Particle Detection Techniques in HEP

Post-graduate lecture series

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The Lectures

Lecture 1 “Introduction”: basic physics of particle detection, global detector design, particle signatures, ..

Lecture 2 “Gaseous Tracking detectors”: ionisation of gas, charge amplification in gas, various tracking chambers, ..

Lecture 3 “Solid State Tracking detectors”: high precision tracking devices, semi-conductor detectors, …

Lecture 4: “Calorimetry”: energy loss by electrons, photons and hadrons, photo-detection, ..

Lecture 5: “Particle identification techniques”: energy loss, time-of-flight, Cherenkov radiation, transition radiation, ..

Lecture 1 “Introduction”

- The purpose of particle detectors
- The ideal particle detector in HEP
- Basic particle detection techniques
- A typical particle detector in HEP
- Particle signatures
- Charged particles in a magnetic field

Useful documentation

General:

- **The Particle Detector BriefBook: http://physics.web.cern.ch/Physics/ParticleDetector/Briefbook**
- **The Review of Particle Physics: http://pdg.lbl.gov**
- **C. Joram CERN summer student lectures: http://joram.web.cern.ch/Joram/lectures.htm**
- **T S Virdee: http://preprints.cern.ch/yellowrep/1999/99-04/p347.pdf**
- **T Ferbel (ed.) “Experimental Techniques in High Energy Physics”, Frontiers in Physics.**

Gaseous tracking detectors:

- **F Sauli: http://documents.cern.ch/archive/cernrep/1977/77-09/Chapter01.pdf**

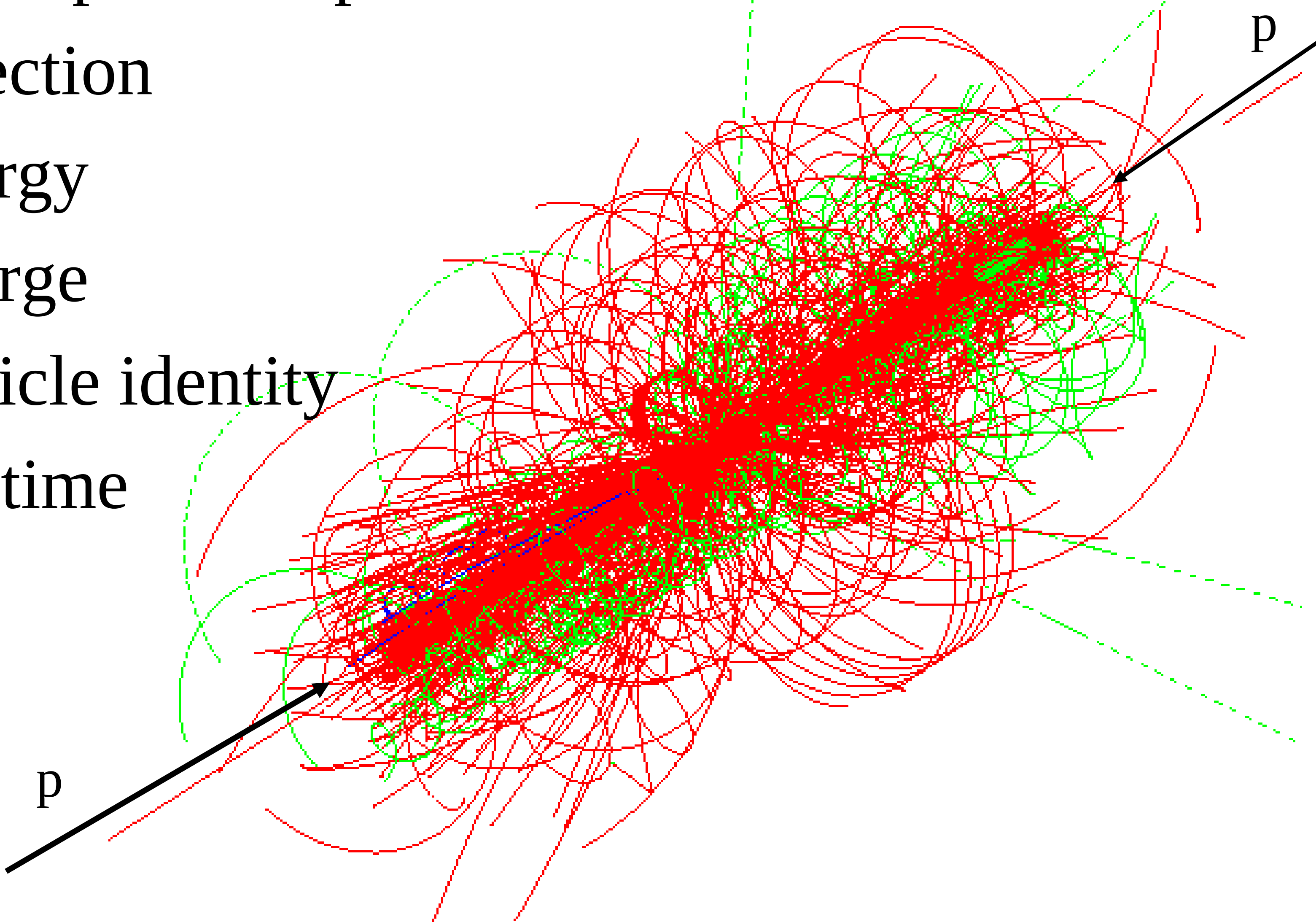
Silicon Detectors:

- **H. Spieler SLAC Lectures: http://www-physics.lbl.gov/~spieler**
- **C J S Damerell (RAL-P-95-008): http://www.slac.stanford.edu/pubs/confproc/ssi95/ssi95-005.html**

What do we want to measure in HEP?

Of ALL particles produced in an interaction:

- Direction
- Energy
- Charge
- Particle identity
- Lifetime



The ideal detector

An apparatus that provides (for all types of particles):

- good particle identification
- precise measurement of energy/momentum
- precise measurement of trajectory (direction/origin)
- coverage of the full (4π) angular region

In addition (in some cases) it should be able to:

- take data at a high rate
- cope with a high particle densities
- survive high radiation doses
- survive 10+ years of operation (with little/no intervention)

A real detector will always be a compromise between the various requirements, existing technology and the availability of money, space, time etc…

Particle detection techniques: the physics

Detect/measure properties particles through their interaction with matter:

- Ionisation of atomic electrons
- Bremsstrahlung and photon conversions
- Inelastic nuclear interactions
- Cherenkov or transition radiation
- Emission of scintillation or fluorescence light

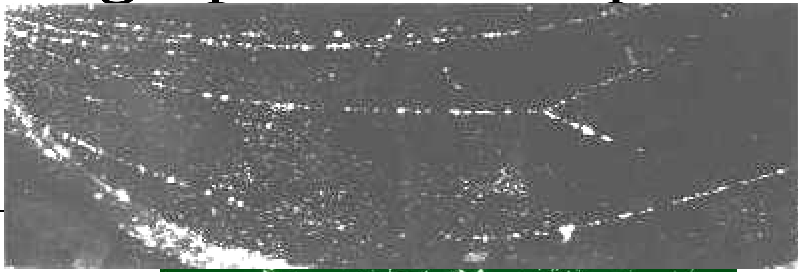
How can we “visualise” these processes?

- Photographic techniques
- By collection of induced charge (from ionisation)
- By detection of photons

Basic detection techniques: Photographic techniques

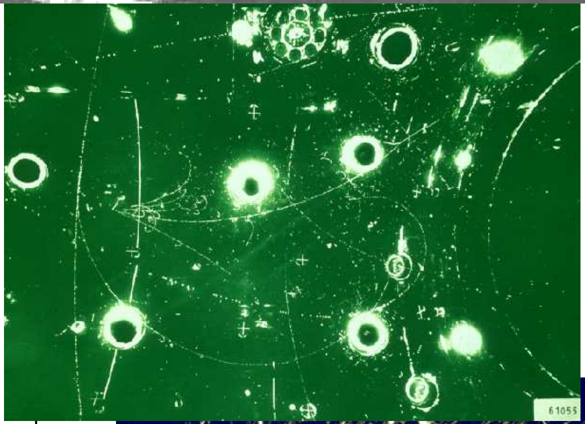
Charged particles ionise atoms along their trajectory.

(I) Ions act as seeds for:

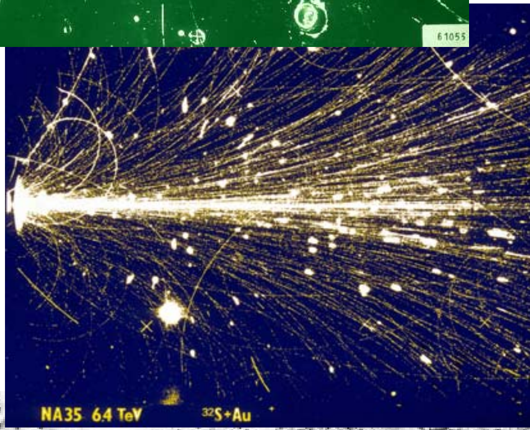


• condensation in super saturated gas (Wilson chamber)

• bubble-formation in super-heated liquid



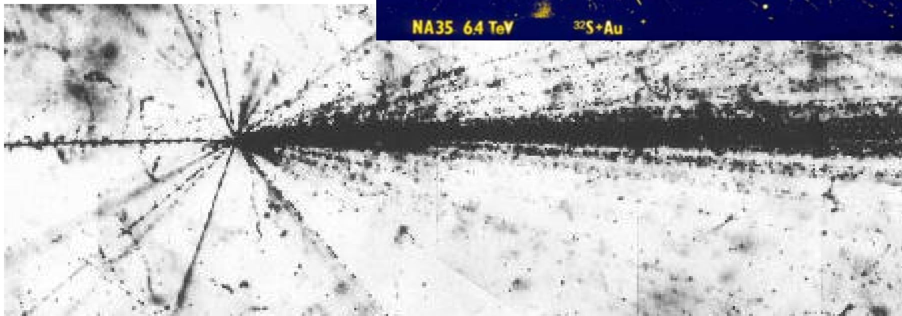
• electrical discharge or plasma formation



All of these provide a visible trajectory that can be recorded photographically

(II) Ionisation can also be made visible chemically (photographic material)

• Photographic emulsion targets



Basic detection techniques: Electrical

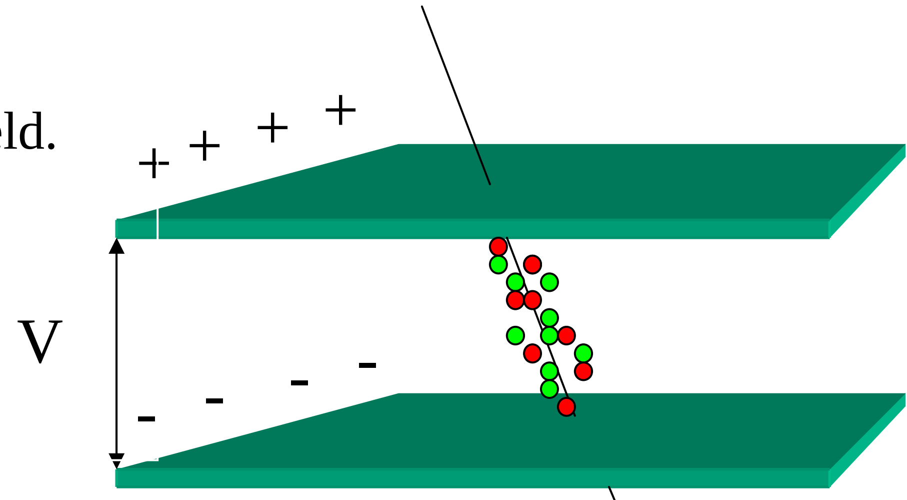
We can also electrically collect the charge produced by the ionisation

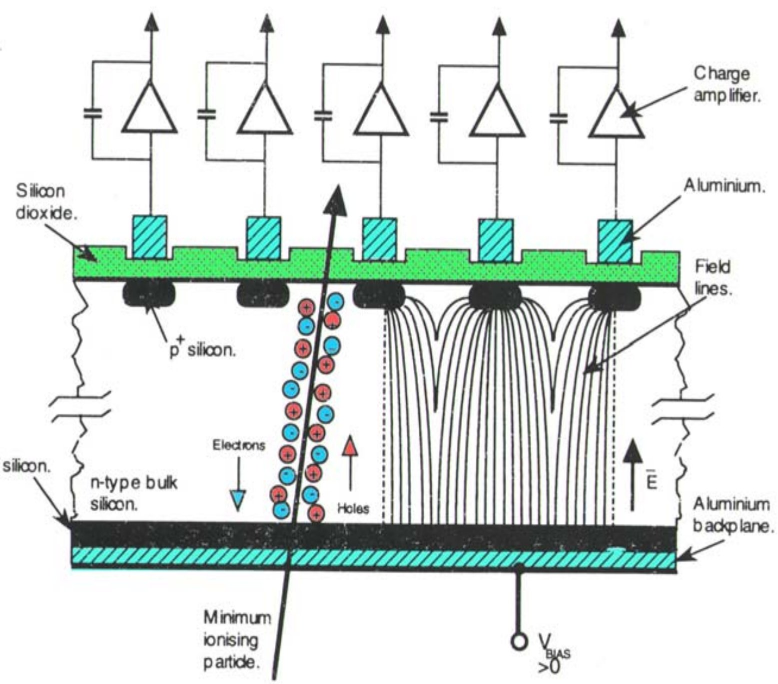
Particle causes ionisation in a material.

Charge is separated/collected by an electric field.

Requirement on material:

- no/few free charge carriers (non-conducting)
- mechanism for transport of charge





<u>Proportional chambers, Drift chambers, ..</u>

Insulating gas/liquid between anode and cathode (transport through drift). Sometimes combined with very low conductivity solids.

<u>Silicon strip detectors, CCDs, ..</u>

Using a semi-conducting material: Mostly in the form of a reverse-biased pn-junction diode.

Basic detection techniques: Photo-detection

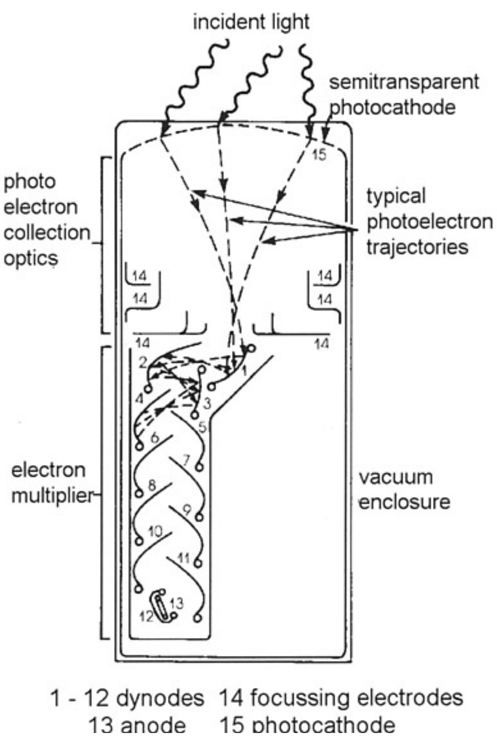
Charged particles can produce photons via scintillation, Cherenkov or transition-radiation etc. To detect these:

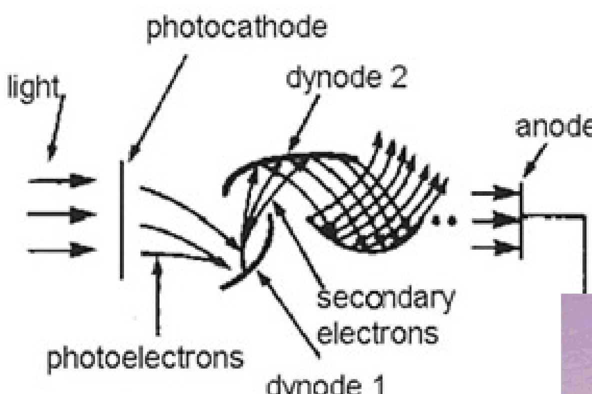
<u>Photo-Multiplier Tube (PMT):</u>

Electrons from photo-electric effect

“Electron multiplier” provides charge cascade

Very sensitive, but also bulky and expensive.





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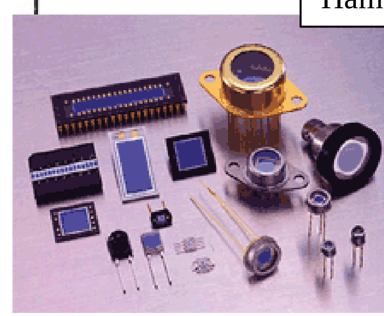
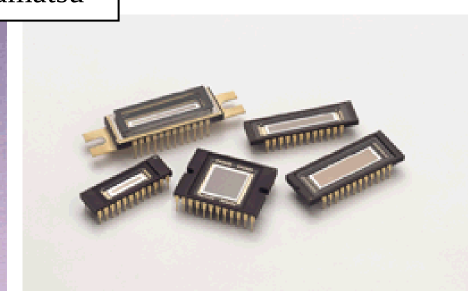




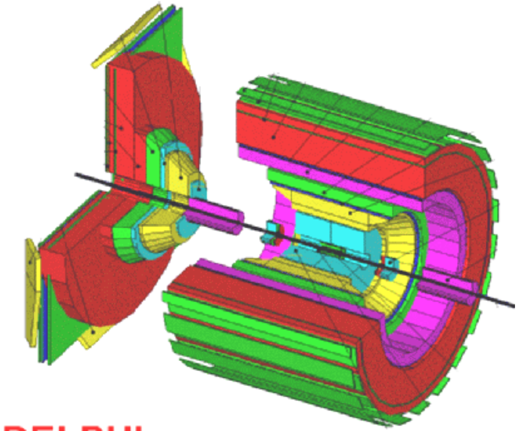
<u>Semi-conductor devices:</u>

Photo-diodes or CCD’s

Global detector layout:

- barrel-shape surrounding beam-pipe
- 2 cone- or wheel-shaped end-caps

Nearly 4π coverage and good accessibility!



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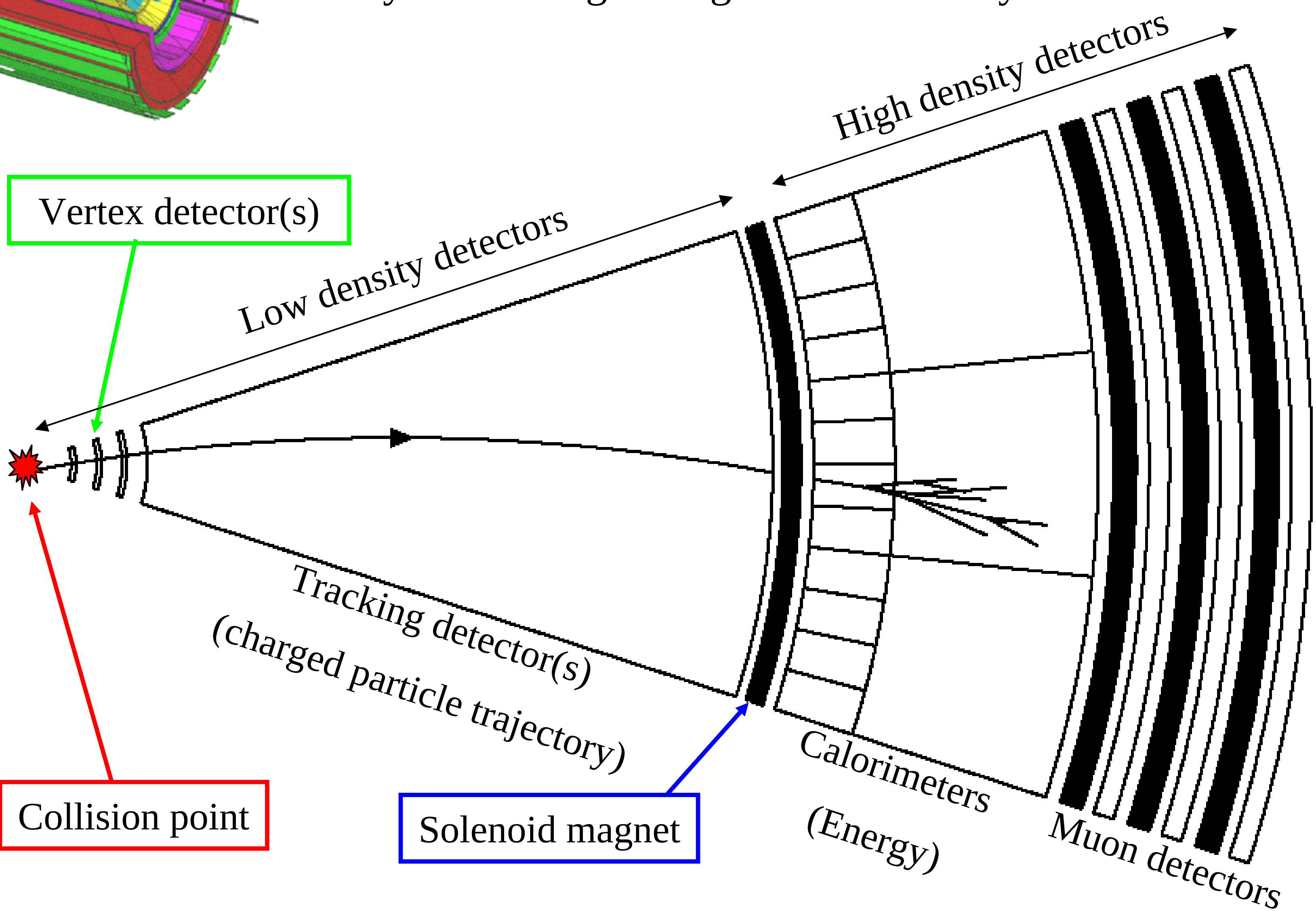
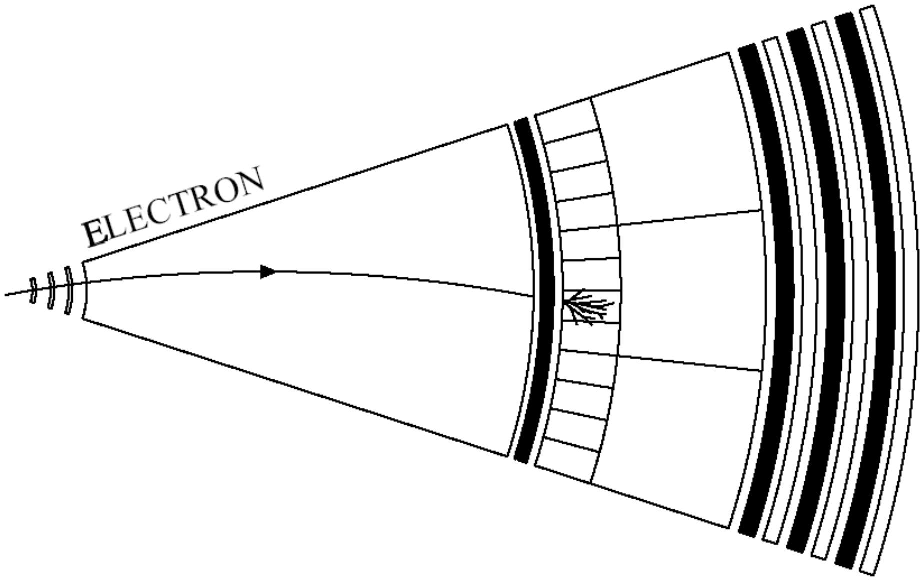
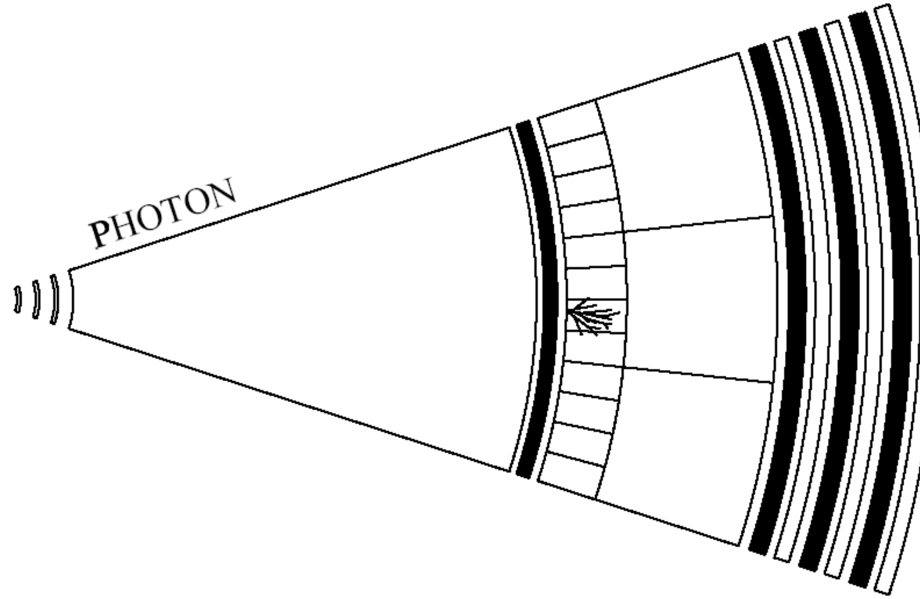


Particle signatures (first glance)





Electrons:

• leave a bent track

• stopped in first layer of calorimeter

(Calorimeter and tracking information)

Photons:

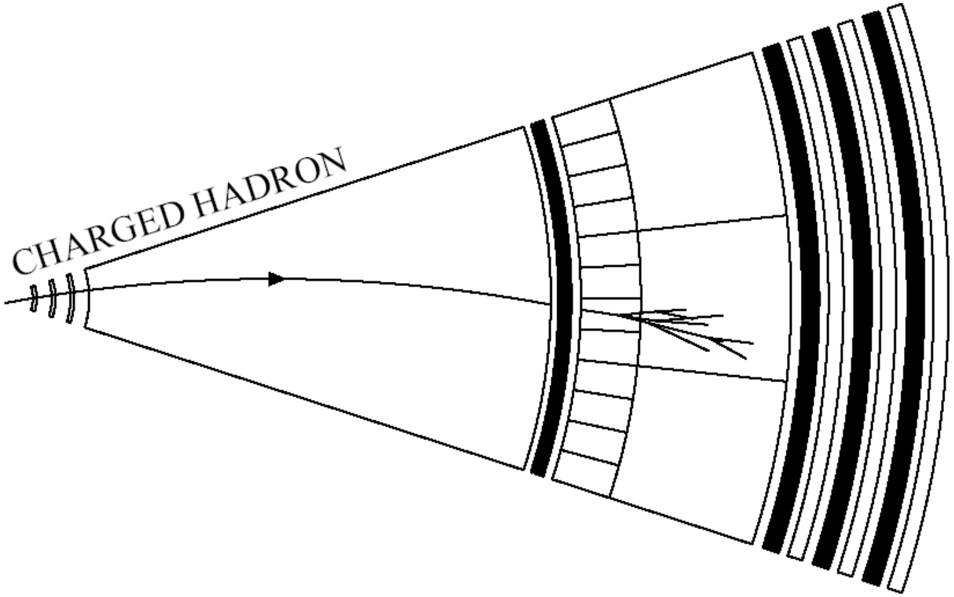
• no track

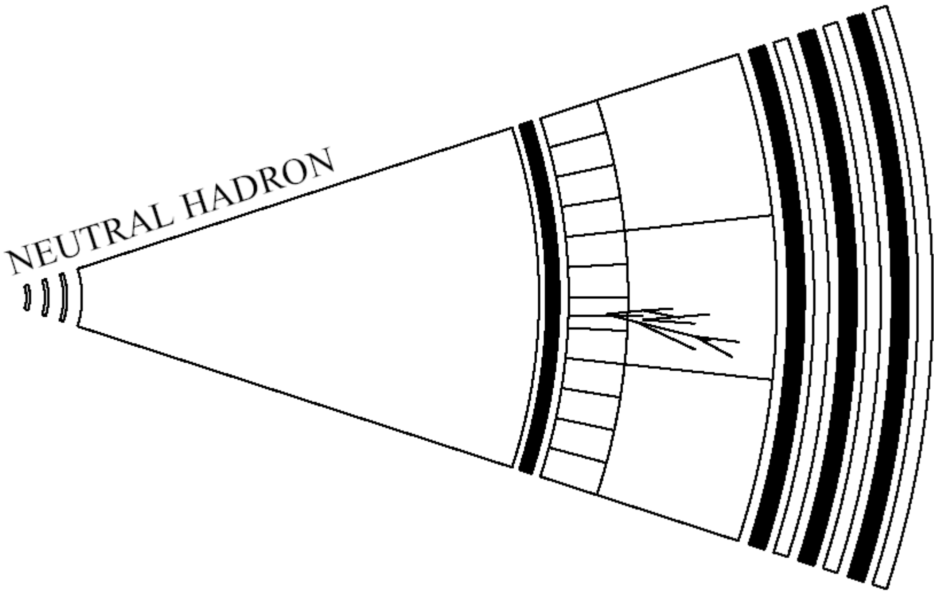
• stopped in first layer calorimeter

(Only calorimeter information!)

First layer of calorimeter: “*Electro-magnetic calorimeter*”

Particle signatures (first glance)





Charged hadrons:

• leave a bent track

• stopped deep in calorimeter

(Calorimeter and tracking information)

Neutral hadrons:

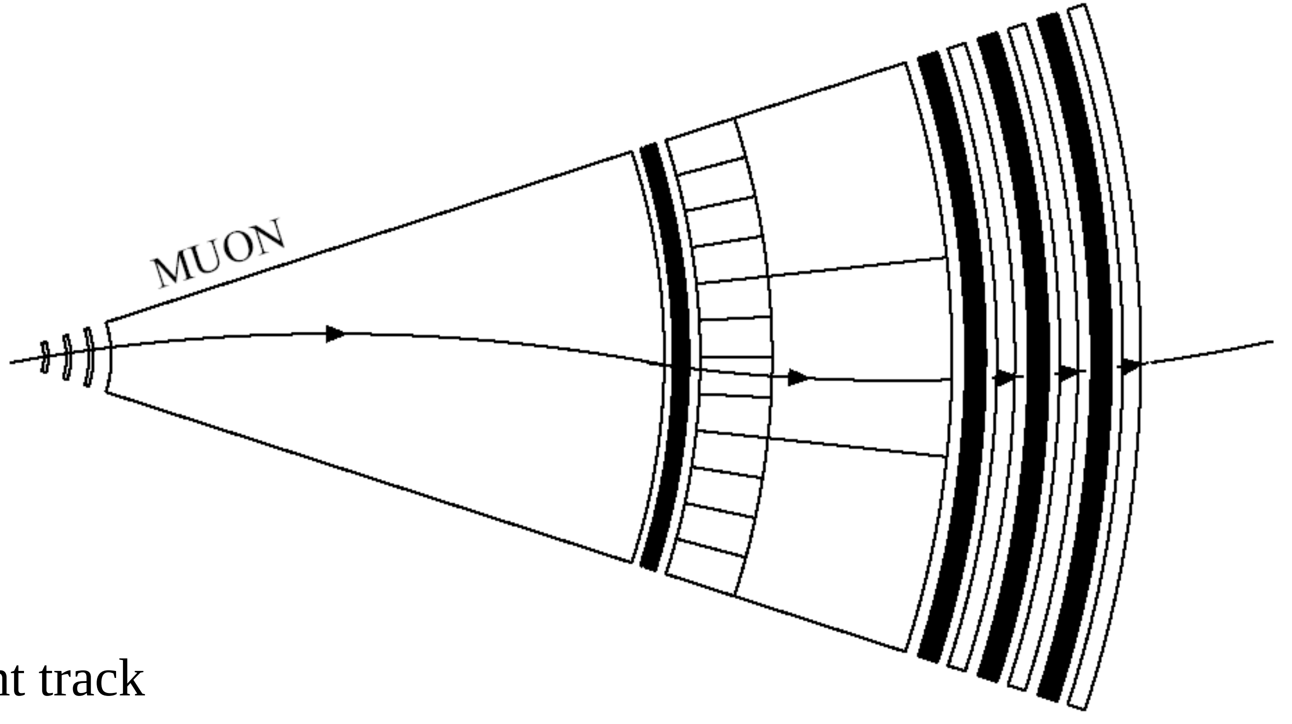
• no track

• stopped deep in calorimeter

(Only calorimeter information!)

Second (+) layers of calorimeter: "*Hadron calorimeter*"

Particle signatures (first glance)



Muons:

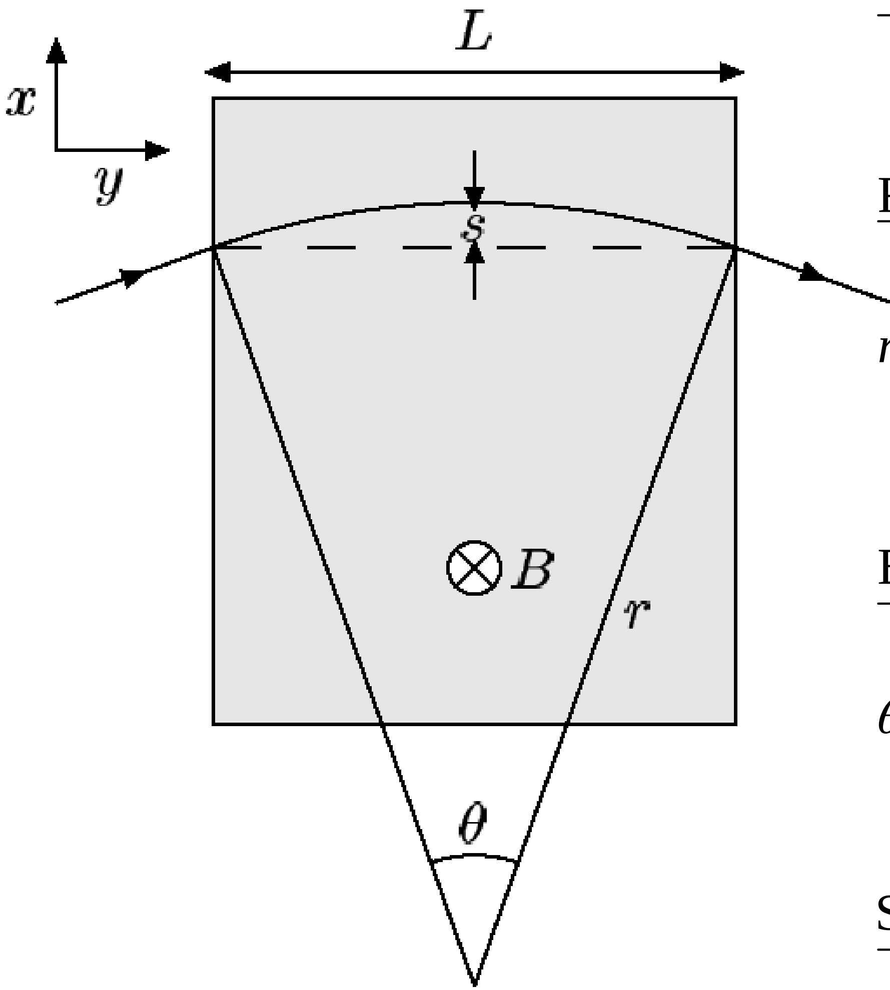
• leave a bent track

• not stopped in calorimeter

• track in muon detectors

(Calorimeter, tracking and muon-detector information)

Charged particle in a magnetic field



Magnetic force: $\vec{F} = q(\vec{v} \times \vec{B})$ or $|F| = qv_{\perp}B$

Centrifugal force: $|F| = \frac{mv_{\perp}^2}{r}$

Radius: $r = \frac{mv_{\perp}}{qB} = \frac{P_{\perp}}{qB}$,

$r = \frac{P_{\perp}}{0.3B}$ ($P_{\perp}$ in GeV/c and B in Tesla)

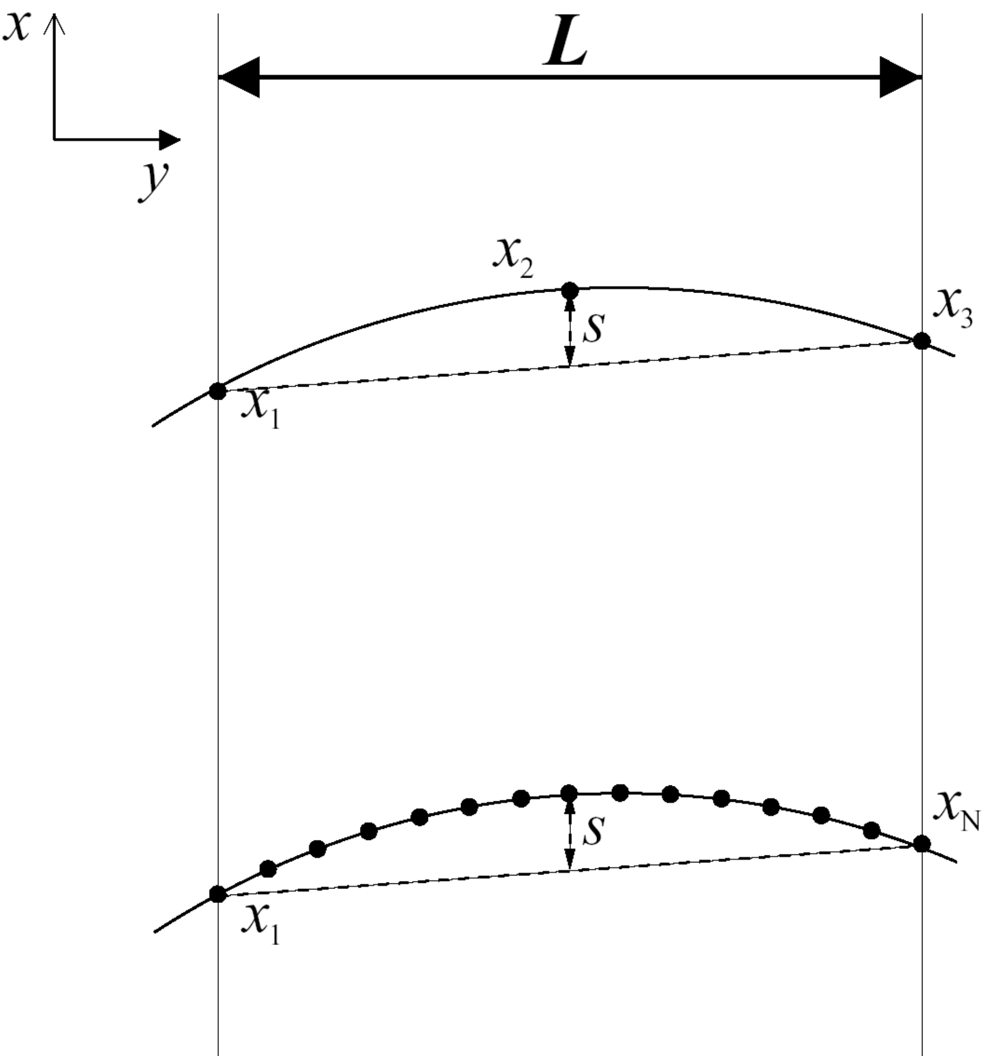
Bending angle: $\frac{\theta}{2} \approx \sin\frac{\theta}{2} = \left(\frac{L/2}{r}\right) \Rightarrow$

$\theta \approx \frac{0.3BL}{P_{\perp}}$

Sagitta:

$s = r - r\cos\frac{\theta}{2} = r\left(1 - \cos\frac{\theta}{2}\right) \approx r\frac{\theta^2}{8} \approx \frac{0.3}{8}\frac{BL^2}{P_{\perp}}$

Measurement of the sagitta



For 3 measured points :

x_1, x_2, x_3 at $y = 0,\ L/2,\ L$

$$s = x_2 - \frac{x_1 + x_3}{2}$$

$$\sigma(s) = \sqrt{\frac{3}{2}}\sigma(x)$$

$$\frac{\sigma(P_\perp)}{P_\perp} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)8P_\perp}{0.3BL^2}$$

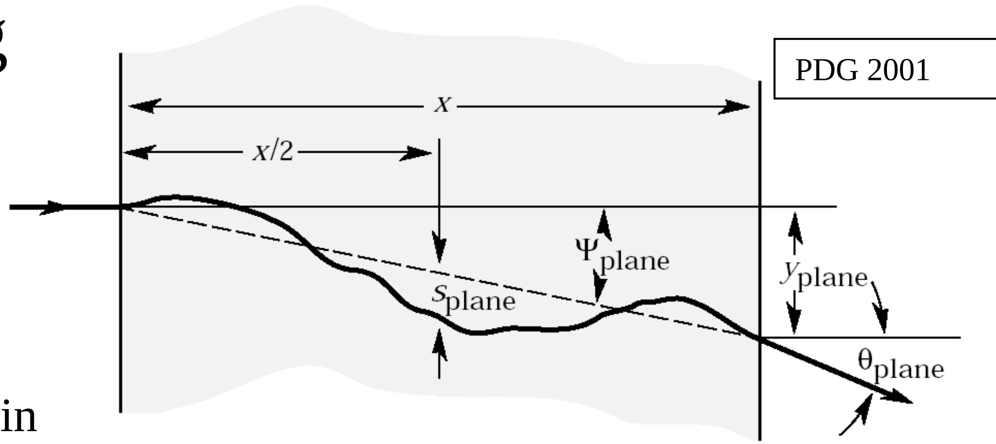
For N equidistant measurements :

$$\frac{\sigma(P_\perp)}{P_\perp} = \frac{\sigma(x)P_\perp}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$

(R.L. Gluckstern, NIM 24 (1963) 381)

Thus for precise measurement momentum we need: high B field, large volume tracking detector, many measurements along the trajectory. But …

Effects of multiple scattering



A charged particle undergoes many “small–angle” scatters.

Mostly Coulomb interactions and some strong interactions (for hadrons).

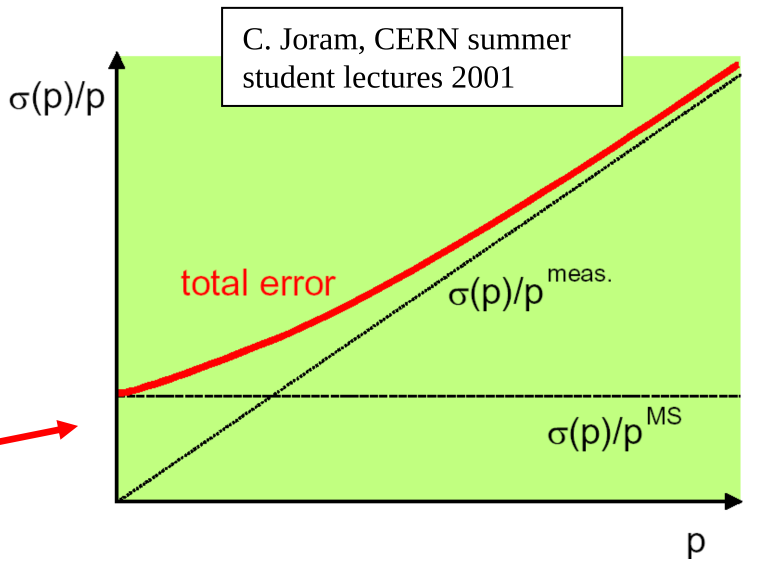
The width of the cumulated angular deflection in the *xy*-plane is:

$$\theta_{\text{plane}}^{\text{rms}} = \theta_0 = \frac{13.6MeV}{p\beta c} z \frac{\sqrt{L}}{X_0}\left[1 + 0.038\ln\left(\frac{L}{X_0}\right)\right]$$

$$s_{\text{plane}}^{\text{rms}} = \frac{L\theta_0}{4\sqrt{3}}$$

$$\frac{s_{\text{plane}}^{\text{rms}}}{s} = \frac{\Delta p_{MS}}{p} \approx 0.05\frac{1}{B\sqrt{LX_0}} \quad \text{(independent of } p\text{!)}$$

$$\frac{\sigma(P_\perp)}{P_\perp} = C_{meas}P_\perp \oplus C_{MS}$$



Multiple scattering scales with the amount of material traversed. (beam-pipe, detectors, magnet,..)

<u>Thus for precise measurement momentum, should also have as little material as possible in the tracking detectors.</u> (also important for precise energy measurement in the calorimeters.)

Next Lecture

I Introduction

II Gaseous tracking detectors

III Semi-conductor trackers

IV Calorimetry

V Particle identification