Basic of Detector

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What I worked for detectors

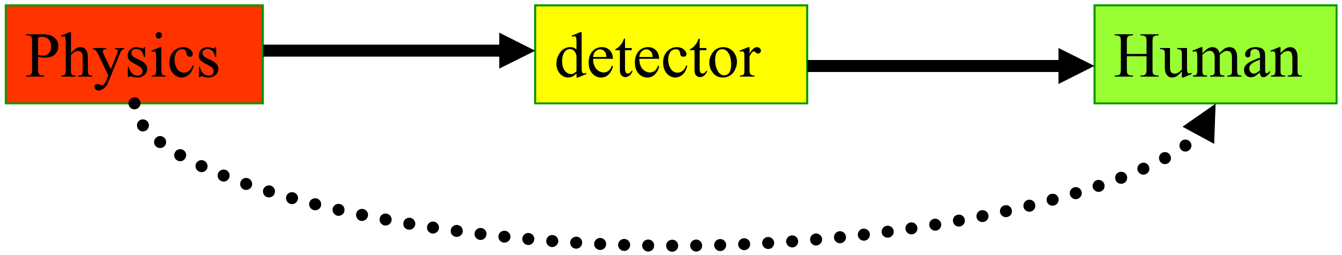
- Electron-Positron collider Experiment at 60GeV
  - Trigger electronics, TRD, EMCAL, Si Sensor
- Proton-Antiproton collider experiment at 1.8TeV
  - Muon detector, Readout electrinics
- Large scale Accelerator control at 8GeV
  - Distributed computing system hardware/software
- Polarize proton-proton/ Heavy Ion collider experiment at 200GeV
  - Muon detector, Si detector
- Start to work for Detectors for RIBF experiment

Working higher energy

Index of this lecture

1. Why/How we need detector?
2. What do we want to measure?
3. Gas Chamber basics
4. Scintillator
5. PHENIX experiment and Silicon Detector
6. Summary

Importance of Detector



- We need detector to understand physics
- Detector innovation can arise new physics
  - Telescope (1590) : Newton mechanics (Late 1600's)
  - Velocity of light measurement (1873): Relativity (1905, 1916)
  - High resolution hydrogen spectroscopy : Quantum mechanics (1925)

Discovery of Charm Quark

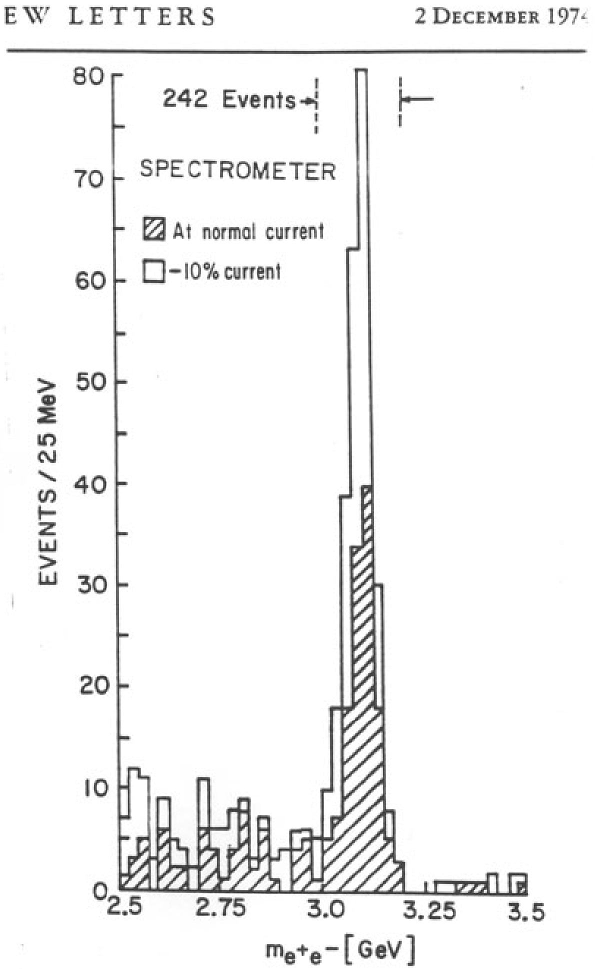
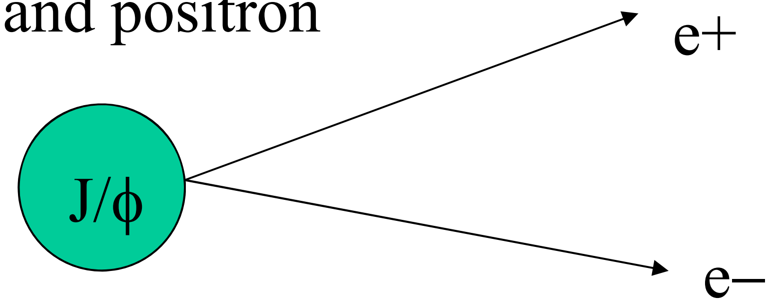


FIG. 2. Mass spectrum showing the existence of J. sults from two spectrometer settings are plotted owing that the peak is independent of spectrometer rents. The run at reduced current was taken two nths later than the normal run.

On 1974 丁肇中 and B. Rchiter discovered independtly.

Novel prize in Physic in 1976. Ting:

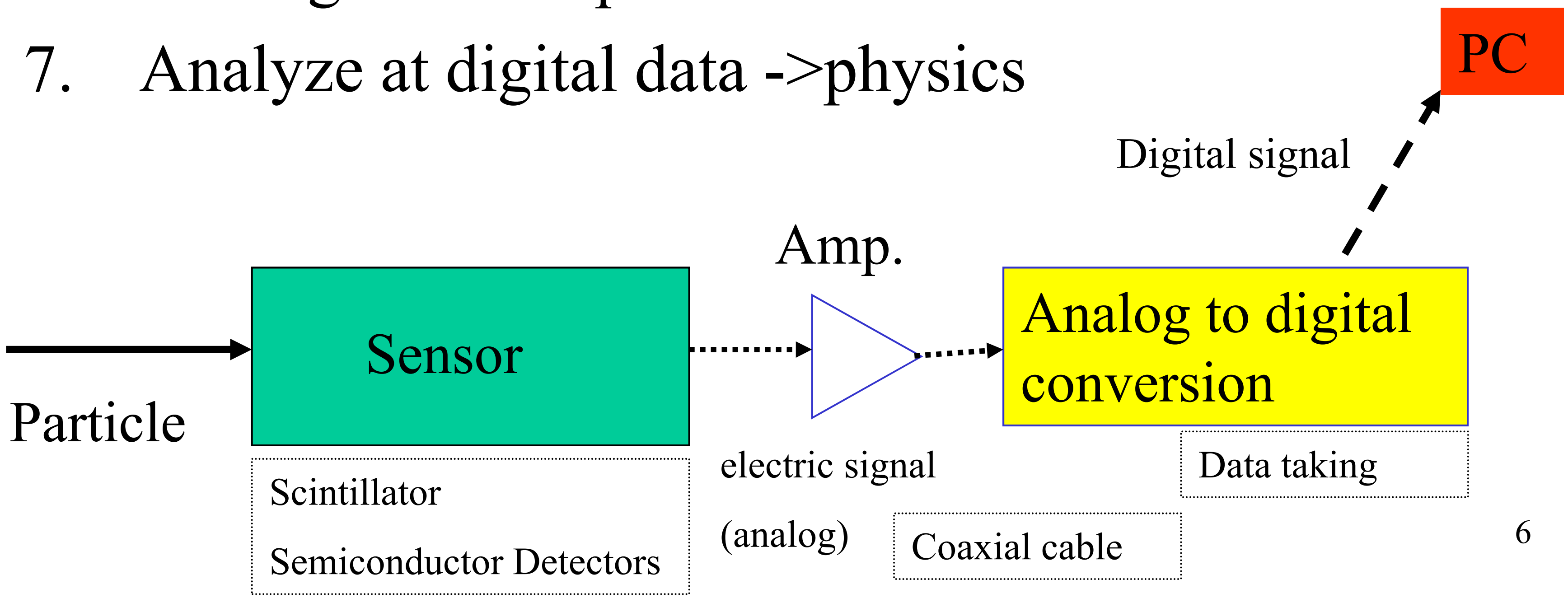
Energetic proton was bombarded to nuclear target, measure the invariant mass of produced electron and positron



Until Ting's discovery, many experiments saw the sign of the similar phenomena, But their resolution of the mass measurement were not good as Ting's experiment.

Major Detector Principle

1. Particle penetrates or stops at detector
2. Particle interacts with material of detector
3. Generating some signal
4. Amplification mechanism
5. Analog to Digital conversion
6. Getting into computer
7. Analyze at digital data ->physics



Particle mass

- Particle has its own mass.
  - electron 0.511MeV
  - μ 105MeV
  - π^+, π^- 140MeV, π^0 135MeV
  - Proton 928MeV
  - J/ψ 3069MeV (discovered by S.C.C. Ting and B. Richter)
  - **Top quark 172GeV (heaviest particle ever observed)**
- If we know the mass of particle, we can identify the particle species.

4-momentum

- Treating the mass at relativity

  $P^2 = E^2 - |\mathbf{p}|^2 = m^2$

Where P : 4-momentum

E : Energy

p : 3-momentum (px, py, pz)

m : invariant mass

4-momentum

- (E, px, py, pz)
- Invariant mass : $m^2 = E^2 - |\mathbf{p}|^2$
- 3-momentum (velocity) $\mathbf{v}/c = \beta = \mathbf{p}/E$

Where c is light velocity

- If we can measure 3-momentum **p**, and Energy E or 3-momentum β, m can be obtained -> identifying particle.

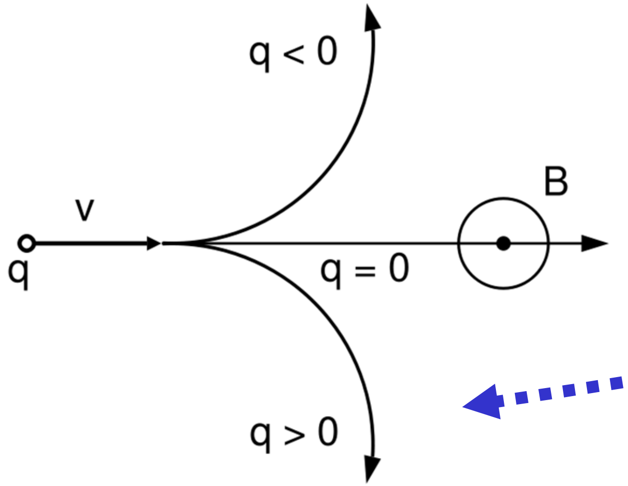
3-momentum measurement

- Momentum can be measured by using Lorentz force

$$\mathbf{F} = q[\mathbf{E} + (\mathbf{v} \times \mathbf{B})],$$

F: force, q: electric charge, **E**: electric field

v: particle velocity = **p**/m, **B**: magnetic field



Constant force

-> Constant curvature

-> particle track trajectory

P [MeV/c] = 3 * r[cm] * B[T]

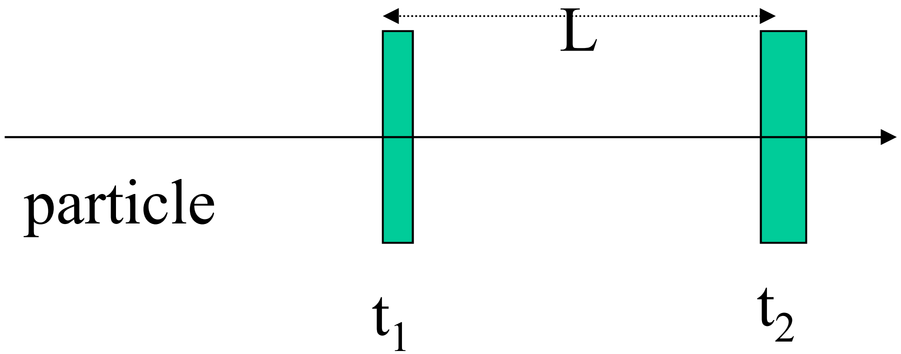
r: curvature radius, B: magnetic field

Energy measurement

- Particle stops at the material and measure all deposited energy by energy loss

- $\beta = \mathbf{p}/E$: particle velocity

  measure timing deference between 2 known location



$\beta = V/c = L/(t_2\text{-}t_1)/c$

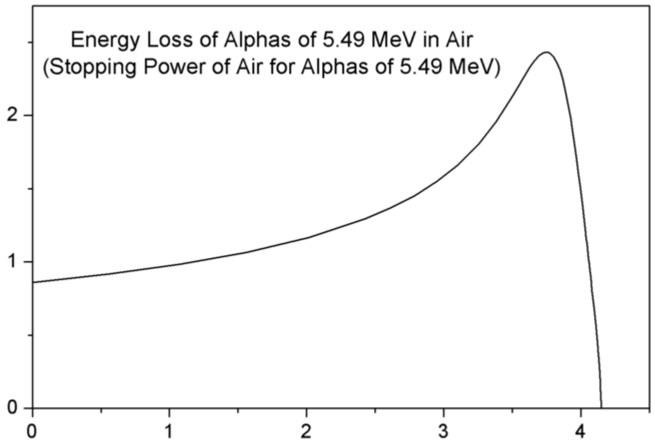
Particle and material interaction

- Particle will hit, penetrate, or stop at material, including gas, liquid, solid.
- Particle has some interaction with material, then we can detect it. -> Detector
- Energy Loss, Multiple Scattering and So.

Energy Loss and stopping power

5.49MeV α particle in air

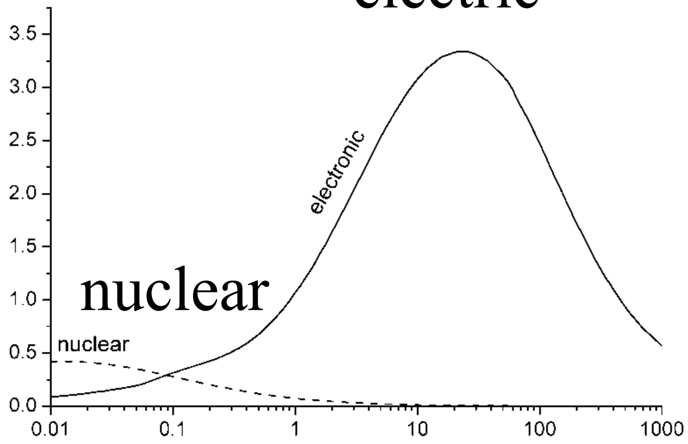
Energy loss [MeV/cm]



Path length [cm]

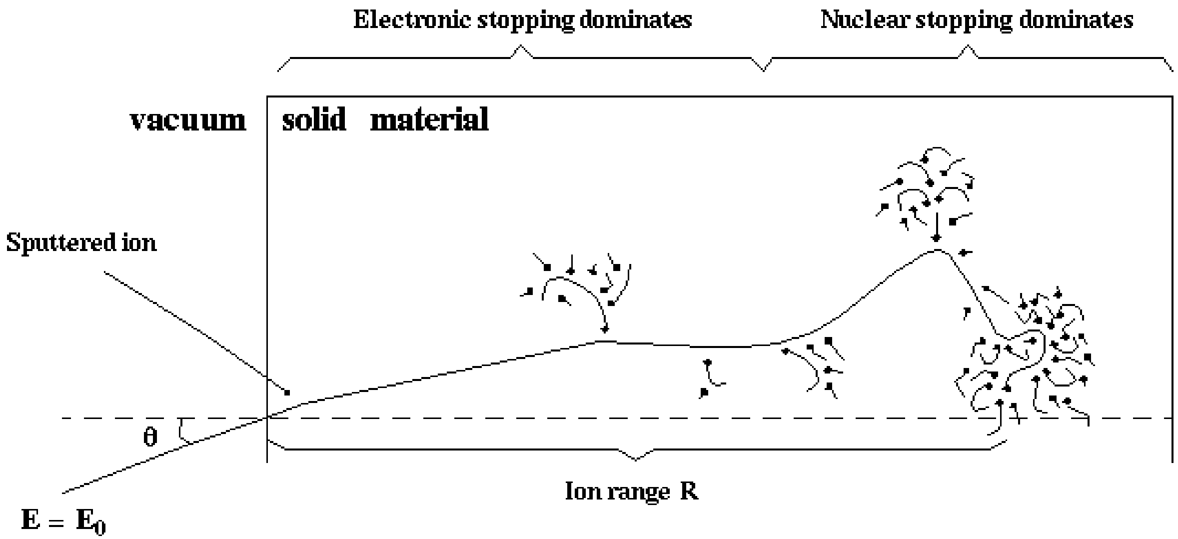
electric

Energy loss [MeV/cm]



nuclear

Particle energy [MeV]



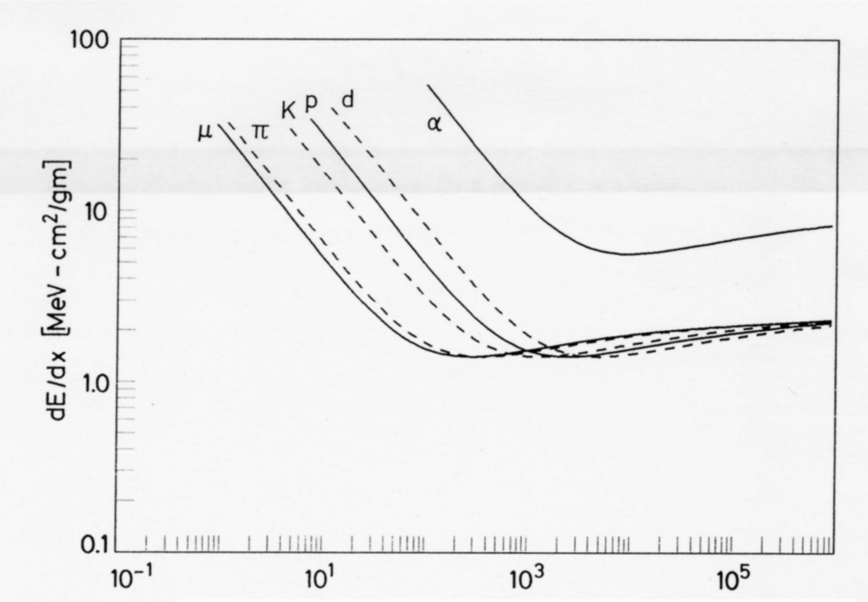
Bethe-Bloch formula

Particle charge

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

Energy loss
[MeV cm^2/g]

β	= *v* / *c*
v	velocity of the particle
E	energy of the particle
x	distance travelled by the particle
c	EnergyLoss.bmpspeed of light
$z\,e$	particle charge
e	charge of the electron
m_e	rest mass of the electron
n	electron density of the target
I	mean excitation potential of the target
ε_0	permittivity of free space



Particle energy [MeV]

Typical Energy Loss

- dE/dX ~ 1MeV cm^2/g for Minimum ionizing particle
- Energy loss / Unit length

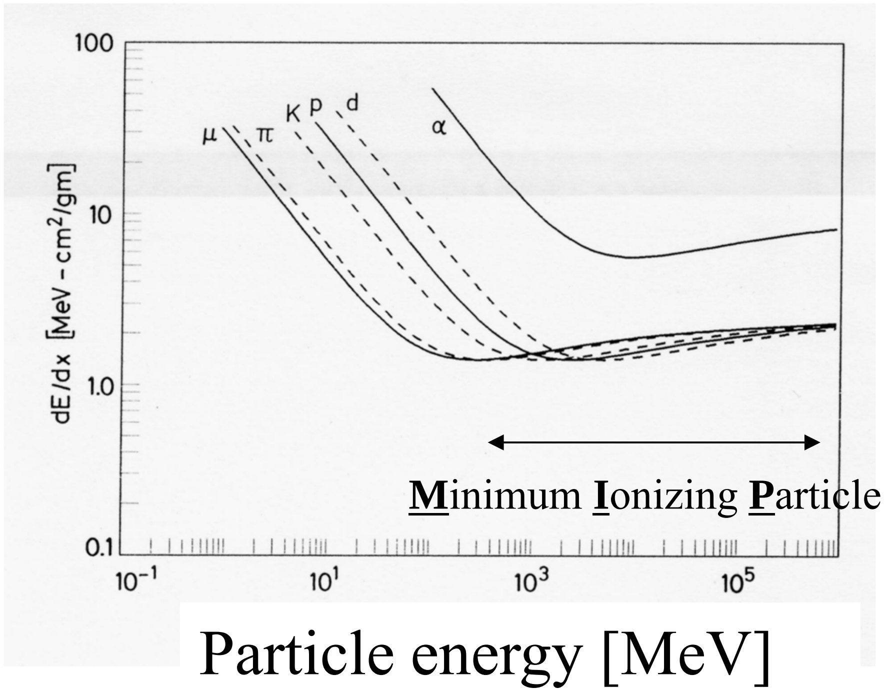
~ 2MeV cm^2/g * Material density [g/cm^3]

For example at Al

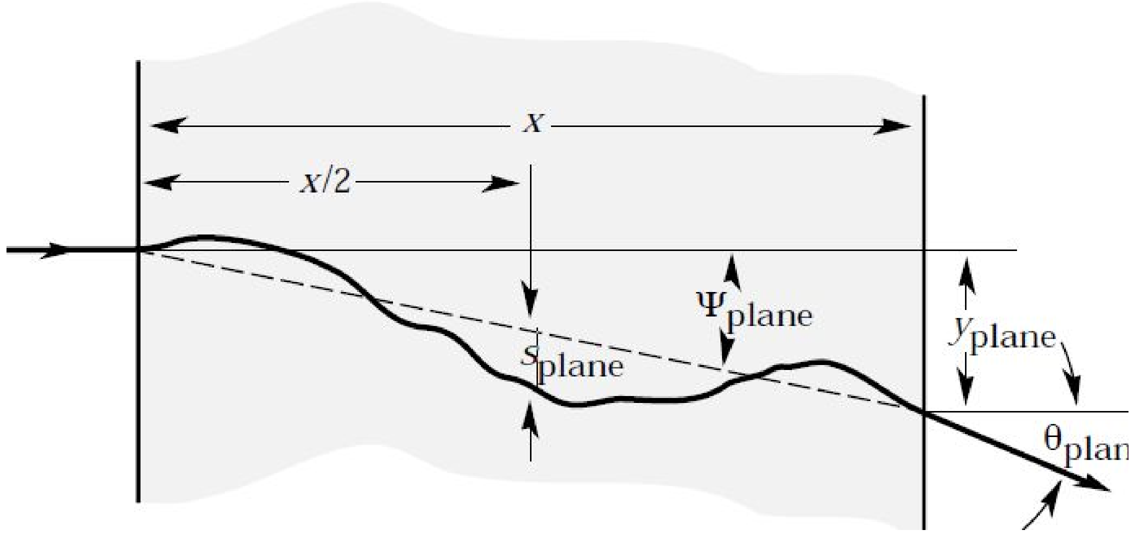
dE/dX = 1.615MeV cm^2/g

Aluminum ρ=2.70g/cm^3

Energy loss =0.60MeV/cm



Multiple Scattering for M.I.P.



$$\theta_0 = \theta^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{2}}\,\theta^{\rm rms}_{\rm space}$$

$$\psi^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,\theta^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,\theta_0\ ,$$

$$y^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,x\,\theta^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,x\,\theta_0\ ,$$

$$s^{\rm rms}_{\rm plane} = \frac{1}{4\sqrt{3}}\,x\,\theta^{\rm rms}_{\rm plane} = \frac{1}{4\sqrt{3}}\,x\,\theta_0$$

$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038\ln(x/X_0)\Big]$$

Z: particle charge

x: material thickness

X_0: radiation length

Atomic and Nuclear properties of materials

Material	Z	A	$\langle Z/A \rangle$	Nucl.coll. length λ_T $\{g\ cm^{-2}\}$	Nucl.inter. length λ_I $\{g\ cm^{-2}\}$	Rad.len. X_0 $\{g\ cm^{-2}\}$	$dE/dx\|_{min}$ $\{$ MeV $g^{-1}cm^2\}$	Density $\{g\ cm^{-3}\}$ $(\{g\ell^{-1}\})$	Melting point (K)	Boiling point (K)	Refract. index (@ Na D)
H_2	1	1.00794(7)	0.99212	42.8	52.0	63.04	(4.103)	0.071(0.084)	13.81	20.28	1.11[132.]
D_2	1	2.01410177803(8)	0.49650	51.3	71.8	125.97	(2.053)	0.169(0.168)	18.7	23.65	1.11[138.]
He	2	4.002602(2)	0.49967	51.8	71.0	94.32	(1.937)	0.125(0.166)		4.220	1.02[35.0]
Li	3	6.941(2)	0.43221	52.2	71.3	82.78	1.639	0.534	453.6	1615.	
Be	4	9.012182(3)	0.44384	55.3	77.8	65.19	1.595	1.848	1560.	2744.	
C diamond	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.725	3.520			2.42
C graphite	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.742	2.210			
N_2	7	14.0067(2)	0.49976	61.1	89.7	37.99	(1.825)	0.807(1.165)	63.15	77.29	1.20[298.]
O_2	8	15.9994(3)	0.50002	61.3	90.2	34.24	(1.801)	1.141(1.332)	54.36	90.20	1.22[271.]
F_2	9	18.9984032(5)	0.47372	65.0	97.4	32.93	(1.676)	1.507(1.580)	53.53	85.03	[195.]
Ne	10	20.1797(6)	0.49555	65.7	99.0	28.93	(1.724)	1.204(0.839)	24.56	27.07	1.09[67.1]
Al	13	26.9815386(8)	0.48181	69.7	107.2	24.01	1.615	2.699	933.5	2792.	
Si	14	28.0855(3)	0.49848	70.2	108.4	21.82	1.664	2.329	1687.	3538.	3.95
Cl_2	17	35.453(2)	0.47951	73.8	115.7	19.28	(1.630)	1.574(2.980)	171.6	239.1	[773.]
Ar	18	39.948(1)	0.45059	75.7	119.7	19.55	(1.519)	1.396(1.662)	83.81	87.26	1.23[281.]
Ti	22	47.867(1)	0.45961	78.8	126.2	16.16	1.477	4.540	1941.	3560.	
Fe	26	55.845(2)	0.46557	81.7	132.1	13.84	1.451	7.874	1811.	3134.	
Cu	29	63.546(3)	0.45636	84.2	137.3	12.86	1.403	8.960	1358.	2835.	
Ge	32	72.64(1)	0.44053	86.9	143.0	12.25	1.370	5.323	1211.	3106.	
Sn	50	118.710(7)	0.42119	98.2	166.7	8.82	1.263	7.310	505.1	2875.	
Xe	54	131.293(6)	0.41129	100.8	172.1	8.48	(1.255)	2.953(5.483)	161.4	165.1	1.39[701.]
W	74	183.84(1)	0.40252	110.4	191.9	6.76	1.145	19.300	3695.	5828.	
Pt	78	195.084(9)	0.39983	112.2	195.7	6.54	1.128	21.450	2042.	4098.	
Au	79	196.966569(4)	0.40108	112.5	196.3	6.46	1.134	19.320	1337.	3129.	
Pb	82	207.2(1)	0.39575	114.1	199.6	6.37	1.122	11.350	600.6	2022.	
U	92	[238.02891(3)]	0.38651	118.6	209.0	6.00	1.081	18.950	1408.	4404.	
Air (dry, 1 atm)			0.49919	61.3	90.1	36.62	(1.815)	(1.205)		78.80	
Shielding concrete			0.50274	65.1	97.5	26.57	1.711	2.300			
Borosilicate glass (Pyrex)			0.49707	64.6	96.5	28.17	1.696	2.230			
Lead glass			0.42101	95.9	158.0	7.87	1.255	6.220			
Standard rock			0.50000	66.8	101.3	26.54	1.688	2.650			

Example

- Aluminum 1cm thickness with electron 50MeV
- Estimate the angle deviation at exit, ignore energy loss.

- Radiation length

X_0=24.01 [g/cm^2] / 2.699[g/cm^3]=8.9[cm]

x/X_0=0.11

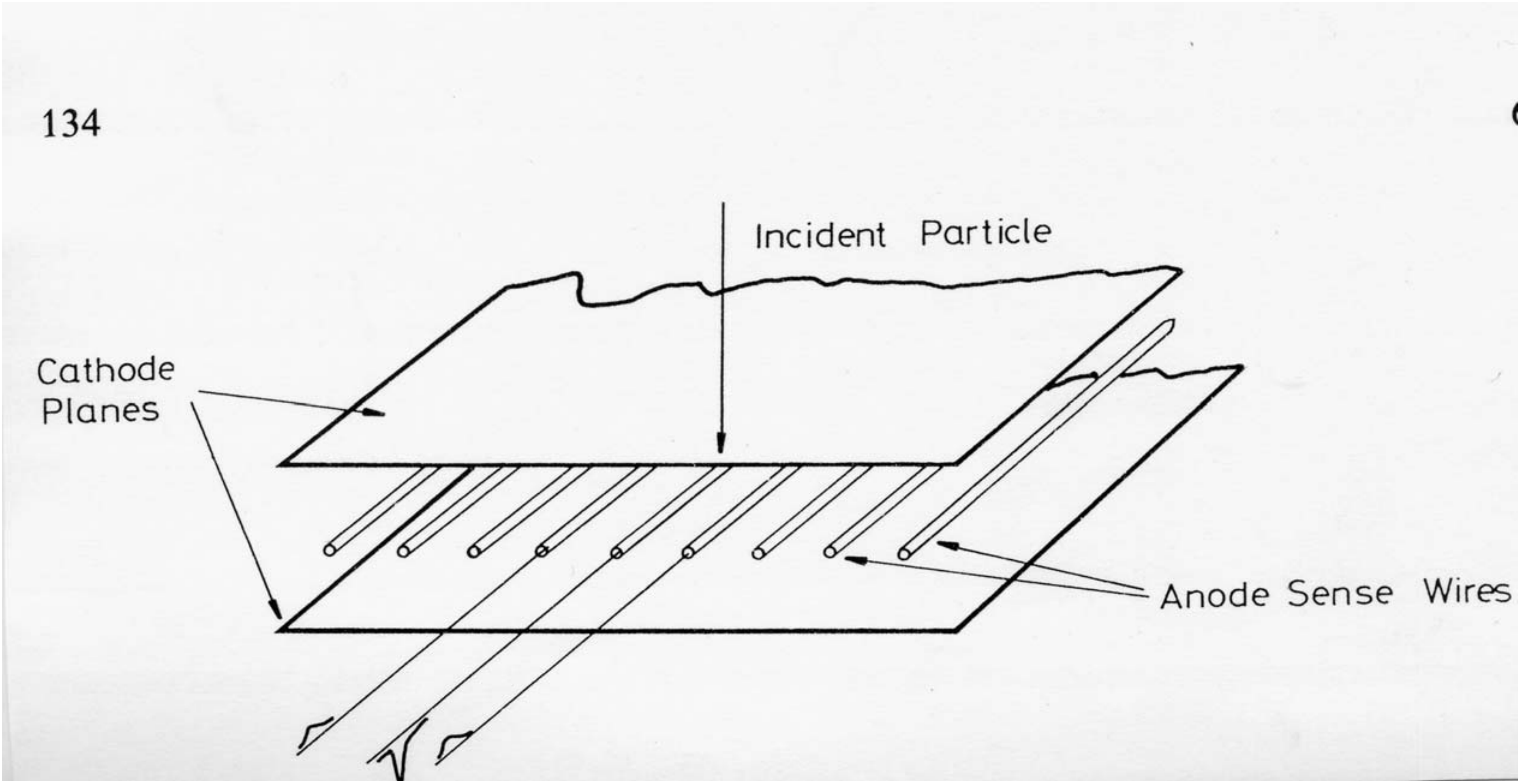
$$\theta_0 = \frac{13.6MeV}{\beta cp[MeV]} z\sqrt{x/X_0}\left[1+0.038\ln(x/X_0)\right]$$

$$= \frac{13.6}{50} * 1 * \sqrt{0.11}\left[1+0.038\ln(0.11)\right]$$

$$= 0.082[rad] = 4.7[\deg]$$

$$= \theta_{plane}^{rms}$$

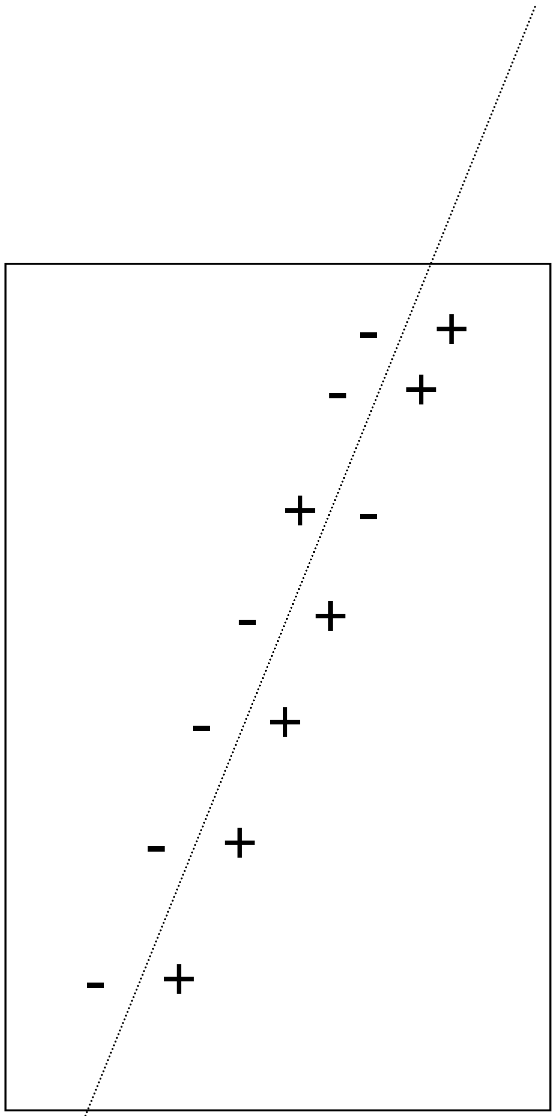
Typical Wire Chamber



Gas Chamber

1. Energetic particle passing through gas.
2. Gas molecules are ionized -> electrons and ions.
3. Electrons and ions are drifted to electro load with minus and plus voltage
4. Avalanche near by wire
5. Getting electrical signal

Ionization



Gas Chamber

- Ionization happens along charged particle track
- #Electorn-Ion pair/unit length = dE/dX / Pair creation energy
- Pair creation Energy
    - H_2 37eV
    - Ar 26eV

Ionization

Table 6.1. Excitation and ionization characteristics of various gases

	Excitation potential [eV]	Ionization potential [eV]	Mean energy for ion-electron pair creation [eV]
H_2	10.8	15.4	37
He	19.8	24.6	41
N_2	8.1	15.5	35
O_2	7.9	12.2	31
Ne	16.6	21.6	36
Ar	11.6	15.8	26
Kr	10.0	14.0	24
Xe	8.4	12.1	22
CO_2	10.0	13.7	33
CH_4		13.1	28
C_4H_{10}		10.8	23

Ar: $dE/dX = 1.519 \text{MeV cm}^2/\text{g}$ electron-ion = 97 /cm

density = 1.662 g/L

pair creation energy = 26 eV

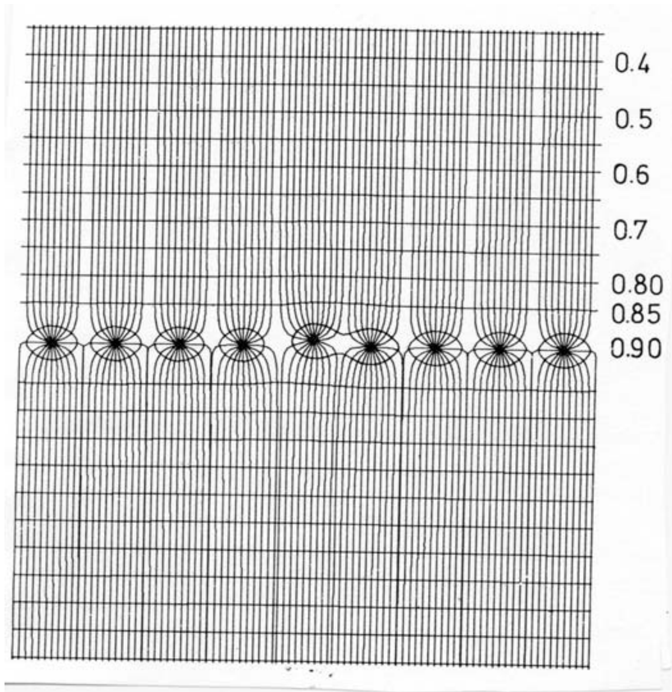
#electron-ion = $1.519 \text{MeV cm}^2/\text{g} * 106 \text{ eV/MeV} * 1.662 \text{g/l} * 1000 \text{cm}^3/\text{l} \quad /26 \text{eV}$

= 97 /cm

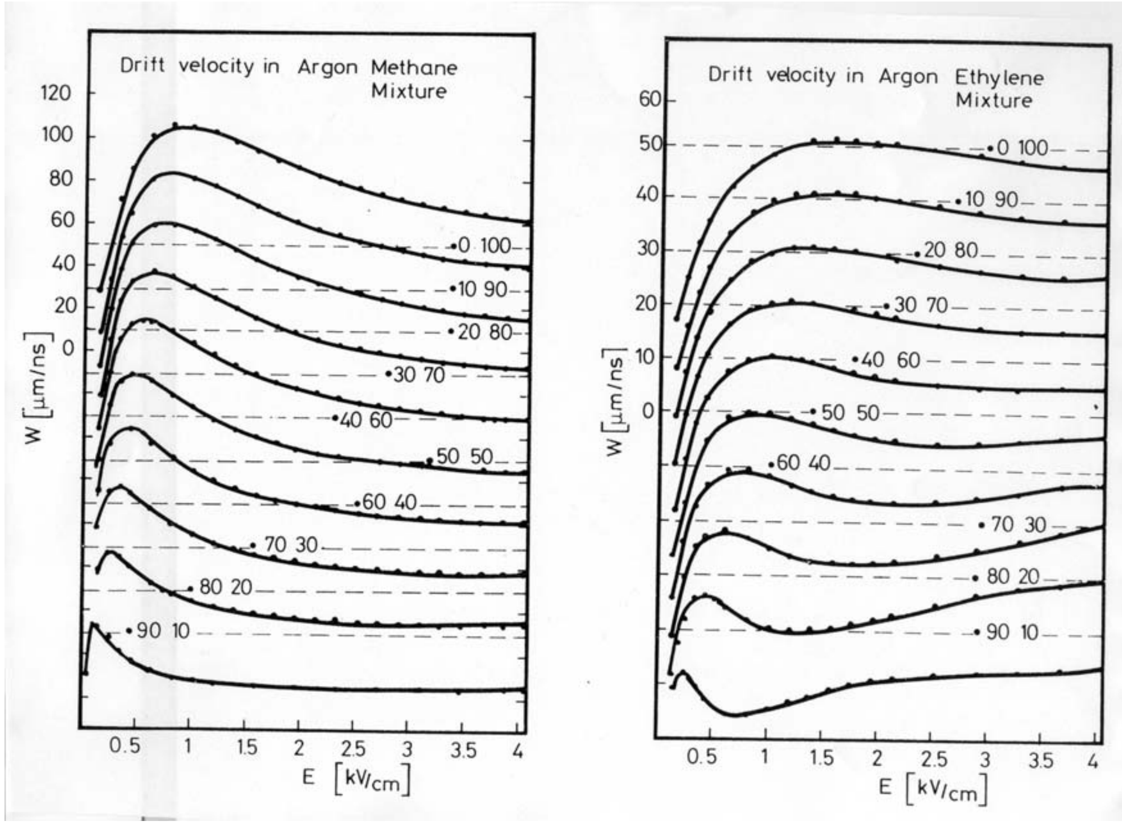
Drift

drift velocity =50~100μm/nsec

= 5mm~10mm / 100 nsec



Drift velocity [μm/nsec]

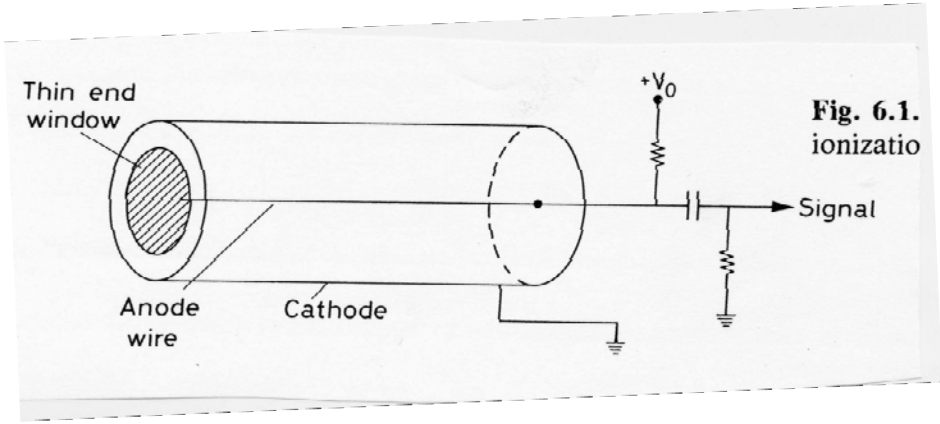


Electric field
and potential

Electric field [KV/cm]

Avalanche

$$E = \frac{1}{r} \frac{V_0}{\ln(b/a)}$$



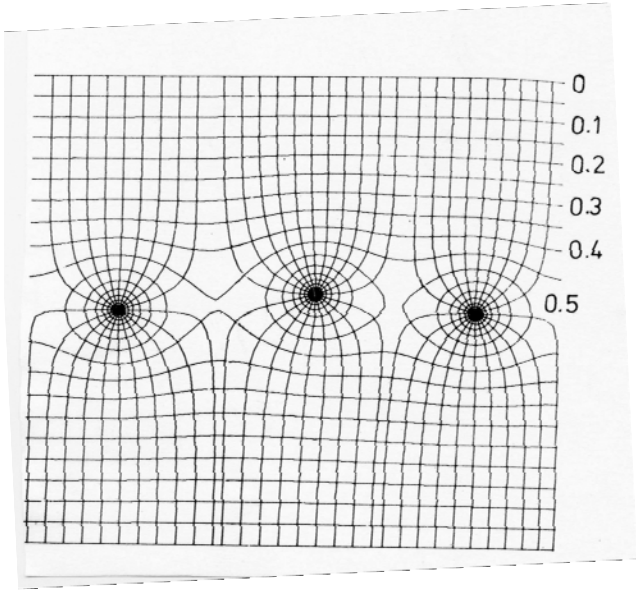
E: electric field

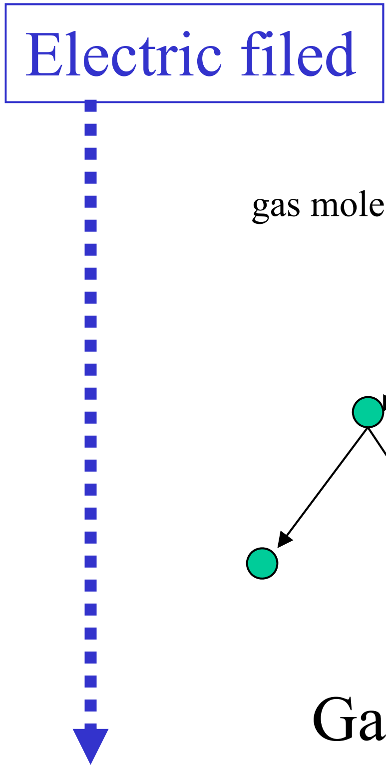
r: distance from wire

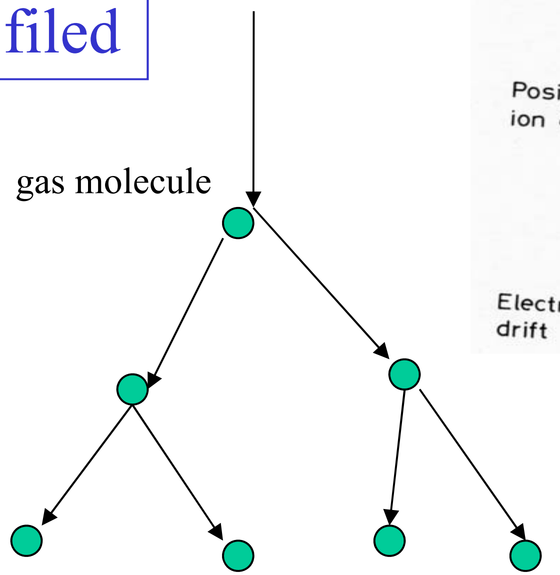
V0: bias voltage

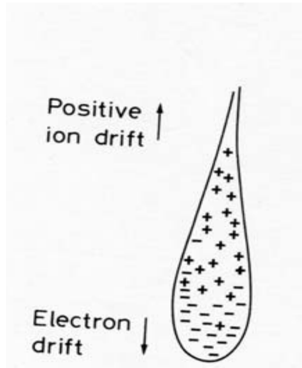
a: radius of cylinder

b: wire radius





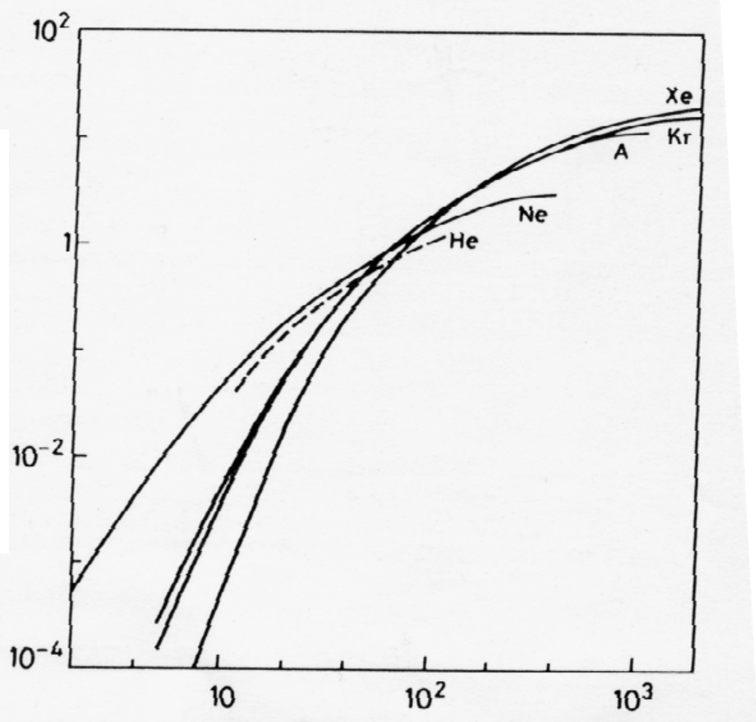




Gas multiplication

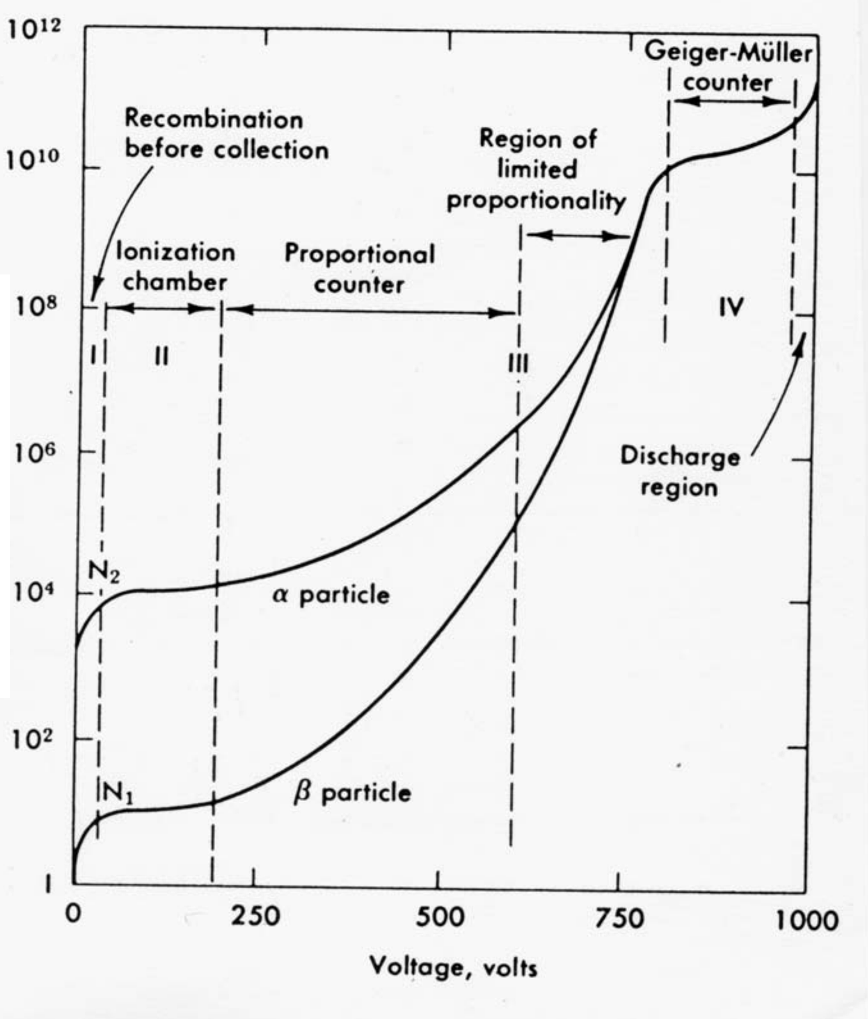
Gas Gain

α/Pressure



Electric field/Pressure [V/cm /mmHg]

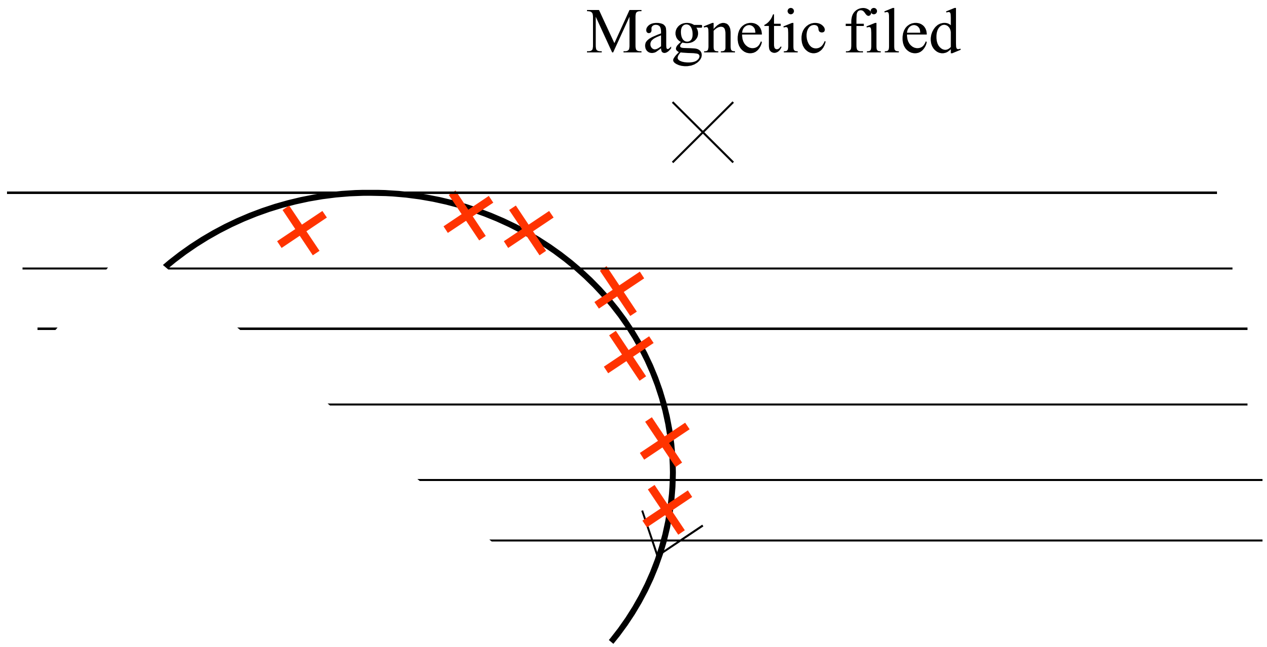
Multiplication



Voltage [V]

$$Mulitplication = \exp\left[\int_{r1}^{r2} \alpha(r)dr\right]$$

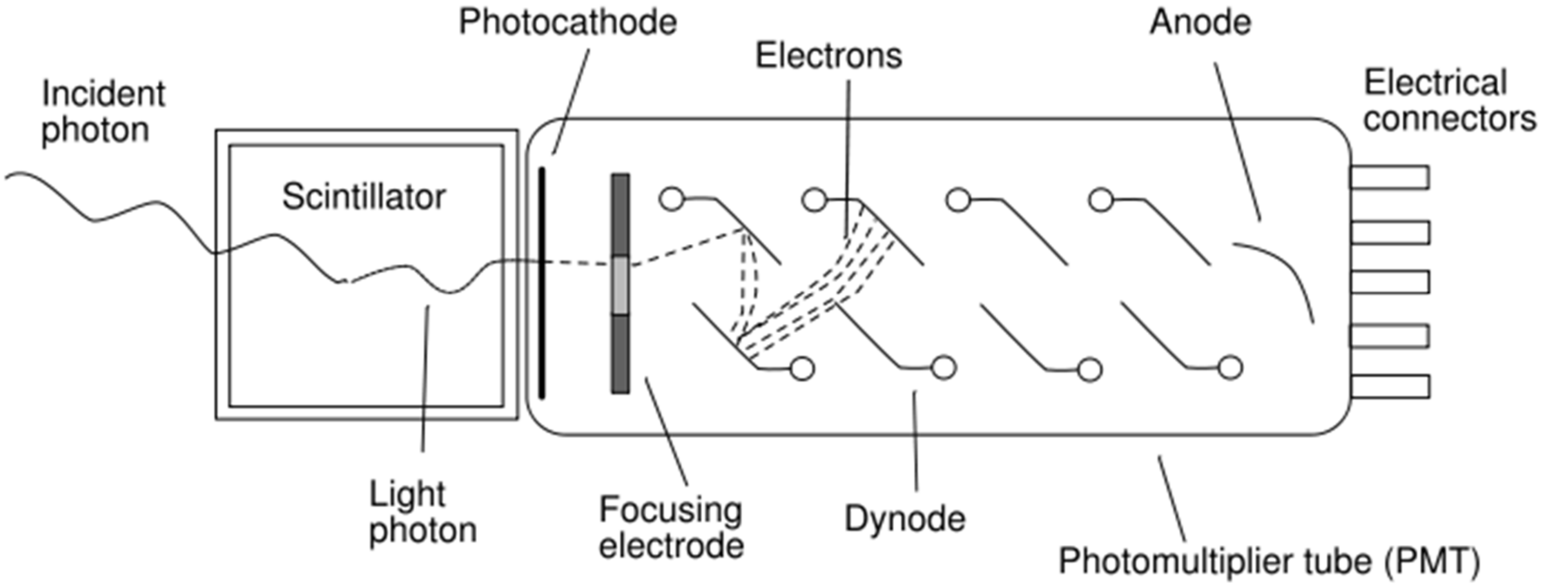
Measurement of the momentum



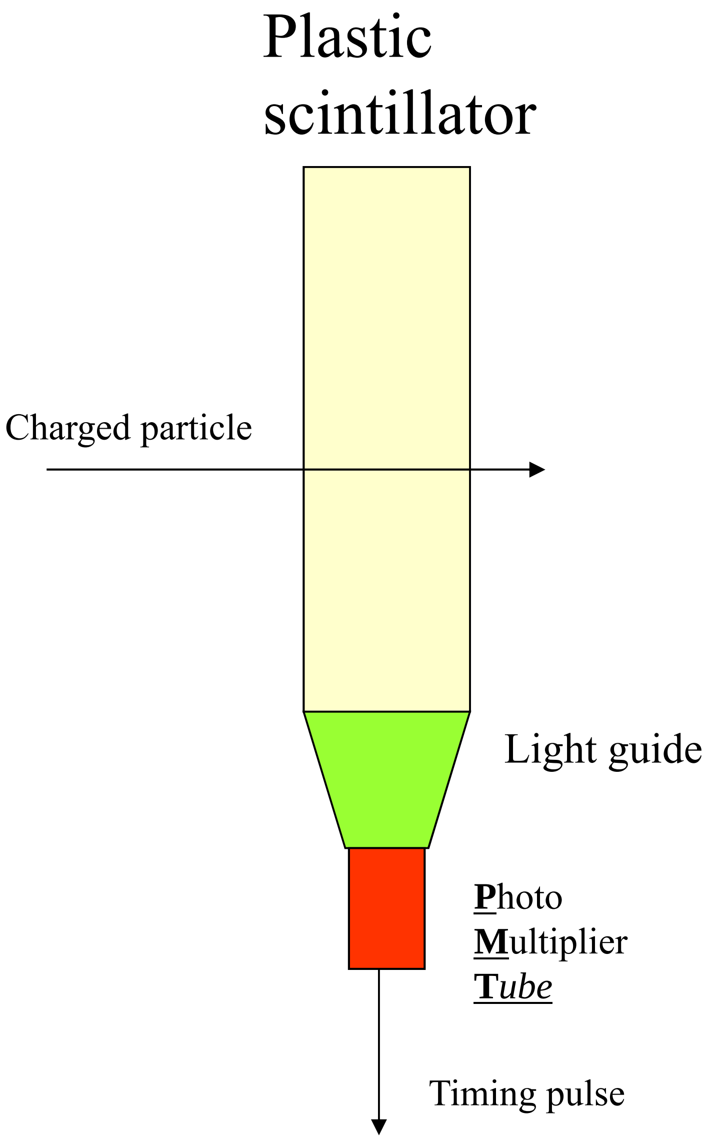
P [MeV/c] = 3 * r[cm] * B[T]

r: curvature radius, B: magnetic field

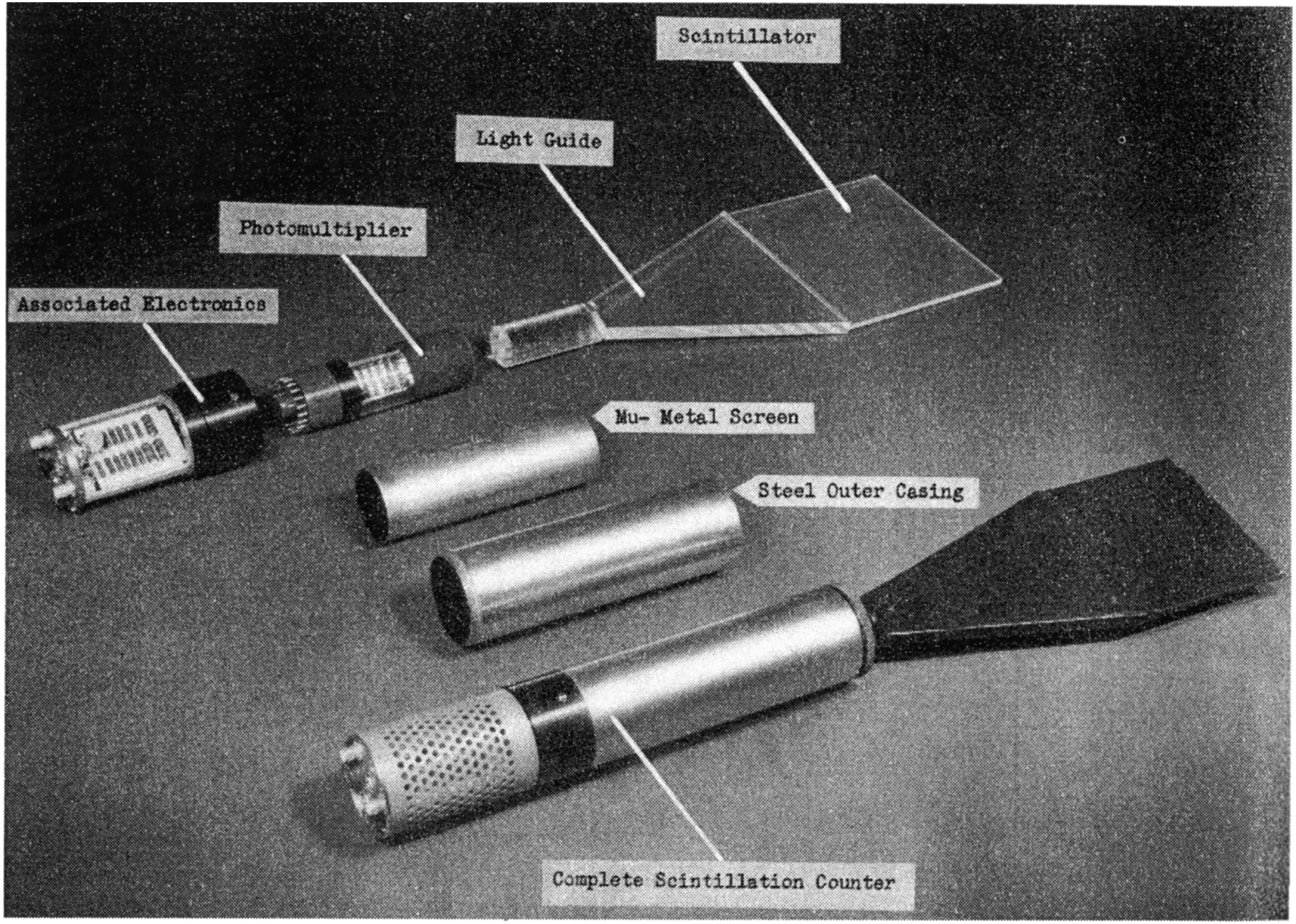
Photo **M**ultiplier **T**ube



Precise Time measurement detector



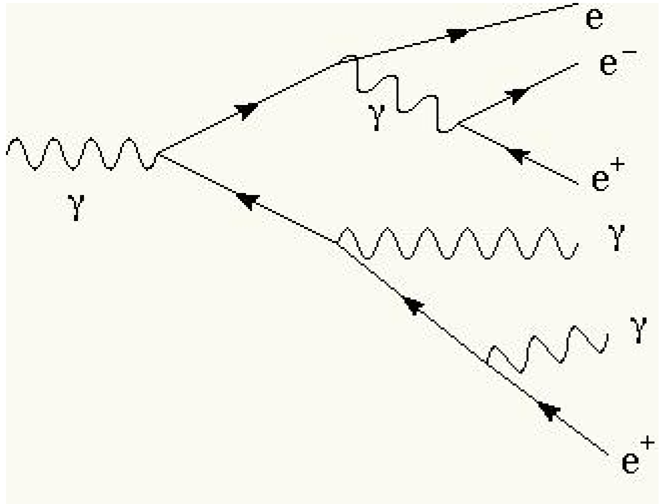
1. Charged particle is penetrating
2. Lower energy electron is exited to upper state
3. Upper state electron drops into lower state and emits a photon
4. Propagate to P.M.T.
5. P.M.T. generates electric pulse.


Scintillator
Light Guide
Photomultiplier
Associated Electronics
Mu- Metal Screen
Steel Outer Casing
Complete Scintillation Counter

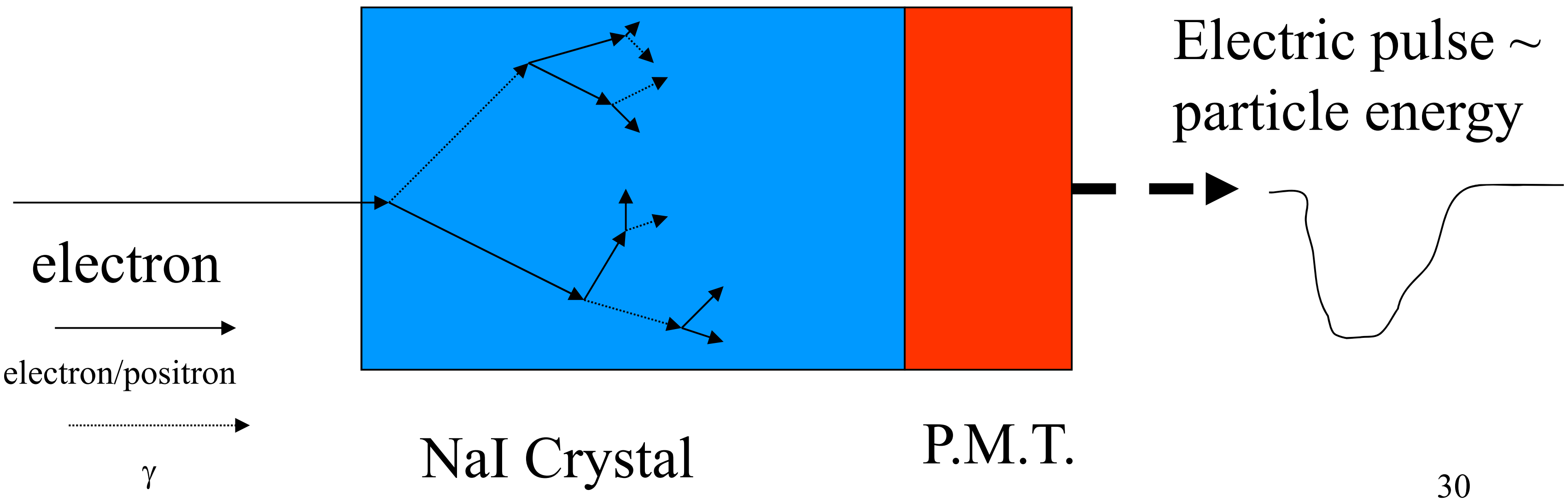
Calorimeter

Mass of electron is 511KeV

$\gamma \to e^+ + e^-$ for $E\gamma > 1.02$MeV



Electric pulse ~ particle energy



Typical Detector System

Wire Chambers

Scitillator

Timing = t1

P [MeV/c] = 3 * r[cm] * B[T]

r: curvature radius, B: magnetic field

Scitillator

Timing =t2

$\beta = V/c = L/(t_2\text{-}t_1)/c$

$E=P/\beta$

$m^2=E^2+P^2$ → Determine 4-momentum

Other Major Detectors (include past)

Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10–150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	50–300 μm[b,c,d]	2 ns	200 ns
Drift chamber	50–300 μm	2 ns[e]	100 ns
Scintillator	—	100 ps/n[f]	10 ns
Emulsion	1 μm	—	—
Liquid Argon Drift [Ref. 6]	~175–450 μm	~ 200 ns	~ 2 μs
Gas Micro Strip [Ref. 7]	30–40 μm	< 10 ns	—
Resistive Plate chamber [Ref. 8]	$\lesssim$10 μm	1–2 ns	—
Silicon strip	pitch/(3 to 7)[g]	*h*	*h*
Silicon pixel	2 μm[i]	*h*	*h*

Position sensitivity

Timing sensitivity

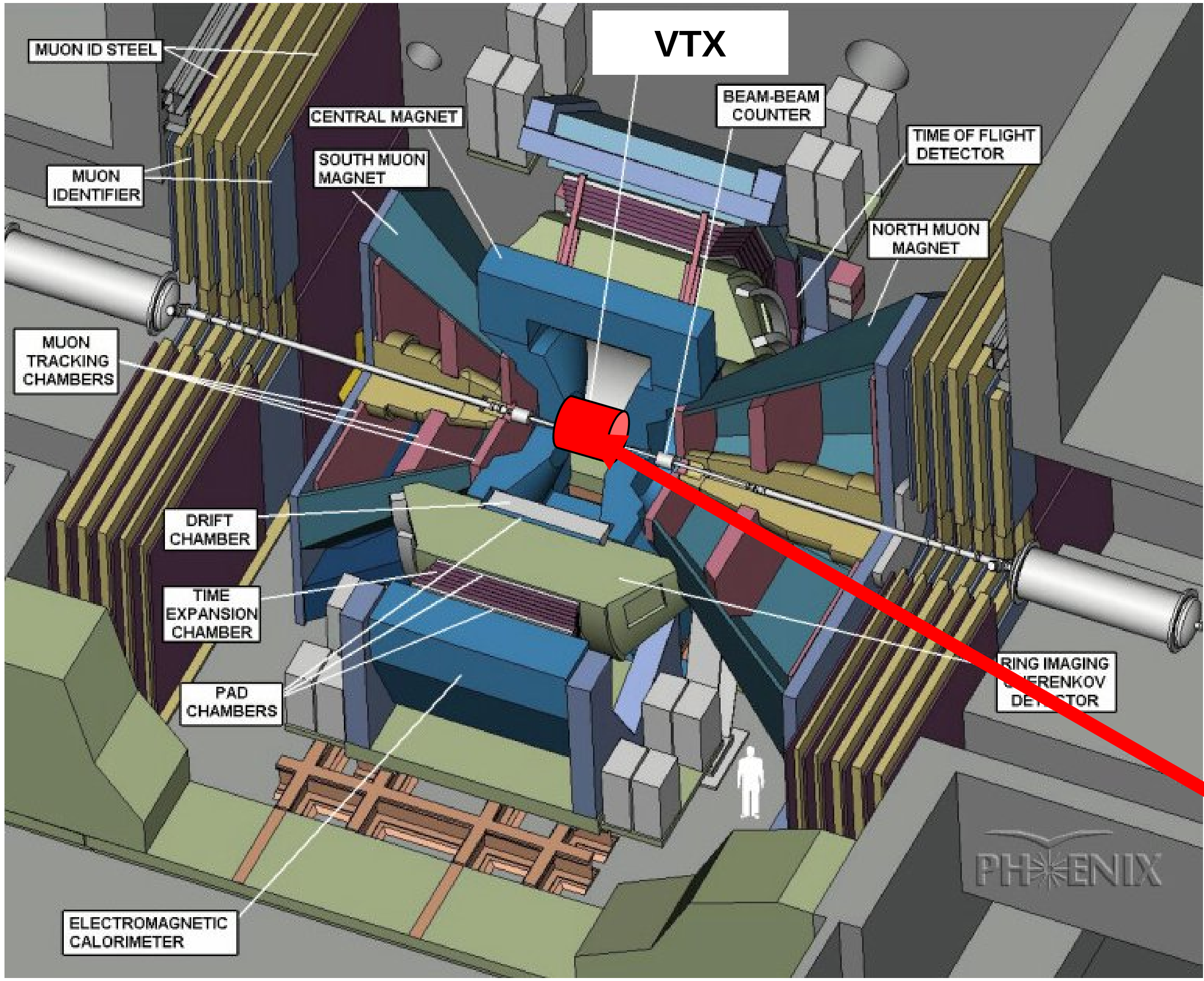
Detector dead time after a hit

Summary

- We need to have detector to investigate nature since you can not feel particles.
- You have to build and/or be familiar with detector for your own experiments.

PHENIX Where is VTX

p, Au



p, Au

- Good particle ID
- High resolution
- High trigger rate

VTX will be installed into inner most detector from beam pipe