Muon Detection at Colliders: Part 1

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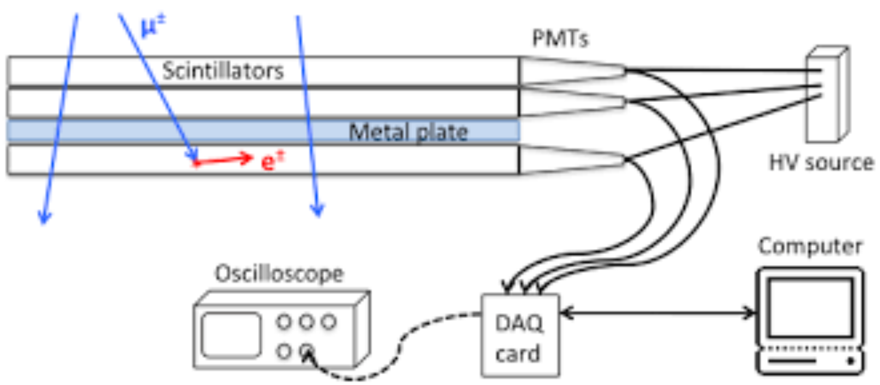
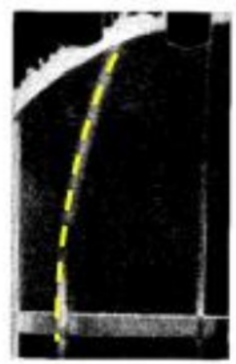
Introduction

- Professor Kevin Black, UW-Madison
  - 1999-2005: D0 Graduate Student , Top Quark Physics and Silicon Track Trigger
  - 2005-2010: ATLAS PostDoc, Exotic Physics Signatures and Muon Reconstruction and Commissioning
  - 2010-2018: ATLAS Faculty, Top Quark Physics, Higgs Physics, Exotics Physics – Muon Trigger
  - 2018-present: CMS Faculty, Exotic physics, Flavor Physics, Top, Higgs, CMS GEM (Gas Electron Multiplier) Forward Muon system upgrade
- Today: Muon detection from first principle and classical Detectors
- Tomorrow: Complications and Future Directions
- Note : much material taken from Franklin (last year ' s school), Vossebeld (European school)

Who ordered that?!

- First of the so called “2nd generation” of particles discovered in cosmic rays
- Measured the mass by velocity and curvature measurement in a cloud chamber
- Appeared not to shower and not have strong interactions



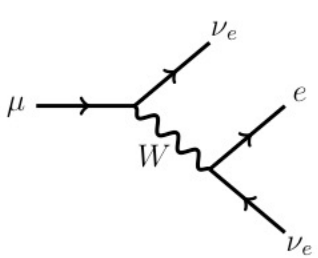


Require coincidence timing of the first two layers of scintillators and a veto on the third and then look for decay of Stopped muon as more scintillation light microseconds later

$$m = \frac{qBr}{v}$$

Overview of the Muon

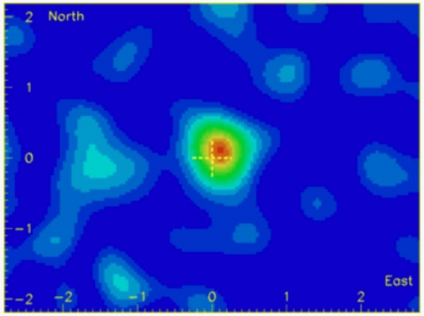
- Lepton like electron , but heavier
- Unstable, decays in a couple of microseconds in its rest frame, decays via weak process
- Interacts mainly through electromagnetic interaction with material



$$\tau = \frac{1}{\Gamma}$$

$$\Gamma \propto \frac{m_\mu^4}{M_W^4} m_\mu c^2$$

Muon

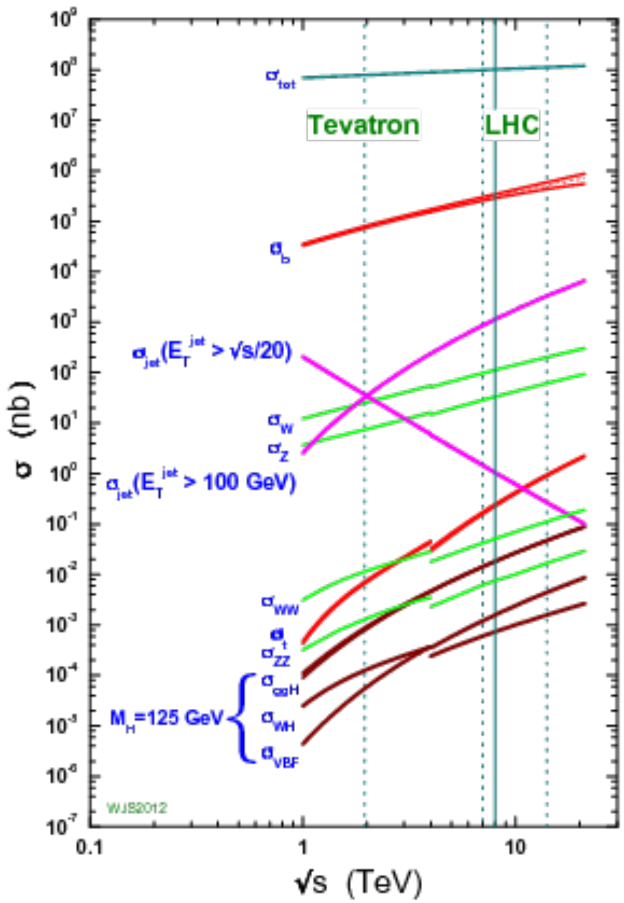


The Moon's cosmic ray shadow, as seen in secondary muons generated by cosmic rays in the atmosphere, and detected 700 meters below ground, at the Soudan II detector

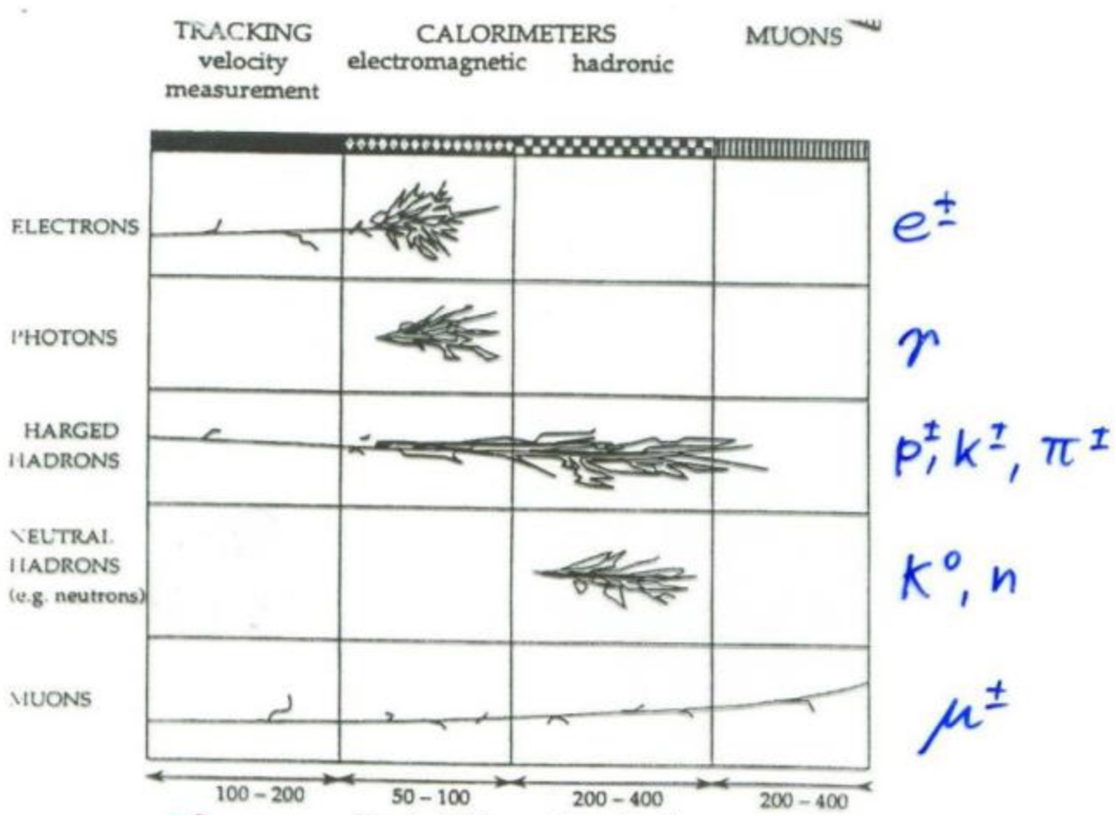
Composition	Elementary particle
Statistics	Fermionic
Generation	Second
Interactions	Gravity, Electromagnetic, Weak
Symbol	μ^-
Antiparticle	Antimuon (μ^+)
Discovered	Carl D. Anderson, Seth Neddermeyer (1936)
Mass	105.658 3755(23) MeV/c^2[1] 0.113 428 9259(25) Da[1]
Mean lifetime	2.196 9811(22) × 10^{-6} s[2][3]
Decays into	e^-, $\bar{\nu}_e$, ν_μ[3] (most common)
Electric charge	−1 *e*
Color charge	None
Spin	$\frac{1}{2}$

Why is muon detection important in hadron collider physics

- Protons are a collection of quarks and gluons held together by the strong force
- There are a large number of collisions that produce events with hadrons in the final state – in particular dijet and multijet events
- Events with high Pt isolated leptons are signs of electroweak processes from W, Z, Higgs, and maybe other decays and indicate relatively rare processes that have occurred!



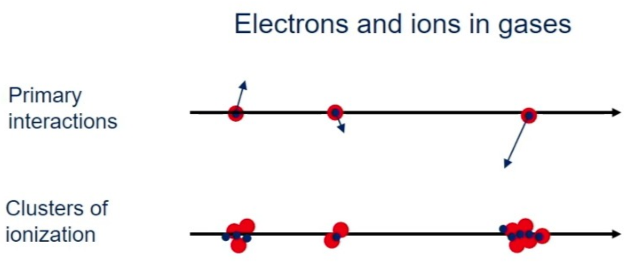
How does the muon interact?

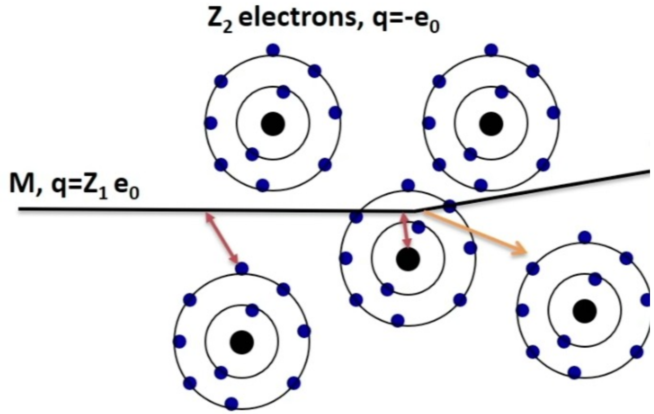


Loses energy through coulomb interaction ionizing the material it goes through

Occasionally will impart enough Energy to produce a 'delta ray' Electron which gets enough energy to create its own track

Muons primarily ionize material along the path they travel





Can lead to primary and then
Secondary ionization as primary
Electrons interact with neighboring
Atoms in the material

Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

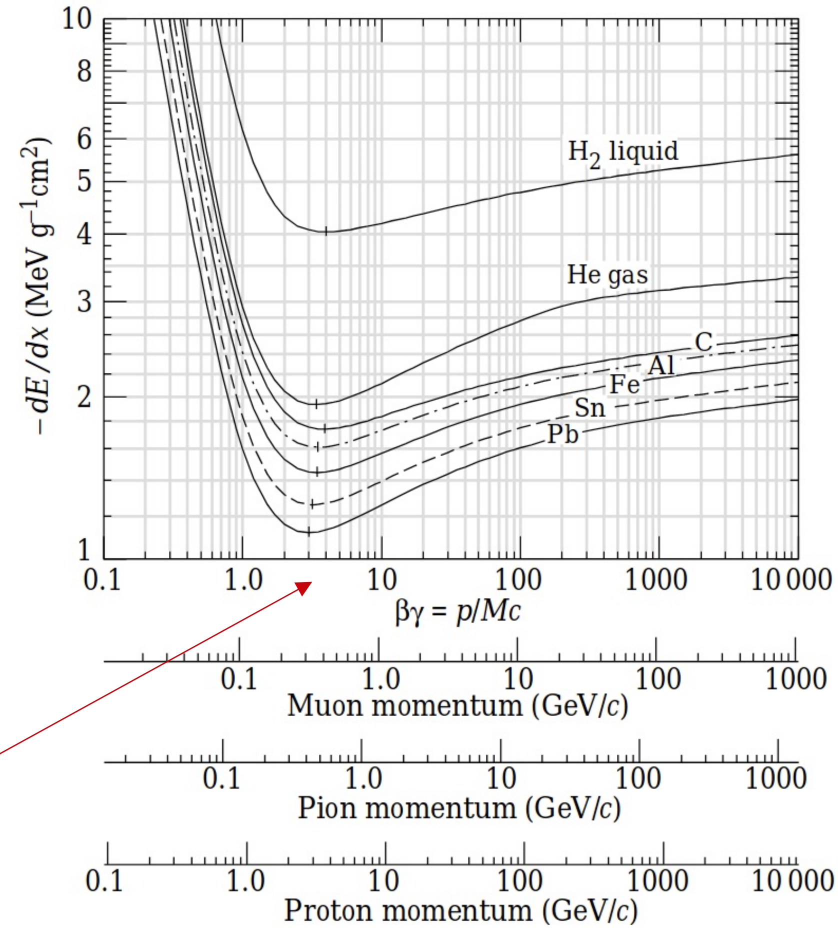
Bethe-Bloch Calculation for energy loss

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right],$$

with

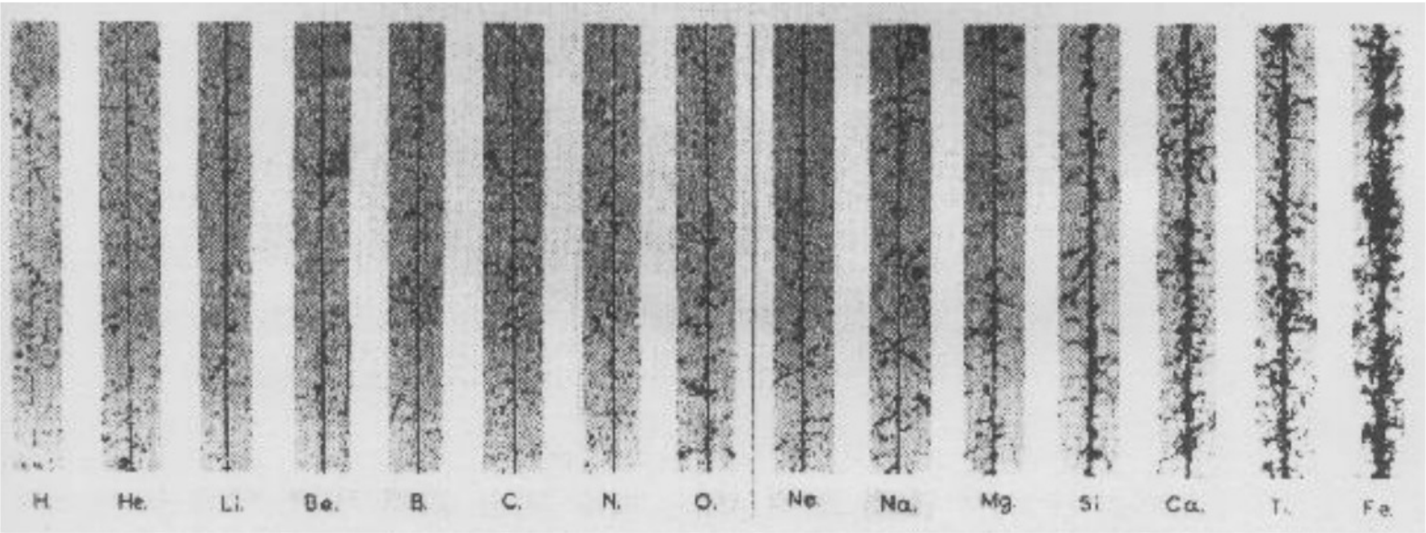
$$2\pi N_a r_e^2 m_e c^2 = 0.1535 \text{ MeVcm}^2/\text{g}$$

r_e: classical electron radius $= 2.817 \times 10^{-13}$ cm
m_e: electron mass
N_a: Avogadro's number $= 6.022 \times 10^{23}$ mol^{-1}
I: mean excitation potential
Z: atomic number of absorbing material
A: atomic weight of absorbing material
ρ: density of absorbing material
z: charge of incident particle in units of e
$\beta = v/c$ of the incident particle
$\gamma = 1/\sqrt{1-\beta^2}$
δ: density correction
C: shell correction
W_{max}: maximum energy transfer in a single collision.



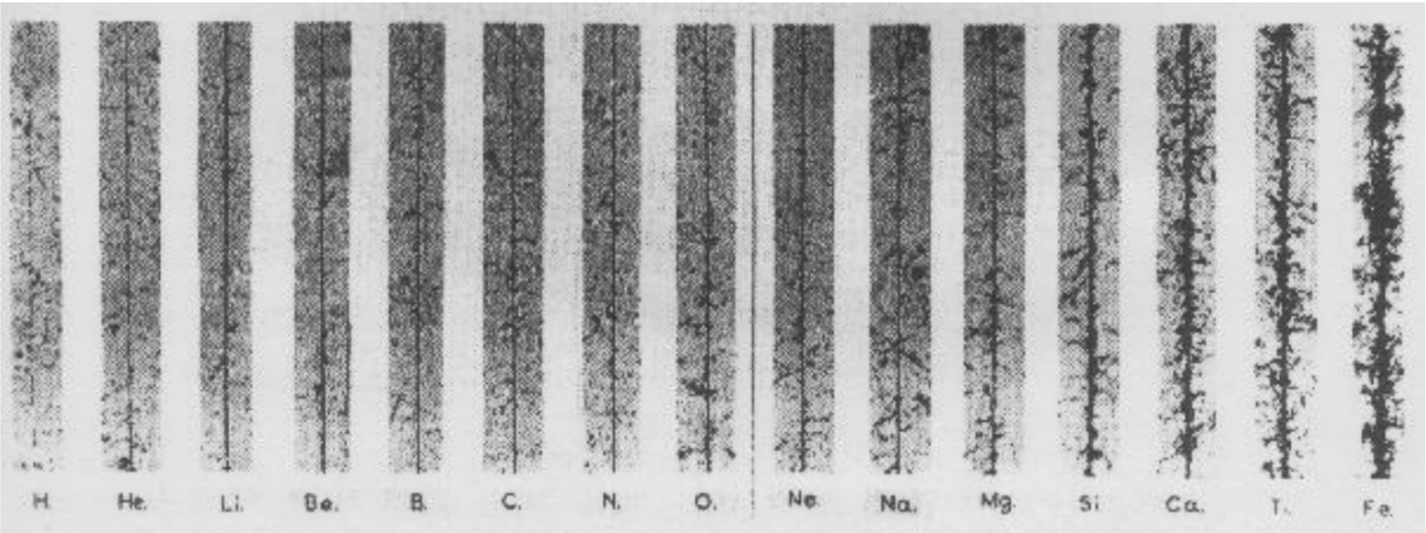
Note: there is a minimum of around
2-3 GeV which logarithmically grows with energy
Known as "minimum ionizing particles"

Some interesting facts



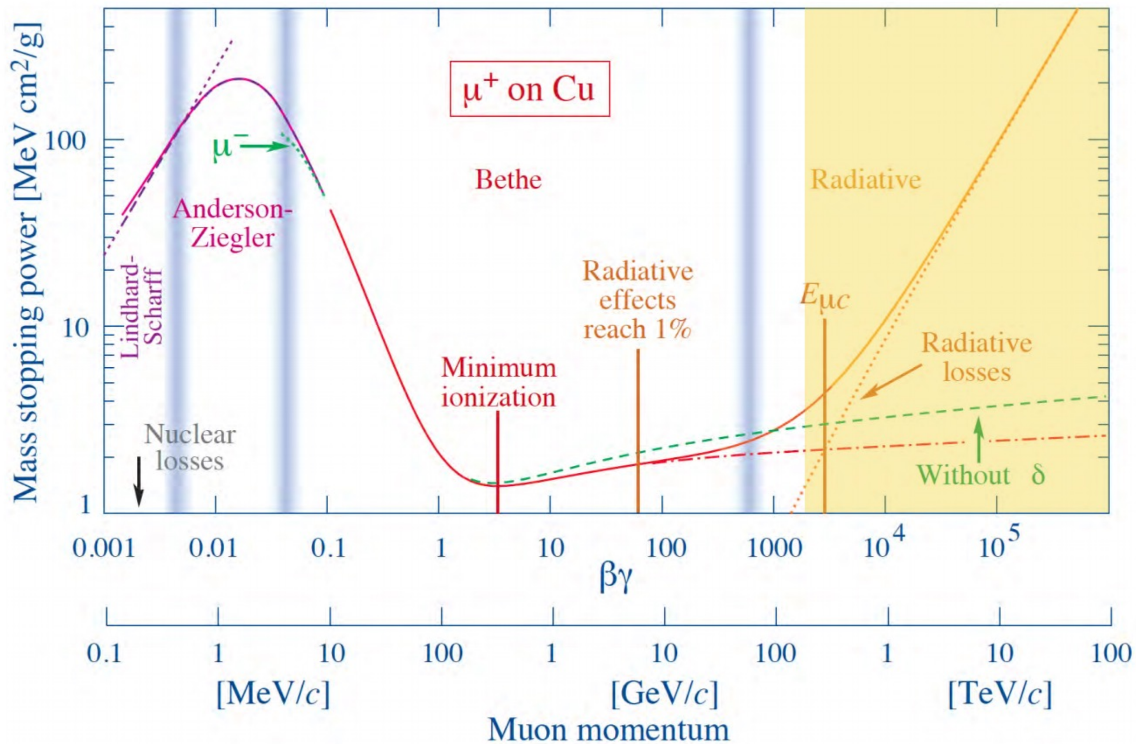
- Energy deposit depends on the square of the charge of the particle transversing the detector

Some interesting facts



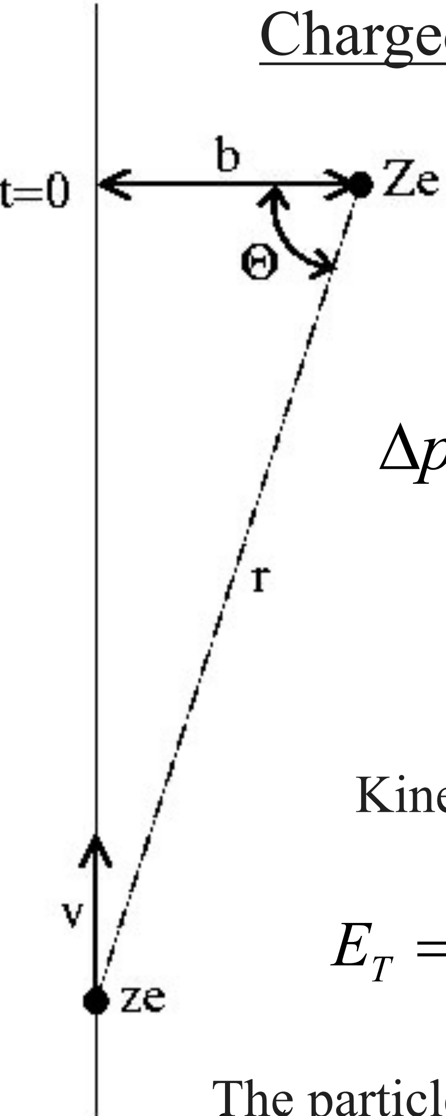
- Energy deposit depends on the square of the charge of the particle transversing the detector
- However, since Z/A is very similar for many material it has only a slight dependence on materials for most materials

Muons on Copper



From 100s of MeV to 1 TeV the most important mechanism is Ionization through close to minimum. At very high energies radiative Loss begins to dominate and eventually muons shower

Charged particles in matter :



$$\tan\theta = \frac{vt}{b}$$

$$t = \frac{b}{v}\tan\theta$$

$$\frac{\mathrm{d}t}{\mathrm{d}\theta} = \frac{b}{v\cos^2\theta}$$

$$F_\perp = \frac{Zze^2}{4\pi\varepsilon_0 r^2}\cos\theta = \frac{Zze^2}{4\pi\varepsilon_0 b^2}\cos^3\theta$$

$$\Delta p = \int_{-\infty}^{\infty} F_\perp \mathrm{d}t = \frac{Zze^2}{4\pi\varepsilon_0 b^2}\int_{-\pi/2}^{\pi/2}\cos^3\theta \frac{b}{v\cos^2\theta}\mathrm{d}\theta = \frac{Zze^2}{2\pi\varepsilon_0 bv}$$

Or (in relativistic notation): $\Delta p = \frac{Zze^2}{2\pi\varepsilon_0 b\beta c}$

Kinetic energy transferred to target:

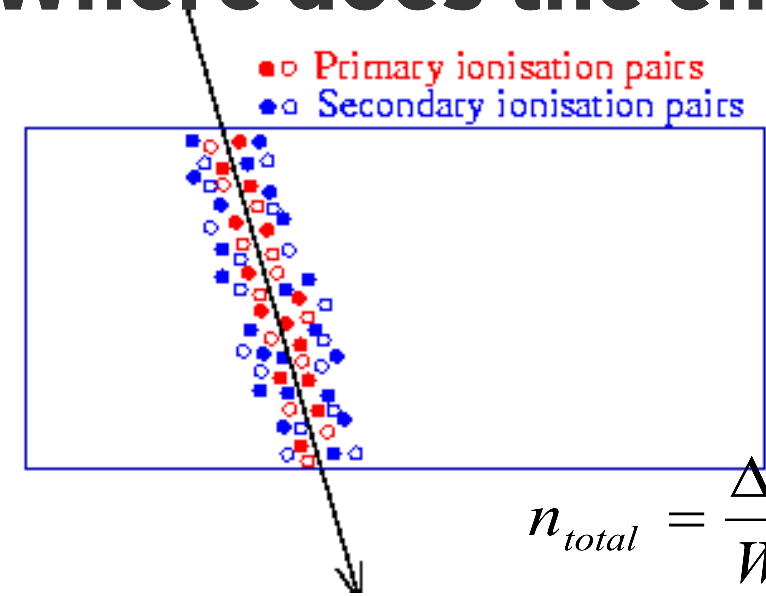
$$E_T = \frac{(\Delta p)^2}{2m_T} = \frac{Z^2z^2e^4}{2m_T(2\pi\varepsilon_0)^2 b^2\beta^2c^2} \propto \frac{Z^2}{m_T}$$

The particle encounters both nuclei and electrons:

$$\frac{E_\mathrm{N}}{E_\mathrm{e}} = \frac{Z^2/(Am_\mathrm{p})}{Z\,1/m_\mathrm{e}} = \frac{Z}{A}\frac{m_\mathrm{e}}{m_\mathrm{p}} \approx \frac{1}{2}\frac{m_\mathrm{e}}{m_\mathrm{p}} \approx 3\times10^{-4}$$

Most energy is lost to electrons!

Where does the energy go?



Ionisation produces electron/ion pairs.

Primary electrons have enough energy to cause secondary ionisation.

$$n_{total} = \frac{\Delta E}{W_i} \left(= \frac{\text{total energy loss}}{\text{effective energy loss per pair}} \right)$$

Gas	Z	A	δ (g/cm³)	E_{ex}	E_i (eV)	I_0 (eV)	W_i	dE/dx (MeV/g cm⁻²)	dE/dx (keV/cm)	n_p (i.p./cm) a)	n_T (i.p./cm) a)
H_2	2	2	8.38×10^{-5}	10.8	15.9	15.4	37	4.03	0.34	5.2	9.2
He	2	4	1.66×10^{-4}	19.8	24.5	24.6	41	1.94	0.32	5.9	7.8
N_2	14	28	1.17×10^{-3}	8.1	16.7	15.5	35	1.68	1.96	(10)	56
O_2	16	32	1.33×10^{-3}	7.9	12.8	12.2	31	1.69	2.26	22	73
Ne	10	20.2	8.39×10^{-4}	16.6	21.5	21.6	36	1.68	1.41	12	39
Ar	18	39.9	1.66×10^{-3}	11.6	15.7	15.8	26	1.47	2.44	29.4	94
Kr	36	83.8	3.49×10^{-3}	10.0	13.9	14.0	24	1.32	4.60	(22)	192
Xe	54	131.3	5.49×10^{-3}	8.4	12.1	12.1	22	1.23	6.76	44	307
CO_2	22	44	1.86×10^{-3}	5.2	13.7	13.7	33	1.62	3.01	(34)	91
CH_4	10	16	6.70×10^{-4}		15.2	13.1	28	2.21	1.48	16	53
C_4H_{10}	34	58	2.42×10^{-3}		10.6	10.8	23	1.86	4.50	(46)	195

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In general we get ~100 pairs/cm

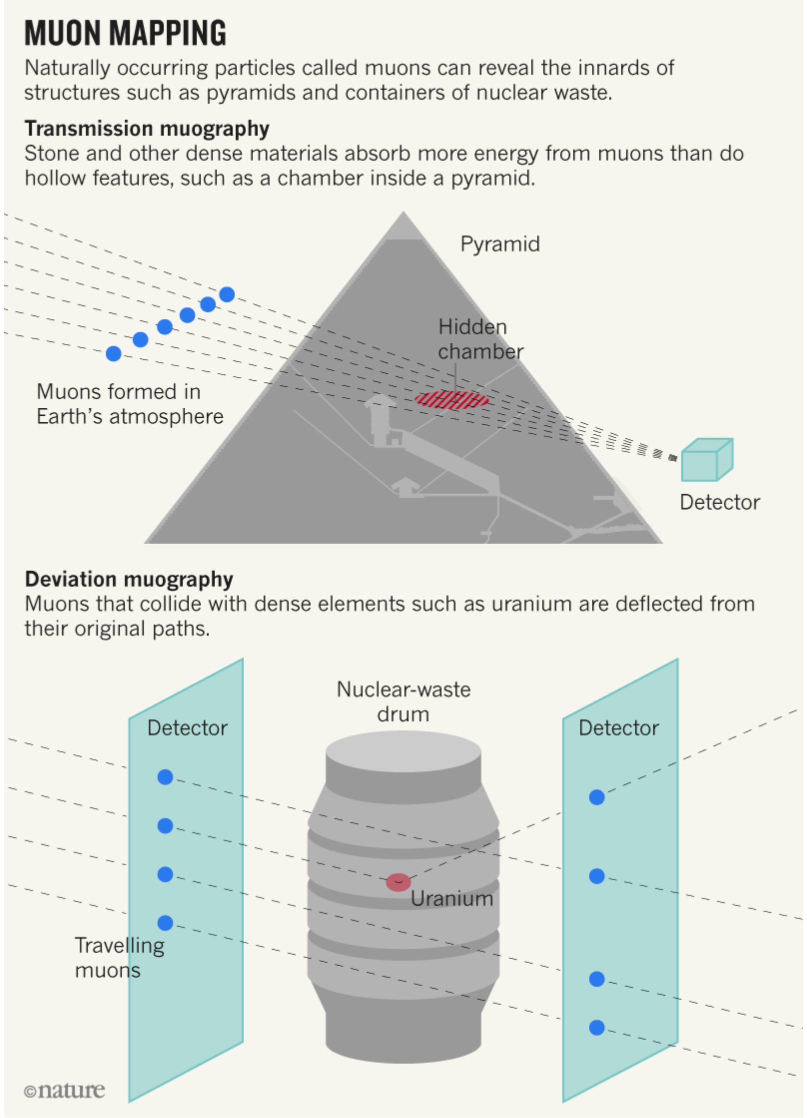
ΔE (for a mip)

Some numbers

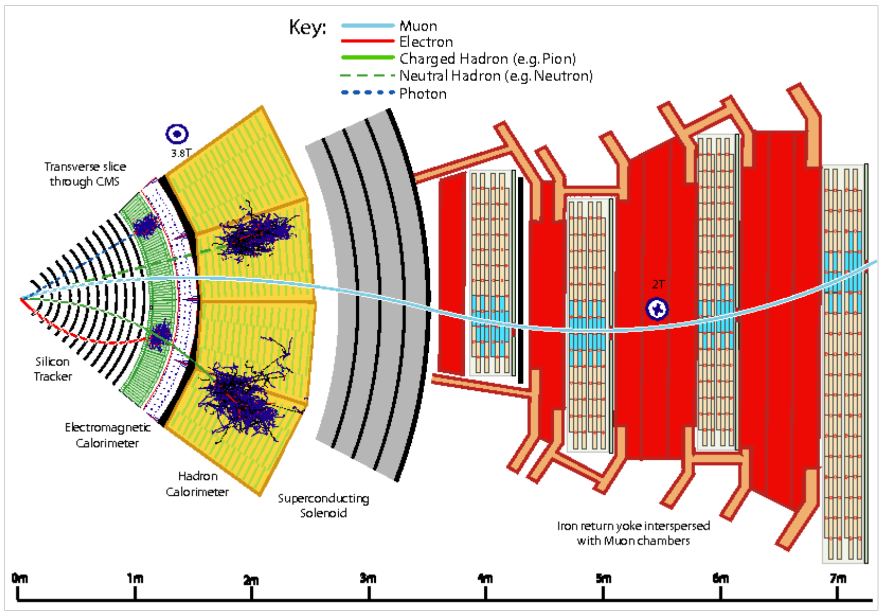
Imagine a MIP muon traversing 1 meter of Fe Z ~0.5A From the plot : a MIP (βɣ~3) deposits dE/dx ~ 1.4 MeV cm^2/gm But ***ρ***= 7.87g/cm^3 so dE/dx = 11 MeV/cm So energy lost over a meter is dE = 1101MeV So a 1 GeV muon can traverse 1 meter of steel of steel!

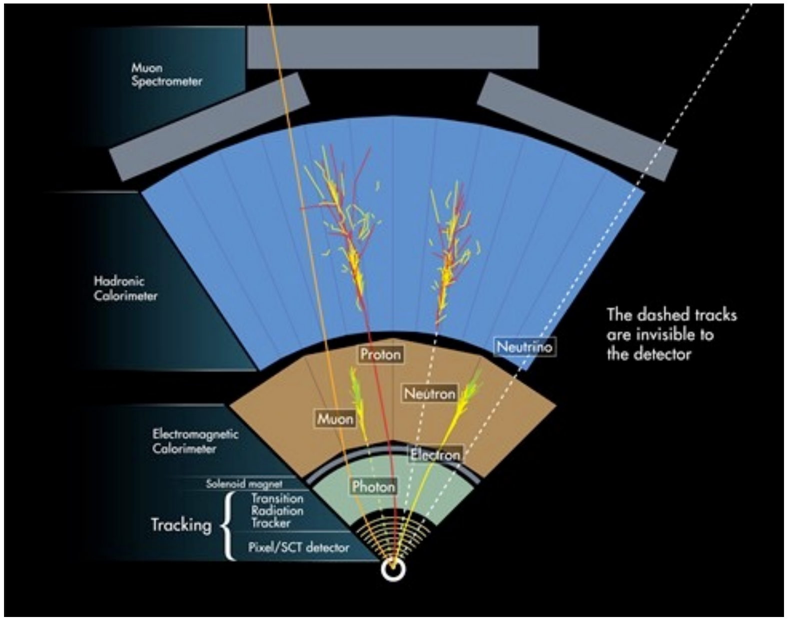
10 GeV – approximately 10 meters and so on

- Most muons produced at the EW scale, LHC, or other modern colliders expected to escape the detector leaving a trail of ionization in the material along the way!



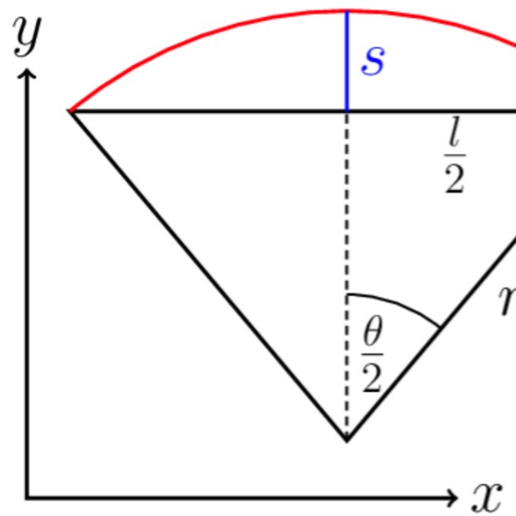
Implications for detector design





- In LHC/Tevatron detectors most particles are contained within the calorimeters. Neutrinos and muons escape. Since muons are charged tracking detectors that can cover the large area/volumes can detect muons with high efficiency and high purity.
- However, need detectors that are cost effective due to the large space they need to instrument

Implications for detector design



- Track Muon and measure the curvature in a B field
- Can be identified by leaving a track in the inner detector and a separate tracking volume outside the volume of the detector

$$p = qrB$$

$$p(\frac{GeV}{c}) = 0.3R(m)B(T)$$

$$L = r\theta$$

$$s = r(1 - cos(\frac{\theta}{2})) \approx \frac{r\theta^2}{8} = \frac{L^2}{8r}$$

$$r = \frac{L^2}{8s}$$

$$\frac{\Delta p}{p} = \frac{\Delta s}{s} = \frac{\sigma_x}{\sqrt{N}} \frac{8p}{9(0.3)L^2 B}$$

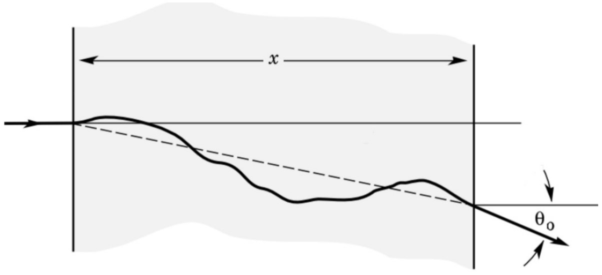
Resolution Formula assuming no material effects

- % resolution
  - Worsens with momentum!
  - Improves with the square of the size of the tracker
  - Improves linearly with the B field
  - Improves with the sqrt(number of measurements)
  - Scales linearity of single measurement resolution
- However
  - Cost must be taken into consideration (Large Volumes and high B fields cost $$)
  - Formula ignores material effects and multiple scattering

$$\frac{\Delta p}{p} = \frac{\Delta s}{s} = \frac{\sigma_x}{\sqrt{N}} \frac{8p}{9(0.3)L^2 B}$$

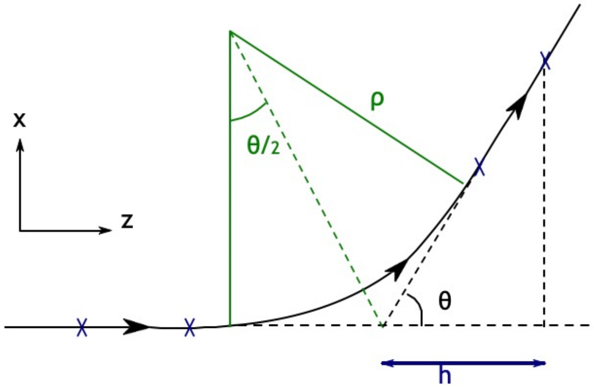
Other contributions to resolution: multiple scattering

- In a real detector, the presence of material means that the detector will have multiple coulomb interactions as the particle traverses the detector
- Interactions with multiple detectors will cause the particle to change angle slightly and statically scatter



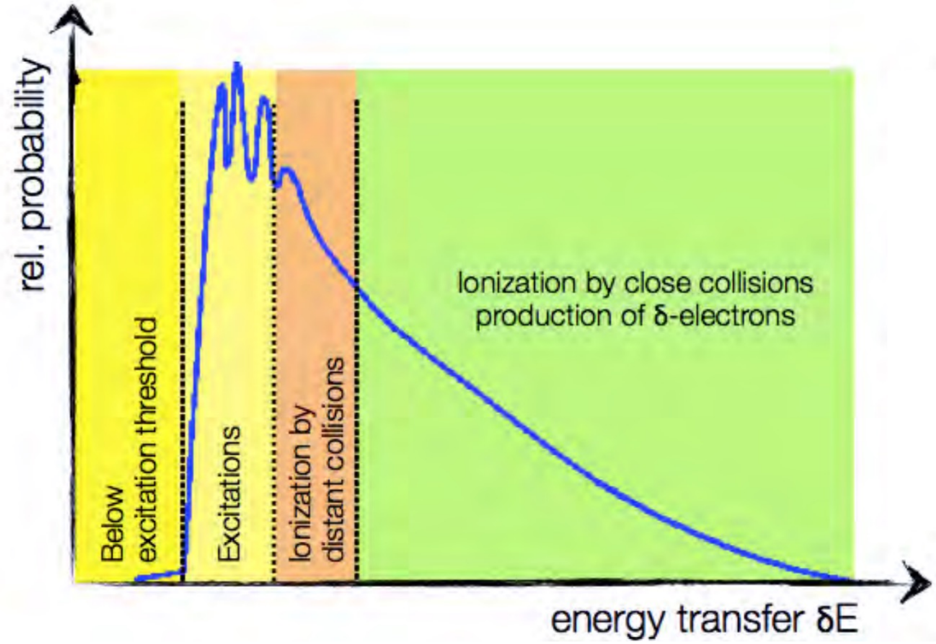
$$\Theta_0 = \frac{0.0136}{\beta c p[\mathrm{GeV/c}]} Z_1 \sqrt{\frac{x}{X_0}}$$

$$(\frac{\Delta p}{p})_{MS} = \frac{\Theta_0}{\Theta} \approx \frac{0.04}{\beta L B}\sqrt{\frac{L}{X_0}}$$



Energy Loss Fluctuations

- When the particle scatters, it also transfers energy to atoms/electrons it scatters off of.
- How much energy is transferred is a statistical process
- So for the same curvature measurement in the tracker could correspond to slightly different momentum incident particles
- Of particular importance to lower energy muons



Examples from existing detectors

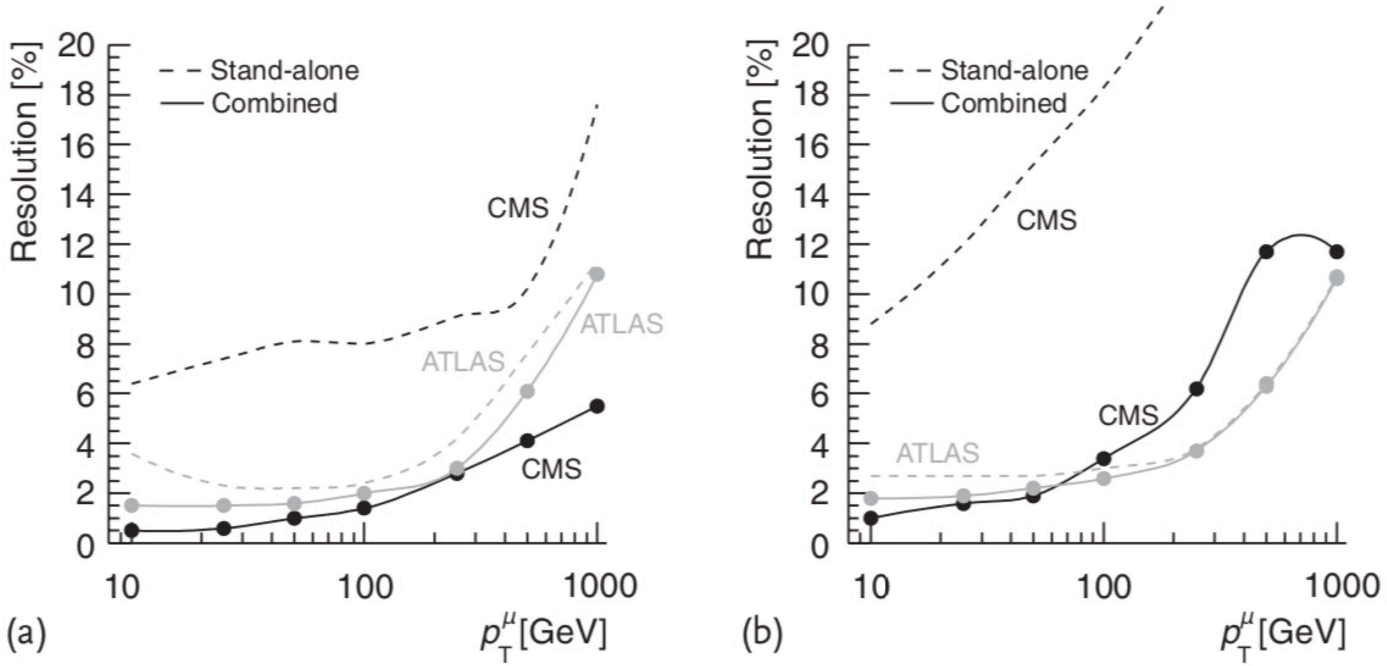
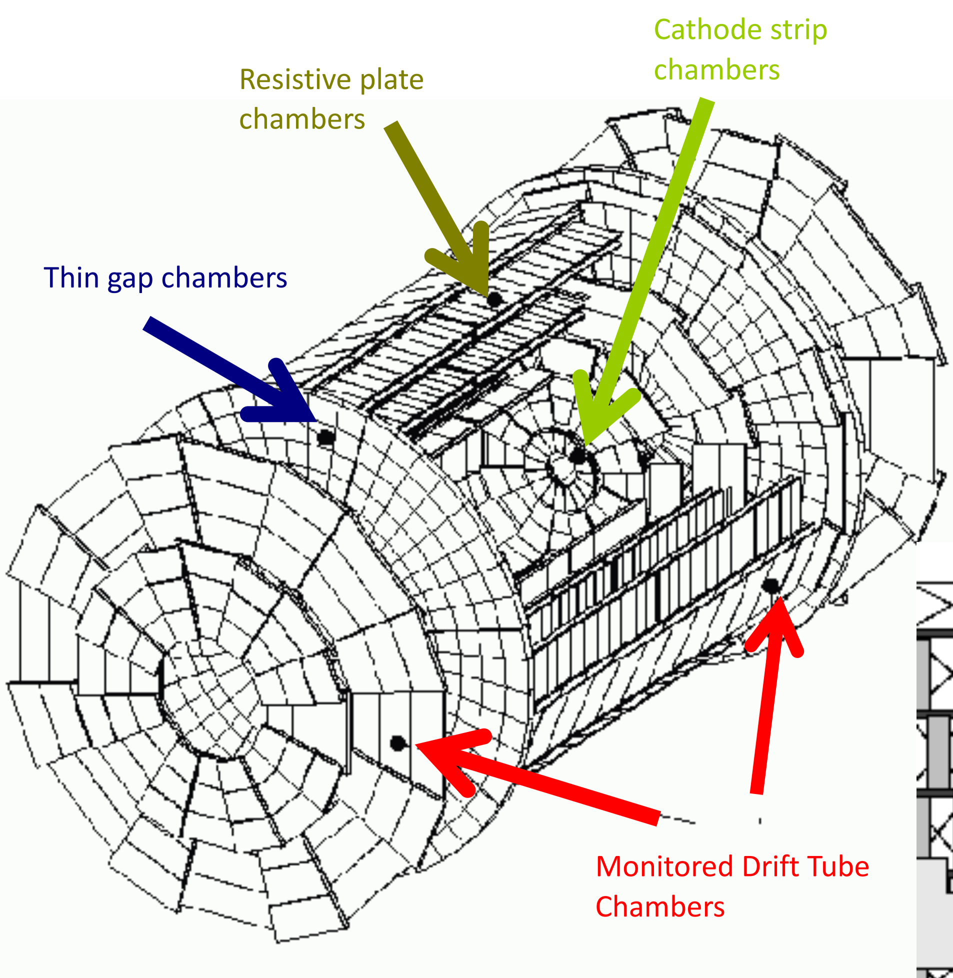
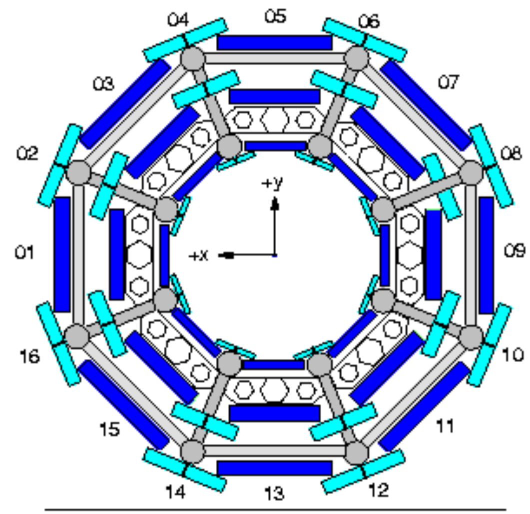
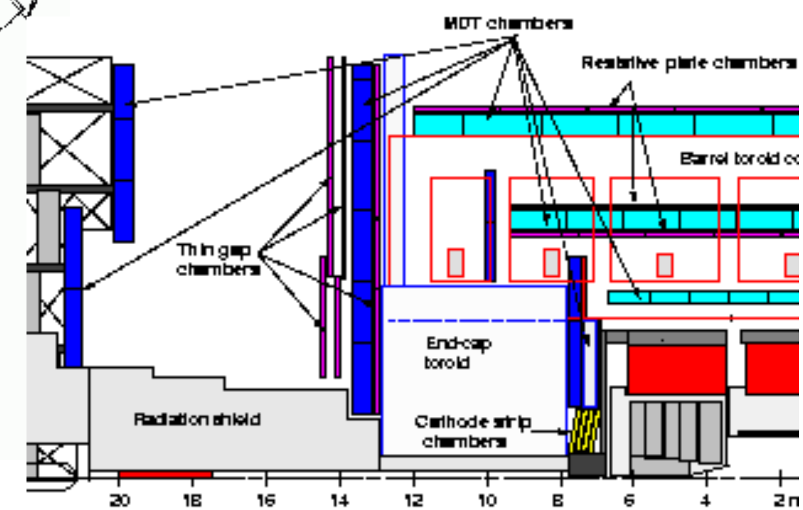


Figure 16.4 Momentum resolution of the ATLAS and CMS detectors after combining the momentum measurements of the inner (a) momentum resolution for muons in the barrel region; (b) momentum resolution for muons in the endcap region.

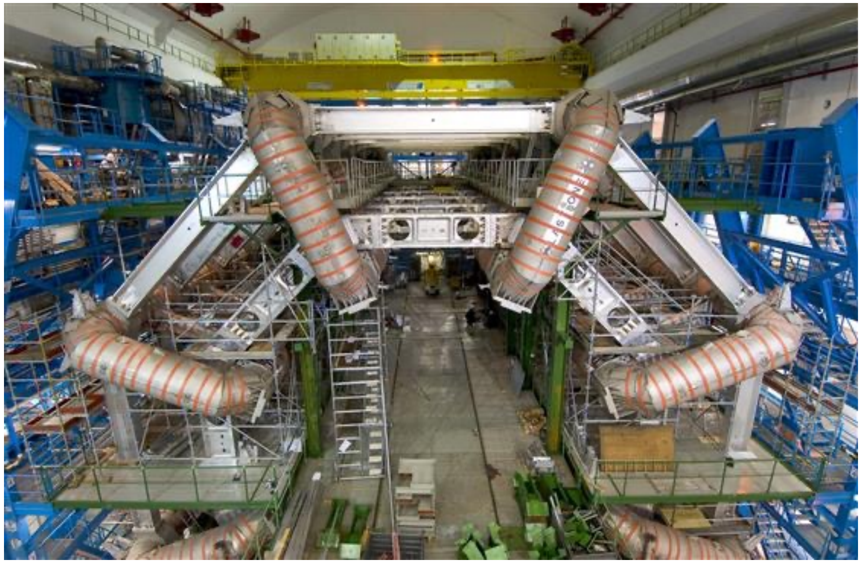
ATLAS muon spectrometer (run1/2)



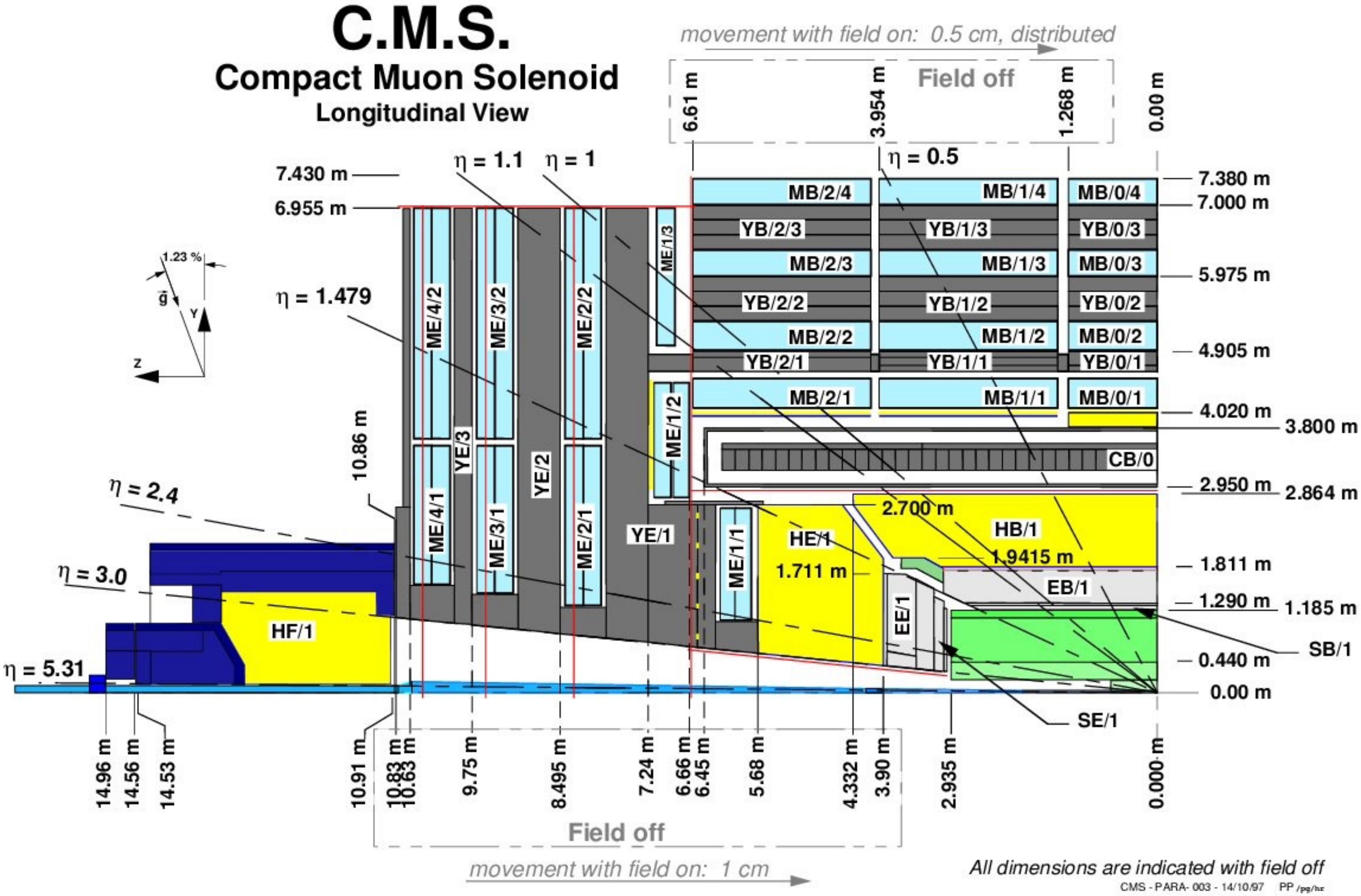




ATLAS Magnets



CMS Muon Spectrometer



CMS Magnet

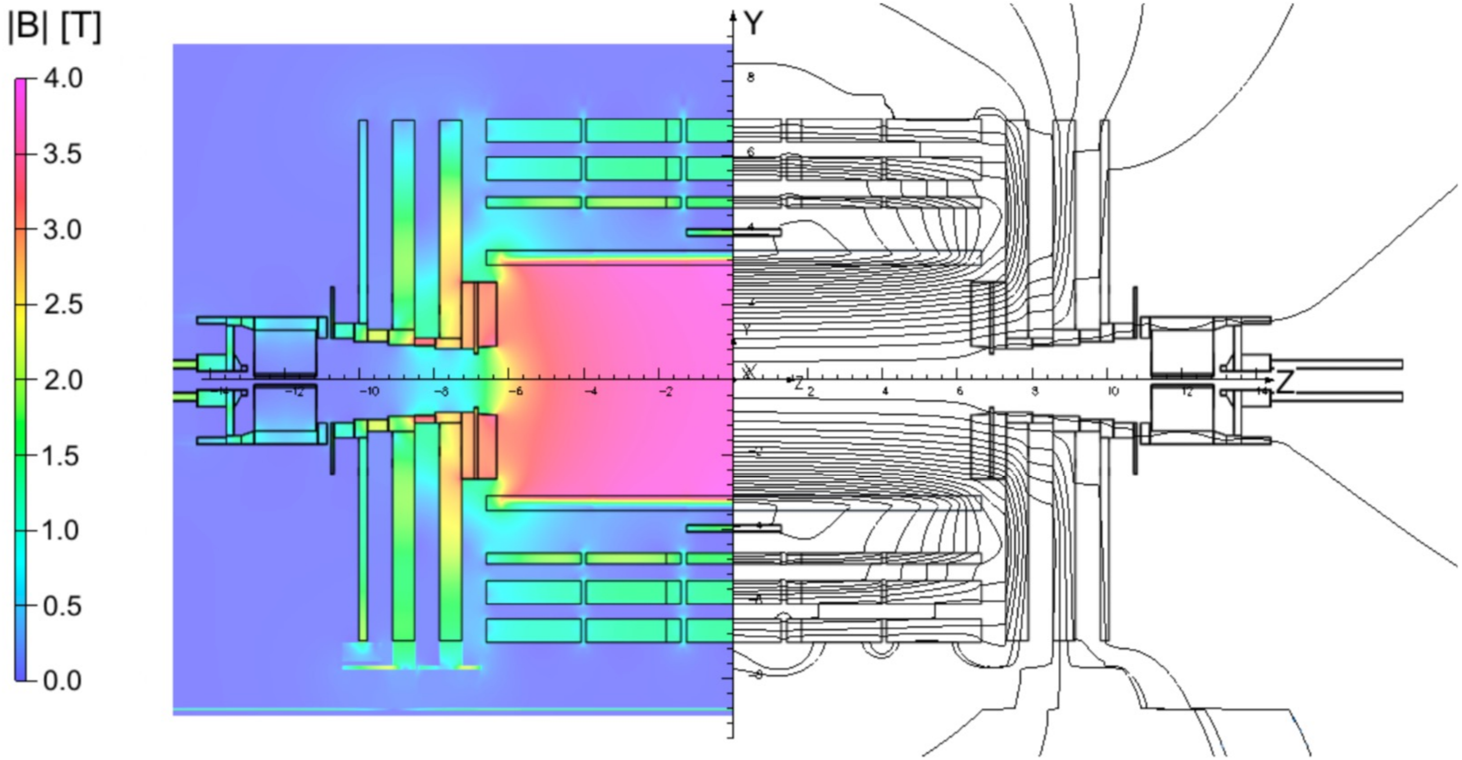


Figure 5: Value of $|B|$ (left) and field lines (right) predicted on a longitudinal section of the CMS detector, for the underground model at a central magnetic flux density of 3.8 T. Each field line represents a magnetic flux increment of 6 Wb.

Key Features

- Magnetic Field to Bend Charged Particles
  - CMS – strong central solenoid only return flux in muon spectrometer
  - ATLAS – smaller central solenoid but 3 toroids in the muon spectrometer
- 3 or 4 stations that make several measurements of the muon position
- Reconstruct a track in the muon spectrometer and also and inner detector
- Large Volume to instrument as the muon spectrometer is outside the calorimeter

Classical Charged Particle Detection in a gas volume

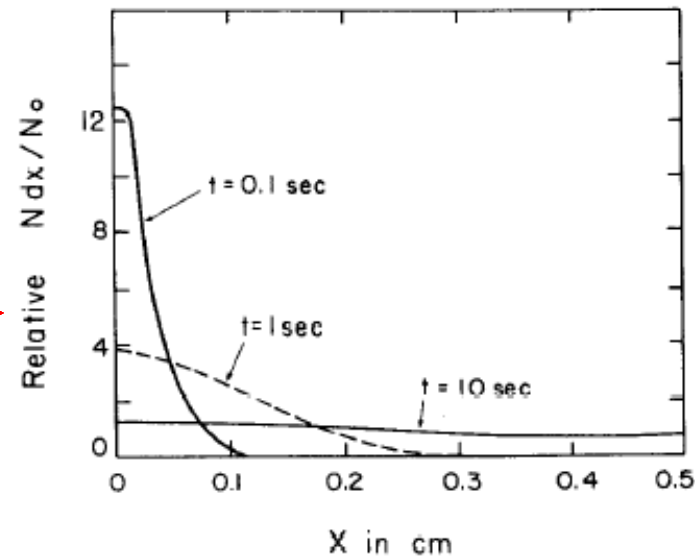
Diffusion: in the absence of an electric field charged particles move randomly loosing their energy quickly by multiple collisions with gas-molecules.

Ions:

$$\frac{\mathrm{d}N}{\mathrm{dx}}(t) = N \frac{1}{\sqrt{4\pi Dt}} \exp\left(-x^2/4Dt\right)$$

Gaussian distribution : $\sigma_x(t) = \sqrt{2Dt}$

D : diffusion coefficient



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Ion diffusion coefficient

Gas	λ (cm)	u (cm/sec)	D^+ (cm²/sec)	μ^+ (cm² sec⁻¹ V⁻¹)
H_2	1.8×10^{-5}	2×10^5	0.34	13.0
He	2.8×10^{-5}	1.4×10^5	0.26	10.2
Ar	1.0×10^{-5}	4.4×10^4	0.04	1.7
O_2	1.0×10^{-5}	5.0×10^4	0.06	2.2
H_2O	1.0×10^{-5}	7.1×10^4	0.02	0.7

Electrons: diffusion is much faster as they have a longer mean free path.

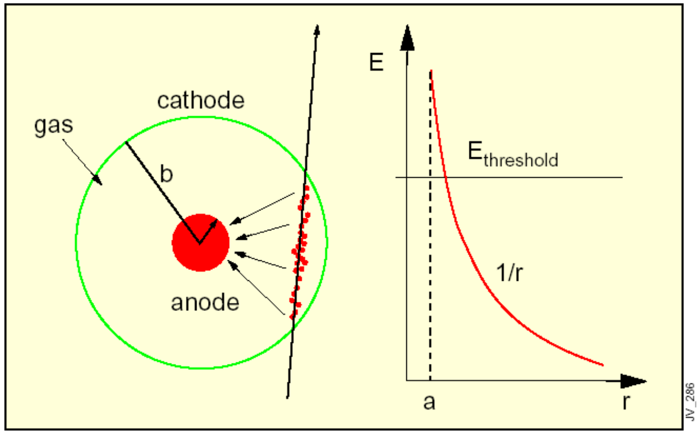
How to detect e/ion pairs produced by a charged particle?

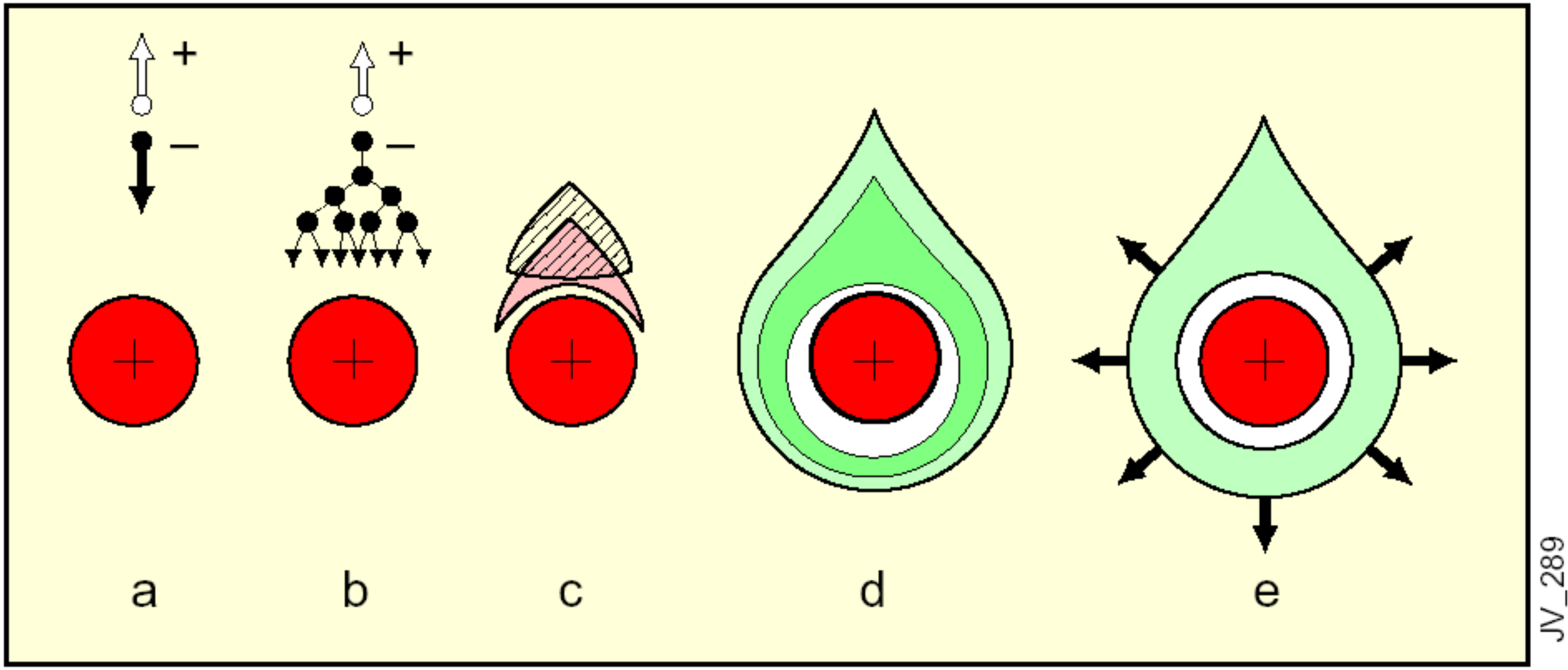
In E-field electrons(ions) drift to anode(cathode)

But, 100 e/ion pairs do not constitute measurable signal
(noise electronic amplifier typically ~1000 electrons or more).

In a strong E- field ($E > E_{threshold}$) electrons can obtain enough energy to cause further ionisation, thus producing an avalanche of e/ion pairs. (***gas amplification***)

Simple particle detector: Gas filled tube with anode wire in the centre. (Using a very thin anode wire is an easy way to achieve a high field.)





a) Electrons(ions) drift towards anode(cathode)

b) Gas avalanche produces more e/ion pairs

c) Ion cloud reduces field and stops avalanche

d,e) Electrons readout on anode, ions drift to cathode.

Behaviour of gaseous detectors depends strongly on the field strength.

I) very low field: partial (or no) charge collection.

II) *Ionisation mode*: charge collection but no amplification

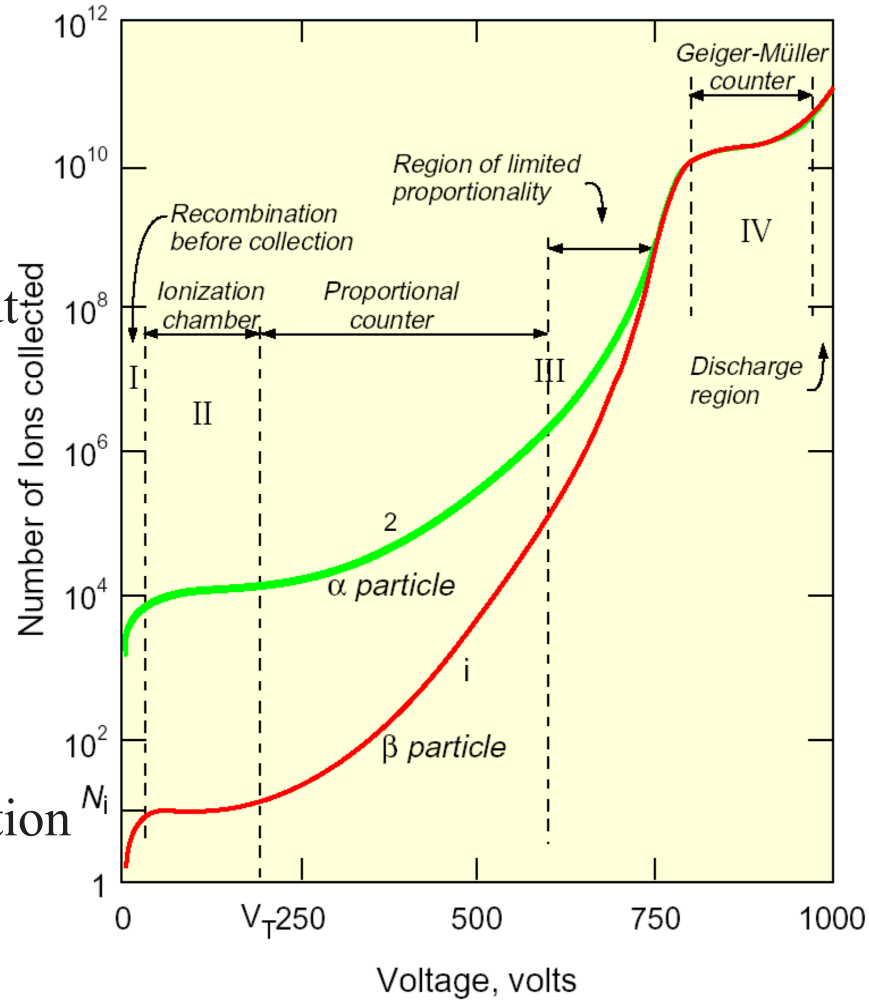
III) *Proportional mode*:

proportional charge amplification.

Gain highly dependent on V!

Streamer mode: proportionality lost by distortion *E*-field by space-charge.

IV) *Geiger or saturated mode*: full ionisation of the gas volume (photo-emission). only stopped by interruption of HV



The choice of gas(-mixture)

The requirements:

- High specific ionisation
- Gas amplification at low working voltage and good proportionality
- High voltage before saturation (high gain achievable)
- High rate capability (fast charge drift & fast recovery) and long lifetime (of detector)

Noble gases:

- Few non-ionising energy loss modes $\Rightarrow$ avalanche multiplication at low V
- Heavy gases (Ar, Xe, Kr) $\Rightarrow$ high specific ionisation
- Excited Ar emits 11.6eV photons $\Rightarrow$ free electrons at cathode $\Rightarrow$ new showers $\Rightarrow$ permanent discharge

Poly-atomic gases:

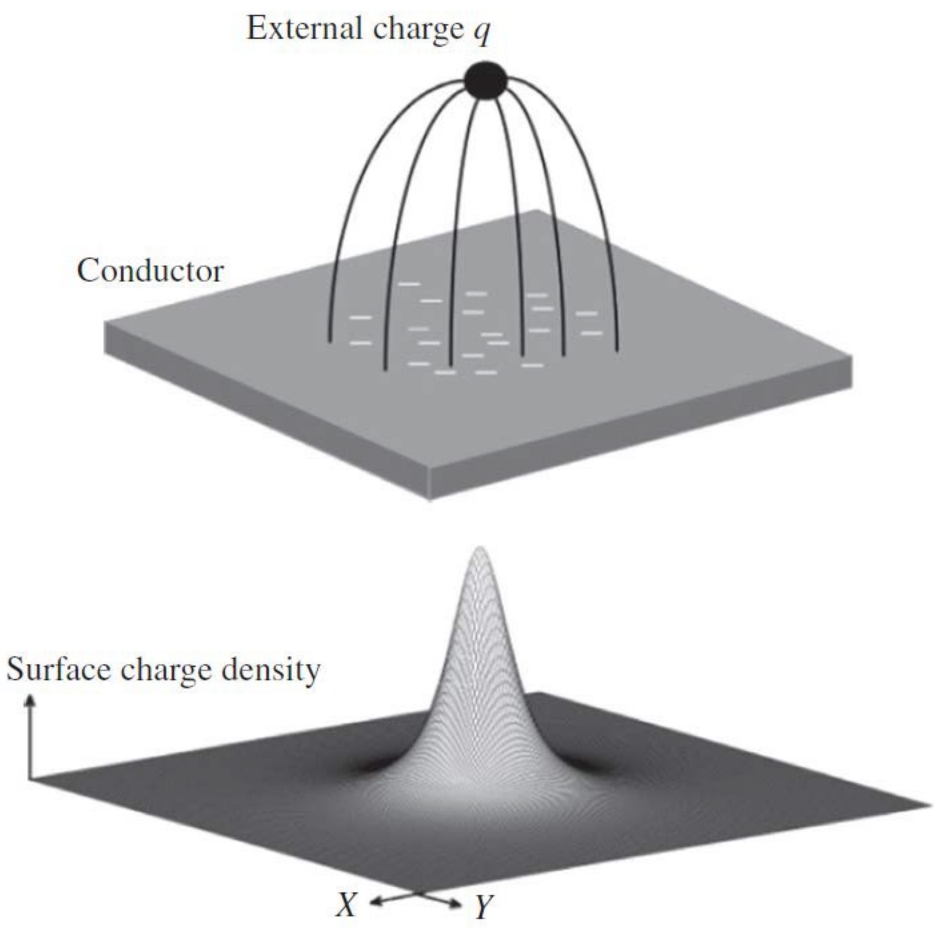
- Many non-ionising states $\Rightarrow$ effective absorption of γ's. (photon-quenching)

  e.g. Methane effectively absorbs γ's 7.9-14.5 eV.

  Organic gases: Methane, CO^{2}, BF^{3}, freons, isobutane ($C^{4}H^{10}$)
- Small admixture of photon-quencher prevents permanent discharge in e.g Ar!
- Absorbed energy is released in break-up/inelastic collisions $\Rightarrow$ formation of radicals $\Rightarrow$ damage detector materials or leave solid or liquid organic deposits on anode or cathode
- In a high rate environment gas may get fully quenched $\Rightarrow$ Gas must be circulated!

  Needed anyway to control gas mixture and because most detectors leak!

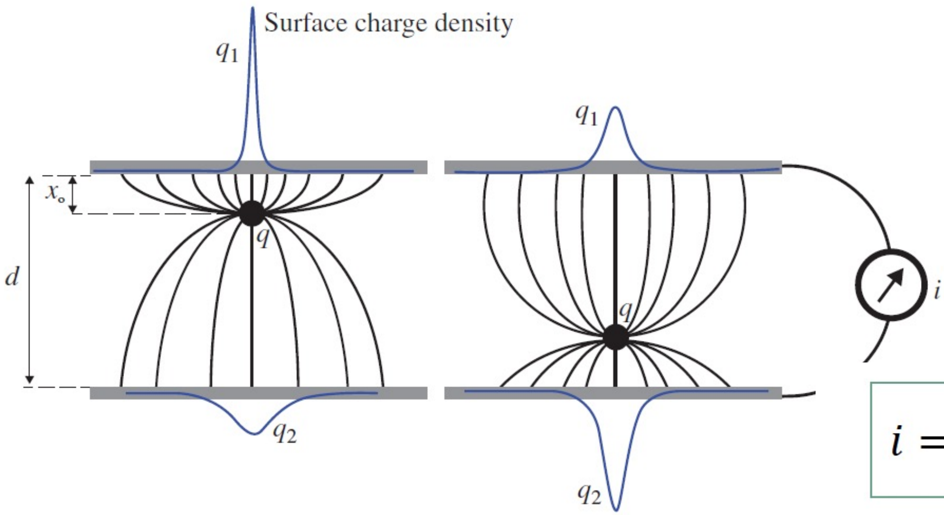
How the signal is seen



- We often talk about "charge collection"
- More accurately, the charge is attracted to oppositely charged conductor and as it moves toward the conductor it induces a charge on the surface of the conductor
- This induced charge forms a current which can be measured and is the signal that we measure

Expected current generated

- Consider a simple parallel plate setup a distance d apart



$$i = \frac{qv}{d}$$

Currents Induced by Electron Motion*

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Summary—*A method is given for computing the instantaneous current induced in neighboring conductors by a given specified motion of electrons. The method is based on the repeated use of a simple equation giving the current due to a single electron's movement and is believed to be simpler than methods previously described.*

Introduction

In designing vacuum tubes in which electron transit-time is relatively long, it becomes necessary to discard the low-frequency concept that the instantaneous current taken by any electrode is proportional to the number of electrons received by it per second. Negative grids, it is known, may carry current even though they collect no electrons and current may be noted in the circuit of a collector during the time the electron is still approaching the collector. A proper concept of current to an electrode must consider the instantaneous change of electrostatic flux lines which end on the electrode and the methods given in the literature for computing induced current due to electron flow are based on this concept.

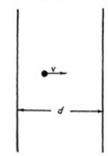

Fig. 1

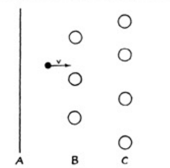

Fig. 2

A method of computing the induced current for a specified electron motion is here explained which is believed to be more direct and simpler than methods previously described. In the more difficult cases, in which flux plots or other tedious field-determination methods must be used, only one field plot is needed by the present method while the usual methods require a large number.

Method of Computation

The method is based on the following equation, whose derivation is given later:

$$i = E_v e v \quad (1)$$

where i is the instantaneous current received by the given electrode due to a single electron's motion, e is the charge on the electron, v is its instantaneous velocity, and E_v is the component in the direction v of that electric field which would exist at the electron's instantaneous position under the following circumstances: electron removed, given electrode raised to unit potential, all other conductors grounded. The equation involves the usual assumptions that induced currents due to magnetic effects are negligible and that the electrostatic field propagates instantaneously.

Simple Example

A simple example is offered in the computation of the instantaneous current due to an electron's motion between two infinite plates (Fig. 1). (The result is a starting point for the analysis of a diode, for example, when the transit-time is long.)

From (1) we obtain immediately

$$i = evE_v = \frac{ev}{d}\cdot$$

In the literature[1] it is stated that this same result is deduced from image theory. This involves the setting up of an infinite series of image charges on each side of the plates for a given position of the electron and a consideration of the total flux crossing one of the planes due to the series of charges, a method which is lengthy and requires no little familiarity with methods of handling infinite series.

The General Case

Consider a number of electrodes, A, B, C, D, in the presence of a moving electron (Fig. 2) whose path and instantaneous velocity are known. A tedious way to find the current induced in, say, electrode

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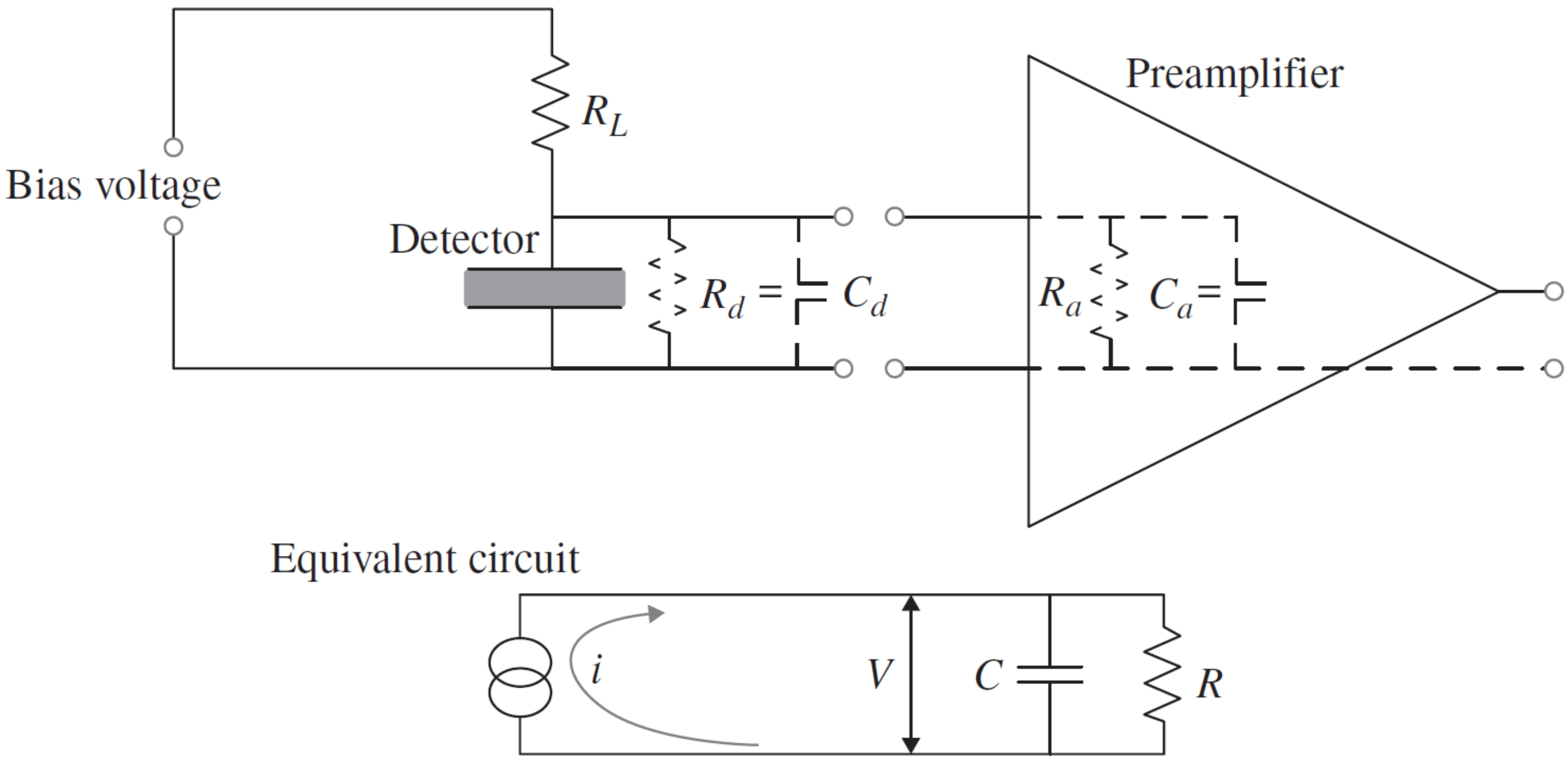
[1] D. O. North, "Analysis of the effects of space charge on grid impedance," Proc. I.R.E., vol. 24, pp. 108–158; February, (1936).

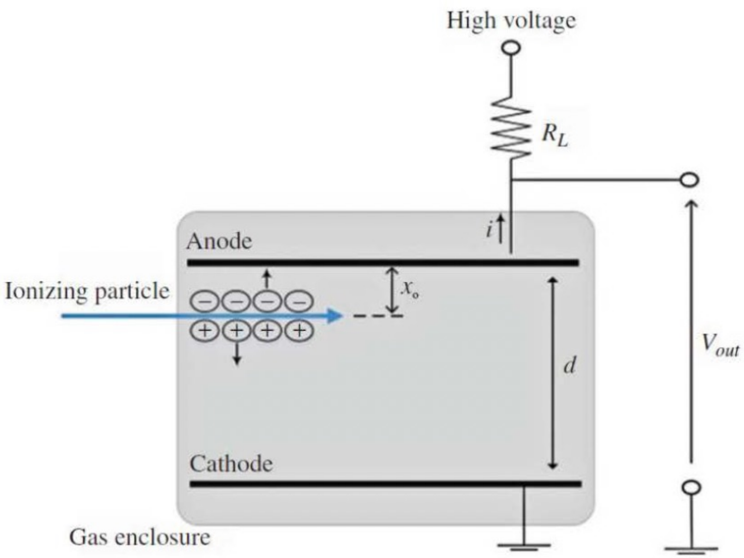
Energy conservation

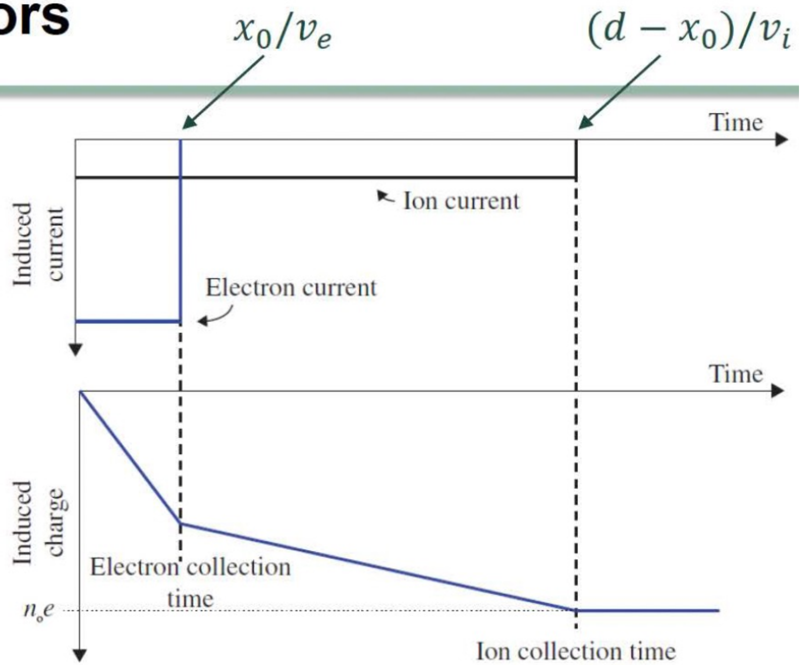
$$qE \cdot dx = Vi \cdot dt \quad \Rightarrow \quad i = \frac{qEdx}{Vdt} = \frac{qv}{d}$$

Needs to be connected to a pre-amplifier



Pulses from ionization detectors





$$i(t) = i_e(t) + i_i(t) = \frac{n_0 e v_e}{d} + \frac{n_0 e v_i}{d}$$

$$v_e = \mu_e E = \frac{e}{m_e \nu_m} E \sim 10^4 \text{ m/s}$$

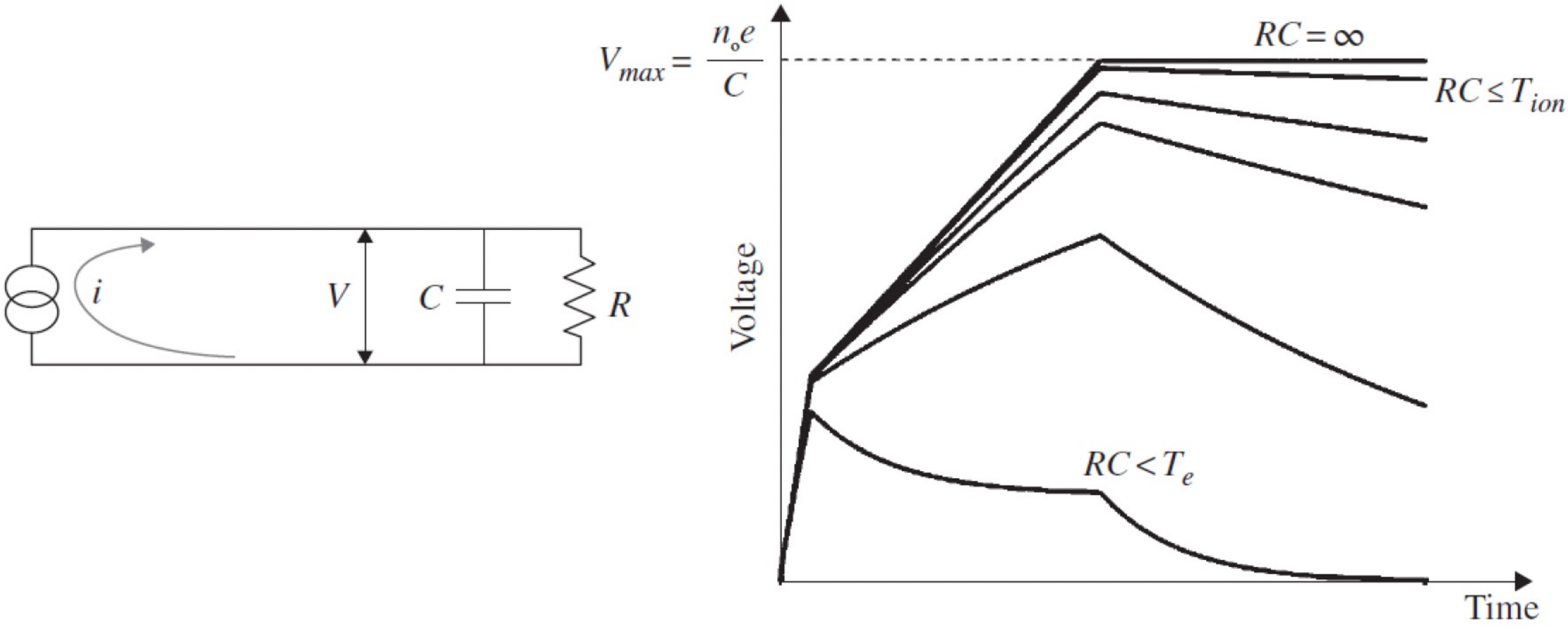
$$v_i \ll v_e$$

$$Q(t) = \int (i_e + i_i) dt = \frac{n_0 e}{d}(v_e + v_i)t \qquad \text{for} \quad 0 \leq t \leq x_0/v_e$$

$$Q(t) = \frac{n_0 e}{d} x_0 + \frac{n_0 e}{d} v_i t \qquad \text{for} \quad x_0/v_e \leq t \leq (d - x_0)/v_i$$

Output voltage pulse for different circuit time constants

- When the detector is connected to the measuring circuit, the equivalent input resistance, R, and capacitance, C, are obtained by combining all the resistors and capacitances at the input of the measuring circuit.
- The shape of a voltage pulse is a function of the time constant of the detector circuits.



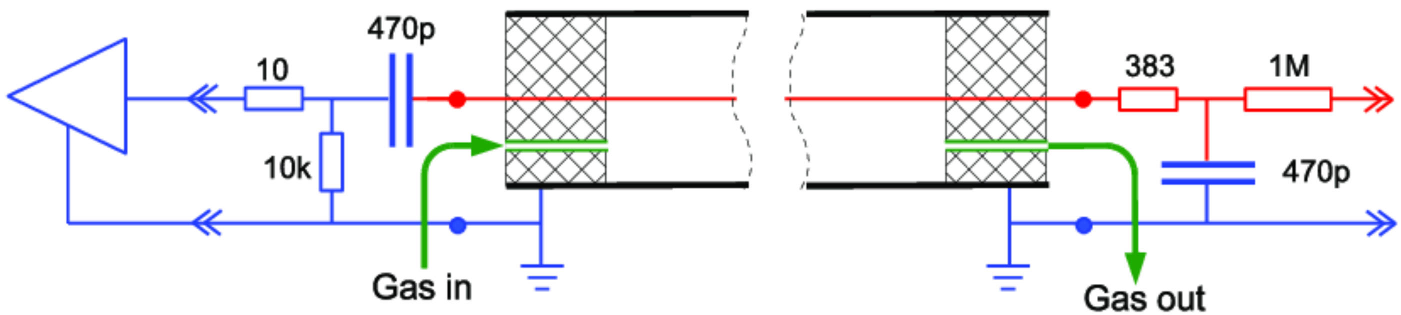
An actual example: ATLAS drift tube

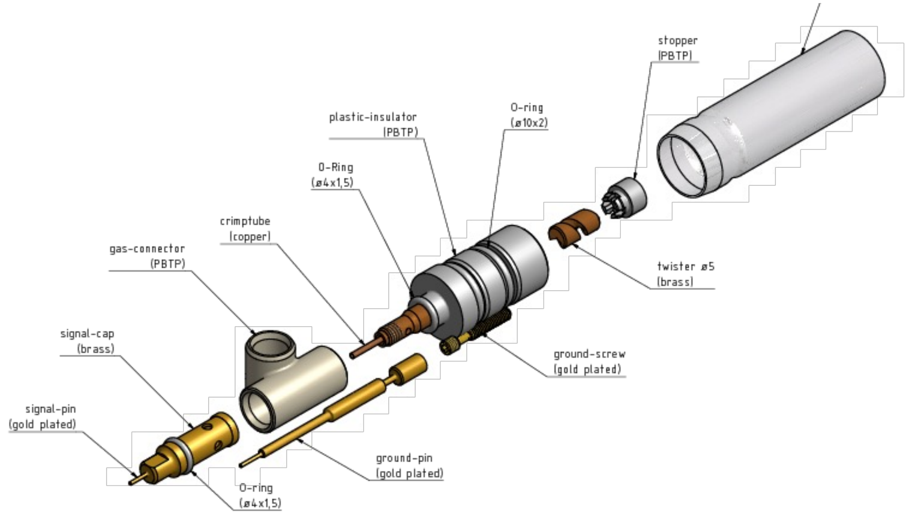
Mezzanine board

Signal hedgehog board

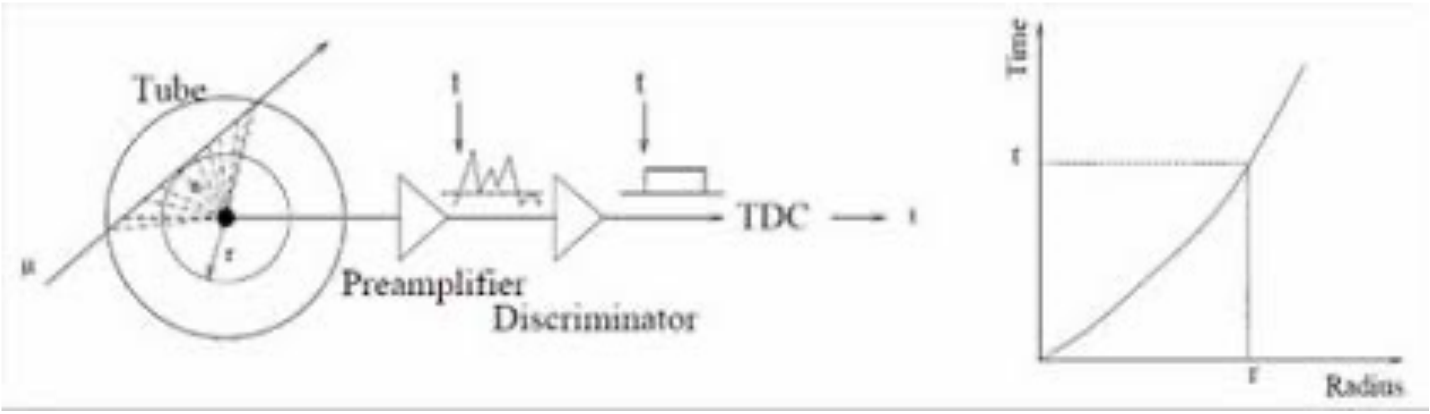
MDT tube with endplugs (schematic)

High-voltage hedgehog board



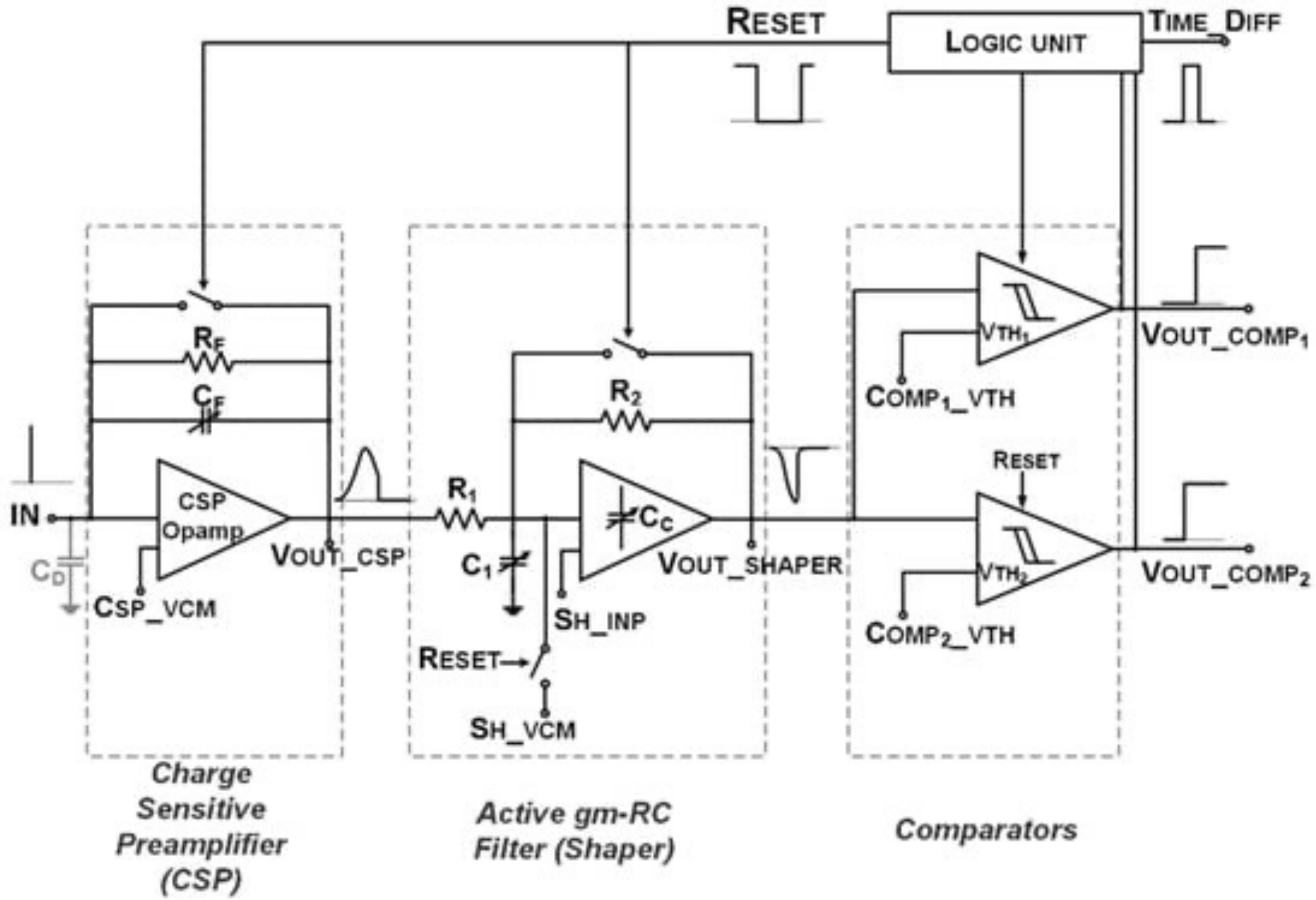


Conceptual Readout



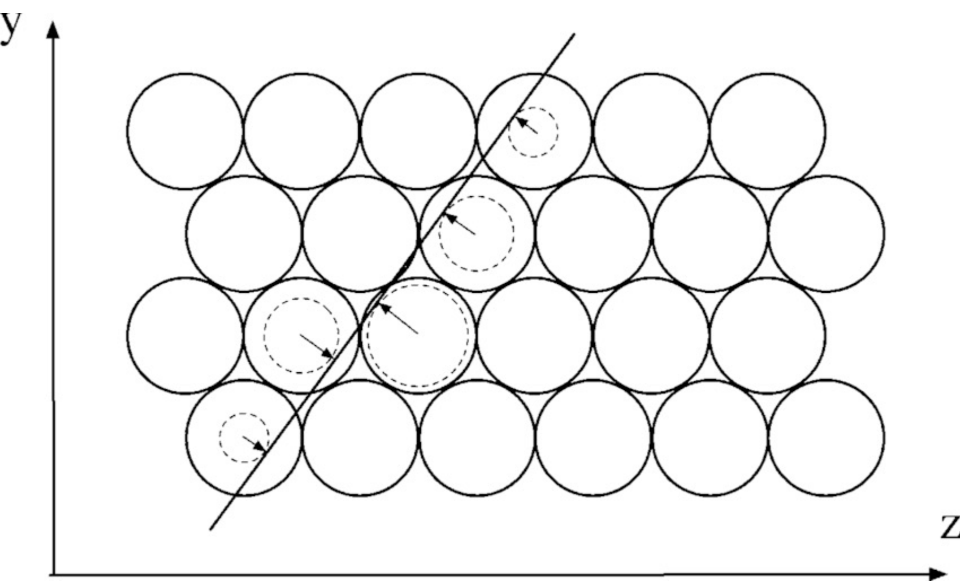
- Amplify the signal induced on the wire
- Look for a signal above a given noise threshold
- Using a reference time from the LHC/trigger measure the time it took for the signal to get to the wire
- Knowing the r(t) relationship calculate how far the signal was from the wire

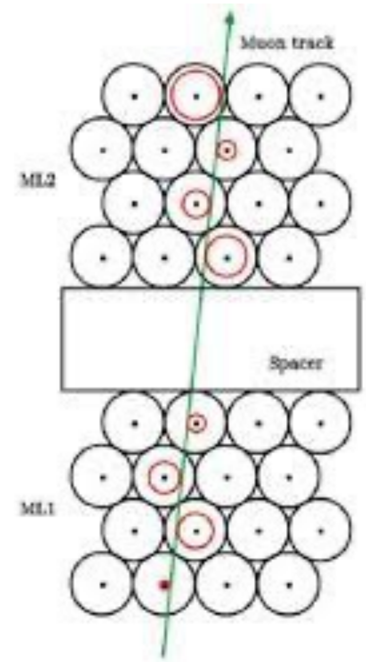
High Level Diagram of actual electronics



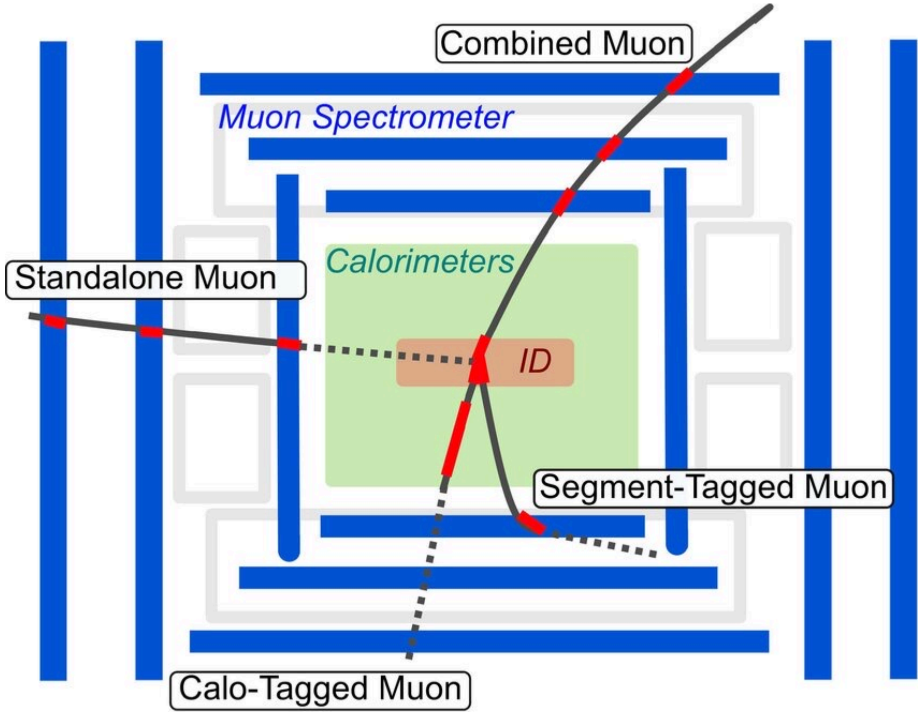
From signals to segments

- Arrange Drift tubes together in stations
- From the hits from the detector reconstruct where the muon passed through and its trajectory



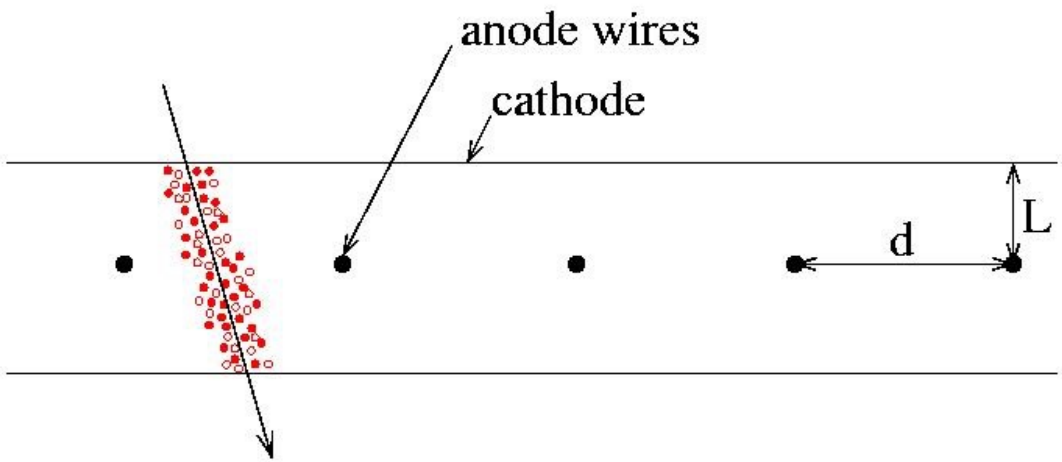


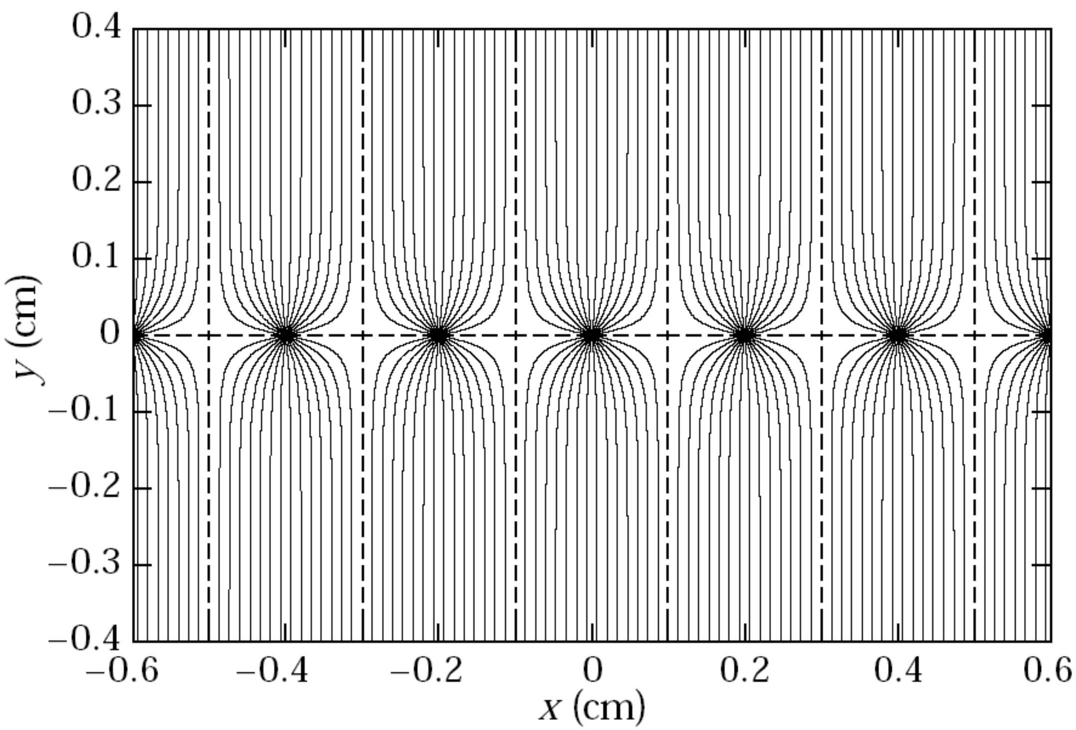
Reconstruct Tracks



- Find segments that point together and point to the interaction region
- Combined with ID track
- Fit all hits together to find best estimate of muon track parameters

Charpak et al. (1968) ⇒ Nobel prize 1992

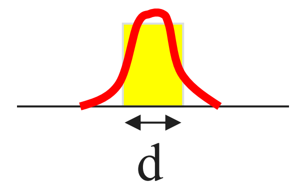




MWPC: Multiwire proportional chamber

Electrons/ions drift along field lines.
Ions ⇒ cathode
Electrons ⇒ nearest anode wire!

If all charge collected on 1 wire, resolution along x determined by wire spacing (pitch): $\sigma_x = \frac{d}{\sqrt{12}}$

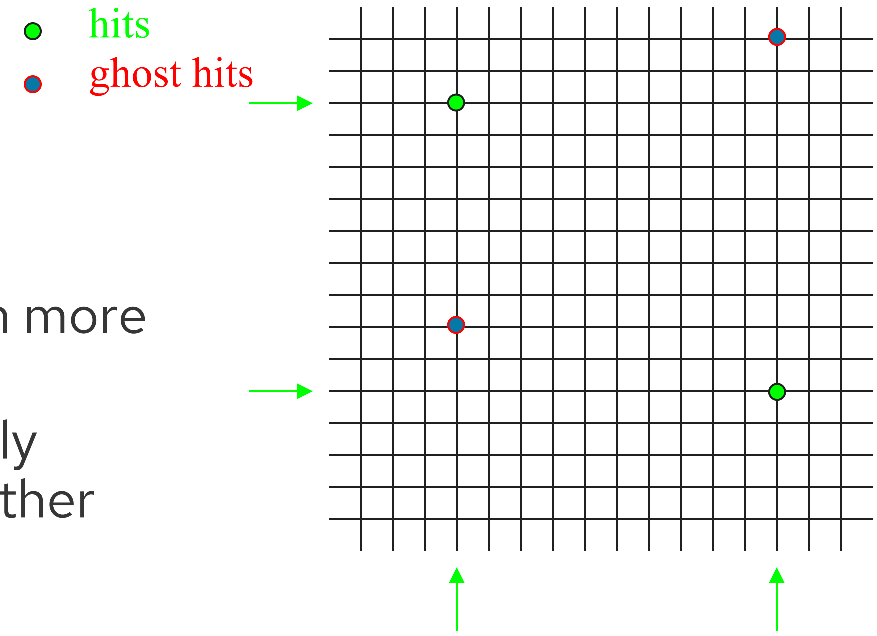
(Gaussian width: )

Charge sharing ⇒ better resolution.

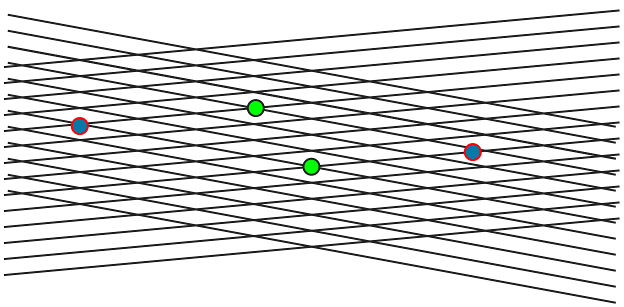
Original worry: Capacitive coupling between wires largely compensated by positive charge in avalanches.

Only sensitive *x*-coordinate.

Y- coordinate: idea #1



- Crossed wire planes:
  - Perpendicular (ghost hits when more than 1 particle**!)**
  - Stereo-angle (few degrees) only ghosts from hits near to each other



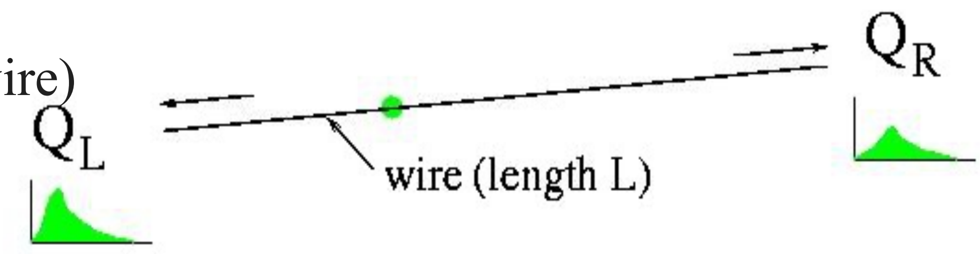
Two measurements in different
Dimensions and particle is where they
Cross
Complication: when multiple particles
Creates ghost hits

Y-Coordinate: idea #2

- Two-sided readout
  - Charge division (resistive wire)

$$y/L = Q_R/(Q_R + Q_L)$$

  - Time difference



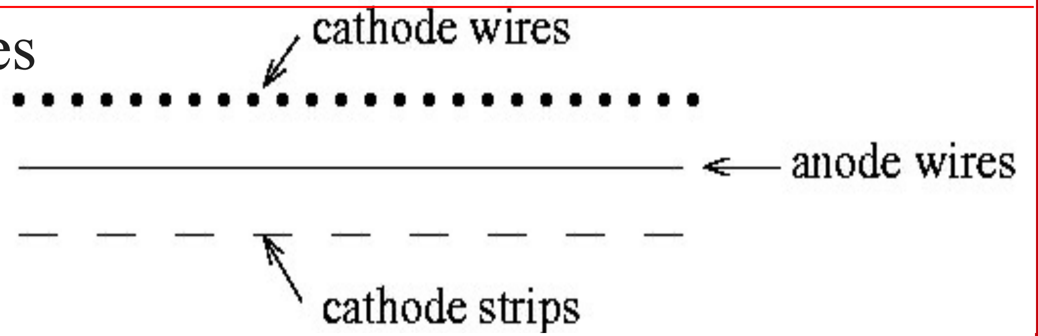
Note: velocity along wire 30 cm/ns so at best $\sigma(x)$ ~ several cm

No Ghosts!
But limited resolution along the direction of the wire due to
Very fast signal propagation along wire – limited by time resolution of readout

Y-coordinate: idea #3

- Segmented cathode planes
  - Strips/wires/pads

(Slow!)



Relies on both ion and electron signals. Ion signal much slower

Various Schemes

Field lines aligned with x-direction via use of field and sense wires. (cathode and anode wires)

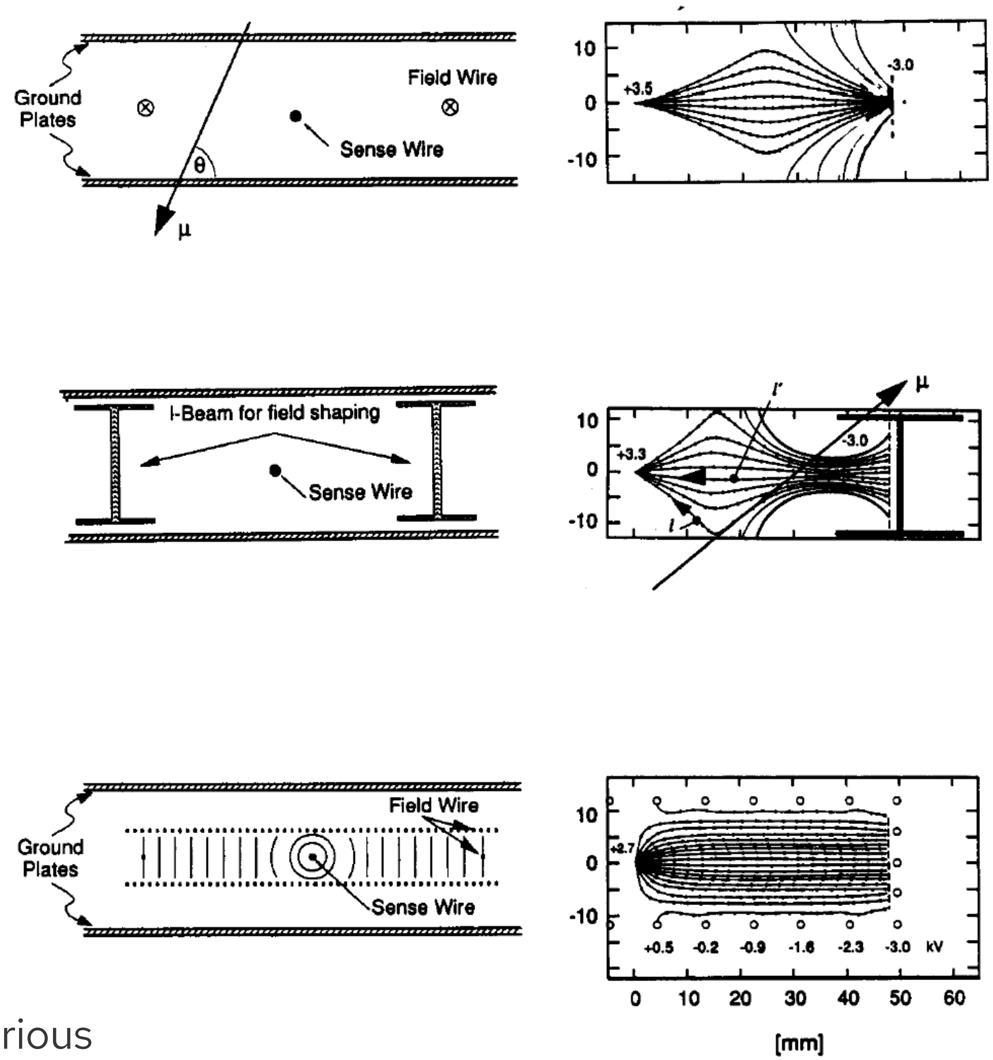
Then x can be measured from the arrival time.

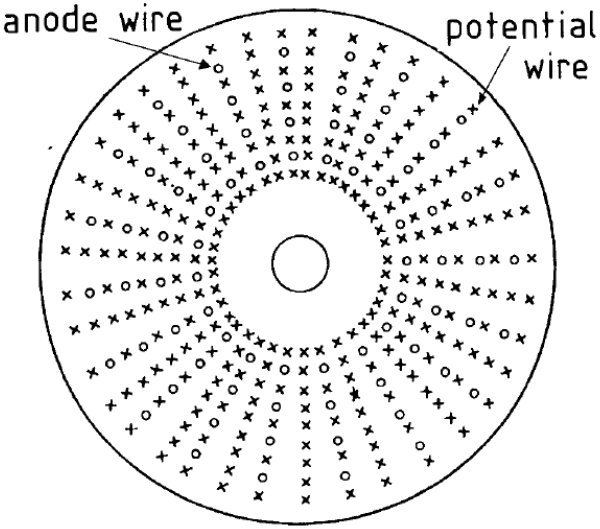
Better x-resolution while using larger wire pitch than in MWPC's.

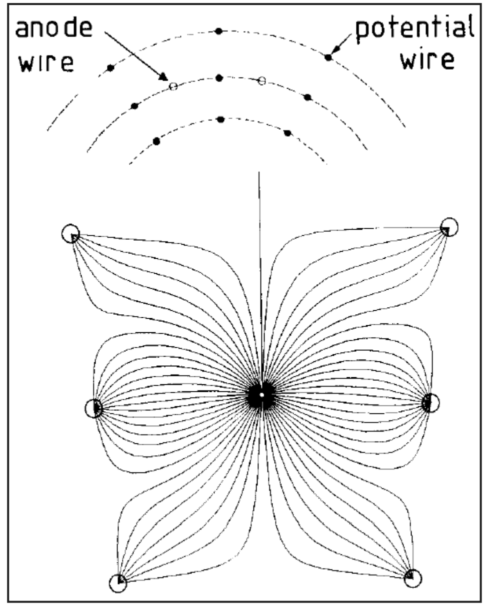
Fewer wires → less electronics, less mechanical support

As field is generated between wires various geometries possible:

- Planar
- Cylindrical
- ...

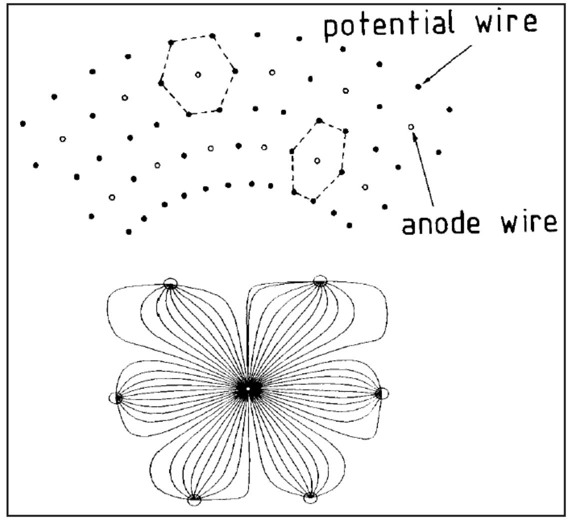






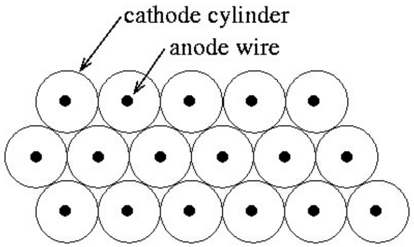
Cylindrical:

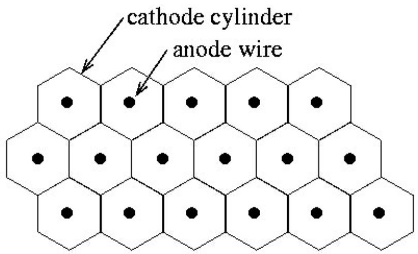
- barrel shape
- wires supported from end plates
- very little material (centrally)
- one broken wire can destroy large section!



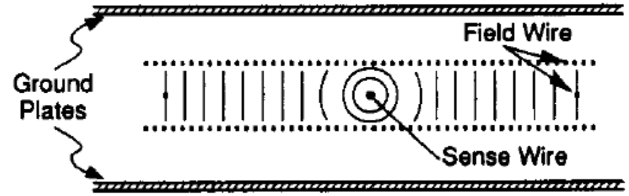
Tubes or cells:

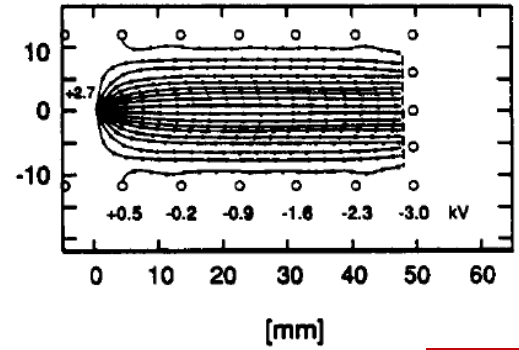
- self supporting
- less material at end-support
- “easier” to build





Position resolution

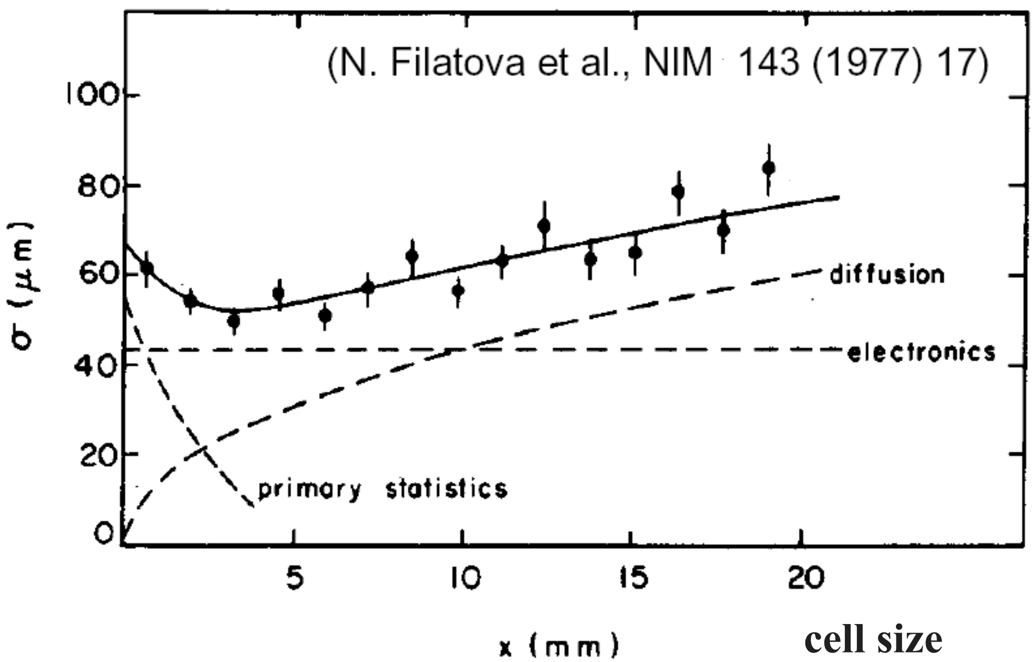


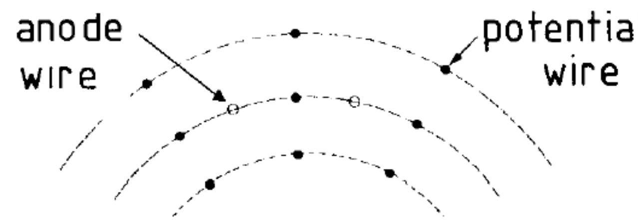


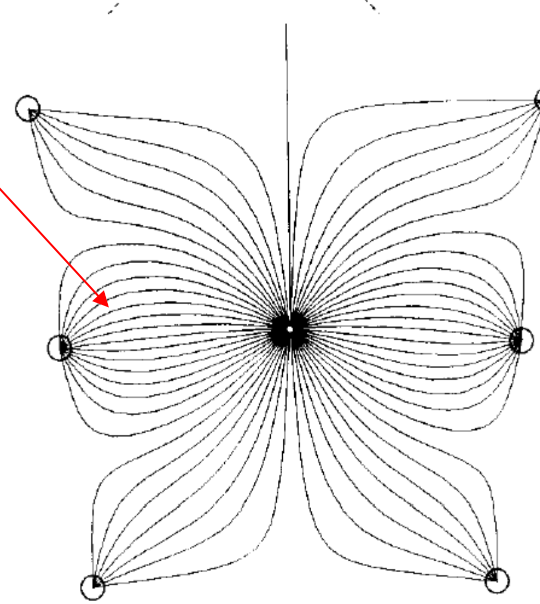
Remember electron drift velocity ~ few cm/μs:

With timing precision of a few ns ⇒ $\sigma(x)$ ~100 μm

- Measurement precision:
  - Statistics primary ionisation (for small "cell"-sizes)
  - Electronics
- Spread in arrival time:
  - Diffusion (especially for long drift paths)
  - Path length fluctuation complex in E-fields

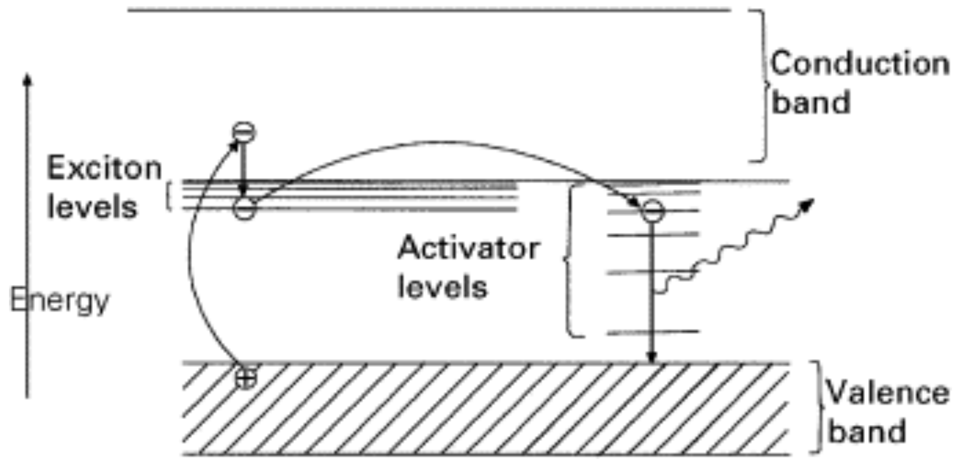


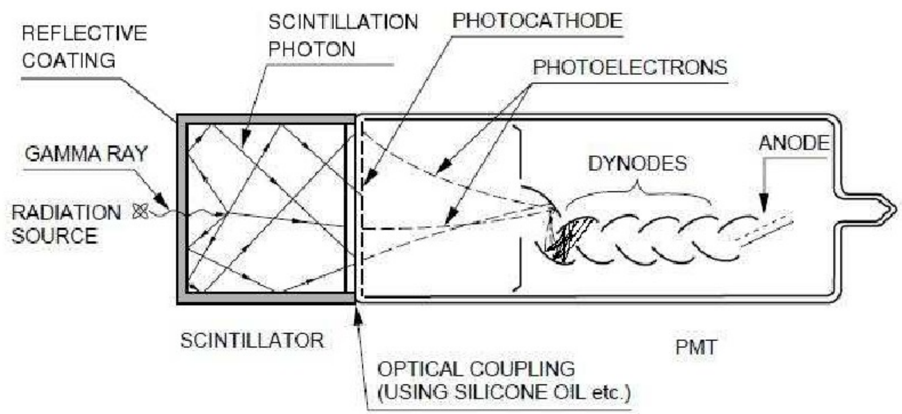




Other Types of Detectors

- Scintillators also have been traditionally used as fast timing detectors
- Detectors that rely on internal excitations as a charged particle traverses the material
- Nano-second timing resolution
- Typically used in conjunction with higher spatial resolution detectors

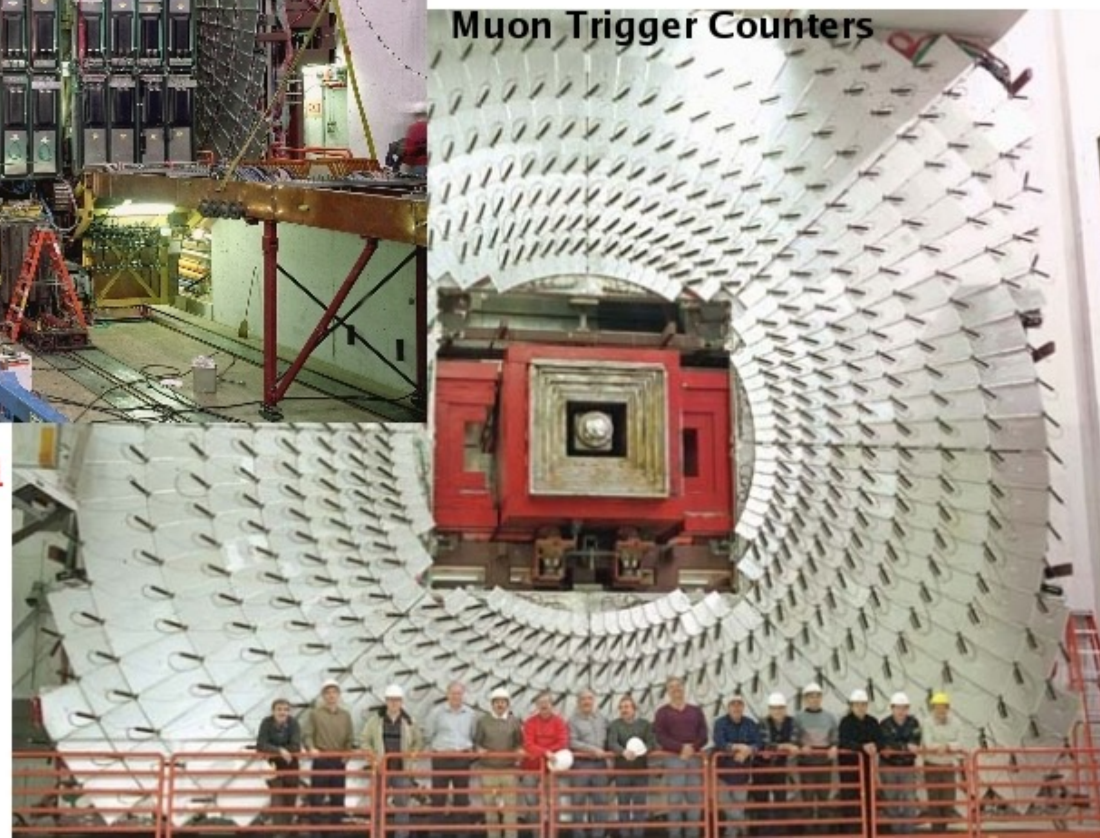




Photomultiplier Tube

Muon System

DØ Detector in Collision Hall, January 2001



Summary

- Today covered muon basics , ‘traditional’ detectors
- Tomorrow complications and problems and future directions

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