

Lecturer: Steve Snow

Subject: Particle Detectors

Webpage: <http://www.hep.man.ac.uk/u/steve/detectors.html>

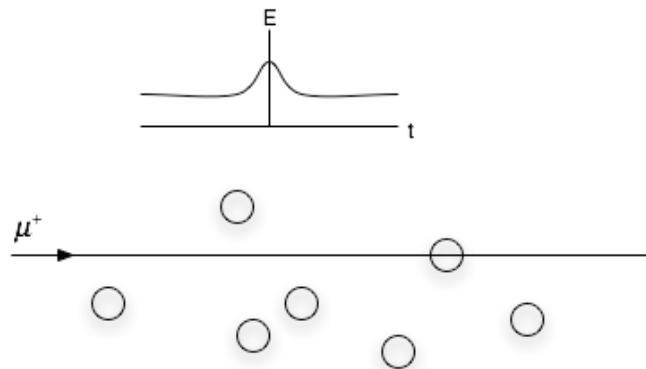
[First three links should cover most of the course.]

Main particles (in order of most important):

- $\mu^\pm$, $c\tau = 660m$. Relatively simple: goes through a long distance before decaying, and not much happens to it until it stops (i.e. no strong force, etc).
- $e^\pm$, γ are very interchangeable from a particle detector point of view. Emitted through Bremsstrahlung, or pair production.
- $\pi^\pm$. $c\tau = 7.8m$
- $K^\pm$. $c\tau = 3.7m$
- K_L^0 , $c\tau = 15m$
- n
- Jets – lots of π^+ , π^- , $\pi^0 (\rightarrow \gamma\gamma)$
- τ (tau's), $c\tau \approx 87\mu m$
- b hadrons, $c\tau \approx 500\mu m$
- c hadrons $c\tau \approx 300\mu m$

NB: $c\tau$ is before time dilation.

Consider μ^+ interactions in a gas. Assume atmospheric pressure.



The muon will pass within 1 Angstrom of approximately 8500 Ar atoms / cm. All the atoms will see will be a sudden peak in the EM field. There is some probability that this will either excite an electron in the atom to a higher energy state, or eject an electron (i.e., the atom is ionised). There are on average 25 ionisations per cm. This is by far the most dominant way that the muon can lose energy, and by which it can be detected.

The maximum energy that an electron can have once it has been ionized from an atom is

$$T_{\max} = 2m_e c^2 \beta^2 \gamma^2.$$

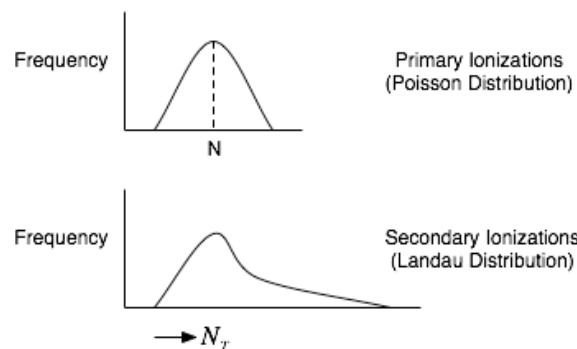
This energy can itself become an ionizing particle, and produce secondary ionization, such that there is a combination of primary and secondary ionization.

[NB: δ -rays are electrons; it's archaic terminology]

Average numbers of ionizations for different gasses:

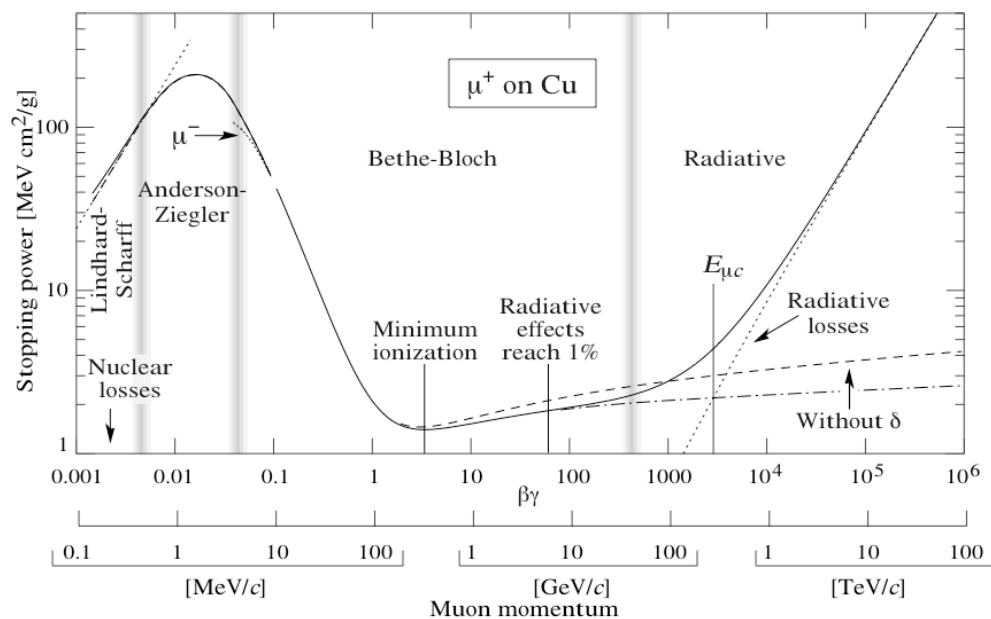
Gas	Number of primary ionizations / cm	Number of secondary ionizations / cm
<i>He</i>	5	16
<i>Ar</i>	25	103
<i>CH₄</i>	27	62
<i>C₂H₆</i>	43	113

The primary ionizations are purely Poisson statistics. Some of the primary ionizations will go on to create a lot of secondary ionizations, while some will create none or a few. The distribution of this is called the Landau distribution, after the person that first calculated it.



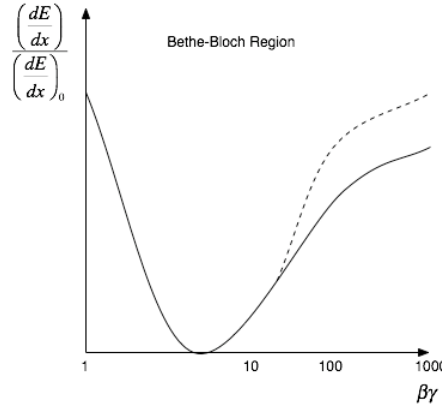
What if the matter is denser, i.e. condensed matter (solid or liquid)? It is not much different. For a μ^+ , the number of ionizations is scaled up by the density factor of 1000. There are a couple of small caveats, though;

- Screening effect, which slightly reduces the number of ionizations produced (polarization of the medium).
- Chemical effect on ionisation energy.



[Image from the Particle Data Group]

Here, the stopping power has units of $MeV cm^2 g^{-1}$. Natural units would be $MeV cm^{-1}$, but this has been normalized by dividing by density (g / cm^3).



The relevant section here is the Bethe-Bloch region, which refers to the typical energies in particle accelerators.

Energy loss per distance traveled in the medium is given by:

$$\frac{dE}{dx} = -Kz^2 \left(\frac{Z}{A} \right) \rho \frac{1}{\beta^2} \left(\ln \left(\frac{2m_e c^2 \beta^2 \gamma^2}{I} \right) - \beta^2 - \frac{\delta(\gamma)}{2} \right)$$

where

- $K = 0.31 \frac{MeV}{g / cm^2}$ is a constant.
- z is the projectile charge, normally 1.
- $\frac{Z}{A}$ is the nuclear charge/weight of the medium, normally close to 0.5.
- ρ is the density
- The top part of the logarithm represents T_{max} , the maximum kinetic energy.
- I is the average energy needed for ionization
- $\delta(\gamma)$ only has an effect at high energies. It governs the relativistic rise, and is to do with the screening effect. Ignore this for now.

Putting in $\beta\gamma = 3$ (this is an arbitrary choice), $I \approx 15eV$, $T_{max} = O(MeV)$ - the logarithmic part turns out to be about 12.

$$0.31 \times \rho \times 9.5 \times (12 - 1) \rightarrow 1.7 \frac{MeV}{g / cm^2} \rho$$

This is fairly typical for all materials.

The average drift velocity of a gas is $v_D = \mu E$, where μ is the mobility. $\mu \propto \frac{1}{\sqrt{m_{ion}}}$,

at least in the regime where the thermal velocity is bigger than that acquired through the EM field. μ is also proportional to the mean free path, λ .

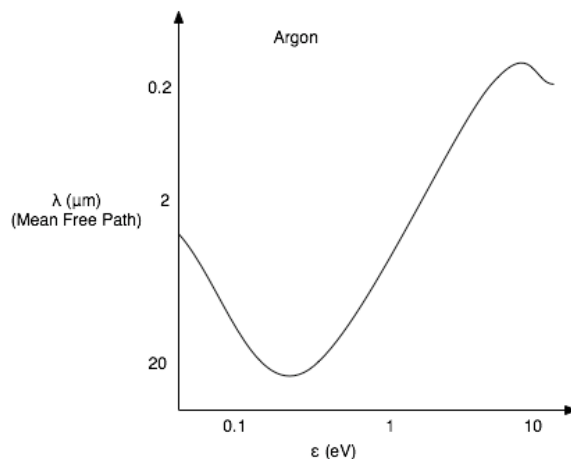
In a liquid, the next particle is about an angstrom away. For a gas, it's around 1000 angstroms away, $\approx 0.1\mu m$.

Typical value of μ (for Ar) is $2cm^2s^{-1}V^{-1}$. So $1kV/cm$ leads to $v_D = 2000cm s^{-1}$.

Electron drift in a gas

Electron drift is very similar to ions, except:

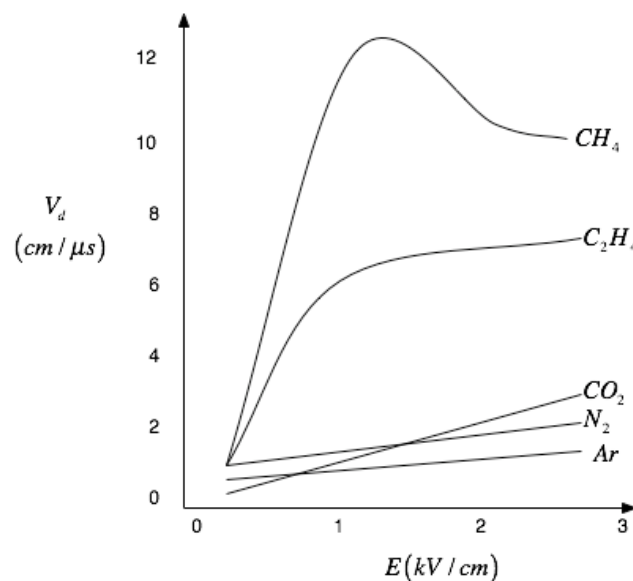
- It will be a lot quicker, due to the $\frac{1}{\sqrt{m_e}}$ factor.
- λ - cross section is lower at $\sim 1eV \rightarrow$ faster



- In some types of gas, the electrons can get attached to the gas atoms themselves and form negative ions. In electro-negative gas, e.g. O_2 , H_2O , Cl_2 there is a higher probability of the electrons sticking – this would turn the atom into an ion drifting in a gas, not an electron, and hence it would be slower.

In He , Ar , X , CH_3 this doesn't happen.

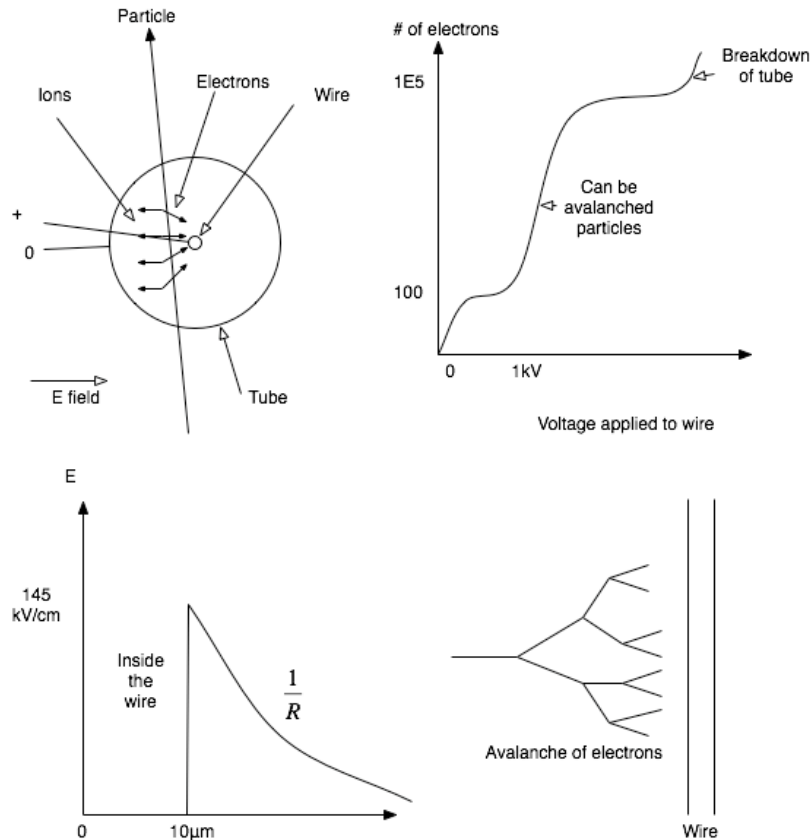
So working out how fast the electrons will move in the gas is complicated, but with the end result being something like:



Typical $v_D^{electrons} \approx 2\text{cm} / \mu\text{s}$. 1000 times faster than ion drift.

Occasionally convenient to get the peak and plateau like in CH_4 - can get a drift velocity independent of the voltage used.

Straw Detectors

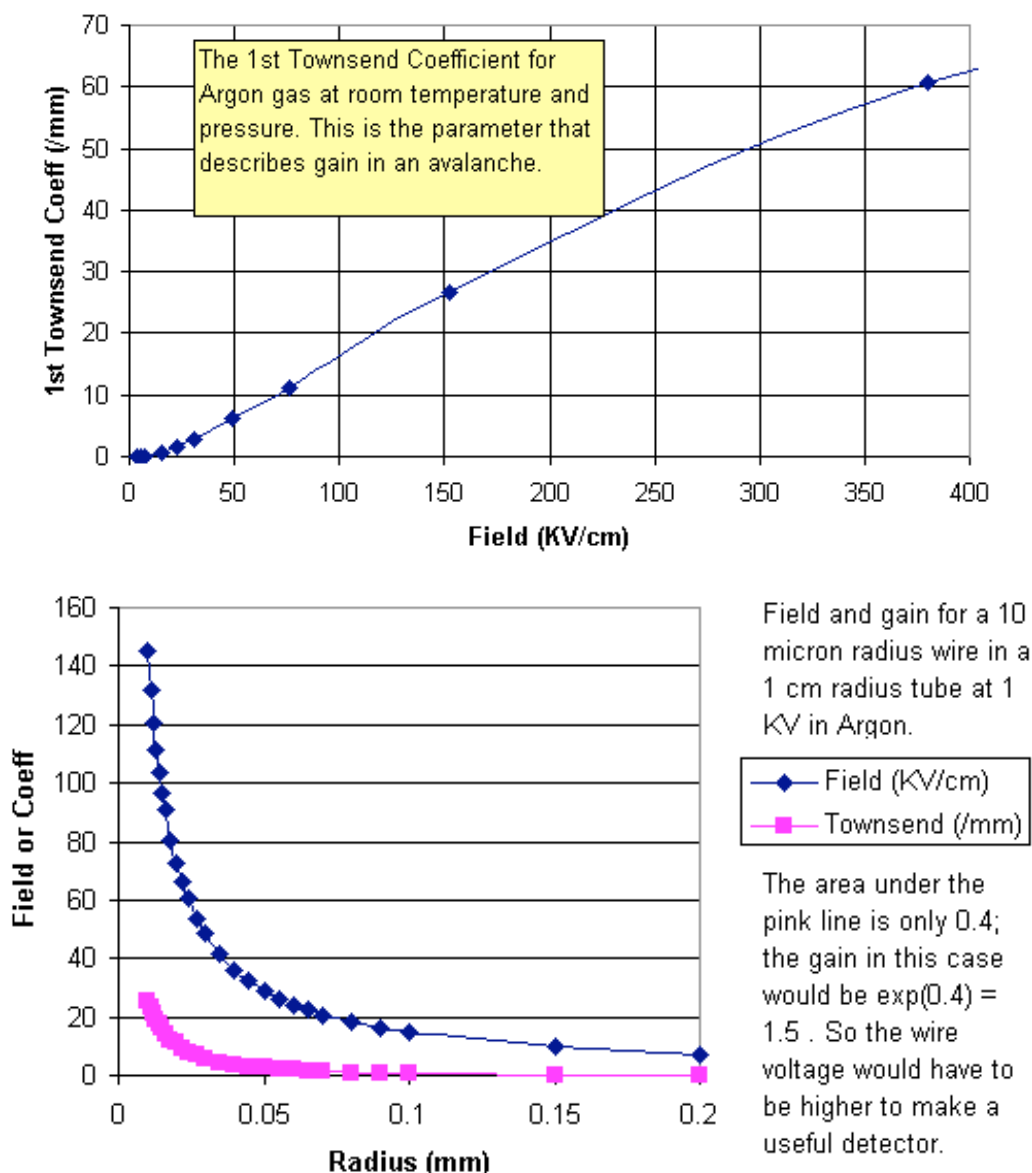


The time for travel for the electrons is $\sim 1\mu\text{s}$, and for the ions it's $\sim 1\text{ms}$. The radius of the wire is $R = 10\mu\text{m}$, the radius of the tube is $R = 1\text{cm}$ (approx).

As electrons get very close to the central wire (last few diameters) they get into a very strong field – so in between collisions, they can have enough energy to ionize atoms – generate more electrons. Avalanche process. Distances between ionizing collisions decrease the closer to the wire the electron is. Noise-free amplification – nice. Wouldn't be able to detect the original 100 – can't build an amplifier which can detect these above the noise level. Can detect the avalanched electrons, though.

Charge you get $\propto$ (charge you started with) $\times 10^5$.

$dN = N\alpha ds$, where α is the 1st Townsend Coefficient. Strong function of voltage.



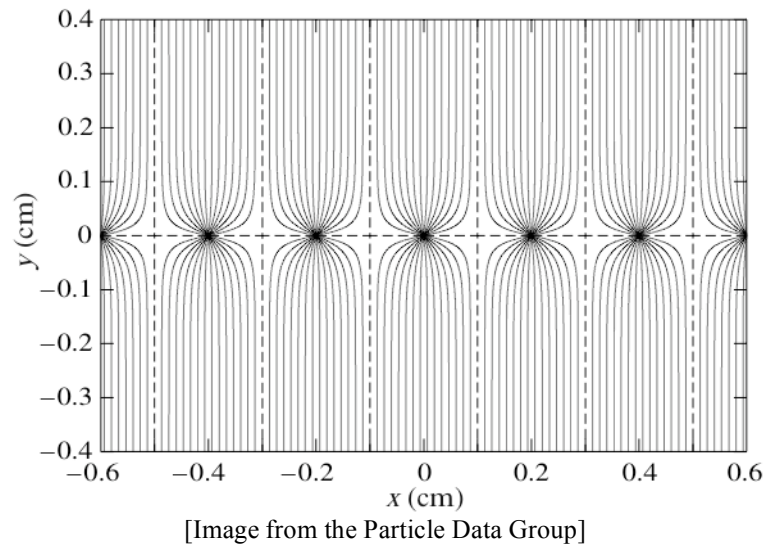
Things that cause problems, and need to be fixed before the detector is working properly:

- UV feedback – to the walls, or just part of the way and ionize an atom in the gas.
- Ion feedback: as the ion nears the metal surface, it has sufficient energy to pull 2 electrons out of the metal, which then heads back to the central wire and creates another avalanche.

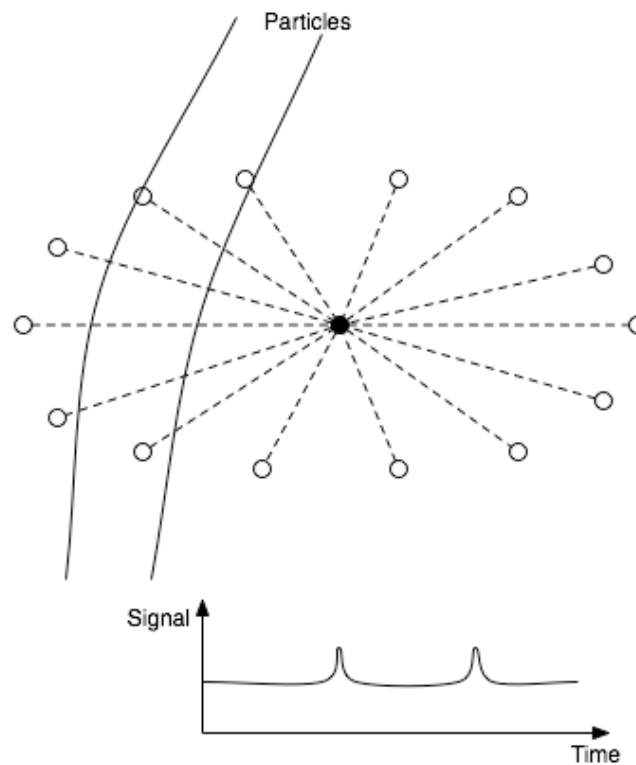
Can solve this by using mixtures of gasses – e.g. Ar and CH_3 . CH_3 can prevent the Ar from emitting a UV photon in the first case. In the latter case, charged Ar can give electron to CH_3 (as it has a higher energy) – which now can only get one electron from the metal wall.

“Black magic” in getting wire chambers to work properly.

Multi-Wire Proportional Chamber

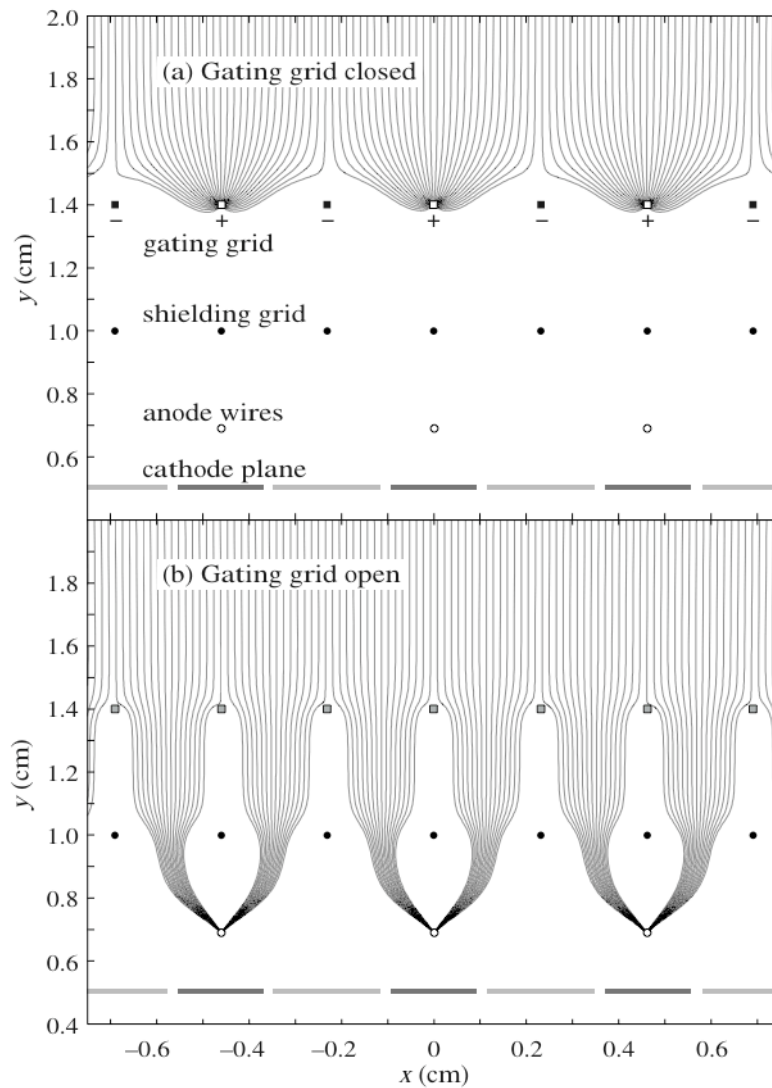


Drift Chamber

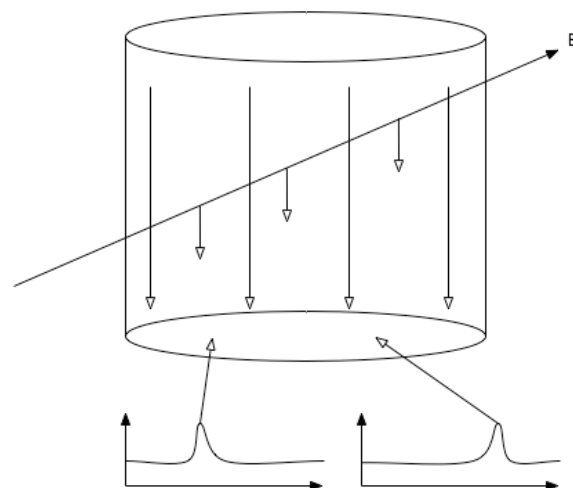


Choose the voltages such that all of the electrons arrive at the central wire at the same time. Can see several particles with only one central wire, and one amplifier channel. Position resolution: How accurately you know the distance to the track is round $50 - 100 \mu m$.

Time Projection Chamber



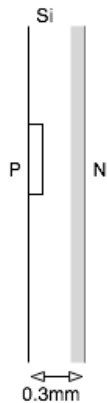
[Image from the Particle Data Group]



You would see a projection of the track onto pixels at the bottom of the chamber. Again see a signal as a pulse, where the time is related to the distance to the track. Wires mean that positive charges coming from the anodes do not go back into the large volume of gas, where they would distort the parallel field lines.

Silicon Detector

These are Solid State Ionisation Chambers.



Intrinsic – low density of donors & acceptors, or cancel [weakly n-type]. Reverse bias.

~100V – region of depletion covers intrinsic area. Very low amount of charge carriers available naturally – can detect the signal better.

Have around 26,000 electron-hole pairs in 0.3mm .

Generally need a semiconductor, or some crystals (diamond is good) where there are no existing charge carriers around.

Takes a few nanoseconds to go from particle creation to receiving the signal.

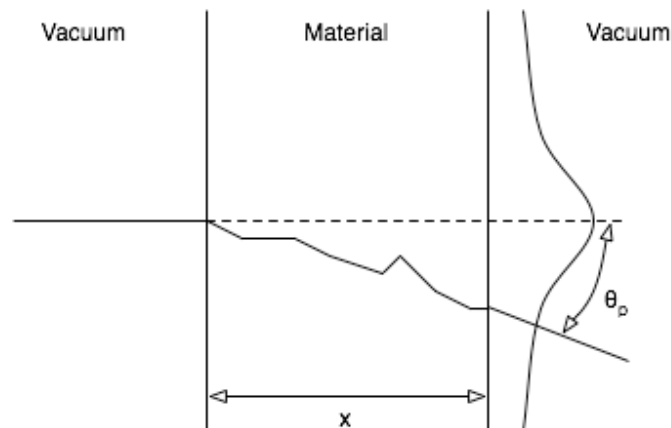
Tens of picofarads – noise is around 1000 electrons – so need around 10,000 electrons to create a detectable signal.

If Si was wider, then more electron-hole pairs, but need a bigger voltage.

Get a resolution depending on the size of the electrode pattern. 'though if very small, then you get some diffusion effect – in practice, don't get near this stage though.

Scattering

This is a change of direction, not energy. It is often called multiple coulomb scattering, and is similar to Rutherford scattering.



θ_p indicates the scattering within a plane P . It is a spread, very close to a Gaussian but not perfectly – it has larger tails. Around the central 98% of this distribution is approximately Gaussian, with a width

$$\theta_p = \frac{13.6 \text{ MeV}}{\beta c p} Z \sqrt{\frac{x}{X_0}} \quad (1)$$

where X_0 is the 'Radiation Length', which scales with the Z^2 and density of the nuclei.

Measurement of Momentum

Want:

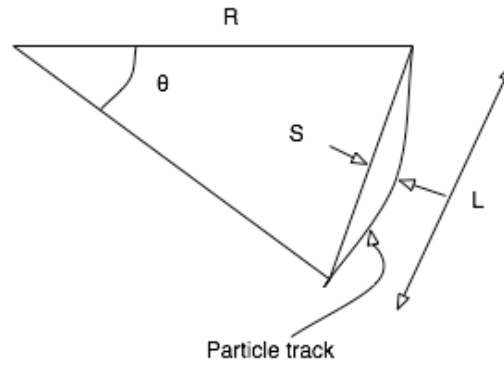
- A strong magnetic field – normally between 1 – 5T .
- A large volume - $O(10m^3)$ (order of)
- Instrumented with many planes of particle detector

$$p_T (\text{GeV} / c) = 0.3 Z B(T) R(m) \quad (2)$$

where Z is again the charge in units of e , which is normally 1.

p_T ranges from $100 \text{ MeV} / c$ (BaBar) to $100 \text{ GeV} / c$ (Atlas LHC)

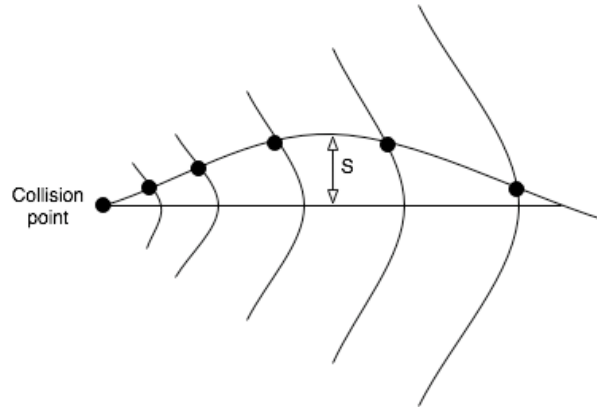
Atlas has $B = 2T$, $R = \frac{100}{0.3 \times 2} = 166m$.



The Sagitta distance S is

$$S = \frac{L^2}{8R} \quad (3)$$

If $L = 1$, $R = 166m$, $S = 0.75mm$.



Uncertainties in S will be caused by the errors in the measurements, and in scattering. The error in S is

$$\delta S = \underbrace{\delta S_D}_{\sigma_D} \oplus \delta S_m \quad (4)$$

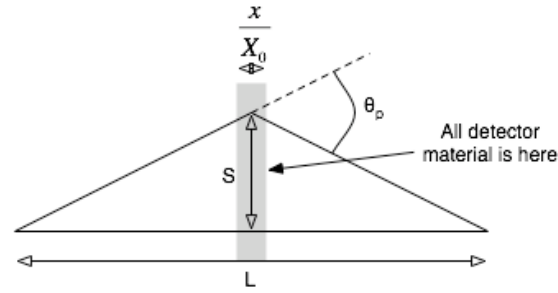
where δS_D is the error from the detector, $\oplus$ indicates added in quadrature, and δS_m is the error caused by the scattering.

Combining equations (3) and (2),

$$p = \frac{0.3 Z B L^2}{8S} \quad (5)$$

with error propagation

$$\frac{\delta p}{p} = \frac{8p}{0.3 B L^2} \delta S \quad (6)$$



$$\begin{aligned}\delta S_m &\approx \theta_p \frac{L}{4} \\ &= \frac{13.6 \text{ MeV}}{p} \sqrt{\frac{x}{X_0}} \frac{L}{4} \quad (7)\end{aligned}$$

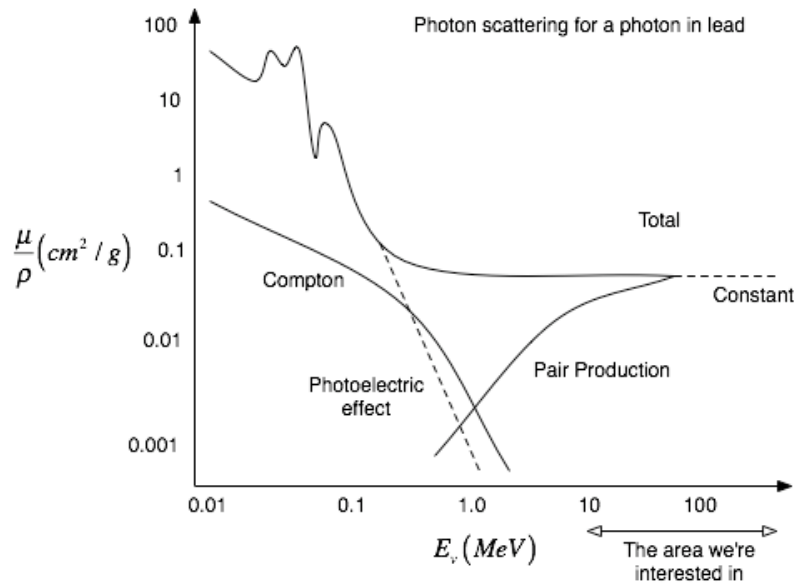
So we get the performance for the detector to be

$$\sigma_D \oplus \frac{A}{p}$$

where A is a constant. Again in Atlas;

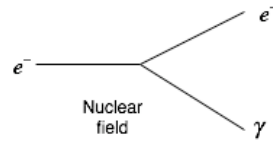
p	$S(\text{mm})$	$\delta S_D(\text{mm})$	$\delta S_m(\text{mm})$
100 GeV	0.75	0.05	0.035
10 GeV	7.5	0.05	0.35
1 GeV	75	0.05	3.5

Radiation Length X_0



For photons $> 10 \text{ MeV}$, pair production dominates. One definition of X_0 is $\frac{7}{9}(\lambda_{pp})$ where λ_{pp} is the mean free path for pair production at high energies (which is roughly constant).

For electrons/positrons e^+, e^- , the dominant effect is Bremsstrahlung.



So another definition of X_0 is

$$\left\langle \frac{dE}{E} \right\rangle = - \frac{dx}{X_0}$$

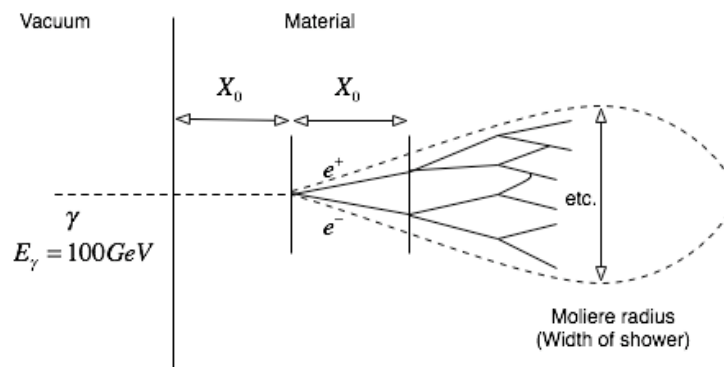
$$\langle E \rangle = E_0 e^{-\frac{x}{X_0}}$$

which is the one that is usually used (although they are equivalent).

$$X_0 = \frac{720 \left(\frac{g}{cm^2} \right)}{\rho} \frac{A}{Z(Z+1) \ln \left(\frac{287}{\sqrt{Z}} \right)}$$

(Don't remember this! It's just for reference).

	$\frac{dE}{dx} \frac{1}{\rho} \left(\frac{MeV}{g cm^{-2}} \right)$	$X_0 \rho \left(\frac{g}{cm^2} \right)$
He	1.9	94
Si	1.7	21
Fe	1.4	14
Pb	1.1	64

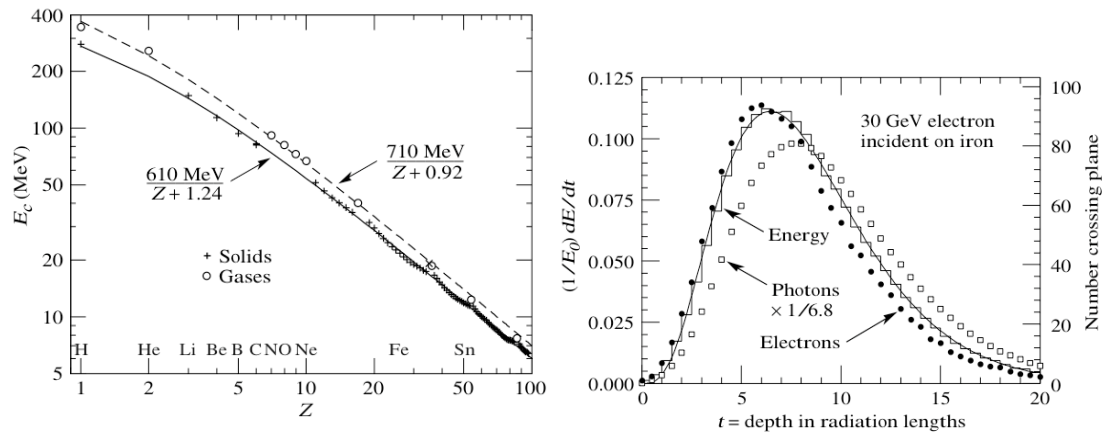


Width of shower is called the “Moliere Radius”, and is

$$R_m = X_0 \frac{21 MeV}{E_c}.$$

This continues until the energy of the electrons and positrons falls to the ‘critical energy’ E_c .

The definition of critical energy is when energy loss by $\frac{dE}{dx}$ in one X_0 is equal to the electron energy.



Hadron Shows

Characteristic interaction length

$$\lambda_I \approx \frac{35 \frac{g}{cm^2}}{\rho} A^{1/3}$$

	$\lambda_I (cm)$	$X_0 (cm)$
<i>Be</i>	41	35
<i>Si</i>	45	9.4
<i>Fe</i>	17	1.8
<i>Pb</i>	10	0.6

- This is complex
 - o Many possible hadronic interactions
 - o Often each one will produce many products.
- Partly EM – e.g. $\pi^0 \rightarrow 2\gamma$
- Energy (ionisation) is dumped by e^+e^- , $\pi^+\pi^-$, p , n , nuclear fragments e.g. α , fission products, delayed (normally lost) decays [e.g. through unstable nuclei]

Calorimeters

These are:

- Massive
- Contain EM or hadronic showers (i.e. they don't let any out the other side). Therefore they measure the energy in a cell, which is equivalent to measuring $\underline{p}$ (as a vector).

Optimised for:	Homogenous	Sampling
EM	Dense, scintillating crystals - BGO – Bismuth, Germanium, Oxygen - CsI – Cesium Ionide - Etc. Cherenkov light. - Lead glass blocks	Converter - usually Pb. - Thickness $\sim 0.5 X_0$ Sensor - plastic scintillator - Si - liquid Argon - proportional gas
Hadronic	N/A	Converter - Fe Sensor - plastic scintillator - liquid Argon - proportional gas - (Si is too expensive)

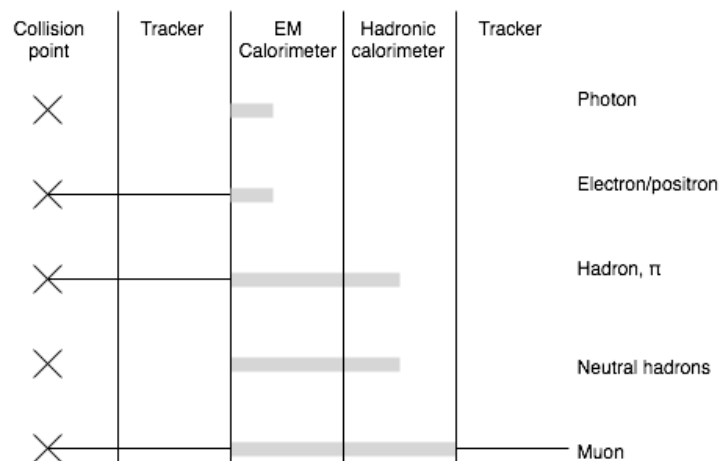
Calorimeter Resolution

$$\frac{\delta E}{E} = \frac{A}{\sqrt{E(\text{GeV})}} \oplus B$$

B term is due to calibration. With enough effort, this is $\leq 1\%$.

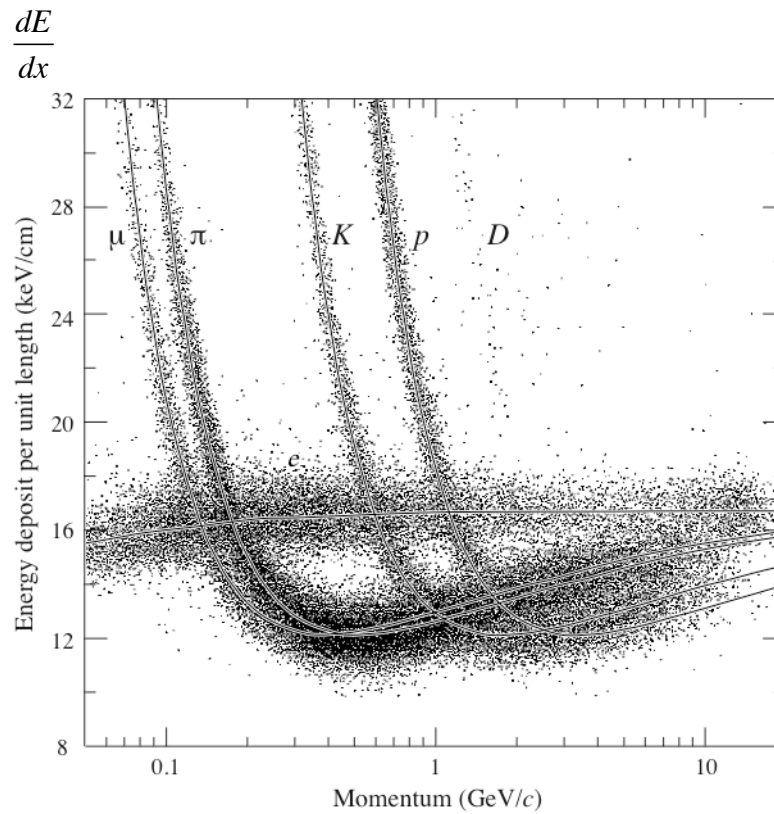
A Term	Homogenous	Sample
EM	2-3%	10-20%
Hadronic	N/A	40-80%

Particle Identification



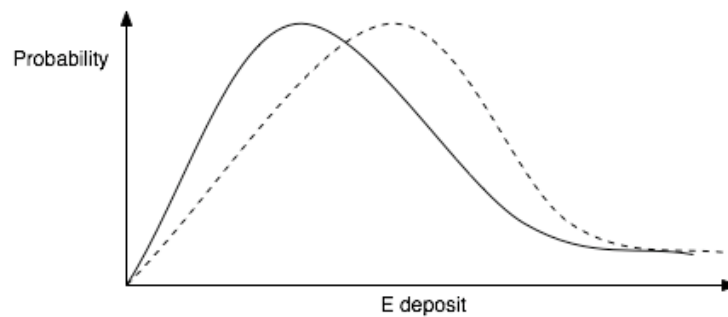
Track gives you $p = m\beta\gamma c$. But there are other processes which can give you β , so you can work out the mass and identify the particle. How do you measure β independent of mass?

- Time of Flight
- Low energies - $\beta = 0.9$, $\Delta t \approx 1\text{ns}$

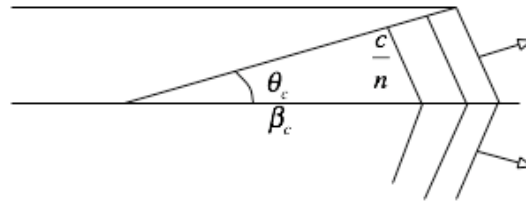


As $\left\langle \frac{dE}{dx} \right\rangle = fn(\beta)$

Landau fluctuations



Take many samples. Rank samples from low to high energy, and throw away the highest 30%, and average the others.

Cherenkov radiation

where n is the refractive index.

$$\cos \theta_c = \frac{\left(\frac{c}{n}\right)}{(\beta c)} = \frac{1}{n\beta}$$

Detect the radiation using a photomultiplier. There are two types of detectors – either the threshold type (yes/no if there is light or not; no indicates $n\beta < 1$), or focusing the light to get a ring image – this is the Imaging type. The diameter of the ring gives θ_c , which gives β .