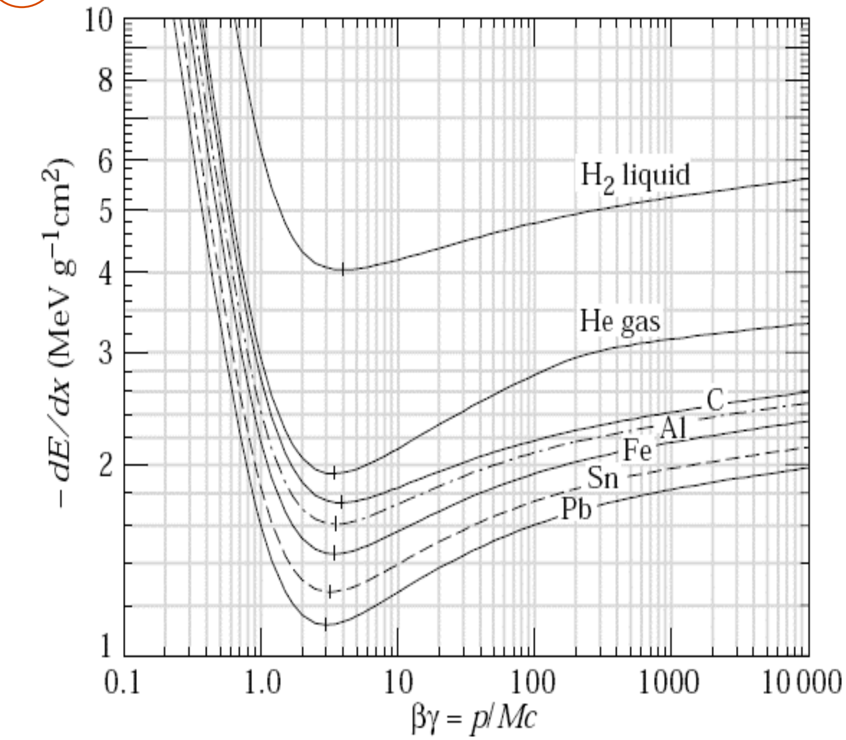
Interaction of particles in matter

- Particle lifetime τ: $N(t) = e^{-t/\tau}$
- Particles we detect ($\tau > 10^{-10}$ s, $c\tau > 0.03$m)
- Charged particles
  - $e^{\pm}$ (stable m=0.511 MeV)
  - $\mu^{\pm}$ ($c\tau$ = 659m m=0.102 GeV)
  - $\pi^{\pm}$ ($c\tau$ = 7.8m m=0.139 GeV)
  - $K^{\pm}$ ($c\tau$ = 3.7m m=0.495 GeV)
  - $p^{\pm}$ (stable m=0.937 GeV)
- Photons γ
- Neutral hadrons
  - n ($c\tau = 2.7\times10^{8}$m m=0.938 GeV)
  - K^0_L ($c\tau$ = 15.5m m=0.498 GeV)

Energy loss: dE/dx

- All charged particles can lose energy via interaction with the EM fields of atoms in matter
- For $\beta\gamma < 10^3$ the dominant energy loss mechanism is via ionization of atoms: $-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$
- Note the β^{-2} dependence and the dependence on Z and A. When $\beta\gamma$ is very large the logarithm dominates.
- Minimum is at $\beta\gamma \approx 3$
- x is measured in g/cm^2, so x = $\rho \times$L



Energy loss - radiation

- Highly relativistic particles ($\gamma > 10^3$ or so) lose energy mostly via "bremsstrahlung" radiation (emitting photons); critical energy E_c is where dE/dx loss equals radiation loss
- This radiation is emitted along the direction of motion
- Energy lost through radiation is proportional to the energy of the particle (constant fractional loss): $dE/dx|_{radiation} = E/X_0$, where X_0 is the "radiation length" and is a feature of the medium ($X_0 \sim Z^{-2}$)
- After a distance X_0 the particle retains a fraction *1/e* of its energy: $dE_{rad}/E = dx/X_0 \rightarrow E(x) = E_{initial} \exp(-x/X_0)$
- In practice, this is always the dominant energy loss mechanism for electrons; for heavier particles dE/dx usually dominates

Electrons

- In most materials electrons lose energy predominantly by radiation above a few 10s of MeV

Fractional energy loss

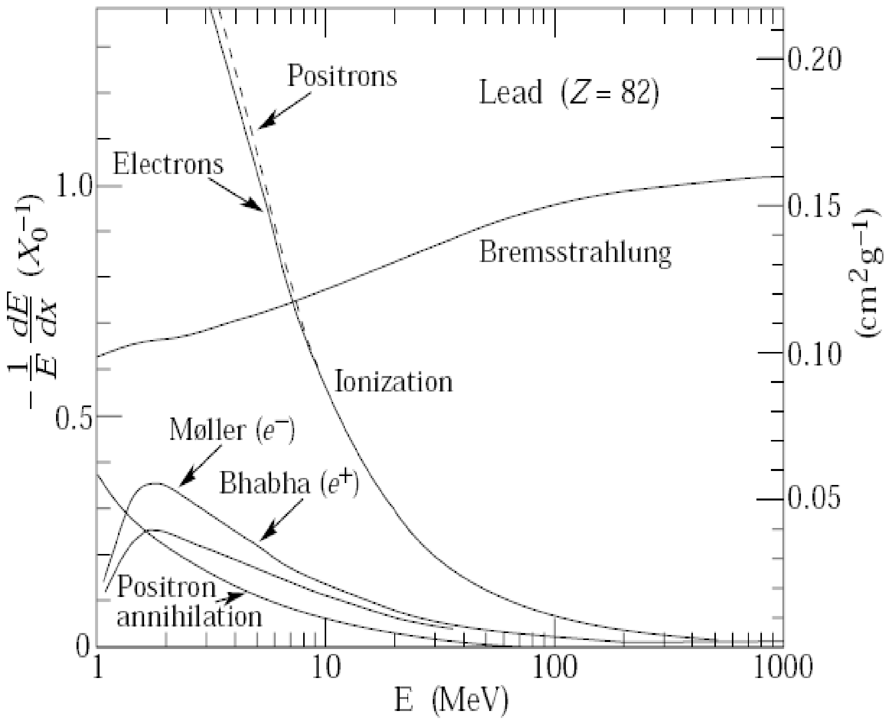
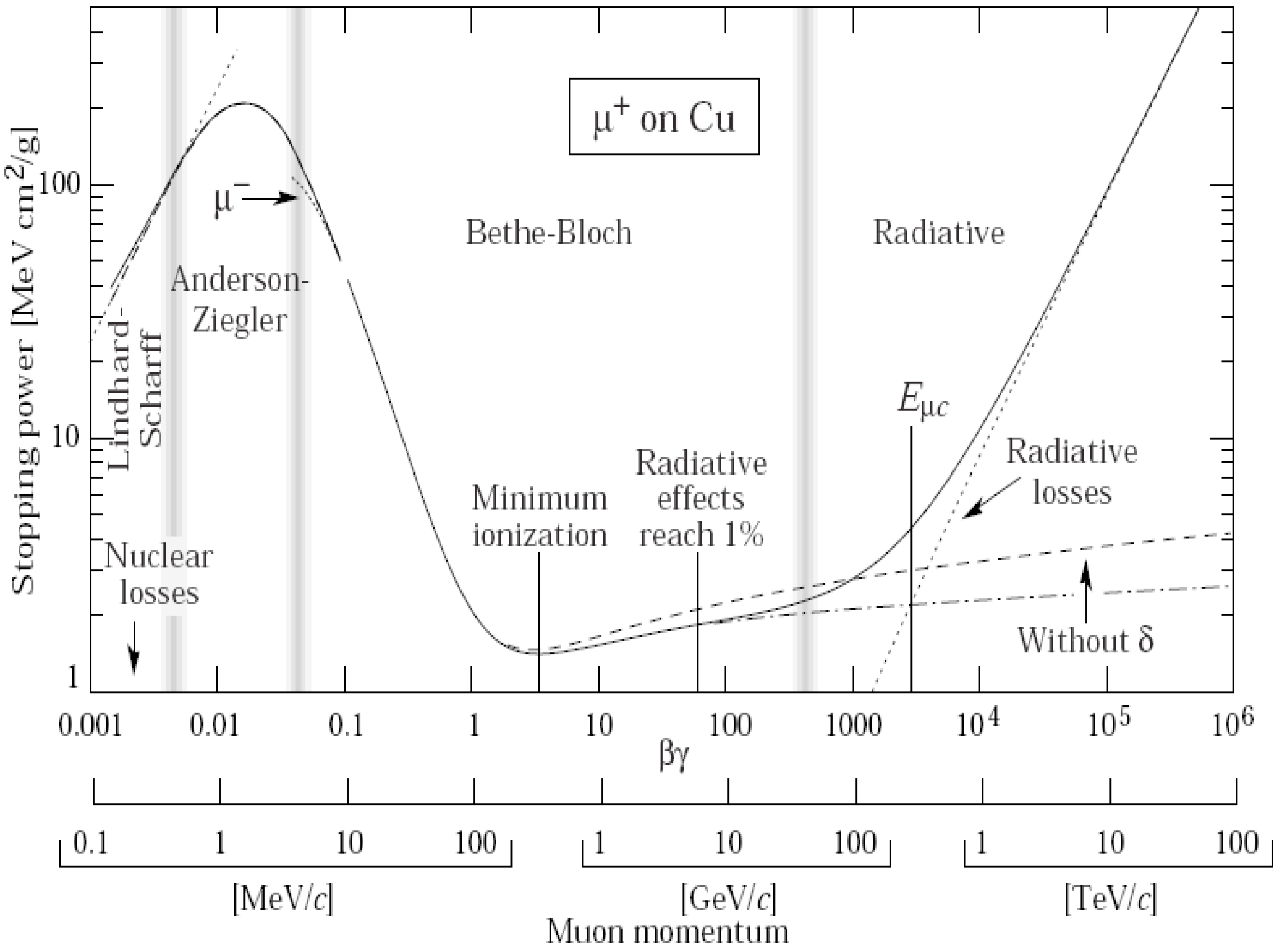


Figure 27.9: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization

Muons

- Muons are like electrons, only ~200 times heavier.
- The mass makes a big difference: dominant energy loss is by dE/dx instead of radiation → much longer range in matter than either electrons (which radiate photons) or hadrons (which interact strongly)
- Put a detector behind enough shielding and the particles that come through are (mostly) muons (consider, e.g., the atmosphere)

Energy loss of μ in Cu



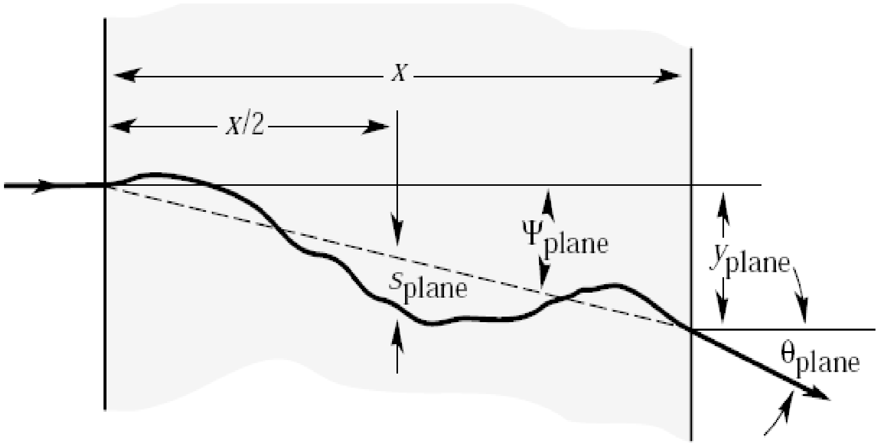
Cherenkov radiation

- Charged particles can exceed the speed of light in media with indices of refraction $n > 1$.
- In this case they produce a cone of Cherenkov radiation with opening angle given by $\cos\theta_c = 1/(n\,\beta)$
- If $\beta < 1/n$ there is no radiation (threshold velocity)
- This type of radiation is useful in determining the particle type (e, μ, π, K or p) when combined with a measurement of particle momentum (measure p and v to determine m)

Multiple Coulomb scattering

- Charged particles scatter off the EM field (mostly of nuclei)
- The net effect of many small random scatters is a deflection in angle given by

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$



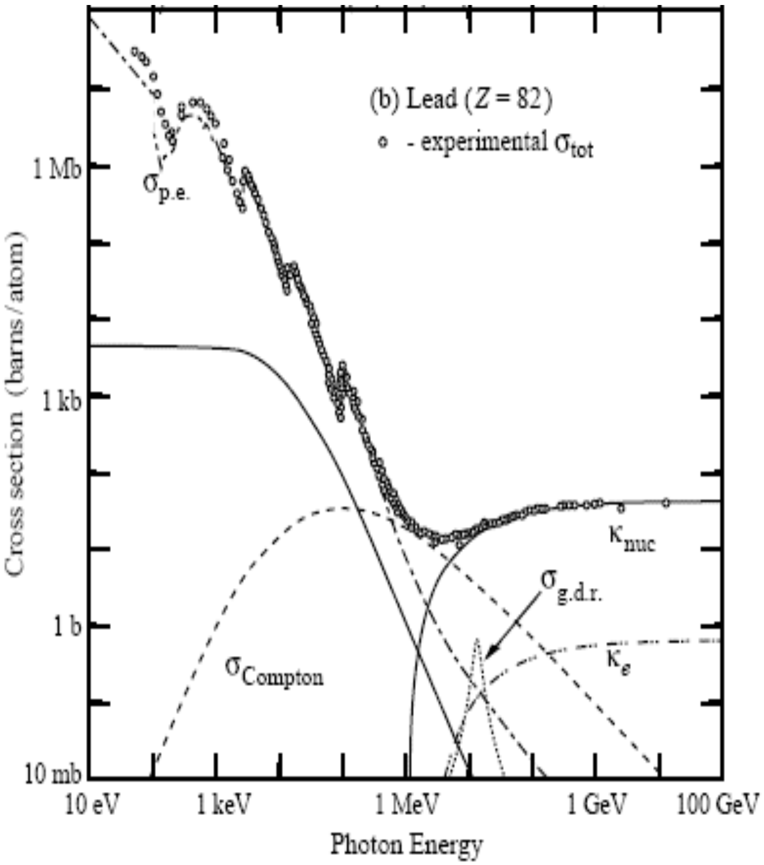
$= \theta_0$

Figure 27.8: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

- These deflections limit the accuracy with which particle trajectories can be measured

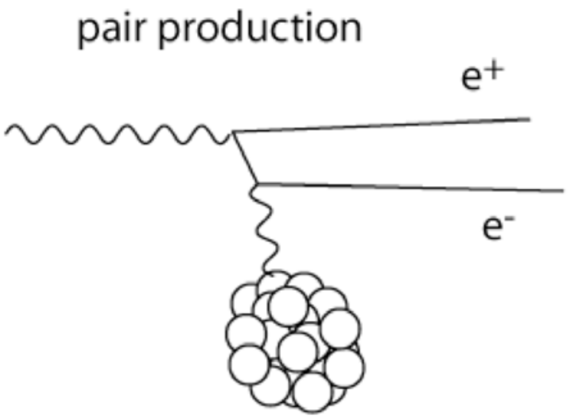
Photons

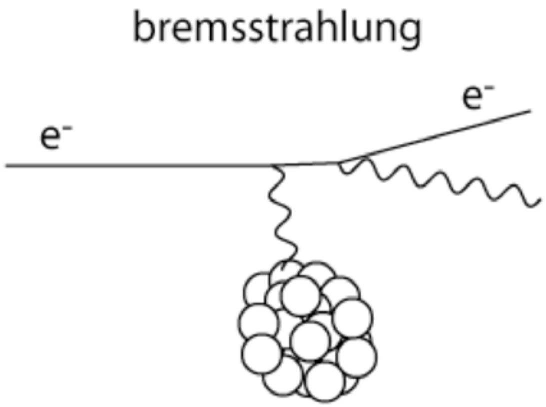
- Photons lose energy via
  - Photoelectric effect
  - Rayleigh scattering
  - Compton scattering
  - e^+e^- pair production
- The photons we're interested in measuring are always in the pair-production region
- The low-energy behavior is relevant to detector design due to electromagnetic showers, which produce many low-energy photons

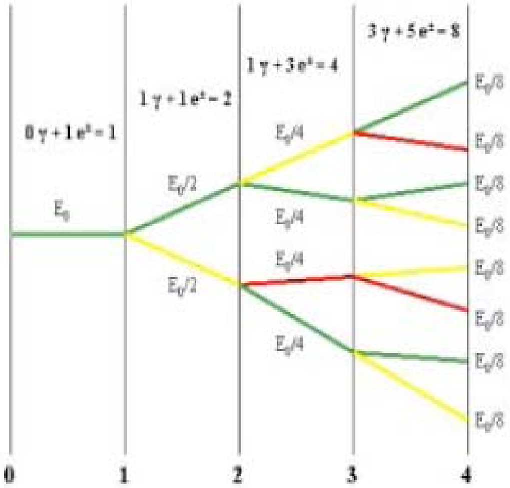


Electromagnetic showers

- Both photons and electrons at high energy initiate a cascade of pair-production and bremsstrahlung that leads to a “shower” of particles



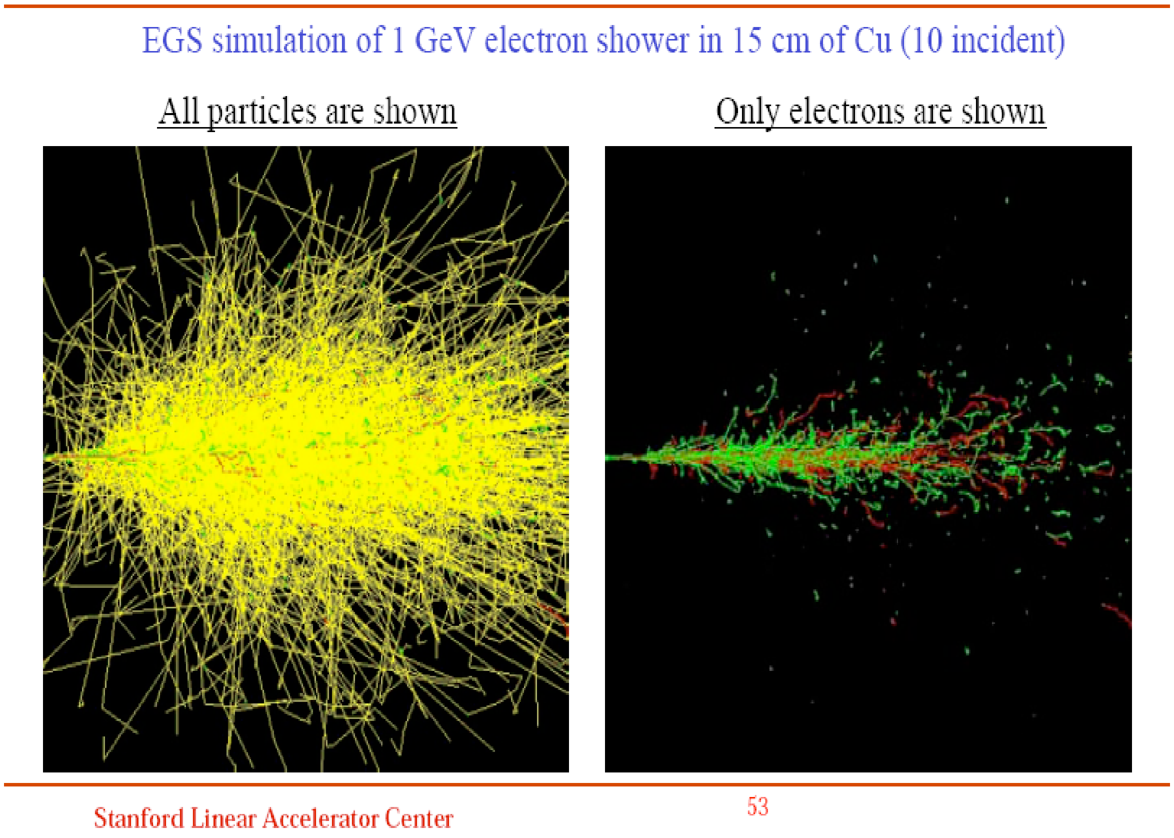




- Once the electrons and photons are at low energies they scatter (see previous slides) and result in a large number of low-energy photons

EM shower picture

- Simulation shows development of a shower; play with it at http://www2.slac.stanford.edu/vvc/egs/basicsimtool.html
- The lateral width of the shower is determined by multiple scattering of the electrons in the medium (Moliere radius)



EGS simulation of 1 GeV electron shower in 15 cm of Cu (10 incident)

All particles are shown

Only electrons are shown

Stanford Linear Accelerator Center

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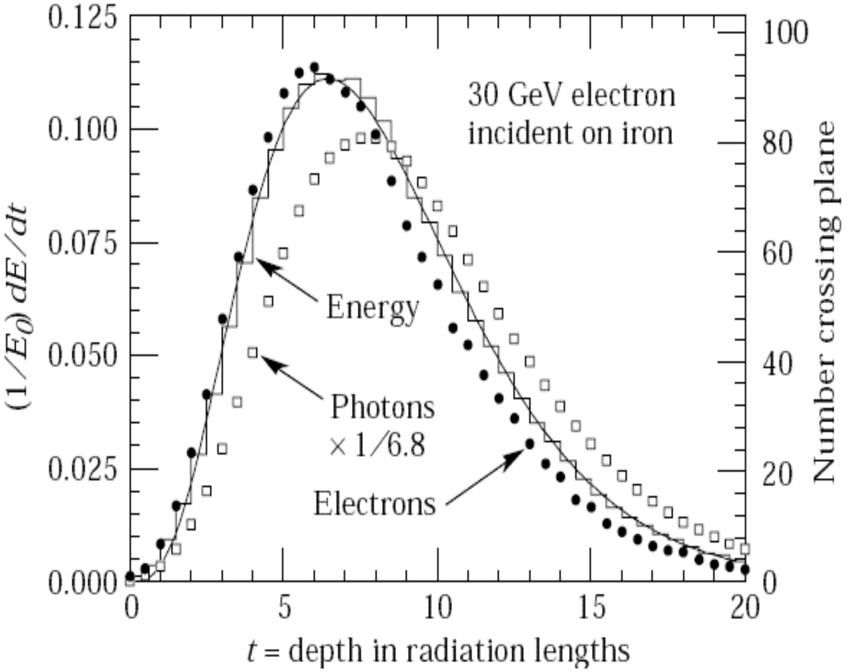
EM shower characteristics

- The energy deposition varies with “depth” in the medium
- Depth measured in radiation lengths X_0
- Photon-induced showers start a bit later than electron-induced showers (initial pair production has to occur); effective radiation length for photons is 9/7 X_0
- The energy of the photons at the end of the shower is proportional to the incident particle energy – a useful feature for building detectors



Hadrons

- All hadrons can interact strongly in matter
- Neutral hadrons (e.g. neutrons) interact *only* this way
- Hadrons create a cascade of particles (a hadronic shower), which produces mini-EM showers (from γ daughters of π^0) and loses *or* gains energy through nuclear interactions
- Hadronic showers are much less uniform and regular than EM showers
- The nuclear absorption length λ is analogous to the radiation length X_0 for EM showers

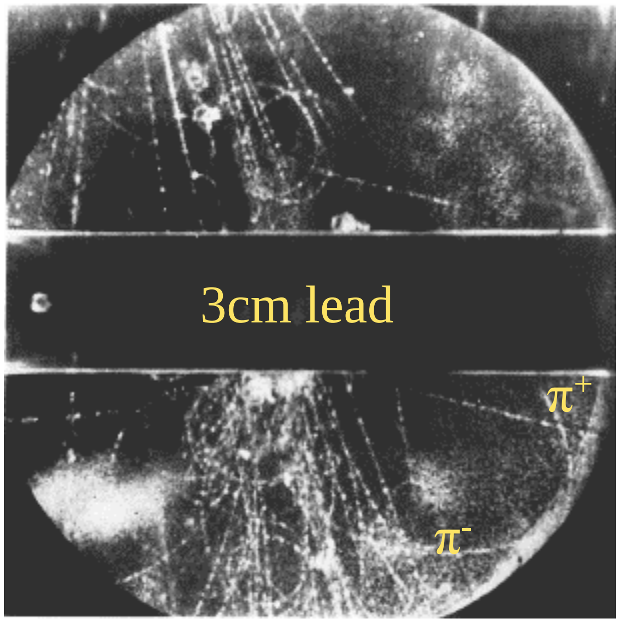
Detector strategies

- "Non-destructive imaging" of charged particles
  - Use ionization energy loss, detect ionization trails
  - Use magnetic field to bend particles, determine momentum
- Determination of particle type
  - Measure speed in addition to momentum
  - Use presence/absence of Cherenkov light
- Absorption of photons / EM calorimetry
  - Use proportionality between incident energy and energy (or number) of photons in cascade
- Absorption of hadrons / hadronic calorimetry
  - Use rough proportionality (poorer resolution than for EM)
- Penetration of large amount of material → muons (or neutrinos)

Detectors of charged particles

- Magnetic field – dipole (for some fixed target detectors), solenoidal (for most colliding-beam experiments) or toroidal (large volume muon detection, e.g. ATLAS)
- Two main types:
  - Ionization based: gaseous mixture (usually including a noble gas, e.g. Ar or He)
  - Solid state, e.g. doped silicon, in which traversing charged particles create electron-hole pairs
- Both in widespread use.

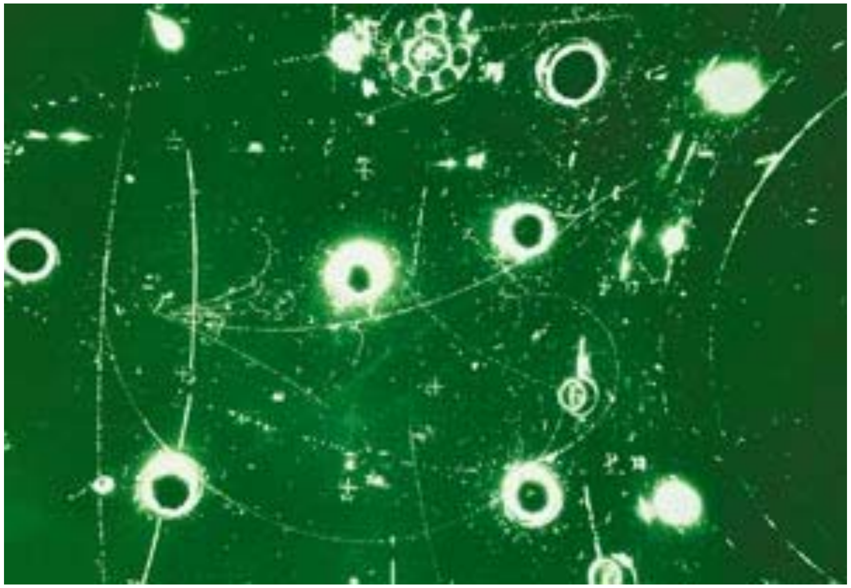
Bubble and cloud chambers

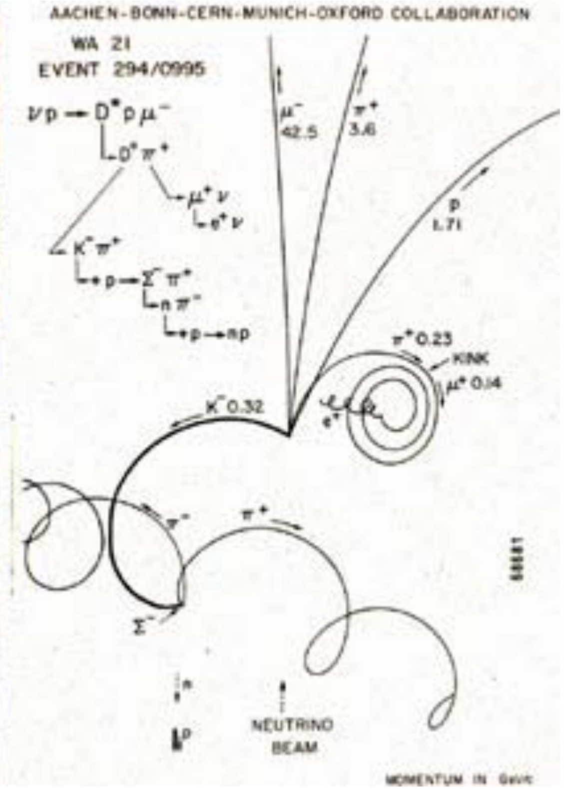


- Early detectors: spark, cloud chambers
  - Spark chambers use HV and initiate a discharge along the ionization trail left by a particle (like lightning); poor spatial precision
  - Wilson cloud chamber uses supercooled vapor; ionization trail seeds phase transition to liquid (little drops form along the trajectory). Photographic readout.
  - Cycle time ~minutes
- Bubble chambers (Glaser)
  - Use superheated liquid; ionization trail seeds phase change to vapor
  - Good spatial resolution
  - Photographic readout (limits rate)
  - Pressure used to recondense liquid; cycle time ~1s

Big Bubble Chambers

- Last and best of the kind: Gargamelle and the Big European Bubble Chamber (CERN, 1970s)
- Small army of “scanners” were needed to search for interesting events and record trajectories numerically





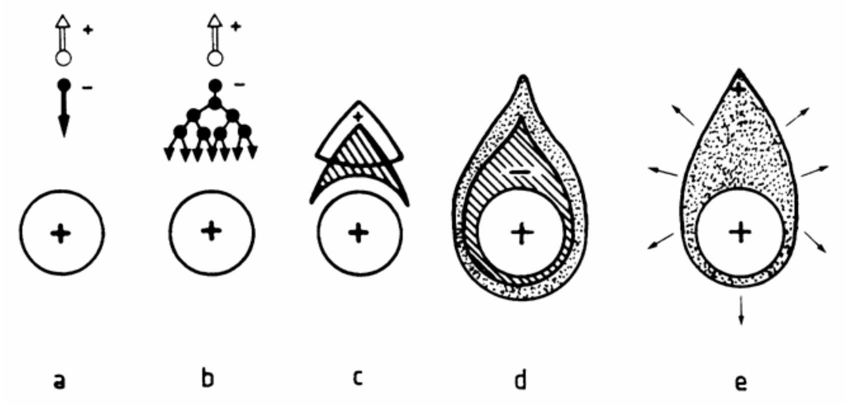
Scintillation detectors

- Ionizing radiation causes some materials (e.g. organic plastics and inorganic crystals) to “scintillate”, i.e. to release photons from the decay of molecules excited by the ionization.
- Scintillation light tends to be in the near UV; need “wavelength shifters” to facilitate optical readout
- Photomultiplier tubes record the generated light
- Scintillators are still in use; they are cheap (so large areas can be instrumented) and sensitive to the passage of a single charged particle.
- The fast decay time (few ns) of many scintillators makes them useful for triggering

Wire chambers

- Multi-Wire Proportional Chambers (Charpak) allow ionization trails to be recorded electronically (no need for scanners!)

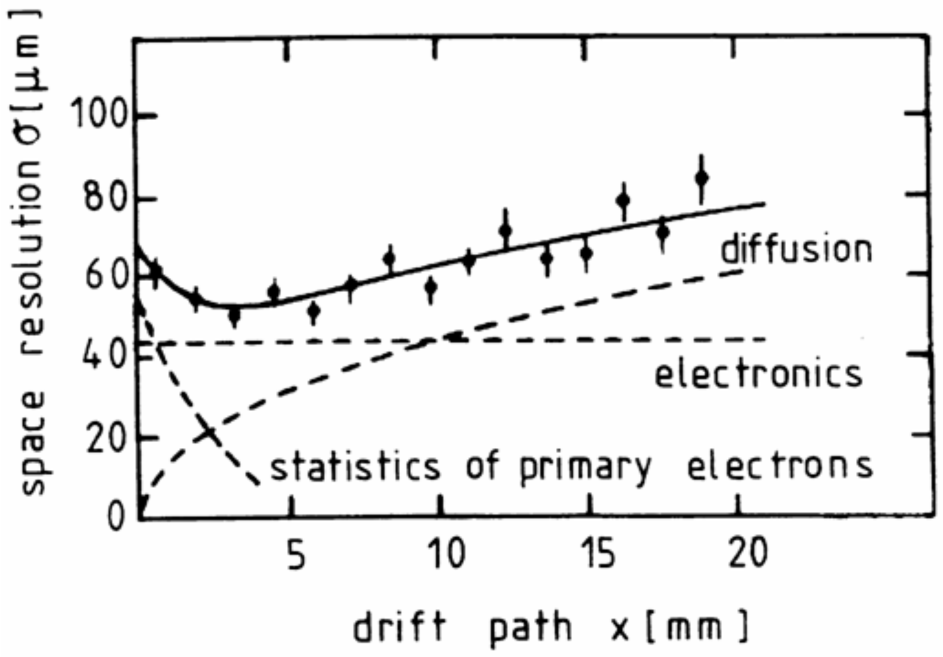
- Ionized electrons drift toward anode wires
- **E** field near anode ~ ΔV/r
- Electrons are accelerated enough to cause an "avalanche" of ionization → amplification of the signal (factor of 10^4 or so)



- Resolution determined by wire spacing
- Better idea: use arrival time to determine position (better resolution with fewer wires)

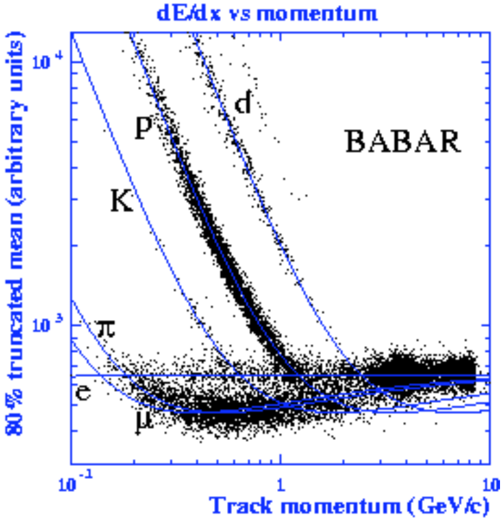
Drift chamber

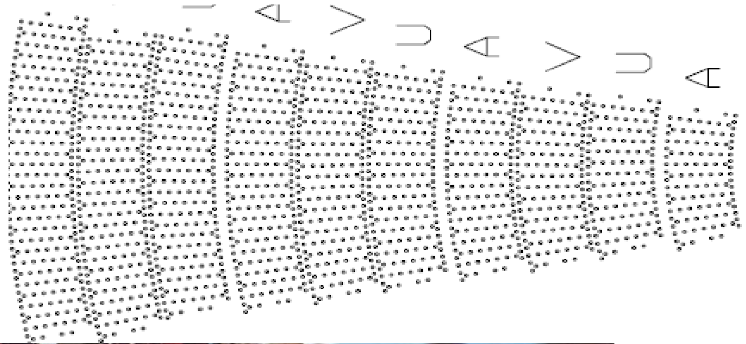
- Ionization produced in a gas drifts in a modest electric field:
  - Drift speed is in the range of 10-100 µm/ns (depends strongly on what gas is used)
  - Record the time required for the ionization to drift to the anode with ~few ns timing precision, allowing ~100 µm measurements
  - Diffusion reduces resolution for long drift paths
  - Charge deposited (proportional to primary ionization) allows a simultaneous measurement of dE/dx energy loss → particle identification

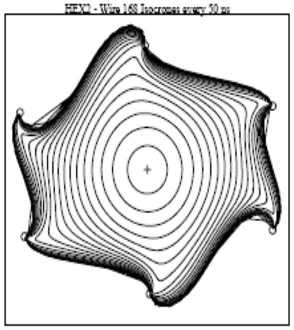


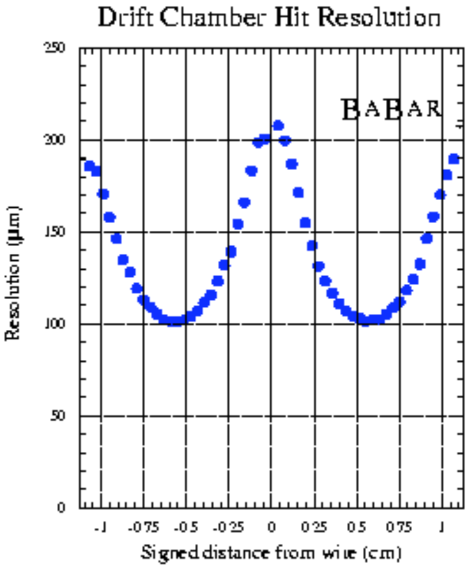
BaBar Drift Chamber

- Detector was strung at TRIUMF in 1997
- ~28000 wires; 7104 sense wires (20μm)
- 2.8m long, 0.2m to 0.8m in radius
- 4 axial and 6 stereo superlayers
- Helium-isobutane (80/20) gas mixture





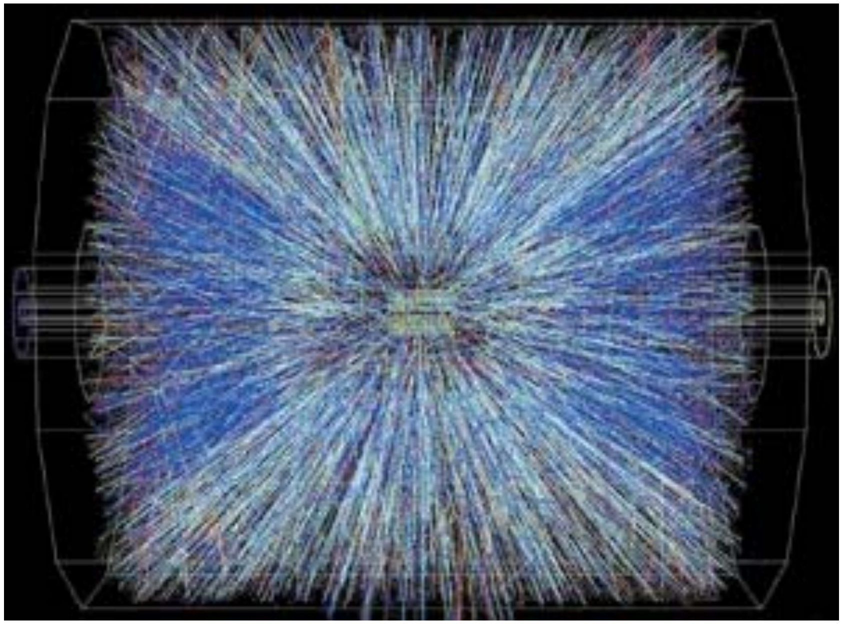




Time projection chamber

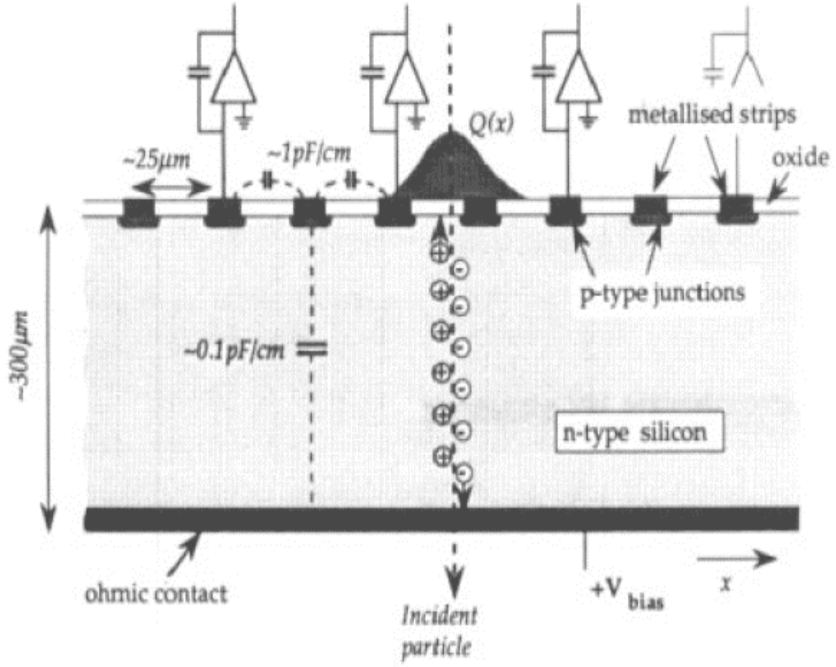
- Ionization trails drifted along axis of cylinder in *parallel **E** and **B** fields* → electrons spiral along field lines, limits diffusion
- Long drifts (2m or more) are feasible
- Readout is entirely on endplates – no wires in the bulk volume
- Almost bubble-chamber—like pictures of trajectories:

STAR TPC at RHIC
(Au-Au collisions)



Silicon detectors

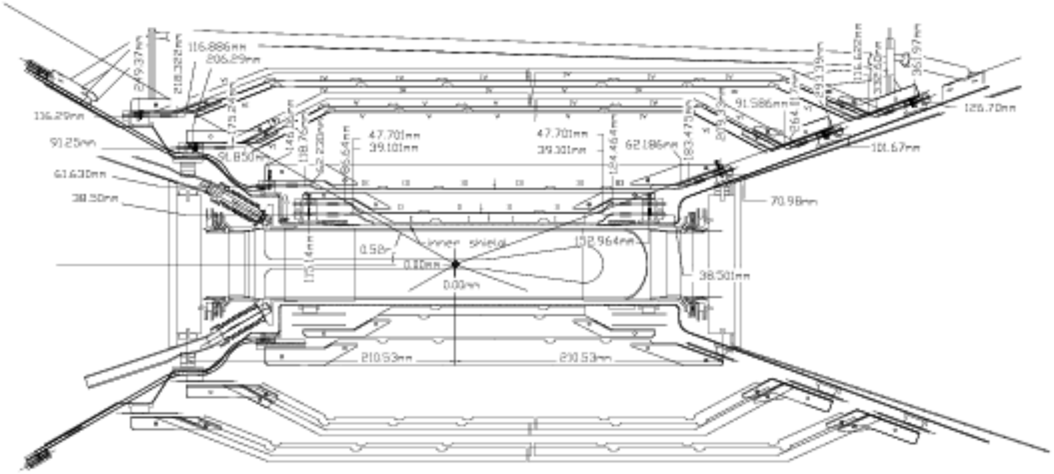
- Basic mechanism is electron-hole production along the path of a traversing charged particle in a reverse-biased region (i.e. where electrons and holes can’t normally be found)
- Charge is collected on either strips or pixels bonded to the surfaces of the silicon wafer

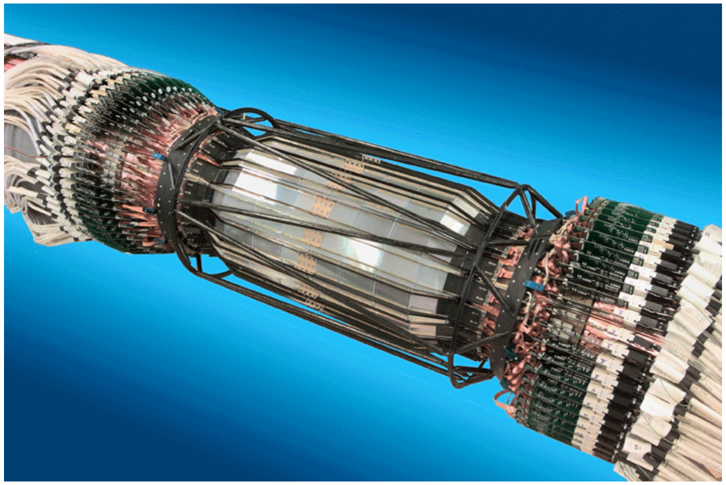


Silicon detectors

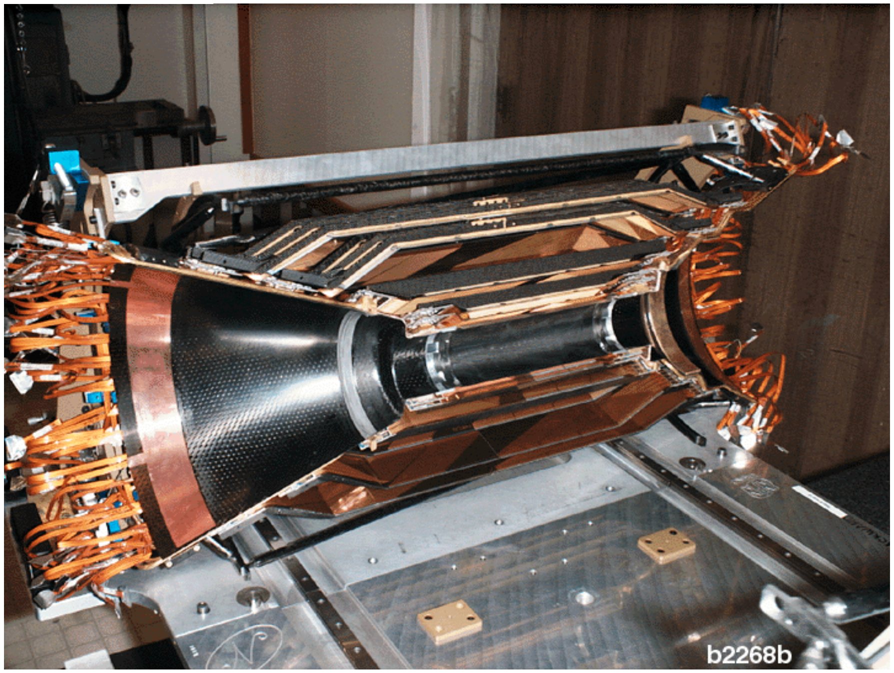
- Excellent spatial resolution (5-50 μm)
  - Large number of electron-hole pairs produced (~10^4 in 300 μm)
  - Diffusion is modest
  - Pitch (distance between strips) is small (25-200 μm); charge-sharing on nearby strips is used to determine track position (weighted average)
- Silicon detectors are relatively expensive, but large area (~100m^2 of Si) detectors are being built for LHC
- Large Silicon detector arrays have up to10 million readout channels → 10^7 amplifiers, 10^7 ADCs, … must use custom analog microchips for readout

BaBar Silicon Tracker





- 5 layers of wafers
- Both r-φ and r-z measured
- Resolution per wafer ≈15 μm
- Slow radiation damage over time (since 1999)



Electromagnetic calorimeters

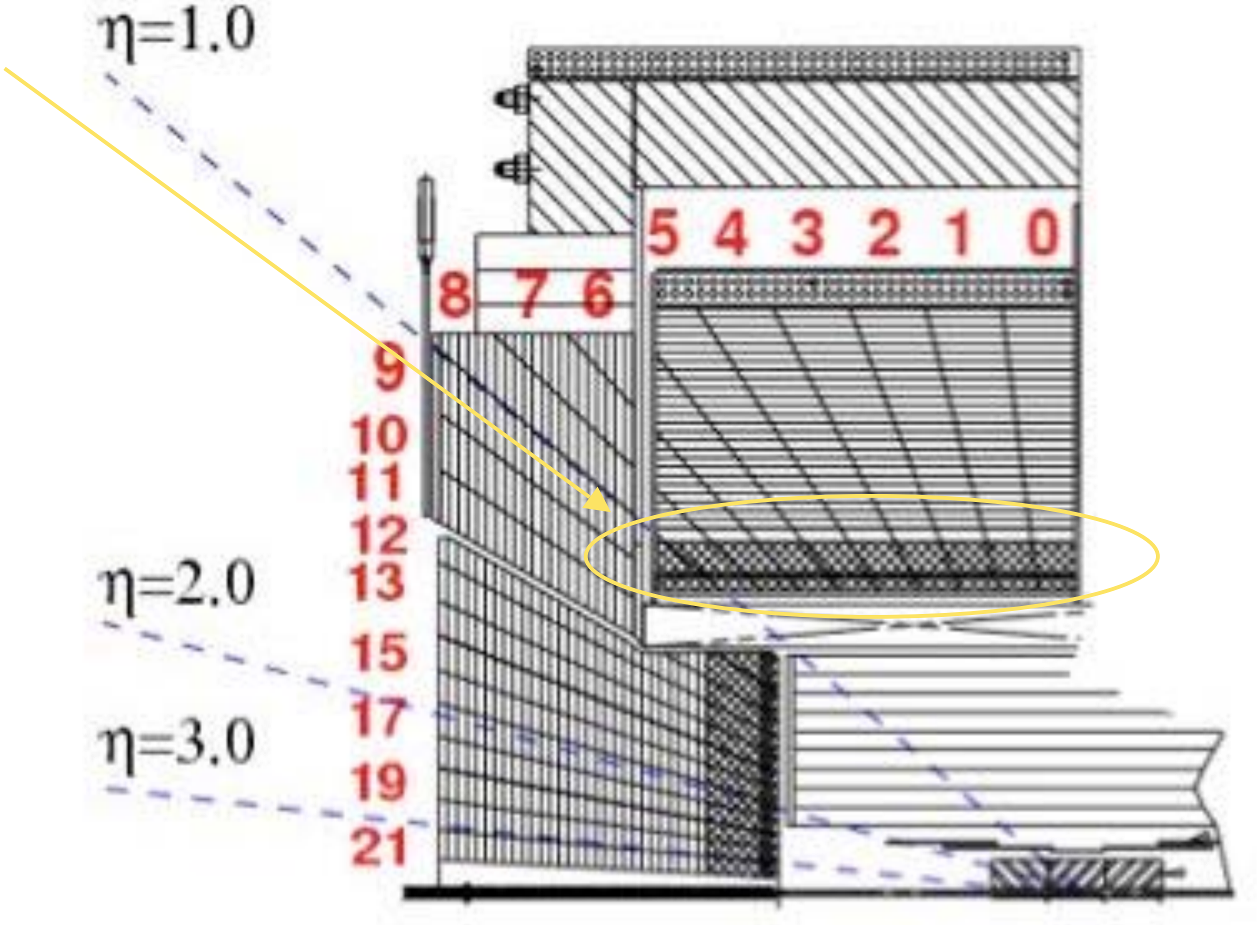
- Two main categories:
  - Sampling calorimeters, consisting of an absorber interspersed with active (readout) layers
  - Homogeneous calorimeters, where the entire volume is active
- Properties of interest
  - Energy resolution
  - Spatial resolution
  - Shower “shape”, i.e. spread and depth

Sampling calorimeters

- Stack of absorber (high Z material) and active medium (e.g. scintillator or wire chamber)
- Measure either the number or the energy of particles produced in the shower via a discrete number of samples
- Allows shower profile (depth) to be determined
- Energy resolution $\sigma_E \sim a/E^{1/2}+b$, where $a \sim 0.1$; dependence on $E^{1/2}$ comes from measuring $N \pm \sqrt{N}$ photons (since E is proportional to N)

CDF sampling calorimeter

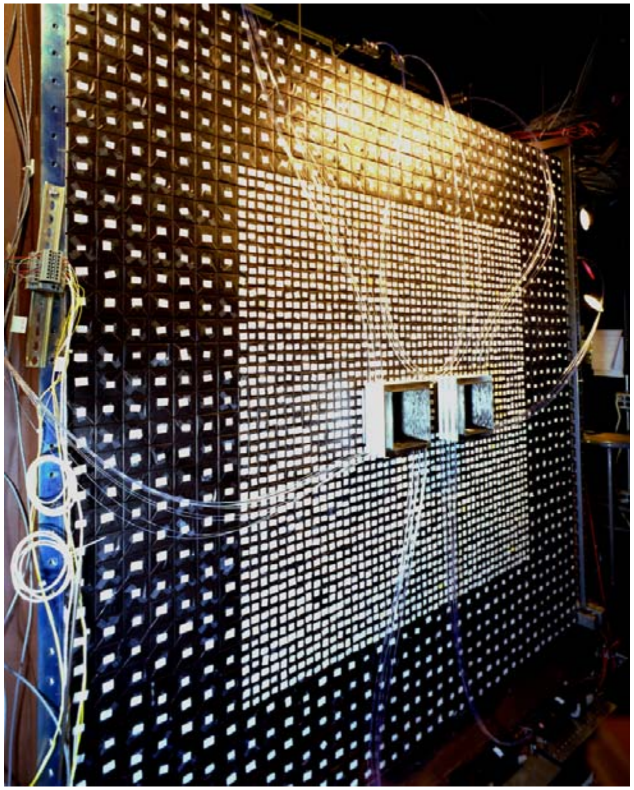
- calorimeter is arranged in projective “towers” that point to the interaction region
- Electromagnetic and hadronic sections are both sampling



Crystal calorimeters

- Shower develops and is read out in the same medium; no sampling fluctuations to reduce resolution
- Light is produced by scintillation or Cherenkov radiation
- Longitudinal segmentation is more difficult than for sampling
- Good energy resolution: $\sigma_E \sim a/E^{1/4}+b$, where $a \sim 0.03$ and E is measured in GeV

CsI crystal being wrapped



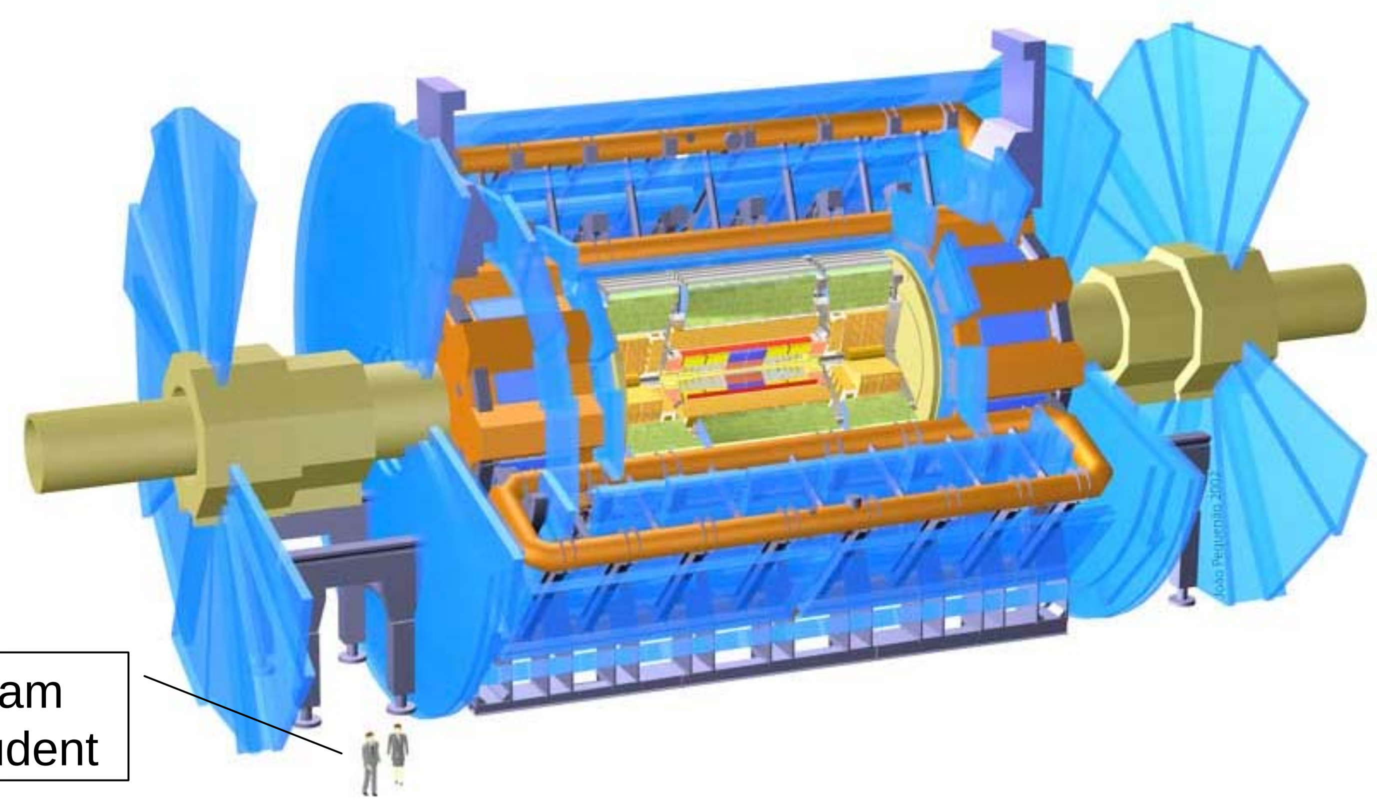
KTeV calorimeter

Hadronic calorimetry

- Very different response to hadrons (e.g. π^+) and γ (which come predominantly from π^0 decay)
- Sampling calorimeters tend to be used (e.g. Cu and liquid Argon for ATLAS)
- Try to design calorimeter to equalize the response to these components of the hadronic shower (compensating)
- Resolution poorer than for electromagnetic calorimetry; typical values $\sigma_E \sim a/E^{1/2}$ with a~0.4-1.0

Muon detectors

- Consist of wire chambers (or scintillators) separated from particle source by substantial shielding
- Sometimes placed in magnetic field to allow independent measurement of muon momentum (e.g. ATLAS)



Sue and Sam
graduate student

Triggering, readout, reconstruction

- Particles from interesting interactions leave signals in the detector, but so do particles from common and uninteresting processes, from electronic noise, etc.
- Reading the information (times and pulse heights for each channel) is impractical; it takes too long, and during the process the detector cannot record new events
- Triggering attempts to decide which events are worth reading out based on a subset of information obtained quickly; reduction factors are often 10^6 or more
- Once a set of events is read out and stored, sophisticated algorithms reconstruct particles from the channels with signals and determine momenta, positions and energies with precision

Modern colliding-beam detectors

- Layered concept – first tracking, then particle identification, then calorimetry, then muon detection
- Many examples – size dictated by maximum particle momentum
- Variety of technologies – dictated by performance, cost, accumulated expertise
- Huge undertaking – requires hundreds of scientists working together

BaBar detector

- covers $\Omega = 0.90\times4\pi$ in CM frame
- Asymmetric
- Si strips at vertex
- Drift chamber
- Ring Imaging Cherenkov detector
- CsI(Tl) calorimeter
- Muon system