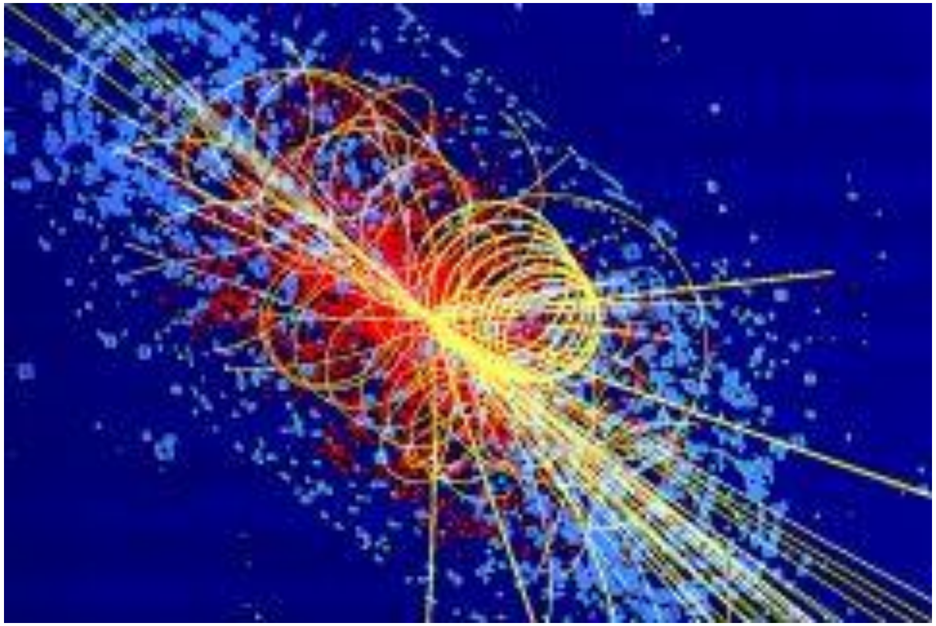
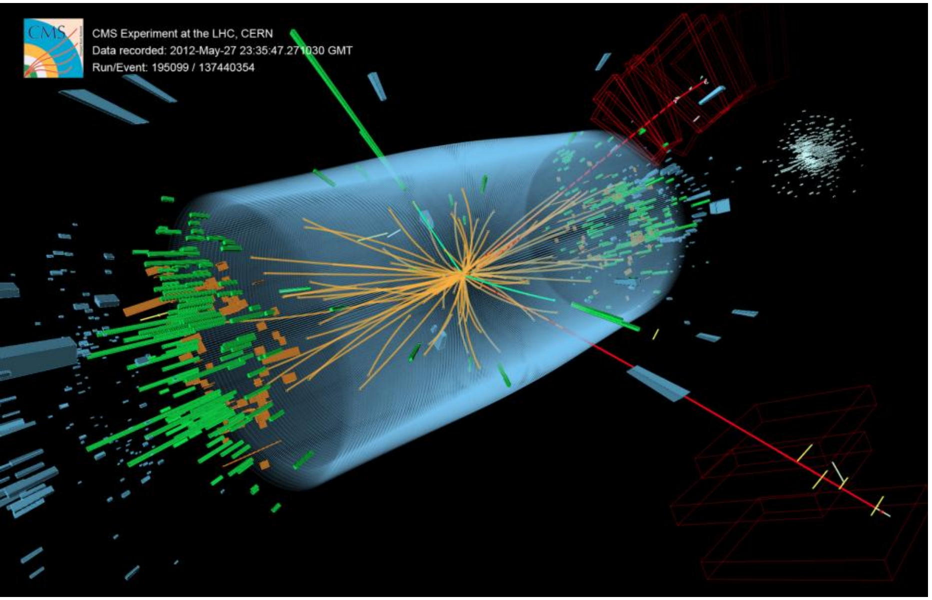
PARTICLE DETECTORS



Saturday Morning Physics

Ronald Lipton
Fermilab

Physics is an Experimental Science



- Our discoveries depend on our tools in Particle Physics these are
  - Accelerators
  - Detectors

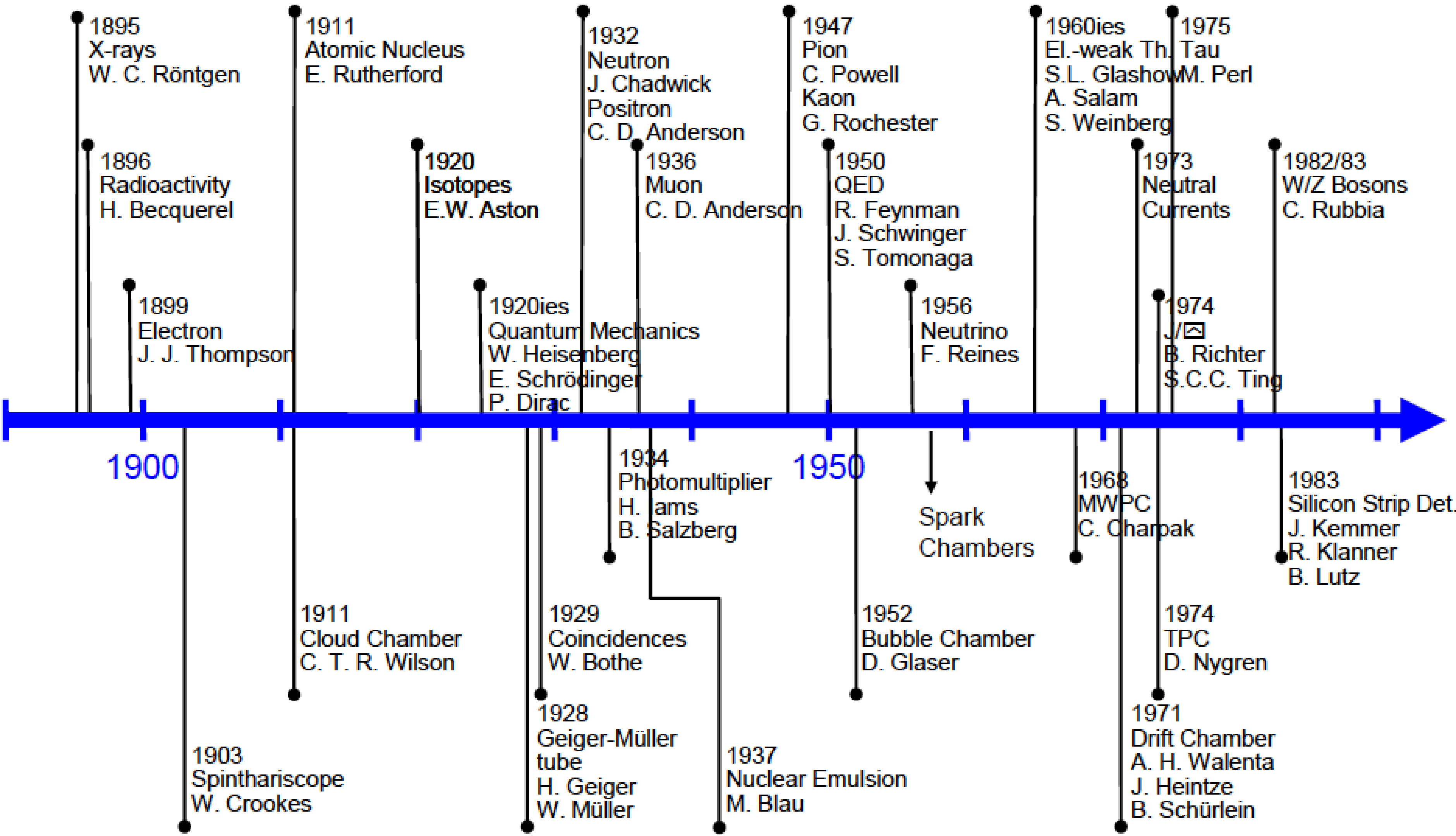
  These go hand-in-hand

  Often new accelerator technologies require new detectors

- The science is enabled by the technology – experiment is crucial to the scientific process
- New detectors have been vital to most significant discoveries in particle physics

For example …

Physics Discovery and Detector Innovation



Detector-related Nobel Prizes

Wilhelm Conrad Röntgen in recognition of the extraordinary services he has rendered by the discovery of the remarkable rays subsequently named after him.

Albert Abraham Michelson for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid.

Robert Andrews Millikan for his work on the elementary charge of electricity and on the photoelectric effect.

Charles Thomson Rees Wilson for his method of making the paths of electrically charged particles visible by condensation of vapour.

Sir James Chadwick for the discovery of the neutron.

Victor Franz Hess for his discovery of cosmic radiation

Lord Patrick Maynard Stuart Blackett for his development of the Wilson cloud chamber method, and his discoveries therewith in the fields of nuclear physics and cosmic radiation.

Cecil Frank Powell for his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method.

Walther Bothe for the coincidence method and his discoveries made therewith.

Pavel Alekseyevich Cherenkov, **Il'ja Mikhailovich Frank** and **Igor Yevgenyevich Tamm** for the discovery and the interpretation of the Cherenkov effect.

Donald A. Glaser for the invention of the bubble chamber.

Luis W. Alvarez for his decisive contributions to elementary particle physics, in particular the discovery of a large number of resonance states, made possible through his development of the technique of using hydrogen bubble chamber and data analysis.

Leon M. Lederman, **Melvin Schwartz** and **Jack Steinberger** for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino.

Georges Charpak for his invention and development of particle detectors, in particular the multiwire proportional chamber.

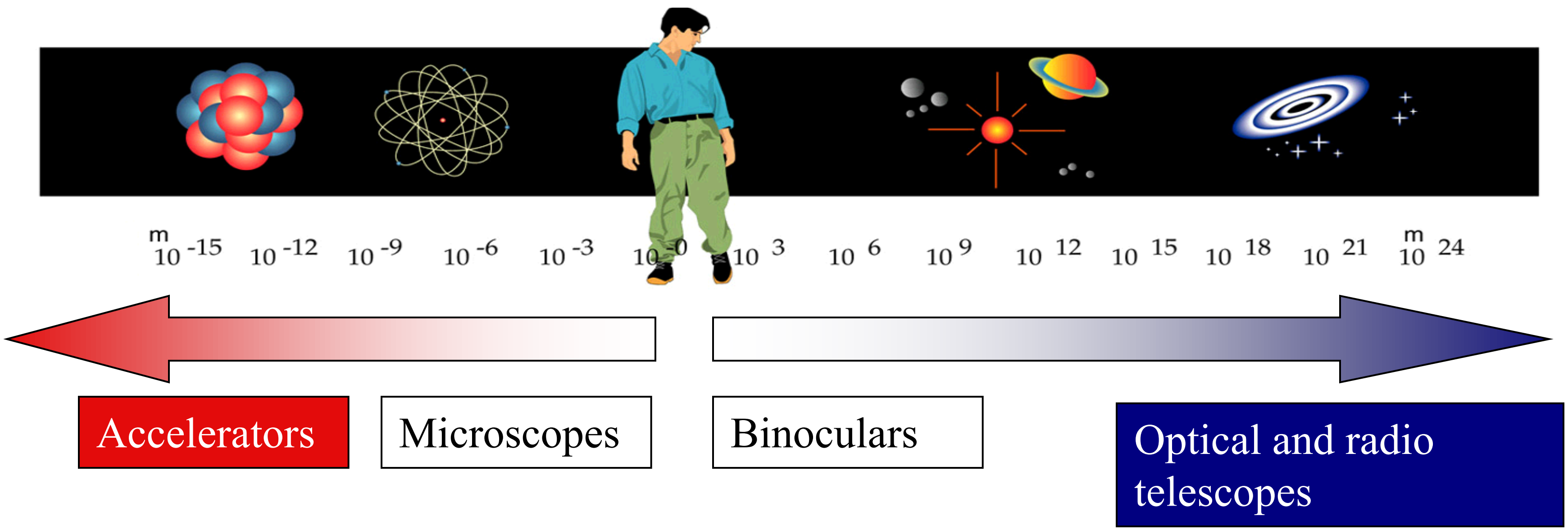
Two Different Physics Examples

- Higgs Boson identification in collider experiments
  - Production and detection in large collider experiments
  - Uses the full capability of those detectors
- Neutrino detection and oscillation
  - Neutrinos interact weakly – can easily pass through the earth
  - Separated production and detection
  - Detectors must be massive, trade for resolution
- Both require large accelerators and detectors – but with very different design

First, some Physics

From Atoms to Quarks

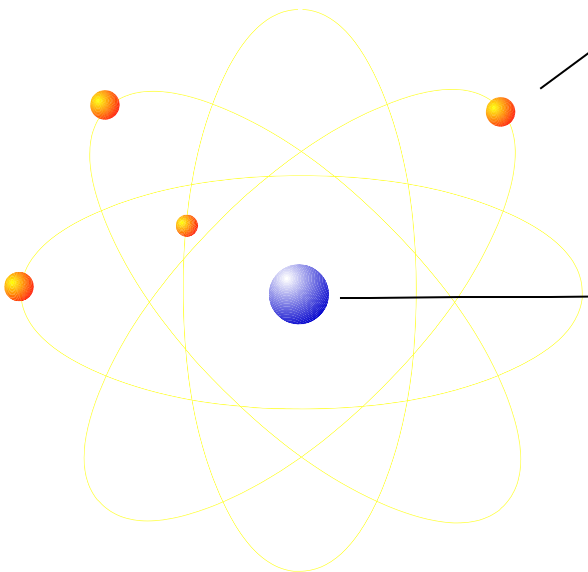
- Particle physics studies the basic building blocks of matter and their interactions



- Particle accelerators are the extensions of microscopes

From Atoms to Quarks

- Fundamental Constituents:

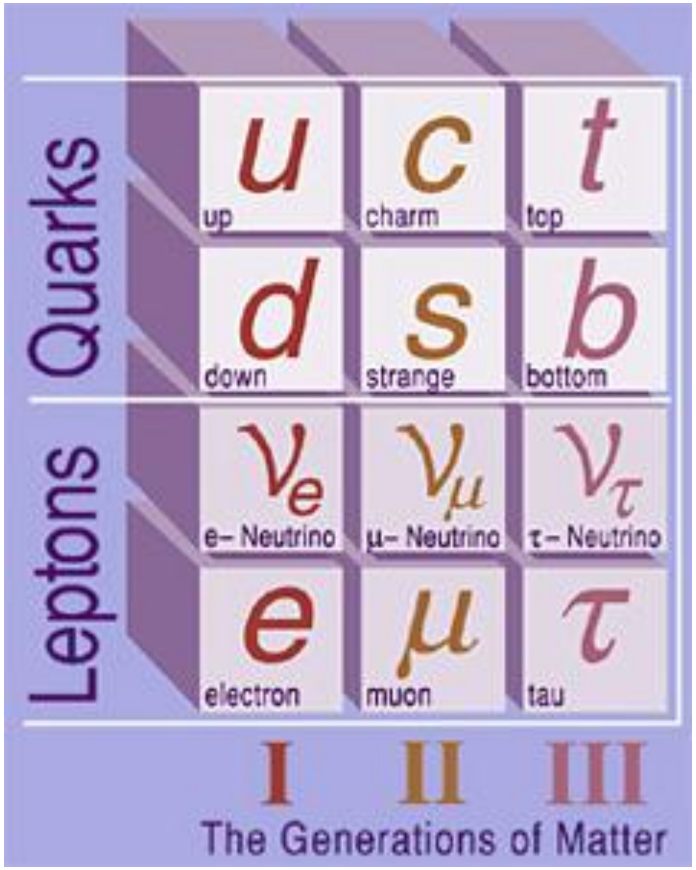


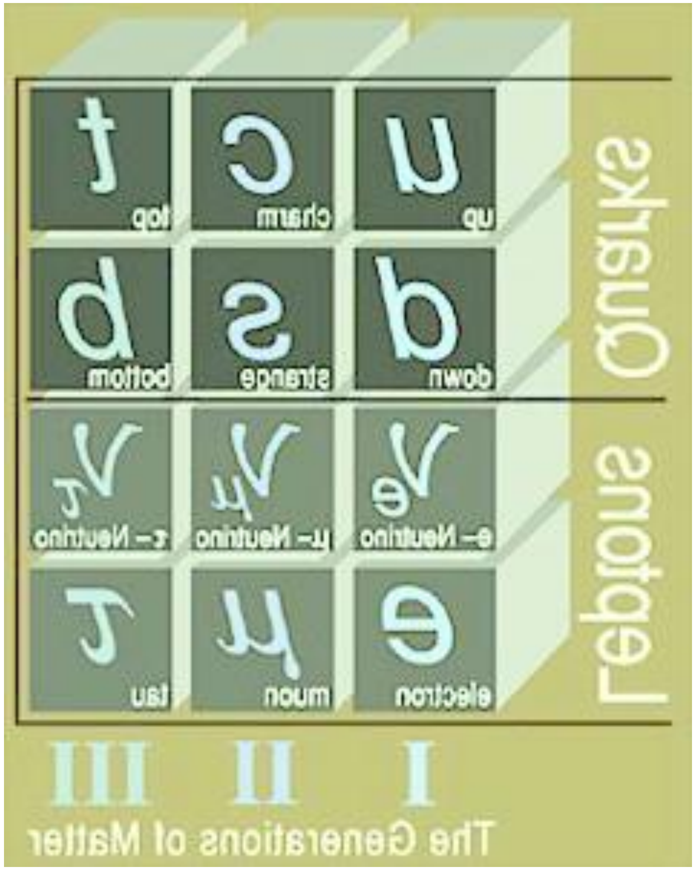
- Leptons:
  - are fundamental
  - appear individually in nature
    - electron + electron neutrino
    - muon + muon neutrino
    - tau lepton + tau neutrino
- Quarks:
  - Particles that make up protons and neutrons and lots of other particles
  - appear in nature only in groups of
    - 2 quarks
      π^{+} = ud
      J/Ψ = cc
      Y = bb
    - 3 quarks
      p = uud
      Λ^{0} = uds
      Λ^{0}_{b} = udb

Mesons

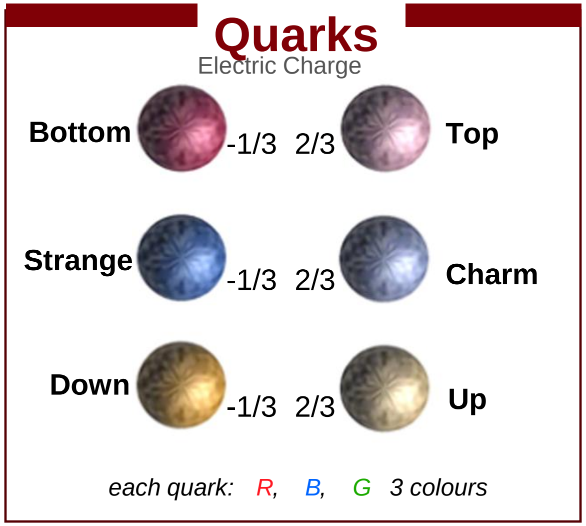
Baryons

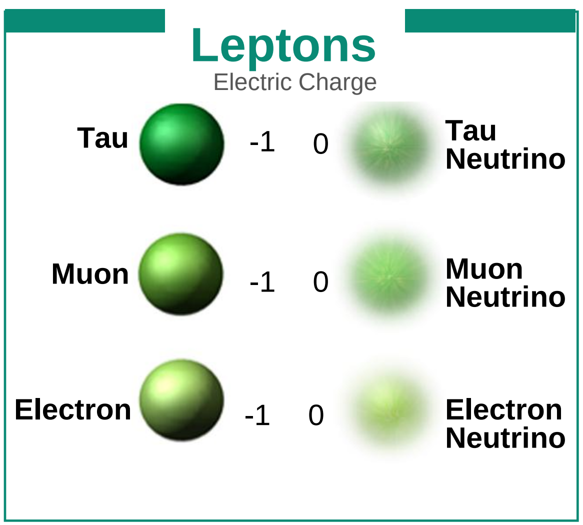
Matter and Antimatter Particles





Matter Particles





Matter Particles and Interactions

Quarks

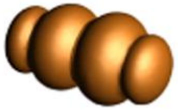
Electric Charge

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

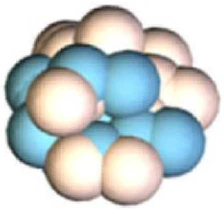
Strong

Gluons (8)



Quarks

Mesons
Baryons



Nuclei

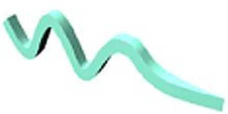
Leptons

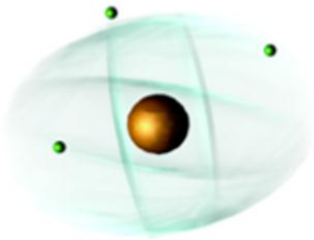
Electric Charge

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

Electromagnetic

Photon

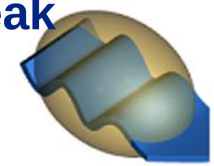


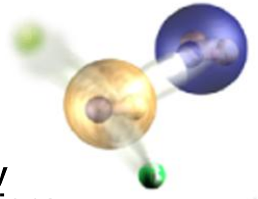


Atoms
Light
Chemistry
Electronics

Weak

Bosons (W,Z)

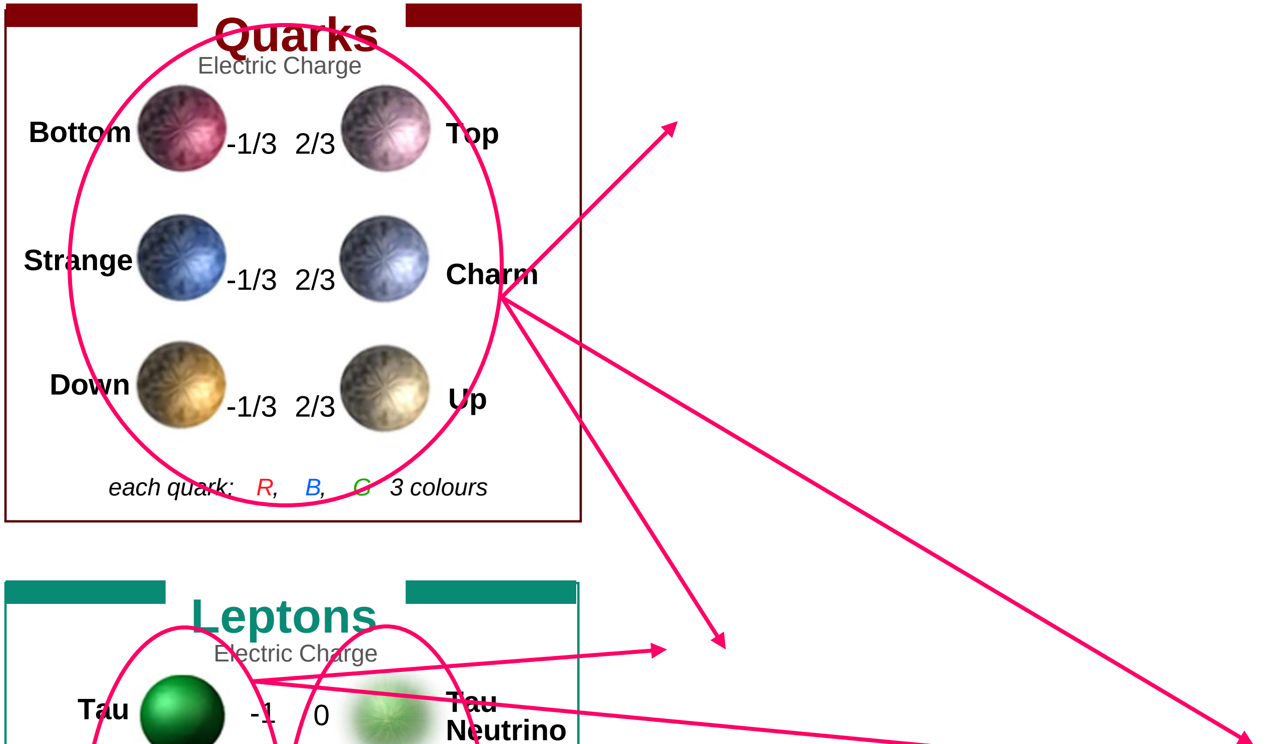


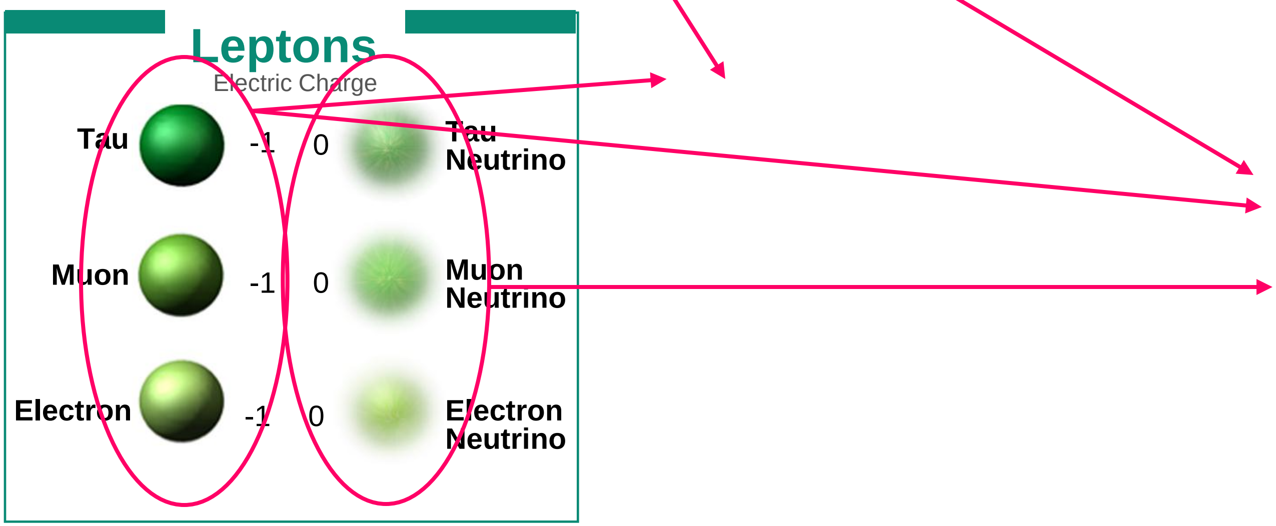


Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun

The particle drawings are simple artistic representations

Matter Particles and Interactions





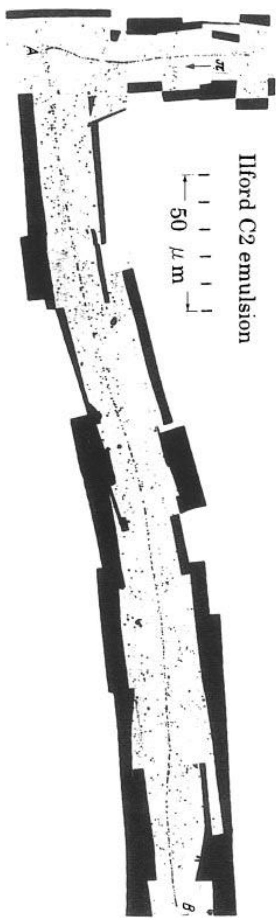
Particle Detectors

What is a Particle Detector ?

- Humans evolved with a limited set of senses. We can sense vibration (sound and touch), electromagnetic radiation in a limited frequency range.
- Particle detectors are extensions of our senses: make particles "visible" by converting small energies deposited by particles into images and data.
- We (as physicists) are very lucky that these very tiny particles, when accelerated to high energies, can cause significant effects on our film, electronics, and materials.

Tracks

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

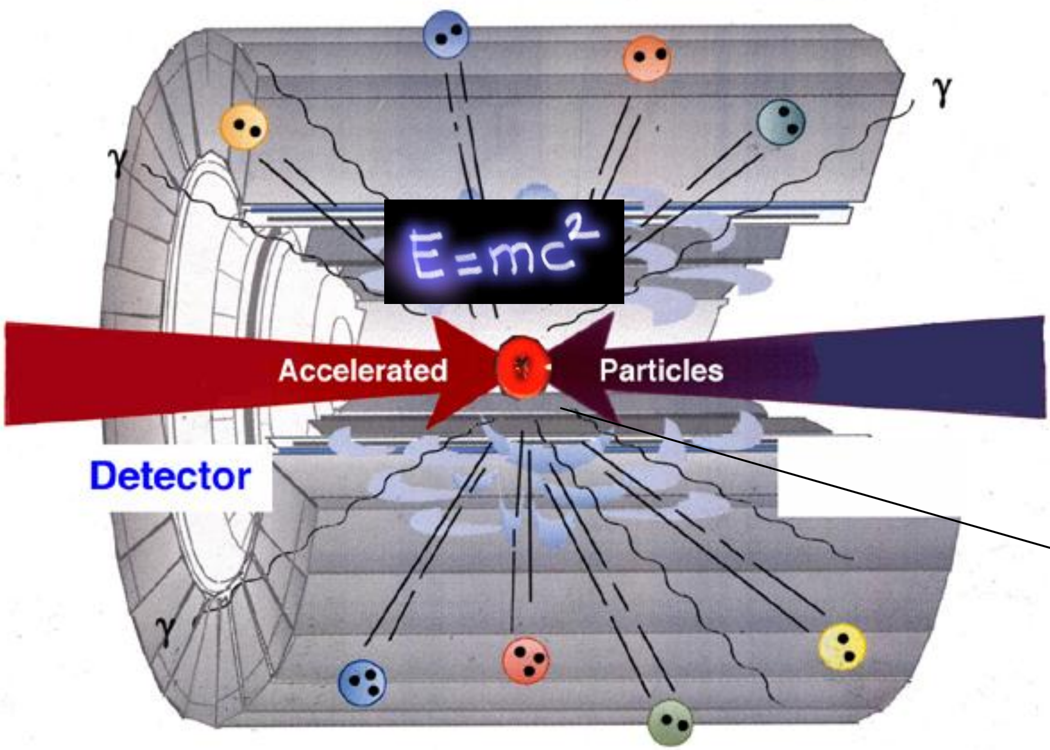


- What do the tracks tell us ?
  - how heavy was the animal ?
  - was the animal running ?
  - being hunted ?
  - tired ?
  - well fed ?
  - Did it have a tail ?
- What do the emulsion tracks tell us?
  - Particle ionization – related to velocity
  - Charge
  - Estimate of mass
  - Fact that it decayed into something else – lifetime

Measurement of Particle Properties

- The purpose of particle detectors is to transform the minute energies deposited by the passage of radiation through matter into information we can use for the science.
- 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
- Purpose is to measure as many properties of all particles as possible
  - To think about - how can you measure the spin of an invisible object?
- 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

First we need to concentrate lots of energy in a small space



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

2) **Collide** particles (recreate conditions after Big Bang)

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

- Generally two methods of collision
  - Collide two particle beams: collider detectors
  - Smash particle beam into stationary target: fixed target experiments
    - Particles from accelerator
    - Natural sources of particles: cosmic rays, neutrinos from the sun, …

What do We need to Know?

- We want to measure the momentum (mass x velocity) and directions of particles
  - If we know the mass we can measure the total energy
  - If we know the energies and directions of daughters we can establish the mass of the parent – most particles we want to learn about are unstable
- Our instruments determine how well we measure that mass

$$E = \sqrt{m^2c^4 + p^2c^2}$$

Einstein's formula

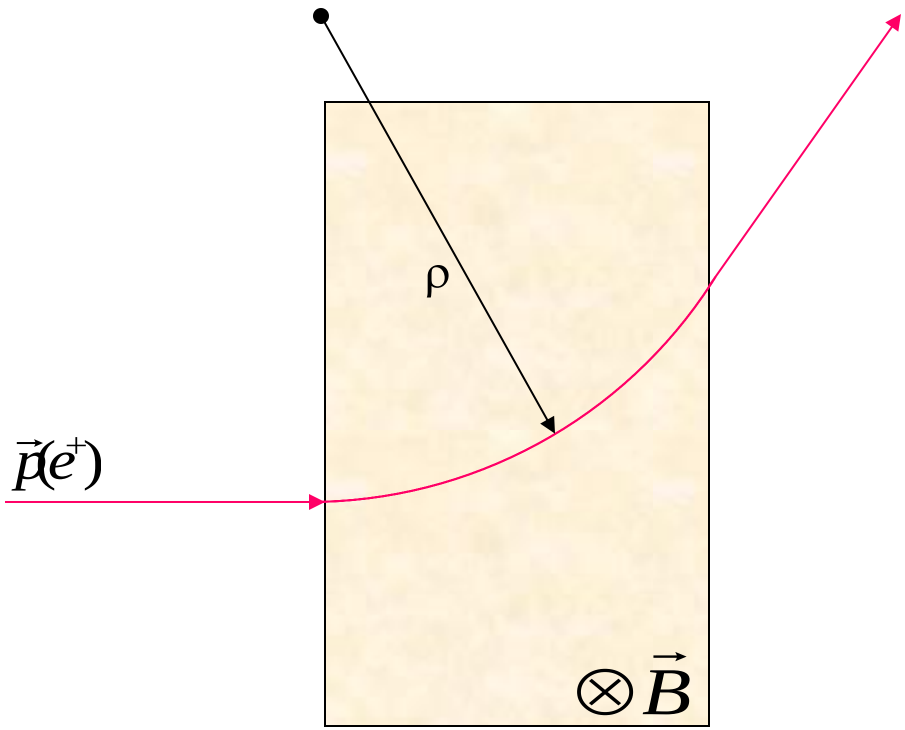
Specialized detectors
Properties of energy deposit
Guess

Curvature in magnetic field
Charge collected in a calorimeter

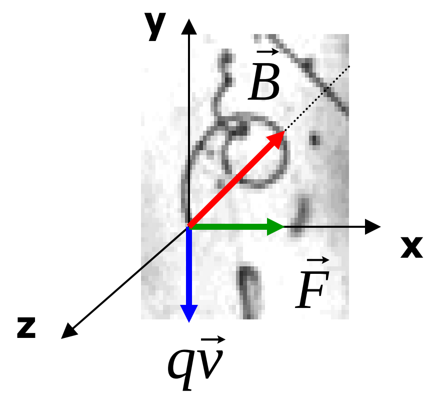
Momentum Measurement

- Charged particle moving in magnetic field will experience Lorentz force (bends)

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



Compton electron in Bubble chamber

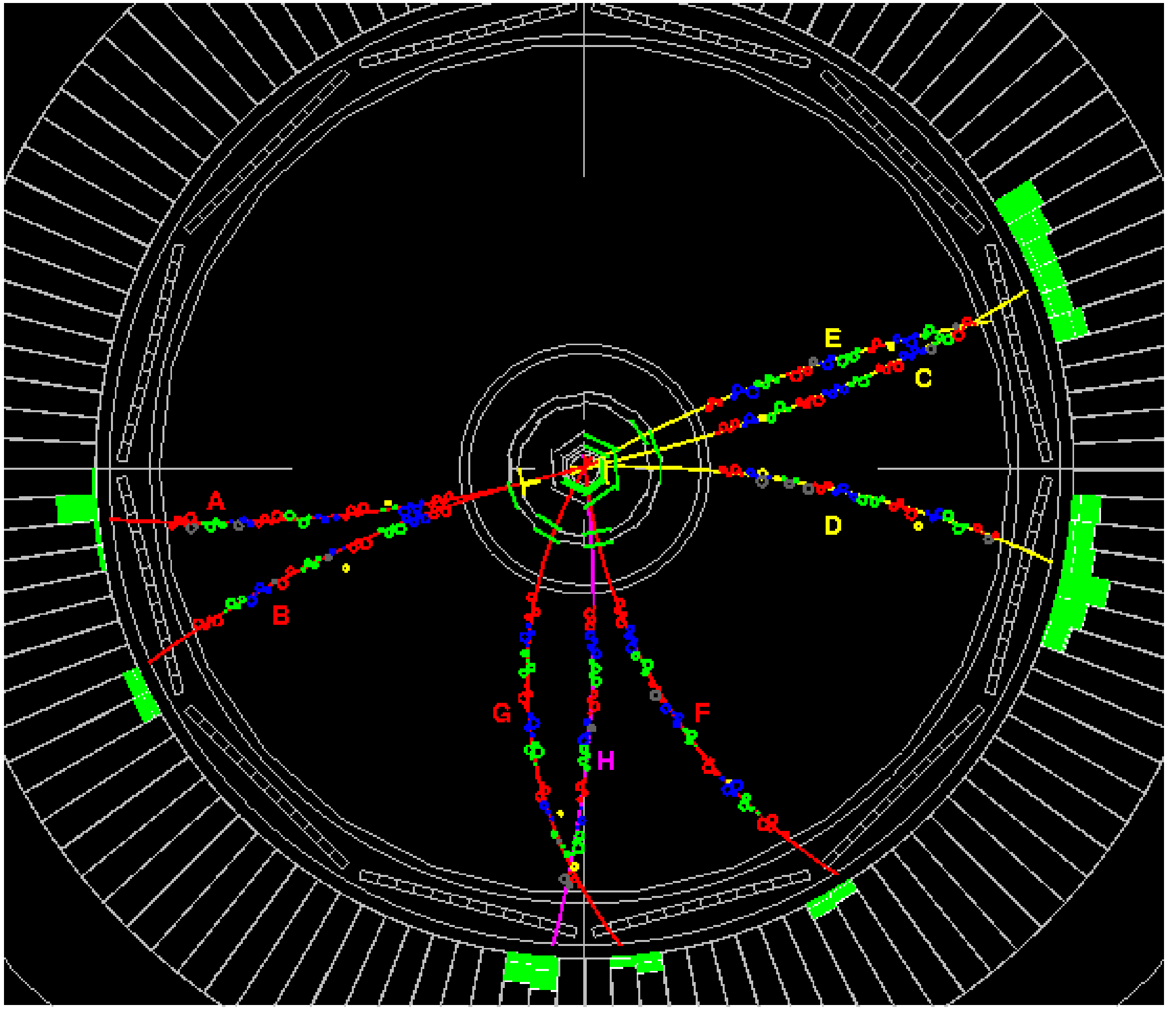


- If particle moves perpendicular to magnetic field: $$p = Bqr$$
- The faster the particle goes, the more magnetic field is needed for the same deflection

Measuring Properties

Track	p = (p_x, p_y, p_z)	E
A	(-0.9, -0.2, -1.0) GeV/c	1.4 GeV
B	(-1.1, -0.3, -0.6) GeV/c	1.3 GeV
C	(1.2, 0.2, 0.8) GeV/c	1.5 GeV
D	(0.9, 0.0, 0.5) GeV/c	1.1 GeV
E	(0.9, 0.5, 0.0) GeV/c	1.2 GeV
F	(0.1, -0.5, 0.0) GeV/c	0.5 GeV
G	(-0.2, -0.3, -0.1) GeV/c	0.4 GeV
H	(0.1, -1.1, 0.6) GeV/c	1.3 GeV

One Event at SLAC BABAR collider



Measure the momenta and charge by curvature of the tracks

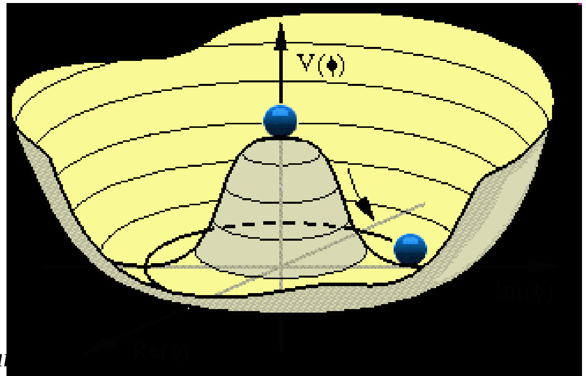
If we add the momenta of tracks A, B, C, D the sum is (.1,-3.,-.3) close to zero – probably came from the same parent

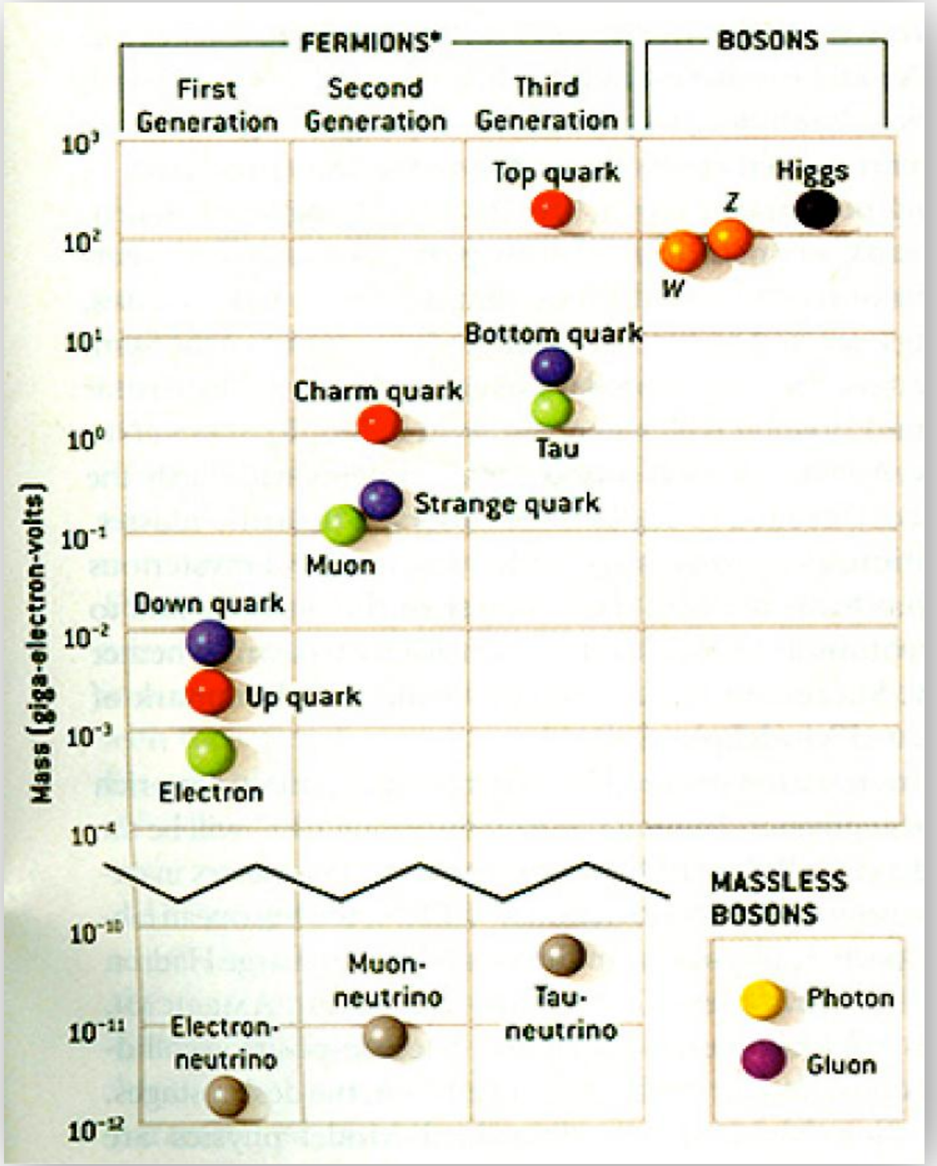
The mass is about 5.3 GeV – the mass of a "B" particle

$$M^2 = (E_1+E_2+E_3+E_4)^2 - (\mathbf{p}_1+\mathbf{p}_2+\mathbf{p}_3+\mathbf{p}_4)^2$$

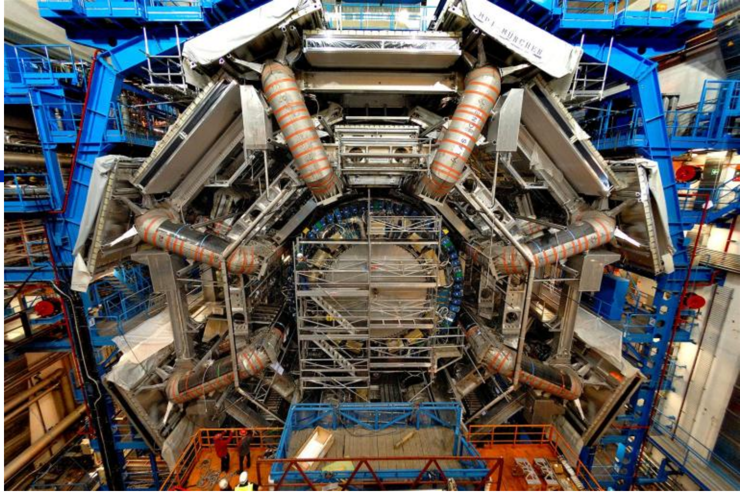
The Higgs – in one slide

- Particle physics theories are based on symmetries of nature
- In a perfectly (gauge) symmetric universe all particles would be massless
  - This symmetry must be violated
- But there are consequences – a new particle must exist
  - It must have 0 spin
  - It must couple to mass – decays into most massive quarks and leptons
  - *It must be part of the fabric of the vaccuum - ???*





Higgs



The Higgs Boson was discovered by CMS and ATLAS at CERN on July 4 2012

- What was needed to discover the Higgs?
- Standard model Higgs has well defined properties
  - Likes to decay into the most massive things around:
  - b quarks, W, Z bosons
- But we are limited by our detectors
  - Easy to see some elementary particles (photons, electrons, muons) but not others (quarks)
  - At LHC 174,000 Higgs made
    - 104,000 decay into b quarks – swamped by background at LHC
    - 397 decayed into 2 photons
    - 10 decayed into 2 Z's which then decayed into $e^+e^-\mu^+\mu^-$ (lepton) pairs
  - At Fermilab Higgs was "detected" in decays to b quarks – Tevatron had lower energy and less b quark background
  - At LHC Higgs was discovered by the few decays into leptons and photons

Higgs Decay reconstruction

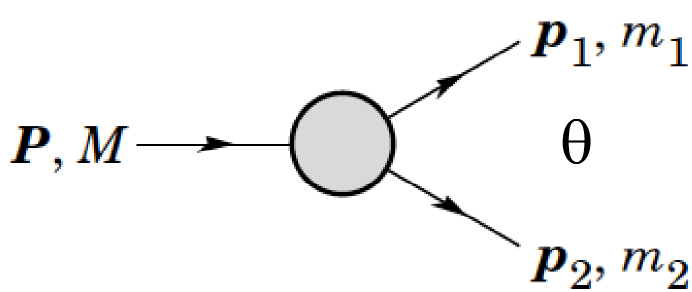
- A Higgs discovery mode was it's decay into to photons (high energy quanta of light)
- Let's see how that goes:

$$E = \sqrt{m^2c^4 + p^2c^2}$$

Einstein's formula

For on particle decaying to two massless photons (c=1)

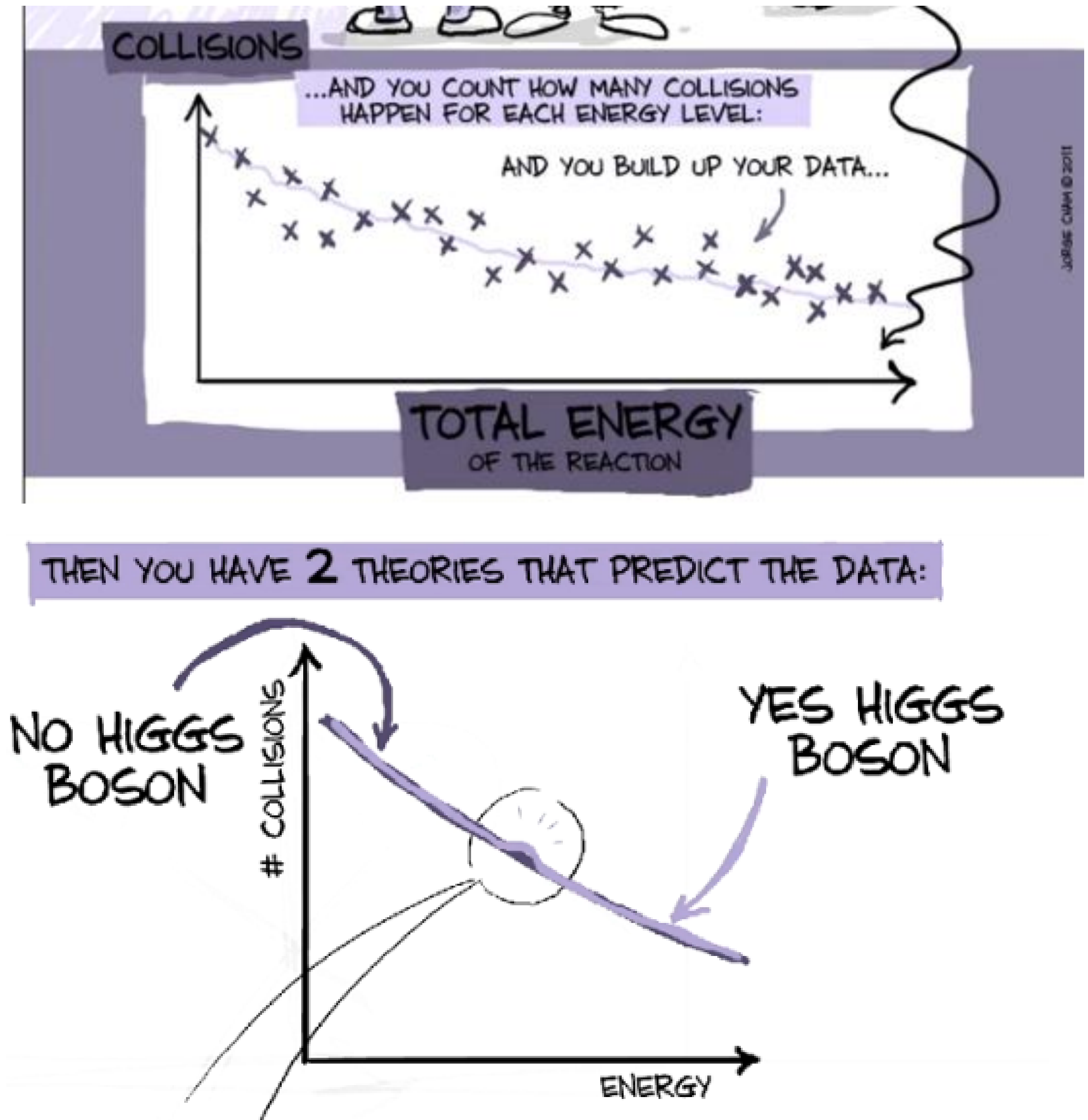
$$m^2 = E_1E_2(1 - \cos\theta)$$



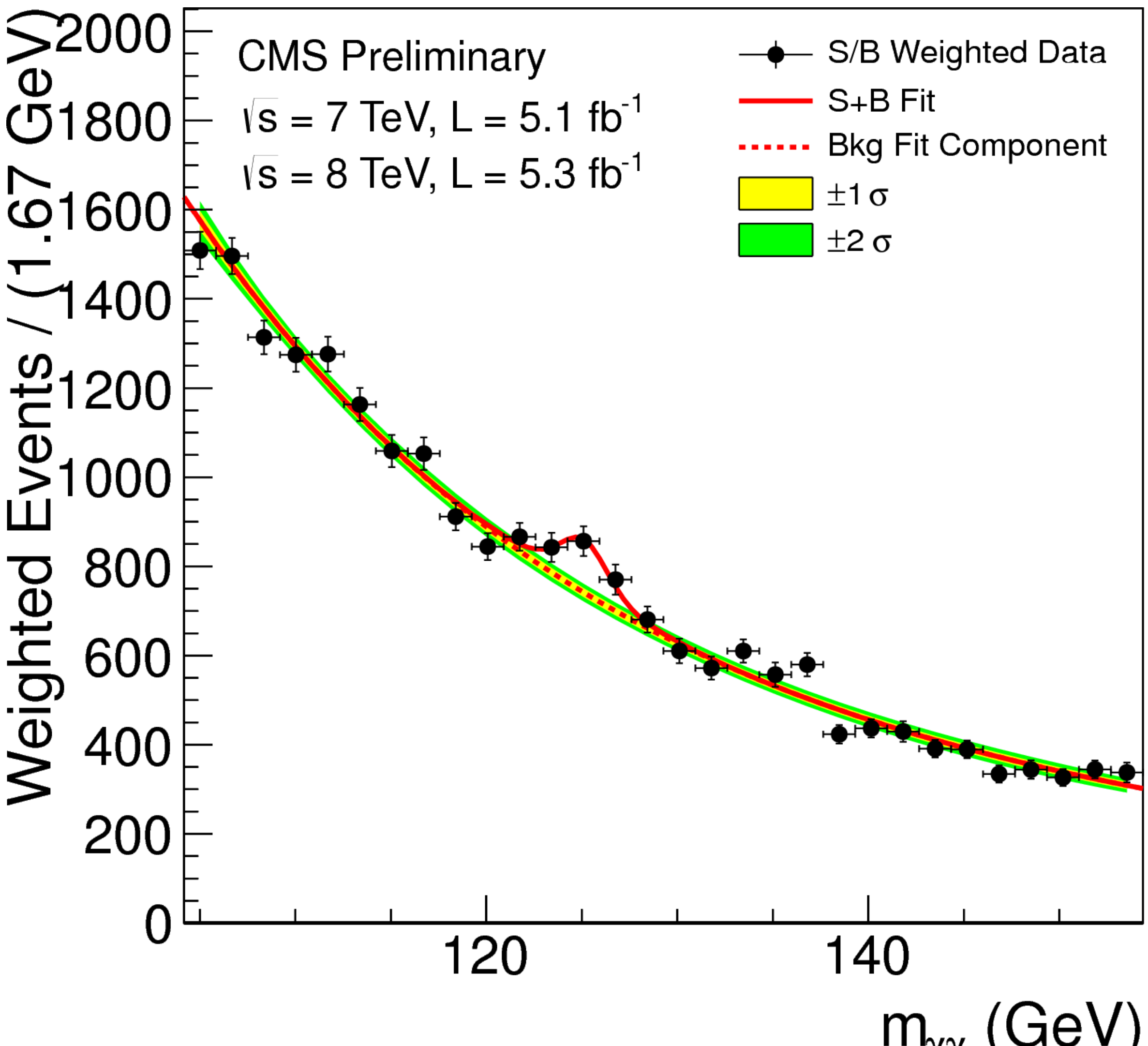
So we need to measure two energies and one angle

Adding things up

For the Higgs we examined trillions of events, most are uninteresting, glancing collisions, but a few have the right properties



Higgs -> γγ "discovery" mass plot

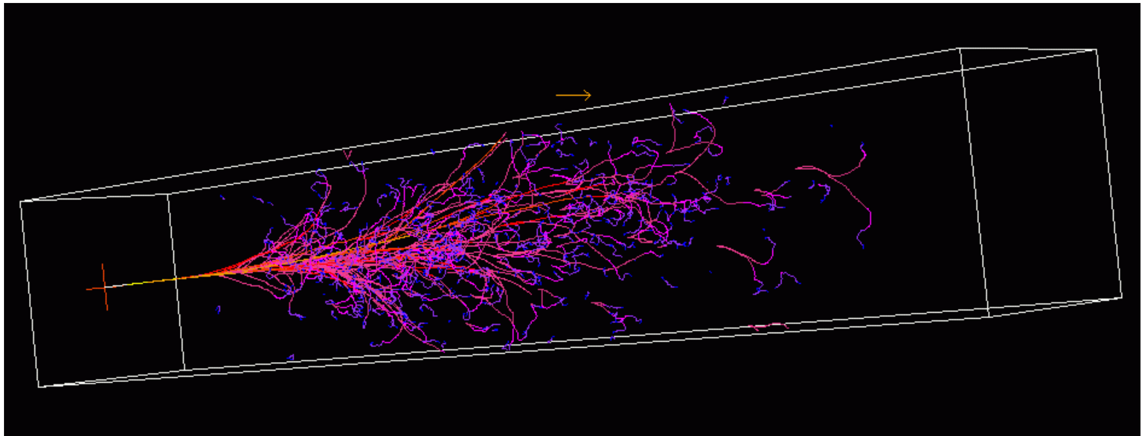


Principles of Particle Detection and Detection Techniques

Interactions

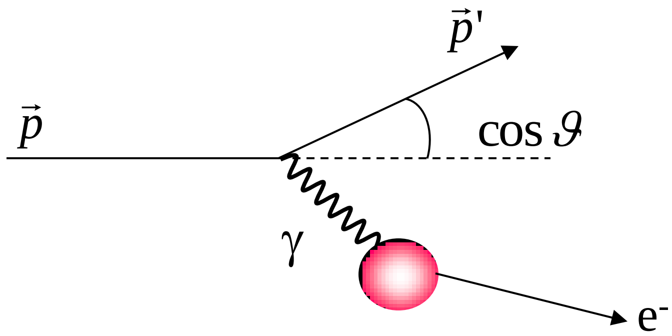
Each particle type has characteristic interactions with matter

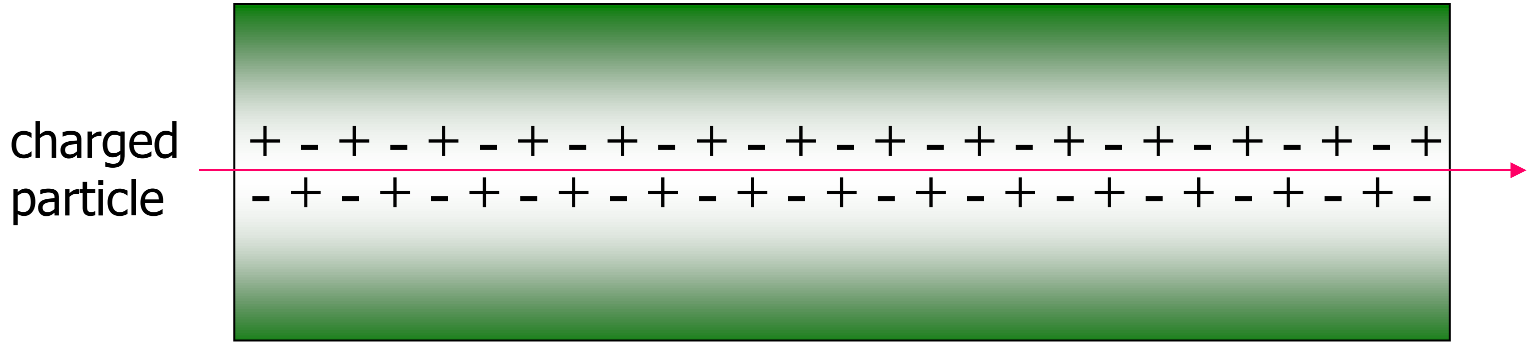
- Charged particles loose energy continuously along path
  - Hadrons – composed of quarks – interact after a short distance in material
  - Leptons (e, μ, τ) interact mostly with atomic electrons – lose energy at a rate depending on their mass
- Neutral particles lose energy when they interact
  - Photons interact with charge in material – can cause “showers’ of paricles
  - Neutrinos almost don’t interact at all
- Most particles decay
  - Only protons (?), photons, electrons appear to be stable…



Interactions of Charged Particles with Matter

- Charged particles pass through material and knocks electrons off atoms
- Leaves positive ions and free electrons





- determine amount of energy lost per unit distance traveled

Language of Particles

- We use relativistic equations – particles are generally fast
- Einstein Equation

$$E = mc^2 = g m_0 c^2$$

$c:$ *speed of light in vacuum*

$E:$ *Energy*

$m_0:$ *rest mass*

- Relativistic factors

$$b = \frac{v}{c} = \frac{pc}{E} \quad (0 \pounds b \pounds 1) \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}} \quad (1 \leq \gamma \leq \infty)$$

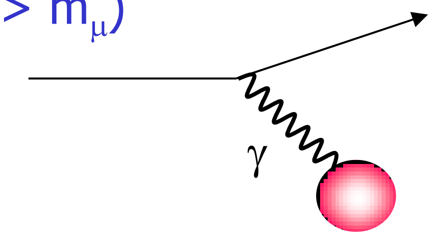
- Units
  - Energy and mass normally expressed in eV: energy an electron gains when passing a potential difference of 1 Volt: 1 eV=1.6 10^{-19} Joule
  - Example: proton has total energy equal to twice its rest mass: $\gamma = 2$

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

β = 0.87: 87% of the speed of light

Energy Loss

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



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

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

$Z = Atomic\ number\ of\ Absorber$

$A = Atomic\ mass\ of\ Absorber$

$I = Mean\ excitation\ energy$

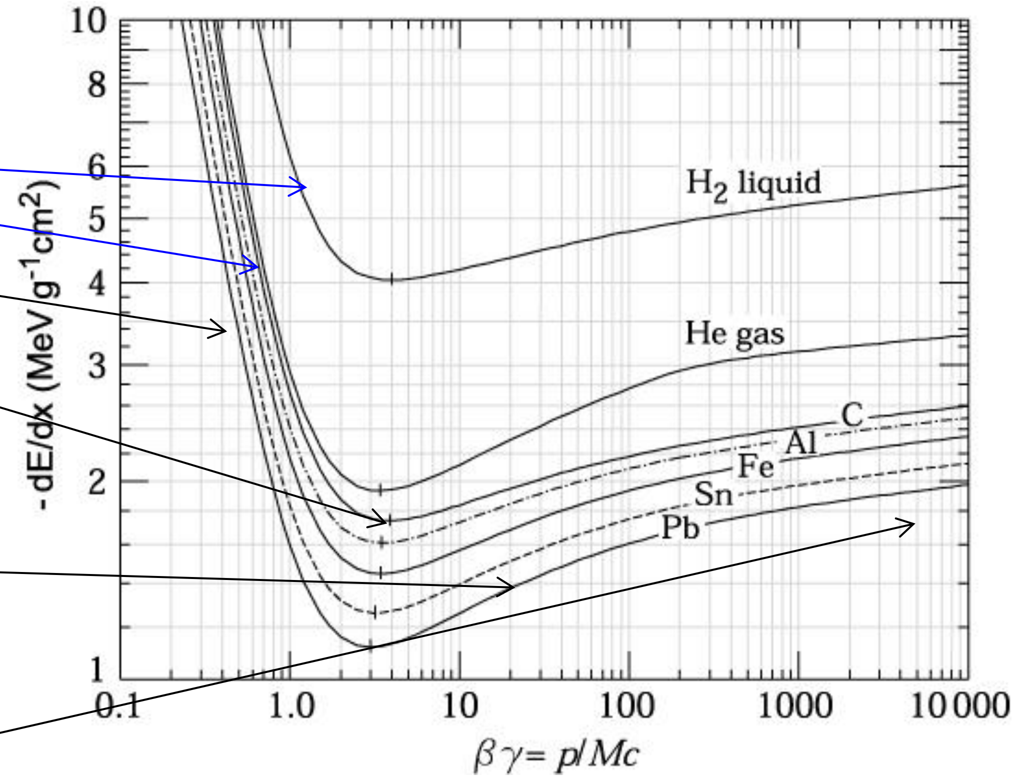
$\delta = density\ effect\ correction$

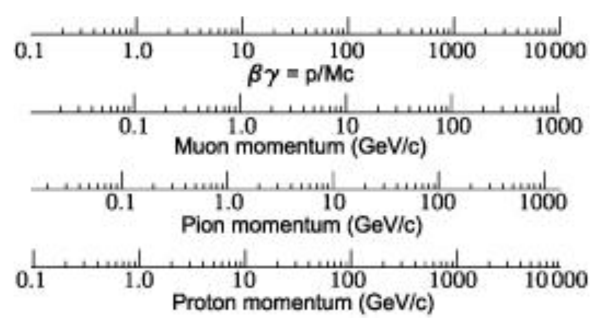
  - dE/dx in units of MeV $g^{-1}\,cm^2$
  - dE/dx depends only on β, independent of M
  - $I \approx I_0 Z$, with $I_0 \approx 10$ eV
  - Z/A does not differ much for most elements, except for hydrogen

Bethe-Bloch

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

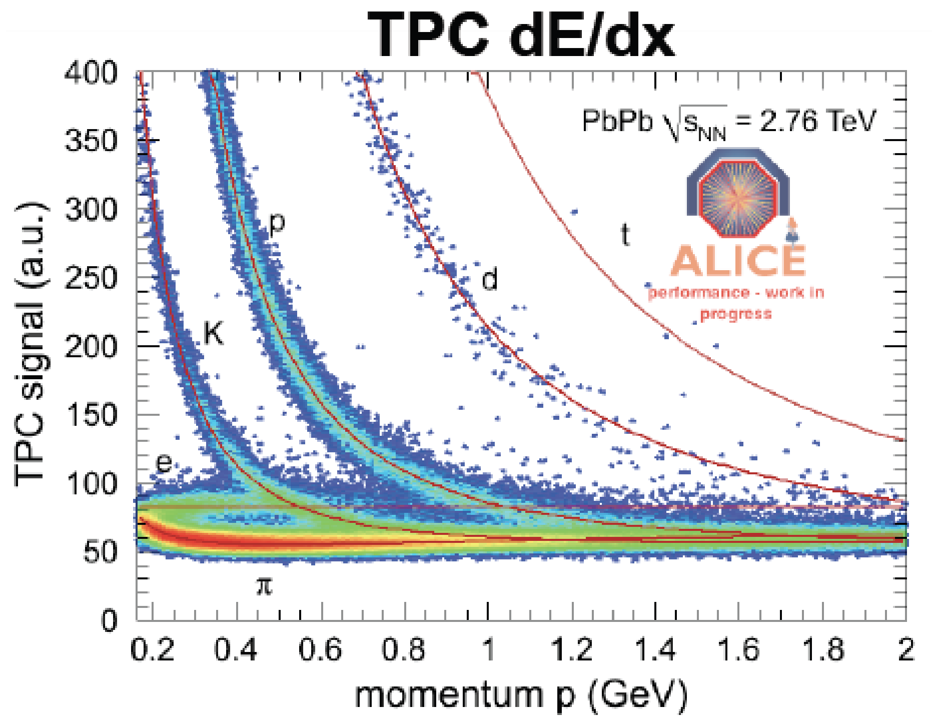
- dE/dx first falls ~ $1/\beta^2$
- dE/dx minimum at 3.0 – 3.5
- dE/dx minimum of 1 – 2 MeV g^{-1} cm^2
  Minimum Ionizing Particle (MIP)
- At high $\beta\gamma$ relativistic rise due to ln $\gamma^2\beta^2$, attributed to relativistic expansion of EM-field: contribution from more distant collisions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

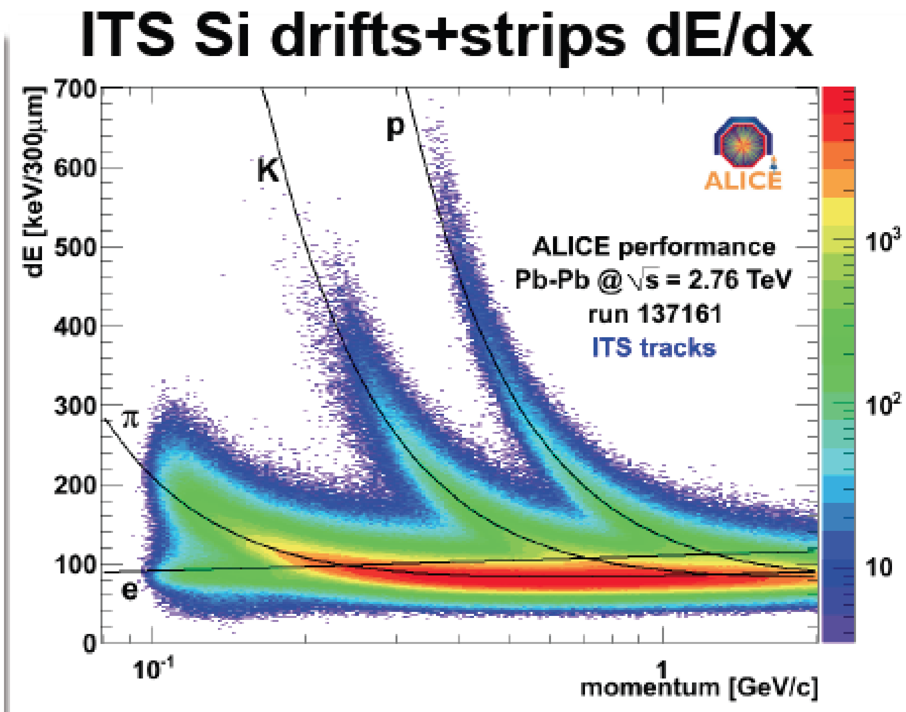




Particle Identification

- Knowing the average energy loss of particle and its momentum, can determine the identity, that is, mass of the particle



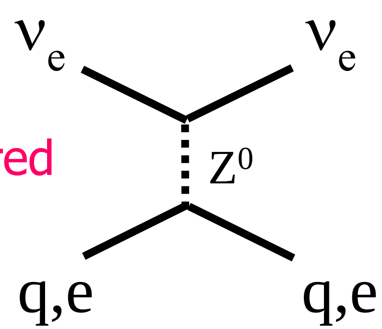


ALICE detector at the LHC

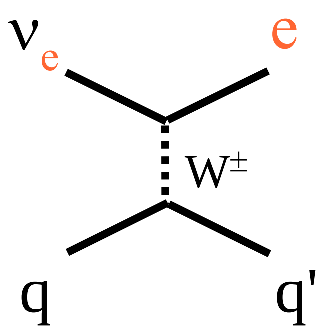
Neutrino Interactions

- Two kinds of weak interactions for neutrinos

Discovered in 70's



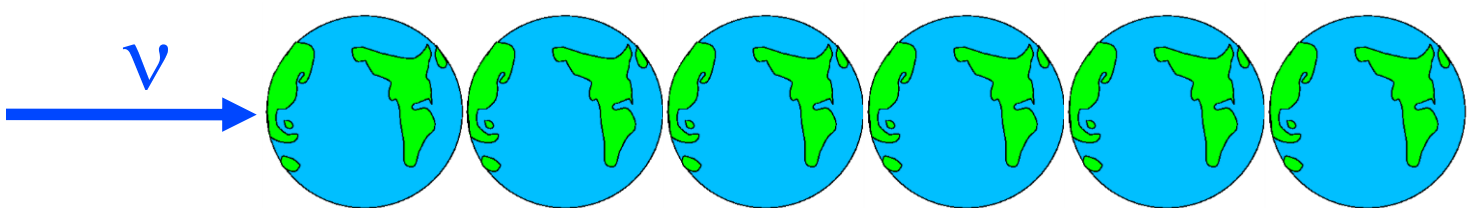
Neutral Current Scattering observed through recoil



Radioactive decay

Flavor changing Charged Current Scattering

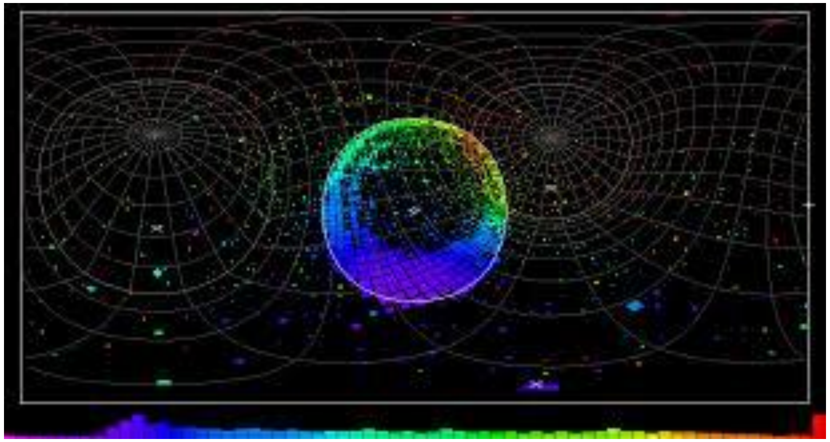
- Neutrinos interact 100,000,000,000 times less often than quarks



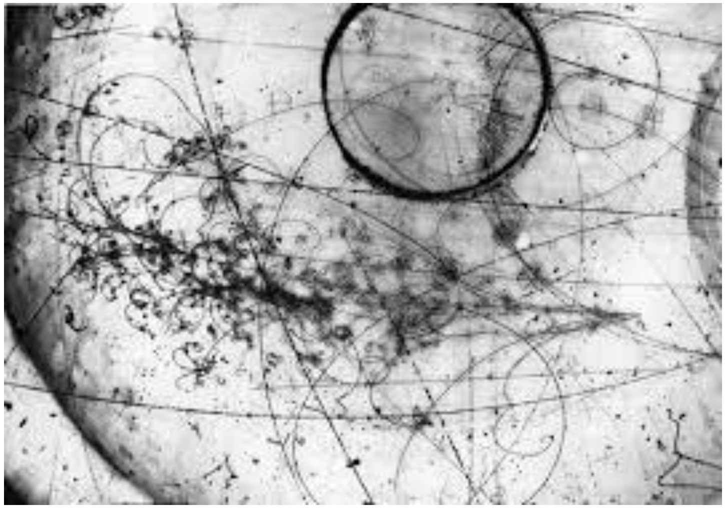
  - A neutrino has a good chance of travelling through 200 earths before interacting at all !

Neutrino Interaction "trails"

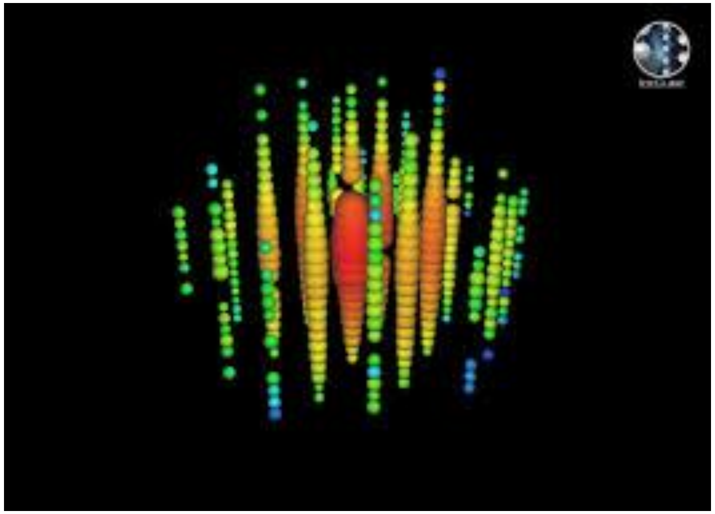
Underground water tank in Japan



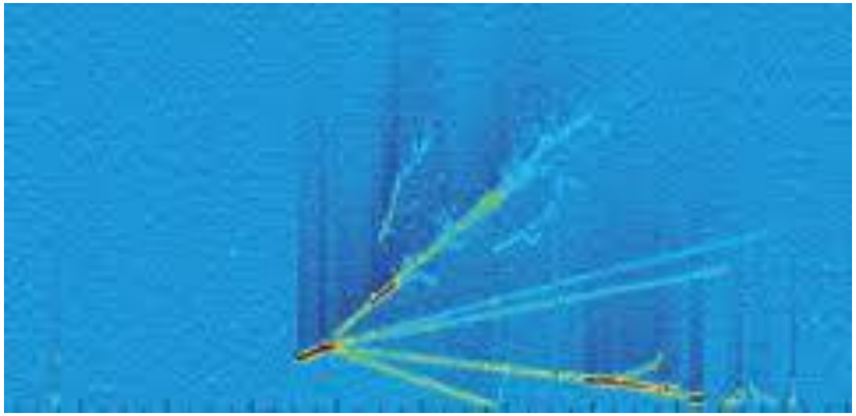
Fermilab Bubble Chamber



South Pole Ice



Liquid Argon at Fermilab

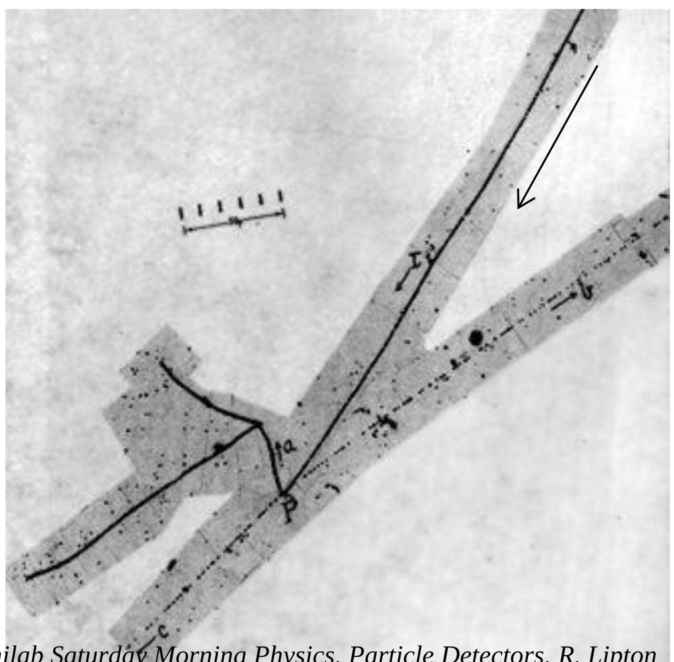


Development of Particle Detectors

Film and Emulsion

- Natural radioactivity was discovered by the darkening of photographic emulsion
- Emulsions developed to be sensitive to radiation were used in the discovery of the pion, charmed particles, and continue to be used for neutrino physics (Opera)

Image of Becquerel's photographic plate which has been fogged by exposure to radiation from a uranium salt.



$K\text{->}\pi^{+}\pi^{-}\pi^{-}$

Start of the tradition of extreme air travel by particle physicists

Do cosmic rays have an extraterrestrial origin?

1911 Victor Hess

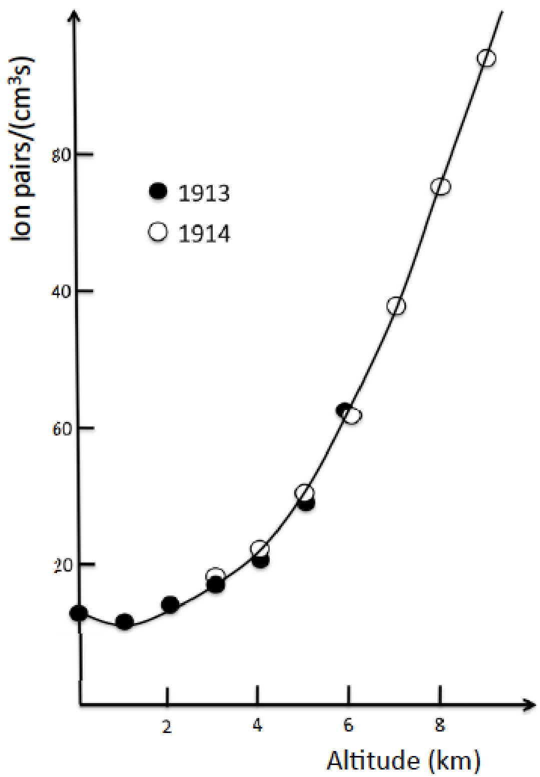
If the ionization came from terrestrial sources then an ionization detector far from the earth's surface should show a decrease in intensity.

Ionization detectors taken to high altitudes in balloons.

Early Ionization Detectors

- The first measurements of radiation effects and cosmic rays used gold leaf electroscopes
- Used to measure cosmic ray flux
  - Discovered the "cosmic" nature of cosmic rays

Hess and Kolhorster



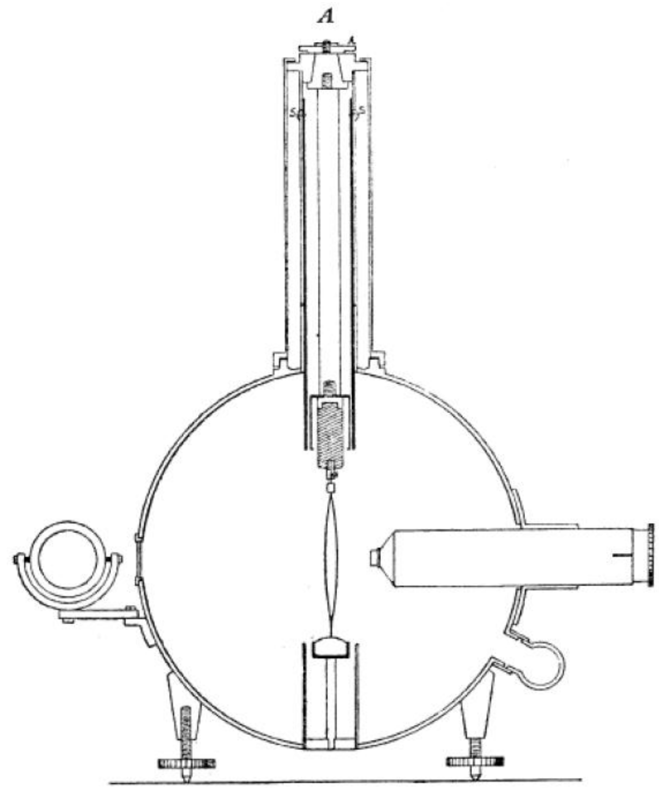


Fig. 1. The Wulf electroscope [27]. The 17 cm diameter cylinder with depth 13 cm was made of Zinc. To the right is the microscope that measured the distance between the two silicon glass wires illuminated using the mirror to the left. The air was kept dry using Sodium in the small container below the microscope. According to Wulf [27], with 1.6 ion pairs per second produced, the tension was reduced by 1 volt, the sensitivity of the instrument, as measured by the decrease of the inter-wire distance.

Seeing Charged Particle Tracks

- As charged particles pass through matter they locally ionize (remove electrons) from the surrounding material
  - We can detect these charges directly
  - It can cause local heating
- If we arrange to have the detector material near a phase transition (boiling or condensing) we can detect the tracks directly
- Cloud chamber – superheated vapor – drops form along path

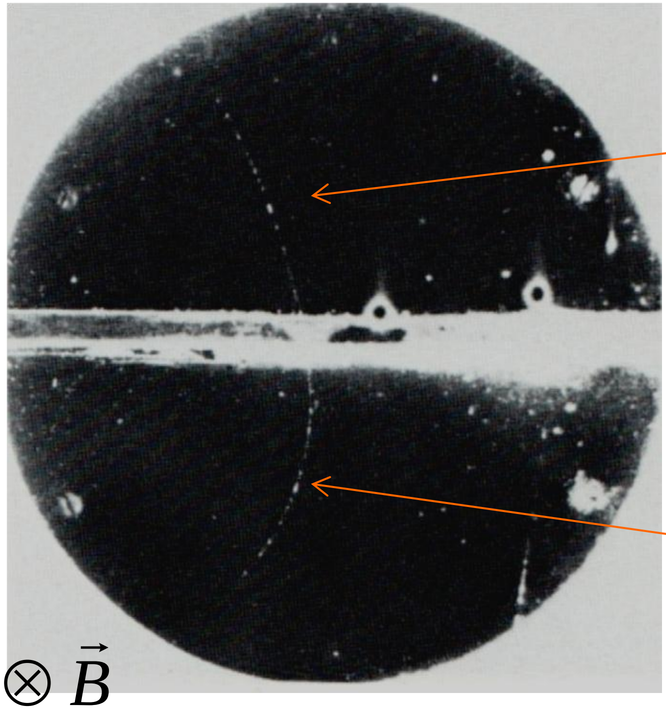
Wilson cloud chamber

$\otimes \vec{B}$

Discovery of the Positron (1932)

- In 1928 Paul Dirac formulated a theory which unified relativity and quantum mechanics
- The theory had one big problem – each particle had a corresponding "cousin" with opposite charge – *antimatter*
- People thought this was ridiculous
- Carl Anderson used a cloud chamber in a magnetic field to measure cosmic rays

- He found tracks with ionization consistent with electrons but the wrong charge!
- Perhaps these were electrons entering from the bottom
- Anderson added 6mm of lead to cause tracks to lose energy and therefore define the direction



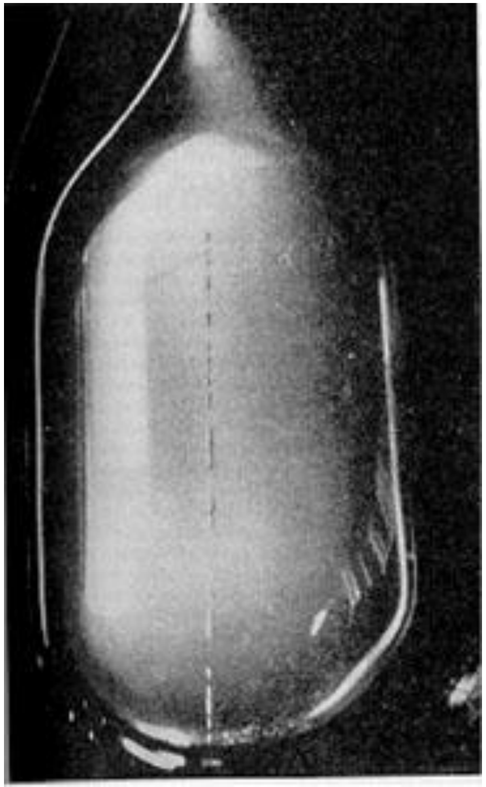
$\otimes \vec{B}$

Slide 40

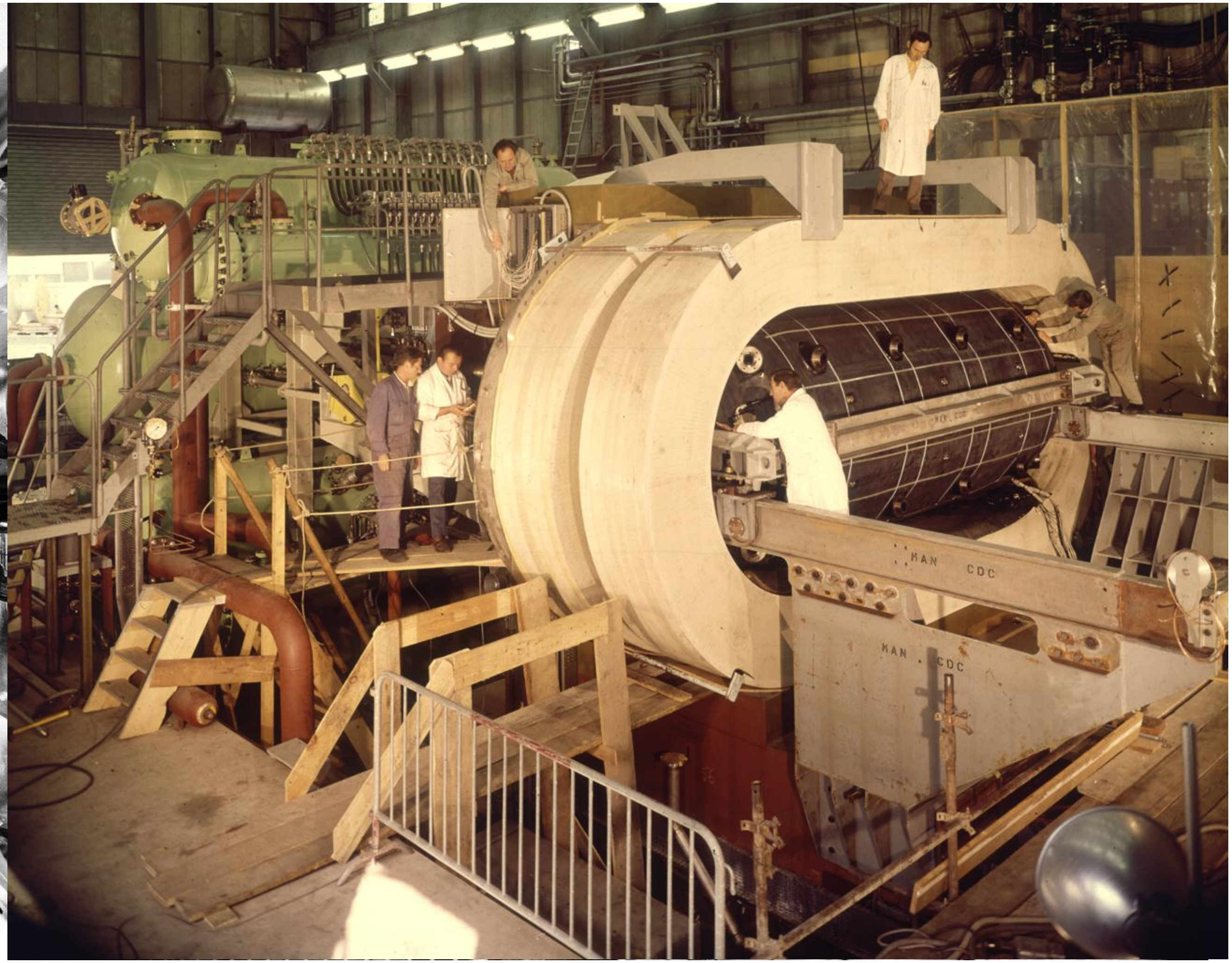
Bubble Chamber

- Invented in 1952 by Donald Glaser, University of Michigan, (Nobel prize 1960)
- Consists of a sealed chamber filled with a liquefied gas
- The liquid is originally at a temperature just below its boiling point
- When the pressure is quickly reduced, by means of a piston, the boiling point is lowered, so that it is lower than the temperature of the liquid, leaving the liquid superheated
- When a charged particle passes through this superheated liquid, bubble formation sets in along the particle track; positive ions act as seeds for bubble formation.
- Bubbles are illuminated and photographed

- Active medium is at the same time target and detector
- Measure dE/dx by counting number of bubbles



Gargamelle at CERN



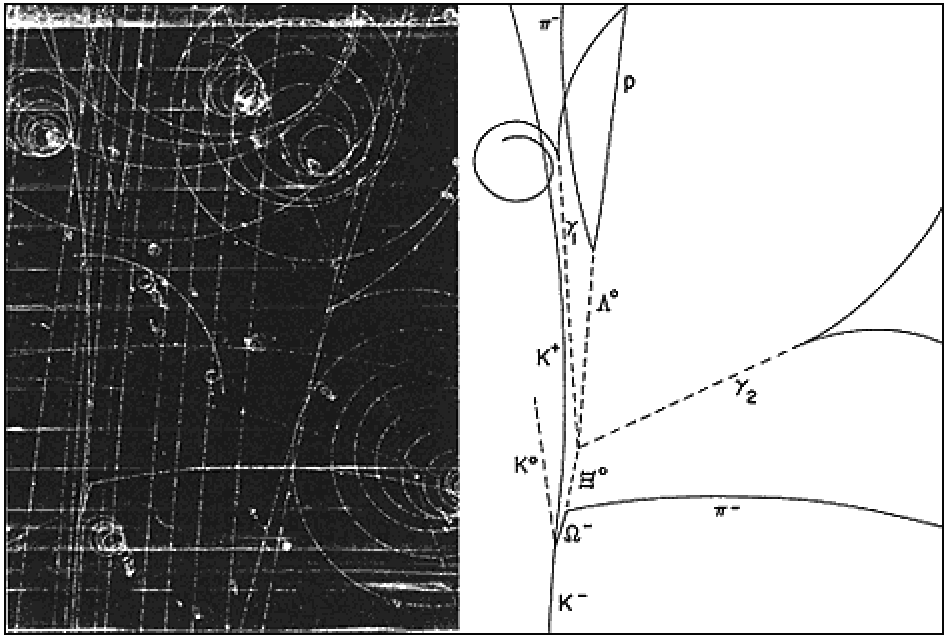
- Discovered neutral currents, 1976

15 ft. Bubble Chamber at Fermilab

- World's largest bubble chamber
  - Many different media used, H_2, D_2,Ne,
  - Now located in courtyard at SiDet

Bubble Chamber Analysis

- Each picture scanned, by hand in the early days
  - Recall: measure dE/dx and p, $m_0 = p/\gamma\beta c$, particle identification
  - Apply energy-momentum conservation for neutrals

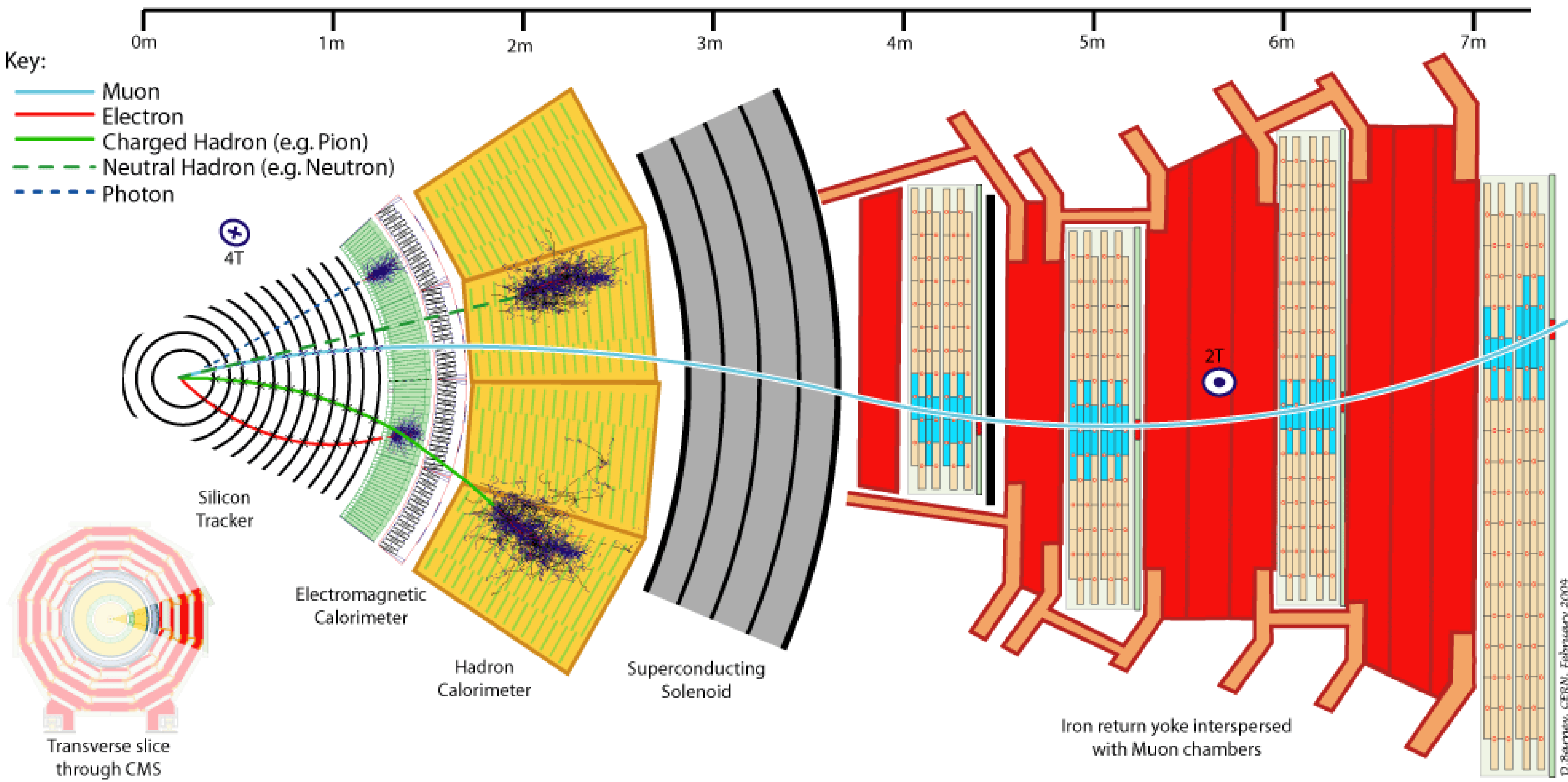


Discovery of Ω^-, baryon composed of 3 strange quarks

- Use of bubble chambers limited
  - Cannot use at storage rings
  - Slow cycle time and difficult to trigger
  - At high β limited particle identification

CMS Slice

- What are the particle signatures in the CMS detector ?

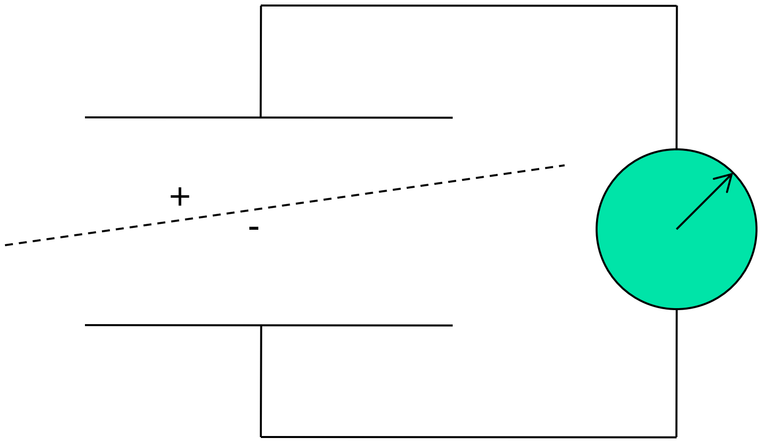


Electronics of Detection

- The basic equation:

$$Q = CV$$

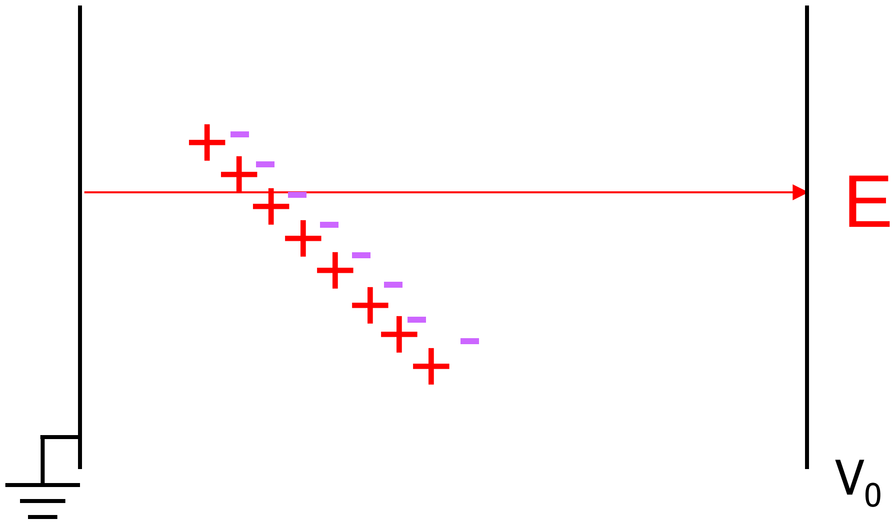
  - Particles ionize the medium
  - Modify the charge on the detector: dQ
  - Measure the resulting voltage change dV



- Art of high sensitivity detector construction. We have two basic tools:
  - Low capacitance electrodes
  - Multiplication of charge (careful here – we might get a spark …)

Ionization and Gas Amplification

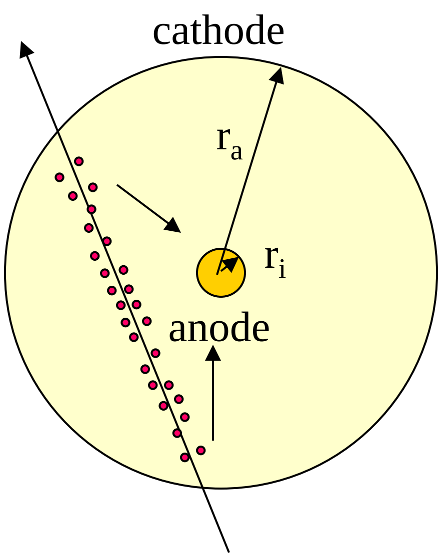
- Seen 'cumbersome' methods to measure particle tracks
- Employ purely electrical detectors
- Use chambers filled with active medium (gas, liquid) and voltage across electrodes
- Various modes of operation
  - In low fields the electrons eventually recombine with the ions: recombination
  - Under higher fields it is possible to separate the charges: ionization mode
  - Under even higher fields obtain gas amplification: proportional mode
    - amplification of factors 10^6 can be obtained: i.e. one e- creates 10^6 e-

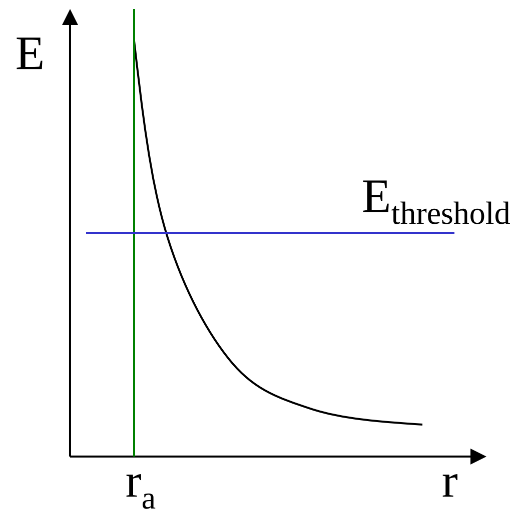


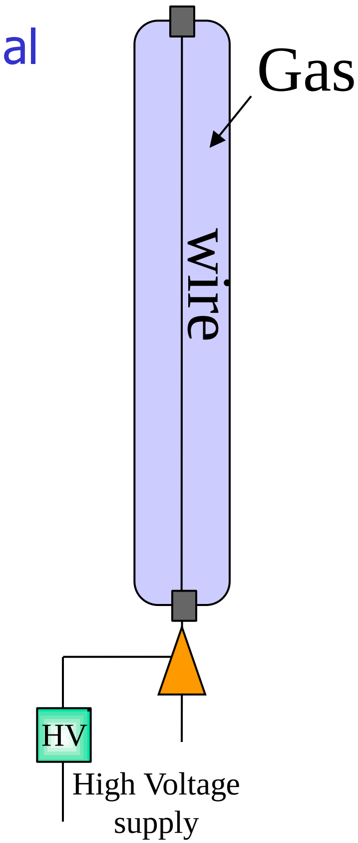
- Note: electrons and ions generally move at very different rate (mobility)

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

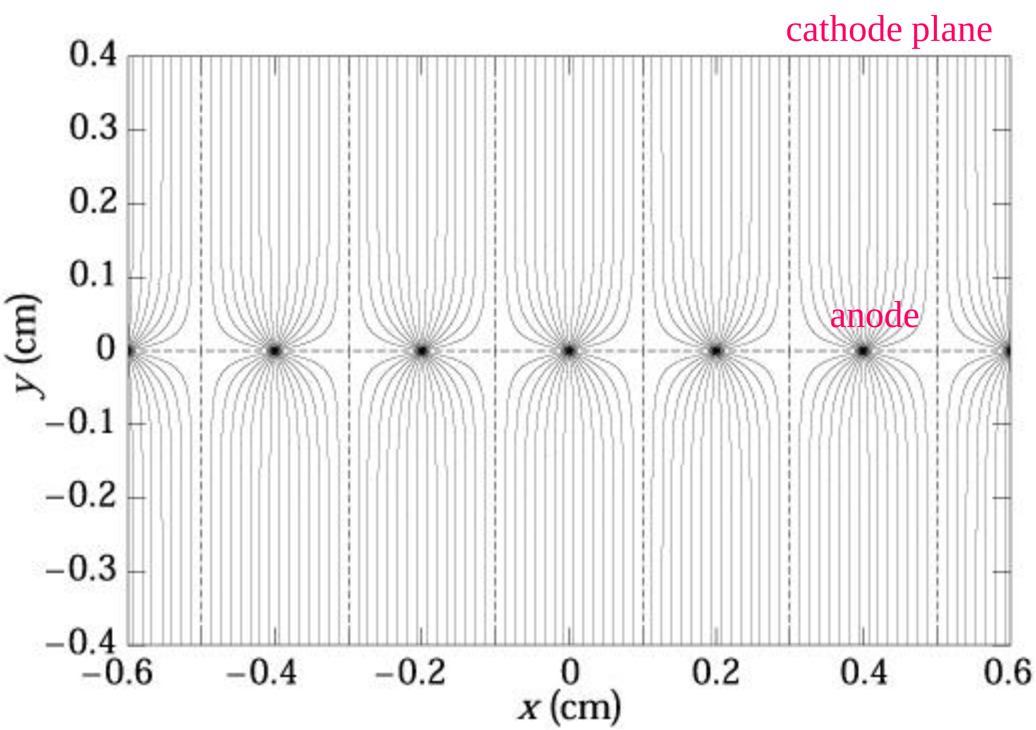
Geiger – Müller Counter

- Particles pass through gas filled tube
- Saturated 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

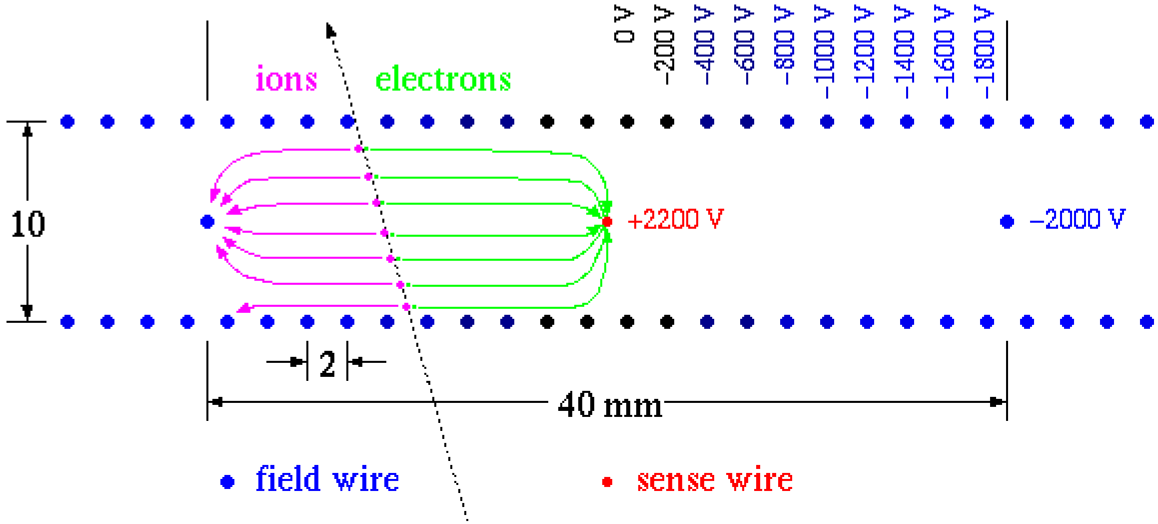
Multi Wire Proportional Chamber (MWPC)

- 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

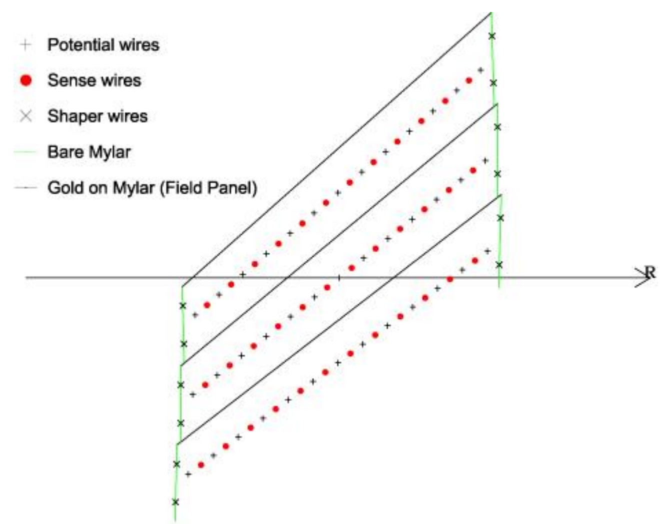


measure arrival time of electrons on sense wire relative to a reference time t_0

$$x = v_D \cdot t_D$$

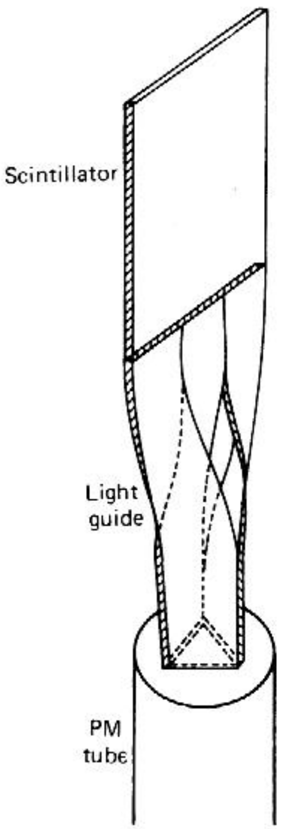
typical drift velocity
$v_D = 5\ cm/\mu s$

- 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



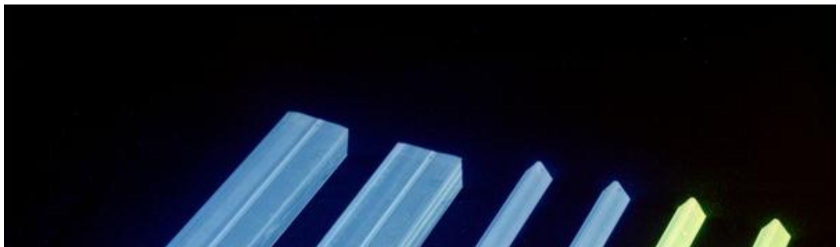
Scintillators

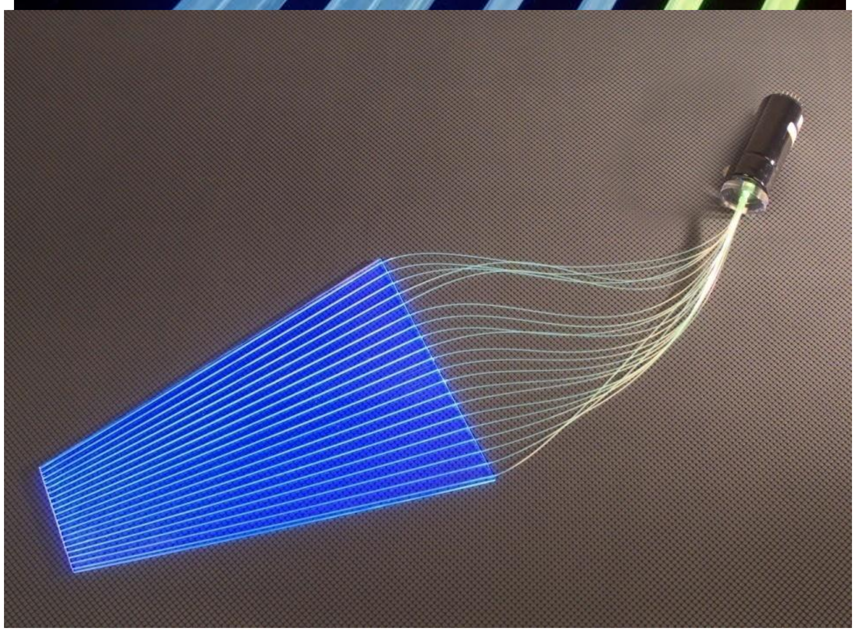
- scintillation: release of energy as optical photon, due to traversing of charged particle (form of luminescence)
- Two material types for scintillators
  - Organic scintillators: liquid, plastic (crystal)
    - The scintillation process is a function of a single molecular process and is independent of the physical state of the scintillator
    - Easy to manufacture in any shape or size; fast signals
  - Inorganic scintillators: crystals
    - Require a crystal lattice to scintillate
    - Generally dense, high stopping power, high light yield
  - Generally scintillators are doped with fluors
    - fluorescence
    - increase light yield
    - match emission wavelengths to detection device
    - faster signals
    - ……
  - Wide range of applications
    - trigger counters
    - tracking detectors
    - calorimetry
    - ……



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





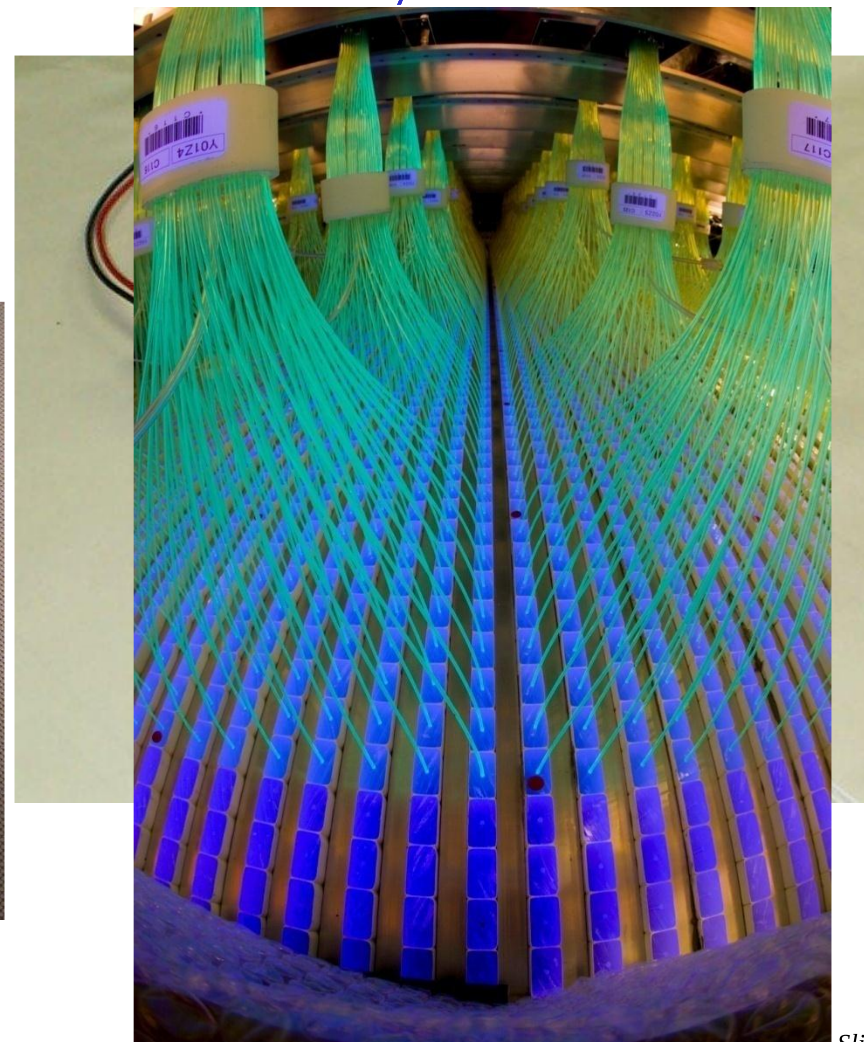
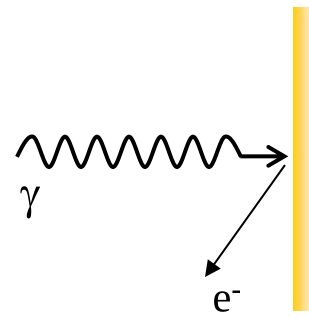
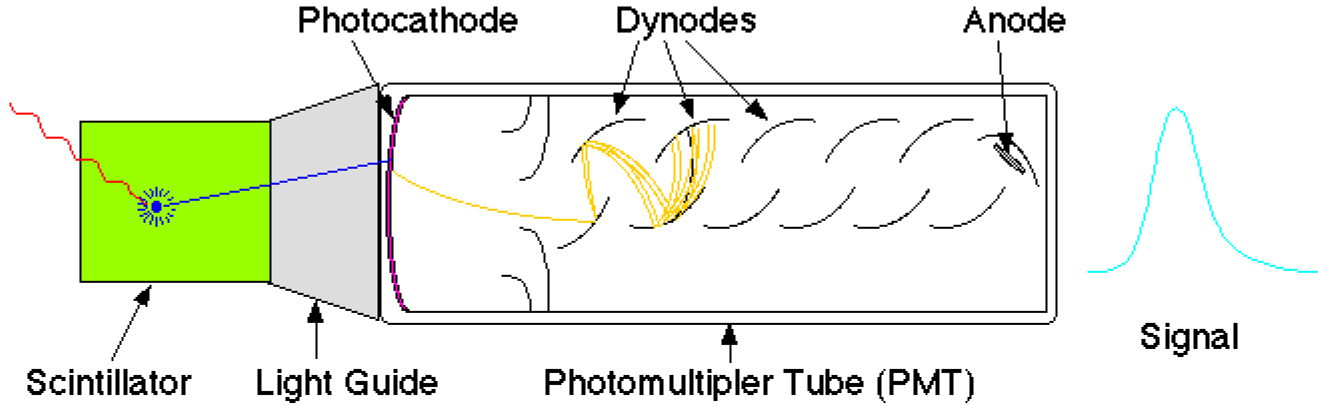


Photo-Multiplier Tube

- 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



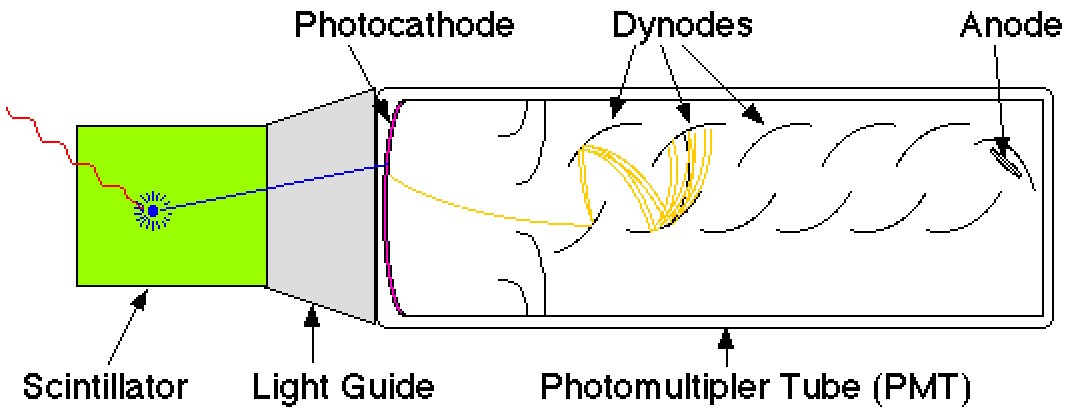
$$Q.E. = \frac{\# \, p.e.}{\# \, \gamma}$$



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

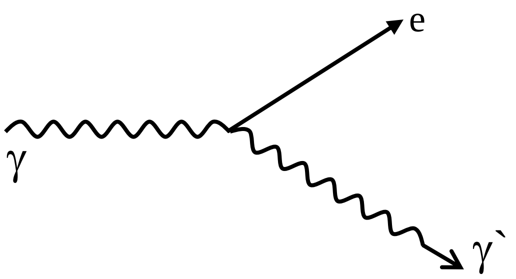
$$M = p^n \text{ , with } n = number\ of\ dynodes$$

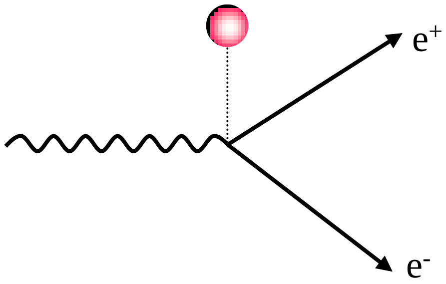
$$= 4^{10} = 10^6$$

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

Photon Detection

- Photon interaction with matter proceeds through three primary processes:
  - Photo-electric effect
  - Compton scattering: $\gamma + e \rightarrow \gamma + e'$
  - Pair production: γ + nucleus $\rightarrow e^+ e^-$ + nucleus
    - Process dominates at high energies

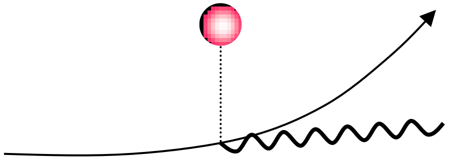




Interaction of Electrons with Matter

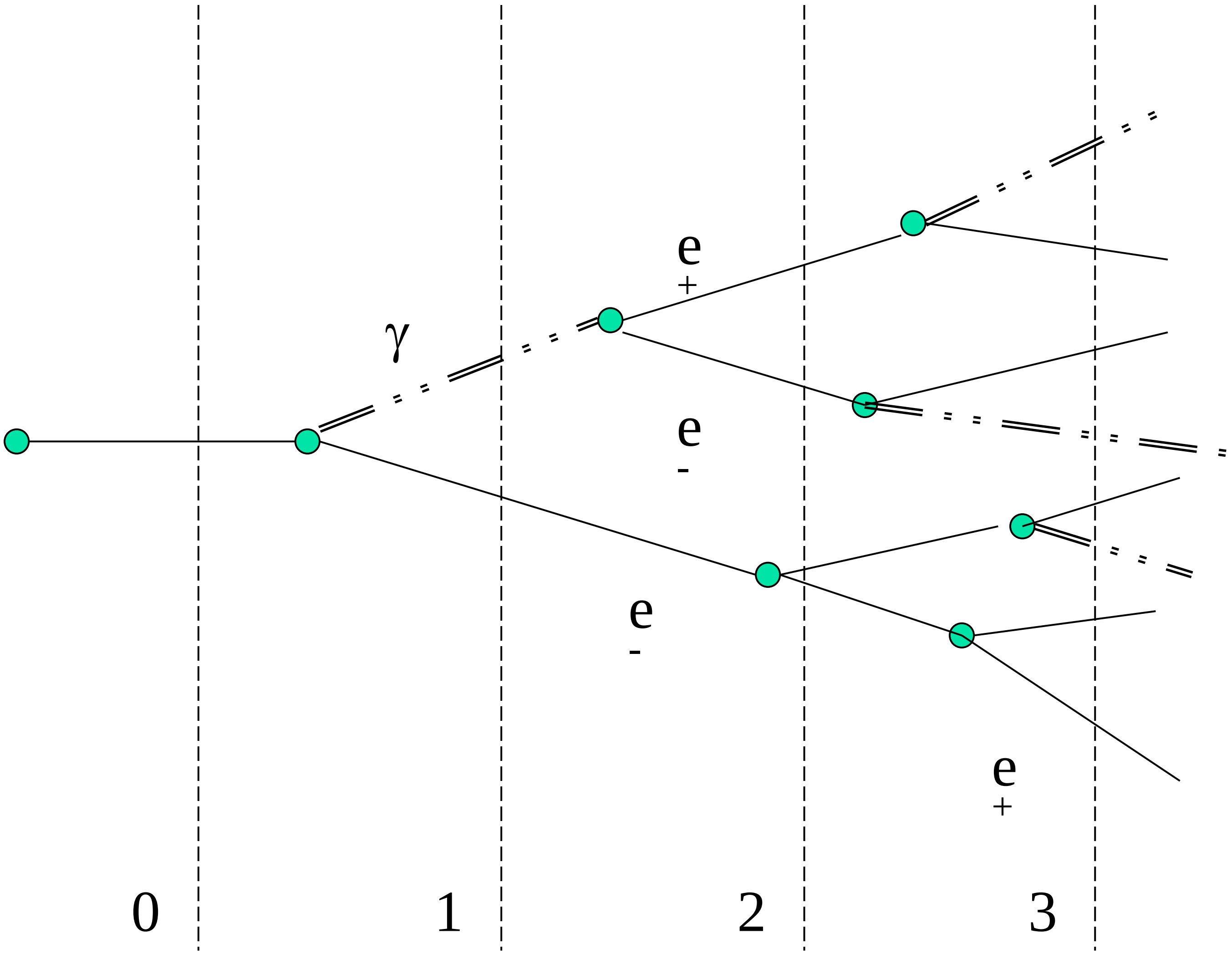
- Crucial difference for electrons
  - mass of scattered object is much lower than that of most objects
    - $m_\mu/m_e = 205$, $m_\pi/m_e = 273$
- Electrons are subject to bremsstrahlung
  - Radiation of real photons in the Coulomb field of the nuclei of the medium
    - Any deflection of electron from its original trajectory accompanied by radiation of photons and deceleration of electrons

$$-\frac{dE}{dx} \propto \frac{E}{m^2}$$



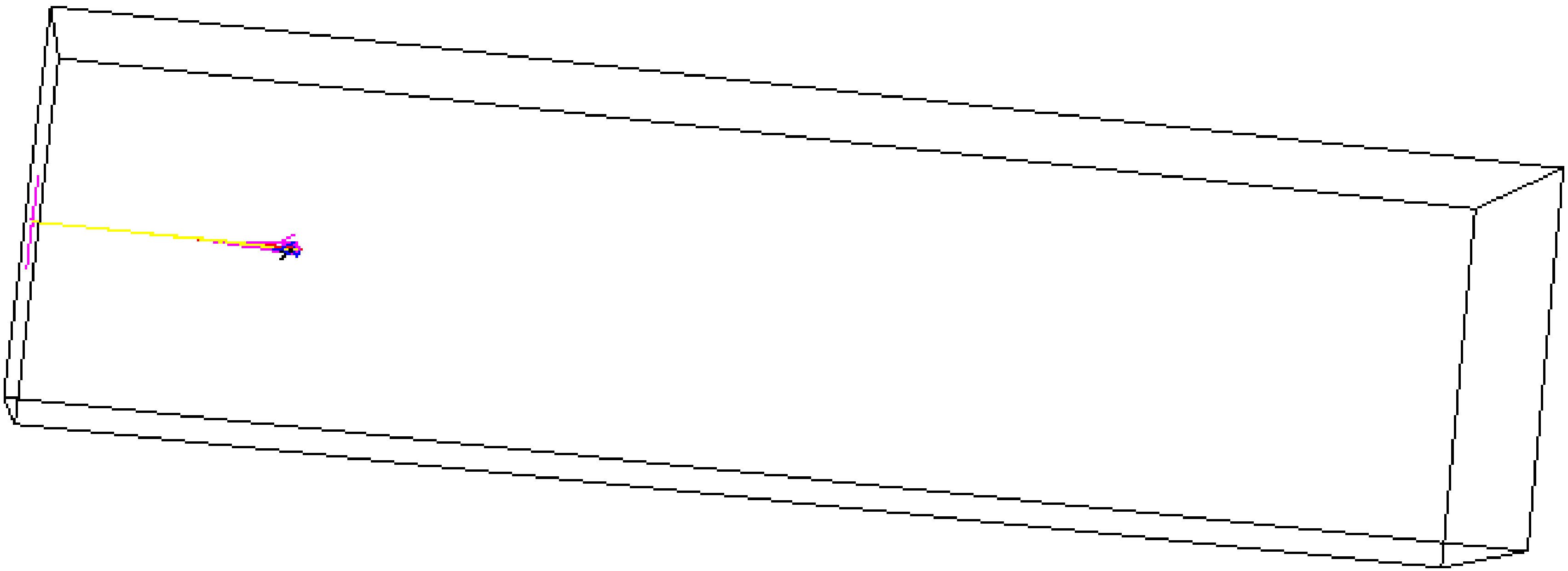
  - Of course, also muons are subject to bremsstrahlung, but only for ultra-relativistic energies
- As a consequence, electrons and photons impinging an a medium will form electromagnetic cascades: showers

EM Shower



Example EM Shower

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



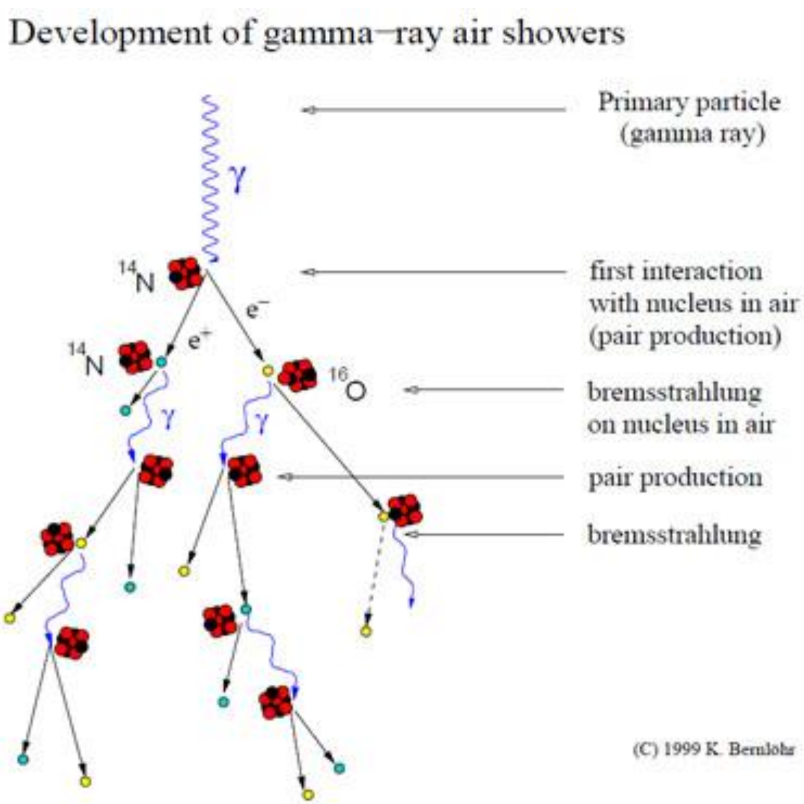
- Longitudinal shower development (depth of shower) increases logarithmically with energy

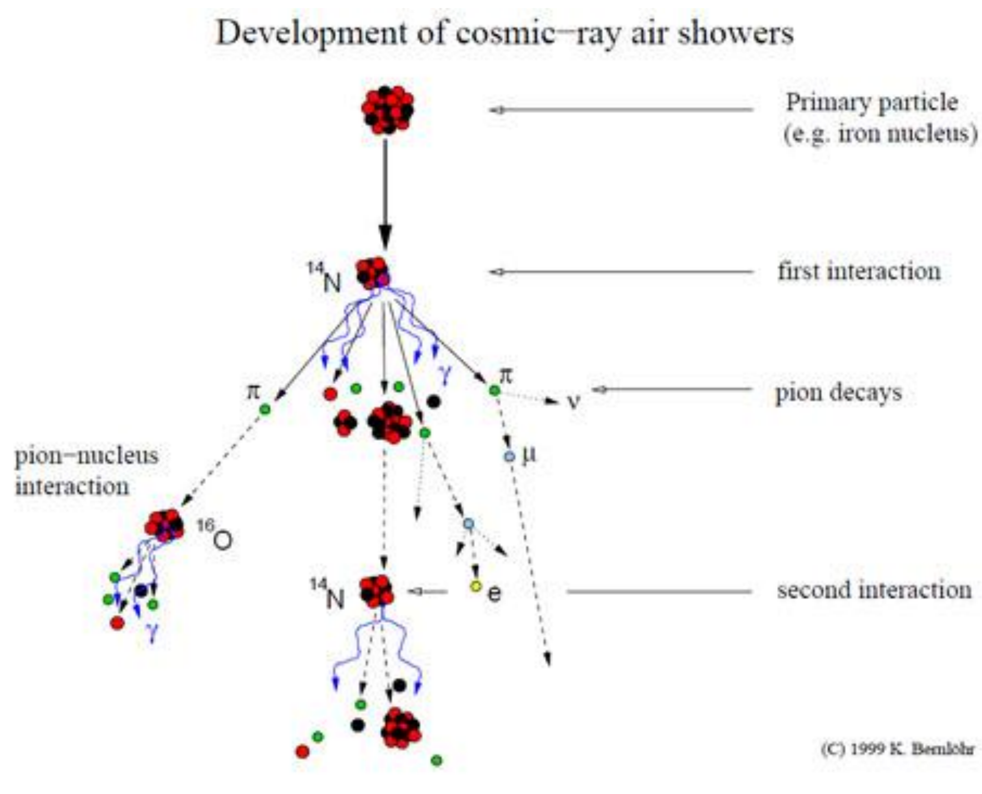
Interaction of Hadrons with Matter

- Many processes involved; much more complex than electromagnetic cascades
- Also form cascades with two components
  - Hadronic component
    - decay of quarks
    - pions, protons, kaons, lambdas with secondary decays
    - muons, neutrinos
  - Electromagnetic component
    - electrons, photons
    - neutral pions $\rightarrow 2\ \gamma$
- Cascades characterized by larger fluctuations

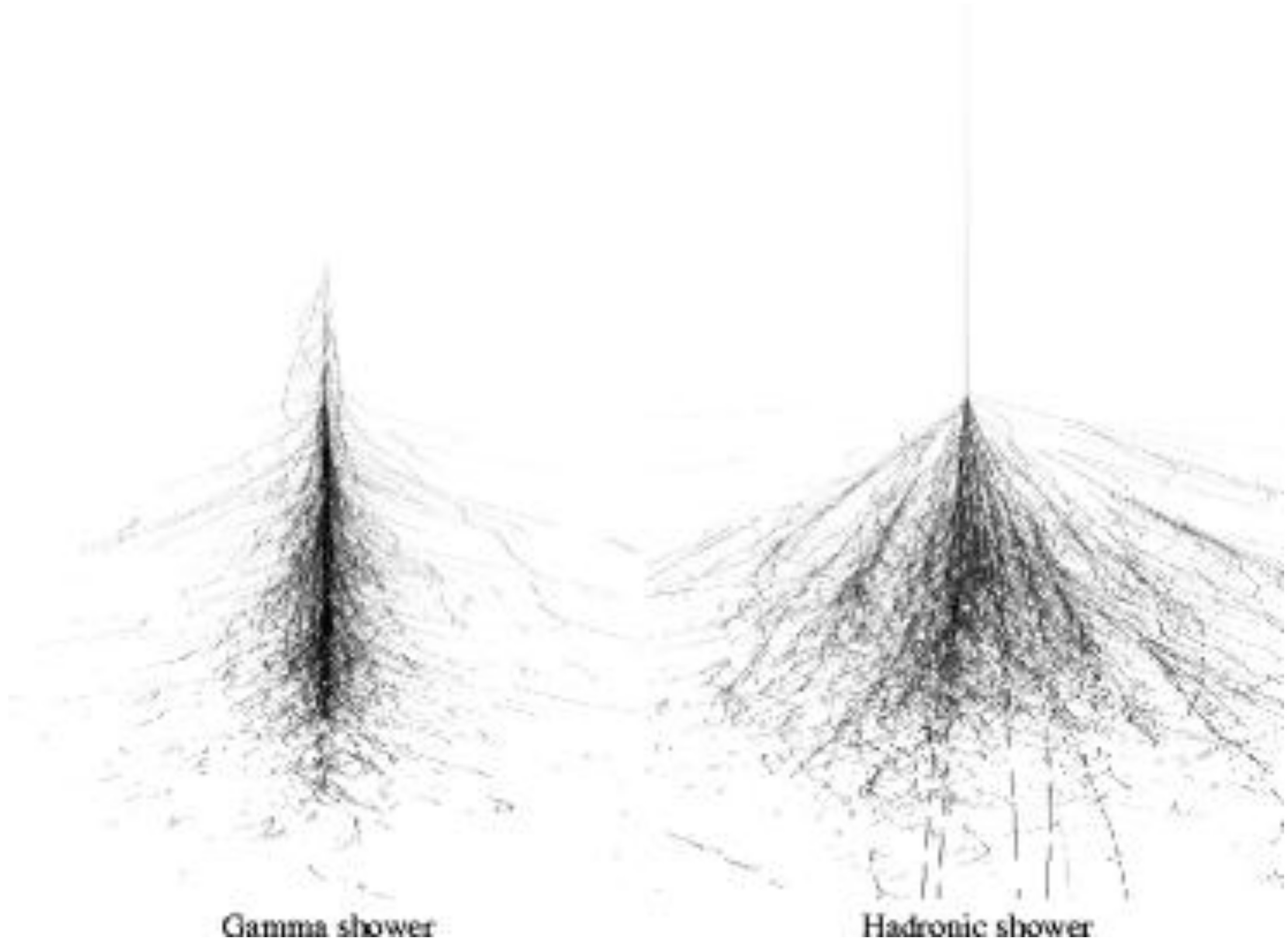
- Technique for electron, photon and hadron measurement: generally destructive
  - Stop complete shower
- Device for measuring total energy is called a calorimeter
  - Separate Calorimeter for electrons/photons: EM calorimeter
  - Separate calorimeter for hadrons: hadronic calorimeter

Hadronic and EM Showers





Hadron and Electromagnetic showers

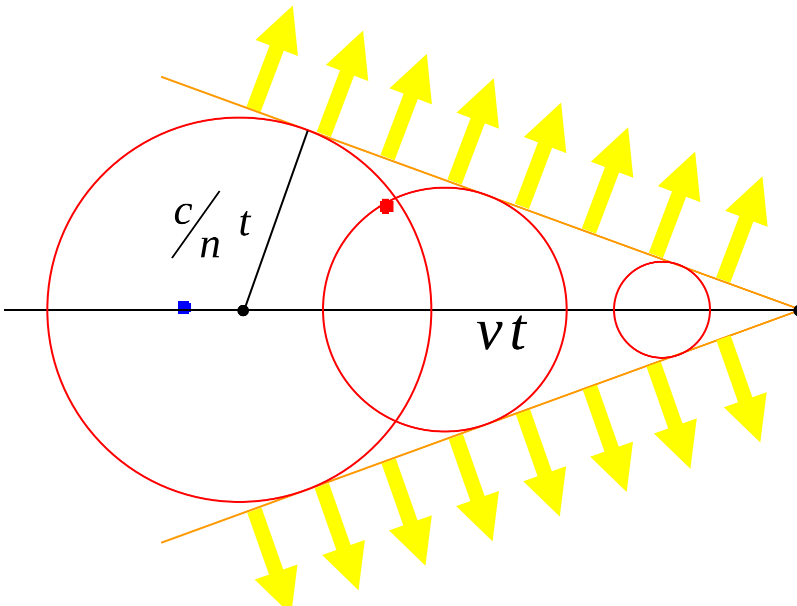


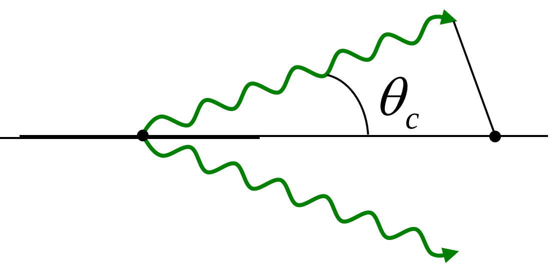
Čerenkov Radiation

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

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

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

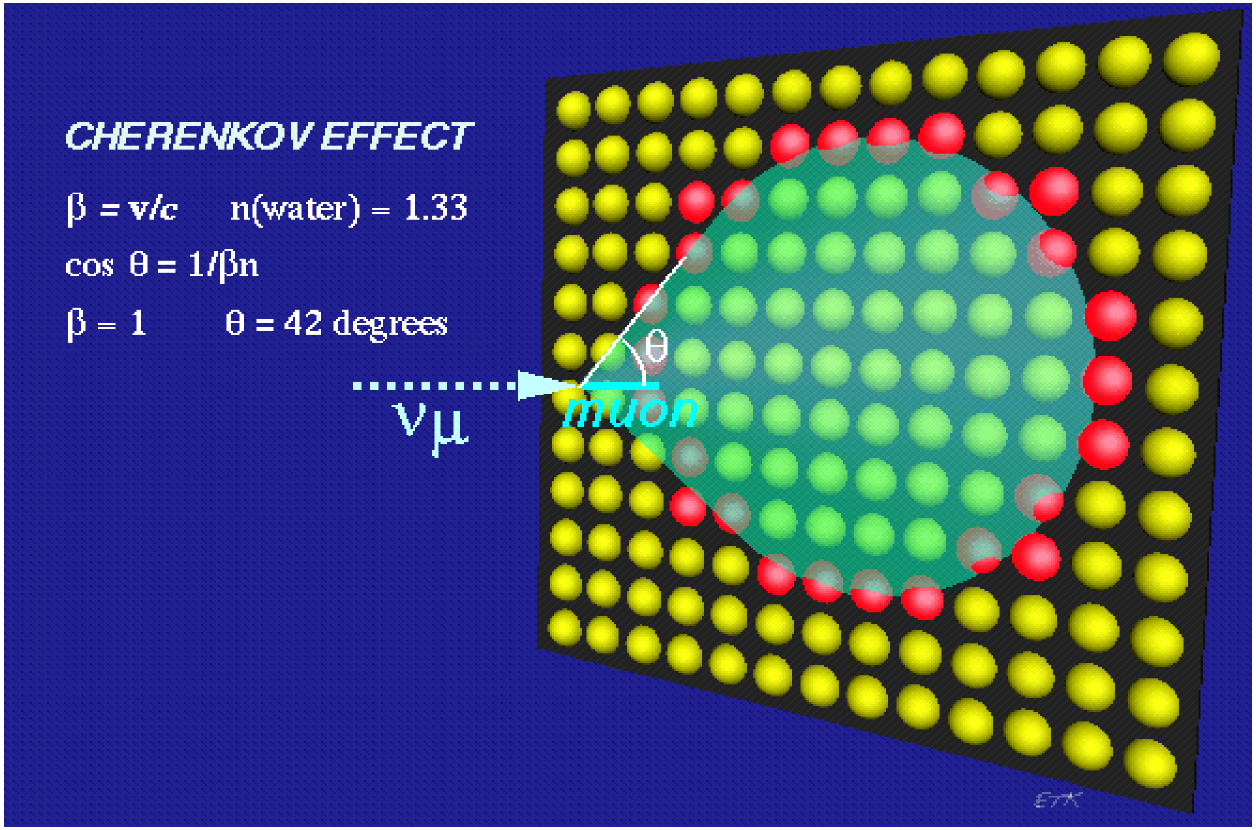




- Cherenkov light is emitted under a constant Cherenkov angle with respect to the particle trajectory

Čerenkov Radiation Detection

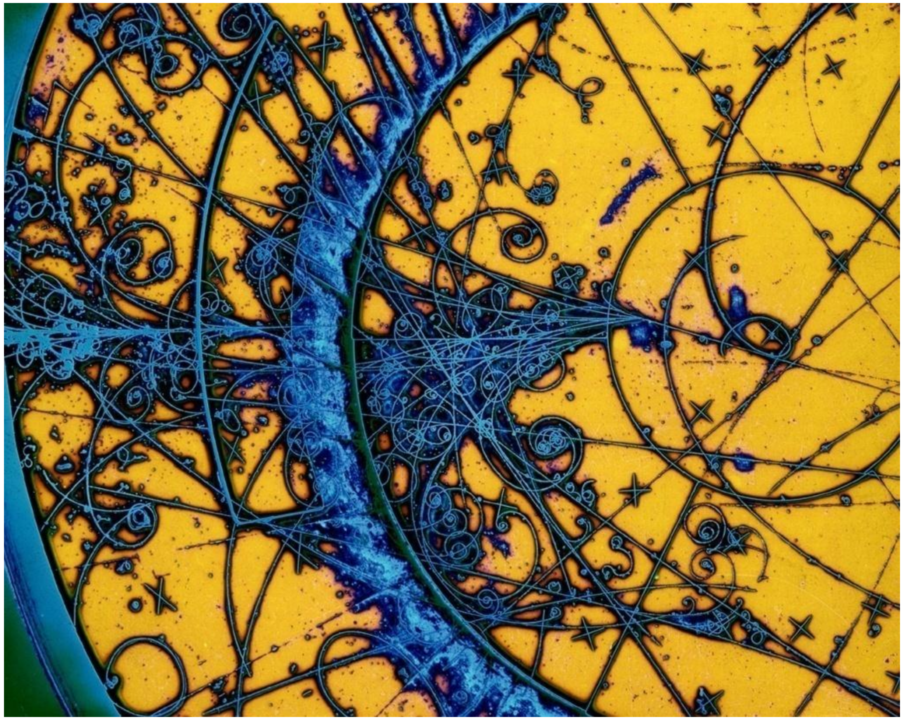
- Wavefront of light travels to end of detector and is collected by PMT
- Cherenkov radiation:
  - modest light output
    - the energy loss due to ionization or excitation is two to three orders of magnitude higher than the energy lost in radiating Cherenkov light
  - Use directionality of light
  -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



Summary Some Detection Techniques

- Ionization Detectors
  - Cloud chamber
  - Bubble chamber
  - Film, emulsions
  - Proportional Counters, Geiger Counters
  - Spark Chambers
  - Drift Chambers
  - Silicon Detectors
- Excitation and Ionization of atoms, molecules
  - Scintillation detectors
- Light Detectors
  - Photomultiplier Tubes
  - Cherenkov Detectors

Particle Detectors



- Part II
  - Solid State Detectors
  - Build your own detector

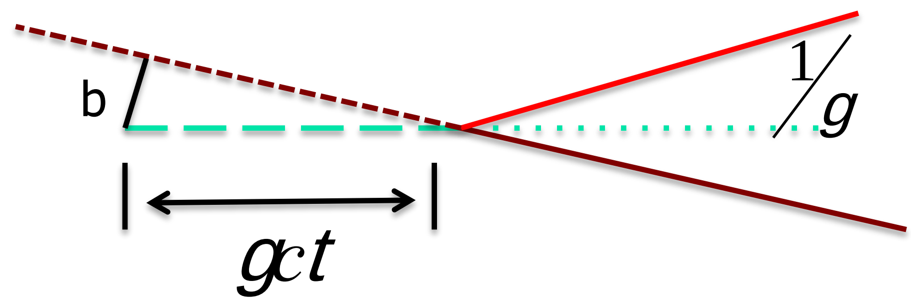
Physics and Detector Development

The discovery of the charmed quark in 1974 at SLAC and Brookhaven was the beginning of a 35 year journey which culminated with the Higgs discovery last summer.

Lifetimes

The key to discovery was the unique lifetimes of heavy quarks:

$$\Gamma \approx \frac{m_c^5 (G_F \cos\theta_c)^2}{192\pi^3} \approx \left(\frac{m_c}{m_\mu}\right)^5 \times 10^7\ \mathrm{sec}^{-1}$$



Lifetimes ~ 10^{-12} and 10^{-13} seconds.

Characteristic distance:

$$b = \gamma c\tau \times \frac{1}{\gamma} \approx c\tau$$

$$\approx 30 - 300\ microns$$

Review of Particle Properties (1978)

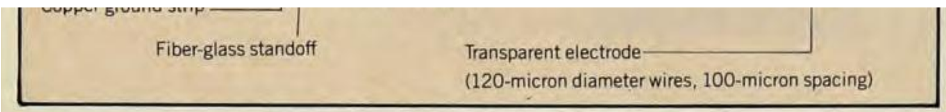
Chamber Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble	± 75μ	≈ 1 ms	≈1/20 s[a]
Streamer	±300μ	≈ 2 μs	≈100 ms
Optical spark	±200μ[b]	≈ 2 μs	≈ 10 ms
Magnetostrictive Spark	±500μ	≈ 2 μs	≈ 10 ms
Proportional	≥±300μ[c,d]	≈50 ns	≈200 ns
Drift	±50 to 300μ	≈ 2 ns[e]	≈100 ns

High Resolution Detector Development

It was clear that a detector that was fast (ns) and had resolution of 10-20 microns would be transformational.

- Resolution to separate charm from background
- Fast to analyze many events and select the 1/1000 that contain charm

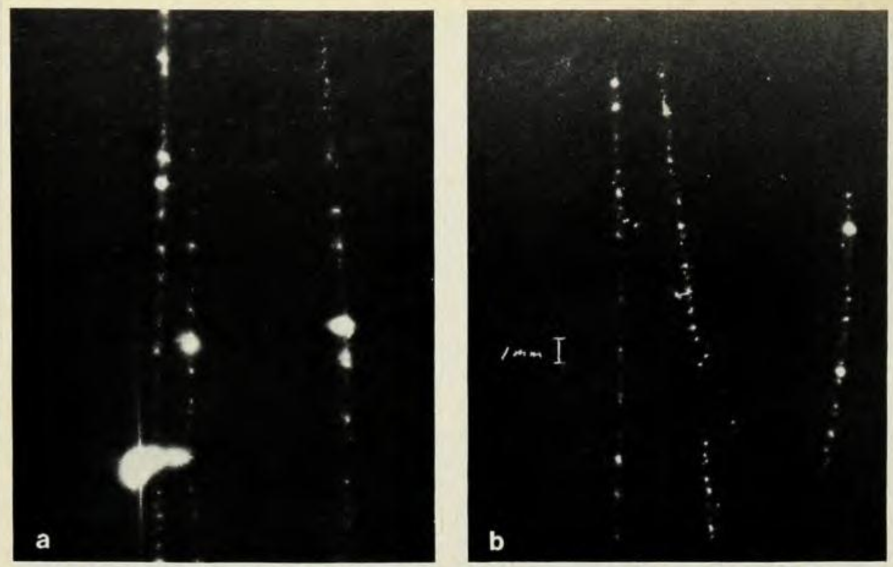
The 10 years after the discovery of charm saw the blossoming of many innovative ideas.



High-resolution streamer chamber developed at Yale University is seen in this cutaway sketch. The aim of the project was to scale the performance of atmospheric-pressure chamber by a factor of 20 in order to obtain a spatial resolution of 15 microns. Figure 3

accurate guide to expected performance.

About three years ago we began a program at Yale University,[7] with support from the Energy Research and Development Agency (now the Department of Energy) and also from the Fermi National Accelerator Laboratory, to develop a high-pressure streamer chamber that would provide spatial resolution in the 10–20 micron range. The basic parameter was the scaling factor, which was chosen to be between 20 and 40. More precisely the mechanical structures, such as pressure vessels, and the optical system were designed to operate up to 40 atmospheres. However, the pulsing system set the limit of operation to slightly more than 20 atmospheres. The table on page 44 below gives the basic parameters, with the scaling assumption, which are needed for 20-atm operation. The table also shows the values that have been achieved in our chamber system and, for reference purposes, the values for a typical atmospheric-pressure streamer chamber.



Ru^{106} decay electrons in the chamber. At 150 psia of a Ne–He mixture, and no image intensification (a) several flares (bright areas) develop. Track length here is 4 cm. To reduce flaring,

Detector Ideas

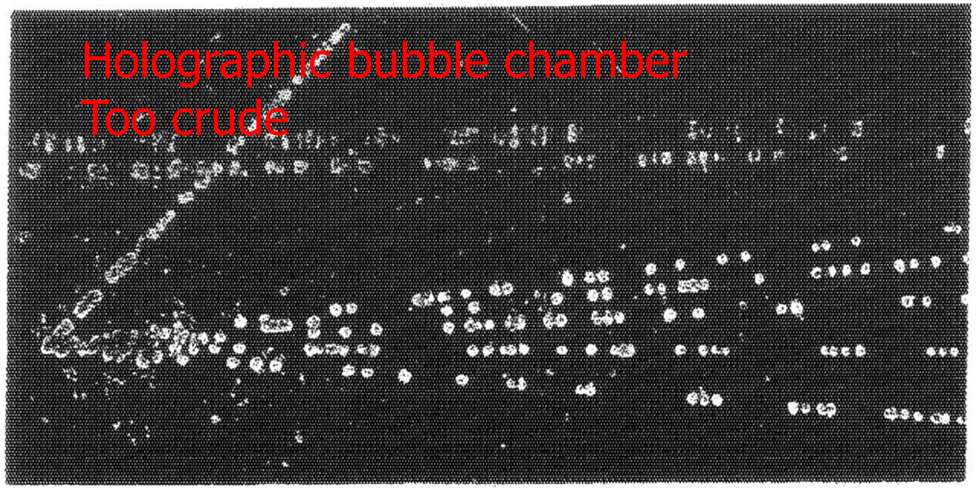


Figure 20. Track hologram recorded in BIBC with 13 μm bubble diameter.

Emulsion films
Way too slow

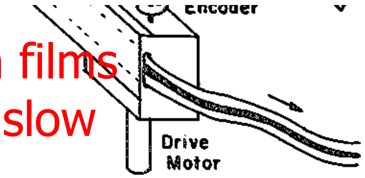
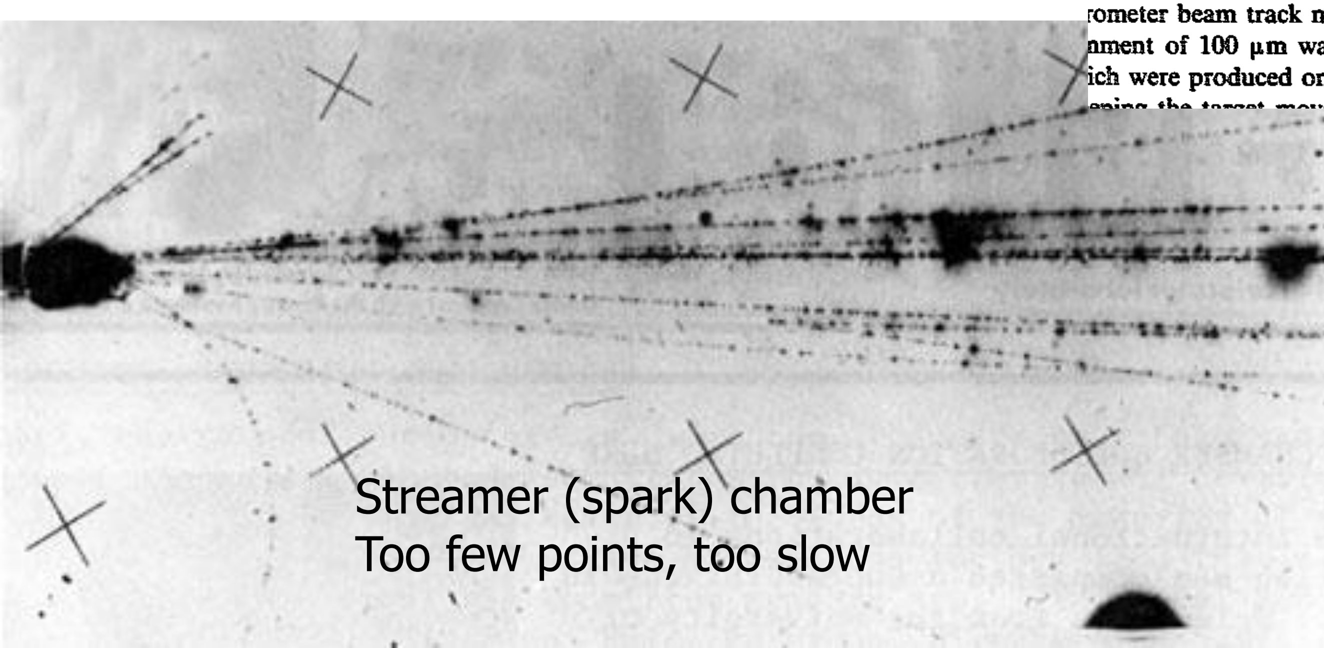


Fig. 5. Emulsion tape drive.

first run the fifth row contained
hile for the second run only one
d. Reference marks added before
proper alignment of the plates

position of both types of modules
nd vertex silicon microstrip coun-
posing a small portion of each
ensity, permitting quick match-up
eter and emulsion tracks in these
m track was found, the module
he spectrometer with the 10 μm
rometer beam track measurement.
nment of 100 μm was done with
ich were produced on the corners

with the first plane 47 mm downstr
target. These detectors were arran
three with the most upstream of t
horizontal readout (vertical strips
and 60° readout rotations with
(Directions x, v, and u). The t
planes were 3 cm square, follow
square and three 10 cm square [
actually 9.67 cm wide by 9.05 cm
three wafers mounted side-by-side,
tion 2.56 cm wide and the outer on
0.05 cm dead-spaces at the junctio



The clear Winner

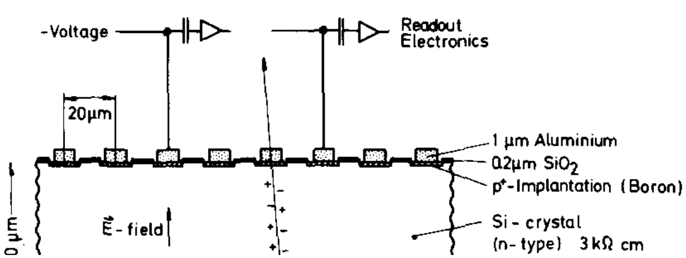
In the early 80s various groups adapted "planar" silicon technology to particle detectors

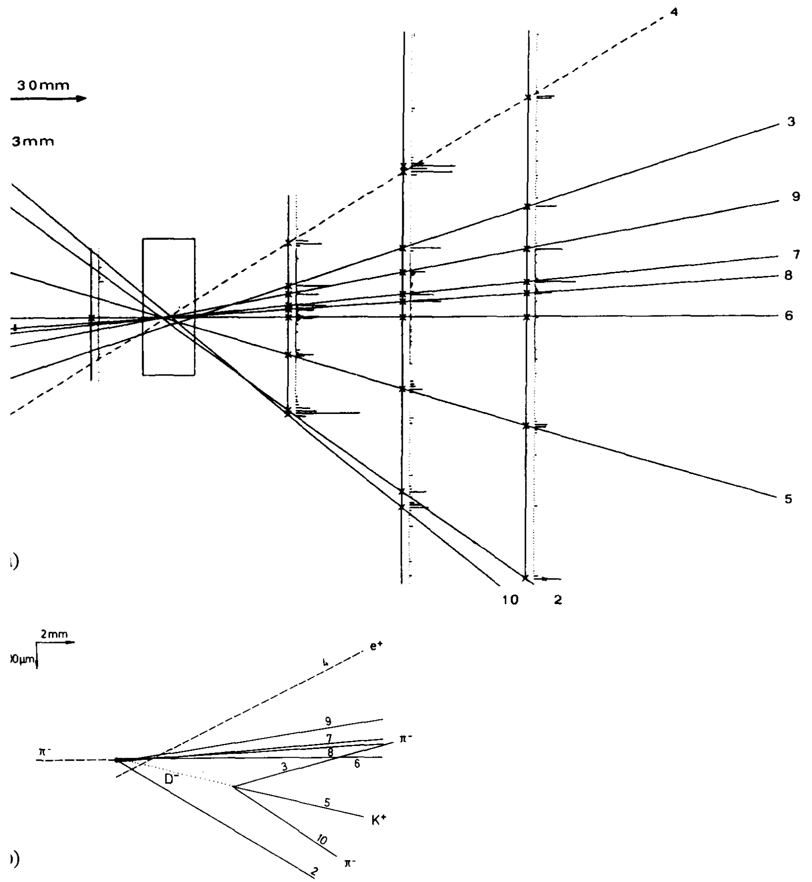
- Fast (~10ns)
- Precise (~10-20 microns)
- Low mass

Because detectors were fast and precise accelerators became "charm factorys"

Spatial accuracy	4.5 μm [a]	7.9 μm [b]
Two particle resolution	60 μm [a]	120 μm [b]

[a] Central part of the detector;
[b] Outer parts of the detector.





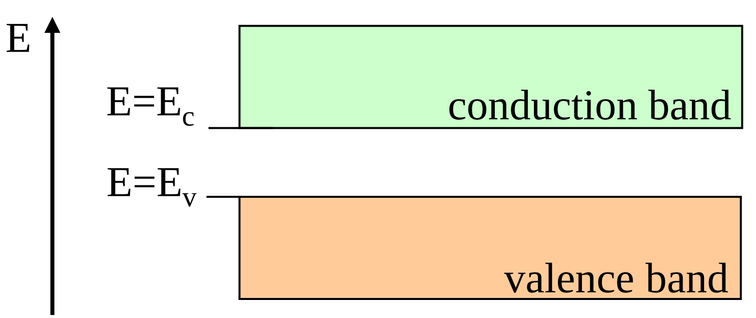
ig. 3. Computer reconstruction of the production and decay of a D^- into $K^+\pi^-\pi^-$ as measured in the NA11 experiment in 200 ieV/c π^- Be interactions. (a) 4 planes of one view. The length of the horizontal lines is proportional to the measured pulse height in ie readout strips. Not shown is the spectrometer for momentum measurement and particle identification. (b) Enlargement of the ertex region. The dotted line shows the direction of the momentum sum of the $K\pi\pi$ system. The triggering positron (dashed line) 'hich is supposed to come from the semileptonic decay of the associated charmed particle in fact does not point to the primary vertex. 'he characteristics of the $K\pi\pi$ system are: mass: $m_{K\pi\pi} = 1.871 \pm 0.008$ GeV/c^2; flight path: $c\tau\gamma = 5.8 \pm 0.3$ mm; momentum of D^-: $p_D = 29.2$ GeV/c; proper life time: $t = 1.25 \pm 0.06 \cdot 10^{-12}$ s.

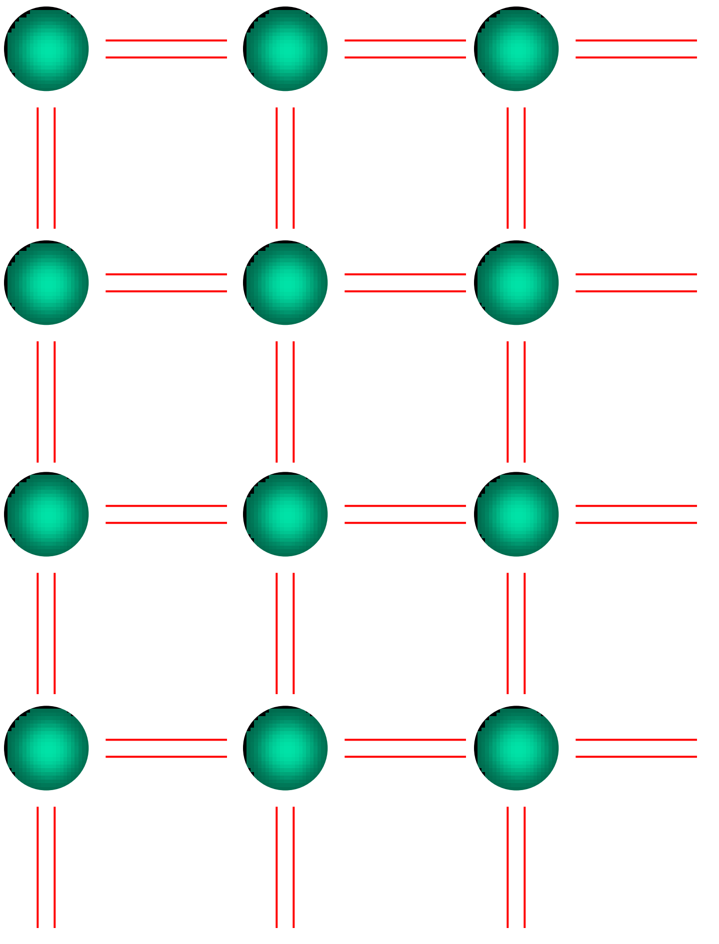
Solid State Detectors

- 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

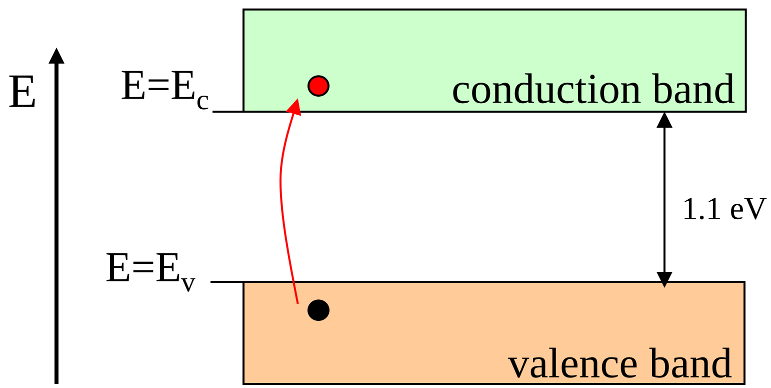
- Si is element number 14 and has four electrons in its outer shell
- Crystalline Si has a diamond crystal structure
  - Each atom has four neighbors
  - Electrons form perfect covalent bonds with its neighbors
- When atoms are brought together and form a solid, the discrete atomic energy levels an electron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

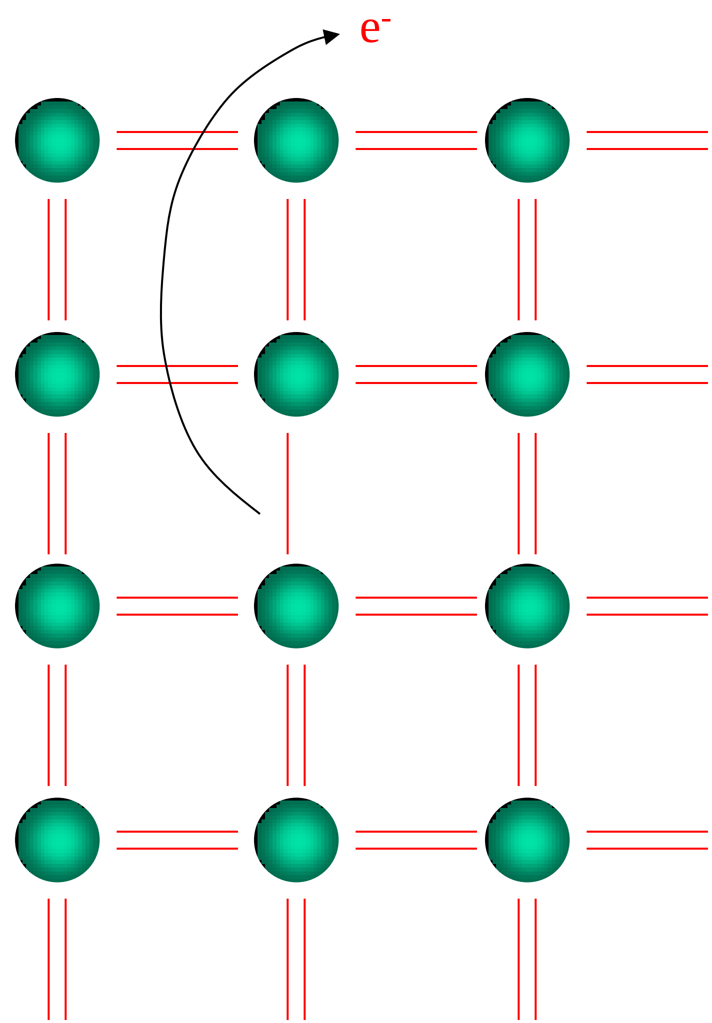




Ionization and Holes

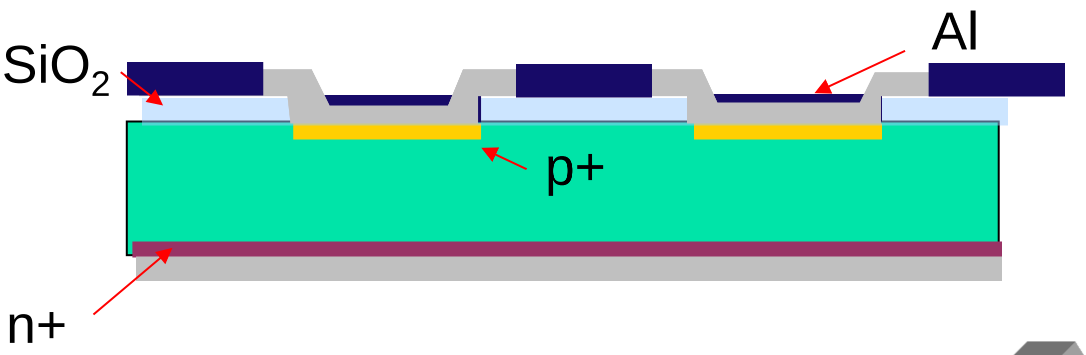
- Ionization can promote electrons from the valence to the conduction band
- Electrical conduction takes place via two modes of electron motion:
  - Can be viewed as motion of e^-'s with charge -q and effective mass m^*_e
  - and can be viewed as motion of holes, +q, m^*_h





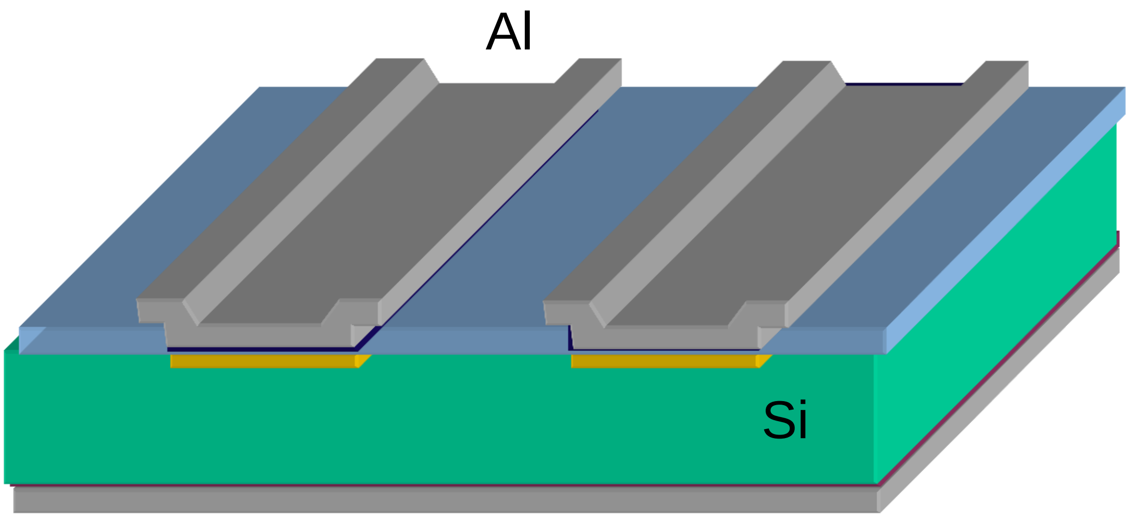
Silicon Strip Detectors

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



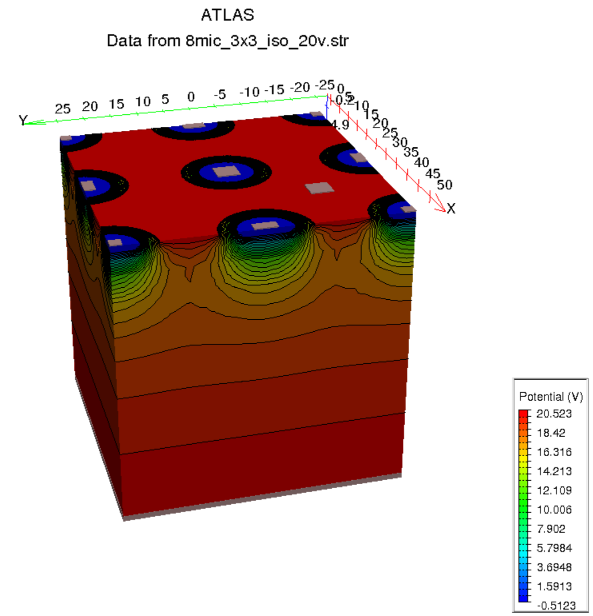
- Distance between strips (pitch) can be as small as 25 μm
- Length of strip can vary from mm's to 10 cm

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

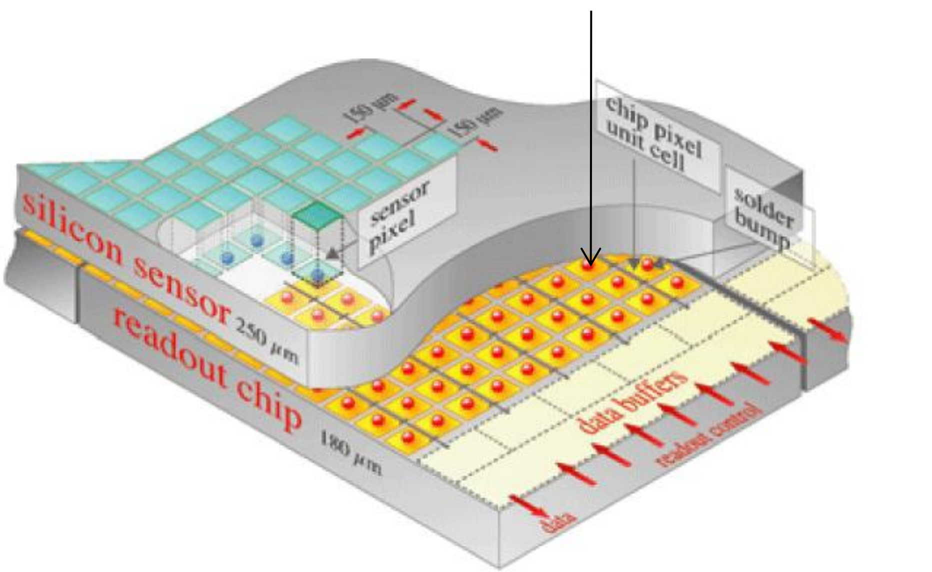


Pixel Detector

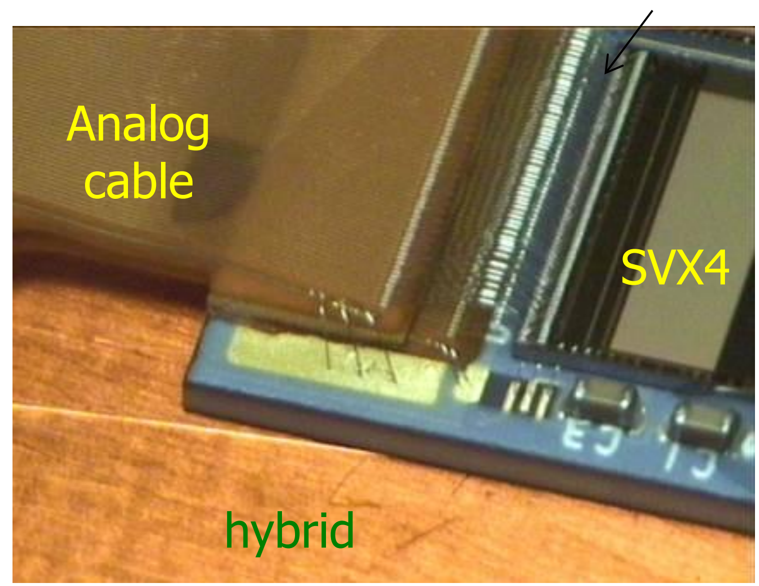
- Instead of strips – use pixels
  - Resolution in 3 dimensions (voxels)
  - Lower capacitance – bigger V per q
- But there are many more channels
  - N^2 channels if the pitch is the same
  - Much more complex to make connections



Pixel Interconnect using bump bonds

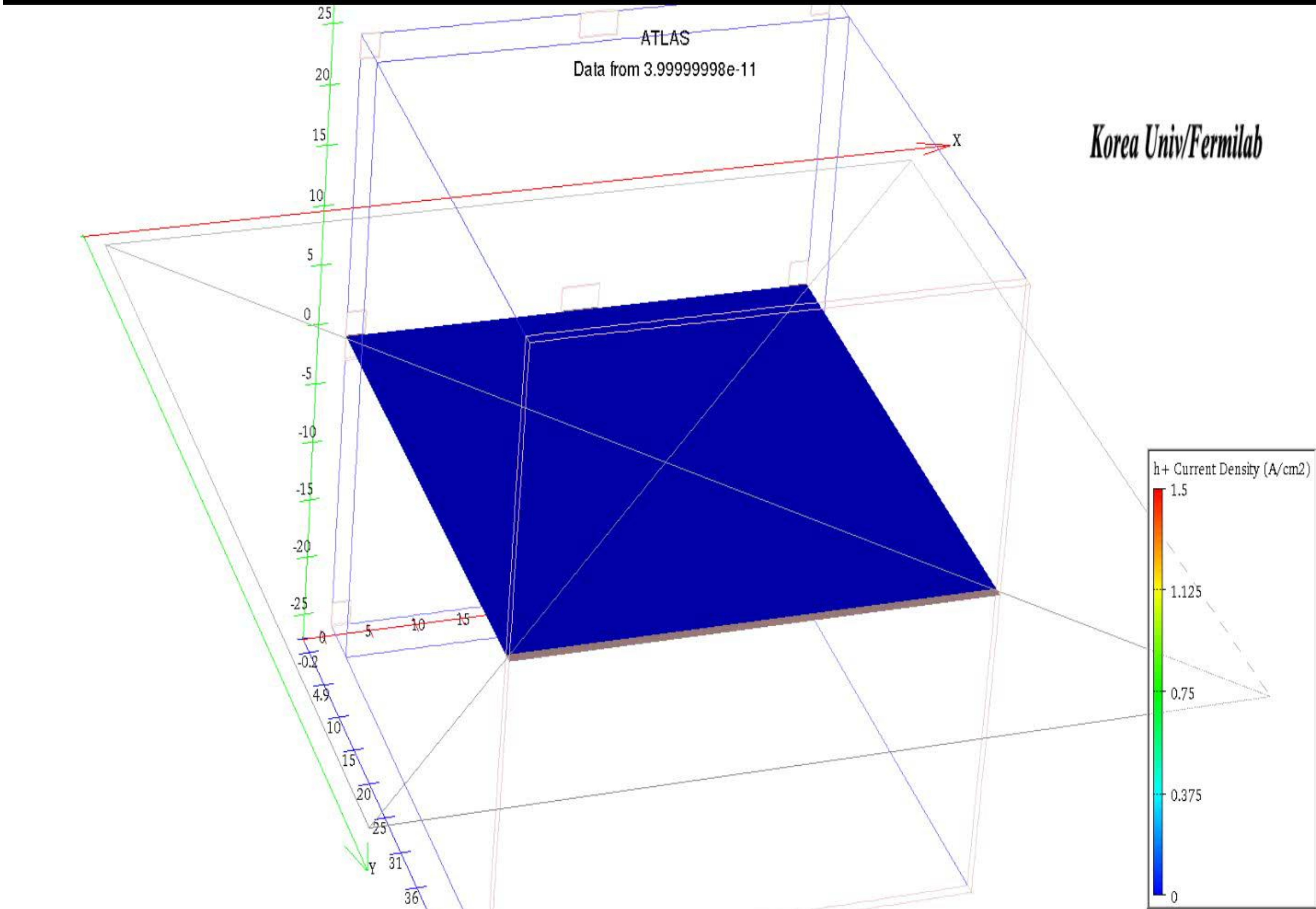


Strip interconnect using wirebonds



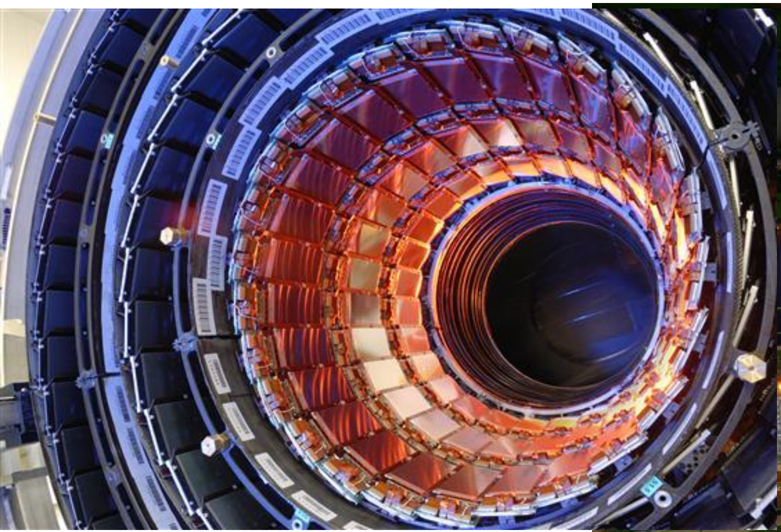
Particle in a Silicon pixel detector Simulation

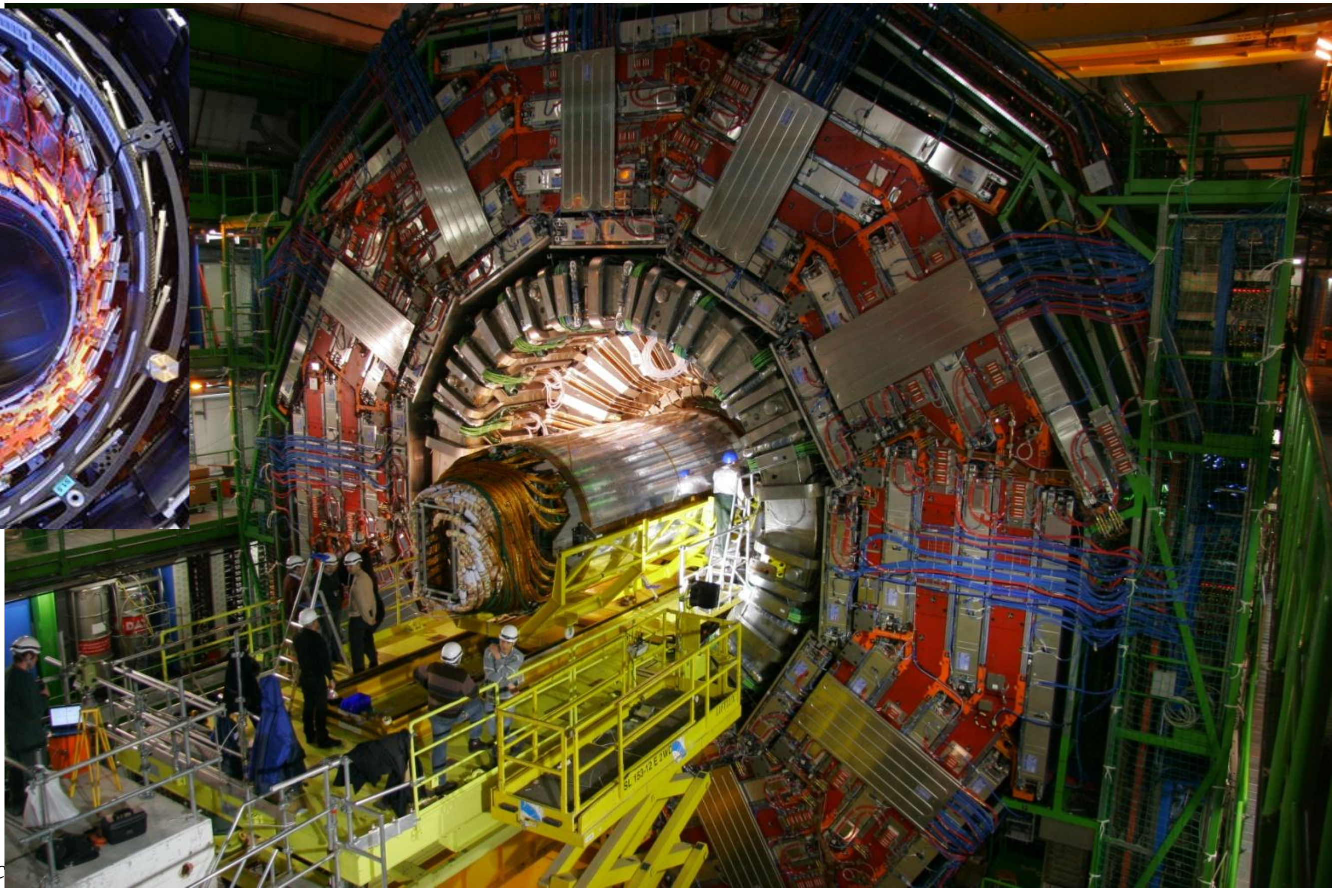
[redacted]



CMS Silicon Tracker

- More than 220 m^2 of silicon
- Bump bonded pixels
- About 80 million channels of electronics

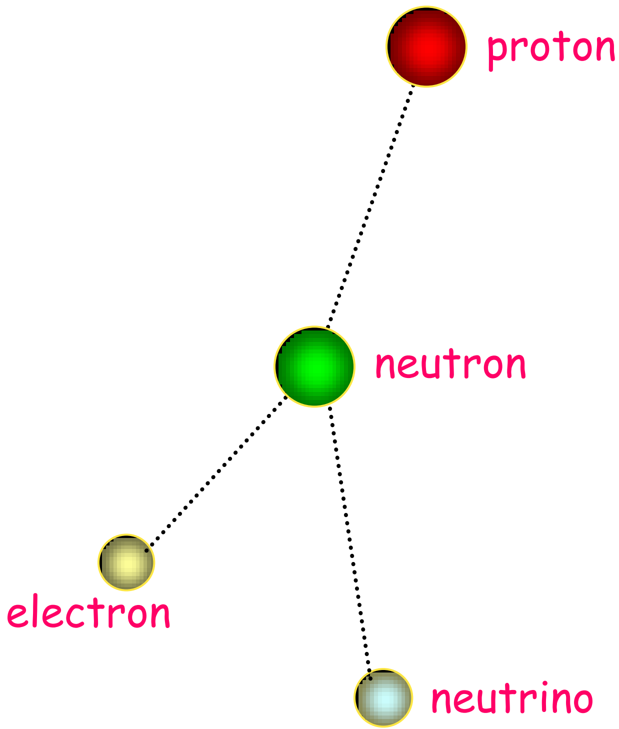


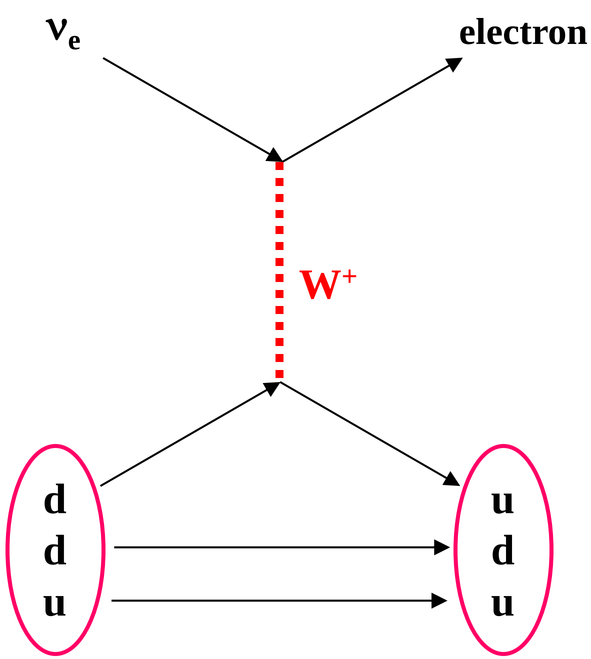


Neutrino Detectors

Neutrinos

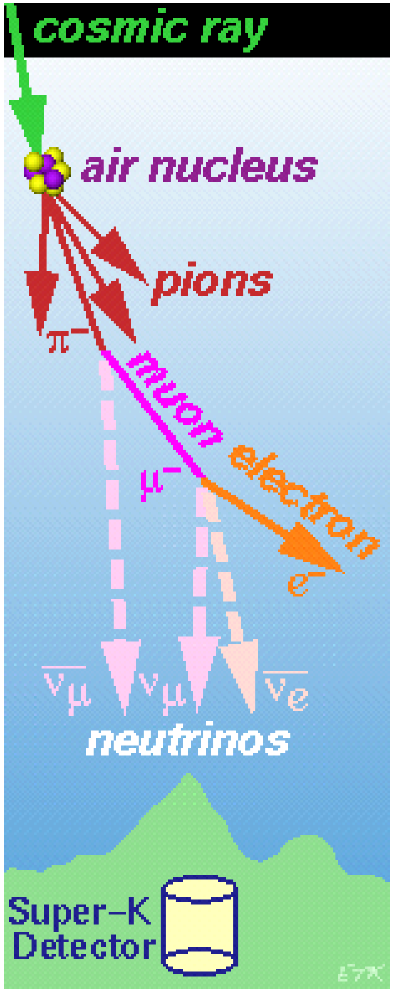
- Postulated in 1930 by Wolfgang Pauli to explain the missing energy in nuclear β-decay to preserve the law of conservation of energy
  - Niels Bohr was ready to abandon this conservation law !
  - 1933, Enrico Fermi theory of nuclear β-decay
    - He was afraid that the neutrino could never be observed, since it interacted so weakly
    - Bethe and Bacher, 1936: "It seems practically impossible to detect neutrinos in the free state"





Neutrino Sources

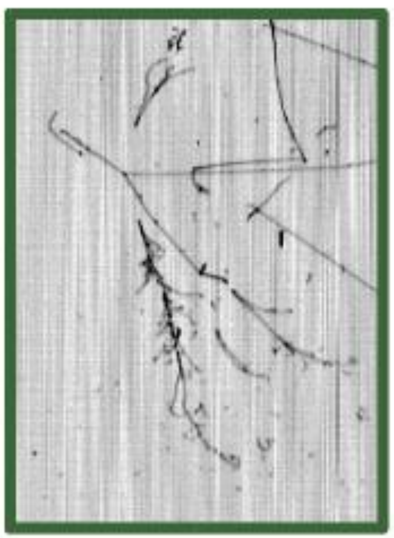
- Cosmic Rays: energetic protons colliding in atmosphere
  - Create pions
  - Pions decay:
    $$\pi^- \to \mu^- \bar{\nu}_\mu$$
    $$\mapsto e^+ \bar{\nu}_e \nu_\mu$$
- Neutrinos from the fusion reactions in the sun
  - $$4\ {}^1H \to {}^4He + 2e^+ + 2\nu_e + 25\ \ MeV$$
- Neutrinos from the cosmos
- Neutrinos from nuclear reactors
- Neutrinos from accelerators

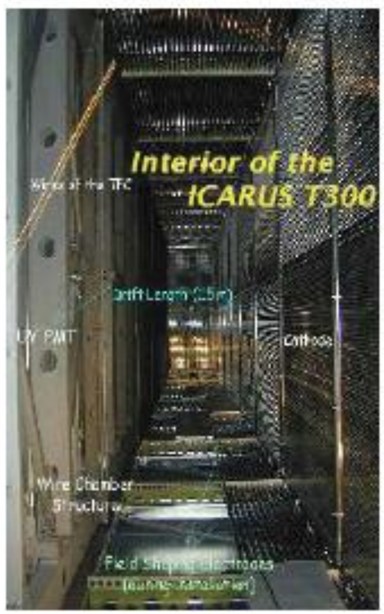


- Because neutrinos interact weakly, how can we detect them ?
  - Increase the number of neutrinos
    - Increase the number of protons to create neutrinos
      - Future Fermilab program to increase neutrino flux
  - Increase the size of the detectors

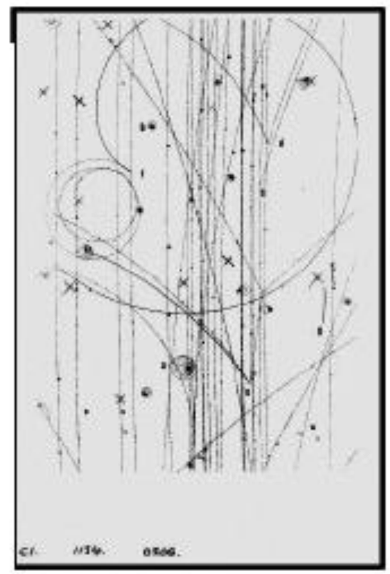
To See Neutrino Reactions You Need

1) lots of neutrinos
2) lots of detector
3) **fine-grained**
   or specialized detectors
4) some combination
   of the above





Liquid Argon



Bubble chambers: limited size....

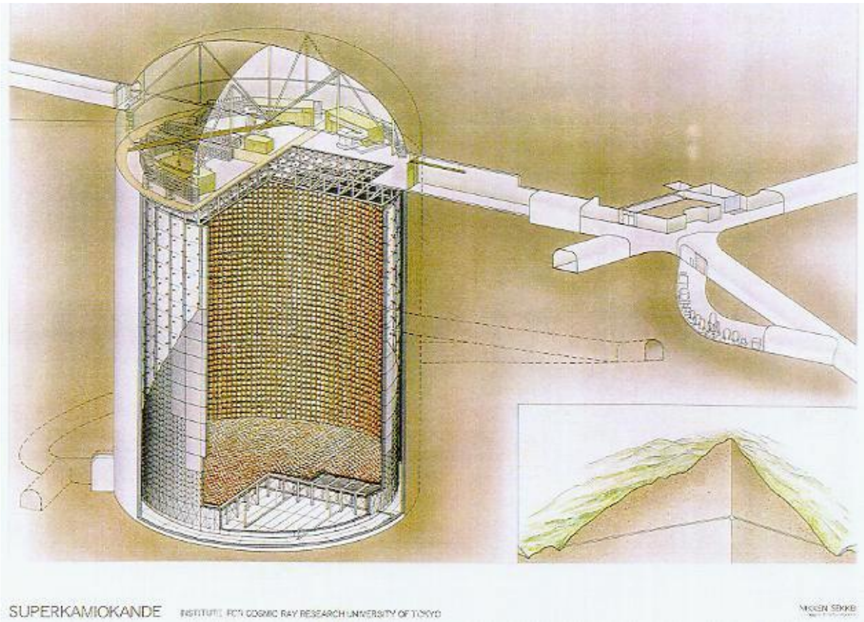
(Fleming)

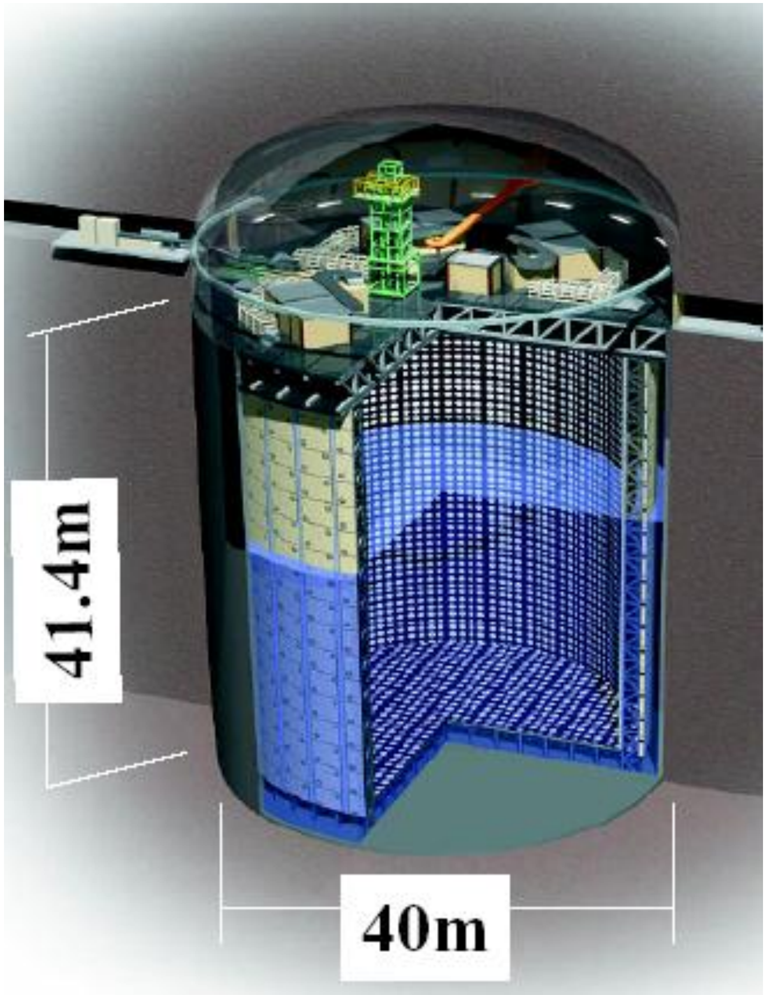
Neutrino Detectors

- Most neutrino detectors are massive detectors of various types
  - Radiochemical detectors
    - Homestake experiment: $n \rightarrow p$; $^{37}Cl \rightarrow {}^{37}Ar$ (Nobel prize 2002)
  - Čerenkov detectors
  - Calorimetric detectors
  - Emulsions
    - For a very specific measurement(s)
      - DONUT (Fermilab), CHORUS (CERN)
      - Opera (Gran Sasso)

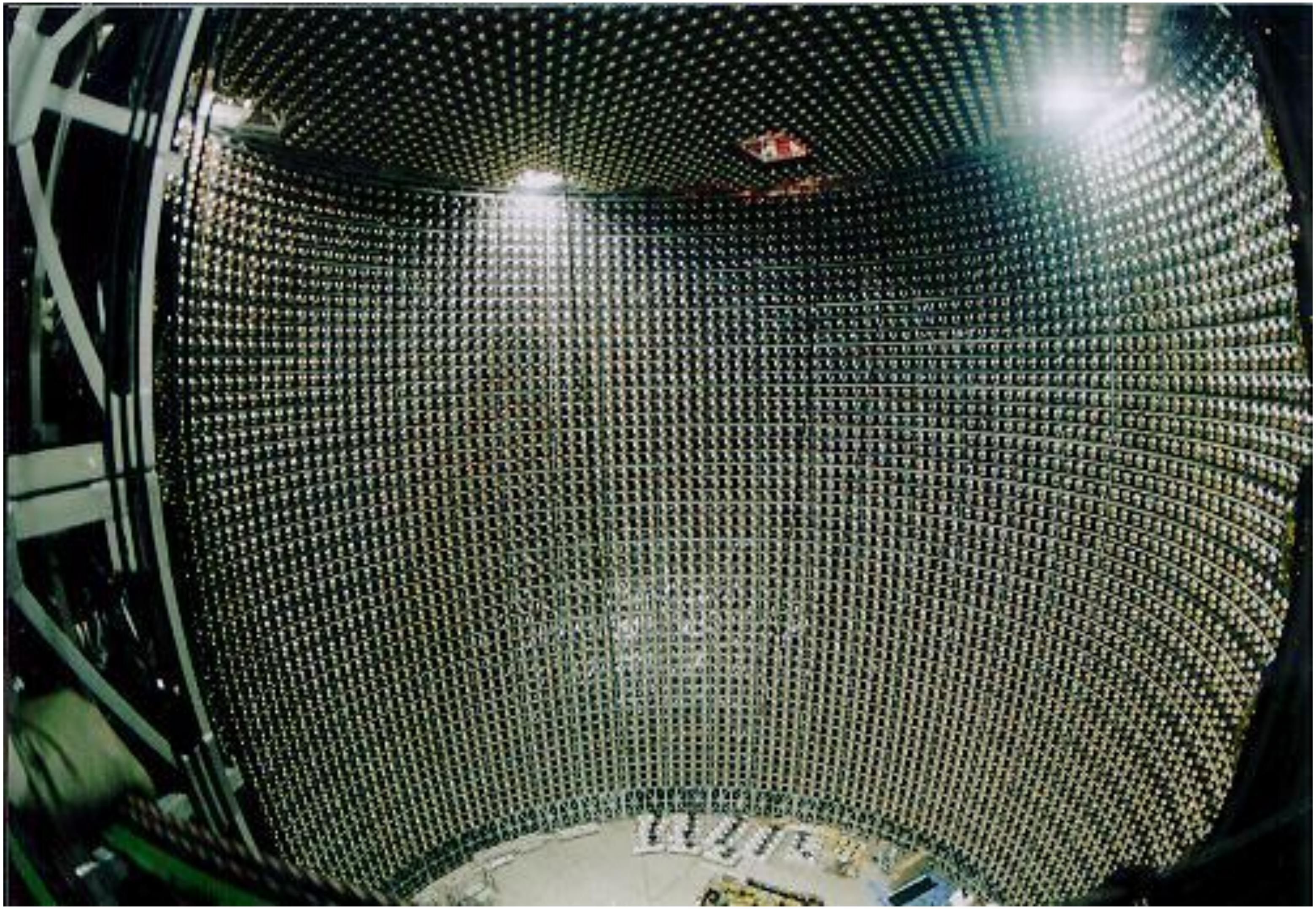
Super-Kamiokande

- Čerenkov detector, underground to shield from cosmic ray muons
  - Huge tank: 40m diameter, 41m high
  - Deeply buried in Mozumi mine near Kamioka in Japan
  - 55,000 tons of ultra pure water
  - Light detected with 11,200 PMT's
  - Reported evidence for neutrino oscillations in 1998: $\nu_\mu \leftrightarrow \nu_\tau$ oscillations

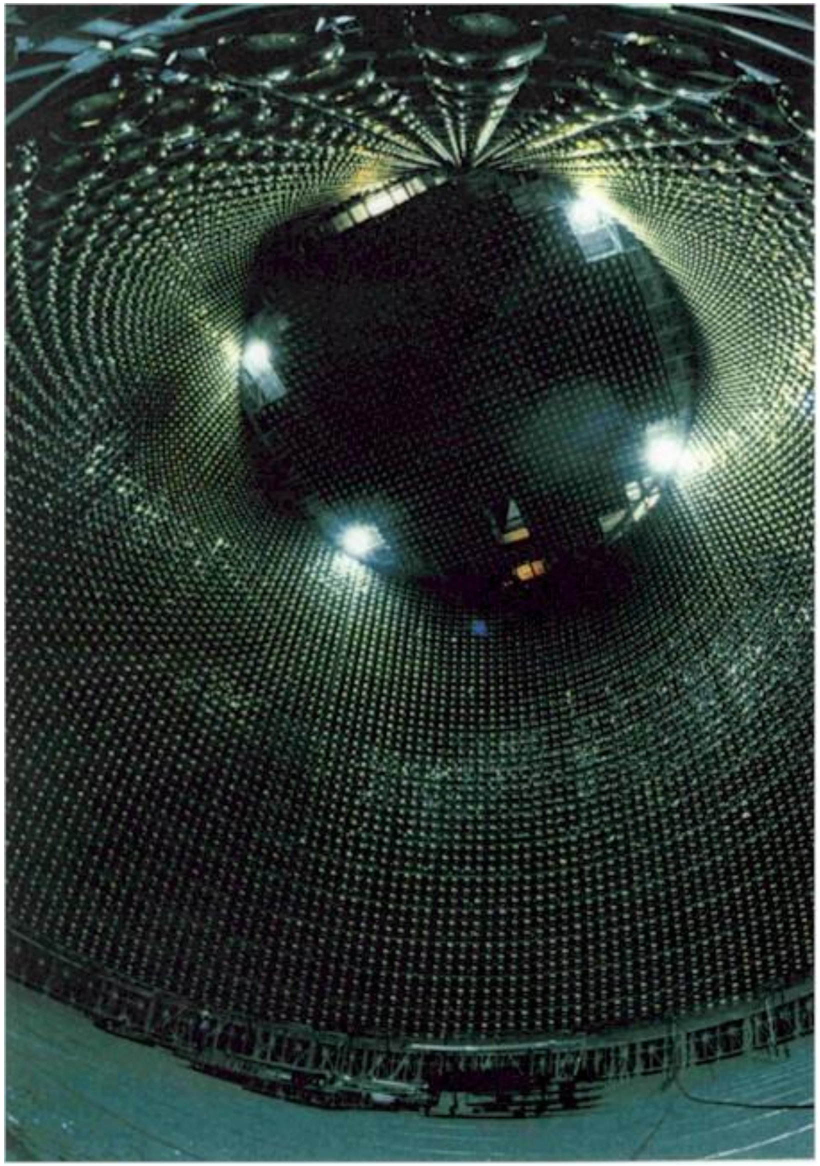


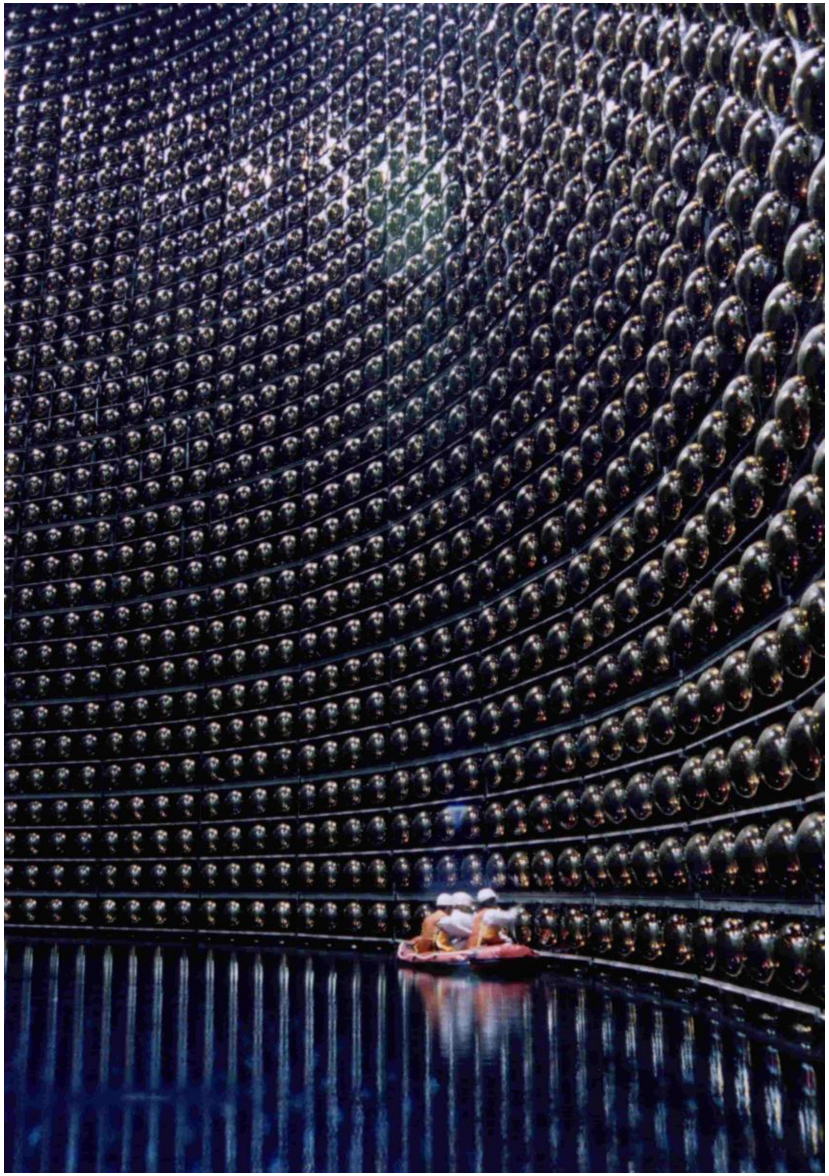


Super-Kamiokande

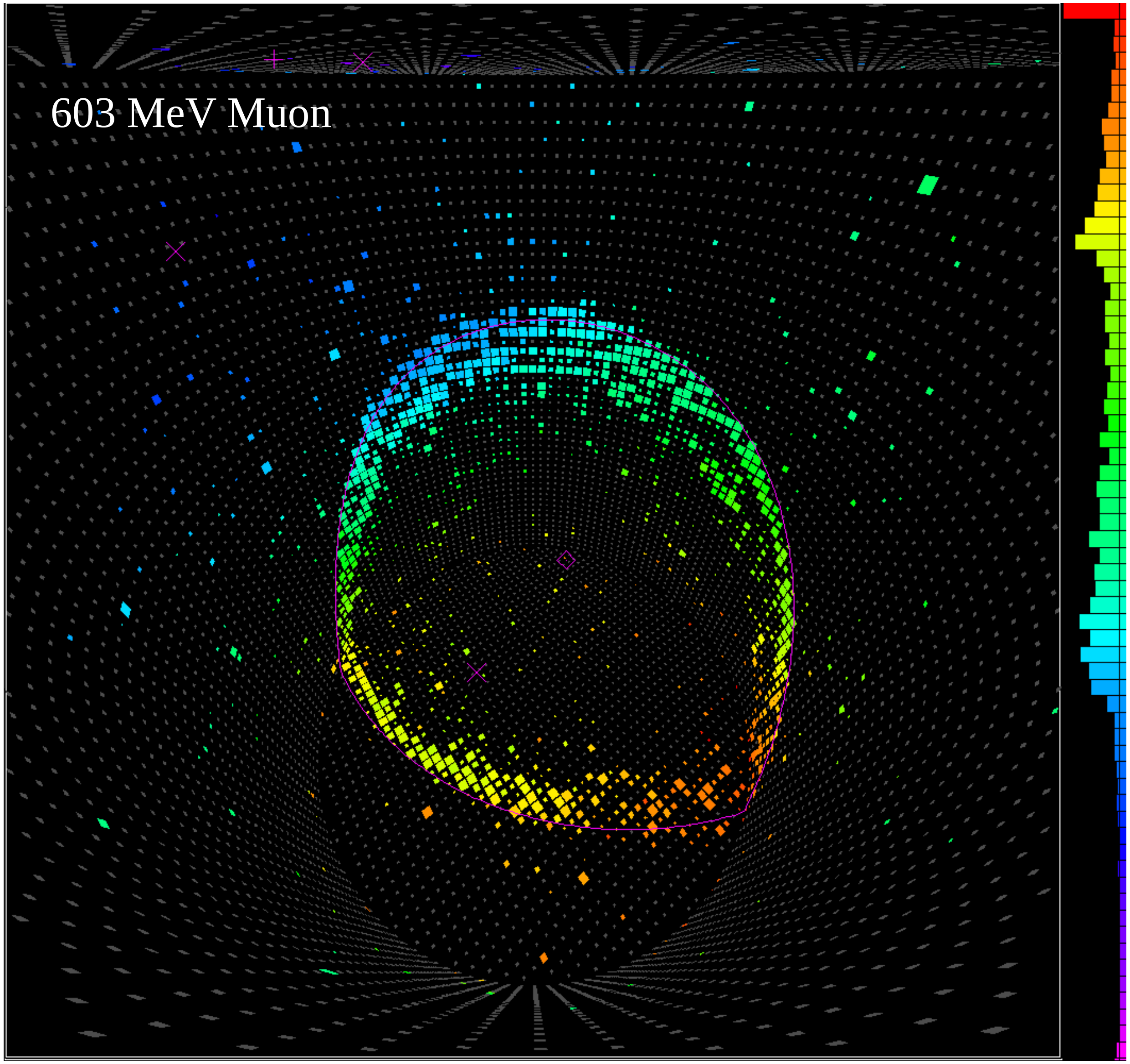


Super-Kamiokande



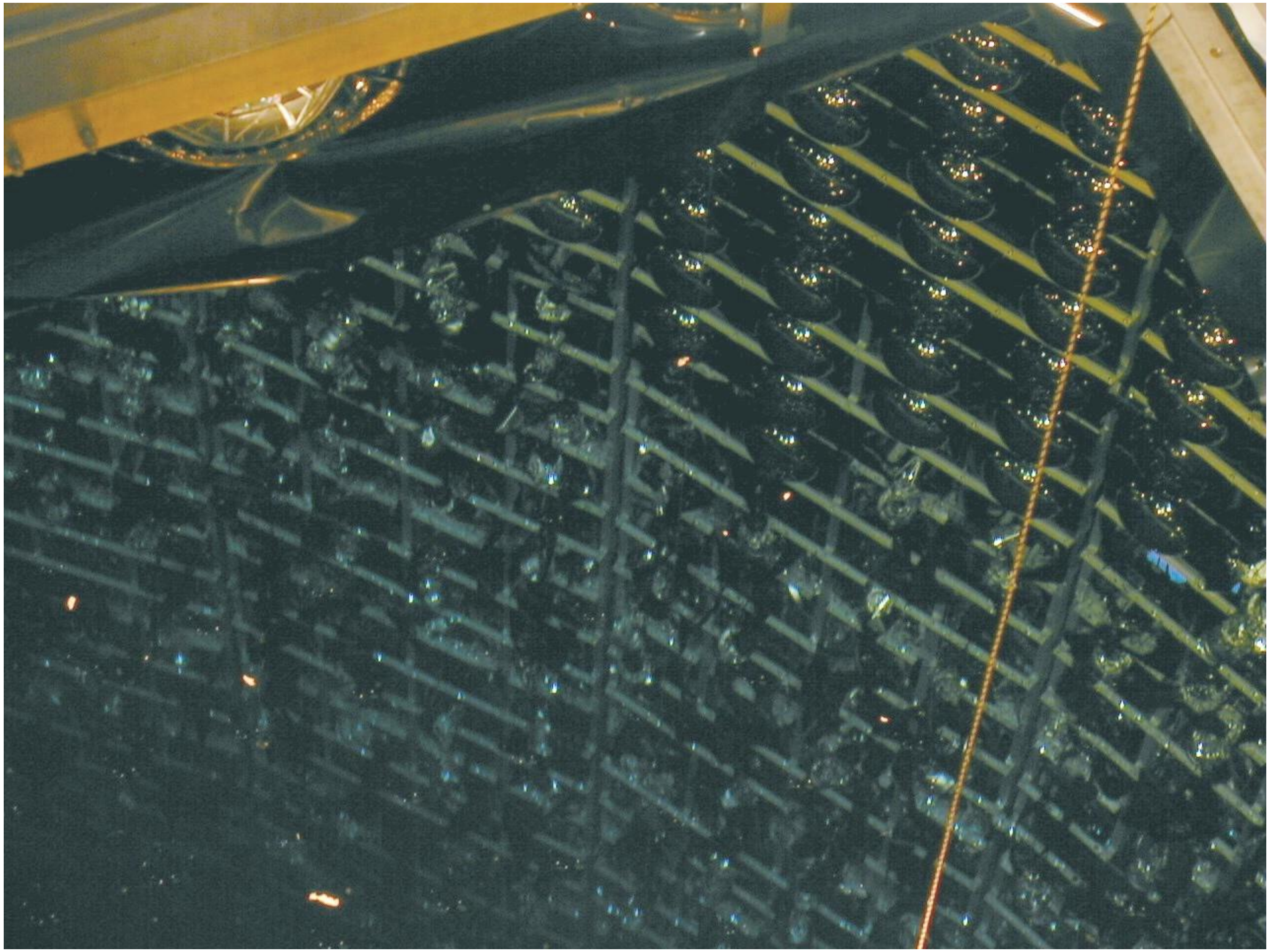


Super-Kamiokande: Events



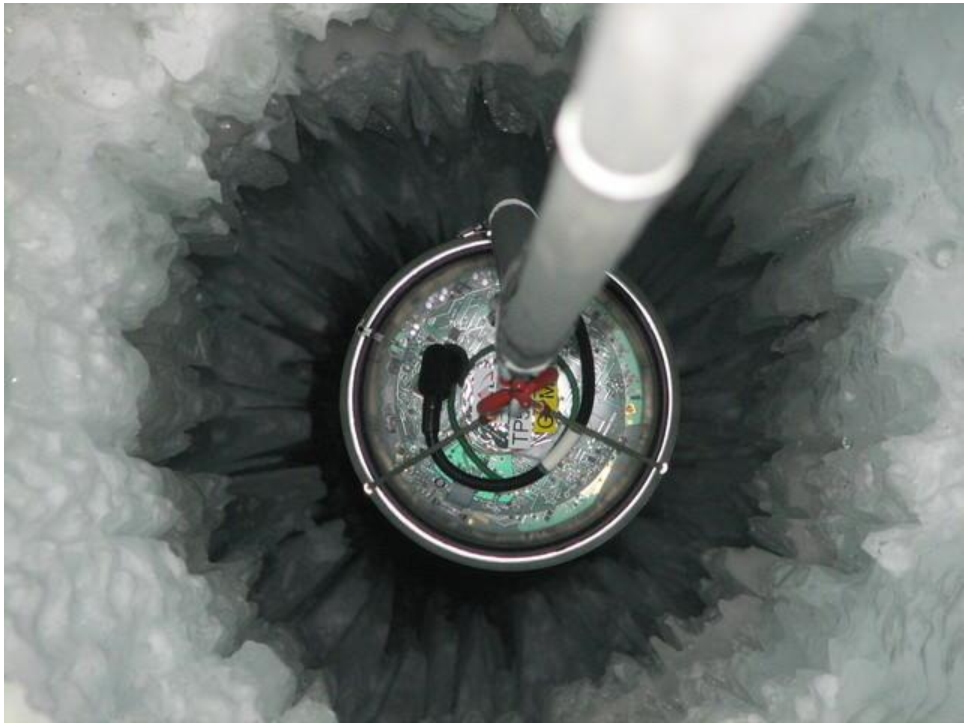
Oops

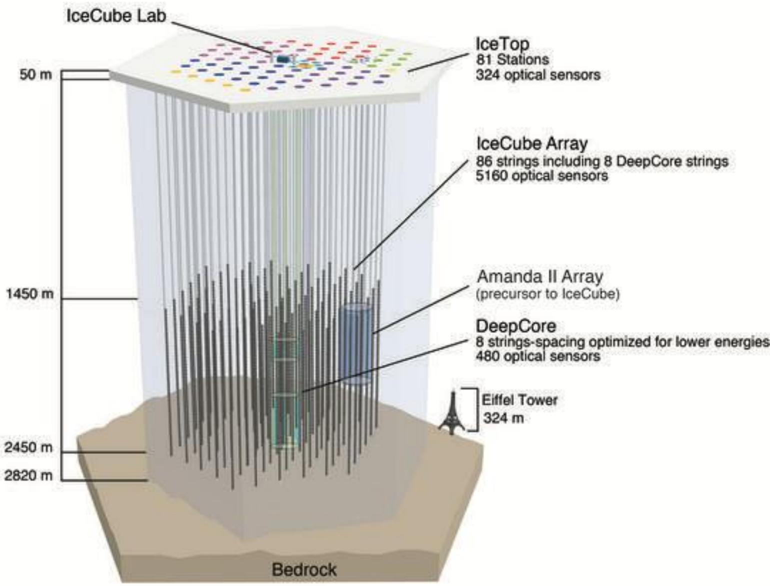
- One PMT imploded in the Super-Kamiokande experiment
  - Created a shock wave that broke half of the PMT's



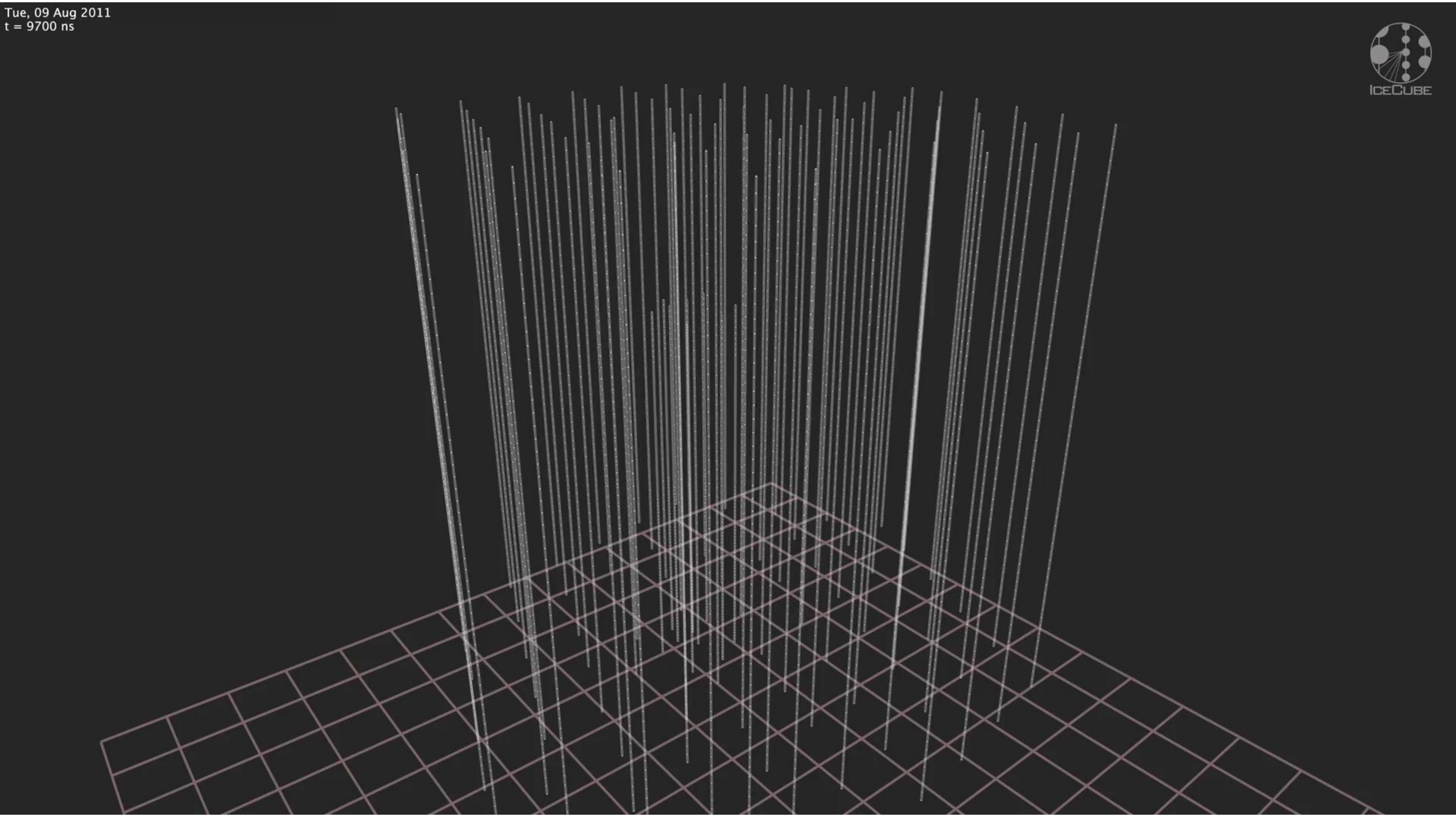
Icecube

- Icecube is an array of phototubes imbedded in the ice at the South Pole designed to study neutrino interactions.
- The detector encompasses a cubic kilometer of ice as the target/detector





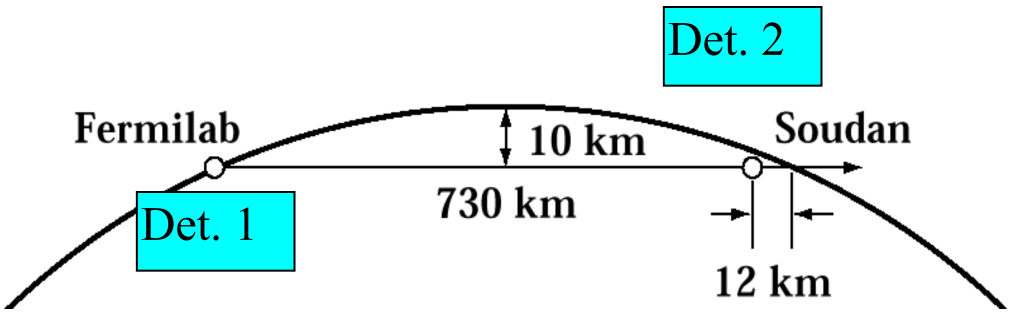
2nd Highest energy Neutrino event



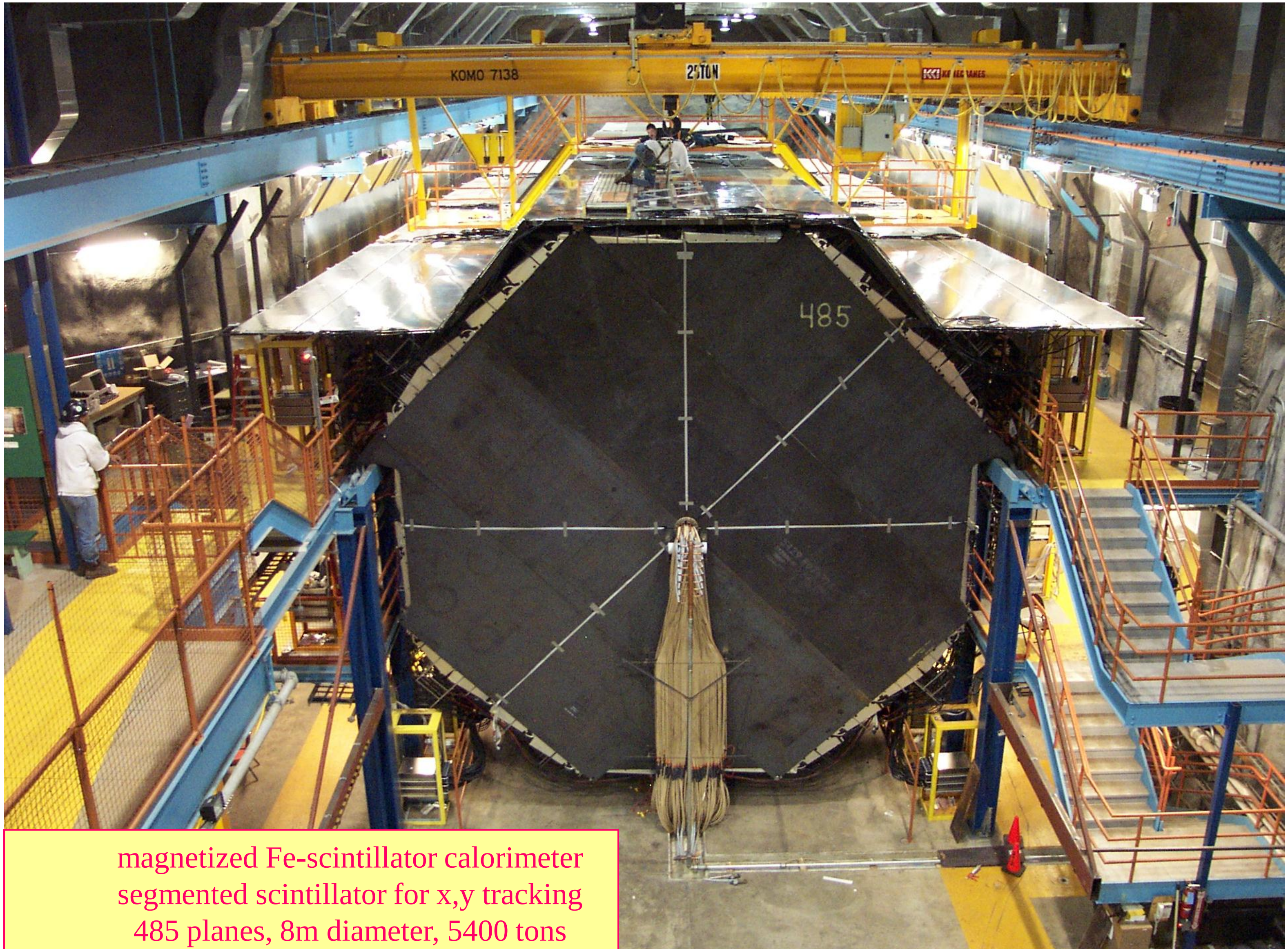
MINOS

- MINOS = Main Injector Neutrino Oscillation Search

- Two detector calorimetric neutrino oscillation experiment
  - Near Detector on Fermilab site
    - 980 tons
  - Far Detector in mine in Soudan (MN)
    - 5400 tons



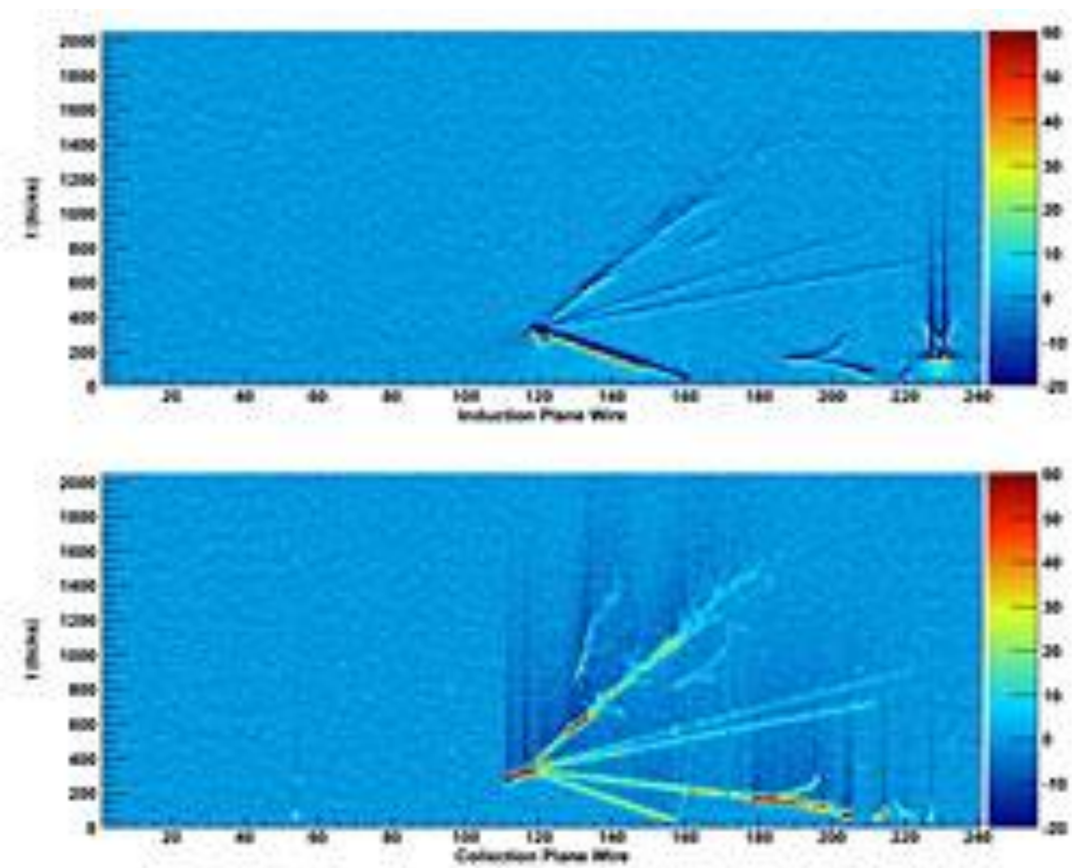
MINOS

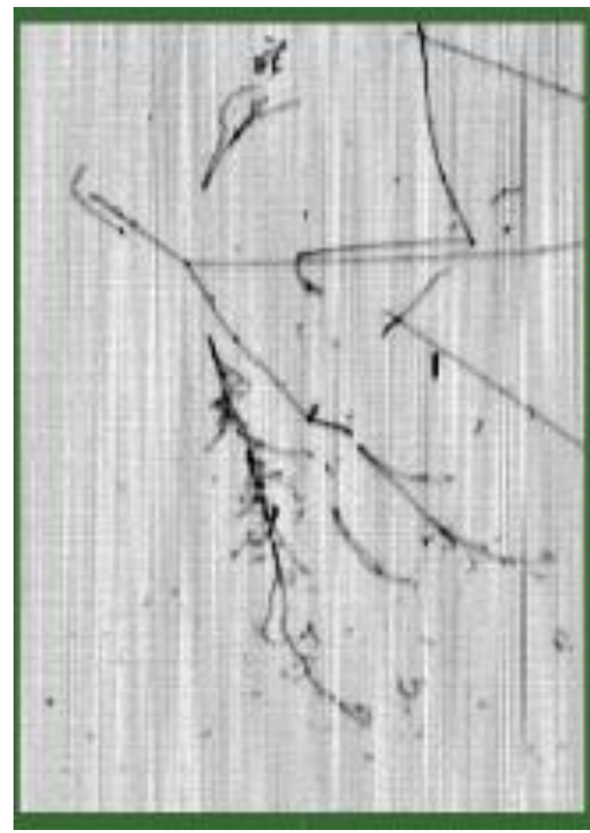


magnetized Fe-scintillator calorimeter
segmented scintillator for x,y tracking
485 planes, 8m diameter, 5400 tons

Liquid Argon TPC

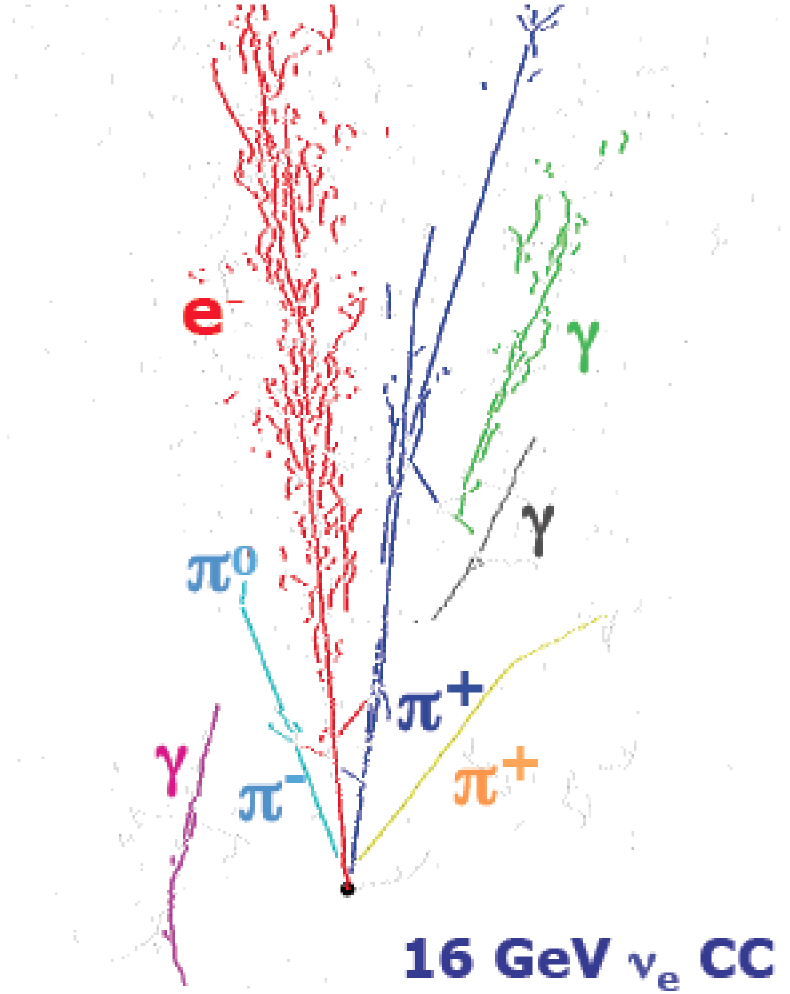
- Large liquid argon Time Projection Chamber – bubble chamber for neutrinos
  - Electrons and argon ions drift in an electric field
  - Charge is collected on stretched wires
  - The readout electronics builds an image of the neutrino interaction





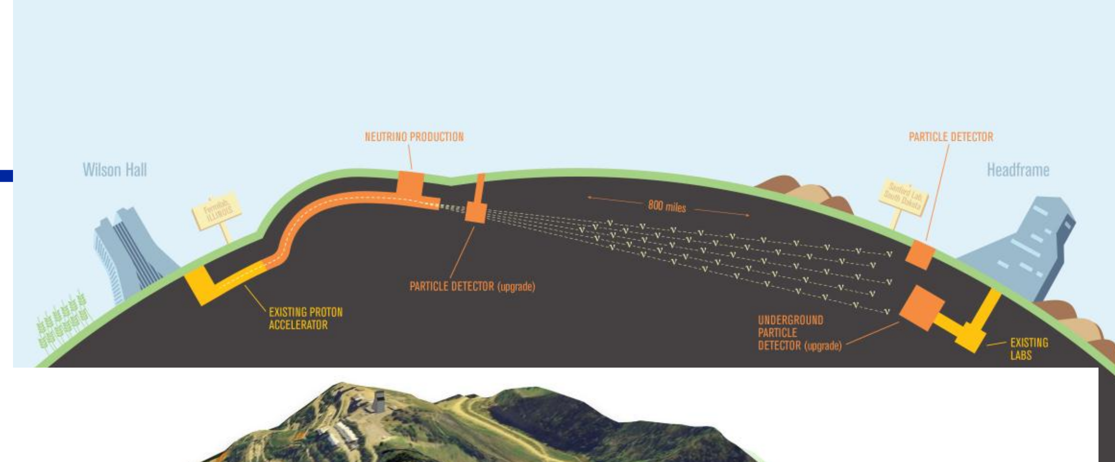
Interactions in a TPC

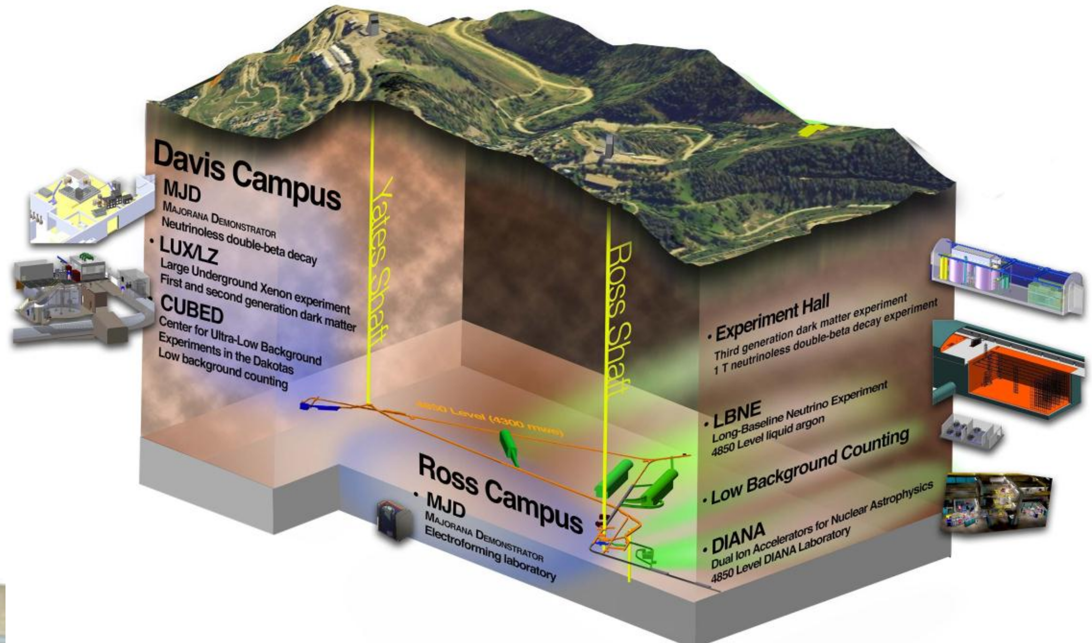
- Simulation of Interactions in liquid argon

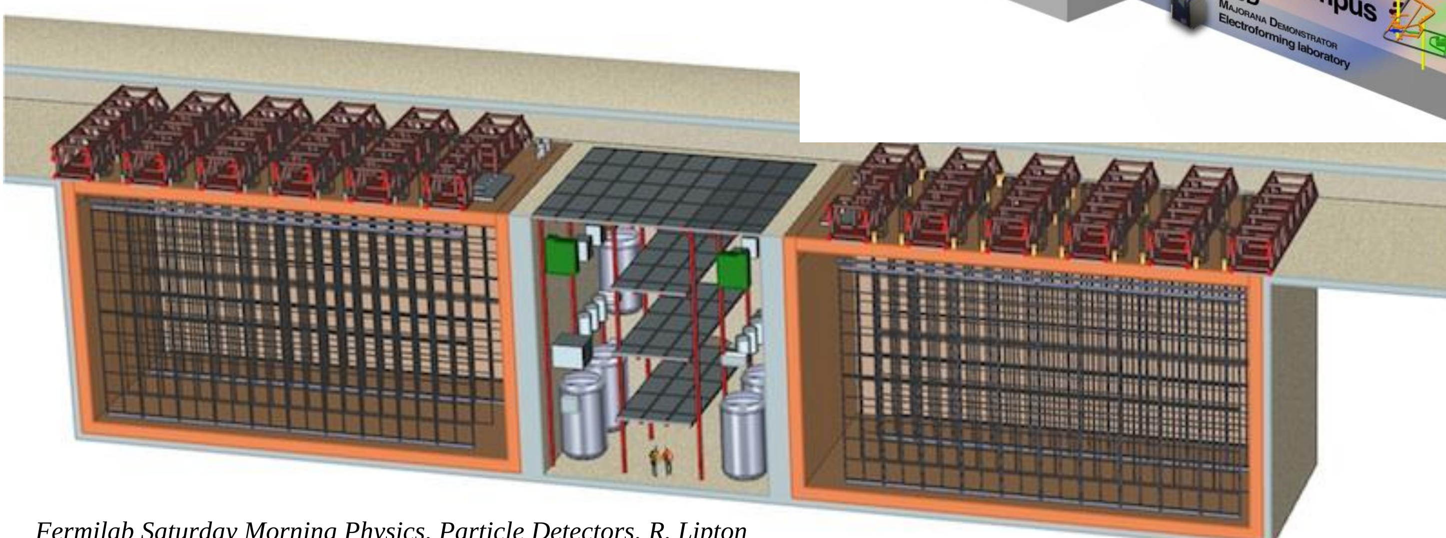


LBNE

LBNE would send a beam of neutrinos 1300 km from Fermilab to a mine 10 a 10 kT detector in Lead, South Dakota



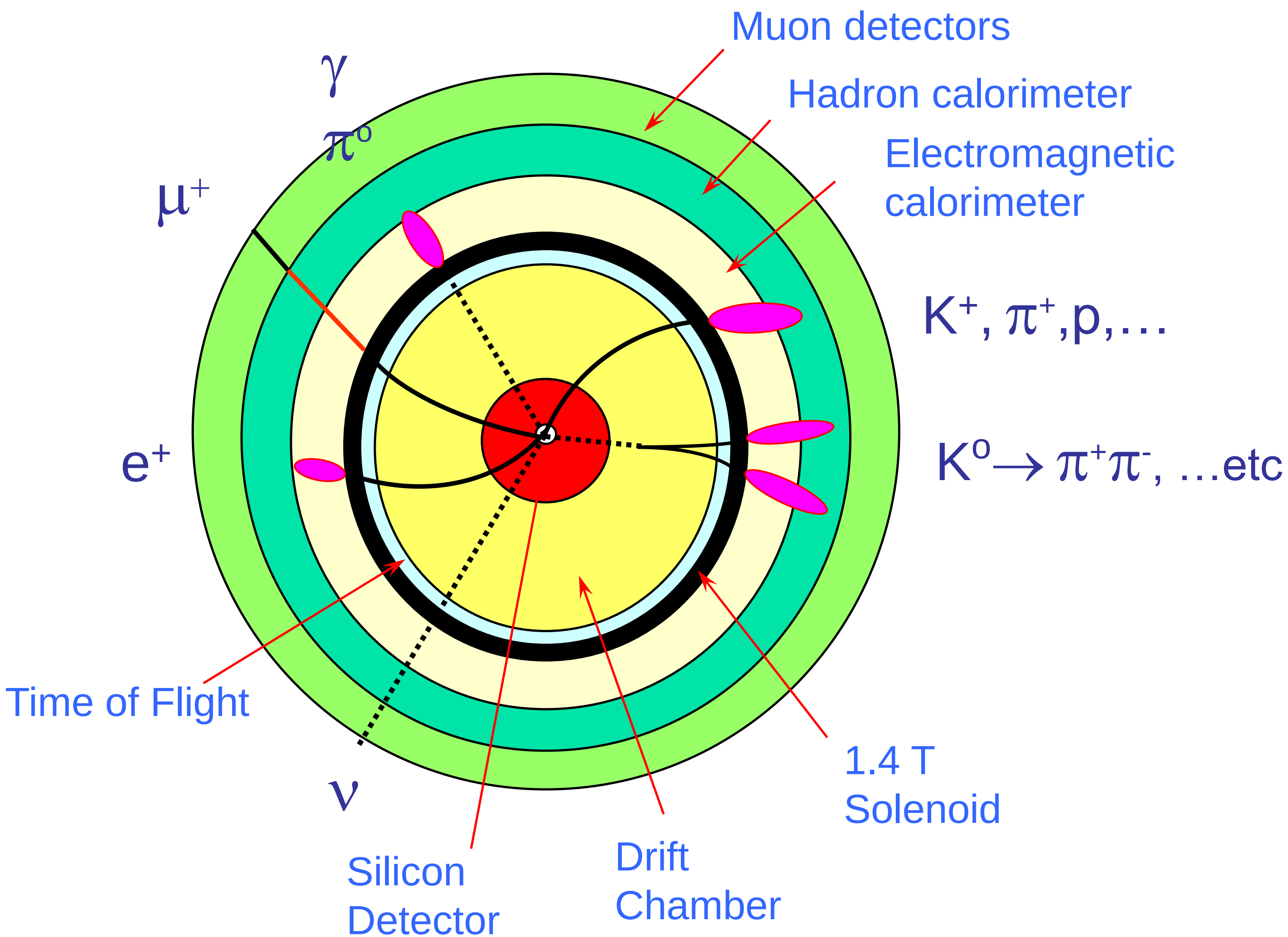




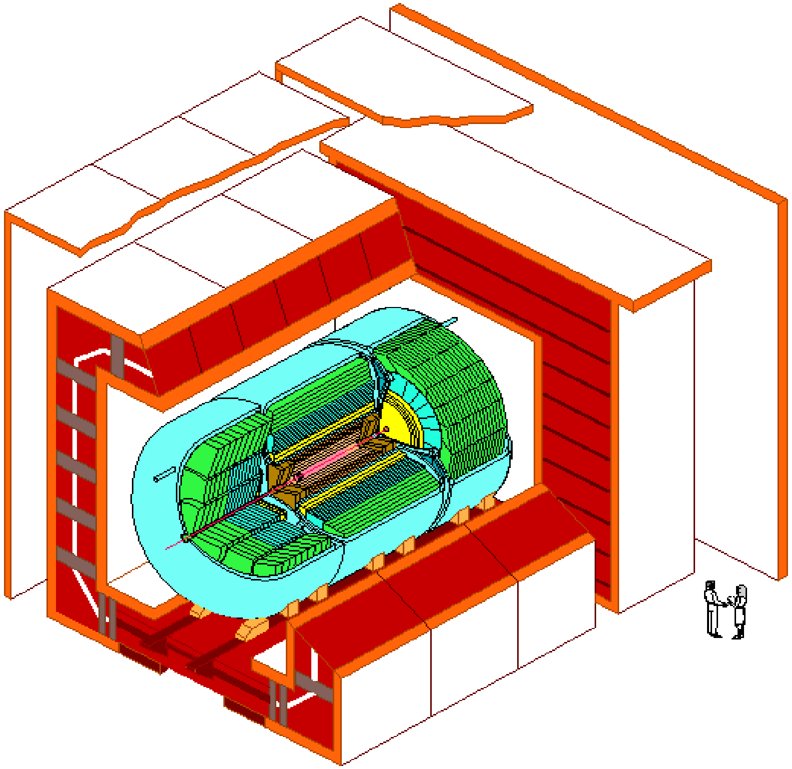
Collider Detectors

Functional Schematic of Collider Detector

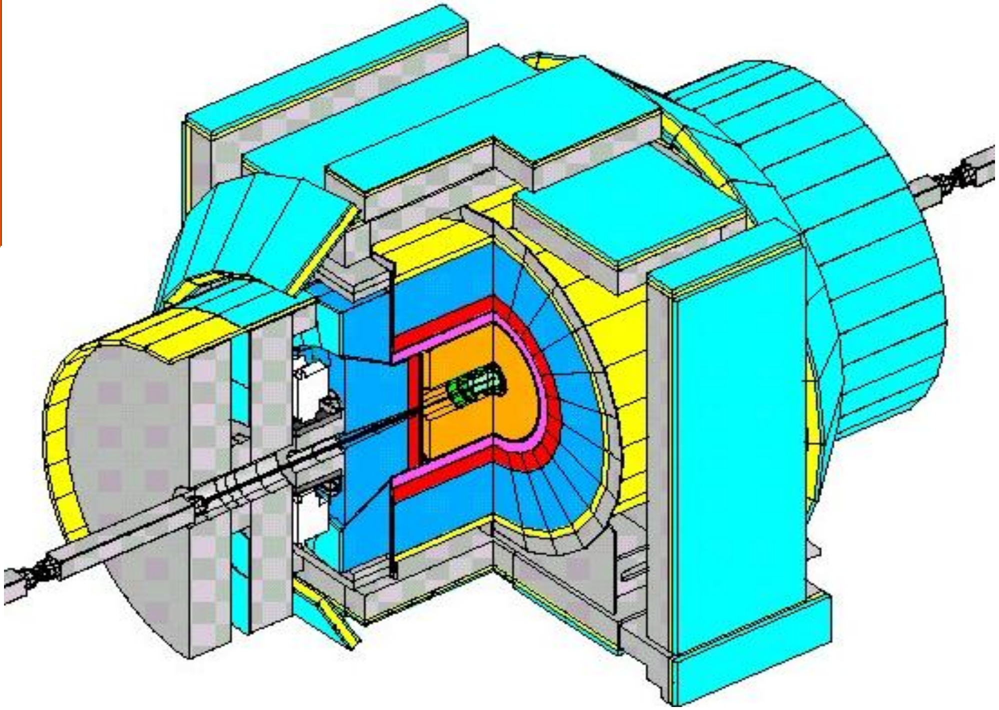
- Nearly all collider detectors are 'shoeboxes'



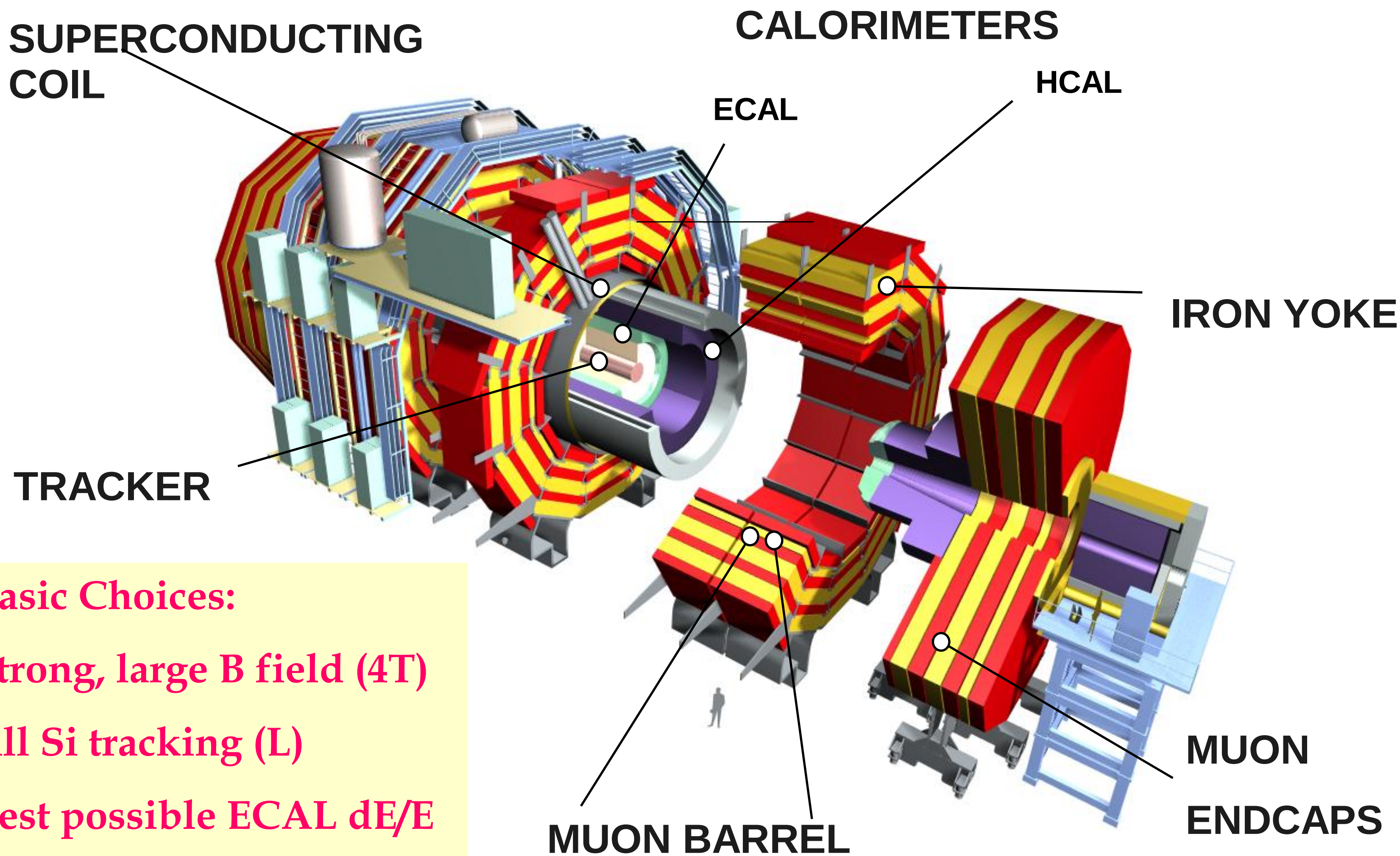
DØ and CDF Detector



- 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



CMS at LHC



Basic Choices:

Strong, large B field (4T)

All Si tracking (L)

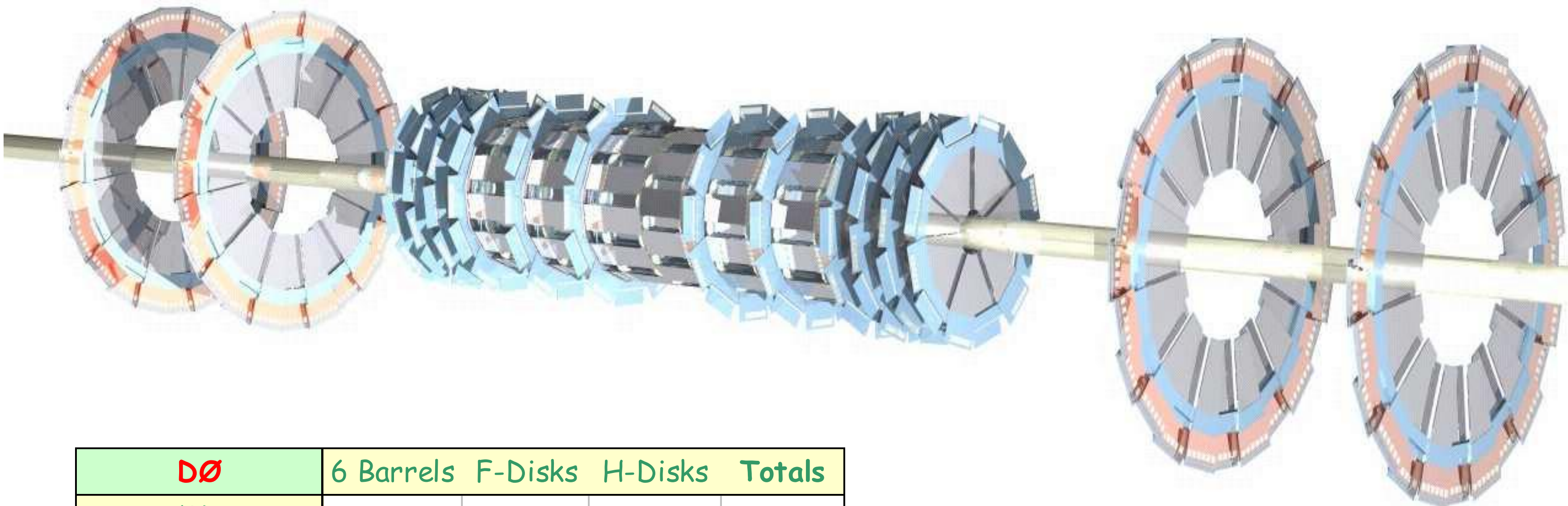
Best possible ECAL dE/E

Robust Muon - yoke

http://cms.web.cern.ch/cms/Resources/CMS_Slice_elab.swf

Silicon Vertex Detector: DØ

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

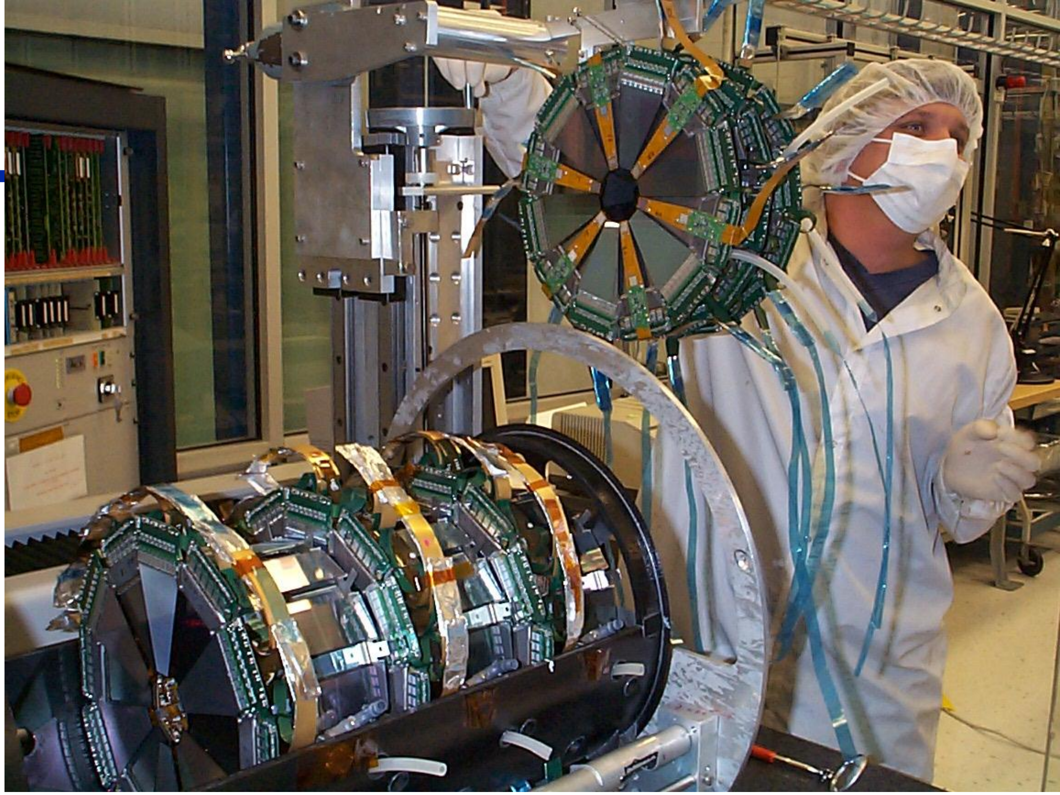


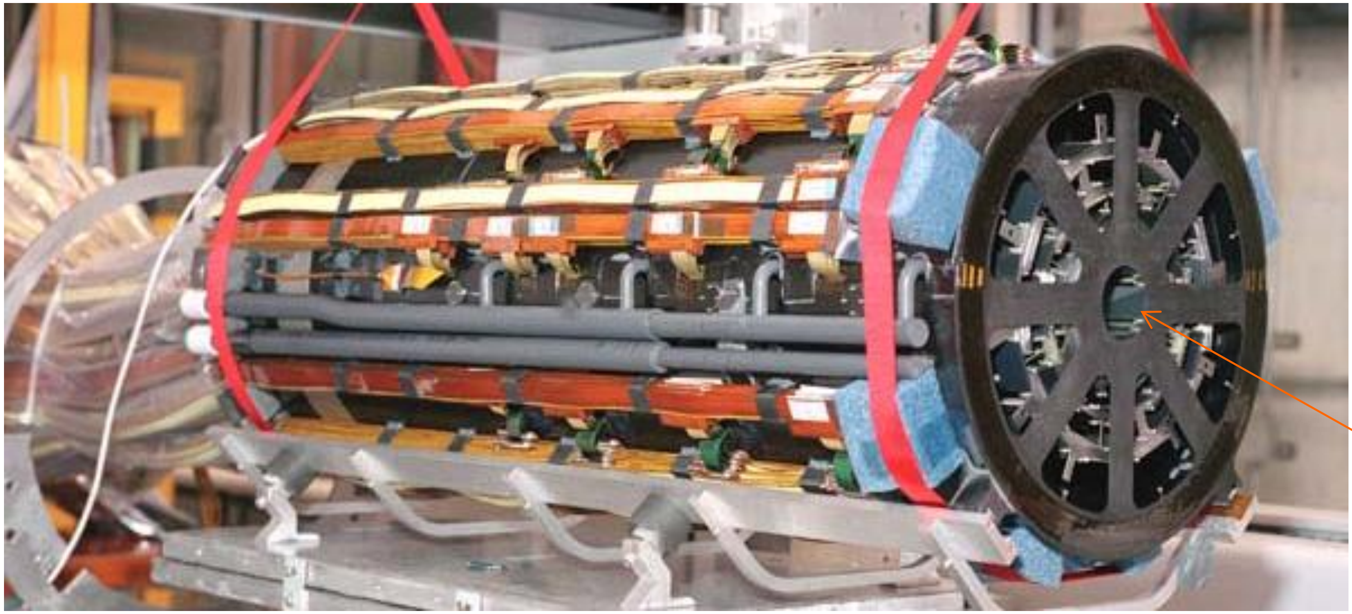
DØ	6 Barrels	F-Disks	H-Disks	Totals
Layers/Planes	4	12	4	**4 - 6**
Δz-coverage	78 cm	30 cm	45 cm	**242 cm**
Channels	387072	258048	147456	**792576**
Sensors	720	144	384	**1248**
Modules	432	144	96	**672**
Readout Length	12.4 cm	7.5 cm	14.9 cm	
ΔR-coverage (cm)	2.7-9.4	2.7-9.7	9.6-23.5	

Silicon Vertex Detector: D0

- D0 silicon vertex detector during assembly at SiDet

During module insertion



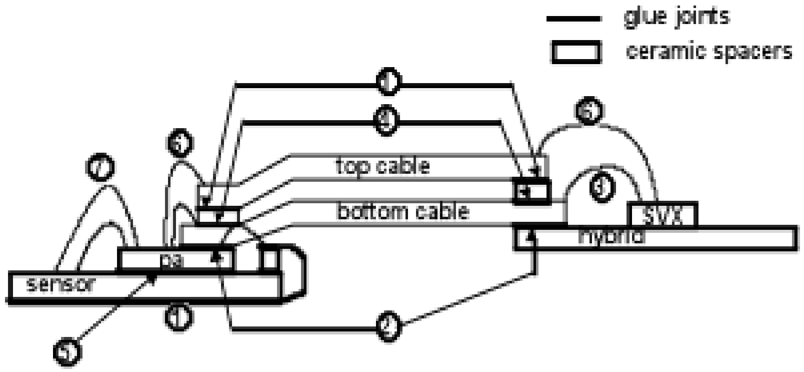


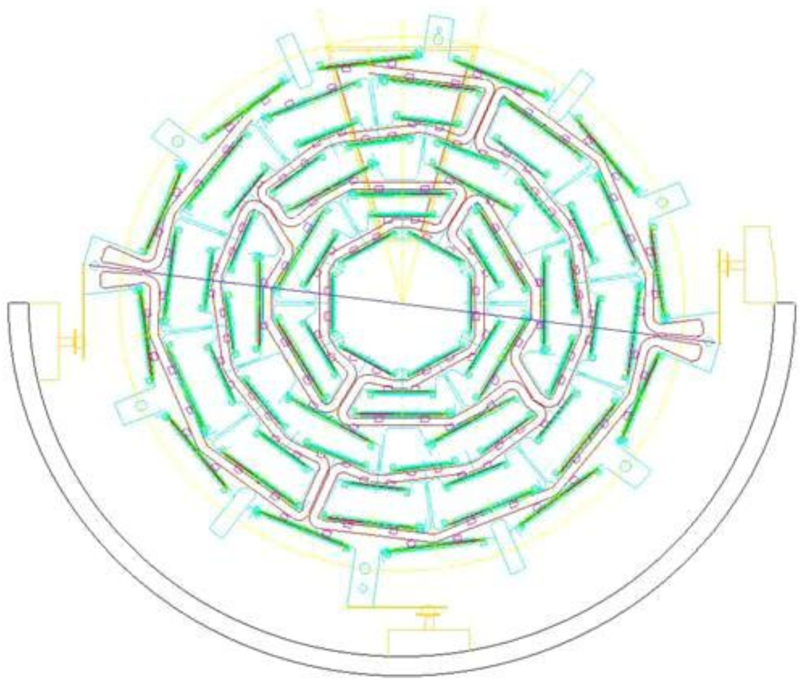
Fully dressed with cables

L0 goes here!

Example – Layer 0

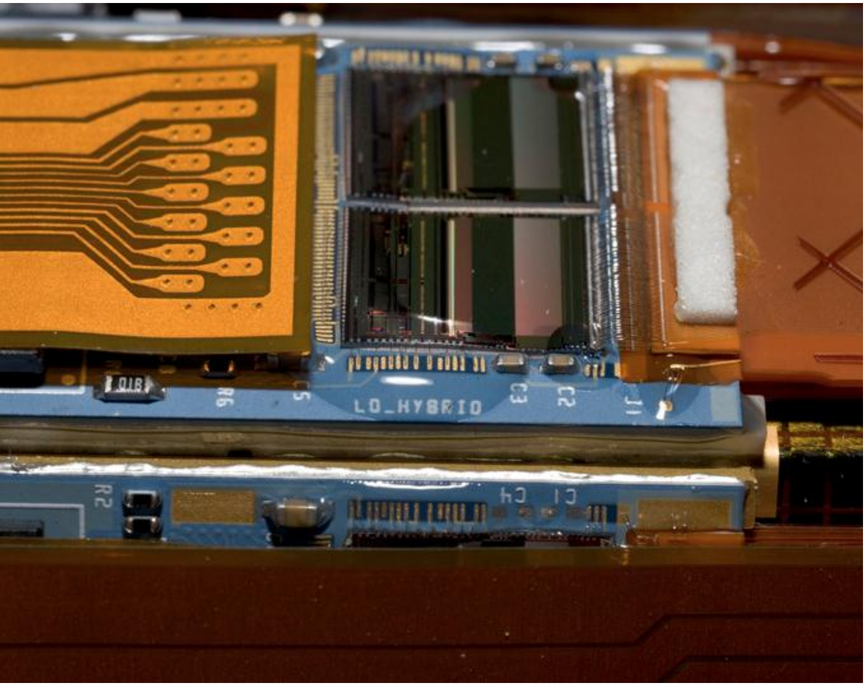
- Most recent silicon detector at Tevatron
  - Fit inside opening in existing detector
    - .5mm radial space
  - Very low mass – cables and electronics out of active area
- These things are works of art (if I say so myself
- Everything has to be designed to work together
  - Sensors (most of what we talk about)
  - Electronics
  - Cables
  - Cooling
  - Mechanical supports
  - Interconnects
  - Assembly fixtures

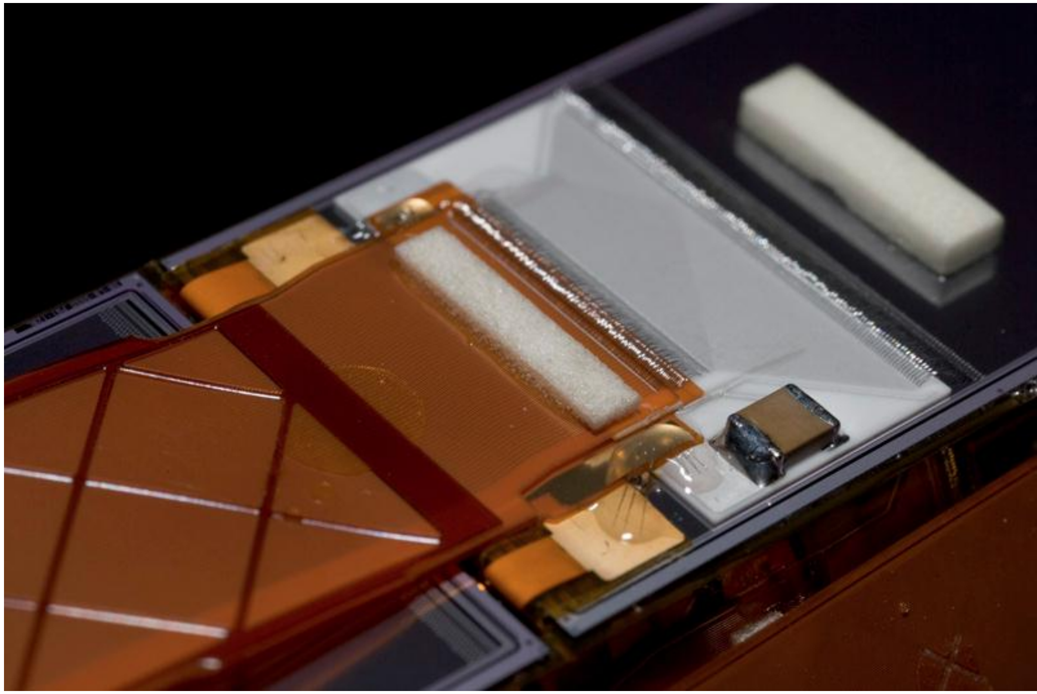




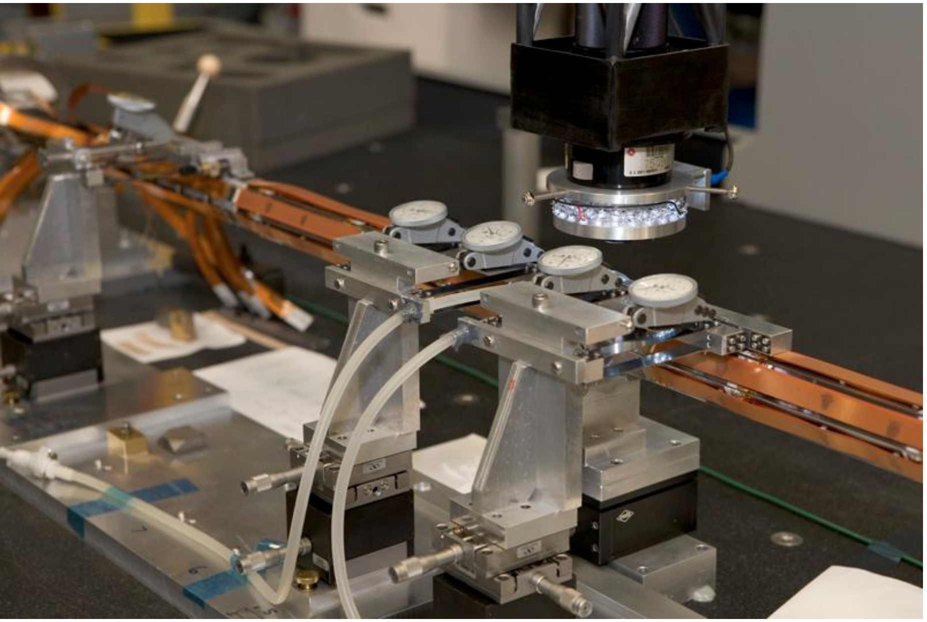
Module Production

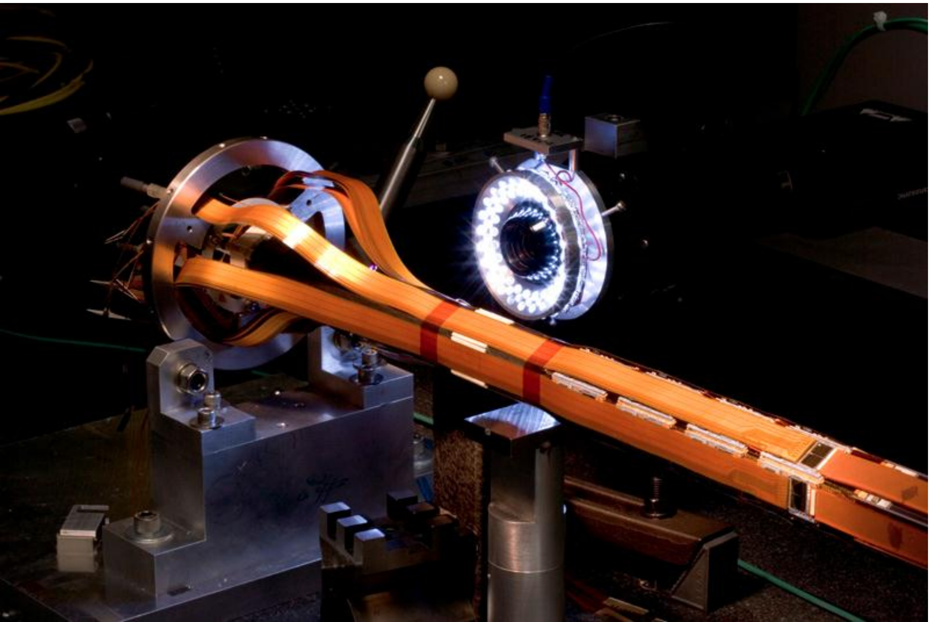
- Design individual components and assemble modules
  - Readout electronics
  - Silicon Sensors
  - Cables

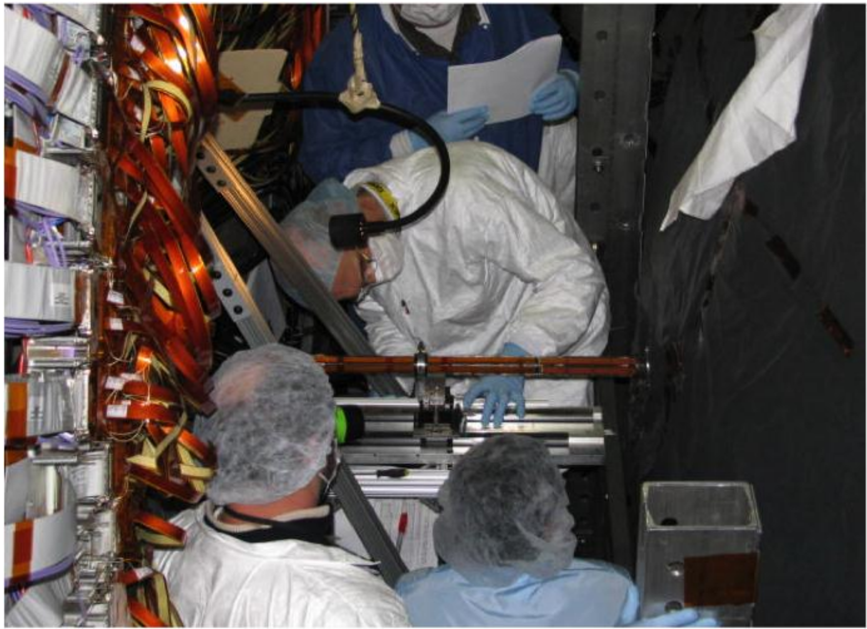




Assembly

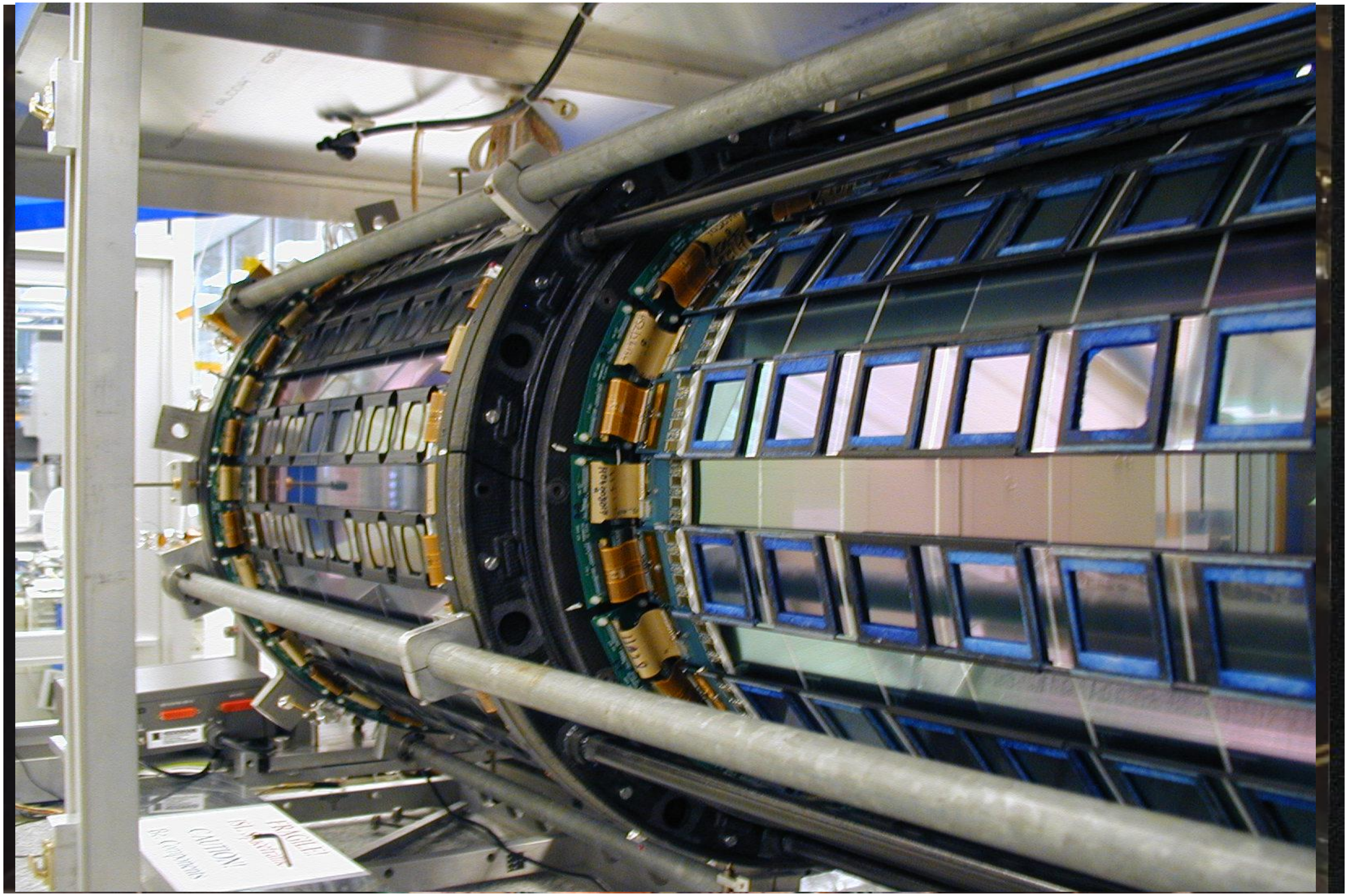






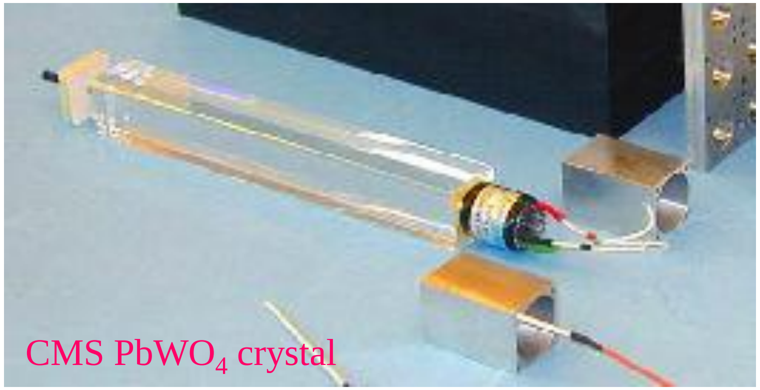
Silicon Vertex Detector: CDF

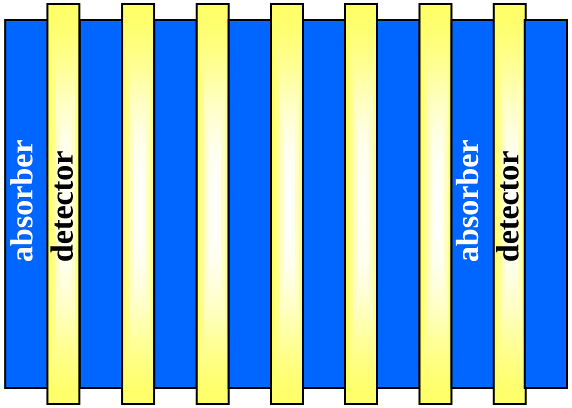
- CDF silicon vertex detector, Intermediate Silicon Layers (ISL)



Calorimetry

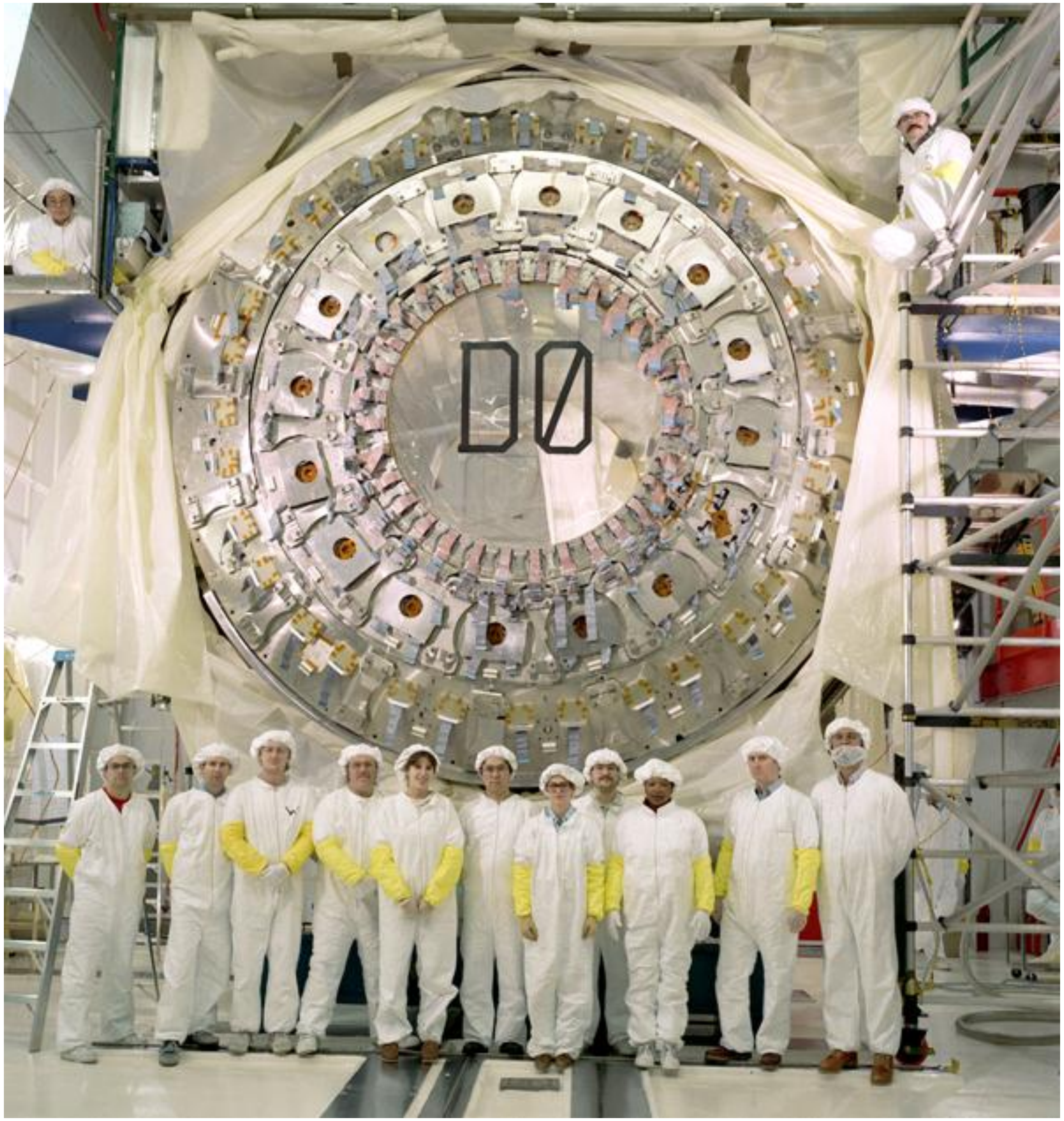
- Calorimetric measurements are generally destructive: total absorption
- Calorimeters normally subdivided longitudinally in electromagnetic section followed by hadronic section
- Calorimeter types:
  - Homogenous calorimeters
    - detector = absorber
    - good energy resolution
    - limited longitudinal segmentation
    - mainly used for electromagnetic calorimeters
      - scintillating crystals with photon readout
      - NaI, CsI, BGO, $PbWO_4$
  - Sampling calorimeters
    - distinct detector and absorber elements
    - limited energy resolution
    - good longitudinal segmentation
    - many different active media
  - No leakage
    - Neutrinos are inferred from missing energy





Calorimeter: DØ

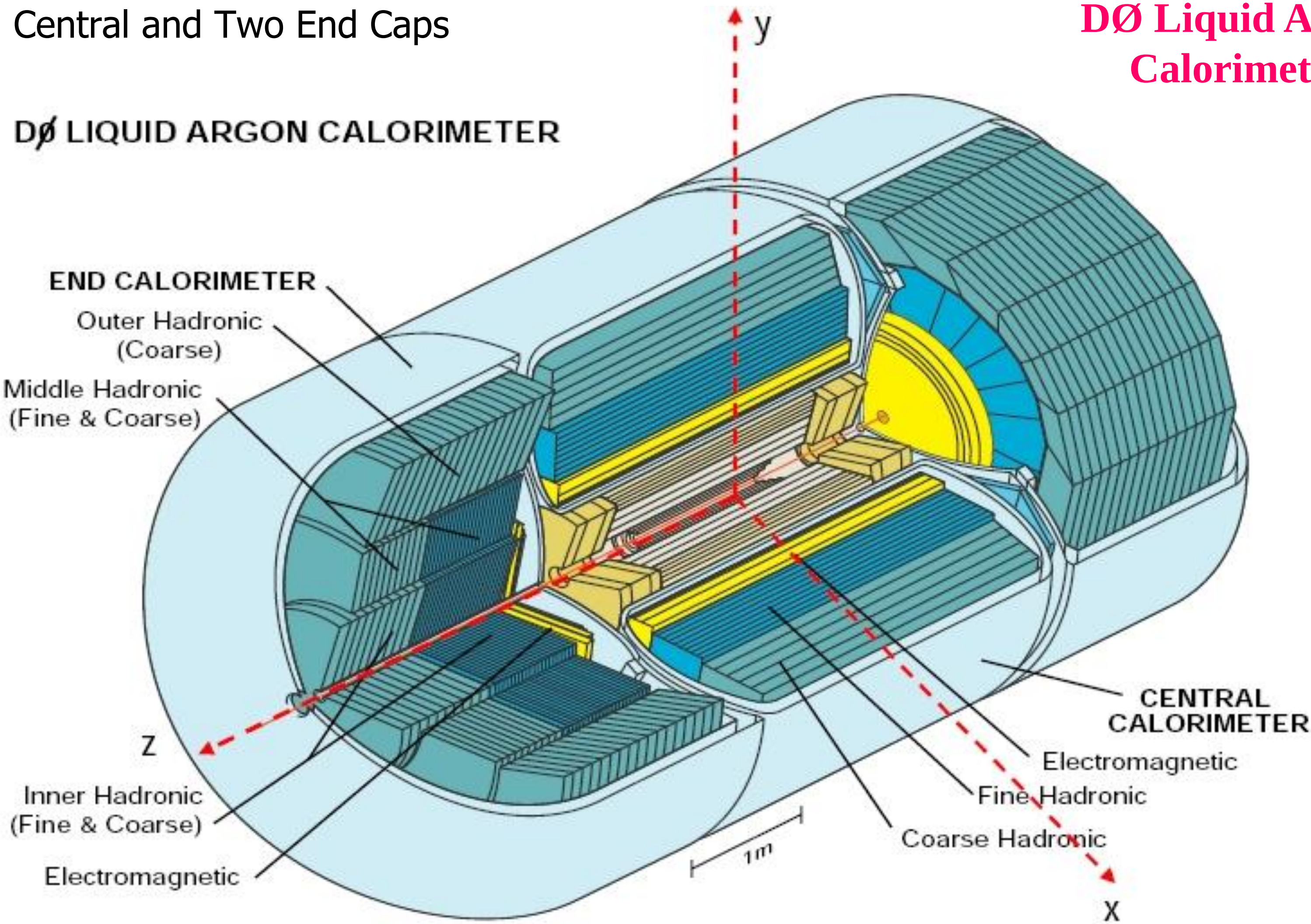
- Uranium-Liquid Argon
  - Absorber: uranium
  - Active: liquid argon
  - Compact, hermetic device
  - Uniform response
  - Stable calibration
  - ‘compensating’
  - Fully absorbing with relatively small diameter detector



Calorimeter: DØ

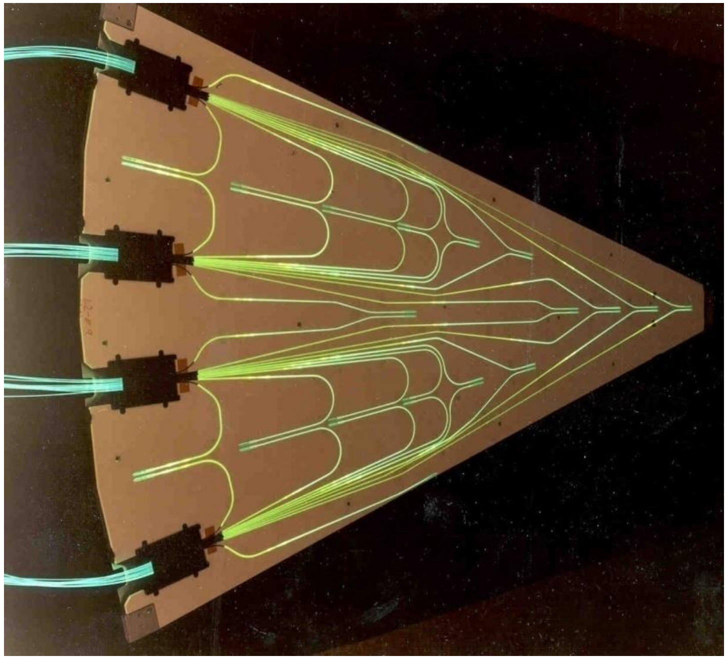
- Three separate calorimeters:
  - Central and Two End Caps

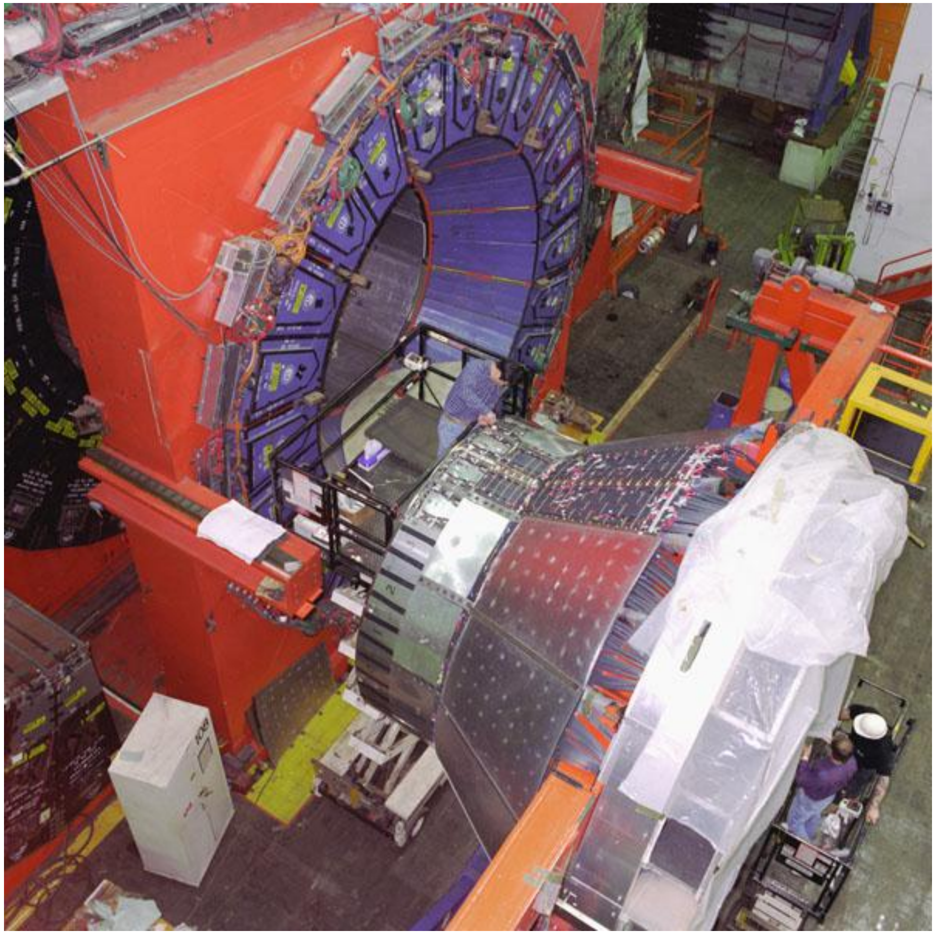
DØ Liquid Argon Calorimeter



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

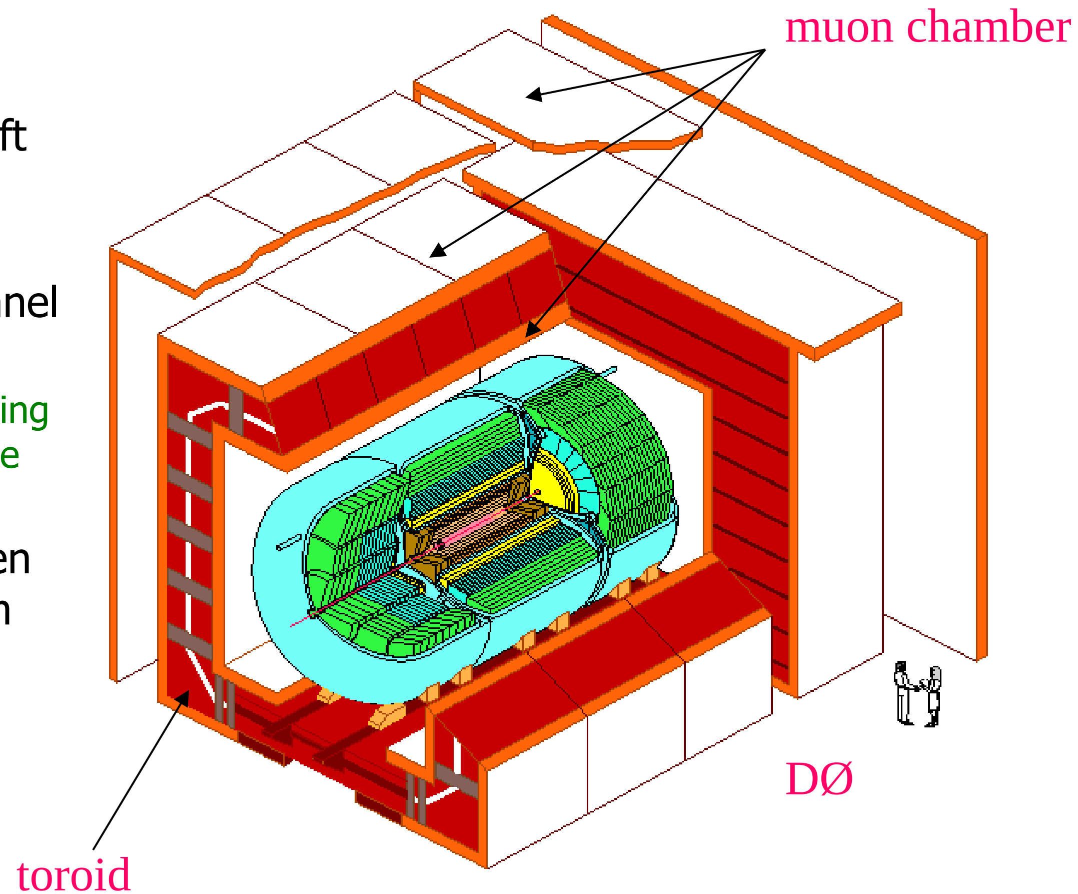




Muon Tracking System

- 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

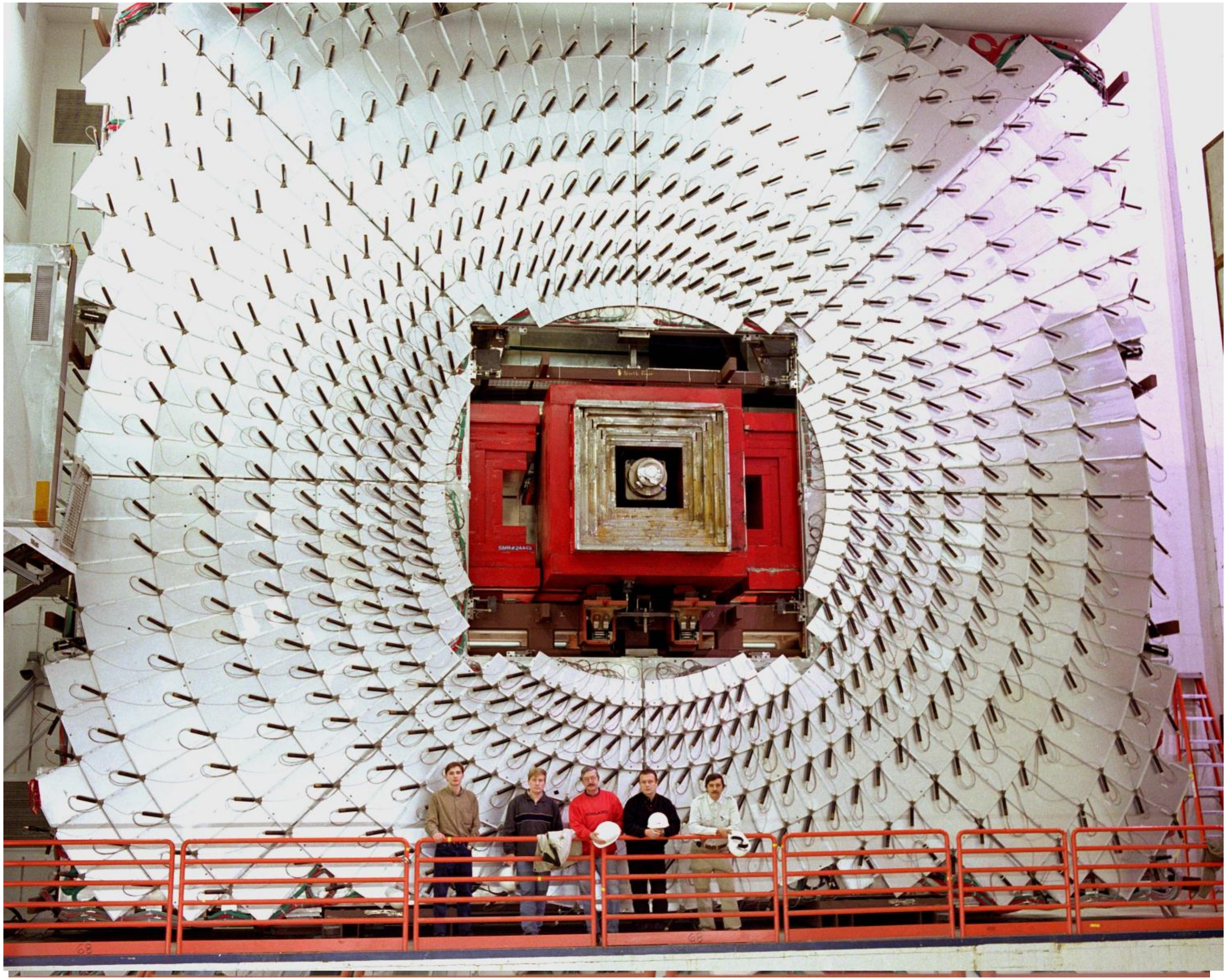
- DØ muon system:
  - Three layers of large area drift chambers
    - Both central and forward
  - Due to large area, large channel count
    - Reduce channel count by using large drifts with less accurate position resolution
  - Fe of toroidal magnet between layers 1 and 2 for momentum measurement
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



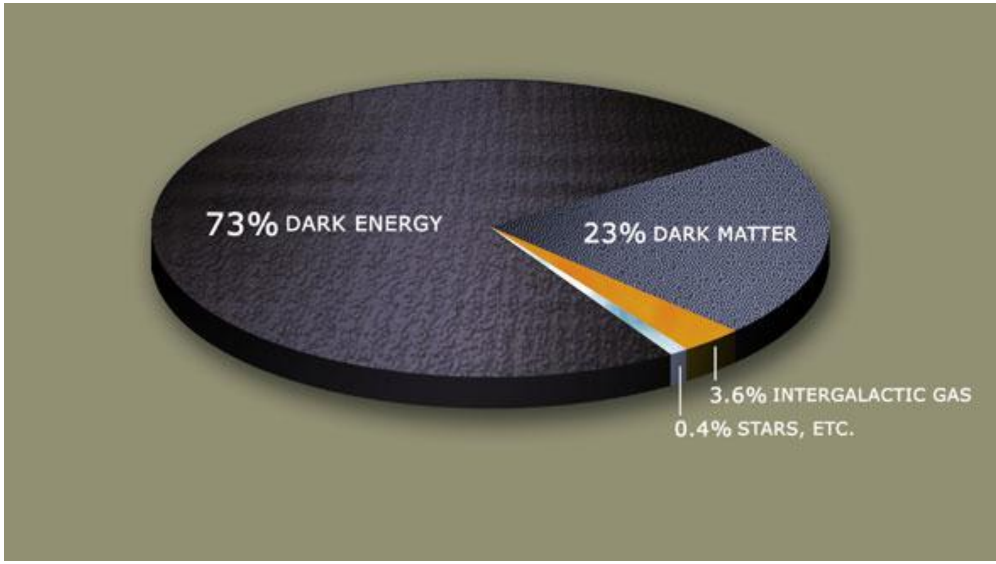
Muon Scintillator Pixel Counter: DØ

- 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



Dark Matter Detection

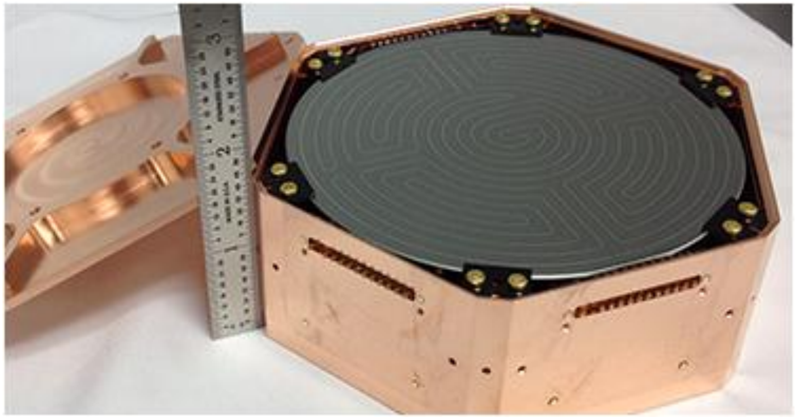


In the last ~20 years it has been realized that everything I told you in the first slides is only a small (4%) part of the story of the "stuff" in our universe.

- 73% is filled by dark energy (ask the astrophysics speaker)
- 23% is "dark matter" – stuff that feels gravity but not the strong or electromagnetic interaction
  - We have "pictures" of DM effects
  - If is a massive particle, moving slowly with respect to the galixy we should detect dark matter as weakly interacting "WIMP wind"
- We can use the same techniques I discussed previously to look for these rarely interacting particles with our detectors

Dark Matter Detectors

- Need lots of mass, high sensitivity
- Rejection of radioactive background



silicon and germanium detectors

COUPP Bubble chamber

Liquid argon and xenon detectors

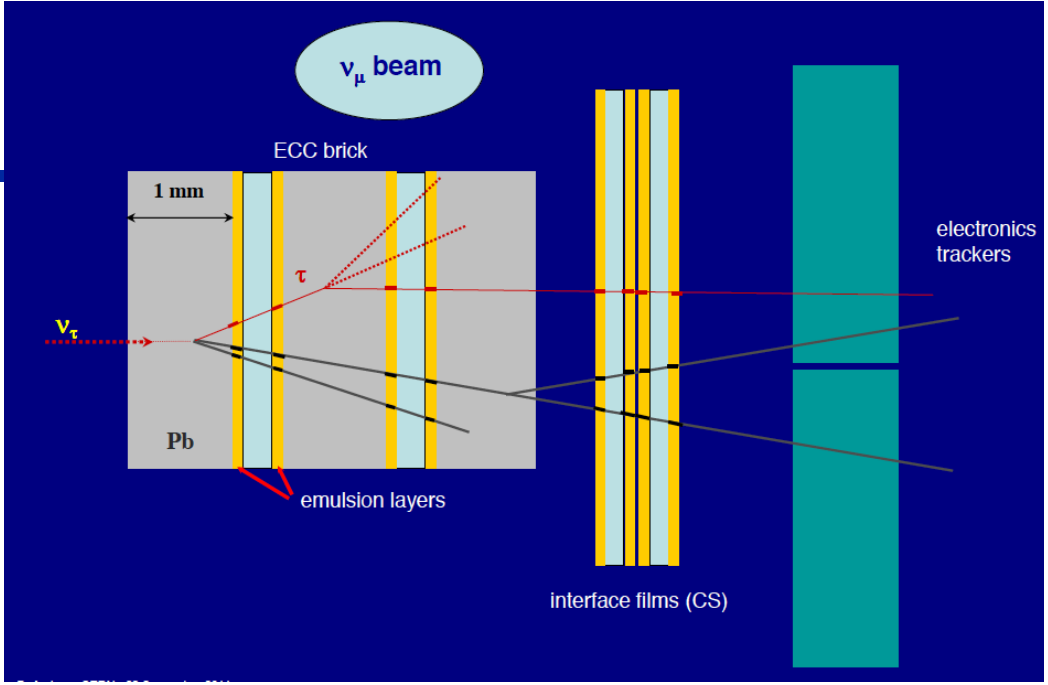
Some Concluding Remarks

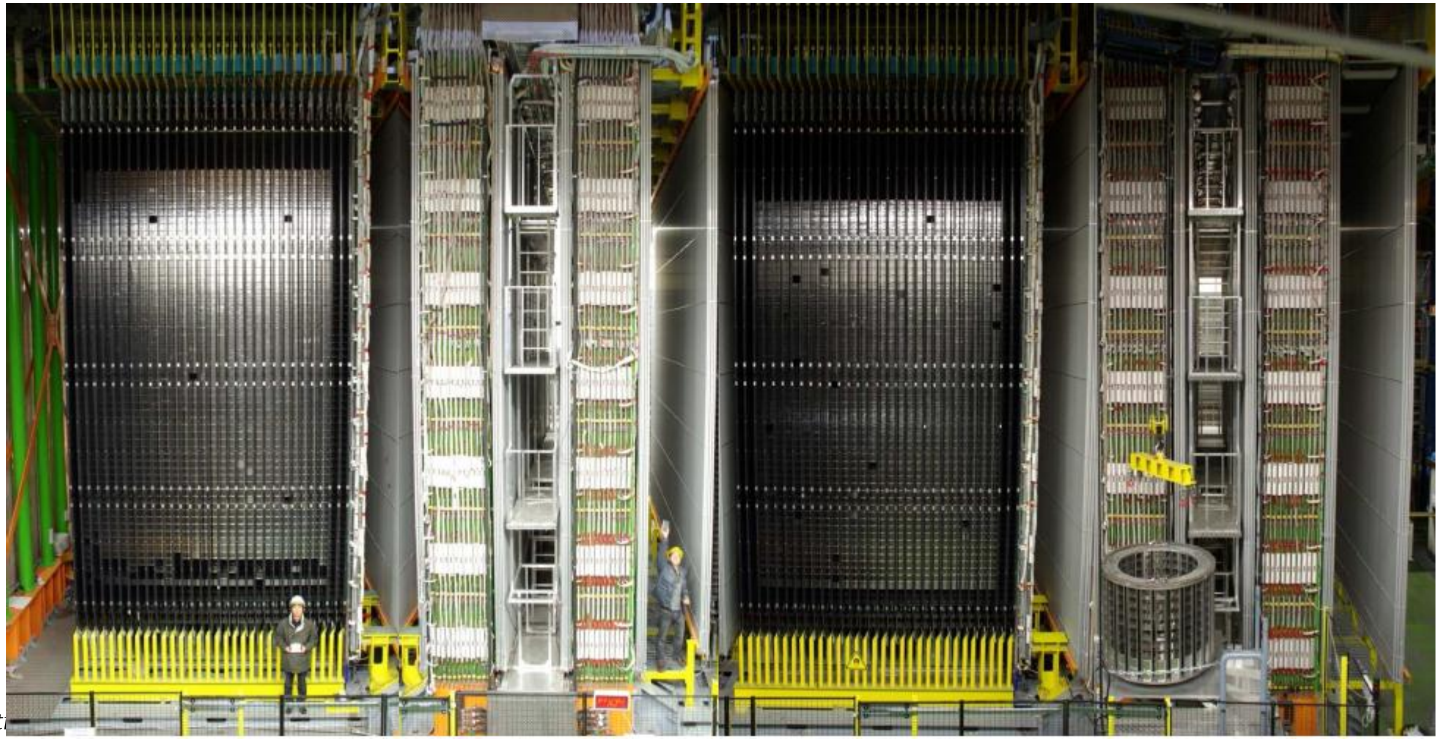
- Hope you got an idea of various detection techniques and what it takes to build a sub-detector and put it together in full system. Don’t be intimidated !

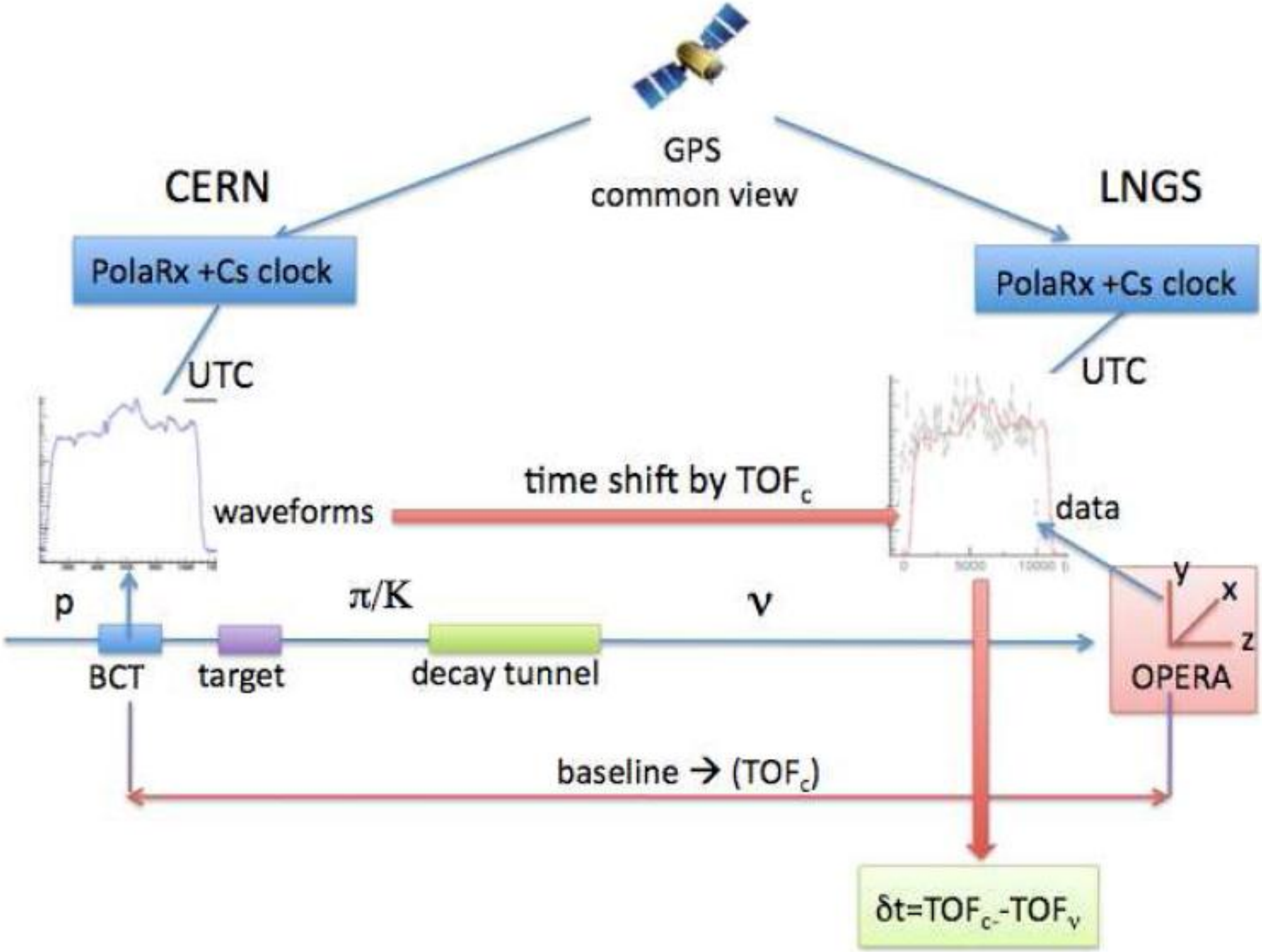
- “…without scientific progress no amount of achievement in other directions can insure our health, prosperity, and security as a nation in the modern world.”

Faster than Light?

- Last year an experiment claimed a measurement of ν velocity faster than light
- A good example of need to understand detector instrumentation



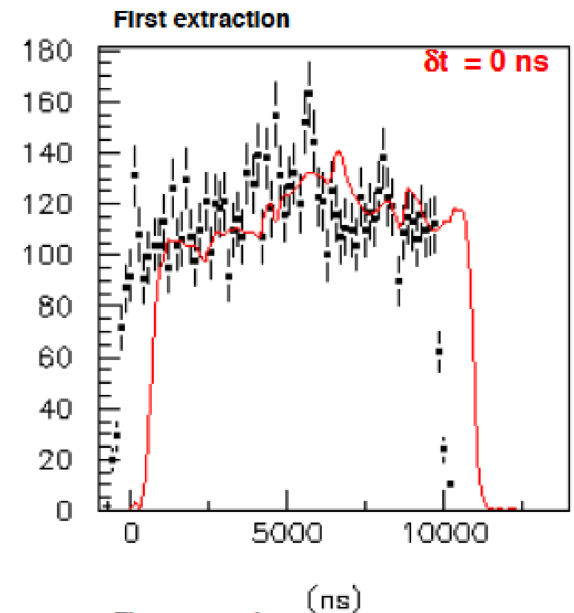


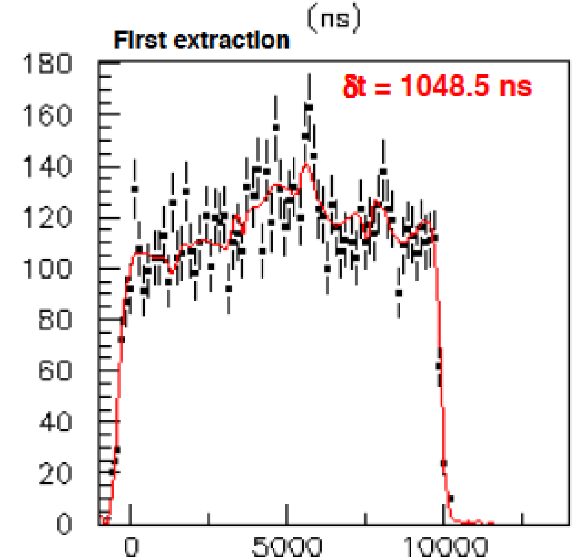


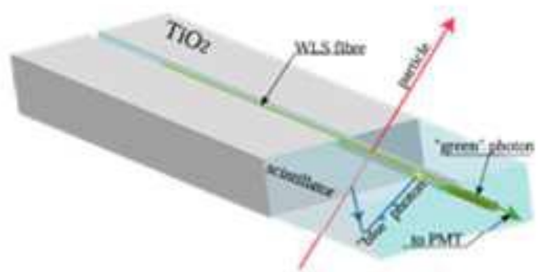
GPS
common view
CERN
LNGS
PolaRx +Cs clock
PolaRx +Cs clock
UTC
UTC
time shift by TOF_c
waveforms
data
p
π/K
ν
y
x
z
BCT
target
decay tunnel
OPERA
baseline → (TOF_c)
$\delta t = TOF_c - TOF_\nu$

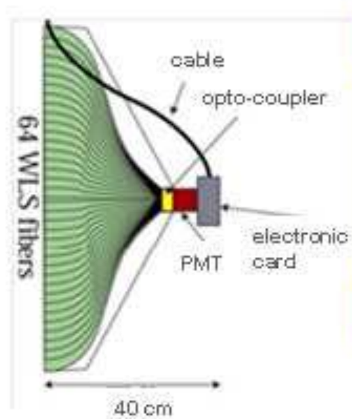
Faster than Light?

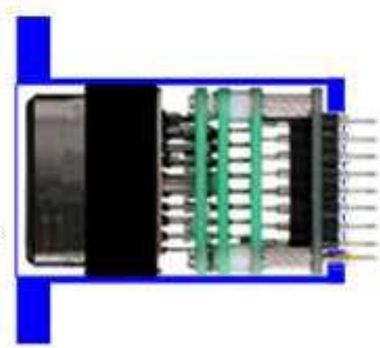
- Need to know
  - Response of the scintillator
  - Delay from photo-cathode to FPGA input: 50.2 ± 2.3 ns
  - Circuit delays
  - Baseline of the experiment
  - Beam signal induced on pickup coil
- Put it all together to shift time distribution





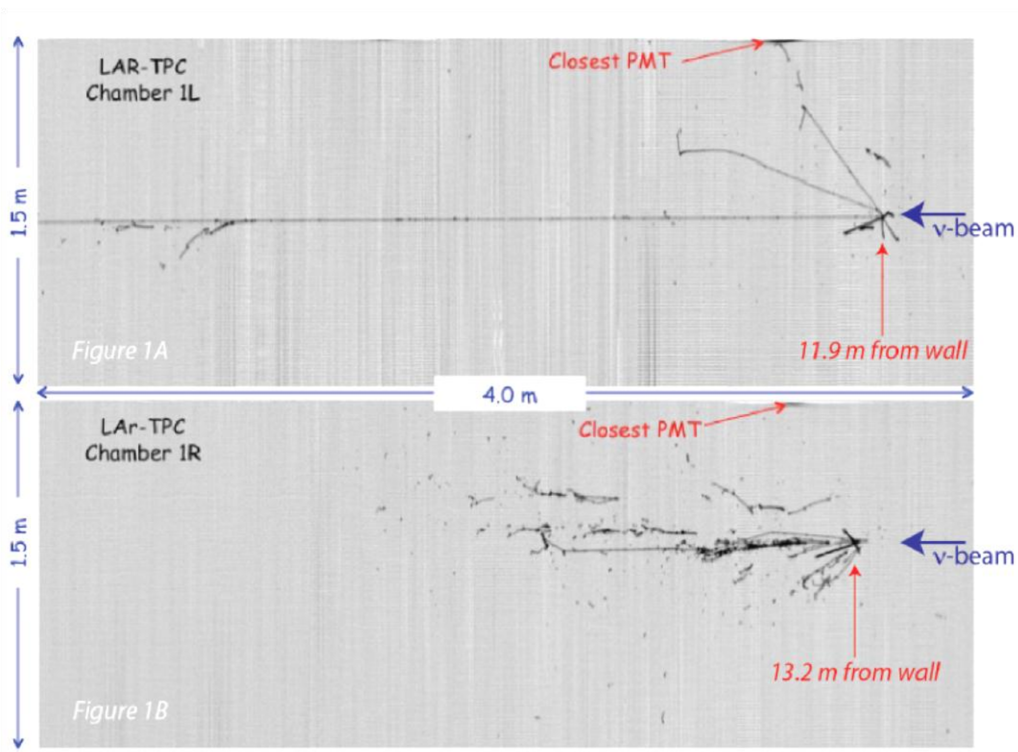


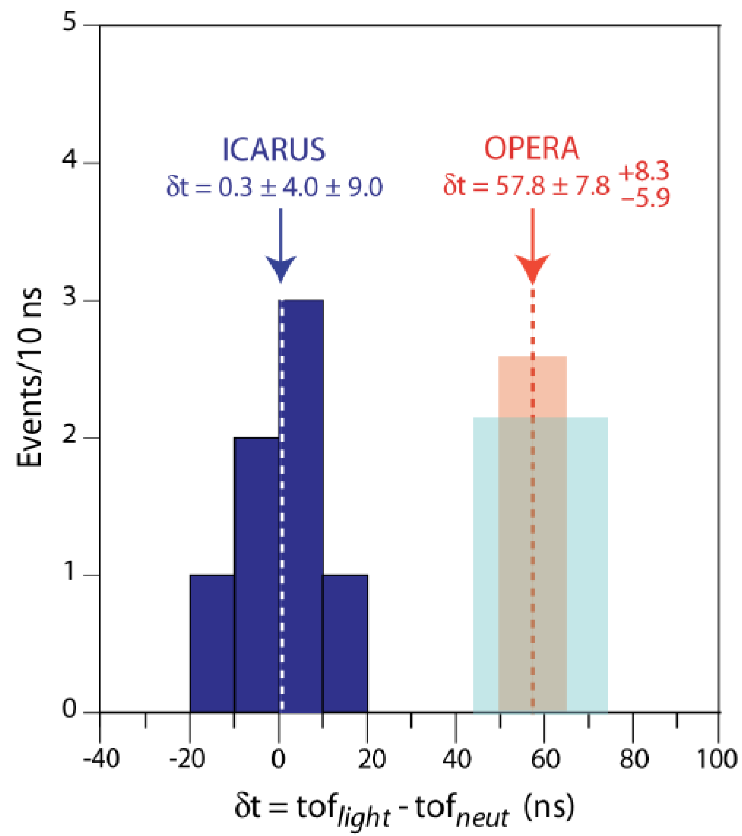




Not so Fast…

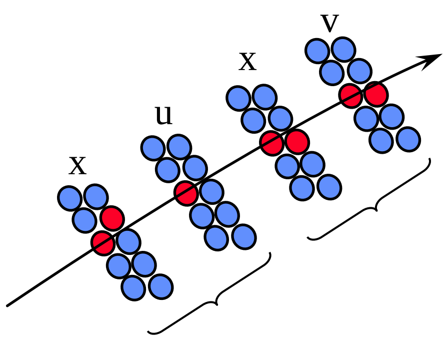
- In 2013 Opera admitted to two errors in their setup
  - Loose optical cable which may have caused a delay in the timing signal
  - Misadjusted oscillator
- Last week another experiment (ICARUS) located in the same laboratory reported on their measurement with a liquid argon TPC
  - Results consistent with v=c

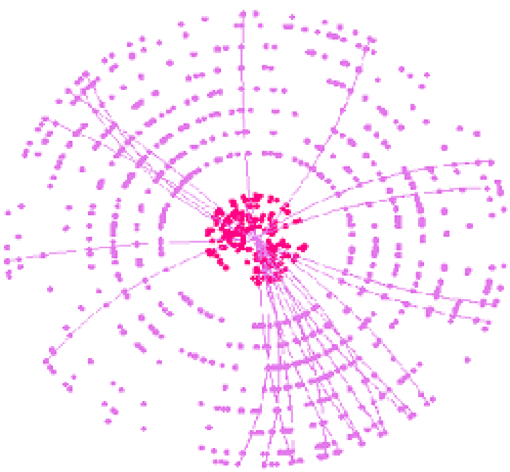


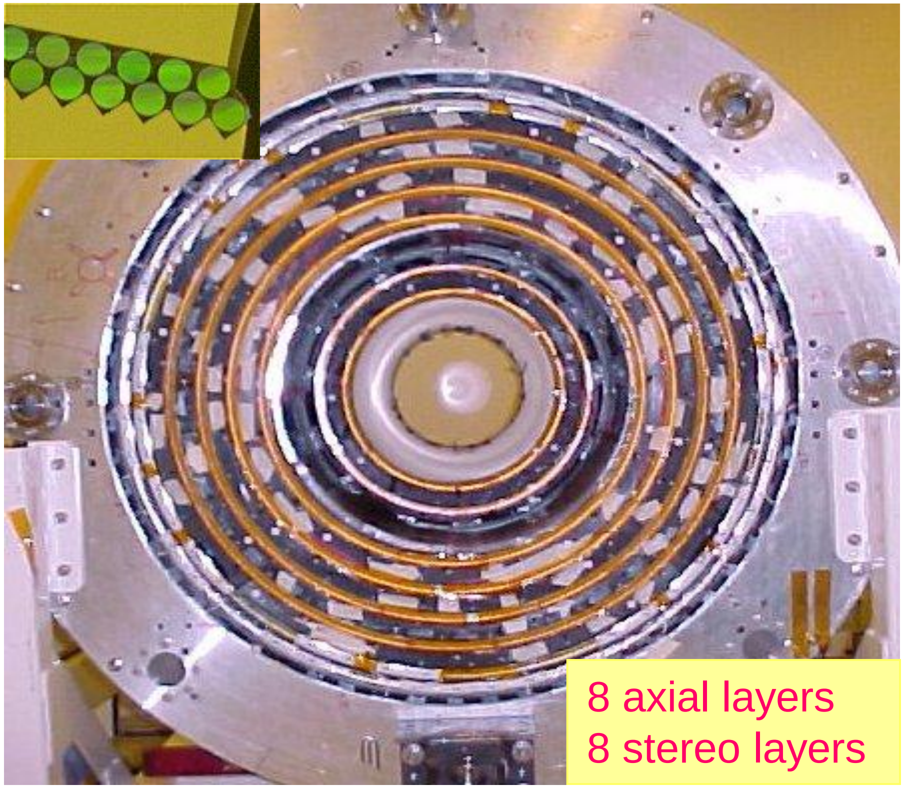


Outer Tracking System

- DØ: scintillating fiber tracker
  - Eight layers of scintillating fiber ribbon doublets (x-u or x-v)
  - 77,000 830 μm fibers



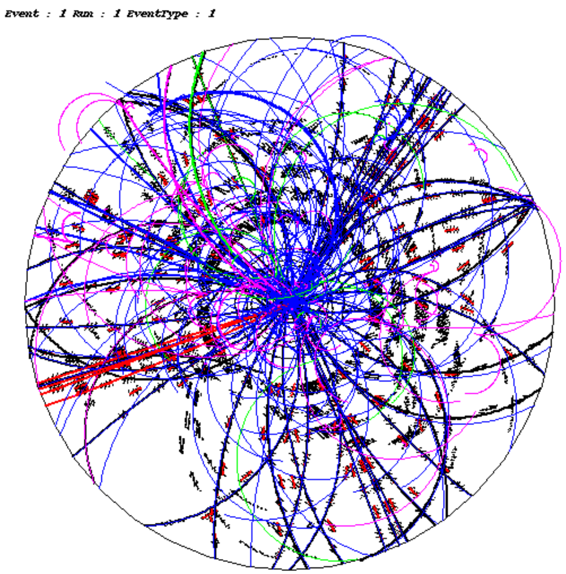




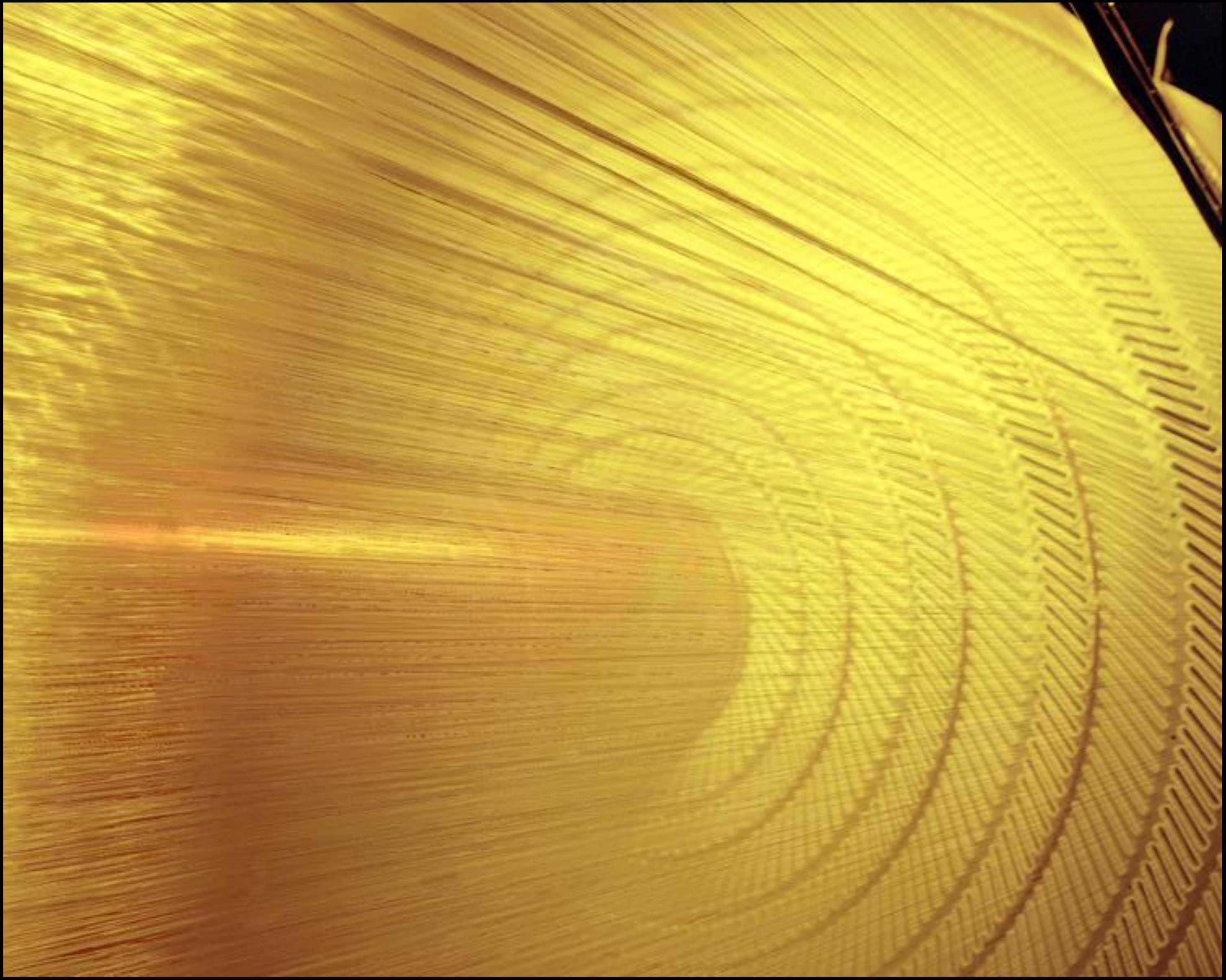
- Fiber light guide to electronics readout
  - Modest light yield
- Fine granularity
- Fast readout

Outer Tracking System

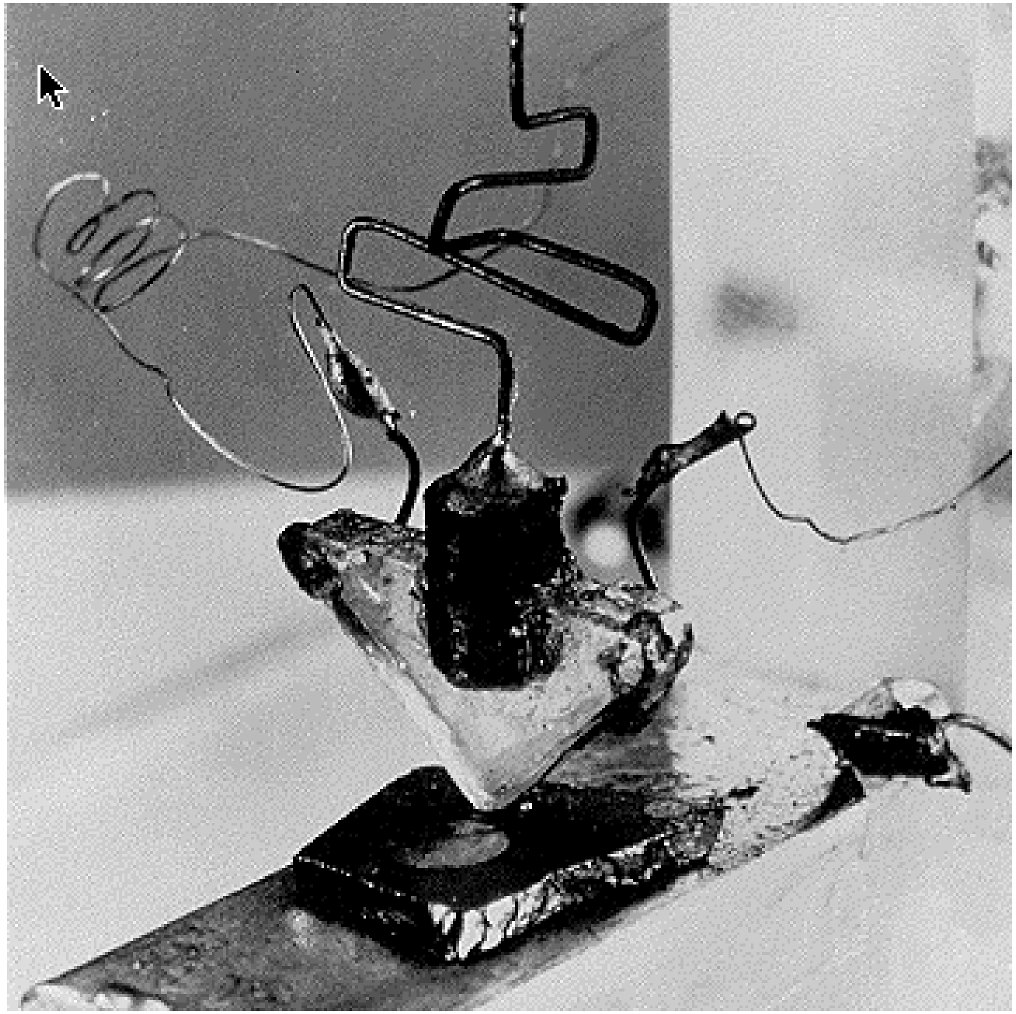
- CDF: Drift chamber
  - Eight planes of axial and stereo sense wires



CDF Central Outer Tracker



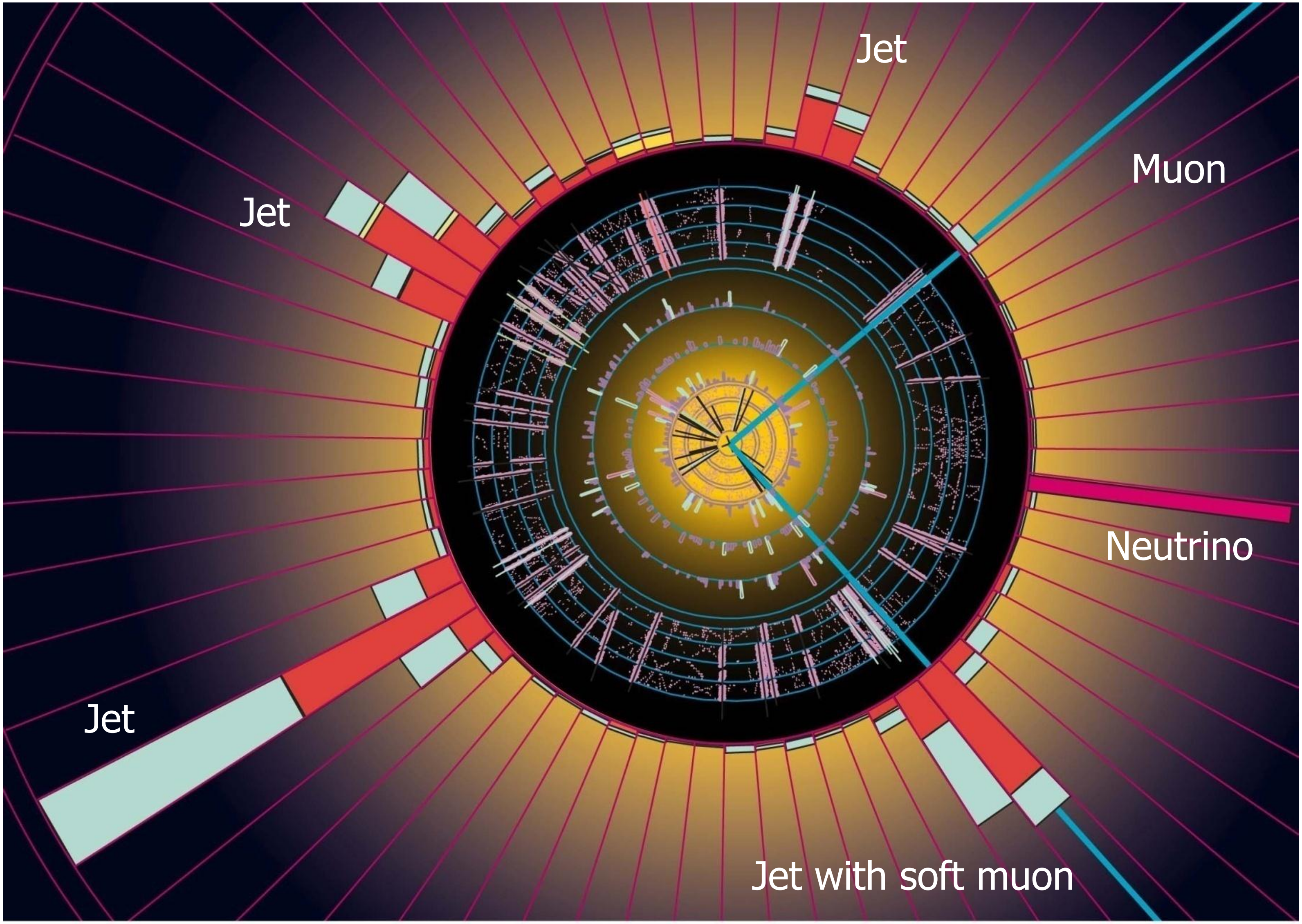
First Transistor



- Discovered doing pure fundamental research !
- Do you think you could have built this in your basement ?

reach for the stars

How about the Top Quark ?



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