Particle Detectors

Part 1

Lectures at the CHIPP winter School 2013

Roberto Carlin (University of Padova and CERN)

INTRODUCTION

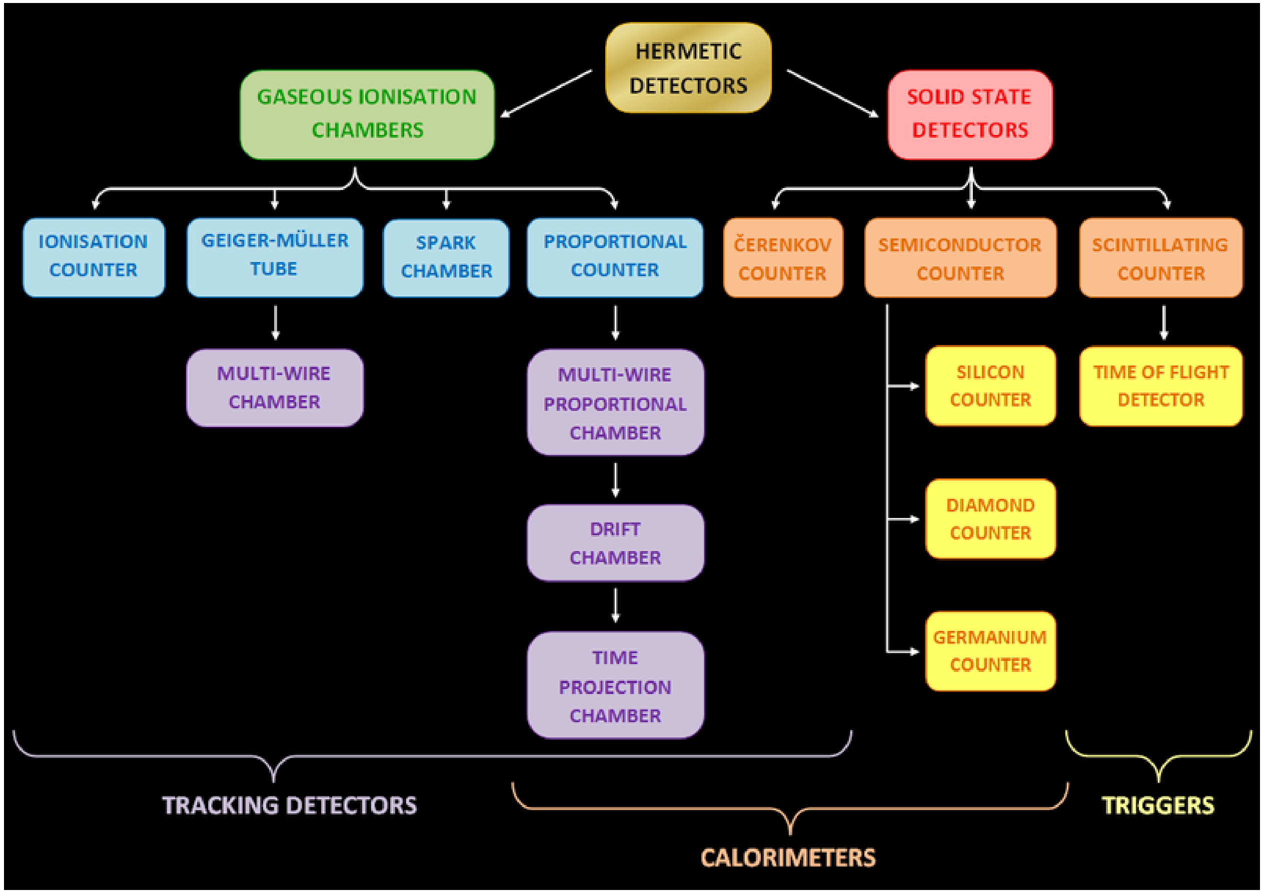
Usual disclaimer

- These lectures cannot cover all of the complex subjects of particle detectors
  - Cannot describe the full variety
  - And even less go in full depth
- Tried to give a balanced overview of the techniques and the reason of their choice
- Tried not to be too CMS-biased

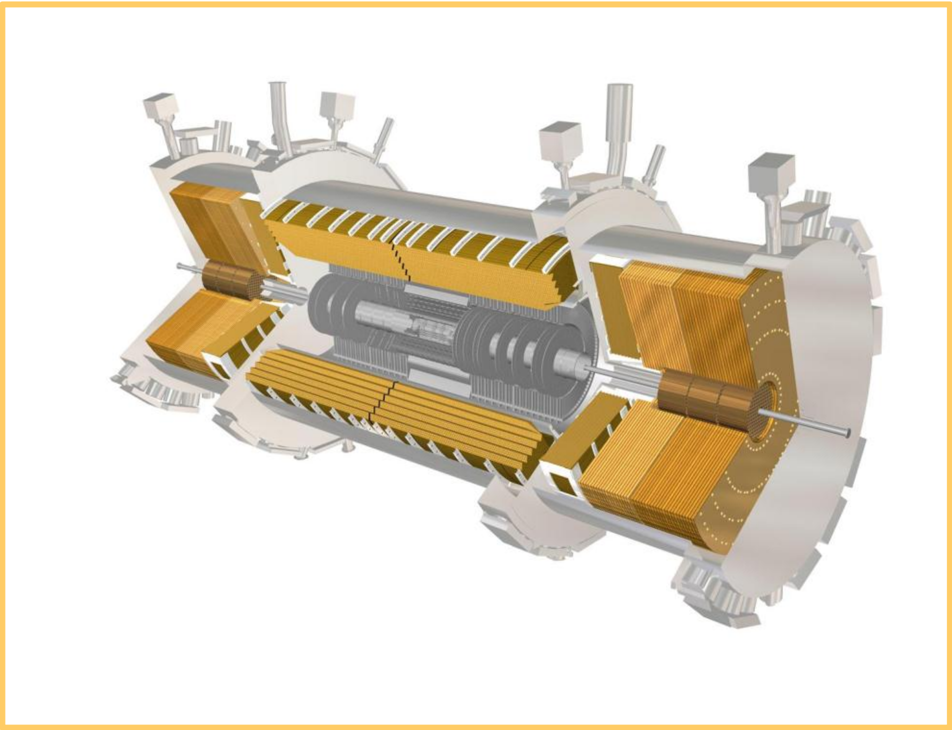
- Working on detector id fun!

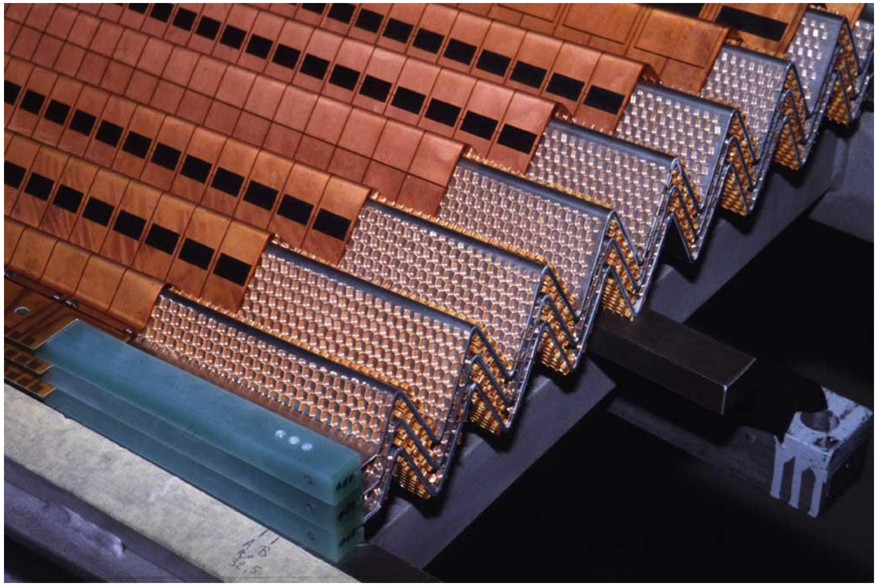
Classification of particle detectors

- Go to Wikipedia and get all information you need



- Well not really
  - The Atlas Liquid Argon “accordion” calorimeter is neither a “gaseous” nor a “solid state” detector



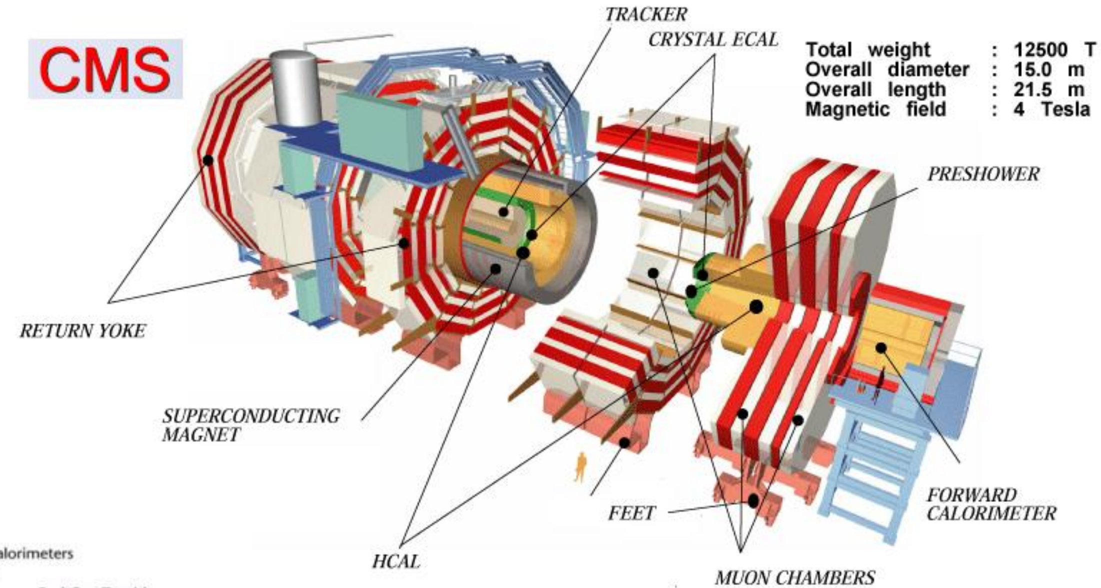


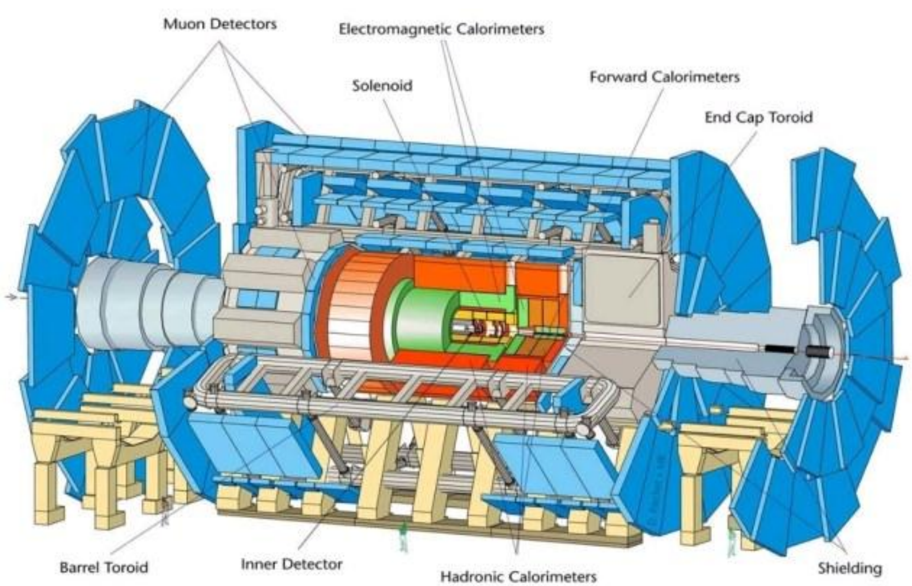
Many possible classifications

- Signal generation
  - Ionization
  - Scintillation light
  - Cherenkov light
  - Transition Radiation
- Use
  - Tracking detectors
    - Vertex, Central, Muons
  - Calorimeters
    - Electromagnetic, Hadron
  - Particle Identification
  - Trigger
- Technologies used
  - Gaseous detectors
    - Multi-wire, Drift chambers, Limited Streamer Tubes, RPCs, GEMs
  - Scintillators
    - Crystals, Plastic, Liquid
  - Semiconductors
    - Pixels, Strip

... and then detectors get combined

- Modern large experiments are complex combination of detectors
  - Often with combined tasks, e.g. calorimeters and muon detectors are used for fast trigger

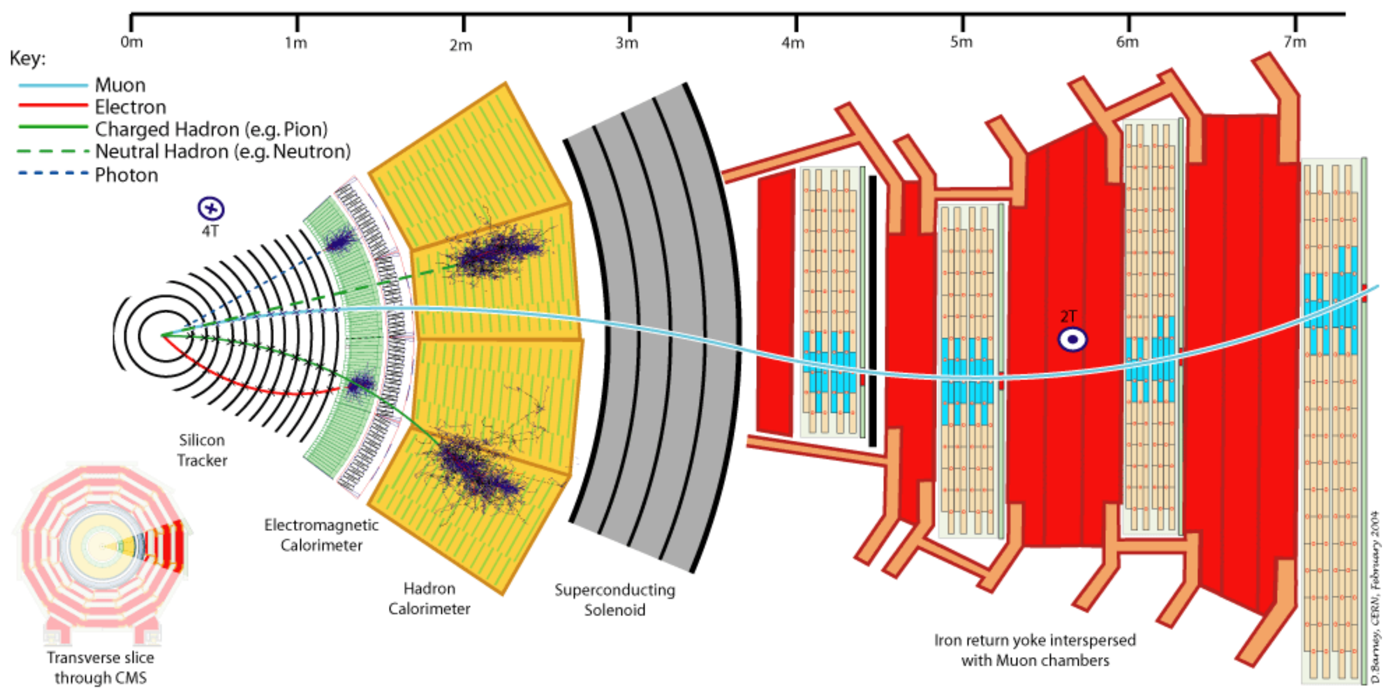




- Similar requirements, the aspect is similar
  - But the specific choice of the technologies are quite different
  - **There is space for imagination**

Plan of the lectures

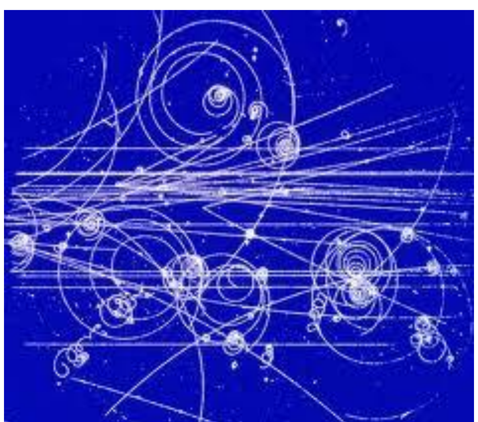
- First some recap on interaction of radiation with matter
- Then a description of the main classes of detectors
  - with the different technologies used to build them
- Finally a real life example (…CMS)

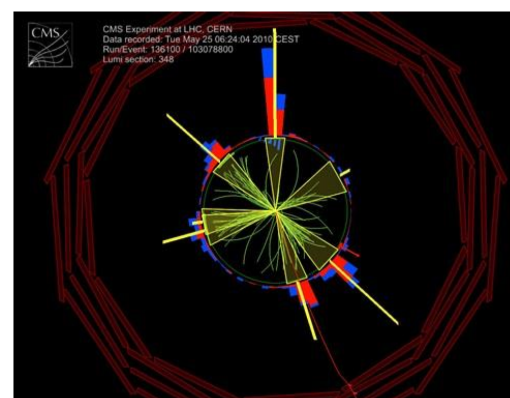


What are the particles we detect?

- Stable particles, or unstable particles with long enough lifetimes to transverse the detectors
  - Other particles are identified, when needed, by their decay produces

- Electrons, muons
- Photons
- Neutrinos
- Charged and neutral nucleons, pions, kaons
  - Most of the times hadrons are inside jets of particles coming from hadronization of the partons

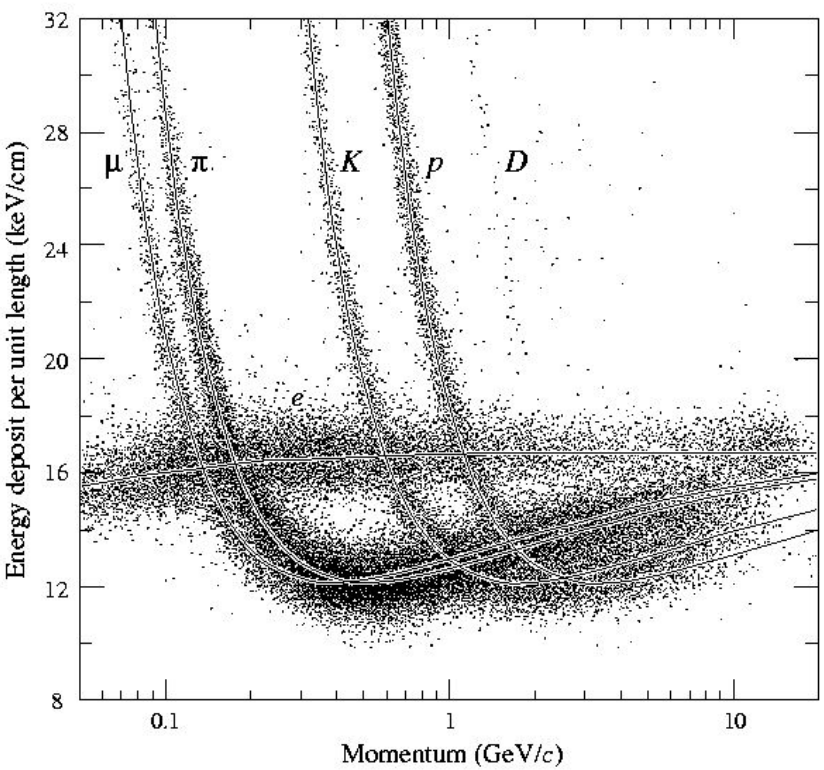




INTERACTIONS WITH MATTER

Bethe-Bloch

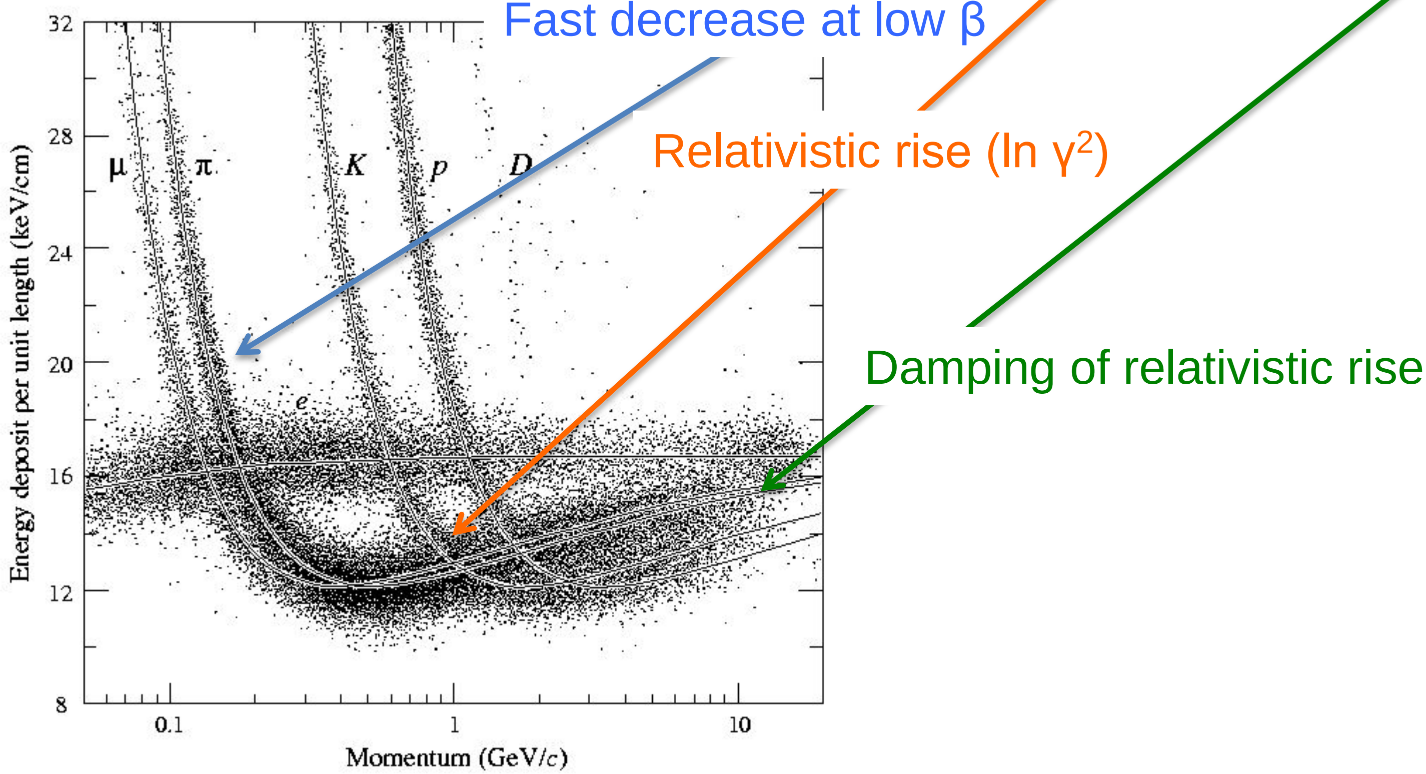
$$-\frac{dE}{dx}\left[\frac{MeV}{cm}\right] = 4\pi N_A r_e^2 m_e c^2 z^2 \rho \frac{Z}{A}\frac{1}{\beta^2}\left(\ln\frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2 - \frac{\delta}{2}\right)$$



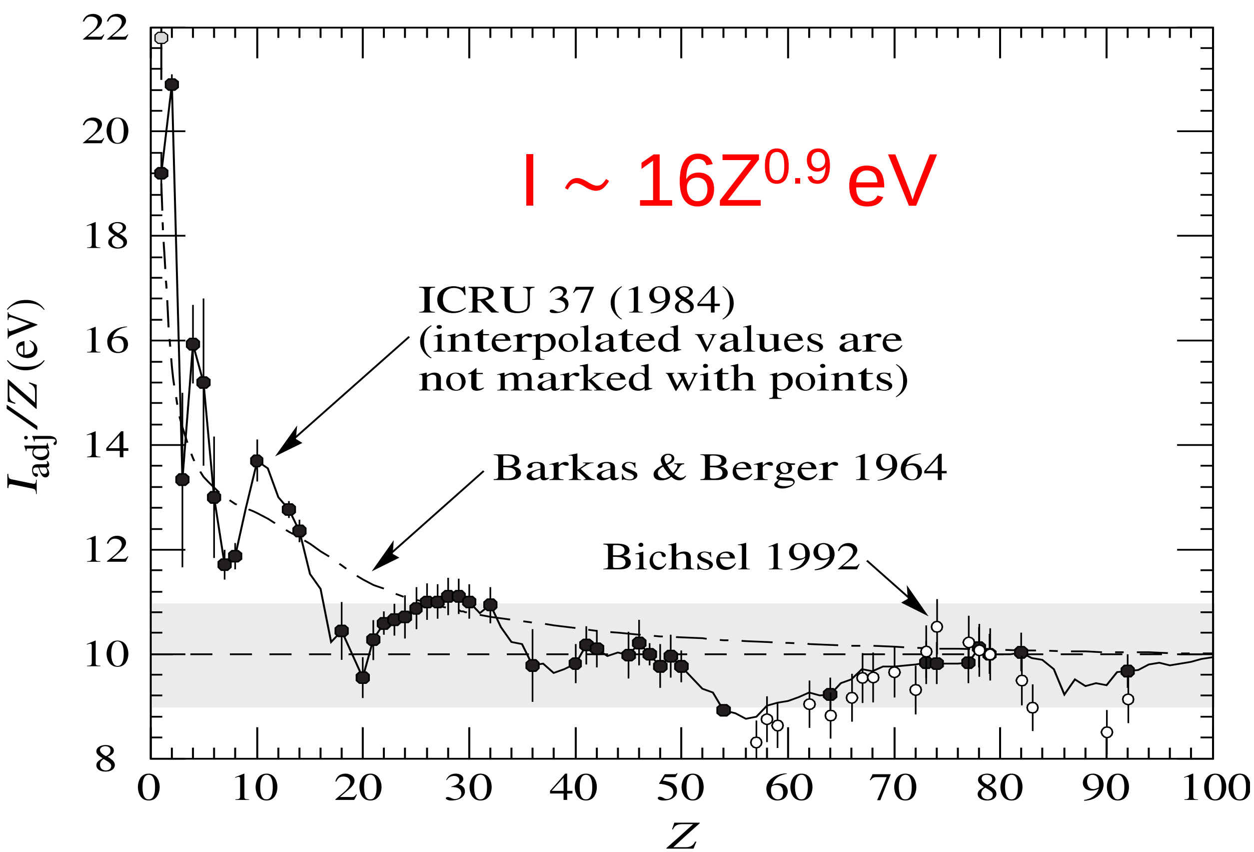
- Energy loss of charged particles per unit length
  - z = charge of the particle
  - Z,A of the absorber
  - I = mean excitation energy of the absorber
  - $4\pi N_A r_e^2 m_e c^2 = D = 0.3071$ MeV/(g/cm^2)
  - δ describes the E.M. screening effect of the absorber

Bethe-Bloch

$$-\frac{dE}{dx}\left[\frac{MeV}{cm}\right] = 4\pi N_A r_e^2 m_e c^2 z^2 \rho \frac{Z}{A}\frac{1}{\beta^2}\left(\ln\frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2 - \frac{\delta}{2}\right)$$

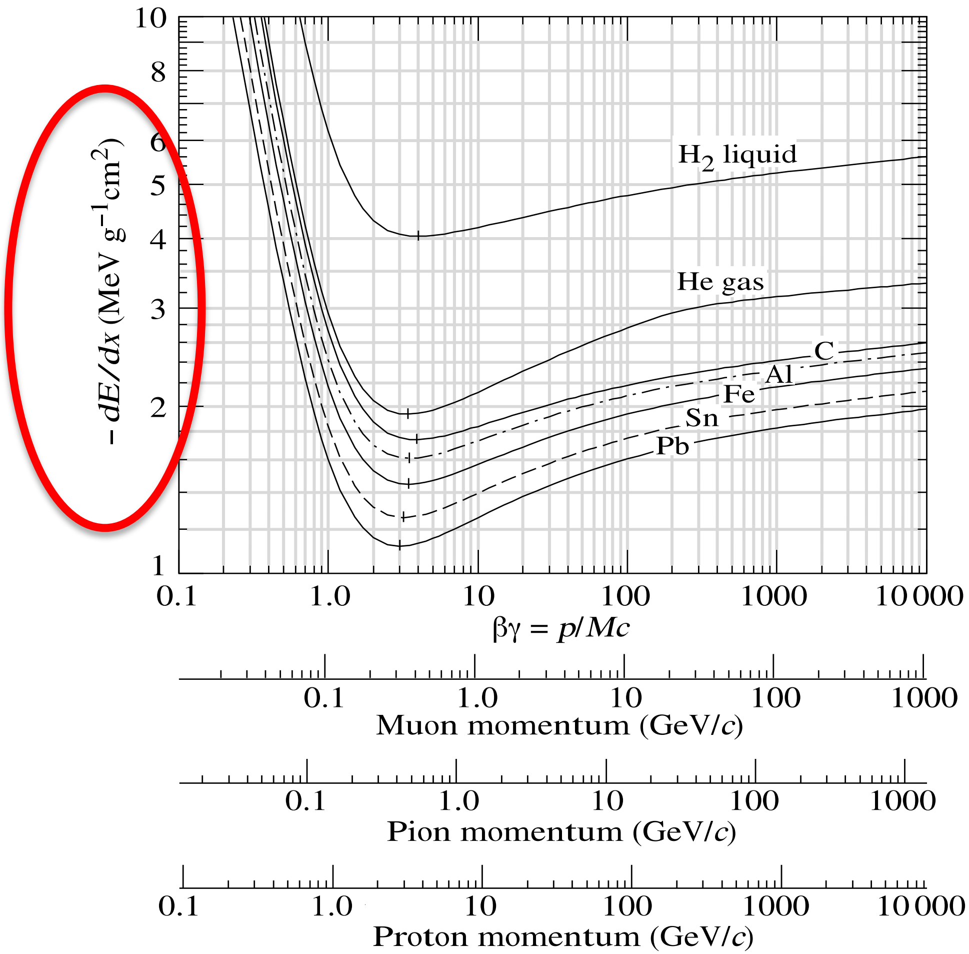


Mean excitation energy: I



- NB for light elements I depends on the phase
  - Atomic hydrogen I=15eV
  - Molecular hydrogen I=19.2eV
  - Liquid hydrogen I=21.8eV

Mass thickness

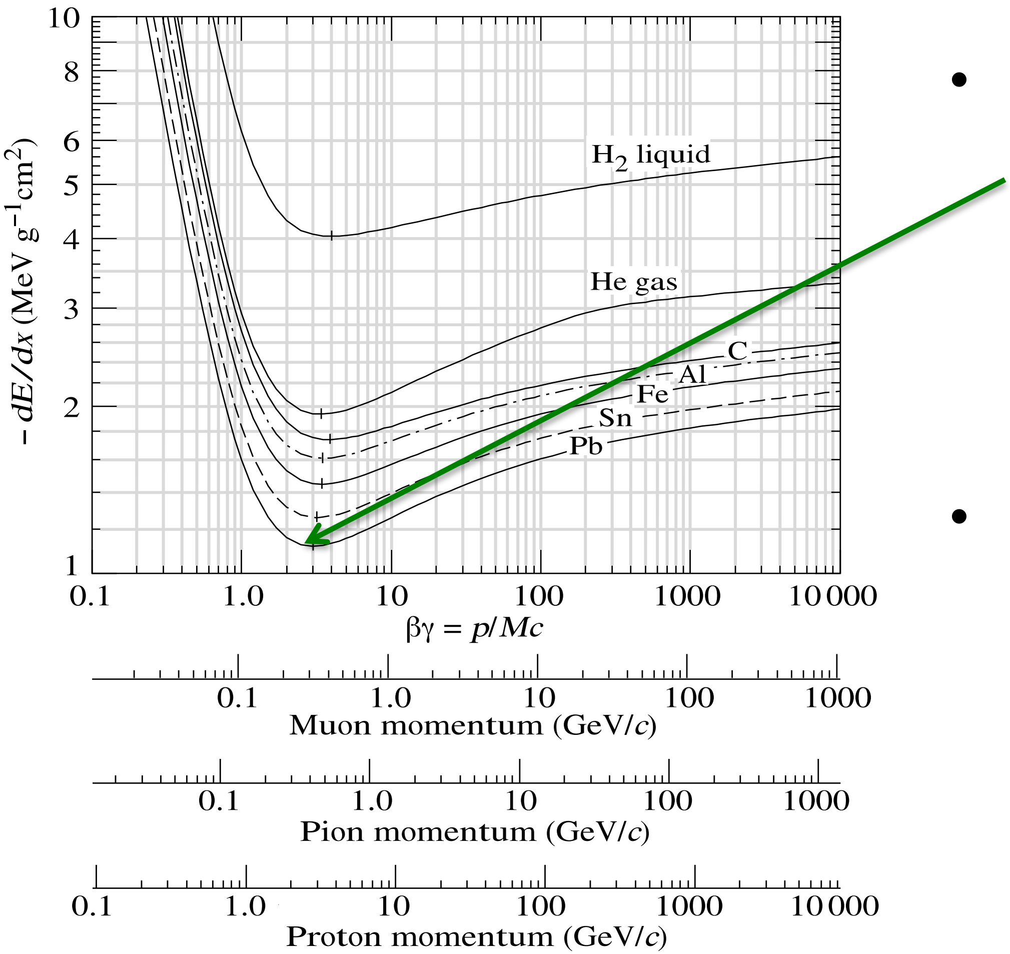


- Useful to express the loss of energy in term of "mass thickness" t

$$-\frac{dE}{dt}\left[\frac{\text{MeV}}{\text{g/cm}^2}\right]$$

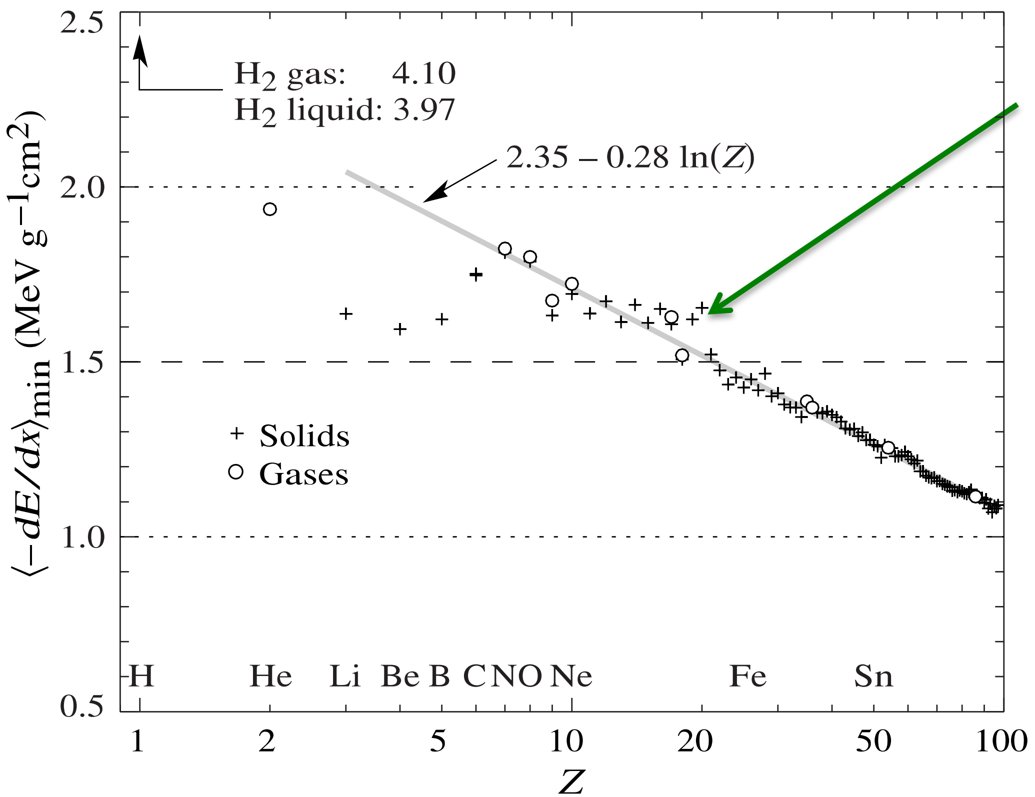
- dt=ρdx [g/cm^2]
- Look at the units to understand what is used

MIP



- Ionization minimum at βγ ~4
  - MIP = minimum ionizing particle (at and above the minimum)
- Dependency on the material is small, apart in the lightest materials
  - in unit of mass thickness, then you have to multiply for the density

dE/dx vs Z



- Notice that, normalized to density, the energy loss at minimum decreases with Z
  - Z/A decreases at high Z

$$-\frac{dE}{dt} = z^2 \frac{Z}{A} f(I)$$

B.B examples

- Argon STP
  - 0 °C, 100 kPa: ρ=1.78×10^{-3} g/cm^3
  - Z=18, A=40, I=16Z$^{0.9}$=215.7 eV

$$-\frac{dE}{dx}=\frac{0.246\cdot 10^{-3}}{b^2}\left(\ln\left(8.463\cdot\frac{b^2}{1-b^2}\right)-b^2\right)\ \mathrm{MeV/cm}$$

- Minimum at β=0.952, βγ=3.12
- dE/dx =2.66 keV/cm (1.49 MeV/(g/cm^2)
- at βγ=100 increases by 1.54

- Liquid Argon
  - ρ=1.4g/cm^3
- dE/dx at minimum = 2.09 MeV/cm

- Aluminium
  - ρ=2.7g/cm^3, Z=13, A=27, I=16Z$^{0.9}$=160.9 eV
  - Minimum atβ=0.954, βγ=3.175
  - dE/dx =4.47 MeV/cm (1.65 MeV/(g/cm^2) at minimum

- Liquid hydrogen
  - ρ=0.07g/cm^3, Z=1, A=1, I=21.8 eV
  - Minimum at β=0.962, βγ=3.504
  - dE/dx =0.287 MeV/cm (4.1MeV/(g/cm^2) at minimum

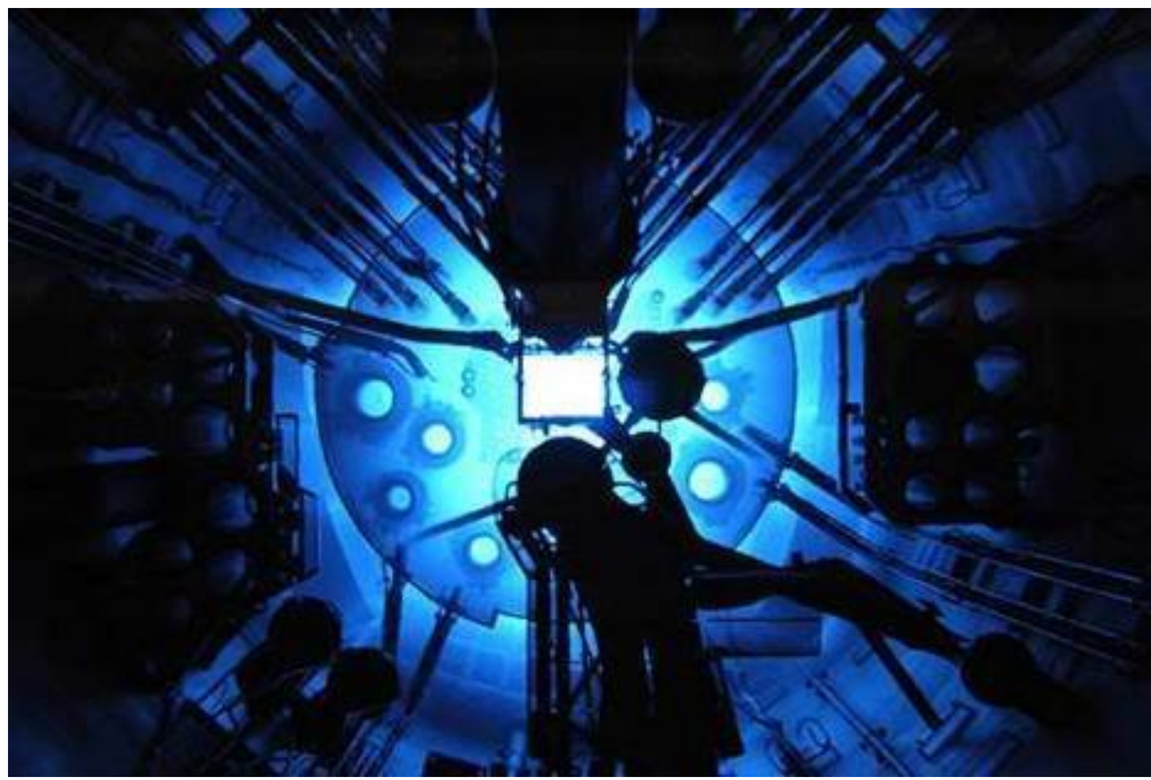
dE/dx and detectable energy

- NB the Bethe Bloch equation describes the energy lost by the particle in an absorber, not the signal useful to detect it
  - In a slab of lead, lot of energy is lost but none is detectable
  - Losses by ionization, or atomic excitations, can be detectable is some material

- Let's look at some phenomena useful for direct detection
  - Cherenkov radiation
  - Transition radiation

Cherenkov

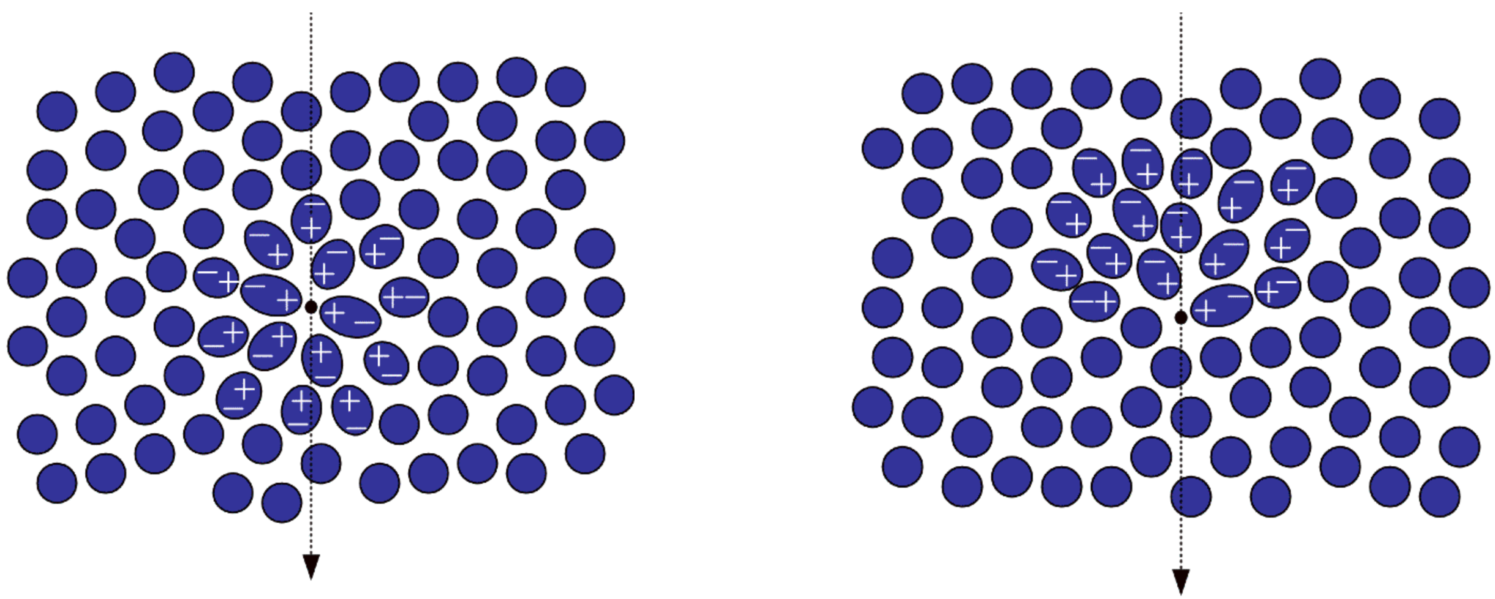
- Electromagnetic shock wave
  - Generated when the speed of the particle in the material is higher than the speed of light



  - $\beta c \geq c/n$
  - $\beta \geq 1/n$
- Has a threshold in β, useful to measure it

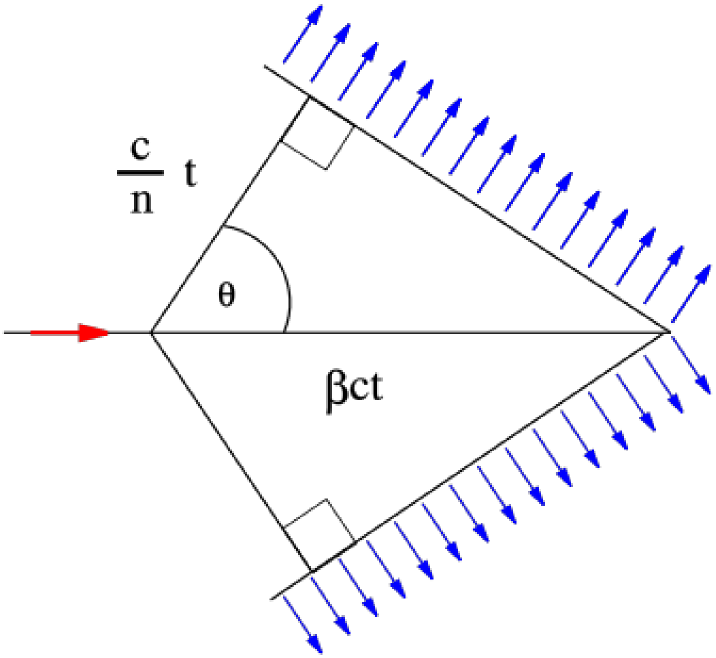
Cherenkov

- $n \approx \sqrt{k_e}$ is the refraction index
  - If v<c/n the induced polarization is symmetrical, no radiation emitted
  - If v>c/n the induced polarization is asymmetrical, dipoles emit radiation



Cherenkov

- From the geometry:
  - $\cos\vartheta_c = 1/n(\omega)\beta$
  - The refraction index depend on the frequency of the light (dispersion)
    - The angle itself depend on the frequency
  - The angle increases with β and n
    - glass, n≈1.5, β≈1 $\vartheta_c \approx 48°$



Cherenkov

- Number of photons emitted:

$$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi z^2\alpha}{\lambda^2}\left(1 - \frac{1}{n(\lambda)^2\beta^2}\right)$$

- Spectrum diverges as $1/\lambda^2$
  - But for small λ, n→1, no Cherenkov emission
  - Light tend to be on the blue side

- Visible photon emitted (400÷700nm) in glass

$$\frac{dN}{dx} = 2\pi z^2\alpha\left(\frac{1}{\lambda_{min}} - \frac{1}{\lambda_{max}}\right)sen^2\theta_C$$

  - 273 photons/cm. Very small number

Transition radiation

- Transition radiation is produced by relativistic charged particles when they cross the interface of two media of different dielectric constant
  - Very interesting characteristics: the emitted energy is proportional to the Lorentz γ

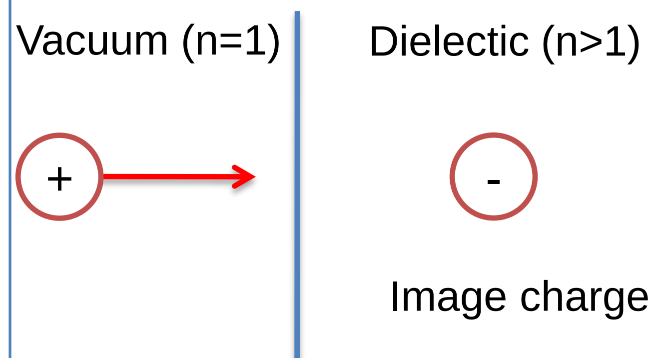
$$E = z^2 \frac{\alpha}{3} \hbar \omega_P \cdot \gamma$$

$$\omega_P = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}, \quad n_e = \rho N_A \frac{Z}{A}$$

  - Very small number of photon emitted per transition

$$N_{TR} \sim \alpha$$

  - Photon energy is in the X-ray region (keV)



Variable dipole emitting E.M. radiation

Bremsstrahlung

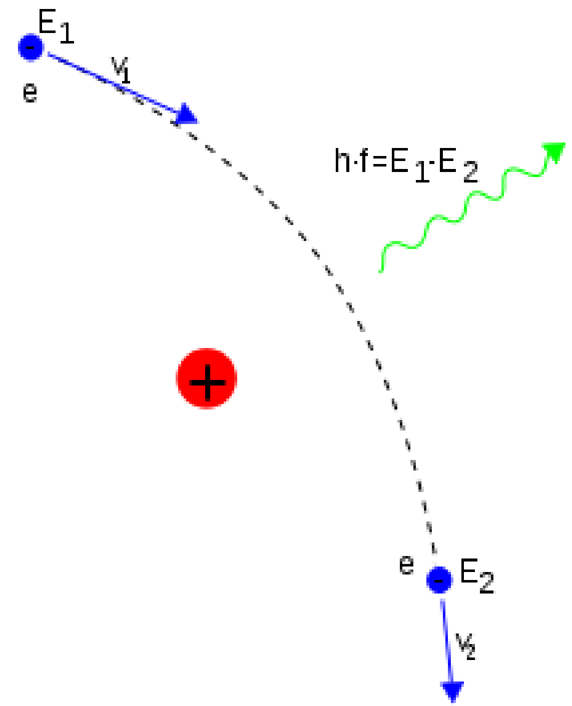
- Radiation emitted by charged particle when decelerated in the field of a nucleus
  - Emission probability is proportional to $1/m^2$ so the effect is typical of electrons

$$s \propto \left(\frac{e^2}{mc^2}\right)^2$$

  - For muons, the radiation probability at the same energy is $1/200^2 = 1/40000$
  - The energy radiated per unit length is proportional to the energy, and function of the material

$$-\frac{dE}{dx} » \frac{E}{X_0} \qquad E = E_0 e^{-\frac{x}{X_0}}$$

  - So the energy decreases exponentially with x, X_0 is called the “radiation length”



Bremsstrahlung

- An approximated formula for X_0:

$$\frac{1}{X_0} = 4\alpha r_0^2 N_A \frac{Z^2}{A} \rho \ln \frac{183}{Z^{1/3}}$$

$$\alpha = \frac{1}{137}$$

$$r_0 = \frac{1}{4\pi\epsilon_0}\frac{e^2}{mc^2}$$

- Or, taking into account electrons in the material and Coulomb corrections

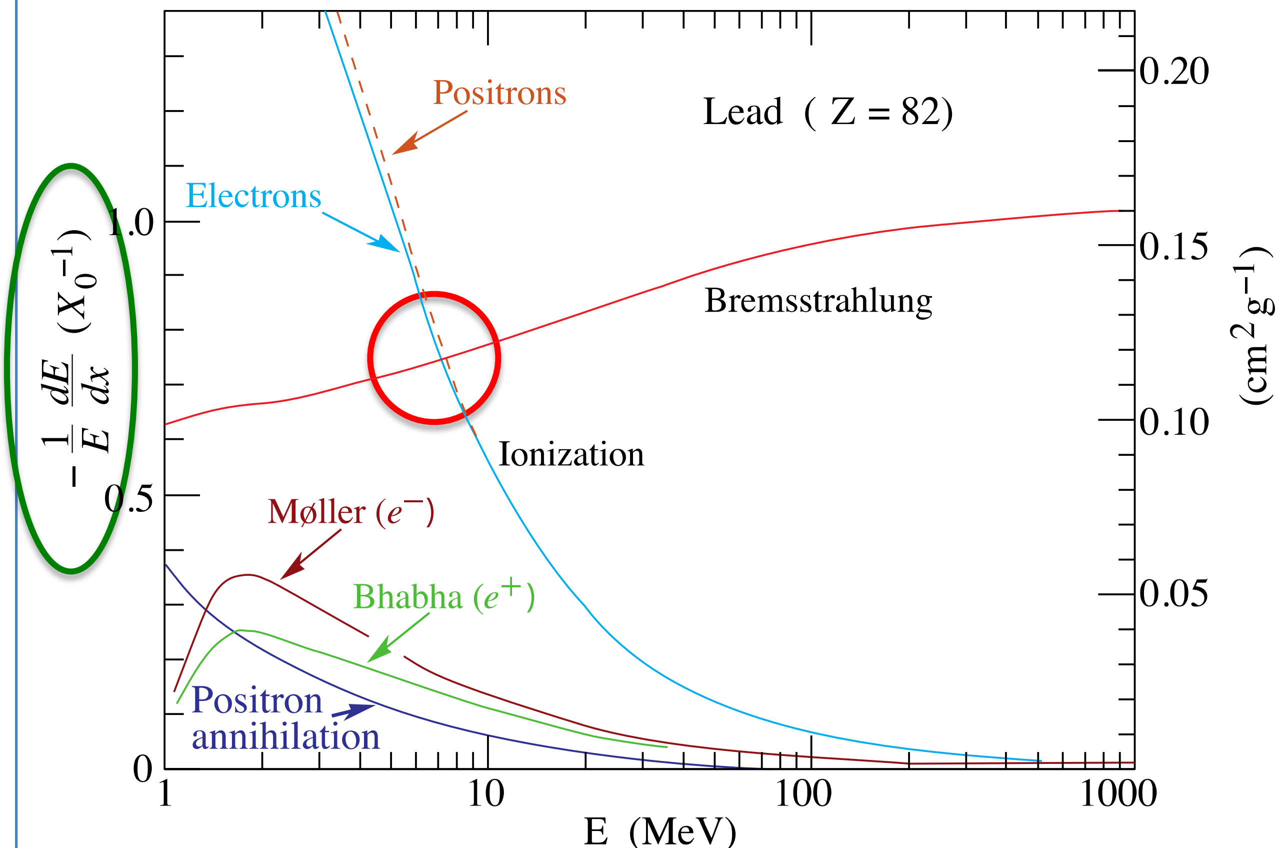
$$\frac{1}{X_0} = 4\left(Z(Z+1)N_A \frac{\rho}{A}\right)\alpha r_0^2 \left(\ln \frac{183}{Z^{1/3}} - f(Z)\right)$$

$$F(Z) = a^2\left(\frac{1}{1+a^2} + 0.202 - 0.036a^2 + 0.008a^4 - 0.002a^6\right)$$

$$a = Z/137$$

Critical Energy

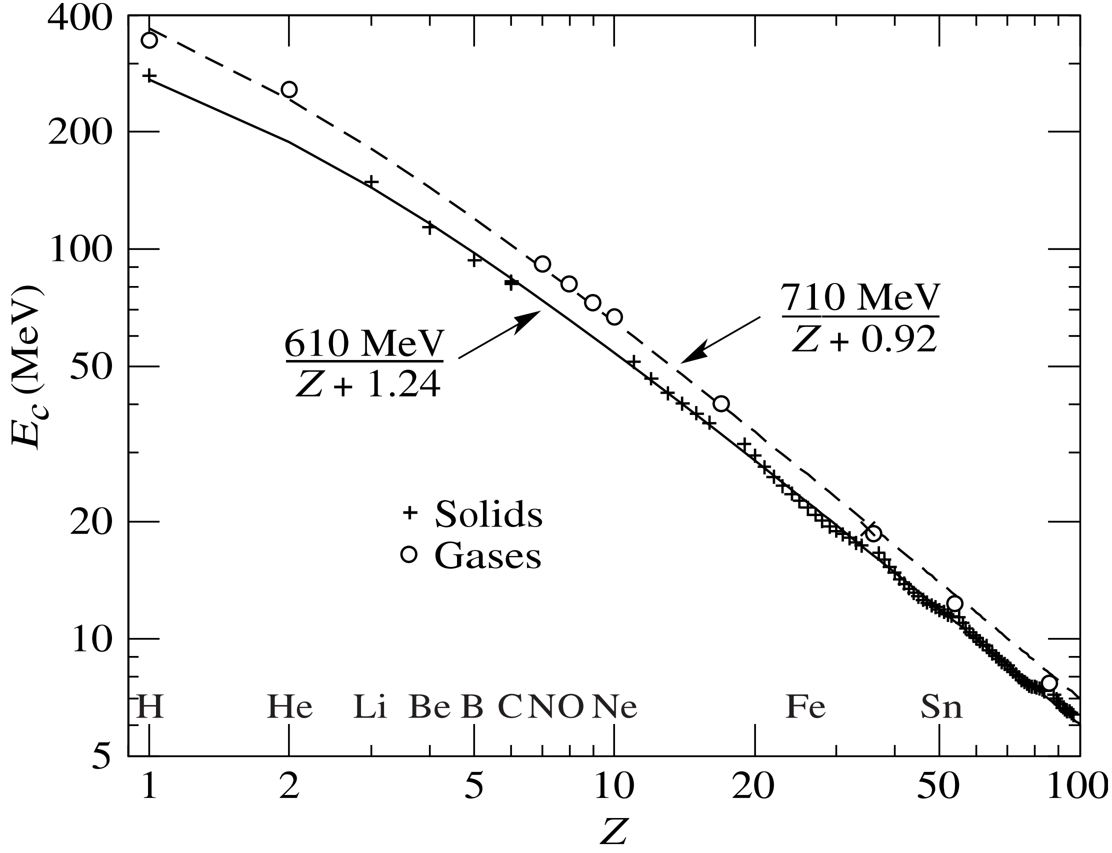
- E_C
  - Energy where the energy lost for bremsstrahlung is equal to that for collisions



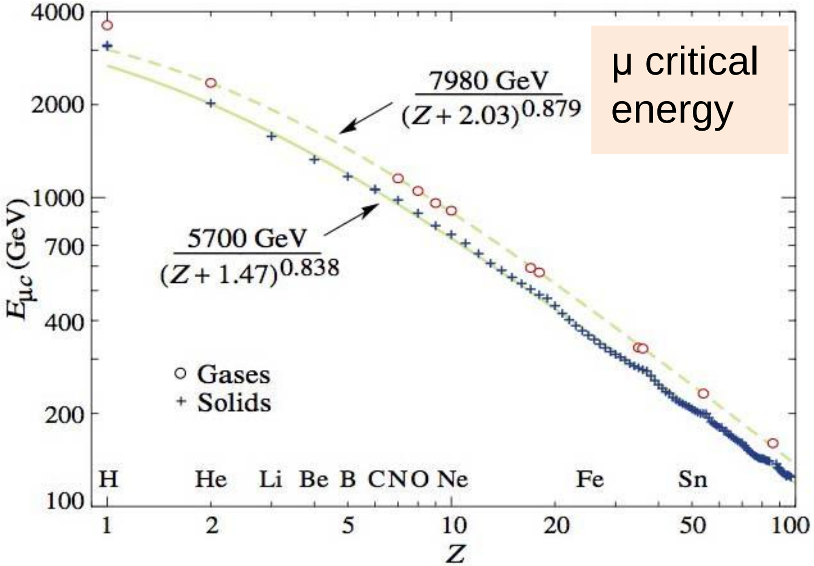
$$\left(\frac{dE}{dx}\right)_{rad} = \left(\frac{dE}{dx}\right)_{coll}$$

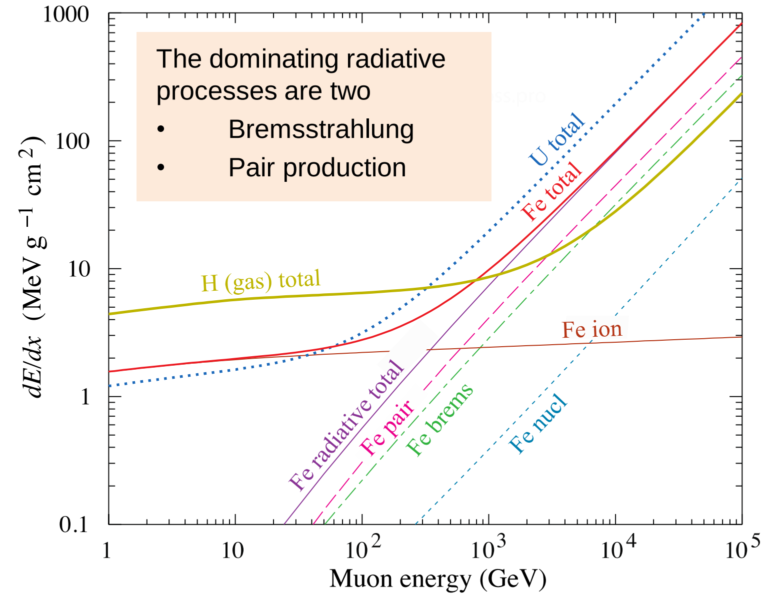
Critical Energy

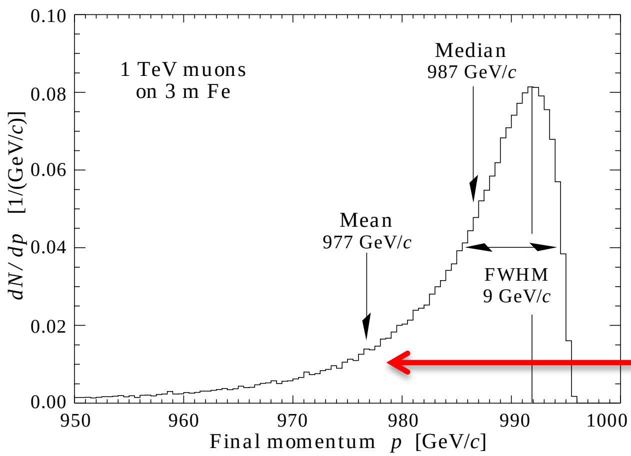
NB the E_C gets smaller at high Z, you lose more energy from bremsstrahlung for longer in heavy materials



Muon radiation losses





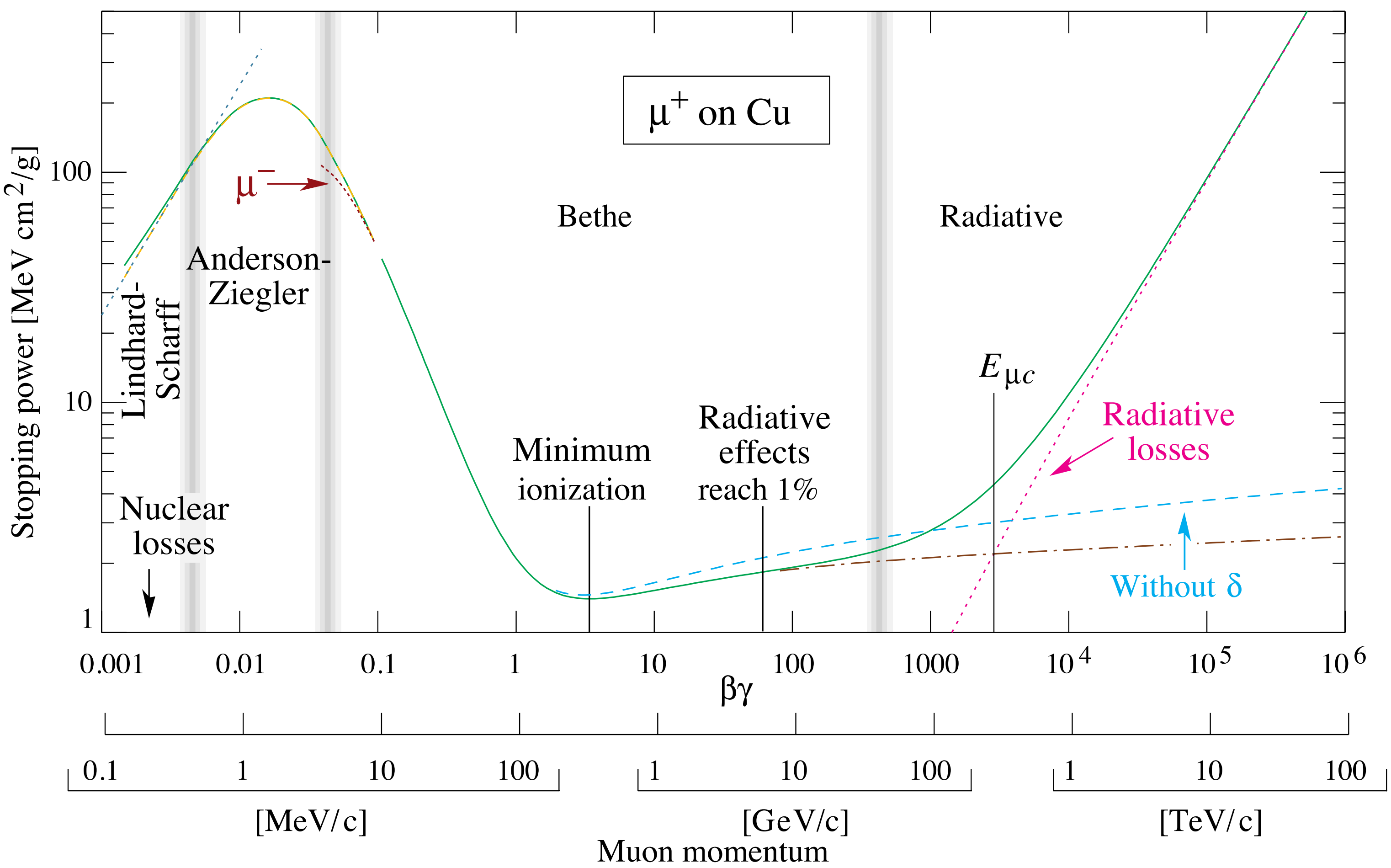


Above few hundreds GeV also muons radiate in heavy absorbers

- Relevant for LHC and cosmic rays
- Expected energy loss from ionization for a 1TeV muon in 3m of Fe less than 5GeV
- Large tails from radiative processes

Summary of energy losses

For charged particle (μ^- through copper in this plot)



Interactions of photon

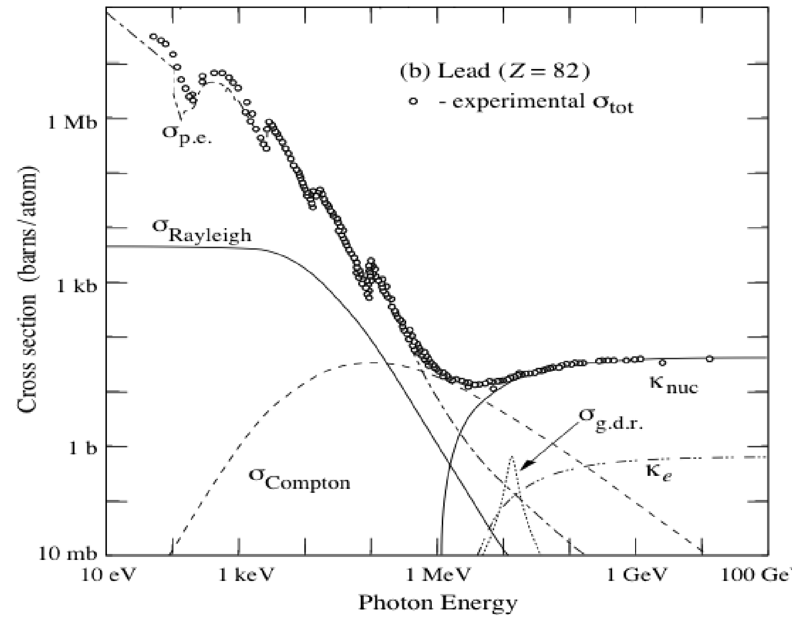
- We cannot talk of energy loss
  - Either photons scatter at large angle, or interact losing all its energy

$$-\frac{dI}{dx} = I\mu$$

$$I(x) = I_0 e^{-\mu x}$$

$$N_f = \frac{I}{h\nu}$$

  - μ = absorption coefficient, measuring the fraction of photon flux lost per unit length
  - Three main phenomena for energies >1keV
    - Photoelectric effect $h\nu << m_e c^2$
    - Compton scattering $h\nu \approx m_e c^2$
    - e^+e^- pair production $h\nu \approx m_e c^2$



- μ (in cm^{-1} o in cm^2/g) is given by the sum of the different processes:

$$\frac{\mu}{\rho} = \frac{N_A}{A}\sigma_{Photo} + Z\frac{N_A}{A}\sigma_{Compton} + \frac{N_A}{A}\sigma_{Pair}$$

- And it depends strongly on the energy of the photon

Photoelectric effect

- The energy is absorbed by an atom, which emits an electron
  - For energetic photons the inner levels are interested 1S = K (≈80% of the cross section)
  - Then the rearrangement may generate emissions of X photons or even an (Auger)

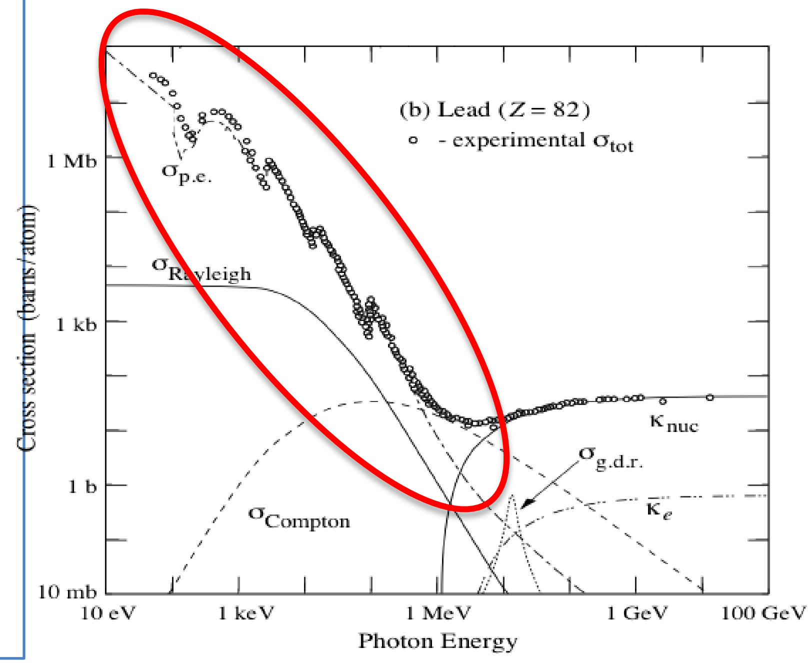
- Very strong dependence on energy and on Z

$$\sigma^{K}_{photo} \approx \sqrt{\left(\frac{32}{\varepsilon^{7}}\right)}\,\alpha^{4} Z^{5} \sigma_{Th}$$

$$\varepsilon = \frac{h\nu}{m_e c^2}$$

$$\sigma_{Th} = \frac{8}{3}\pi r_e^2$$

  - Sharp variation close to the atomic levels



Pair production

- $\gamma \rightarrow e^+e^-$
  - There is a threshold energy
    - $h\nu \geq 2m_ec^2$=1.022MeV
  - To conserve momentum and enery, it happens with a spectator nucleus

- Approximated cross sections

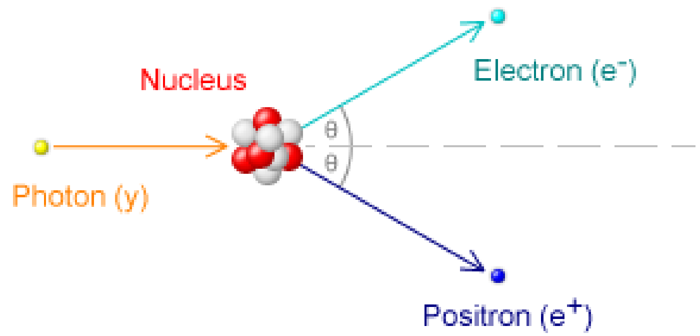
$$for\ 2m_ec^2 << hn << \frac{m_ec^2}{a} Z^{-1/3}$$

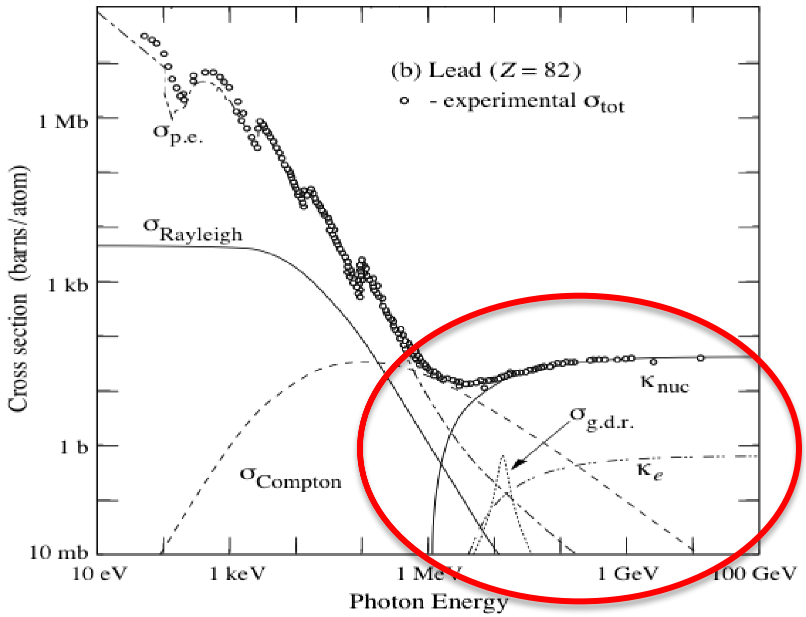
$$s_{Pair} = 4Z^2 a r_e^2 \left[\frac{7}{9} \ln\left(\frac{2hn}{m_ec^2} - f(z) \right) - \frac{109}{54} \right]$$

$$for\ hn >> \frac{m_ec^2}{a} Z^{-1/3}$$

$$s_{Pair} = 4Z^2 a r_e^2 \left[\frac{7}{9} \ln\left(183 Z^{-1/3} - f(z) \right) - \frac{1}{54} \right]$$

- At high energy does not depend on hv





Pair production

- So for high energy photons

$$\mu_{Pair} = \rho \frac{N_A}{A} \sigma_{Pair} = \frac{1}{\lambda_{Pair}}$$

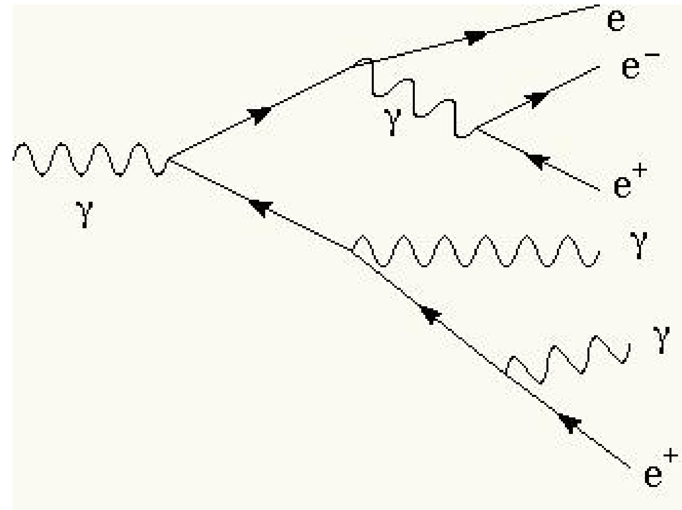
$$\frac{1}{\lambda_{Pair}} \approx \frac{7}{9} 4Z(Z+1)\alpha r_e^2 \left[\ln\left(183Z^{-1/3}\right)\right] \approx \frac{7}{9}\frac{1}{X_0}$$

$$\lambda_{Pair} \approx \frac{9}{7} X_0 \approx 1.3 X_0$$

$$I = I_0 e^{-\frac{x}{1.3X_0}}$$

- Very similar to the energy loss of electrons for bremmstrahlung

$$E = E_0 e^{-\frac{x}{X_0}}$$

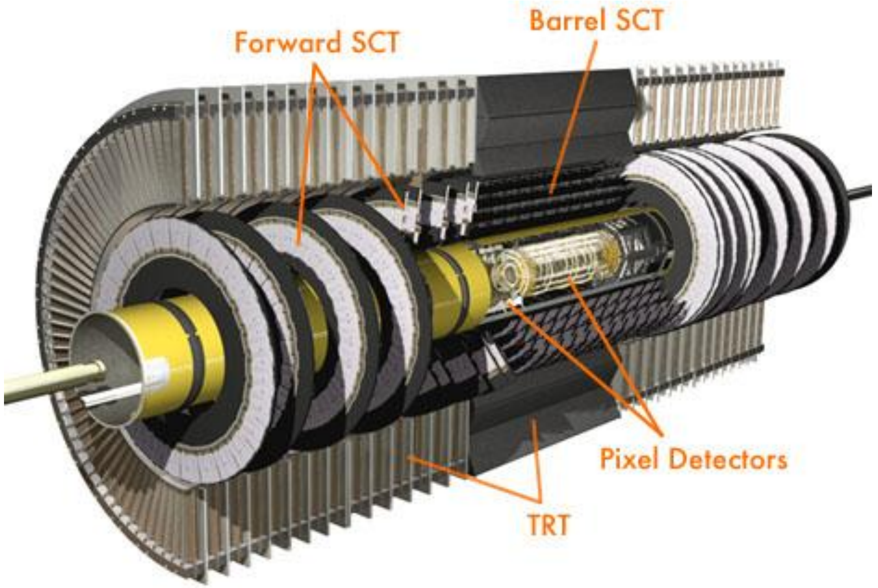


- Electromagnetic shower
  - Combined process of bremmstrahlung and pair production
  - Will come back to that when discussing the calorimeters

TRACKING DETECTORS

Essential multi-purpose detectors

- Measurements of:
  - tracks momentum
    - From deflection in magnetic field
  - Event topology
  - Primary and secondary vertexes
  - dE/dx
  - trigger



Momentum measurement

- Bending in magnetic field
  - constant, orthogonal to the velocity

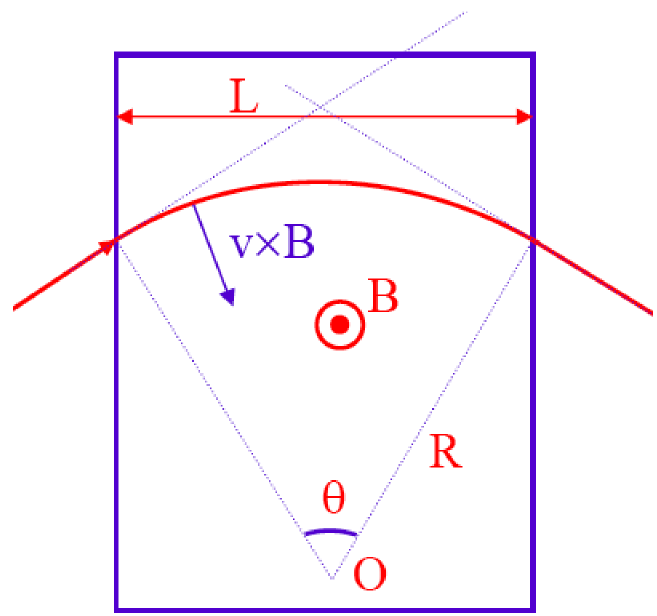
$$R = \frac{p}{qB}$$

if p is in GeV/c q is unit charge, B in Tesla and R in meters

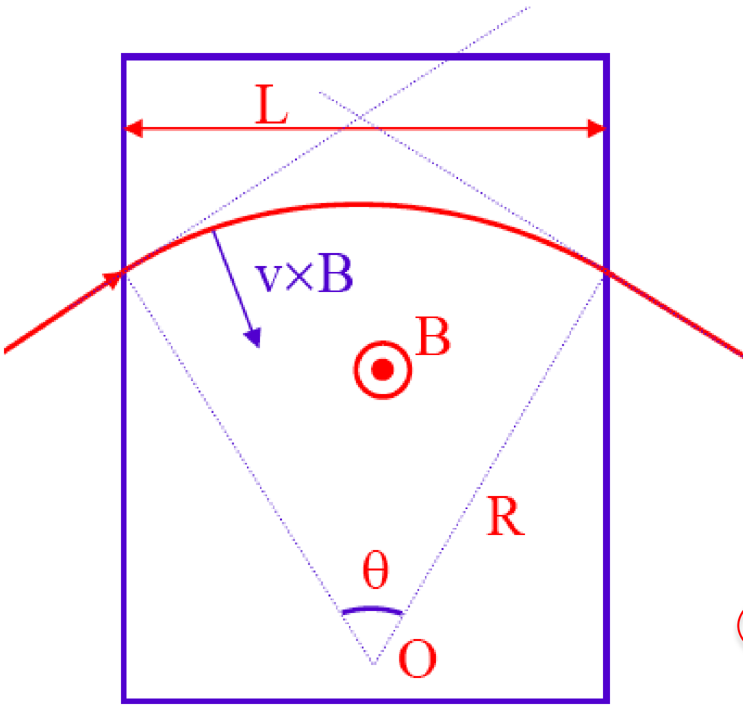
$$p = p\left[GeV/c\right] \times \frac{10^9 \times 1.6 \times 10^{-19}}{3 \times 10^8}$$

$$R = \frac{p \times \dfrac{10^9 \times 1.6 \times 10^{-19}}{3 \times 10^8}}{1.6 \times 10^{-19} \times B} = \frac{10}{3}\frac{p}{B}$$

$$p \approx 0.3RB$$



Momentum measurement



$L \approx R\theta$ for small angles

$$\theta = \frac{L}{R} = 0.3\frac{BL}{p}$$

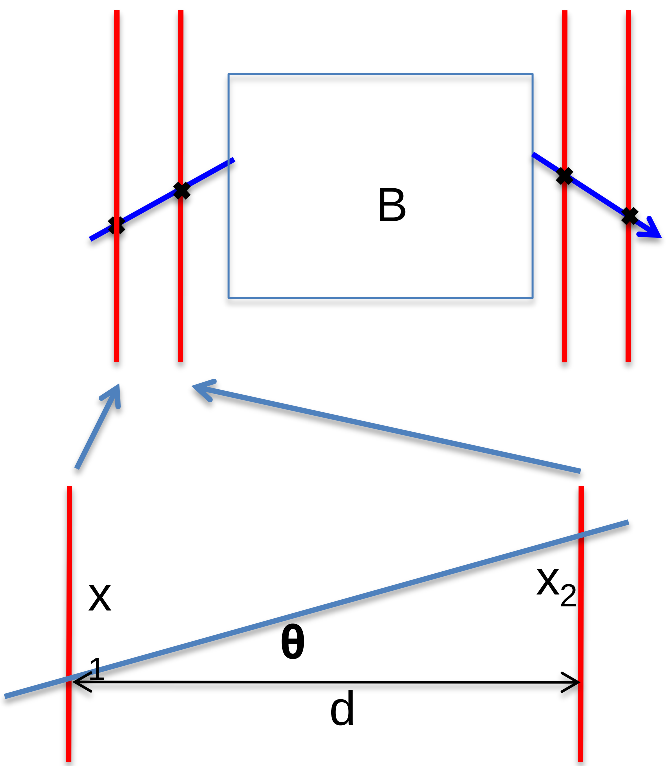
$$\theta = \frac{0.3}{p}\int B\,dl \text{ (if B is not uniform)}$$

$$p = \frac{0.3}{\theta}\int B\,dl$$

$$\frac{\sigma(p)}{p} = \frac{\sigma(\theta)}{\theta} = \frac{p}{0.3\int B\,dl}\sigma(\theta)$$

- p can be derived from the bending angle
- Given the error on the angle, σ(p)/p increases lineraly with p

Measuring the deflection



- To measure the bending we need two directions
  - At least two precise points before and after the magnet

$$q \text{ » } \frac{x_2 - x_1}{d}$$

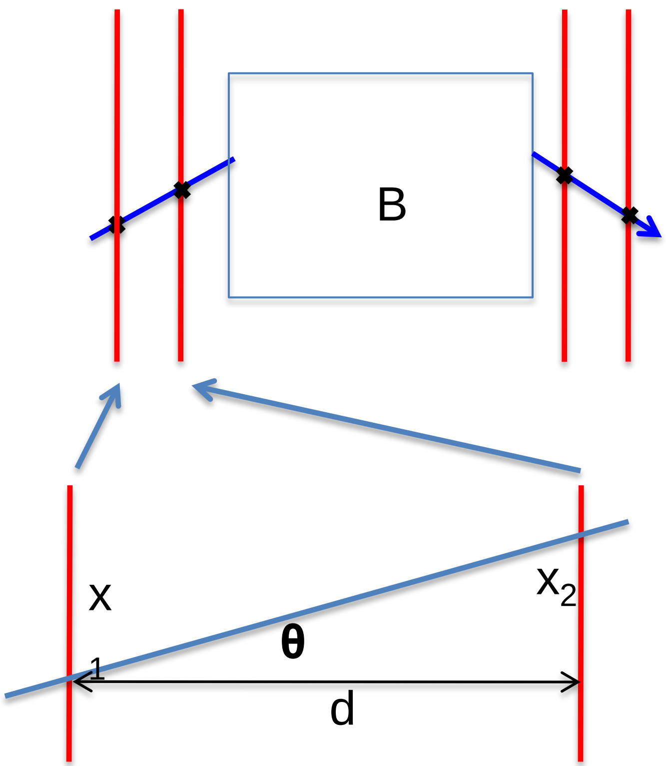
$$s(q) = \frac{1}{d}\sqrt{s^2(x_1) + s^2(x_2)} = \frac{\sqrt{2}}{d} s(x)$$

$$q_{bending} = q_1 - q_2$$

$$s\left(q_{bending}\right) = \sqrt{2} s(q) = \frac{2}{d} s(x)$$

$$\frac{s(p)}{p} = \frac{p}{0.3 \text{ò} Bdl} s(q) = \frac{2p}{0.3d \text{ò} Bdl} s(x)$$

Example



$$\frac{\sigma(p)}{p} = \frac{p}{0.3\int B\,dl}\,\sigma(\theta) = \frac{2p}{0.3d\int B\,dl}\,\sigma(x)$$

$$\int B\,dl = 1Tm \qquad d = 1m \qquad \sigma(x) = 200\,\mu m$$

$$\frac{\sigma(p)}{p} = 1.3\cdot 10^{-3}\,p \quad \text{with } p \text{ in } GeV/c$$

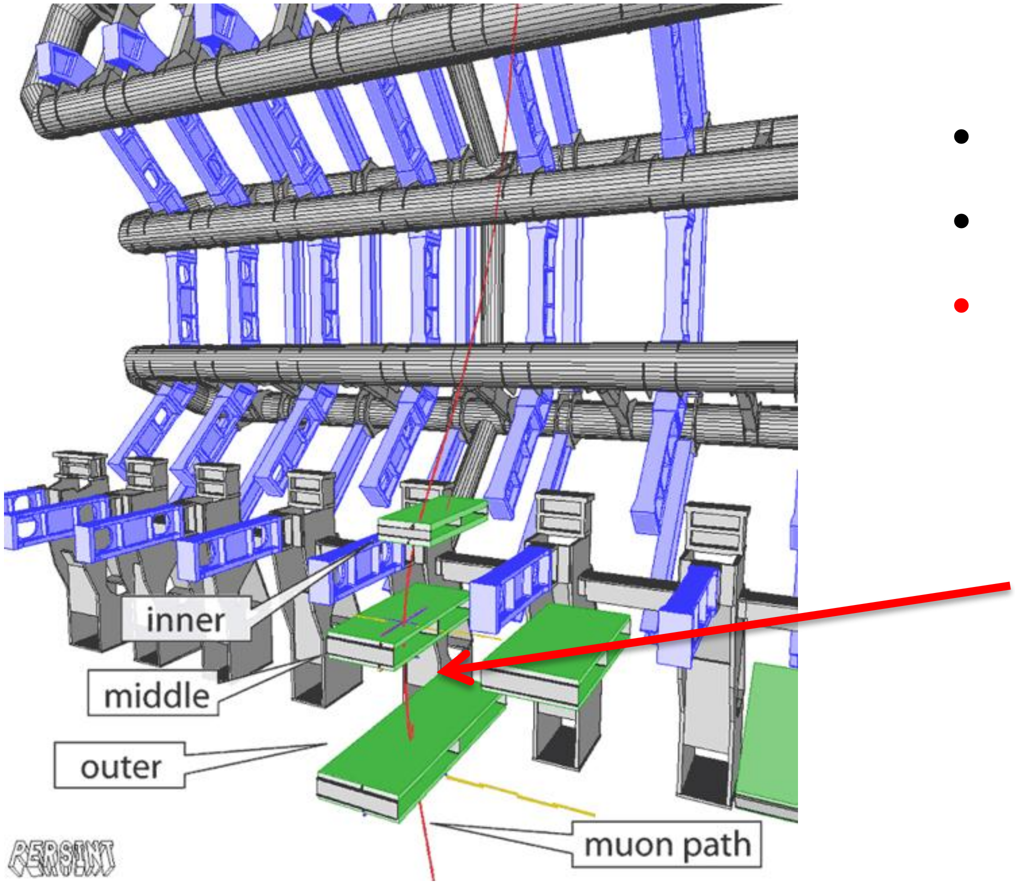
$$p = 1GeV/c \rightarrow \sigma(p)/p = 1.3\cdot 10^{-3} \approx 0.1\%$$

$$p = 10GeV/c \rightarrow \sigma(p)/p = 1.3\cdot 10^{-2} \approx 1\%$$

$$p = 100GeV/c \rightarrow \sigma(p)/p = 1.3\cdot 10^{-1} \approx 10\%$$

Use of bending measurement

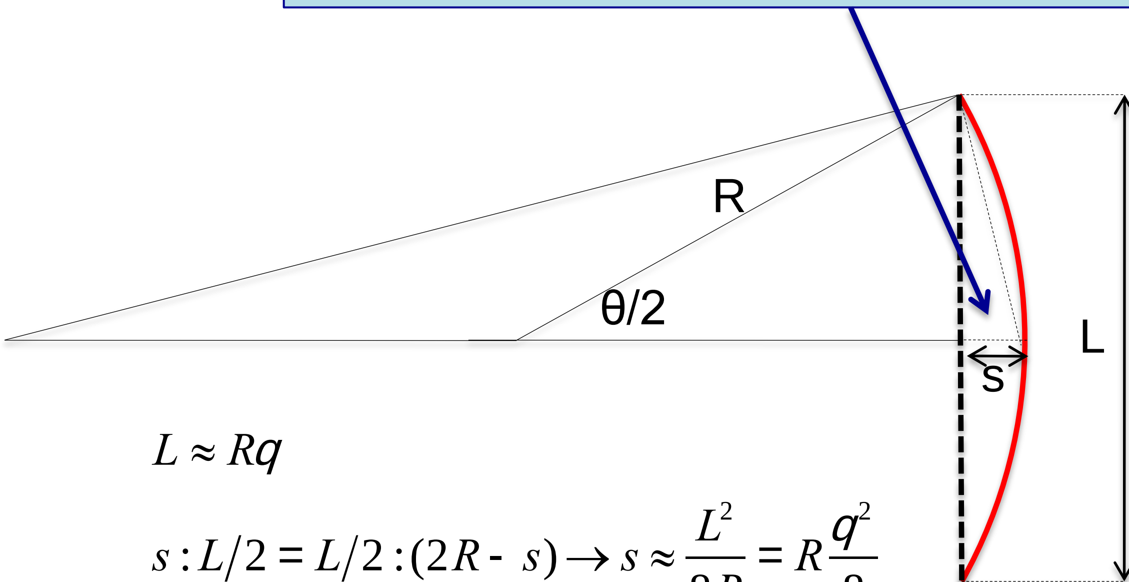
- Bending typically used to measure p for



- Beams
- Fixed target experiments
- Muons
  - bending in magnetized iron
  - or even in air like in Atlas

Sagitta

The track is measured inside the magnetic field



$$L \approx R\theta$$

$$s : L/2 = L/2 : (2R - s) \rightarrow s \approx \frac{L^2}{8R} = R\frac{\theta^2}{8}$$

$$s = 0.3\frac{BL^2}{8p} \quad \text{(if B uniform, p in GeV/c)}$$

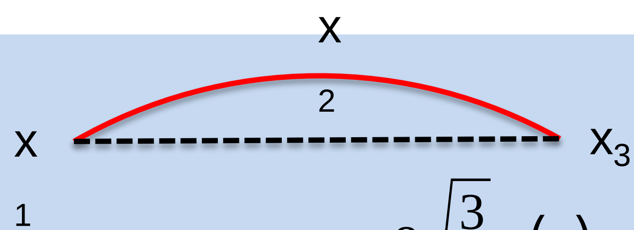
$$\frac{\sigma(p)}{p} = \frac{\sigma(s)}{s} = \frac{8\sigma(s)}{0.3BL^2}p$$

- Again σ(p)/p grows with p
- The precision can be improved by
  - Improving the precision of the position
    - Also measuring in more points
  - Increasing B
  - Increasing the lever arm

Sagitta

- Need at least 3 points to make the measurement

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



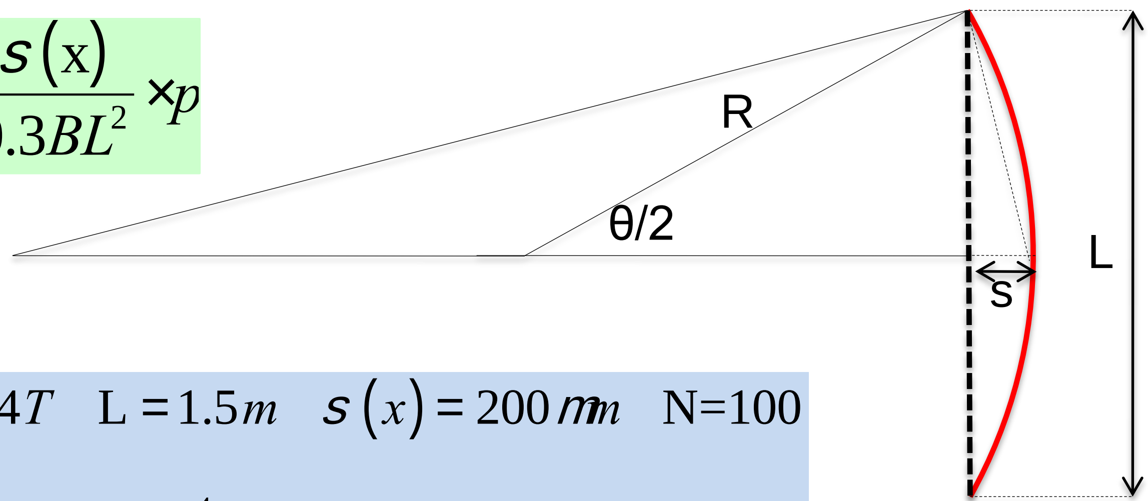
$$\sigma(s) = \sqrt{\frac{3}{2}}\,\sigma(x) \rightarrow \frac{\sigma(\mathrm{p})}{p} = \frac{\sigma(\mathrm{s})}{s} = \frac{8\sqrt{\frac{3}{2}}\,\sigma(\mathrm{x})}{0.3BL^2}\,p$$

- With many points one gets to the following

$$\frac{\sigma(\mathrm{p})}{p} = \sqrt{720/(N+4)}\,\frac{\sigma(\mathrm{x})}{0.3BL^2} \times p$$

Example

$$\frac{s(\mathrm{p})}{p} = \sqrt{720/(N+4)}\,\frac{s(\mathrm{x})}{0.3BL^2}\times p$$



$$B = 1.4T \quad \mathrm{L} = 1.5m \quad s(x) = 200\,mm \quad \mathrm{N{=}100}$$

$$\frac{s(p)}{p} = 5.6\cdot 10^{-4}\,p \qquad \text{whith } p \text{ in } GeV/c$$

$$p = 2GeV/c \rightarrow s(p)/p = 1.1\cdot 10^{-3} \approx 0.1\%$$

$$p = 20GeV/c \rightarrow s(p)/p = 1.1\cdot 10^{-2} \approx 1\%$$

$$p = 200GeV/c \rightarrow s(p)/p = 1.1\cdot 10^{-1} \approx 10\%$$

$$s(p)/p = 100\% \rightarrow p \approx 2TeV$$

Detectors for tracking

- The requirements are clear
  - Be able to measure with high precisions the charged track positions
    - Most times in magnetic field
  - Other possible requirements
    - Minimize dead material (see later the multiple scattering)
    - Linearity if used to measure also dE/dx

- Two main classes of detectors
  - Gas detectors
    - Multi-wire chambers, drift chambers, limited streamer tubes, resistive plate chambers, GEMs …
  - Semiconductor detectors
    - SI strips, Pixels

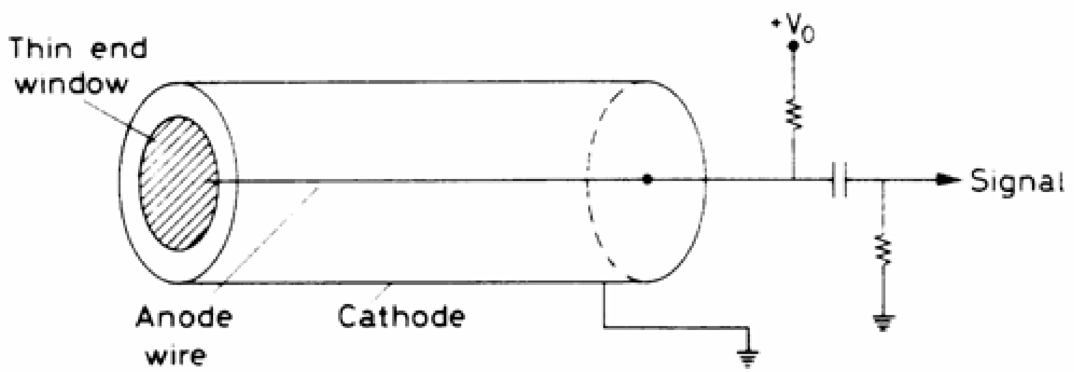
Gas detectors

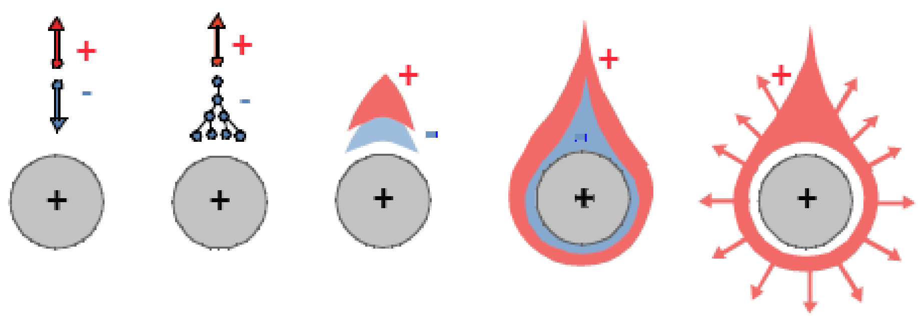
- Some of the energy lost by a charged particle ionizes the gas
  - Primary ionization
    - The charged particle extracts an electron from an atom
  - Secondary ionization
    - The extracted electron is energetic enough to further ionize the gas
  - W measures the ratio between the energy lost by the particle and the number of ions produced
    - For instances, a MIP produces abu0t 100 ion per cm of Ar at STP

	H_2	He	Ar	CH_4
pot. ion. (eV)	15.4	24.6	15.8	13.1
W (eV)	36.6	41.3	26.4	27.3
dE/dx (keV/cm)	0.34	0.32	2.44	1.48

- With an electric filed, the electrons and ions can be made drift, to be collected by the electrodes
- The signal is very small
  - 100 e = 1.6×10^{-2} fC
  - Too small even for modern amplifier
- Need a mechanism to amplify the signal in the gas
  - High electric field, avalanche ionization

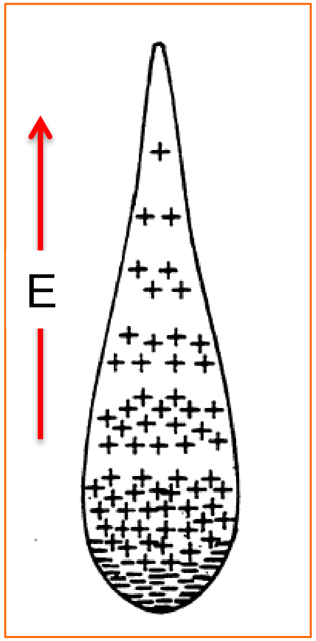
Wire chambers





- Basic mechanism
  - The anode (+) is a thin wire
  - The field between cathode and anode make the electron drift to the wire
  - Close to the wire, the field grows as 1/r and it becomes high enough to generate an avalanche
  - Most of the charge is generated in the last steps around the wire

Avalanche



- Basic mechanism
  - An electron from an ionization gets accelerated in the E field and quickly reaches an energy enough to further ionize the gas
    - Max probability to ionize is around 100 eV
  - Every mean free path for ionization λ_I the number of electrons doubles
    - $1/\lambda_I$ is called "first Townsend coefficient" α
    - The drift velocity of ions is very small w.r.t. that of the electrons, the ion cloud is left behind
  - Gain factor M

$$dn = n a\, dx$$

$$n = n_0 e^{ax} \rightarrow M = \frac{n}{n_0} = e^{ax}$$

$$M = e^{\int_{x_1}^{x_2} a(x)dx} \quad \text{where E changes}$$

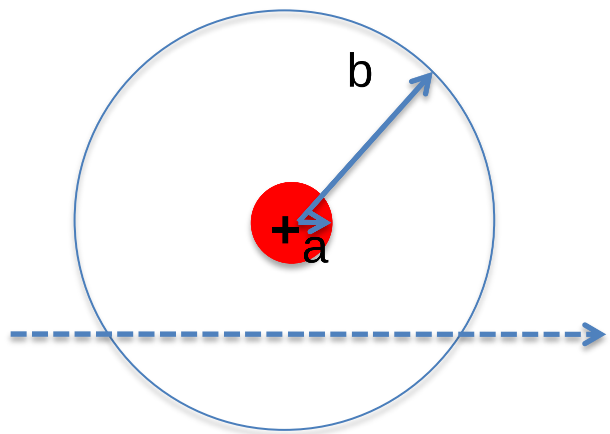
- At too high gains, there is a total discharge in the gas
  - Caused by photon emitted by the excited atoms that ionize elsewhere the gas
  - Gain limit depend mostly on the gas mixture

Wire chambers

$$C' = \frac{2\pi\varepsilon}{\ln b/a} \quad \text{capacity per meter}$$

$$E(r) = \frac{C' V_0}{2\pi\varepsilon_0}\frac{1}{r} = \frac{V_0}{\ln b/a}\frac{1}{r}$$

$$U(r) = -\frac{C' V_0}{2\pi\varepsilon_0}\ln\frac{r}{a} = -\frac{V_0}{\ln b/a}\ln\frac{r}{a}$$



example

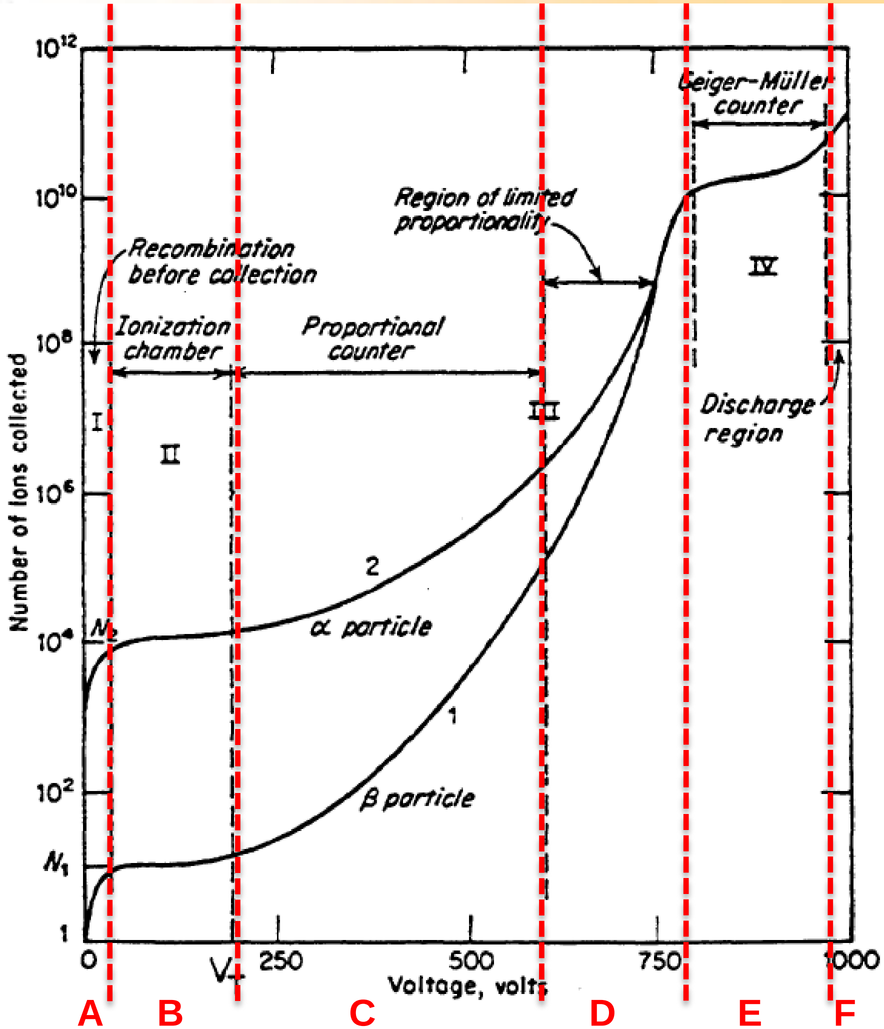
$$a = 20\,\mu m,\quad b = 5\,mm,\quad V_0 = 2\,kV$$
$$\rightarrow C' = 10\ pF/m$$
$$\rightarrow E(a) \sim 2 \cdot 10^7\ V/m$$

- The multiplication gain from the avalanche can be approximated to

$$M = const \times e^{CV_0}$$

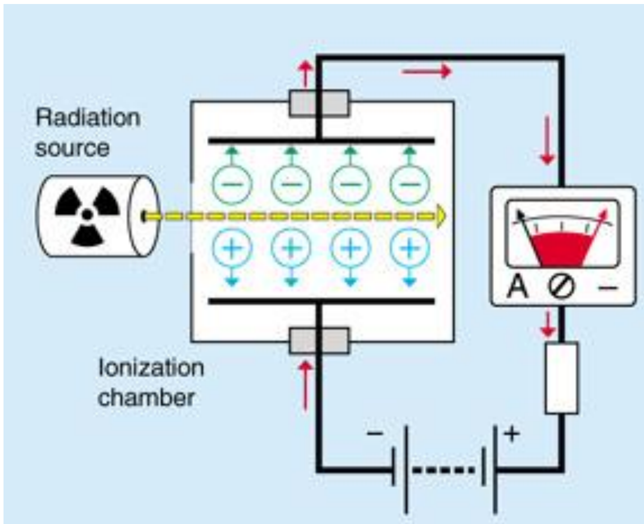
  - Grows exponentially with V_0
  - The constant depends on the gas

Wire chambers

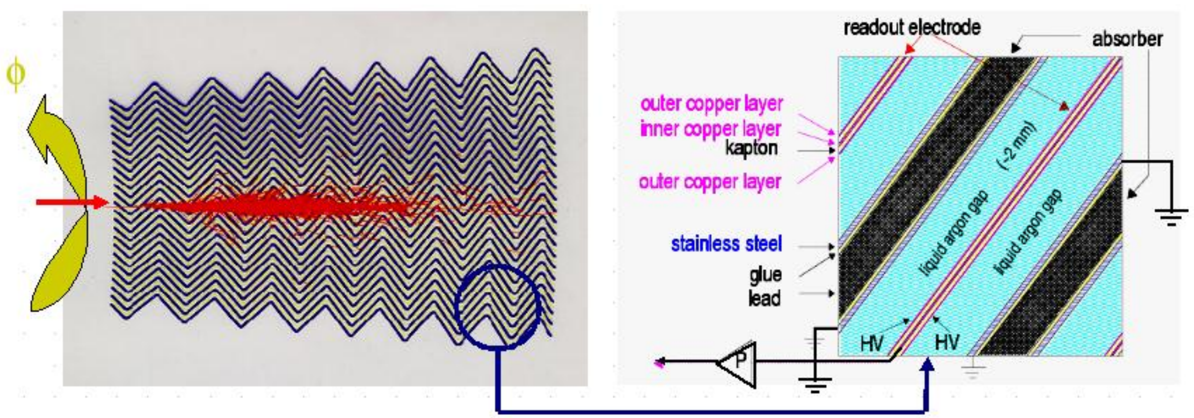


- Amplification regimes
  - A. Electric field is not enough to collect all the charge, e-ions will recombine
  - B. The charge is collected without gain (ionization chamber)
  - C. Gain is modest ($M \leq 10^5$) and the collected charge is proportional to the initial signal (proportional chamber)

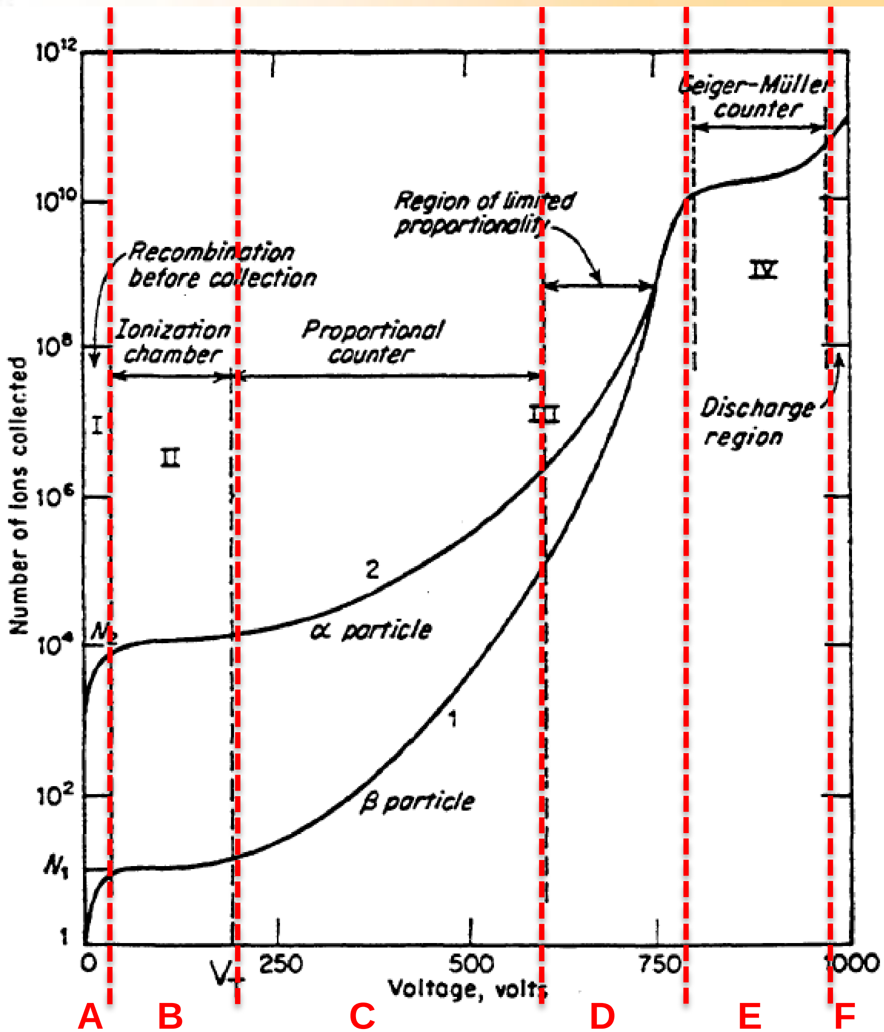
Ionization chambers



- NB, if we use liquid instead of gas, the density is about 10^3 higher and the ionization yield is enough to give enough signal without gain
  - E.g. ≈10^5 ions/cm in liquid argon (LAr) calorimeters



Wire chambers



- Amplification regimes
  - D. Gain is high, space charge effect generate saturation (limited proportionality)
  - E. The avalanche propagates all along the wire because of the emitted photons (Geiger)
  - F. Complete breakdown (discharge even without particle crossing)

Wire chambers

Choice of regime

- Proportional
  - Allows to measure dE/dx
  - Small signal
- Limited proportionality
  - Larger signal, easier electronics readout
- Geiger-Müller
  - Very large signal
  - Slow, large recovery times

Choice of gas

- Principal component is a noble gas (Ar)
  - Easy to generate avalanches, not many degree of freedom to absorb energy
  - Photons from recombination can extract electron from the electrodes and generate discharges
- A polyatomic gas is added to absorb the photons (quencher)
  - Typically hydrocarbons CH_4, C_3H_8, C_4H_{10} but also CO_2
  - ≈20% of quencher is enough to provide $M \approx 10^5$
- Electrons can be extracted on the cathode by the impacting ions
  - A small fraction of electronegative gasses can be added to reduce the mean free path of electron capture (0.4% CF_3Br, freon)
  - risk to lose efficiency for large drift paths
  - Needed to go into limited-proportionality regime
- Magic mixture : 70%Ar, 29.6% Isobutane, 0.4% Freon

Drift of charges in E field

- $v_D = \mu E$ (μ= mobility)
  - Typical situation of motion with viscous friction
- <u>For ions</u>

$$v_D = \mu_+ E = const \cdot \frac{E}{p} \quad \left(\Rightarrow \mu_+ \propto \frac{1}{p}\right)$$

  - The drift velocity scales like E/p (reduced electric field)

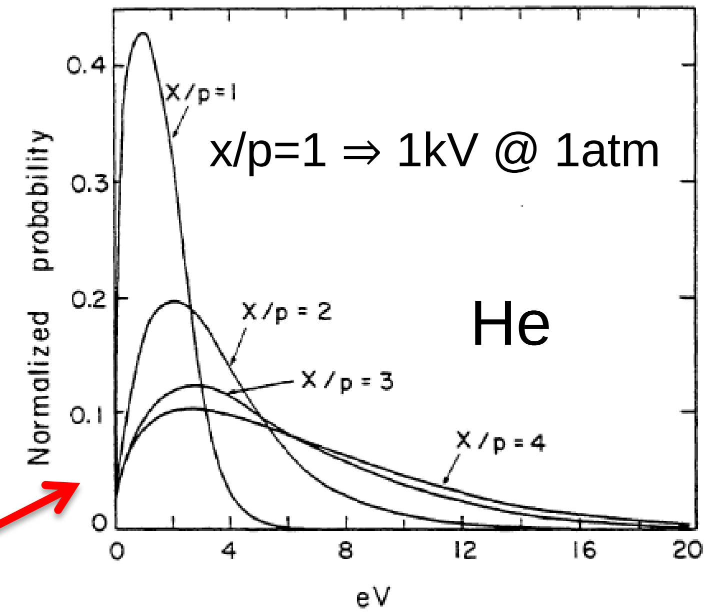
in Ar at STP, with E=1kV/cm

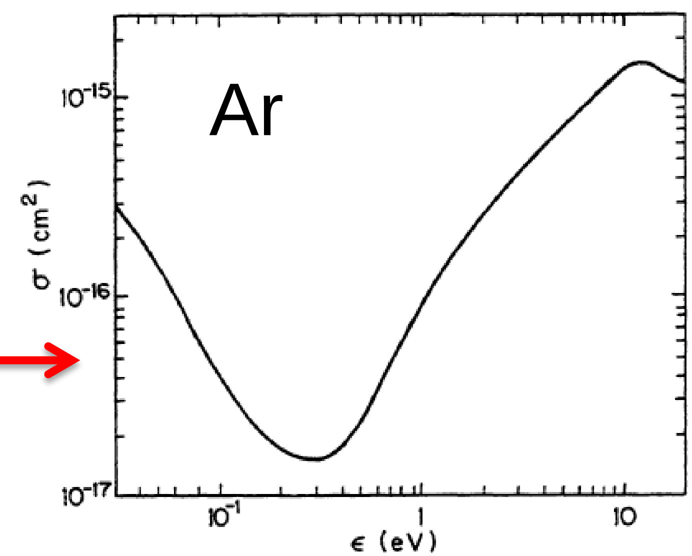
- v_D = 1.7×1000 = 1.7 cm/ms
- (λ = mean free path between scatterings)

gas (STP)	λ [cm]	μ [cm/s / V/cm]
H_2	$1.8\ 10^{-5}$	13.0
He	$2.8\ 10^{-5}$	10.2
Ar	$1\ 10^{-5}$	1.7
O_2	$1\ 10^{-5}$	2.2

Drift of charges in E field

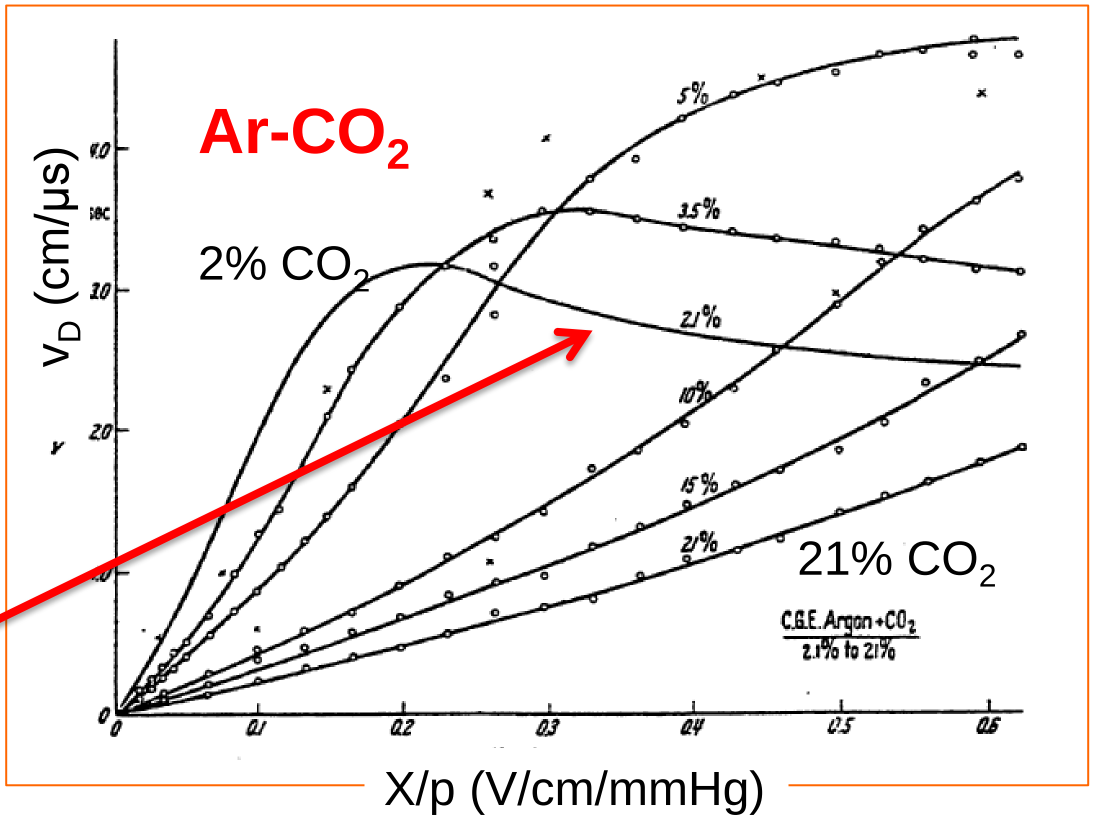
- <u>Electrons</u> gain much more energy between scatterings
  - Their energy can get similar or larger to the thermal energy ($kT \approx 0.025$eV)
  - The e-gas scattering cross section varies strongly with energy (Ramsauer effect)





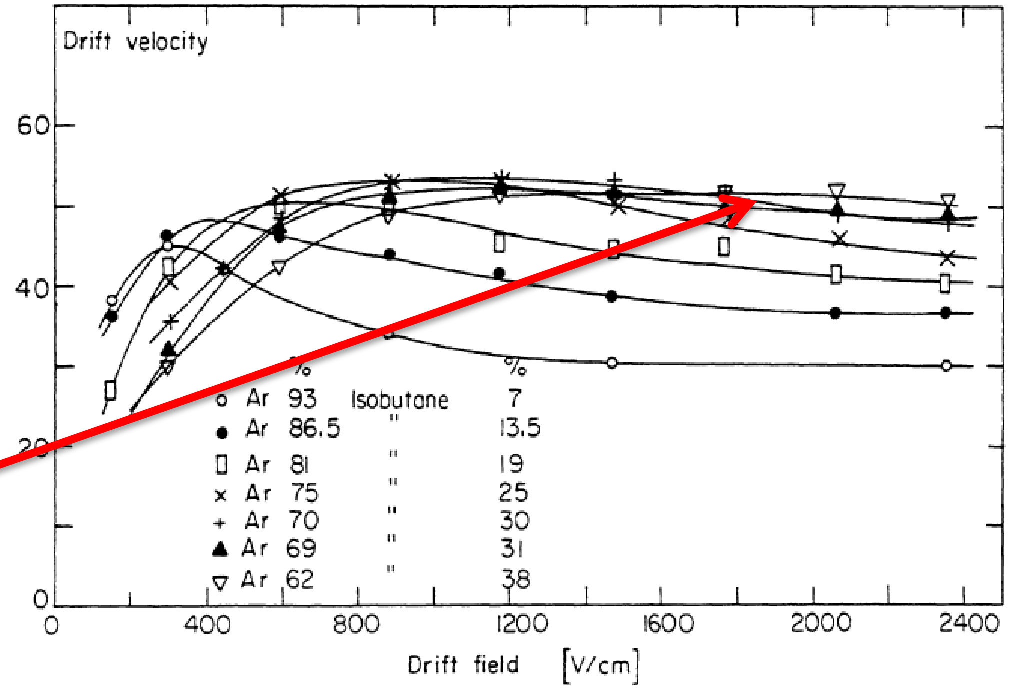
Drift of charges in E field

- We can still write vD=μE but the mobility is not anymore only proportional to 1/p
  - It is also very sensitive to the gas mixture as the cross section vary a lot
  - Drift velocity can also decrease with increasing E field



Drift of charges in E field

- For some gas mixture the drift velocity saturates
  - Including the "magical" mixture
  - Typical values 5 cm/μs (50μm/ns, 200ns for cm)



- Can be a very useful feature, v_D does not depend anymore on the details of the E field

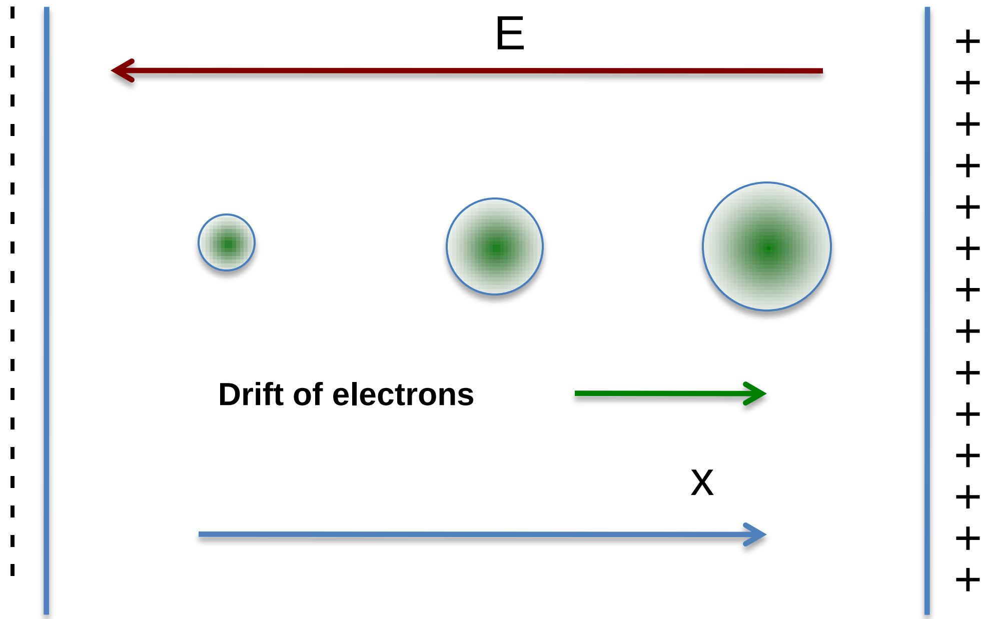
Diffusion

- Another important effect is the diffusion
  - Growth in size of the cloud of drifting charges

$$\frac{dN}{dx} = \frac{N_0}{\sqrt{4pDt}} e^{\frac{x^2}{4Dt}}$$

$$s = \sqrt{2Dt}$$

  - The distribution is described by a coefficeint D, and grows as √(Dt)



- There is a correlation between D and mobility

$$D / m \mu \; k_B T / e$$

Effects of B field on drift

- Described by the “Langevin” equation

$$m\frac{d\vec{v}}{dt} = -\frac{e}{m}\vec{v} - e\left(\vec{E} + \vec{v} \times \vec{B}\right) + \vec{\hbar}(t)$$

- The solution is

$$\vec{v}_D = -\frac{m}{1 + w^2 t^2}\left[\vec{E} + \frac{\vec{E} \times \vec{B}}{B} wt + \frac{\vec{E} \cdot \vec{B}}{B^2}\vec{B} w^2 t^2\right]$$

- Where τ is the mean free time between collision and ω=eB/m

Effects of B field on drift

- Condition E ⊥ B

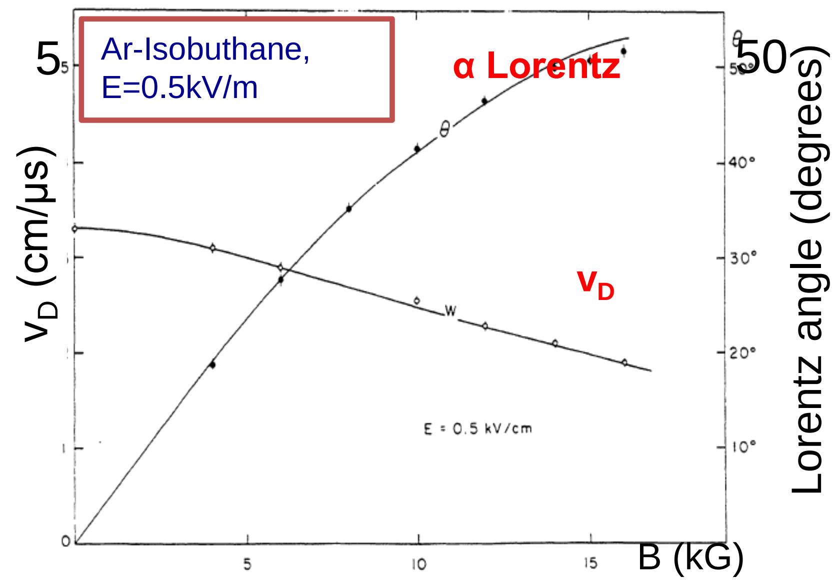
$$\vec{v}_D = -\frac{m}{1+w^2t^2}\left[\vec{E} + \frac{\vec{E}\times\vec{B}}{B}wt + \frac{\vec{E}\cdot\vec{B}}{B^2}\vec{B}w^2t^2\right]$$

$$v_{D^\wedge} = \frac{wt}{1+w^2t^2}mE$$

$$v_{D\|} = \frac{1}{1+w^2t^2}mE$$

$$v_D = \sqrt{v_{D\|}^2 + v_{D^\wedge}^2} = \frac{1}{\sqrt{1+w^2t^2}}mE$$

$$tga = \frac{v_{D^\wedge}}{v_{D\|}} = wt$$



- v_D gets reduced
- The drift has an angle w.r.t E (Lorent'z angle)

Effects of B field on drift

- condition E || B

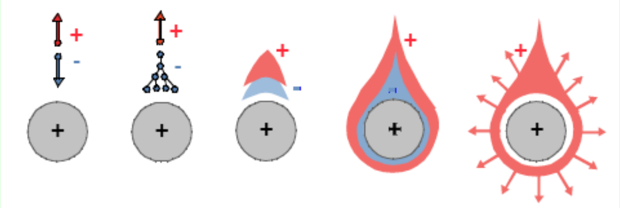
$$\vec{v}_D = - \frac{m}{1+w^2t^2}\left[\vec{E} + \frac{\vec{E}\times\vec{B}}{B}wt + \frac{\vec{E}\cdot\vec{B}}{B^2}\vec{B}w^2t^2\right]$$

$$v_{D||} = \frac{m}{1+w^2t^2}\left(E + 0 + w^2t^2E\right) = \frac{mE}{1+w^2t^2}\left(1+w^2t^2\right) = mE$$

- v_D does not change
- But the transverse diffusions is limited by B

Wire chambers signal

- In the avalanche, most of the charge is generated in the latest λ_I before the wire



  - For wires of 20μm mostly within 100μm
  - The signal is generated by the work the E field does to move the charges
    - Cylindrical detector of length l, avalanche of charge Q generated at radius r

$$V^- = +\frac{Q}{2\pi\varepsilon_0 l}\ln\left(\frac{a}{r}\right)$$

$$V^+ = -\frac{Q}{2\pi\varepsilon_0 l}\ln\left(\frac{b}{r}\right)$$

$$V^+ + V^- = -\frac{Q}{2\pi\varepsilon_0 l}\ln\left(\frac{b}{a}\right) = -\frac{Q}{C}$$

  - Electrons are already very close to collection, most of the work is done to drift back the ions

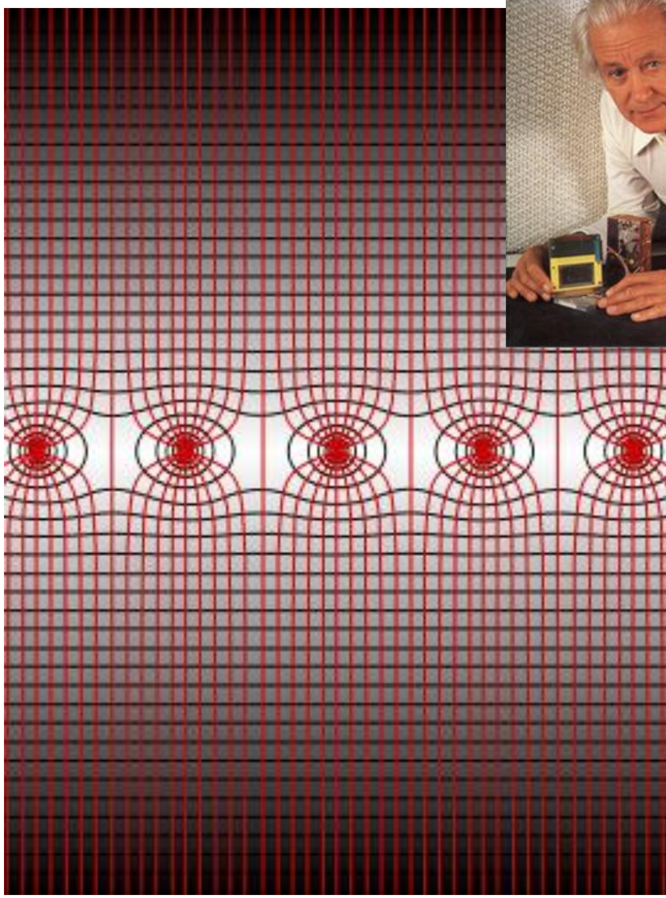
- The total time to integrate the signal is typically long
  - Depends on the drift velocity of ions and on the distance anode-cathode
  - Typically 100μs ÷ 1ms
    - $\mu^+=1.7\ cm^2s^{-1}V^{-1}atm^{-1}$ (mobility of ions), V_0=2kV, a=20μm, b=0.5cm, l=1m, p=1Atm
    - T ≈200μs

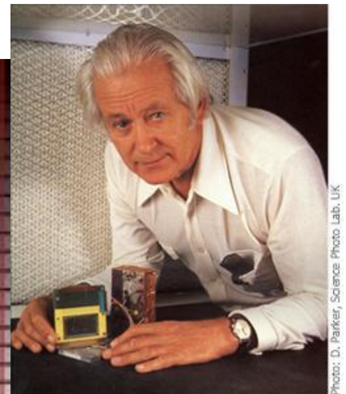
- But the leading edge of the signal is very fast
  - Time to collect ½ charge

$$t_{1/2} \approx \frac{a}{b}T$$

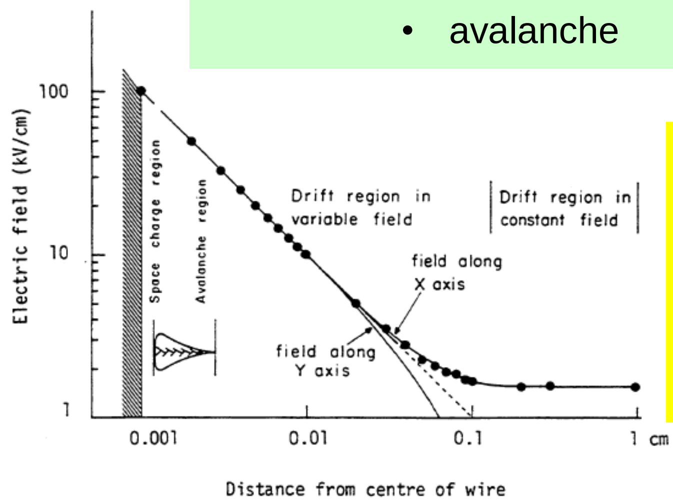
  - With previous values one gets $t_{1/2}$=800ns

MWPC



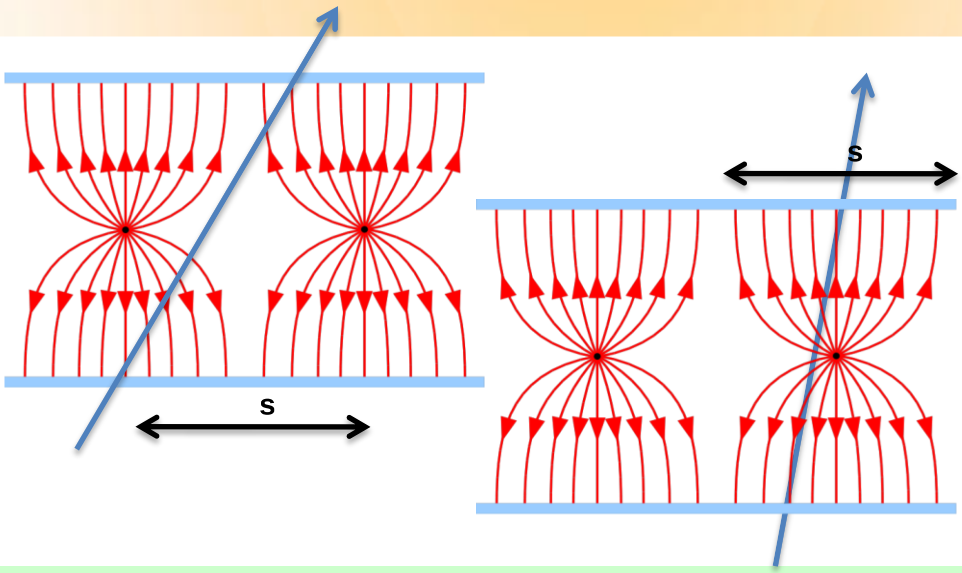


- Multi Wire Proportional Chambers
  - Charpack 1968 (Nobel Prize 1992)
  - Set of parallel anode wires tightly spaced, between parallel cathodes
  - E field essentially uniform in most of the detector
    - Drift field to collect charges
  - Becomes very intense close to the anode
    - avalanche



- Typical values
  - Wire spacing 2mm
  - Anode-cathode distance 4mm
  - V~3kV
  - Magic mixture

MWPC resolution



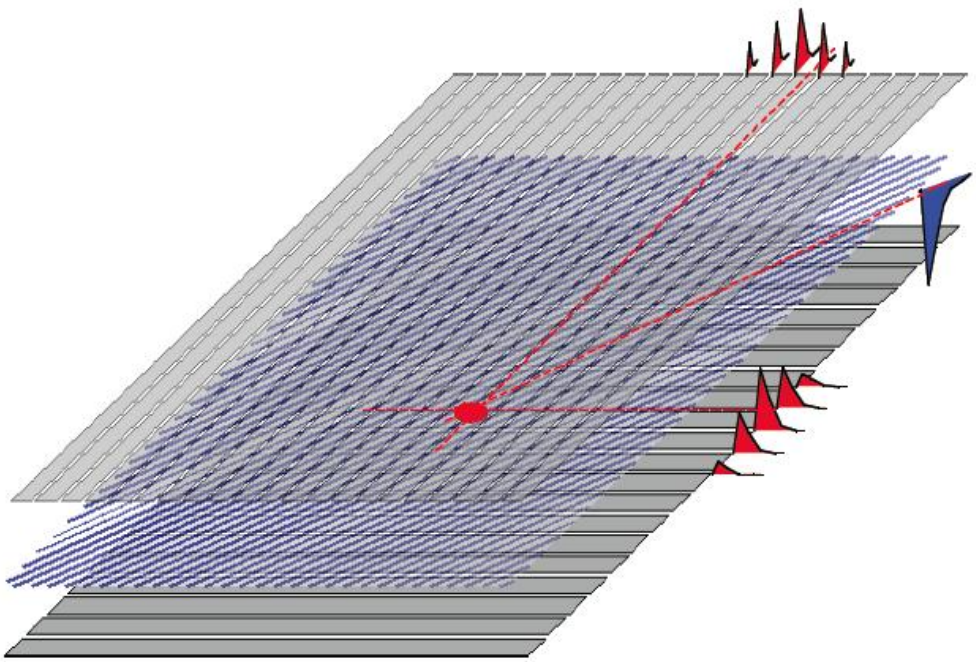
- If wires are readout

$$s_x = \frac{s}{\sqrt{12}}$$

$$s_x = \frac{2}{\sqrt{12}} = 0.6mm \quad \text{for 2 mm wire spacing}$$

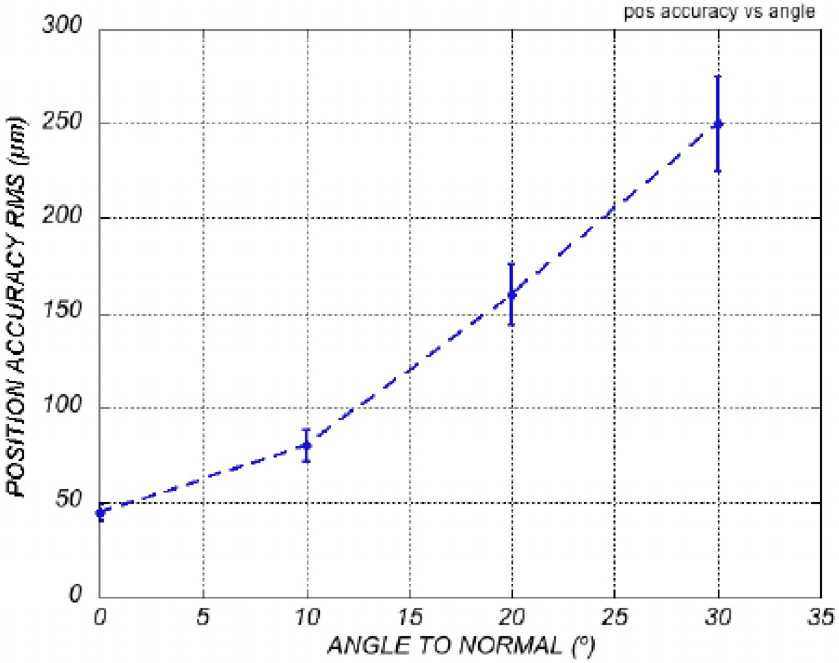
  - For non perpendicular tracks more wires can give signal
  - The resolution does not change

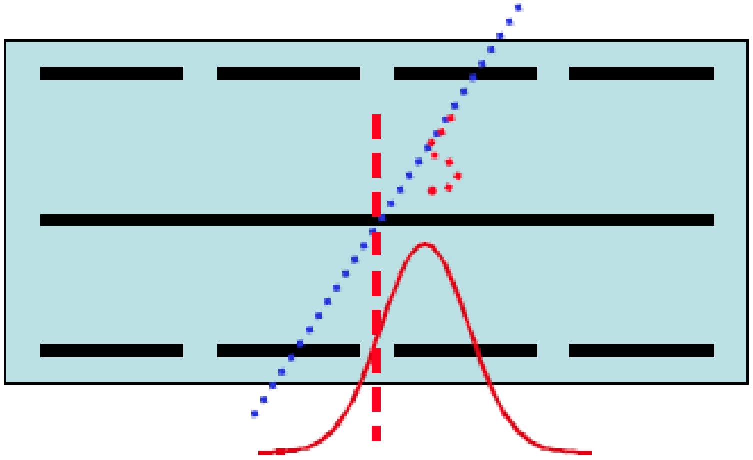
MWPC resolution



- Cathodes can be readout too
  - Signal induced on more adjacent “strips” (or groups of cathode wires)
  - Position along the anode wire can be reconstructed with a resolution ≈100-200μm
    - Across the wires nothing changes, the avalanche position is ON the wire
  - Sometimes both cathodes with orthogonal strips are readout
    - Anode at HV, no decoupling capacitors
  - To get high resolution on both coordinates one can use sets of consecutive MWPC with perpendicular anode directions

MWPC resolution

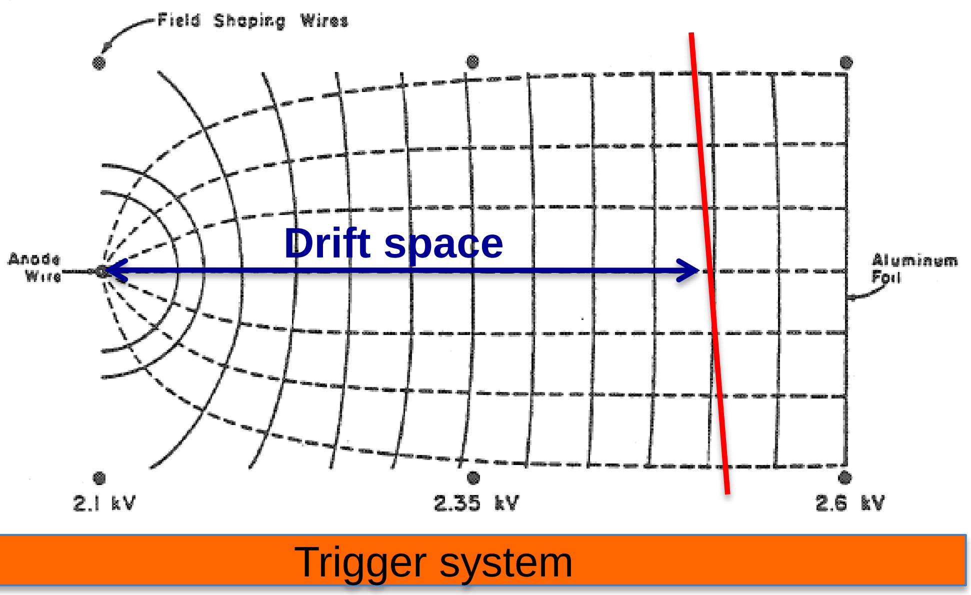




- Notice
  - Statistical fluctuations of the primary ionization, and emission of δ rays can influence the resolution, in particular for tracks not orthogonal to the chamber

Drift chambers

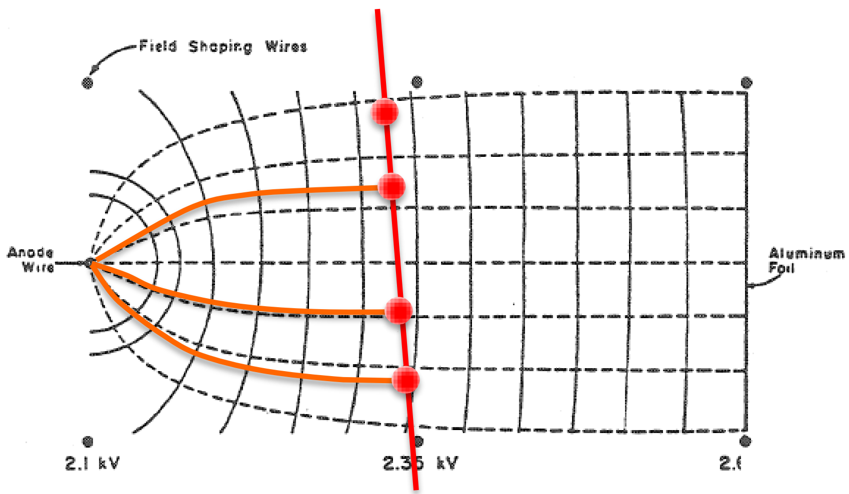
- Drift chamber are wire chamber with a long drift path
- The track position is measured by the drift time in a possibly uniform E field
  - Need an external system to give the “start” to the time measurement
  - The “stop” is generated by the signal on the wire



Typical drift velocity are 50μm/ns (with magical mixture)

- Need order of ns resolutions to get space resolutions around 100μm

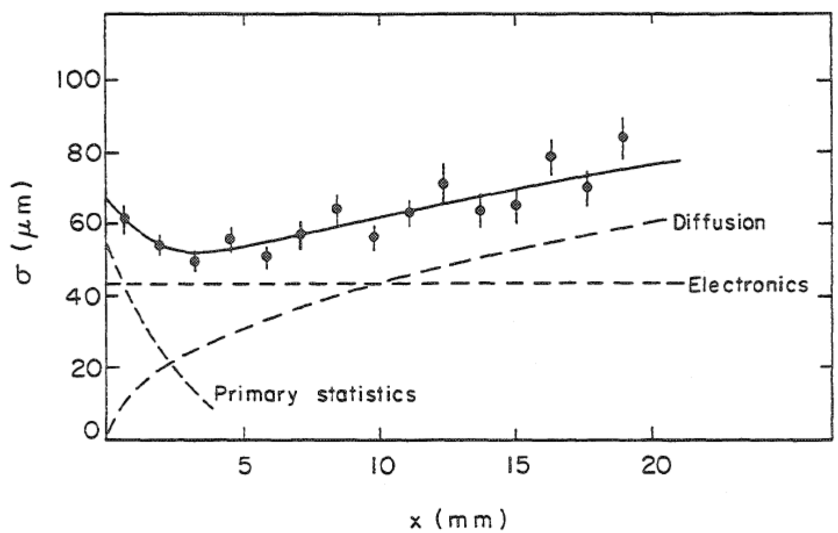
Drift chambers resolution



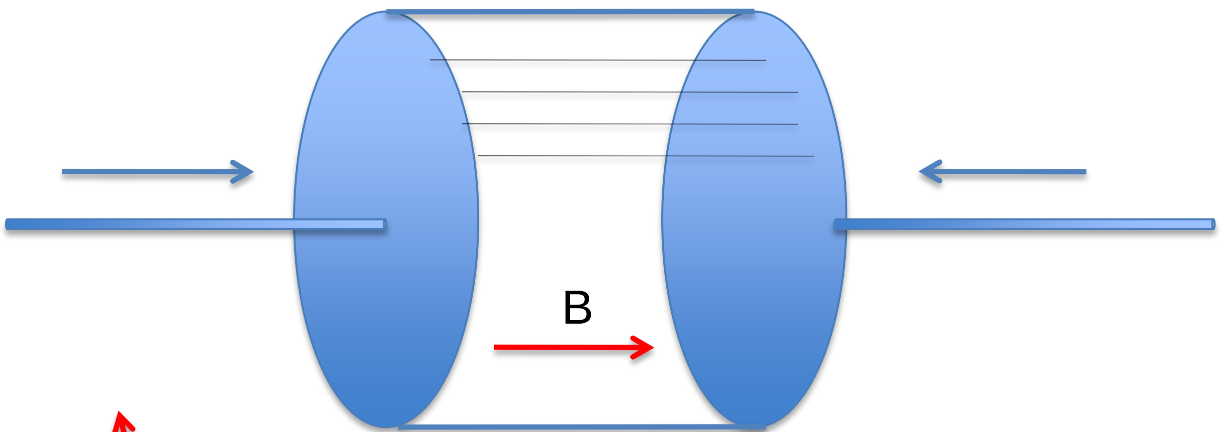
Three important effects

- Electronic noise
- Longitudinal diffusion of the charge
  - Proportional to √t and so to √x for constant drift velocity
- Primary ionization statistics
  - Drift path of primary clusters can be different

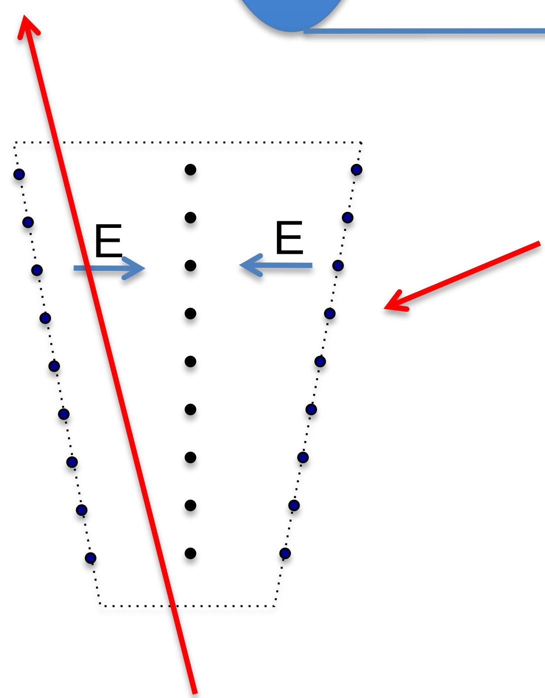
Resolution below 100μm can be achieved with drift spaces of several cm



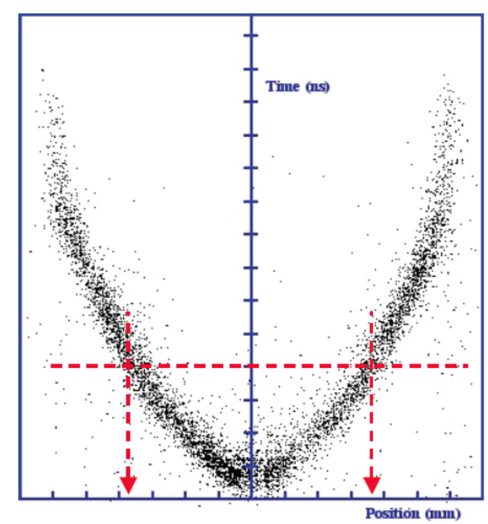
Drift chambers



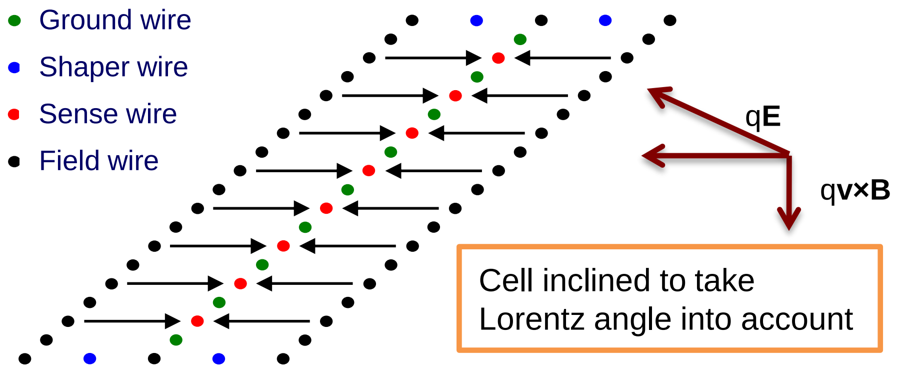
- Often used as central detectors in colliders
    - B parallel to wires so orhtogonal to E

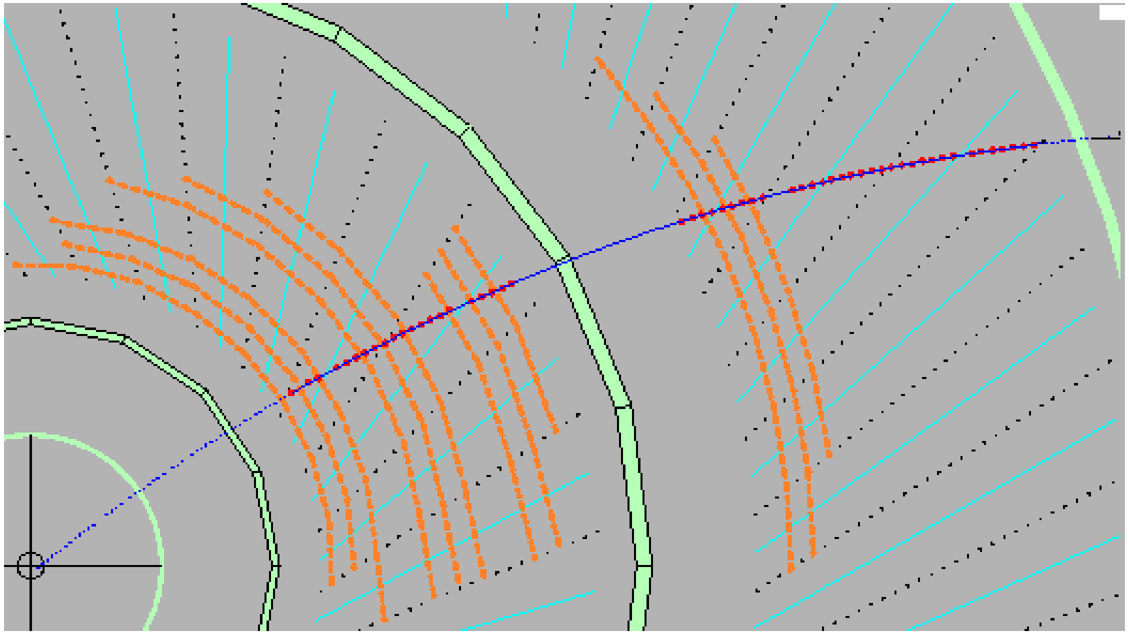


- Typical drift cell
- Time-space relationshiop
    - Notice the left-right ambiguity

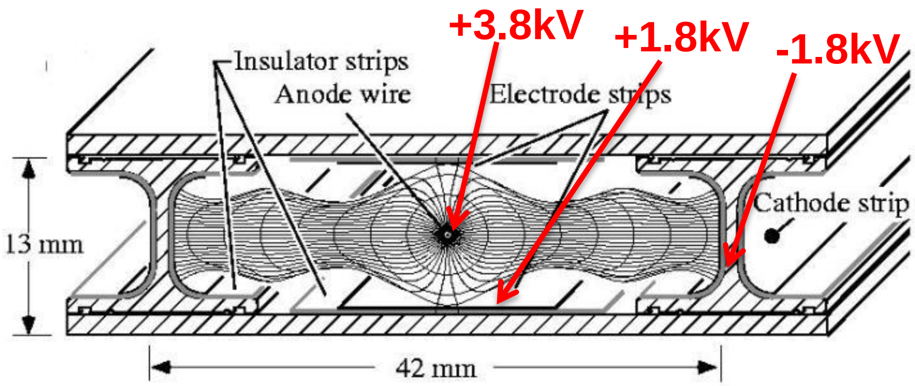


Examples of drift chmbers



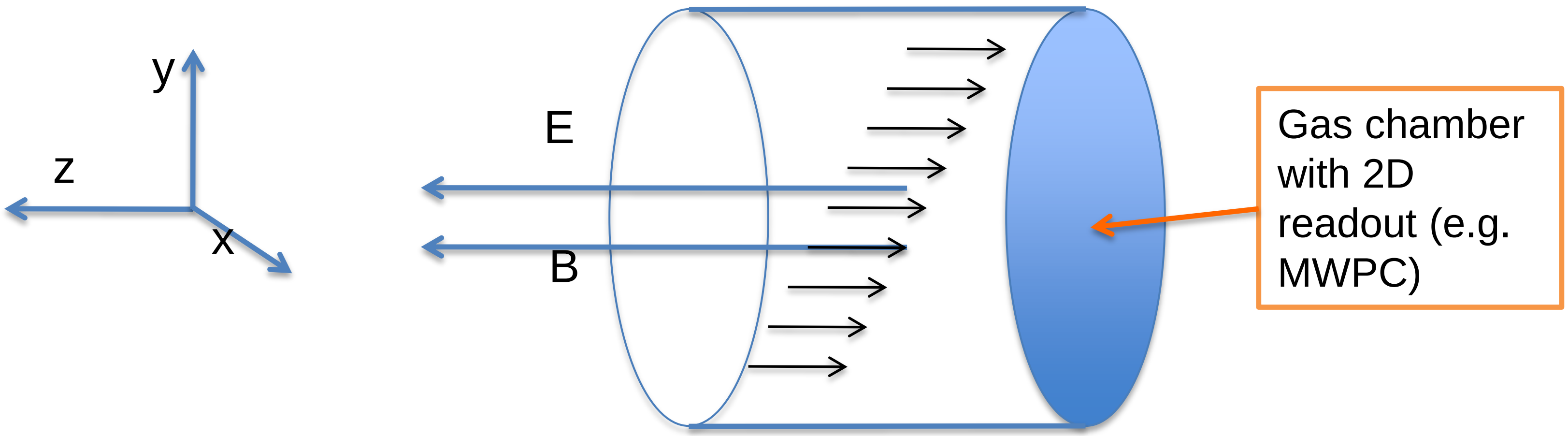


Examples of drift chmbers



- Drift chambers of the barrel muon detector of CM
  - Homogeneous drift field
    - Linear space/time relationship using careful filed shaping
    - Easier to use in fast trigger
  - Aluminium structure
    - Relatively heavy, not a problem for a muon detector
    - 50μm anode wire
  - Gas mixture 85% Ar 15% CO_2
    - Non flammable
  - Maximum drift time ≈400ns
    - Space resolution ≈ 100μm

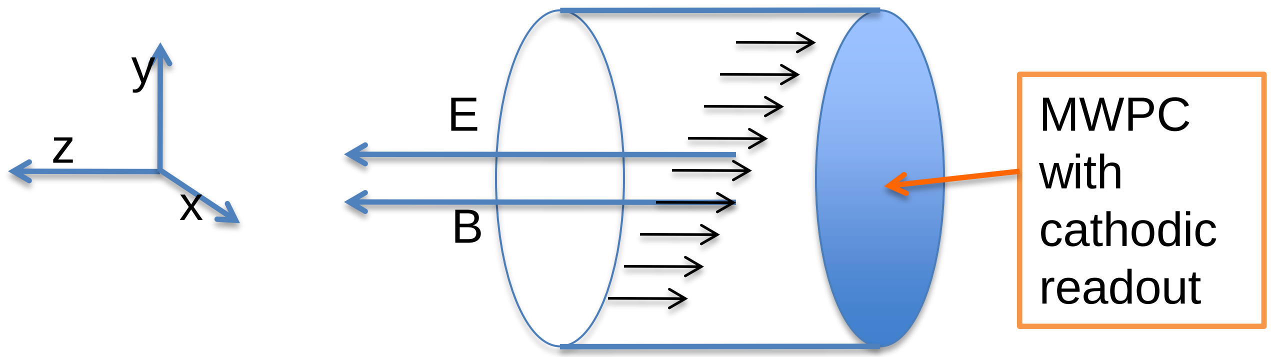
Time Projection Chambers



Time Projection Chamber (TPC)

- Long drift path
  - z readout with drift time
- At the extremity a MWPC or similar (GEM)
  - Reading x,y coordinates

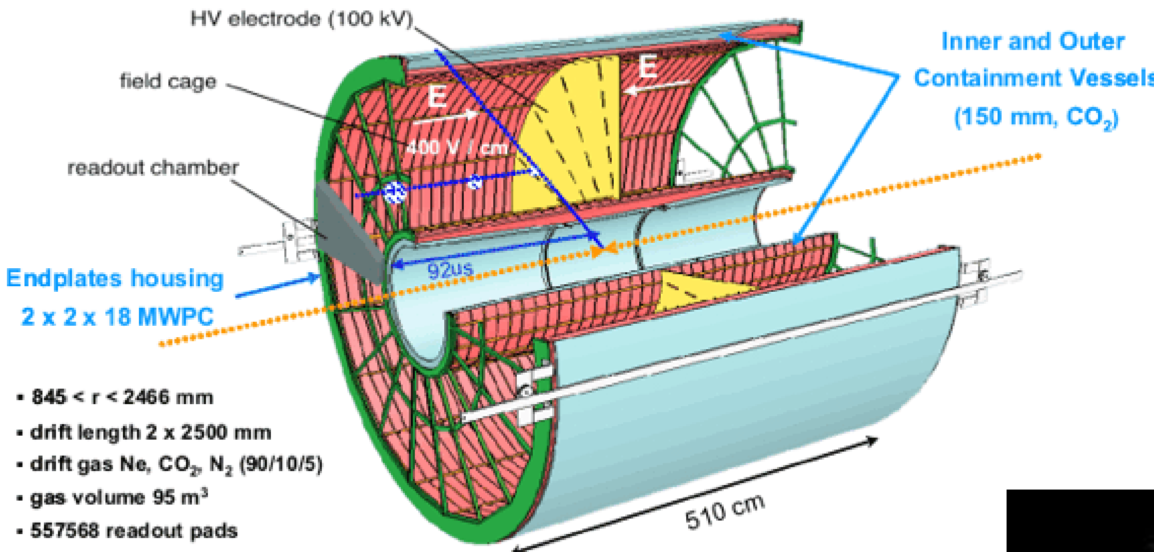
Time Projection Chambers

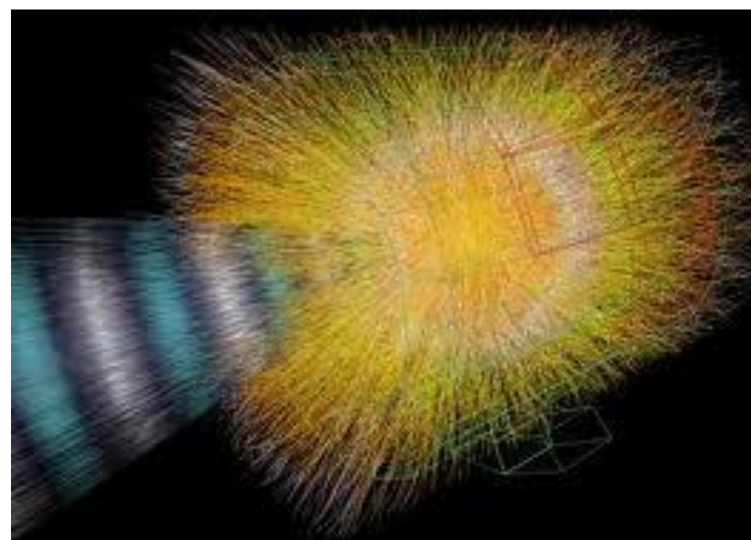


- Advantages
  - A true tridimensional readout is possible helps pattern recognition
  - Transverse diffusion limited by B, improves x,y, resolution
  - Very little material

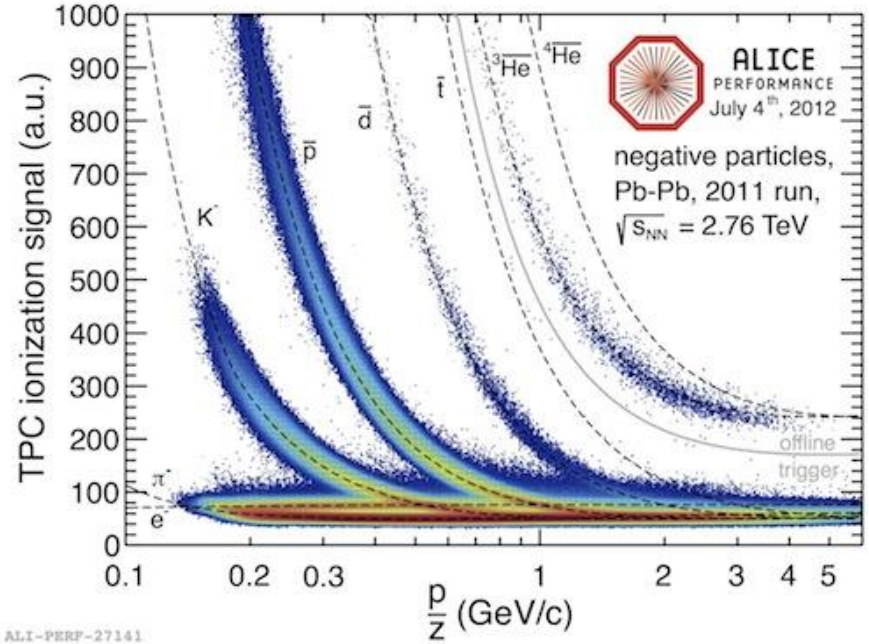
- Disadvantages
  - Long drift paths(10÷100 μs)
    - Sensitive to electronegative impurities
    - Not well suited to very high bunch crossing rates

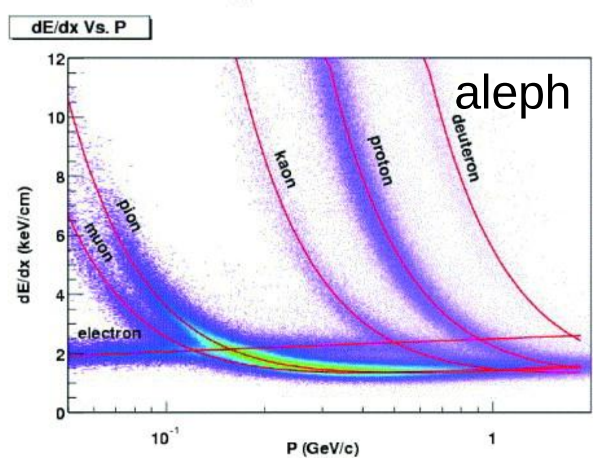
The TPC of ALICE at LHC





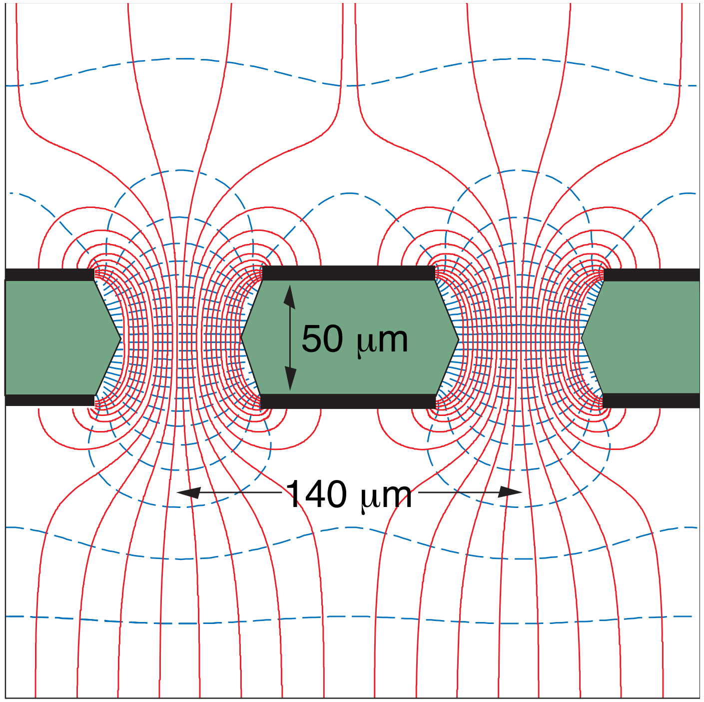
The TPC of ALICE at LHC





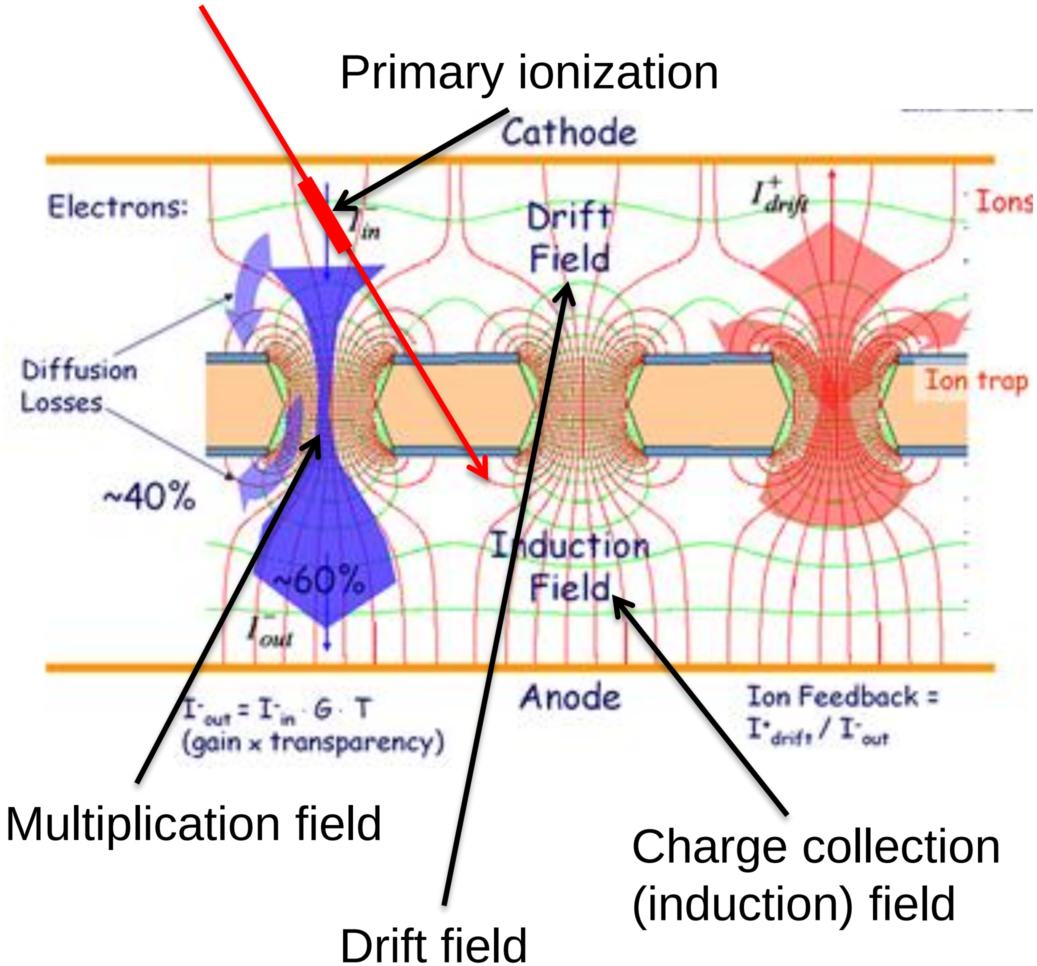
- In the TPC the gain is typically small
  - Long drift times, no electronegative gasses possible
  - Work in proportional mode
  - Large number of samples per track
- Very well suited to measure dE/dx
  - To perform PID

GEM

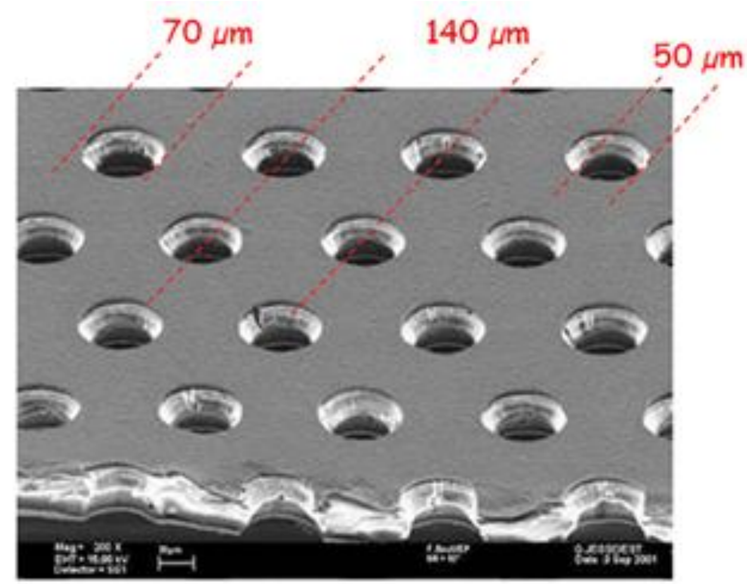


- Gas Electron Multiplier
  - Kapton foil, metallized on both sides with micro-holes
    - Using lithographic techniques
  - HV between the two layers generates an amplification region
    - 400-500V on 50μm
  - It is possible to have multiple layers of GEMs with reduced gain/layer
    - Reduced risck of discharge

GEM



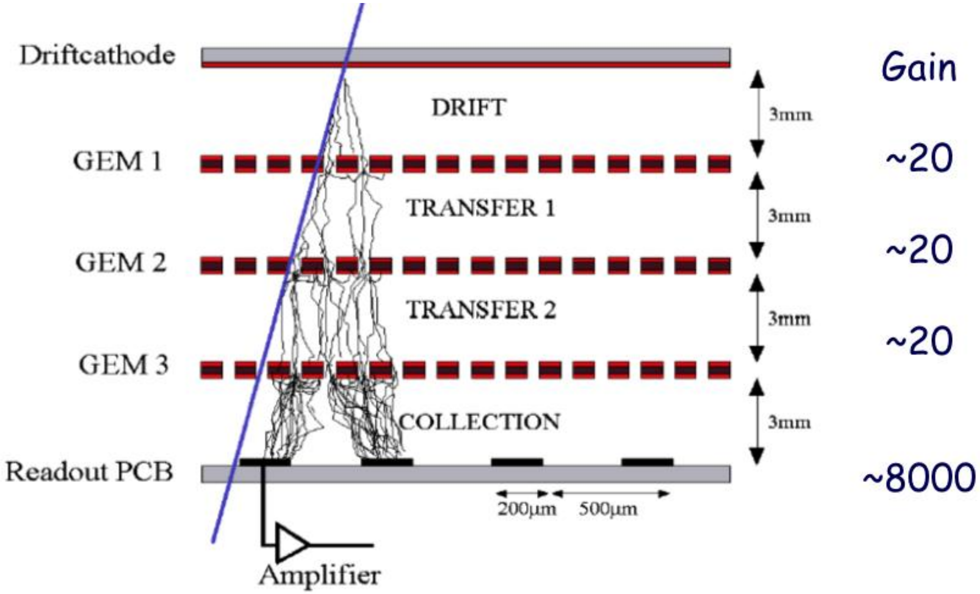
Primary ionization
Cathode
Electrons:
Drift Field
Ions
Diffusion Losses
Ion trap
~40%
~60%
Induction Field
Anode
I⁻out = I⁻in · G · T
(gain x transparency)
Ion Feedback =
I⁺drift / I⁻out
Multiplication field
Drift field
Charge collection (induction) field



70 μm
140 μm
50 μm

GEM

Example with multi-layer configuration

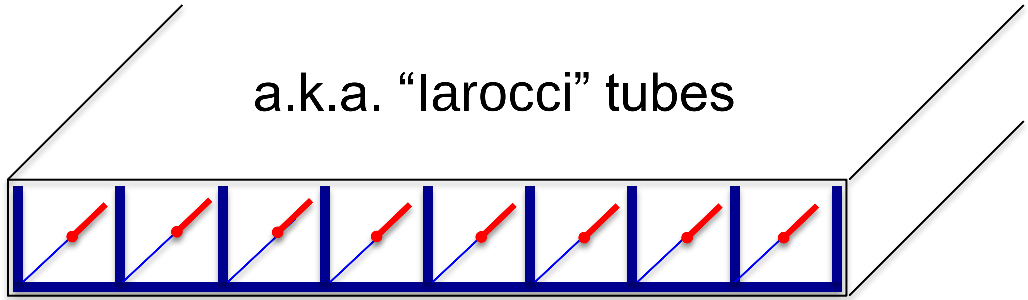


Normally gain is higher (100-1000/ layer

Advantages

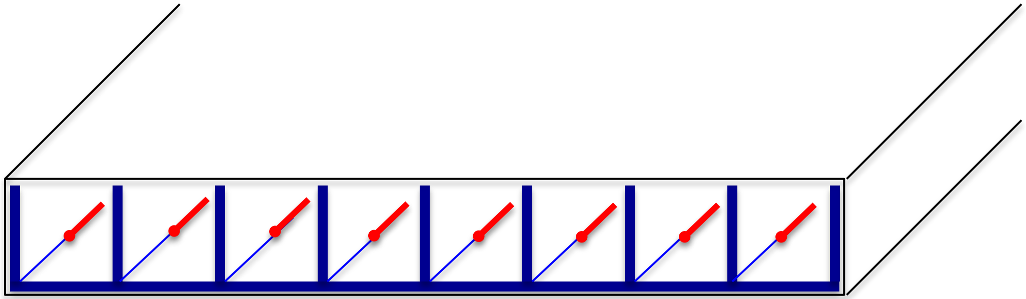
- very good space resolution
  - Down to 30 um
- Very good separation of adjacent tracks
- Ability to sustain high rates
  - Ion are readily collected by nearby electrodes

Limited Streamer Tubes



- Mechanically a multiwire chamber
  - 100 μm thick anode wire
    - Typically 1 cm spacing
  - Structure made by plastic, painted by a resistive material to provide cathodes
  - HV 4.5 ÷ 5kV (at STP)
    - Need high field as the wire is thick
  - Very economical construction, suited to cover very large surfaces
    - Muon detectors, cosmic rays large area detectors

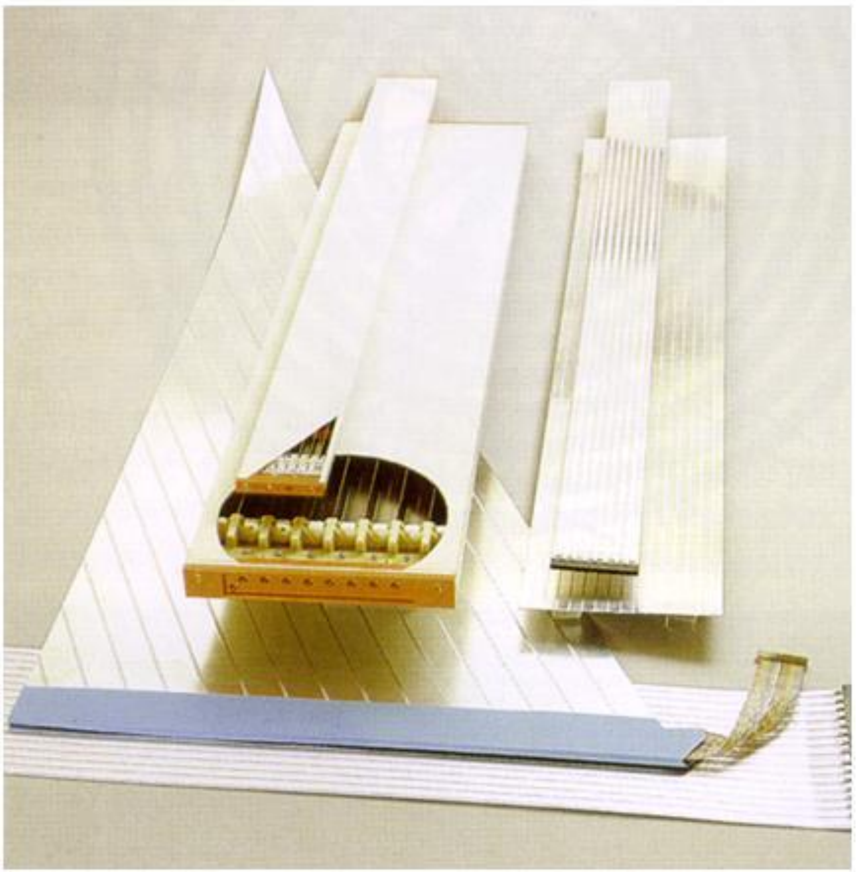
Limited Streamer Tubes



Typical gas mixtures
- Ar - isobutane 30-70%
- CO_2 - Ar – isobutane 89-8-3%

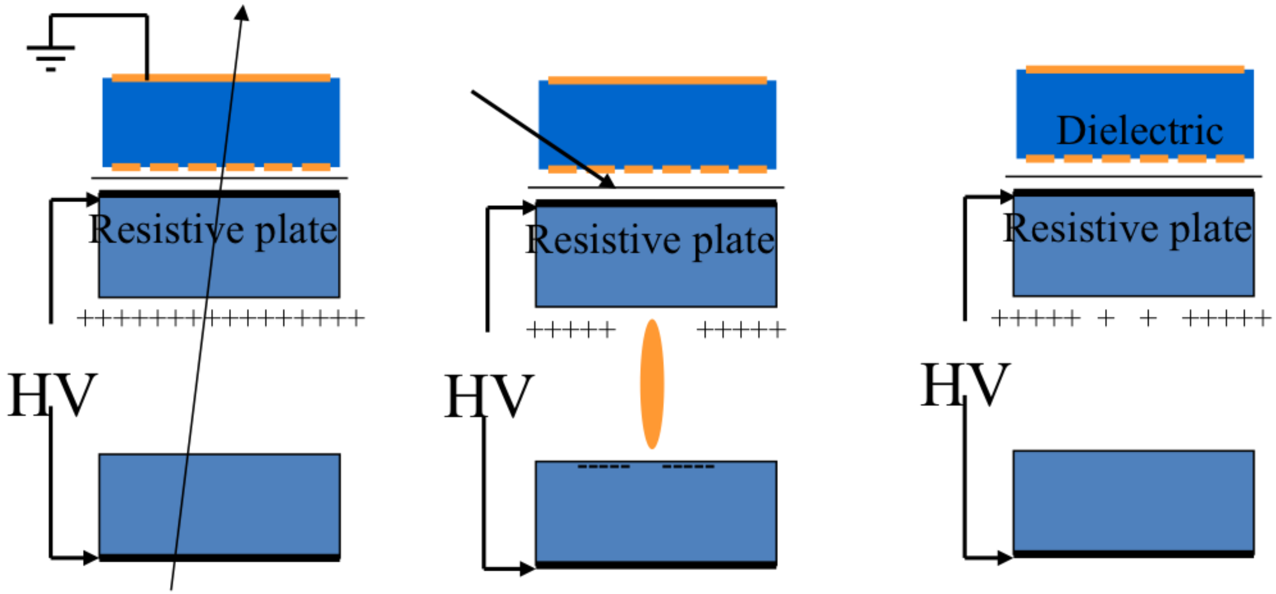
- Work in limited streamer mode:
  - The E field is large in a big region of space, a plasma filament is generated by the avalanche
  - Lots of photons generated, need strongly quenching from the gas
  - Due to the resistive cathodes, the local E field close to the streamer gets reduced, and the streamer ends

Limited Streamer Tubes



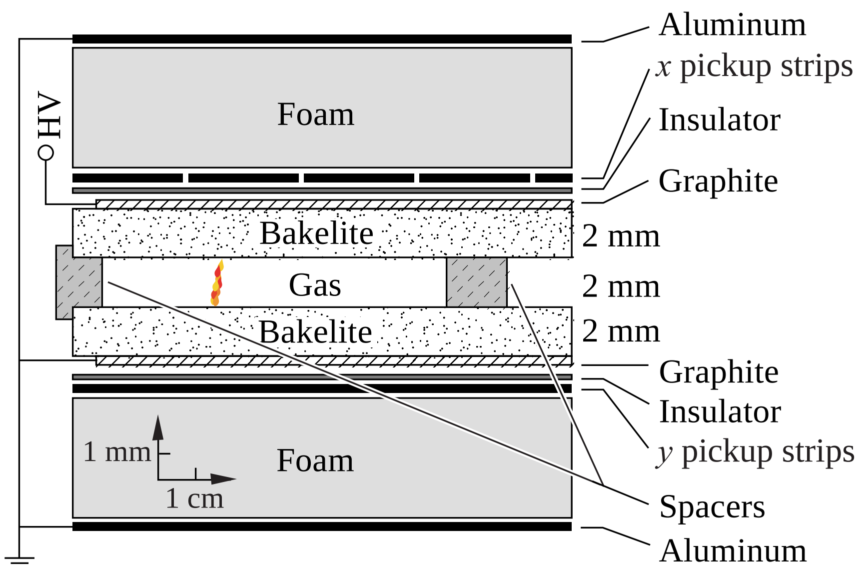
- Large signal
  - ≈ 30pC
- Can be readout by external strips
  - Graphite cathodes are transparent to the fast signals
  - Resolution is
    - Wires pitch/√12 across wires
    - Strip pitch/√12 if digital readout, down to 500μm if analog (centroid) readout

Resistive Plates Chambers



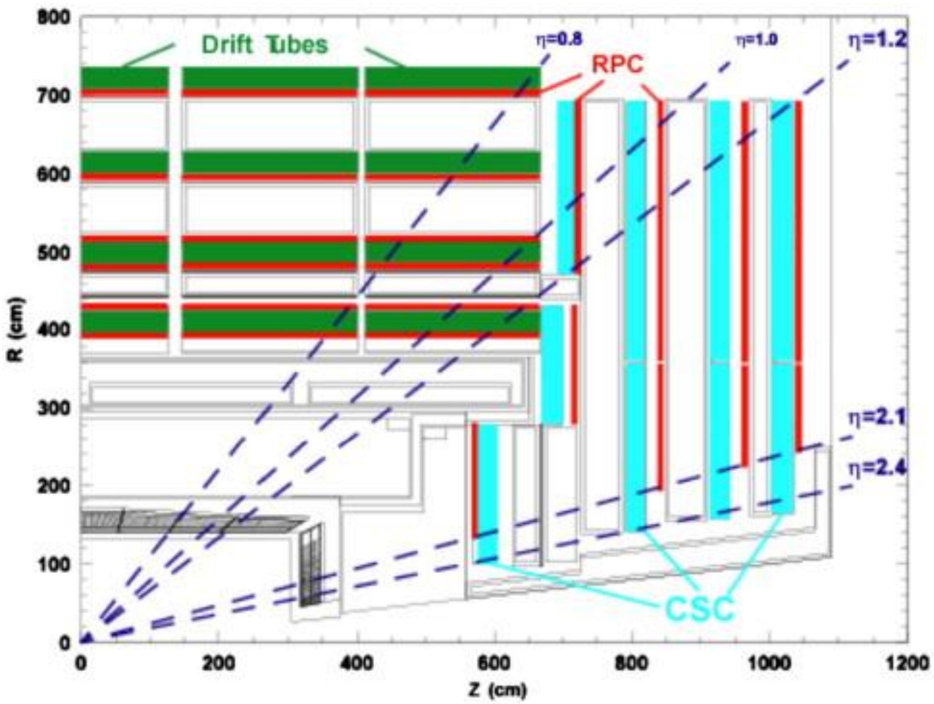
- Flat detectors with large E field between planes
  - Avalanche in the whole space between the planes, quenching concept similar to LST
  - Large signal, readout through external strips/pads
  - No drift, very fast (ns resolution)

Resistive Plates Chambers



- Can be made with bachelite (cheap) or resistive glass
    - HV = 8-10kV
- No wire structure, readout in x-y coordinate with the same resolution
- Very high resistivity, cannot sustain very high particle fluxes

Resistive Plates Chambers



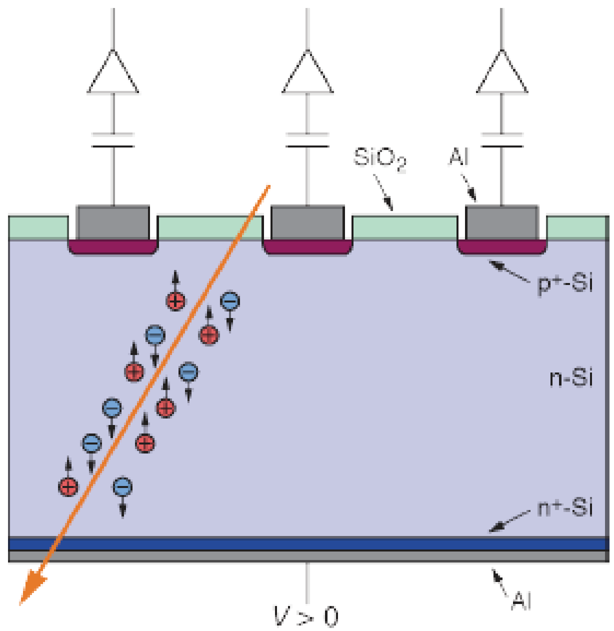
- Fast: used by both Atlas and CMS as detectors for muon trigger
  - Only trigger detector in Atlas, complementing other chambers in CMS

- Notice, in LHC the RPC are used in "avalanche" mode and not in "streamer mode"
  - Reduced gain (10^6 w.r.t.10^8)
  - Very complex gas mixture to provide high quenching
  - Higher capability to stand particle fluxes (1kHz/cm^2 w.r.t 10-100Hz/cms^2)

SILICON DETECTORS

What are Si detectors?

- Semiconductor (Solid State) detector
  - Essentially, a ionization chamber that collect ionization produced in a solid detector
    - (will discuss later some case where there is also amplification)
  - Need to have a way to collect charge generated inside a solid
- Generally used as position detectors with high resolution



Advantages and disadvantages

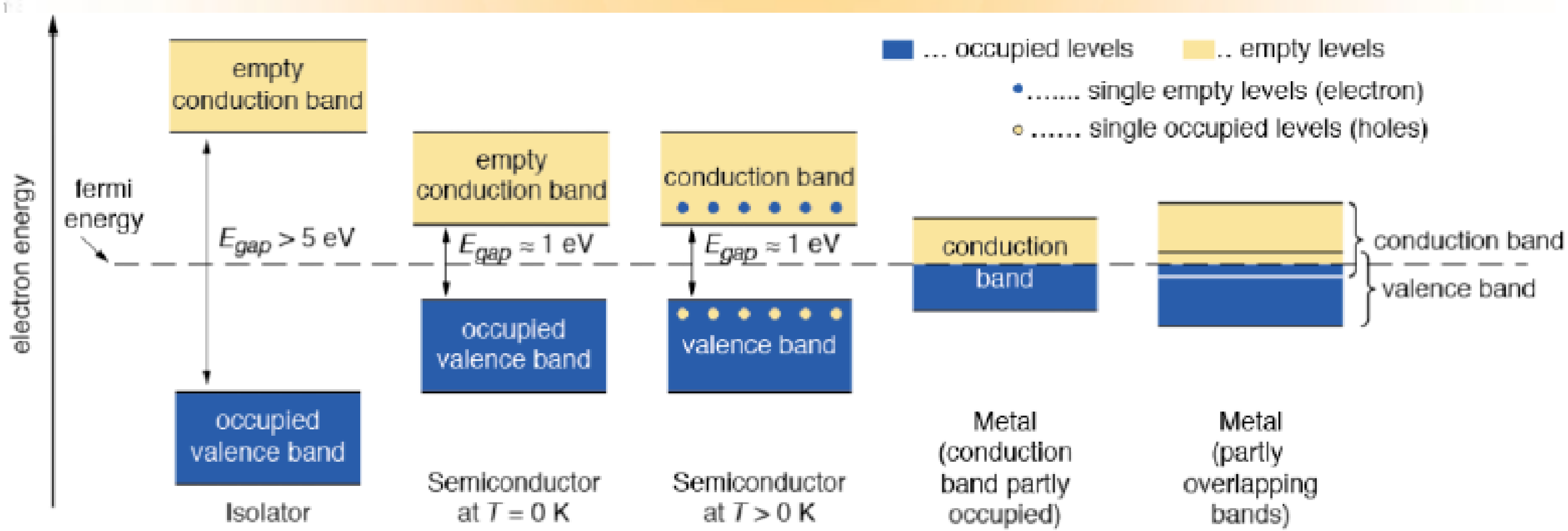
advantages

- High density w.r.t other position detectors (gas chambers)
  - Smaller diffusion which translates in better resolution
- Low ionization energy
  - Few eV to generate a e-h pair, effective in translating energy loss in signal
- Large industrial experience
  - Can use frontier technologies developed for microchips
- Radiation hard

disadvantages

- High density
  - Higher multiple scattering
- No internal gain
  - With exceptions

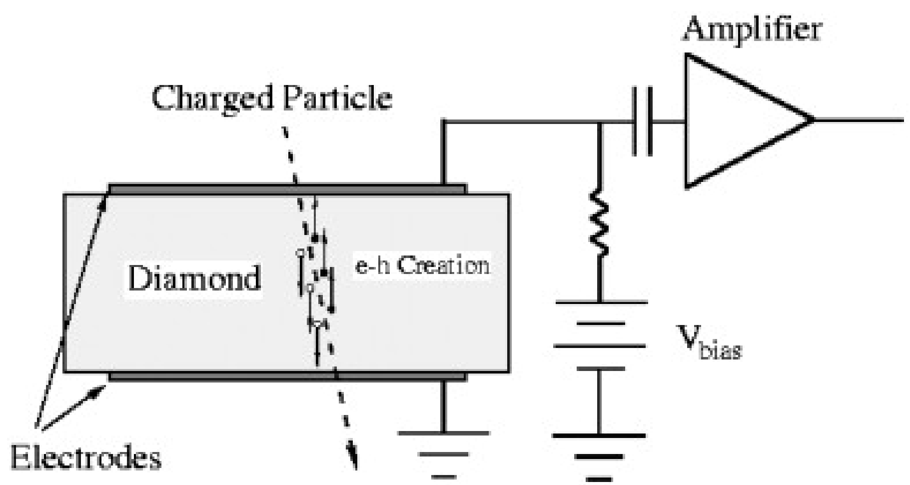
Requirements for solid state detectors

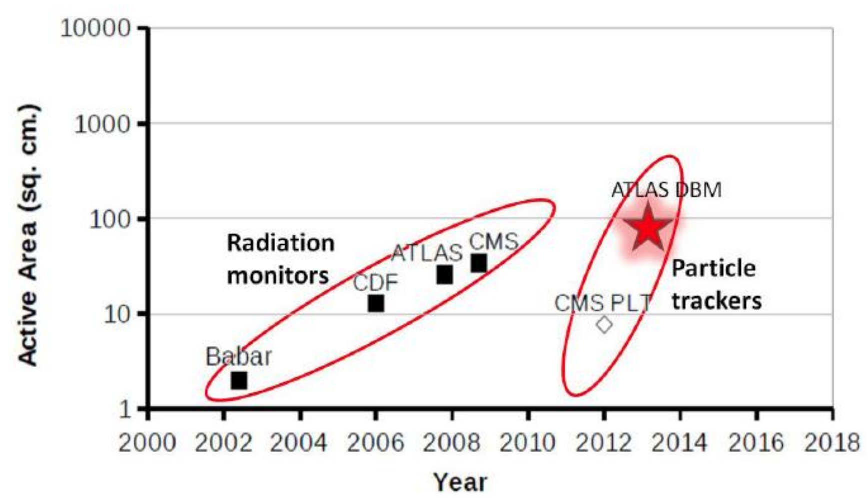


- Signal to noise ratio (SNR) has to be high enough
  - High signal
    - Low ionization energy → small band gap
  - Low noise
    - Small number on intrinsic charge carrier → large band gap

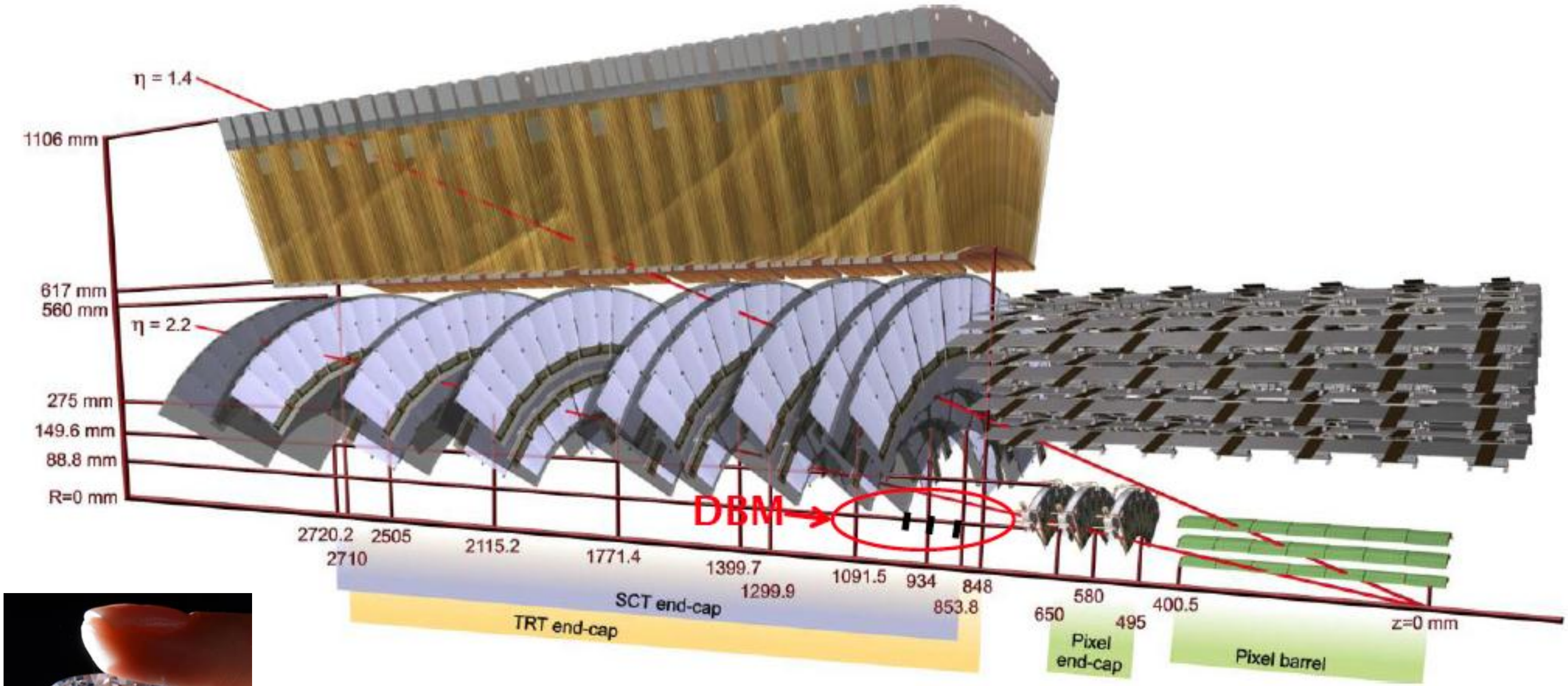
Requirements for solid state detectors

- Diamond, ideal material, band gap $E_g \approx 6eV$
  - Turn out to be expensive (even artificial diamond)
  - Used where extreme radiation hardness is needed
    - "a diamond is forever"
    - Can stand $\approx 10^{16} p/cm^2$
    - Beam condition monitors at LHC
  - Large detectors being designed, to measure with high precision the luminosity at high intensities of LHC
    - Atlas Diamond Beam Monitor
    - CMS Pixel Luminosity Telescope





Atlas DBM



Weigh equivalent to this diamond (76 carats, 1 carat = 200mg)

Requirements for solid state detectors

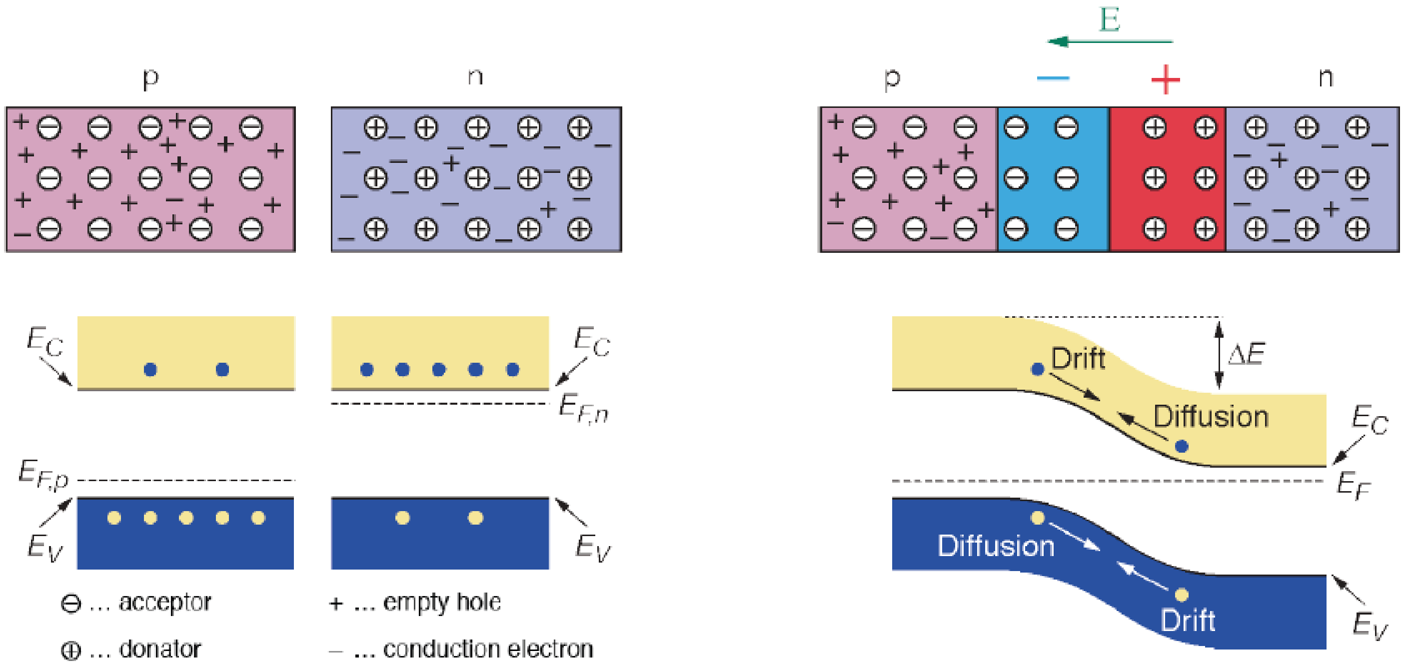
- What if we use intrinsic silicon?
  - Ionization energy I_0=3.62eV
  - dE/dx = 3.87 MeV/cm
  - Density of carriers at T=300K: $n_i=1.45\times10^{10}/cm^3$
- Take a detector with
  - Thickness d=300μm
  - Surface A=100μm×6cm=0.06cm²

Signal $$\frac{dE/dx \cdot d}{I_0} = \frac{3.87\cdot 10^6 eV/cm \cdot 0.03 cm}{3.62 eV} \approx 3.2\cdot 10^4 e^- h^+ \ pairs$$

Noise $$n_i \times d \times A = 1.45\times 10^{10}\, cm^{-3} \times 0.03 cm \times 0.06 cm^2 \approx 2.61\times 10^7 e^- h^+ \ pairs$$

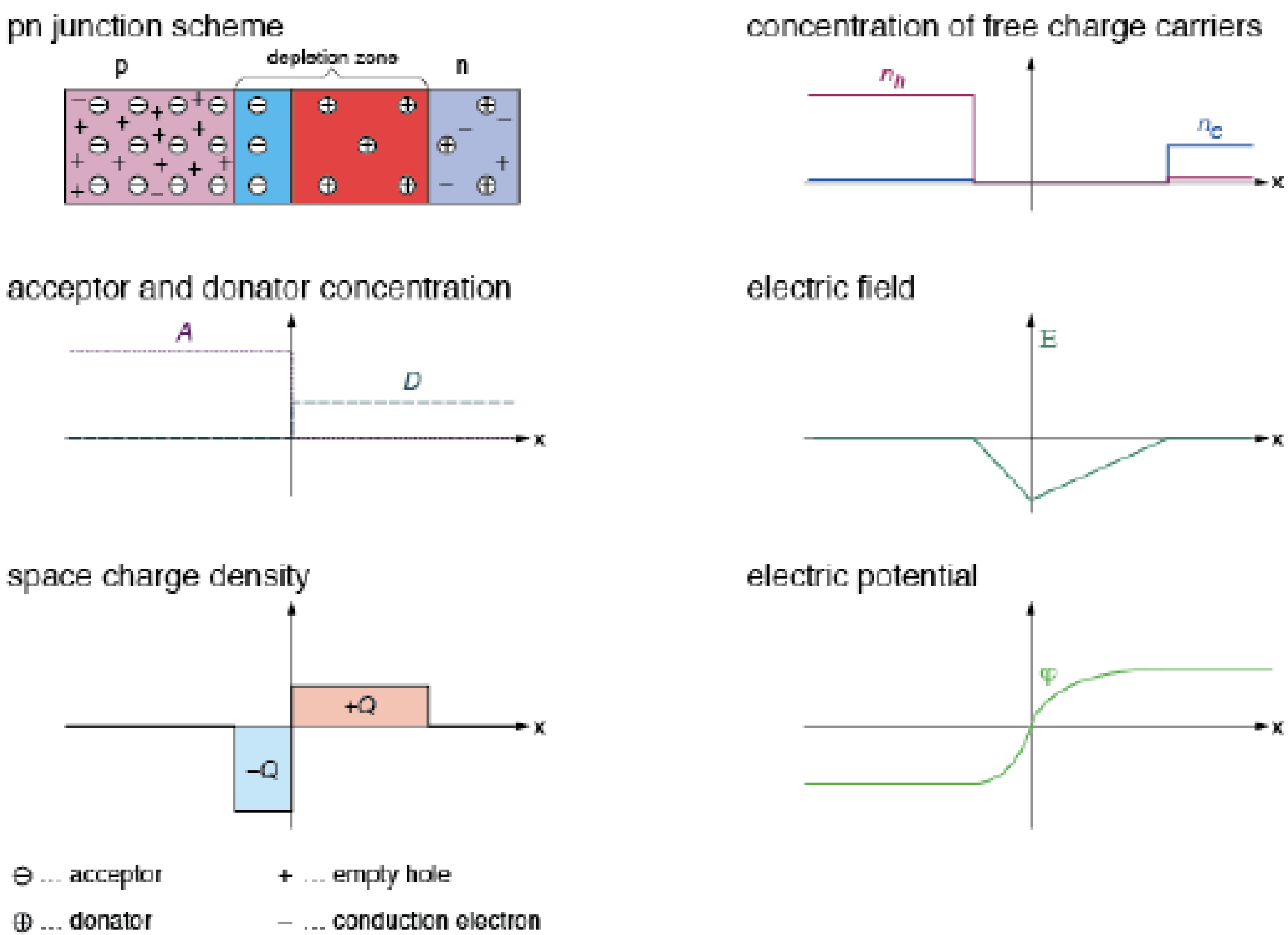
Noise is 3 order of magnitude larger than signal
- Need to remove intrinsic charge carriers
- **p-n junction with large depleted volume**

p-n junction



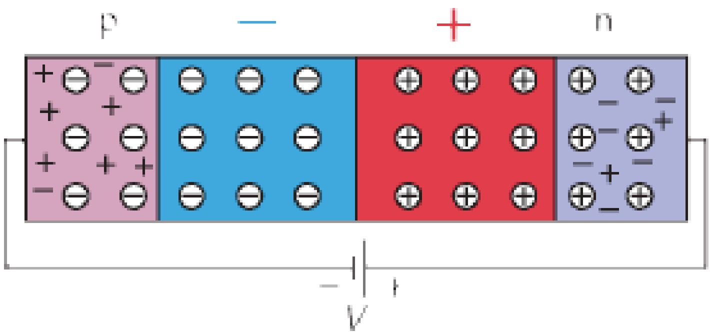
- Two semiconductors, doped p and n are put in contact
- Because of the gradient of the carrier densities, electrons diffuse to P zone, holes to N zone until the electrostatic field that is created stops the process
- Close to the junction there is now a region empty of carriers (depletion layer)

p-n junction

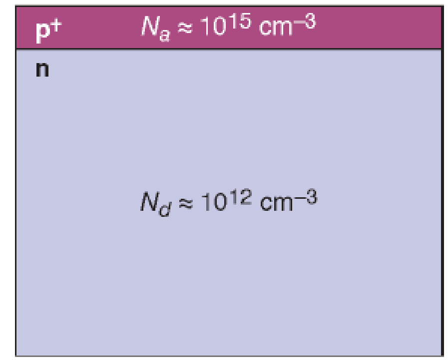

pn junction scheme
p
depletion zone
n
concentration of free charge carriers
n_h
n_e
x
acceptor and donator concentration
A
D
x
electric field
E
x
space charge density
+Q
−Q
x
electric potential
φ
x
⊖ ... acceptor
+ ... empty hole
⊕ ... donator
– ... conduction electron

p-n junction

p-n junction reversely polarized



- By applying an external **bias voltage** $V_N > V_P$ electron and holes move away from the depleted region making it bigger
- The current through the junction is small, the **depletion region can be used as a detector**



p^+n junction

- Typical Si detector are largely asymmetric in term of dopant concentration
- The depletion region is asymmetric
- Its width **W** can be shown to be

$$N_A >> N_D \Rightarrow x_P << x_N$$

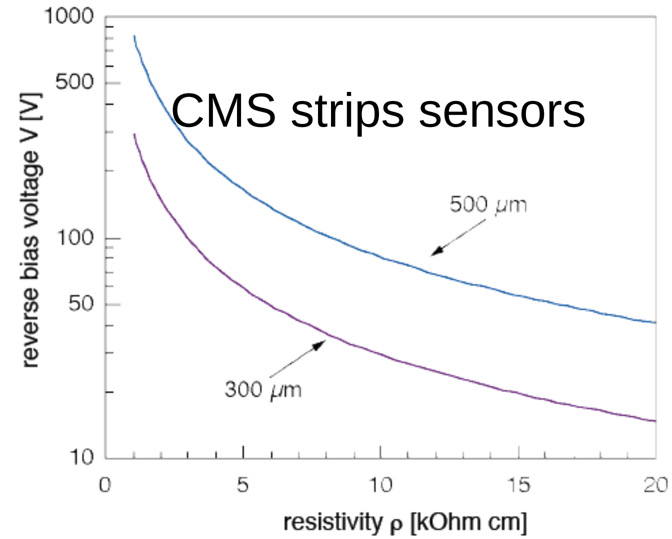
$$W \approx x_N \approx \sqrt{\frac{2\epsilon|V|}{qN_D}}$$

depletion voltage and leakage current

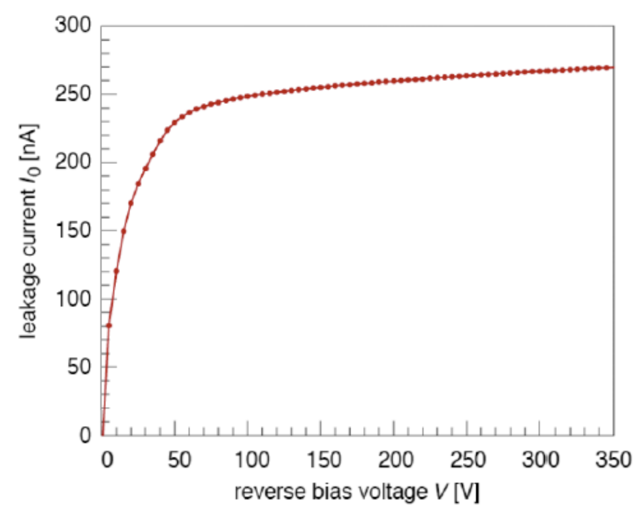
- **Depletion voltage**
  - Minimum voltage for which the device is fully depleted
  - Normally one works slightly over-depleted

$$V_{depletion} = \frac{qN_D W^2}{2e}$$

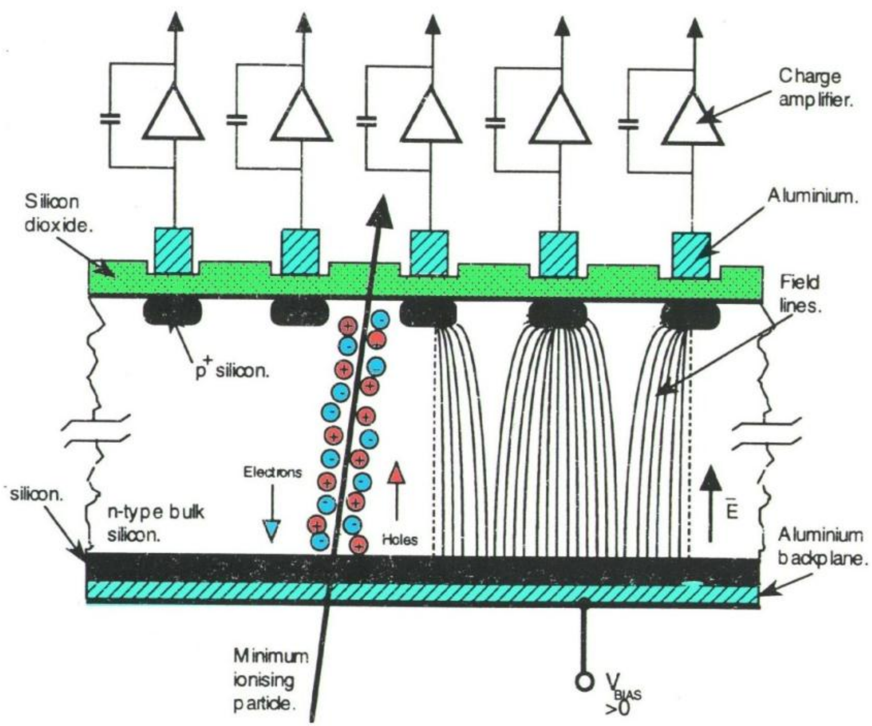
  - Low doping of the bulk → High resistivity → Low depletion voltage



- **Leakage current**
  - Dominated by the e/h pairs generated thermally
  - They get separated by the E field and move to the electrodes
  - It depends on the quality of the silicon, on the process and on the damages from radiation



Si strip detector

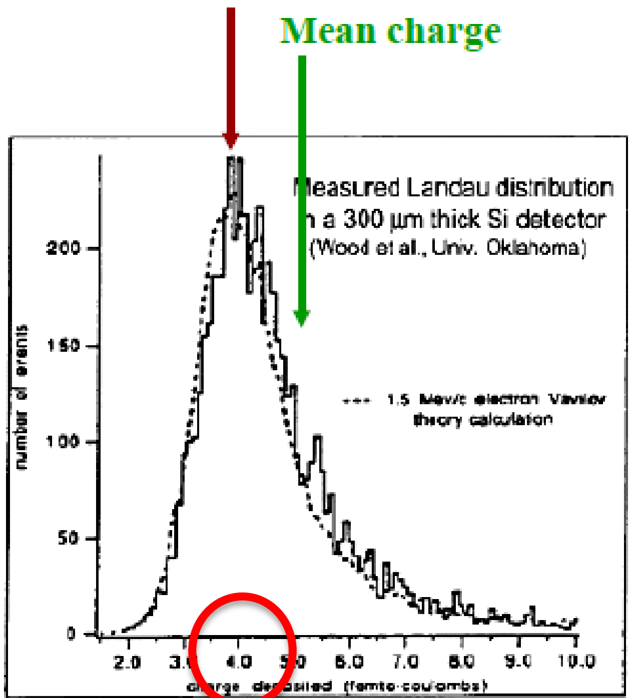


- Microstrip Si detector
  - A MIP releases 24000 e/h pair for a Si thickness of 300μ
  - The pairs in the the depletion region drift in the E field creating the signal
    - The signal is small ≈ 4fC and need to be amplified
    - An amplifier is connected to *each* strip
  - From the signal on the strips one measures the position of the particle
  - Similar to a MWPC, but no internal amplification
    - MWPC: $100e^{-} \times 10^{5} = 10^{7}e^{-}$

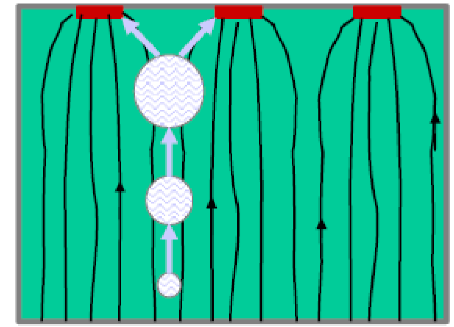
Si strips signal

Most probable charge ≈ 0.7× mean

Mean charge



- Charge released in 300µm
  - $32500e^- \approx 5.2$fC (mean)
  - $24000e^- \approx 3.8$fC (most probable)



- Collection time and diffusion

$$t = \frac{d}{v} = \frac{d}{\mu E} = \frac{d^2}{\mu V}$$

- With d=300µm, E=2.5kV/cm

$$t_e = 9ns$$
$$t_h = 27ns$$

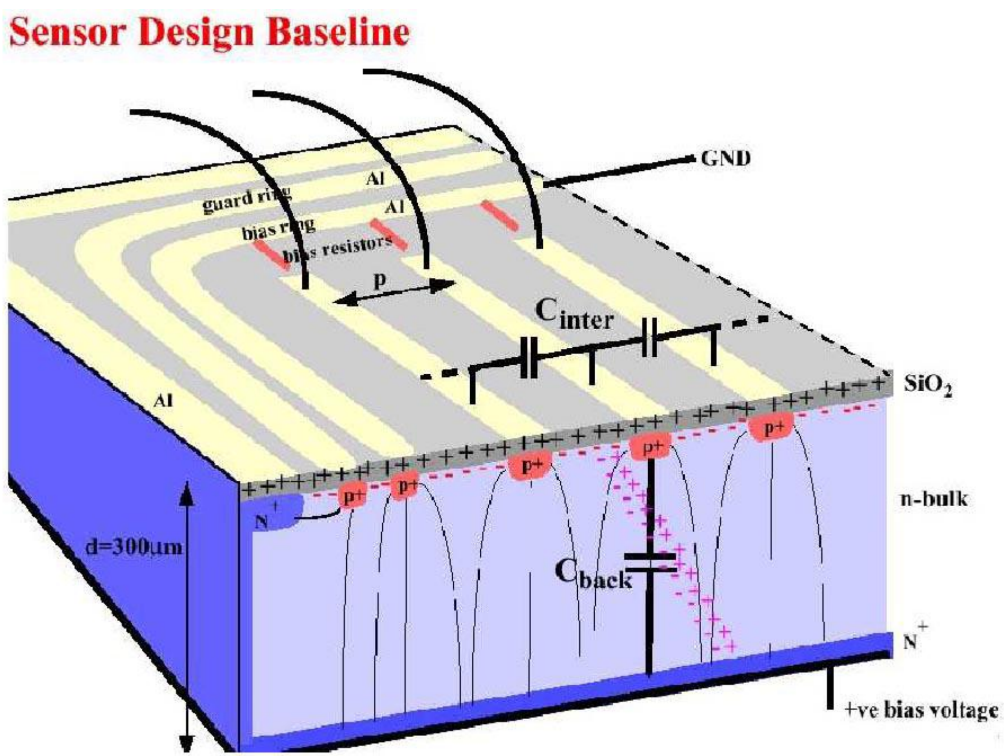
fast

- While drifting the charge diffuses

$$\sigma_D = \sqrt{2Dt}$$
$$D = \frac{kT}{q}\mu$$

- Typical value σ_D=6µm

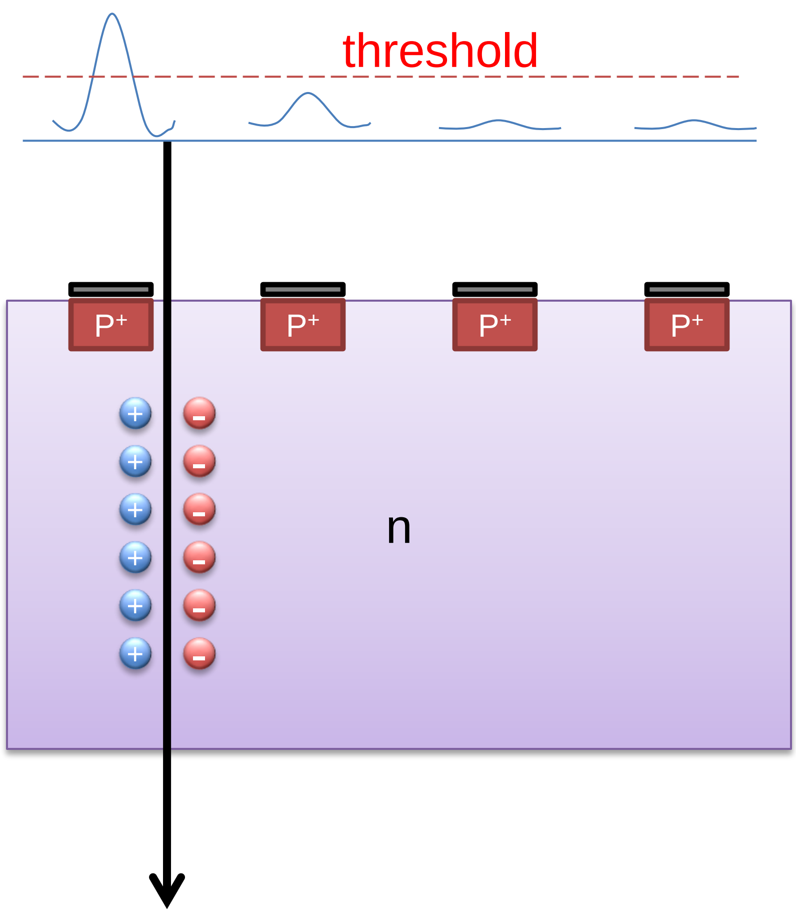
Si strips sensor



Typical parameters

- Strip pitch 25-250μ
- Thickness 300μ
- DC or AC coupling of the strips
- P^+n (n doped bulk)
  - $N_a \approx 10^{15}$ cm^{-3}
  - $N_d \approx 10^{12}$ cm^{-3}
  - ρ > 2kΩ
- V 100V (E=3kV/cm)

Si strips resolution



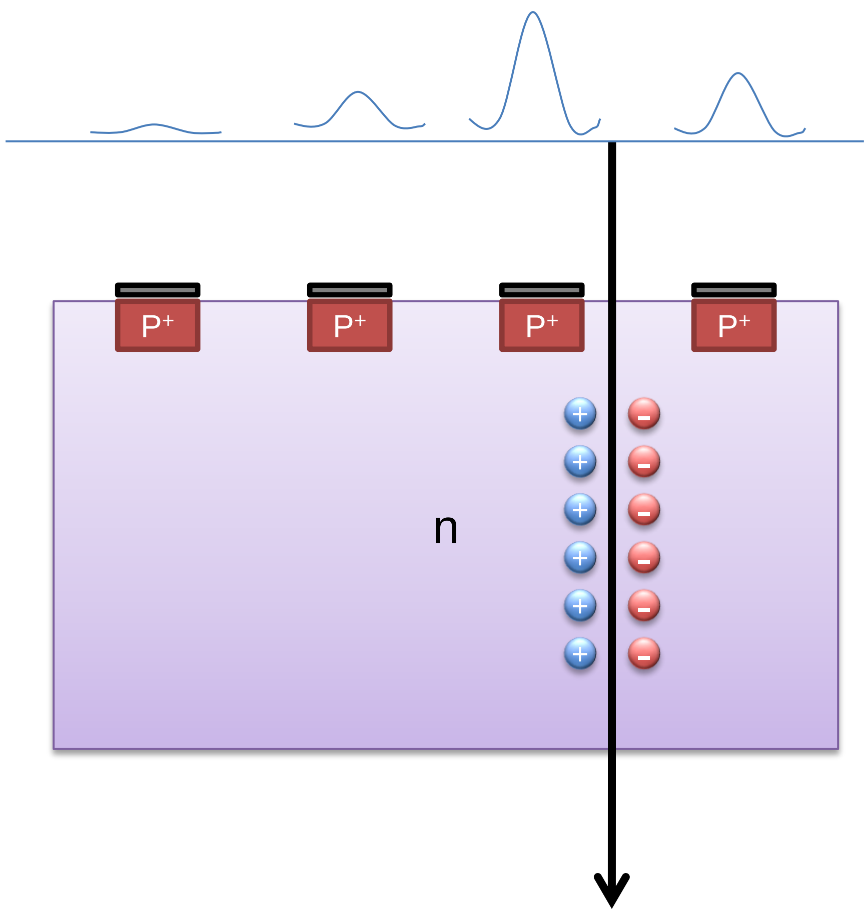
Binary readout

- Position = centre of the strip
- Resolution
  - If strip pitch = p

$$\sigma_X \approx \frac{p}{\sqrt{12}}$$

  - If p = 50μm → σ = 14μm

Si strips resolution



Analog readout

- Position = centroid of the signal

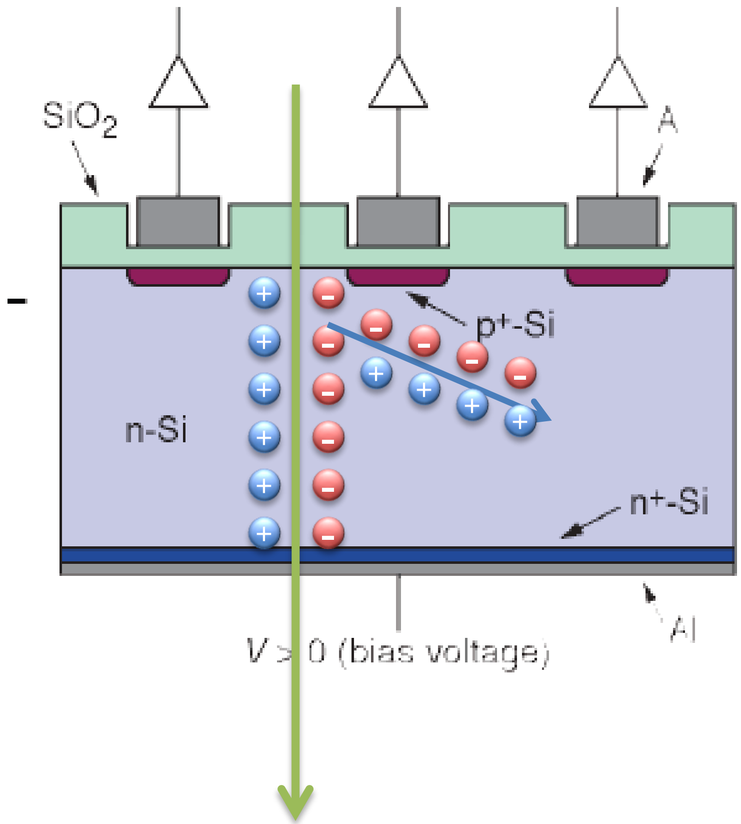
$$x = \frac{h_1 x_1 + h_2 x_2}{h_1 + h_2}$$

- Resolution

$$\sigma_X \approx \frac{p}{SNR}$$

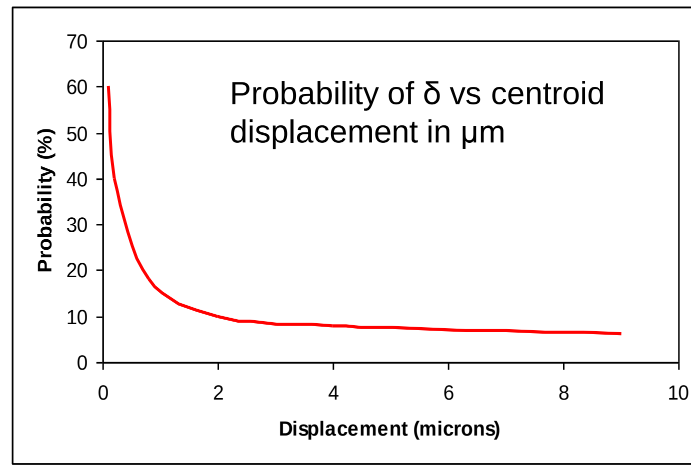
  - $\sigma < 10\mu m$

Si strips resolution



δ rays can affect the position reconstruction

- Shift of the centroid by few μm



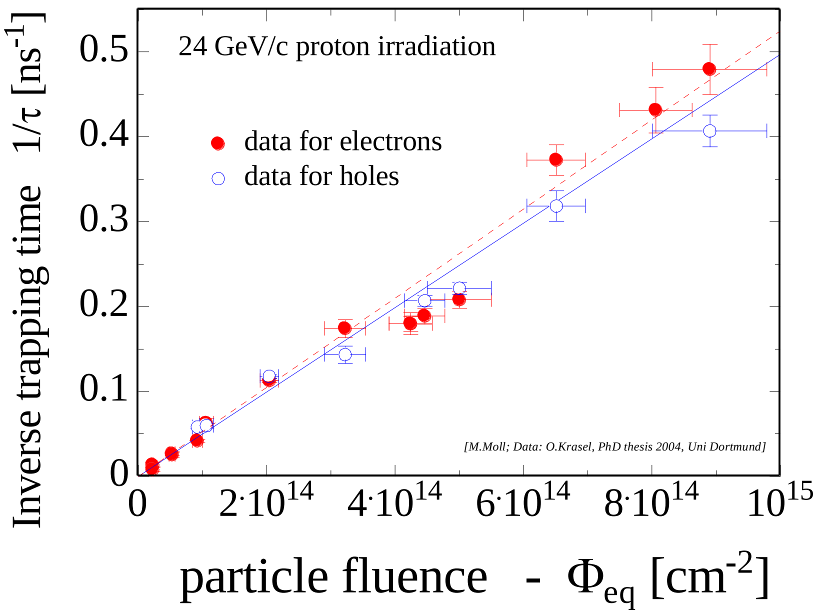
- Charge diffusion can instead help to increase the charge sharing between strip, better analogue resolution

Si radiation damage

- Lattice damage (Non Ionizing Energy Loss)
  - Decrease of charge collection efficiency
  - Changes in depletion voltage
    - Larger V, not full depletion
  - Increase of leakage current

- Surface damage (Ionizing Energy Loss)
  - Trapping of charges is the SiO_2 layers
    - Noise, breakdown

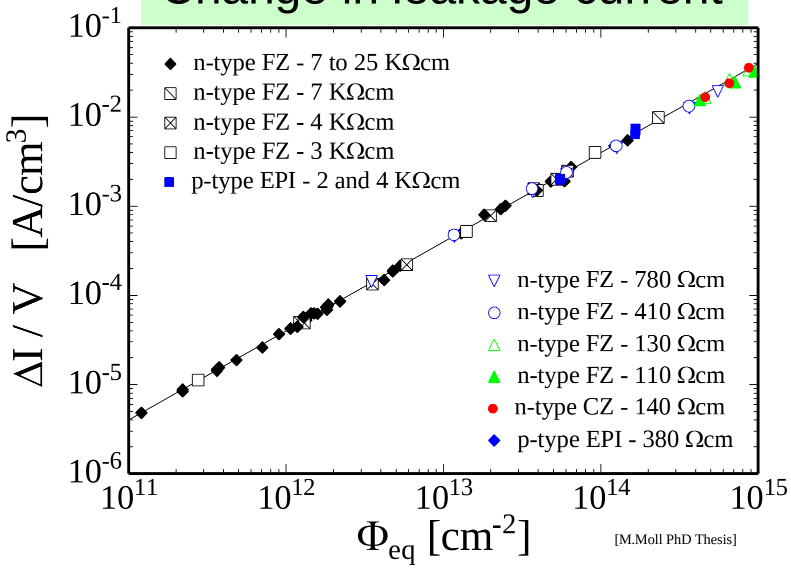
Deterioration in Q collection



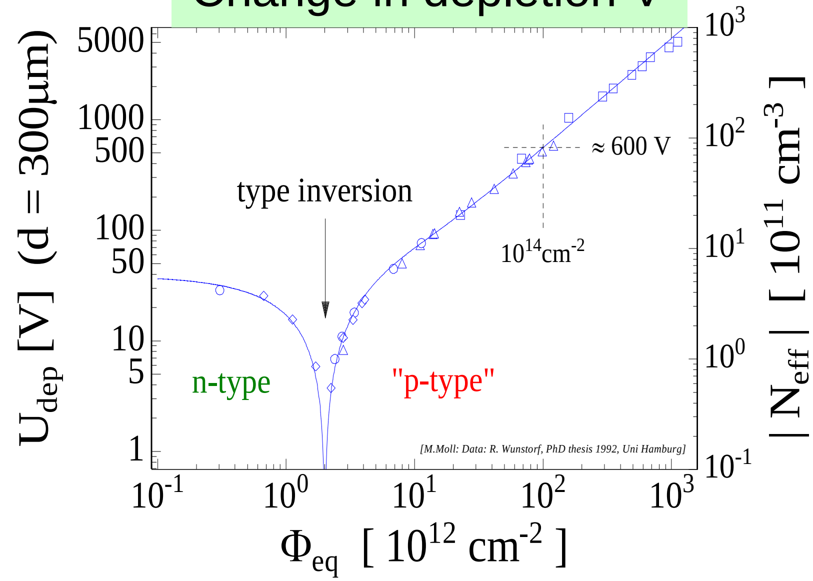
Caused by trapping from radiation induced defects

Si radiation damage

Change in leakage current



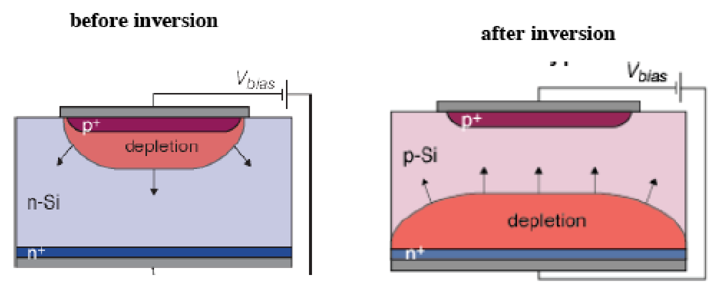
Change in depletion V



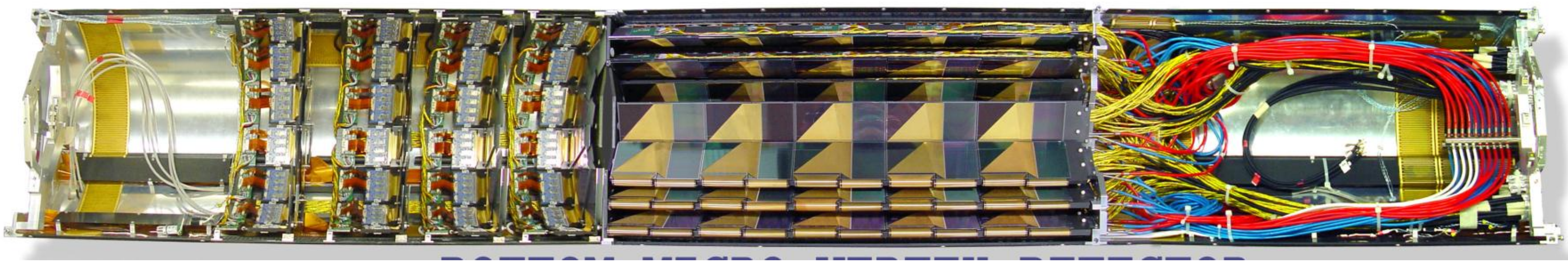
$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

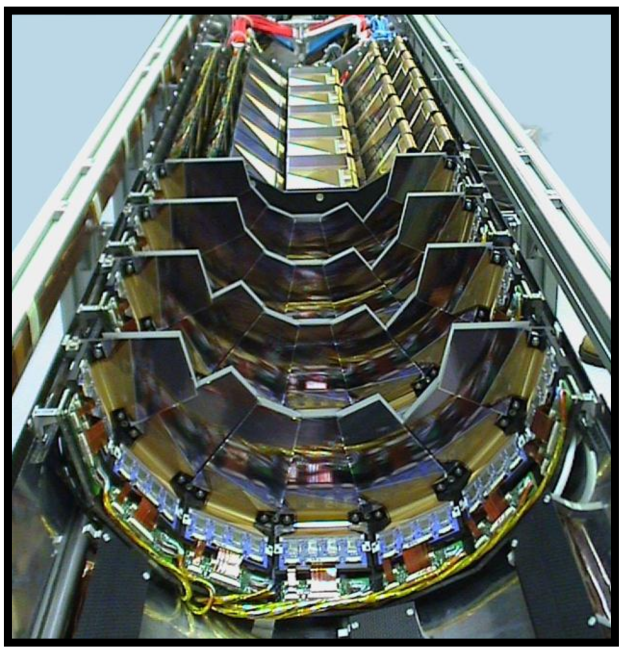
Damage parameter α

- Change of leakage current per unit of volume and fluence
- Constant over many order of magnitudes of fluence



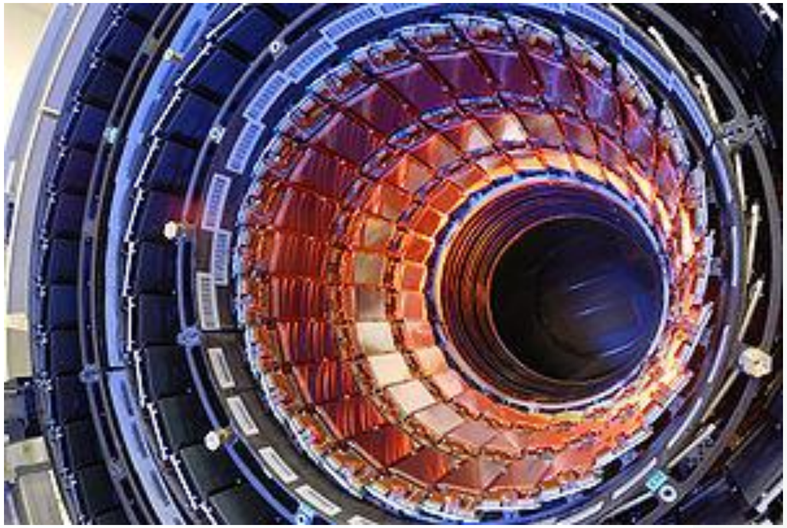
Example: ZEUS MVD (yr 2000)

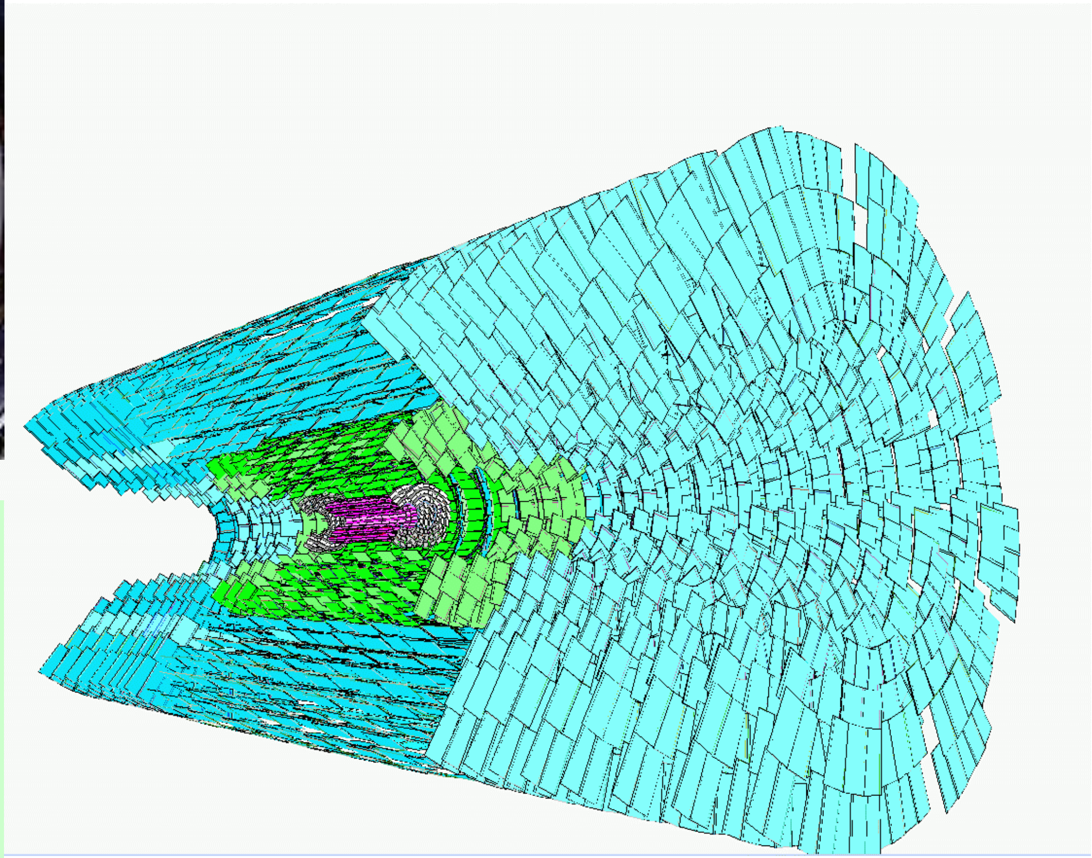




- 3 barrel layers, 2 forward wheels
  - Outer diameter 25cm
  - Length ≈ 1m
  - Resolution ≈ 15μ for normal tracks
  - ≈ 3% X_0 per layer
  - ≈ 2.5m^2 of Si planes

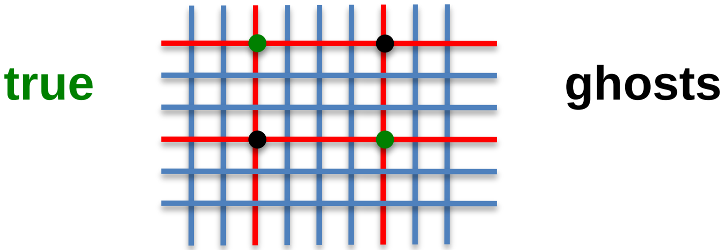
Example: CMS tracker



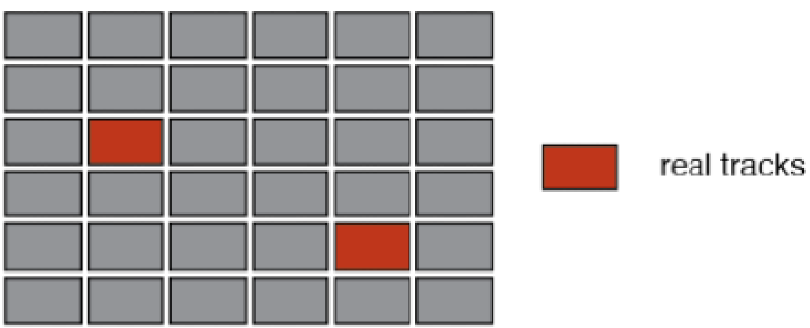


- 10 barrel layers and 2×9 end cap layers
- $223m^2$ of Si sensors
  - 600 thin (300μ) sensors, 20000 thick (500μ) sensors
- 10 millions channels

Pixel detectors



- In case of bi-dimensional x-y readout, high hit density generates ghost hits
- Pixel detectors solve this ambiguity

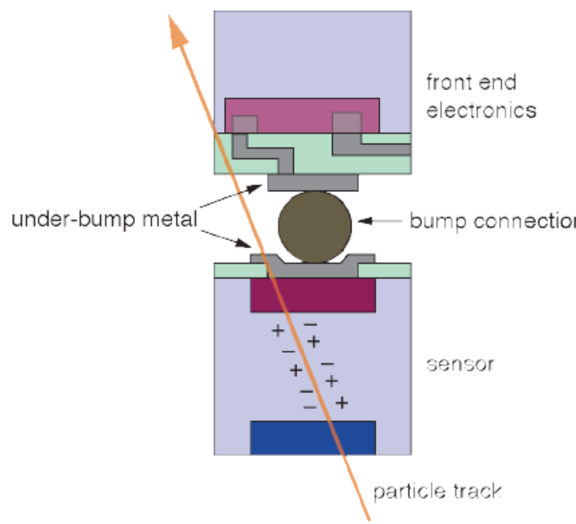


Advantages

- Small area → small capacity → large SNR
- Small volume small dark current/channel

Disadvantages

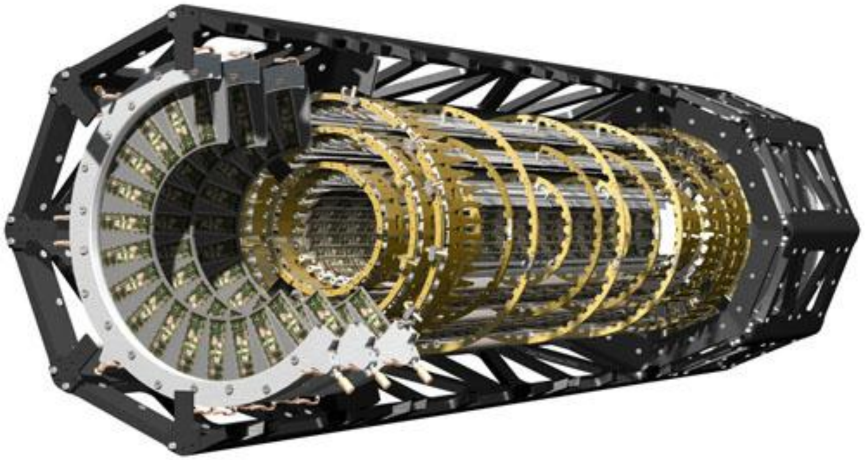
- Large number of channels (N^2 compared to strip readout)
- Large number of electrical connections and amplifiers
  - Big power dissipation



Bump-bonding to electronics

- Expensive
- Limit pixel size
- Increases material budget (X_0)

Pixel detectors

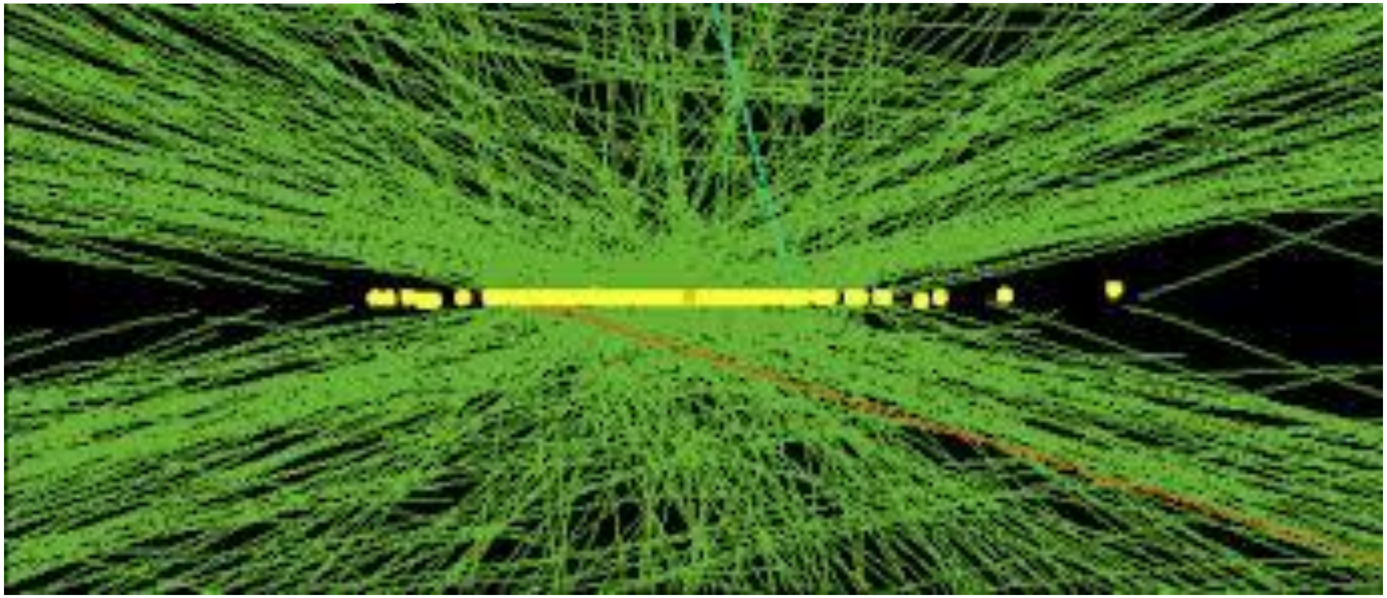


Largely used in the central regions of the LHC experiments

- Very high density of particles close to the interaction point
- In 2012, pile-up (number of overlapping event) up to 35 average

Atlas pixel detector

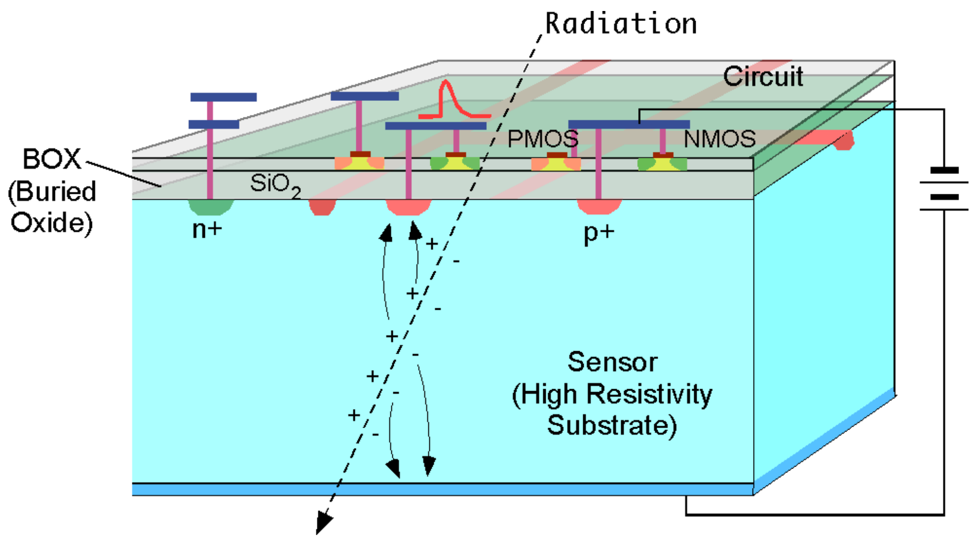
- 80 million channels
- 1.7 m^2



Developments: monolithic pixel detectors

Is it possible to integrate on the same Si the sensor and its electronics?

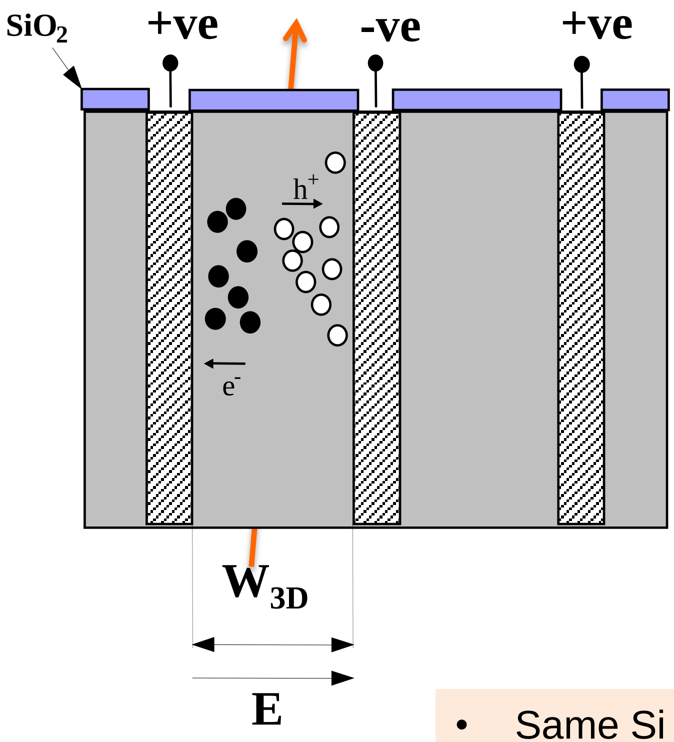
- **Detectors** → need large signals, large depletion regions → **high resistivity** (low doping)
- **Electronics** → large integration in small spaces →small junctions → **low resistivity** (high doping)



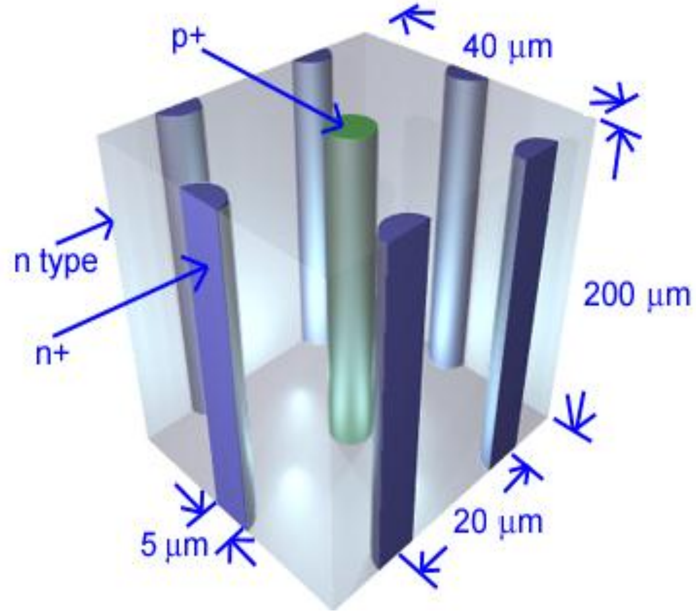
MAPS SOI (Silicon On Insulator)

- Commercial process, electronics separated from the wafer by a small (200nm) layer of SiO_2
- High-resistive substrate, holes through the oxide, P^+ implants → apply depletion V and collect charges
- **Problems**
  - Coupling between electronics and depletion voltage
  - Sensitive to ionizing radiation (charge trapped in the SiO_2 layers)

3D detectors



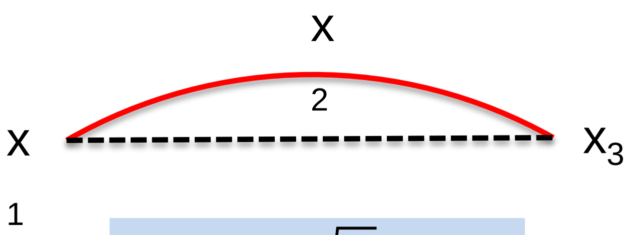
Bulk



Candidate for the new inner barrel layer of Atlas pixel detector

- Same Si thickness of the 2D detectors
  - Same signal
- Carriers move laterally
  - Low bias V and fast collection time if electrodes are close
  - Detector thickness becomes an independent parameter
- **More complex fabrication process**

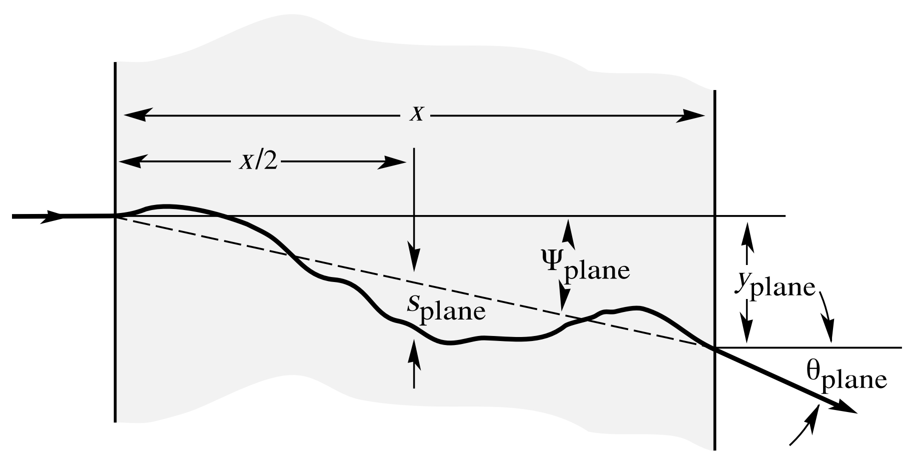
Multiple scattering



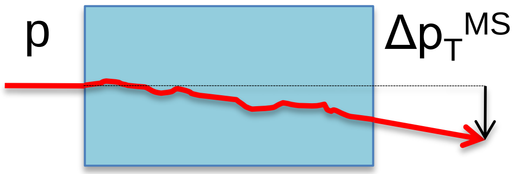
$$\frac{s(p)}{p} = \frac{8\sqrt{\frac{3}{2}}\, s(x)}{0.3BL^2}\, p$$

- Many choices of tracking detectors with resolution from ≈1mm to ≤ 10μm
  - Is it all we need to take into account?

- **No**
  - Even at infinite detector resolution, the momentum determination is limited by the effect of scattering of the particle in the detector



Multiple scattering



$$\theta_{RMS}(L) \approx \frac{14\,MeV}{p \cdot c\beta}\sqrt{\frac{L}{X_0}} \quad \longleftrightarrow \quad \theta_{Bending} = \frac{0.3}{p}\int B\,dl$$

considering $\beta \approx 1$

$$\Delta p_T^{MS} \approx p\theta_{RMS} \approx 14\sqrt{\frac{L}{X_0}}\,MeV/c$$

$$\left.\frac{\sigma(p)}{p}\right|^{MS} = \frac{\Delta p_T^{MS}}{\Delta p_T^{Bending}} = \frac{14\sqrt{\frac{L}{X_0}}\,MeV/c}{p\theta_{bending}} = \frac{14\sqrt{\frac{L}{X_0}}\,MeV/c}{0.3\int B\,dl}$$

- The contribution of the MS to σ(p)/p is a constant term, does not depend on p
  - So it limits the resolution at low p
  - Is very important when bending is in iron (muon detectors)

Examples

In Iron

$$\text{Fe}: \quad X_0 = 1.76\text{cm} \quad B = 1.8\text{T}$$

$$\left.\frac{s(p)}{p}\right|^{MS} = 0.19\frac{1}{\sqrt{L[m]}}$$

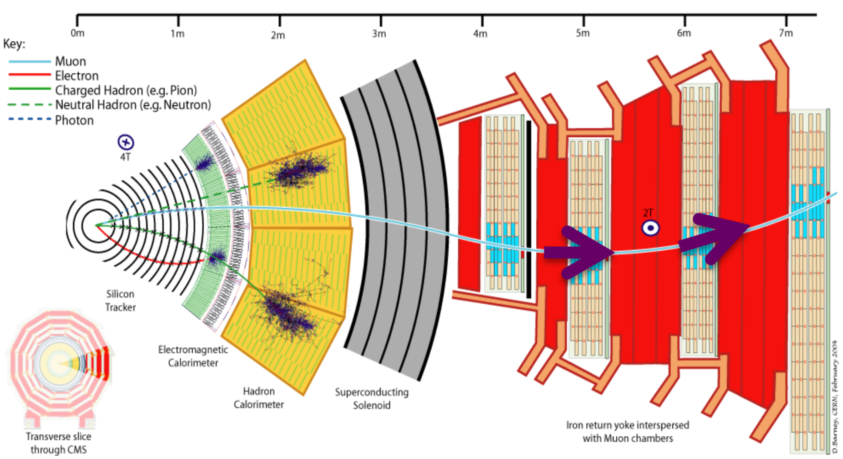
$$L = 3m \rightarrow \left.\frac{s(p)}{p}\right|^{MS} = 11\%$$

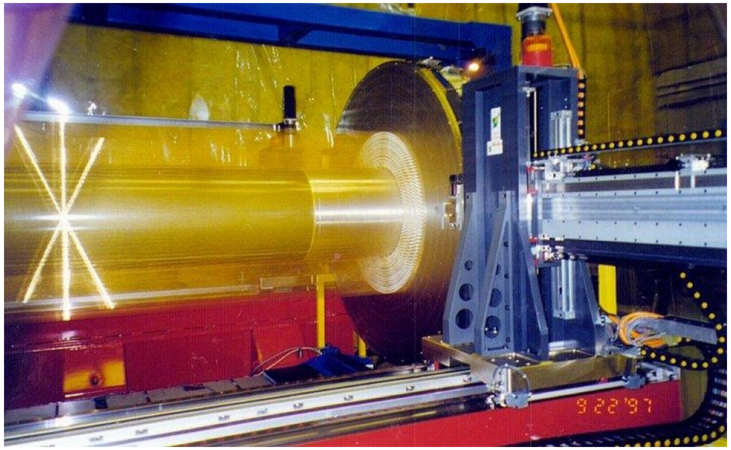
In gas

$$\text{Air:} \quad X_0 \approx 300m \quad B=1.8\text{T}$$

$$\left.\frac{s(p)}{p}\right|^{MS} = 1.4\cdot 10^{-3}\frac{1}{\sqrt{L[m]}}$$

$$L = 1m \rightarrow \left.\frac{s(p)}{p}\right|^{MS} = 0.14\%$$





Tracking resolution summary

- In general the resolution of a tracking detector is the sum of two terms
  - For example, for the central drift chamber of ZEUS it was $\frac{s(p)}{p} = 0.005p \oplus 0.007$
- Depending on the momentum range, one can optimize
  - For low momentum, optimize the radiation length
    - E.g. Babar used helium as noble gas
  - At high momenta the term proportional to p dominates
    - Need to increase B, lever arm and resolution
    - E.g. CMS is using a full-silicon central detector, certainly not optimized for dead material