Particle Detection
in
High-Energy Physics Experiments
Part -II

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Particle detection Principle

In order to detect a particle

- it must interact with the material of the detector
- transfer energy in some recognizable fashion

i.e. The detection of particles happens via their energy loss in the material it traverses ...

Possibilities:

Energy loss
by multiple reactions

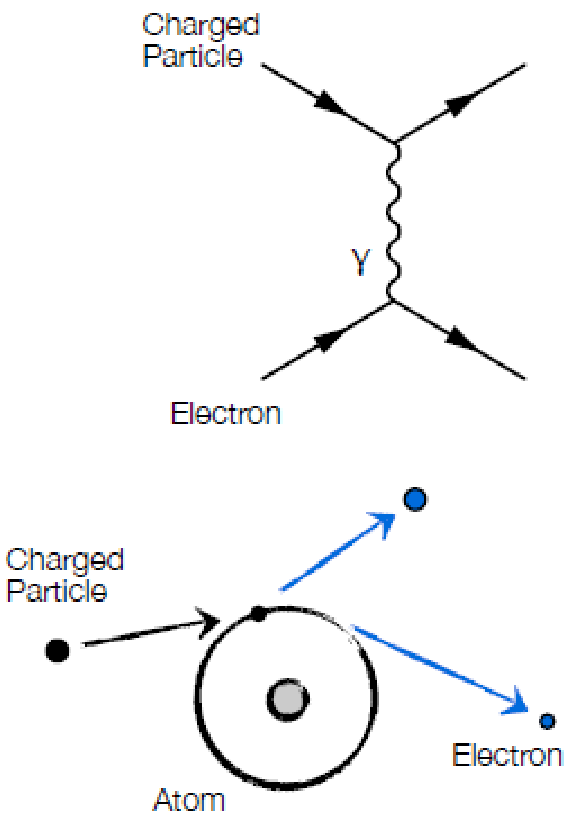
Charged particles	Ionization, Bremsstrahlung, Cherenkov ...
Hadrons	Nuclear interactions
Photons	Photo/Compton effect, pair production
Neutrinos	Weak interactions

Total energy loss
via single interaction

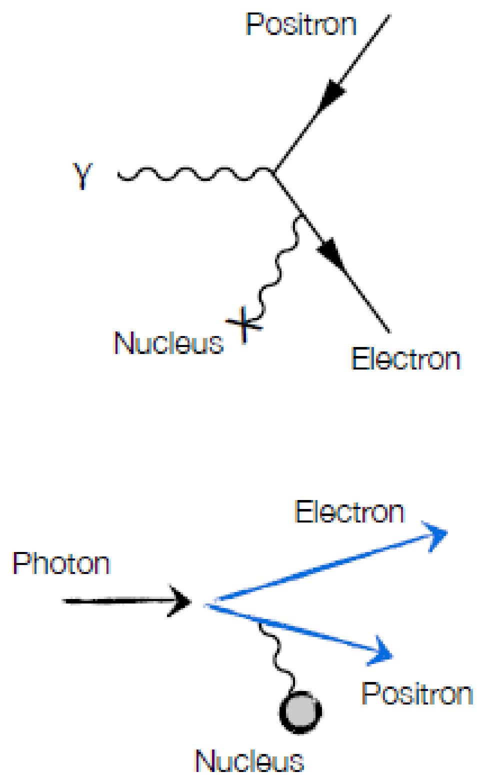
→ charged particles

Particle Interactions: Examples

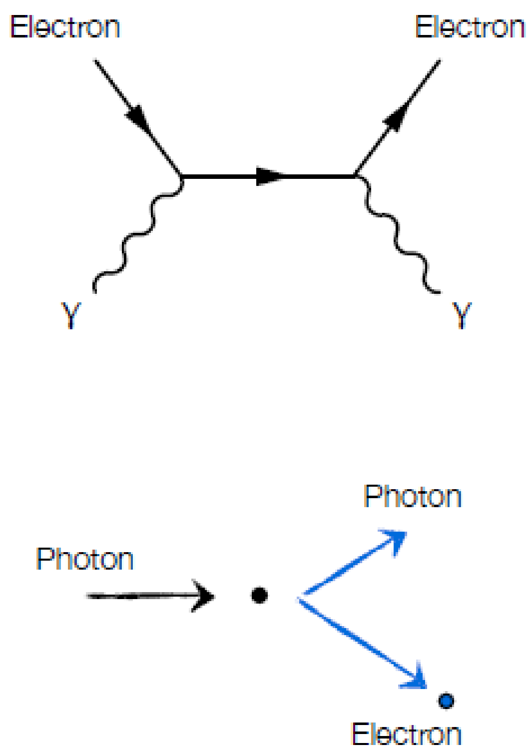
Ionization:



Pair production:



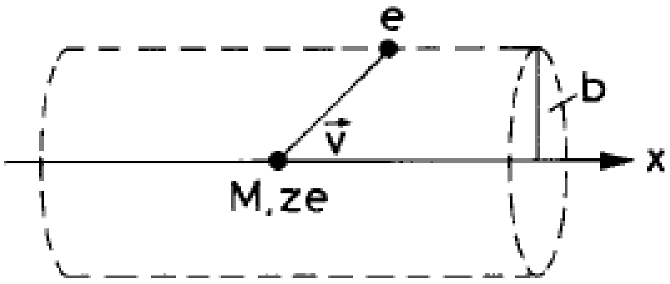
Compton scattering:



Energy Lass by Ionisation : Bethe-Bloch Formula

Particle with charge ze and velocity v moves through a medium with electron density n.

Electrons considered free and initially at rest.



Interaction of a heavy charged particle with an electron of an atom inside medium.

Momentum transfer:

Symmetry!

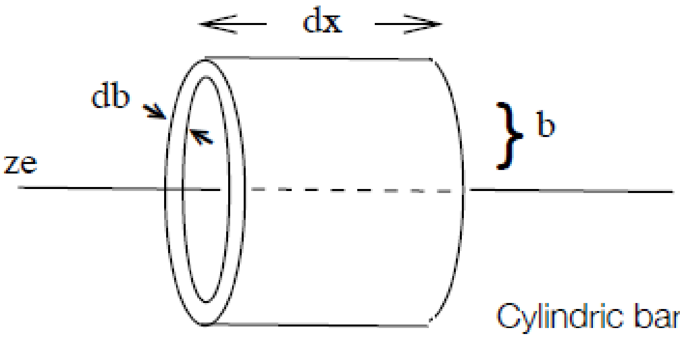
$$\Delta p_{\perp} = \int F_{\perp} dt = \int F_{\perp} \frac{dt}{dx} dx = \int F_{\perp} \frac{dx}{v} \qquad \Delta p_{||} \ : \ \text{averages to zero}$$

$$= \int_{-\infty}^{\infty} \frac{ze^2}{(x^2+b^2)} \cdot \frac{b}{\sqrt{x^2+b^2}} \cdot \frac{1}{v}\, dx = \frac{ze^2 b}{v} \left[\frac{x}{b^2\sqrt{x^2+b^2}} \right]_{-\infty}^{\infty} = \frac{2ze^2}{bv}$$

Bathe-Block: - Classical derivation

Energy transfer onto single electron
for impact parameter b:

$$\Delta E(b) = \frac{\Delta p^2}{2m_e}$$



Cylindric barrel
with N_e electrons

Consider cylindric barrel → $N_e = n\cdot(2\pi b)\cdot db\,dx$

Energy loss per path length dx for
distance between b and b+db in medium with electron density n:

Energy loss!

$$-dE(b) = \frac{\Delta p^2}{2m_e}\cdot 2\pi n b\, db\, dx = \frac{4z^2e^4}{2b^2v^2m_e}\cdot 2\pi n b\, db\, dx = \frac{4\pi\, n\, z^2 e^4}{m_e v^2}\frac{db}{b}dx$$

Diverges for b → 0; integration only
for relevant range [b_{min}, b_{max}]:

Bohr 1913

$$-\frac{dE}{dx} = \frac{4\pi\, n\, z^2e^4}{m_e v^2}\cdot\int_{b_{min}}^{b_{max}}\frac{db}{b} = \frac{4\pi\, n\, z^2e^4}{m_e v^2}\ln\frac{b_{max}}{b_{min}}$$

Bethe-Bloch Formula

$$\boxed{-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]} \; [\cdot \rho]$$

density

$K \quad = 4\pi N_A r_e^2 m_e c^2 = 0.307 \text{ MeV g}^{-1} \text{ cm}^2$

$T_{max} = 2m_e c^2\beta^2\gamma^2/(1 + 2\gamma\, m_e/M + (m_e/M)^2)$

[Max. energy transfer in single collision]

z : Charge of incident particle

M : Mass of incident particle

Z : Charge number of medium

A : Atomic mass of medium

I : Mean excitation energy of medium

δ : Density correction [transv. extension of electric field]

$N_A = 6.022 \cdot 10^{23}$

[Avogardo's number]

$r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.8$ fm

[Classical electron radius]

$m_e = 511$ keV

[Electron mass]

$\beta = v/c$

[Velocity]

$\gamma = (1-\beta^2)^{-2}$

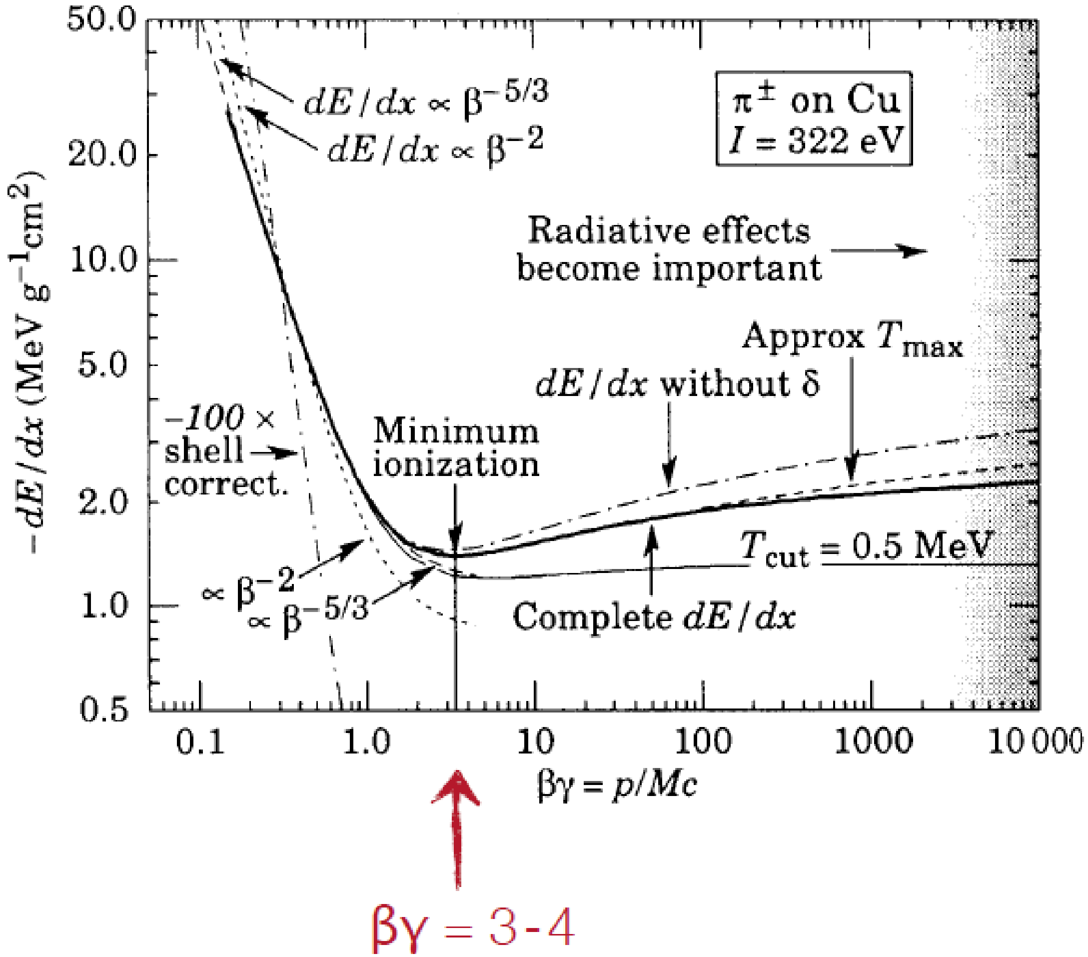
[Lorentz factor]

Validity:

$.05 < \beta\gamma < 500$

$M > m_\mu$

Energy loss of pions in Cu



Minimum ionising Particles:
$\beta\gamma$ = 3-4

dE/dx falls : β^{-2}

dE/dX rises: $\ln(\beta\gamma)^2$ Relativistic rise

Saturation at large $\beta\gamma$ due to Density effect (correction δ)

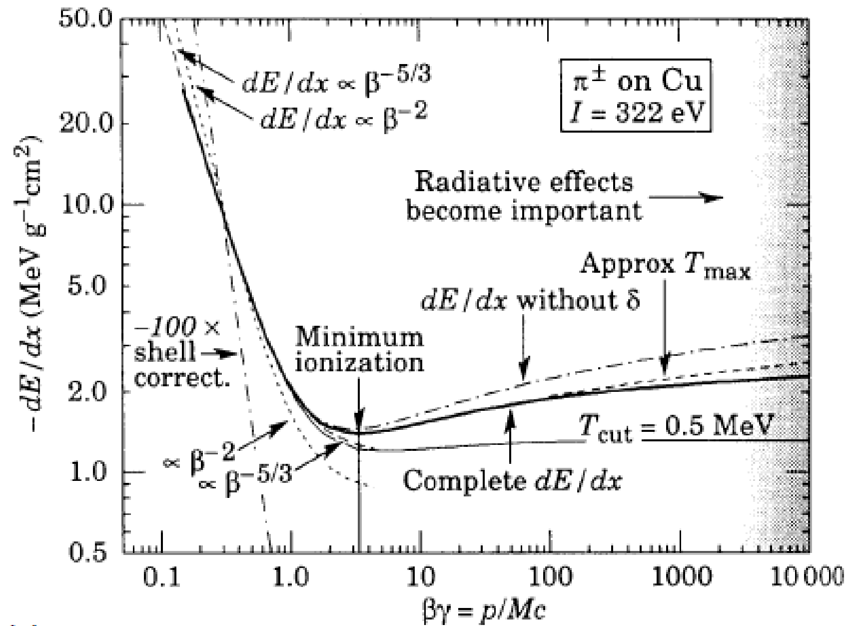
Understanding Bethe-Bloch

$1/\beta^2$-dependence:

Remember:

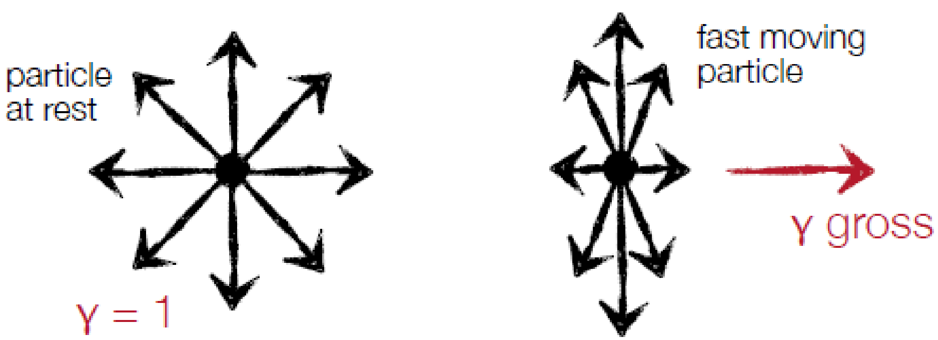
$$\Delta p_\perp = \int F_\perp dt = \int F_\perp \frac{dx}{v}$$

i.e. slower particles feel electric force of atomic electron for longer time ...



Relativistic rise for $\beta\gamma > 4$:

High energy particle: transversal electric field increases due to Lorentz transform; $E_y \rightarrow \gamma E_y$. Thus interaction cross section increases ...



Corrections:

low energy : shell corrections

high energy : density corrections

Understanding Bethe-Bloch

Density correction:

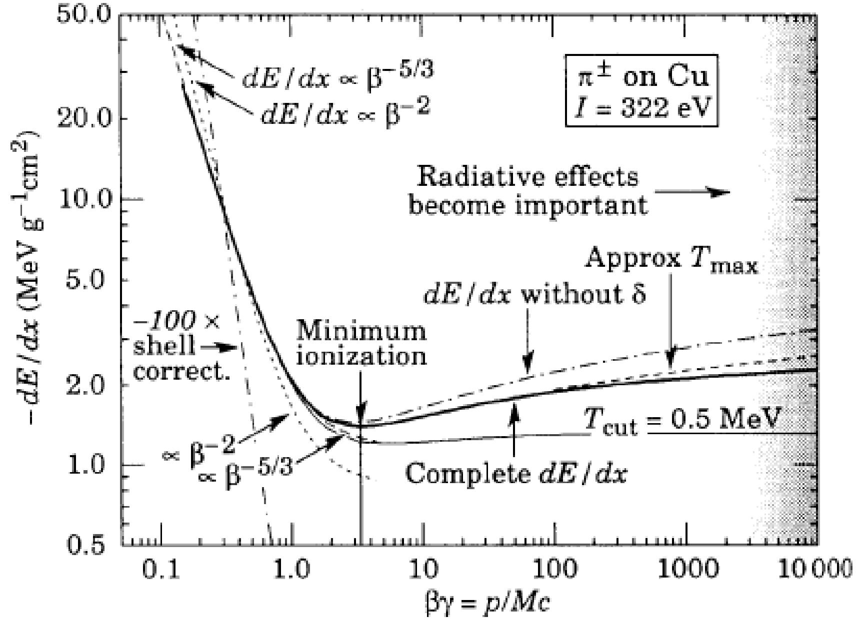
Polarization effect ...
[density dependent]

➙ Shielding of electrical field far from particle path; effectively cuts of the long range contribution ...

More relevant at high γ ...
[Increased range of electric field; larger b_{max}; ...]

For high energies:

$$\delta/2 \rightarrow \ln(\hbar\omega/I) + \ln\beta\gamma - 1/2$$



Density effect leads to saturation at high energy ...

Shell correction:

Arises if particle velocity is close to orbital velocity of electrons, i.e. $\beta c \sim v_e$.

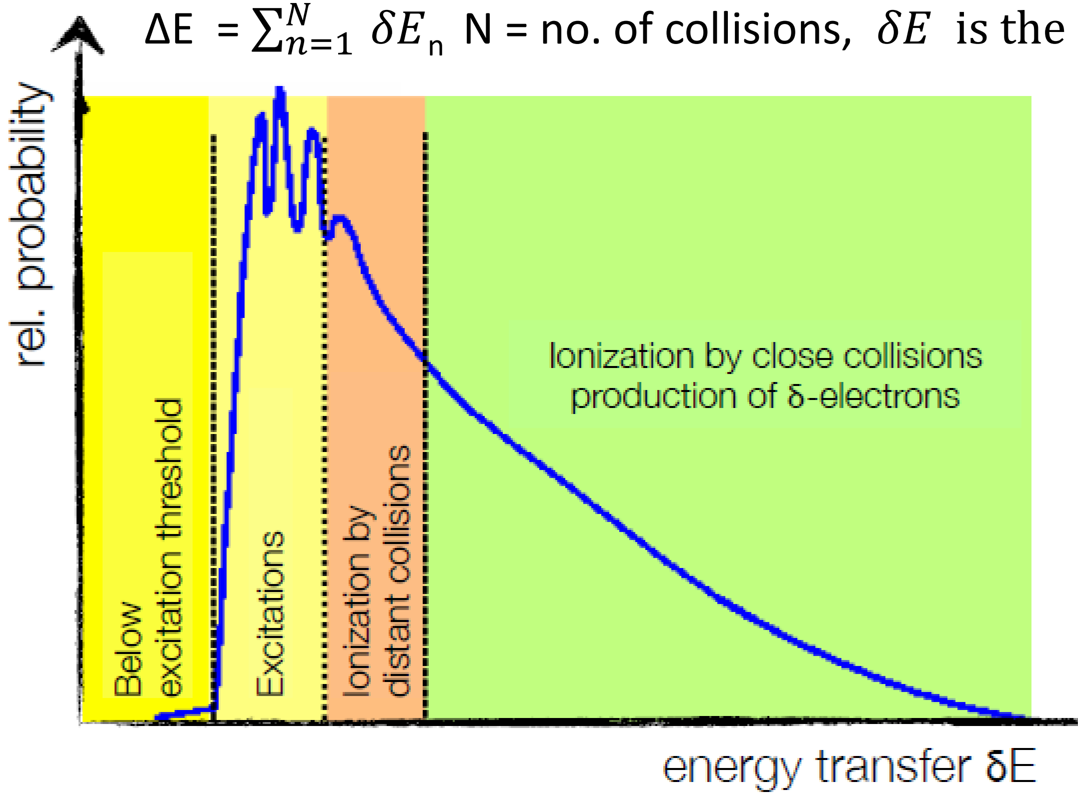
Assumption that electron is at rest breaks down ...
Capture process is possible ...

Shell correction are in general small ...

dE/dx Fluctuations

Bethe-Block describe the mean energy loss. ; measurement via energy loss ΔE in a material with thickness ΔX with

$\Delta E = \sum_{n=1}^{N} \delta E_n$ N = no. of collisions, δE is the energy loss in a single collision

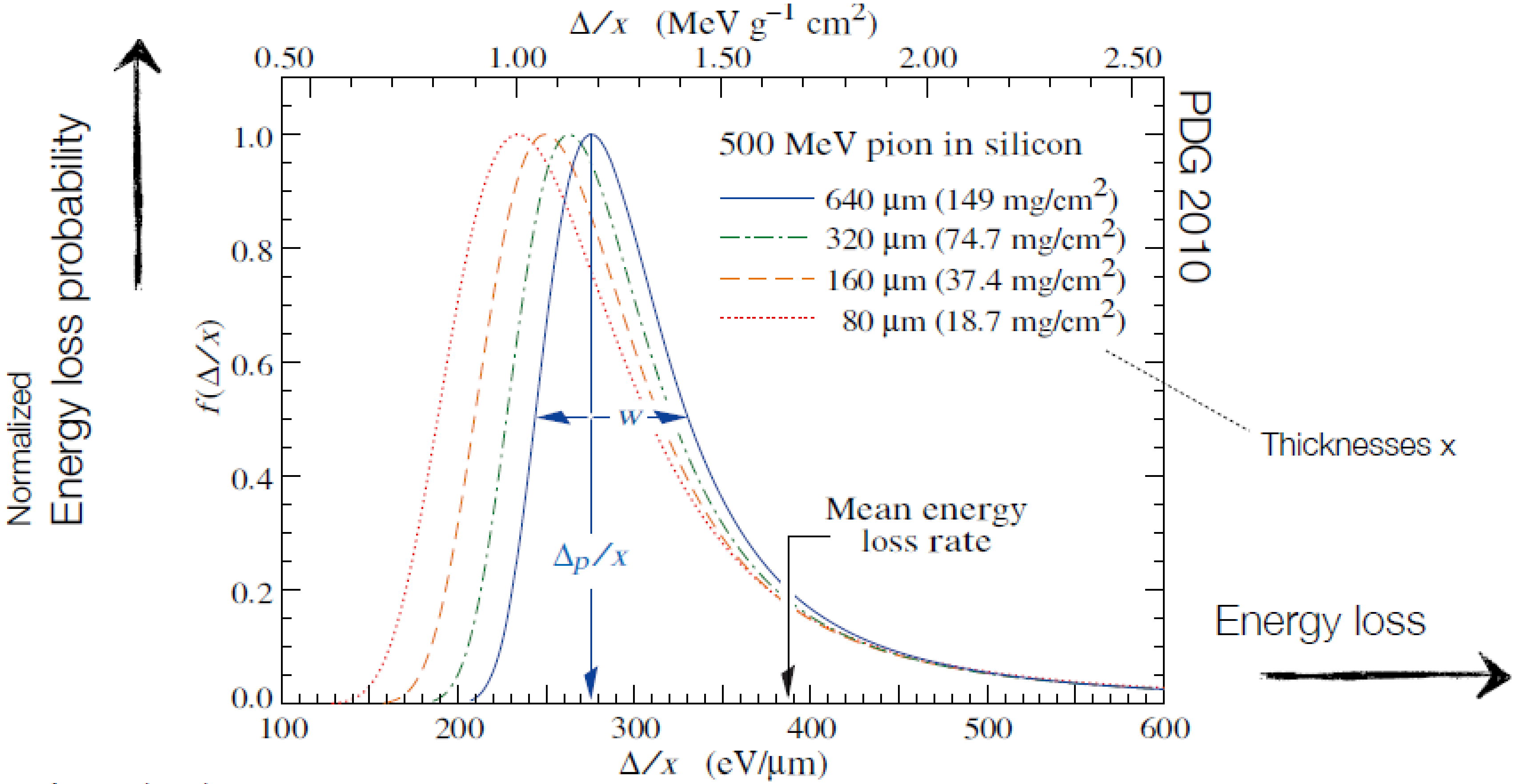


Ionisation loss δE is statistically Distributed.

So called
Energy loss "straggling "

It is a complicated problem-
e.g. thin absorbers gives
Landau distribution.

dE/dX Fluctuations – Landau Distribution



Particle Energy Deposit:

$\beta\gamma > 3.5$:

$$\left\langle \frac{dE}{dx} \right\rangle \approx \left.\frac{dE}{dx}\right|_{\min}$$

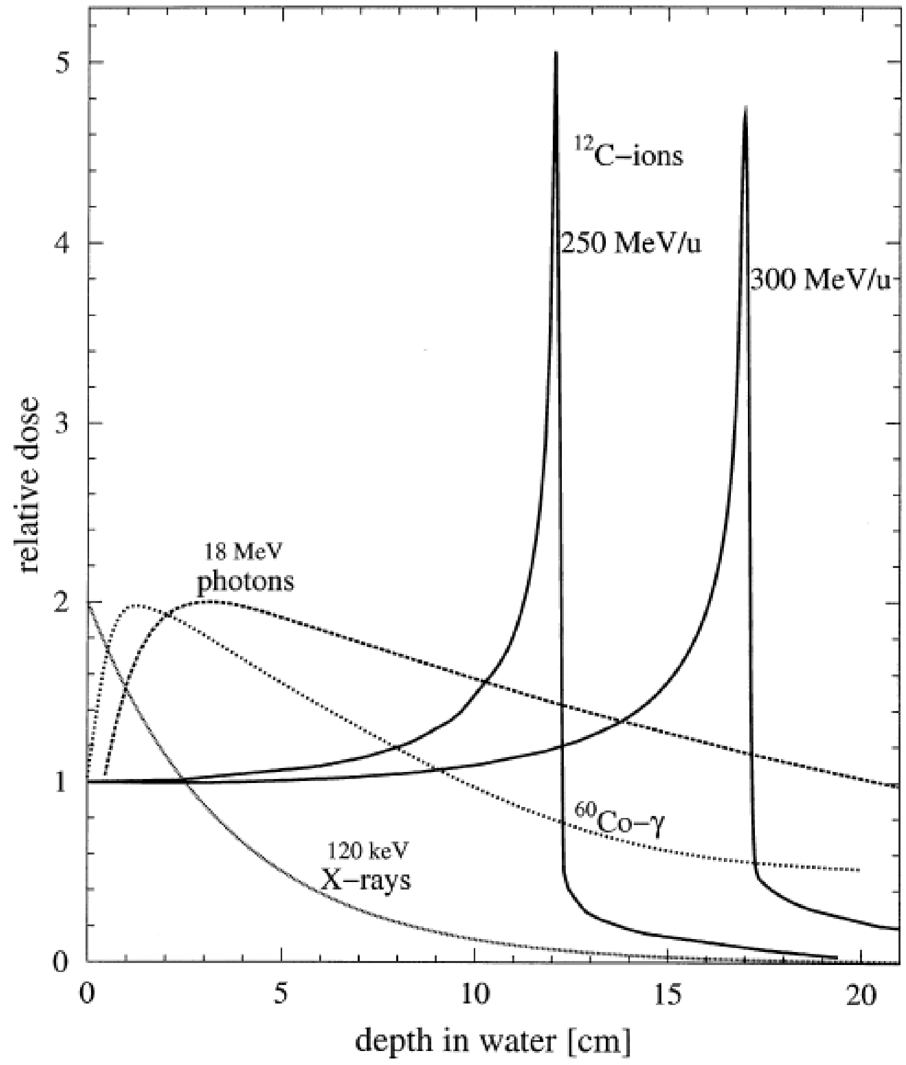
$\beta\gamma < 3.5$:

$$\left\langle \frac{dE}{dx} \right\rangle \gg \left.\frac{dE}{dx}\right|_{\min}$$

Applications:

Tumor therapy

Possibility to precisely deposit dose at well defined depth by E_{beam} variation



Energy loss by electrons

Bethe-Bloch formula needs modifications

Incident and target electrons have same mass
Scattering of identical indistinguishable particles

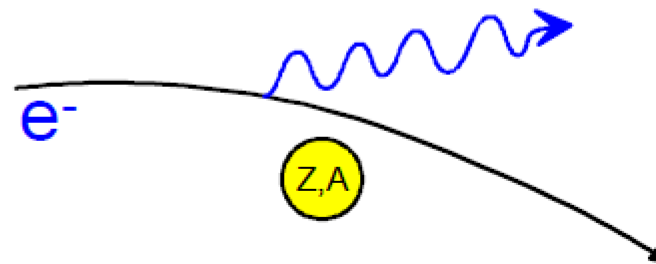
$$-\left\langle \frac{dE}{dx} \right\rangle_{\text{el.}} = K \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{m_e \beta^2 c^2 \gamma^2 T}{2I^2} + F(\gamma) \right]$$

[T: kinetic energy of electron]

Different energy loss for electrons and positrons at low energy as positrons are not Identical as electrons. Need different treatment

Bremsstrahlung

Bremsstrahlung arises if particles
are accelerated in Coulomb field of nucleus



$$\frac{dE}{dx} = 4\alpha N_A \, \frac{z^2 Z^2}{A} \left(\frac{1}{4\pi\epsilon_0} \frac{e^2}{mc^2} \right)^2 E \; \ln \frac{183}{Z^{\frac{1}{3}}} \propto \frac{E}{m^2}$$

i.e. energy loss proportional to $1/m^2$ ➞ main relevance for electrons ...

... or ultra-relativistic muons

Consider electrons:

$$\frac{dE}{dx} = 4\alpha N_A \, \frac{Z^2}{A} r_e^2 \cdot E \; \ln \frac{183}{Z^{\frac{1}{3}}}$$

$$\frac{dE}{dx} = \frac{E}{X_0} \qquad \text{with} \quad X_0 = \frac{A}{4\alpha N_A \, Z^2 r_e^2 \; \ln \frac{183}{Z^{\frac{1}{3}}}}$$

[Radiation length in g/cm²]

➞ $$E = E_0 e^{-x/X_0}$$

After passage of one X_0 electron has lost all but $(1/e)^{th}$ of its energy

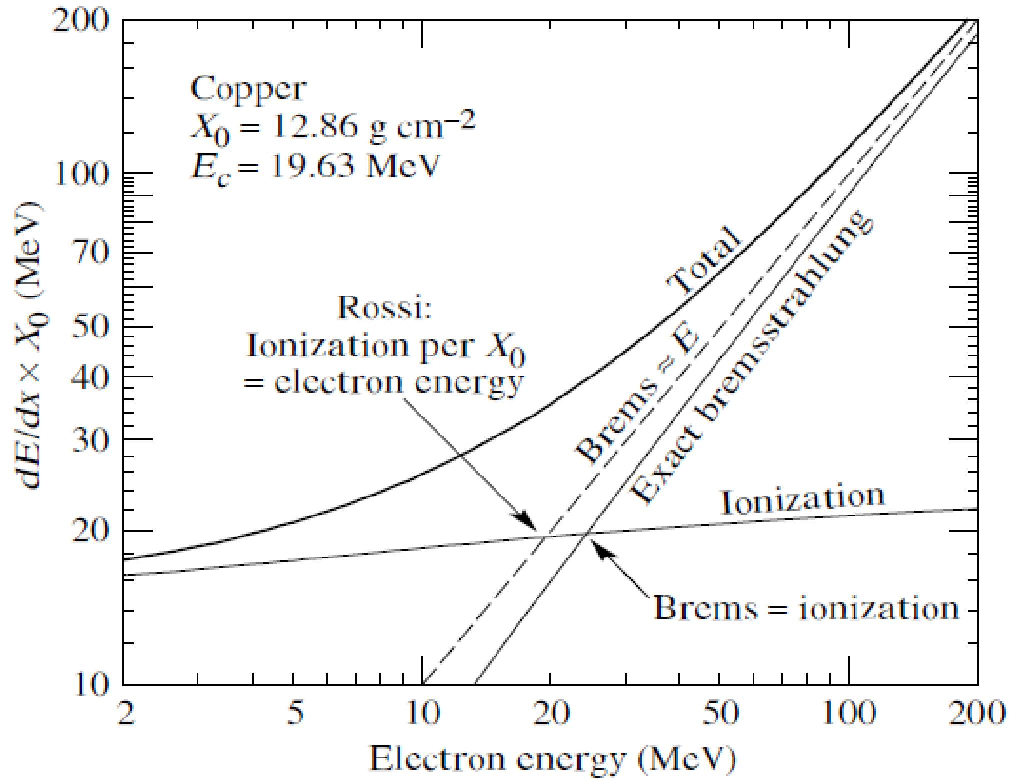
[i.e. 63%]

Bremsstrahlung- Critical Energy

Critical energy:

$$\frac{dE}{dx}(E_c)\bigg|_{\text{Brems}} = \frac{dE}{dx}(E_c)\bigg|_{\text{Ion}}$$

$$\left(\frac{dE}{dx}\right)_{\text{Tot}} = \left(\frac{dE}{dx}\right)_{\text{Ion}} + \left(\frac{dE}{dx}\right)_{\text{Brems}}$$



Approximation:

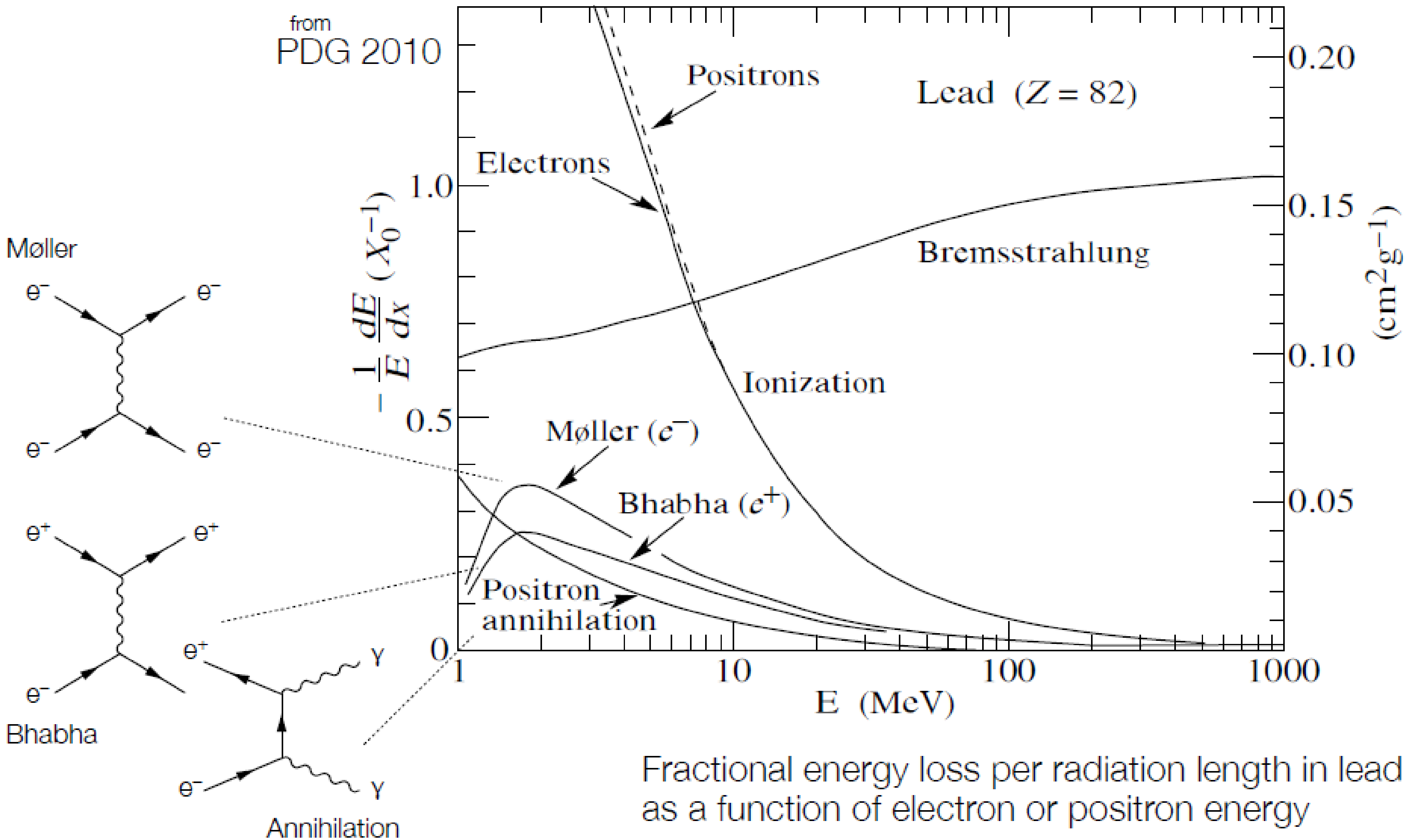
$$E_c^{\text{Gas}} = \frac{710\ \text{MeV}}{Z + 0.92}$$

$$E_c^{\text{Sol/Liq}} = \frac{610\ \text{MeV}}{Z + 1.24}$$

Example Copper:

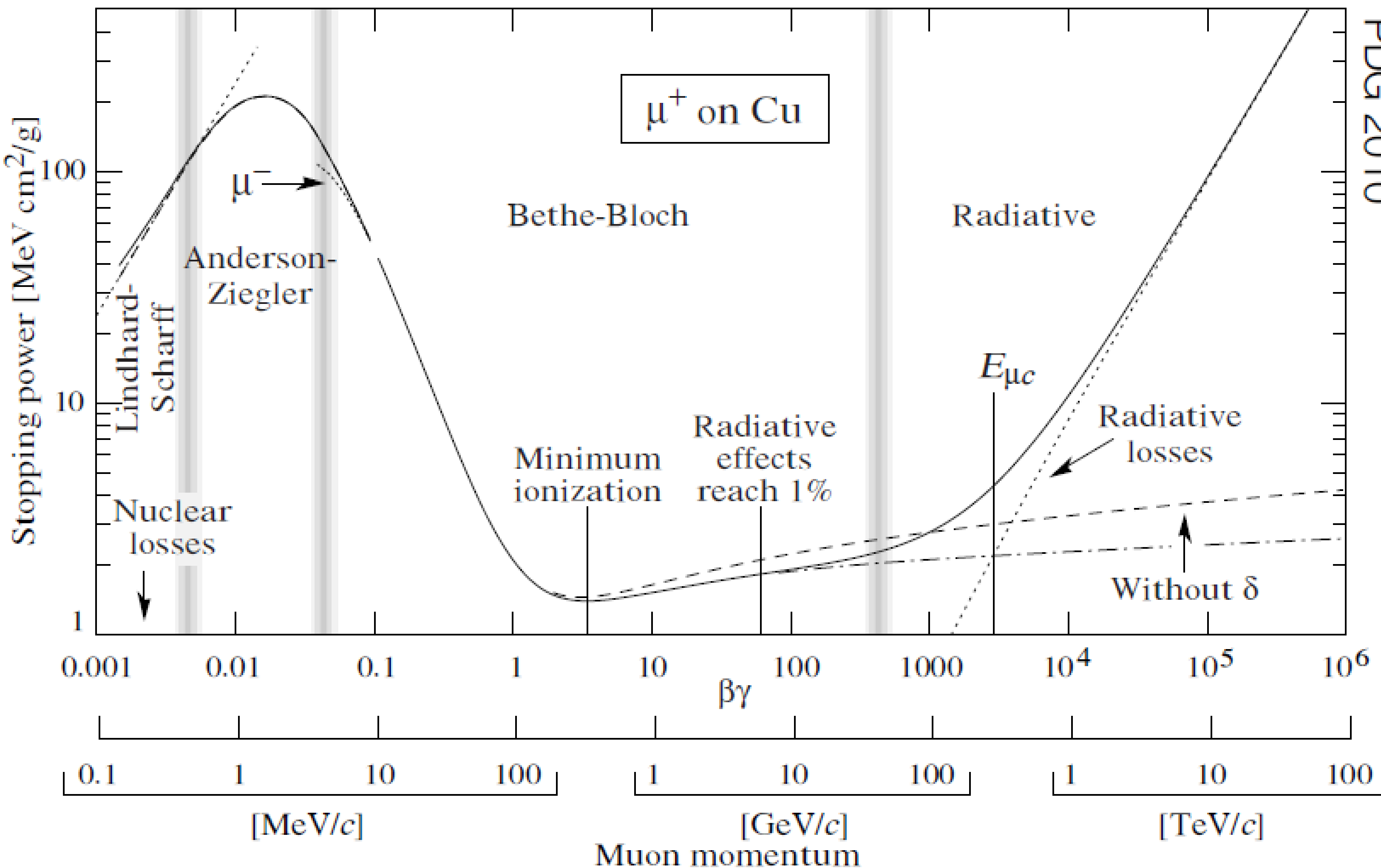
$E_c \approx 610/30$ MeV ≈ 20 MeV

Total Energy loss of Electrons:



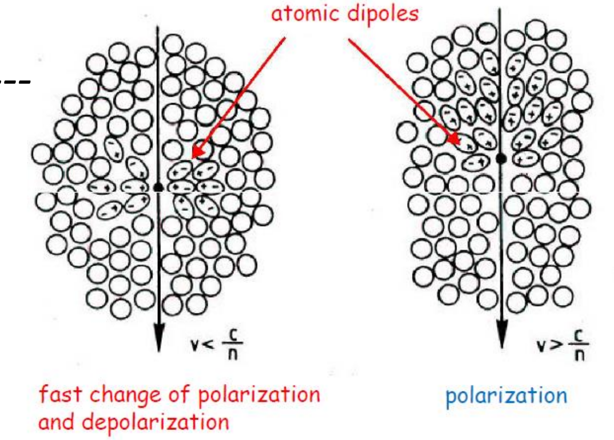
Fractional energy loss per radiation length in lead as a function of electron or positron energy

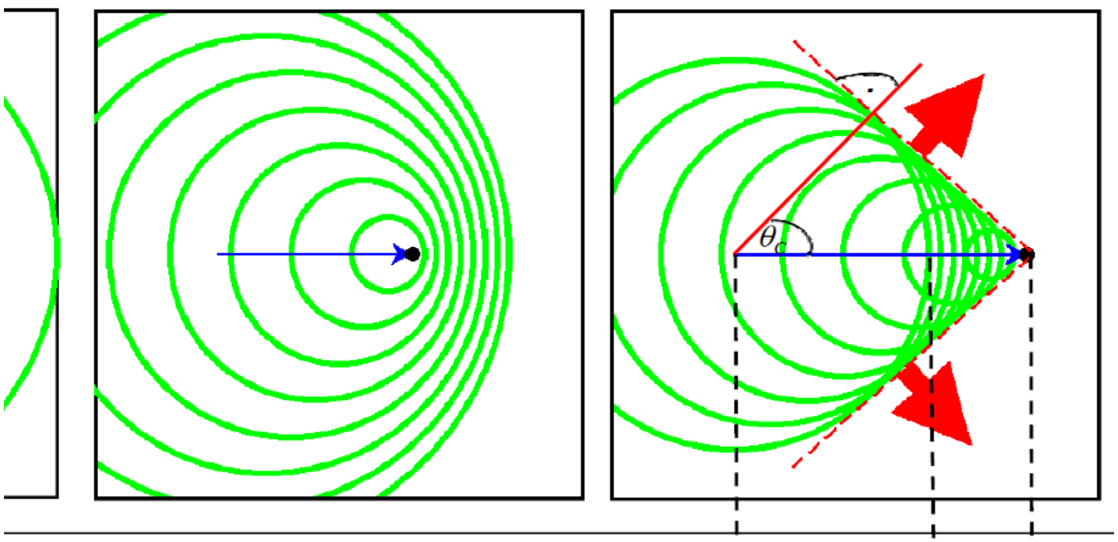
Total Energy Lass - Muons



Cherenkov Radiation:

- *The fast time dependent change of the polarisation of the medium can create observable Coherent effects --- Cherenkov radiation*
- *For v < c/n fast reduction of induced field in the medium*
- *For v > c/n propagation of EM wave in possible and observed*





$$\cos\theta_C = \frac{(c/n) \cdot \Delta t}{\beta c \cdot \Delta t} = \frac{1}{\beta n}$$

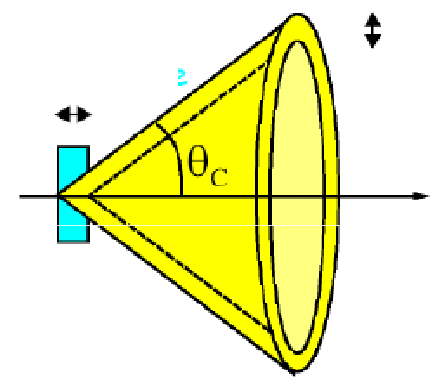
$\cos\theta_C$ is a real number for $\beta \geq \frac{1}{n}$

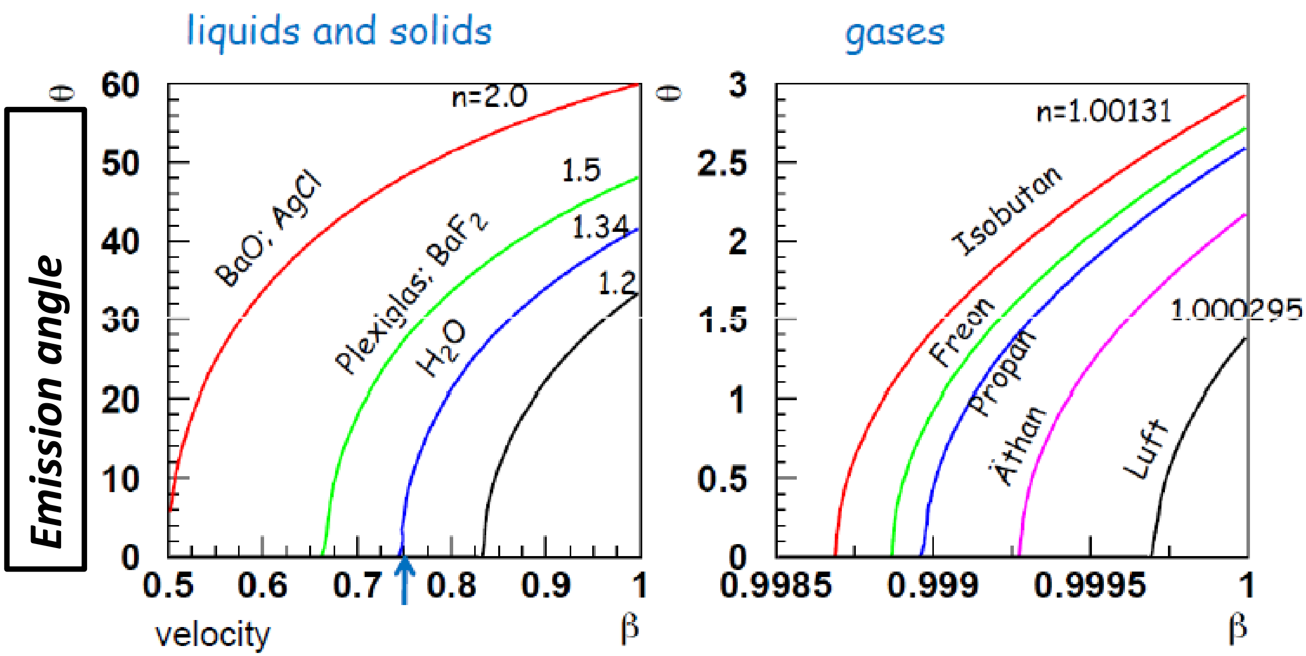
Cherenkov Radiation in various media

Emission angle θ_C relative to direction of velocity depends only on particle velocity β.

$$\text{threshold}: \beta_{thresh} = \frac{1}{n} \Rightarrow \text{opening cone}: \theta_C \approx 0^\circ$$

$$\text{max. opening cone}: \beta \approx 1 \Rightarrow \arccos\theta_C = \frac{1}{n}$$





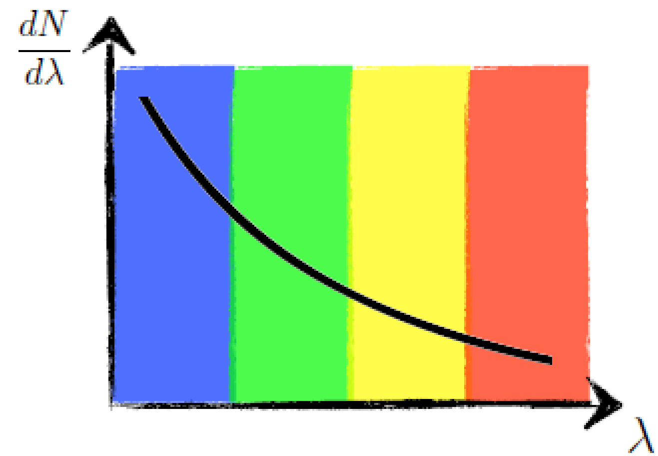
Corresponds to electron energies ~ 260 keV-> reactor

Cherenkov Radiation - Properties

Number of emitted photons per unit length:

from 4

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



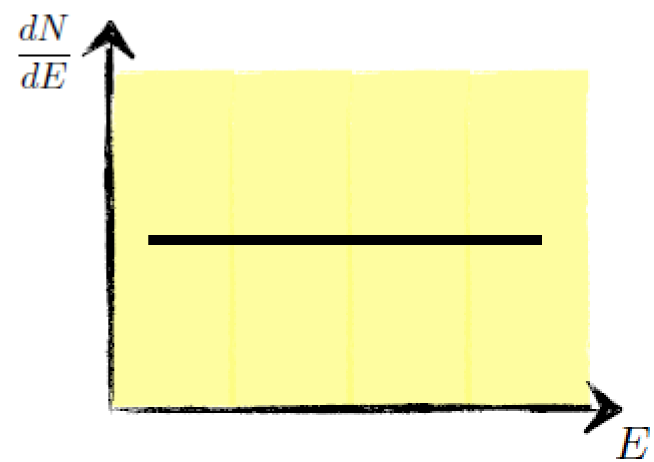
Integrate over sensitivity range:
[for typical Photomultiplier]

$$\frac{dN}{dx} = \int_{350\text{ nm}}^{550\text{ nm}} d\lambda \frac{d^2N}{d\lambda dx}$$

$$= 475\ z^2 \sin^2\theta_C \text{ photons/cm}$$

$$\frac{d^2N}{dEdx} = \frac{z^2\alpha}{\hbar c}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{z^2\alpha}{\hbar c}\sin^2\theta_C$$

$$\approx \text{const}$$



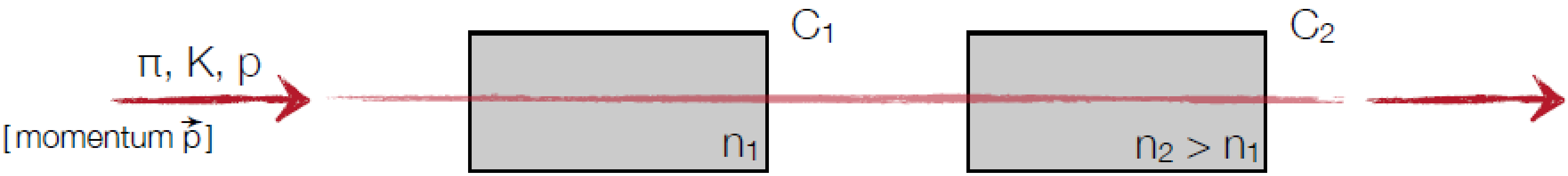
For single charged particle:

$$\frac{d^2N}{dEdx} = 370\ \sin^2\theta_C \text{ eV}^{-1}\text{ cm}^{-1}$$

Cherenkov Radiation- Application

Threshold detection:

Observation of Cherenkov radiation → $\beta > \beta_{thr}$



Choose n_1, n_2 in such a way that for:

n_2 : $\beta_\pi, \beta_K > 1/n_2$ and $\beta_p < 1/n_2$

n_1 : $\beta_\pi > 1/n_1$ and $\beta_K, \beta_p < 1/n_1$

Light in C_1 and C_2 → identified pion

Light in C_2 and not in C_1 → identified kaon

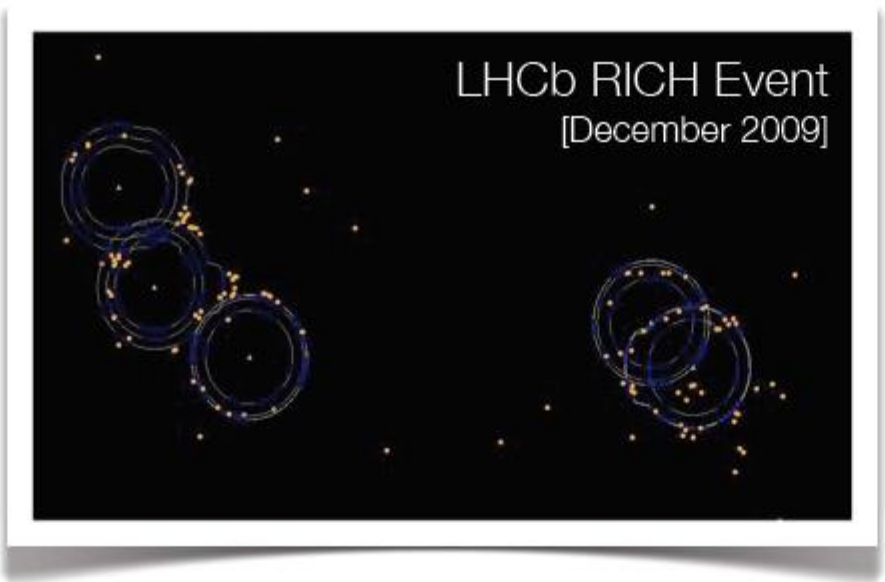
Light neither in C_1 and C_2 → identified proton

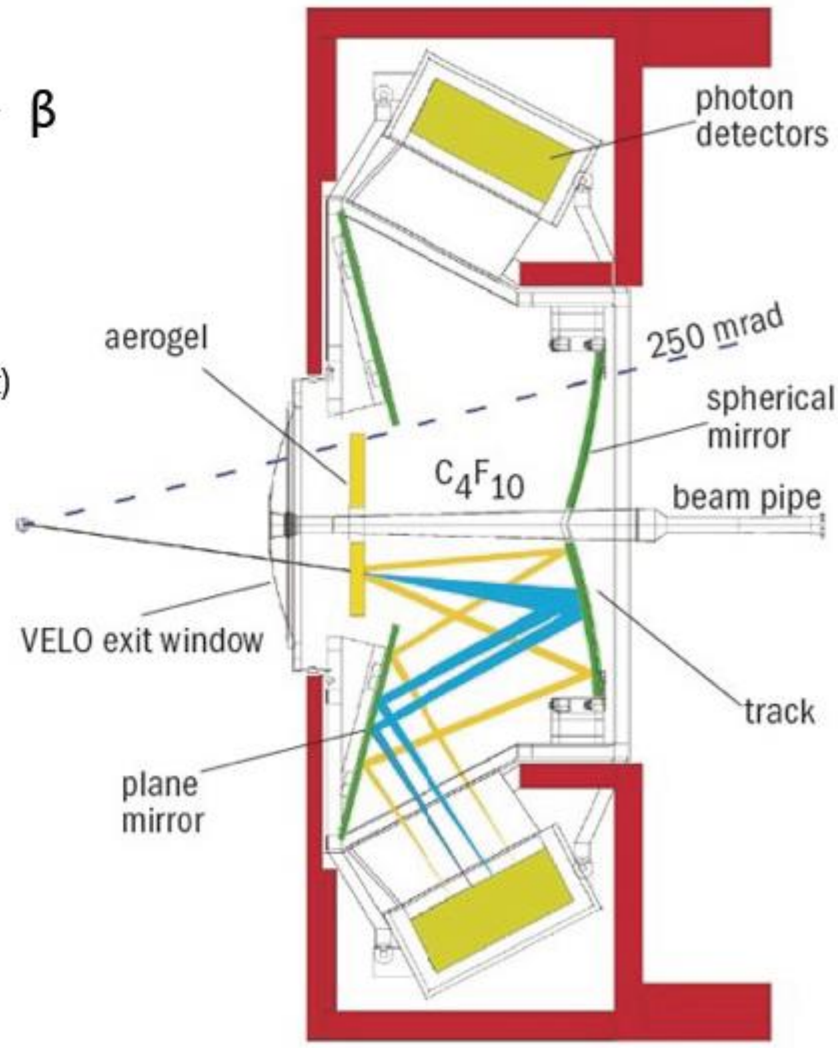
Cherenkov Radiation: Application

Measurement of Cherenkov angle:
Use medium with known refractive index n ➛ β

Principle of:

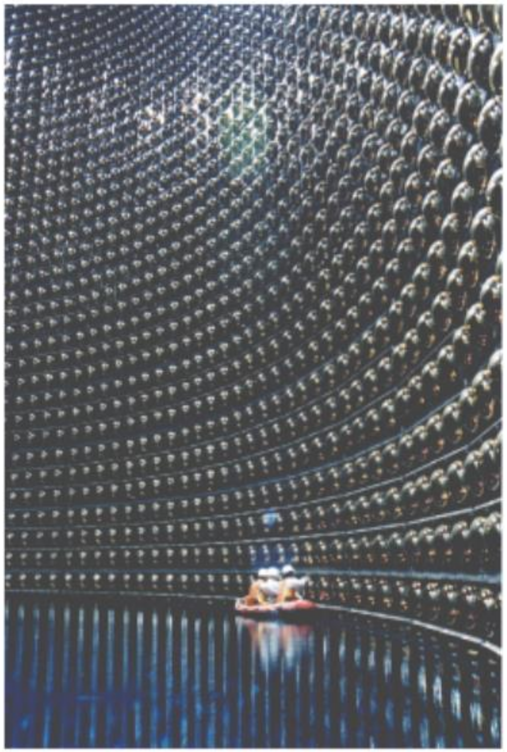
RICH (Ring Imaging Cherenkov Counter)
DIRC (Detection of Internally Reflected Cherenkov Light)
DISC (special DIRC; e.g. Panda)

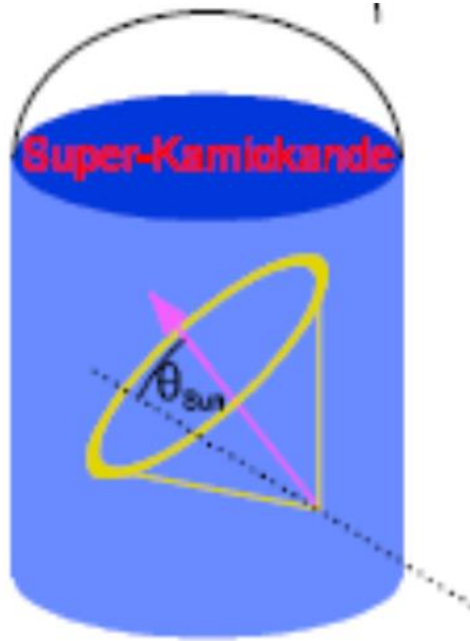


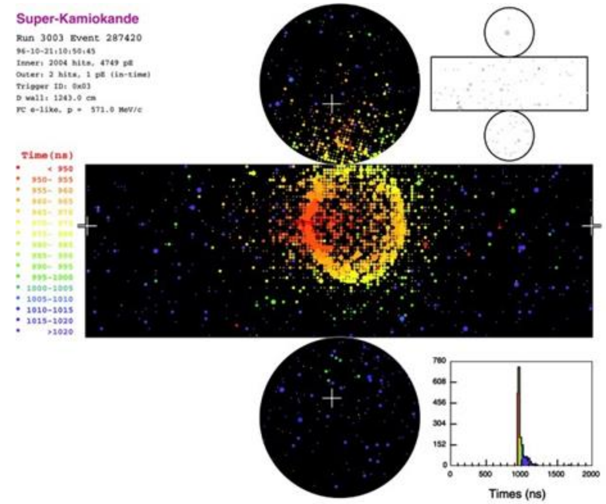


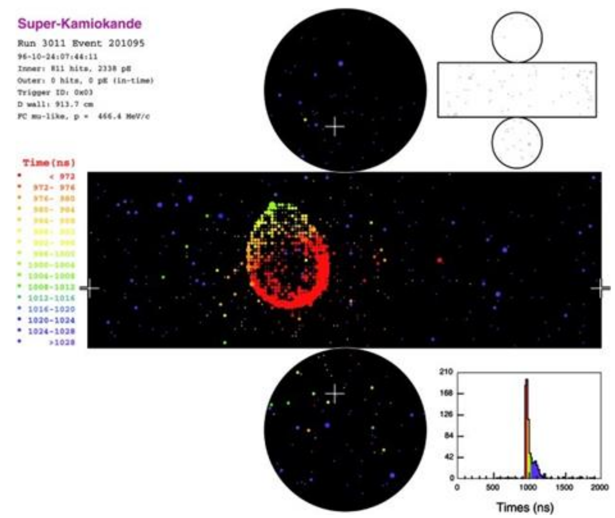
LHCb RICH

Cherenkov Ring : Super-Kamiokande



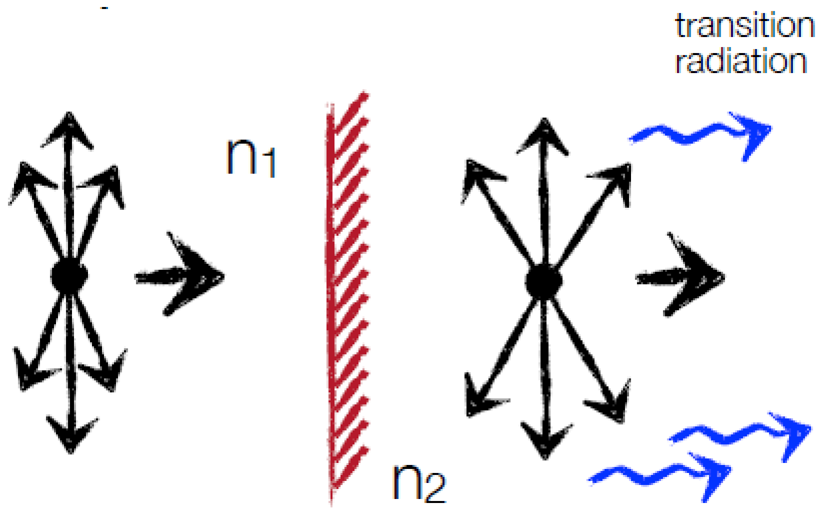




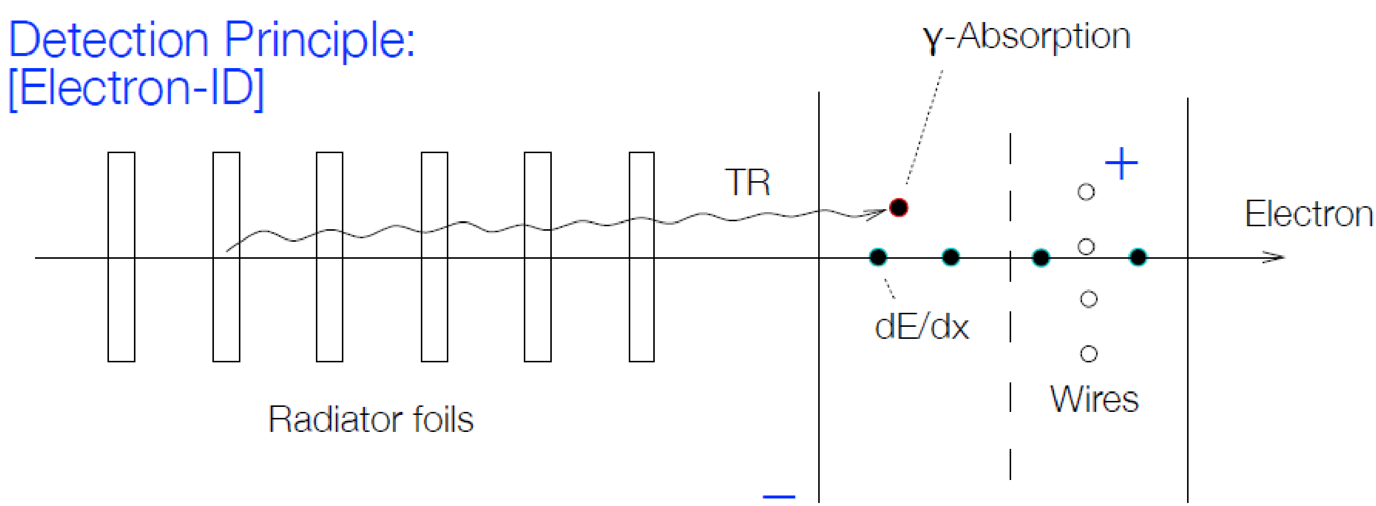


Transition Radiation Detector

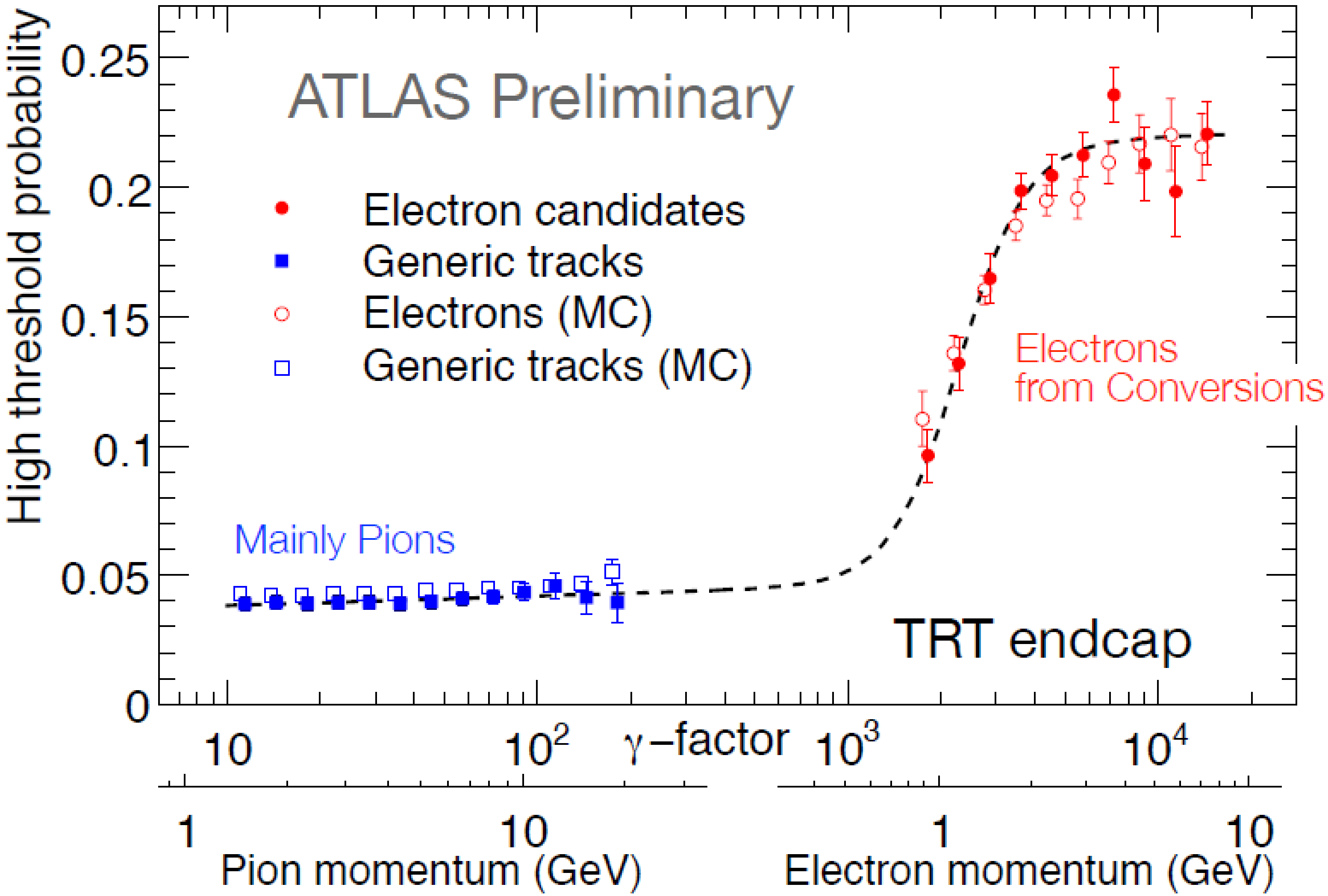
Transition radiation occurs if a relativistic Particle (large γ) passes the boundary between two media of different refraction indices.



This effect can be explained due to rearrangement of electric fields.



Transition Radiation: ATLAS Example



Interactions of photons with matter

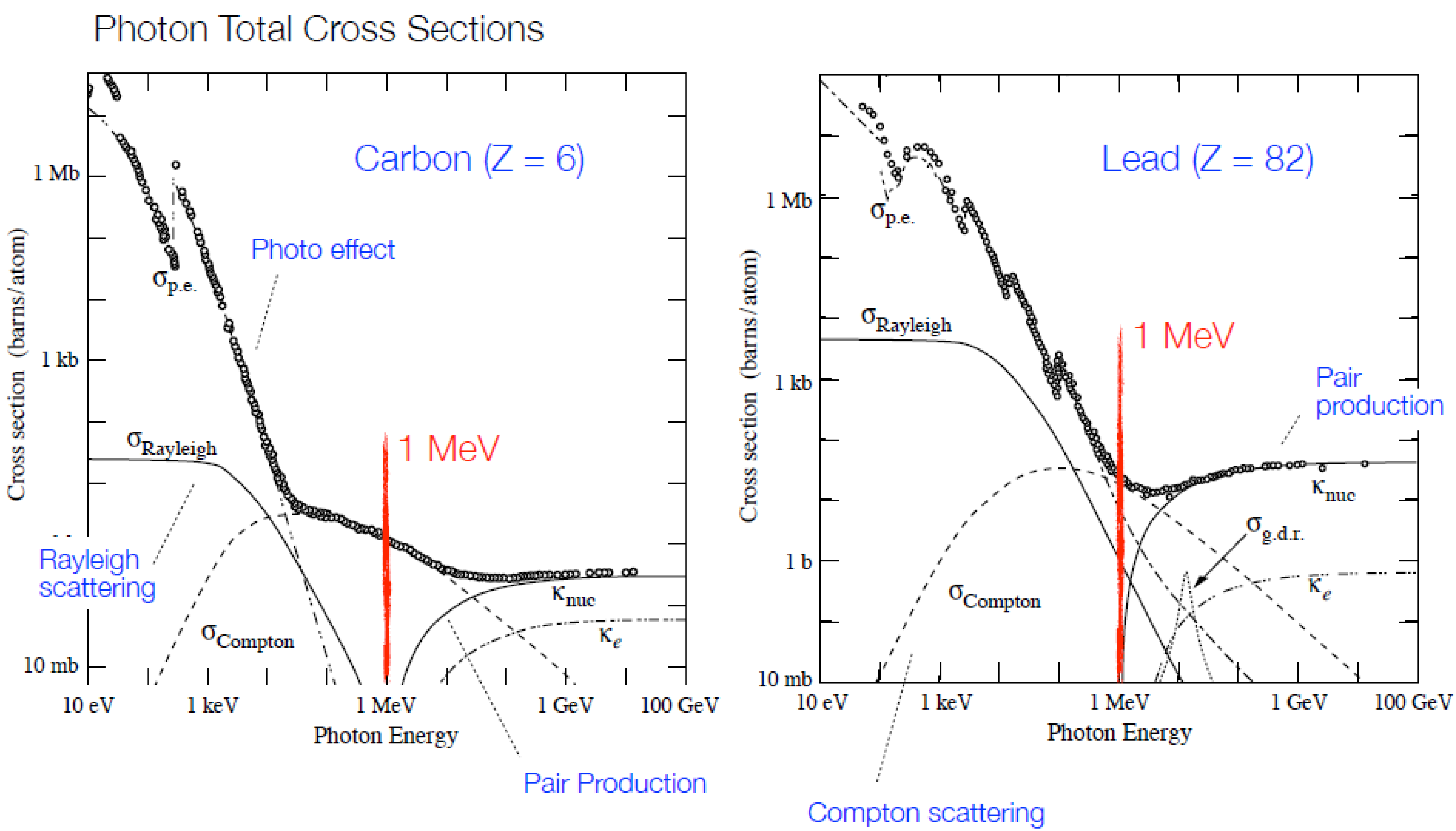
- *Photons are far more penetrating than charged particles of similar energy.*
- *Photon interact with matter through the following processes:*
  - *Photoelectric effect.*
  - *Compton effect.*
  - *Pair production*
- *Interaction Probability:*
  - *linear attenuation coefficient, μ*

    The probability of an interaction per unit distance traveled

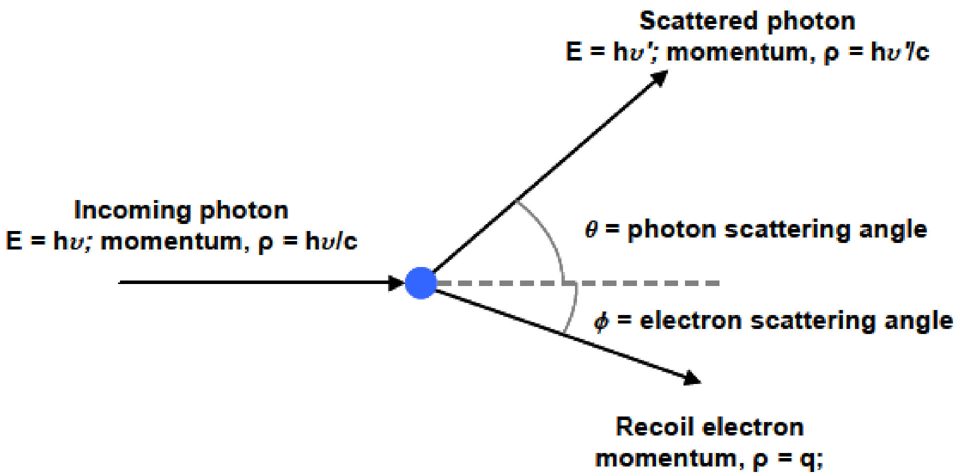
    Dimensions of inverse length (eg. cm-1)

    $N = N_0 \, e^{-\mu X}$
  - *The coefficient μ depends on photon energy and on the material being traversed.*
- *mass attenuation coefficient :* μ/ρ
- *The probability of an interaction per g* cm^{-2} *of material traversed.*
- *Units of* $cm^2 \, g^{-1}$

Interactions of photons with matter



Compton Scattering



Maximum energy transfer

$$E_{e(max)} = h\nu \frac{2\alpha}{1+2\alpha}$$

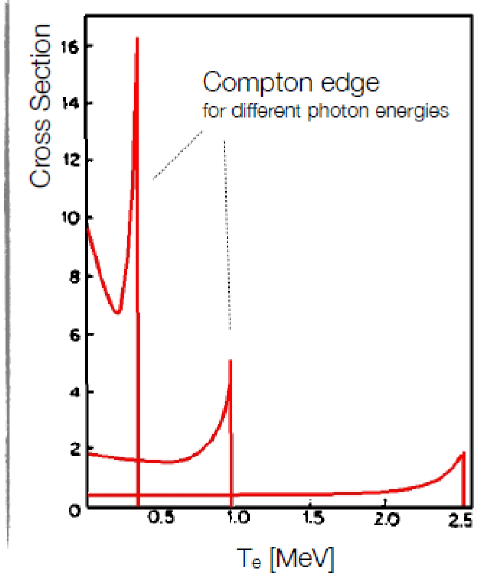
and

$$h\nu'_{min} = h\nu \frac{1}{1+2\alpha}$$

$$h\nu' = h\nu \frac{1}{1+\alpha(1-\cos\theta)}$$

$$E_e = h\nu \frac{\alpha(1-\cos\theta)}{1+\alpha(1-\cos\theta)}$$

where $\alpha = \dfrac{h\nu}{m_0 c^2}$



Photon Interactions: Pair Production

Energy threshold:

$$E_\gamma \geq 2m_ec^2(1+m_e/m_n)$$

2 x electron mass

Kinetic energy
transferred to nucleus

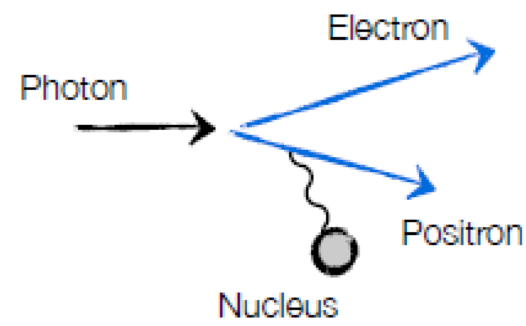
Cross Section:

Rises above threshold, but reaches saturation for large E_γ [screening effect] ...

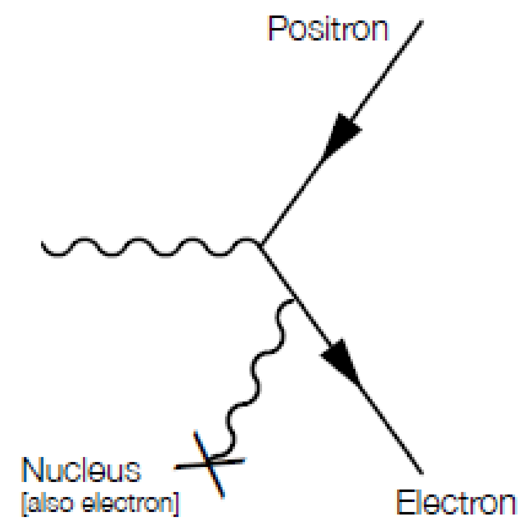
For $E_\gamma \gg m_ec^2$:

$$\sigma_{\text{pair}} = 4\,Z^2\,\alpha r_e^2 \left(\frac{7}{9}\ln\frac{183}{Z^{\frac{1}{3}}} - \frac{1}{54}\right)$$

$$\approx 4\,Z^2\,\alpha r_e^2 \left(\frac{7}{9}\ln\frac{183}{Z^{\frac{1}{3}}}\right)$$



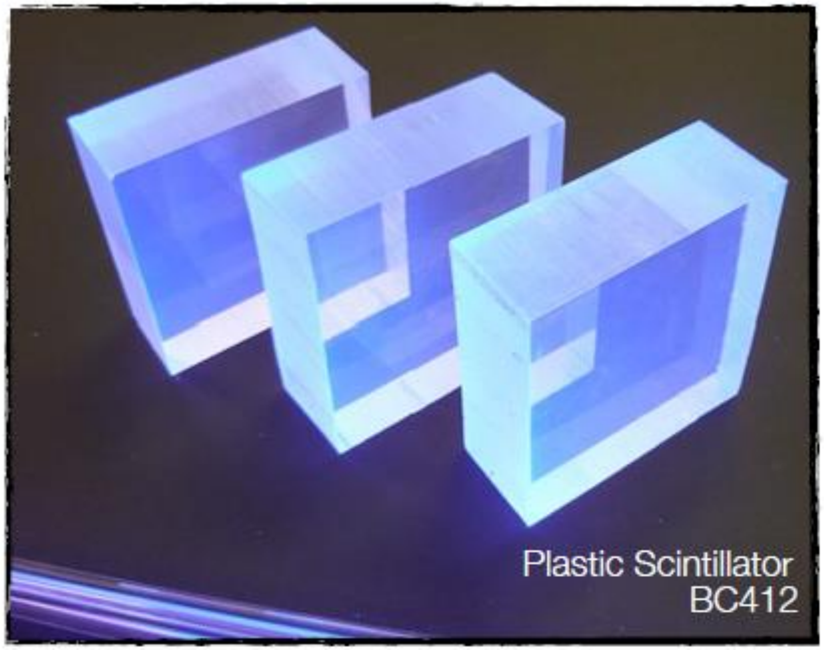
γ + atom $\rightarrow$ $e^+ + e^-$



Scintillators:

Principle:

dE/dx converted into visible light
Detection via photosensor
[e.g. photomultiplier, human eye ...]



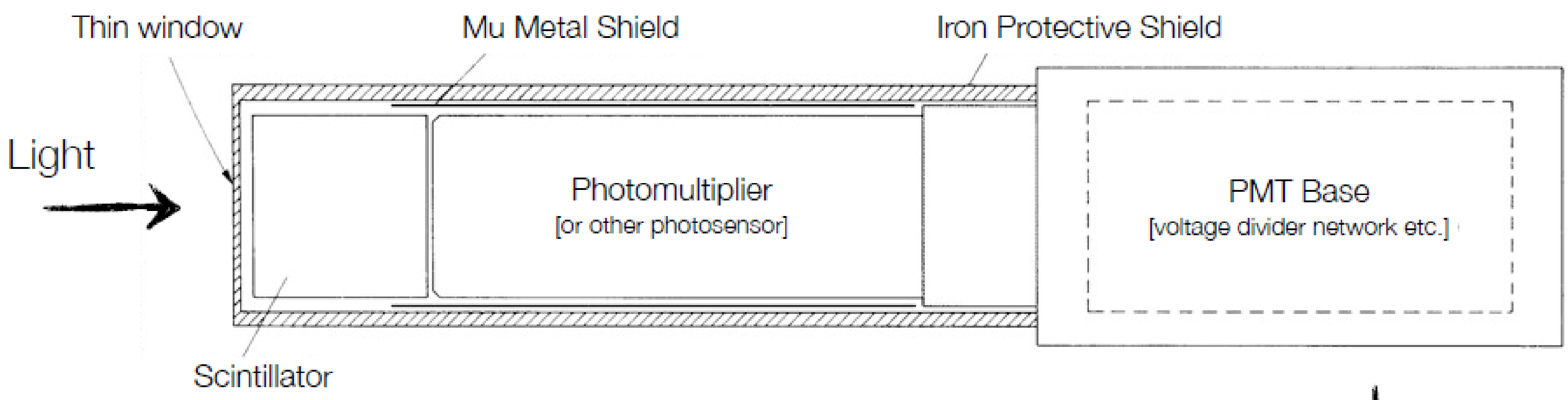
Main Features:

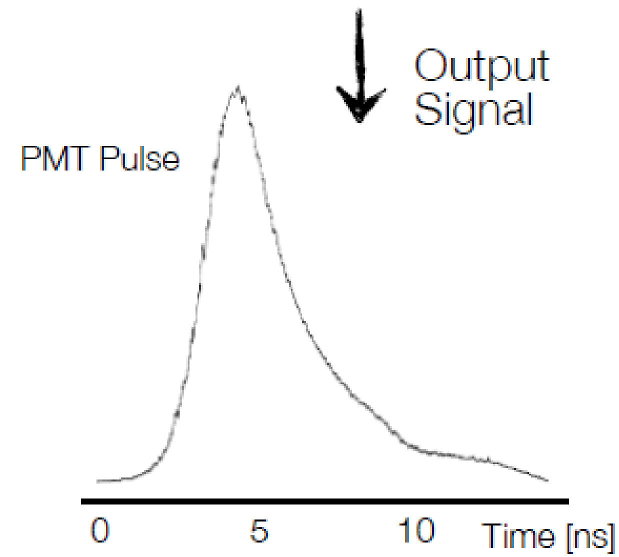
Sensitivity to energy
Fast time response
Pulse shape discrimination

Requirements

High efficiency for conversion of excitation energy to fluorescent radiation
Transparency to its fluorescent radiation to allow transmission of light
Emission of light in a spectral range detectable for photosensors
Short decay time to allow fast response

Scintillators: Basic setup





Scintillator Types:

Organic Scintillators
Inorganic Crystals
Gases

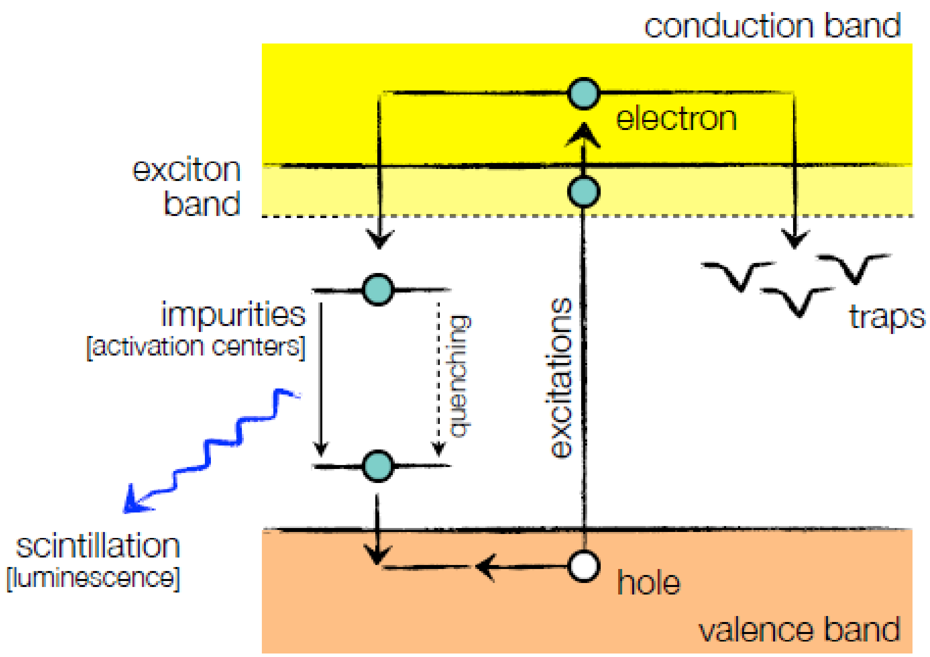
Photosensors

Photomultipliers
Micro-Channel Plates
Hybrid Photo Diodes
Visible Light Photon Counter
Silicon Photomultipliers

Scintillation Mechanism in Inorganic crystals:

Materials:

Sodium iodide (NaI)
Cesium iodide (CsI)
Barium fluoride (BaF_2)
...



Energy bands in impurity activated crystal

showing excitation, luminescence, quenching and trapping

Mechanism:

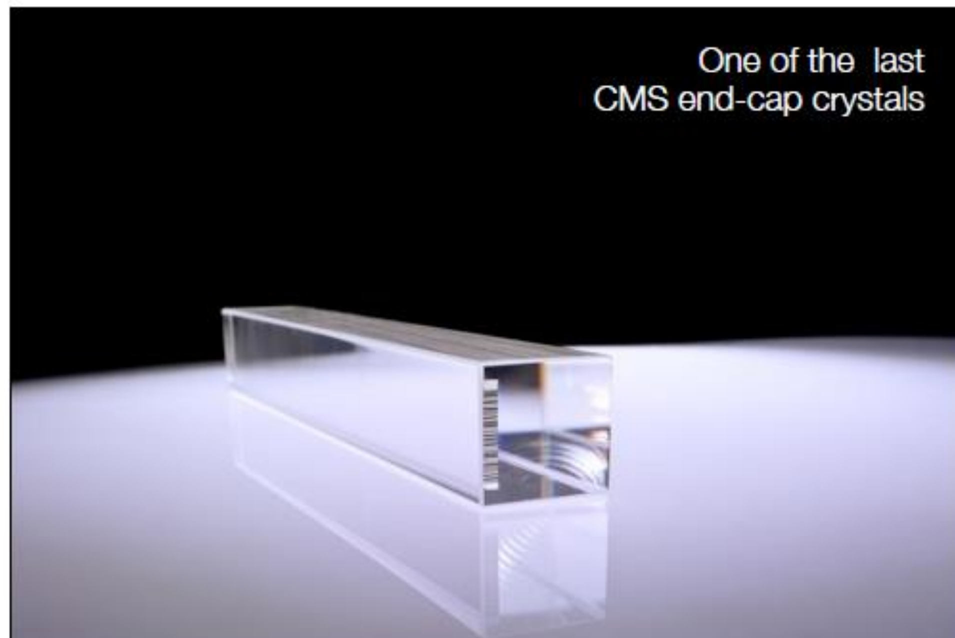
Energy deposition by ionization
Energy transfer to impurities
Radiation of scintillation photons

Time constants:

Fast: recombination from activation centers [ns ... μs]
Slow: recombination due to trapping [ms ... s]

Inorganic crystals:

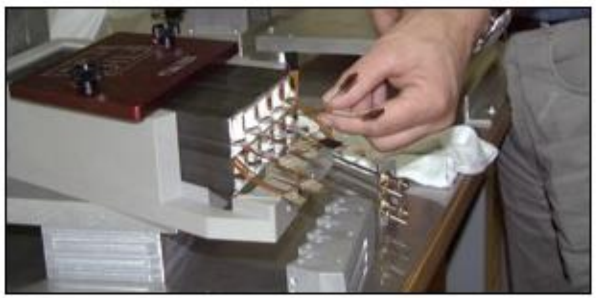
Example CMS
Electromagnetic Calorimeter

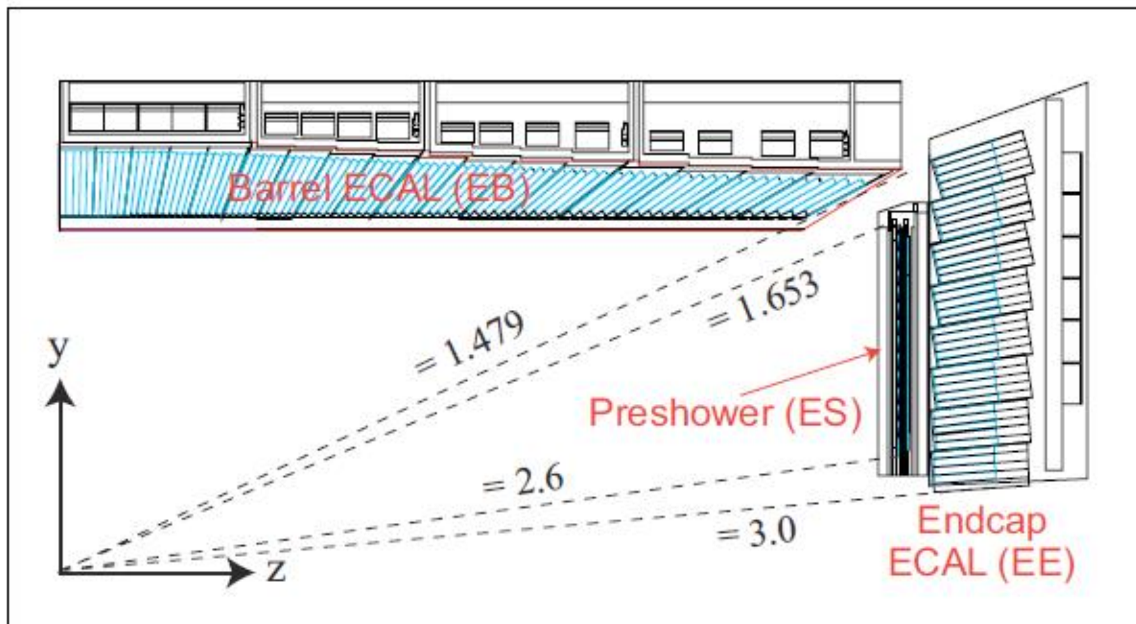


Application: CMS EM Calorimeter

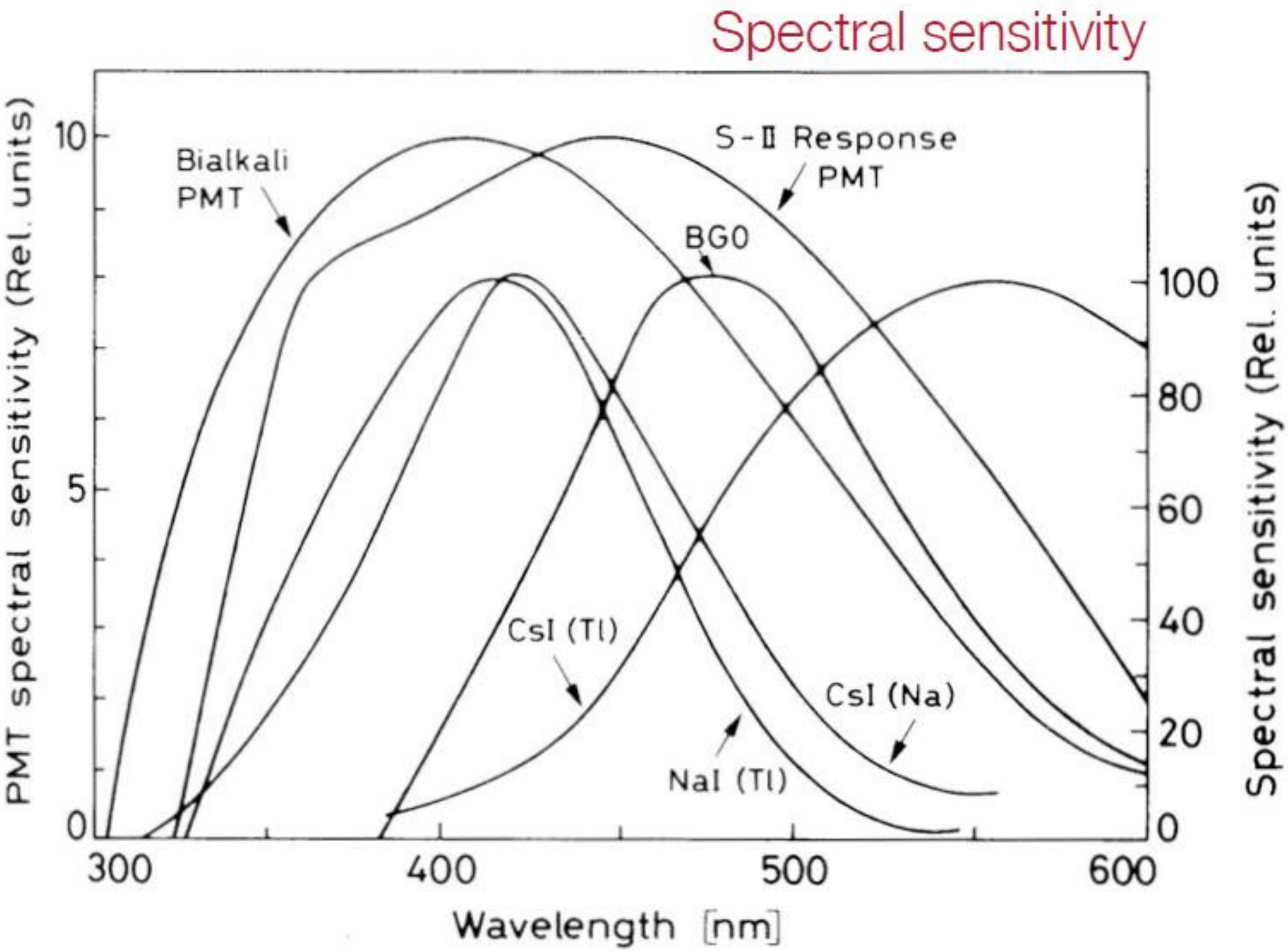
Scintillator : $PBWO_4$ [Lead Tungsten]
Photosensor : APDs [Avalanche Photodiodes]

Number of crystals: ~ 70000
Light output: 4.5 photons/MeV





Light output & PMT Sensitivity



Inorganic Scintillators - Properties

Scintillator material	Density [g/cm³]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [μs]	Photons/MeV
NaI	3.7	1.78	303	0.06	$8 \cdot 10^4$
NaI(Tl)	3.7	1.85	410	0.25	$4 \cdot 10^4$
CsI(Tl)	4.5	1.80	565	1.0	$1.1 \cdot 10^4$
$Bi_4Ge_3O_{12}$	7.1	2.15	480	0.30	$2.8 \cdot 10^3$
CsF	4.1	1.48	390	0.003	$2 \cdot 10^3$
LSO	7.4	1.82	420	0.04	$1.4 \cdot 10^4$
$PbWO_4$	8.3	1.82	420	0.006	$2 \cdot 10^2$
LHe	0.1	1.02	390	0.01/1.6	$2 \cdot 10^2$
LAr	1.4	1.29 *	150	0.005/0.86	$4 \cdot 10^4$
LXe	3.1	1.60 *	150	0.003/0.02	$4 \cdot 10^4$

* [illegible]

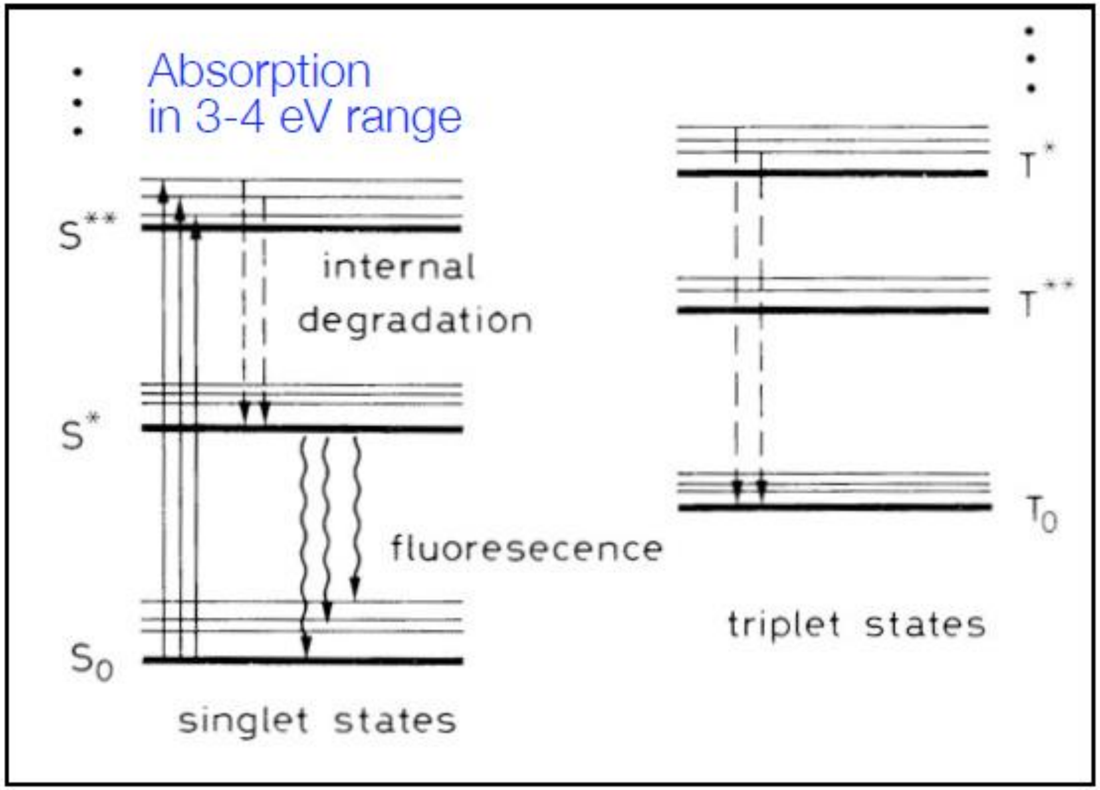
Organic Scintillators:

Molecular states:

Singlet states
Triplet states

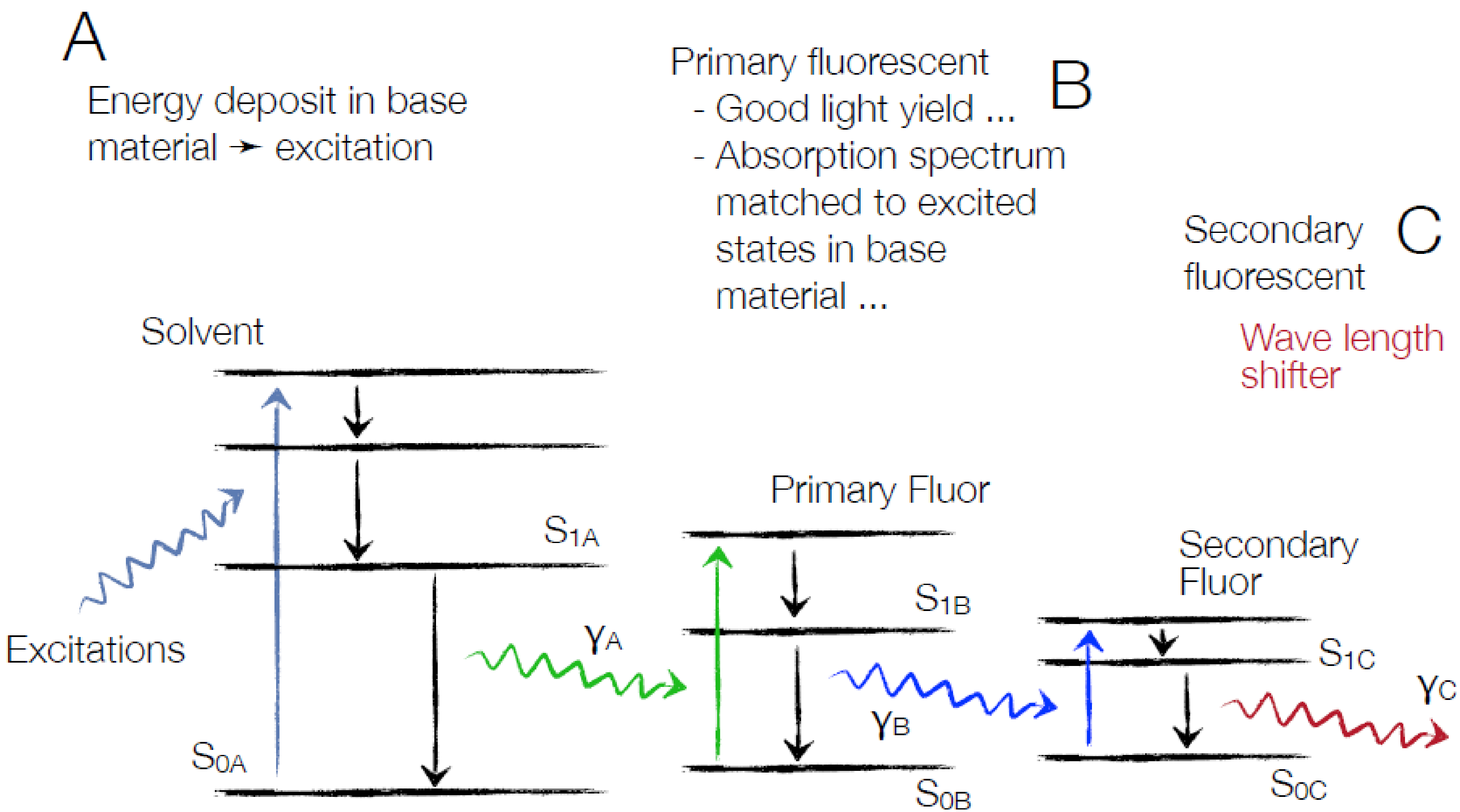
Fluorescence in UV range
[~ 320 nm]

➥ usage of wavelength shifters



Fluorescence : $S_1 \rightarrow S_0$ [< 10^{-8} s]
Phosphorescence : $T_0 \rightarrow S_0$ [> 10^{-4} s]

Plastic & Liquid scintillators:



Wavelength shifting:

Principle:

Absorption of
primary scintillation light

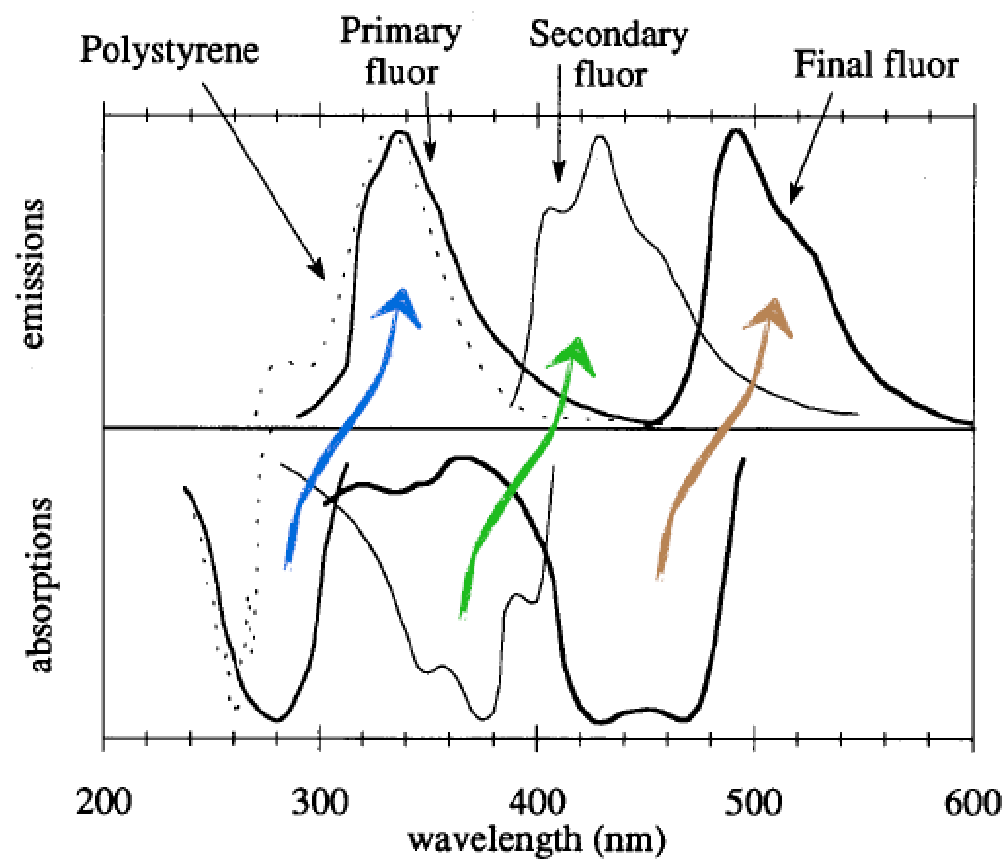
Re-emission at
longer wavelength

Adapts light to spectral
sensitivity of photosensor

Requirement:

Good transparency
for emitted light

Schematics of
wavelength shifting principle



Properties of Organic Scintillator:

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4 \cdot 10^3$
Antracene	1.25	1.59	448	30	$4 \cdot 10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2 \cdot 10^4$
NE102*	1.03	1.58	425	2.5	$2.5 \cdot 10^4$
NE104*	1.03	1.58	405	1.8	$2.4 \cdot 10^4$
NE110*	1.03	1.58	437	3.3	$2.4 \cdot 10^4$
NE111*	1.03	1.58	370	1.7	$2.3 \cdot 10^4$
BC400**	1.03	1.58	423	2.4	$2.5 \cdot 10^2$
BC428**	1.03	1.58	480	12.5	$2.2 \cdot 10^4$
BC443**	1.05	1.58	425	2.2	$2.4 \cdot 10^4$

* Nuclear Enterprises, U.K.
** Bicron Corporation, USA

Inorganic vs. Organic Scintillator

Inorganic Scintillators

Advantages	high light yield [typical; $\varepsilon_{sc} \approx 0.13$] high density [e.g. $PBWO_4$: 8.3 g/cm^3] good energy resolution	
Disadvantages	complicated crystal growth large temperature dependence	Expensive

Organic Scintillators

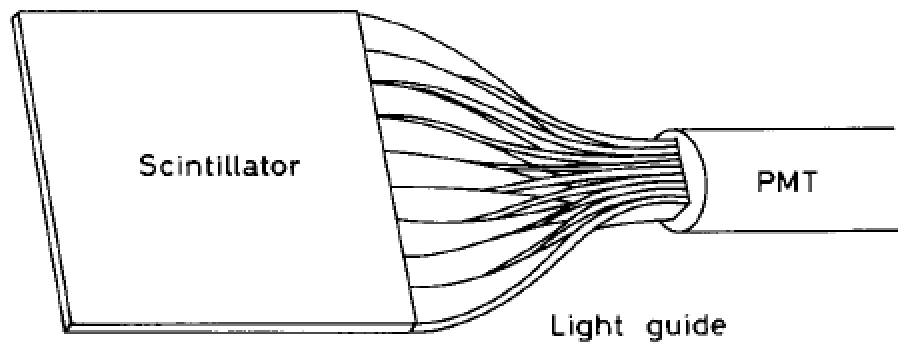
Advantages	very fast easily shaped small temperature dependence pulse shape discrimination possible	
Disadvantages	lower light yield [typical; $\varepsilon_{sc} \approx 0.03$] radiation damage	Cheap

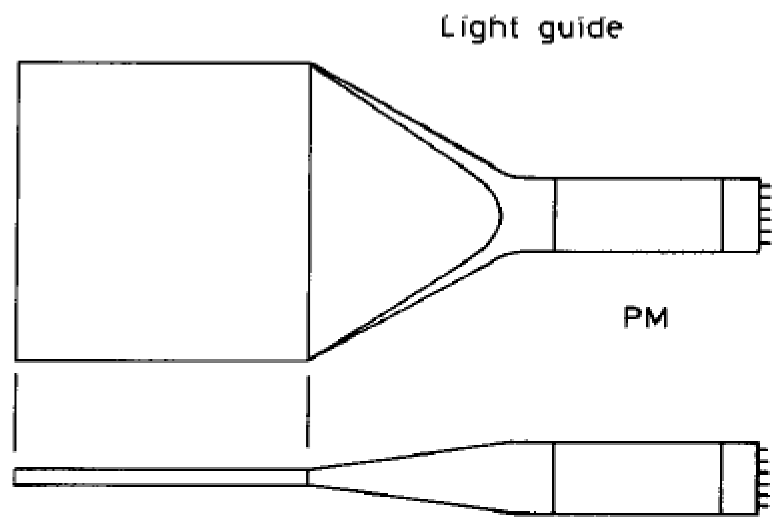
Transferring light from scintillator to photo detectors:

Scintillator light to be guided to photosensor

➛ Light guide
[Plexiglas; optical fibers]

Light transfer by
total internal reflection
[maybe combined with wavelength shifting]





'fish tail'

Photon Detection:

Purpose : Convert light into a detectable electronic signal
Principle : Use photo-electric effect to convert photons to photo-electrons (p.e.)

Requirement :

High Photon Detection Efficiency (PDE) or
Quantum Efficiency; Q.E. = $N_{p.e.}/N_{photons}$

Available devices [Examples]:

- Photomultipliers [PMT]
- Micro Channel Plates [MCP]
- Photo Diodes [PD]
- HybridPhoto Diodes [HPD]
- Visible Light Photon Counters [VLPC]
- Silicon Photomultipliers [SiPM]

Photomultipliers

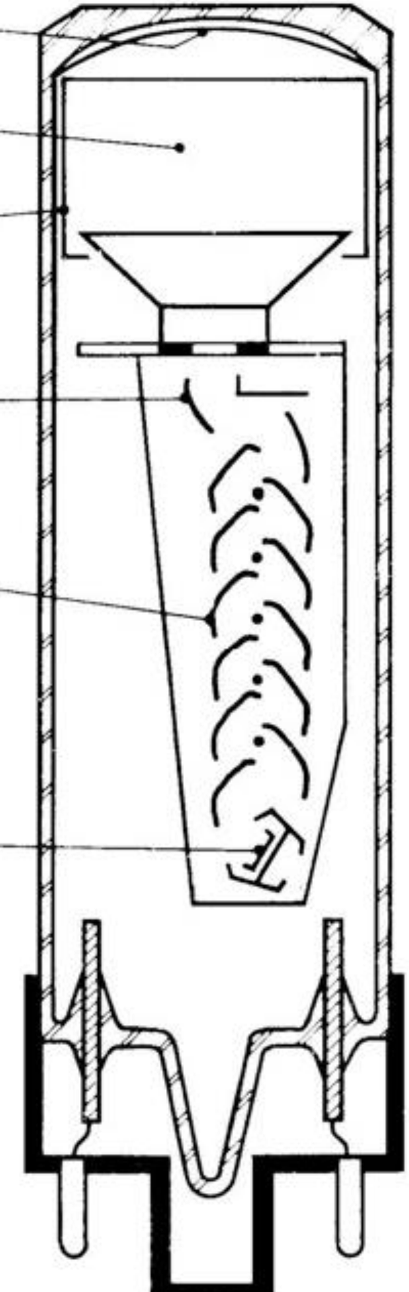
Principle:

Electron emission
from photo cathode

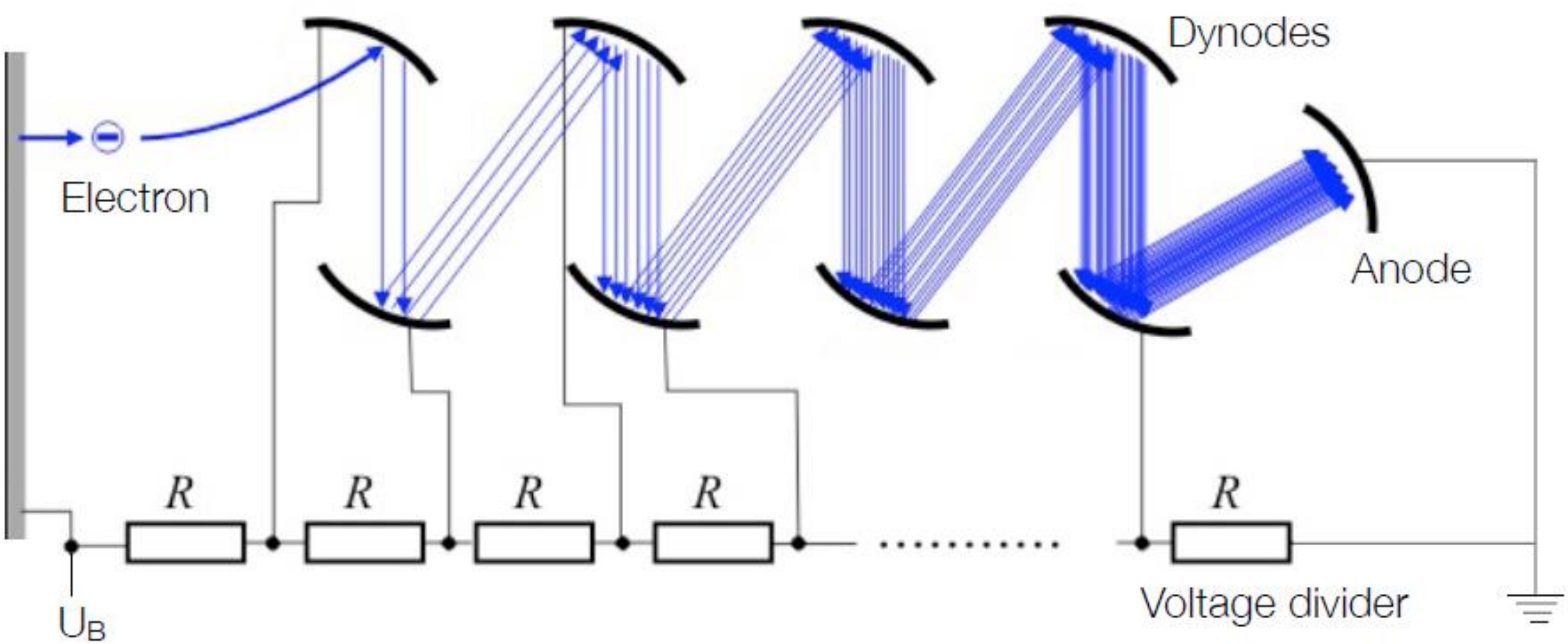
Secondary emission
from dynodes; dynode gain: 3-50 [f(E)]

Typical PMT Gain: > 10^6
[PMT can see single photons ...]

PMT
Collection



PMT Dynode gain:



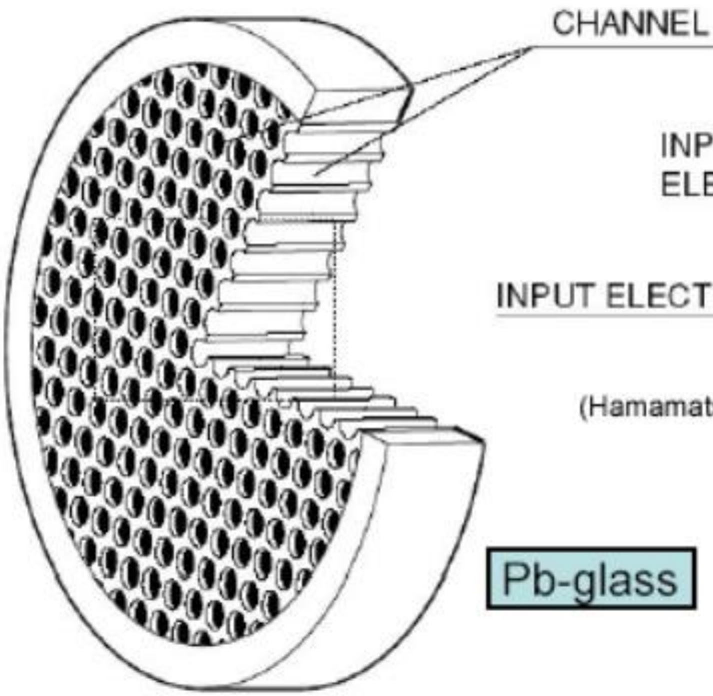
Multiplication process:

Electrons accelerated toward dynode
Further electrons produced ➔ avalanche

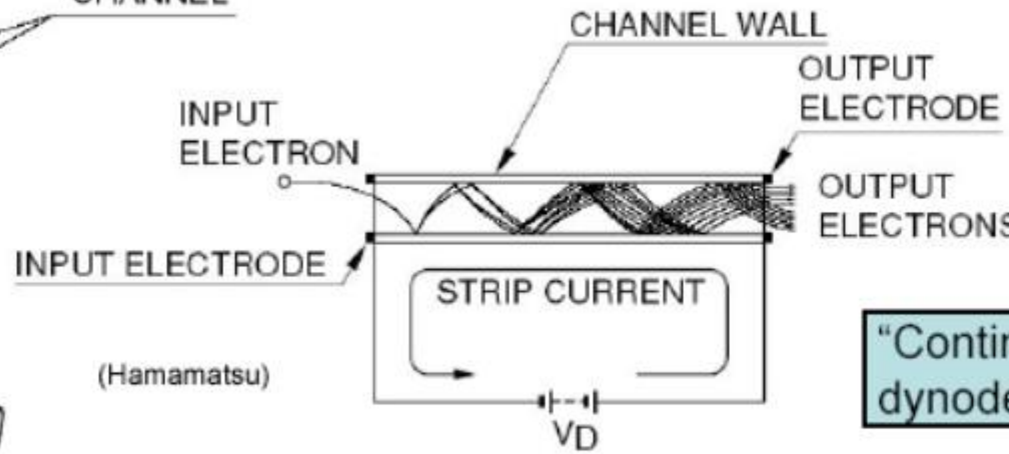
Secondary emission coefficient:
$\delta = \#(e^- \text{ produced})/\#(e^- \text{ incoming})$

Typical: $\left.\begin{array}{l}\delta = 2 - 10 \\ n = 8 - 15\end{array}\right]$ ➔ $G = \delta^n = 10^6 - 10^8$

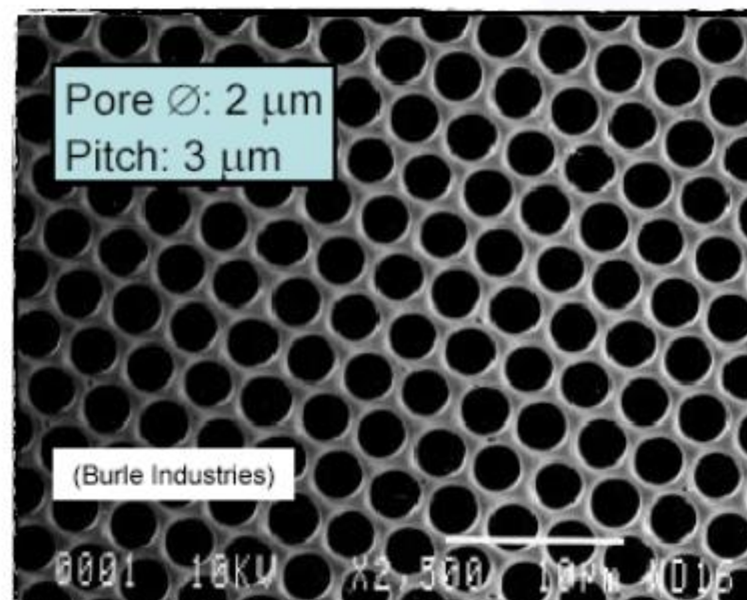
Micro Channel Plate:



Pb-glass



"Continuous" dynode chain



"2D Photomultiplier"

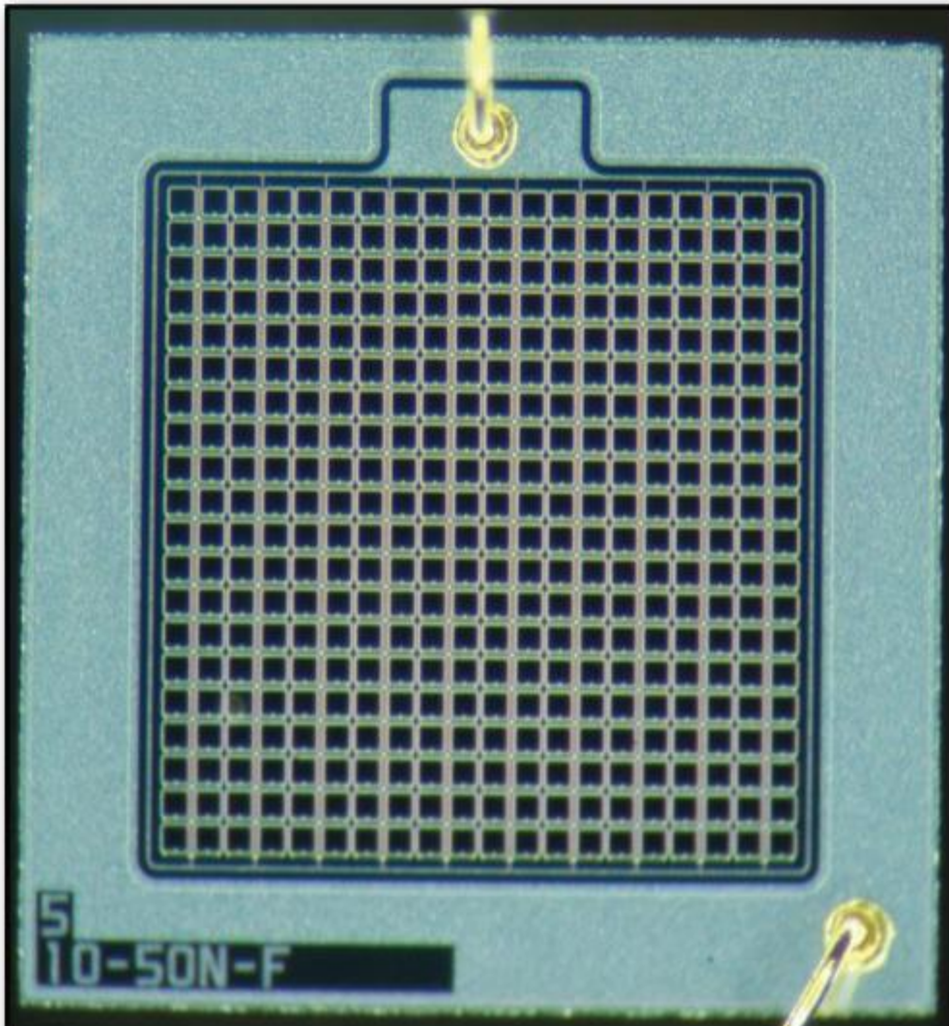
Gain: $5 \cdot 10^4$

Fast signal [time spread ~ 50 ps]

B-Field tolerant [up to 0.1T]

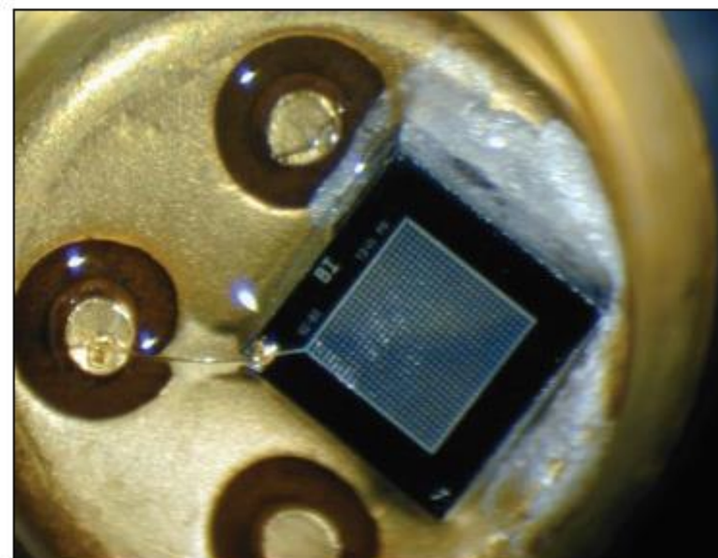
But: limited life time/rate capability

Silicon Photomultipliers:



HAMAMATSU
MPPC 400Pixels

One of the first SiPM
Pulsar, Moscow



Use of Scintillators:

- ***Time of flight detector***
- ***Energy measurement (Calorimeter)***
- ***Hodoscopes (Fiber trackers)***
- ***Trigger system***