INFN
LNF
tituto Nazionale di Fisica Nucleare

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Introduction to Calorimetry

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Principles

Simulation

Operation

FEE

DAQ

Hands-on Laborator

Commissioning

Calibration

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MUSE

Outline of the lecture

A calorimeter primer

- → Calorimeter concept
- → Calorimeter kind: etherogeneous/homogeneous
- → Electromagnetic showers
- → Energy resolution terms
- → Hadronic showers
- → Compensating calorimeters

- → Homogenous calorimetry
- → Scintillation crystals
- → Photodetectors

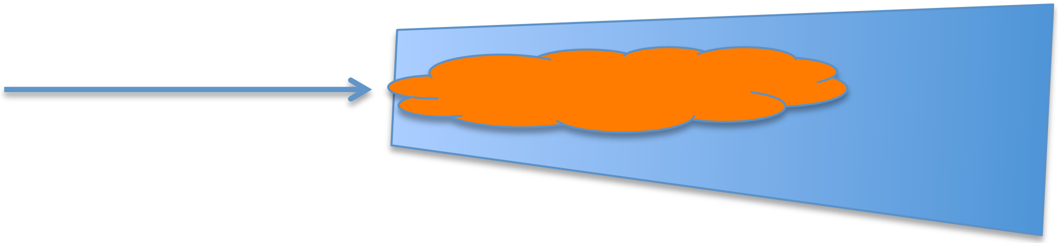
What is a calorimeter ? (1)

☐ The main usage of a calorimeter (HEP) **is to measure the particle energy.**

☐ They typically do this by means of totally absorbing energy in the calorimeter material **(destructive measurement)**

☐ **What kind of particle can be measured ?**
neutral and charged
- em calorimeter (photons, π^0, electrons)
- hadron calorimeters (n, p, $\pi^{+/-}$,K, Jets …..)

☐ **Basic assumption of the response → Linearity**
Q (response pC) = a (Calib Constant) x Ep (Particle Energy)

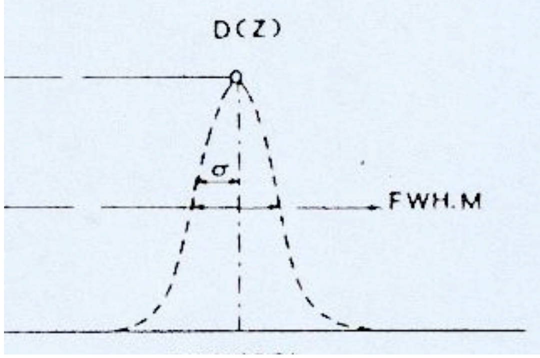


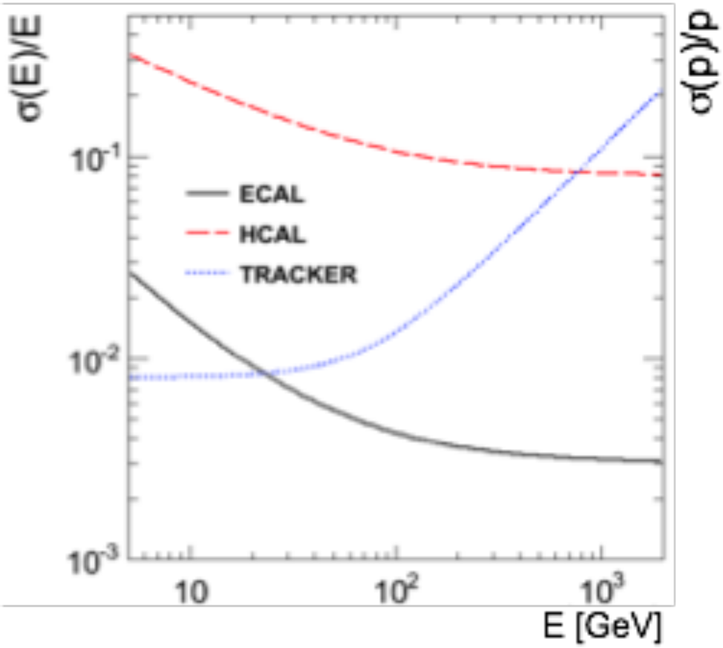
What is a calorimeter ? (2)

Calorimeter and trackers are complementary in HEP.

Many good reasons to have it one in your detector:

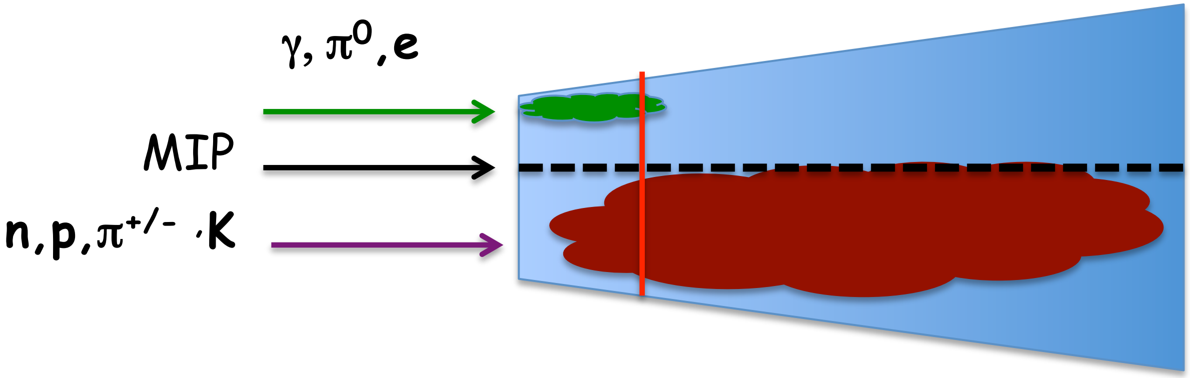
- ☐ **Energy resolution improves for increasing energy** (like k/sqrt(Ep), stochastic measurement)
- ☐ **Tracker momentum resolution deteriorates** for increasing momentum (larger sagitta errors)
- ☐ **Calorimeters can be extremely fast** and easy to be **used for triggering**.
- ☐ **Tracking + calorimeter helps:**
  - → **PID** (ex photons/e, e/pi-mu, …)
  - → **Energy flow** (i.e. tracking correction of energy deposits to improve Jets determination .. Started LEP-CDF , CMS-Atlas improved)
- ☐ **In 4-π detectors missing energy** becomes also very important **(neutrinos)**





How many calorimeter kinds ? (1)

Calorimeters have assumed any form since they were born but basic sub-division remains for dimension scale and methods of operation:



Electromagnetic, Hadronic

E.M. …. well described shower γ, π^0,e

radiation length (X_0)

Had .. not well described shower n,p,$\pi^{+/-}$,K

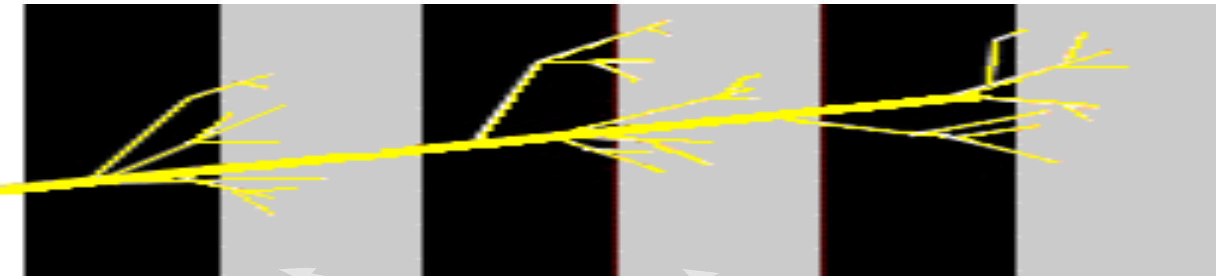
interaction length (Λ)

How many calorimeter kinds?

Heterogeneous: Sampling signal in active material, mostly absorbed in passive material. Possibility of longitudinal segmentation. Many choices.

Can be both EM and hadronic calorimeter. Can be fast.

Are cheap. Can be adapted to many situation → Poor resolution.



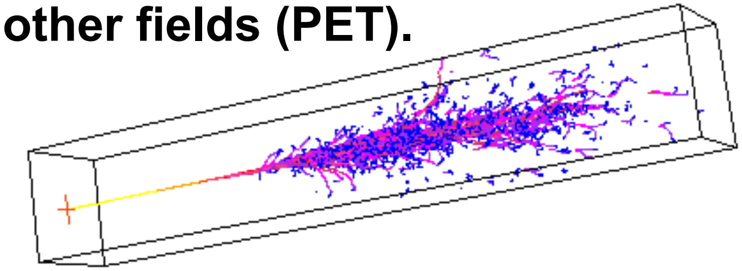
Homegeneous: signal is fully absorbed in active material.

Small longitudinal segmentation. Limited choice of material. Expensive.

Cannot be hadronic calorimeter. Very good resolution.

Timing can be great with some expedients.

Can be used also in other fields (PET).



Signal generation

1. A particle deposits its full energy in the calorimeter media
2. The energy is converted into a measurable signal

(charge / light / sound / heat)

The most used materials → gases / semiconductors / scintillators ……

- semiconductors: dE/dx or photon-absorption (Silicon Trackers/Vertex)
- + drift of e-**h** **eV per e-hole pair**
- gases: dE/dx or photon-absorption (Trackers)
  + charge diffusion **20-40 eV per e-ion pair**
- scintillators: dE/dx or photon-absorption (Calorimeters)
  + light emission **400-1000 eV per photon**

generated charges/photons yield the measurable signal:
statistical process = the more the better !

Primer of EM showers (1)

Dominant processes at high energies (E > few MeV) :

Photons : Pair production

Electrons : Bremsstrahlung

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

$$= \frac{7}{9}\frac{A}{N_A X_0}$$

[X_0: radiation length]
[in cm or g/cm^2]

Absorption coefficient:

$$\mu = n\sigma = \rho \frac{N_A}{A} \cdot \sigma_{\text{pair}} = \frac{7}{9}\frac{\rho}{X_0}$$

X_0 = radiation length in [g/cm^2]

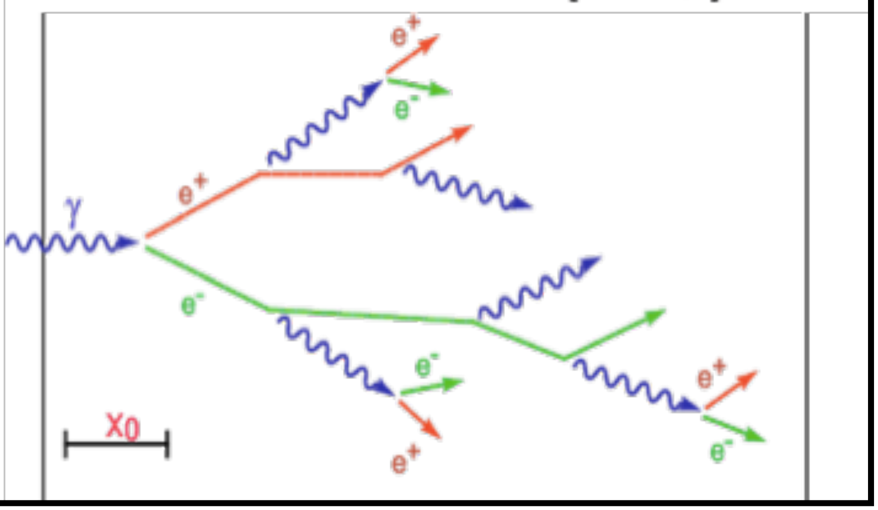
$$\boxed{X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}}$$

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E \ln \frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

$$\rightarrow E = E_0 e^{-x/X_0}$$

After passage of one X_0 electron has only (1/e)th of its primary energy ...

[i.e. 37%]



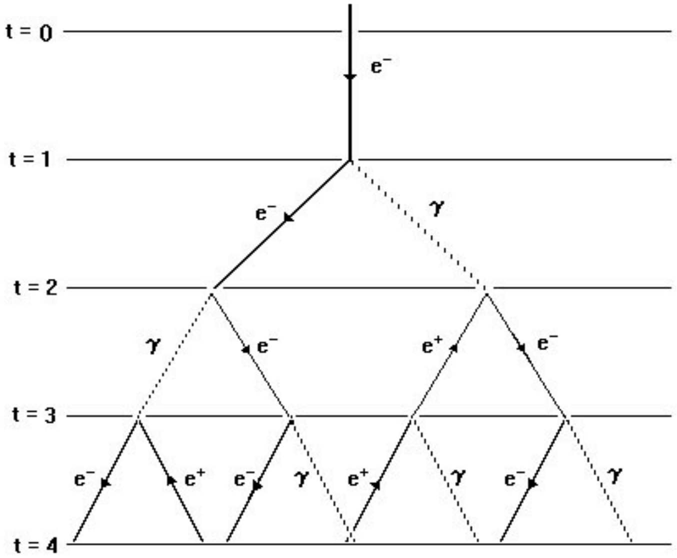
Primer of EM showers (2)

An alternating sequence of interactions
creates a cascade

Simplified shower model [Heitler]

$E > E_c$: shower development governed by X_0

- e$^-$ loses energy via Bremsstrahlung
- γ pair production with ***mean free path 9/7 X$_0$***



$$E_c \approx \frac{610\text{MeV}}{Z+1.24}$$

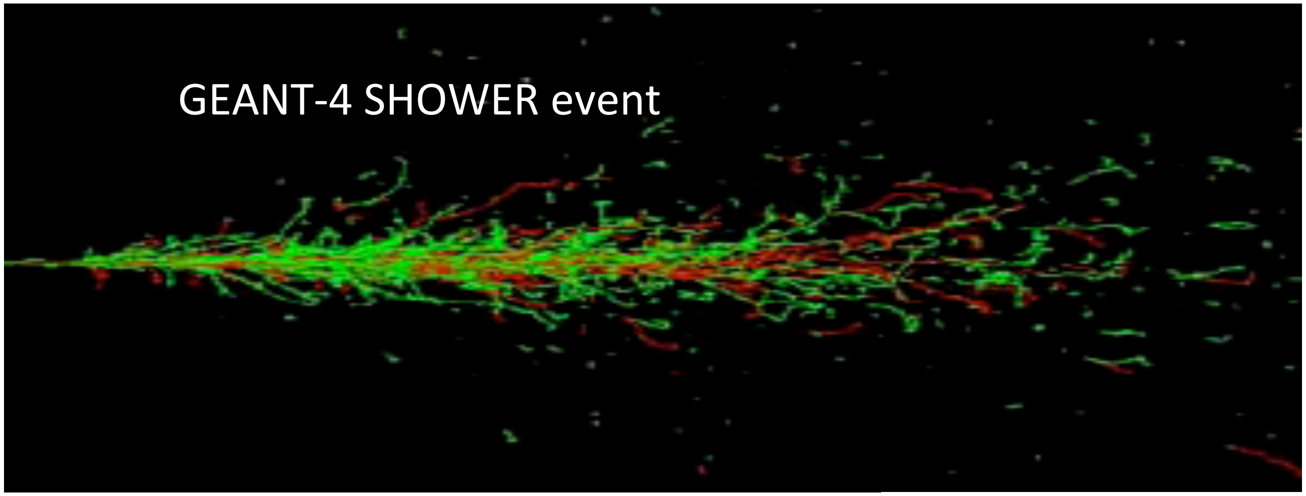
$$N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_c}$$

- N. particles doubles every X_0 of material,
- Energy gets reduced by 2 @ each iteration
- Shower continues until the particles energy reaches E_c

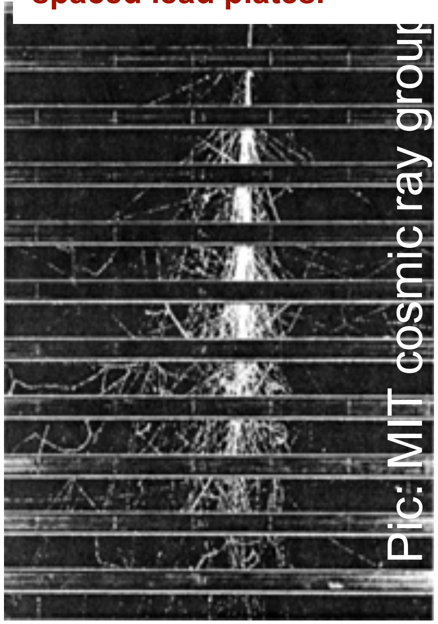
Shower max @ tmax = $\ln(E_0/E_c)/\ln 2$
After this point dE/dx, Compton and photoelectric effects take over.
Shower energy deposition diminishes and then stops. It is referred as shower tail.

t (95 %)= [t(max) + 0.008 Z + 9.6] in X_0 units

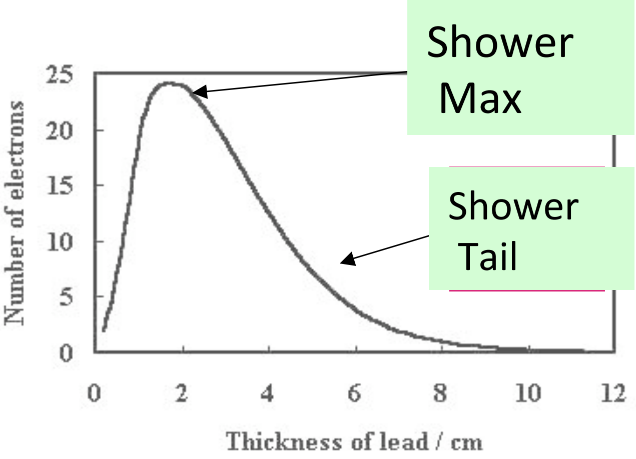
Primer of EM showers (3)



Cloud chamber photo of EM cascade between spaced lead plates.



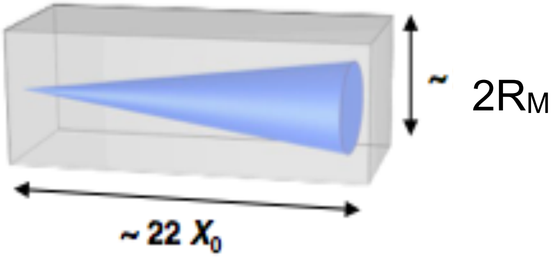
Longitudinal development



$$dE/dt = E_0\, ct^{\alpha} \exp(-\beta t)$$

$$t = X/X_0$$

Transverse development



Multiple scattering dominates in Transverse development

$$R_M = \frac{21\,\text{MeV}}{E_c(MeV)} X_0 \quad [g/cm^2]$$

75% E_0 in $1R_M$;
95% in $2R_M$;
99% in $3.5R_M$

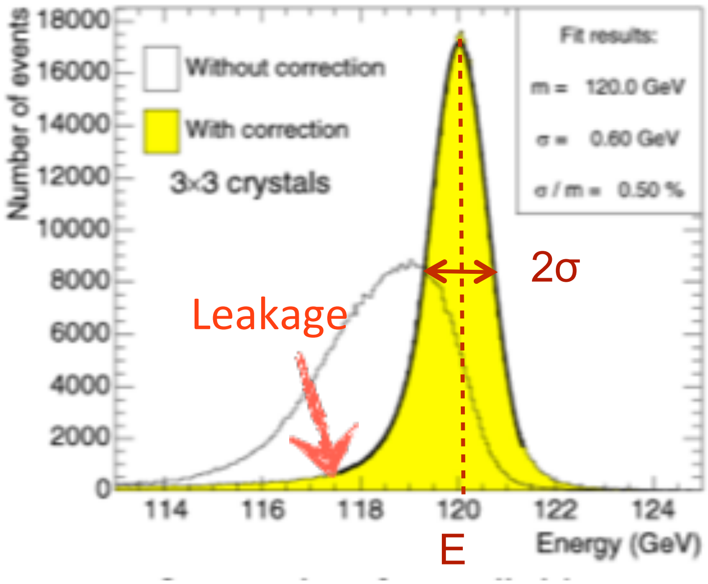
Energy Resolution terms

- The **energy resolution** is parametrized as:

$$\frac{\sigma(E)}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{b}{E}\right)^2 + c^2}$$

or

$$\boxed{\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c}$$



- ❑ **Stochastic term** **a**
  - E ∝ N ➔ σ ∝ 1/√N : all statistical effects contribute
    i.e. intrinsic and sampling fluctuations, photoelectron statistics

- ❑ **Noise term** **b** (energy independent term) **relevant at low E**
  - Electronic noise, radioactivity

- ❑ **Constant term** **c** (linearly dependent of energy) **dominates at high E**
  - inhomogeneities, calibration uncertainties, radiation damage, (leakage), …

Calorimeter Types: homogeneous (1)

Detectable signal is proportional to the total track length of e+ and e- in the active material, intrinsic limit on energy resolution is given by the fluctuations in fraction of initial energy that generates detectable signal

$$N_{tot} \propto \frac{E_0}{E_C} \xrightarrow{\text{Total track length}} T_0 = N_{tot} X_0 \approx \frac{E_0}{E_C} X_0$$

Detectable track length $T_r = f_s T_0$

f_s fraction of N_{tot} with $E > E_s$

$$\rightarrow \boxed{\frac{\sigma(E)}{E} \propto \frac{\sigma(T_r)}{T_r} \propto \frac{1}{\sqrt{T_r}} \propto \frac{1}{\sqrt{E_0}}}$$

Fluctuations in track length:
Poisson process

Fix E_0 $\rightarrow$ $\boxed{\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{f_s}} \sqrt{\frac{E_C}{X_0}} \propto \frac{1}{\sqrt{f_s}} \sqrt{\frac{Z}{A}}}$ $\rightarrow$

- maximize f_s
- minimize Z/A

Calorimeter Types: homogeneous(2)

Homogeneous calorimeters: all the energy is deposited in an active medium.
Absorber ≡ active medium → All e+e- over threshold produce a signal
Excellent energy resolution

Compare processes with different energy threshold

Scintillating crystals

$$E_s \cong \beta E_{gap} \sim \text{eV}$$

$$\approx 10^2 \div 10^4 \gamma / \text{MeV}$$

$$\sigma / E \sim (1 \div 3)\% / \sqrt{E(\text{GeV})}$$

→ Lowest possible limit

Cherenkov radiators

$$\beta > \frac{1}{n} \rightarrow E_s \sim 0.7\text{MeV}$$

$$\approx 10 \div 30 \;\; \gamma / \text{MeV}$$

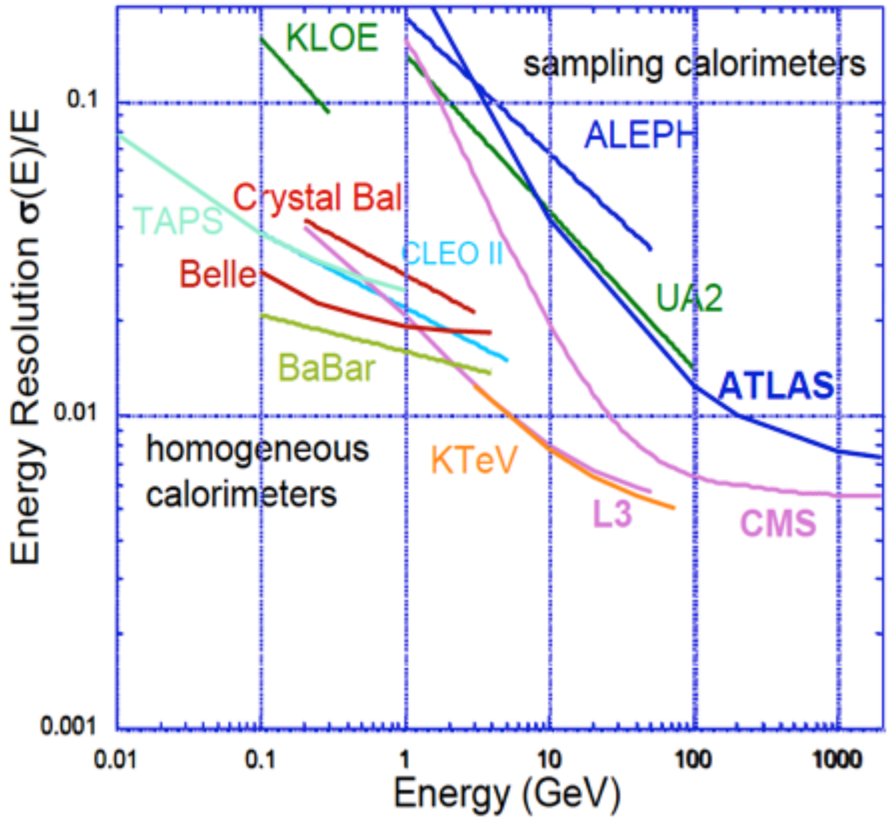
$$\sigma / E \sim (10 \div 5)\% / \sqrt{E(\text{GeV})}$$

Calorimeter Types: Sampling

A structure of passive and active material. Cheaper. Only a fraction (**Sampling Fraction, f_S**) of the deposited energy is detected (1-5%)

$$\frac{\sigma(E)}{E} \propto \frac{\sigma(T_r)}{T_r} \propto \frac{1}{\sqrt{T_r}}$$

$$T_r = f_s T_0 = f_s N_{tot} X_0^{abs} \approx f_s \frac{E}{E_C^{abs}} X_0^{abs}$$



Resolution scales with absorber thickness $t_{abs}=d/X_0$

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{N_r}} \propto \frac{1}{\sqrt{f_s}} \sqrt{\frac{E_C t_{abs}}{E}}$$

σ(E)/E ~ 10-30% / ✓ (E)

Notable exception: KLOE-like calorimeter (tomorrow)

Hadronic showers

Hadron showers are more complicated than EM.

→***We need to consider the strong interaction*** with detector material.

In nuclear collisions, the following objects are produced:

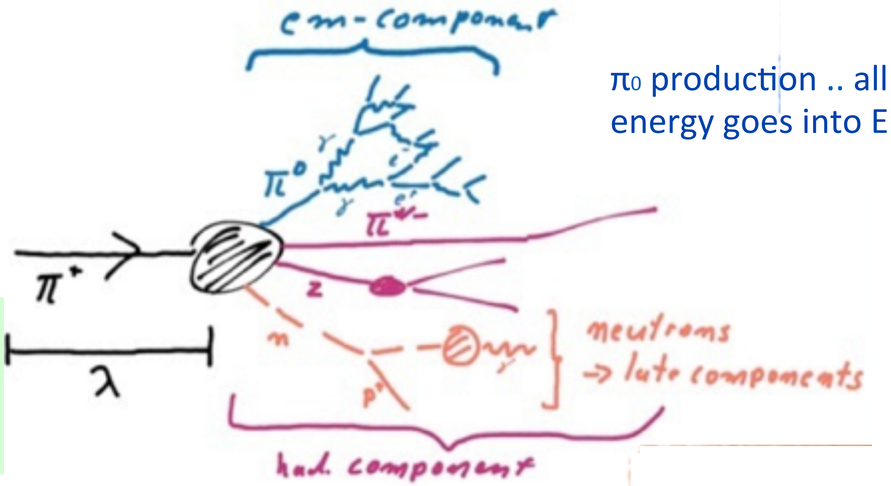
- → high energetic secondary hadrons [O(GeV)]
- → electromagnetically decaying particles (π0,η) initiate EM showers
- → spallation p/n and nuclear excitation from soft nuclear processes [O(MeV)]
- → part of the energy is invisible: binding energy of nuclei, ν, μ, soft γ's

Different scale: hadronic interaction length

	λ_I	X_0
Polystyren	81.7 cm	43.8 cm
PbWO	20.2 cm	0.9 cm
Fe	16.7 cm	1.8 cm
W	9.9 cm	0.35 cm

$$\lambda_I = \frac{A}{N_A \sigma_{total}}$$

σ_{tot} = total cross section for nuclear processes

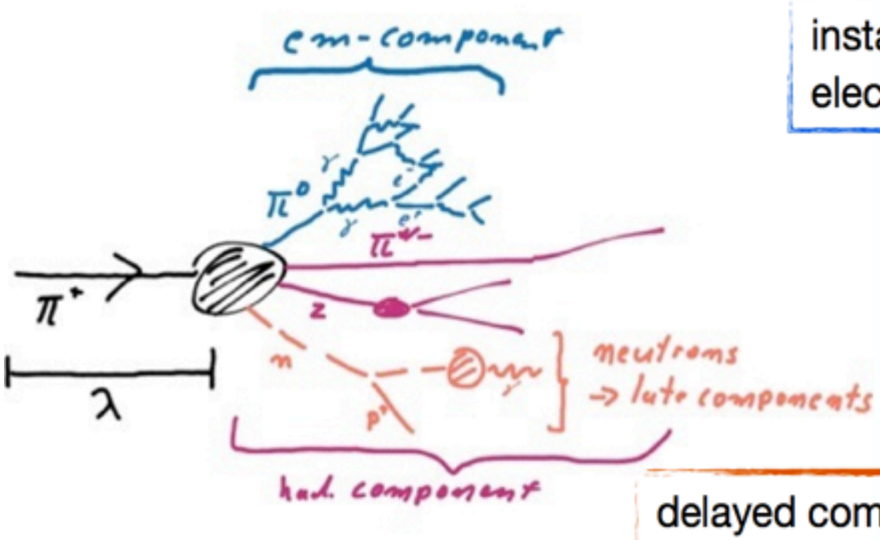


π_0 production .. all energy goes into EM

Compare X_0 for high-Z materials, we see that the size needed for hadron calorimeters is large compared to EM calorimeters.

The structure of hadronic showers

- hadronic showers have a complex structure also in time



instantaneous, detected via energy loss of electrons and positrons in active medium

instantaneous component: charged hadrons detected via energy loss of charged hadrons in active medium

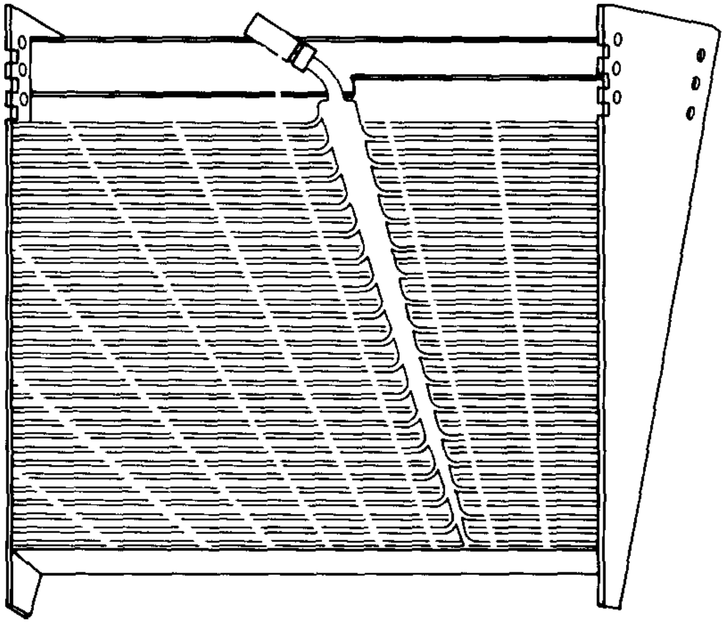
delayed component:

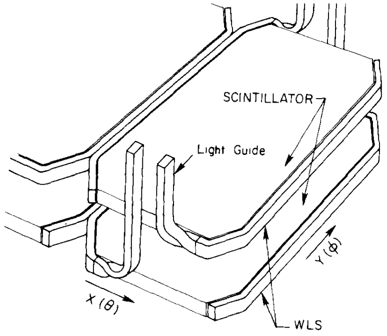
- neutrons from evaporation and spallation
- photons, neutrons, protons from nuclear de-excitation following neutron capture
- momentum transfer to protons in hydrogenous active medium from slow neutrons

f_{EM} = fraction of primary hadron energy deposited via EM processes

- Importance of delayed component strongly depends on target nucleus
- Sensitivity to time structure depends on the choice of active medium

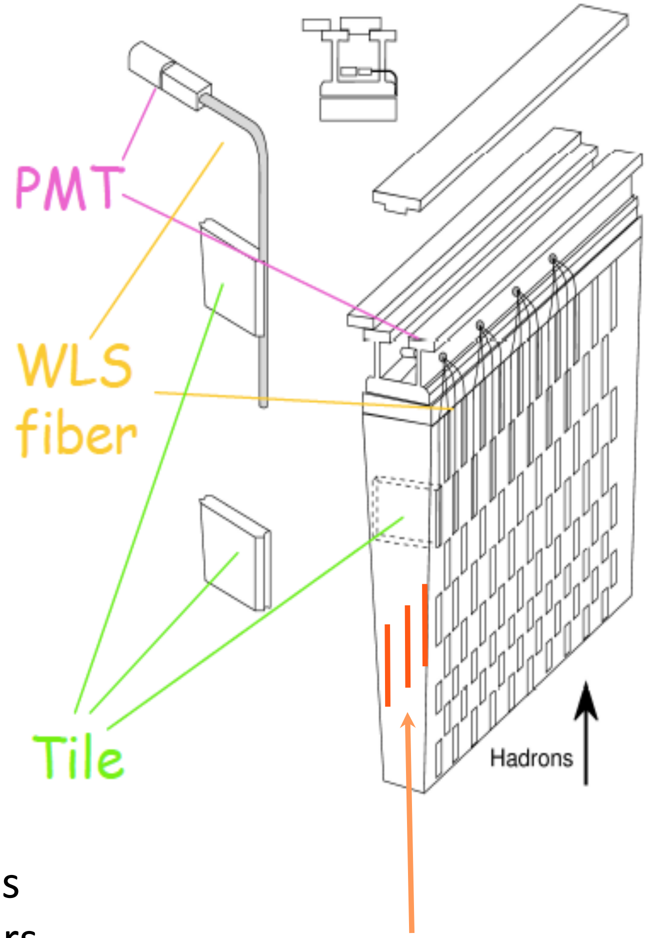
Example of hadronic calorimeters





CDF: Fe/scintillator with transversal orientation, WLS bars and plexi-light guides

Improvements with WLS fibers
LESS cracks



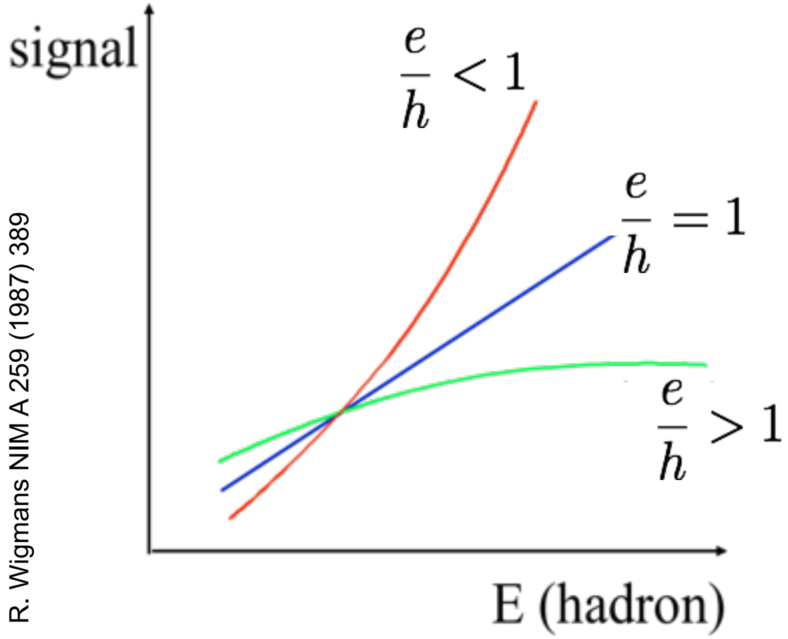
ATLAS: Fe/scintillator vertical orientation

Hadronic Calo: Compensation (1)

- A hadron calorimeter shows in general different response to hadronic and electromagnetic shower components $\boxed{R_h = eE_e + hE_h}$

- The fraction of the energy deposited hadronically depends on the energy

$$\boxed{\frac{E_h}{E} = 1 - f_{EM} = 1 - k\ln E(GeV) \quad k \approx 0.1}$$



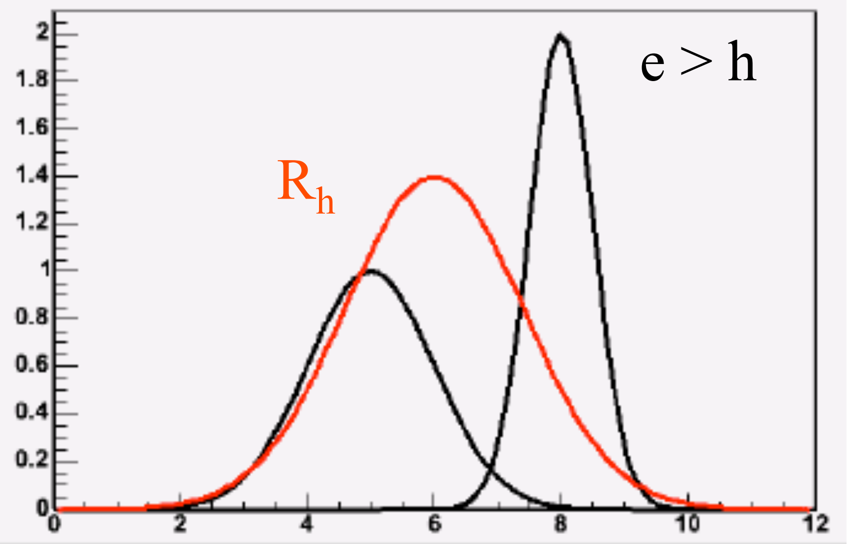
R. Wigmans NIM A 259 (1987) 389

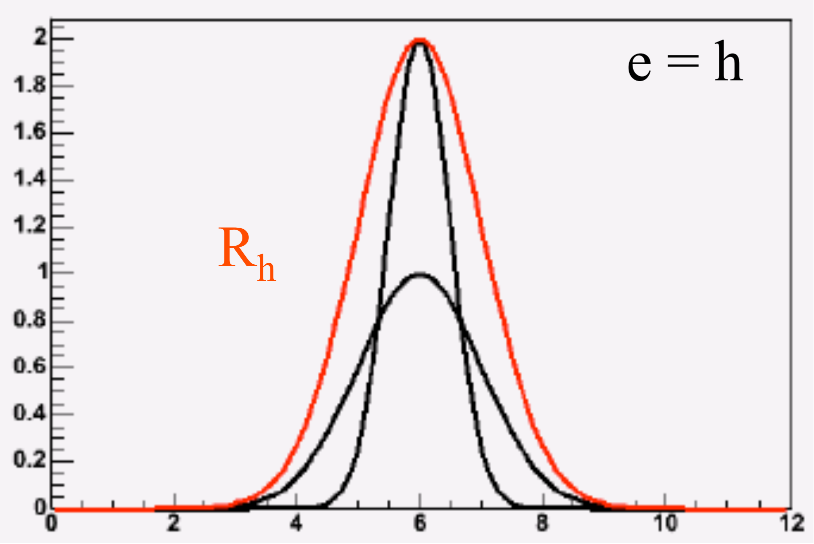
→ Calorimeter response to hadrons becomes not-linear

→ Energy resolution degrades

$$\boxed{\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} + d\left(\frac{e}{h} - 1\right)}$$

Hadronic calo: Compensation (2)



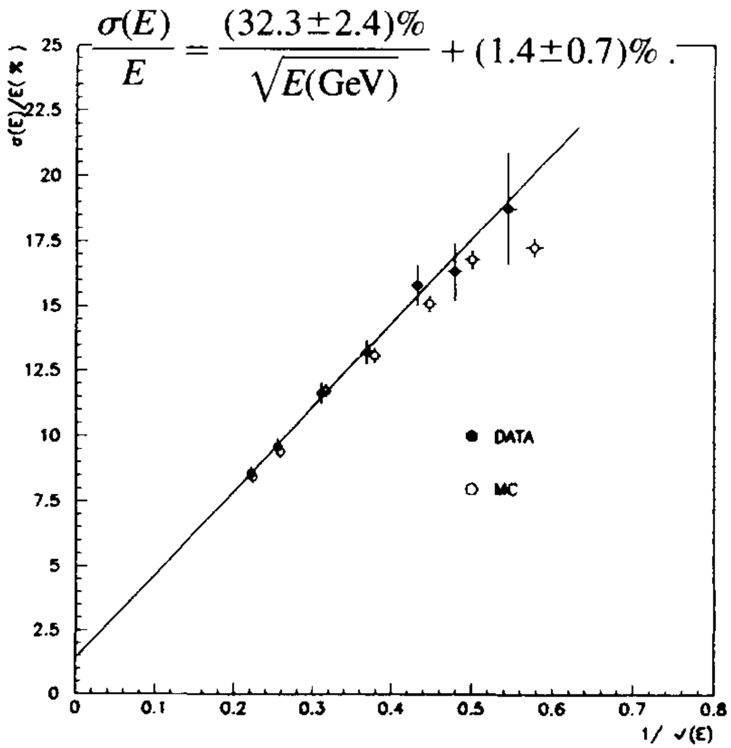


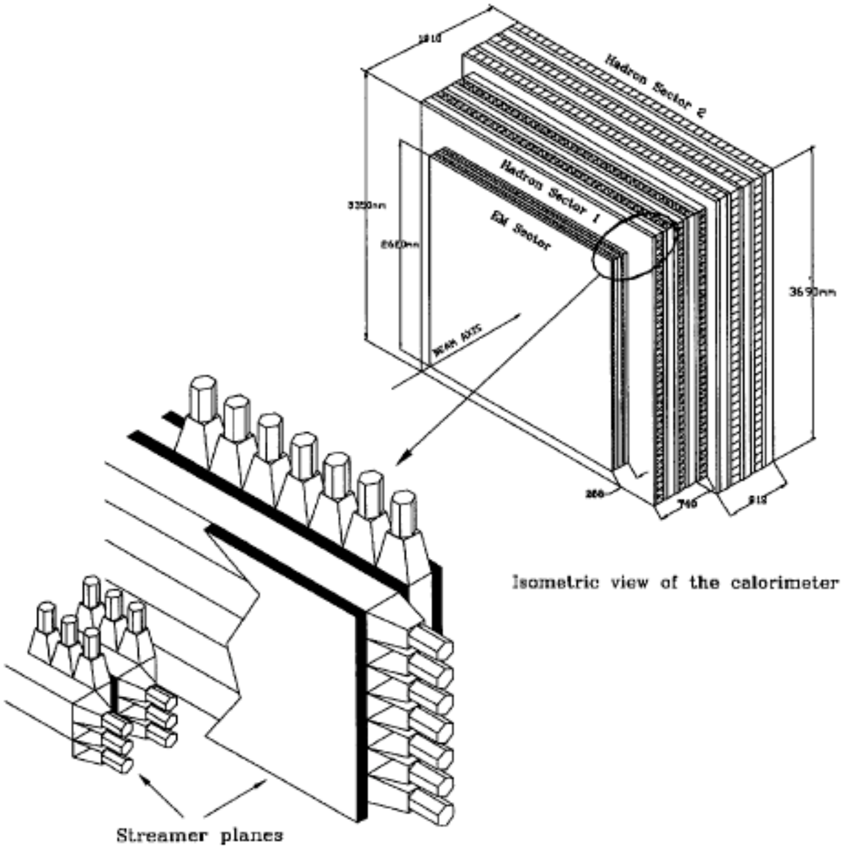
- To “Compensate” a Hadronic Calorimeter means make **e/h → 1**

- To do so .. there are typically 3 ways (example for common e/h >1)
  → A) enhance sensitivity to low neutrons → boost h (H-enriched)
  → B) add special absorbers for neutrons (Uranium)→ boost h
  → C) Reduce electron response → correcting sampling fraction

Magic Thumb Rule (Wigmans) Fs (Lead/Fiber= 4/1)

Chorus example of compensation





The ZEUS Calorimeter with U plates got a good compensation (e/h) and similar resolution for Eh > 5 GeV: σ(E)/E = 35%/sqrt(E/GeV)

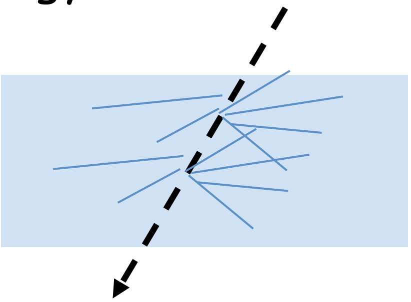
More detailed discussion on compensation and nowadays trends and developments will be shown on Friday by Dr. Gabriella Gaudio → **DREAM project**

Scintillators and photosensors

Scintillation process

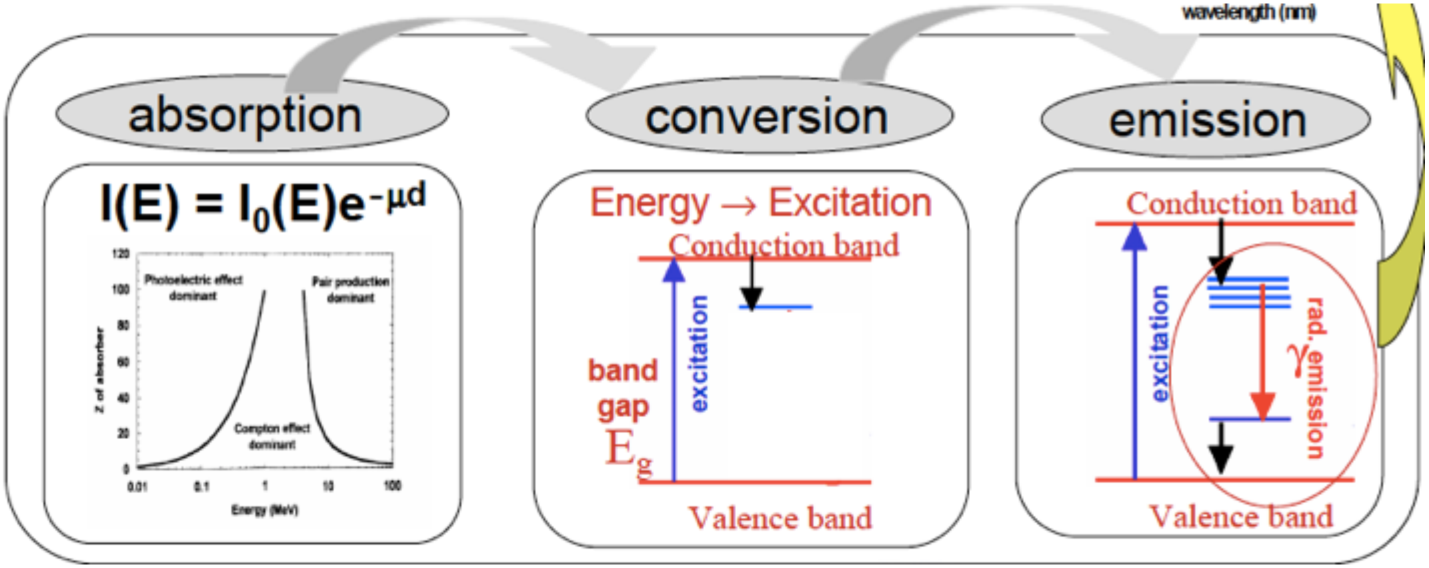
Basic principle: a charged particle crossing a scintillator loses energy, exciting atoms or molecules of the material

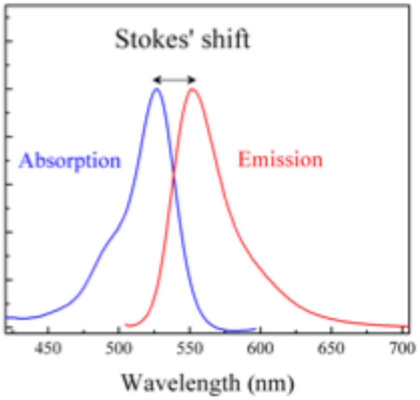
➪ **photon emission** (UV-visible) follows



Light emission:

- can be instantaneous, <10^{-8} s, (fluorescence) or delayed, ms to hours(phosphorescence)
- Has one or two exponential decay time t_D (fast, fast/slow)





$\lambda_{em} > \lambda_{ex}$

Scintillators: characteristics

Relevant characteristics for particle detection:

- ✗ Light Yield (LY) number of photons produced for a given absorbed energy
- ✗ Transparency to the emitted radiation
- ✗ Spectral emission compatible with light detectors (photosensors), where light is collected and then converted into electrons via photo-electric effect
- ✗ Linearity of response
- ✗ Time response
- ✗ Density, X_0, Rm

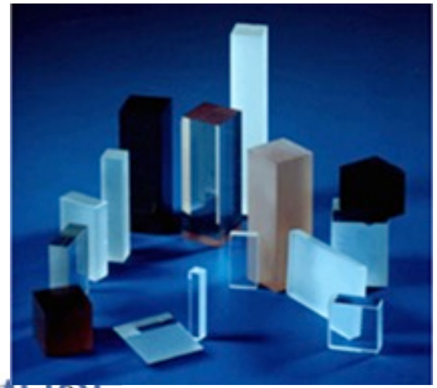
Types of scintillators

Organic scintillators

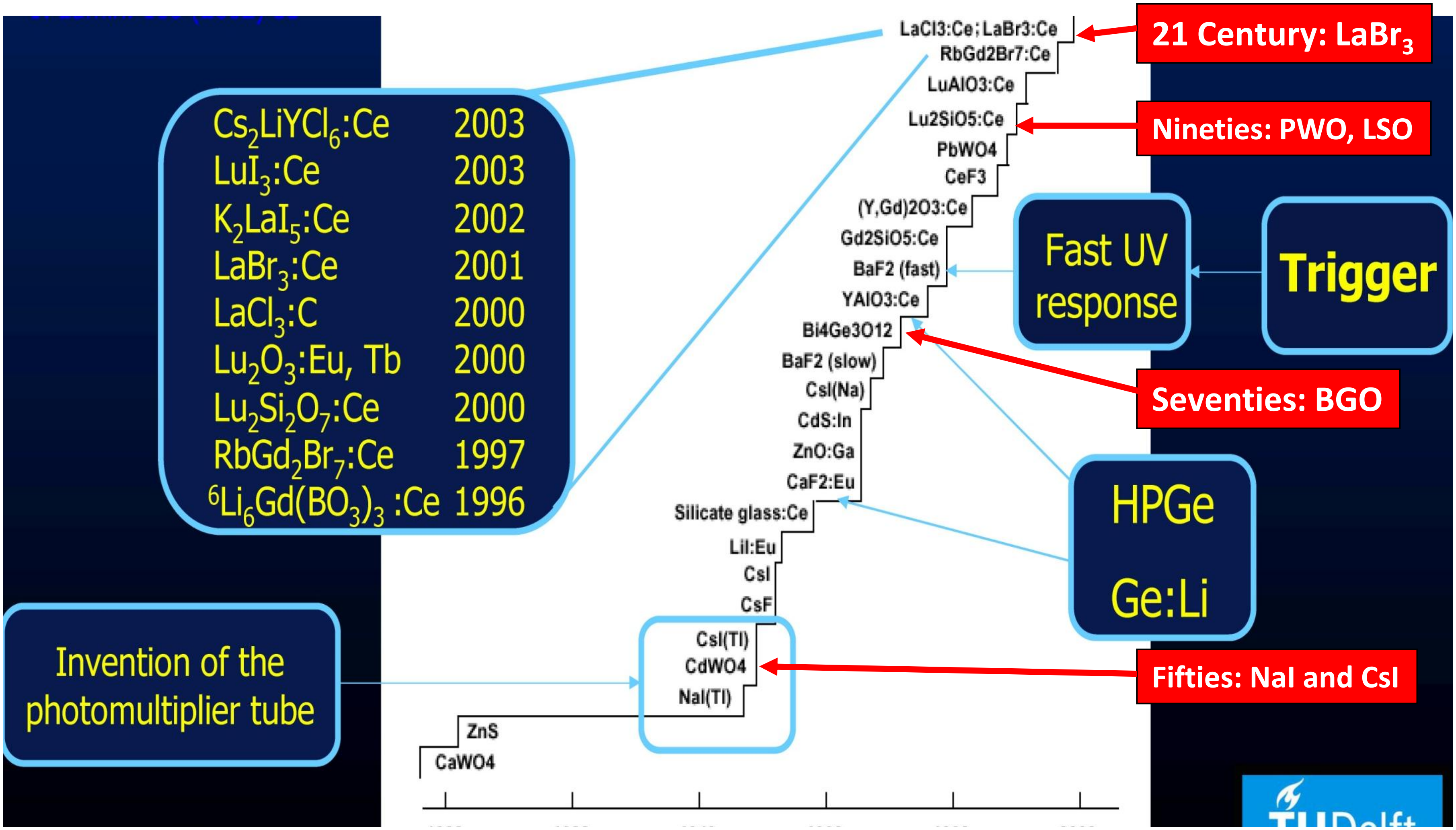
- ✗ Complex organic molecules (typically soluted in plastics materials) where UV light is emitted after excitation of molecular levels. Other molecules (wave length shifters) are then added to transfer light into visible radiation
  - ➢ **Fast emission time** (2.5-10 ns)
  - ➢ **Low scintillation efficiency** (< 2 k photons / MeV)
  - ➢ **Low density** (1 g/cm^3)
  - ➢ Can be easily **machined to any shape (fibers)**

Inorganic scintillators

- ✗ Crystals (alkali, alkaline earth and rare earth), usually doped with impurities uniformly dispersed throughout the crystal lattice
  - ➢ **High scintillation efficiency** (10-70 k photons / MeV)
  - ➢ **Slow emission time** (100-600 ns)
  - ➢ **High density** (4-7 g/cm^3)



Types of scintillators



Cs_2LiYCl_6:Ce	2003
LuI_3:Ce	2003
K_2LaI_5:Ce	2002
$LaBr_3$:Ce	2001
$LaCl_3$:C	2000
Lu_2O_3:Eu, Tb	2000
$Lu_2Si_2O_7$:Ce	2000
$RbGd_2Br_7$:Ce	1997
$^6Li_6Gd(BO_3)_3$:Ce	1996

Invention of the photomultiplier tube

Fast UV response

Trigger

HPGe

Ge:Li

21 Century: $LaBr_3$

Nineties: PWO, LSO

Seventies: BGO

Fifties: NaI and CsI

- ➢ Discovery and development of new scintillators driven by basic R&D in physics
- ➢ HEP has played a major role in developing new scintillators at an industrial scale and affordable costs (CsI, BGO, PbWO)

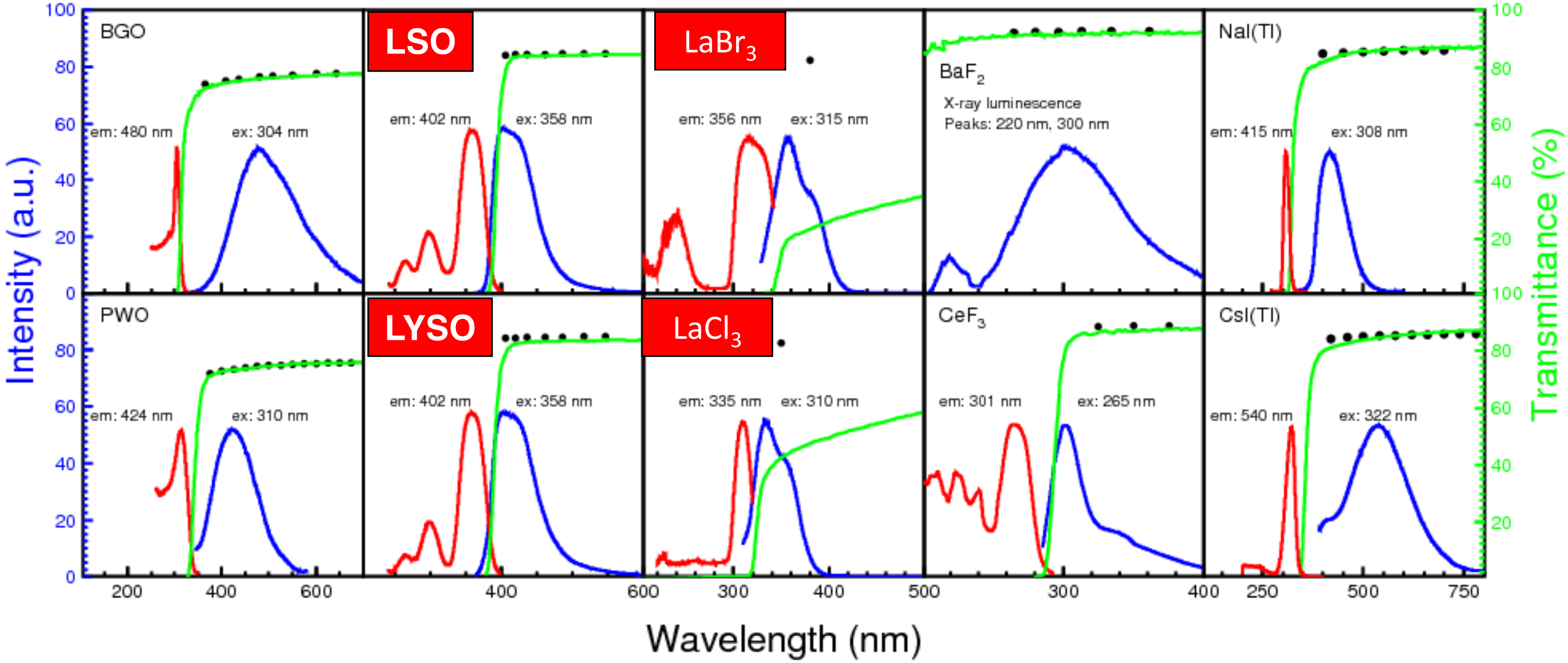
Crystals for HEP

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF$_2$	BGO	LYSO(Ce)	PWO
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3
Melting Point (°C)	651	621	621	1280	1050	2050	1123
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20
Hygroscopicity	Yes	Slight	Slight	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	420 310	300 220	480	402	425 420
Decay Time [b] (ns)	245	1220	30 6	650 0.9	300	40	30 10
★ Light Yield [b,c] (%)	100	165	3.6 1.1	36 4.1	21	85	0.3 0.1
d(LY)/dT [b] (%/ °C)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5

Broad variety of scintillator parameters: relative importance depends on the application

★ Typical LY of NaI ~ 40000 γ/MeV

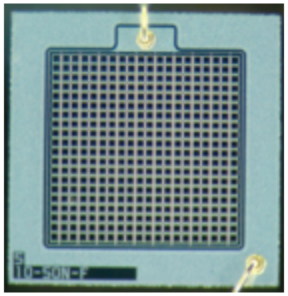
Emission Spectra

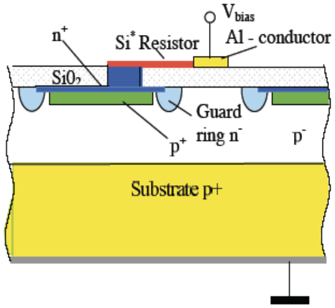


Detecting the light: Photosensors

Light is guided to a photo-detector (i.e. photomultiplier tube, silicon photomultiplier) and converted into charge:

- **Conversion of a photon into electrons** via photo-electric effect
- **Amplification of the electron signal** by factor 10^5-10^6 via secondary emissions on dynodes or avalanche in silicon





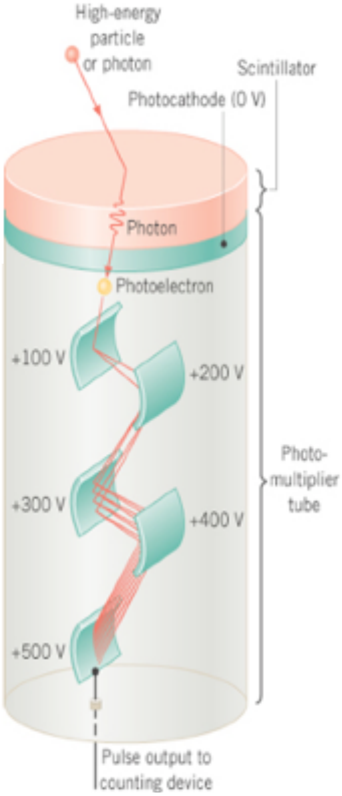


Photo-detector requirements:

- cover a large range of wave lengths (UV to IR)
- good efficiencies, single photon detection possible
- cover large active areas (SuperKamiokande O 46cm)
- **PMT (SiPM) are (not) sensitive to B-Field**

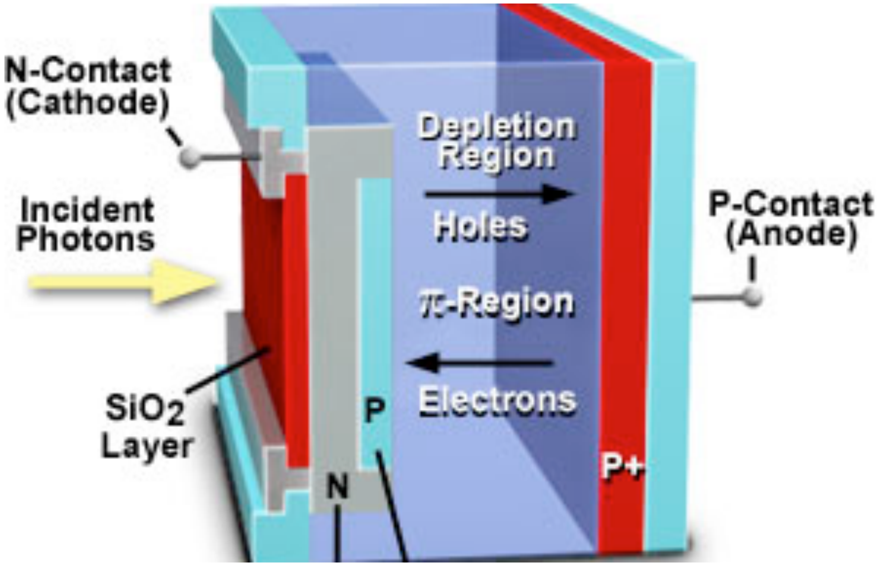
Silicon Photosensors

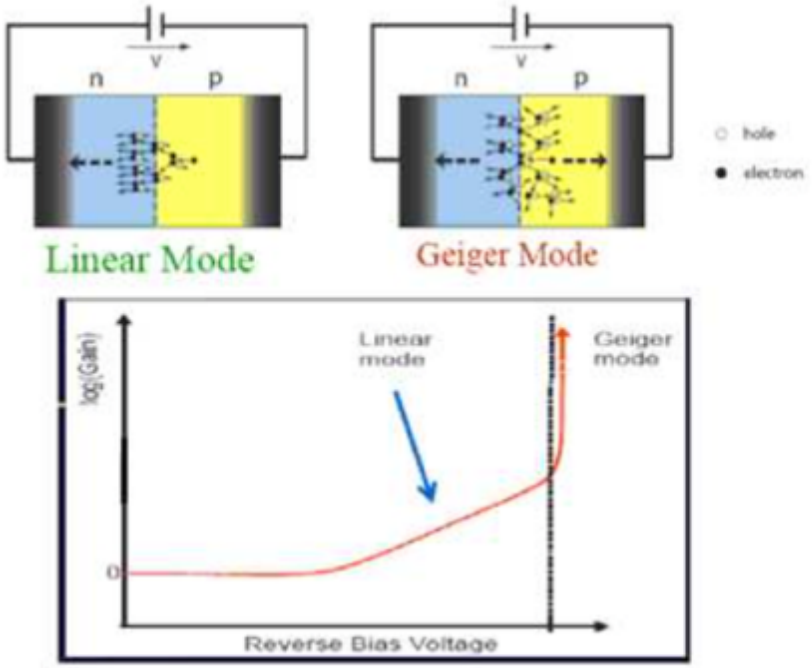
- A silicon photo-sensor is "in practice" a reverse Silicon N-P junction with a photo sensitive layer where "photo-electrons" are extracted.
- The reverse bias helps to create a large depleted region and reduce to negligible values the "dark current", Id, i.e. the current seen without any signal in input
- **3 work regimes:**

→ **Photodiode (G=1)** all e- produced in the photosensitive layer are collected at the anode.

→ **APD (G=50-2000)** , or Avalanche Photodiode, working in proportional regime and

→ **Geiger APD ($G=10^5$-10^6)** working in Geiger mode





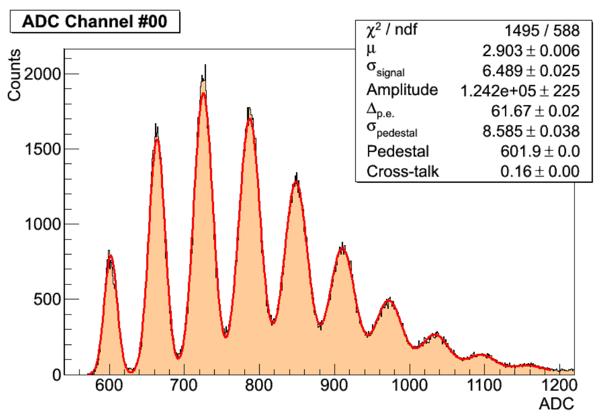
Silicon Photomultipliers (SiPM)

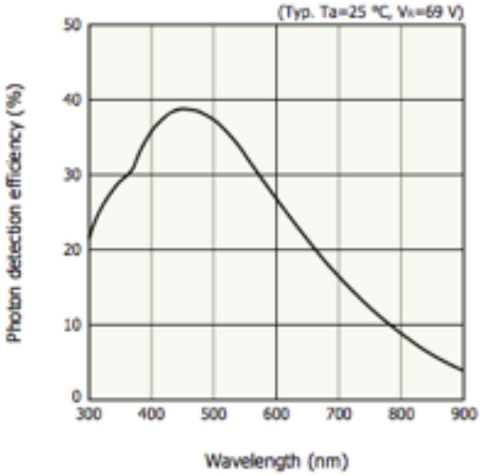
The basic SIPM element (pixel) is a combination of Geiger-APDs and quenching resistors

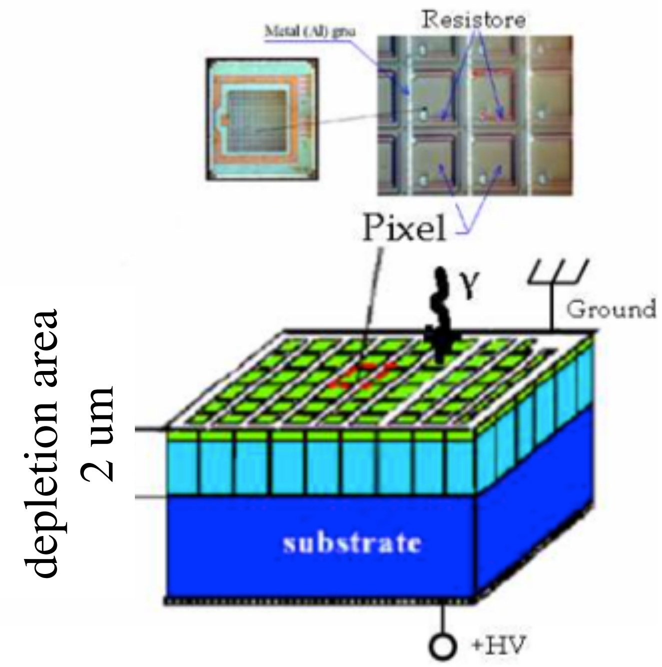
→ a large number of pixels are electrically connected and arranged in two dimensions;

→ Each pixel generates a pulse of the same amplitude when it detects a photon .

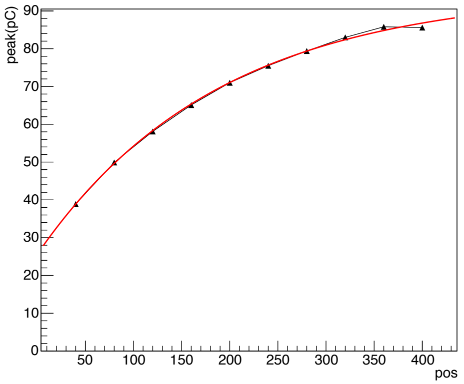
→ The output signal from multiple pixels is the superimposition of single pixel pulses.







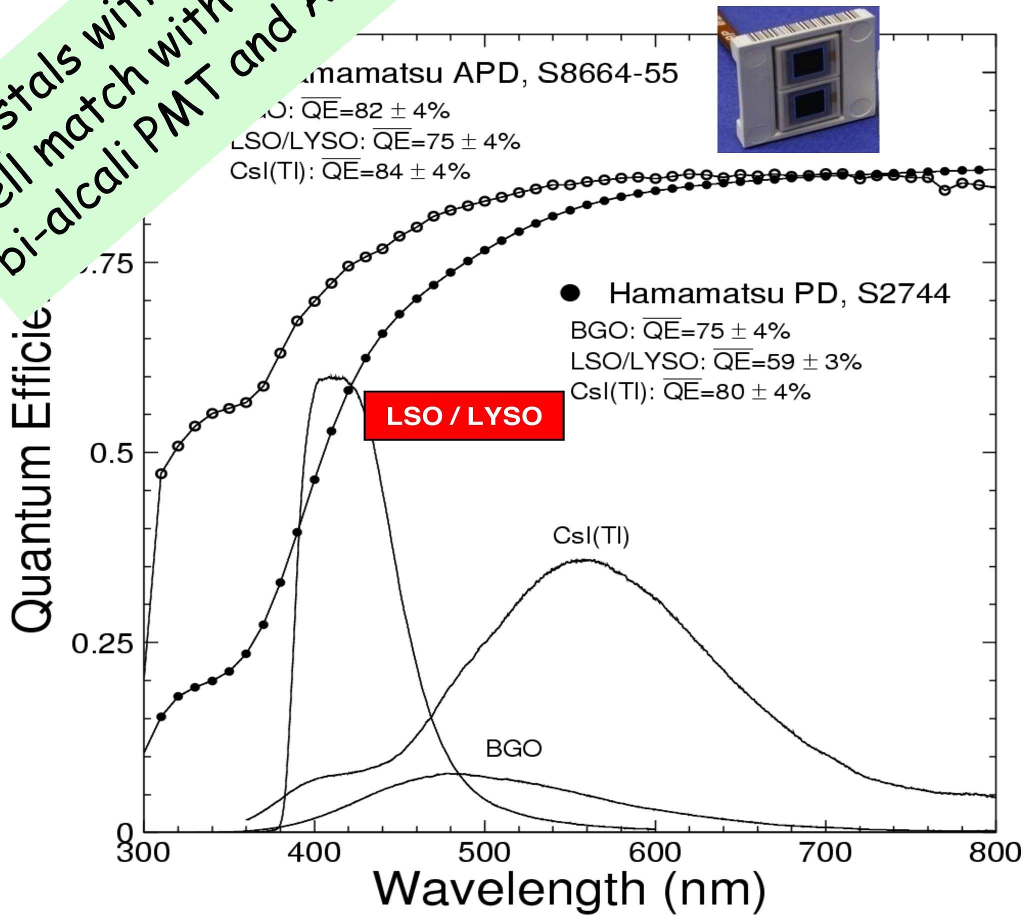
- Single photon counting
- Photon Detection Efficiency
- "Intrinsic" not-linearity on the response.



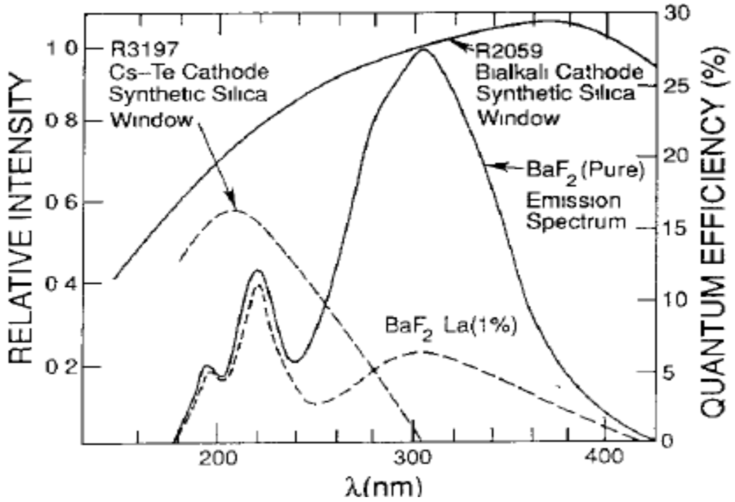
Photosensors & Scintillator matching

Coupling scintillator light emission spectrum to Quantum Efficiency of photosensors is essential

Crystals with λ > 400 nm well match with standard bi-alcali PMT and APD



BaF$_2$
Fast and Slow components



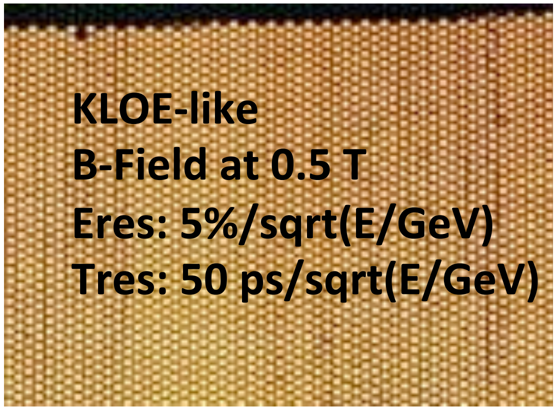
Forecast for tomorrow lesson

Tomorrow we will describe few practical example at low energy:

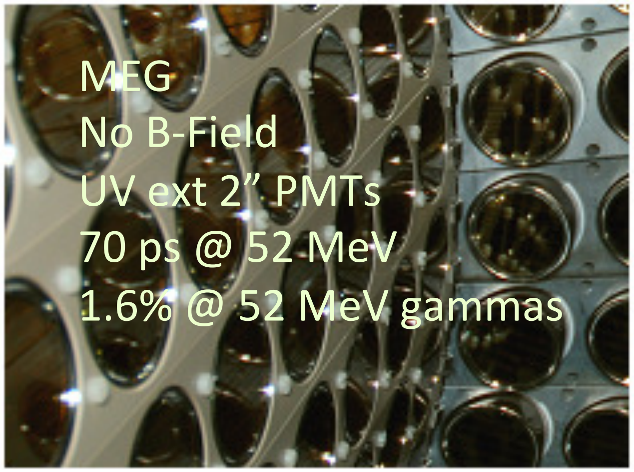
→ Electromagnetic , homogeneous!

Many possible "on-paper" solutions depending on requirements:

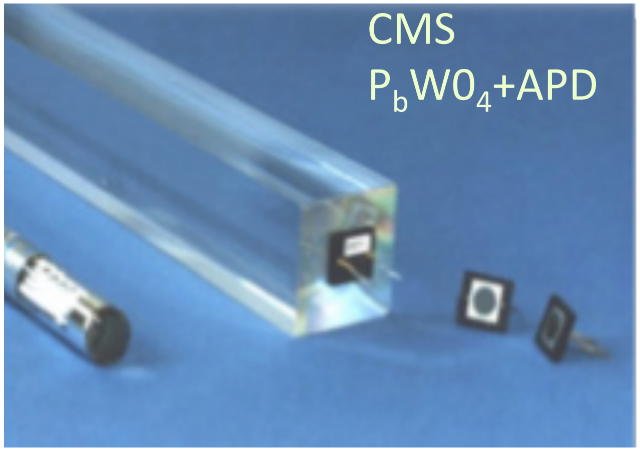
- High sampling heterogeneous calorimeter (KLOE-like)
- Homegeneous Liquid Xenon (MEG-like)
- Homogeneous Crystal like detector (kTeV, BaBar, CMS …)
- At low energy, Mu2e for the high intensity regime.



KLOE-like
B-Field at 0.5 T
Eres: 5%/sqrt(E/GeV)
Tres: 50 ps/sqrt(E/GeV)



MEG
No B-Field
UV ext 2" PMTs
70 ps @ 52 MeV
1.6% @ 52 MeV gammas

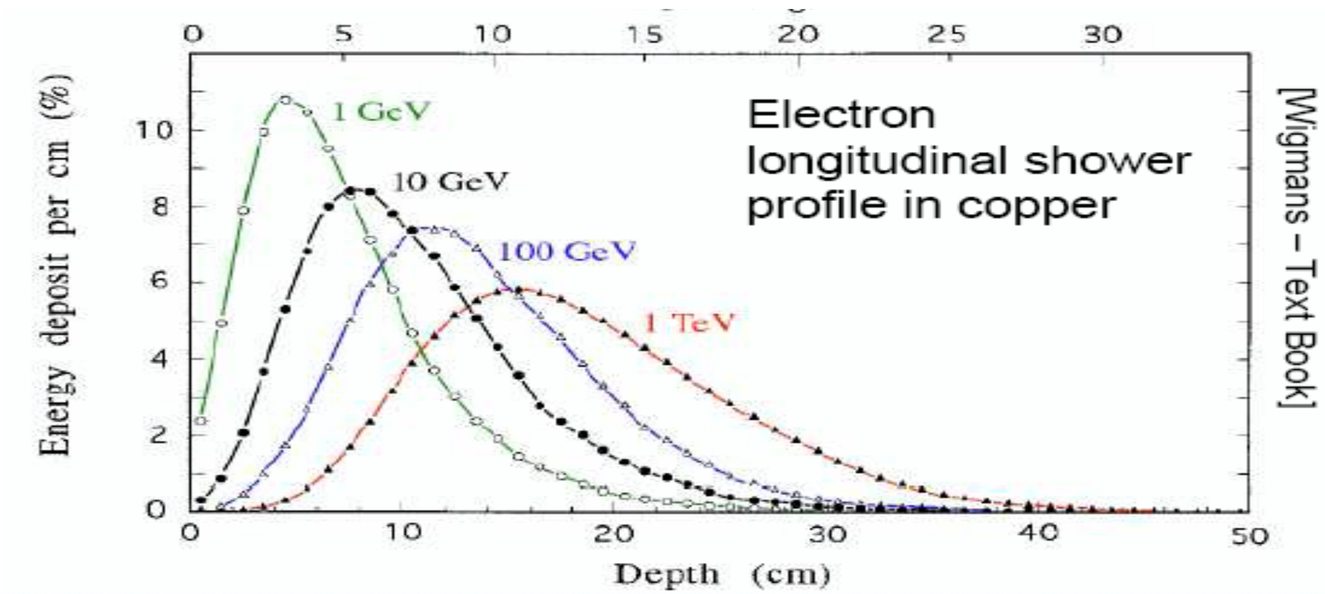


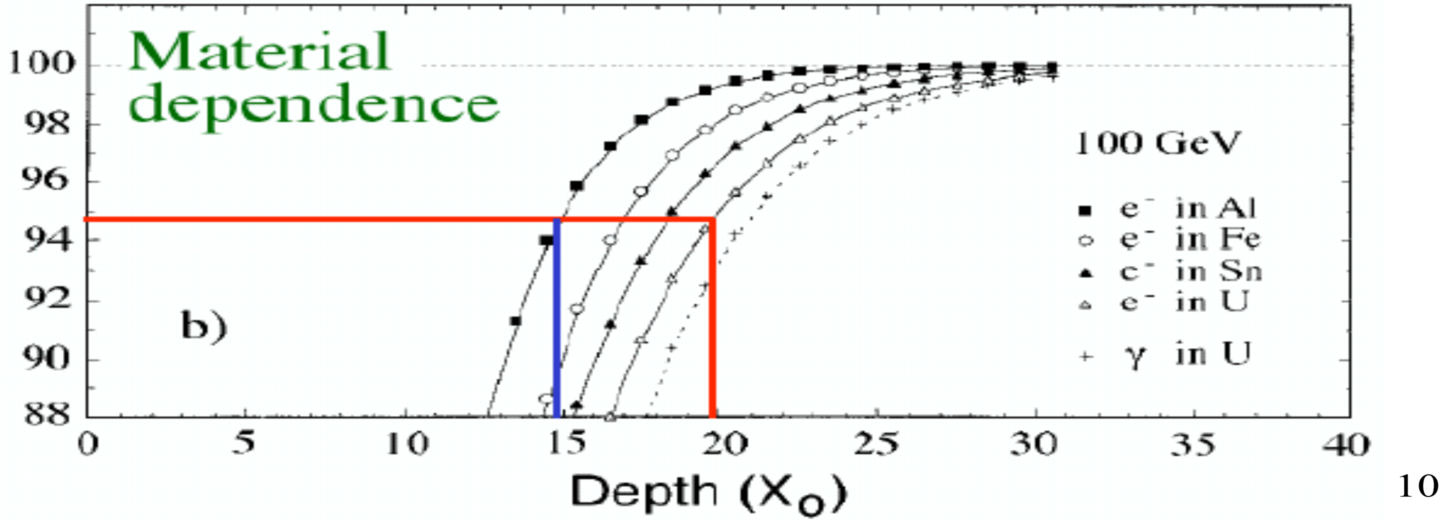
CMS
P_bW0_4+APD

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E(GeV)}} \oplus \frac{0.125}{E(GeV)} \oplus 0.3\%$$

ADDITIONAL MATERIAL

Longitudinal development





Silicon PMT : quenching

- The MPPC (multi-pixel photon counter) is one of the devices called silicon photomultipliers (SiPM) or Geiger APD. It is a photon-counting device **that uses multiple APD pixels operating in Geiger mode;**

- The Geiger mode allows obtaining a **large output by the discharge even when detecting a single photon**. Once the Geiger discharge begins, it continues as long as the electric field is maintained.
- One specific example for halting the Geiger discharge is a technique using a so-called quenching resistor connected in series with each APD pixel. This quickly stops the multiplication in the APD since a voltage drop occurs when the output current flows.

MPPC Structure