Particle Detectors

(Horst Wahl, Quarknet lecture, June 2002)

Outline:

- particle physics experiments – introduction
- interactions of particles with matter
- detectors
- triggers
- D0 detector
- CMS detector

- Webpages of interest
  - http://www.fnal.gov (Fermilab homepage)
  - http://www.hep.fsu.edu/~wahl/Quarknet (has links to many particle physics sites)
  - http://www.fnal.gov/pub/tour.html (Fermilab particle physics tour)
  - http://ParticleAdventure.org/ (Lawrence Berkeley Lab.)
  - http://www.cern.ch (CERN -- European Laboratory for Particle Physics)

Particle physics experiments

- Particle physics experiments:
  - collide particles to
    - produce new particles
    - reveal their internal structure and laws of their interactions by observing regularities, measuring cross sections,...
  - colliding particles need to have high energy
    - to make objects of large mass
    - to resolve structure at small distances
  - to study structure of small objects:
    - need probe with short wavelength: use particles with high momentum to get short wavelength
    - remember de Broglie wavelength of a particle $\lambda = h/p$
  - in particle physics, mass-energy equivalence plays an important role; in collisions, kinetic energy converted into mass energy;
    - relation between kinetic energy K, total energy E and momentum p :

$$E = K + mc^2 = \sqrt{(pc)^2 + (mc^2)c^2}$$

How to do a particle physics experiment

- Outline of experiment:
  - get particles (e.g. protons, antiprotons,…)
  - accelerate them
  - throw them against each other
  - observe and record what happens
  - analyse and interpret the data
- ingredients needed:
  - particle source
  - accelerator and aiming device
  - detector
  - trigger (decide what to record)
  - recording device
  - many people to:
    - design, build, test, operate accelerator
    - design, build, test, calibrate, operate, and understand detector
    - analyze data
  - lots of money to pay for all of this

About Units

- Energy - electron-volt
  - 1 electron-volt = kinetic energy of an electron when moving through potential difference of 1 Volt;
    - 1 eV = 1.6×10^{-19} Joules = 2.1×10^{-6} W•s
    - 1 kW•hr = 3.6×10^{6} Joules = 2.25×10^{25} eV

- mass - eV/c^2
    - 1 eV/c^2 = 1.78×10^{-36} kg
    - electron mass = 0.511 MeV/c^2
    - proton mass = 938 MeV/c^2
    - professor's mass (80 kg) $\approx$ 4.5×10^{37} eV/c^2

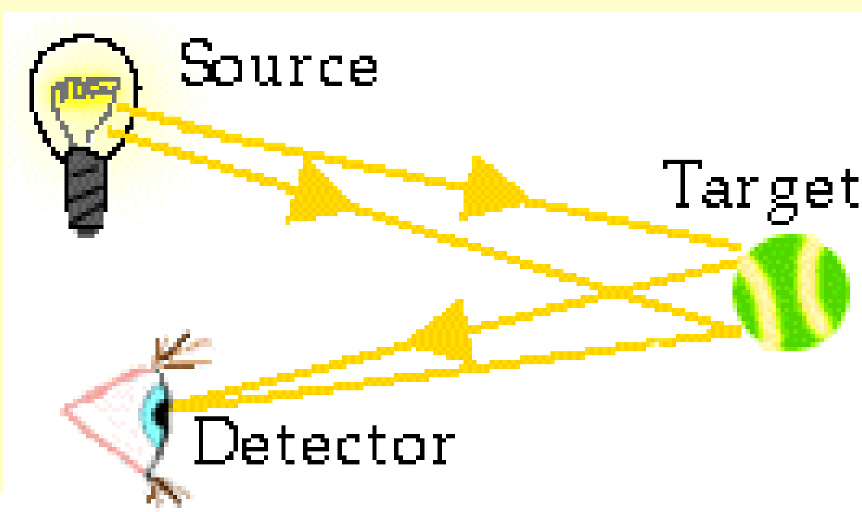
- momentum - eV/c:
    - 1 eV/c = 5.3×10^{-28} kg m/s
    - momentum of baseball at 80 mi/hr $\approx$ 5.29 kgm/s $\approx$ 9.9×10^{27} eV/c

WHY CAN'T WE SEE ATOMS?

- "seeing an object"
  - = detecting light that has been reflected off the object's surface
- light = electromagnetic wave;
- "visible light"= those electromagnetic waves that our eyes can detect
- "wavelength" of e.m. wave (distance between two successive crests) determines "color" of light
- wave hardly influenced by object if size of object is much smaller than wavelength
- wavelength of visible light:
  between 4×10^{-7} m (violet) and 7×10^{-7} m (red);
- diameter of atoms: 10^{-10} m
- generalize meaning of seeing:
  - seeing is to detect effect due to the presence of an object
- quantum theory $\Rightarrow$ "particle waves",
  with wavelength $\propto 1/(m\ v)$
- use accelerated (charged) particles as probe, can "tune" wavelength by choosing mass m and changing velocity v
- this method is used in electron microscope, as well as in "scattering experiments" in nuclear and particle physics

Detectors

- Detectors
  - use characteristic effects from interaction of particle with matter to detect, identify and/or measure properties of particle; has "transducer" to translate direct effect into observable/recordable (e.g. electrical) signal
  - example: our eye is a photon detector; (photons = light "quanta" = packets of light)
  - "seeing" is performing a photon scattering experiment:
    - light source provides photons
    - photons hit object of our interest -- some absorbed, some scattered, reflected
    - some of scattered/reflected photons make it into eye; focused onto retina;
    - photons detected by sensors in retina (photoreceptors -- rods and cones)
    - transduced into electrical signal (nerve pulse)
    - amplified when needed
    - transmitted to brain for processing and interpretation



Particle interactions with matter

- electromagnetic interactions:
  - excitation
  - ionization
  - Cherenkov radiation
  - transmission radiation
  - bremsstrahlung
  - photoelectric effect
  - Compton scattering
  - pair production
- strong interactions:
  - secondary hadron production,
  - hadronic showers
- detectors usually have some amplification mechanism

Interaction of particles with matter

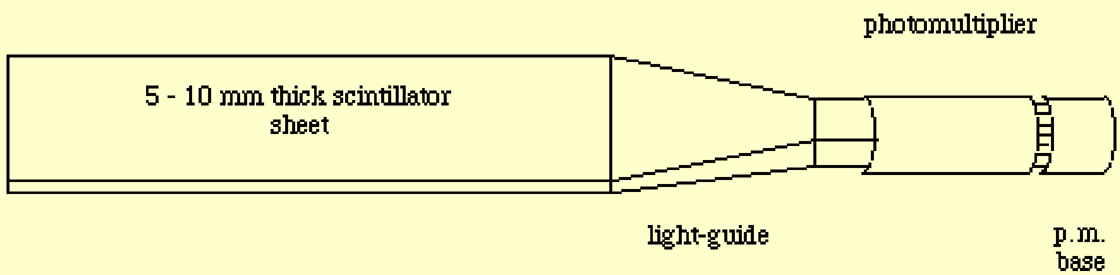
- when passing through matter,
  - particles interact with the electrons and/or nuclei of the medium;
  - this interaction can be weak, electromagnetic or strong interaction, depending on the kind of particle; its effects can be used to detect the particles;
- possible interactions and effects in passage of particles through matter:
  - **excitation** of atoms or molecules (e.m. int.):
    - charged particles can excite an atom or molecule (i.e. lift electron to higher energy state);
    - subsequent de-excitation leads to emission of photons;
  - **ionization** (e.m. int.)
    - electrons liberated from atom or molecule, can be collected, and charge is detected
  - **Cherenkov radiation** (e.m. int.):
    - if particle's speed is higher than speed of light in the medium, e.m. radiation is emitted -- "Cherenkov light" or Cherenkov radiation, which can be detected;
    - amount of light and angle of emission depend on particle velocity;

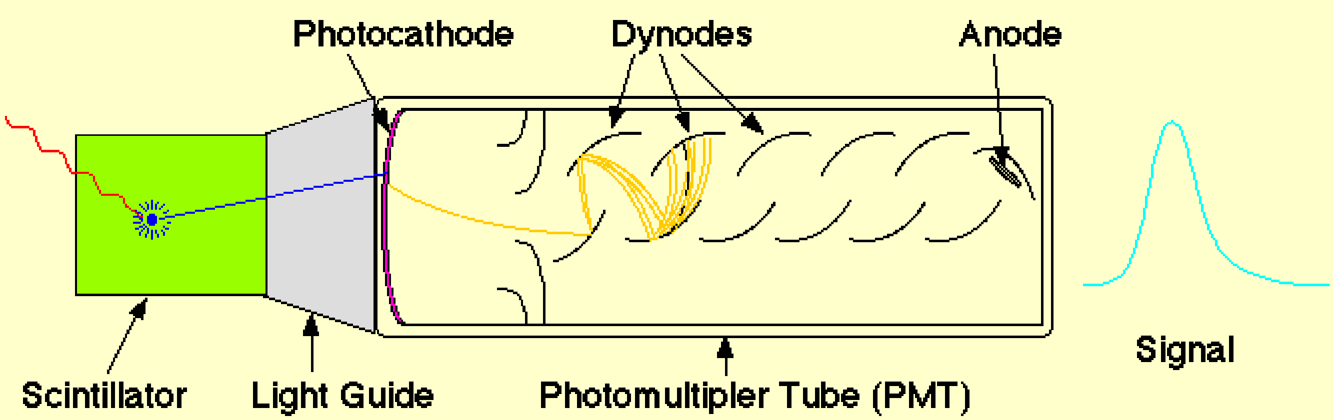
Interaction of particles with matter, cont'd

- **transition radiation** (e.m. int.):
  - when a charged particle crosses the boundary between two media with different speeds of light (different "refractive index"), e.m. radiation is emitted -- "transition radiation"
  - amount of radiation grows with (energy/mass);
- **bremsstrahlung** (= braking radiation) (e.m. int.):
  - when charged particle's velocity changes, e.m. radiation is emitted;
  - due to interaction with nuclei, particles deflected and slowed down emit bremsstrahlung;
  - effect stronger, the bigger (energy/mass) ⇒ electrons with high energy most strongly affected;
- **pair production** (e.m. int.):
  - by interaction with e.m. field of nucleus, photons can convert into electron-positron pairs
- **electromagnetic shower** (e.m. int.):
  - high energy electrons and photons can cause "electromagnetic shower" by successive bremsstrahlung and pair production
- **hadron production** (strong int.):
  - strongly interacting particles can produce new particles by strong interaction, which in turn can produce particles,... "hadronic shower"

Scintillation counter

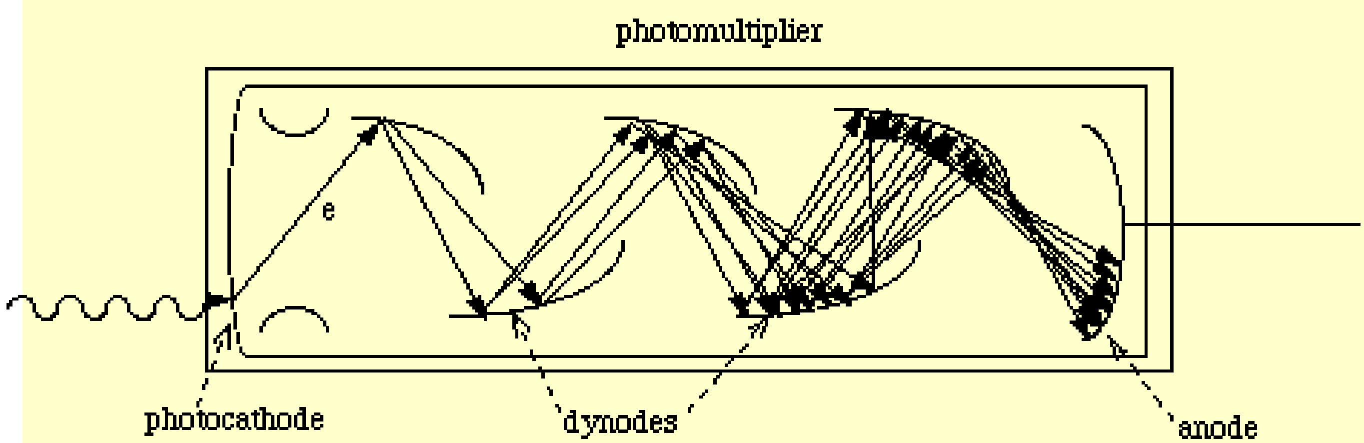
- Scintillation counter:
  - energy liberated in de-excitation and capture of ionization electrons emitted as light - “scintillation light”
  - light channeled to photomultiplier in light guide (e.g. piece of lucite or optical fibers);
  - scintillating materials: certain crystals (e.g. NaI), transparent plastics with doping (fluors and wavelength shifters)





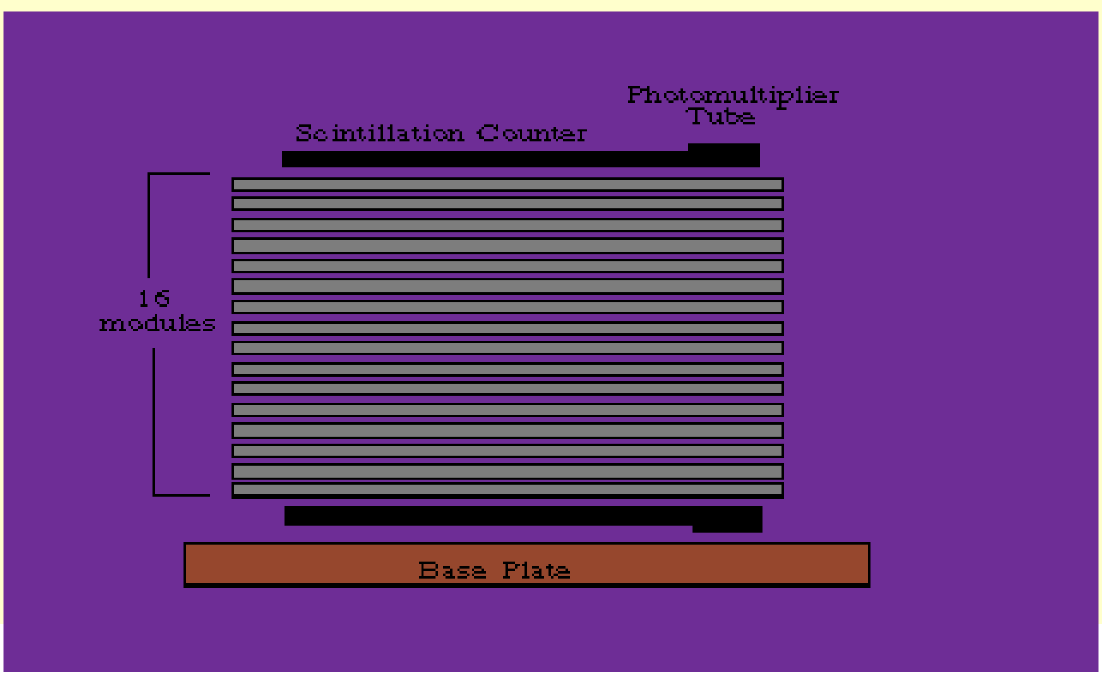
Photomultiplier

- photomultiplier tubes convert small light signal (even single photon) into detectable charge (current pulse)
- photons liberate electrons from photocathode,
- electrons “multiplied” in several (6 to 14) stages by ionization and acceleration in high electric field between “dynodes”, with gain $\approx$ 10^4 to 10^{10}
- photocathode and dynodes made from material with low ionization energy;
- photocathodes: thin layer of semiconductor made e.g. from Sb (antimony) plus one or more alkali metals, deposited on glass or quartz;
- dynodes: alkali or alkaline earth metal oxide deposited on metal, e.g. BeO on Cu (gives high secondary emission);

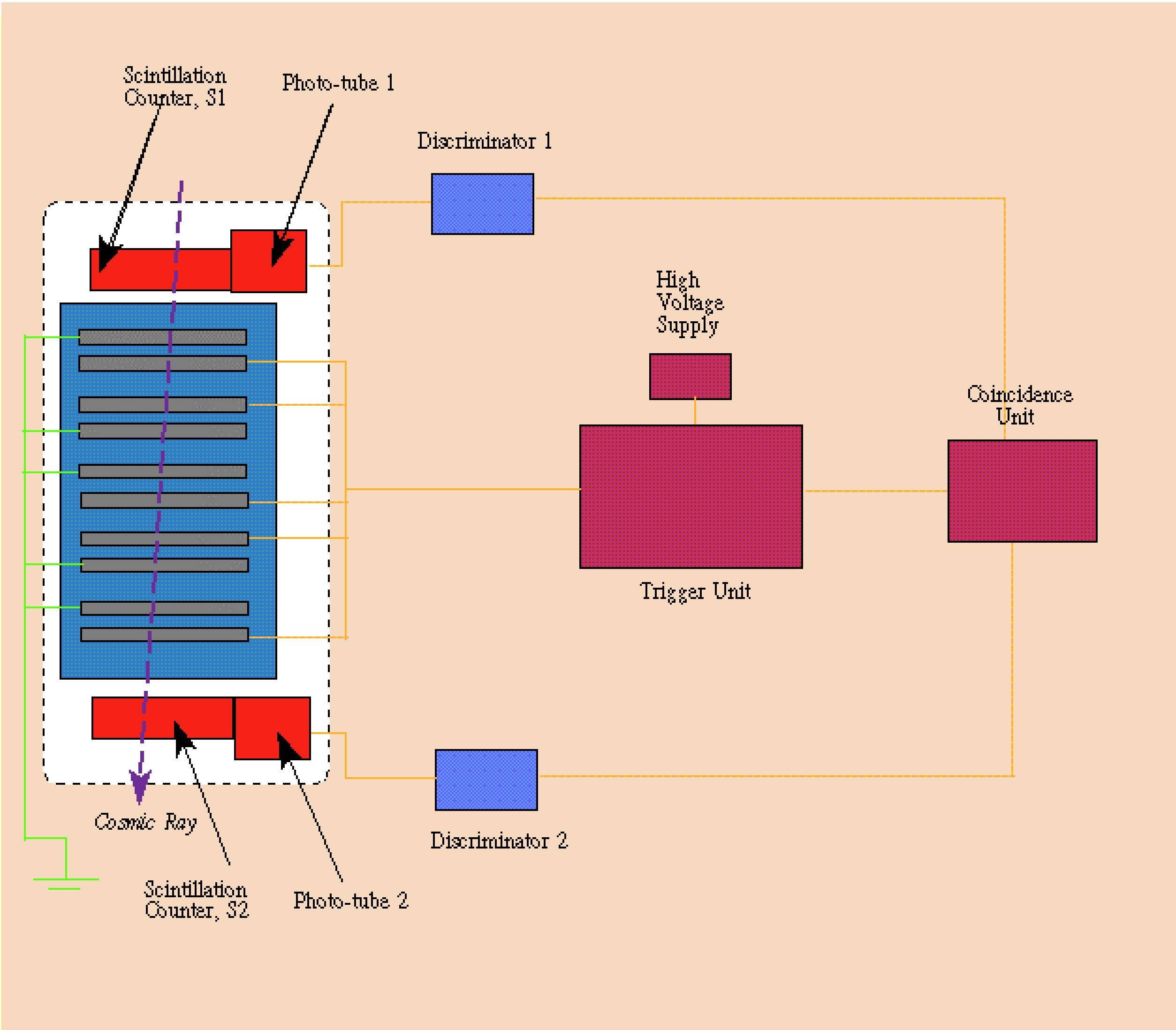


Spark chamber

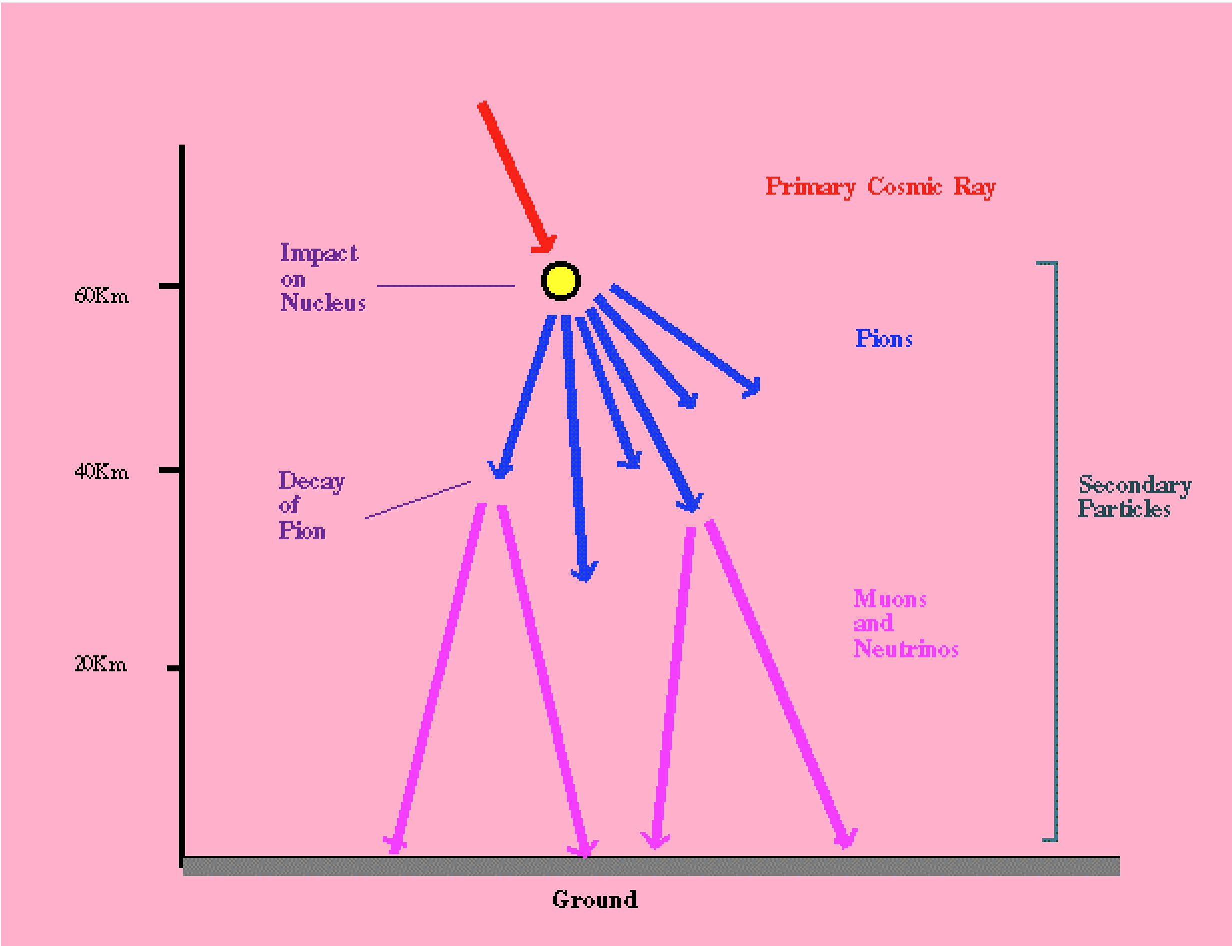
- gas volume with metal plates (electrodes); filled with gas (noble gas, e.g. argon)
- charged particle in gas ⇒ ionization ⇒ electrons liberated; ⇒ string of electron - ion pairs along particle path
- passage of particle through "trigger counters" (scintillation counters) triggers HV
- HV between electrodes ⇒ strong electric field;
- electrons accelerated in electric field ⇒ can liberate other electrons by ionization which in turn are accelerated and ionize ⇒ "avalanche of electrons", eventually formation of plasma between electrodes along particle path;
- gas conductive along particle path ⇒ electric breakdown ⇒ discharge ⇒ spark
- HV turned off to avoid discharge in whole gas volume

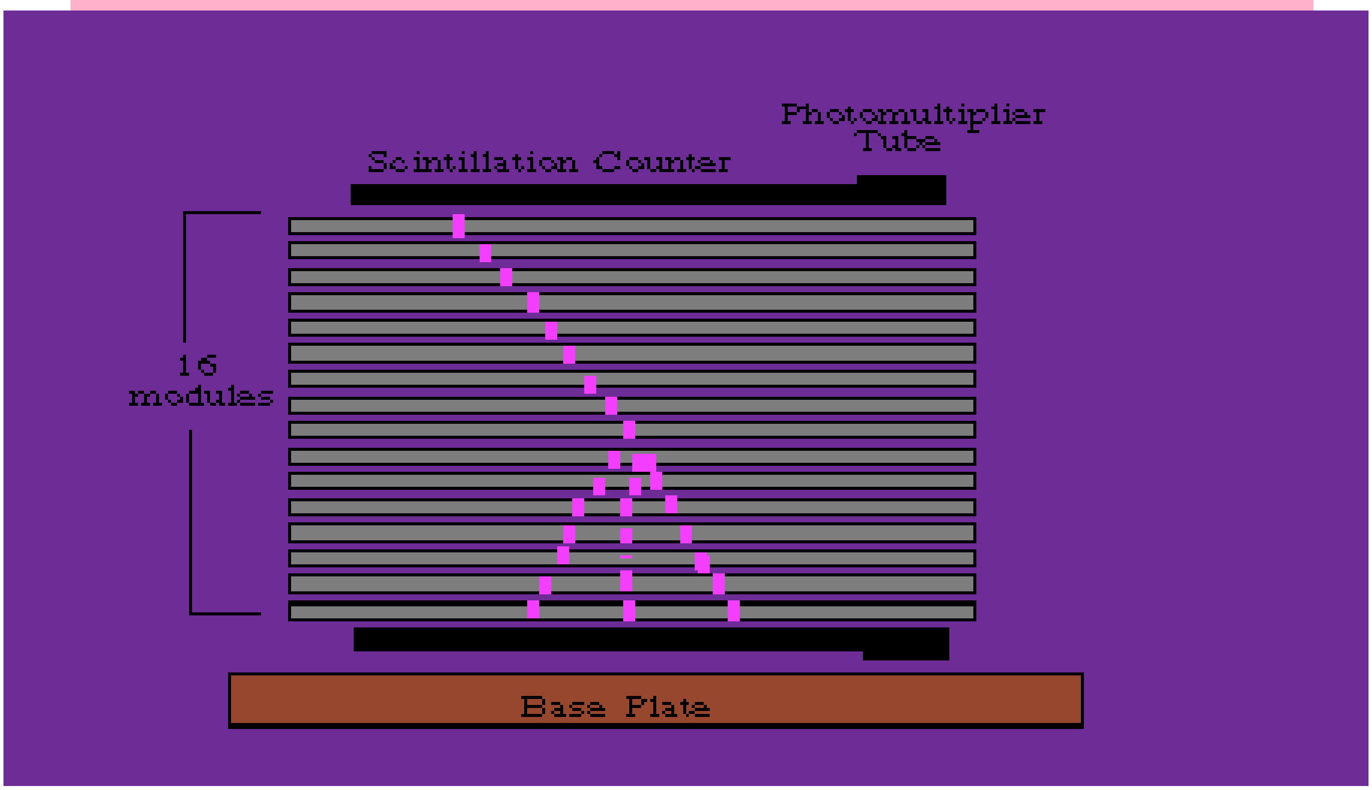


Parts of sparkchamber setup



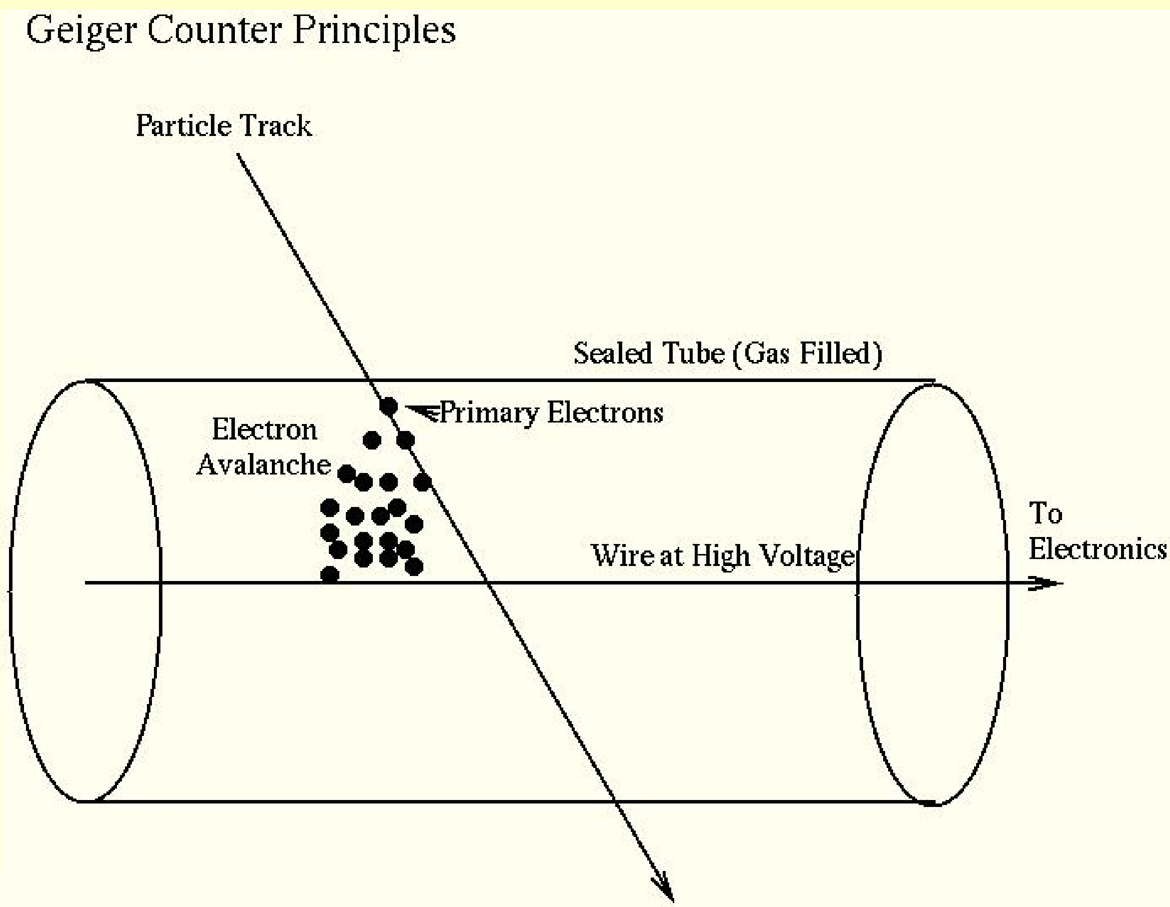
What we see in spark chamber





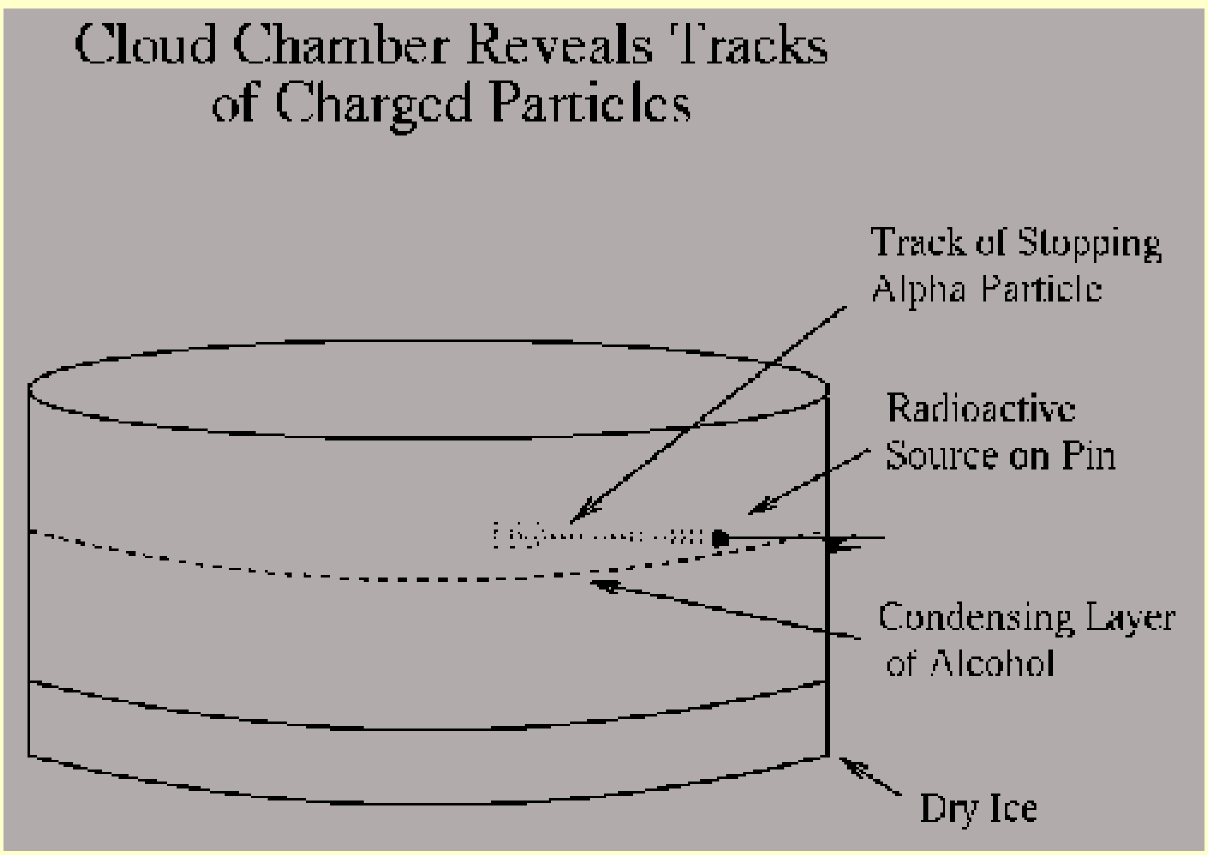
Geiger-Müller counter:

- metallic tube with thin wire in center, filled with gas, HV between wall (-, “cathode”) and central wire (+,”anode”); ⇒ strong electric field near wire;
- charged particle in gas ⇒ ionization ⇒ electrons liberated;
- electrons accelerated in electric field ⇒ liberate other electrons by ionization which in turn are accelerated and ionize ⇒ “avalanche of electrons”; avalanche becomes so big that all of gas ionized ⇒ plasma formation ⇒ discharge
- gas is usually noble gas (e.g. argon), with some additives e.g. carbon dioxide, methane, isobutane,..) as “quenchers”;



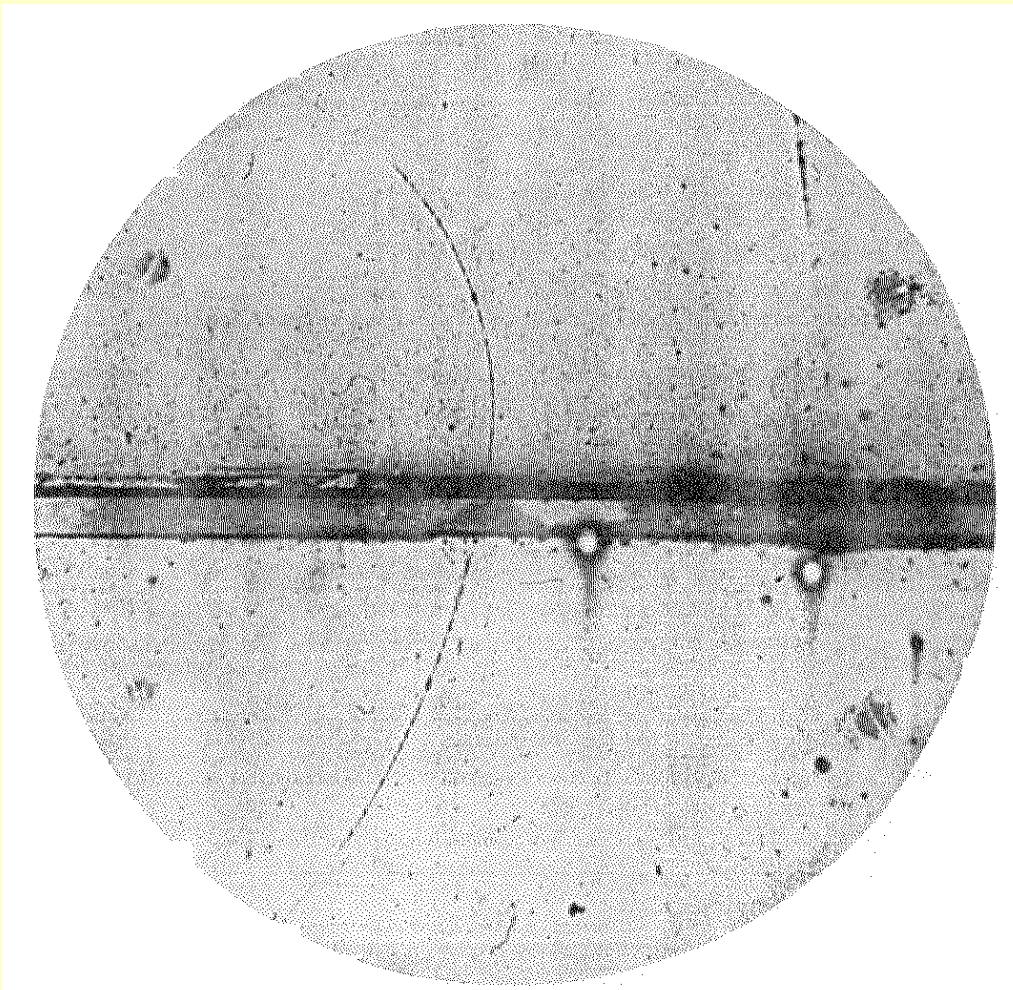
Cloud chamber

- Container filled with gas (e.g. air), plus vapor close to its dew point (saturated)
- Passage of charged particle ⇒ ionization;
- Ions form seeds for condensation ⇒ condensation takes place along path of particle ⇒ path of particle becomes visible as chain of droplets



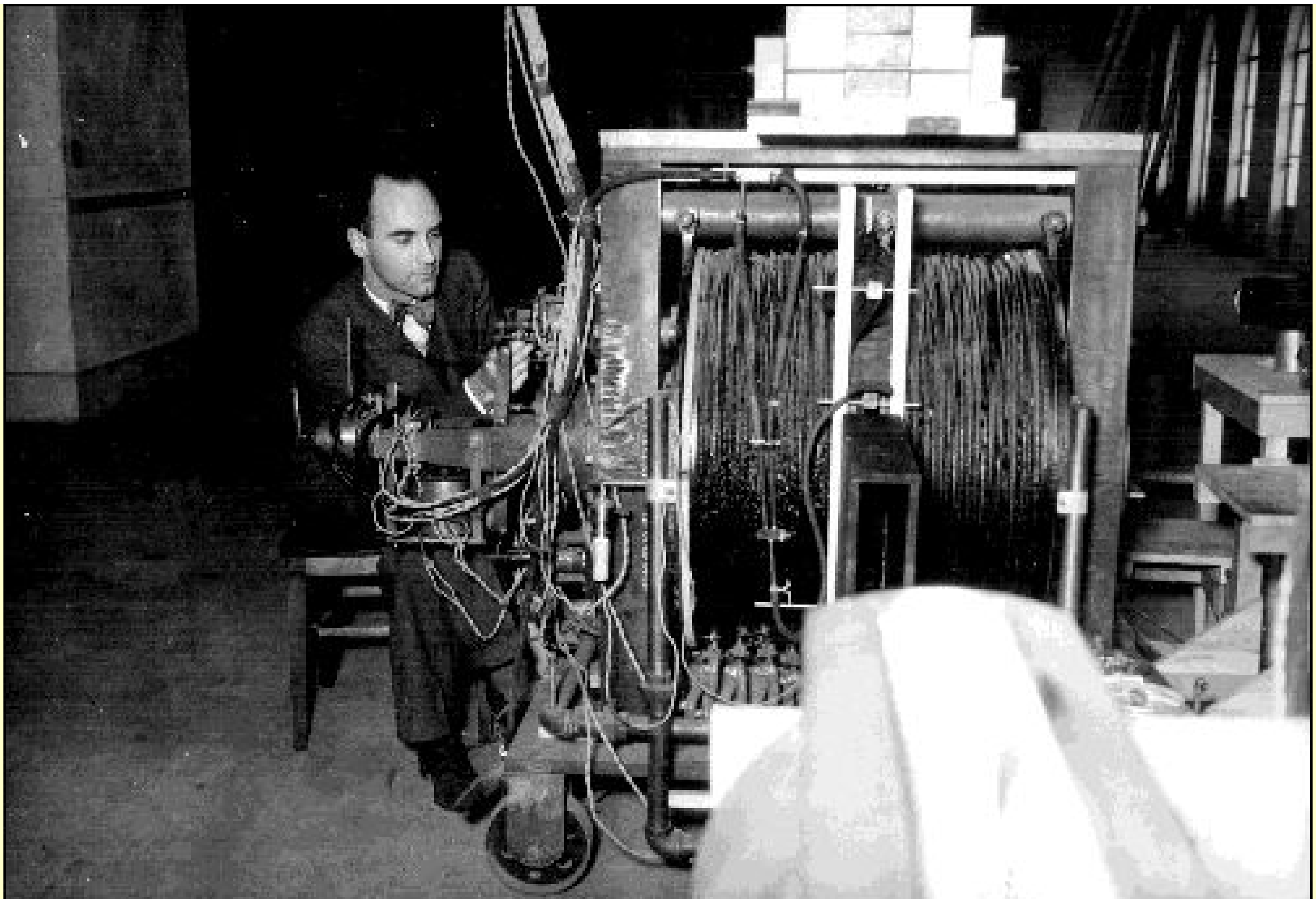
Positron discovery

- Positron (anti-electron)
  - predicted by Dirac (1928) -- needed for relativistic quantum mechanics
  - existence of antiparticles doubled the number of known particles!!!



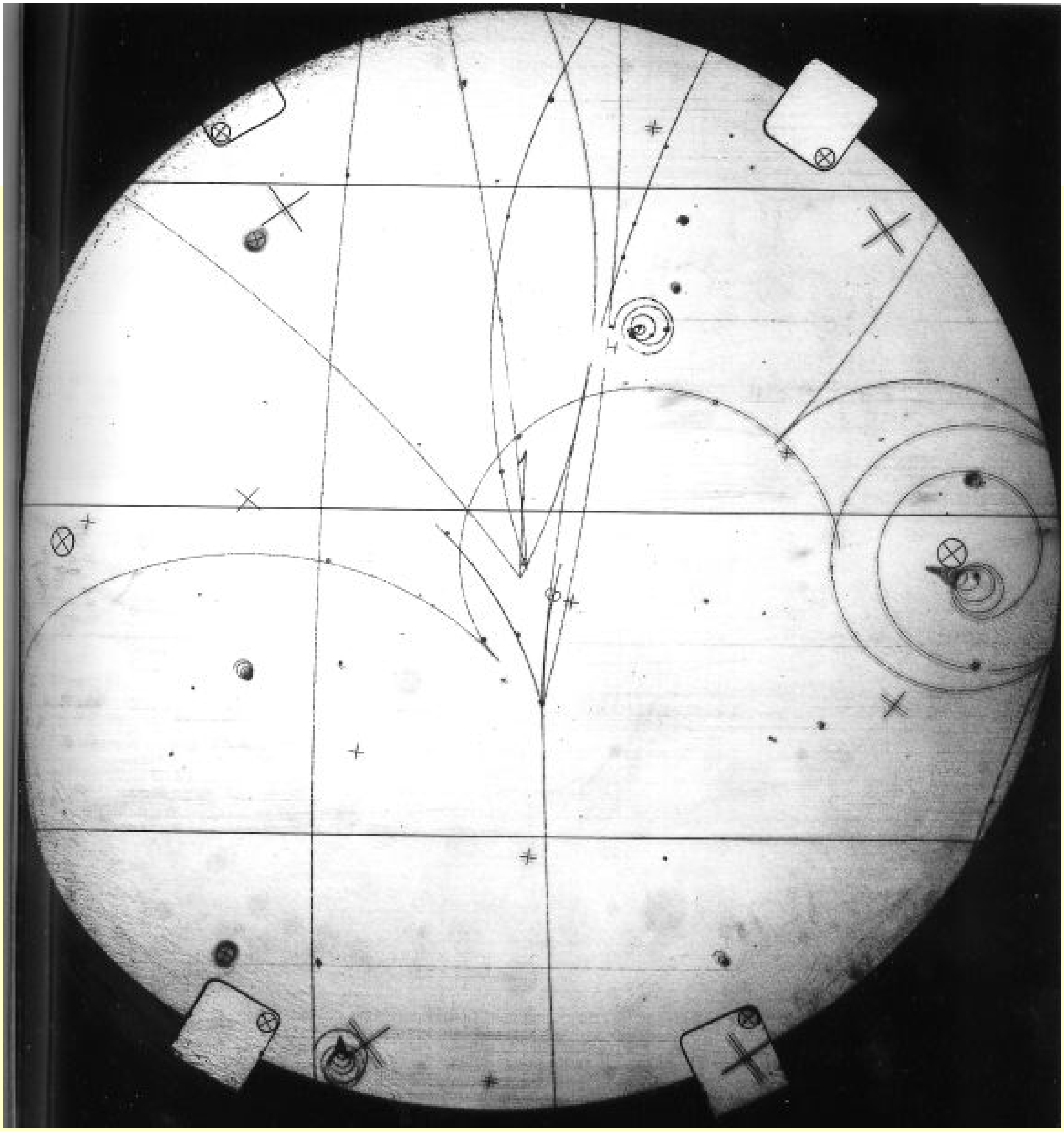
  - positron track going upward through lead plate
    - photographed by Carl Anderson (August 2, 1932), while photographing cosmic-ray tracks in a cloud chamber
    - particle moving upward, as determined by the increase in curvature of the top half of the track after it passed through the lead plate,
    - and curving to the left, meaning its charge is positive.

Anderson and his cloud chamber



Bubble chamber

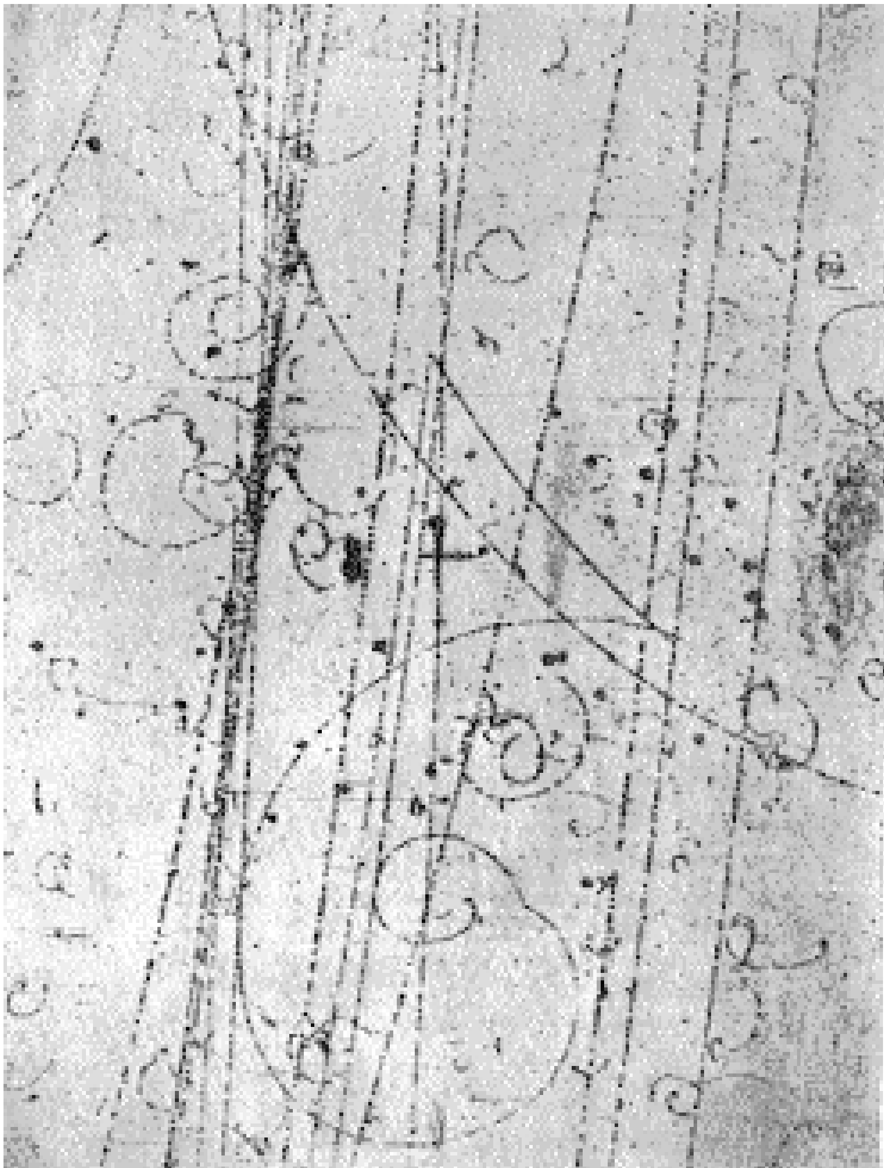
- bubble chamber
  - Vessel, filled (e.g.) with liquid hydrogen at a temperature above the normal boiling point but held under a pressure of about 10 atmospheres by a large piston to prevent boiling.
  - When particles have passed, and possibly interacted in the chamber, the piston is moved to reduce the pressure, allowing bubbles to develop along particle tracks.
  - After about 3 milliseconds have elapsed for bubbles to grow, tracks are photographed using flash photography. Several cameras provide stereo views of the tracks.
  - The piston is then moved back to recompress the liquid and collapse the bubbles before boiling can occur.
- Invented by Glaser in 1952 (when he was drinking beer)

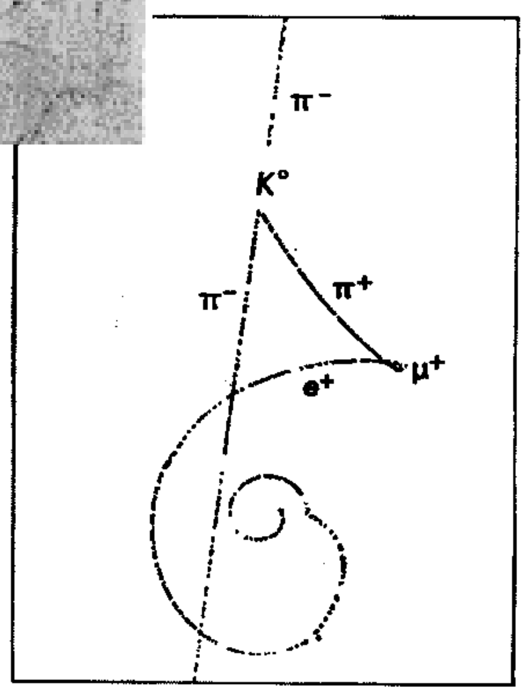


- pbar p $\rightarrow$ p nbar K^0 K^- π^+ π^- π^0
- nbar + p $\rightarrow$ 3 pions
- $\pi^0 \rightarrow \gamma\gamma$, $\gamma \rightarrow e^+ e^-$
- $K^0 \rightarrow \pi^+ \pi^-$

"Strange particles"

- Kaon: discovered 1947; first called "V" particles





K^0 production and decay
in a bubble chamber

Proportional tube

- proportional tube:
  - similar in construction to Geiger-Müller counter, but works in different HV regime
  - metallic tube with thin wire in center, filled with gas, HV between wall (-, "cathode") and central wire (+,"anode"); ⇒ strong electric field near wire;
  - charged particle in gas ⇒ ionization ⇒ electrons liberated;
  - electrons accelerated in electric field ⇒ can liberate other electrons by ionization which in turn are accelerated and ionize ⇒ "avalanche of electrons" moves to wire ⇒ current pulse; current pulse amplified ⇒ electronic signal:
  - gas is usually noble gas (e.g. argon), with some additives e.g. carbon dioxide, methane, isobutane,..) as "quenchers";

Wire chambers

- multi wire proportional chamber:
  - contains many parallel anode wires between two cathode planes (array of prop.tubes with separating walls taken out)
  - operation similar to proportional tube;
  - cathodes can be metal strips or wires ⇒ get additional position information from cathode signals.

- drift chamber:
  - field shaping wires and electrodes on wall to create very uniform electric field, and divide chamber volume into "drift cells", each containing one anode wire;
  - within drift cell, electrons liberated by passage of particle move to anode wire, with avalanche multiplication near anode wire;
  - arrival time of pulse gives information about distance of particle from anode wire; ratio of pulses at two ends of anode wire gives position along anode wire;

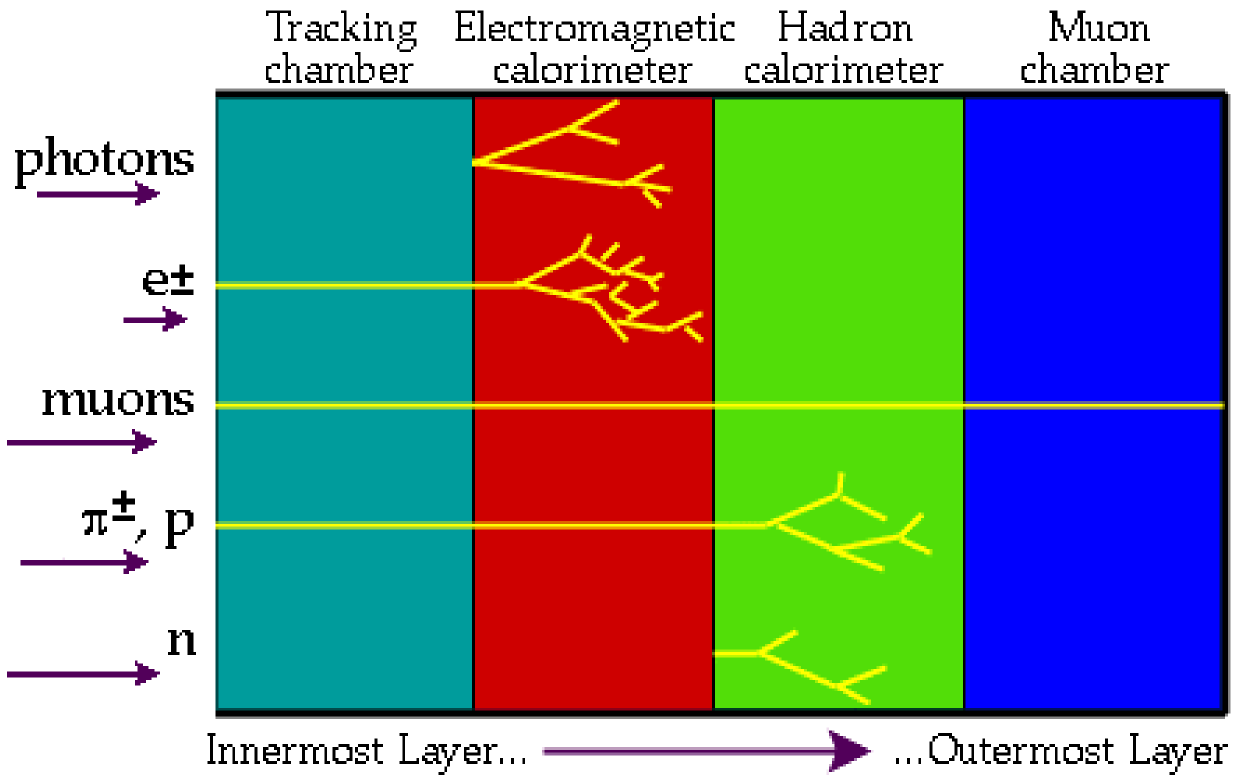
Particle detectors, cont'd

- Cherenkov detector:
  - measure Cherenkov light (amount and/or angle) emitted by particle going through counter volume filled with transparent gas, liquid, aerogel, or solid ⇒ get information about speed of particle.
- calorimeter:
  - "destructive" method of measuring a particle's energy: put enough material into particle's way to force formation of electromagnetic or hadronic shower (depending on kind of particle)
  - eventually particle loses all of its energy in calorimeter;
  - energy deposit gives measure of original particle energy.
- Note: many of the detectors and techniques developed for particle and nuclear physics are now being used in medicine, mostly diagnosis, but also for therapy.

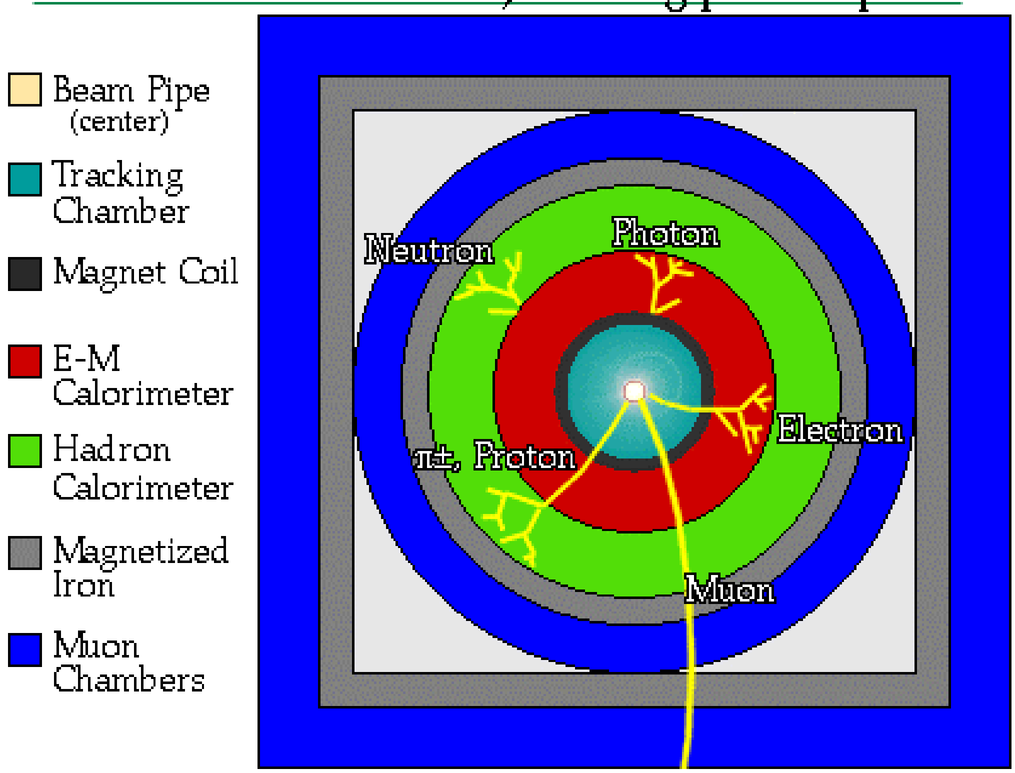
Calorimeters

- Principle:
  - Put enough material into particle path to force development of electromagnetic or hadronic shower (or mixture of the two).
- Total absorption calorimeter:
  - depth of calorimeter sufficient to “contain” showers originating from particle of energy lower than design energy
  - depth measured in “radiation lengths” for e.m. and “nuclear absorption lengths” for hadronic showers
  - most modern calorimeters are “sampling calorimeters” – separate layers of high density material (“absorber”) to force shower development, and “sensitive” layer to detect charged particles in the shower.
  - total visible path length of shower particles is proportional to total energy deposited in calorimeter
  - segmentation allows measurement of positions of energy deposit
  - lateral and longitudinal energy distribution different for hadronic and e.m. showers – used for identification
  - absorber materials: U, W, Pb, Fe, Cu,..
  - sensitive medium: scintillator, silicon, liquid argon,..

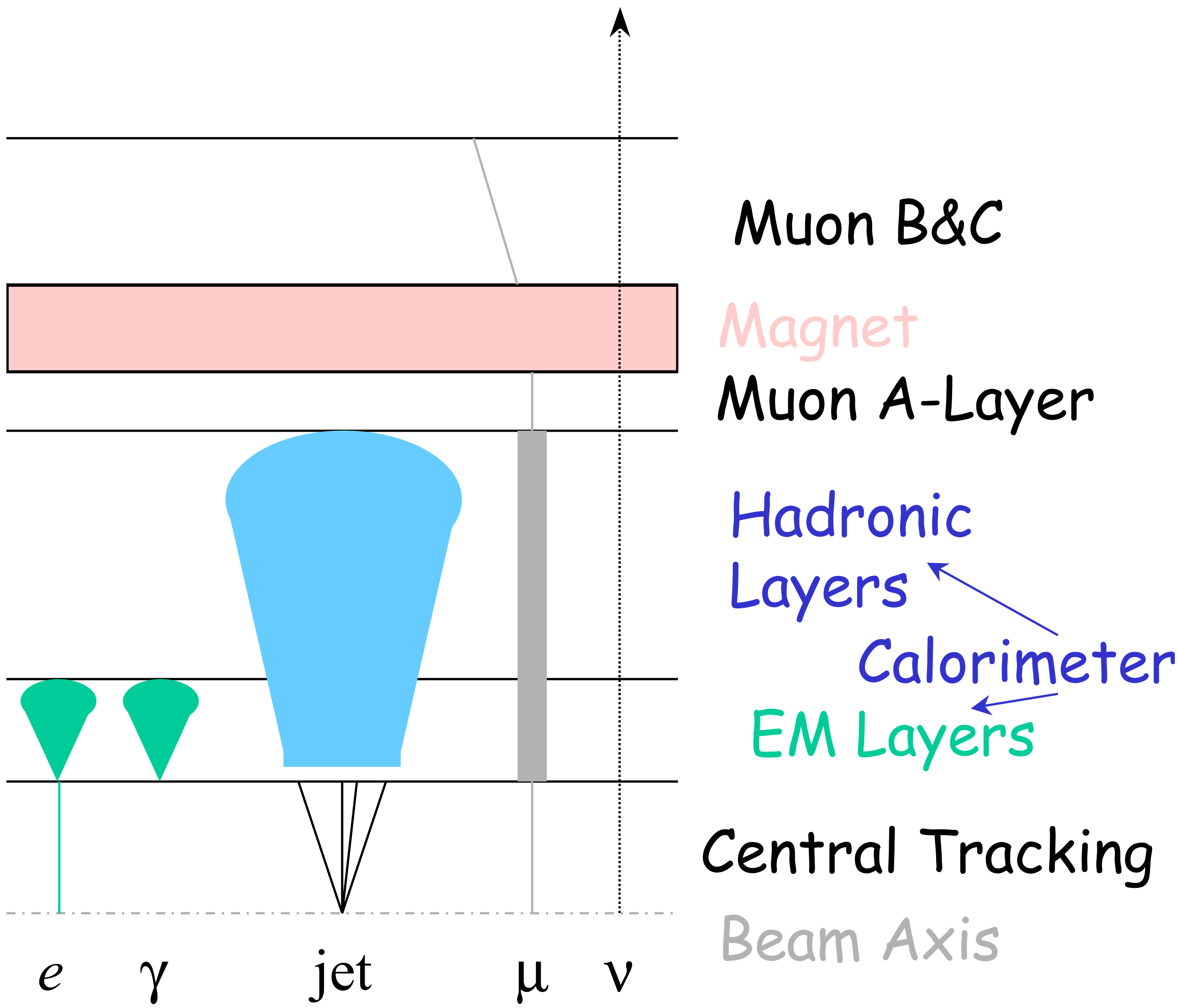
Identifying particles



A detector cross-section, showing particle paths

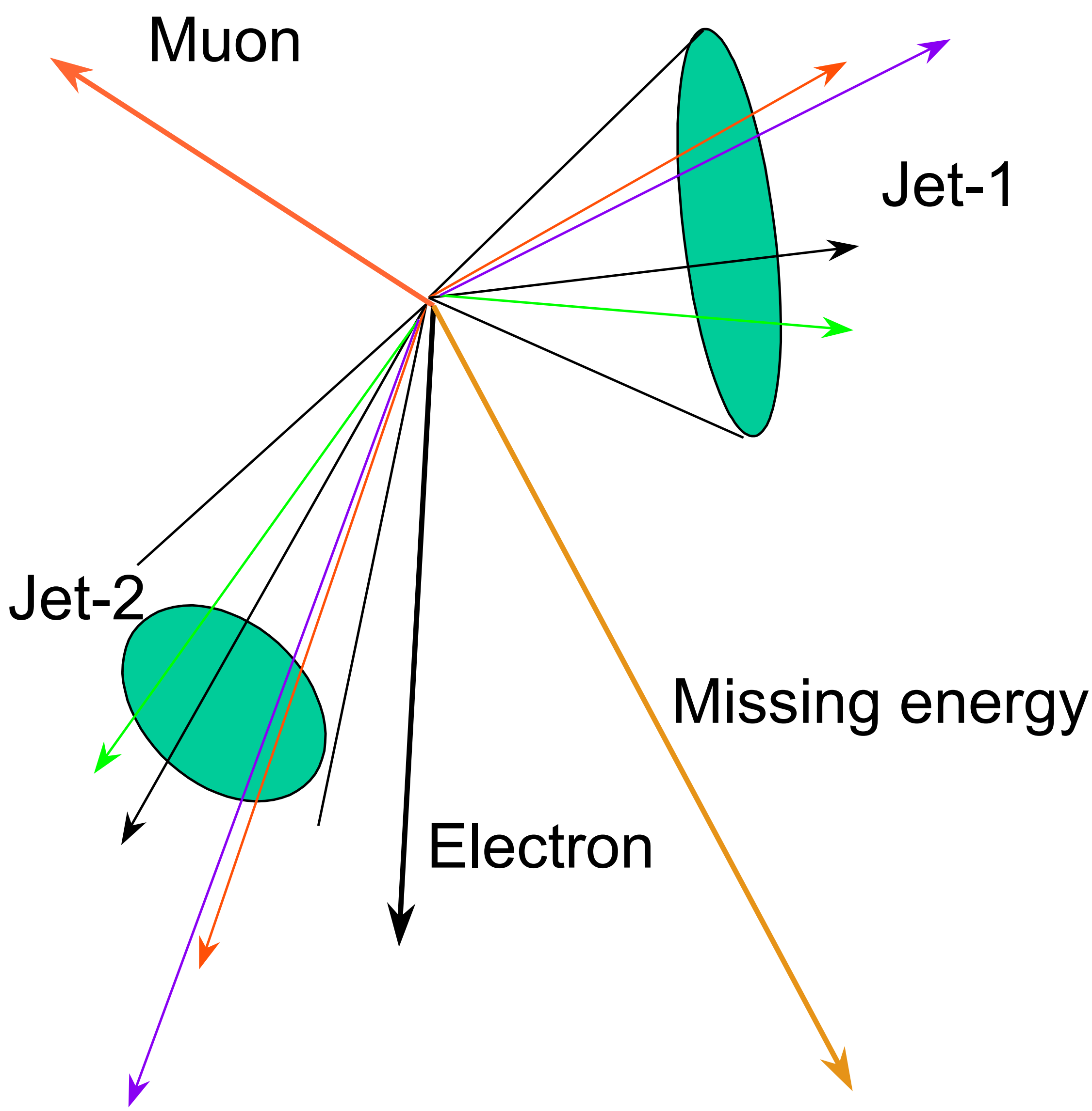


Particle Identification



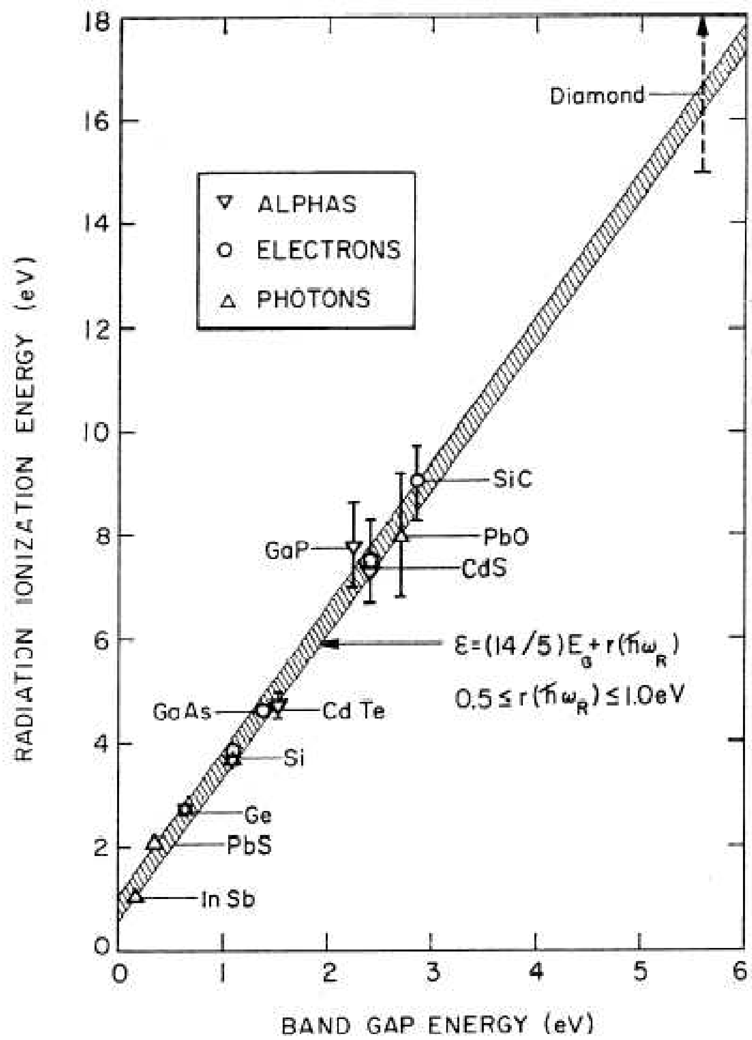
What do we actually "see" in a top event

$$t\bar{t} \rightarrow e\mu + jets$$



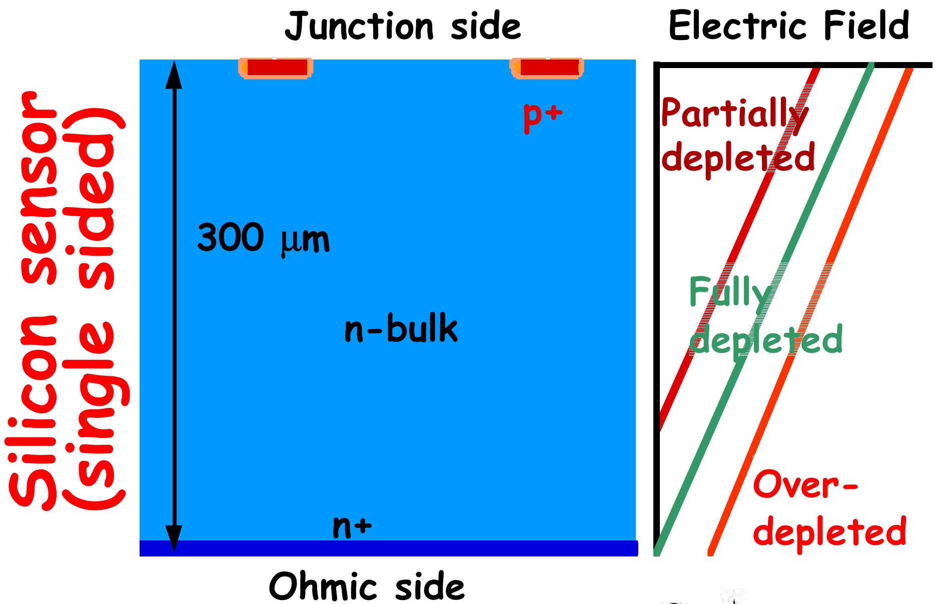
Silicon detectors

- Silicon has properties which make it especially desirable as a detector material
  - low ionization energy (good signal)
  - long mean free path (good charge collection efficiency)
  - high mobility (fast charge collection)
  - low Z (low multiple scattering)
  - Very well developed technology



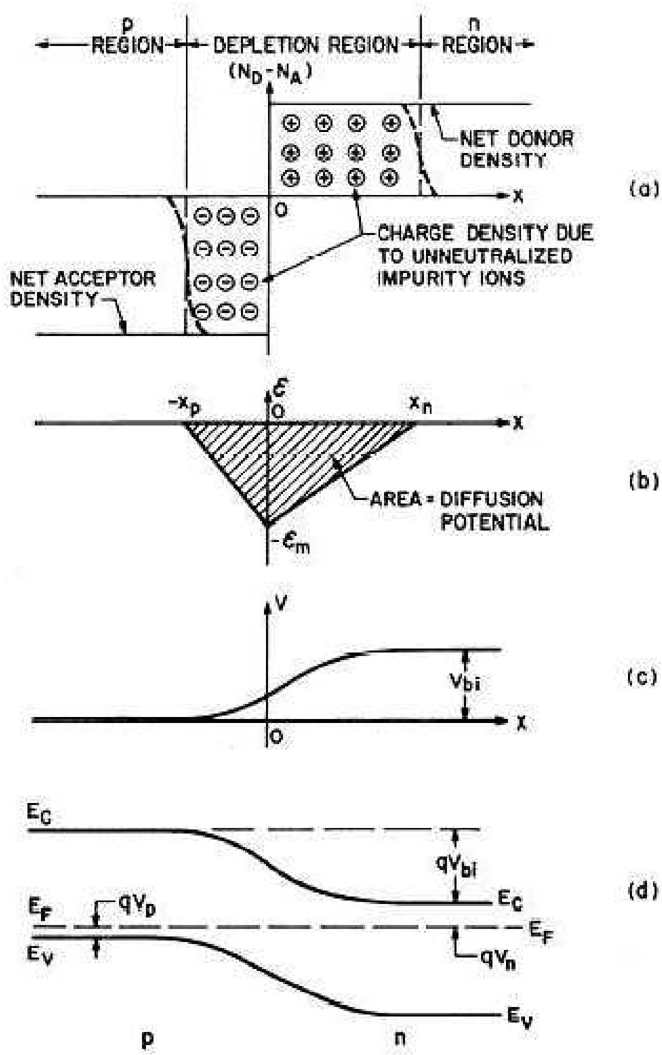
C.A. Klein, J. Applied Physics **39** (1968) 2029

Diode depletion



Silicon detectors have:

- lightly doped bulk (usually n)
- heavily doped contacts
- unusually large depleted area.
- Diffusion of charge carriers will form a local depleted region with no applied voltage



(from Sze, *Physics of Semiconductor Devices*)

Solid State Detector Physics - band structures

- Silicon detectors are typically high resistivity >1 KΩ-cm "float zone" silicon
- The small energy gap between impurity "donor" or "acceptor" levels means most mobile electrons and holes are due to dopants.

band diagram | density of states | Fermi-dirac distribution | carrier concentrations

Intrinsic

n-type

p-type

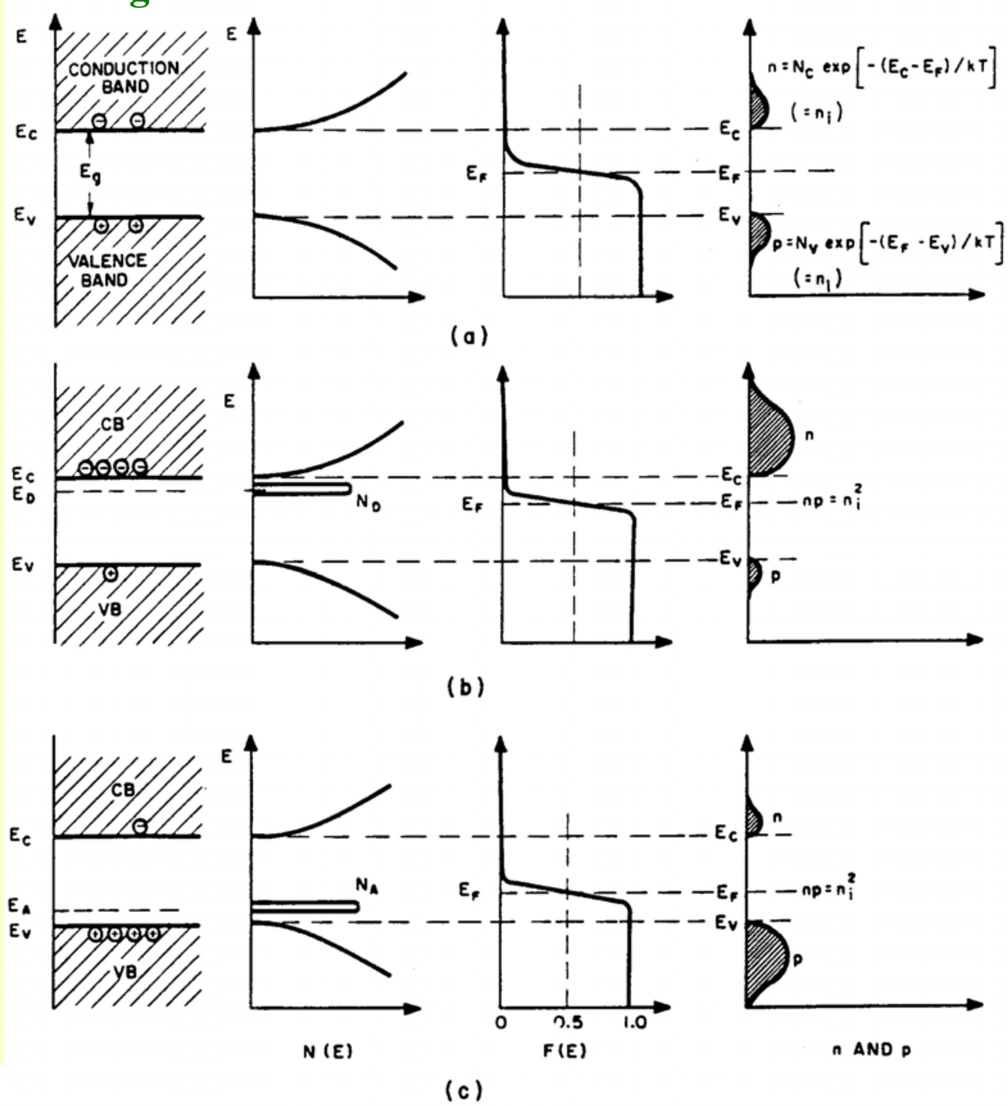


Fig. 14 Schematic band diagram, density of states, Fermi–Dirac distribution, and the carrier concentrations for (a) intrinsic, (b) n-type, and (c) p-type semiconductors at thermal equilibrium. Note that $pn = n_i^2$ for all three cases.

Solid State Detector Physics - device characteristics

Resistivity: $$\rho = \frac{1}{q(\mu_n N_n + \mu_p N_p)}$$

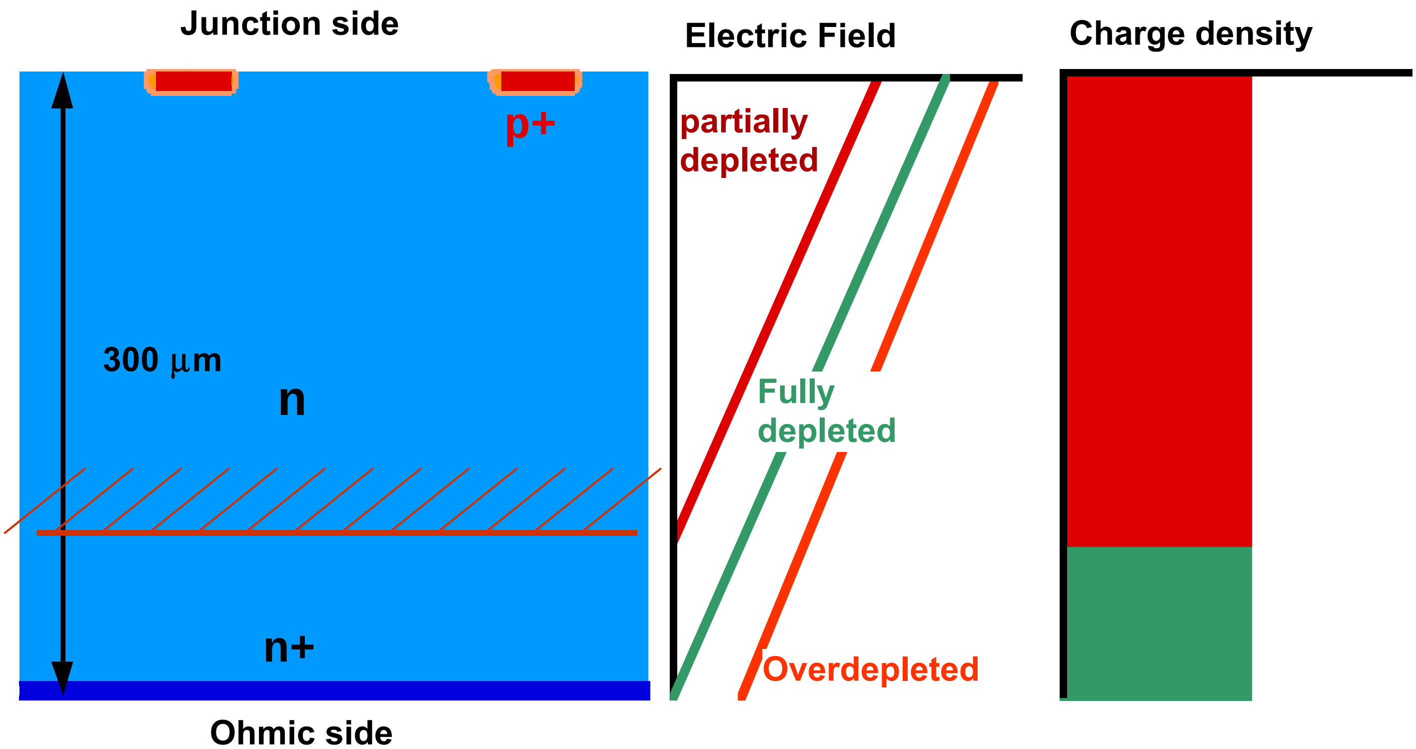
Depletion voltage: $$d = \sqrt{\frac{2\varepsilon V_{bias}}{qNeff}} \qquad V_{fd} = \frac{N_{eff}\, q\, D^2}{2\varepsilon}$$

Electric Field: $$E(x) = \frac{2V_{fd}}{D}\left(1 - \frac{x}{D}\right) + \frac{V_{bias} - V_{fd}}{D}$$

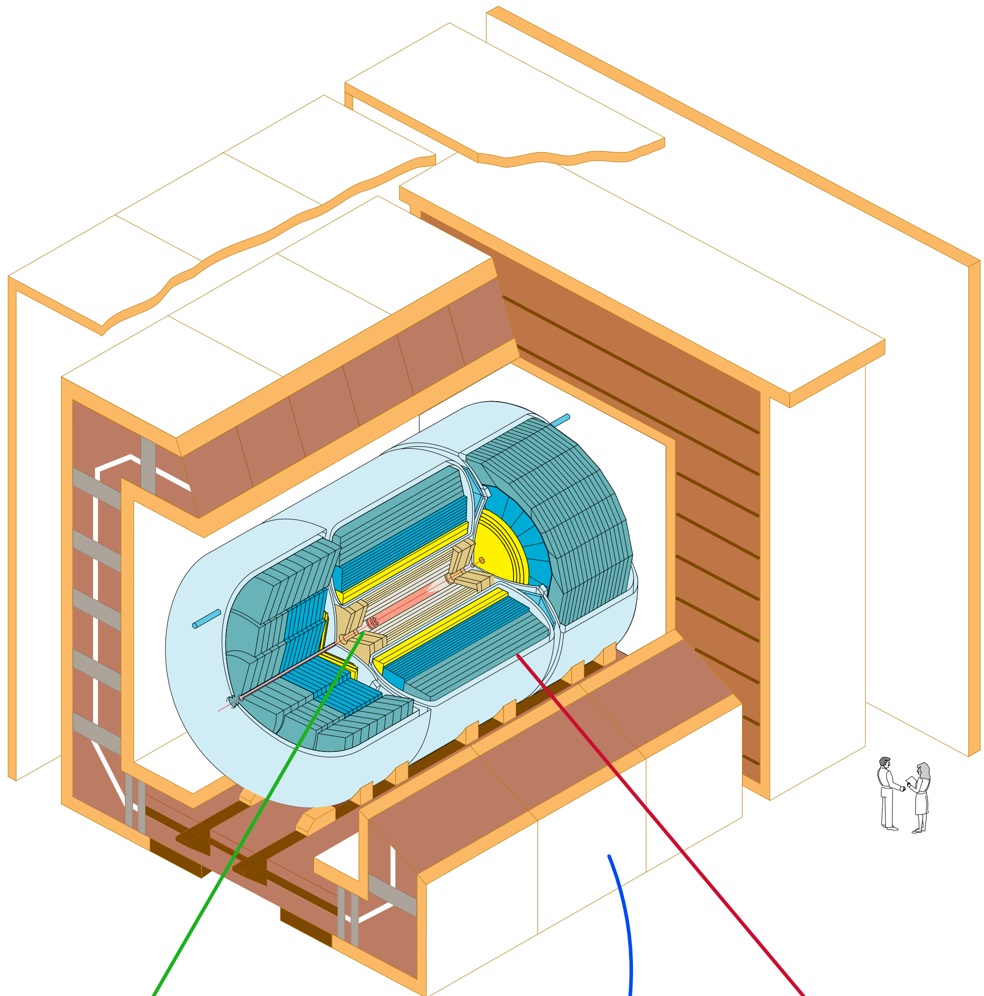
$\mu_{e,h}$ = **electron, hole mobility**

N_{eff} = **Effective carrier concentration**

x = distance from junction **D = silicon thickness**



The D0 detector



TRACKING

σ(z vertex)=6 mm
σ(rφ) = 60 μm (VTX)
= 180 μm (CDC)
= 200 μm (FDC)

MUON

$|\eta| < \mathbf{3.3}$

$\frac{\delta \mathbf{p}}{\mathbf{p}} = 0.2 \oplus 0.01p$

CALORIMETRY

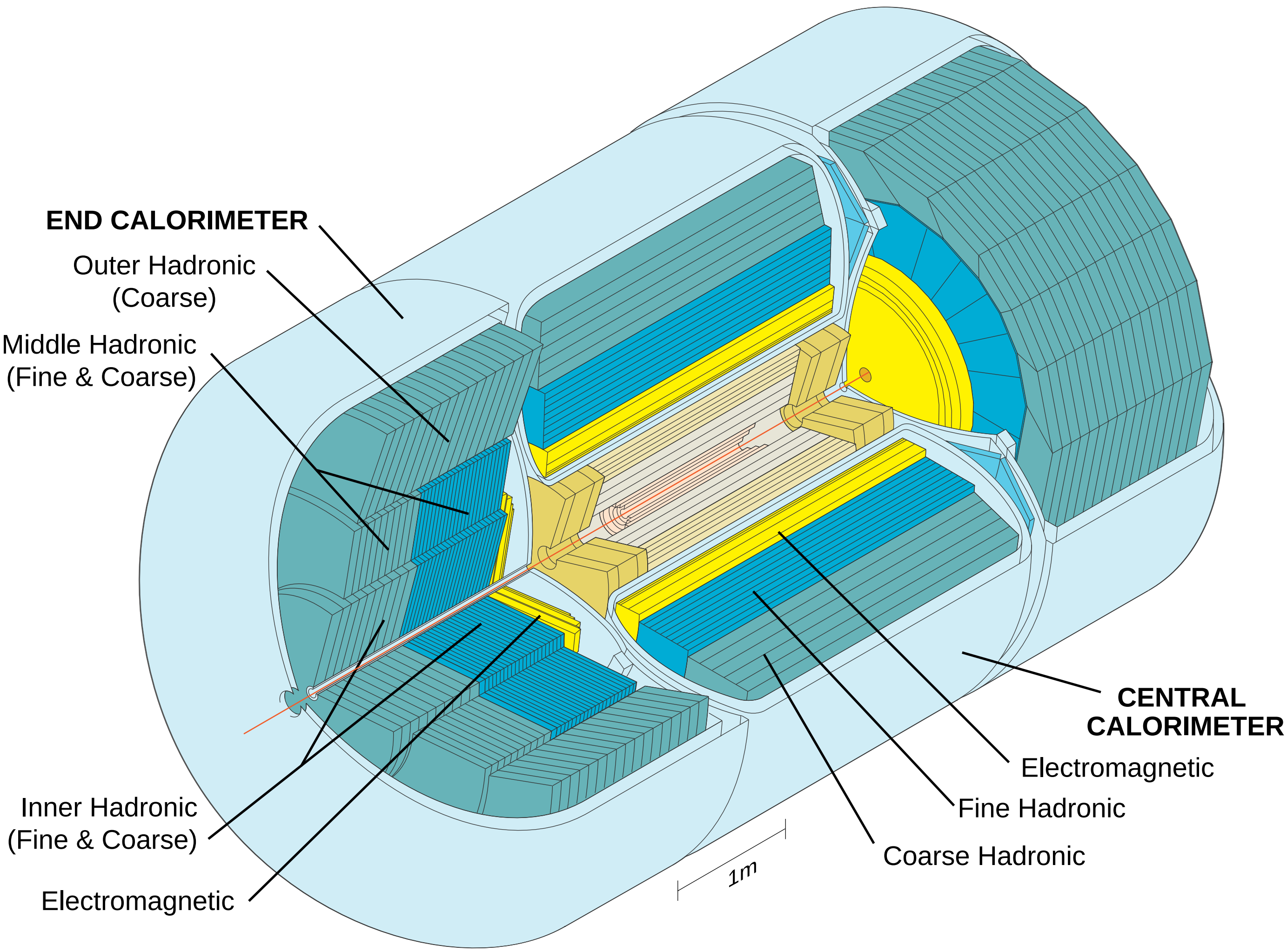
$|\eta|<4$

$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

$\sigma(EM) = 15\% / \sqrt{E}$

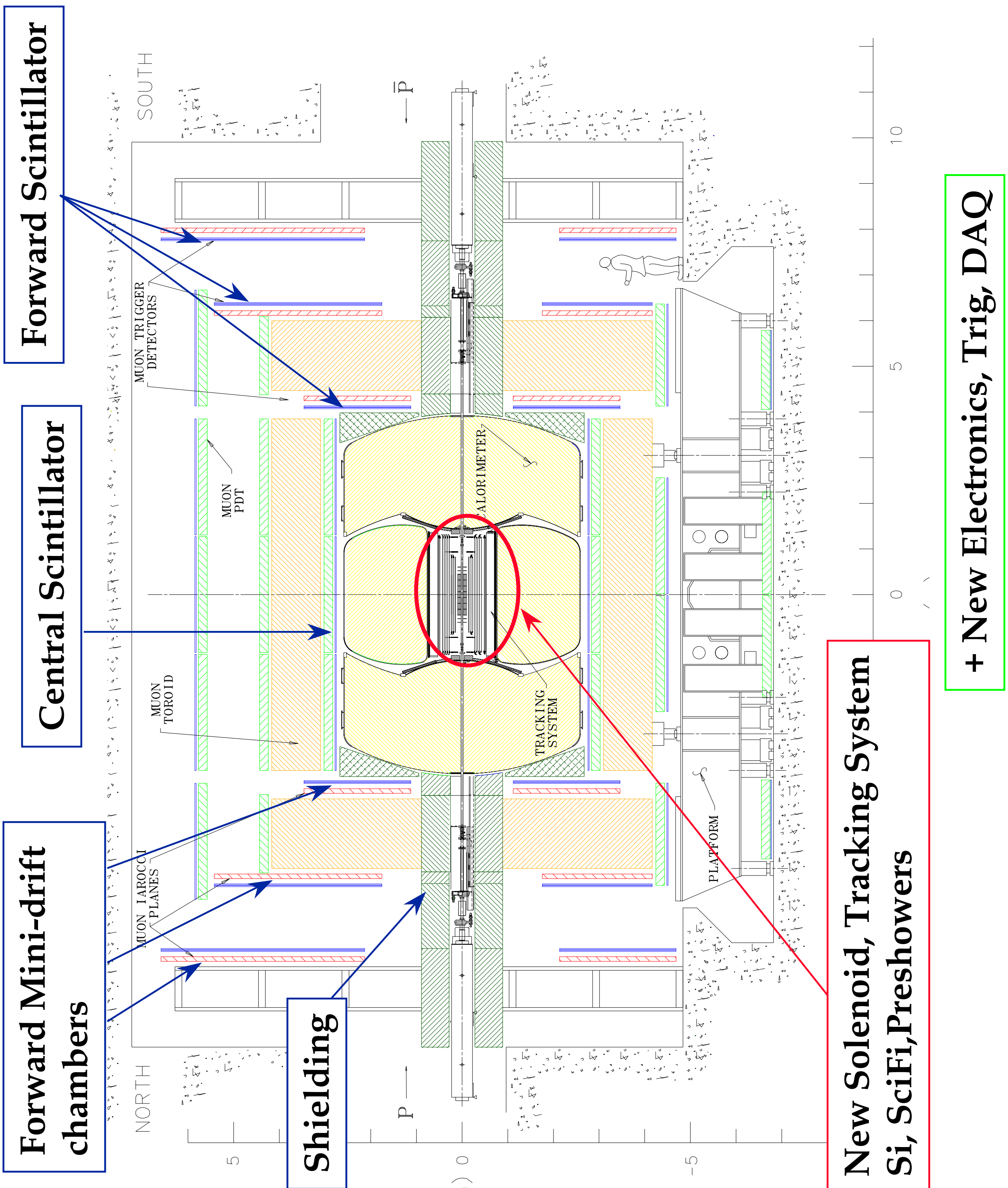
$\sigma(HAD) = 50\% / \sqrt{E}$

DØ Calorimeter



- Uranium-Liquid Argon sampling calorimeter
  - Linear, hermetic, and compensating
- No central magnetic field!
  - Rely on EM calorimeter

DØ Upgrade



Forward Scintillator
Central Scintillator
Forward Mini-drift chambers
Shielding
New Solenoid, Tracking System Si, SciFi,Preshowers
+ New Electronics, Trig, DAQ
MUON TRIGGER DETECTORS
MUON PDT
MUON TOROID
MUON IAROCCI PLANES
CALORIMETER
TRACKING SYSTEM
PLATFORM
SOUTH
NORTH
P
P̄

DØ Upgrade Tracking

- Silicon Tracker
  - Four layer barrels (double/single sided)
  - Interspersed double sided disks
  - **793,000 channels**
- Fiber Tracker
  - Eight layers sci-fi ribbon doublets (z-u-v, or z)
  - 74,000 830 μm fibers w/ VLPC readout

- Preshowers

Central

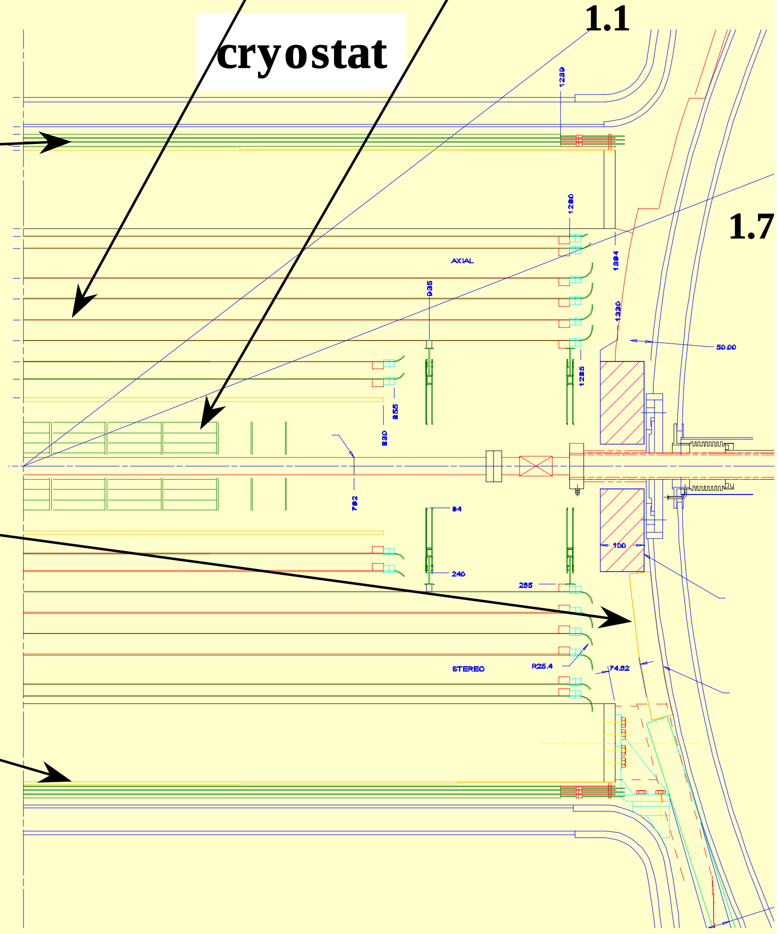
- Scintillator strips
  - 6,000 channels

Forward

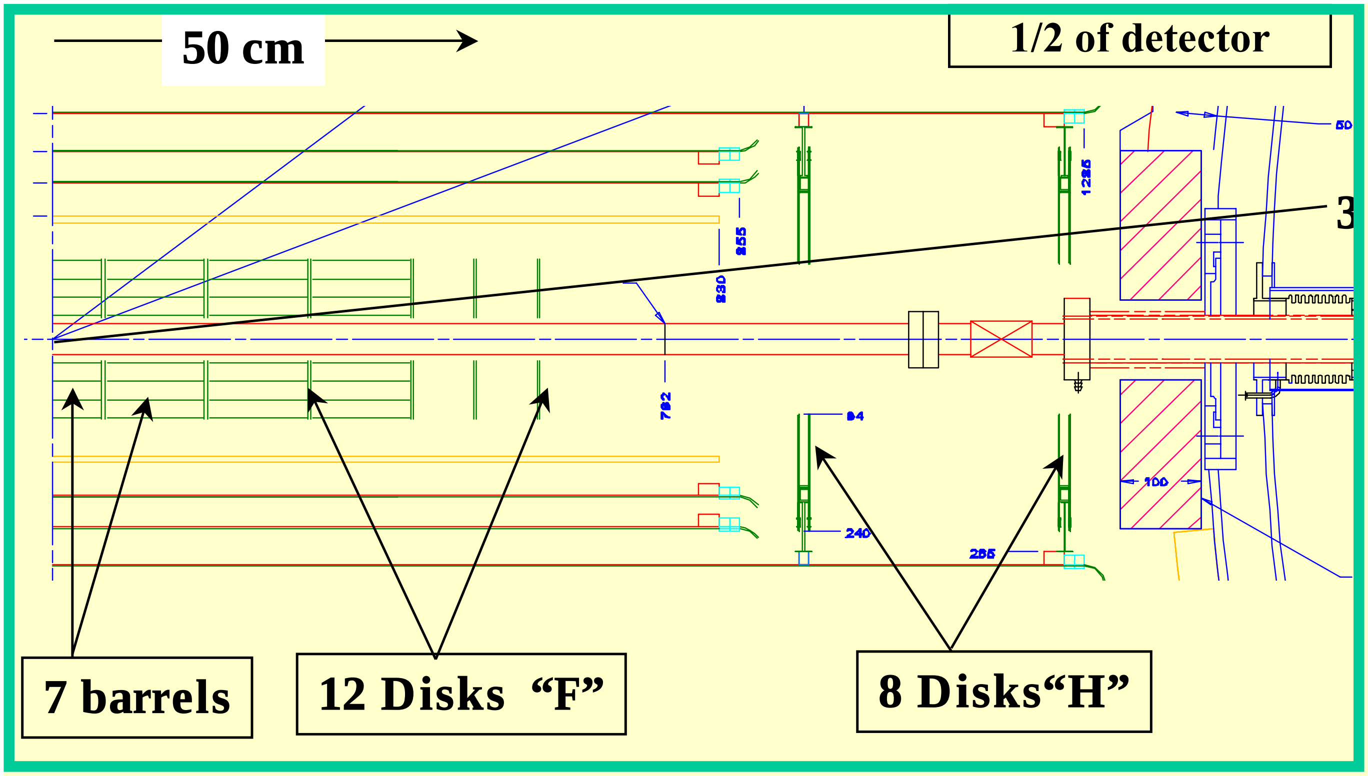
- Scintillator strips
- 16,000 channels

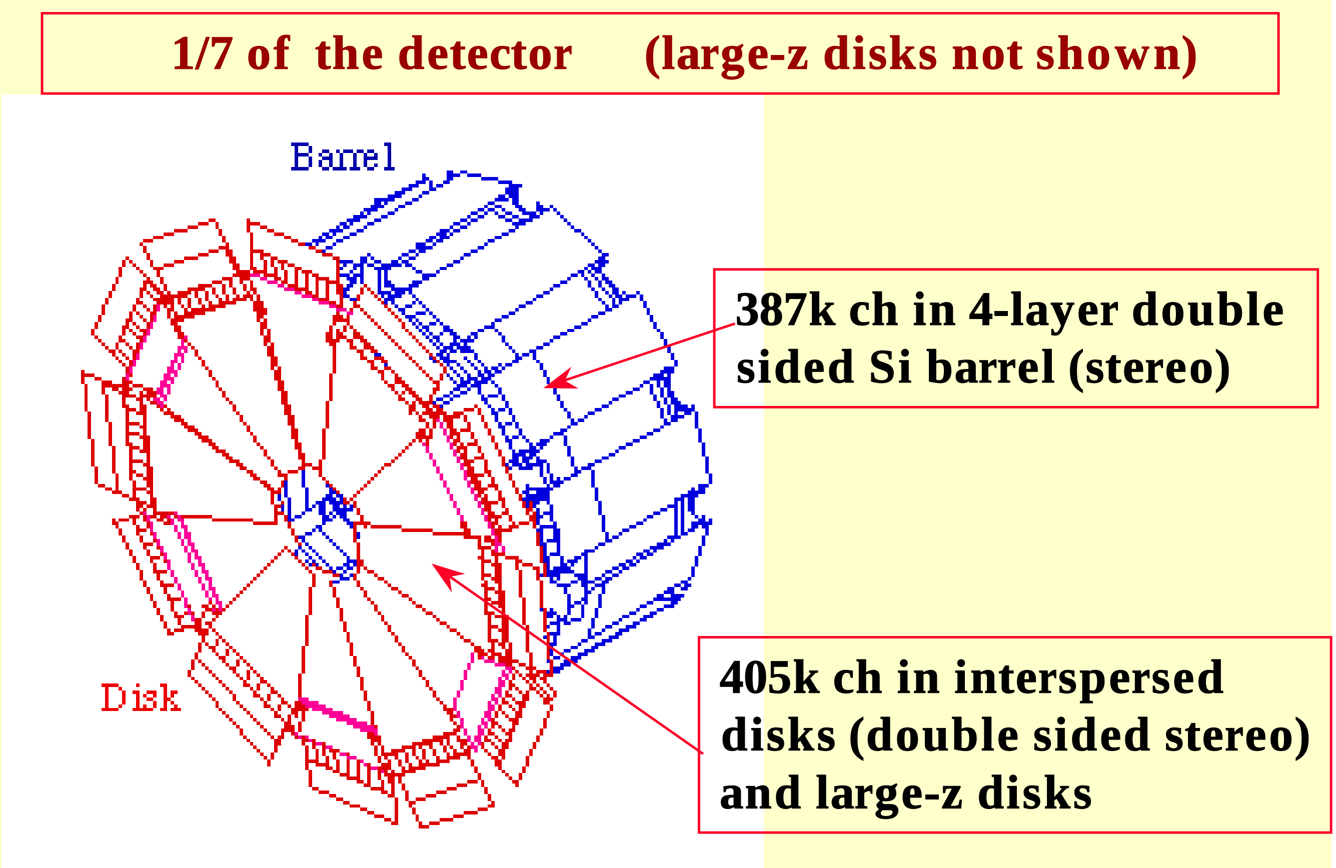
Solenoid

-2T superconducting



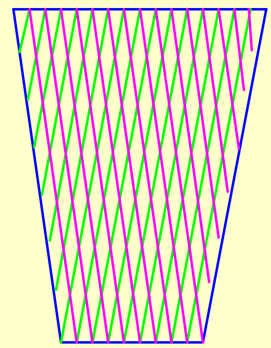
Silicon Tracker



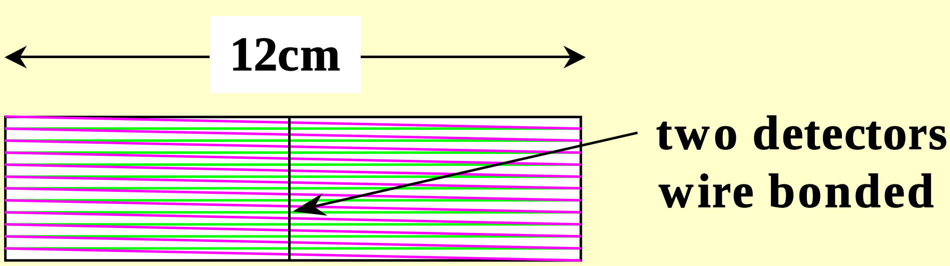


Silicon Tracker -Detectors

- Disks
  - "F" disks wedge (small diameter):
    - 144 double sided detectors, 12 wedges = 1disk
    - 50μm pitch, +/-15 stereo
    - 7.5cm long, from r=2.5 to 10cm, at z=6,19,32,45,50,55 cm
  - "H" disk (large diameter):
    - 384 single sided detectors
    - 50 μm pitch
    - from r=9.5-20 cm, z= 94, 126 cm



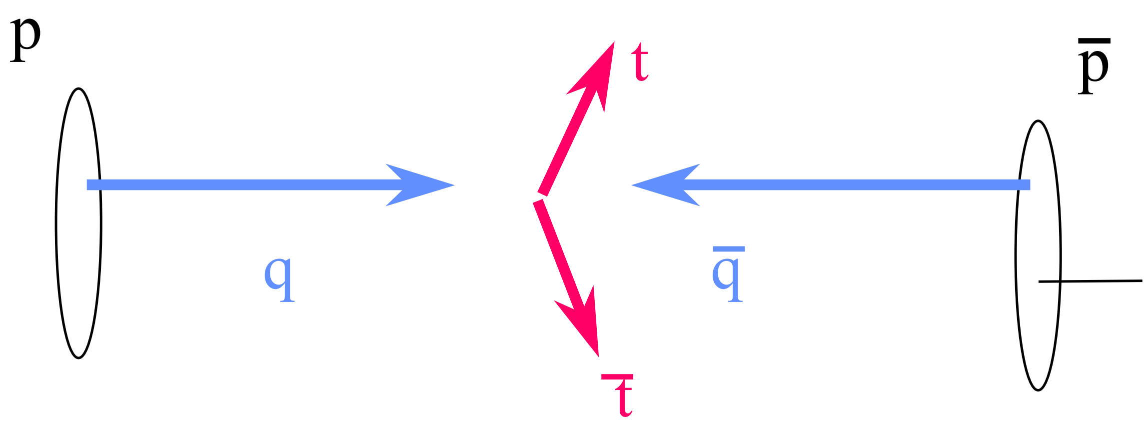
- Barrels
  - 7 modular, 4 layer barrel segments
  - single sided:
    - layers 1 , 3 in two outermost barrels.
  - double sided:
    - layers 1, 3 have 90^{o} stereo (mpx'd 3:1) 50 & 100μm pitch, 2.1 cm wide
    - layers 2,4 have small angle stereo (2^{o}) 50 & 62.5μm pitch, 3.4 cm wide



Trigger

- Trigger = device making decision on whether to record an event
- why not record all of them?
  - we want to observe "rare" events;
  - for rare events to happen sufficiently often, need high beam intensities $\Rightarrow$ many collisions take place
  - e.g. in Tevatron collider, proton and antiproton bunches will encounter each other every 132ns
  - at high bunch intensities, every beam crossing gives rise to collision $\Rightarrow$ about 7 million collisions per second
  - we can record about 20 to (maybe) 50 per second
- why not pick 10 events randomly?
  - We would miss those rare events that we are really after:
    e.g. top production: ≈ 1 in 10^{10} collisions
    Higgs production: ≈ 1 in 10^{12} collisions
  - $\Rightarrow$ would have to record 50 events/second for 634 years to get one Higgs event!
  - Storage needed for these events: $\approx 3 \times 10^{11}$ Gbytes
- Trigger has to decide fast which events not to record, without rejecting the "goodies"

Sample cross sections



Process	**σ(pb)**		**events**
collision	**8×10^{10}**		**8 trillion**
2 jets	**3×10^{6}**		**300 million**
4 jets	**125,000**		**12,500,000**
6 jets	**5,000**		**500,000**
W	**25,000**	**x 100 pb^{-1}**	**2,500,000**
Z	**11,000**		**1,100,000**
WW	**10**		**1000**
tt	**5**		**500**
Higgs	**0.1**		**10**

Luminosity and cross section

- Luminosity is a measure of the beam intensity (particles per area per second)
  ($L \sim 10^{31}/cm^2/s$)

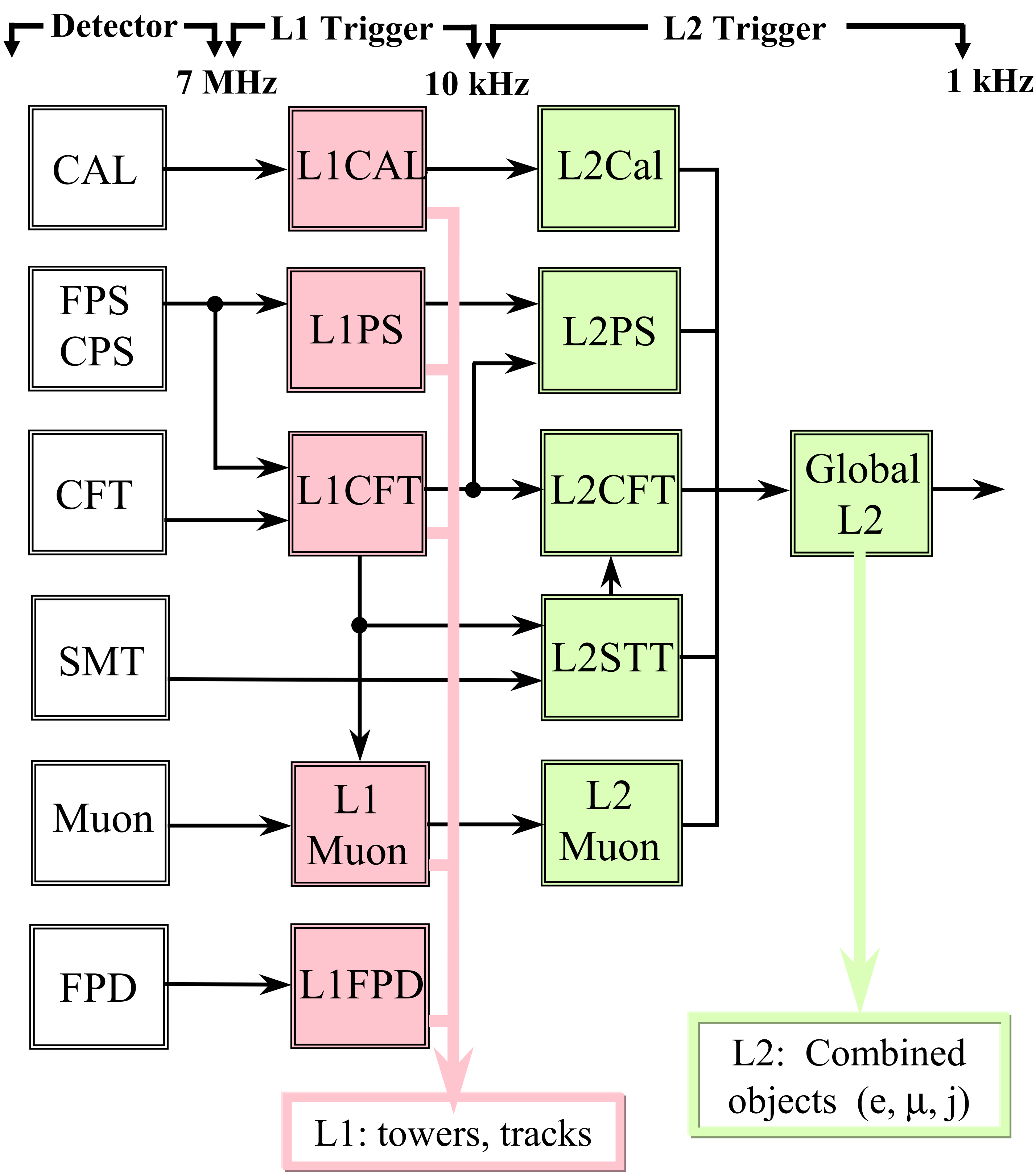
- "integrated luminosity" is a measure of the amount of data collected (e.g. ~100 pb^{-1})

- cross section σ is measure of effective interaction area, proportional to the probability that a given process will occur.
  - 1 barn = 10^{-24} cm^2
  - 1 pb = 10^{-12} b = 10^{-36} cm^2 = 10^{-40} m^2

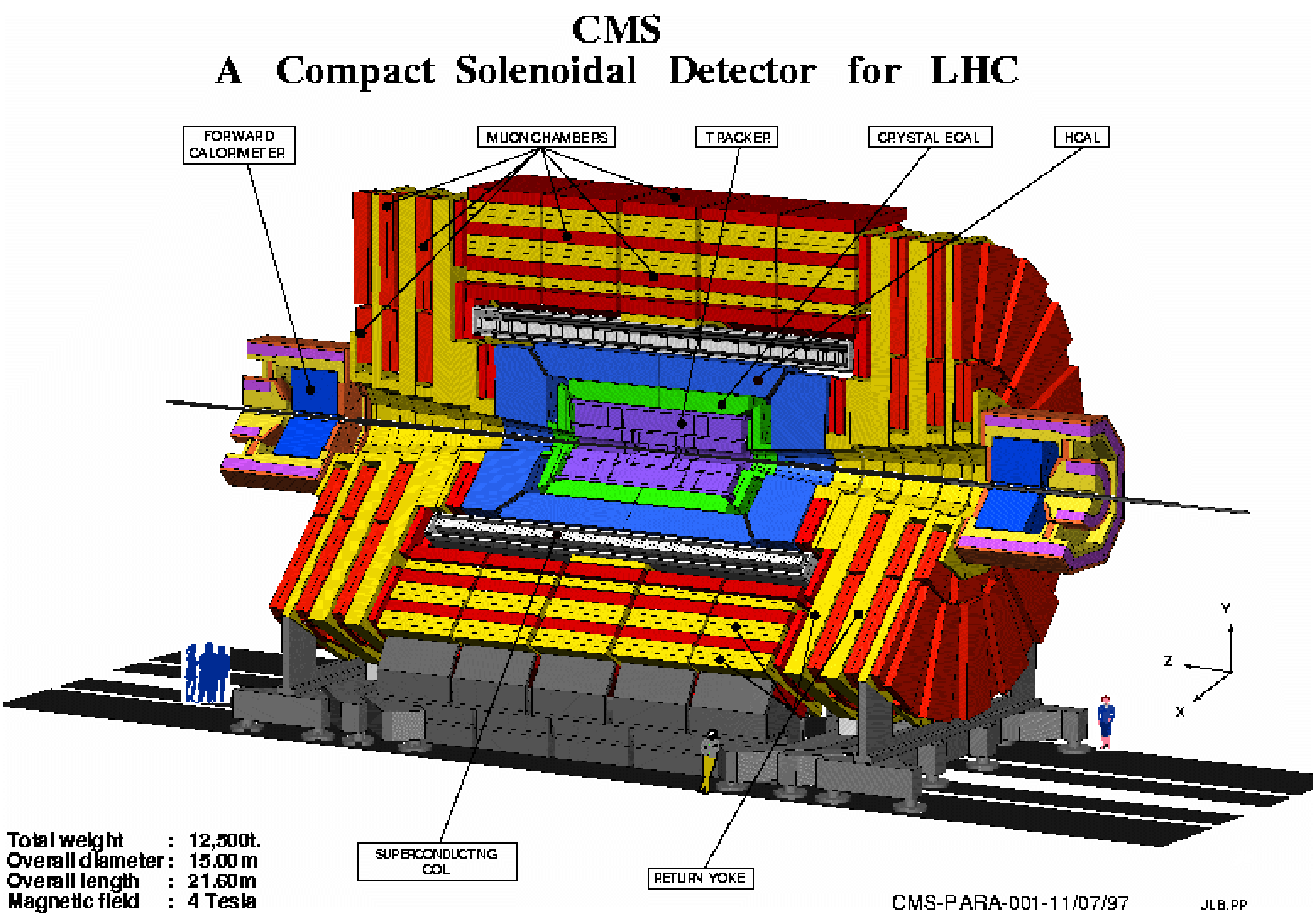
- interaction rate:

$$dn/dt = L \times \sigma \quad \Rightarrow \quad n = \sigma \int L dt$$

Trigger Configuration



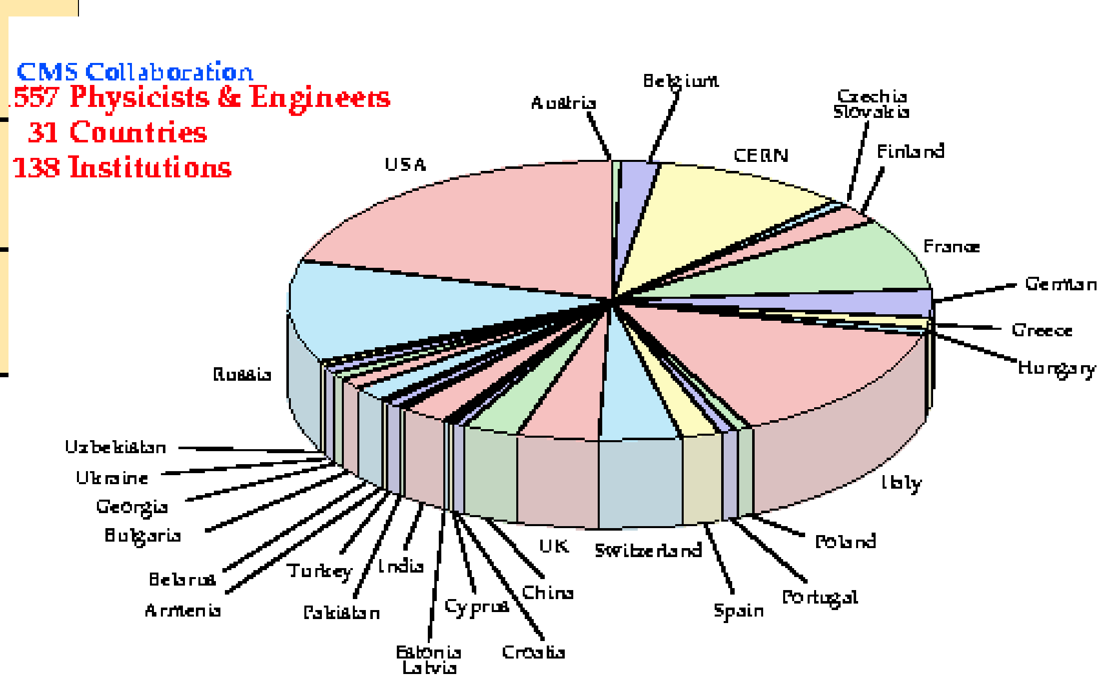
CMS Detector Subsystems



The CMS and US CMS Collaborations

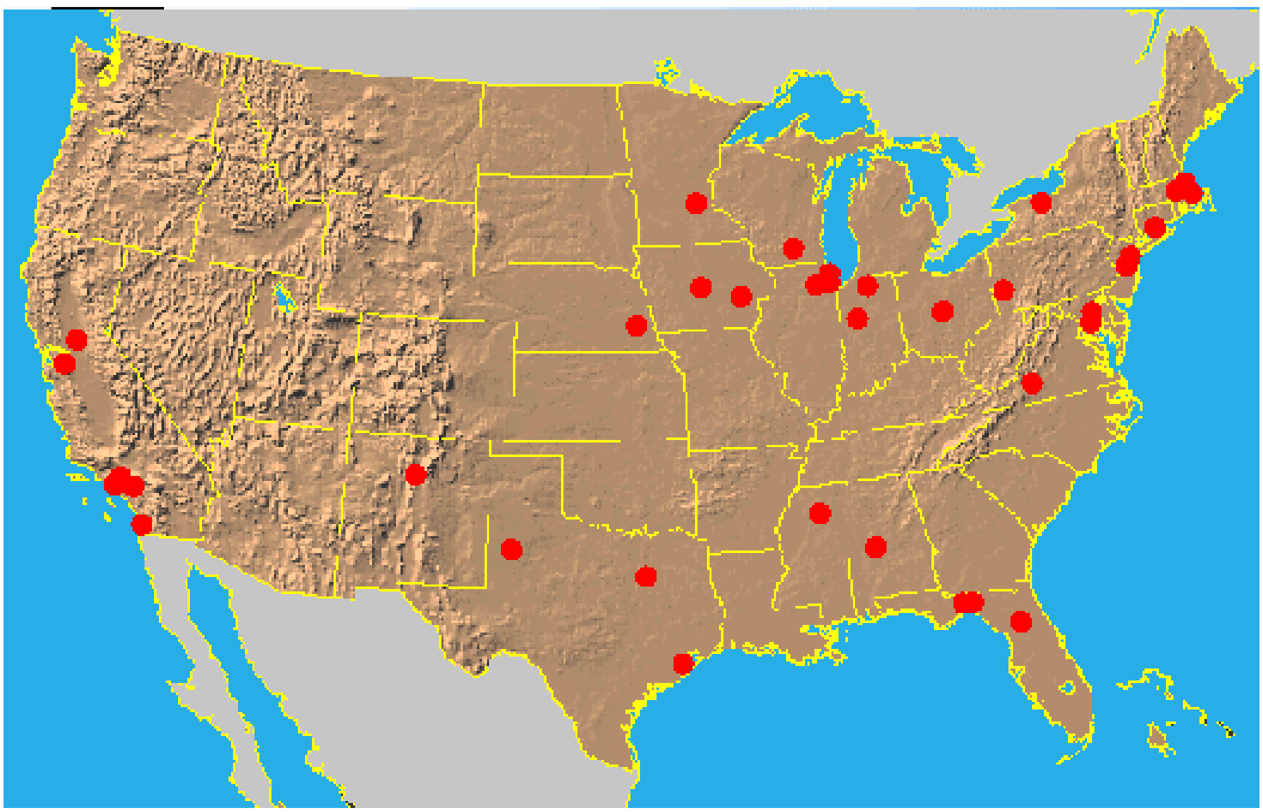
	Number of Laboratories
Member States	60
Non-Member States	38
USA	40
Total	138

	Number of scientists
Member States	850
Non-Member States	389
USA	318
Total	1557

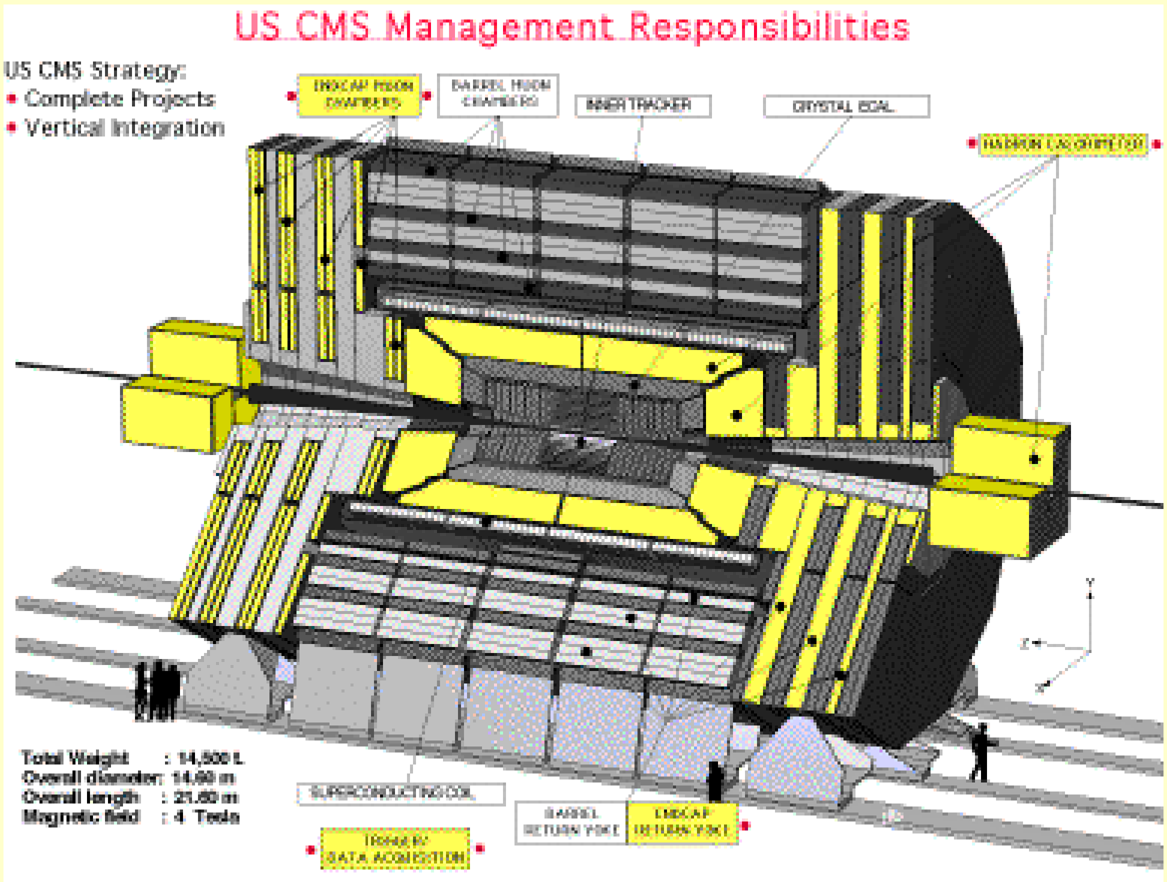


US CMS Demographics

US CMS Collaboration: 365 members from 37 institutions

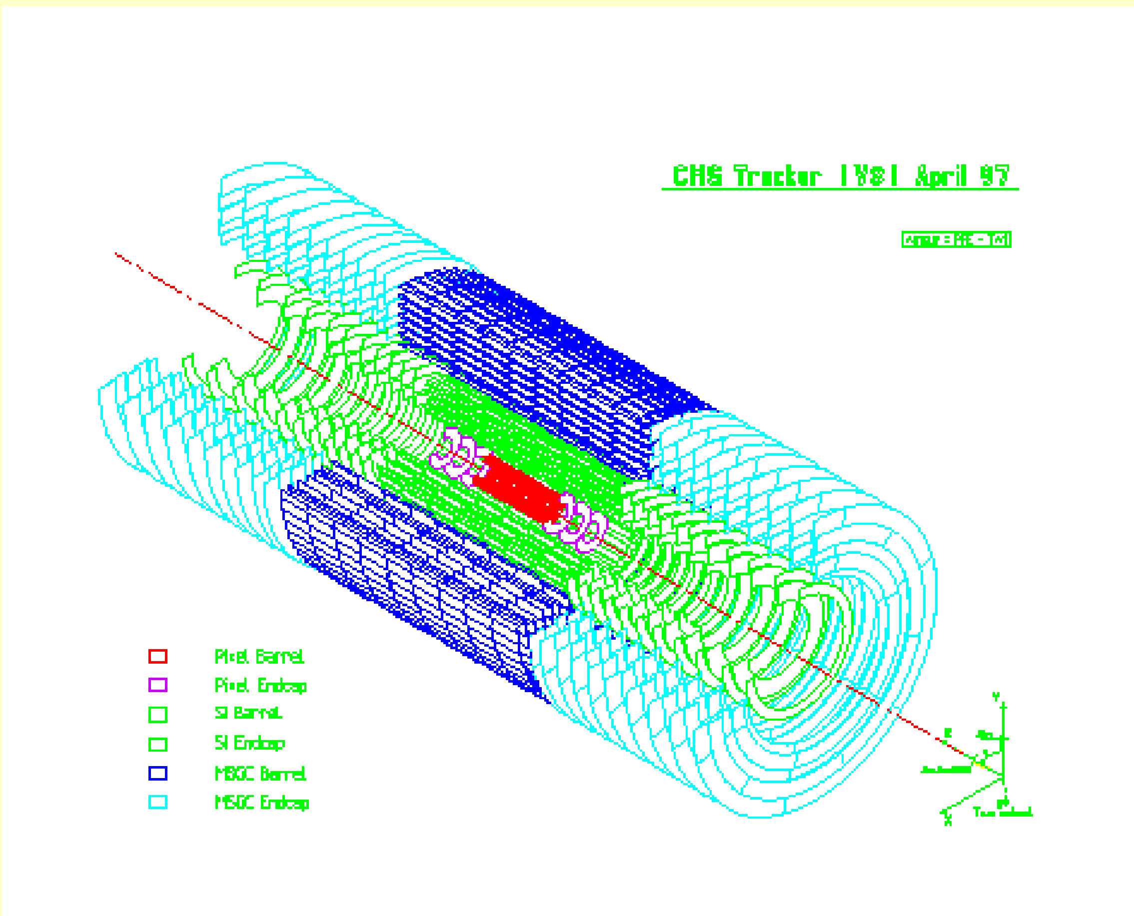


- US CMS Management Responsibilities in CMS

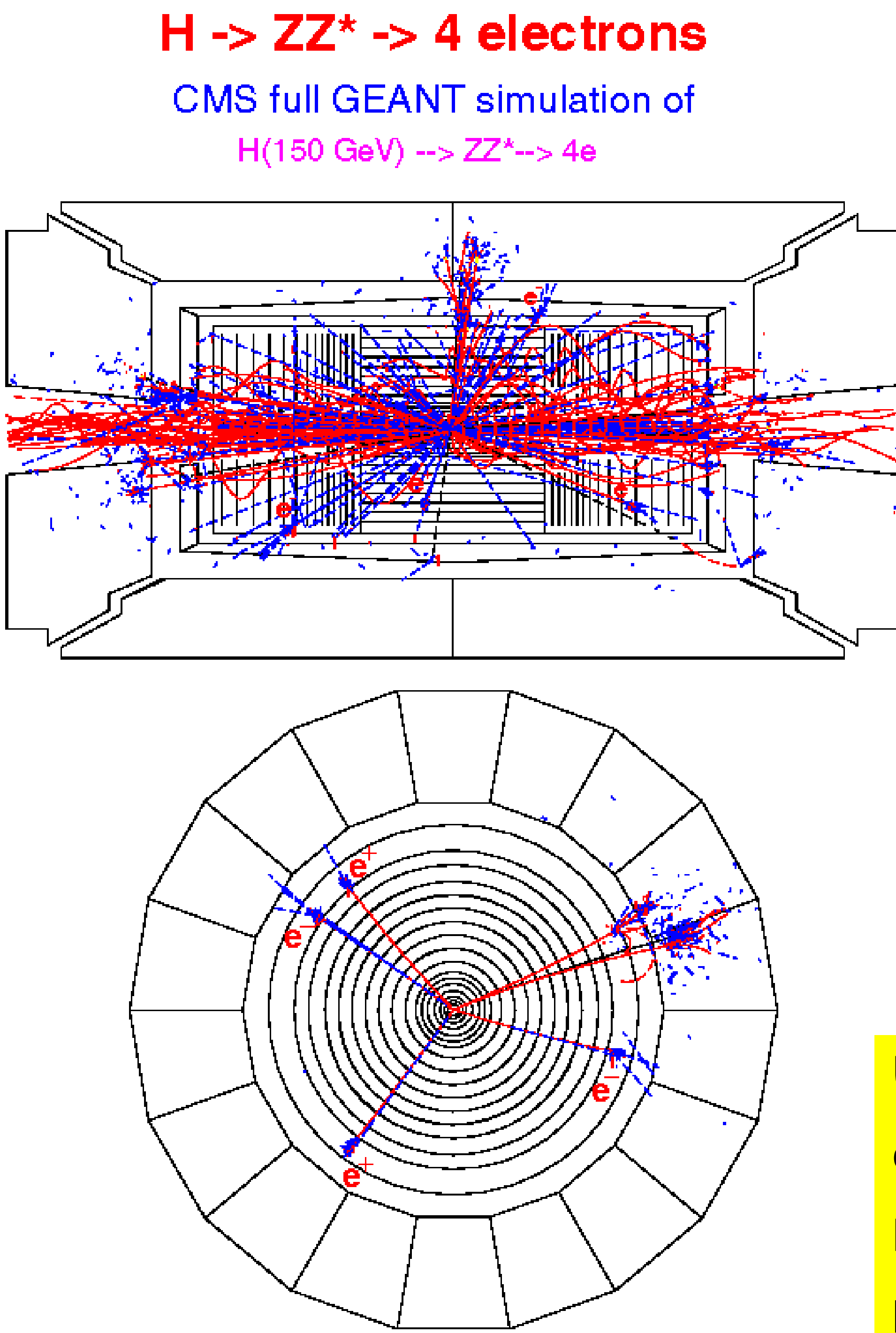


CMS Tracking System

- The Higgs is weakly coupled to ordinary matter. Thus, high interaction rates are required. The CMS pixel Si system has ~ 100 million elements so as to accommodate the resulting track densities.



If M_H > 160 GeV use H --> ZZ --> 4e or 4μ



US CMS

does APD +

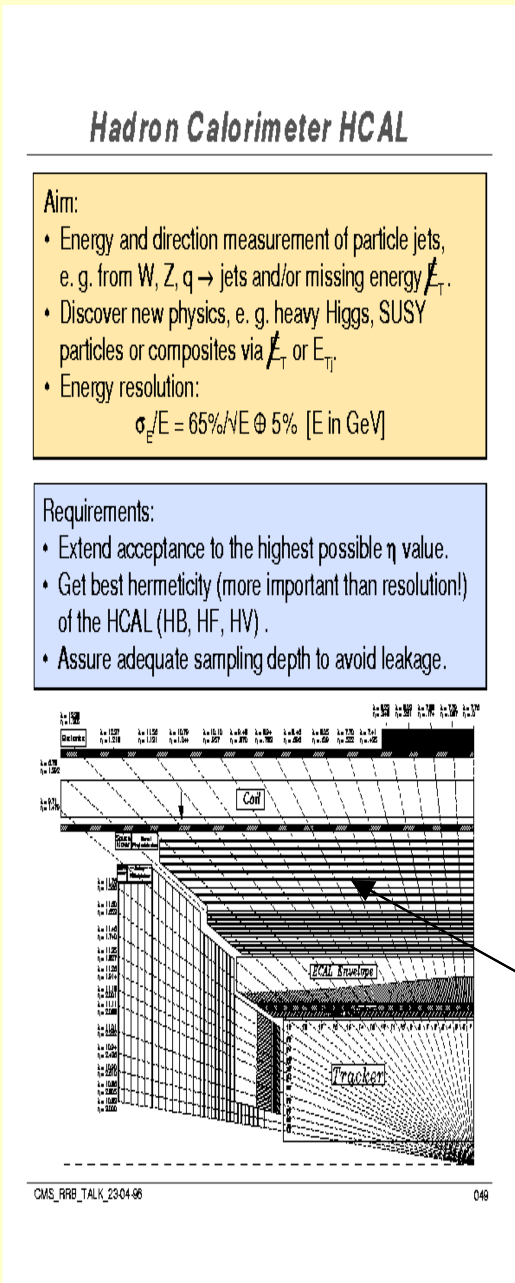
FPU +

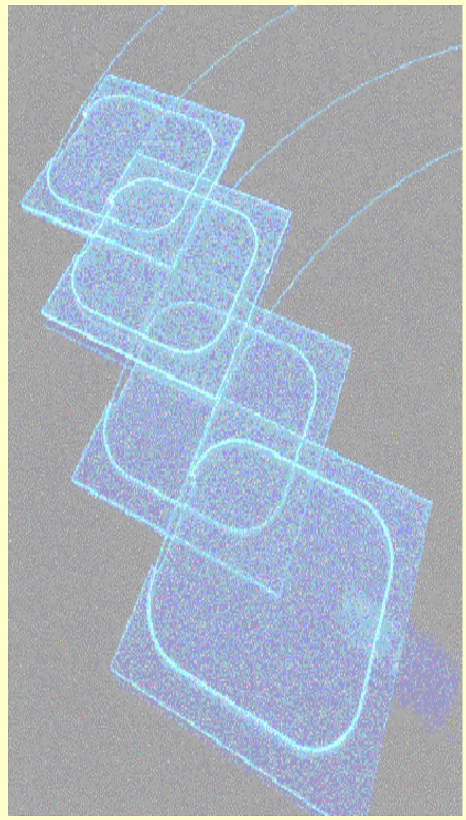
bit serializer

+ laser monitoring

The Hadron Calorimeter

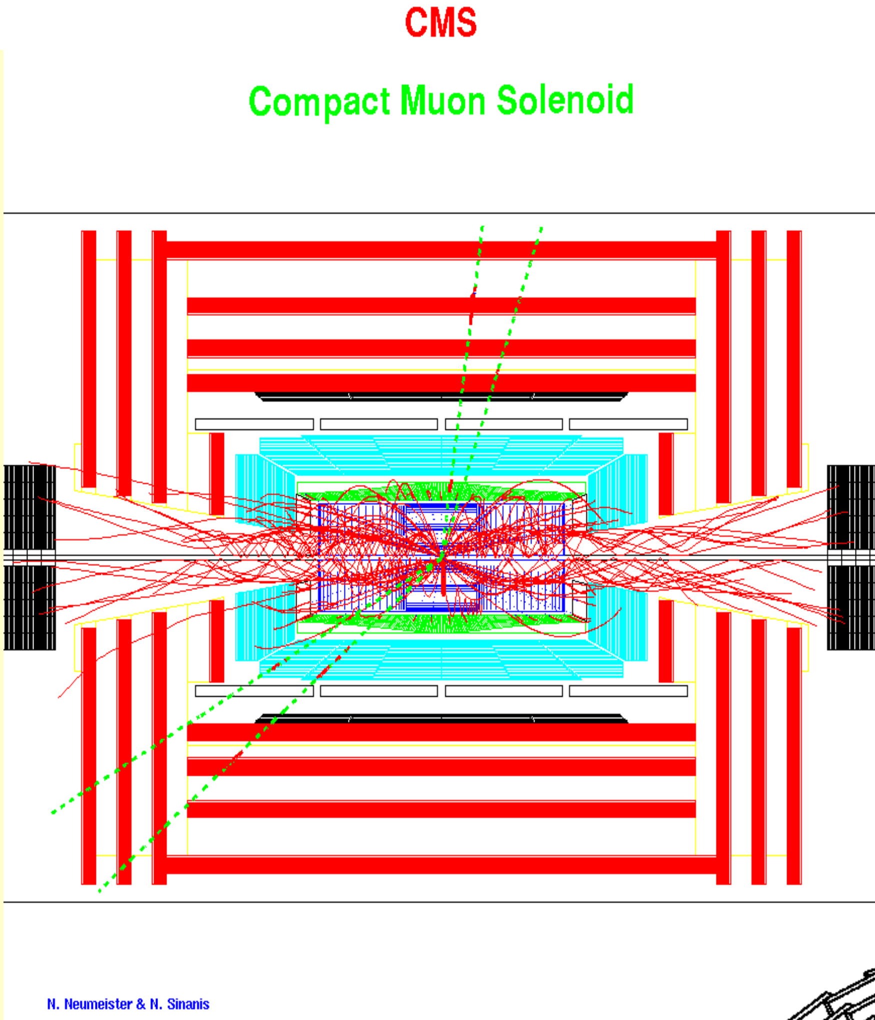
- HCAL detects jets from quarks and gluons. Neutrinos are inferred from missing Et.

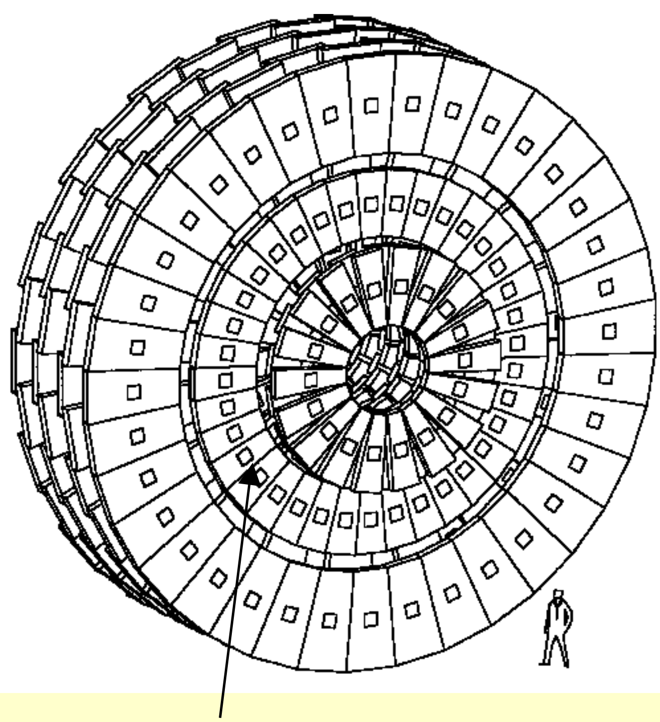




US CMS does all HB and all HCAL transducers and electronics

The CMS Muon System

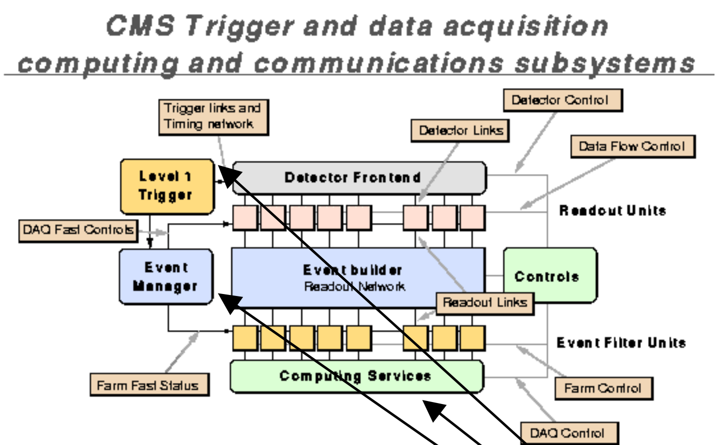




- The Higgs decay into ZZ to 4μ is preferred for Higgs masses > 160 GeV. Coverage to $|\eta| < 2.5$ is required ($\theta > 6$ degrees)

US CMS - ALL ME CSC

CMS Trigger and DAQ System



CMS data acquisition main parameters	
Average event size	= 1 MByte
Level-1 Maximum trigger rate	100 kHz
No. of Readout units (200-5000 Byte/event)	1000
Event builder (1000·1000 switch) bandwidth	= 500 Gbit/s
Event filter computing power	= $5\cdot10^6$ MIPS
Data production	= TByte/day
No. of readout crates	= 300
No. of electronics boards	= 10000

1 GHz interactions

40 MHz crossing rate

< 100 kHz L1 rate

<10 kHz "L2" rate

< 100 Hz L3 rate to storage medium

US CMS - L1 Calorimeter Triggers and L1 ME Triggers and L2 Event Manager and Filter Unit

CMS in the Collision Hall