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1. Introductory remarks

To describe an event, one must/may need to know:

1. time when the event occurred:
   → detectors with fast response on passage of a particle

2. direction of particles
   → charged particles: measure the ionization track left behind
   → neutral particles: measure center of gravity of a electromagnetic/hadronic shower

3. momentum or energy or velocity of particles
   → momentum of charged particles from track curvature in magnetic field
   → energy from the electromagnetic or hadron shower size
   → velocity from time of flight (TOF), from $dE/dx \sim 1/v^2$, from Cherenkov light angle $\cos\theta_c = 1/(nv)$
   → energy-momentum from the energy-momentum conservation laws

4. identification of particles
   → use specifics of interactions (dE/dx for charged particles, em showers for γ/e, no showers for μ, …)
   → evaluate mass from (p vs v)
   → secondary decays within the detector volume (reconstruct an explicitly secondary vertex)

5. spin
   → momentum conservation laws
   → angular distributions (statistical method based on analysis of many events)

Primary detector performance parameters

- Time resolution, δt
- Spatial resolution, δx
- Energy resolution, δE
- Detection efficiency, ε
- Probability of misidentification, δ
- Two-particle spatial resolution, Δx
- Two-particle time resolution or rate capabilities, Δt or Rate

Derived detector performance parameters

- Momentum resolution is usually driven by δx and the strength of magnetic field)
- Velocity errors, depending on a method used, would be driven by δt for TOF, by δE for dE/dx energy losses measurement, δx for Cherenkov angle θ_c evaluation

Other important considerations

- Cost
- Lifetime
- Stability in time
- …

2. Fast response detectors (timing)

Scintillator and Photo-Multiplying tube (PMT)

Scintillator as we already know transform ionization and excitation energy losses to light this light can be gathered and delivered to the photomultiplier window, to photocathode. A photomultiplier tube, useful for light detection of very weak signals, is a photoemissive device in which the absorption of a photon results in the emission of an electron. These detectors work by amplifying the electrons generated by a photocathode exposed to a photon flux.

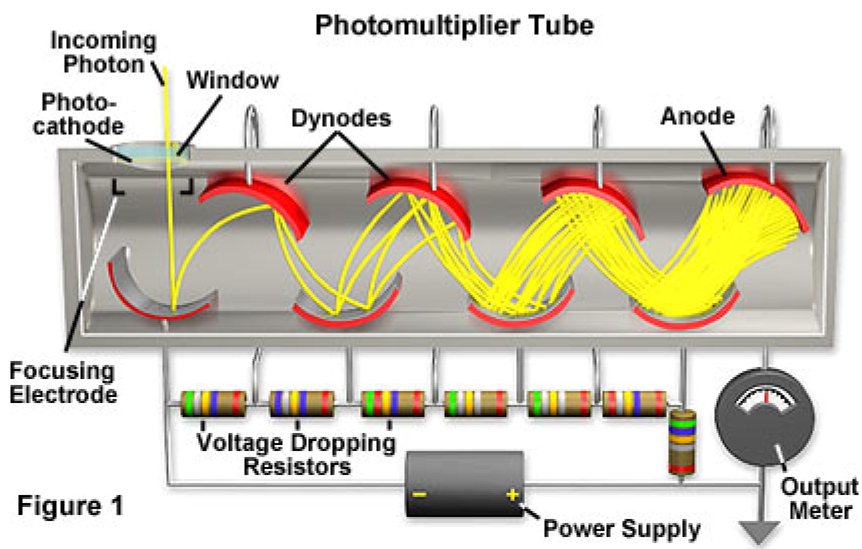


Figure 1

In such a way we can measure time when particle gone through the scintillator. Time resolution in these detectors can be as good as 50 - 200 psec. With rate limitations about 10 MHz.

Resistive Plate Chambers

Other detectors for time measurements are **Resistive Plate Chambers.** These detectors can also be very fast with time resolution about 50 psec. Rate limitations for these type of detectors are about 10 Hz/cm^2 in a spark mode or about 1 kHz/cm^2 in an avalanche mode.

RPC consist of a gas volume bounded by two parallel plates. The plates are made of resistive material, with electrodes covering the outer surfaces. By applying a high voltage to these electrodes, a strong electric field is generated across the gas volume. Through-going charged particles create clusters of positive ions and electrons in the gas. If the electric field is sufficiently strong, these electrons avalanche as they move towards the anode. This avalanche induces a signal on the external electrodes. At higher values of the electric field, the avalanche grows large enough to initiate a streamer; in this case the high resistivity of the plates keeps this discharge localized.

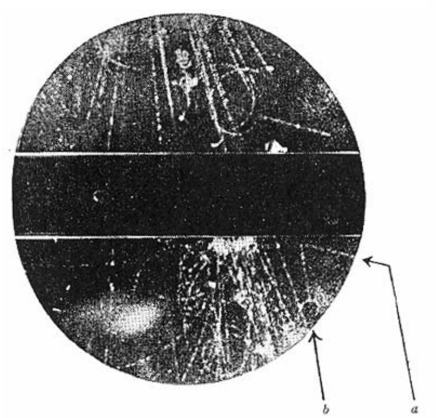
3. 1 Tracking Detectors: Cloud Chambers

Wilson Chamber (Cloud Chamber) is the earliest tracking detector. In over-saturated vapor, primary ionization clusters left behind a charged particle will become centers of condensation. Droplets will follow the track of a particle, their number per unit of length being proportional to the density of ionization (dE/dx). Condition of over-saturation can be achieved by a fast expansion of the chamber volume, which, in its turn, can be triggered by an external particle detector. A picture of droplets is then taken and chamber is compressed again.

Used from the beginning of the 20^{th} century till mid-1950s.

- moderate spatial resolution (mm to sub-mm?)
- p from curvature in magnetic field
- v from dE/dx
- slow
- moderate volume

Charles Thomson Rees Wilson shared the Nobel Prize of 1927 for his method of charged particles detection.



3.2 Tracking Detectors: Emulsions

Emulsions films consist from crystals of AgBr and AgCl suspended in a body of gel. An ionizing particle passing through the emulsion breaks up these molecules. After developing the film, the released metallic Silver grains are locked to the main body of the emulsions while the remnant part is wahed away. With the help of a microscope, these grains, usually of about a half micron diameter, can be observed as black dots. F. Powell from Bristol is credited for developing this method of detecting tracks of charged particles.

Emulsions have been used as tracking devices since mid-1940s and are still in use.

- Exceptional (not surpassed by any other detector) spatial resolution: 0.2 μm
- v from density of grains (dE/dx)
- p can be estimated from the scale of multiple scattering
- analysis is painstaking
- small volumes
- records everything (no trigger possible); in contemporary applications, the external tracking information may be used to point to the area of interest and microscope scanning

In 1950 F. Powell received the Nobel Prize for his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method.

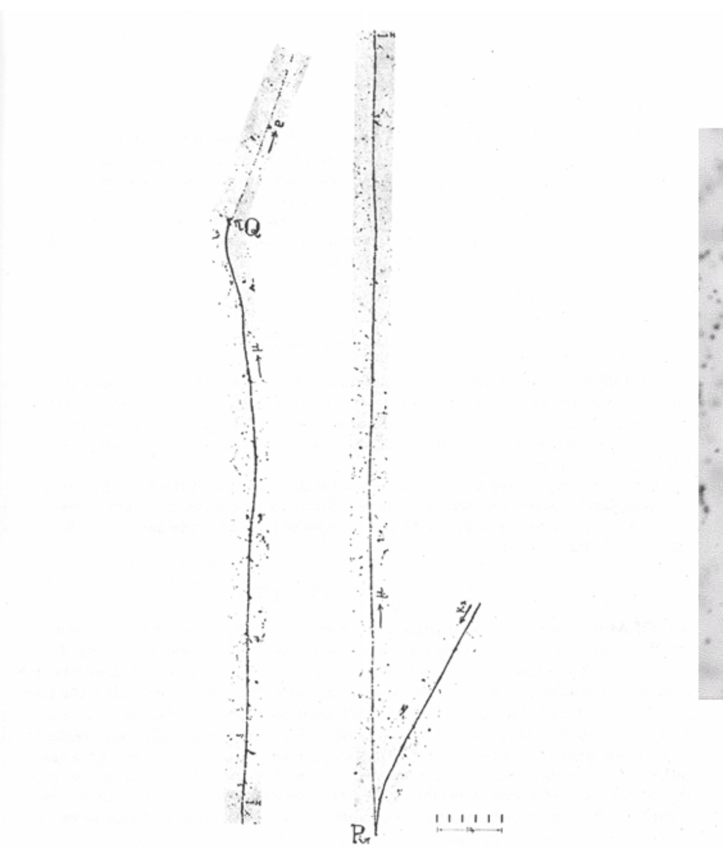
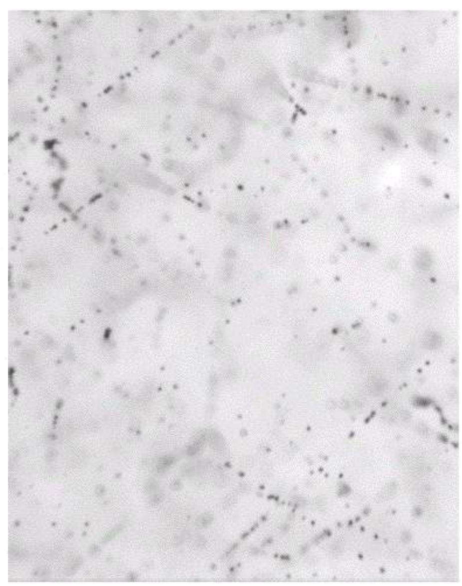


Figure 3.1: A κ (K) meson stops at P, decaying into a muon and neutrals. The muon decays at Q to an electron and neutrals. The muon track is shown in two long sections. Note the lighter ionization produced by the electron, contrasted with the heavy ionization produced by the muon near the end of its range. The mass of the κ was measured by scattering and grain density to be 562 ± 70 MeV (Ref. 3.4).

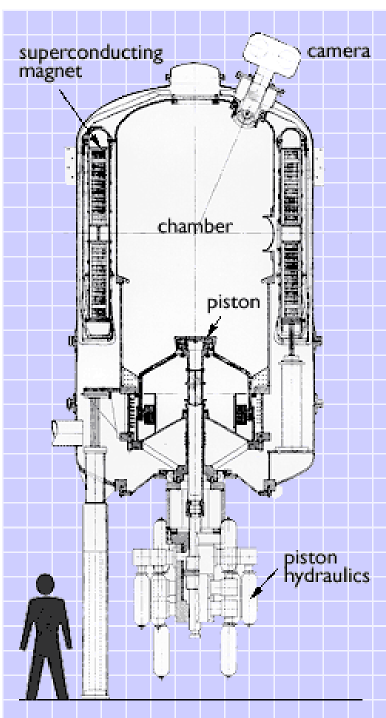


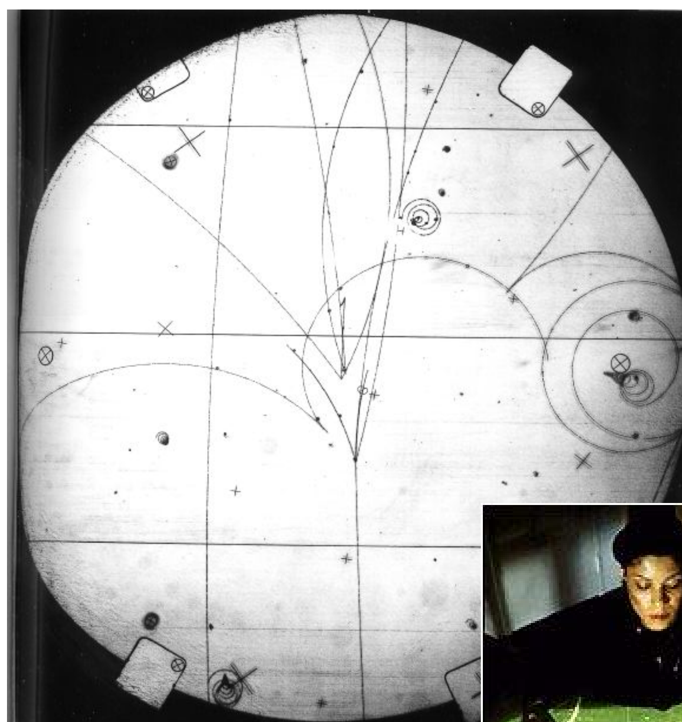
3.3 Tracking Detectors: Bubble Chambers

Bubble chamber is a container with pressured liquid (e.g., liquid hydrogen at 5 atm) close to, but below the boiling point. Charged particles going through the chamber leave behind cluster of ionization. If the pressure is dropped for a short time, the boiling temperature drops and the liquid becomes overheated. Boiling is about to begin, bubbles are formed on ionization clusters and start growing. In xxx ms, when bubbles are about 1 mm in size, pictures from different angles are taken and pressure is restored. The increased pressure brings the liquid back below the point of boiling and all bubbles collapse. Multiple pictures take from different directions allow for unambiguous 3D reconstruction. This technique was invented by **Donald Glaser** from Berkeley in 1952 and was extensively used in particle physics from mid-1950s for more than 25 years.

- good spatial resolution: 100 μm
- v from density of grains (dE/dx)
- p from bending in magnetic field
- large sensitive volumes (good for neutrino physics)
- slow, practically no trigger capabilities
- analysis is painstaking

In 1960 D. Glaser received the Nobel Prize for the invention of the bubble chamber.





Picture above to the right is from the Stanford 1 m hydrogen bubble chamber, exposed to 9 GeV antiprotons. A careful study of this photograph reveals the reaction to be

$$\bar{p}p \rightarrow p\pi^+K^-\pi^-\pi^0K^0\bar{n}$$

- slow proton is identified by its heavier ionization
- $\bar{K}^0$ subsequently decays into a pair of charged pions
- $\bar{n}$ annihilates with a proton a short distance downstream, to produce three charged particles
- π^0 decays into two photons, which (unusually for a hydrogen chamber) both convert into e^+e^- pairs
- external particle detectors were used to identify K^-

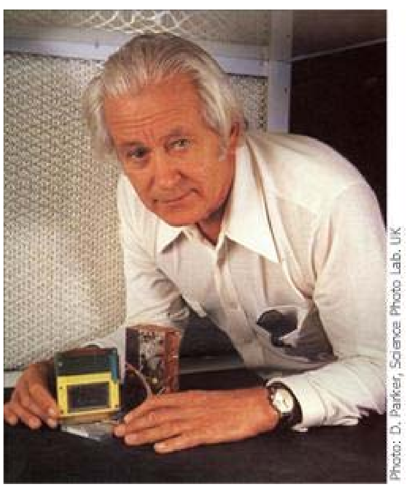
3.4 Tracking Detectors: Wire Chambers

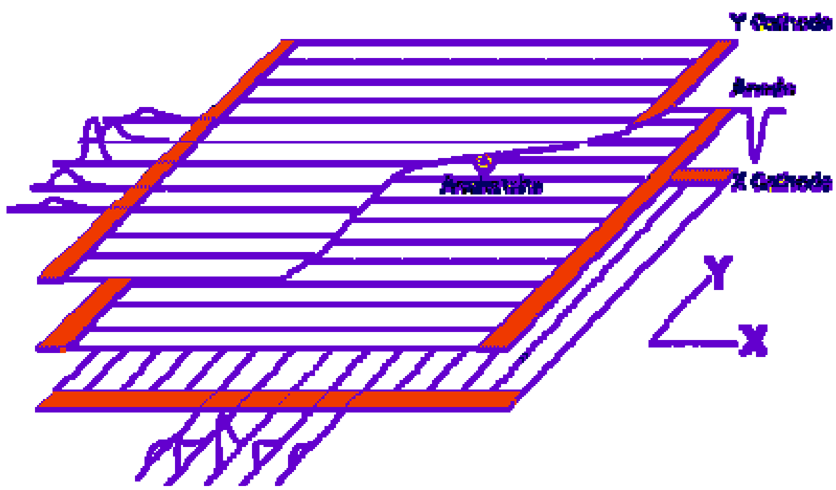
Proportional Counter, invented by **Rutherford** in early 1900s, is a tube (e.g., 1 cm in diameter) with a thin wire (typically, 20-100 μm in diameter) stretched along its axis. A positive high voltage potential is applied to the wire. A charged particle going through the tube leaves about 100 ionization electron per cm. These will drift toward the positively charged wire and result in a weak current in the external electric circuit. However, the signal would be too weak for detection even with contemporary electronics. Rutherford reasoned that if the applied voltage is large, the electric field near, but at some distance away from the wire may become strong enough to accelerate electrons drifting towards the wire to energies sufficient for producing secondary ionization, which will result in an avalanche-like process of electron number multiplication. The total charge collected on the wire (Q) can be easily $G=10^5$ times the initial ionization left behind by a charged particle (q). The factor G is commonly called gas gain. Note that the total charge, which is now large and can be easily detected/measured, is proportional to the initial ionization, from where the name proportional counter is derived.

If one increases high voltage further in attempt to reach even larger gas gains, the avalanche development process may transit into
- a plain spark or
- a Geiger-Muller discharge propagating along the entire length of the wire or
- a streamer discharge, which would be still well localized in the place of the original avalanche.

Amount of quenching gas, usually comprised of complex organic molecules, defines which of these three regimes will actually happen.

Multi-wire proportional chamber (MWPC)
The basic structure of a simple MWPC is shown in the right. Planes of such detectors has proved to be indispensable in high energy physics. Many innovative ways of MWPC construction and obtaining spatial track coordinates are due to **G. Charpak** (Nobel Prize in 1992 for his inventions and development of particle detectors, in particular the multiwire proportional chamber).





Planar 1D MWPCs:

→ x from Yes/No wire readout

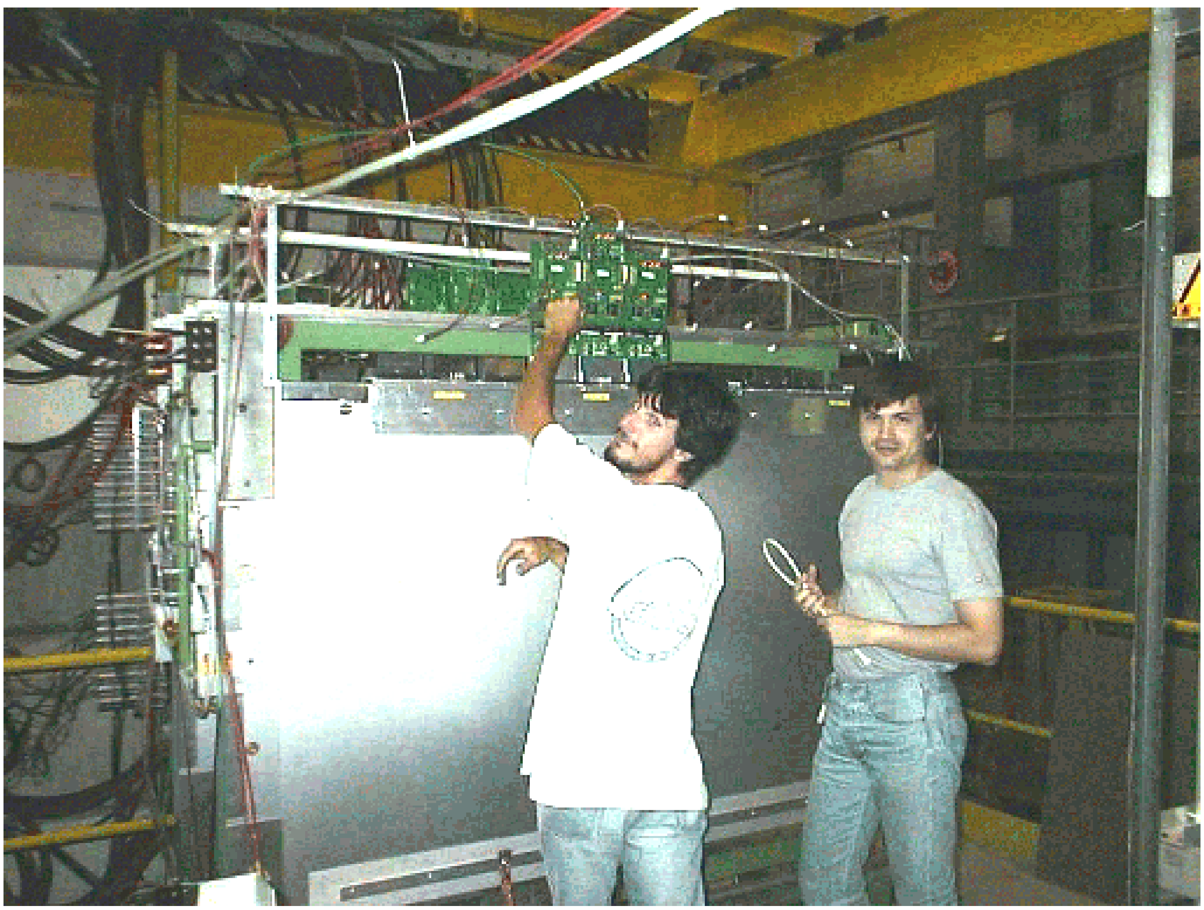
- ~1 mm spatial resolution: (wire pitch)/√12
- response within ~100 ns
- cheap electronics

Planar 2D MWPCs:

→ x from Yes/No wire readout

→ z along the wires from
1) charge division between L/R ends of a wire (wires need to be resistive): ~1% of wire length
2) time difference between signals on L/R ends of a wire: ~0.1 ps → ~3 cm
3) sampling of an induced charge on cathode wires/strips and calculating center of gravity: ~30-100 μm

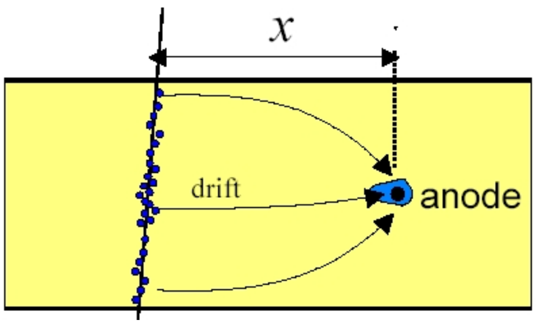
- first two have true 2D readout (no combinatorial combinations, or ghosts, in case of many tracks
- resolution along z for all three is mostly limited by precision of electronics

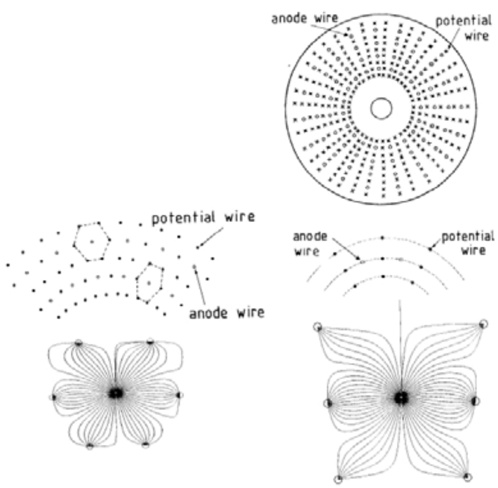


Drift chambers (planar and cylindrical):

Track distance from a hit wire is evaluated from the time difference Δt between a fast trigger and actual time of a signal appearing on a wire:

- the delay is due to electrons drift with v~50 μm/ns almost independent of electric field strength
- r = v·Δt, resolution δr~50-200 μm
- δr is driven by primary ionization statistics, diffusion of ionization in gases, path fluctuation and electronics.



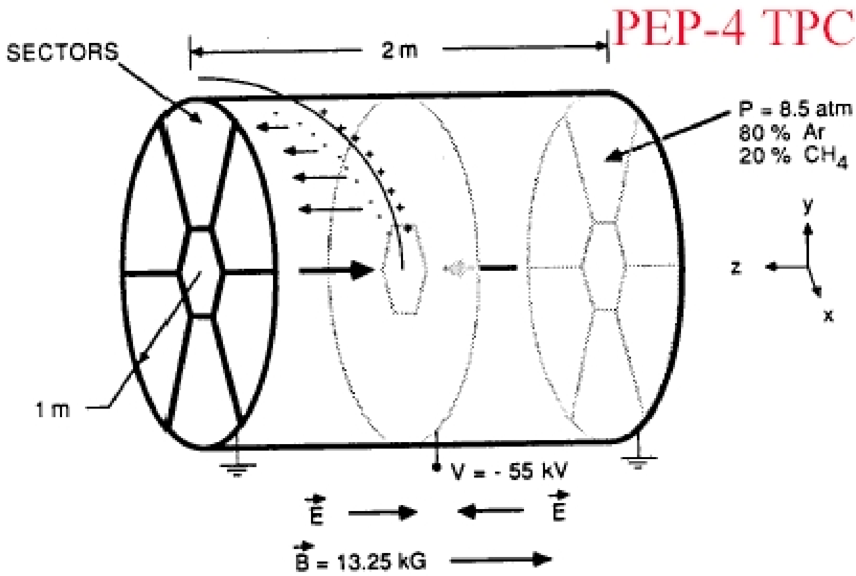


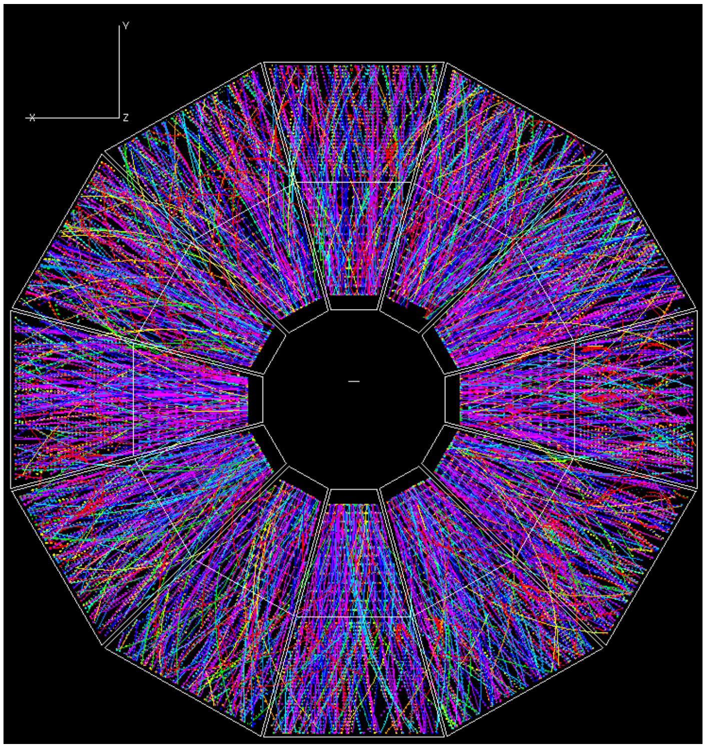
TPC (Time Projection Chamber)

Variation of a drift chamber where drift distances can be as large as meters. Almost the whole volume of such detectors is wireless—all wires and cathode pads are on the TPC endplates.

→ true 2D readout (no ghosts)

→ good only when rate of events is not too large (e+e- colliders, nucleus-nucleus colliders)





Au+Au event at RHIC Collider at Brookhaven

3.5 Tracking: Si detectors

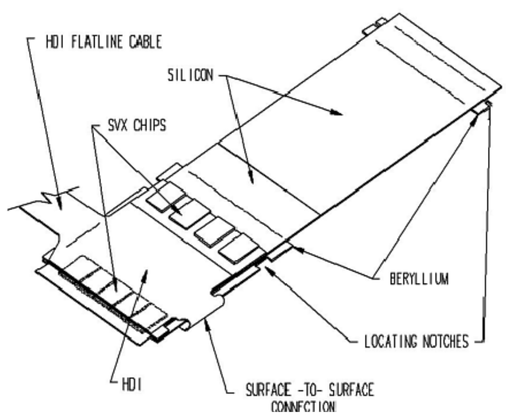
Operational principles of this kind of detectors are similar to gaseous detectors with electron-hole pairs being produced as a result of ionization losses.

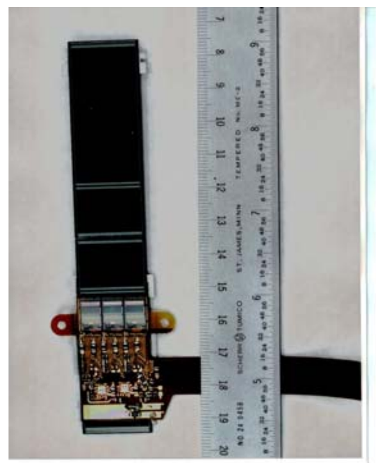
Large density of electrons (a few thousand times larger than in gases) and small average energy needed for ionization (~3 eV vs ~30 eV in gases) allows one to obtain a rather large and easily detectable signals in thin (~300 μm) substrates from plain ionization—no additional multiplication mechanisms (like gas gain on thin wires) are needed…

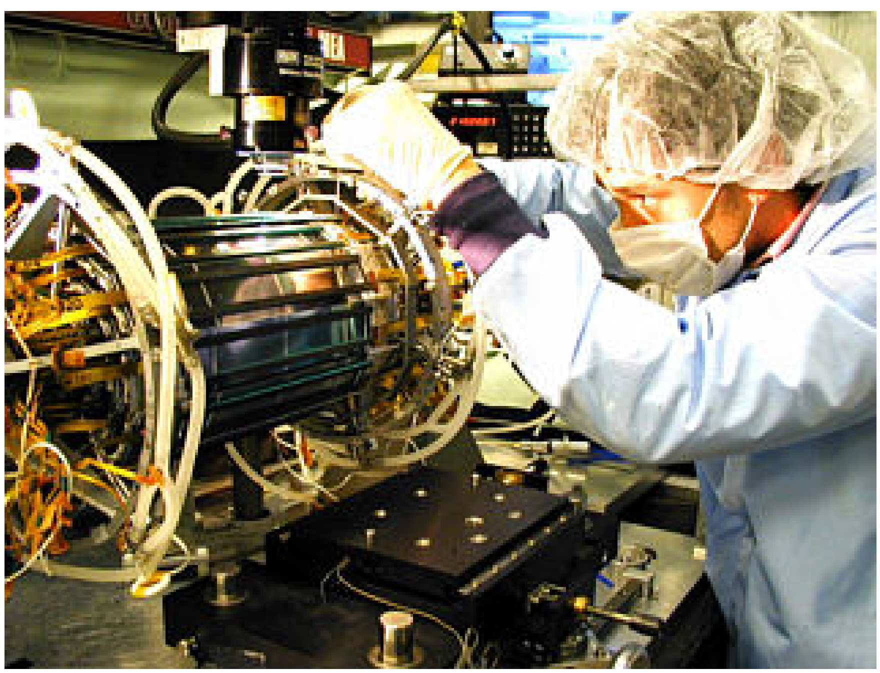
Electrons/holes are usually collected by electrodes segmented in either narrow strips (being as narrow as 20-100 μm, often called micro-strips) or small pixels of similar size.

Detectors are:
- intrinsically fast: a) thin and b) fast drift of both electrons and holes,
- precise: e.g., ~5 μm from center of gravity method on signals shared between 50 μm wide strips
- have good two-track resolution (due to small strip/pixel size).

These features make them ideal of vertex tracking…





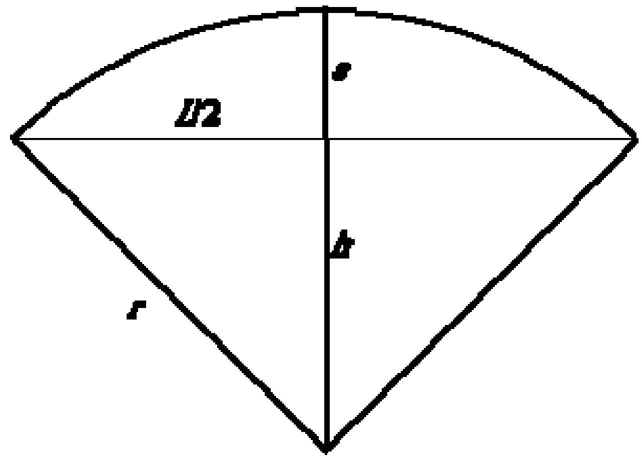


3.6 Measuring momentum of charged particles

Due to the Lorenz force, a charged particle moves along a circle trajectory. The radius of the circle depends on particle's momentum perpendicular to the magnetic field and magnetic field strength:

$$R = \frac{p_\perp}{eB},$$

where *e*=0.3 if p is in GeV, B is in Tesla, and R is in meters.



Assuming that we have three measurements per track (end points and the middle point), one would measure a sagitta, $s = x_2 - \frac{x_1 + x_3}{2}$. For the case when L<<R,

$$s = R(1-\cos\alpha) \sim \frac{1}{2}R\alpha^2 = \frac{(R\alpha)^2}{2R} = \frac{eBL^2}{8p_\perp}.$$

<u>A finite spatial resolutions</u> of the three measurements (σ_x, assuming it is the same for the three measurements) will result in sagitta measurement error, $\sigma_S = \sqrt{3/2}\sigma_x$.

From the last two equations: $\frac{\delta p_\perp}{p_\perp} = \frac{\sigma_S}{s} = \sqrt{3/2}\sigma_x \frac{8p_\perp}{eBL^2} = \sqrt{96}\ \sigma_x \frac{p_\perp}{eBL^2}$.

In general, for large number N of uniformly distributed measurements: $\frac{\delta p_\perp}{p_\perp} = \sqrt{\frac{720}{N+4}}\sigma_x \frac{p_\perp}{eBL^2}$.

Note the resolution becomes worse with momentum and improves as $1/BL^2$.

<u>Multiple scattering</u> due to presence of material inside the tracker (gas, wires, or even iron slabs as in the case of muon detectors), will result in wiggling of the track and consequently to mis-measurements of the curvature. This will obviously spoil momentum measurements:

$$\left(\frac{\delta p_\perp}{p_\perp}\right)_{ms} = \frac{13.6\sqrt{L/X_0}}{eBL}.$$

Note it is momentum independent (!) and improved only as 1/BL.

4 Calorimeters

→ Measure particle's energy by completely absorbing them
→ Measure particle's coordinates across calorimeter surface
→ Play an important role in identification of particles: e vs. μ vs. (charged hadron)

1. e/γ: electromagnetic cascade is measured in a dedicated relatively fine segmented Electromagnetic Colorimeter (ECAL)
2. π/K/p: hadronic cascade is measured in much bulkier Hadron Calorimeter (HCAL)
3. Jets of hadrons often produced in high energy collisions: Hadron Calorimeter

→ Allow one to measure neutral particles (not visible in detectors based on dE/dx)
→ Resolution improves with particle energy (opposite to p-measurements that become worse with energy)
→ Size needed to absorb a particle almost does not change with energy (grows ~logarithmically)
→ Often have fast and have good time resolution

Two kinds: homogeneous and sampling

4.1 Electromagnetic calorimeters

→ particle type: e and γ
→ electromagnetic shower
→ T, total length of all charged tracks in a shower, is proportional to E, the incident particle energy
→ measure scintillation light, Cherenkov light, ionization losses:
→ all being proportional to T, will be also proportional to E
→ Energy resolution: $\frac{\delta E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$

Example of a homogeneous lead glass calorimeter (Cherenkov light):

X_0 ~ 2 cm (from PDG)
E_c ~ 12 MeV (from PDG)
R_M ~ (21 MeV)/$E_c \cdot X_0$ ~ 4 cm

$L_{max}/X_0 \sim \ln(E/E_c)/\ln 2 \sim 13$ for E=100 GeV
$L_{95\%} \sim L_{max} + 10X_0 \sim 23X_0$ ~ 46 cm → length of crystals ~ 50 cm
$R_{95\%} \sim 2R_M$ ~ 8 cm → sides ~ 4-6 cm

Light is collected by PMT (typical efficiency: ~25% in a window of λ=400-500 ns, or ε=3-2.4 eV).

$N_{charged} = (2/3)\cdot N_{total} = (2/3)\cdot 2\cdot N_{max} = (2/3)\cdot 2\cdot (E/E_c) = ((2/3)\cdot 2\cdot E/(12\text{ MeV}) \sim 100\cdot E(\text{GeV})$
T (cm) = $N_{charged} \cdot X_0 = 100\cdot E(\text{GeV})\cdot(2\text{ cm}) = 200\cdot E(\text{GeV})$
Cherenkov photons produced in glass ~200 $cm^{-1}eV^{-1}$, from where
Number of generated photons in the detectable range $\Delta\varepsilon$: $N_\gamma \sim 200\cdot T\cdot\Delta\varepsilon \sim 120\cdot T$
Photons reaching back edge of a crystal at best ~50% (consider full internal reflection), $N_\gamma \sim 60\cdot T$
Photons reaching PMT at best 50% (consider geometrical acceptance), $N_\gamma \sim 30\cdot T$
Photons detected by PMT: $N_\gamma \sim 30\cdot T\cdot(\text{eff}) = 30\cdot 200\cdot E(\text{GeV})\cdot 0.25 = 1500\cdot E(\text{GeV})$

Poisson fluctuations in number of photons $\delta N \sim \sqrt{N}$
Contribution to the energy measurement resolution $\delta E/E = \delta N/N \sim 2.5\%/\sqrt{E(\text{GeV})}$.
There are also fluctuations in shower development, fraction of light captured inside crystal (internal reflection), fraction of light reaching PMT, etc. → The final resolution can be only worse…
The part of the resolution that depends on energy as $1/\sqrt{E}$ is called stochastic.

Errors in calibration, variations in transparency of crystal, etc. result in energy measurement errors proportional to energy… → $\delta E/E$ = b (constant)

Noise of amplifiers, noise due to backgrounds contribute to the energy measurement errors. These contributions are energy independent → $\delta E/E$ = c/E. They get very small with energy and often can be neglected.

OPAL Lead Glass Calorimeter: $\frac{\delta E}{E} = \frac{5\%}{\sqrt{E(Gev)}} \oplus 2\%$

Scintillating crystal calorimeters may be better (much more light): $\frac{\delta E}{E} = \frac{2\%}{\sqrt{E(Gev)}} \oplus 0.5\%$

Example of a sampling lead-scintillator calorimeter:

1) more compact: e.g., X_0 ~ 0.6 cm for lead
2) cheaper design (sandwich of lead and scintillator plates
3) one measures only a small fraction of T (i.e., only the part in the gaps between lead plates)
   → smaller fraction of T → larger Poisson fluctuations
   → the visible fraction as detected in scintillators fluctuates…
   → stochastic term of the resolution is typically substantially worse (14%/$\sqrt{E}$ for CDF);
   however, for very large energies may not be as important due to the constant term b

4.1 Hadron calorimeters

→ hadrons (π, K, p, n)
→ hadron shower, interaction length is large (λ~17 cm for Fe) → all sampling

$$\frac{\delta E}{E} = \frac{a}{\sqrt{E(Gev)}} \oplus b$$

Resolution is much worse:
1) Emin ~ 200 MeV → number of particles produced is much smaller
2) particles produced: mostly pions (π±, π0), some K, p, n; shares fluctuate
3) π0 decay to photons → em shower that gives very different response (usually larger)
4) K0, n do not ionize material (invisible from point of view of detecting media)
5) ~30% of all energy goes on disintegration of nuclei, most of this energy is invisible

Typical iron-scintillator calorimeter: a~50-100%, b~few-10%

Compensated calorimeter to ~equalize em and hadronic responses (see point 3 above)
→ U absorber with well tuned thickness of U-Scintillator plates
→ high Z: em shower is denser and only a smaller fraction of reaches scintillator (this reduces em response
→ uranium fission induced by neutrons increases hadronic response

Good U-based calorimeters: δE/E ~ 25%/√E

4.1 Bolometric calorimeters

Bolometric calorimeter evaluates the absorbed energy by measuring the change in temperature:
ΔT = E / C, were C is the specific heat constant of material used.

C ~ T^3
→ one gains a much better sensitivity and resolution by cooling the calorimeter to cryogenic temperatures.

Semiconductor crystals also allow for a simultaneous measurement of ionization (electric signal)—an extra handle in discriminating signals of different origin...

These detectors become more and more popular in dark matter searches…

5. Particle identification

5.1 Specific interactions: γ, e, μ, hadrons, ν

Electrons leave a track of ionization in low-material detectors (e.g. wire chambers) and result in dense/short electromagnetic showers when hit a dense material (calorimeters)

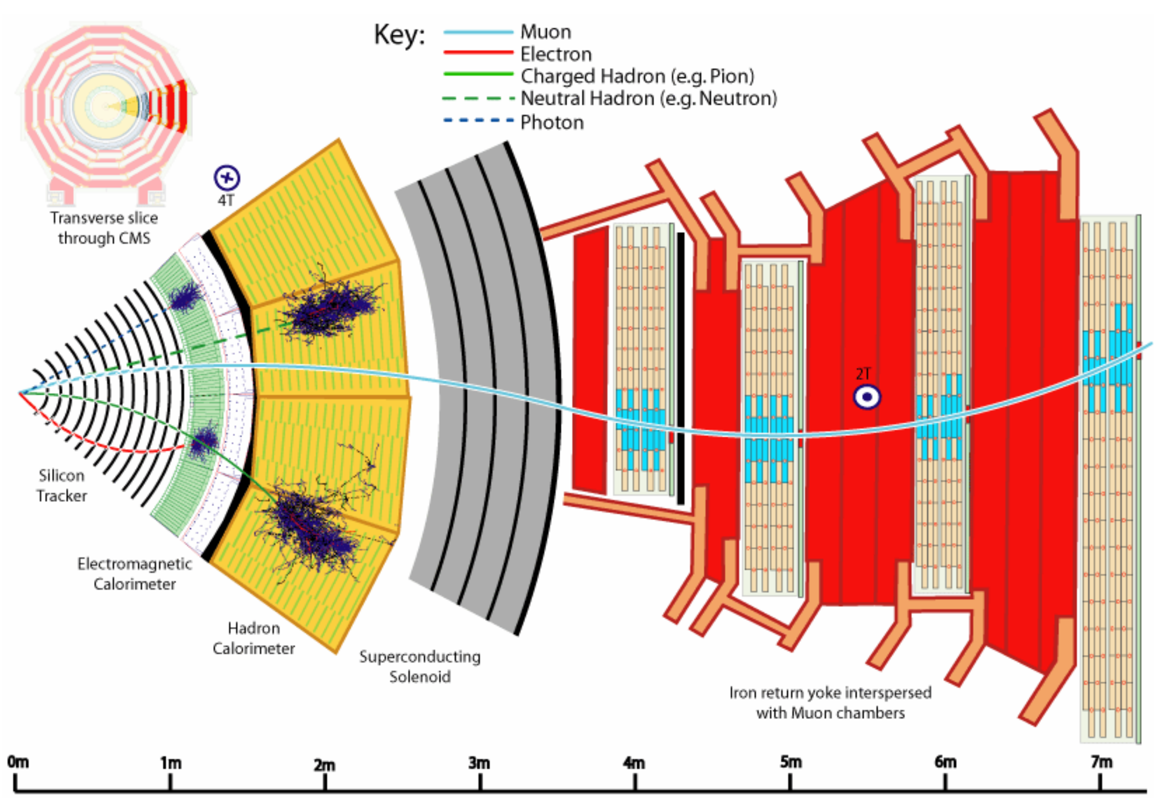
Photons leave no ionization in low-material detectors (e.g. wire chambers) and result in dense/short electromagnetic showers when hit a dense material (calorimeters)

Hadrons charged hadrons (p, $\pi^{\pm}$, $K^{\pm}$) leave tracks of ionization in low-material detectors (e.g. wire chambers) and result in broad and long hadronic-interaction showers when hit a dense material (calorimeters). Neutral hadrons (n, K^0) give only hadronic showers. IMPORTANT: in high energy collisions, hadrons often appear in a form of jets (as a result of fragmentation of high energy quarks/gluons) and for many analyses one needs to identify jets and measure their energy (and need not worry about individual hadrons inside jets).

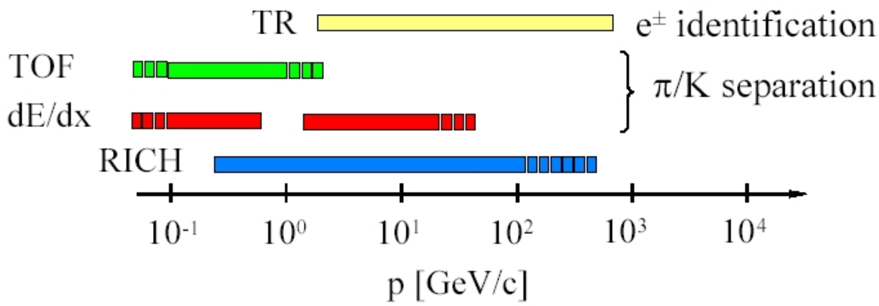
Muons leave a track of ionization in low-material detectors (e.g. wire chambers) and result in electromagnetic showers when hit a dense material (calorimeters)

Neutrinos escape the detector and their presence among collision products can be inferred from missing energy or imbalance of the total momentum

All others are inferred, e.g. via decay products (invariant mass peaks, displaced vertices, etc.)

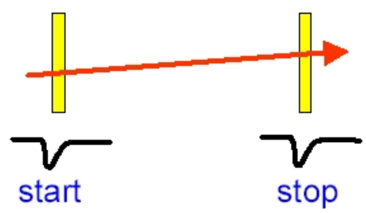


5.2 Matching momentum and velocity: π, K, p (TOF, dE/dx, Cherenkov)

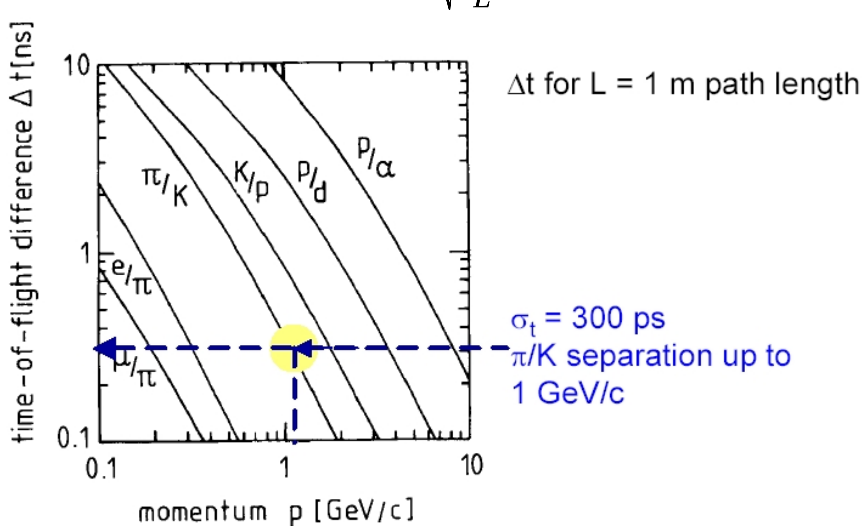


Time of Flight (TOF) detectors

Fast detectors that can measure the time of flight, time it took a particle to fly a distance L: v=L/t.

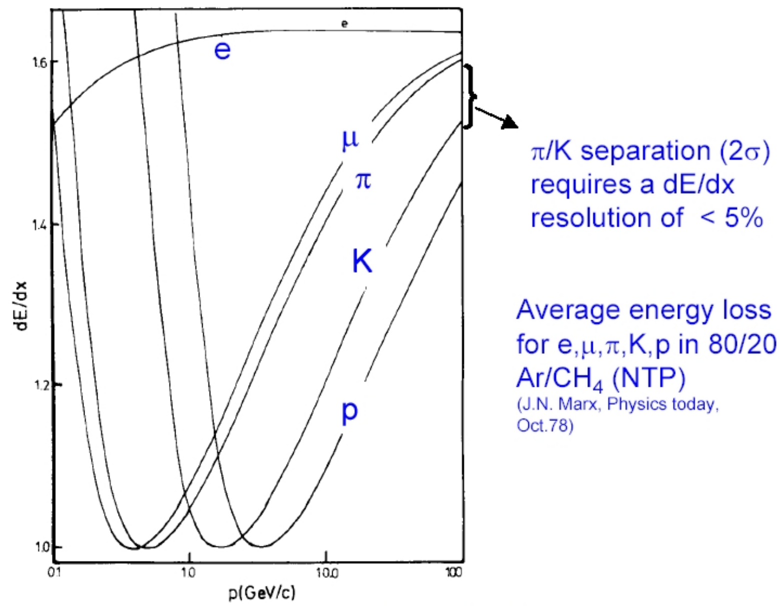


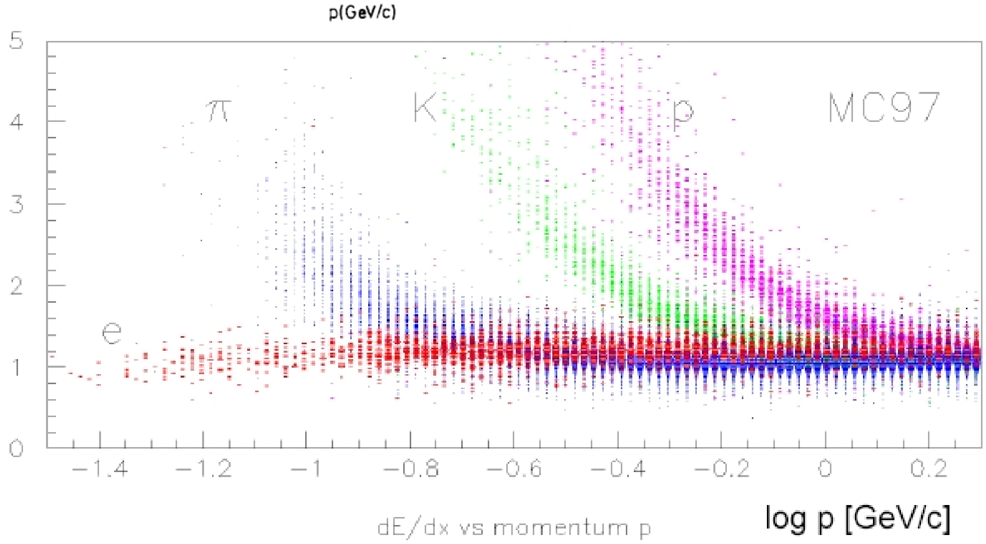
Combine TOF with momentum measurement: $m = p\sqrt{\frac{c^2t^2}{L^2} - 1}$.



dE/dx-detectors

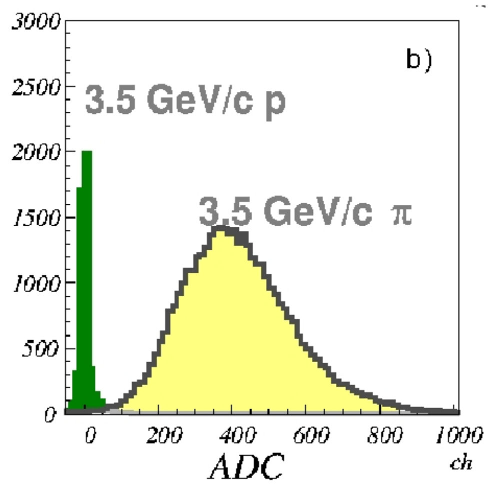
Measure density of ionization along particle's track $\frac{dE}{dx} \propto \frac{1}{\beta^2}\ln\left(\beta^2\gamma^2\right)$ and evaluate particle's velocity. The methode works well for small velocities where dependence of dE/dx on v is very steep and also has some limited precision at velocities corresponding to the relativistic rise of dE/dx. The main problem of these method is the large fluctuations (mostly due to δ-electrons)



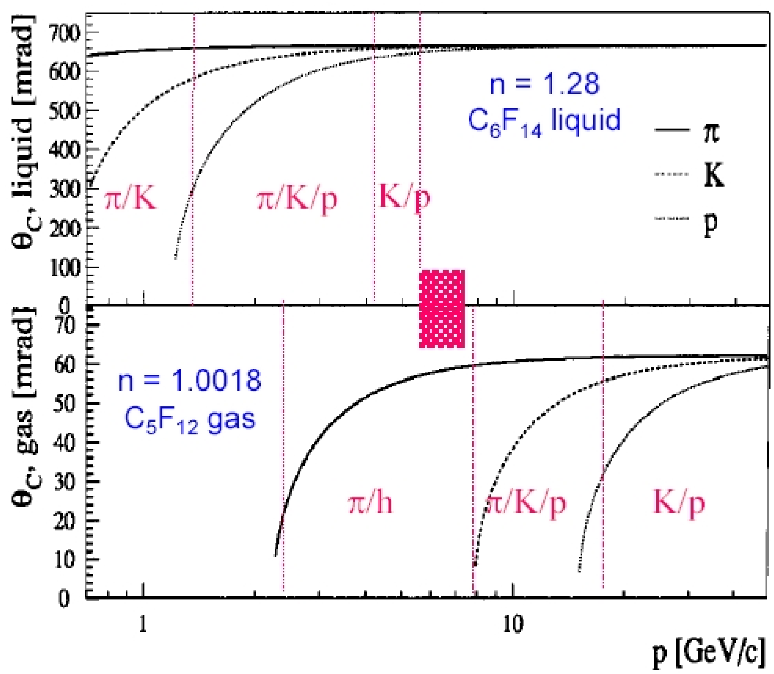


Cherenkov radiation detectors

Threshold Cherenkov detectors
use the threshold property of the Cherenkov light (v>1/n)



Ring Imaging Cherenkov detectors ("RICH")
measure radiation angle of Cherenkov light: v=1/(n·cosθ).



5.3 Enhancing electron identification (Transition Radiation detectors)