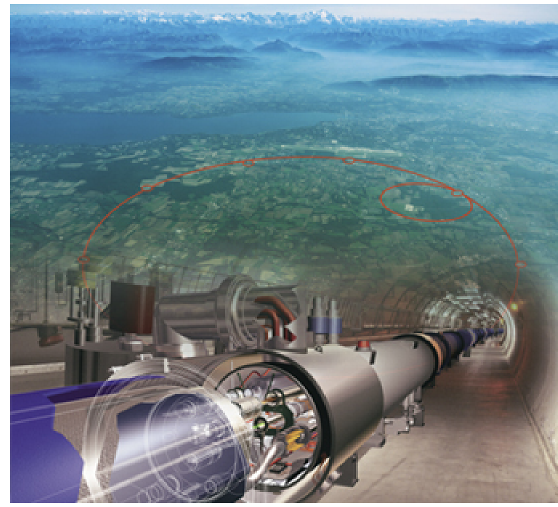
Accelerators and Detectors

Outline

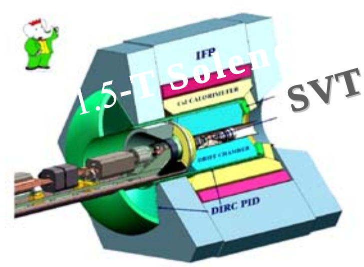


Accelerators

- Linear Accelerators
- Cyclotrons and Synchrotrons
- Storage Rings and Colliders
- Particle Physics Laboratories

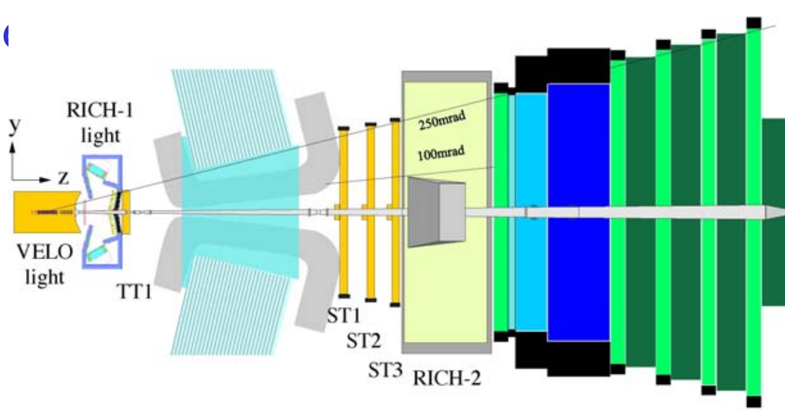
Interactions of Particles with Matter

- Charged Particles
- Neutral Particles, Photons



Detectors in Particle Physics

- Position sensitive devices
- Calorimeters
- Particle Identificati



Experiments

- Mainly at colliders

Particle Accelerators

Accelerator Principle

Charged particles are accelerated to high energies using electromagnetic fields

e-, e+, p, anti-p, ionised nuclei, muons

Why are Accelerators used?

Higher energies or momenta allow to probe shorter distances

de Broglie wavelength

$$\lambda = \frac{\hbar c}{pc} = \frac{197\ \mathrm{MeV \cdot fm}}{p\,[\mathrm{GeV/c}]}$$

e.g. 20 GeV/c probes 0.010 fm

Cockroft-Walton Accelerator

High DC voltage accelerates particles through steps created by a voltage divider

Limited to ~ 1 MV

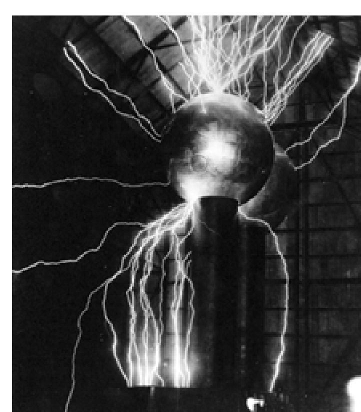
Fermilab Injector

Ionised hydrogen, H_2^- source accelerated to 750 kV

Van de Graaff Accelerator

charge transported by belt

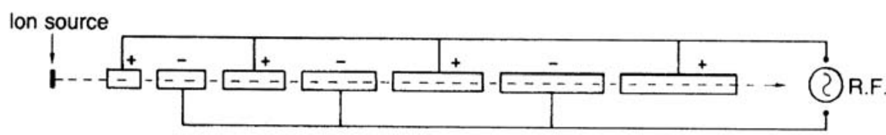
Limited to ~ 10 MV



Linear Accelerators - Linac

Working Principle - Linac

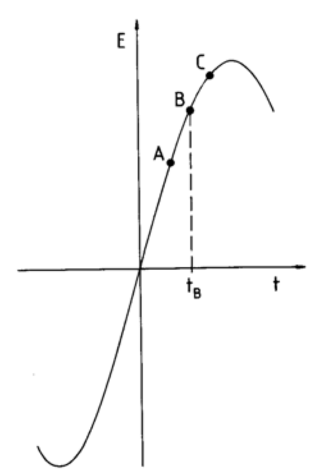
Charged particles in vacuum tubes
accelerated by Radio Frequency (RF) waves



RF tubes increase in length size a
particle speed increases (protons, for e- v≅c)

Radio Frequency Acceleration

Radio Frequency fields O(few 100 MHz)
Field strengths – few MV/m - klystrons
transported by RF cavities
Oscillating RF polarities produce
successive accelerating kicks
to charged particles
when RF is decelerating
particles shielded in RF tubes
Particles in phase with RF



Fermilab Injector

400 MeV protons, 150 m long

Stanford Linear Accelerator (SLAC)

Largest Linac - 3 km long, 50 GeV e- and e+

Circular Accelerators

Cyclotron

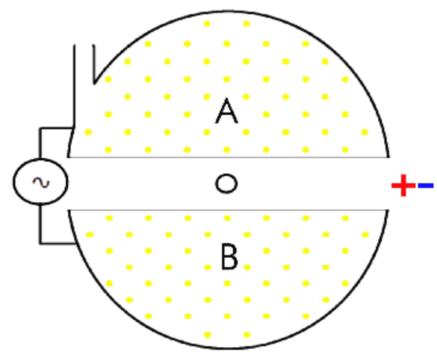
Charged particles are deflected in magnetic field B

Lorentz Force $\vec{F}_L = e\vec{v} \wedge \vec{B}$

$\boxed{p[GeV/c] = 0.3B[T]\rho[m]}$

radius of curvature ρ

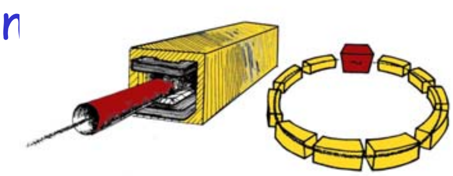
Particle accelerated by RF
in magnet with E perp. B
Protons, limited to ~ 10 MeV
relativistic effects



Synchrotron

B-field and RF synchronised
with particle speed
radius ρ stays constant
Superconducting dipole magnets
B-fields up to 8 Tesla
Quadrupole magnets focus beam
alternate focusing and defocusin
in horizontal and vertical plane

SpS at CERN



Synchrotron Radiation

Accelerated particles radiate
Energy loss per turn
most important for e-

$$\Delta E = \frac{4\pi}{3} \frac{e^2 \beta^3 \gamma^4}{\rho}$$

Storage Ring - Colliders

Beams from synchrotron or linac
have bunch structure

Secondary Beams

Accelerated beam from synchrotron or linac
on target $\rightarrow$ e, μ, π, p, K, n, ν, ${}_{Z}^{A}X$ beams
Many different types of experiments

Storage Rings

Particle beams accelerated in synchrotron
and stored for extended periods of time

Colliders

Two counter-rotating beams collide at
several interaction points around a ring

Luminosity

$$L = \frac{N_1 N_2}{r_x r_y} f n_B$$

N_i # of particles in beam I
n_B # of bunches/beam
$r_{x,y}$ beam dimension in x,y
f revolution frequency

Fermilab

Chicago, http://www.fnal.gov

Tevatron

Current highest E_{CoM}
energy collider
1 TeV p on 1 TeV anti-p
maximum 10^{12} anti-p

Storage Ring - Colliders

CERN

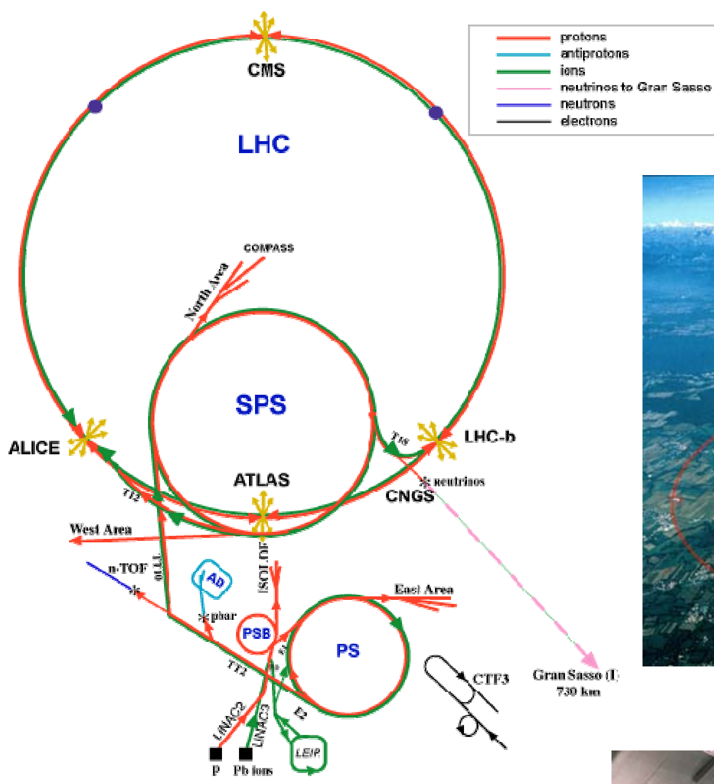
Geneva, Switzerland, http://www.cern.ch

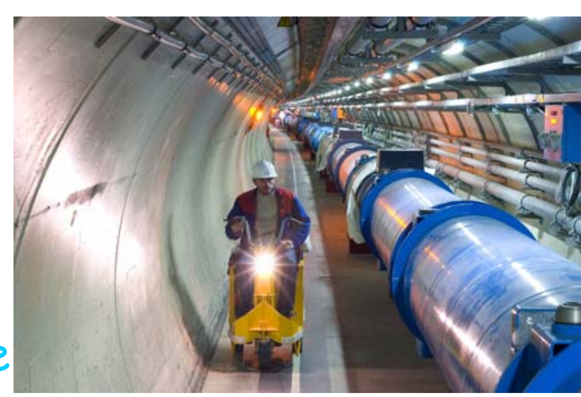
PS -- 29 GeV, injector for SPS

SPS -- 450 GeV p onto 450 GeV anti-p

injector for LEP/LHC

LEP -- 100 GeV e- onto 100 GeV e+





LHC -- will start in 2007

7 TeV p onto 7 TeV p

4 experiments

ATLAS, CMS, LHCb, Alice

Particle Physics Laboratories

CERN, Fermilab

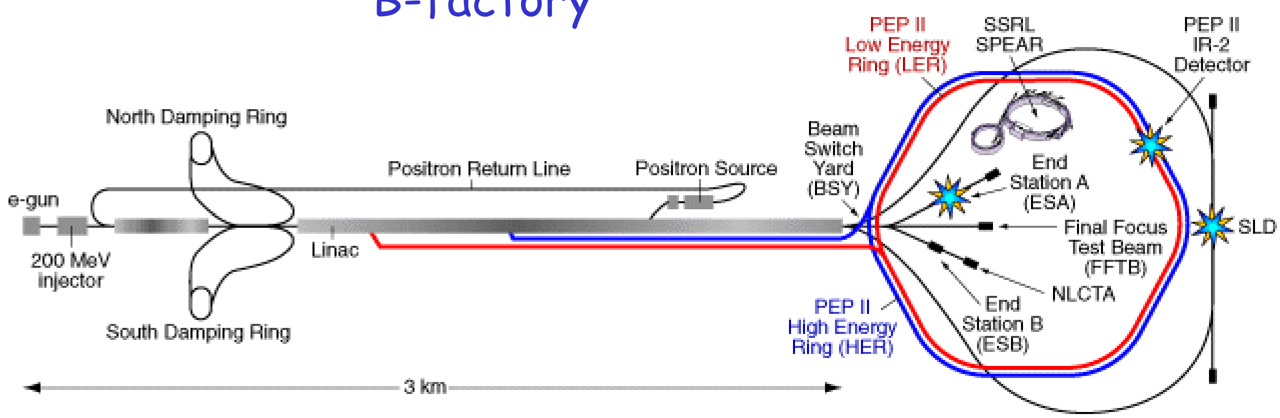
See previous slides

SLAC

California, http://www.slac.stanford.edu

SLC -- 50 GeV e- onto 50 GeV e+

PEP-II -- 9.0 GeV e- onto 3.1 GeV e+ B-factory



DESY

Hamburg, http://www.desy.de

HERA -- 920 GeV p onto 30 GeV e-

KEK

Japan, http://www.kek.jp

KEKB -- 8.0 GeV e- onto 3.5 GeV e+ B-factory

JPARC -- 50 GeV synchroton (in construction)

Cornell

Ithaca, NY, http://www.lns.cornell.edu

CESR -- 3… 6 GeV e- onto 3 … 6 GeV e+

Interactions with Matter

Basic Principles

Mainly electromagnetic interactions,
ionization and excitation of matter
"Applied QED", lots of other interesting physics

Charged Particles

Electrons, positrons

Heavier particles: μ, π, K, p, ...

- Energy loss
  - Inelastic collisions with the atomic electrons
- Deflection
  - Elastic scattering from nuclei
- Bremsstrahlung
- Photon emission (Scintillation, Cherenkov)

Neutral Particles

Photons

- Photo electric effect
- Compton scattering
- Pair Production

Neutrons, Neutral hadrons

- Nuclear reactions

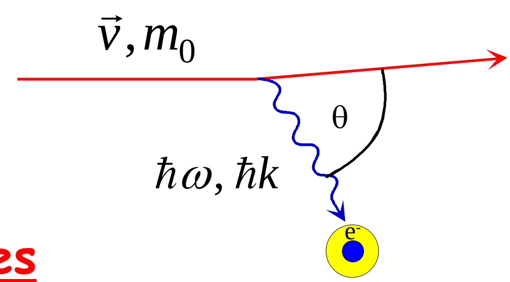
Neutrinos

- Weak reactions

Energy Loss

Coulomb Scattering

Traversing charged particle
scatters off atomic electrons
of medium, causes ionisation



Energy loss of charged particles

by ionisation

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

Bethe-Bloch

N_0 - Avogadro's number
Z, A - atomic and mass number of medium
x - path length in medium in g/cm^2
$x = \rho t$ mass density ρ and thickness t in cm
dE/dx measured in [MeV g^{-1} cm^2]
α - fine structure constant
$r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.82$ fm (classical e radius)
β, γ - speed and Lorentz boost of charged particle
Maximum energy transfer T_{max}
Mean excitation energy I

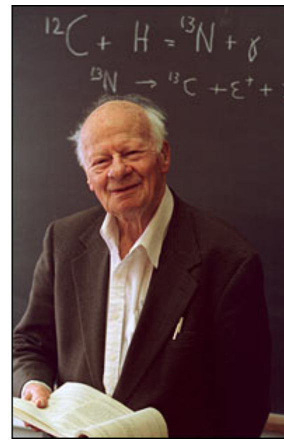
$$T^{\max} = \frac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e / M + \left(m_e / M \right)^2} \qquad I \approx I_0 Z \ \text{ with } \ I_0 = 10\,\text{eV}$$

Valid for "heavy" particles ($m \geq m_\mu$)

e- and e+ ($m_{proj} = m_{target}$) → Bremsstrahlung
dE/dx ~ 1/m_{target} → scattering off nuclei very small

Bethe-Bloch

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



dE/dx Energy Dependence

only on $\beta\gamma$ — independent of m_{proj}

For small β — $dE/dx \propto 1/\beta^2$

Minimum Ionising Particles

For $\beta\gamma \approx 4$ or $\beta \approx 0.97$ (MIP)

Relativistic rise

For $\beta\gamma \gg 1$ — $\ln \gamma^2$ term

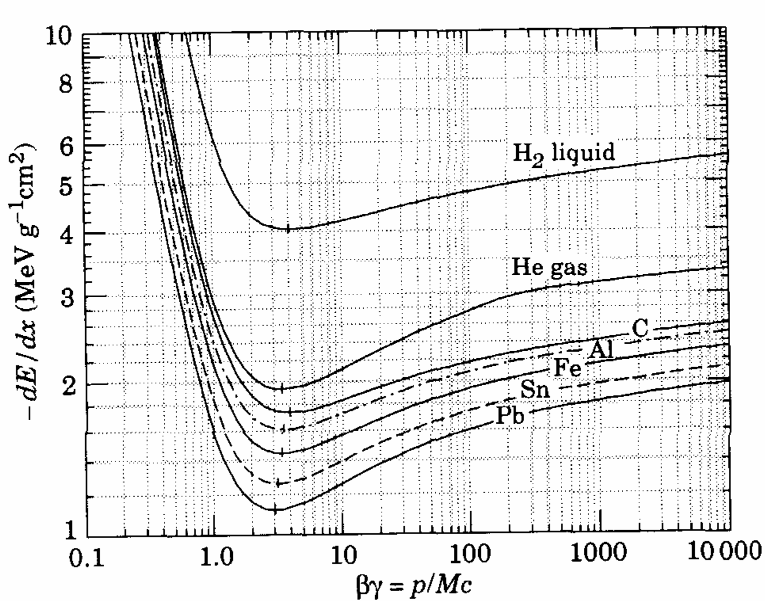
Relativistic expansion of transverse E-field

larger for gases than dense media

Density effect — δ term

Cancels relativistic rise cancelled at very high γ

polarization of medium screens more distant atoms



dE/dx rather independent of Z except hydrogen

$$\frac{dE}{dx} \approx 1 \ldots 2 \ MeV\, g^{-1} cm^2$$

Interaction of Photons

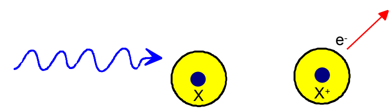
How do Photons interact?

Photons are neutral

Photons can create charged particles

or transfer energy to charged particles

Photoelectric effect



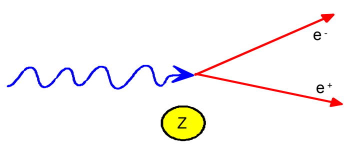
$$\gamma + \text{atom} \to \text{atom}^{+} + e^{-}$$

Compton scattering

e+e- Pair Production

in Coulomb field of nucleus

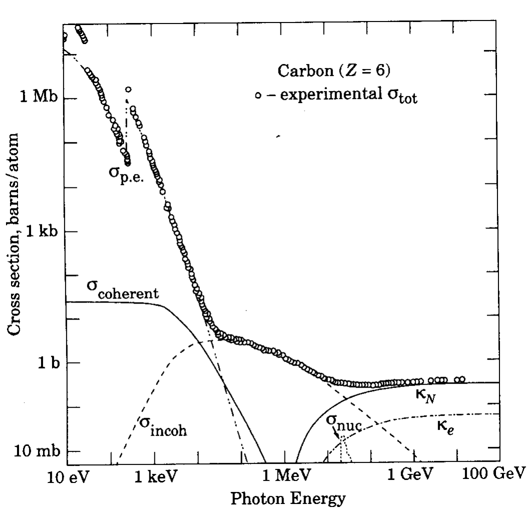
which absorbs recoil, requires $E_\gamma \geq 2m_e c^2$



$$\gamma \; + \; nucleus \quad \to \quad e^+ e^- \; + \; nucleus$$

γ energy does not degrade, intensity is attenuated

Absorption of Photons in Matter



I: Intensity

x: Target thickness

$$I_\gamma = I_0 \exp(-\mu x)$$

$$\mu = \mu_{photo} + \mu_{Compton} + \mu_{pair} + \ldots$$

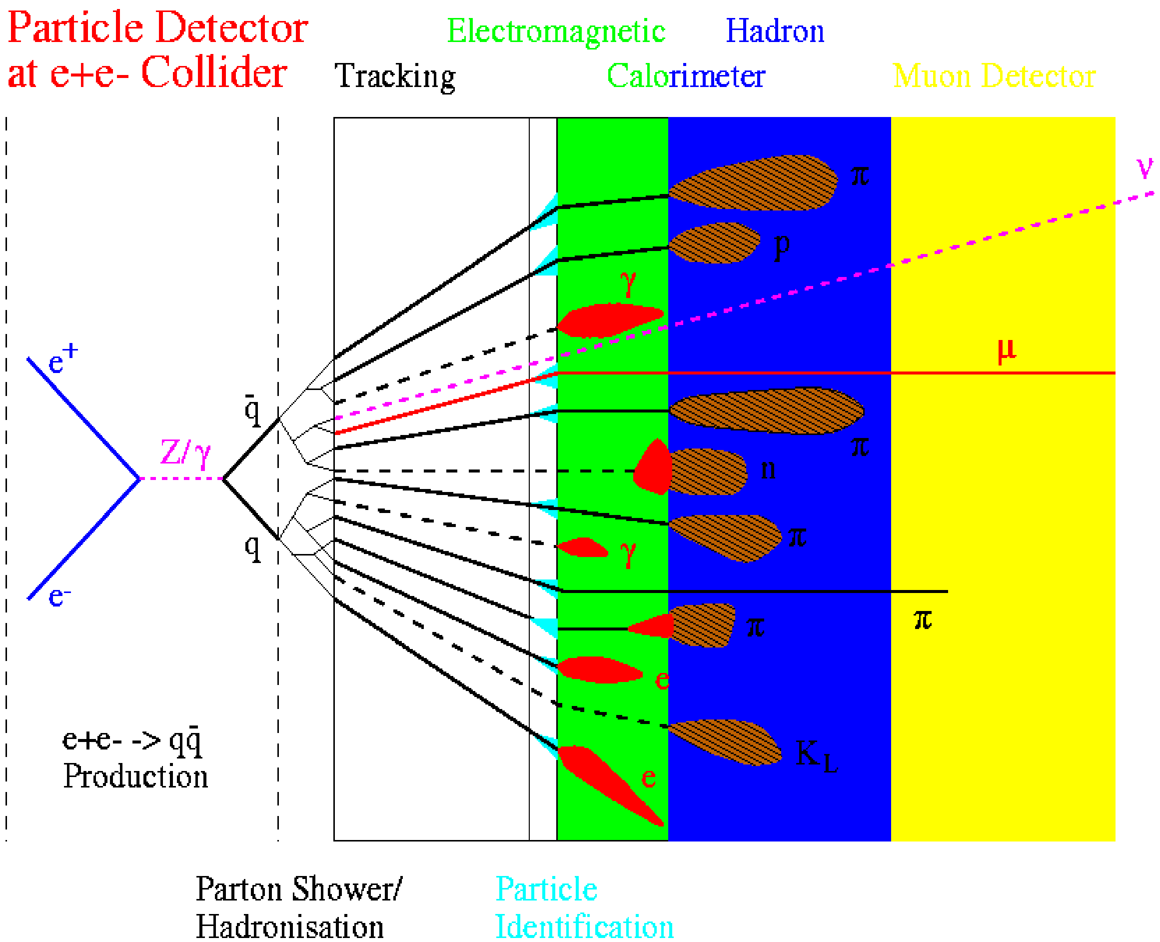
μ: Mass attenuation coefficient

$$\mu_i = \frac{N_A}{A} \sigma_i \quad [cm^2 / g]$$

Particle Detection

Experimental Measurements

Momentum, energy, and mass identification
of charged and neutral long-lived particles
e, μ, π, K, p, γ, n, ν



Hadrons versus Quarks

Experiments/detectors measure hadrons
Theory predicts quark and parton distributions
Hadronisation by Monte Carlo methods

Charged Particle Tracking

Momentum Measurement

Charged particle trajectories are curved in magnetic fields $\boxed{p_\perp[GeV/c] = 0.3B[T]\rho[m]}$

measure transverse momentum

Tracking Detectors (before 1970)

mostly optical tracking devices - cloud chamber, bubble chamber, spark chamber, emulsions

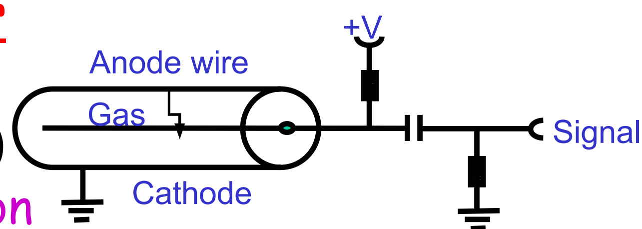
Slow for data taking (triggering) and analysis

Geiger-Mueller Counter

Ionisation in gas

O(100 e- ion-pairs/cm)

Avalanche multiplication near wire with gain up to 10^6



Multi-Wire-Proportional Chamber MWPC

Many wires in a plane act as individual counters

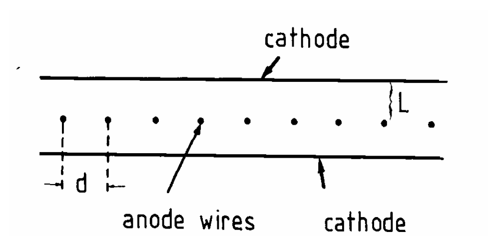
Typical dimensions: L = 5 mm

d = 1 mm, a = 20 μm

signal ∝ ionisation

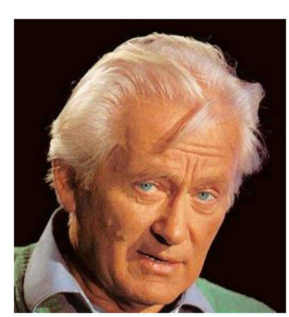
Fast, high rate capability

Spatial resolution limited by wire spacing



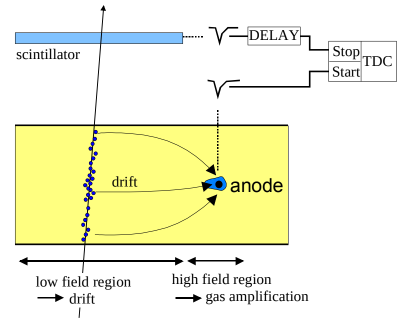
Charpak

Inventor of MWPC



Tracking Detectors

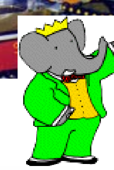
Drift Chamber



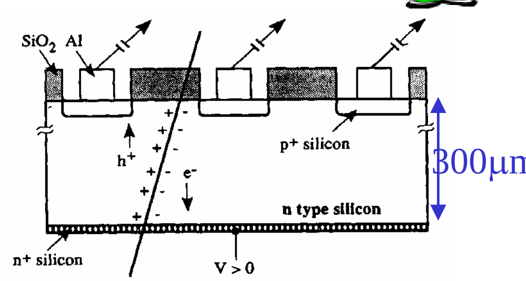
- Measure also drift time
- Drift velocities 5 … 50 mm/μs
- Improved spatial resolution 100 … 200 μm
- Fewer wires, less material
- Volumes up to 20 m^3
- Best for e+e- detectors

BaBar experiment (SLAC)

- ~29000 wires
- ~7000 signal wires



Silicon Detectors



- Metal strips, pads, pixels evaporated on silicon wafer
- Semi-conductor device
- Reverse bias mode
- Typically 50μm spacing and 10 μm resolution

CMS experiment (LHC)

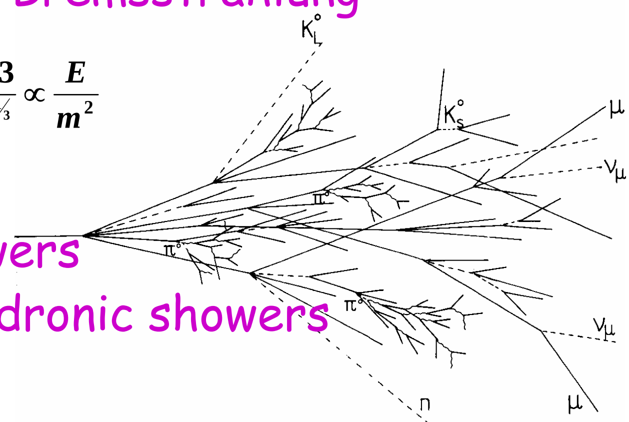
- 250 m^2 silicon detectors
- ~ 10 million channels

Calorimeters

Shower Cascades

Electron lose energy by Bremsstrahlung

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{1/3}} \propto \frac{E}{m^2}$$



High energy e- (e+) or γ

-> electromagnetic showers

π, K, p, n, … produce hadronic showers

Sampling Calorimeter

Alternate between

absorber materials

(Fe, Pb, U) and

active layers (e.g. plastic scintillators)

Homogeneous Calorimeter

Measures all deposited energy

Examples: scintillating crystals

(NaJ, CsI, BGO, …)

or cryogenic liquids (argon, krypton, xenon)

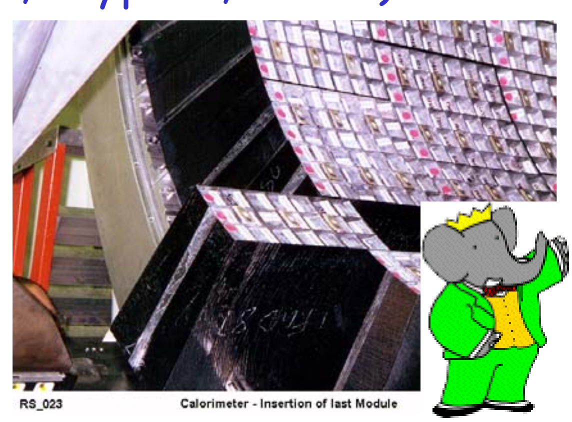
Energy measurement

Better resolution for

electromagnetic shower

BaBar experiment

6580 CsI (Tl) crystals



RS_023 Calorimeter - Insertion of last Module

Particle Identification

How do we measure Particle type?

Uniquely identified by its mass m

Particles have different interactions

Momentum $p = m\gamma\beta c$ of charged particles

measured with tracking detectors

Electrons, Photons

Electromagnetic Calorimeter (crystal)

Comparison with momentum (electron)

Shower shape (electrons, photons)

Charged Particle Identification

Have momentum $p = m\gamma\beta c$ $\gamma^2 = 1/(1-\beta^2)$

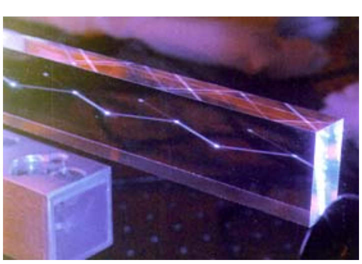
Need to measure particle velocity $v = \beta c$

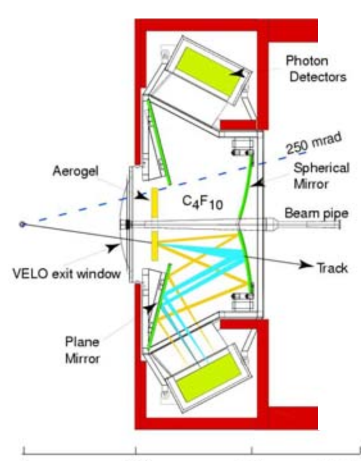
Charged particles radiate Cherenkov photons in medium with speed v larger than c/n (refr. index n)

$$\boxed{\cos\theta_C = \frac{1}{n\beta} \quad \text{with} \quad n = n(\lambda) \geq 1}$$

Cherenkov angle measures $v = \beta c$

Ring Imaging Cherenkov Detector





Muons

Most penetrating particle

little Bremsstrahlung

a few metres of iron and only muons are left