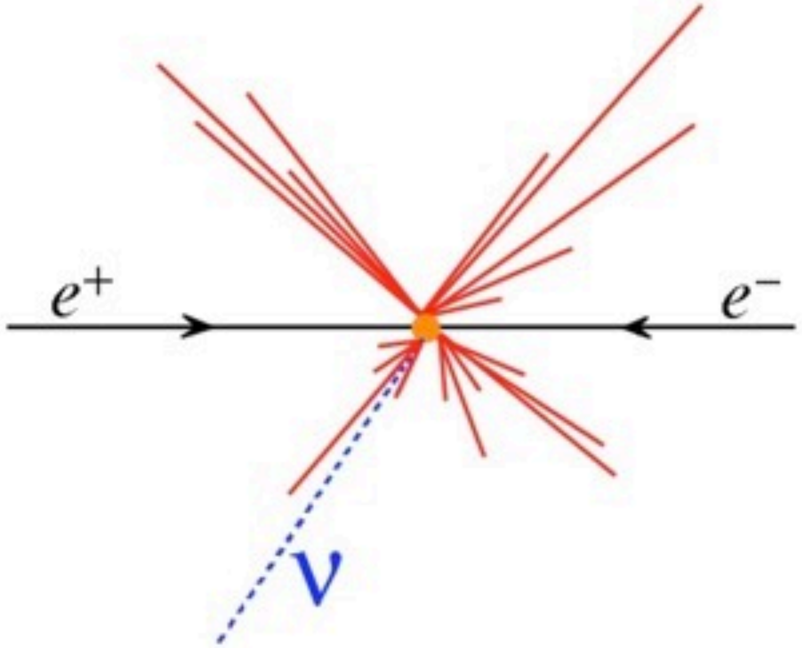
Why calorimetry?



- Measure *charged + neutral* particles
- Obtain information on *energy flow*:
  Total (missing) transverse energy, jets, *etc*.
- Obtain information *fast*
  → recognize and select interesting events in real time *(trigger)*
- Performance of calorimeters *improves with energy*
  (~ $E^{-1/2}$ if statistical processes are the limiting factor)

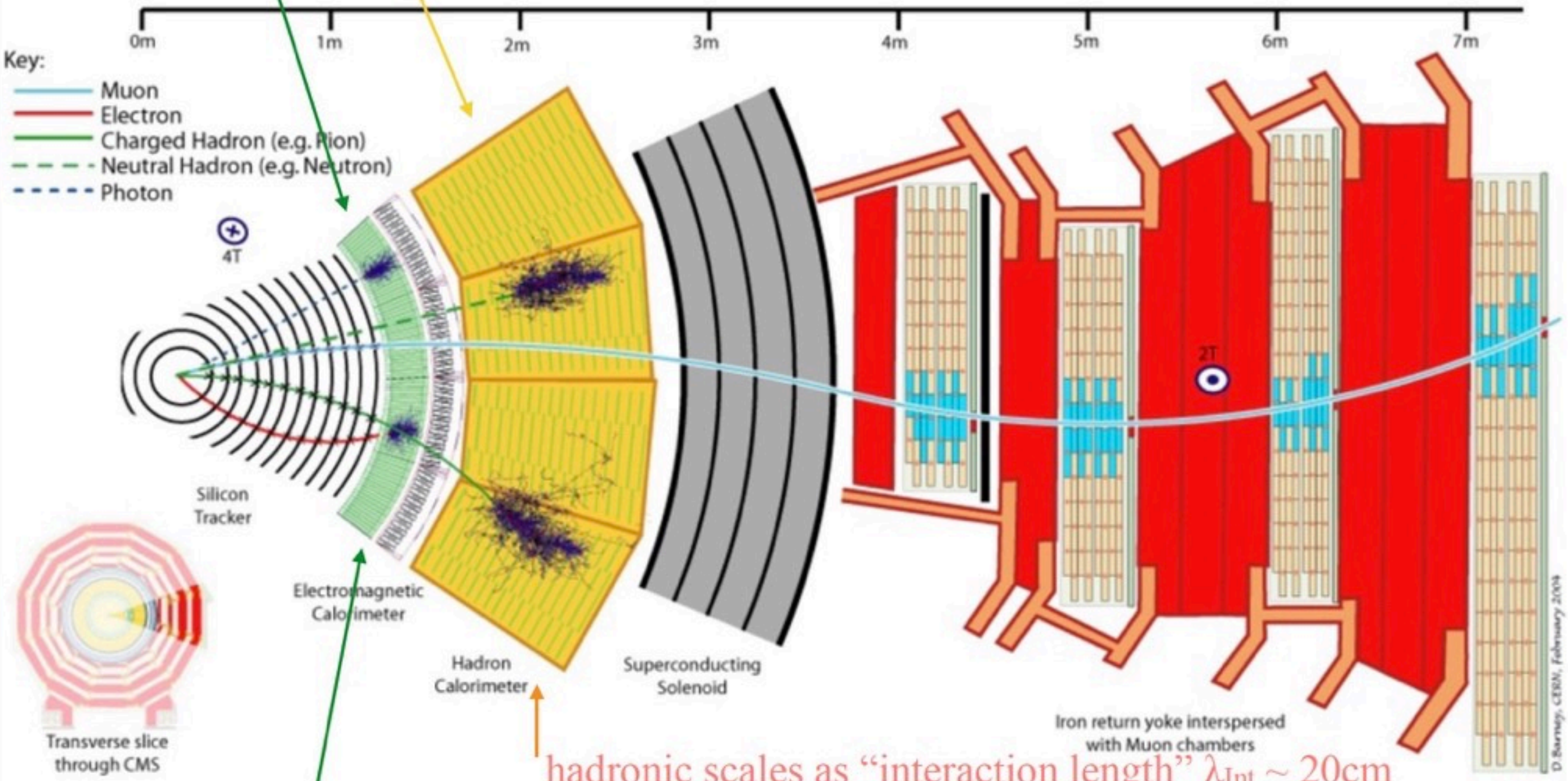
$$\text{If } E \propto \text{signal, i.e. } E \propto \#\text{ signal quanta } n \longrightarrow \sigma(E) \propto \sqrt{n}$$

$$\longrightarrow \text{energy resolution } \frac{\sigma(E)}{E} \propto 1/\sqrt{n} \propto 1/\sqrt{E}$$

Calorimeters & particle interactions:

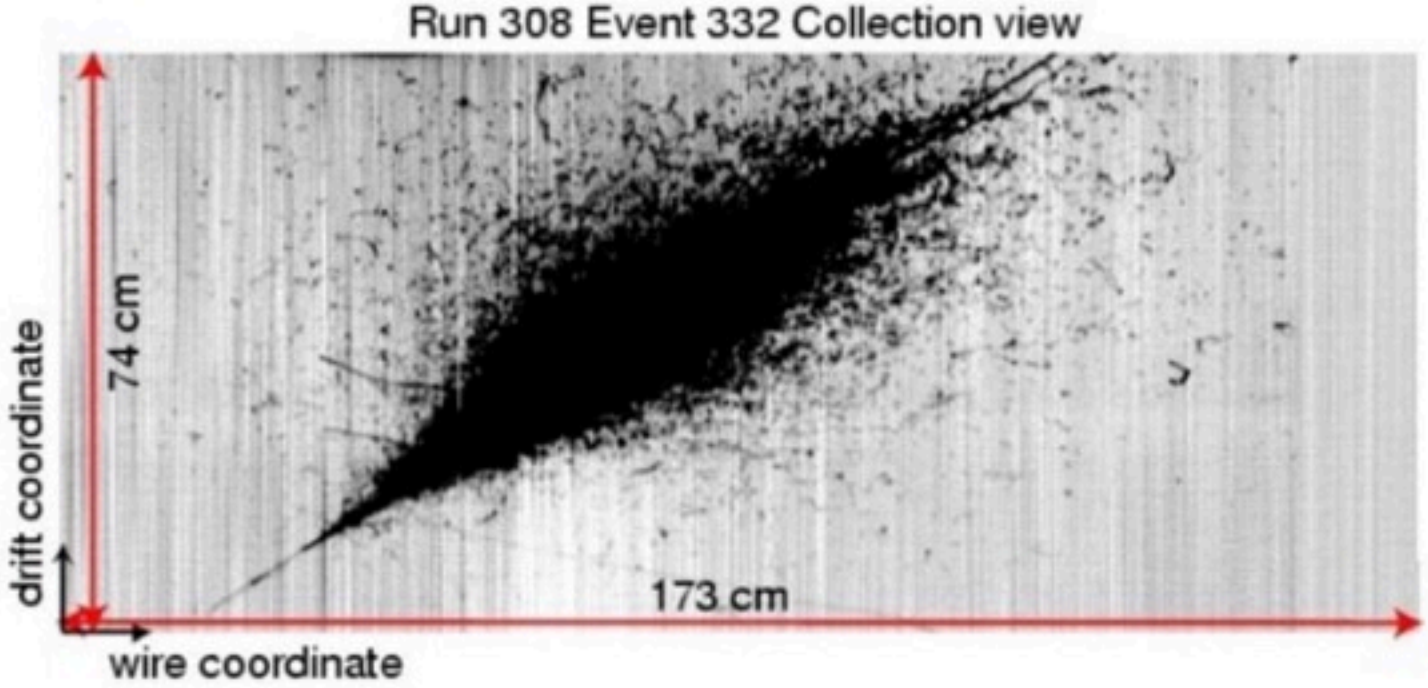
Compact Muon Solenoid (CMS) experiment ("standard" detector geometry)

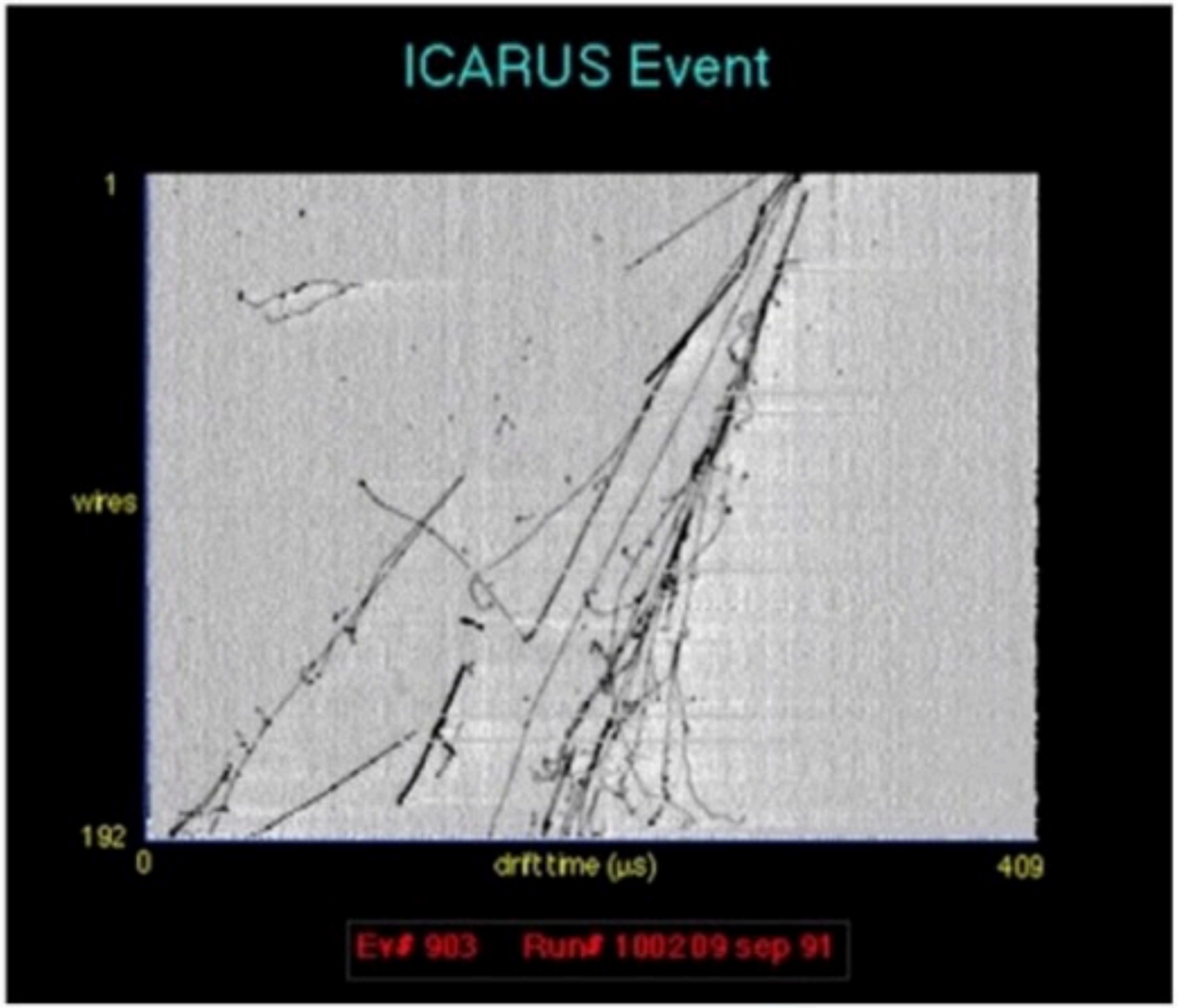
EM hadronic

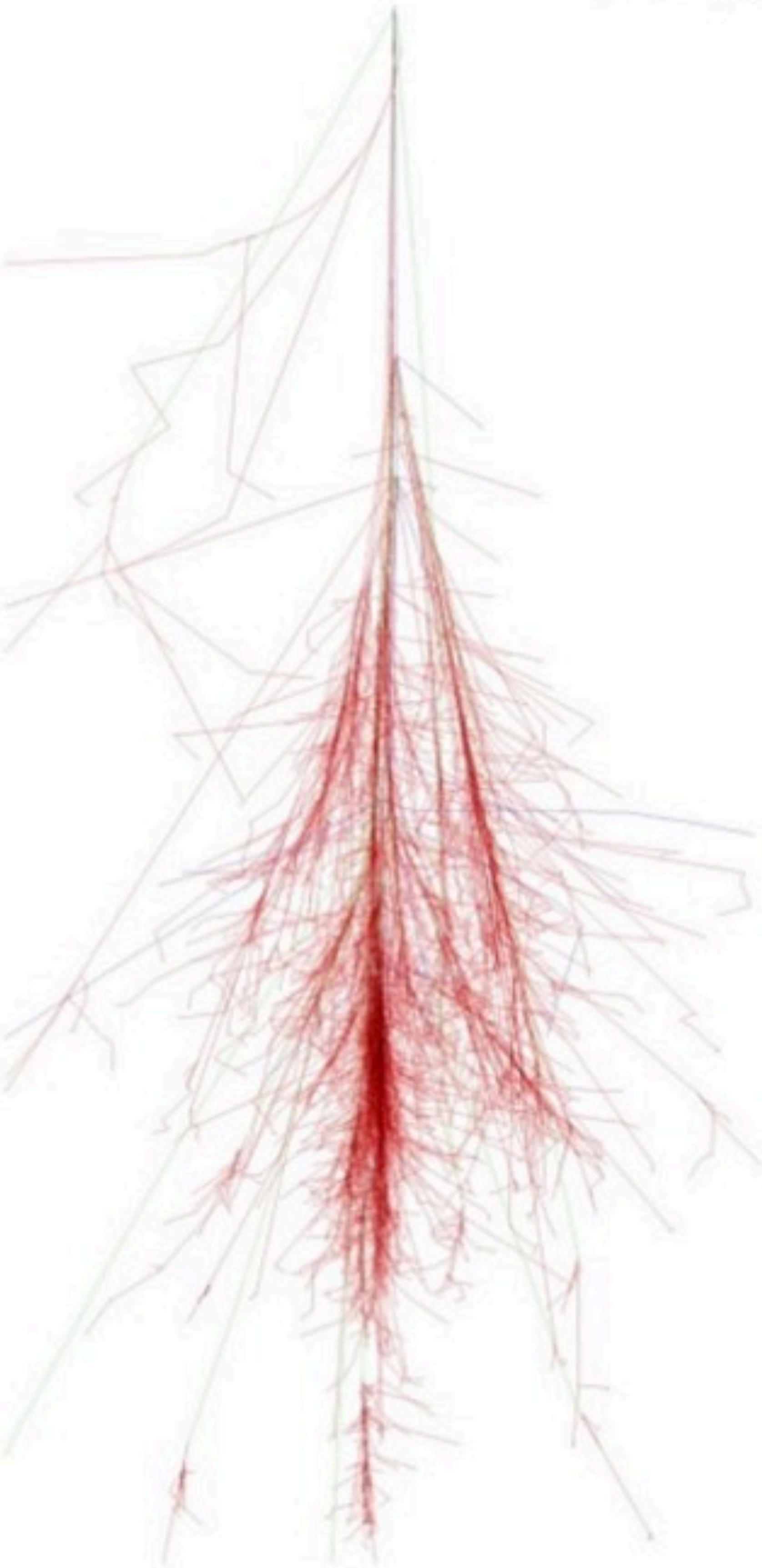


hadronic scales as "interaction length" $\lambda_{\mathrm{Int}} \sim 20\mathrm{cm}$

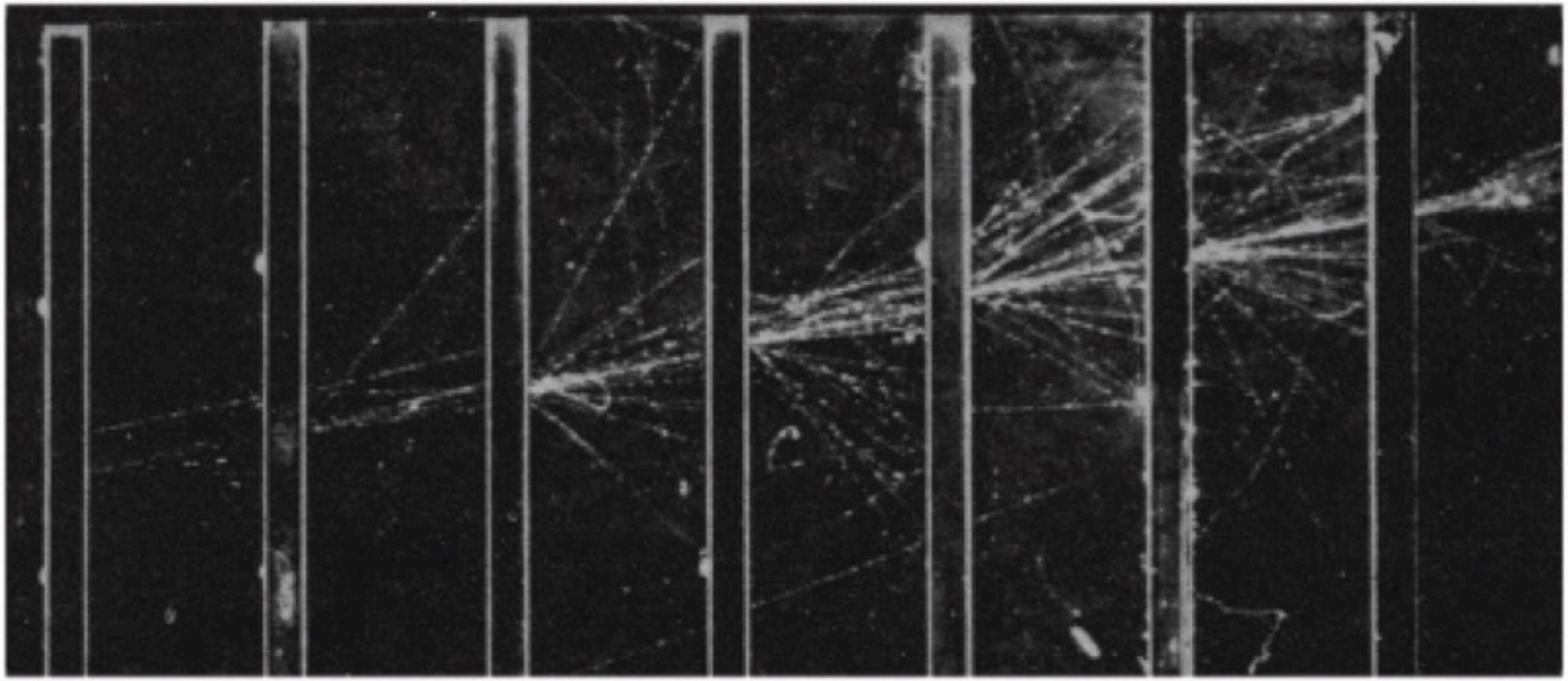
EM scales in depth as "radiation length" $X_0 \sim 1\mathrm{cm}$


Run 308 Event 332 Collection view
74 cm
drift coordinate
173 cm
wire coordinate

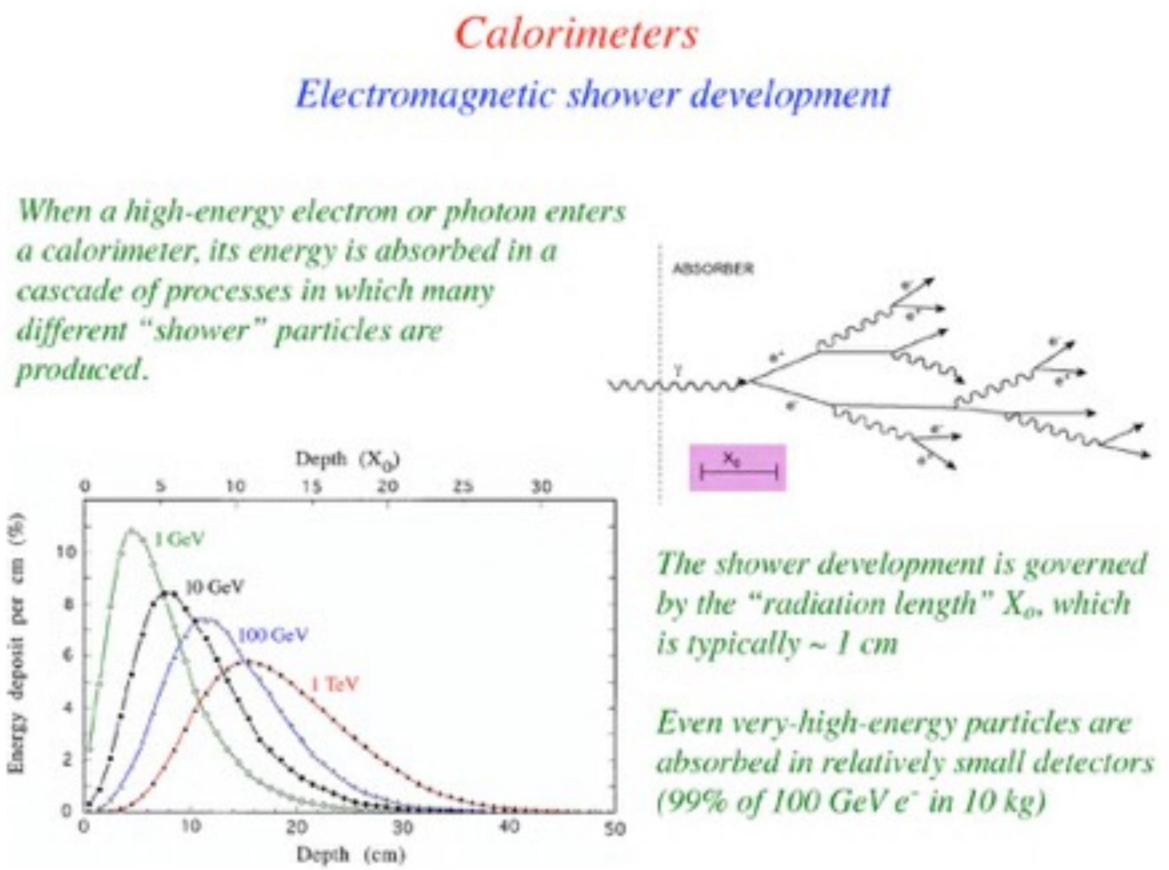

ICARUS Event
1
wires
192
0
drift time (µs)
409
Ev# 903 Run# 100209 sep 91



Electromagnetic “shower” in Pb plates; each plate is probably 2-3 Xo



Electromagnetic EM “showers”



Calorimeters

Electromagnetic shower development

When a high-energy electron or photon enters a calorimeter, its energy is absorbed in a cascade of processes in which many different “shower” particles are produced.

The shower development is governed by the “radiation length” X_o, which is typically ~ 1 cm

Even very-high-energy particles are absorbed in relatively small detectors (99% of 100 GeV e^- in 10 kg)

E_{e^-} = incident electron energy, say $E_{e^-} = 100$ GeV

E_c = energy at which dE/dx(ionization) $\approx dE/dx$(bremsstrahlung):

$E_c^{Cu} \approx 20$ MeV (copper)

$X_0 \approx 1.4$ cm

Total number of particles in shower: $E_{e^-}/E_c \approx 5,000$

Sampled every 1/4-radiation-length, ($t = 0.25X_0 \approx 0.35$ cm)

Total number of samples: $N = 5,000/t \approx 20,000$

$\sigma_N/N \sim 1/\sqrt{N} \sim 1/\sqrt{20,000} \approx 0.7\%$ at 100 GeV.

$\sigma/E \approx 7\%/\sqrt{E}$ (a pretty normal EM calorimeter resolution)

Sampling fluctuations and the e.m. energy resolution

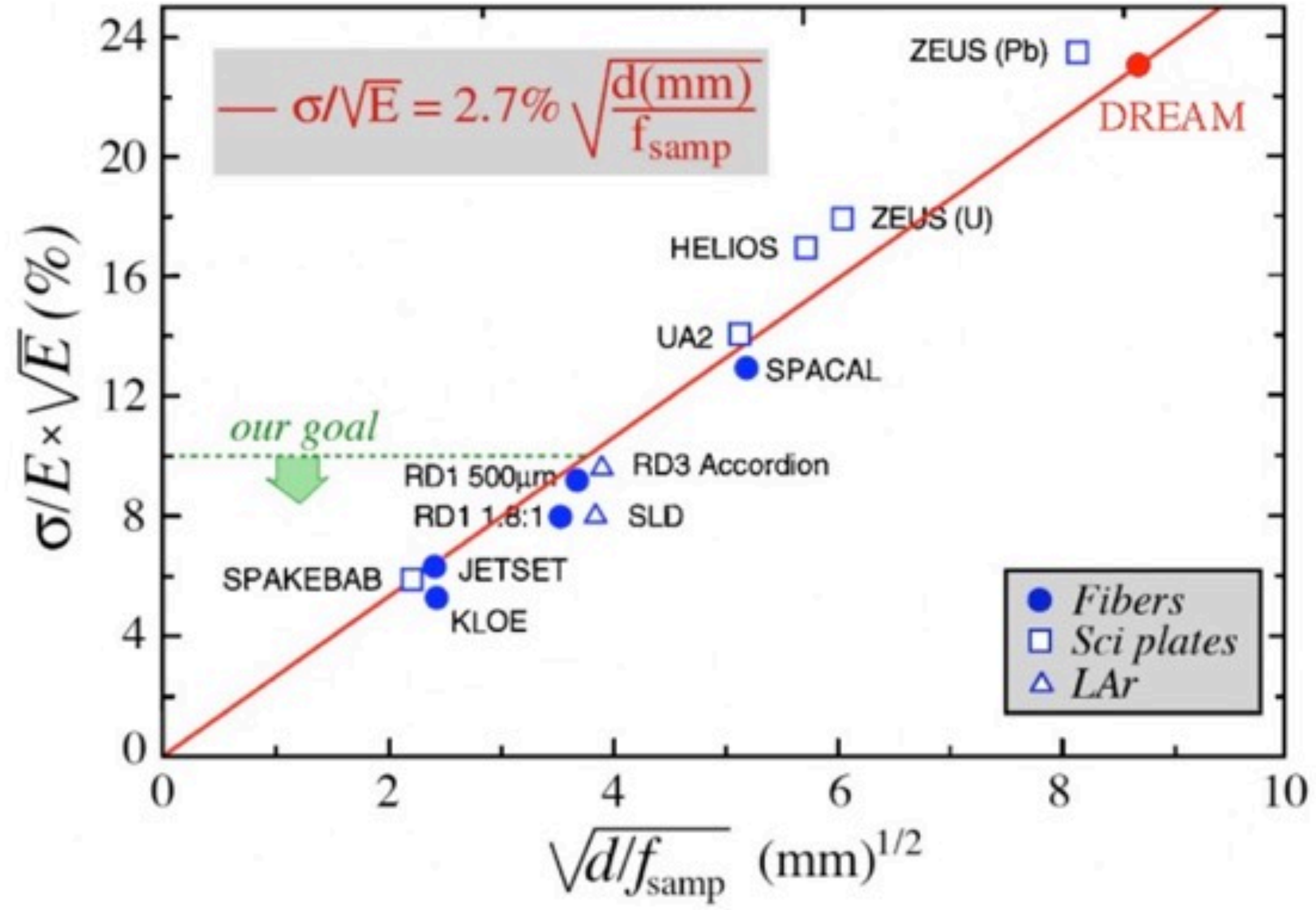
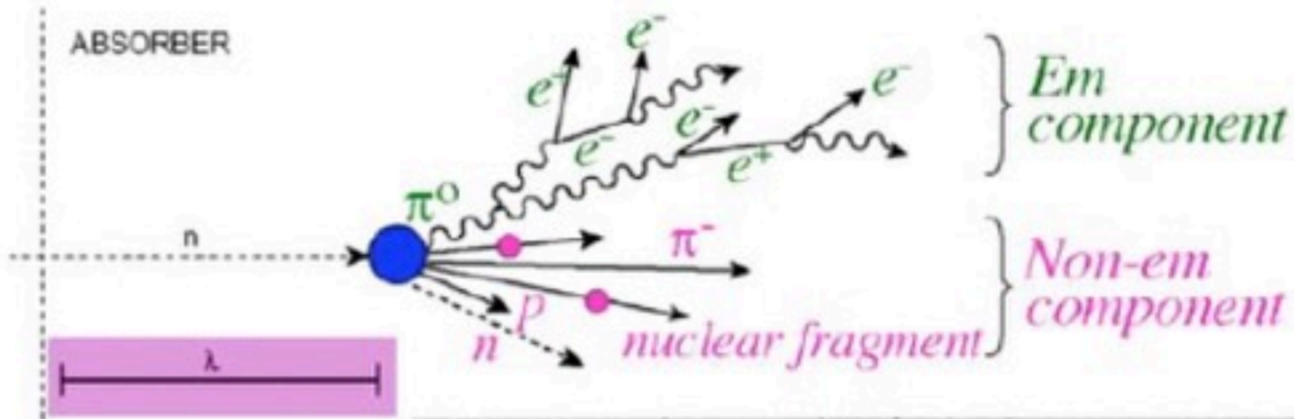


Figure 23: The em energy resolution of sampling calorimeters as a function of the parameter $(d/f_{samp})^{1/2}$, in which d is the thickness of an active sampling layer (*e.g.* the diameter of a fiber or the thickness of a liquidargon gap), and f_{samp} the sampling fraction for mips [20].

Hadronic calorimeters - what happens inside the absorber volume

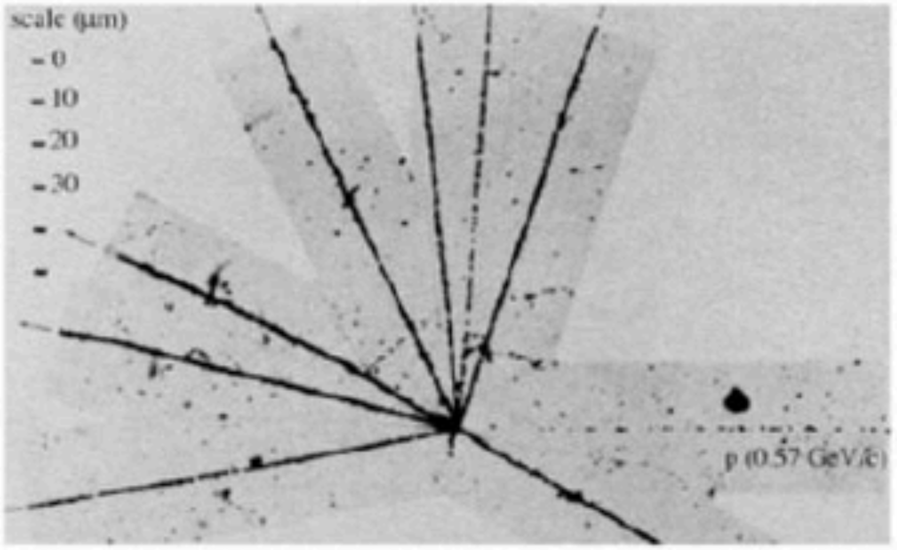


Electromagnetic component

- electrons, photons
- neutral pions → 2 γ

Hadronic (non-em) component

- charged hadrons $\pi^\pm$,$K^\pm$ (20%)
- nuclear fragments, p (25%)
- neutrons, soft γ's (15%)
- break-up of nuclei (*"invisible"*) (40%)



- Main fluctuation: $\pi^\pm$ and $\pi^0 \to \gamma\gamma$ ("EM fraction" fluctuation)
- Next fluctuation: binding energy losses —> liberated neutron kinetic energies.

The mean detector response:
to electrons is called "*e*" "electromagnetic"
to everything else is called "*h*" "hadronic"

"Compensation" means that *e/h* = 1

This may look like a calorimet
to some people, but it is really
just a Dagwood sandwich.

Most calorimeters are not compensating;

- a lot of layers does not make a good calorimeter
- many depth sections does not improve anything
- mean values, e.g., <EM>, <neutral hadron>, etc., have nothing to do with resolution

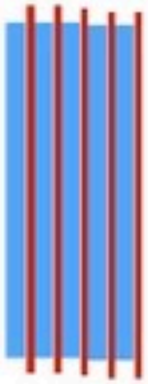
The energy resolution depends only on those physical effects which

fluctuate

and reducing or compensating for these fluctuations.

There are 100’s of possibilities for filling the calorimeter volumes:

“sampling”

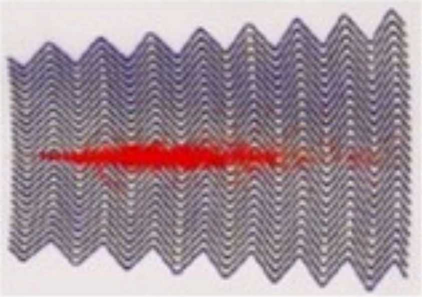


absorber: Fe, Cu, Cu/Zn, Pb, W, U

sensitive medium: RPC, scintillator, LAr, Cerenkov, …

Classic, like CMS

“



Novel “accordion” in ATLAS: W+LAr

“

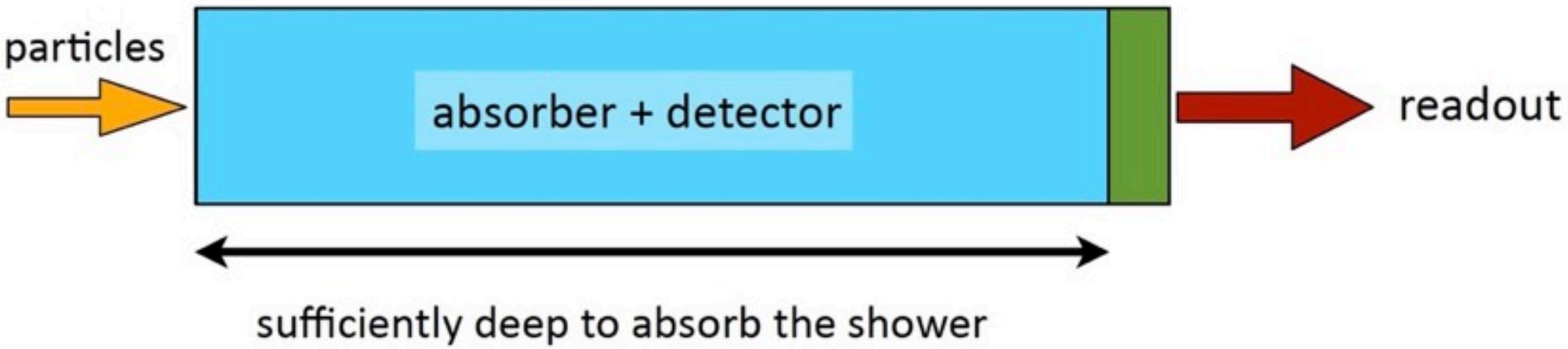
Pb & Cu, filled with optical fibers,
SPACAL, DREAM

“homogeneous”

crystals (glasses): BGO,
PWO, CsI, …

liquids: scintillator,
H_2O, LAr, LXe, …

- In high-energy physics, we distinguish two basic calorimeter designs:
- Homogeneous Calorimeters:



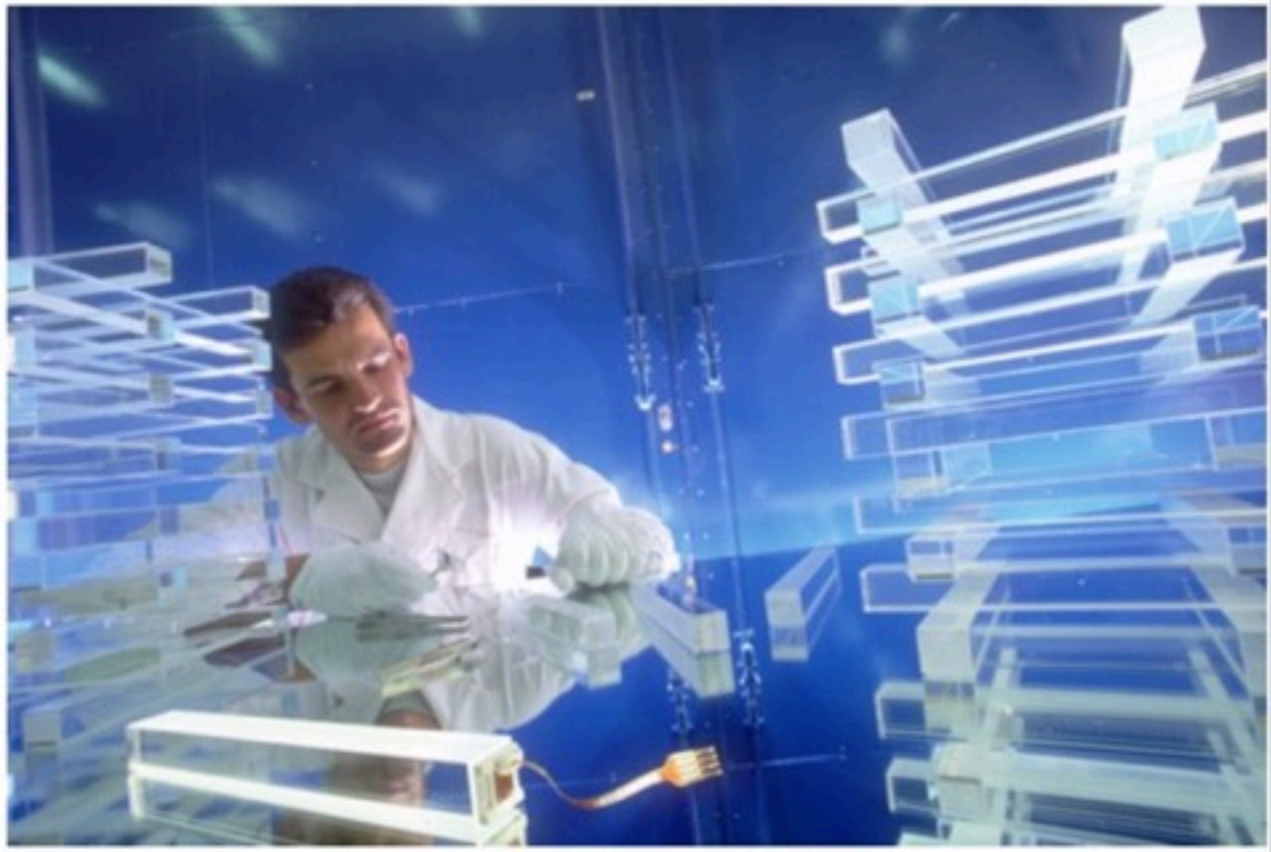
- The shower develops in the sensitive medium
  - Potentially optimal energy resolution: Complete energy deposit is measured
  - Challenging readout: No passive readout structures in detector volume
- Up to now only used as electromagnetic calorimeters (Why? Be patient for the next lecture...)

Crystals for Homogeneous Calorimeters

- Wish list:
  - high density, short radiation length, small Moliere radius: Compact detectors
  - high light output: high energy resolution
  - in some applications: Fast response - Allow operation in high occupancy environment

A classic: NaI(Tl): Used in many spectroscopic experiments
High light yield, 40 photons / keV,
density 3.7 g/cm^3, decay time 230 ns

The biggest crystal calorimeter: CMS @ LHC
$PbWO_4$ - High density: 8.3 g/cm^3
decay time 10 ns (fast component)
light yield: 0.12 photons / keV



Calorimetry: Homogeneous calorimeters

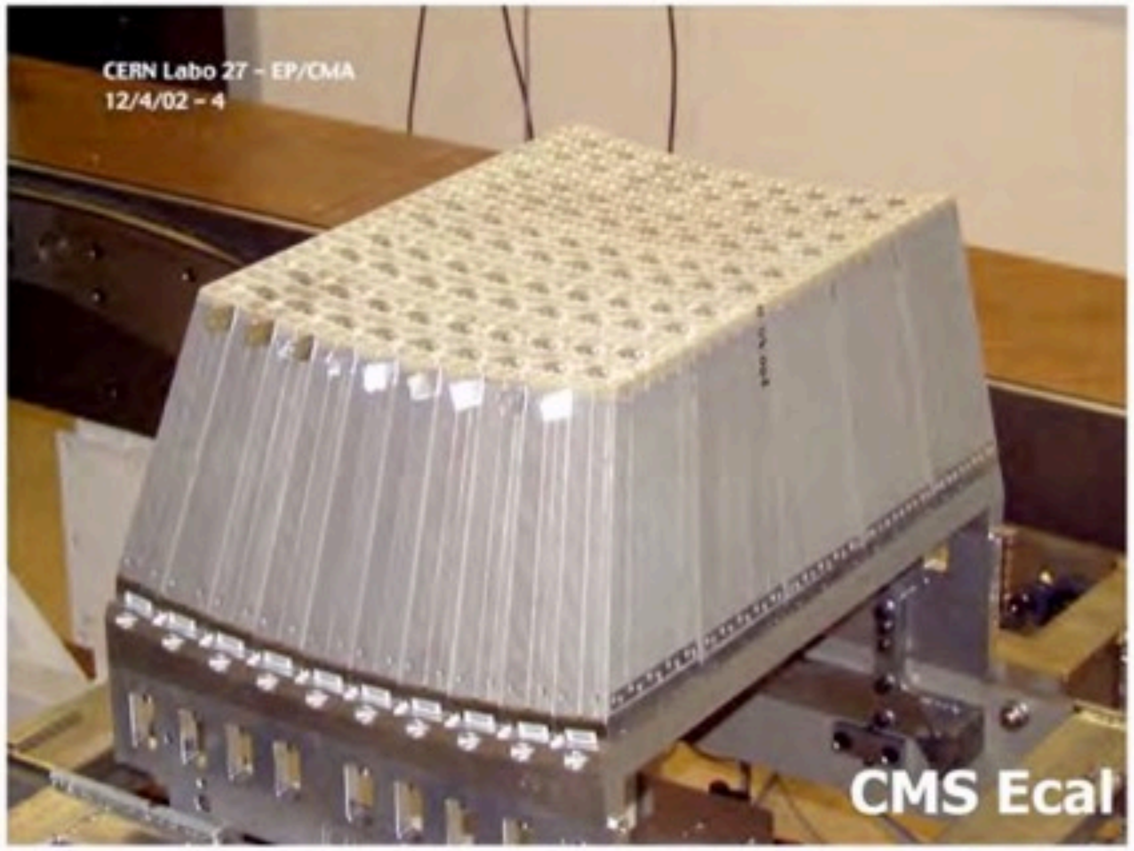
- *High-density crystals used as electromagnetic calorimeters*
  Example: CMS ECAL, $PbWO_4$*. Density 8.3 g/cm*^{3}*, radiation length 8.9 mm.*

- *Very good energy resolution*

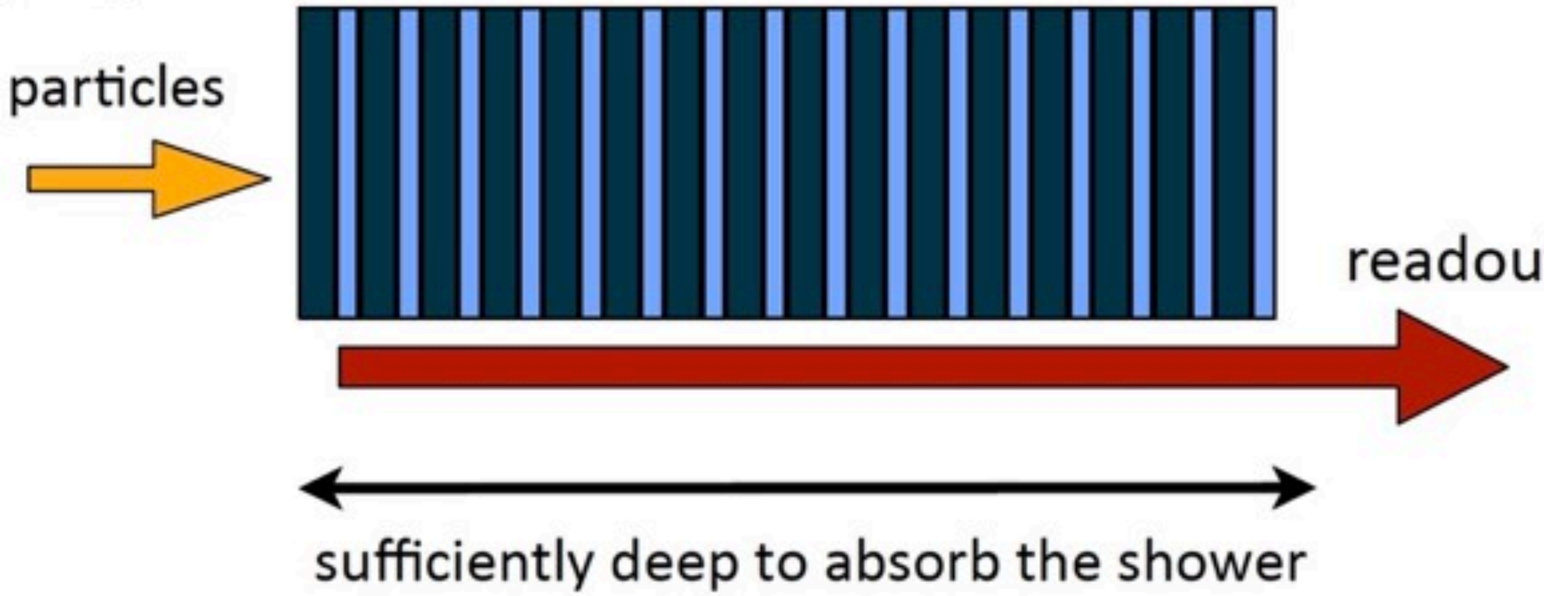
- *Very expensive*

- *Radiation damage a problem*

- *Other crystals:*
  NaI(Tl), CsI, BGO, BaF_2



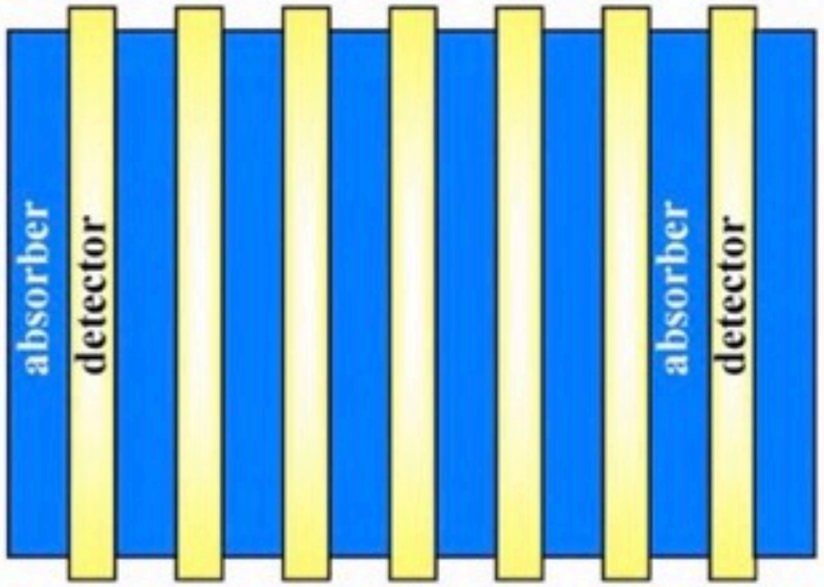
- Sampling Calorimeters:

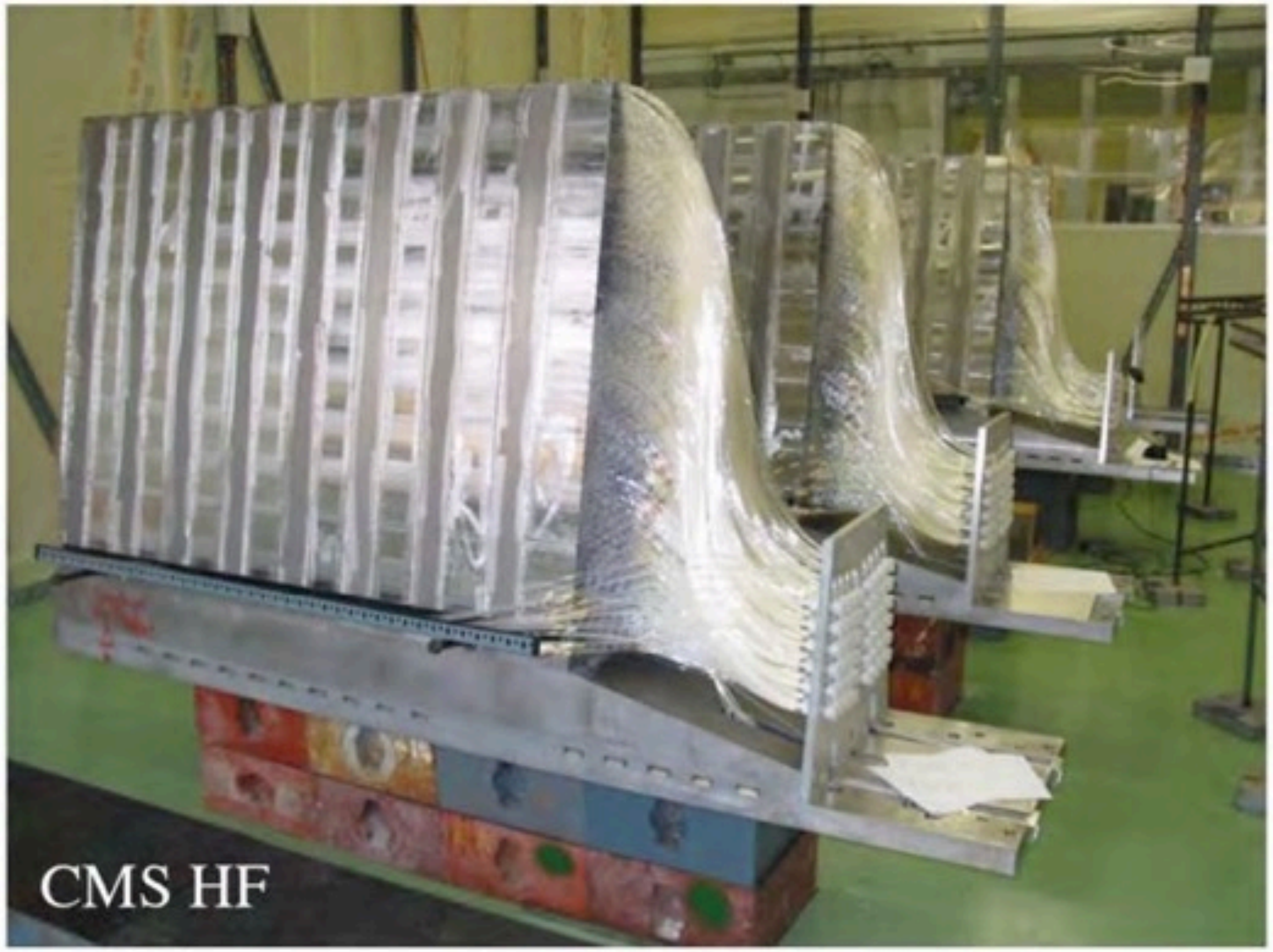


- The shower develops (mostly) in dense absorber medium, particles are detected in interleaved active structures
    - Potentially reduced energy resolution: Only a fraction of the deposited energy is detected: Sampling fraction - Fraction of energy lost in active medium by penetrating muons, increases with increasing density and thickness of active medium
    - High flexibility in readout choice - Passive components can be treated as absorbers

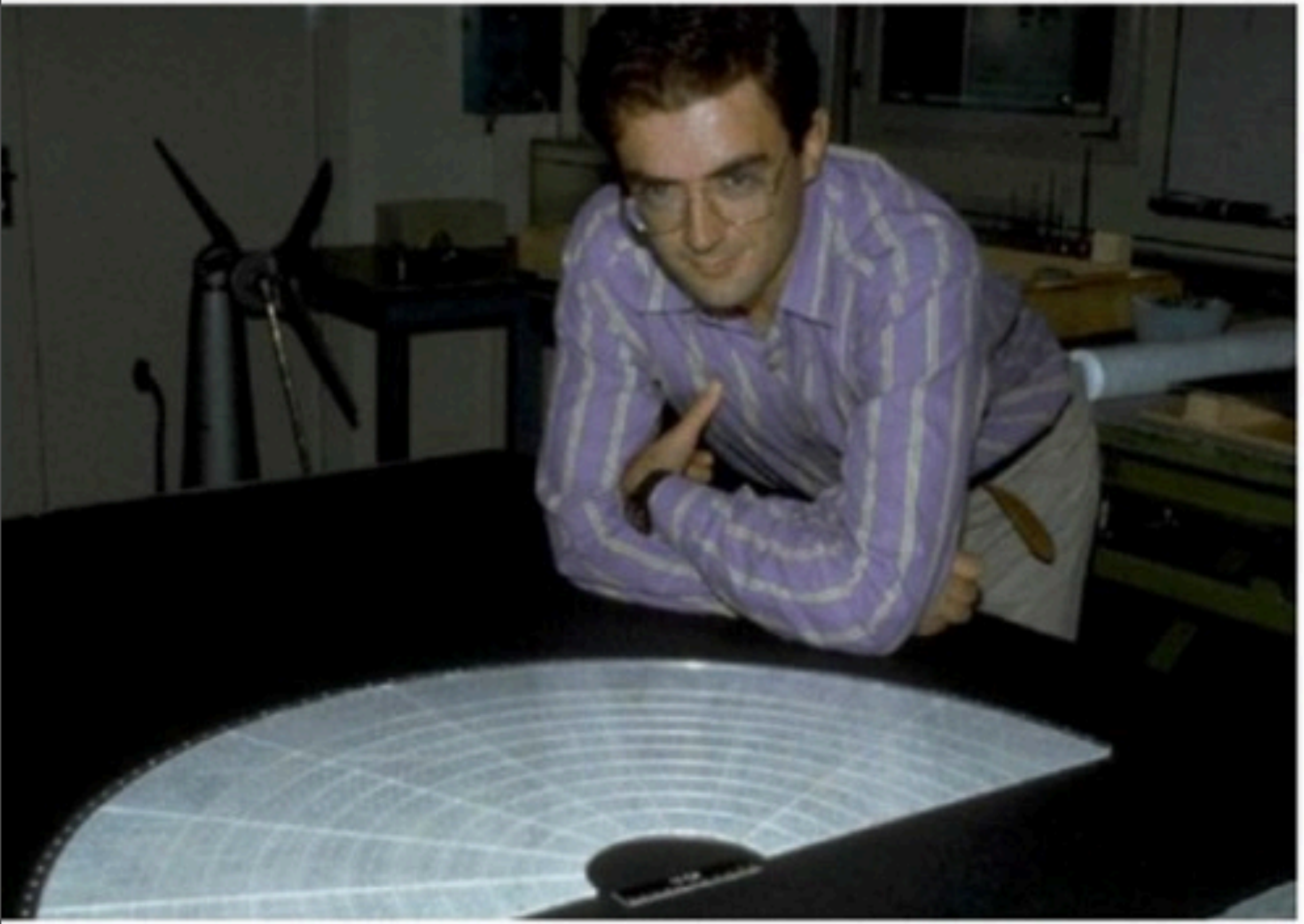
Calorimetry: Sampling calorimeters

- *Different absorber and detector materials*
- *Better segmentation, energy resolution worse*
- *Absorber media: Fe, Cu, Pb, U, W*
- *Active media: Scintillator, LAr, gas…*

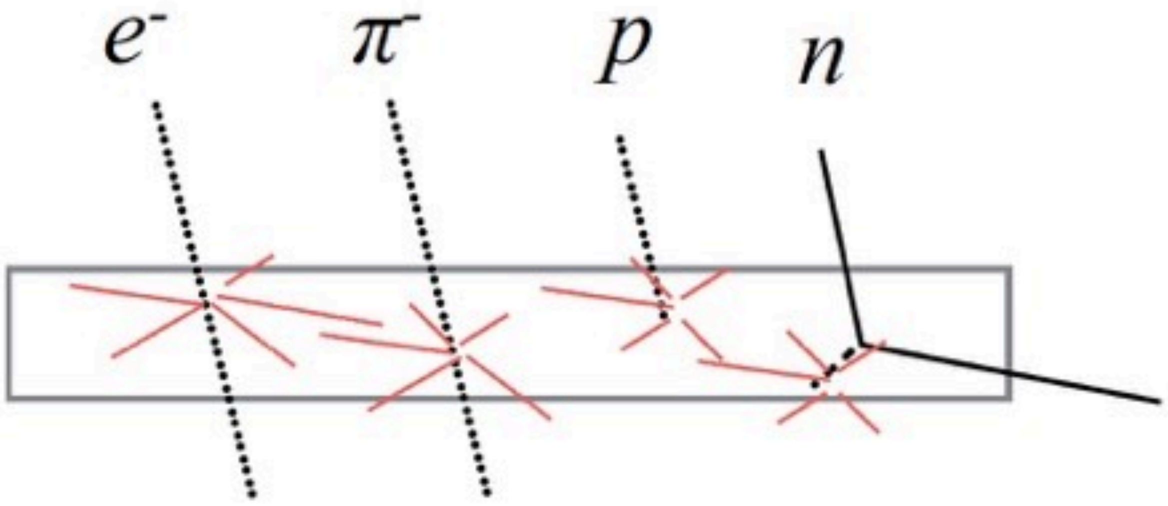




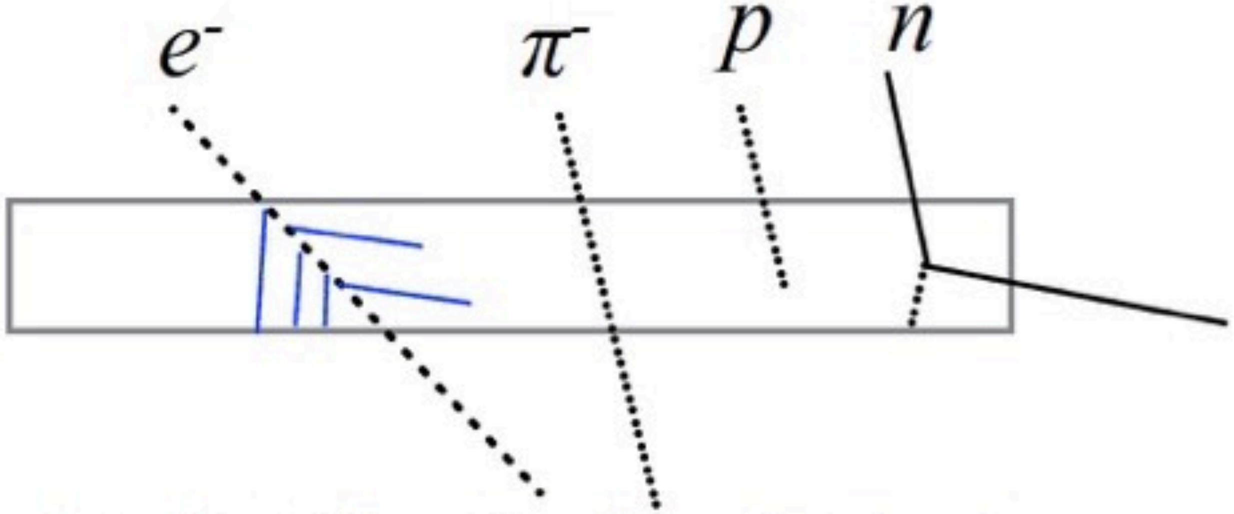
Planar transverse sampling: plastic scintillator sheets between absorber plates



Fibers embedded longitudinally in an absorber

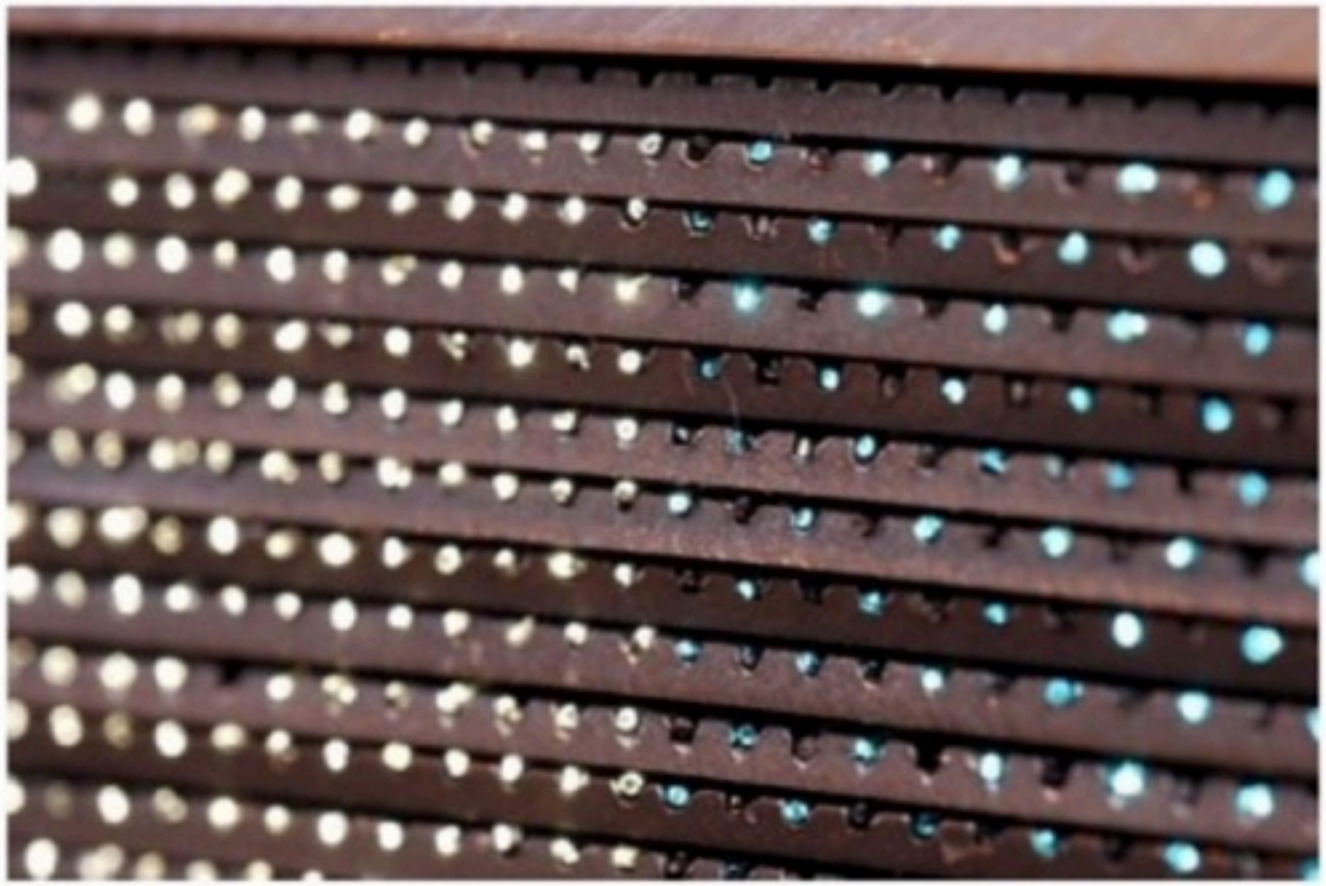


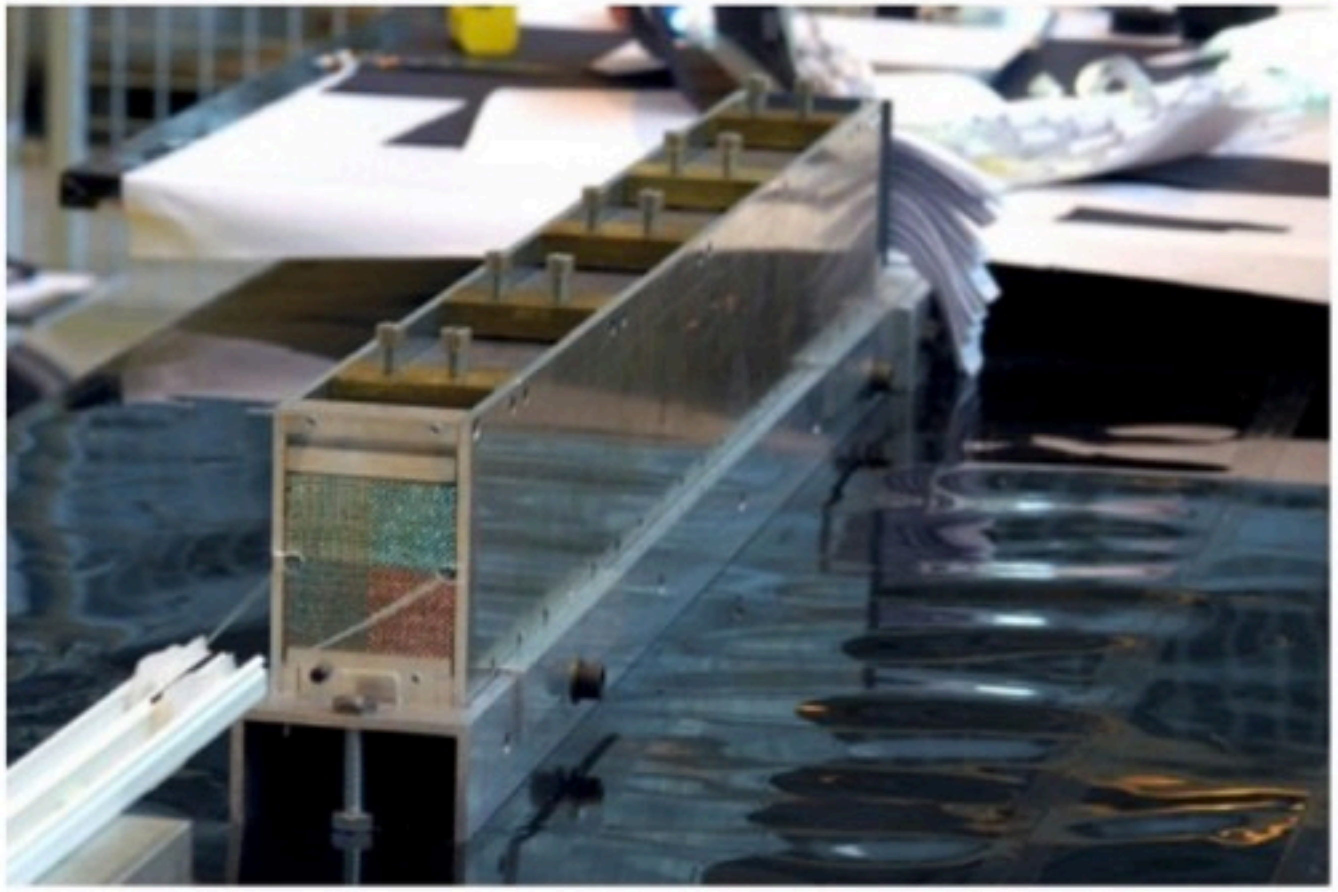
Scintillating fiber - red light, random



Cerenkov (clear) fiber - blue light, directional

S > C





Signal —> Number of particles (N) —> Energy (E)
Poisson fluctuation —> $\sqrt{N}$ —> σ
Energy resolution: $\sigma/E \sim k/\sqrt{N} \longrightarrow k/\sqrt{E}$

The brief history of excellent hadronic calorimetry (it's a short list):

SPACAL: "compensating"; Pb-scintillating fiber; 20 tonnes; ~1 μs

$\sigma/E \sim 30\% / \sqrt{E} \oplus 1\%$ (beam module)

ZEUS: nearly compensating; U-scintillator;

$\sigma/E \sim 35\% / \sqrt{E}$ (beam module)

ATLAS: iron-scintillator

$\sigma/E \sim 50\% / \sqrt{E} \oplus 3\%$ (4π calorimeter)

DREAM/RD52: S and C fibers inside Pb and Cu absorbers

$\sigma/E \sim 4\%$ at 200 GeV π^+ (leakage limited) (beam module)

Scintillators

- Scintillators emit light when excited by ionizing radiation - Luminescence
- Two types of scintillators:
    - Inorganic scintillators - Crystalline solids or glasses, often doped with fluorescent ions
    - Organic scintillators - Hydrocarbon compounds, solid, liquid, crystalline (the latter is not used in high-energy physics) - Most common in HEP: Plastic scintillators

    - Inorganic scintillators have high density and often high light output, but typically a slow response: Used for homogeneous calorimeters
    - Organic scintillators can be made in arbitrary shapes, are cheap to produce and typically have a very fast response: Used in sampling calorimeters

Detecting the Light

- The classic solution: Photomultiplier

sensitive to magnetic fields

requires HV

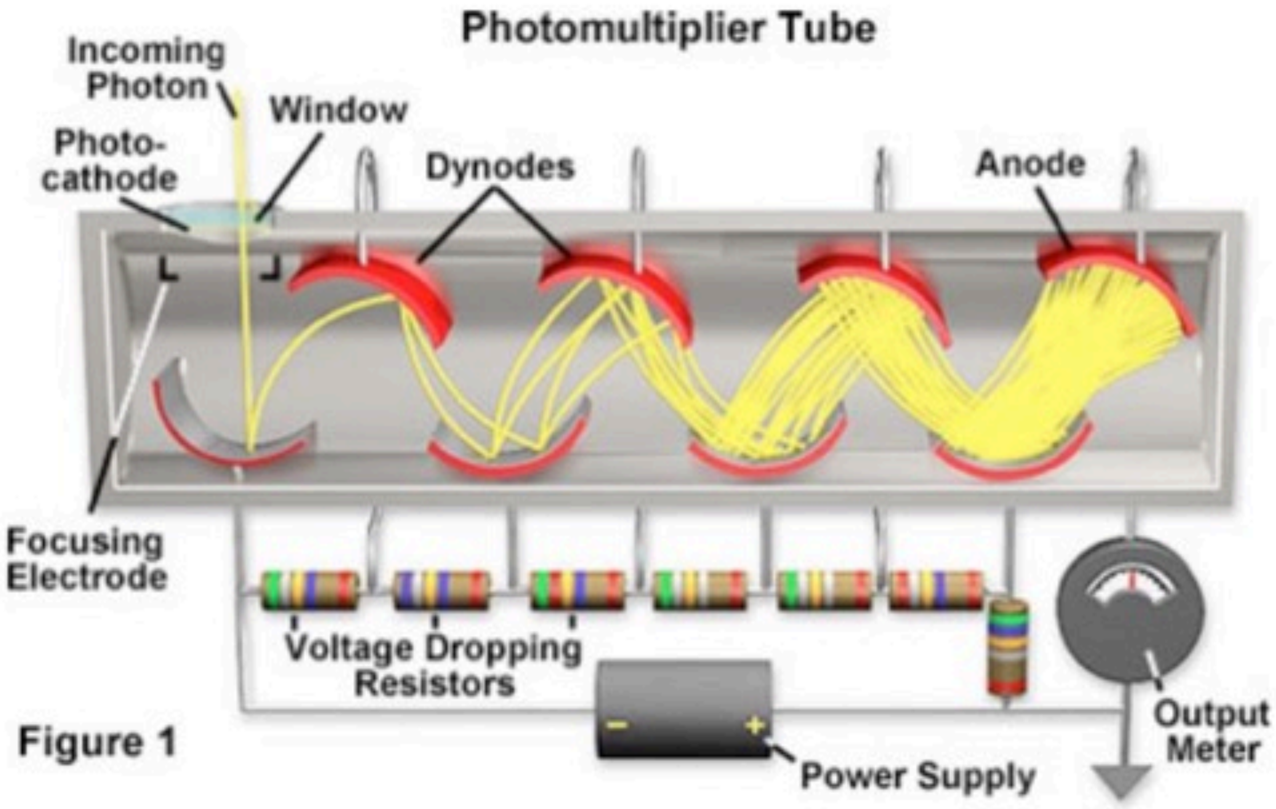


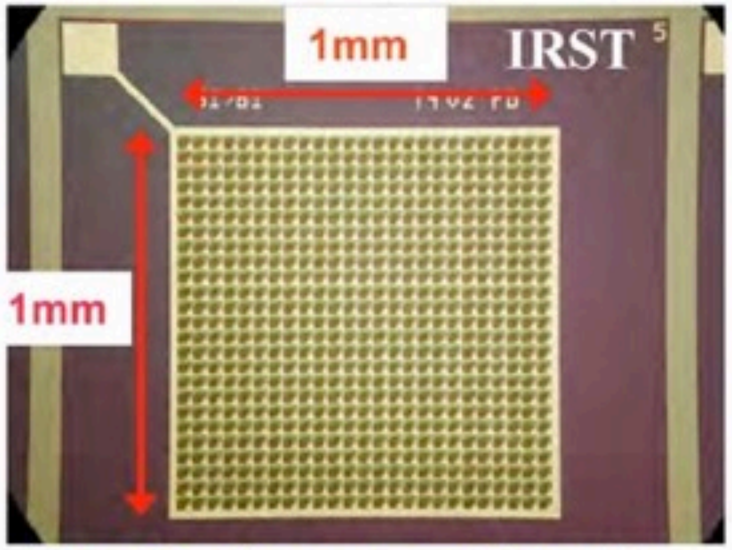
image: Hamamatsu

- Nowadays: More and more alternatives
    - Avalanche photo diodes
    - Silicon Photomultipliers
    - ...

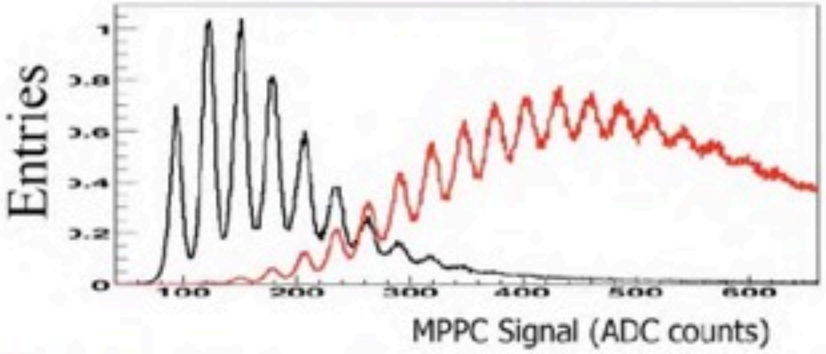
Photodetectors

- *Photocathode + secondary emission multiplication*
  - *- PMT*
  - *- Multichannel PMT*
  - *- Microchannel plates*

- *Solid-state devices*
  - *- Photodiodes (no gain)*
  - *- Avalanche photodiodes (gain 10 - 100)*
  - *- Solid-state photomultipliers (SiPM)* →
  - *- Visible light photon counters (VLPC)*



Si pixels operating in Geiger mode

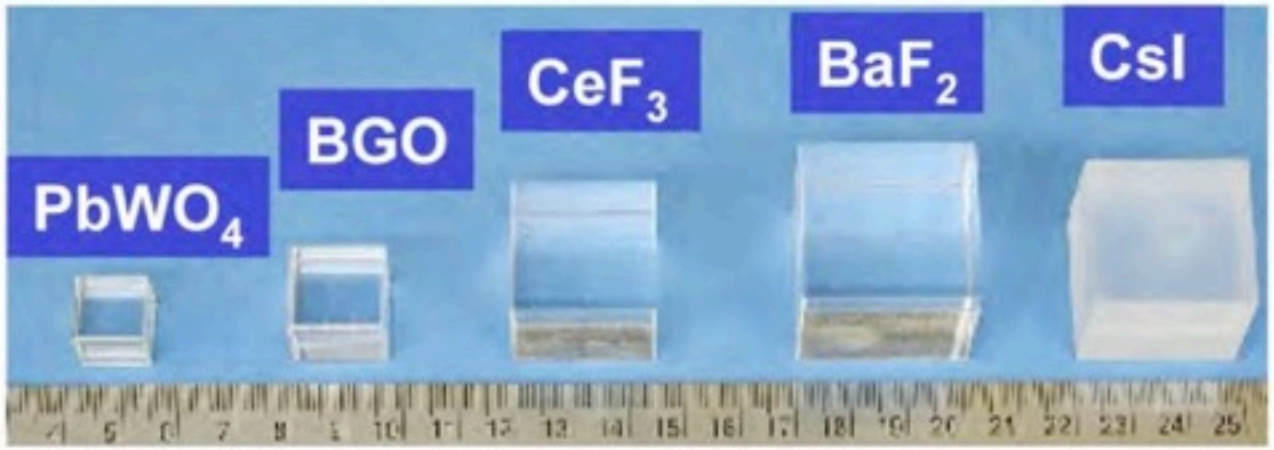


- *Hybrids: photocathode + electron acceleration + silicon*

Scintillator types

- *Organic: liquid, plastic*
  - Up to 10,000 photons per MeV
  - Low Z, ρ~1gr/cm^3
  - Doped, large choice of emission wavelength
  - ns decay times
  - relatively inexpensive
  - Easy to manufacture in any shape or size,
  - The scintillation process is a function of a single molecular process and is independent of the physical state of the scintillator

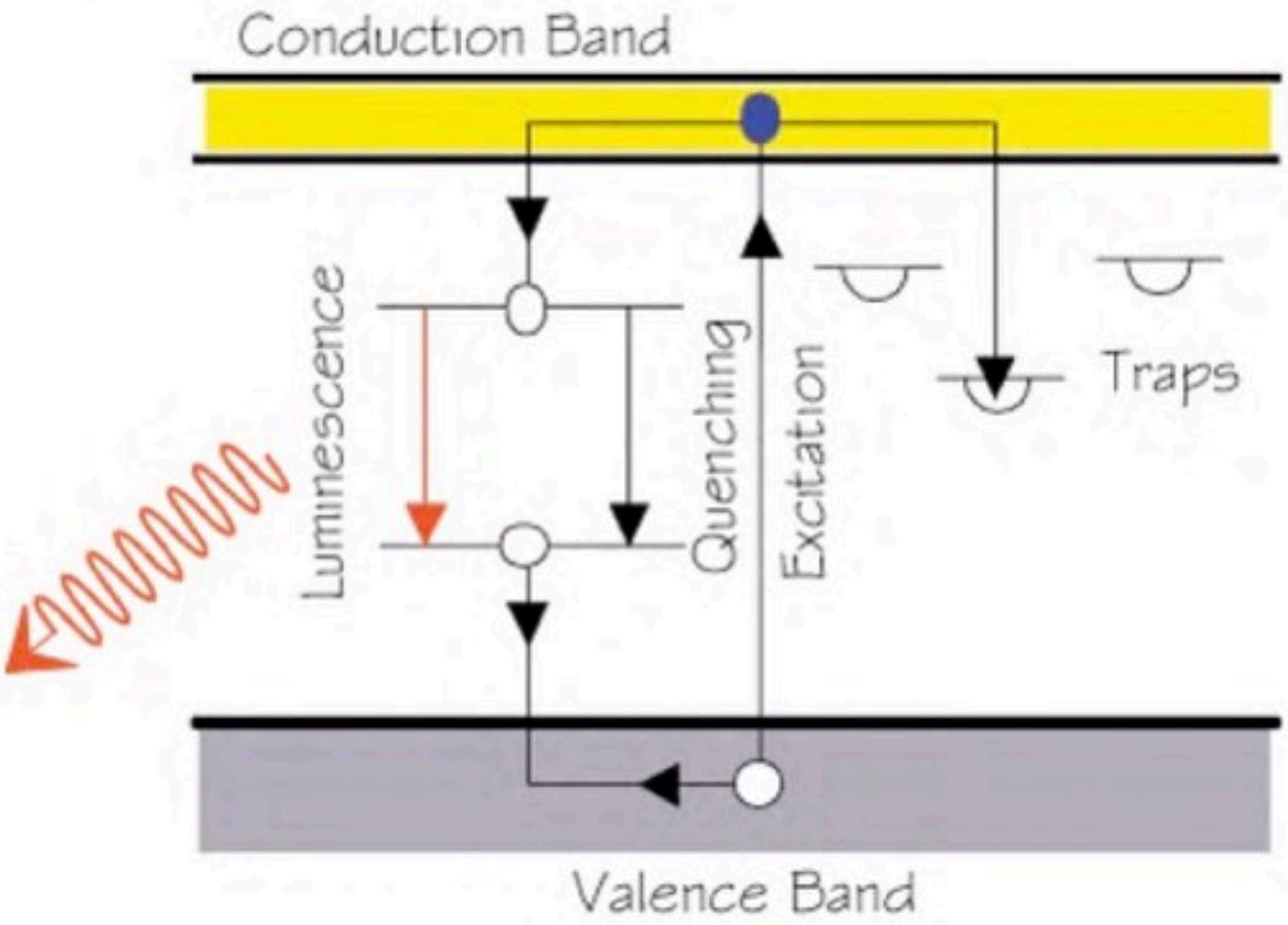
- *Inorganic: crystals*
  - High light yield, up to 40,000 photons per MeV
  - High Z, large variety of Z and ρ
  - Undoped and doped
  - ns to μs decay times
  - Expensive
  - Difficult to grow crystals
  - Require a crystal lattice to scintillate

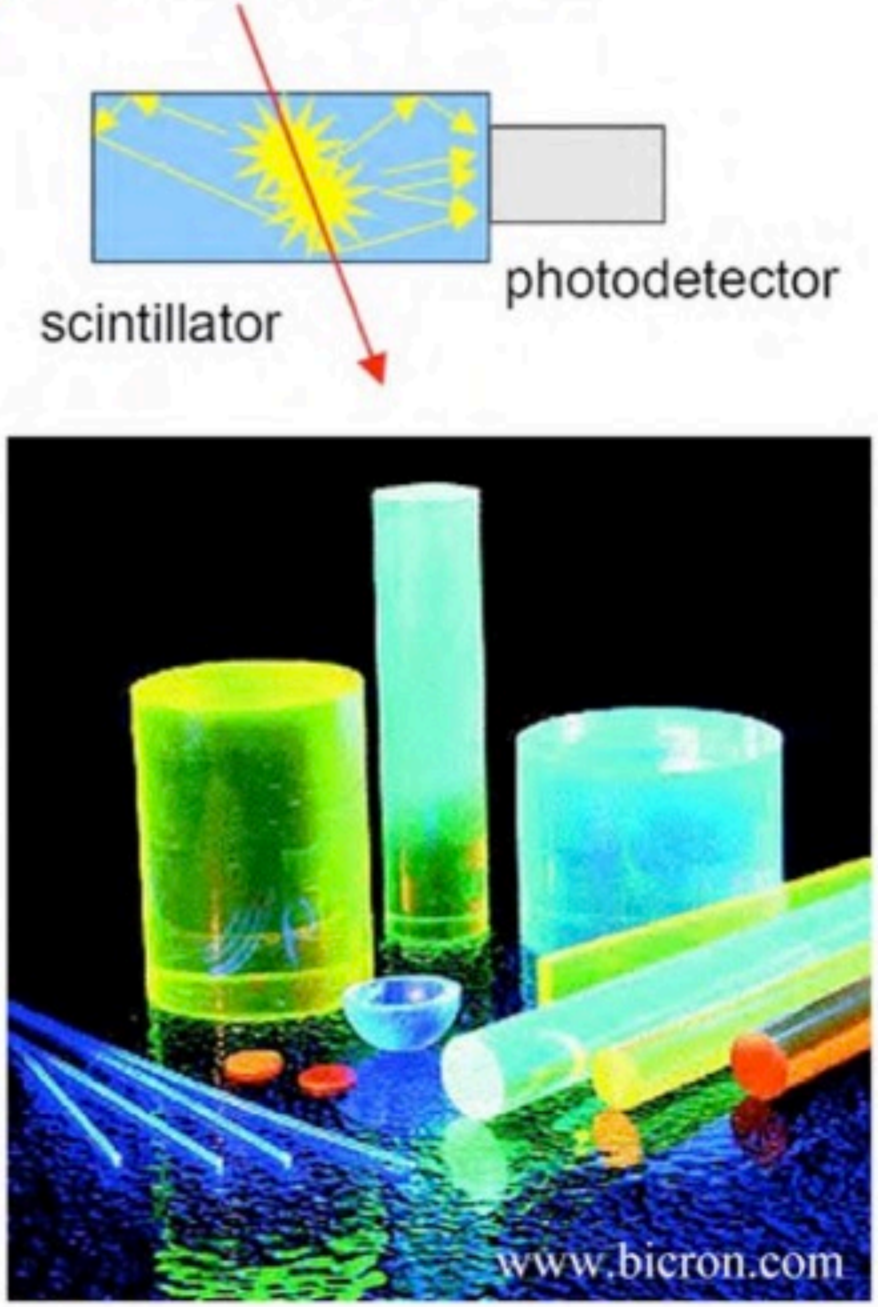


- *Wide range of applications*
- *Match emission wavelengths to detection device*

Scintillation detectors ("scintillators")

- *Many materials emit light when traversed by ionizing particles Scintillation caused by excited molecules falling back to ground state*
- *Scintillation counters most widely used particle detectors (Rutherford used ZnS)*
- *Impurities often play crucial role*





These examples are mostly for optical readout of calorimeters, preferred at fast colliders, but slower readout from wire chambers, RPCs, MMG, and ionization chambers (LAr, e.g.) are all possible.

This brief, and nearly random, walk through calorimeters does not do the subject justice. I am sorry!