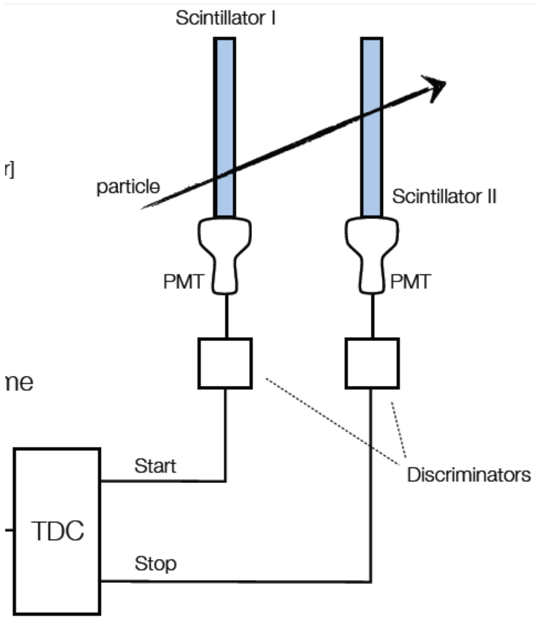
Particle identification

- Two major applications for particle identification:
  - identification of beam particles
  - identification of decay products
- To identify long-lived (but still weakly decaying) neutral particles like the hyperons Λ_0 and Ξ_0, and short-lived particles (τ, charm, beauty, resonances), the determination of the 4-vector of all decay products is necessary to be able to calculate the invariant mass of the final state and identify the original particle.
- PID reduces to identify all stable particles : p, n, $K^{\pm}$, K^0_L, $\pi^{\pm}$, $e^{\pm}$, $\mu^{\pm}$, γ
- Special signatures for neutrals:
  - Photons : Total energy deposited in electromagnetic shower; use energy measurement, shower shape and information on neutrality (e.g. no track)
  - Neutrons : Energy in calorimeter or scintillator (Li, B, ^{3}He) and information on neutrality (e.g. no track)
  - K_0, Λ, ... : Reconstruction of invariant masses
  - Neutrinos : Identify products of charged and neutral current Interactions

Cherenkov : Riv.Nuovo Cim. 28 (2005) no.8-9, 1-130

LHC expt : Nucl. Instrum. Meth. A666 (2012) 148-172

Time of flight : Particle identification



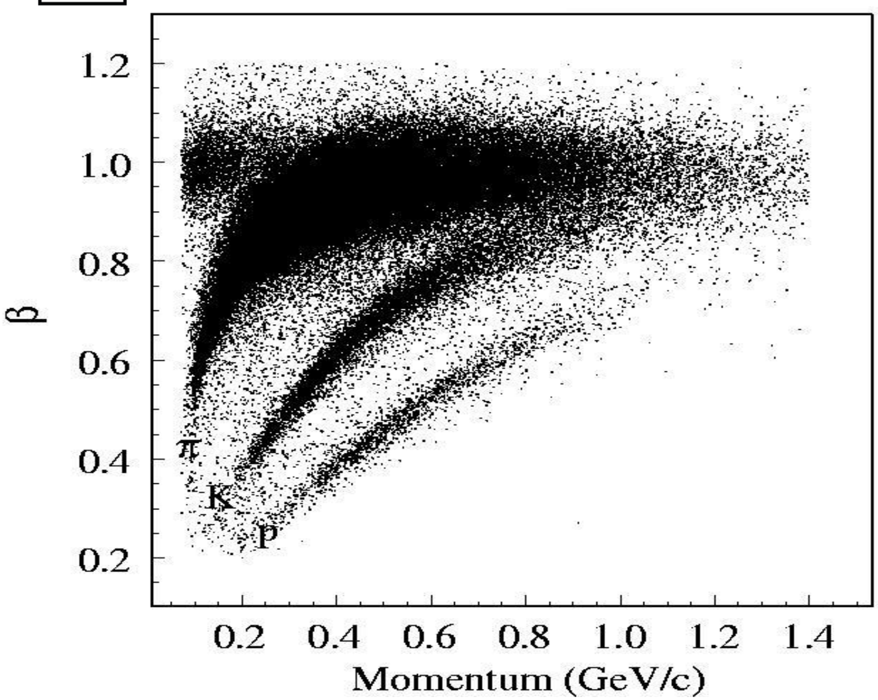
$$\Delta t = \frac{L}{\beta_1 c} - \frac{L}{\beta_2 c} = (L/c)\left(\sqrt{1+m_1^2c^2/p^2} - \sqrt{1+m_2^2c^2/p^2}\right)$$

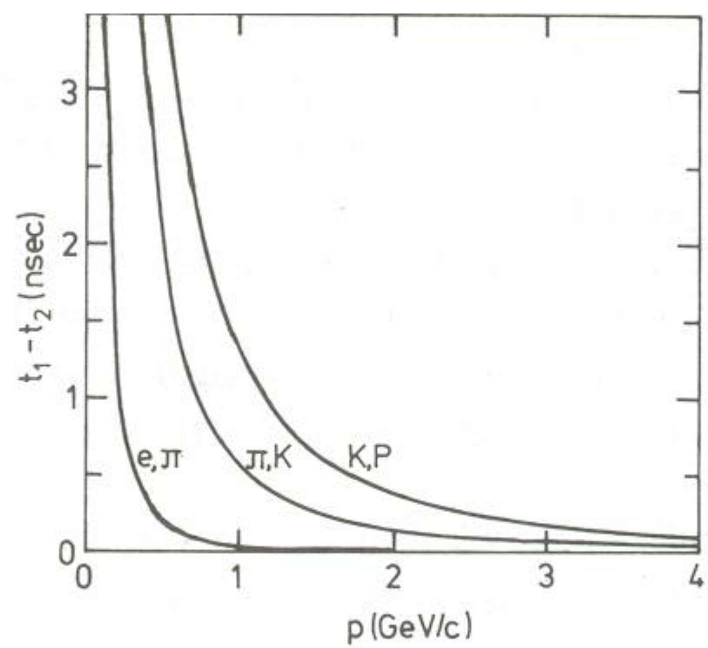
$$\approx (m_1^2 - m_2^2)Lc/(2p^2)$$

An example : Pion/Kaon separation [$m_k \approx 500$ MeV, $m_\pi \approx 140$ MeV] : Assume p=1 GeV and L=2m.

$$\Delta t = (500^2 - 140^2)MeV^2/c^4 \frac{2m\cdot c}{2(1000)^2 MeV^2/c^2}$$

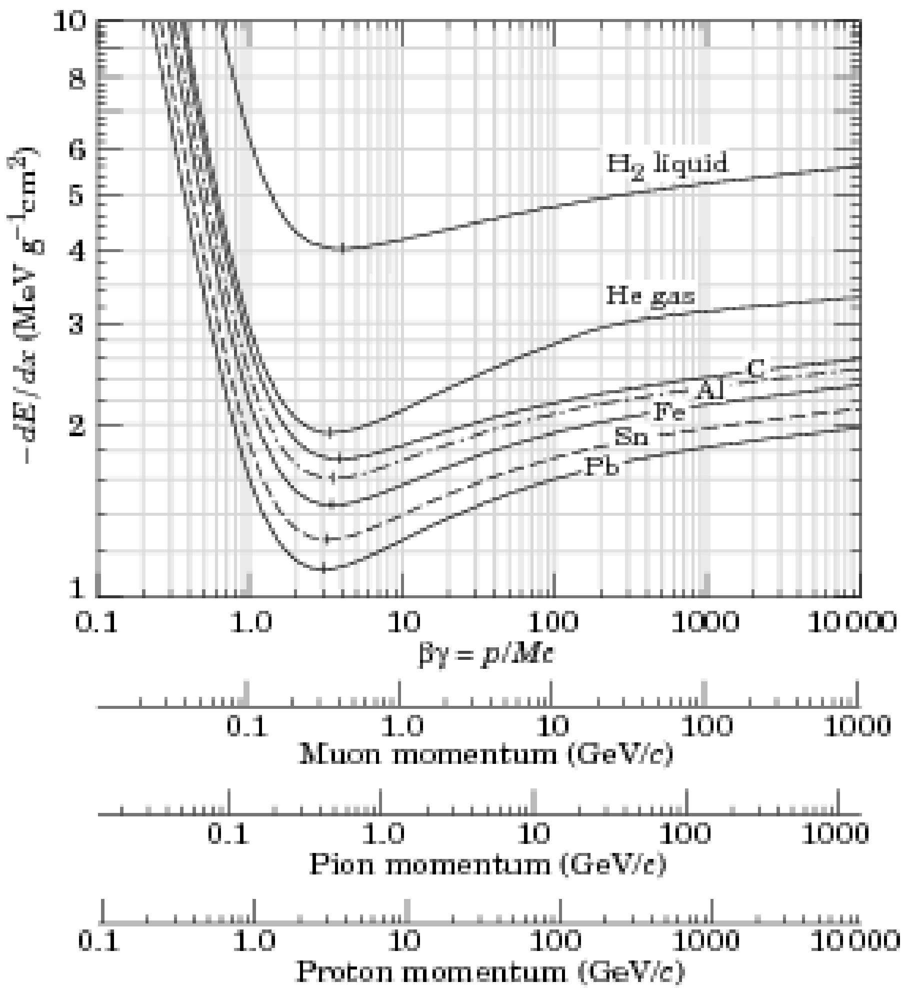
$$= \frac{0.2304m}{c} = \frac{0.2304m}{3\cdot 10^{-4} m/ps} \approx 770 ps$$

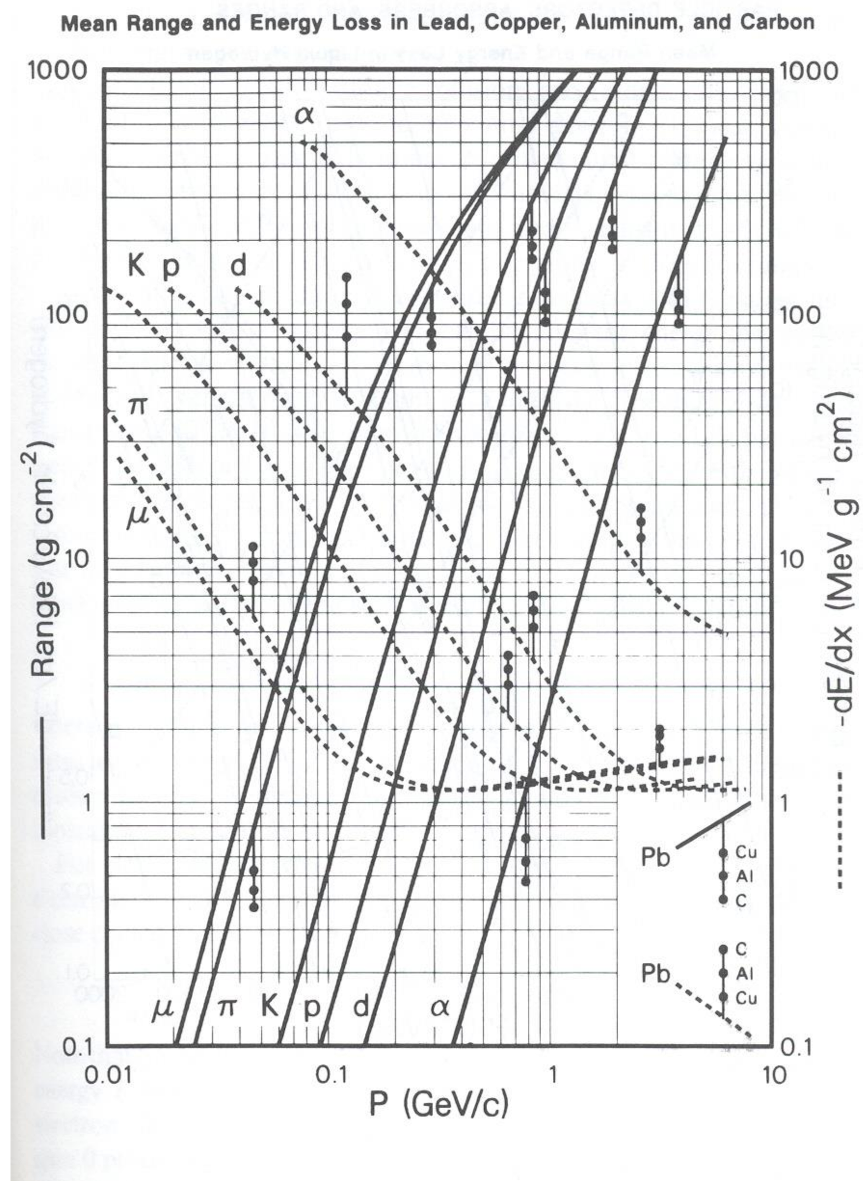




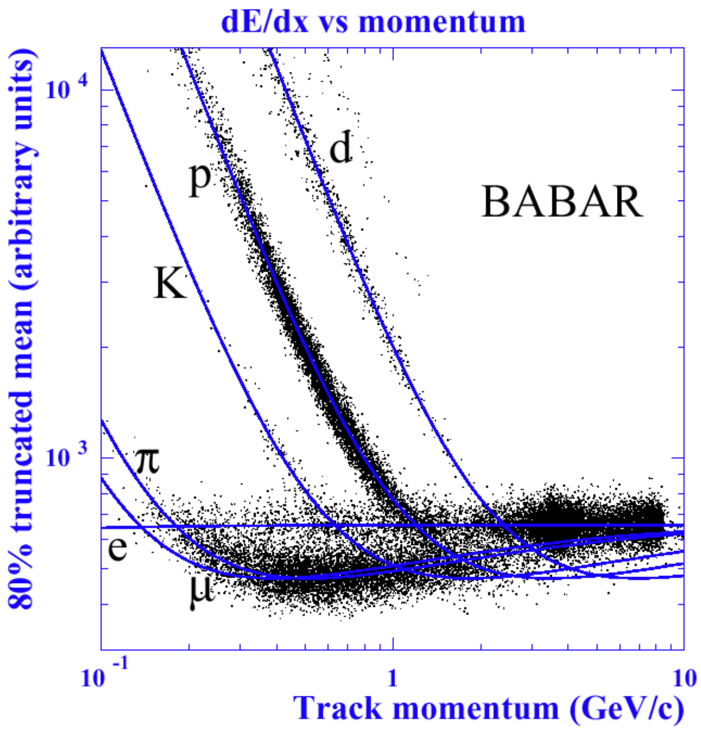
dE/dx and particle identification

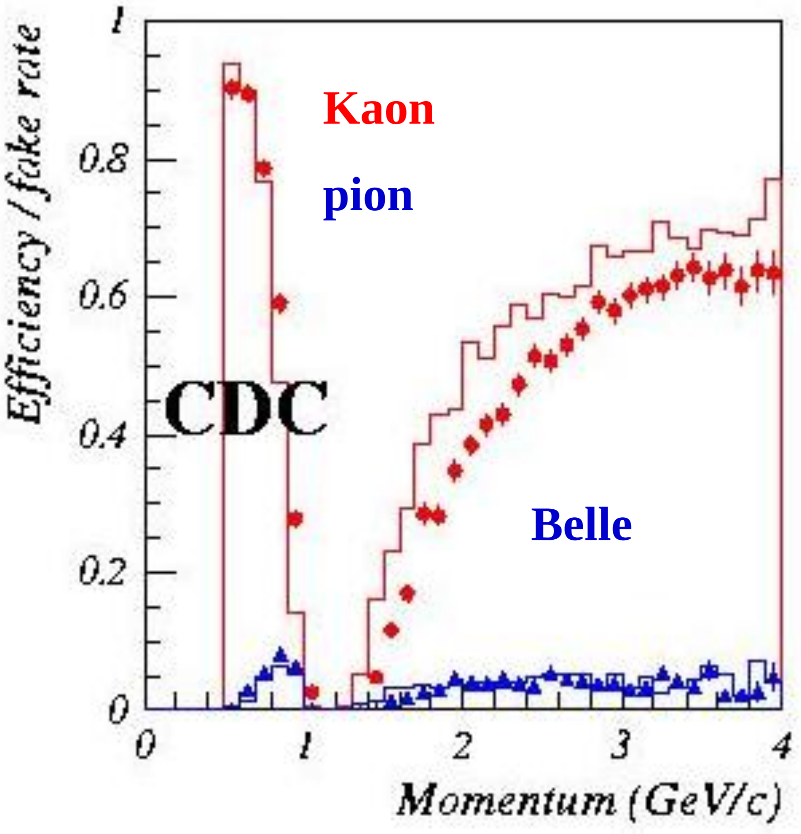
$$\frac{dE}{dx} = D_e \left(\frac{Z_1}{\beta}\right)^2 n_e \left[\ln \frac{2mv^2\gamma^2}{I} - \beta^2 - \frac{\delta(\gamma)}{2} - \frac{C(I,\eta)}{Z} \right]$$





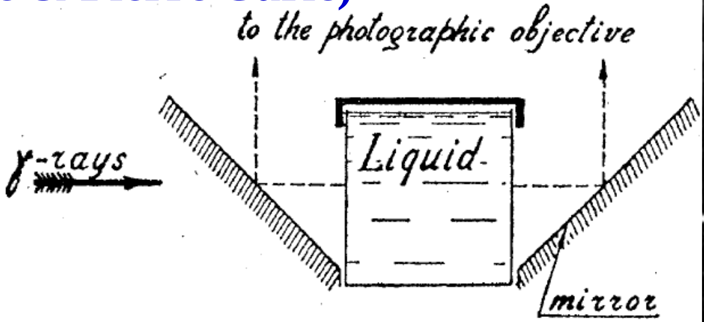
dE/dx and particle identification



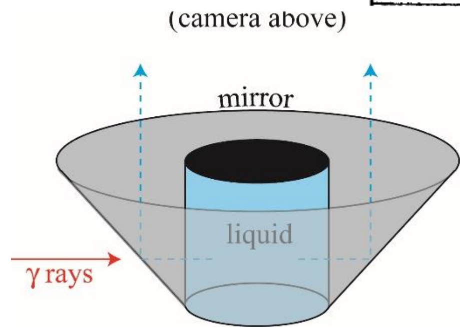


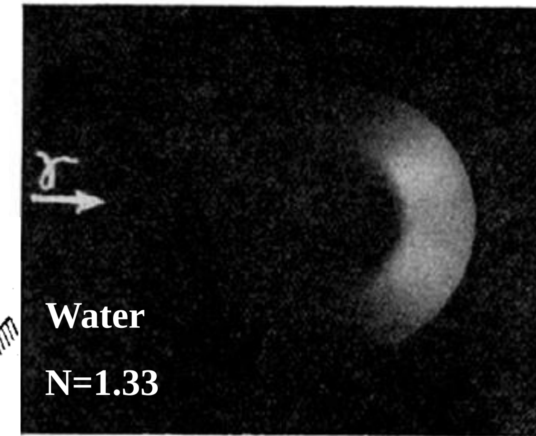
Cherenkov light

- ~1900 : “Blue glow”, seen in fluids containing concentrated Radium (Marie & Pierre Curie)



1. Vessel with liquid
2. Mirror
3. Cherenkov photon towards the photographic film.





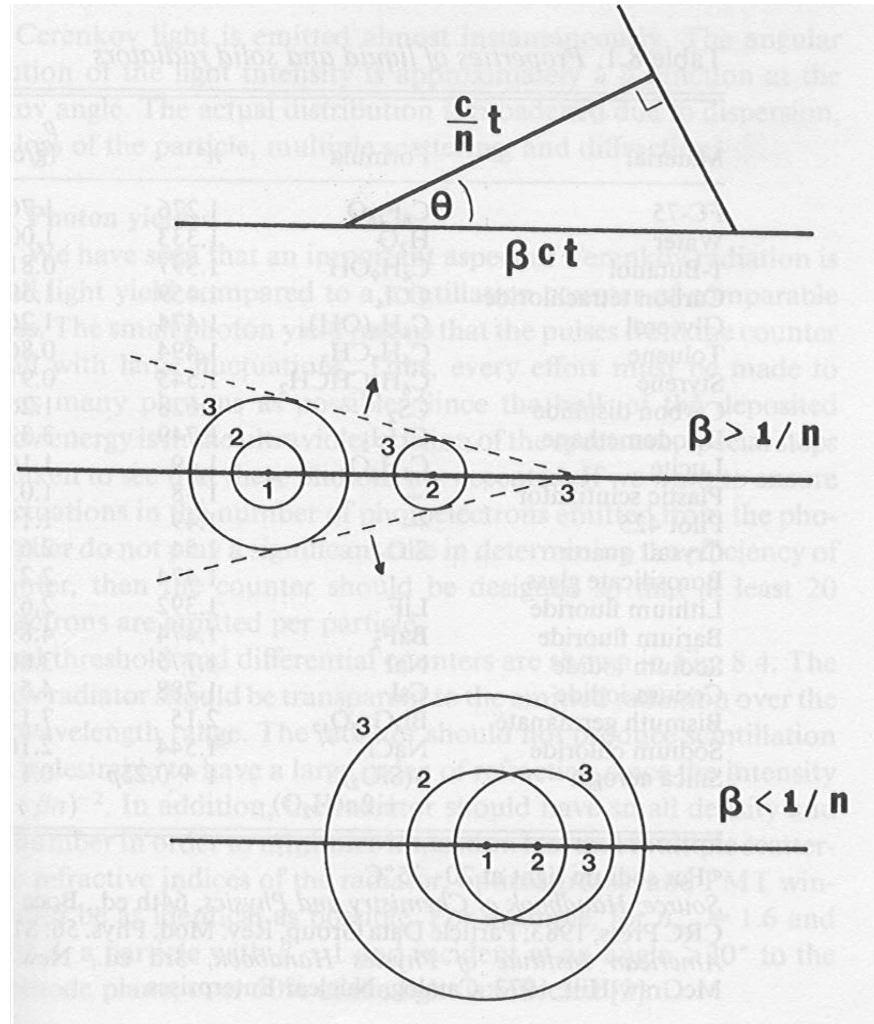
Apparatus used by Cherenkov to study the angular distribution of cherenkov photons (incident gamma ray produces electron by compton scattering in the liquid)

What did he observe ?

1. Light intensity is proportional to the electron path length in the medium
2. Light comes only from the “fast” electrons above a velocity threshold, in his apparatus
3. Light emission is prompt and the light is polarised
4. The wavelength spectrum of the light produced is continuous. No special spectral lines
5. The angular distribution of the radiation, its intensity, wavelength spectrum and its dependence on the refractive index agree with the theory proposed by his colleagues Frank and Tamm

Discovery and theory : 1934-37; Nobel prize 1958 to Cherenkov, Frank and Tamm

Cherenkov Radiation : Occurs when the velocity of a charged particles exceeds the velocity of light in a dielectric medium. Polarisation of particles in the vicinity of trajectory.
Electromagnetic shock wave



- **The direction of emission of Cherenkov light,** ***Cos θ = 1/ n β,***
- ***Criteria : nβ ≥ 1 (or $\gamma > 1/(1-1/n^2)^{1/2}$)***
- **The amount of energy emitted per unit frequency interval dω by a particle of charge Ze,**

$$\frac{dE}{dx d\omega} = \frac{Z^2 e^2}{c^2}\left(1-\frac{1}{\beta^2 n^2}\right)\omega; \quad \frac{dN}{dx} = 2\pi\alpha \int_{\beta n>1} \left(1-\frac{1}{\beta^2 n^2}\right)\frac{d\lambda}{\lambda^2}$$

$$\frac{dN}{dx} = 2\pi\alpha \sin^2\theta \left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right); \; for \;\; 350-500 \;\; nm; \quad \frac{dN}{dx} = 390\sin^2\theta \;\; photons/cm$$

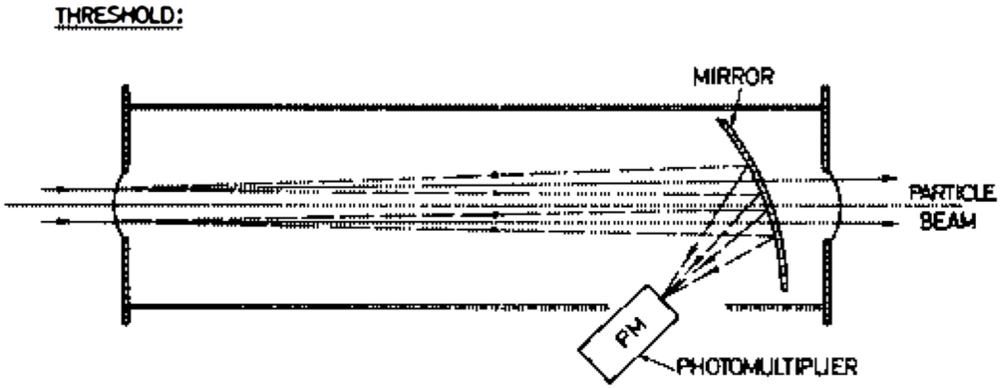
Cherenkov detector

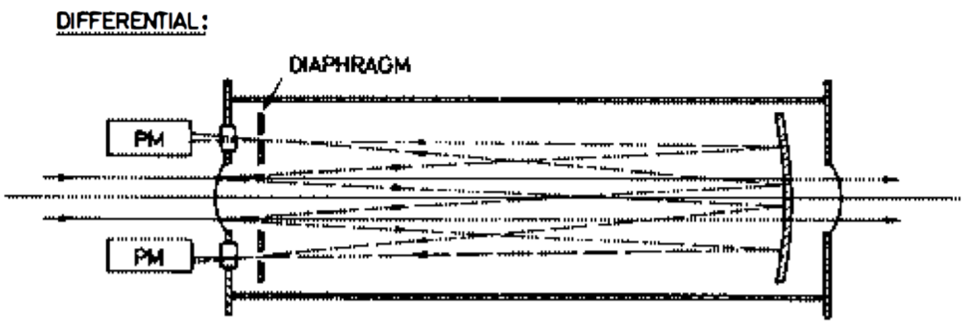
Material	n−1	γ_{th}
Glass	0.46-0.75	1.37-1.22
Scintillator	0.58	1.29
Plexiglass(acrylic)	0.48	1.36
Water	0.33	1.52
Aerogel	0.025-0.075	4.5-2.7
Pentane (NTP)	1.7×10^{-3}	17.2
CO2 (NTP)	4.3×10^{-4}	34.1
He (NTP)	3.3×10^{-5}	123

There is large gap in r.i., consequently γ_{th} for gas and liquid/solid.

Gas radiator : $(\gamma\beta)_{th} \propto 1/P^{1/2}$, increases of pressure brings momentum threshold down

Silica aerogel : $n(SiO_2)+2n(H_2O)$





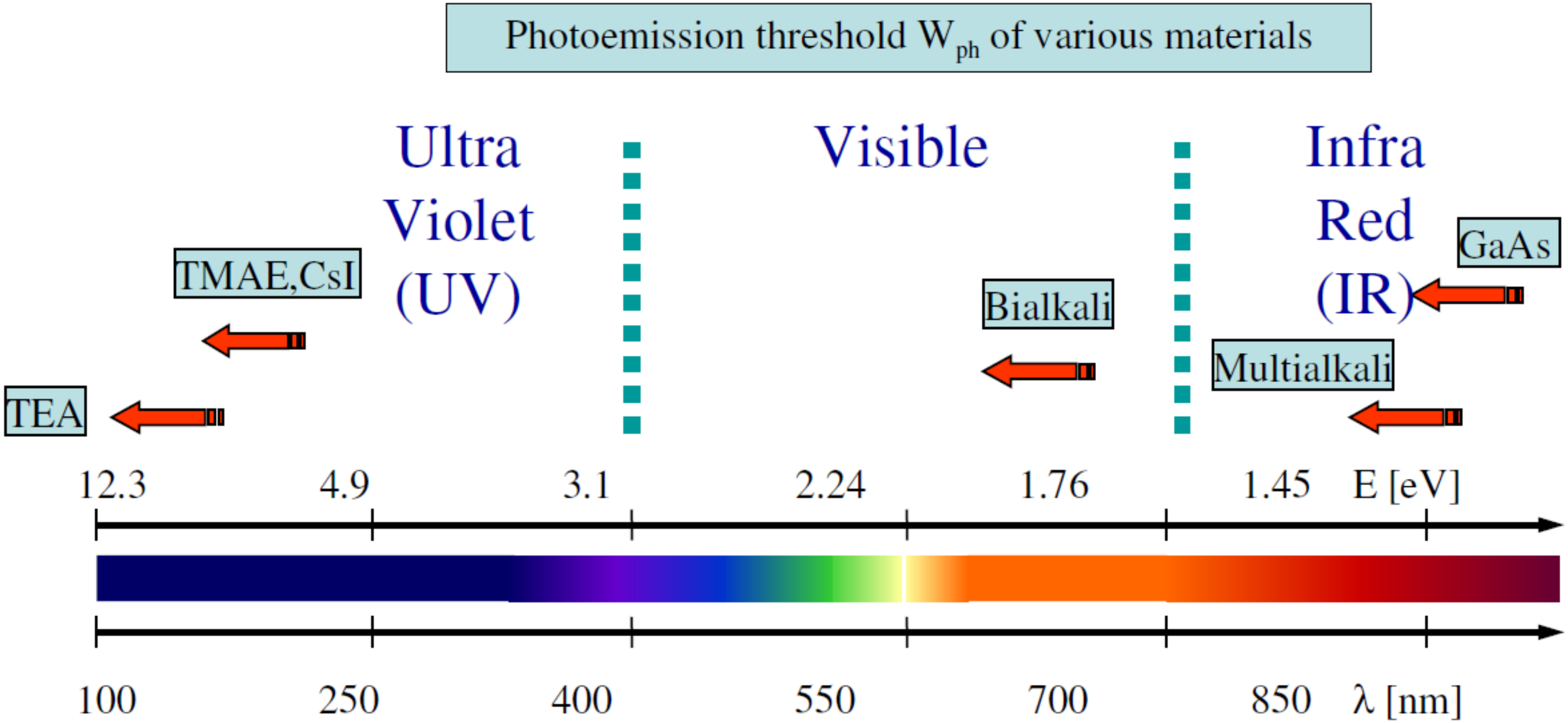
Threshold counter : For a momentum range only lighter particle emits cherenkov photon, early experiments through gaseous medium

Differential counter : Identification of particle through the measurement of velocity by accepting photons in a small annulus around some angle θ

- $\Delta\beta/\beta \sim 5\times 10^{-7}$ can be achieved $\Rightarrow \Delta\gamma/\gamma \approx \gamma^2\beta^2\times\Delta\beta/\beta = 0.4\%$ at $\gamma=200$
- Only suitable for well collimated beam of particles, not from secondary particles

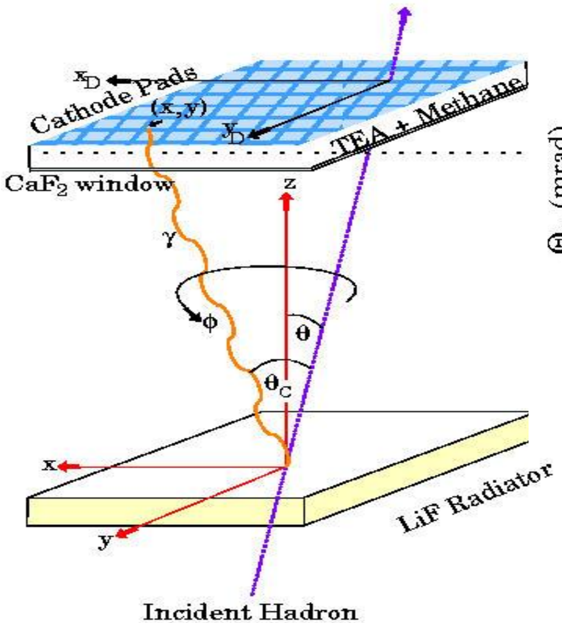
Detection of Cherenkov light

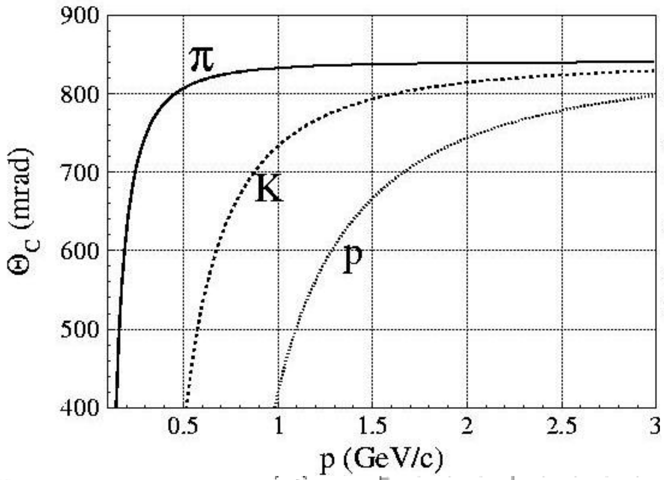
- **Energy of cherenkov photons : eV**
  - **Photoeffect dominants (phton is absorbed, transmits energy onto electron)**
  - **Strong Z and E dependence**
- **Ideal photo cathode : absorb all photons and emits all electrons, but Q.E. ~20-40%**

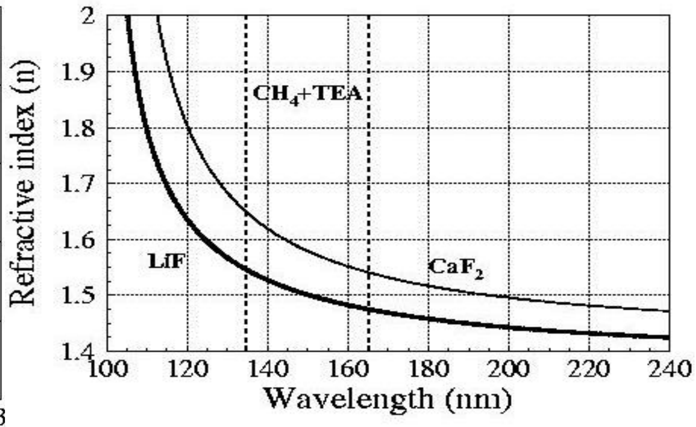


Differential Counter

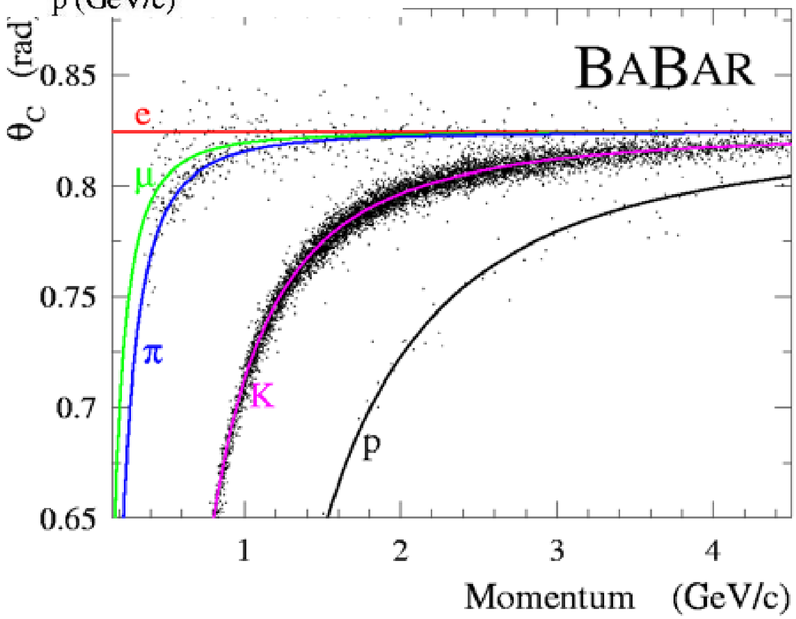
- **The formula cos(θ) = 1/nβ was predicted by Heaviside in 1888**







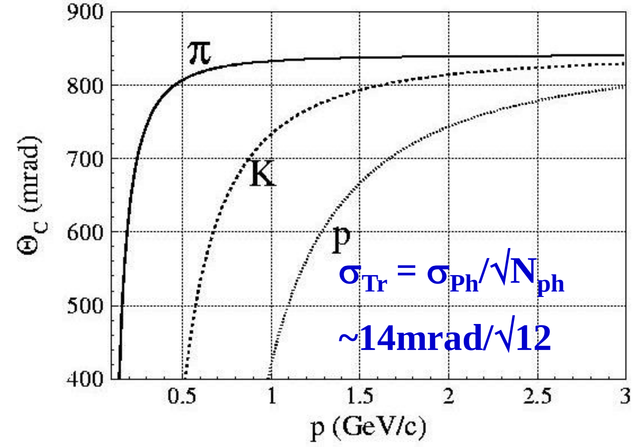
$$D^{*-} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^-_{slow}$$

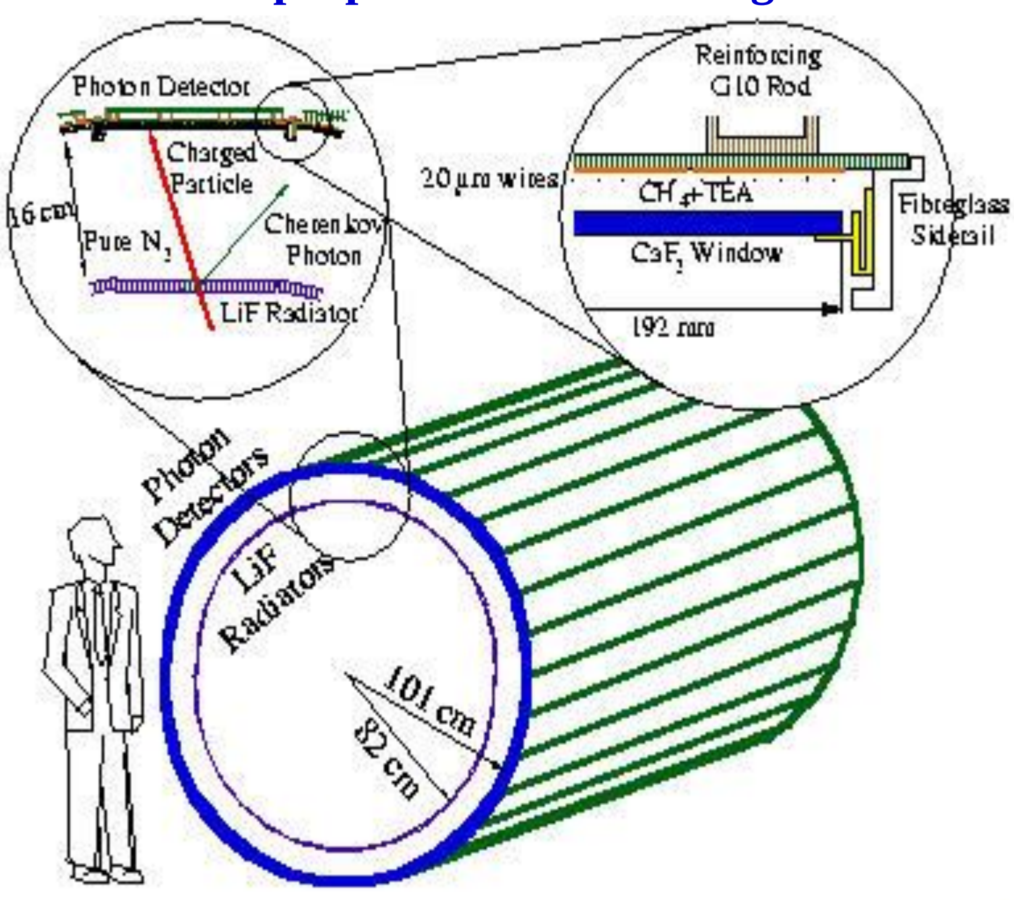


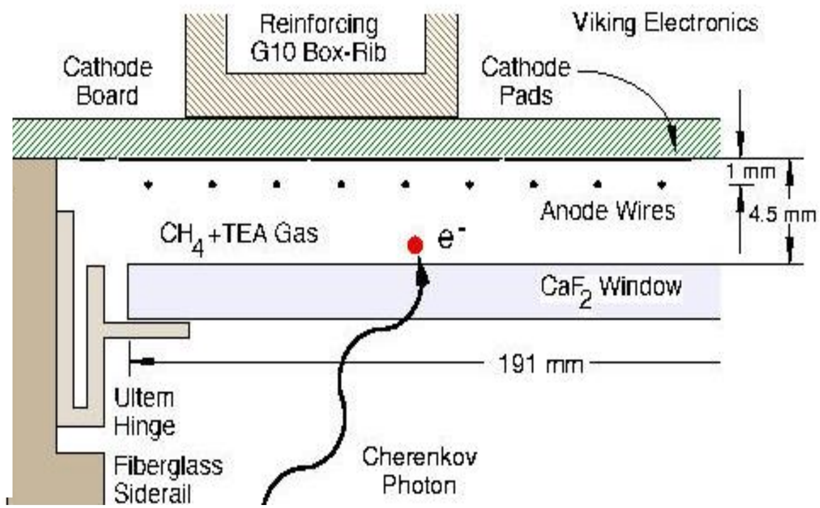
Slow pion is used to identify flavor

Ring Imagaing Cherenkov Counter (RICH)

- Concentrated on UV photon for large yield
- Radiating gas must be transparent in the UV, which restrict to a few gases, only noble gases and N_2
- Window also transparent to UV, LiF (11.8 eV)/MgF_2 (10.8 eV)/CaF_2 (10.0 eV)/BaF_2 (9.1 eV)/Sapphire Al_2O_4 (8.7 eV)/ quartz (7.3 eV)
- Detector : proportional/ drift/ Geiger and 2D readout



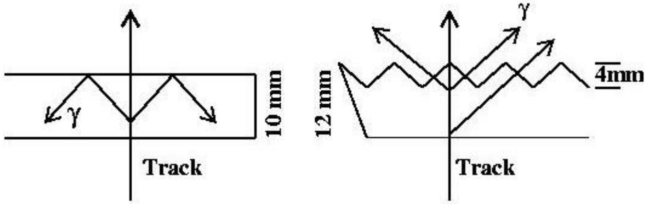




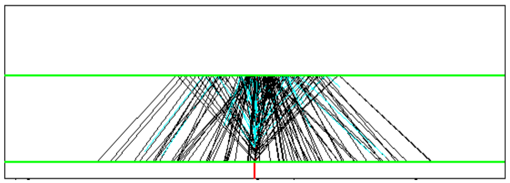
CLEO-III Sawtooth radiator

Flat vs

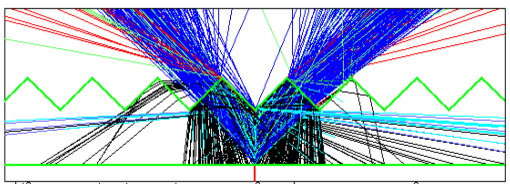
Sawtooth



Flat

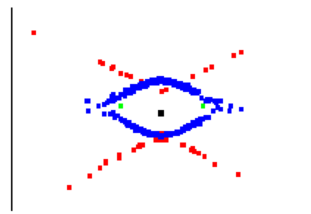


Sawtooth



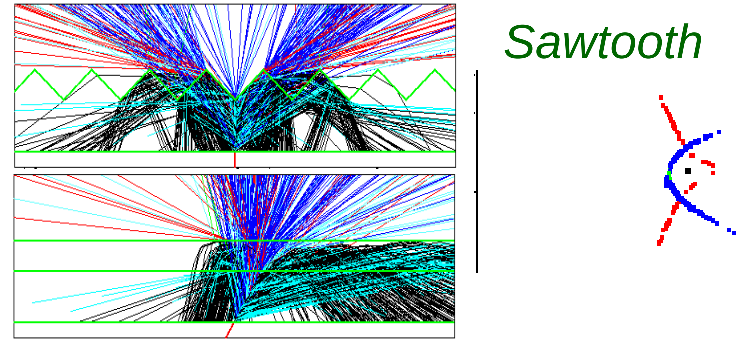
At <6° incidence:

Total internal reflection

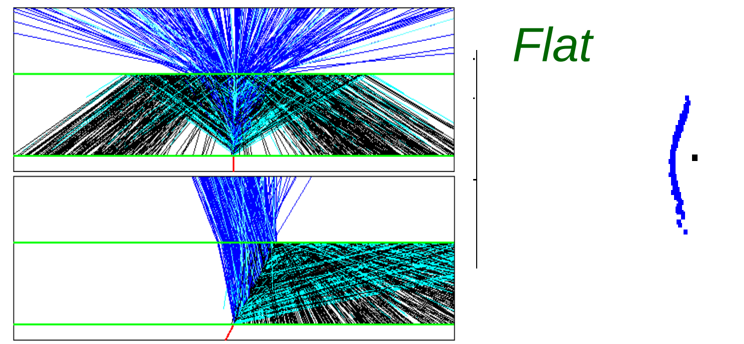


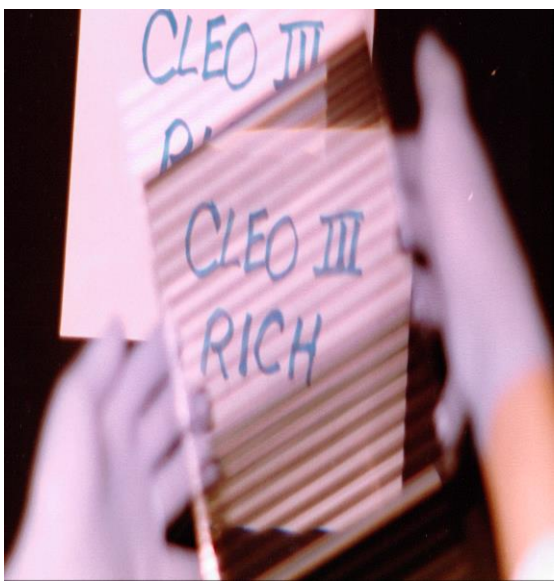
At 32° incidence:

Sawtooth



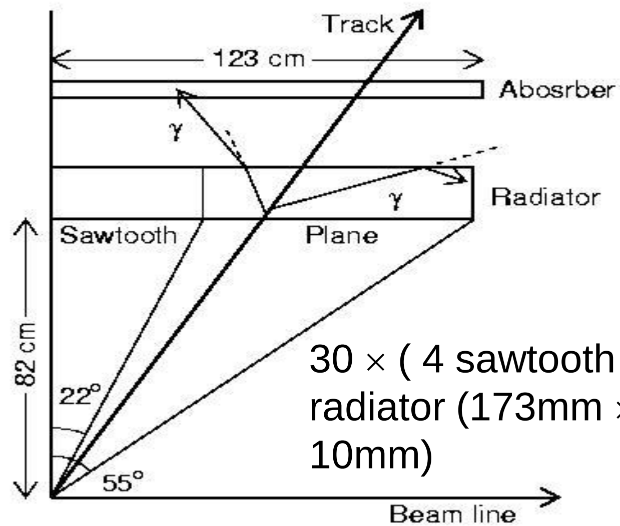
Flat





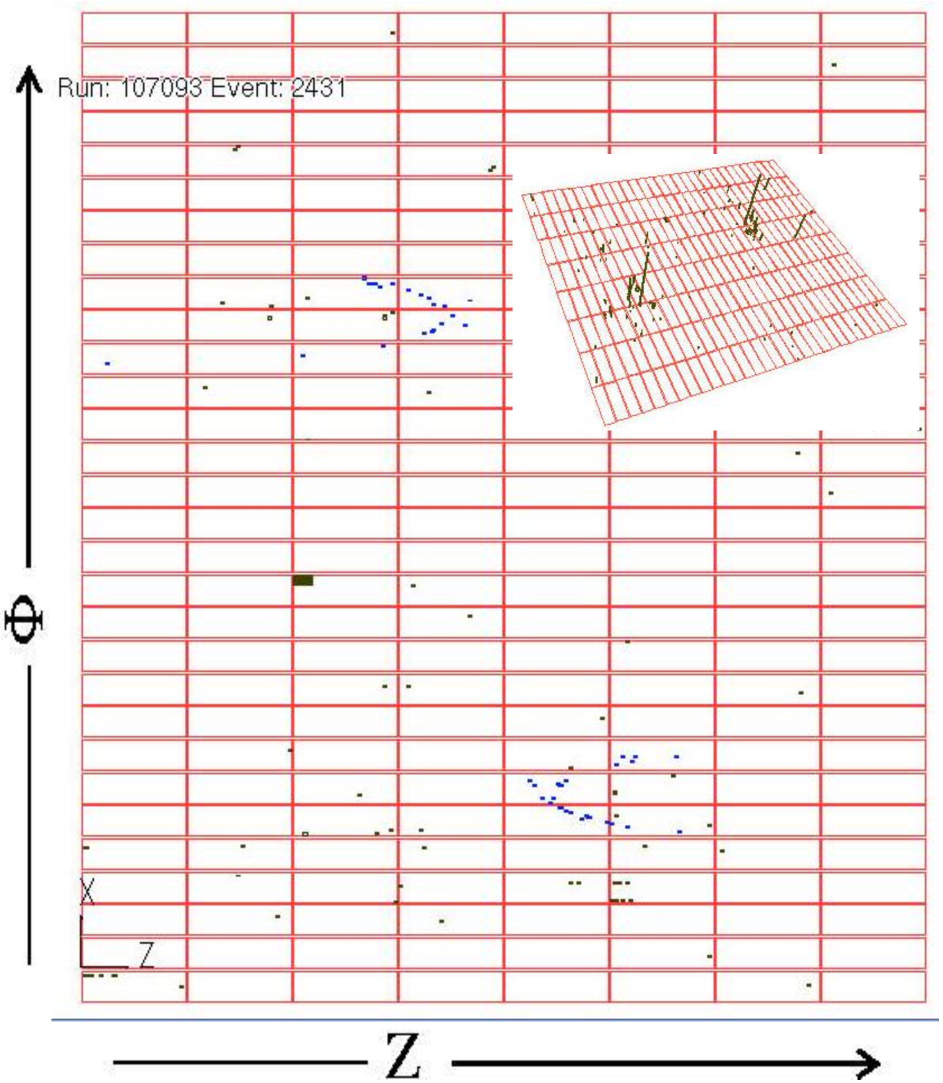
Use 42° sawtooth

Because of several possible paths, fake rate is worse than prediction from $\sigma_{\theta\ track}$, but still better than plane radiator

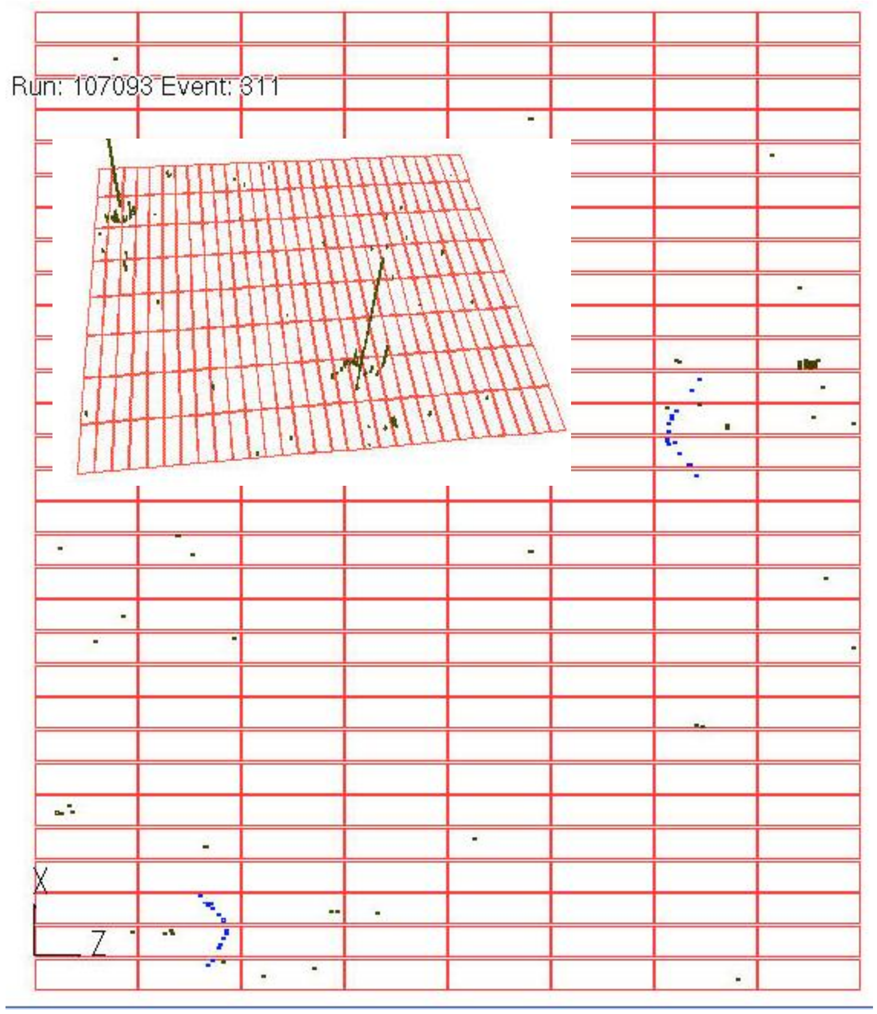


30 × (4 sawtooth + 10 plane) radiator (173mm × 170mm × 10mm)

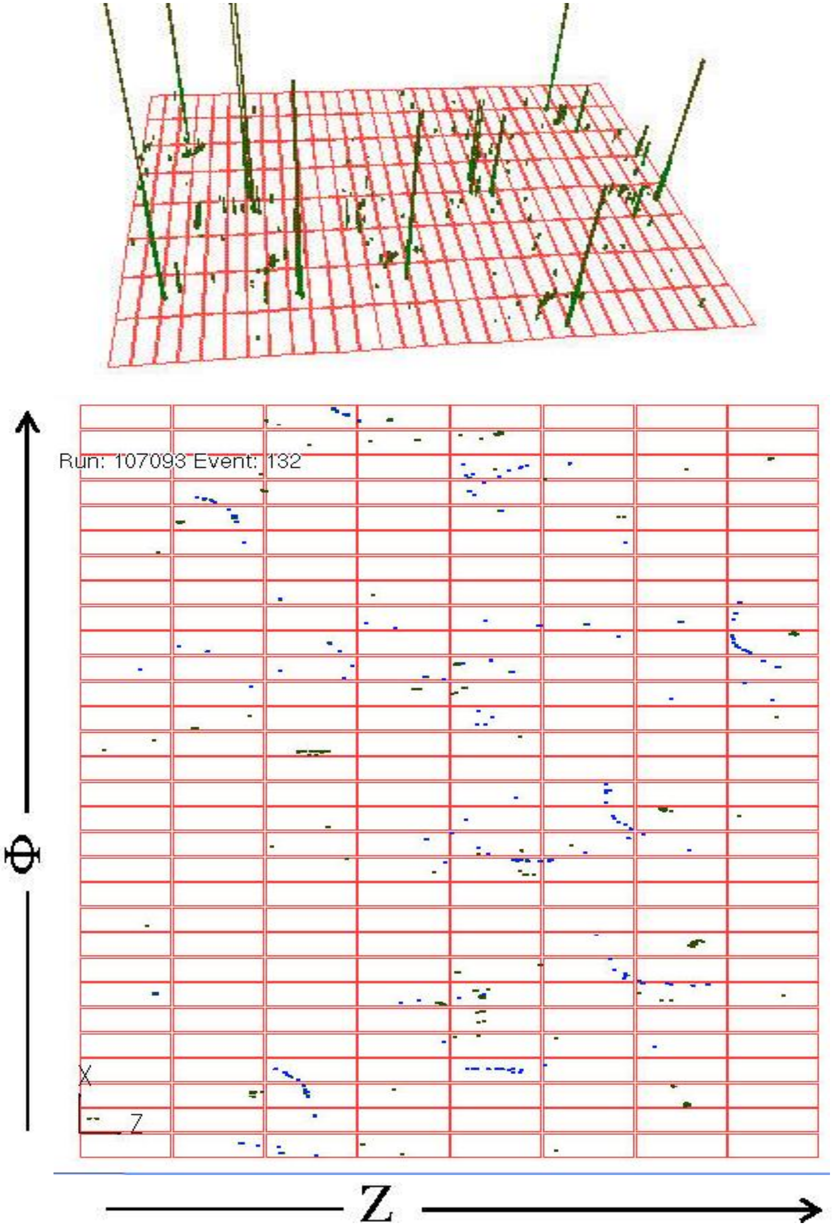
Bhabha event- sawtooth images

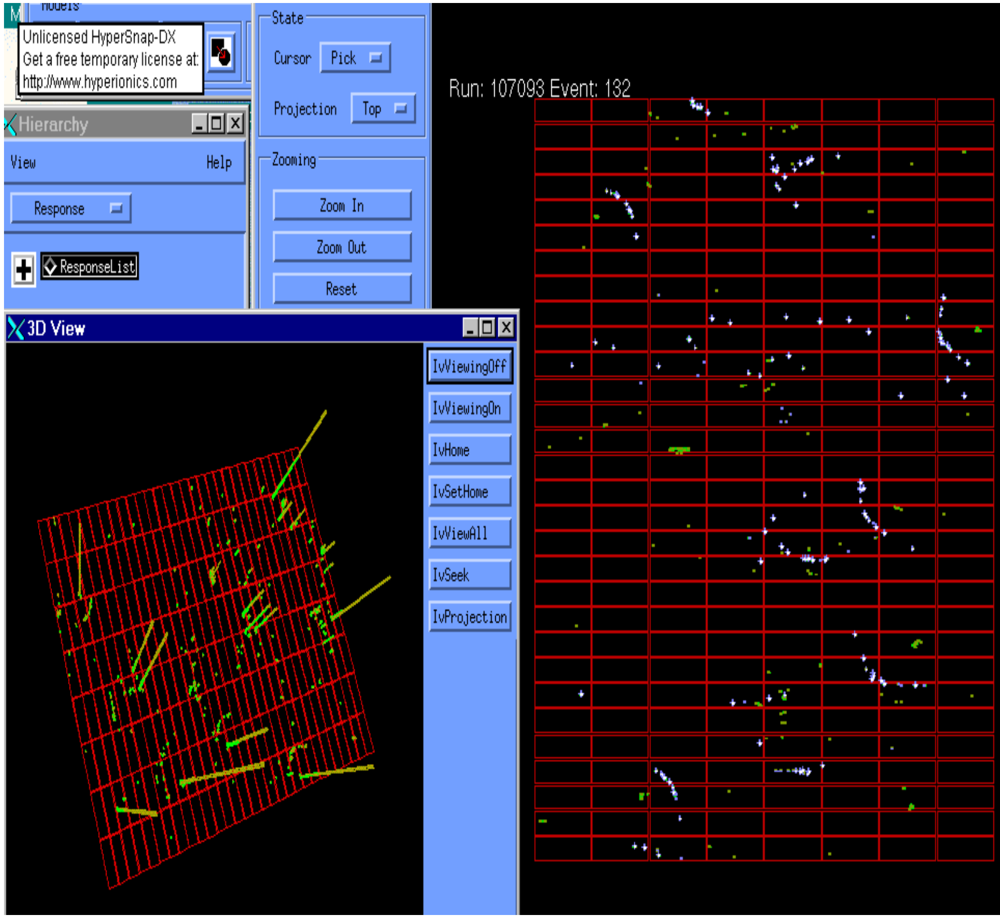


Bhabha event-plane radiator images



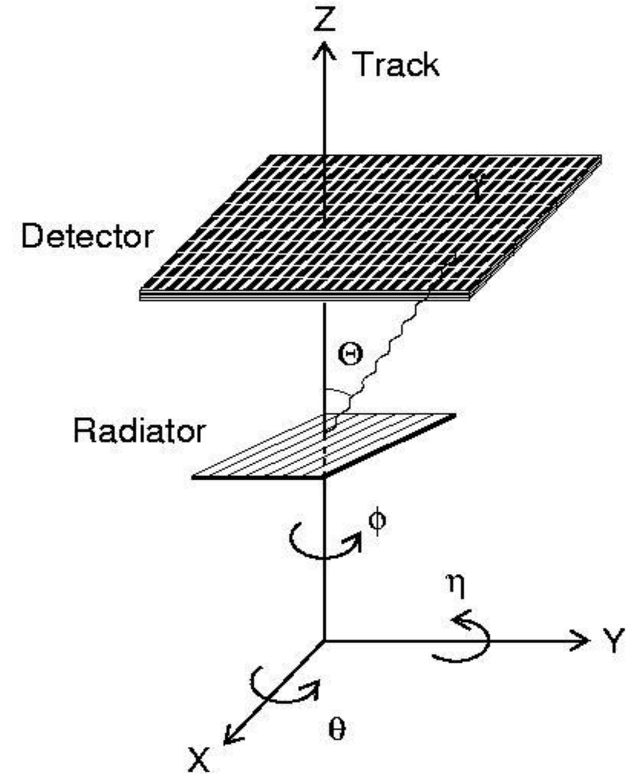
Hadronic event (RICH)

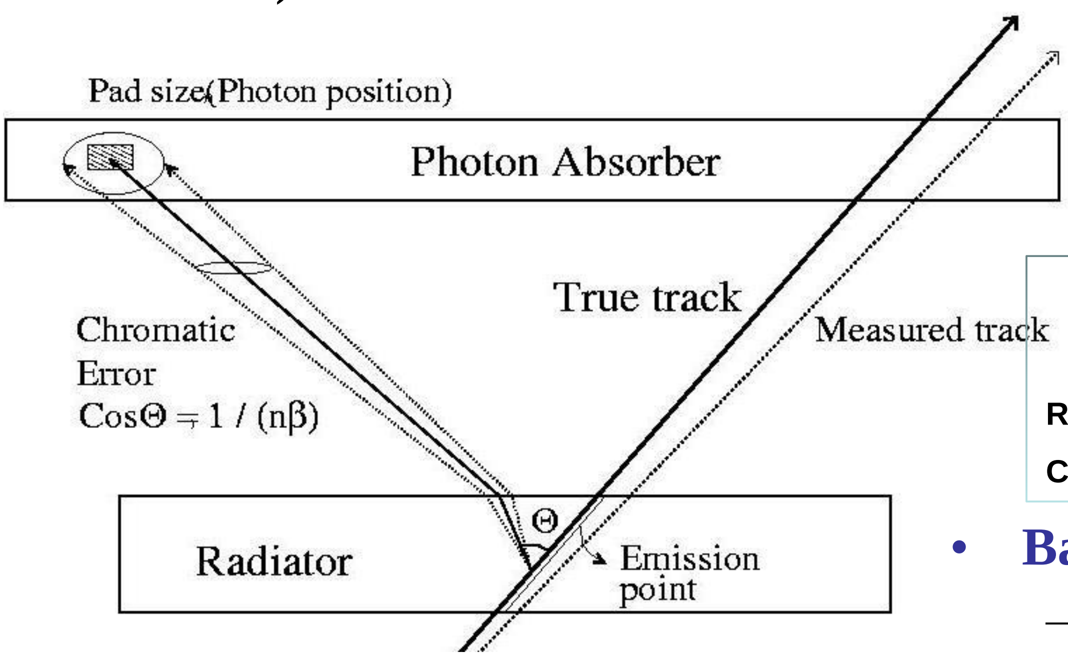




Source of error

- **Intrinsic**
  - **Chromatic ($\sigma_\theta(E) = (d\theta /dn)\ (dn /dE)\ \sigma_E$)**
  - **Emission point ($l_{rad}/ \sqrt{12}$)**
- **Detector**
  - **Photon position (depends on pad size and charge distribution)**
  - **Tracking error(Track position and momentum error)**





	ΔX	ΔY	ΔZ	Δϕ	Δθ	Δη
	μm	μm	μm	mrad	mrad	mrad
Radiator (photon)			200	1	2	2.5
Chamber (electron)	<50	<50		1		

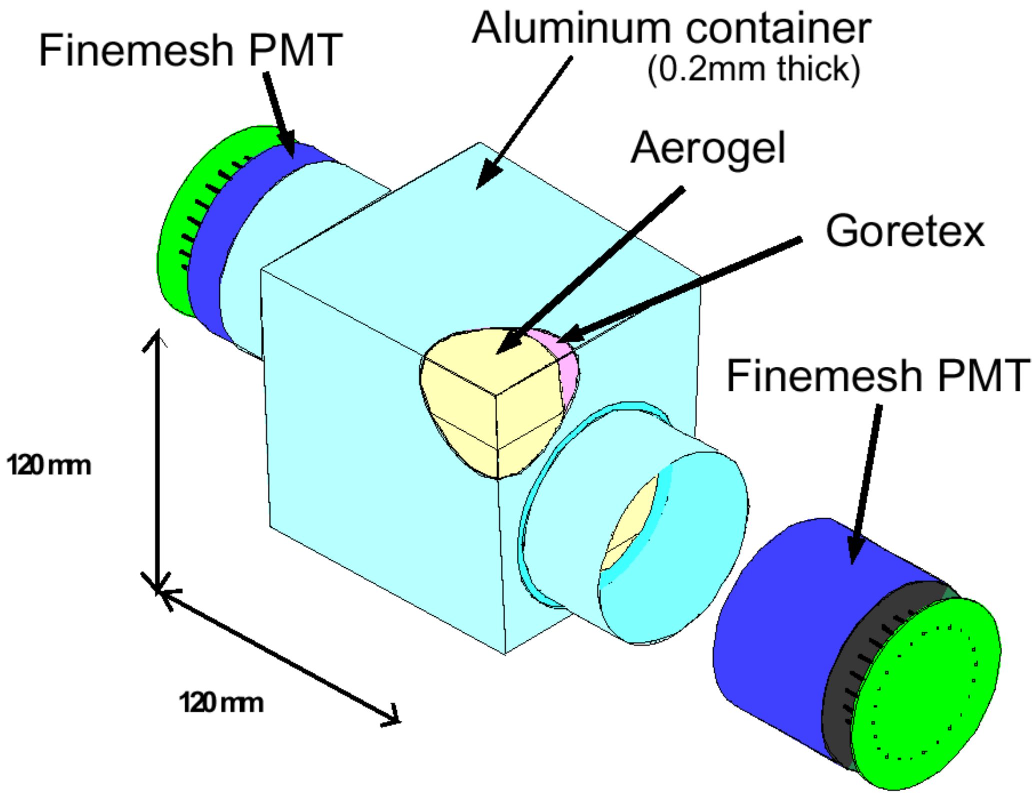
- **Background**
  - **Electronic noise**
  - **Photon from other track**

Threshold Cherenkov detector at Belle

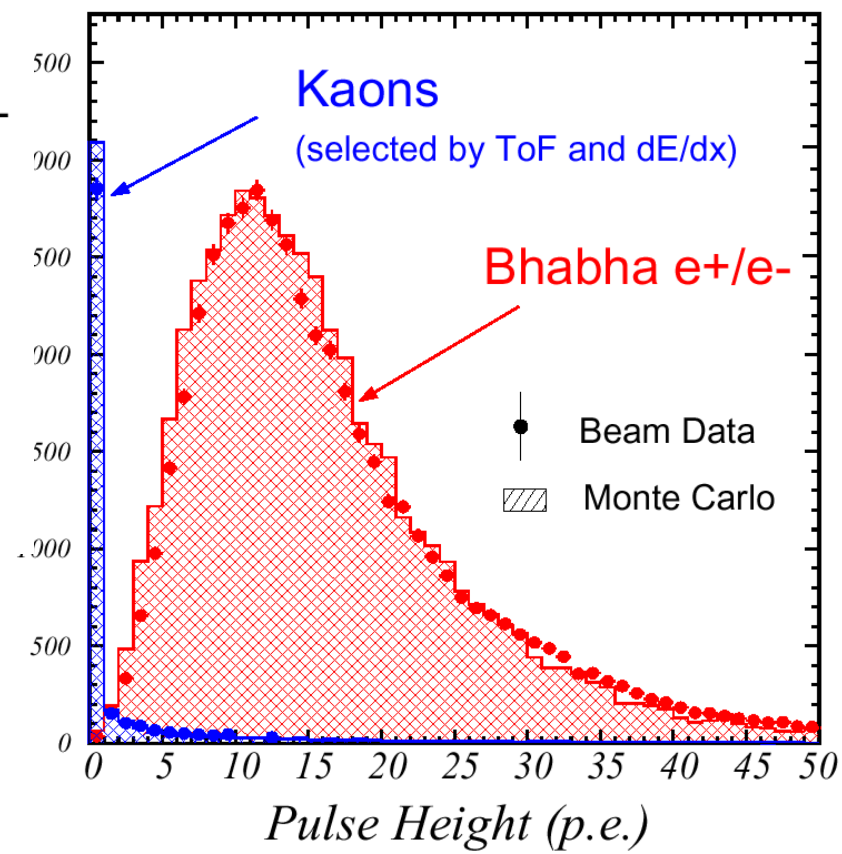
Differential counter

CLEO : Transmitted photon

BABAR : Reflected photon



Barrel Module



Transition radiation

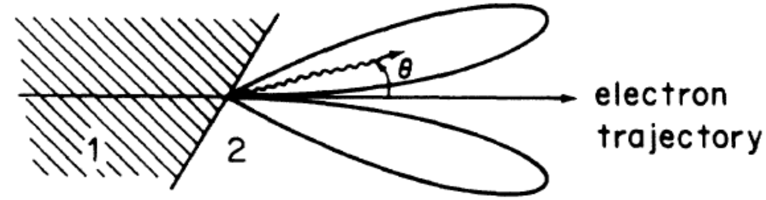
A charged particle emits transition radiation when it crosses the interface between two dielectric medium

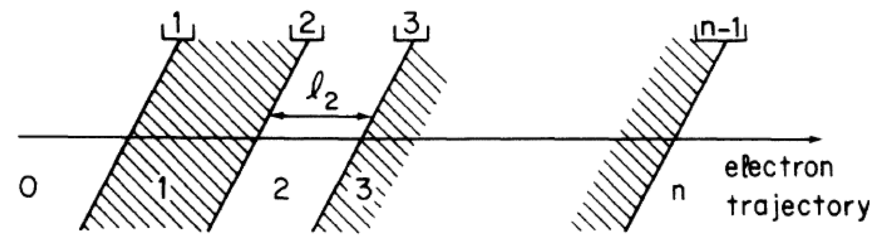
Phys. Rev. D12 (1975) 1289 NIM 140 (1977) 413

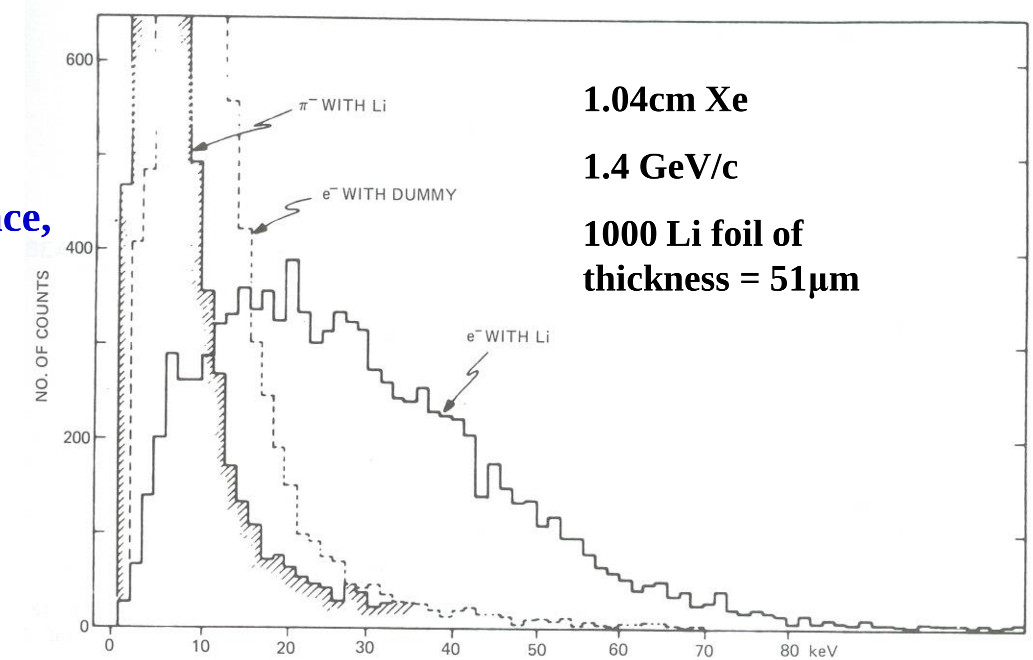
- **Particle in low dielectric medium**
  - **Polarisation effect in the surrounding medium are small**
  - **Electric field associated with the moving charge has a large spatial extent**
- **When the particle entered the region of higher dielectric constant**
  - **Polarisation effect reduces the extent of the electric field**
  - **Redistribution of charge will give rise to transition radiation**
- **Emitted photon is primarily X-ray**
- **The mean number of X-rays emitted/surface, $\langle N \rangle \sim (1/2)\alpha$**
- **The X-ray are emitted strongly forward direction, $n(w)\gamma\theta \leq 1$**

$$\frac{d^2W}{dw\, d\Omega} = \frac{\alpha}{\pi^2}\left|\frac{\theta}{\gamma^{-2}+\theta^2+\xi_1^2} - \frac{\theta}{\gamma^{-2}+\theta^2+\xi^2}\right|^2;$$

$$\xi = w_p^2/w^2; w_p^2 = \frac{4\pi\, ne^2}{m}$$ **Plasma frequency**

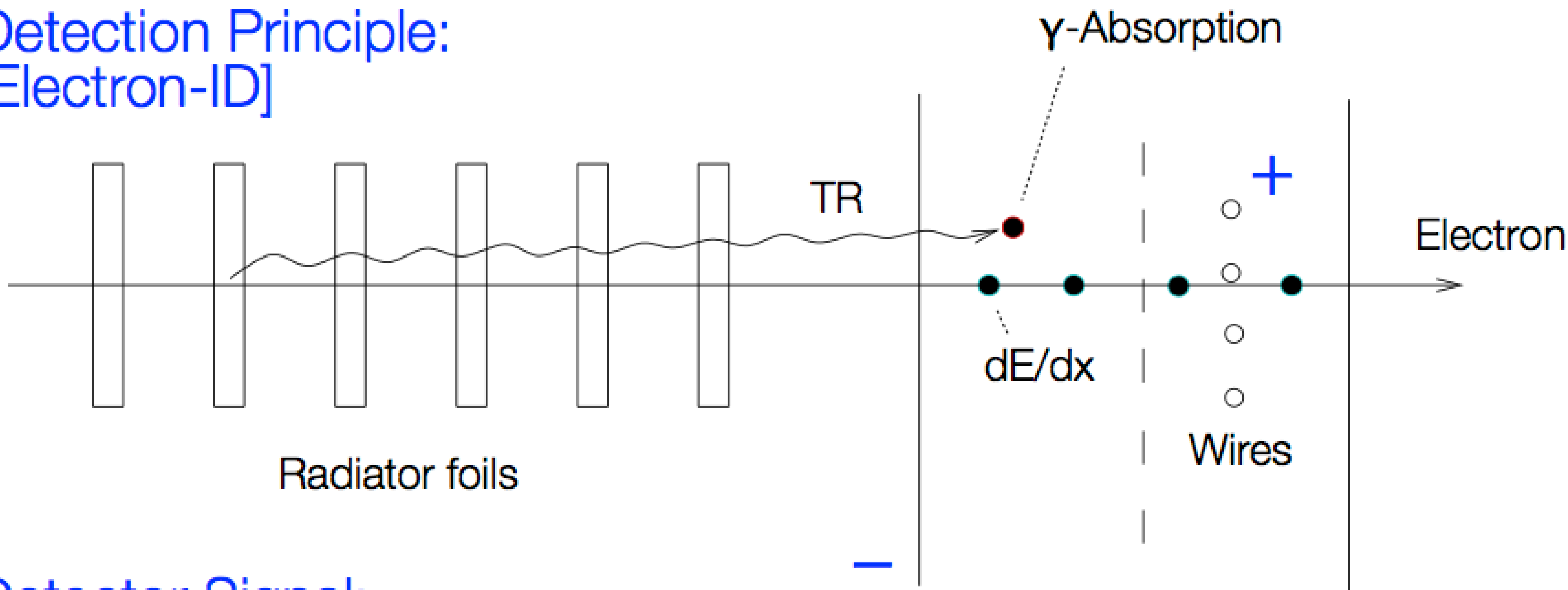




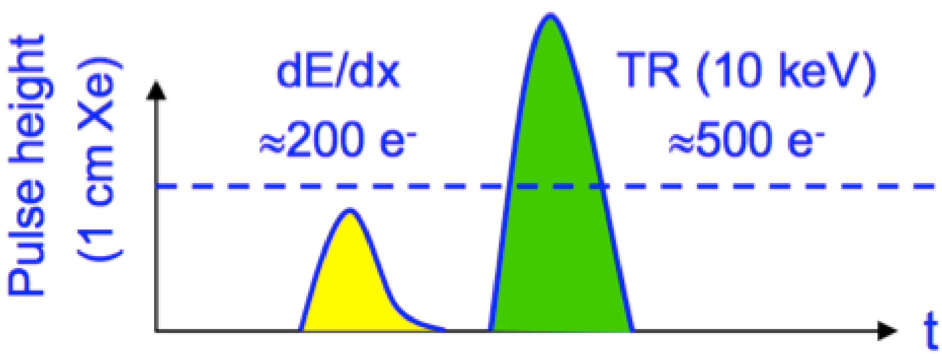


Identification of particles with Transition Radiation

Detection Principle: [Electron-ID]



Detector Signal:

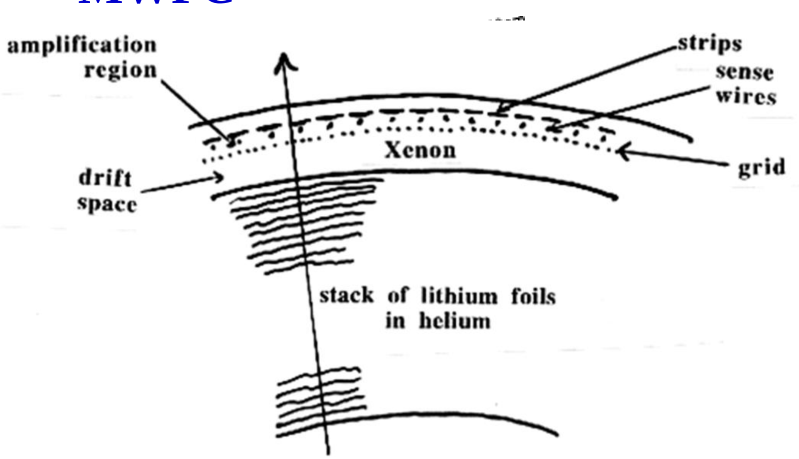


- Detector should be sensitive to $3 \leq E_{\gamma} \leq 30$ keV.
  - ✓ Gaseous detectors
- In gas $\sigma_{\text{photo effect}} \propto Z^5$
- Gases with high Z are required
  - ✓ e.g. Xenon (Z=54)

Lithium as radiator

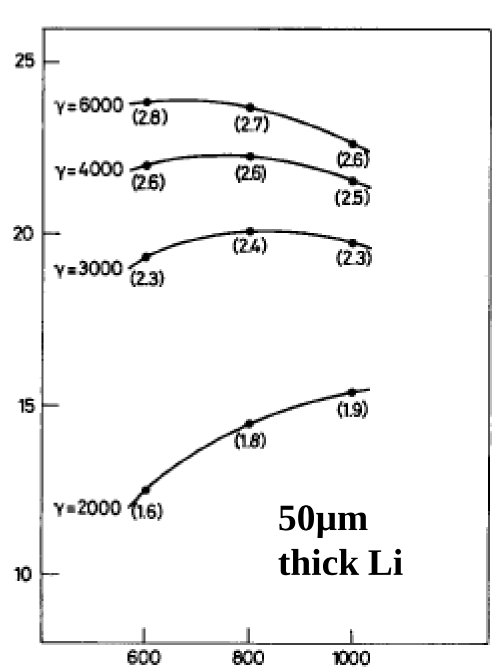
Practical transition radiation detector : Made up of stacks of thin foils, thereby providing many interfaces followed by an X-ray detector

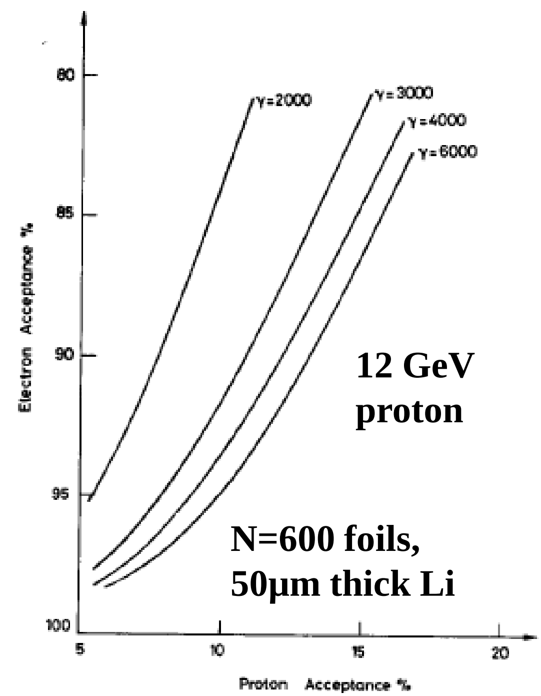
- X-ray absorption in material $\propto Z^{3.5}$
- Atomic number of the foil should be as low as possible
- Use Lithium foils ~ 50 – 100 µm thick, LiH is the best, but hazardas
- For X-ray detector Xe/CO_2 filled MWPC



- Its extreme softness, its flammability and its tendency to react with water.
- Large humidity : Foil loose its metallic bonding, converted into a white powder

Number of foil	Thickness of foils (µm)	Radiation length	Interaction length
650	~53±5	0.022	0.034
700	~53±5	0.025	0.037





Transition radiation : Summary

- **Intensity of radiation is logarithmically proportional to γ**

Angular distribution strongly forward peaked
[Interference; coherence condition]

$$\theta \leq 1/\gamma$$

Coherent radiation is generated only over a very small formation length

Plasma frequency
[from Drude model]

$$D = \gamma c/\omega_p$$

Volume element from which coherent radiation is emitted ...

$\rho_{max} = \gamma v/\omega$
[transversal range ...
... with large polarization]

$$V = \pi D \rho^2_{max}$$

Maximum energy of radiated photons limited by plasma frequency ...
[results from requiring $V \neq 0 \rightarrow \omega = \gamma\omega_p$]

$$E_{max} = \gamma\hbar\omega_p$$

[X-Rays → large γ!!]

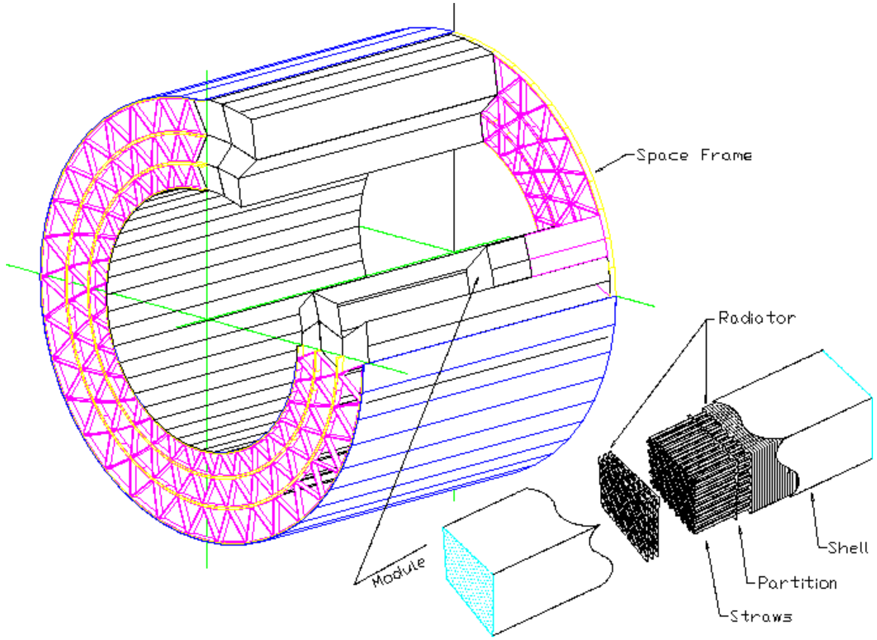
Typical values:

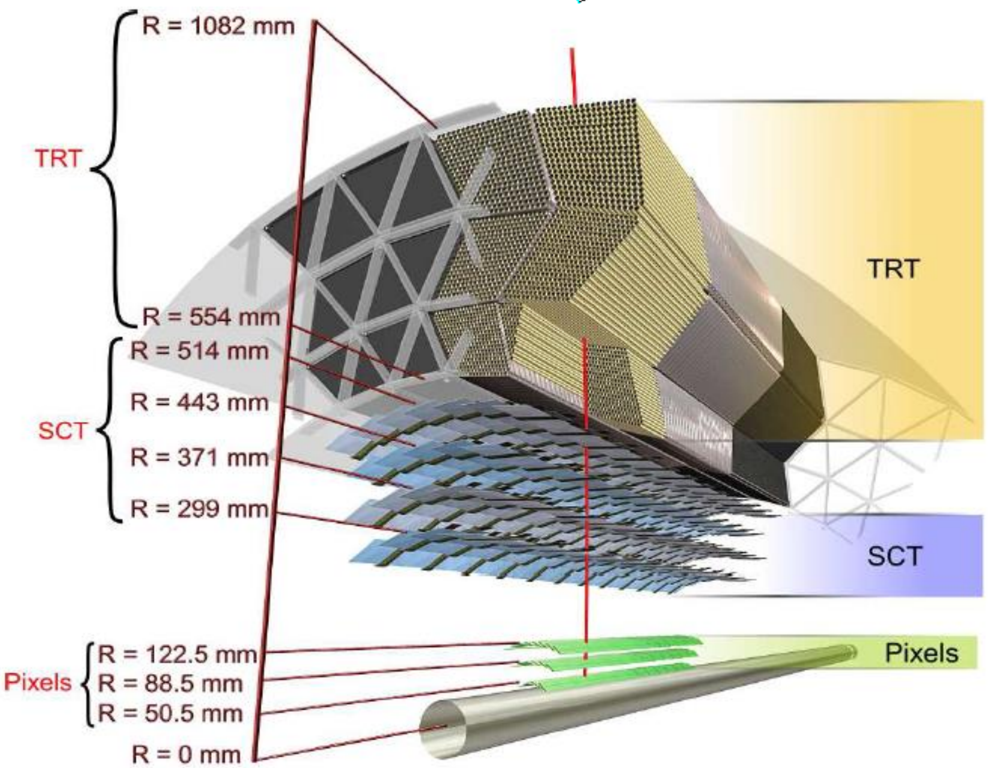
	CH_2:	$\hbar\omega_p = 20$ eV; $\gamma = 10^3$
	[Air:	$\hbar\omega_p = 0.7$ eV]

$$D = 10\ \mu m$$

[d > D: absorption dominates]

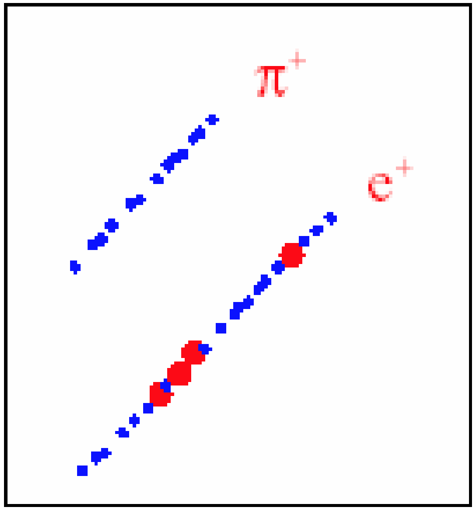
ATLAS TRT : Electron identification





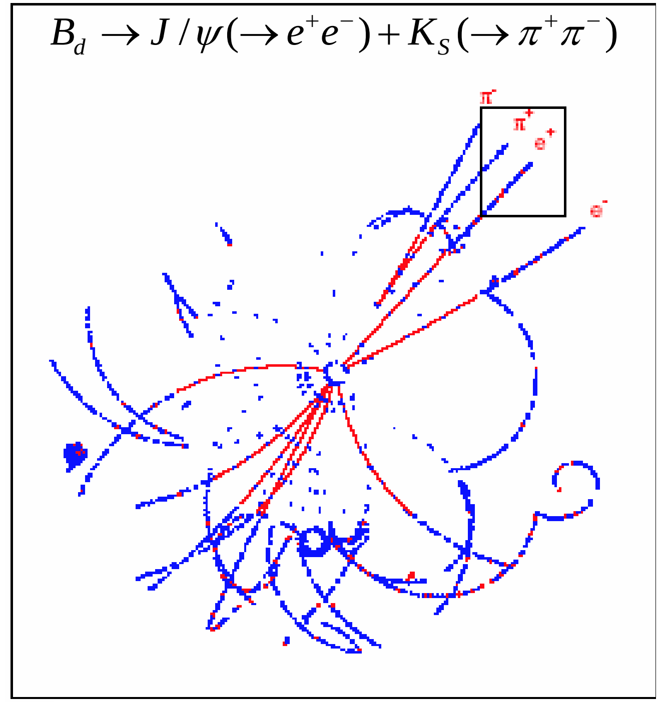
- **Polypropylene serving as the transition radiation material**
- **73 layers of straws interleaved with 19 μm-φ polypropylene fibres (barrel) and 160 straw planes interleaved with 19 μm thick foils (end-cap)**
- **7-10 hits from transition radiation are expected for electrons with energies above 2 GeV**
- **Each straw is 4 mm in diameter, made of 400 μm thick carbon fibre and equipped with a 30 μm diameter gold-plated W-Re wire as anode, attenuation length, λ~4m, propagation time ~4ns/m**
- **Xe(70%), CO_2(27%), O_2(3%), with 5-10mbar over pressure**
- **gain=2.5×10^4 at –1530V@cathode,**
- **Spatial resolution of 170 μm per straw**

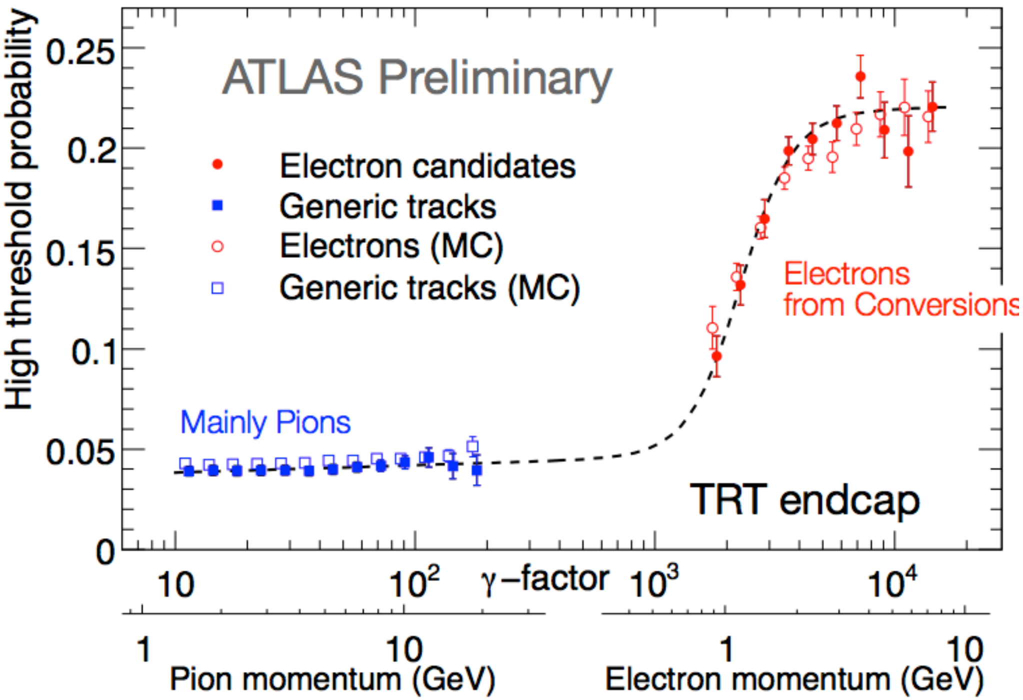
Performance of ATLAS TRT

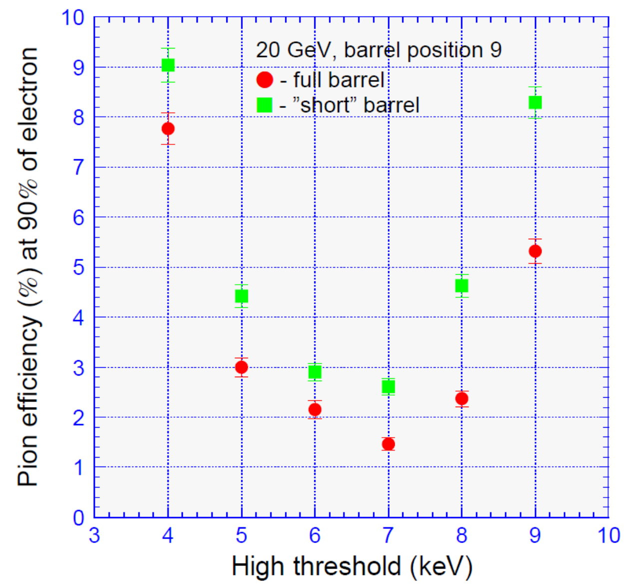


Blue dots: ionizing hits

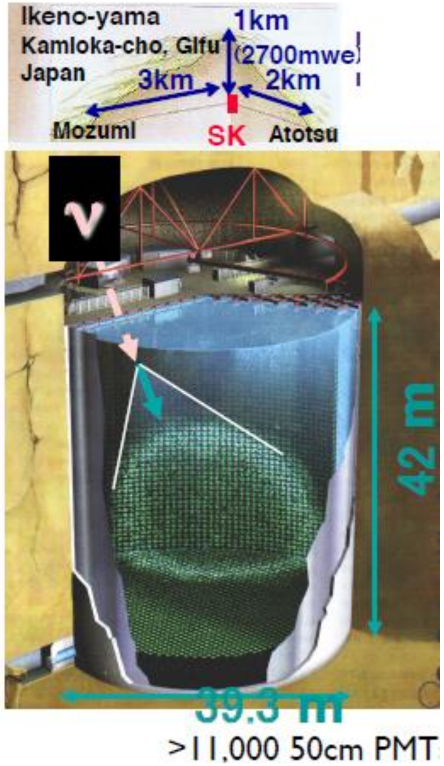
Red dots : TR hits



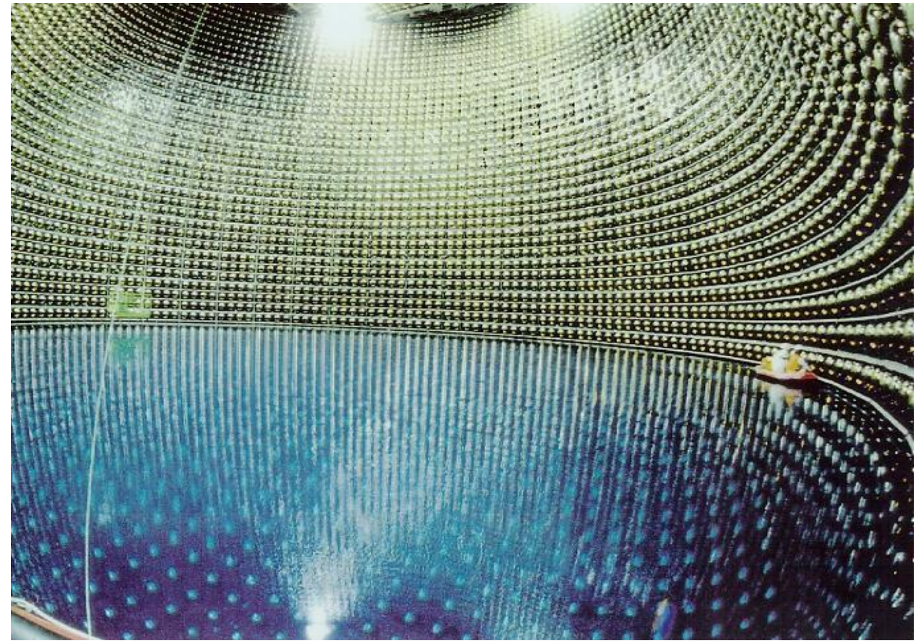


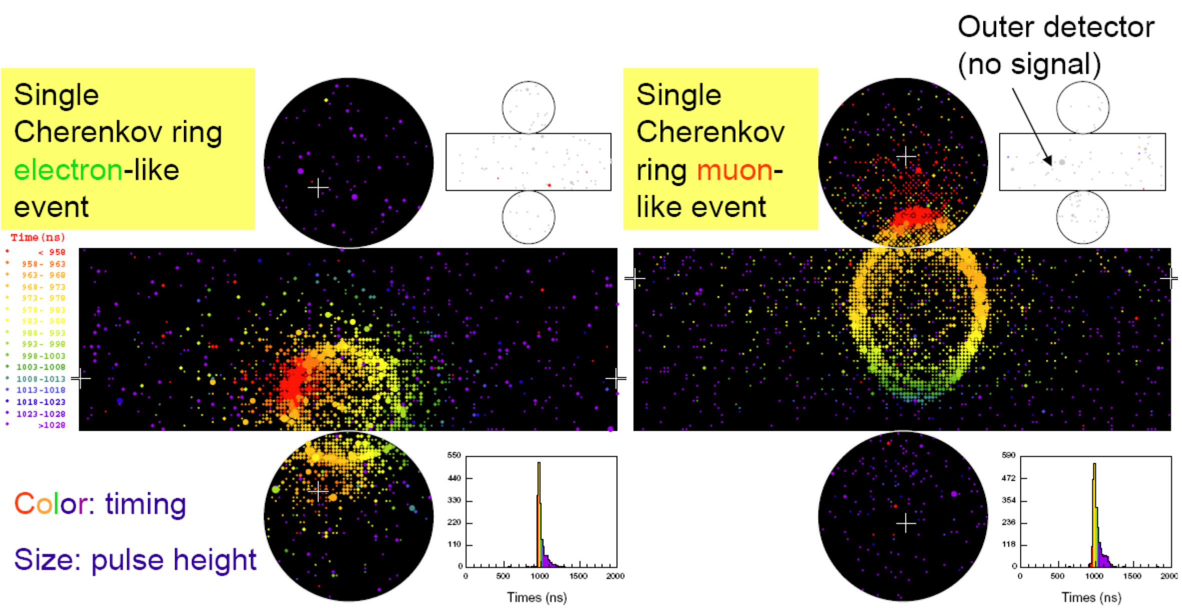


SuperKamiokande



- Kamokande Detected neutrinos from Supernova 1987A and reported less than expected atmospheric muon neutrino events.
- Super-Kamiokande was proposed by Yoji Totsuka and funded in 1991. It became operational in 1996.



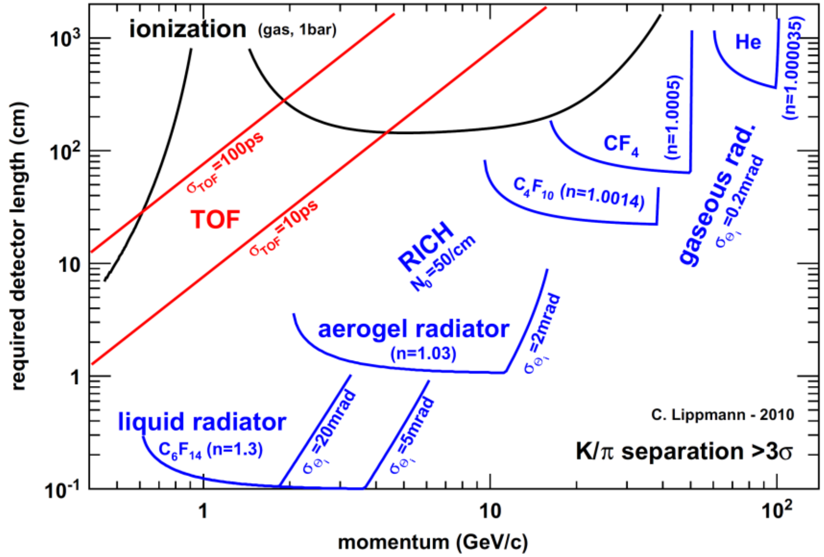


Data from Kamiokande in 1988
Phys. Lett. B 205, 416–420
Atmospheric neutrino anomaly

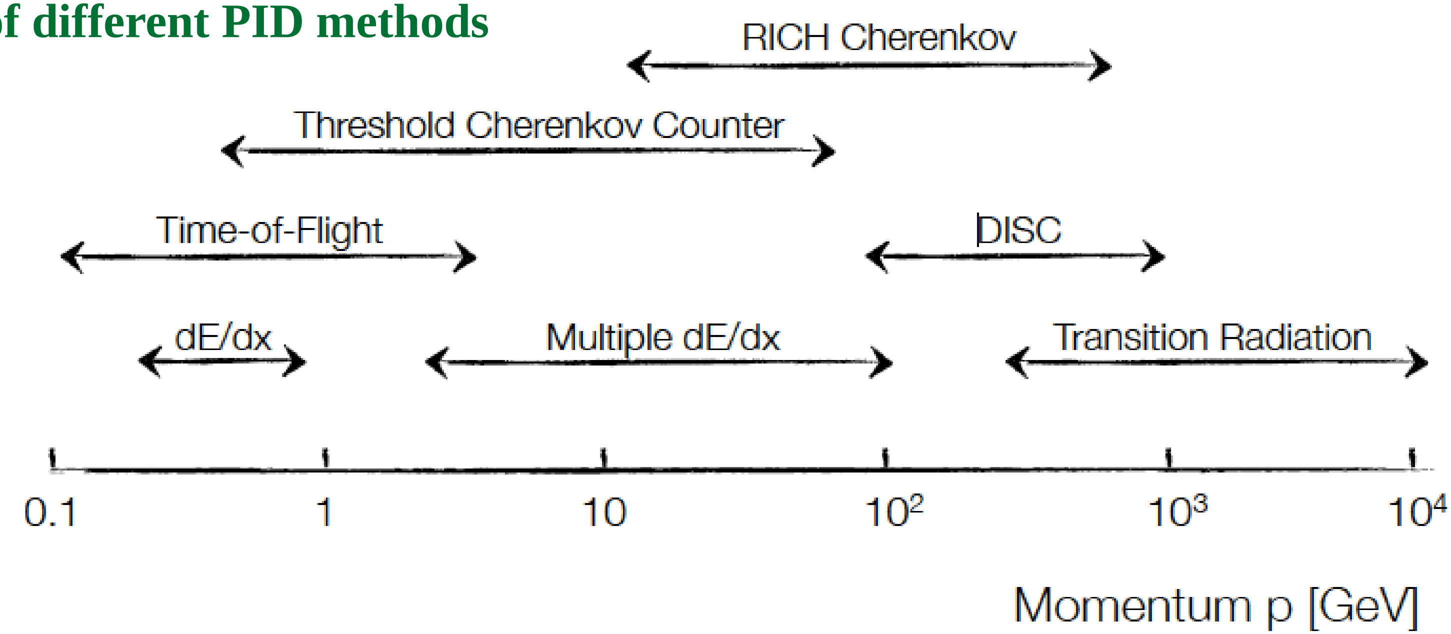
	Data	M.C.
e-like events	93 ± 9.6	88.5
μ- like events	85 ± 9.2	144.0

Charged Particle identification

- **Velocity:**
  - **Time-of flight** $\Delta t \propto 1/\beta$
  - **Cherenkov angle** $\cos\theta = 1/n\beta$
  - **Transition radiation** $\gamma \geq 1000$
- **Energy loss: Bethe-Bloch** $\frac{dE}{dx} \propto \frac{z^2}{\beta^2} \ln(a\beta\gamma$
- **Total energy: Calorimeter** $E = \gamma mc^2$

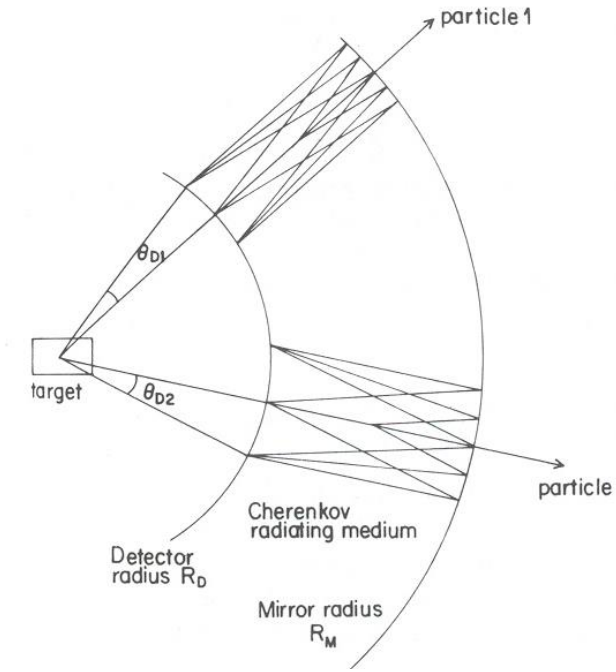


π/K Separation : Comparison of different PID methods



Directional Isochronous Self Collimating (DISC) counter

- **The image consists of a ring in the focal plane of the mirror with radius**
- **$r = f \tan\theta$, f=focal length of mirror, radius of curvature of mirror (R_M) =2f = $2R_D$**
- **Characteristics of ideal detector :**
  - **Large spherical surface (solid angle coverage)**
  - **Uniform sensitivity**
  - **Localising spatial position of photon**
  - **High quantum efficiency**
  - **Good time resolution**



- **Slit width $\Delta r \Rightarrow$ angular range $\Delta\theta = \cos^2\theta \, \Delta r/f$**
- **Velocity resolution, $\Delta\beta/\beta = \tan\theta \, \Delta\theta$**
- **The minimum angular resolution is limited by dispersion, , $\Delta\theta_{disp} = \Delta n/(n \tan\theta)$**
  - **Affected by beam divergence, optical aberration, multiple scattering, energy loss, diffraction, granularity (finite size) of detector.**
  - **Small optical disp : He, Ne, SF_6**
  - **Less multiple scattering, H_2, CH_4, He.**

$$\left(\frac{\Delta\gamma}{\gamma}\right)_1 = \gamma^2\beta^3 n \;\sin\theta\,\Delta\theta; \quad \frac{\Delta\gamma}{\gamma} = \left(\frac{\Delta\gamma}{\gamma}\right)_{N_e} = \frac{1}{\sqrt{N_e}}\left(\frac{\Delta\gamma}{\gamma}\right)_1 = \frac{1}{\sqrt{N_e}}\gamma^2\beta^3 n\left(\sqrt{\frac{N_e}{N_0 L}}\right)\Delta\theta = \frac{\gamma^2\beta^3 n}{\sqrt{N_0 L}}\Delta\theta = \frac{\gamma^2\beta^3 n}{\sqrt{N_0 L}}\frac{\Delta r}{R_D}$$