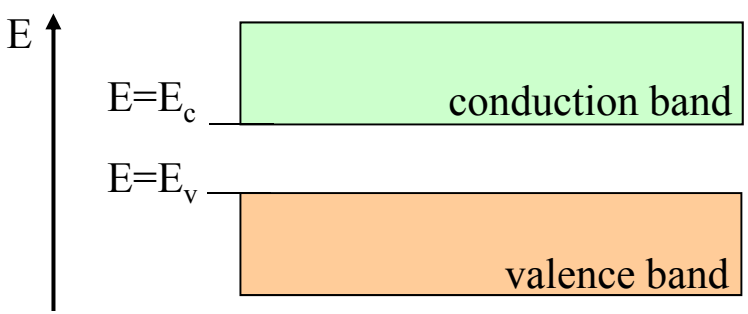
Solid State Detectors

- Tracking detectors thus far use gas as active medium
  - Energy required for e^--ion pair creation about 30 eV
  - Long drift times, slow charge collection
  - Limited hit resolution
  - ……
- Benefit from the enormous progress in the IC industry
- Employ solid state detectors: Silicon
  - Energy required for e^--hole creation 3.6 eV
  - Fast charge collection (high mobility)
  - Better hit resolution
  - Rigidity of solid state detector allows self supporting structures
  - High efficiency and low dead time
  - Good signal to noise ratio, but no charge multiplication
  - Integrated electronics

Silicon

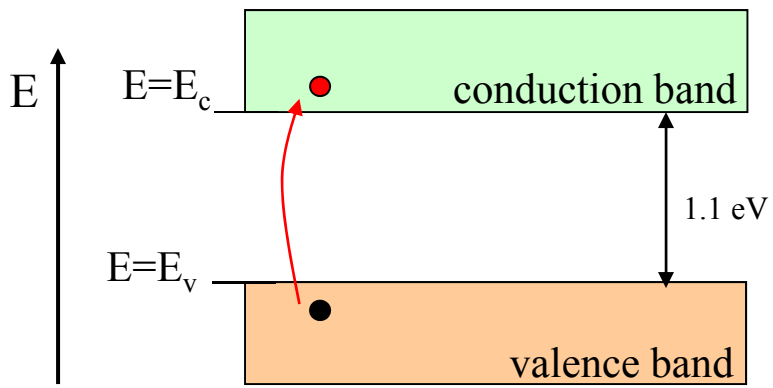
- Si is element number 14 and has four electrons in its outer shell
- Crystalline Si has a diamond crystal structure
  - Each atom has four neighbors
  - Electrons form perfect covalent bonds with its neighbors
- When atoms are brought together and form a solid, the discrete atomic energy levels an electron can occupy become bands of energy levels
  - continuous band: conductor
  - intermediate gap: semi-conductor
  - large gap: insulator
- Silicon is a semi-conductor

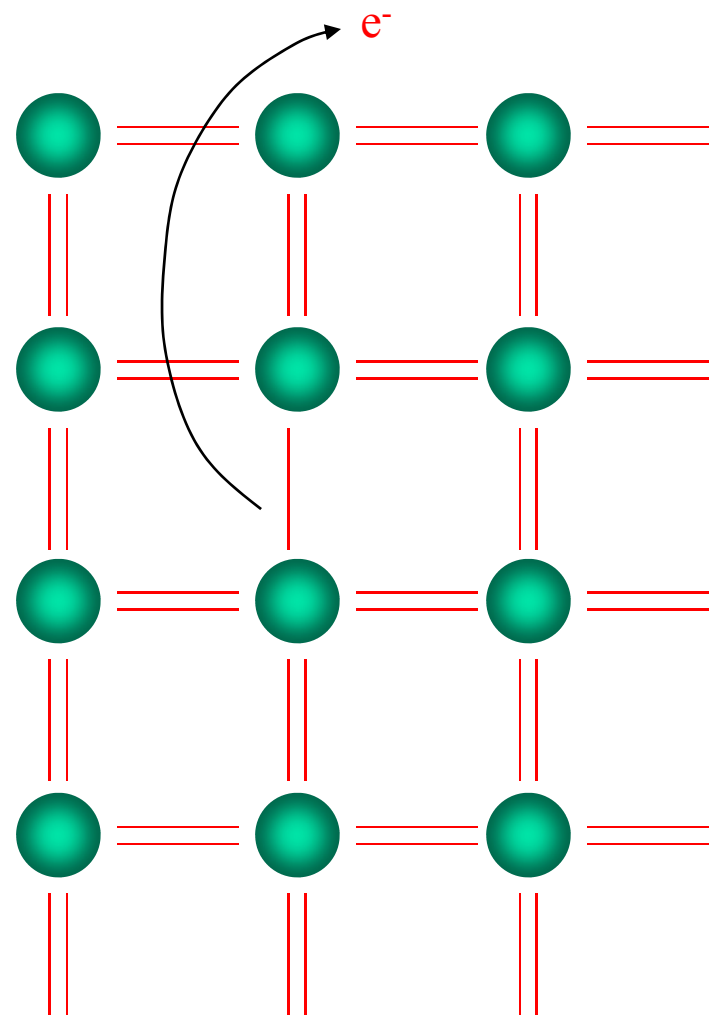




Ionization and Holes

- Ionization can promote electrons from the valence to the conduction band
- Electrical conduction takes place via two modes of electron motion:
  - Can be viewed as motion of e^-'s with charge -q and effective mass m^*_e
  - and can be viewed as motion of holes, +q, m^*_h

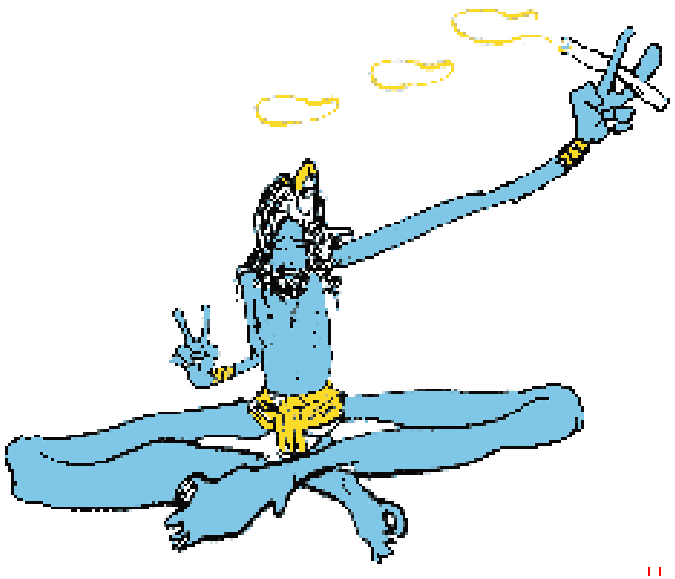


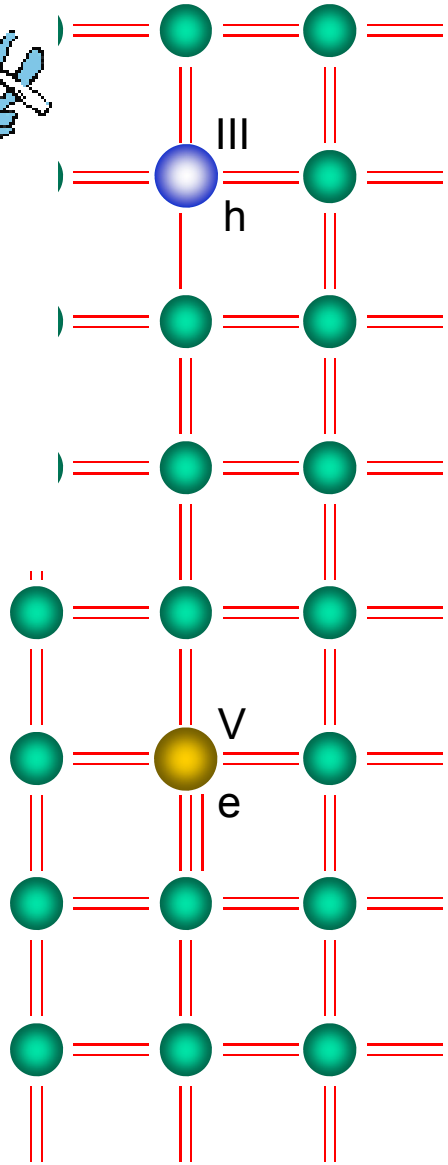


Silicon Neighbors

Doping

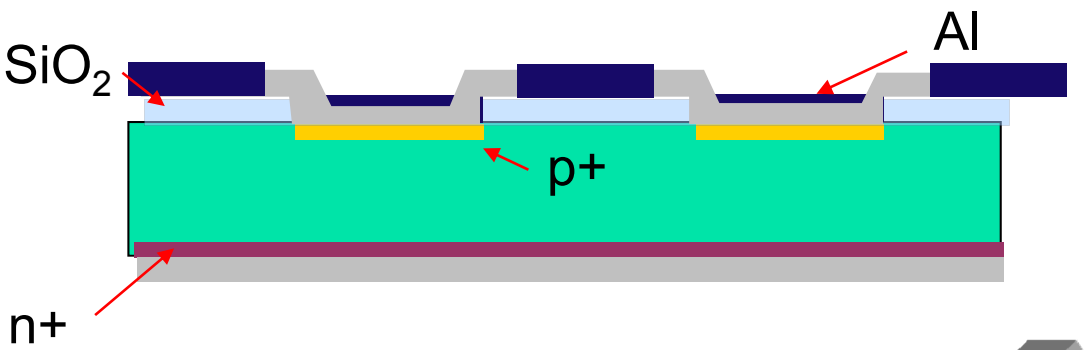
- Intrinsic properties of Si can be changed substantially by impurities: doping
- Add group III element (e
  - only three electrons in
  - acceptor type atoms
  - majority carriers=holes
  - p-type
- Add group V element (e.
  - have five electrons in o
  - donor type atoms
  - majority carrier=e's
  - n-type
- Combining p- and n-type silicon to make diodes, transistors, … all integrated in one piece of silicon
- Use extensive expertise in IC industry to make silicon tracking detectors



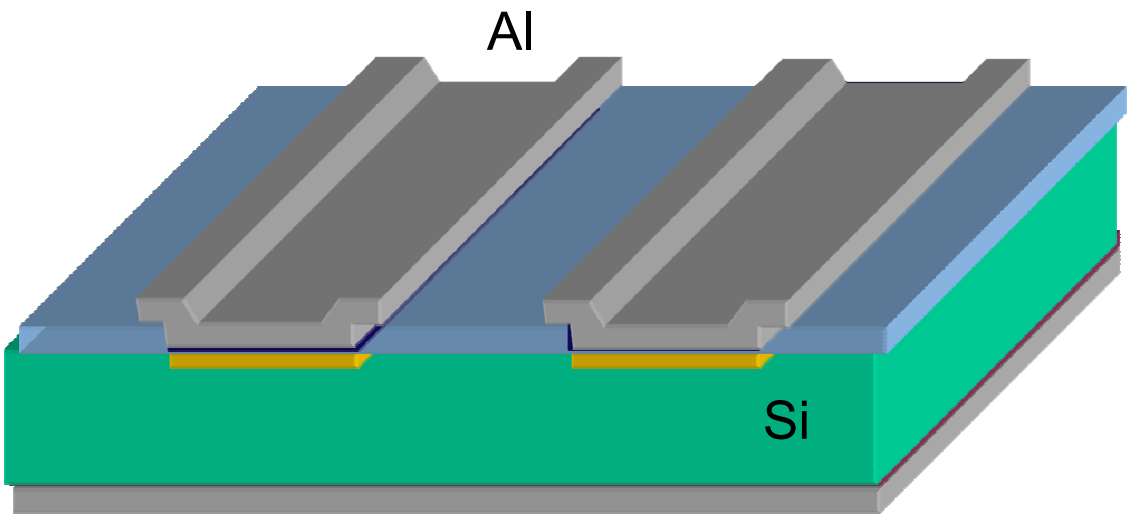


Silicon Strip Detectors

- Using processing from IC industry, can build silicon strip detectors



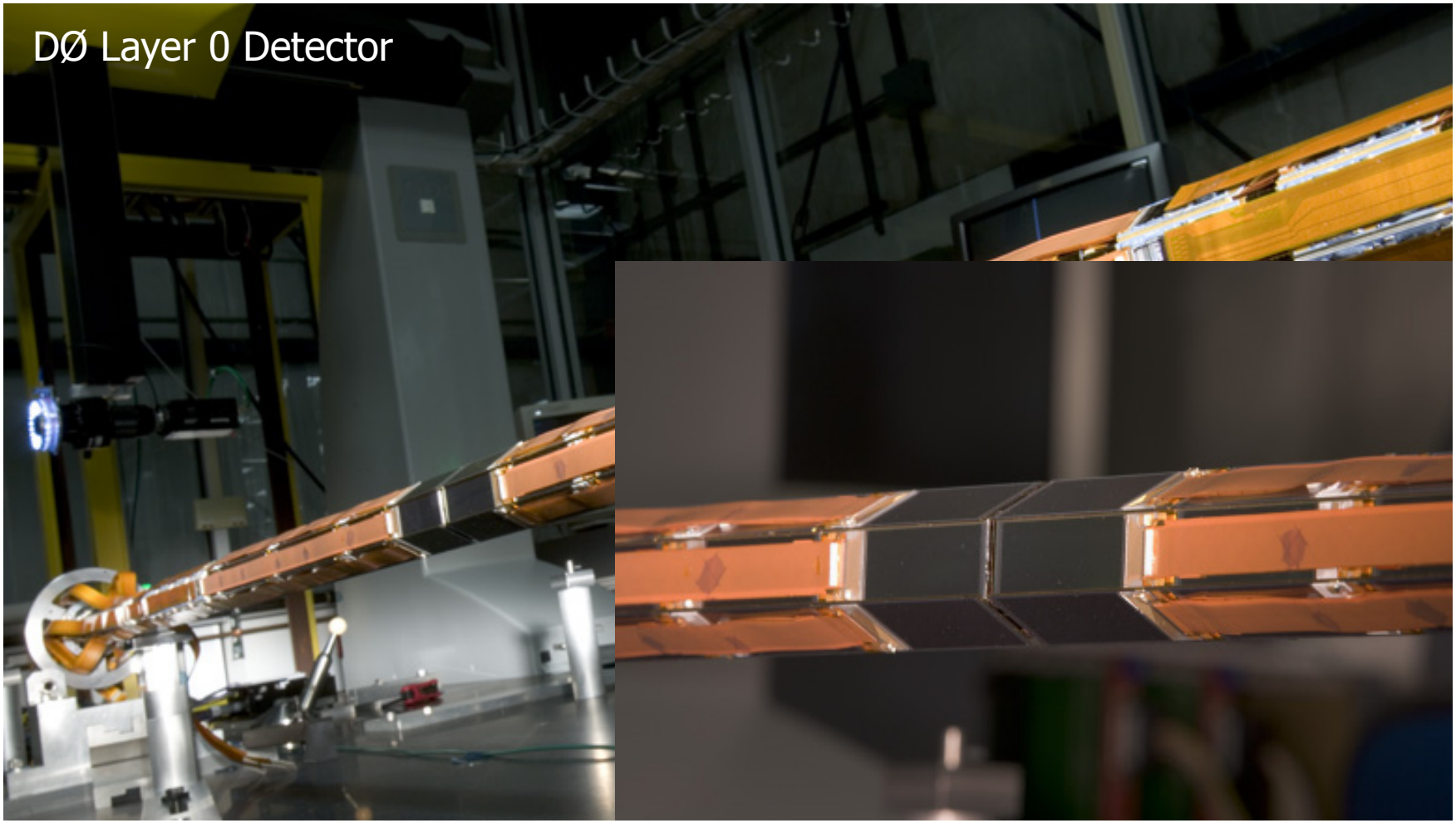
- Distance between strips (pitch) can be as small as 25 μm
- Length of strip can vary from mm's to 10 cm



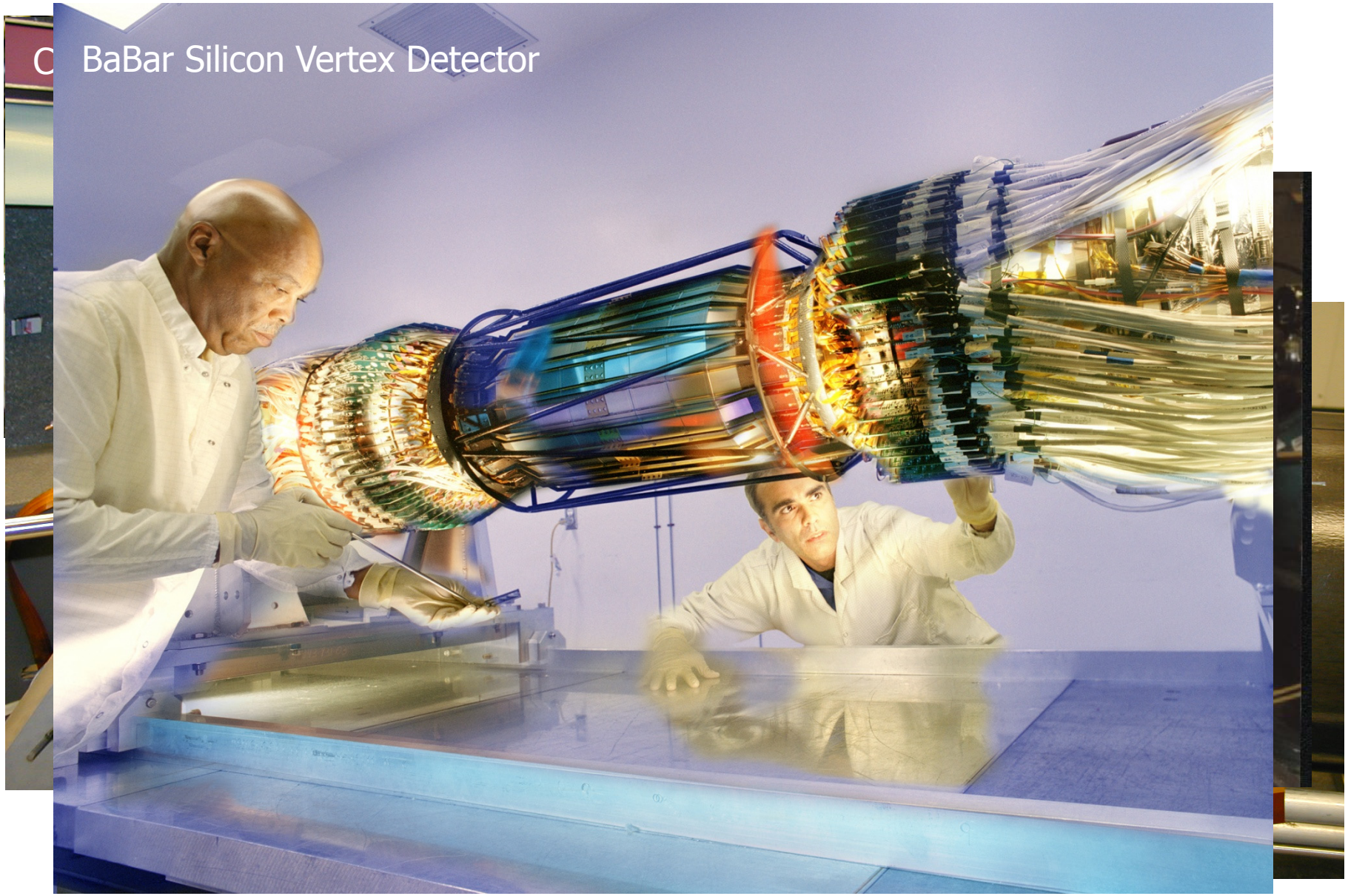
- Each strip acts as detector
  - Much better resolution than drift chamber
  - Robust and fast signal
  - Expensive

Silicon Vertex Detector

- The closer you get to the interaction point, the higher the precision for track reconstruction

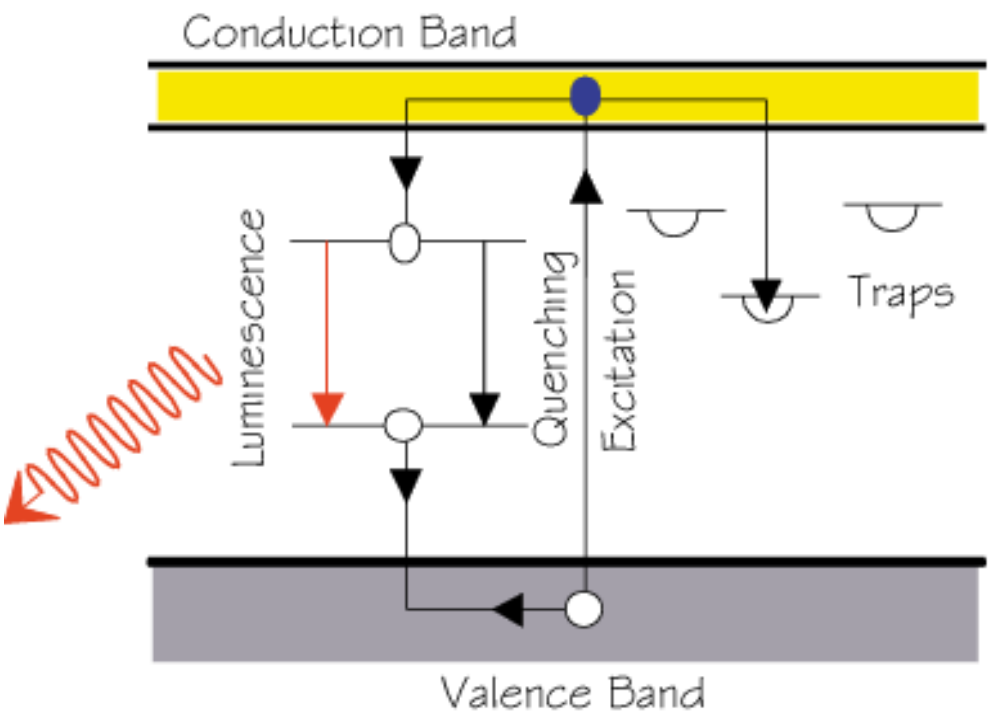


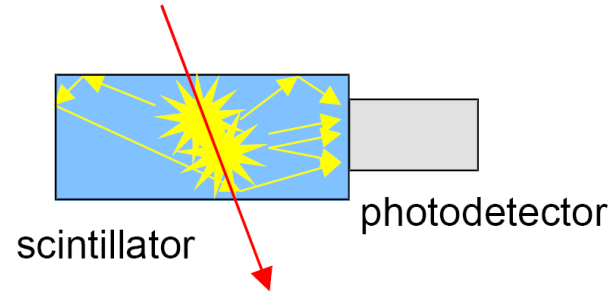
Silicon Vertex Detectors

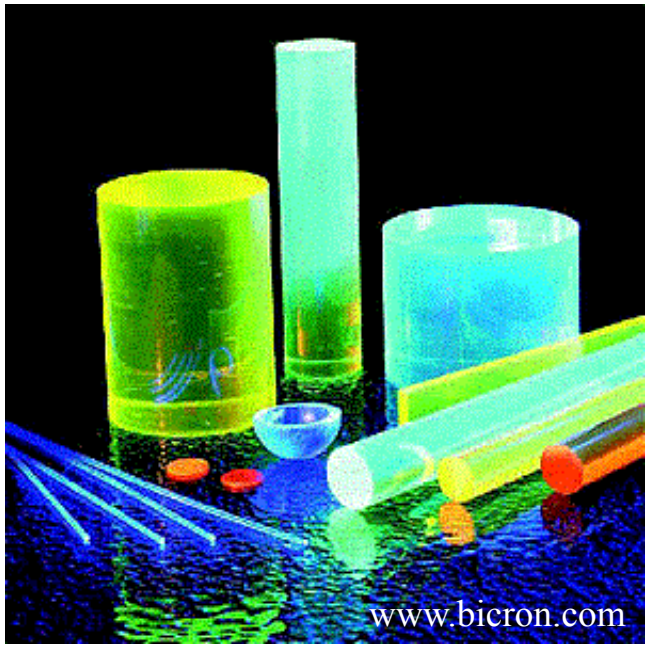


Scintillators

- Scintillation: charged particle traversing matter leaves behind a wake of excited molecules. Certain types of molecules, depending on their band structure, will release a small fraction of this energy as optical photons.
- Energy levels in impurity activated crystals

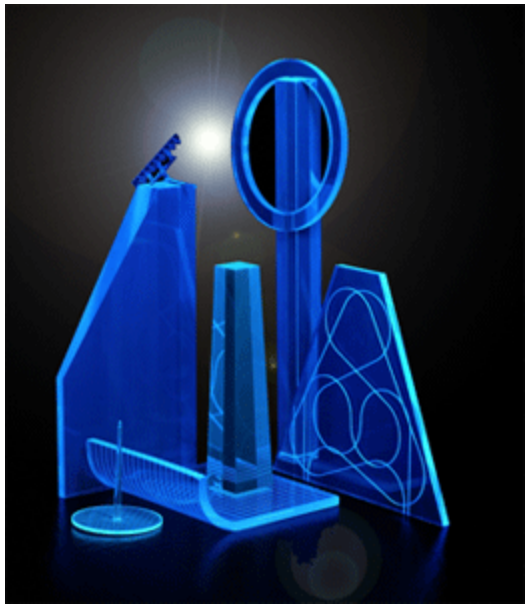




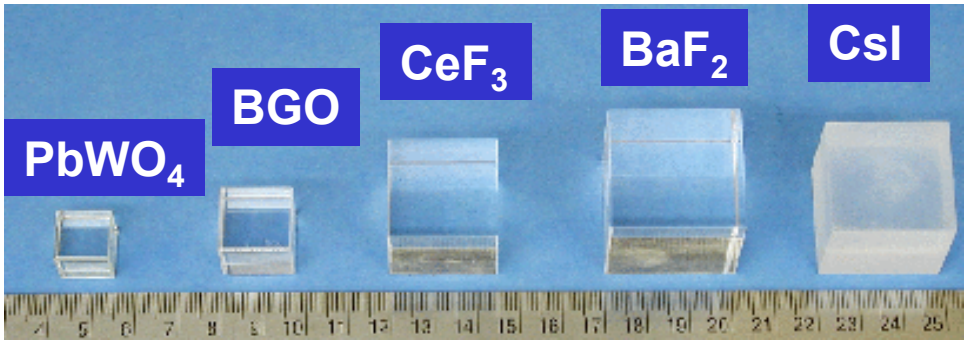


Scintillator Types

- Organic scintillators: liquid, plastic
  - Up to 10,000 photons per MeV
  - Low Z, $\rho \sim 1 gr/cm^3$
  - Doped, large choice of emission wavelength
  - ns decay times
  - relatively inexpensive
  - Easy to manufacture in any shape or size,
  - The scintillation process is a function of a single molecular process and is independent of the physical state of the scintillator



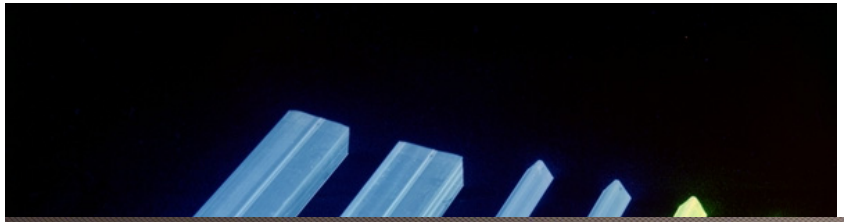
- Inorganic scintillators: crystals
  - High light yield, up to 40,000 photons per MeV
  - High Z, large variety of Z and ρ
  - Undoped and doped
  - ns to μs decay times
  - Expensive
  - Difficult to grow crystals
  - Require a crystal lattice to scintillate

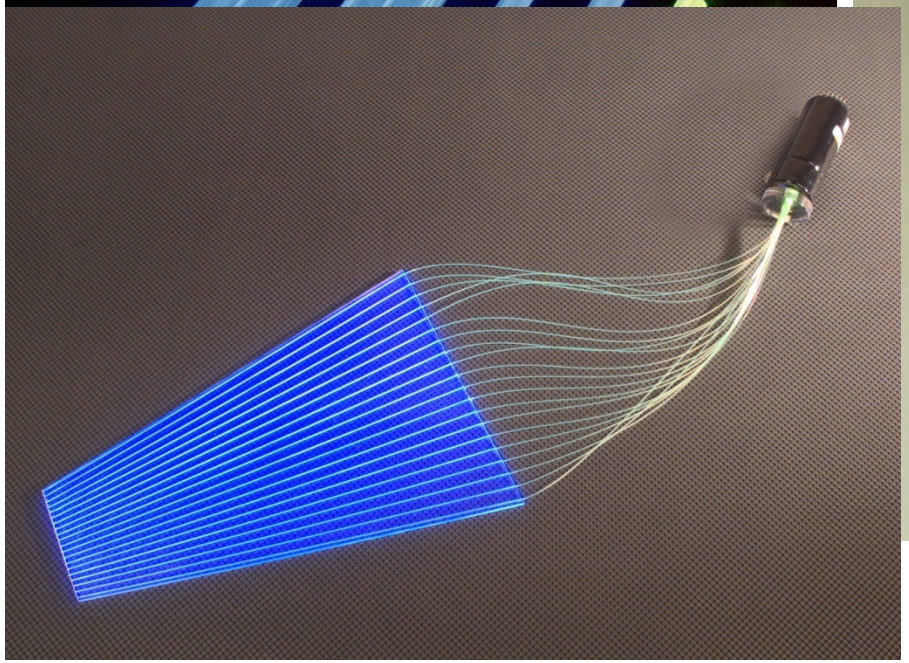


- Wide range of applications
  - trigger counters
  - tracking detectors
  - calorimetry
- Match emission wavelengths to detection device

Light Guide and Wavelength Shifter

- Scintillation guide needs to be guided to photo-detector; transfer by total internal reflection, light guide
- Spectrum needs to be optimally matched to detector sensitivity: WLS





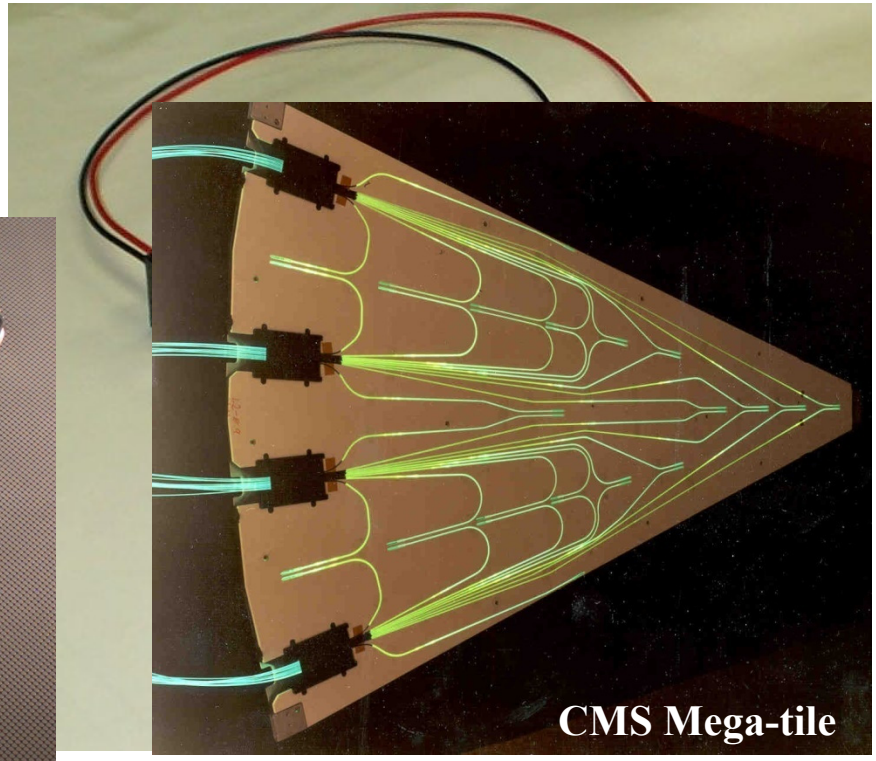
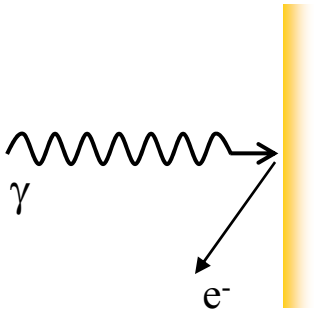
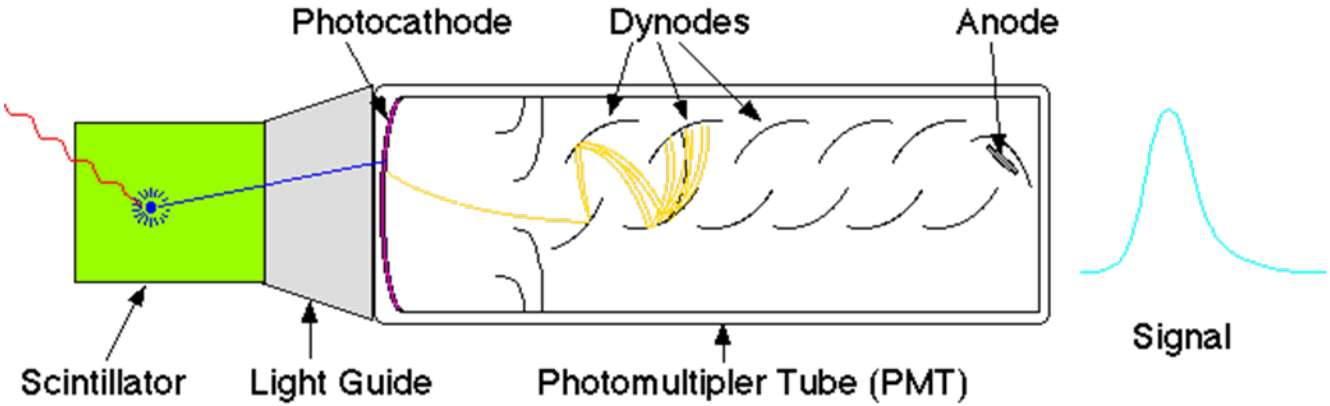


Photo-Detector: Photo-Multiplier Tube

- Photo detection: convert light into electrical signal through photo-electric effect
  - Photon hits photo-cathode and liberates an electron (=photoelectron)
  - Photocathode:
    - Generally made of antimony (Sb) and one or more alkali metals (Cs, Na, K)
    - Need to be thin, so photo-electrons can escape
    - Wavelength of scintillator light needs to match response spectrum
  - Photocathode quantum efficiency



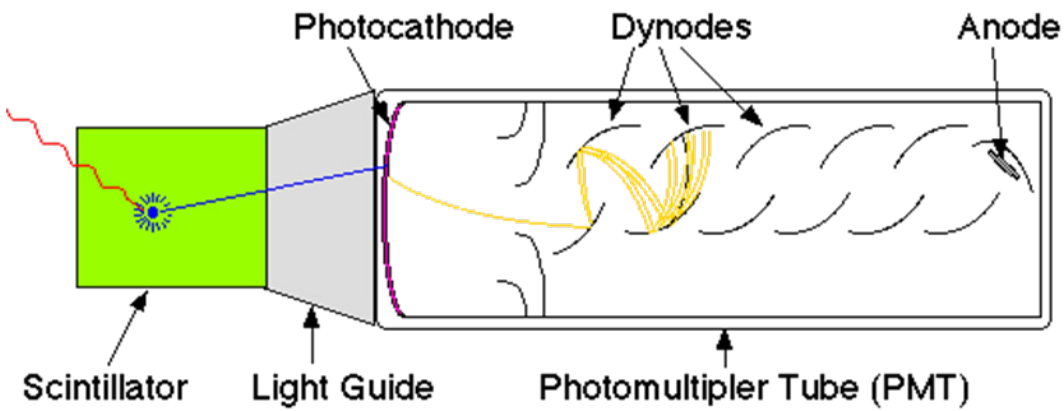
$$Q.E. = \frac{\# p.e.}{\# \gamma}$$



generally Q.E. ~ 10-30%

PMT Signal Amplification

- Liberated electron amplified through series of dynodes



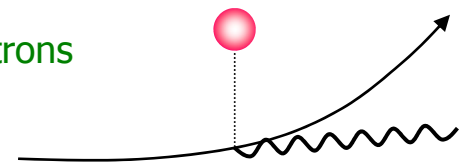
- Secondary emission of electrons, with coefficient p. Usually p~4
- Total amplification

$$M = p^n \text{ , with } n = \text{number of dynodes}$$
$$= 4^{10} = 10^6$$

- PMT's come in all sizes, shapes and channel counts; they are light bulbs in reverse

Interaction of Electrons with Matter

- Bethe-Bloch formula does not hold for electrons
  - Crucial difference for electrons (positrons): mass of scattered object is the same as the object it scatters off
    - $m_\mu/m_e = 205$, $m_\pi/m_e = 273$
- Electrons are subject to bremsstrahlung
  - Radiation of real photons in the Coulomb field of the nuclei of the medium
    - Any deflection of the electron from its original trajectory accompanied by radiation of photons and deceleration of electrons

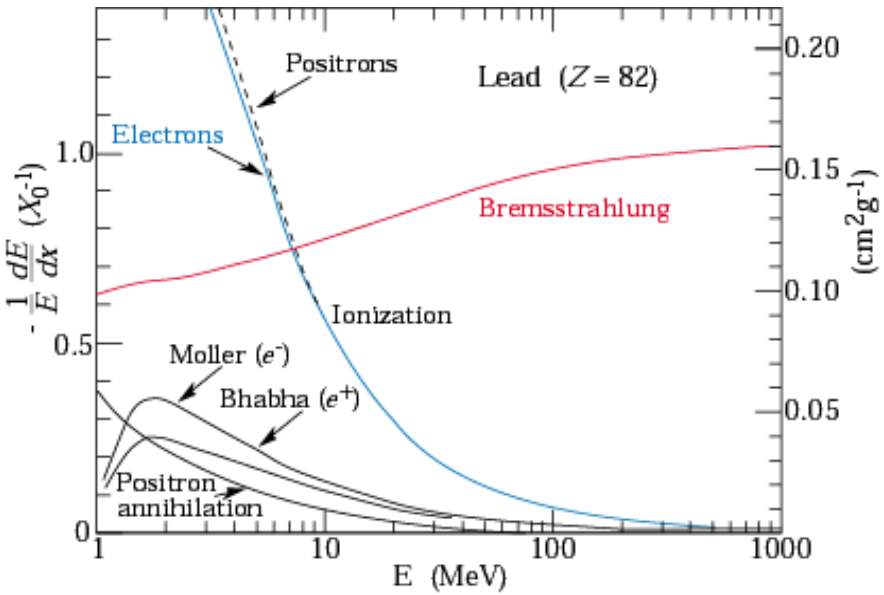


$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln \frac{183}{Z^{1/3}} \propto \frac{E}{m^2}$$

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

X_0: radiation length (g/cm^2)

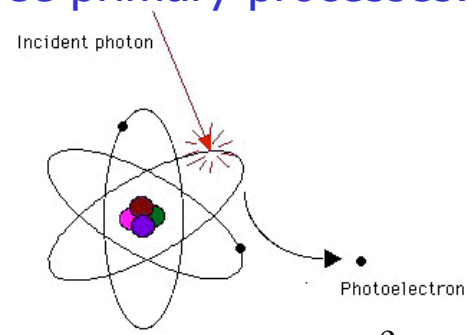
- Of course, also muons are subject to bremsstrahlung, but only for ultra-relativistic energies



Interaction of Photons with Matter

- A photon is neutral. In order to be detected, a photon has to create charged particles and/or transfer energy to charged particles
- Photon interaction with matter proceeds through three primary processes:
  - Photo-electric effect
    - Cross section rises as Z^5

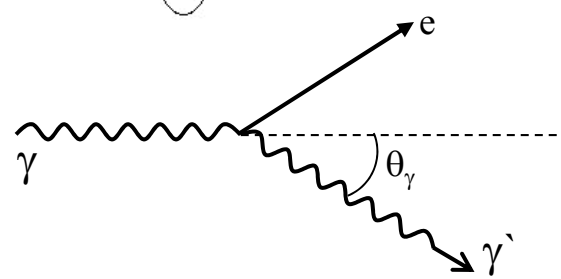
$$\sigma_{ph-el} \propto Z^5 \frac{1}{\varepsilon} \qquad \varepsilon = \frac{E_\gamma}{m_e c^2}$$



  - Compton scattering: $\gamma + e \rightarrow \gamma' + e'$

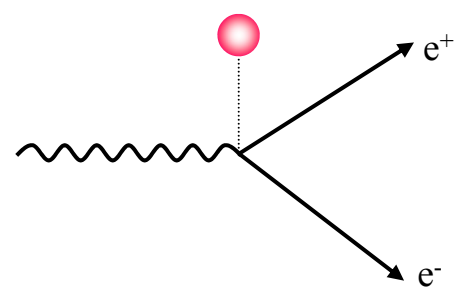
$$E'_\gamma = E'_\gamma \frac{1}{1+\varepsilon(1-\cos\vartheta_\gamma)} \qquad E_e = E_\gamma - E'_\gamma$$

$$\sigma_c \propto \frac{\ln\varepsilon}{\varepsilon}$$



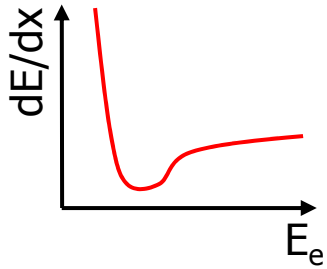
  - Pair production: γ + nucleus $\rightarrow e^+ e^-$ + nucleus
    - Process independent of energy
    - Dominates at high energies

$$\sigma_{pair} \propto Z^2$$

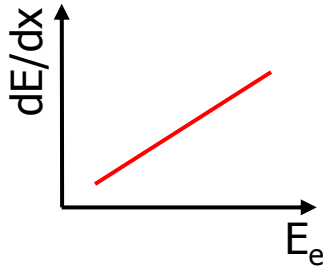


Electro-Magnetic Interactions

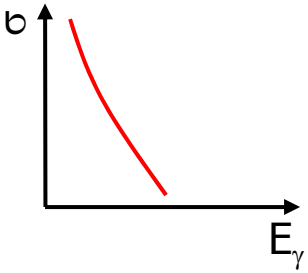
- e^+/e^-
  - Ionization



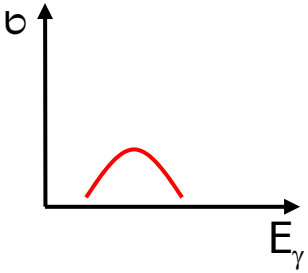
  - Bremsstrahlung



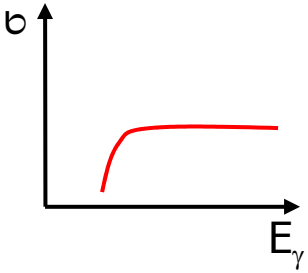
- γ
  - Photoelectric Effect



  - Compton Effect

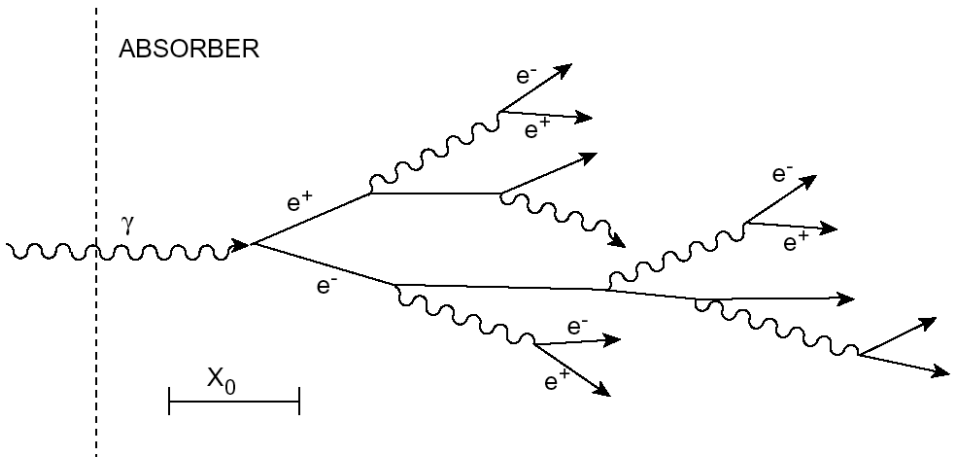


  - Pair Production

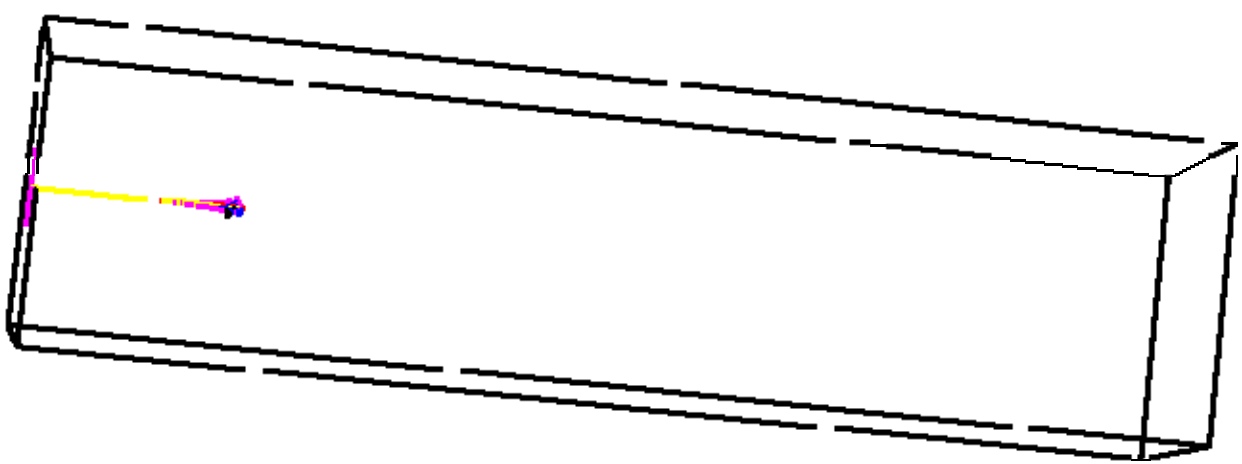


Electro-Magnetic Cascades

- Because of the correlated nature of $e^-/e^+/\gamma$ interactions, they lead to EM cascades (showers) of particles

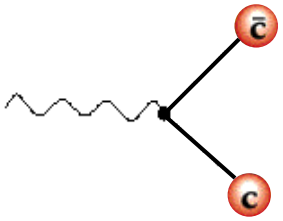


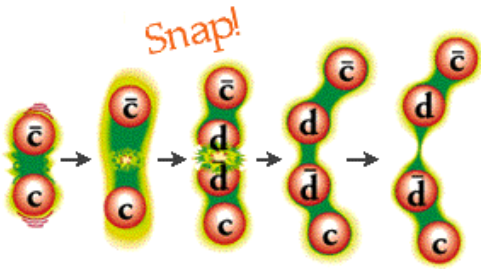
- OPAL Lead glass crystal, 37x10x10 cm^3, no magnetic field, 80 GeV e^-



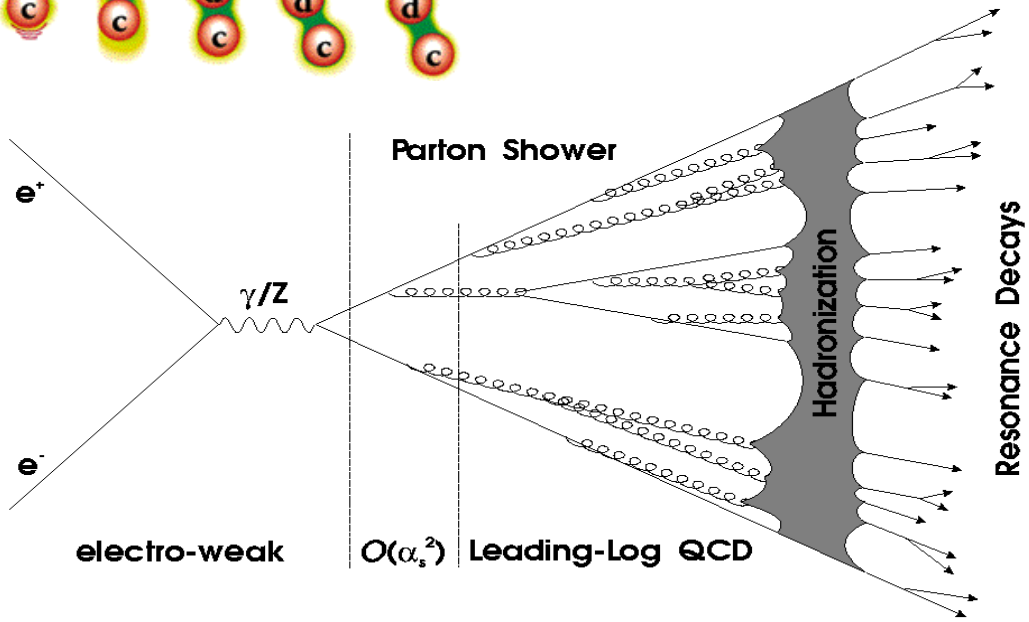
Interaction of Hadrons with Matter

- Because of conservation of quantum numbers, quarks are produced in pairs
- When quarks, held together by the strong force, separate, it is energetically more advantageous to create a new quark-anti-quark pair
  - Free quarks cannot be observed; also due to conservation of color charge
  - Moreover, quarks will radiate gluons (cf. bremsstrahlung)



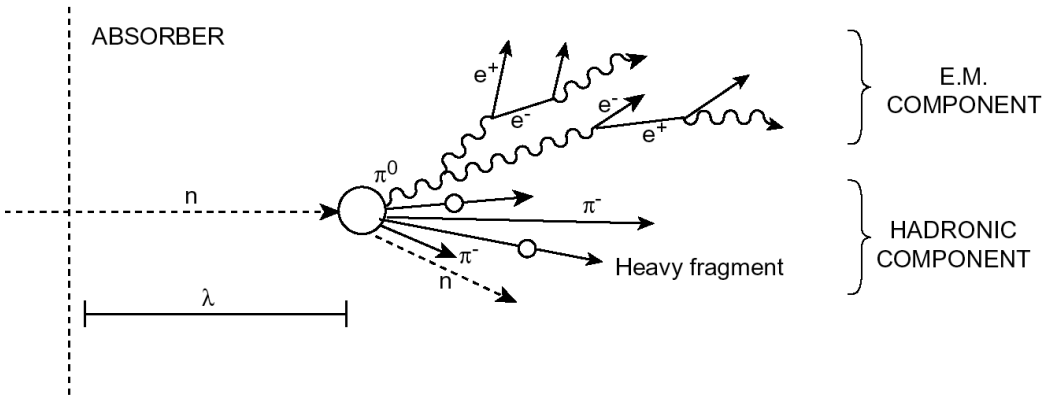


- Fragmentation
  - Quarks will fragment
- Hadronization
  - Fragments will thermalize into hadrons



Hadronic Cascades

- Many processes involved in hadronic showers; much more complex than electromagnetic cascades. In short, hadron showers are a mess
- Two components in hadron showers
  - Hadronic component
    - charged hadrons p,$\pi^{\pm}$,$K^{\pm}$
    - nuclear fragments
    - neutrons, neutrino's, soft γ's
    - break-up of nuclei
  - Electromagnetic component
    - electrons, photons
    - neutral pions $\rightarrow$ 2 γ

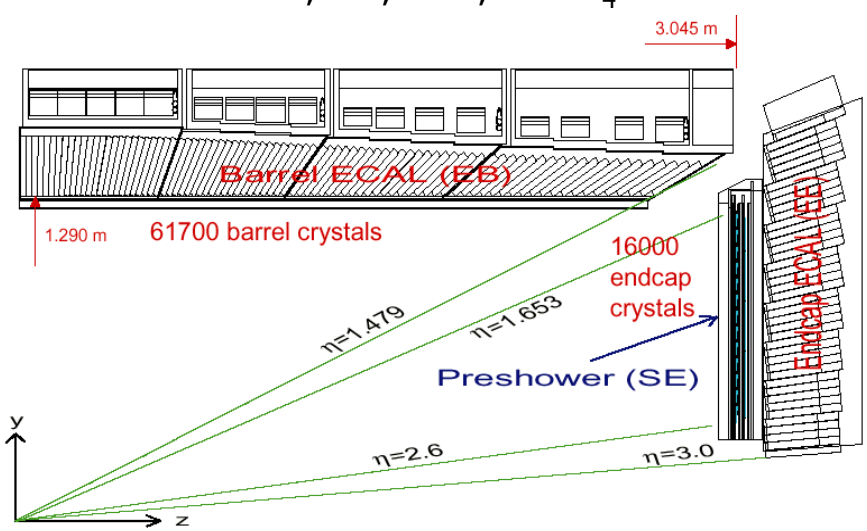


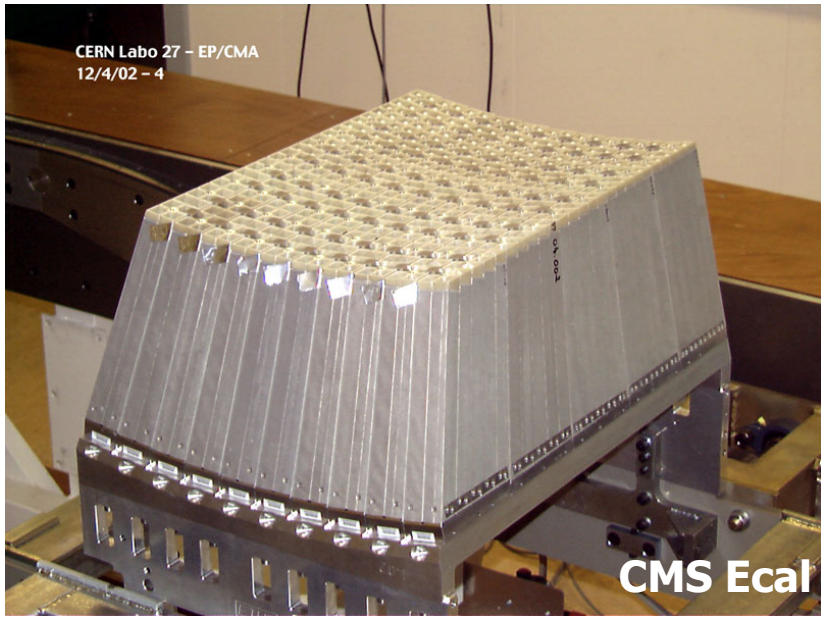
- Showers contain neutrals (not measured in tracking devices)
- Cascades are characterized by larger fluctuations

- Calorimeter for measure of total energy for $e^+/e^-/\gamma$/hadrons
  - Technique is destructive; total absorption: particle and energy get absorbed
  - Technique works for both
    - Charged particles: complementary information to momentum measurement
    - Neutral particles: only way to obtain kinematic information

Calorimetry

- Calorimeters normally subdivided into an electromagnetic section – EM showers are compact -- followed by a hadronic section; fully contain shower
- Calorimeter types:
  - Homogenous calorimeters
    - detector = absorber
    - good energy resolution
    - limited longitudinal segmentation
    - mainly used for EM calorimeters
      - scintillating crystals
      - Photon readout
      - NaI, CsI, BGO, $PbWO_4$

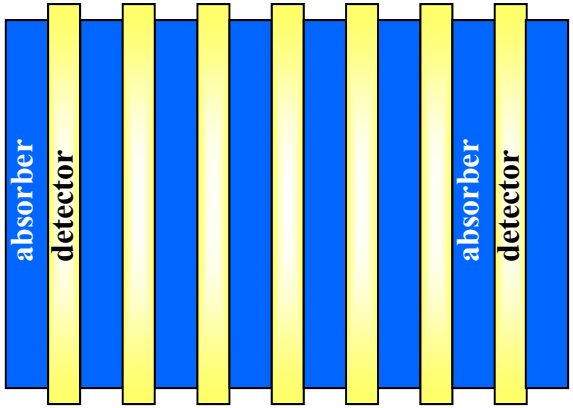


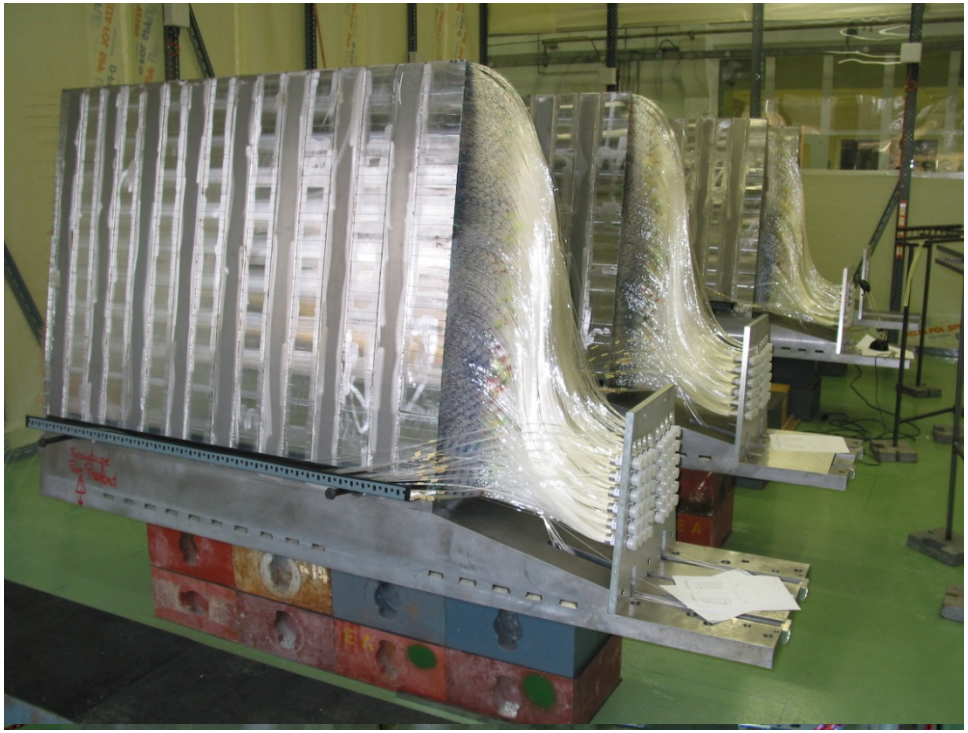


CMS Electromagnetic Calorimeter

Calorimetry

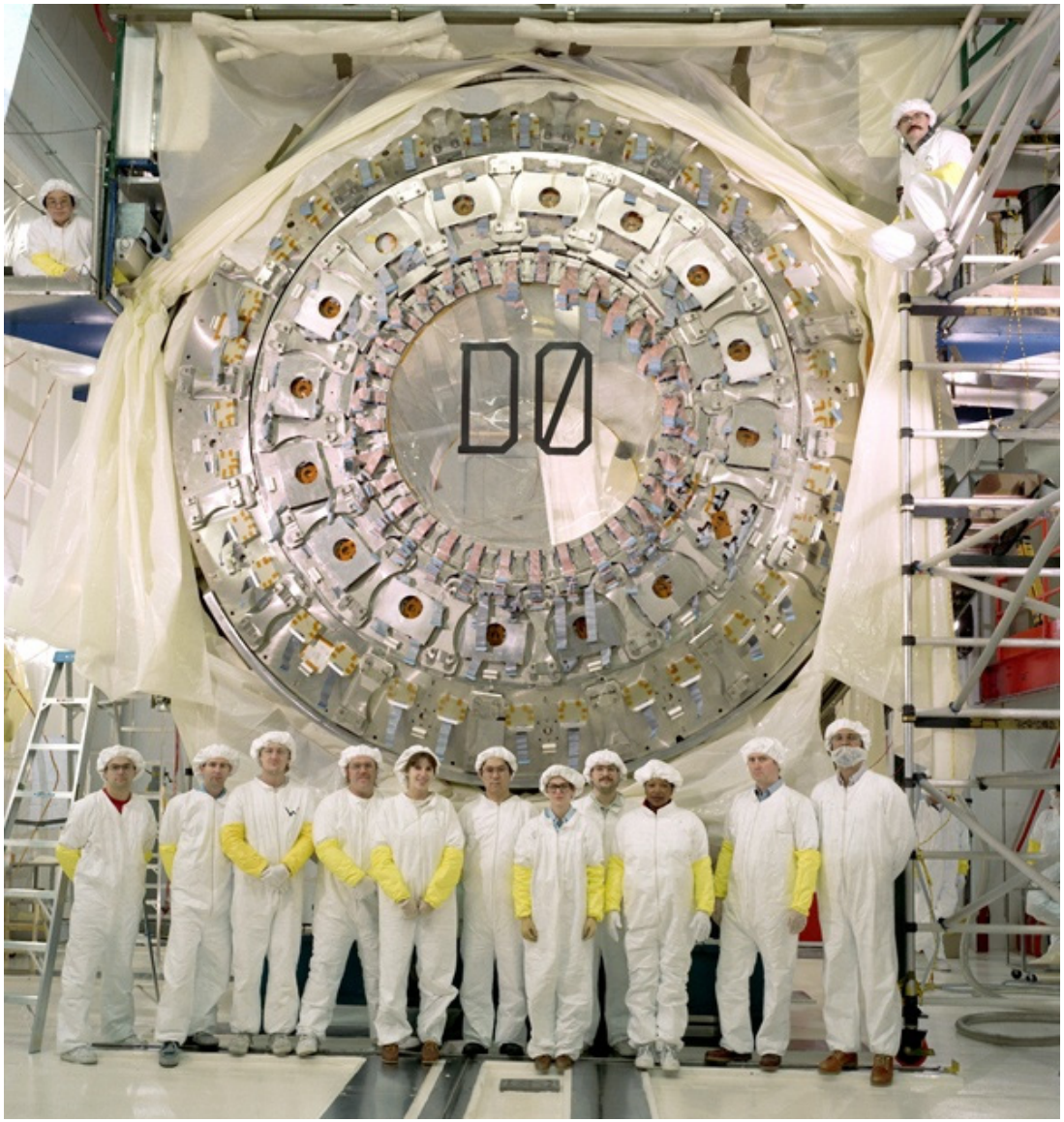
- Calorimeter types:
  - Sampling calorimeters
    - distinct detector and absorber elements
    - limited energy resolution
    - good longitudinal segmentation
    - Many different active media: gas, LAr, scintillator, …
    - Many different absorbers: lead, Uranium, W, Cu, …



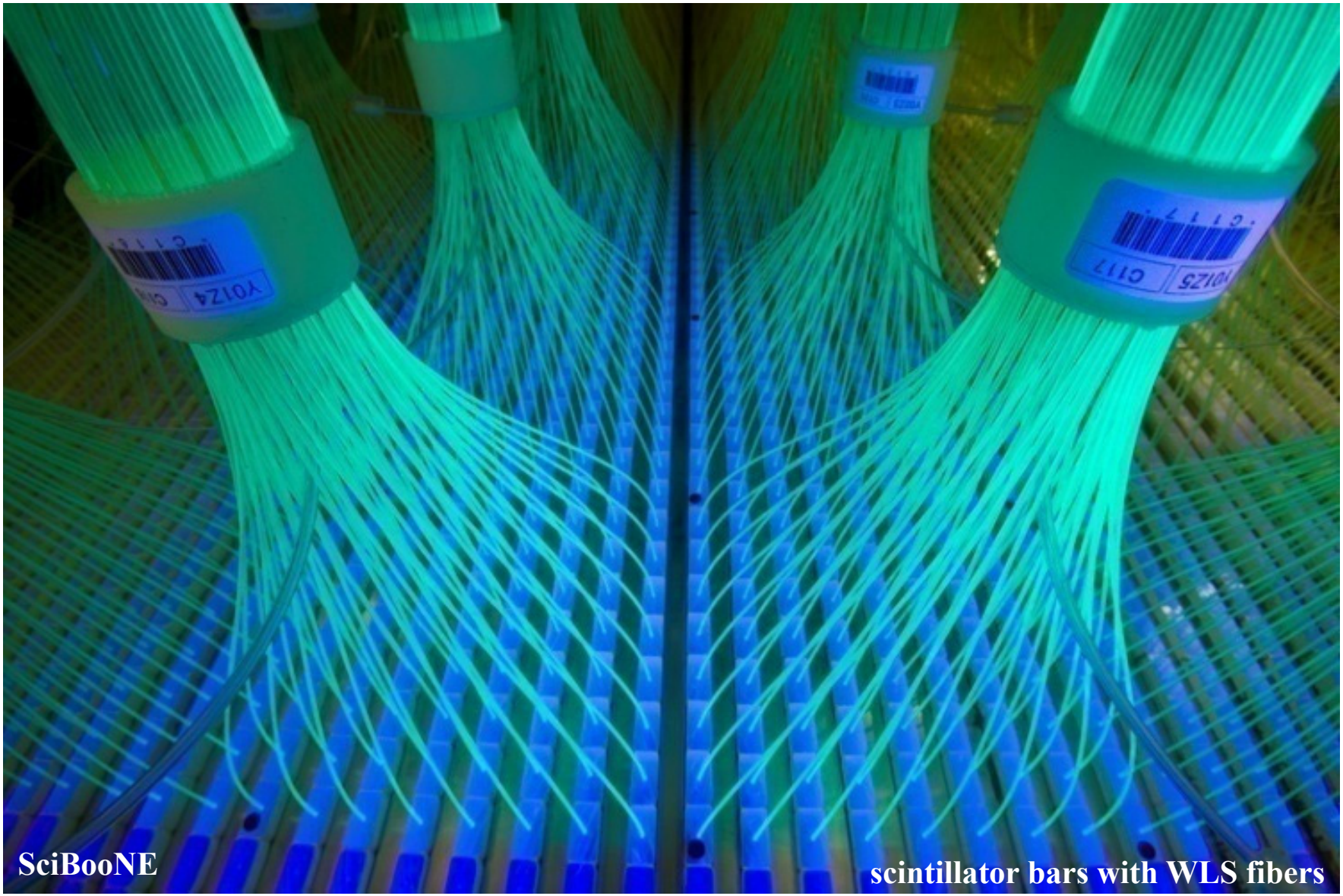


Calorimeter: DØ

- Uranium-Liquid Argon
  - Absorber: uranium
  - Active: liquid argon
  - Compact, hermetic device
  - Uniform response
  - Stable calibration
  - 'compensating'
  - Fully absorbing with relatively small diameter detector



Calorimeter: SciBooNE

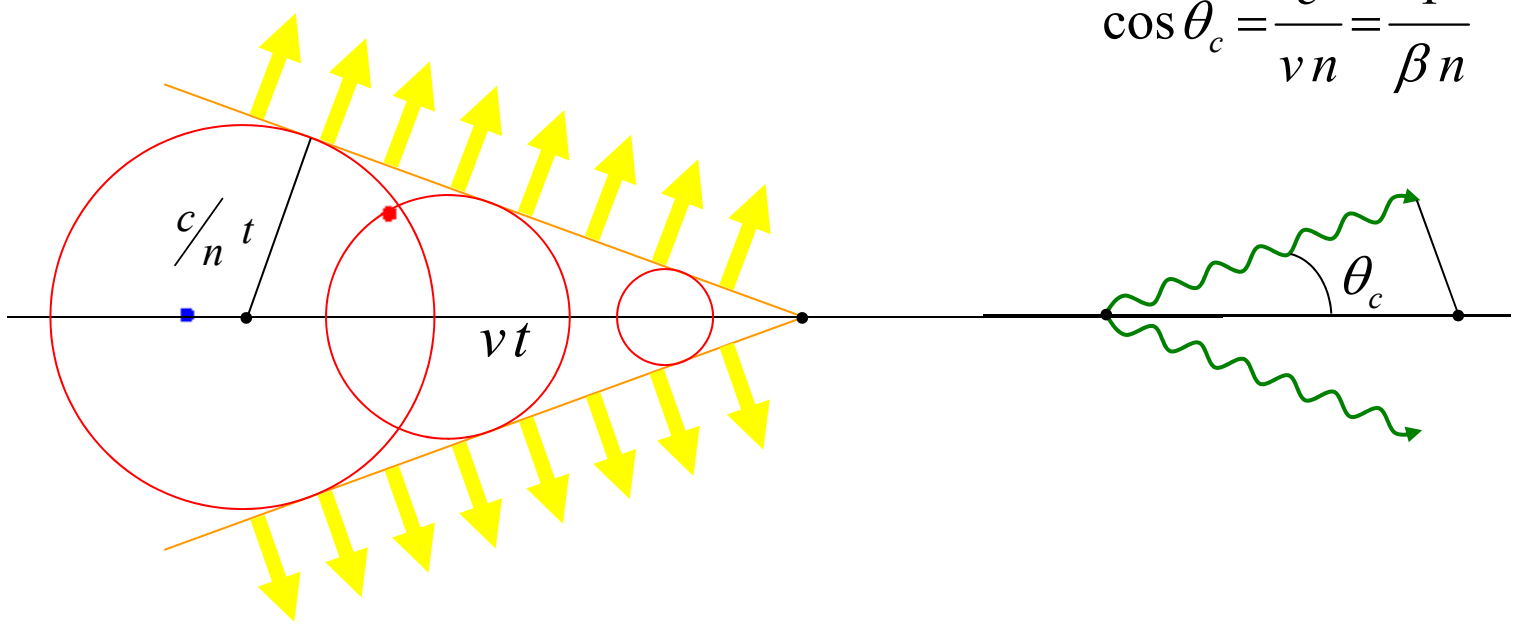


Čerenkov Radiation

- When the charged particle velocity is faster than the speed of light in that medium, it emits Cherenkov radiation: "sonic boom of light"

$$v \geq v_t = \frac{c}{n} \quad , n = index\ of\ refraction$$

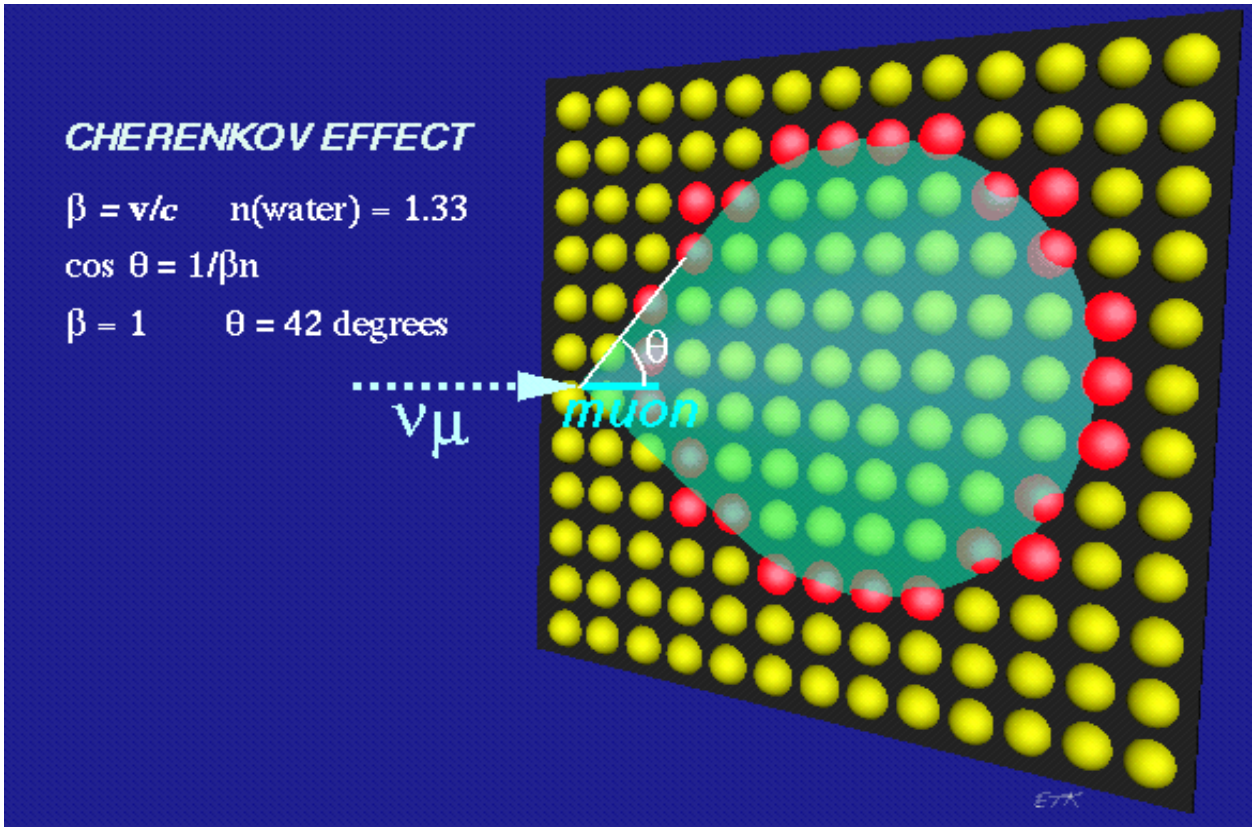
$$\cos\theta_c = \frac{c}{v\,n} = \frac{1}{\beta\,n}$$



- Cherenkov light is emitted under a constant Cherenkov angle with respect to the particle trajectory

Čerenkov Radiation Detection

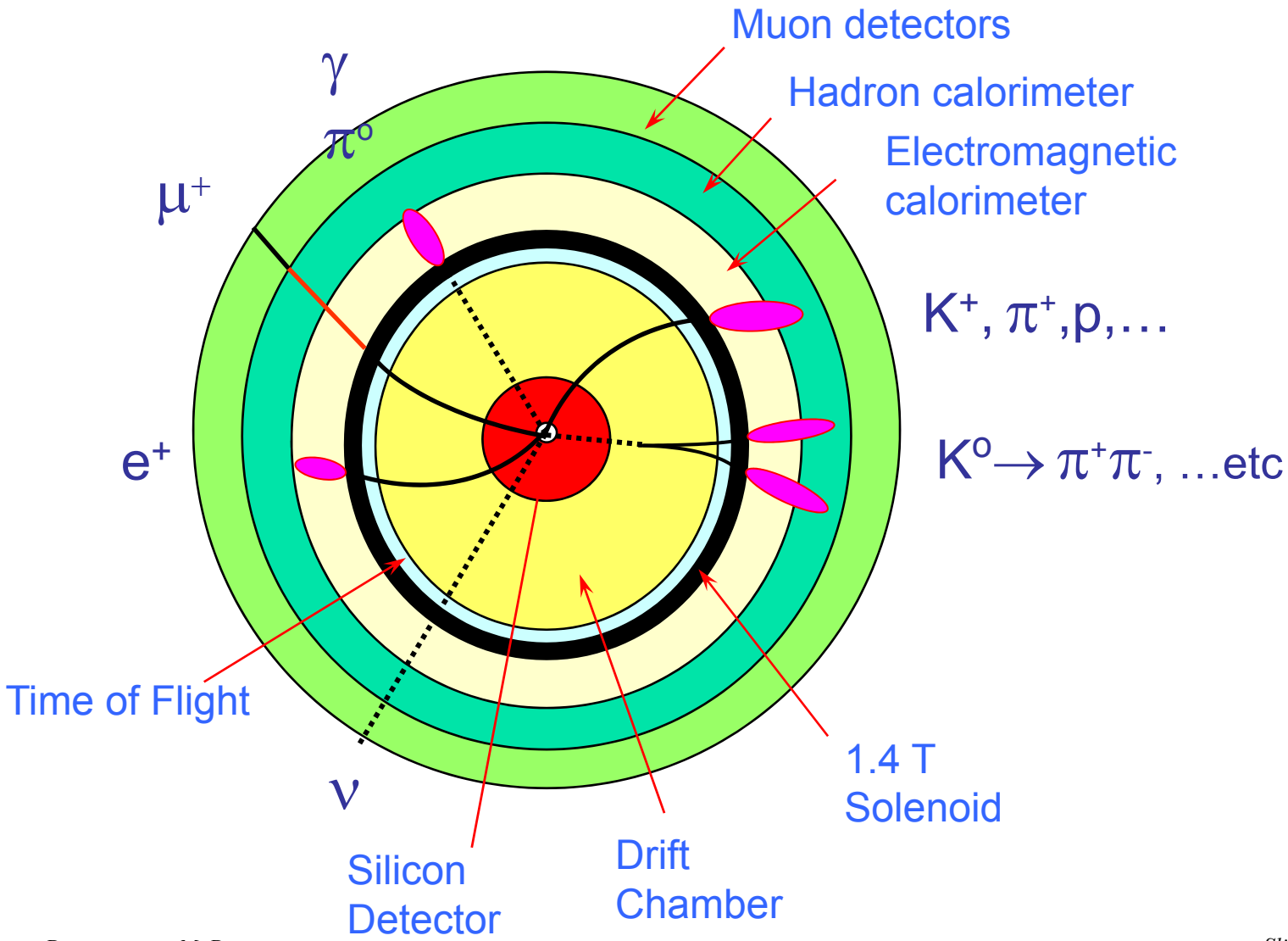
- Wavefront of light travels to end of detector and is collected by PMT
- Cherenkov radiation:
  - modest light output
    - the energy loss due to ionization or excitation is two to three orders of magnitude higher than the energy lost in radiating Cherenkov light
  - Use directionality of light
  - Particles quickly loose energy and Cherenkov radiation stops when velocity falls below Cherenkov threshold velocity



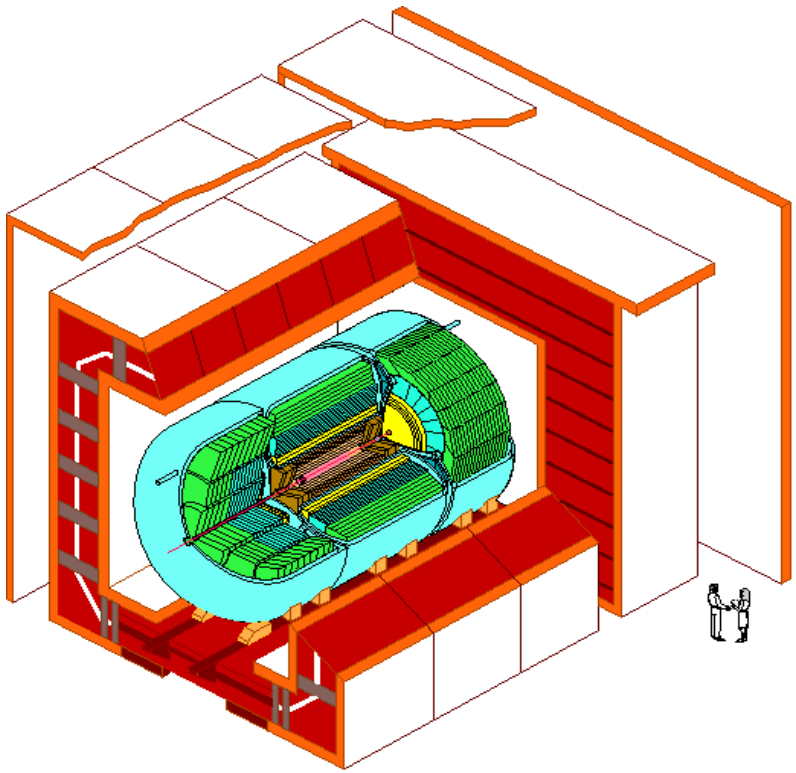
Collider Detectors

Functional Schematic of Collider Detector

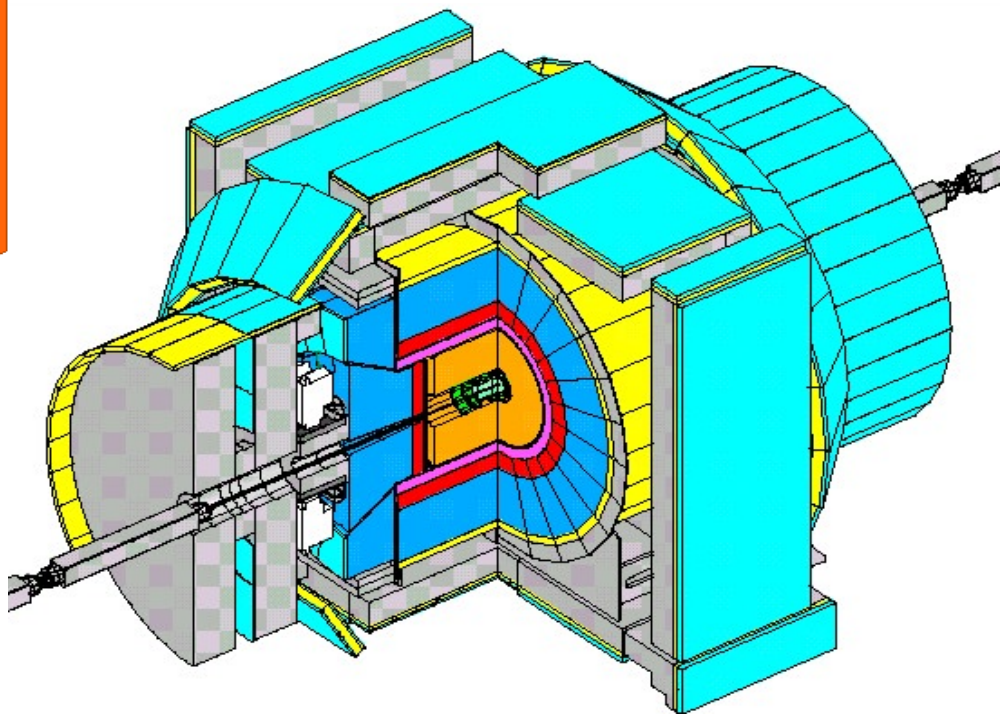
- Nearly all collider detectors are 'shoeboxes'



DØ and CDF Detector

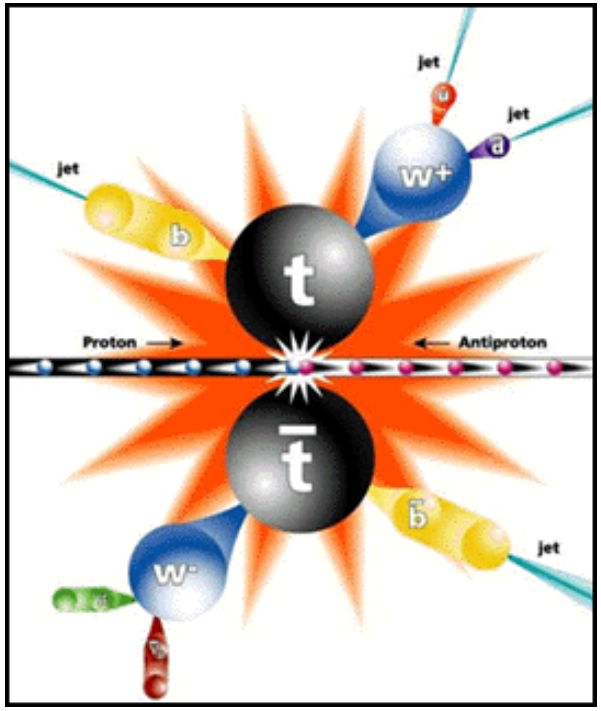


- 4π Detectors, want complete coverage, no 'cracks' so no energy escapes detection
- Two detectors to measure same physics, but some very different approaches in detector technology

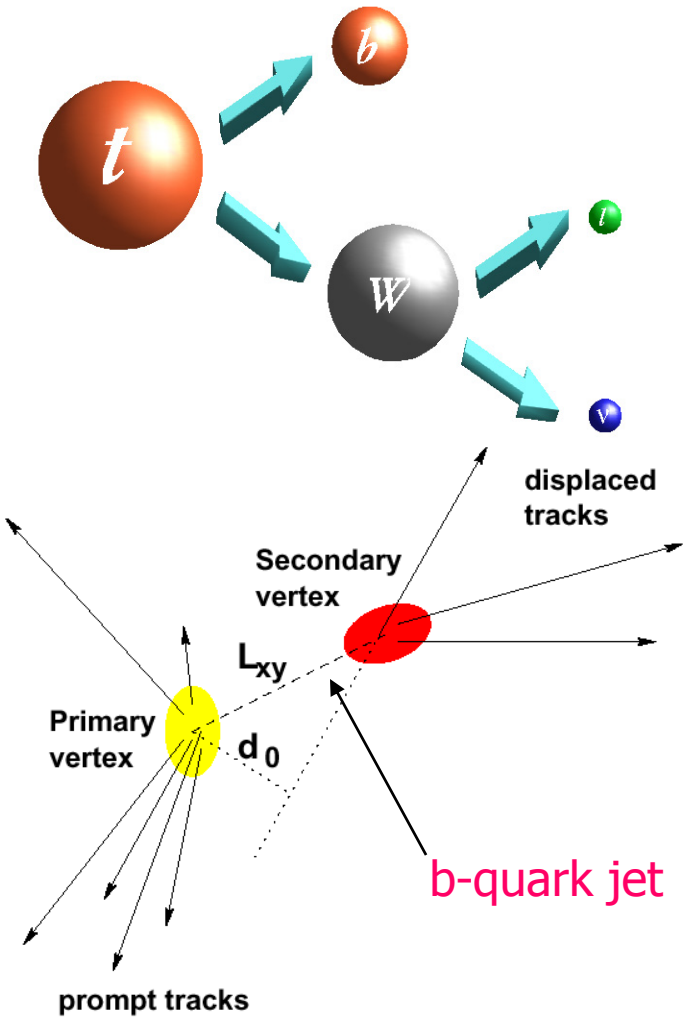


Top Quark

- Example: what is needed to discover the top quark ?
- Production of top quark and expected event signature

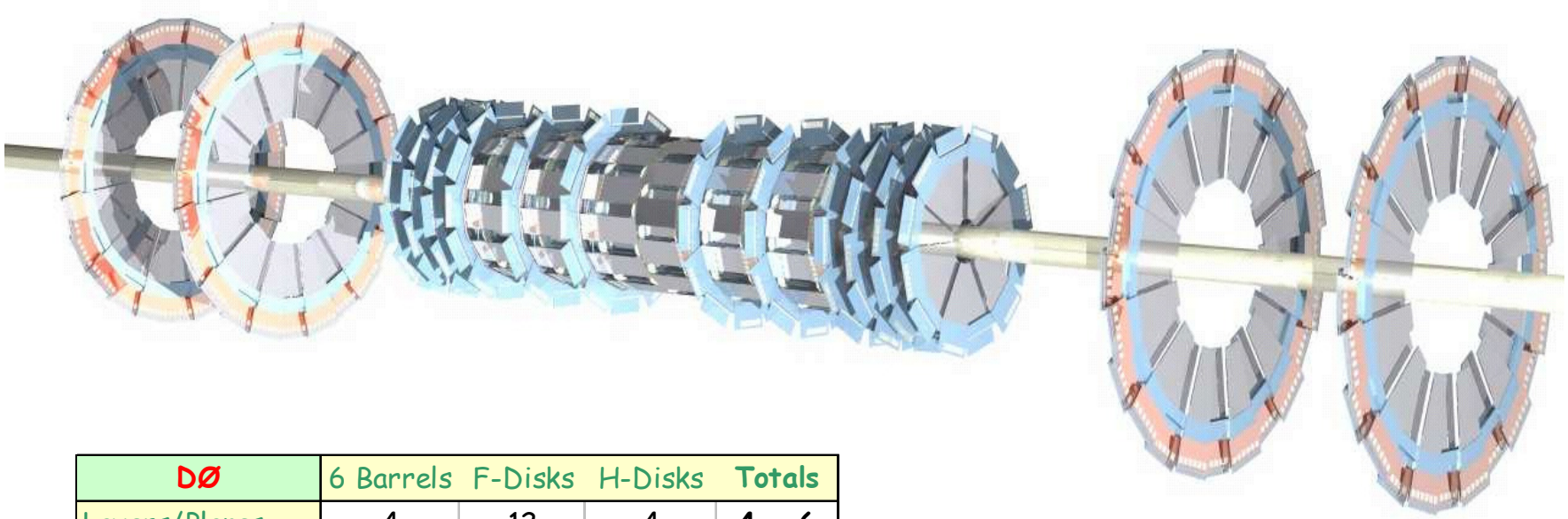


- top quark decays immediately 10^{-24} s
- W-decays right away 10^{-24} s
- b-quark lives long, 10^{-12} s, but decays before it sees a detector



Silicon Vertex Detector: DØ

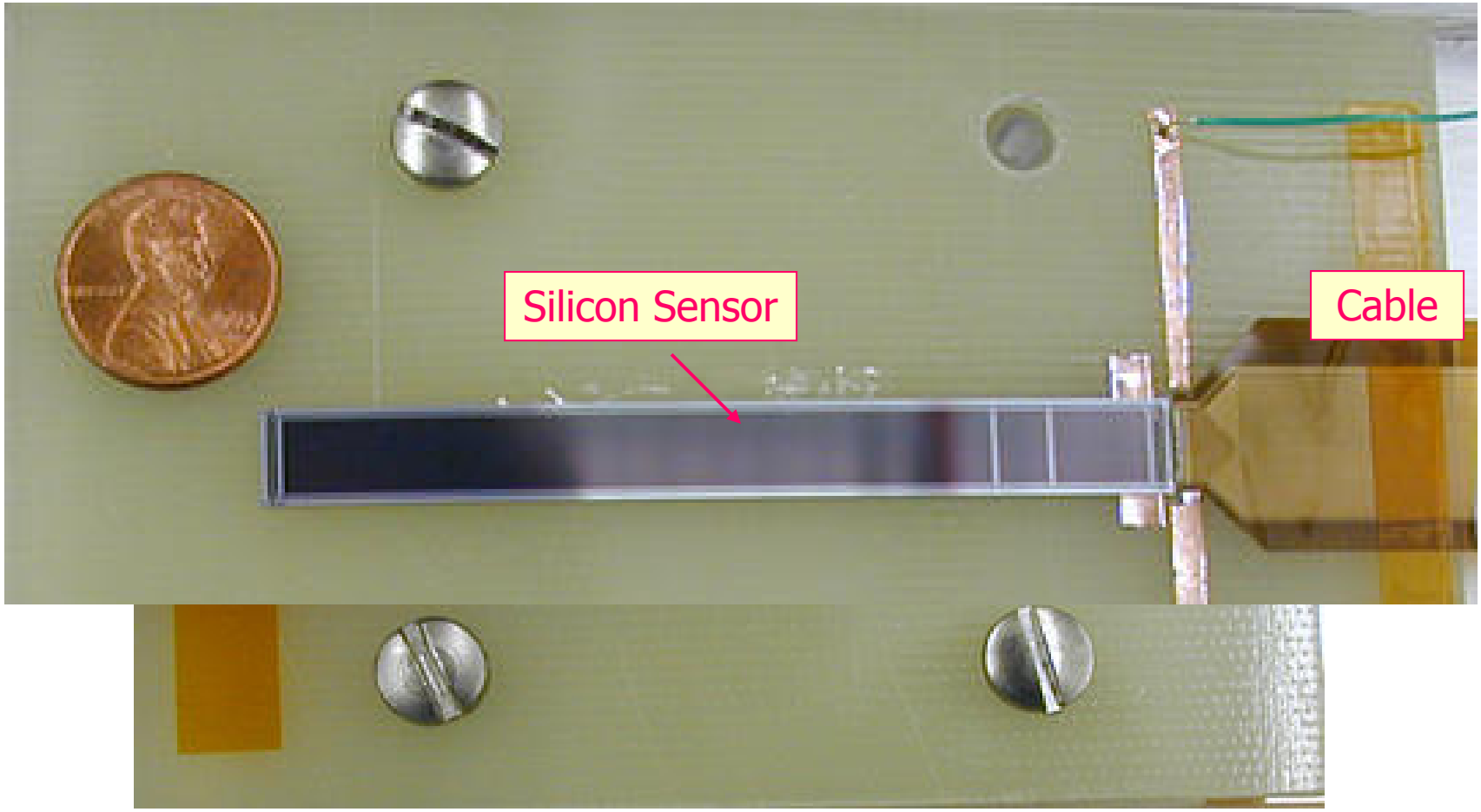
- Measure as precisely as possible the decay vertex (secondary vertex) of b-quarks to discriminate top-quarks from the background



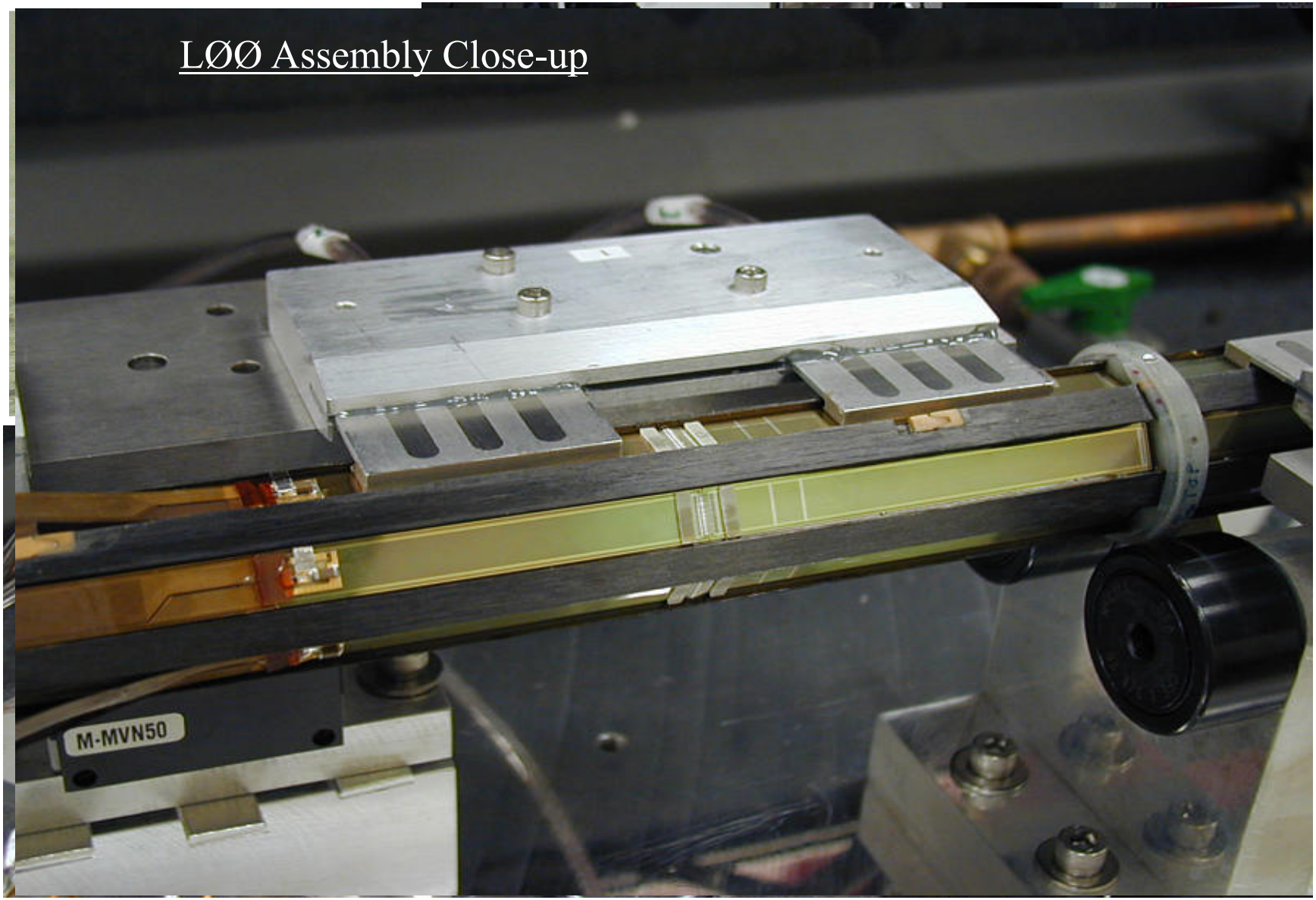
DØ	6 Barrels	F-Disks	H-Disks	**Totals**
Layers/Planes	4	12	4	**4 - 6**
Δz-coverage	78 cm	30 cm	45 cm	**242 cm**
Channels	387072	258048	147456	**792576**
Sensors	720	144	384	**1248**
Modules	432	144	96	**672**
Readout Length	12.4 cm	7.5 cm	14.9 cm	
ΔR-coverage (cm)	2.7-9.4	2.7-9.7	9.6-23.5	

Silicon Vertex Detector: CDF

- CDF Layer-00

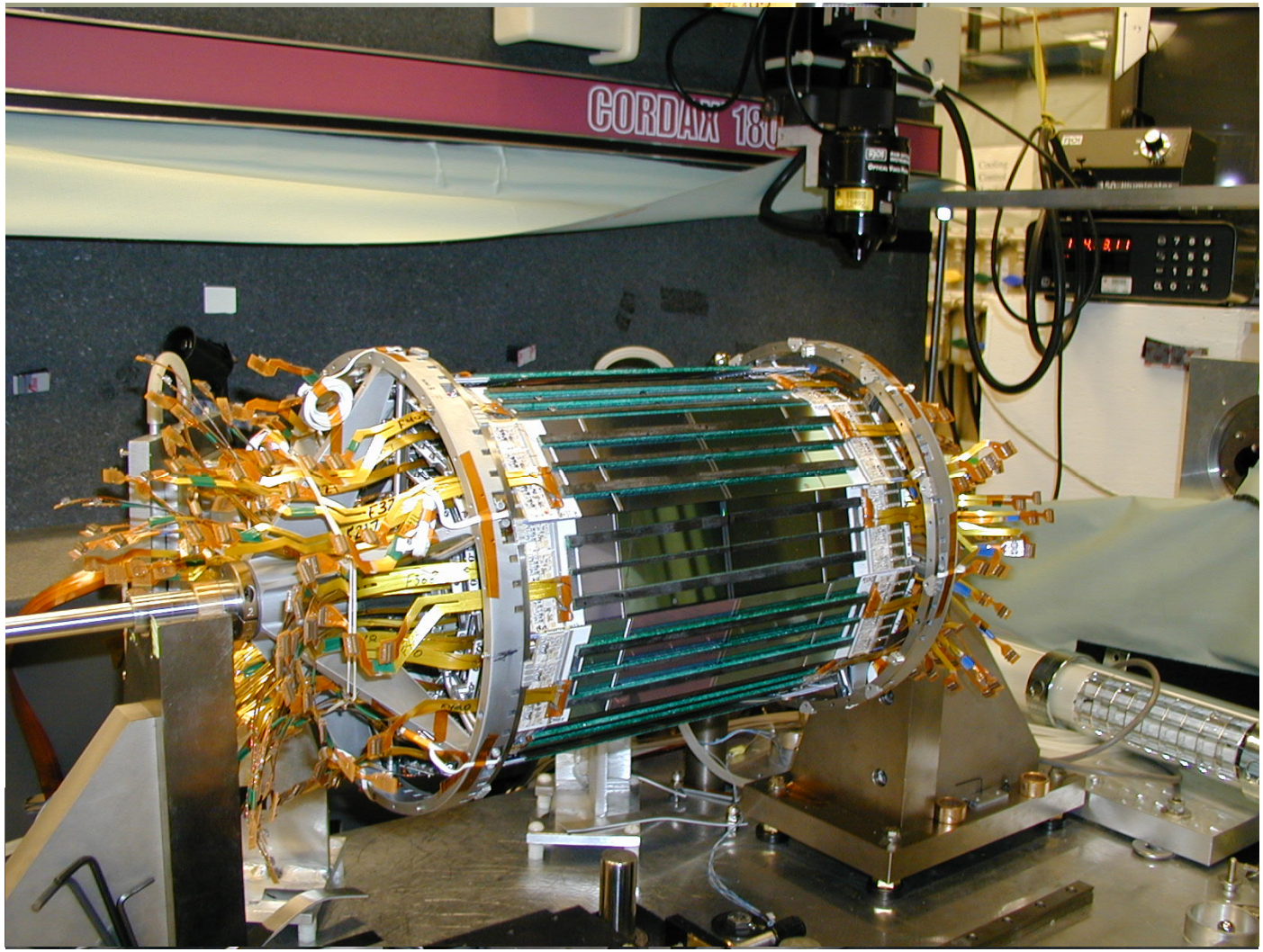


Assembly



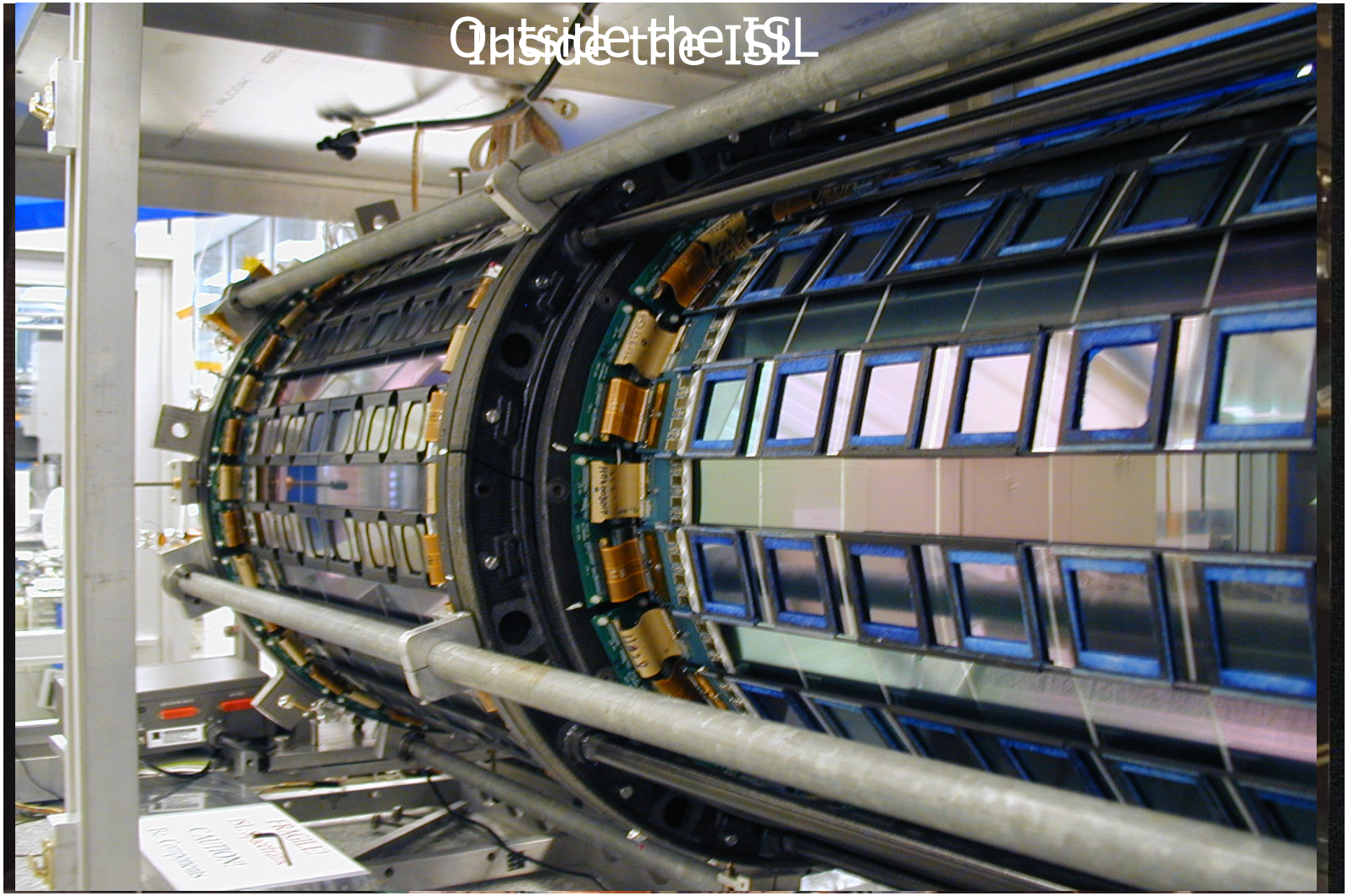
Silicon Vertex Detector: CDF

- CDF silicon vertex detector, SVXII



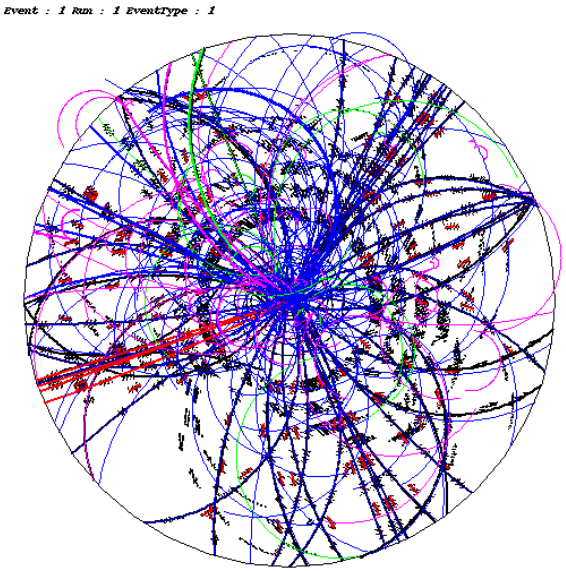
Silicon Vertex Detector: CDF

- CDF silicon vertex detector, Intermediate Silicon Layers (ISL)



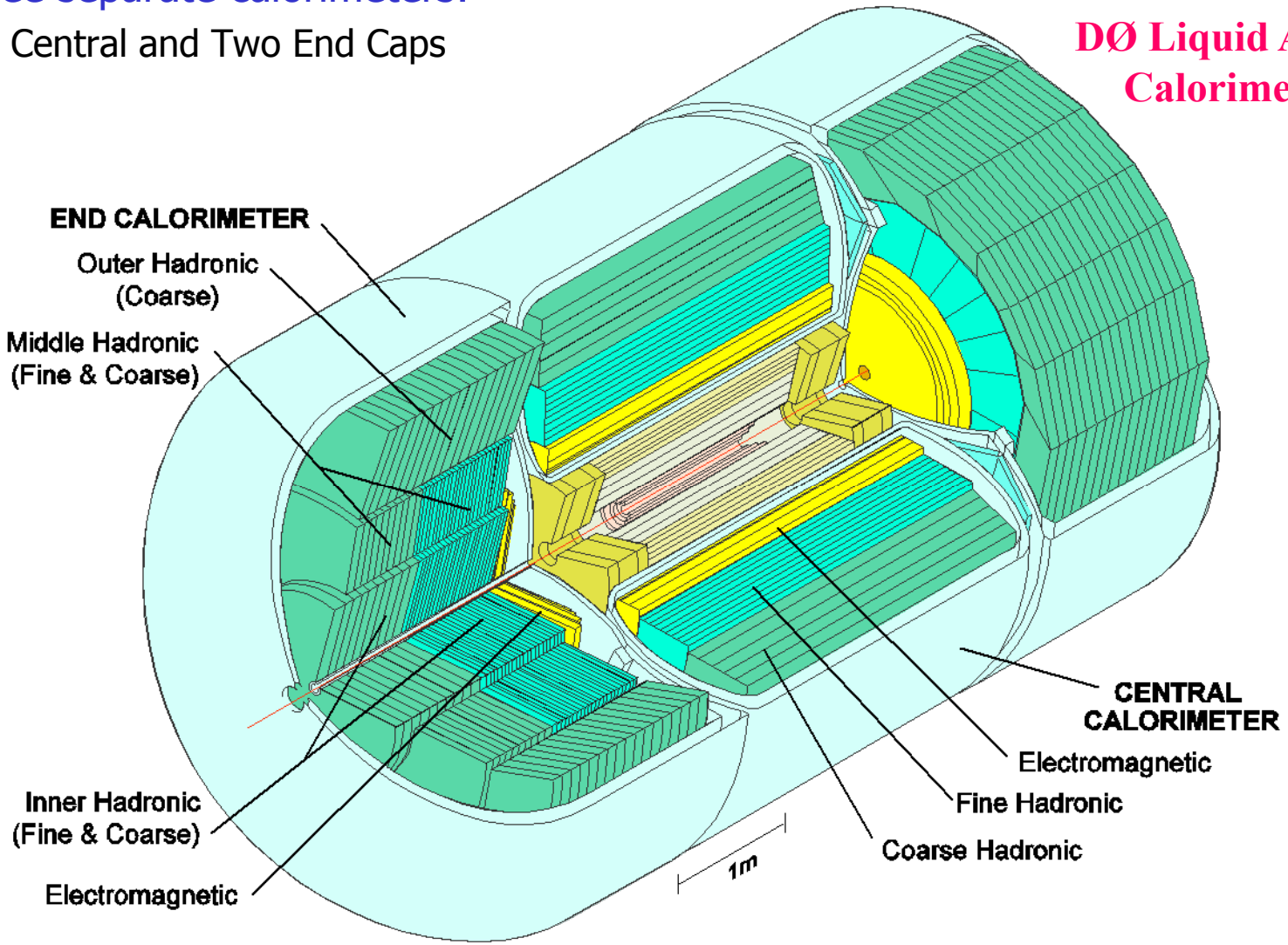
Outer Tracking System

- CDF: Drift chamber
  - Eight planes of axial and stereo sense wires



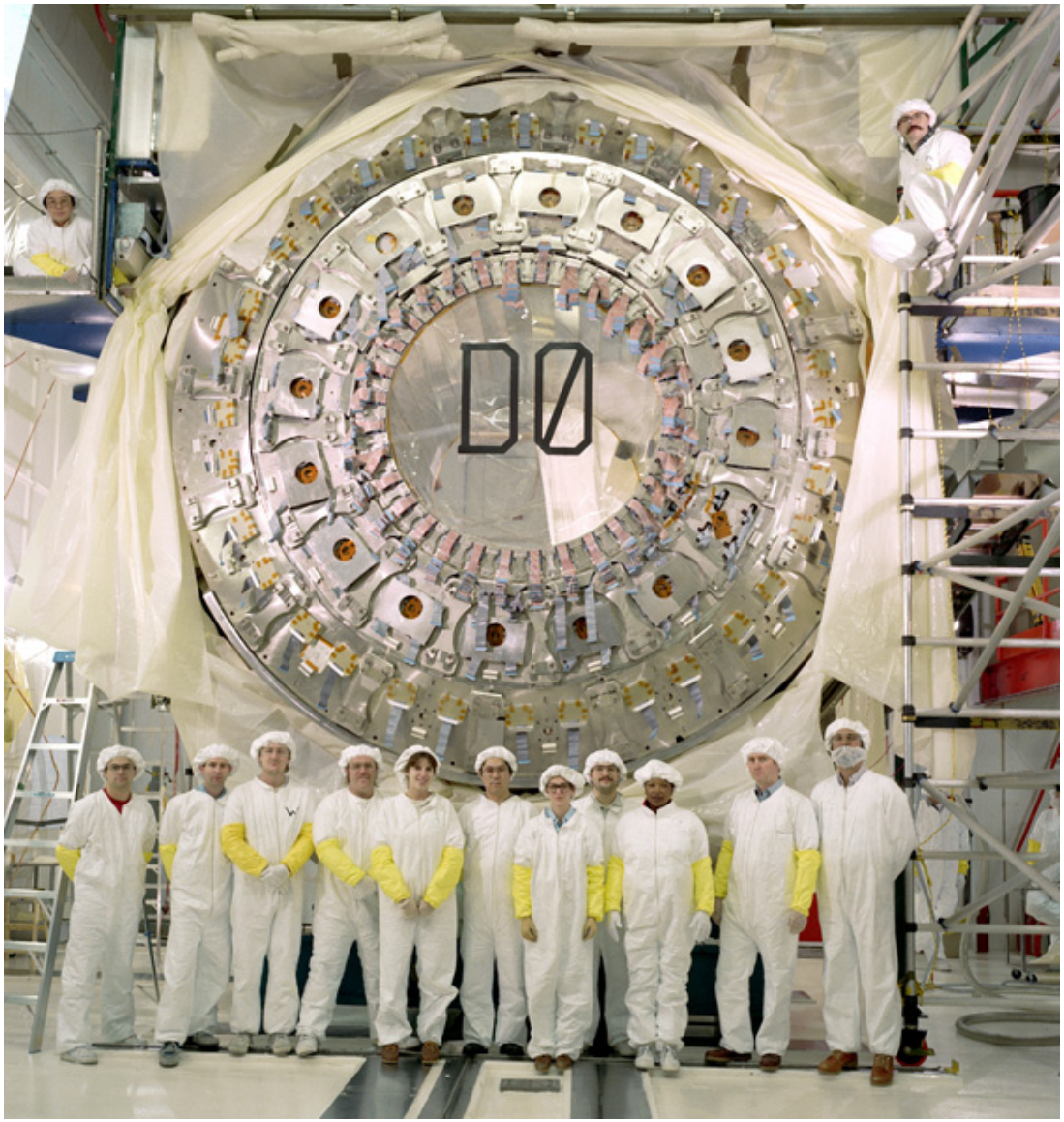
Calorimeter: DØ

- Three separate calorimeters:
  - Central and Two End Caps



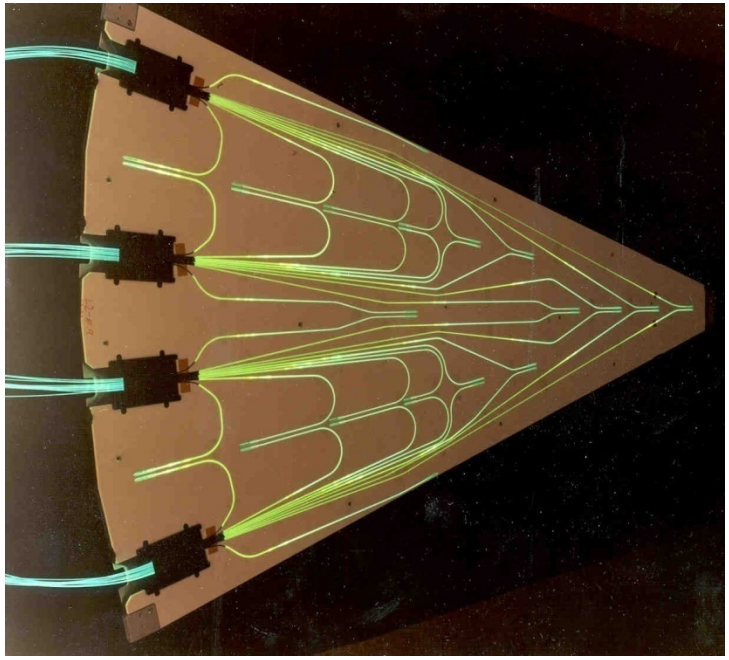
Calorimeter: DØ

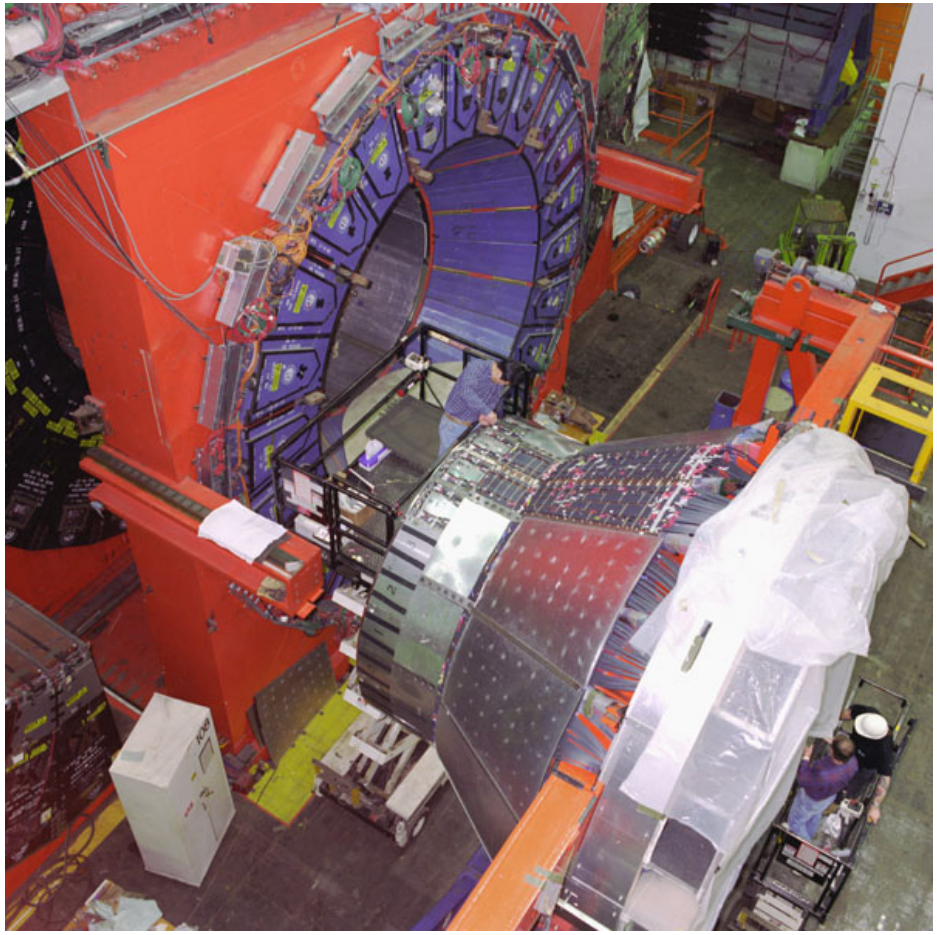
- Uranium-Liquid Argon
  - Absorber: uranium
  - Active: liquid argon
  - Compact, hermetic device
  - Uniform response
  - Stable calibration
  - 'compensating'
  - Fully absorbing with relatively small diameter detector



Calorimeter: CDF

- Lead/steel-scintillator sampling calorimeter
  - Central and plug EM and hadronic calorimeters : scintillator with WLS
  - Fast response time
  - External calibration
  - Need for cable access

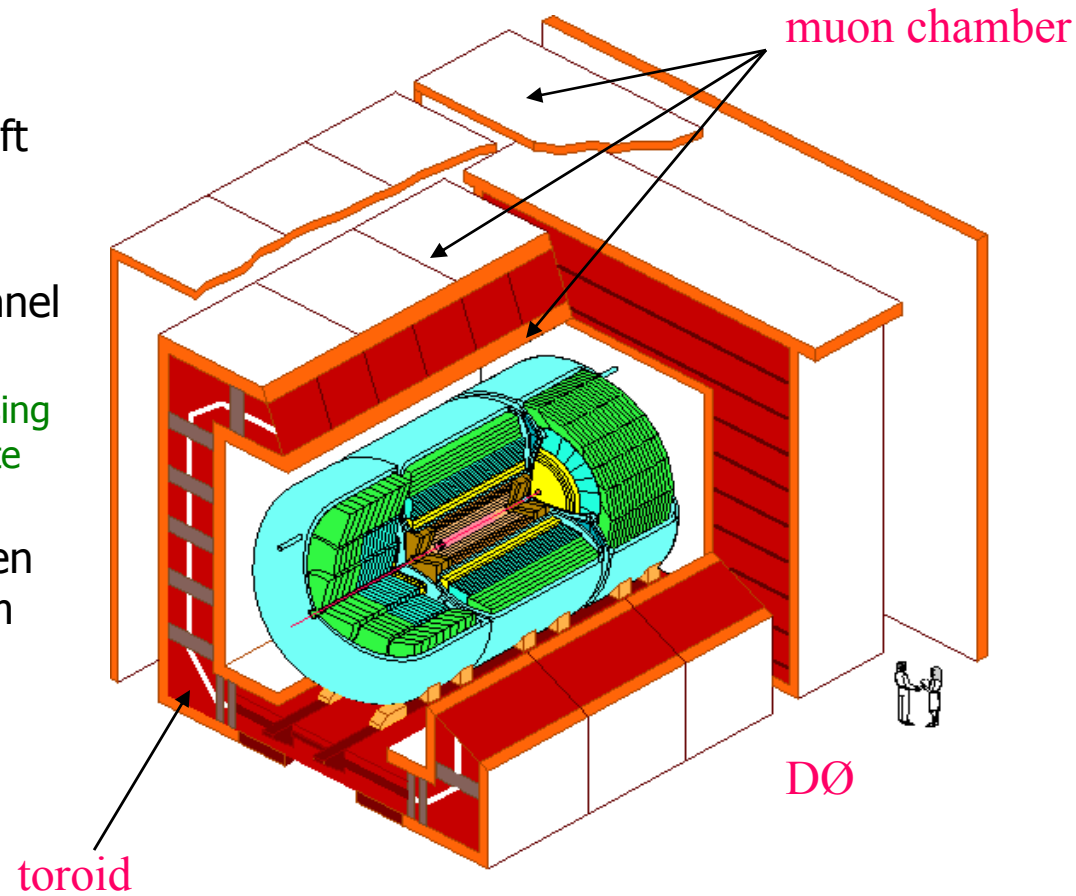




Muon Tracking System

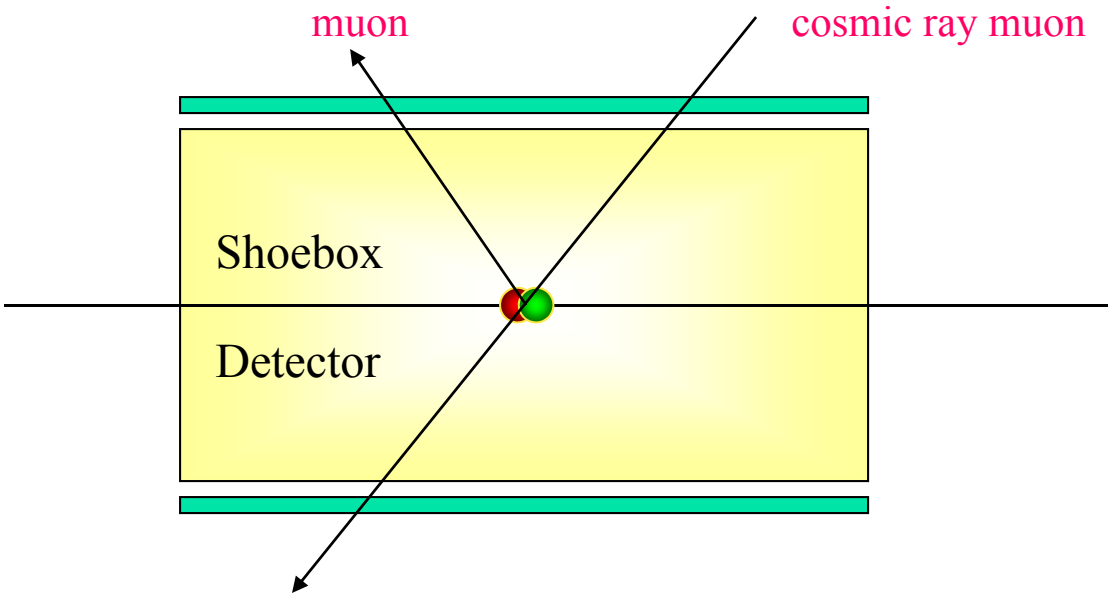
- Muons are minimum ionizing and penetrate the whole calorimeter
- Complement the detector with large area drift chambers to detect the muons
  - Want large lever arm to adequately measure momentum

- DØ muon system:
  - Three layers of large area drift chambers
    - Both central and forward
  - Due to large area, large channel count
    - Reduce channel count by using large drifts with less accurate position resolution
  - Fe of toroidal magnet between layers 1 and 2 for momentum measurement
    - Multiple scattering !



Cosmics

- But wait, muons are the only particles that traverse the whole detector, but there are also muons in cosmic rays ? How do we distinguish them?
- Use timing with scintillators !



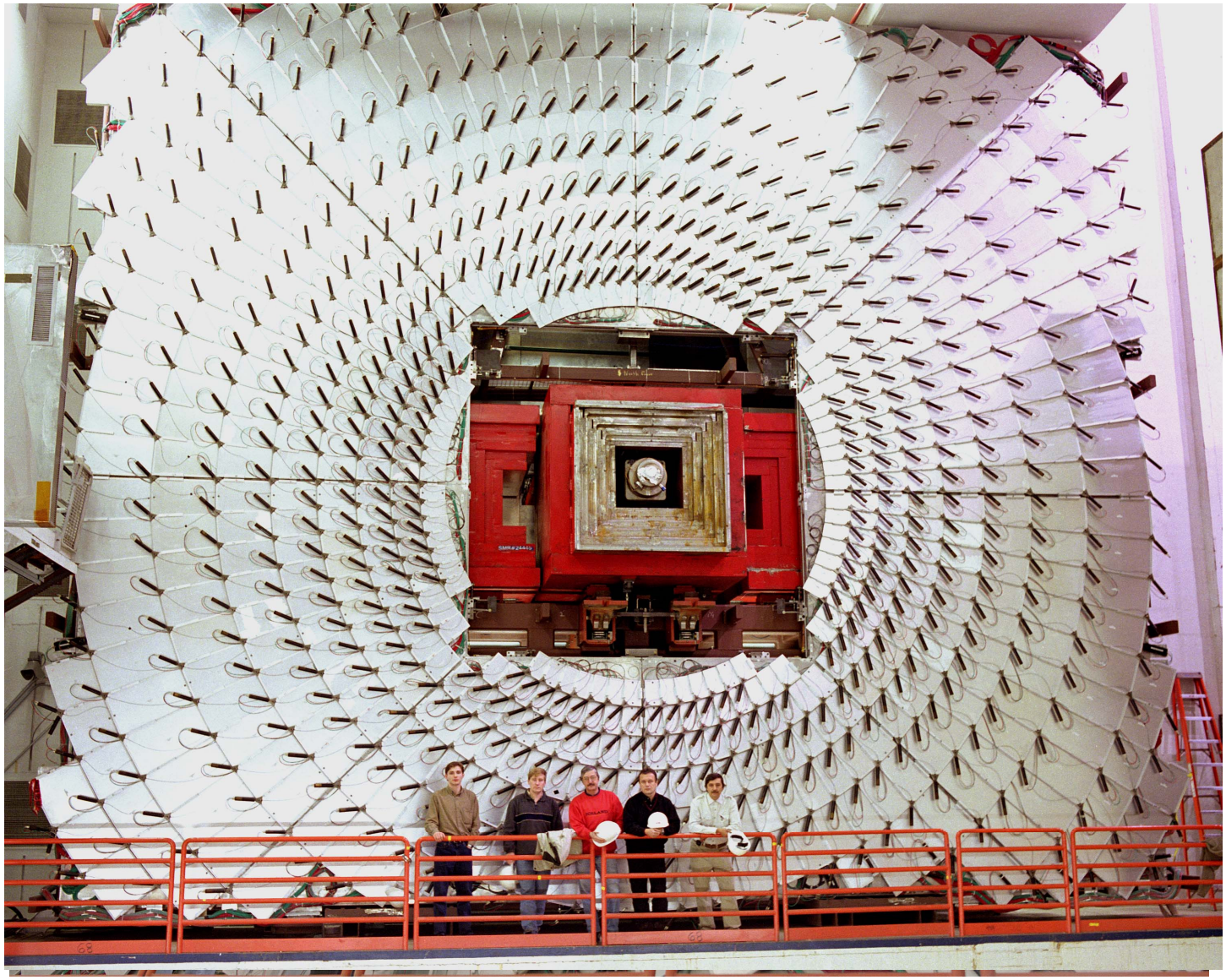
- Two handles on timing
  - Absolute time: scintillator hit has to concur with beam crossing in accelerator
  - Relative time: time difference between two hits should not be consistent with time of flight of muon
- Bonus: can use scintillator hit in track finding

Muon Scintillator Pixel Counter: DØ

- Completely cover detector from all sides with scintillator muon 'veto shield'

- Single pixel counter
  - Scintillator with WLS fiber
  - PMT readout
  - calibration signal
  - scintillator covered with plastic to make it light tight
  - Position resolution of single hit a few cm

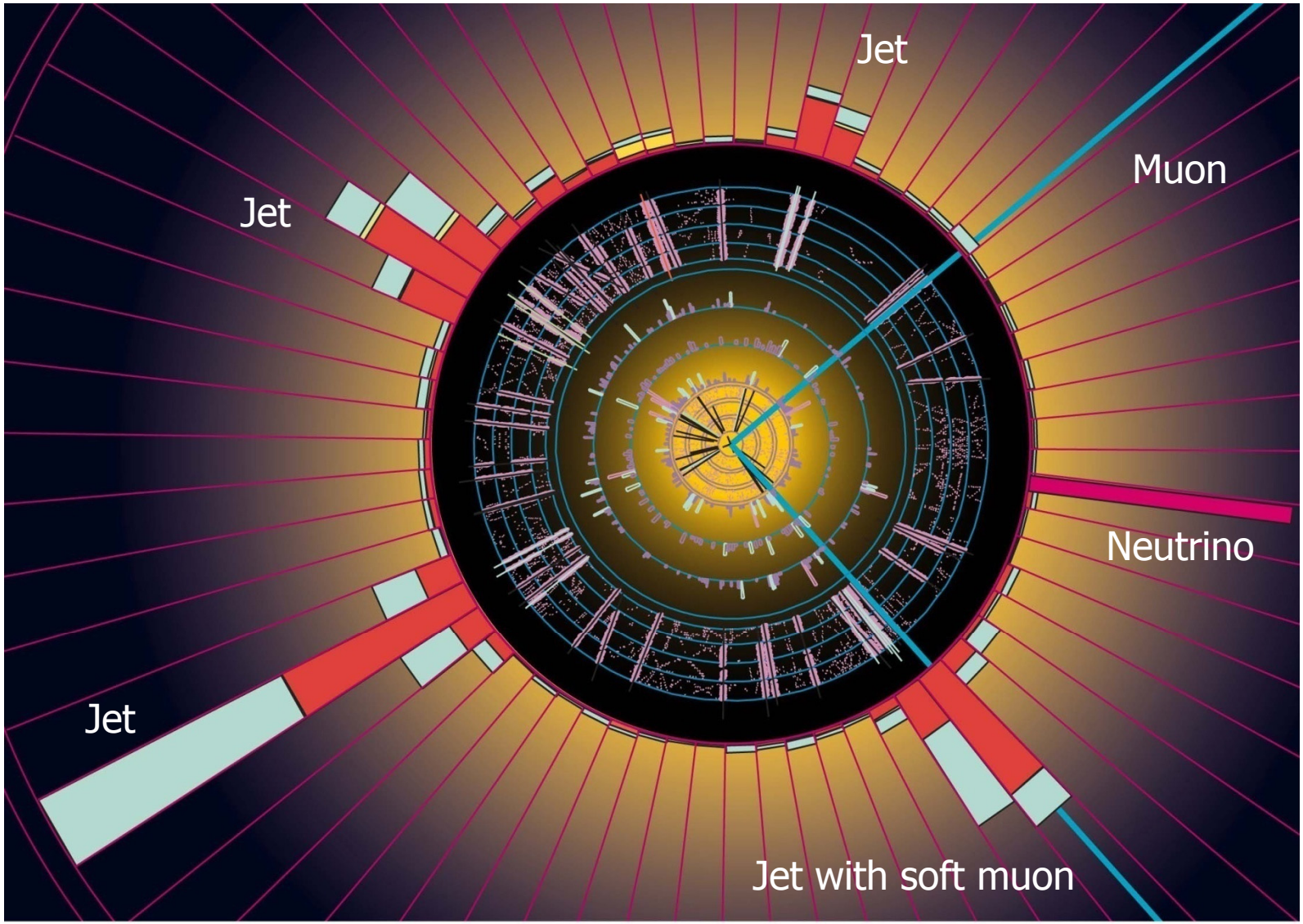
Muon Scintillator Wall



Neutrinos at Colliders

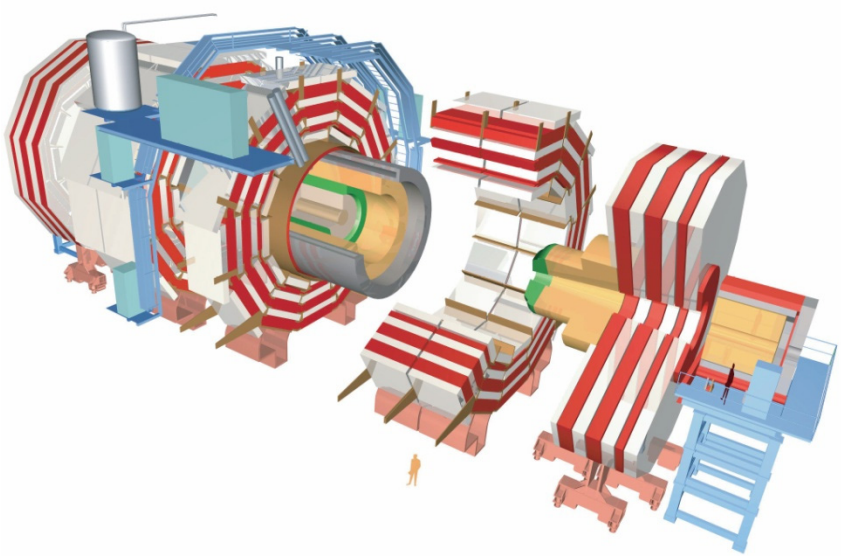
- In a collider environment neutrinos come from the decay of a particle, like a W-boson.
- There are some notable differences with neutrino physics experiments:
  - Neutrinos highly energetic
  - Neutrinos are produced singly
    - Given their small cross section there is no way in hell to have them interact in the detector
- In a collider detector, presence of a neutrino can only be inferred from missing energy:
  - There is an imbalance in observed energy
    - Conclude that a particle escapes: neutrino
  - It is therefore crucial for collider experiments to be hermetic, to have no cracks, so that each particle that is produced (besides neutrinos) is actually detected
    - Shoebox concept

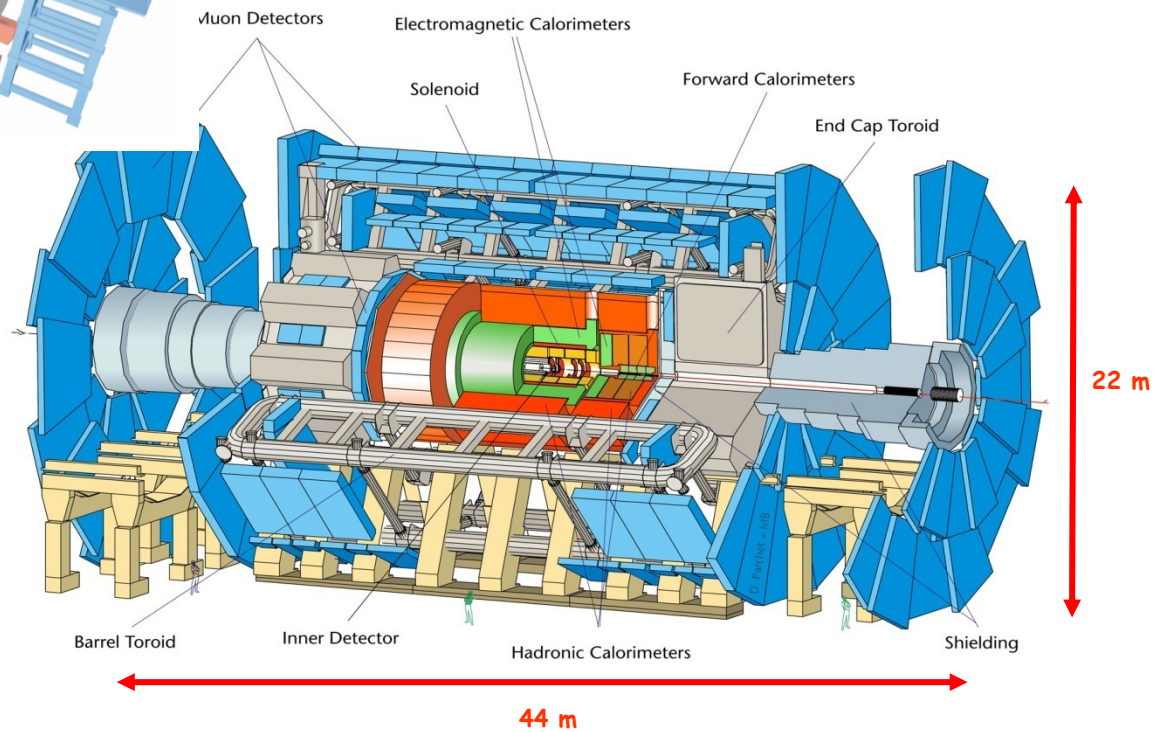
How about the Top Quark ?



Fermilab #97-1889D

ATLAS and CMS Detector





CMS Slice

- What are the particle signatures in the CMS detector ?

At Home

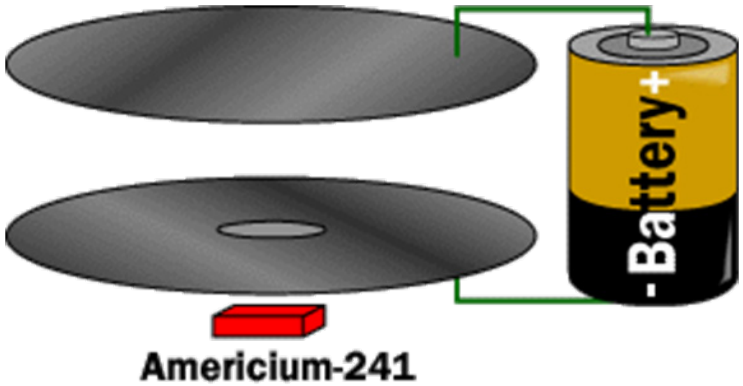
Smoke Detectors

- Smoke Detectors consist of two basic parts
  - a sensor to sense the smoke
  - a very loud electronic horn to alert (wake up) people

- The most common type of smoke detector used today are:
  - Ionization detectors

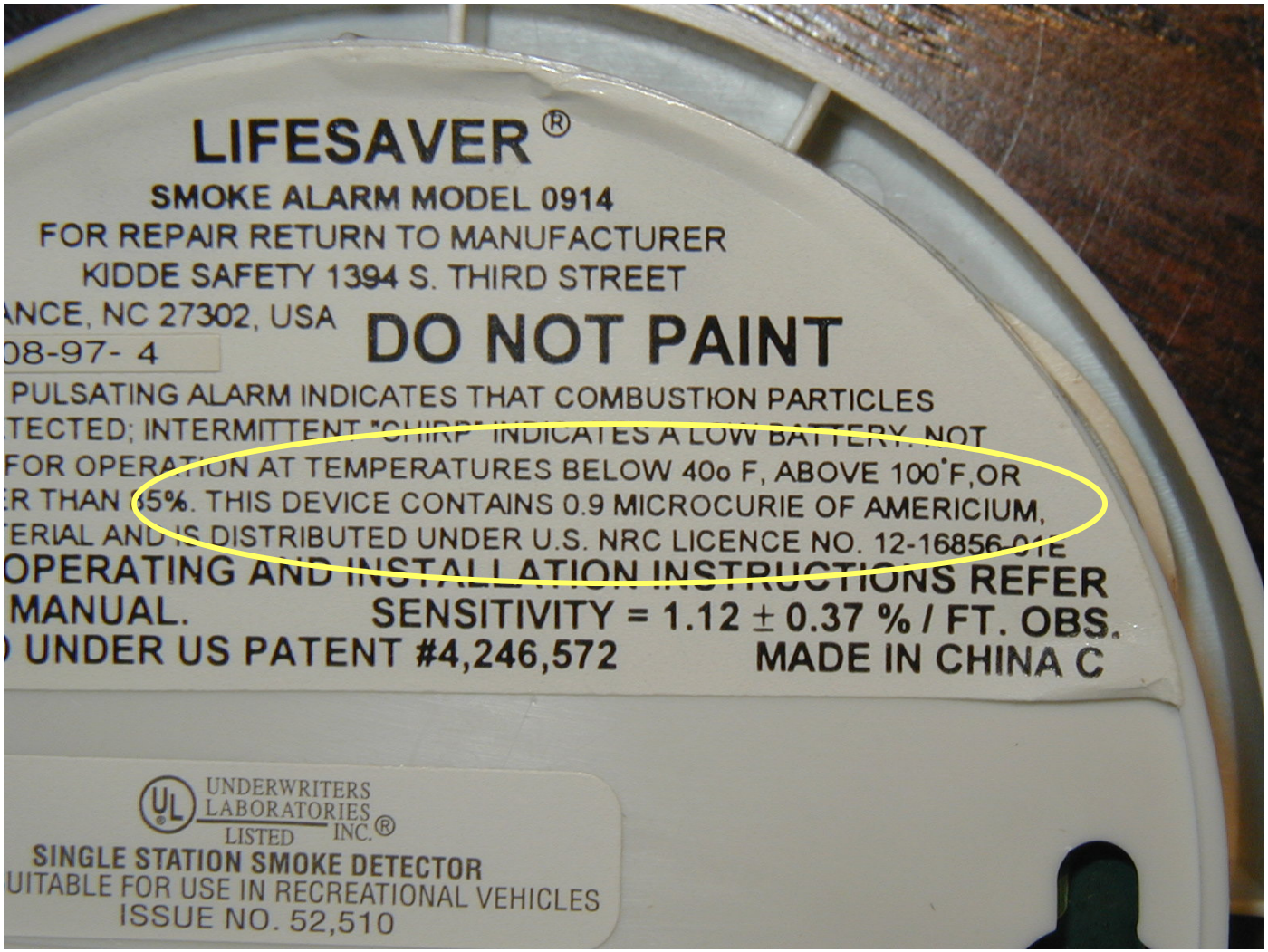
Smoke Detectors (Ionization)

- Ionization smoke detectors use an ionization chamber and a source of ionizing radiation to detect smoke
- Inside the ionization detector is a small amount of radioactive Americium-241
  - Typically 1/5000th of a gram of ^{241}Am, in the form of AmO_2 (Americium-oxide)
  - Half-life of 432 years, emits alpha particles (He nuclei)
    - Discovered during the Manhattan project; first sample of Am produced at U. of Chicago
    - Natural byproduct of nuclear reactors; Costs about $1500 for one gram
- Alpha particles emitted by ^{241}Am collide with the oxygen and nitrogen in air in the detector's ionization chamber and produce ions
- A small electric voltage applied across the chamber collects the ions, causing a steady small electric current to flow between two electrodes.
- When smoke enters the space between the electrodes, the alpha radiation is absorbed by smoke particles. This causes the rate of ionization of the air and therefore the electric current to fall, which sets off an alarm (recall dE/dx, energy loss mechanism)



Smoke Detector: Instructions

- Backside information on regular household smoke detector



A Concluding Observation

- Quarks and leptons are the basic building blocks of nature
- Science and education are the basic building block of an advanced civilization
- Without fundamental research there is no progress of society !

References

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  - Many excellent articles can be found in Ann. Rev. Nucl. Part. Sci.
- Other sources
  - CERN academic lecture series: http://agenda.cern.ch/tools/SSLPdisplay.php?stdate=2006-07-03&nbweeks=6
  - Particle Data Book, Phys. Lett. B592, 1 (2004): http://pdg.lbl.gov/pdg.html
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