Some applications of Calorimetry

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Lecture at the 2nd Detector School of Kyungpook University
January 2021

- *Applications based on the first law of thermodynamics*
- *Calorimeters in high-energy particle physics*
- *Searches for dark matter*

Calorimetry: definition

Calorimetry is the measurement of the transfer of energy in a physical process. Energy may or may not be converted from one form into another in this process.

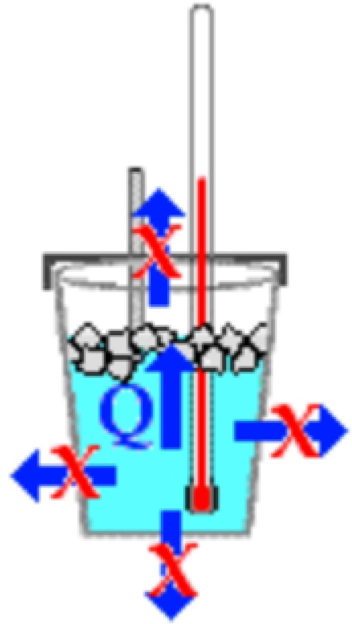
Units:

1 calorie = energy needed to increase the temperature of 1 gram of liquid water by 1 degree Celsius

$1\ cal = 4.18\ Joule$
$\quad = 2.61\ 10^{19}\ eV$

$1\ TeV = 3.83\ 10^{-8}\ cal$

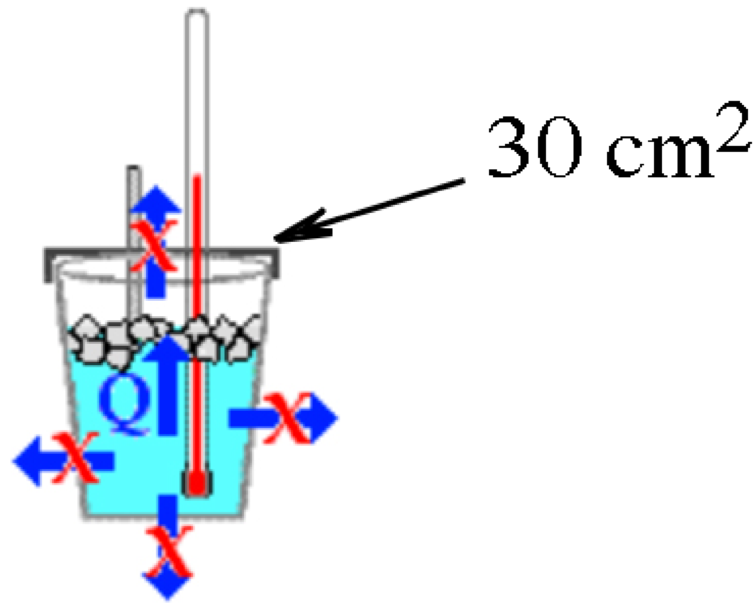
Coffee cup calorimetry



Add a 10 g ice cube (0^o C) to 100 g water (20^o C)
The final temperature is 11^o C.
What is the latent heat of ice?

$$100 \times 9 = 10 \times 11 + 10 \times E_L \longrightarrow E_L = 79 \; cal/g$$

Coffee cup calorimetry (2)



Put coffee cup with 110 g of water @ 11^o C in the Sun
After one hour, the temperature has risen to 38^o C
What is the solar constant?

The cup has received 110 x 27 = 2970 calories
That is 0.825 cal/s = 3.45 J/s = 1150 J/m^2.s
That is 1.15 kW/m^2

Non-destructive assay of fissile materials using calorimetry

Calorimetry

A measurement of the thermal power of a sample, calorimetry can be used to quantify the mass of plutonium when additional details about the relative fraction of different plutonium isotopes is known.

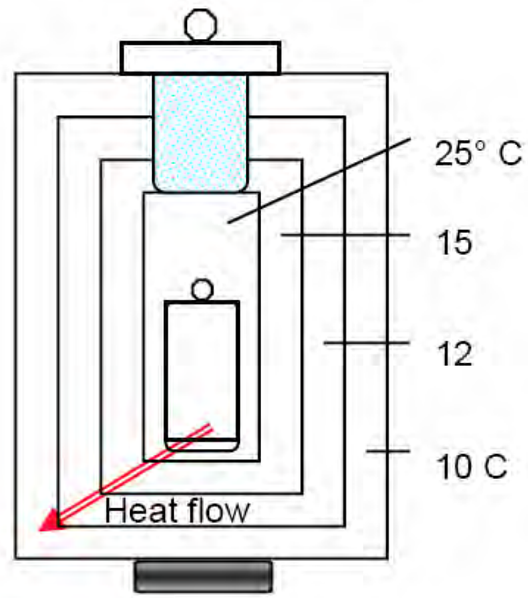
- Calorimetry assays are independent of sample geometry, nuclear material distribution in the sample, and matrix material composition
- Heat standards are directly traceable to National Standards and plutonium standards are not needed
- The assay is comparable to chemical assay in precision and accuracy if the isotopic composition is well known
- The assay is applicable to a wide range of material forms and plutonium can be measured in the presence of uranium.

Ref: "Non Destructive Assay" - esarda2.jrc.it/internal_activities/WC-MC/Web-Courses/07-NDA-Peerani.pdf

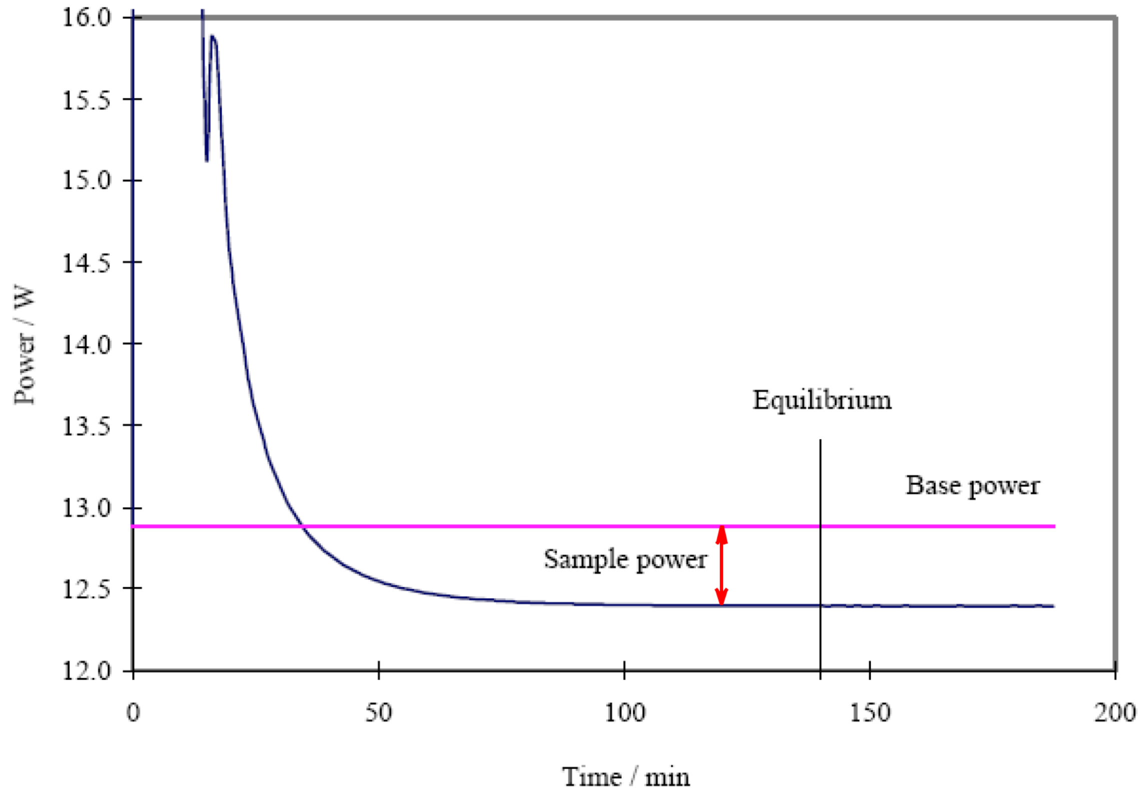
Plutonium Air-Flow Calorimeter

Ref: "Non Destructive Assay" - esarda2.jrc.it/internal_activities/WC-MC/Web-Courses/07-NDA-Peerani.pdf

Calorimeter Equipment



Schematic view of an isothermal calorimeter



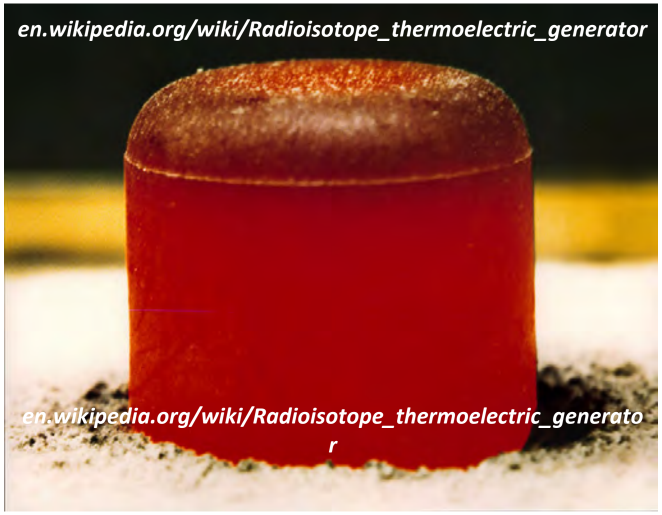
First, the empty calorimeter is heated and the power required to maintain a particular equilibrium temperature level is determined (pink line). Then, a self-heating sample is placed inside the calorimeter and the new power level needed to maintain the same equilibrium temperature is determined (blue line).

Ref: "Non Destructive Assay" - esarda2.jrc.it/internal_activities/WC-MC/Web-Courses/07-NDA-Peerani.pdf

Specific Power of Key Isotopes

Isotope	Primary Decay Mode	Specific Power (mW/g)
^{238}Pu	α	567.57
^{239}Pu	α	1.9288
^{240}Pu	α	7.0824
^{241}Pu	β	3.412
^{242}Pu	α	0.1159
^{241}Am	α	114.2
^{3}H	β	324

The very high specific power for ^{238}Pu explains the use of this isotope in radioisotope thermoelectric generators (RTGs), which are long-life power sources used in deep-space exploration vehicles



This is a photo of a ^{238}Pu fuel pellet of the type used in the NASA Cassini and Galileo probes; it produced 62 W of heat

Ref: "Non Destructive Assay," citing Hyde, E. K., "The Nuclear Properties of the Heavy Elements, III, Fission Phenomena," Dover Publications, New York, New York (1971), and Evans, R. D., "The Atomic Nucleus", McGraw-Hill Book Co., New York, New York (1955)

The Passive Gamma-Ray Signatures

Isotope	Energy (keV)	Activity (γ/g-s)
^{238}Pu	152.7	5.90 x 10^{6}
	766.4	1.387 x 10^{5}
^{239}Pu	129.3	1.436 x 10^{5}
	413.7	3.416 x 10^{4}
^{240}Pu	45.2	3.80 x 10^{6}
	160.3	3.37 x 10^{4}
	642.5	1.044 x 10^{3}
^{241}Pu	148.6	7.15 x 10^{6}
	208.0	2.041 x 10^{7}
^{241}Am	59.5	4.54 x 10^{10}
	125.3	5.16 x 10^{6}

Half life

88 yr

24000 yr

6600 yr

14 yr

432 yr

"Nuclear" calorimetry

A closer look at the heat production by ^{239}Pu (1.9 mW/g)

- ^{239}Pu decays to ^{235}U by means of α decay
  Each α particle carries ~ 6 MeV kinetic energy
- The decay rate $dN/dt = -\lambda N$
  1 gram of ^{239}Pu contains $6.02\ 10^{23}/239 = 2.52\ 10^{21}$ nuclei (= N)
  The decay constant $\lambda = 1/\tau = \ln 2/T_{1/2} = 0.693/(24000 \times 3.15\ 10^{7}) = 9.2\ 10^{-13}$/s
- The decay rate of 1 gram of ^{239}Pu is thus $2.52\ 10^{21} \times 9.2\ 10^{-13} = 1.85\ 10^{9}$/s
  That corresponds to 1.85 GBq, or 50 milliCurie
- The energy released in this process amounts to $1.85\ 10^{9} \times 6 \cdot 1.6\ 10^{-13} = 1.8\ 10^{-3}$ J/s
  In other words, 1.8 mW per gram of ^{239}Pu

- *NB 1.9 mW corresponds to 60 kJ/year. What happens when consumed?*
  Plutonium is chemically similar to calcium, and accumulates in bones
  Assuming a total bone mass of 20kg, the dose rate from 1 g ^{239}Pu is 3 kGy/yr
  This is 5 orders of magnitude more than the max allowable dosis

Calorimetry in particle physics

Calorimeters are instruments to measure the energy of individual particles, produced in scattering experiments at accelerators or elsewhere (e.g. cosmic rays absorbed in the Earth's atmosphere)

Reminder: 1 TeV = 3.83 10^{-8} calories

A temperature increase of the detector is therefore not a practical method to measure this energy

Therefore, rather than measuring the increase of the average velocity of the ~10^{23} atoms of which the instrument consists, the effects on atoms in the vicinity of the passing particle are measured in these detectors

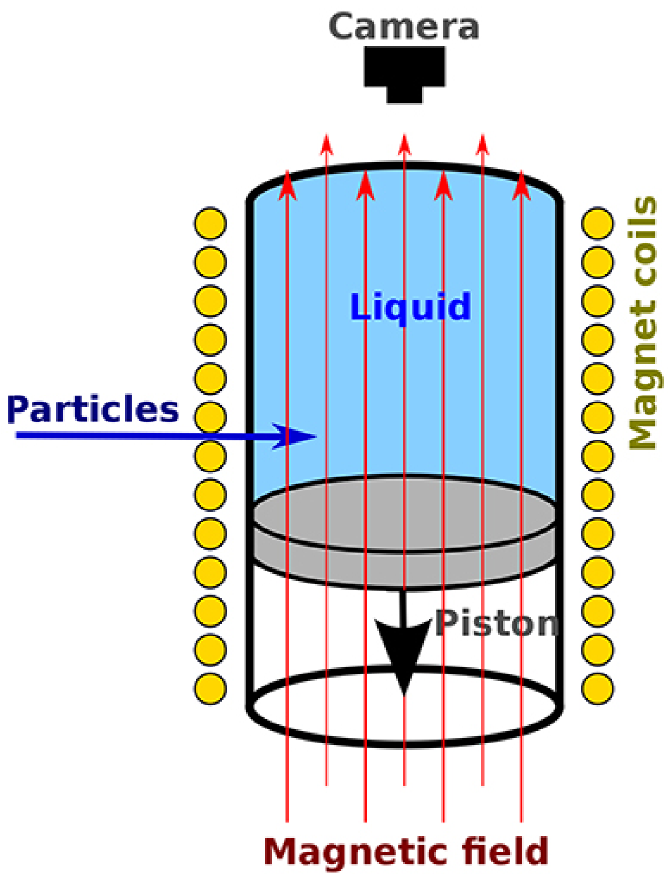
Local thermal effects in a particle detector

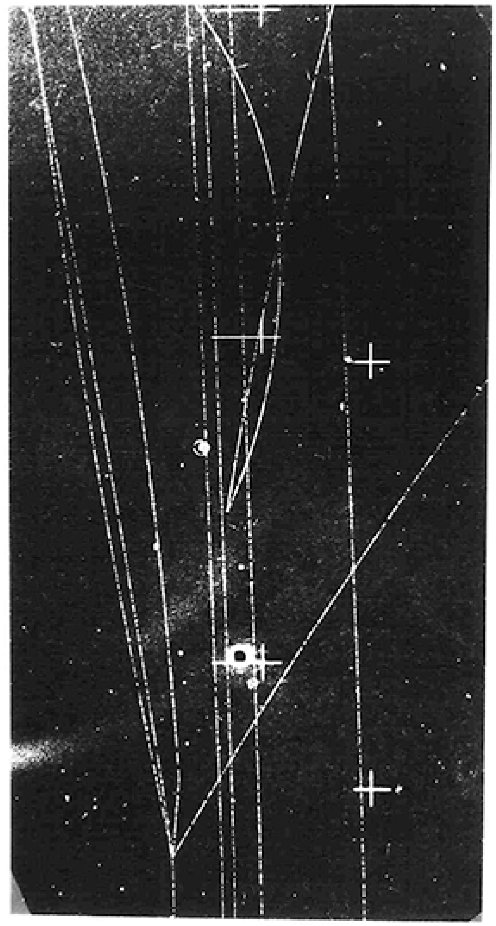
A passing charged particle heats the liquid along its track, causing it to boil. The trajectory of the particles is thus indicated by tracks of gas bubbles in this BUBBLE CHAMBER

The particle momentum is determined from bending in the magnetic field

NB This is NOT considered a calorimeter

Only a fraction of the energy carried by the particles is absorbed





Calorimeters for particle physics experiments

- In particle physics, a calorimeter is a (massive) detector in which the particles to be detected are completely STOPPED

  The absorption process is usually referred to as "shower development"

- The signals may be provided by:

  - Scintillator: The total amount of light produced in the absorption process is a measure for the energy of the incoming particle
  - Liquid argon: The charge liberated in the stopping process provides the signals
  - Water: The Čerenkov light serves as the source of information

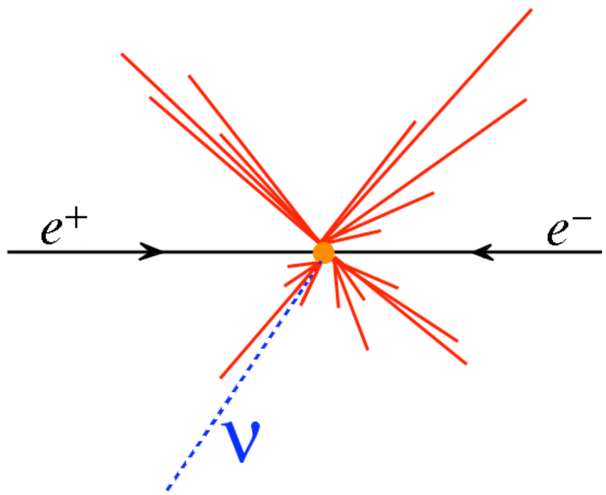
- The segmentation of the instrumented volume makes it possible to determine the momentum vector of the particles.

  The signals in the different calorimeter "towers" indicate the shower axis, and thus the direction of the incoming particle.

- The particle type may be derived from the shower profile, the time structure of the signals, ...

Why calorimetry?

- Measure *charged + neutral* particles
- Obtain information on *energy flow*: Total (missing) transverse energy, jets, *etc.*

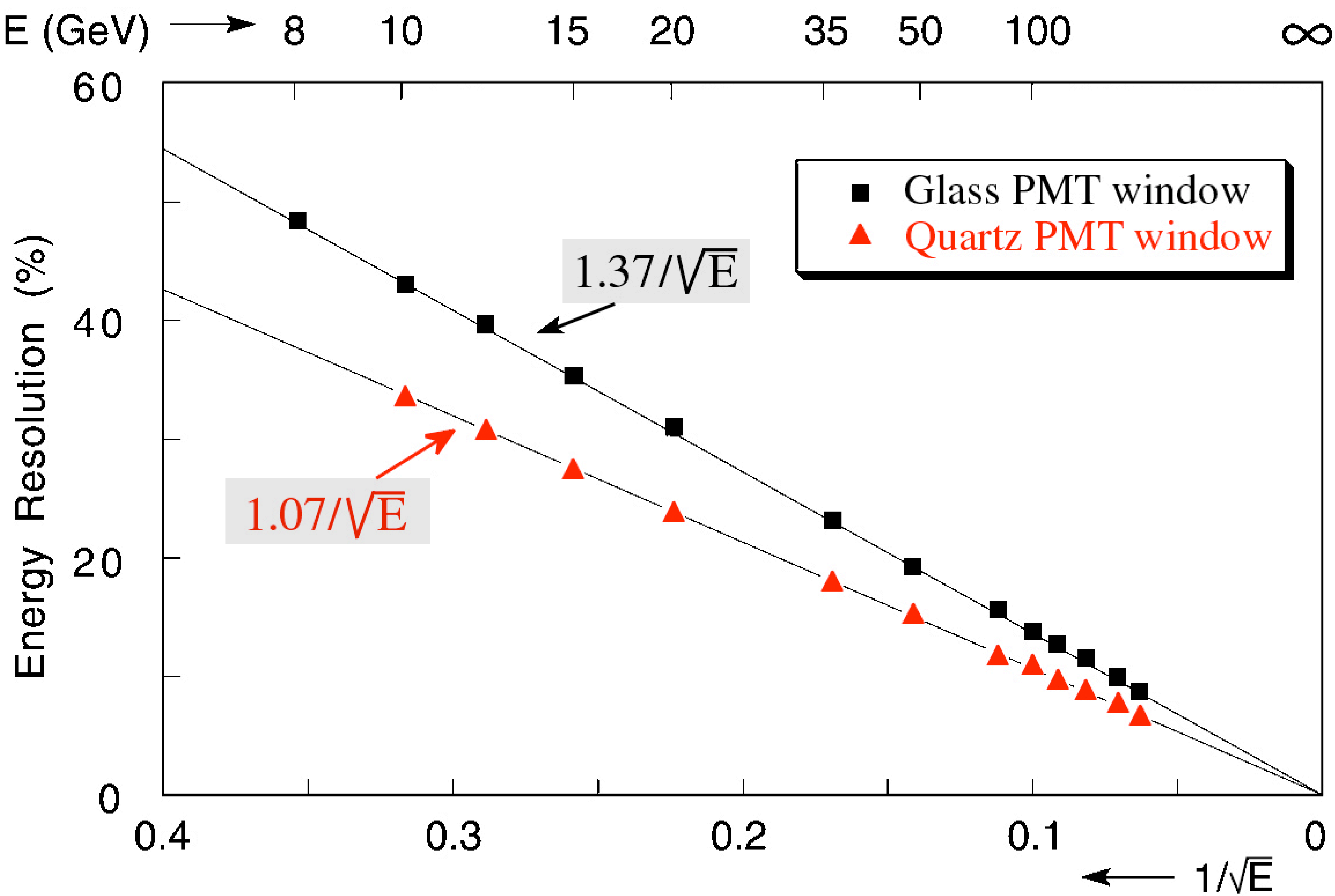


- Obtain information *fast*
  → recognize and select interesting events in real time *(trigger)*
- Performance of calorimeters *improves with energy* ($\sim E^{-1/2}$ if statistical processes are the limiting factor)

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

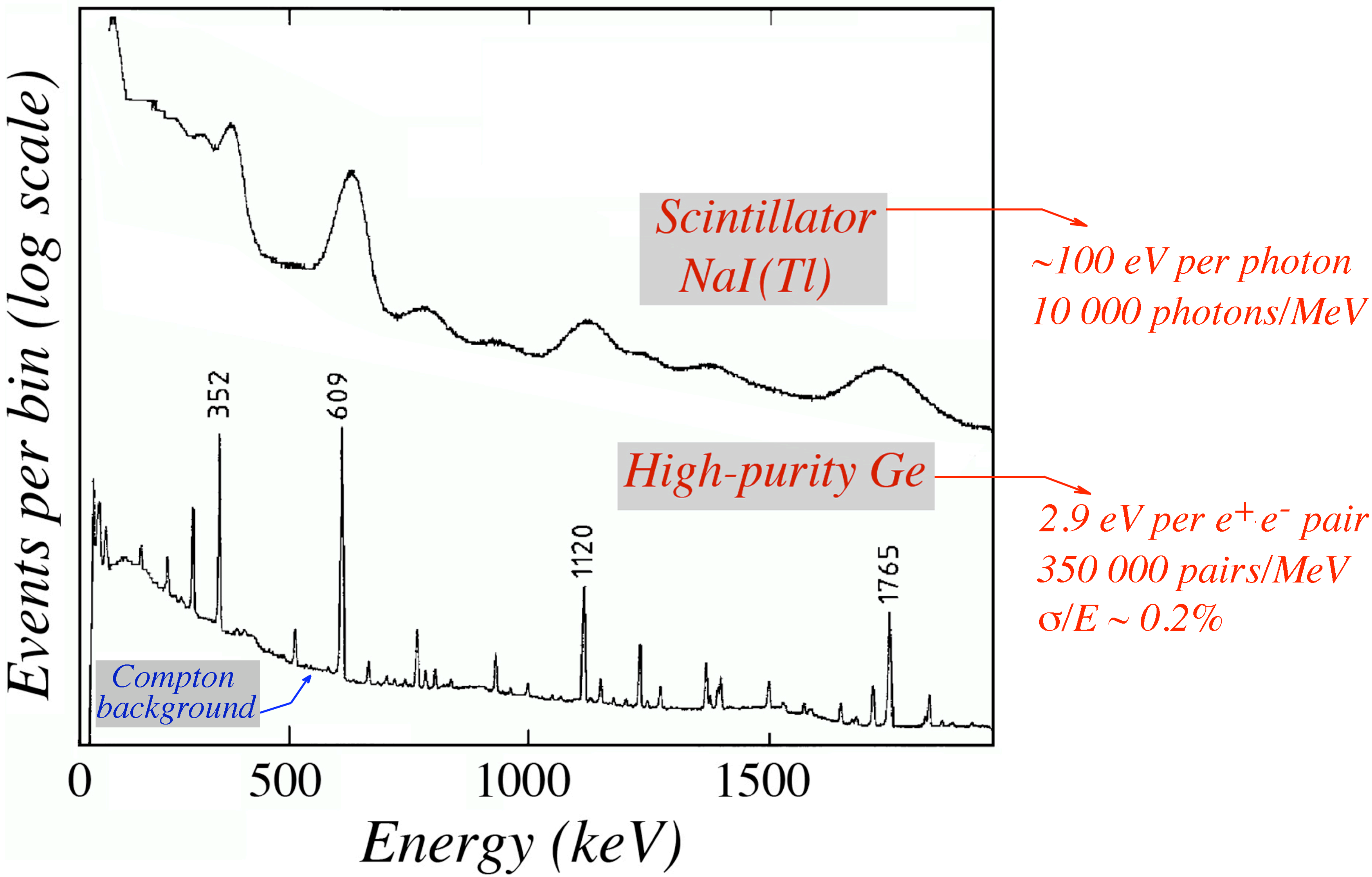
$$\rightarrow \text{energy resolution } \frac{\sigma(E)}{E} \propto 1/\sqrt{n} \propto 1/\sqrt{E}$$

In an ideal calorimeter, resolution scales as $E^{-1/2}$



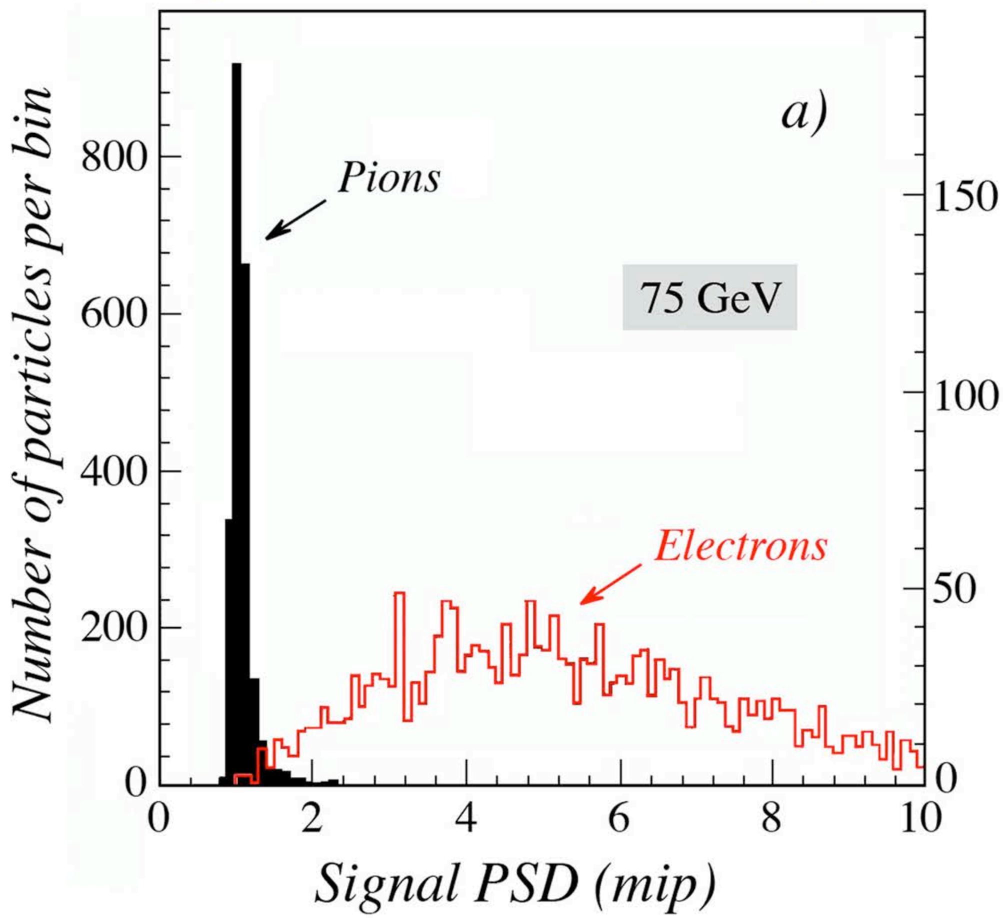
Nuclear γ ray detectors

Energy resolution dominated by signal quantum fluctuations (?)

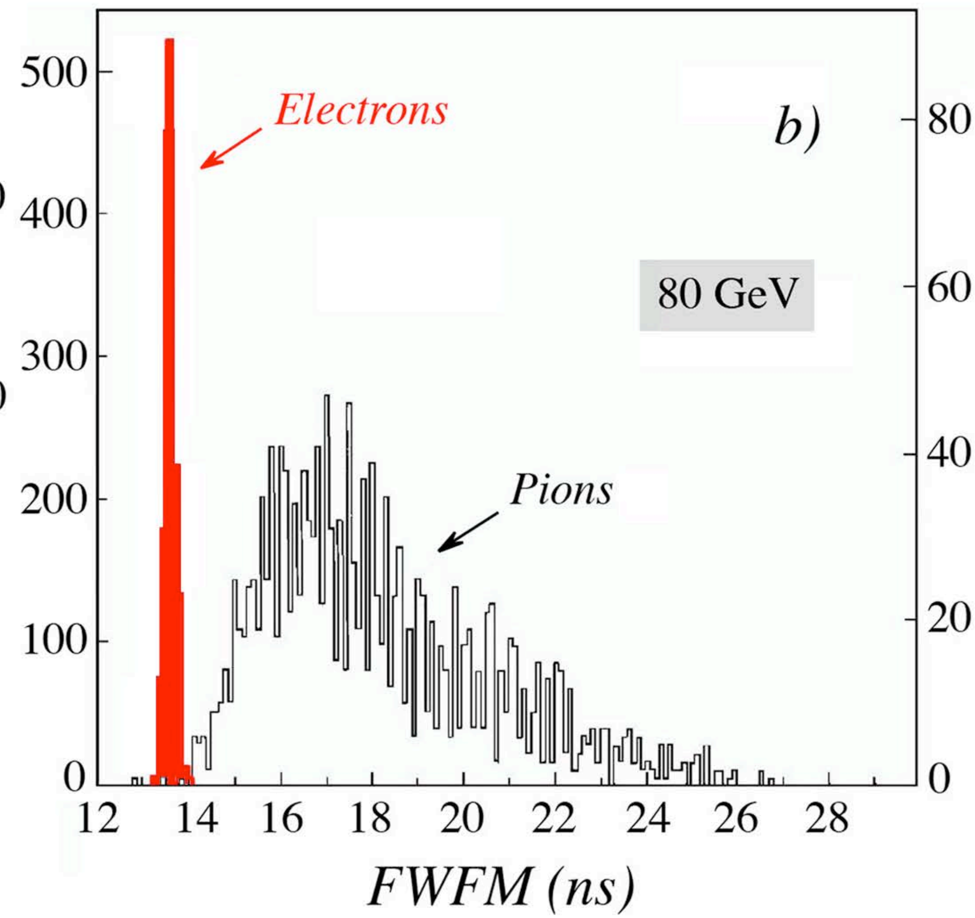


Particle identification with calorimeters

Using shower profile
(pre-shower detector)



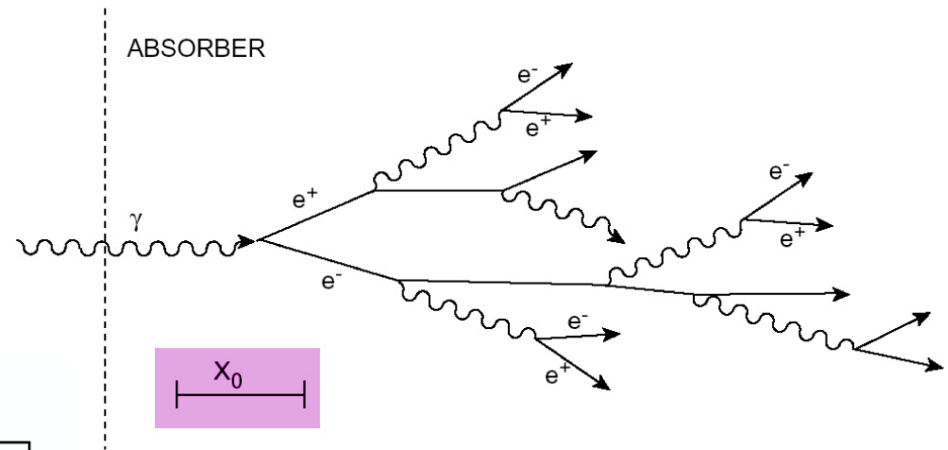
Using time structure
of the signals

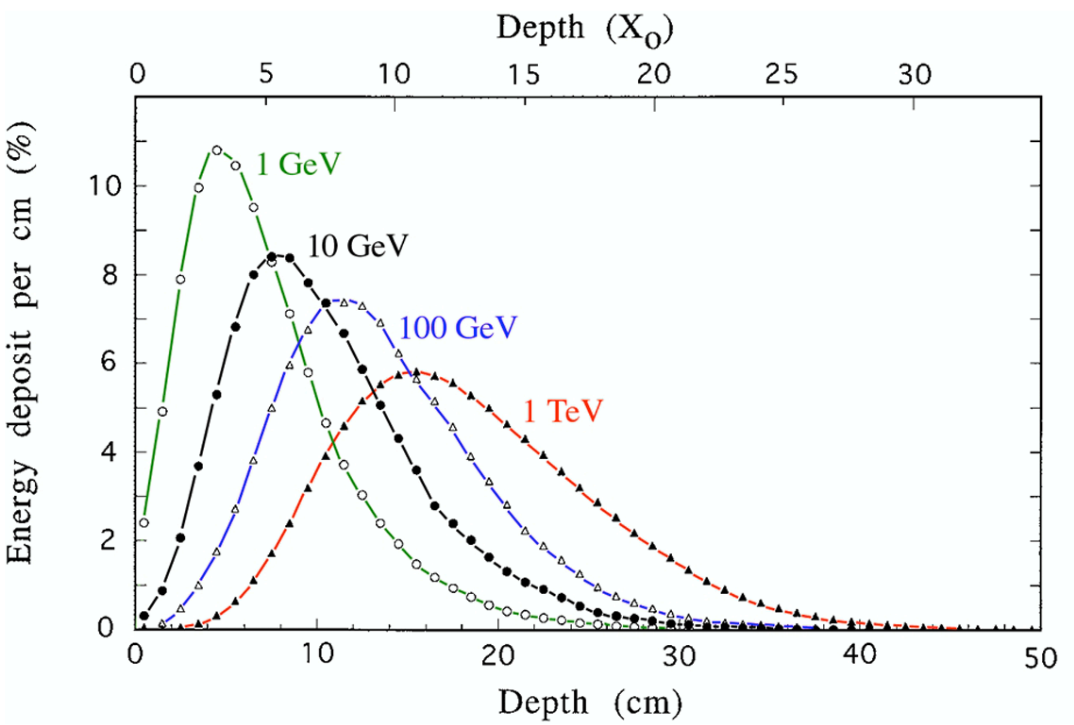


Calorimeters

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.



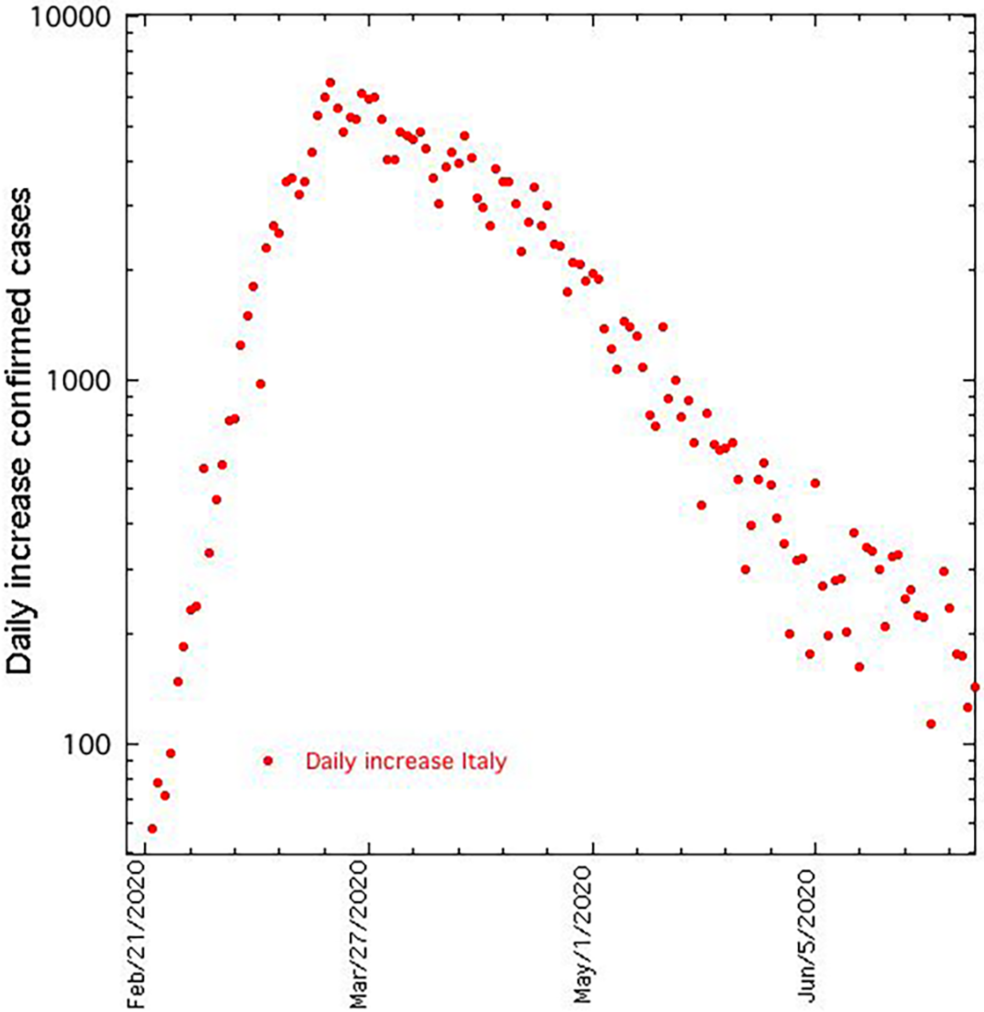


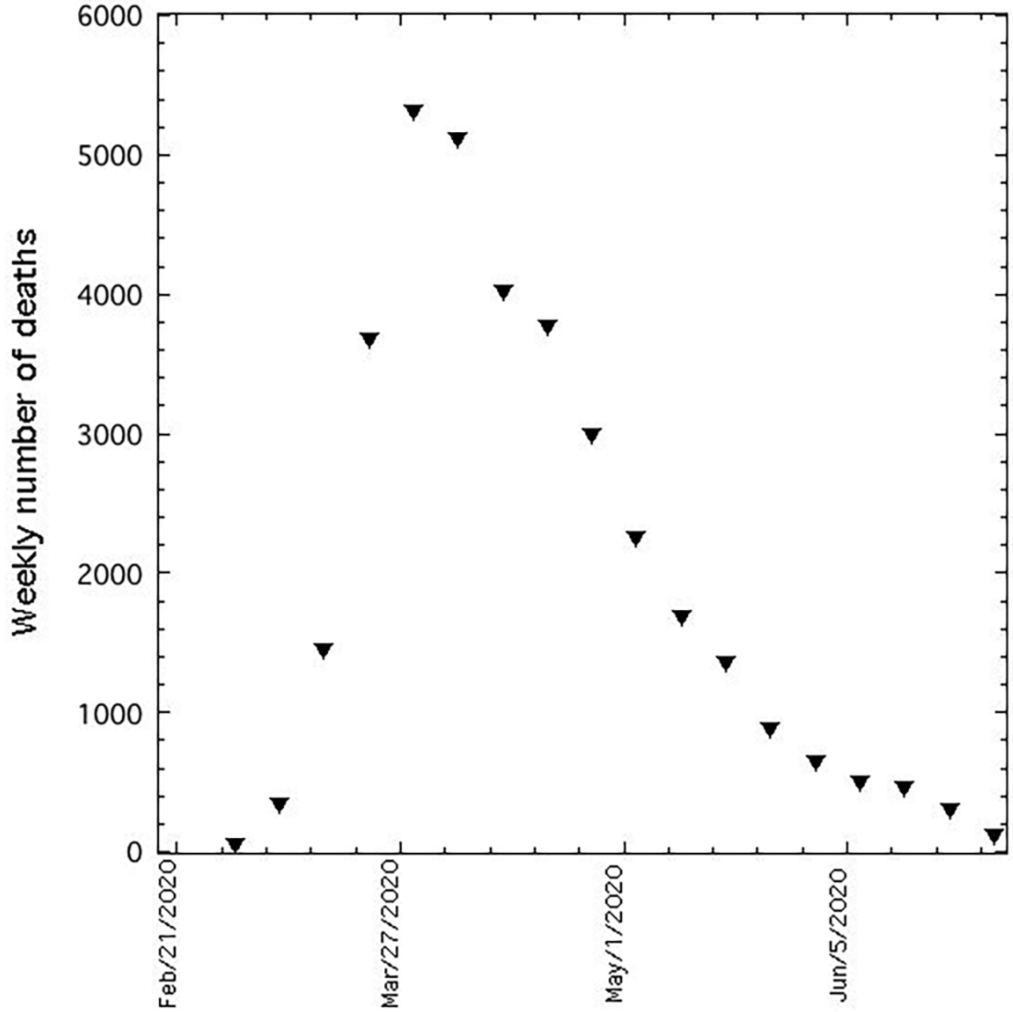
The shower development is governed by the "radiation length" X_o, which is typically ~ 1 cm

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

An example of a similar mechanism in a completely unrelated situation

COVID-19 infections (left, log scale) and fatalities (right, linear) in Italy





Calorimetry: Homogeneous calorimeters

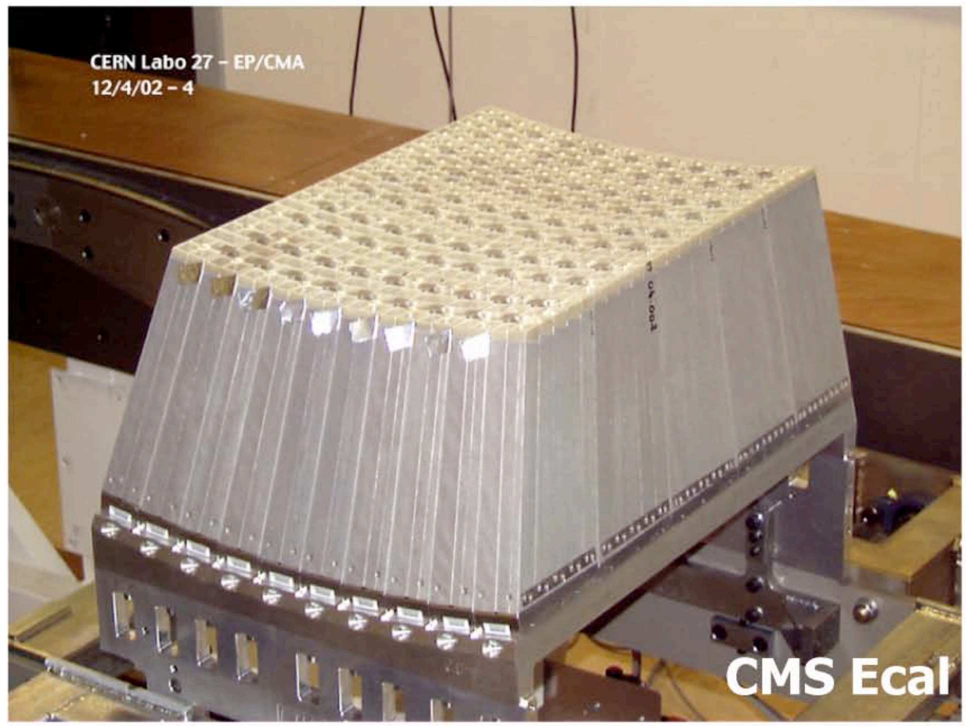
- *High-density crystals used as electromagnetic calorimeters*
  Example: CMS ECAL, $PbWO_4$. Density 8.3 g/cm^3, radiation length 8.9 mm.

- *Very good energy resolution*

- *Very expensive*

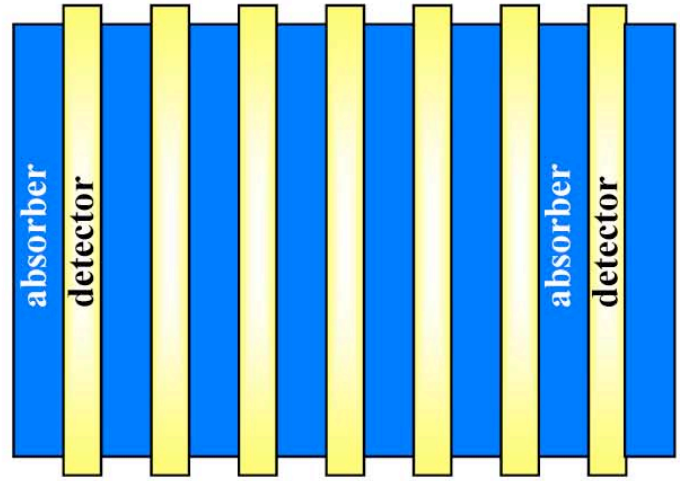
- *Radiation damage a problem*

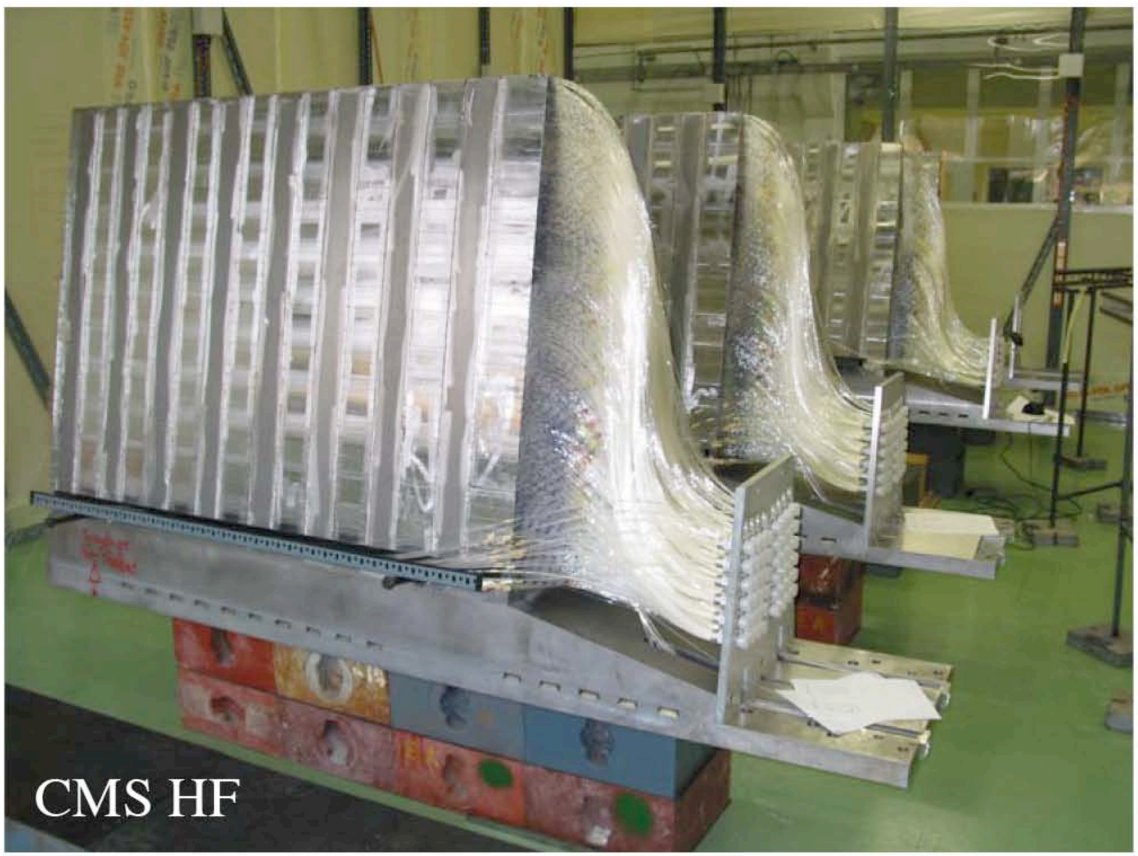
- *Other crystals:*
  NaI(Tl), CsI, BGO, BaF_2



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…*





Whereas electromagnetic calorimeters (intended for e,γ detection) are typically very precise and very well understood instruments

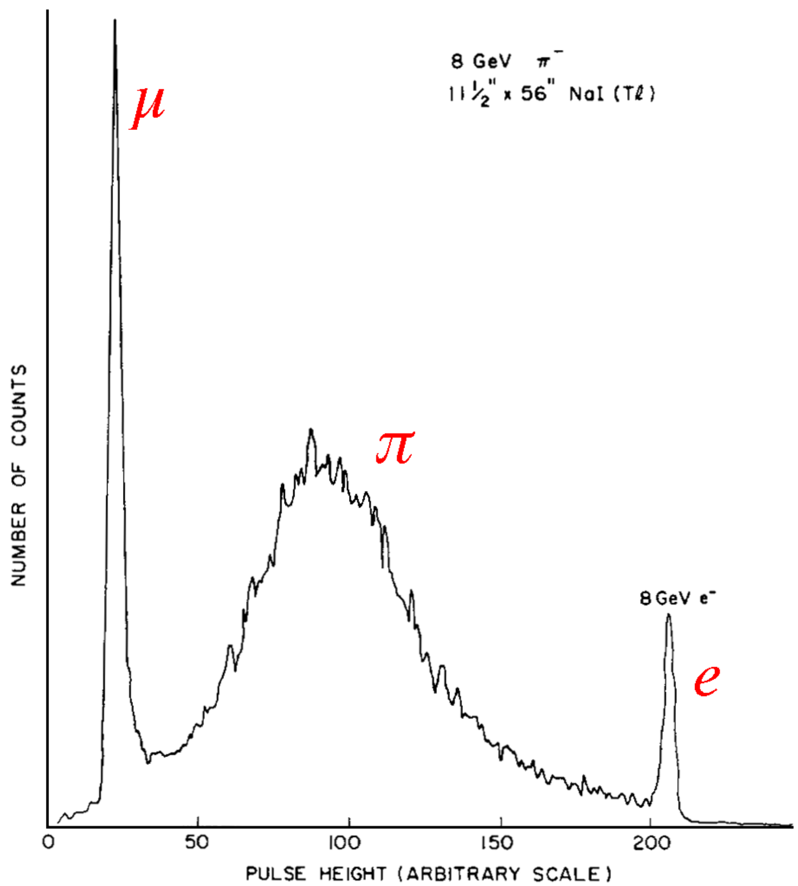
Hadron calorimeters are usually far from ideal

Early indication that hadron calorimetry is different!

NIM 75 (1969) 130

450 kg of NaI (Tl) crystals

Tested with 8 GeV particle beams

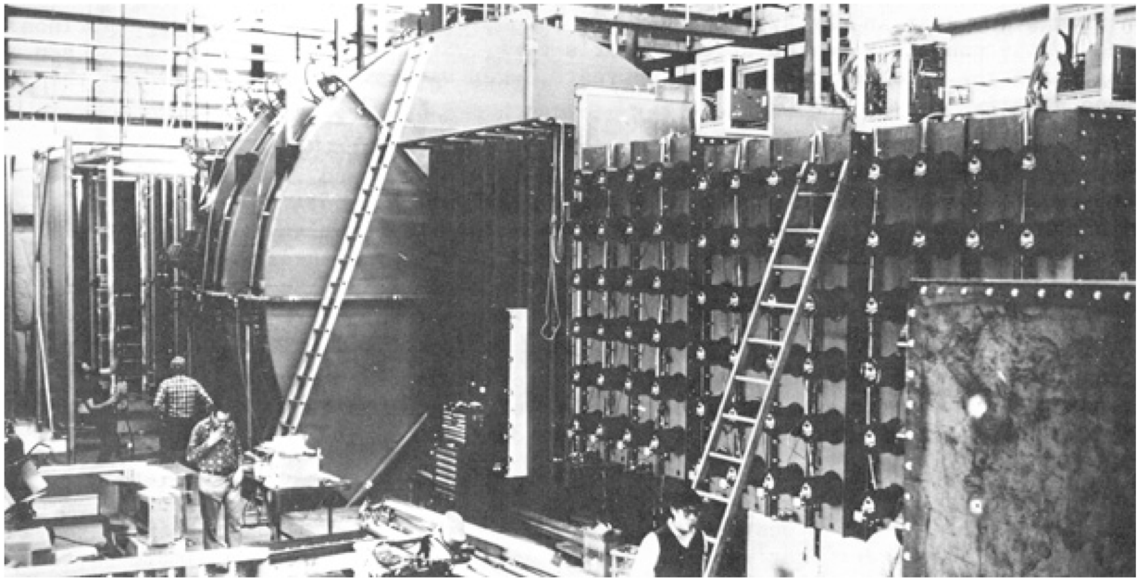


Conclusions of authors:

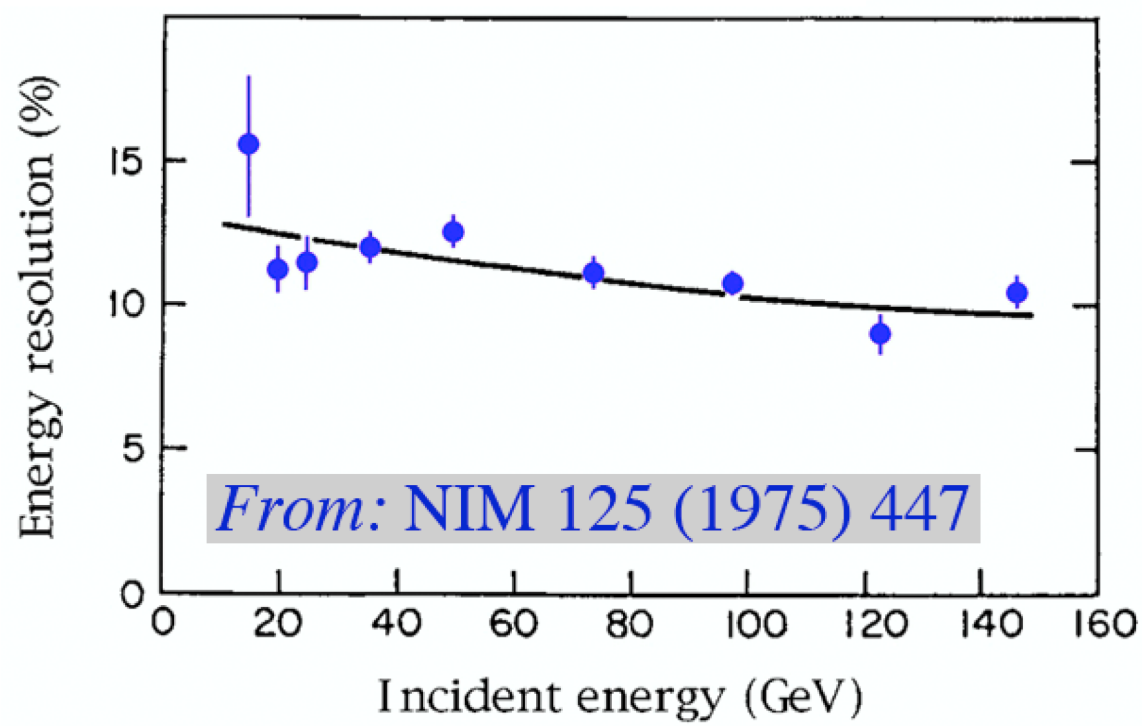
- *50% of energy leaks out*
- *MC: much less leakage*
- *Same results at 4, 12, 16 GeV*
- *Resolution did NOT improve with E*

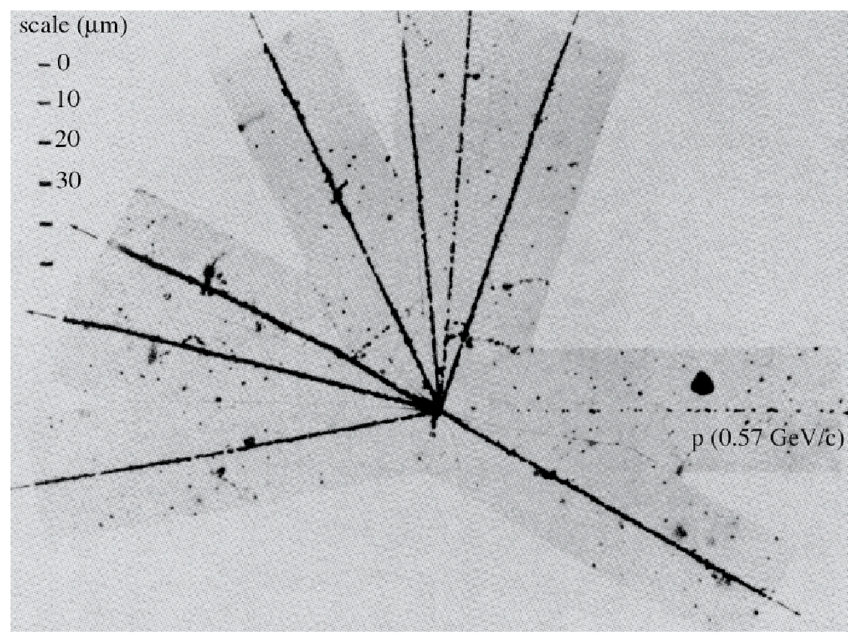
Energy resolution of a homogeneous hadron calorimeter

(60 tonnes of liquid scintillator)



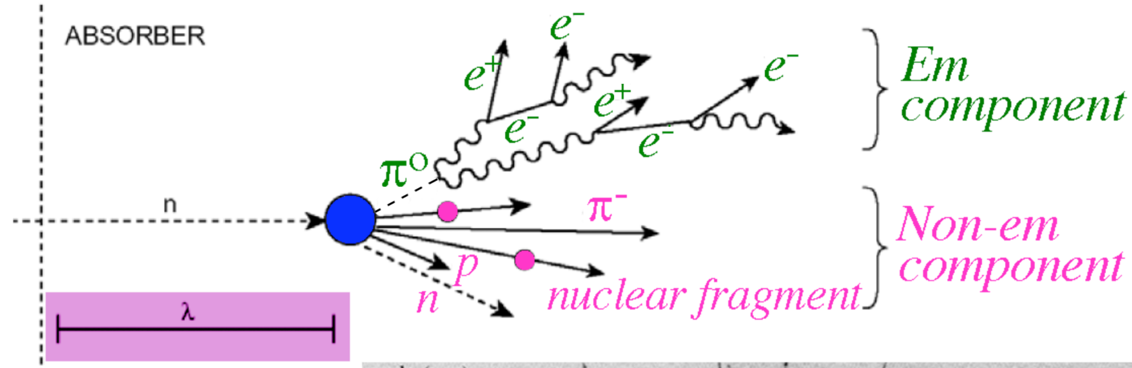
Statistical processes are NOT the limiting factor here. Resolution is limited by fluctuations in invisible energy losses in the non-em shower component, e.g. in nuclear interactions



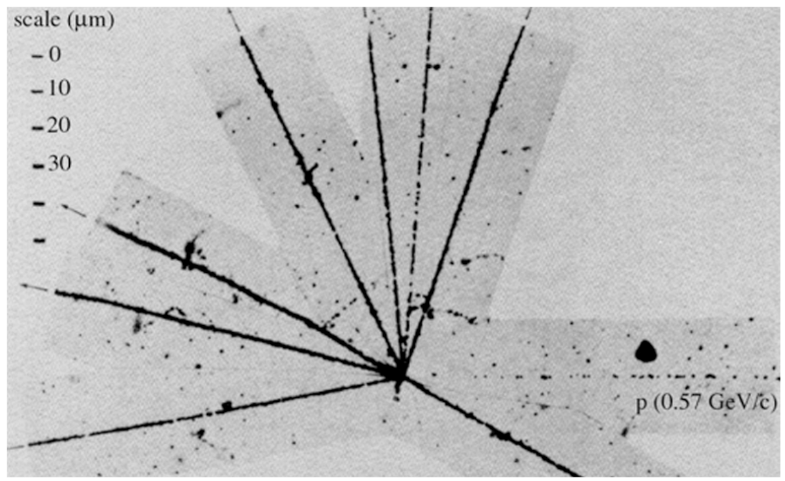


The physics of hadronic shower development

- *A hadronic shower consists of two components*

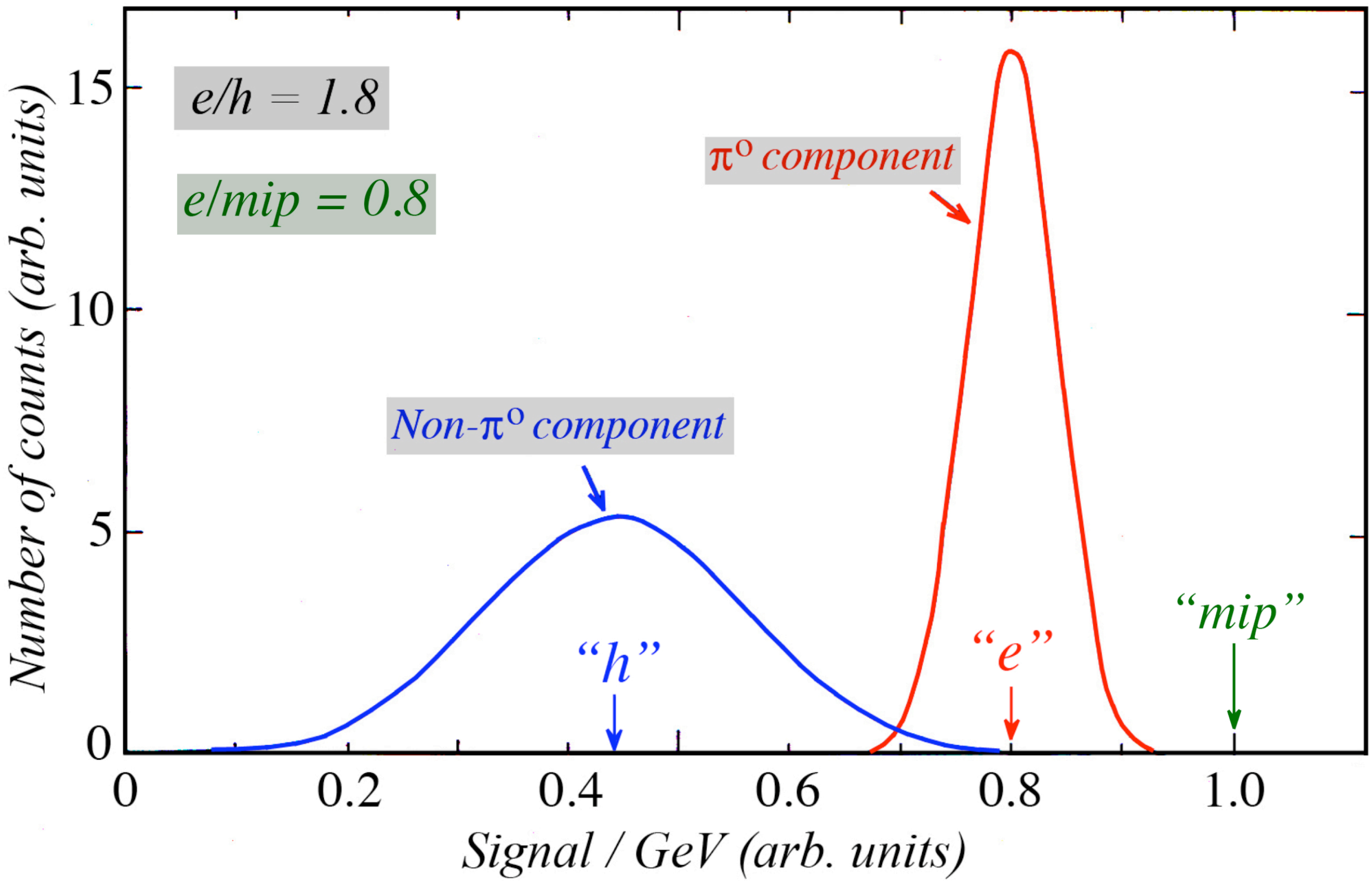


- *Electromagnetic component*
  - electrons, photons
  - neutral pions → 2 γ
- *Hadronic (non-em) component*
  - charged hadrons π±,K± (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft γ's (15%)
  - break-up of nuclei (*"invisible"*) (40%)



- *Important characteristics for hadron calorimetry:*
  - *Large, non-Gaussian fluctuations in energy sharing em/non-em* (f_{em})
  - *Large, non-Gaussian fluctuations in "invisible" energy losses*

The calorimeter response to the two shower components is NOT the same



This effect is quantified by the e/h ratio. For example, in crystal calorimeters, e/h ~ 2, i.e. 50% of the non-em energy deposit is invisible

Consequences for LHC calorimeters

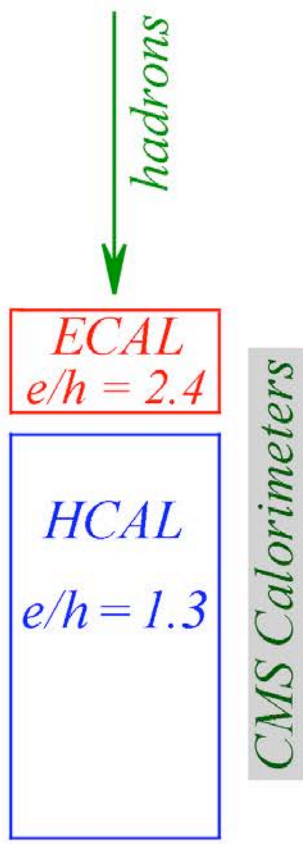
Hadronic response and signal linearity (CMS)

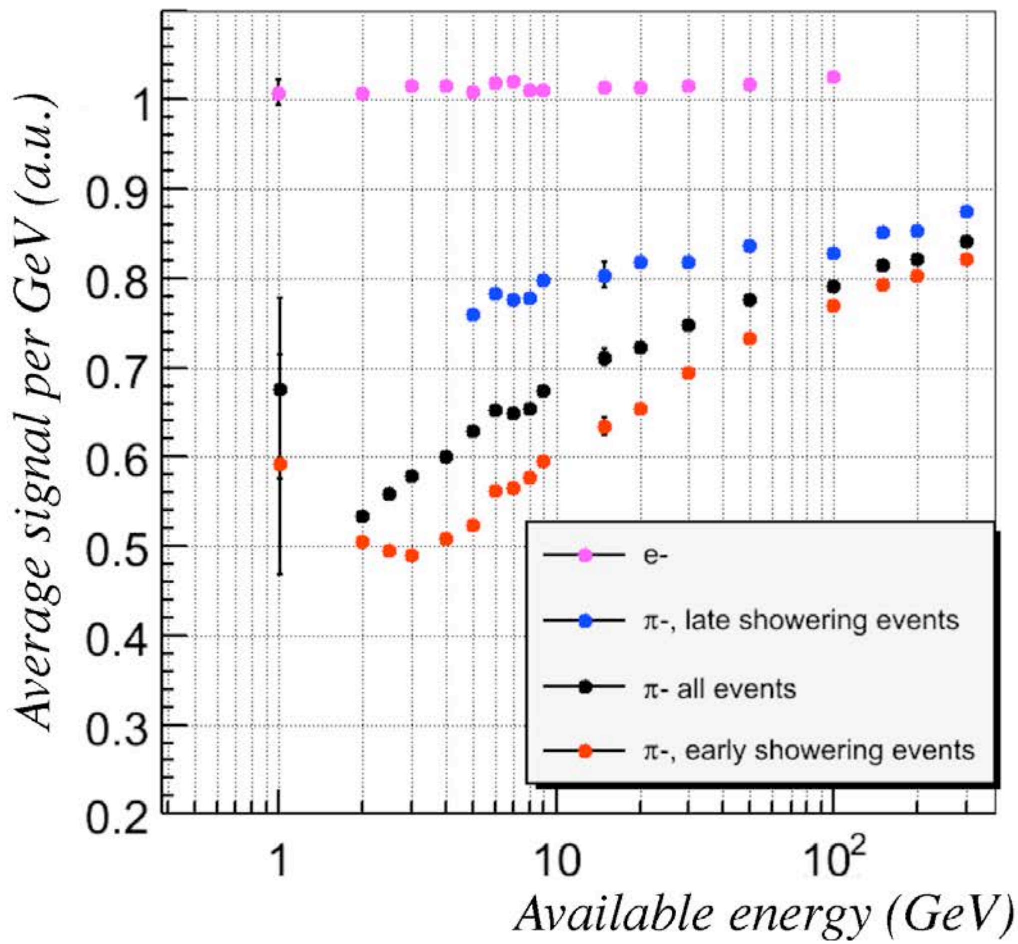
CMS pays a price for its focus on em energy resolution

ECAL has $e/h = 2.4$, while HCAL has $e/h = 1.3$

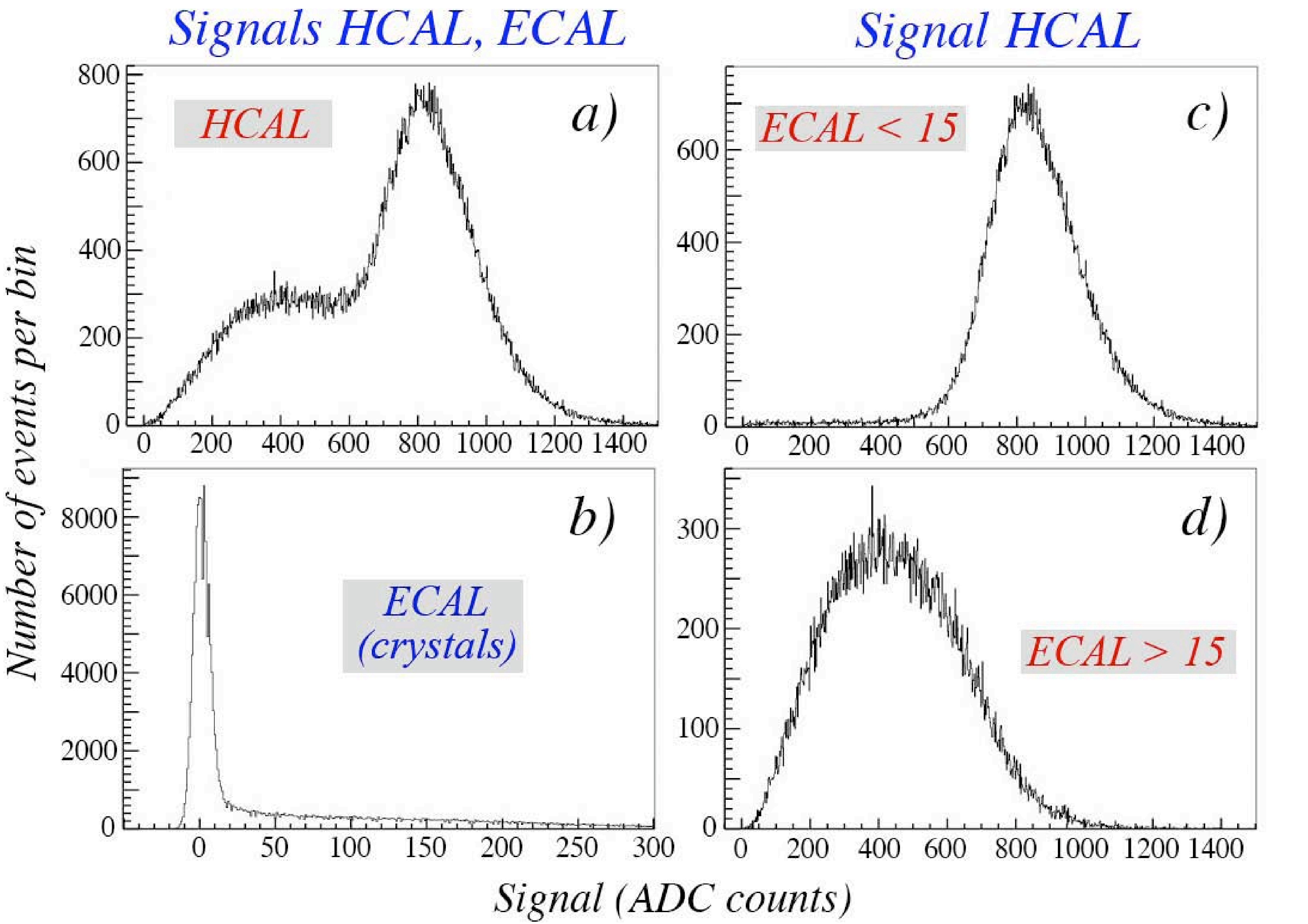
⟶ *Response depends strongly on starting point shower*

Data from: CMS note 2007/012





Pion signals in crystal ECAL + scintillator HCAL



Why is e/h ≠ 1?

Dominant effect:

Nuclear binding energy losses

Secondary effects:

Escaping muons and neutrinos (meson decay)

What to do about this?

Use a measurable quantity that is correlated to these losses

1) The total kinetic energy of neutrons produced in the shower development

2) The electromagnetic shower fraction (anti-correlated)

Methods to improve hadron calorimeter performance

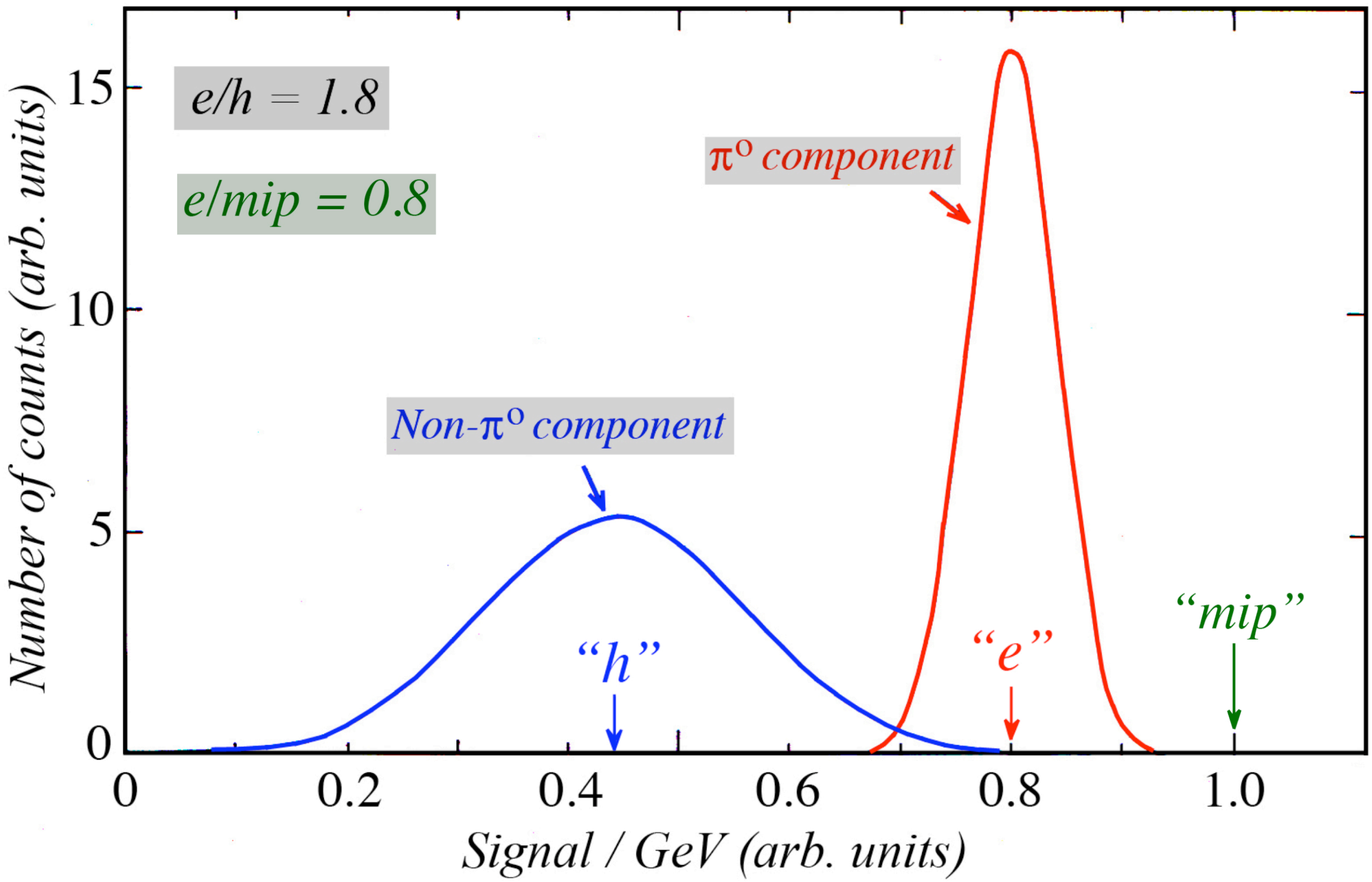
1) Equalize the response to em and non-em shower components

e/h = 1 (compensation)

This can be achieved by exploiting a combination of 2 phenomena, which both only work in sampling calorimeters:

a) Suppression of em response for high-Z absorber material
b) Boosting the non-em response for hydrogenous active material

The calorimeter response to the two shower components is NOT the same



This effect is quantified by the e/h *ratio. For example, in crystal calorimeters, e/h ~ 2, i.e. 50% of the non-em energy deposit is invisible*

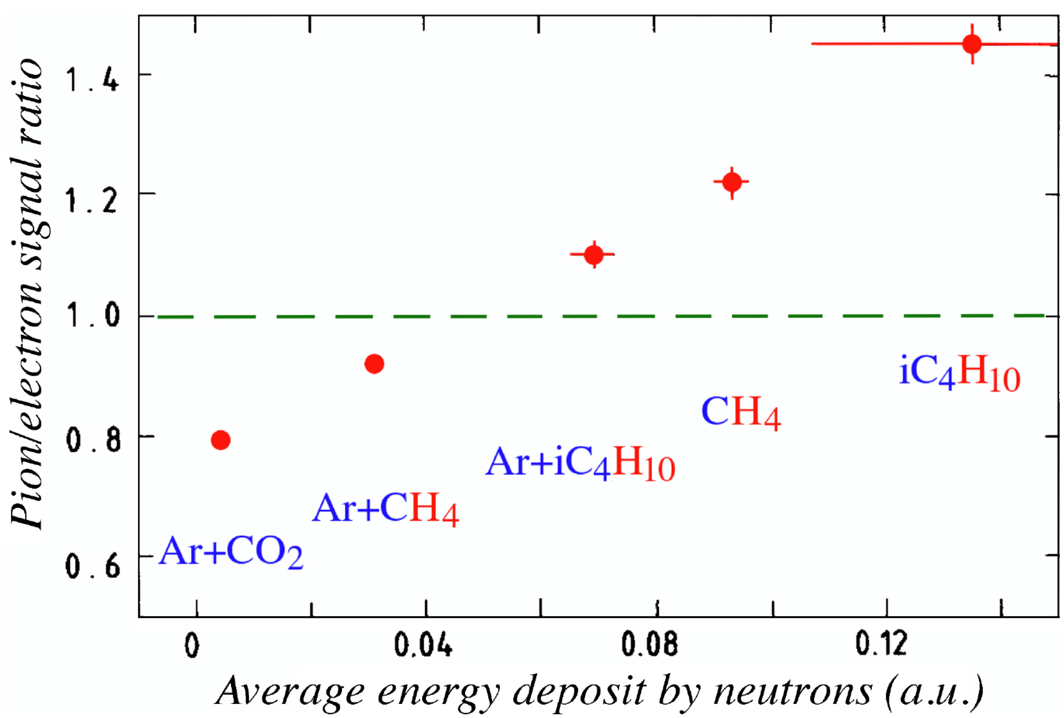
Compensation

Exploit the fact that neutrons may be sampled much more efficiently than ionizing particles

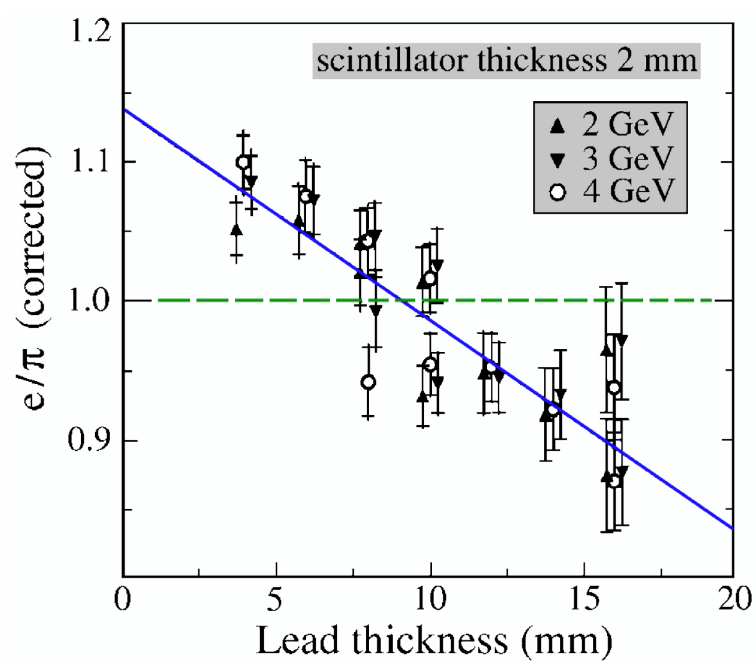
Ingredients: high-Z absorber, hydrogen-rich active material

Need very specific (small) sampling fraction to get e/h = 1.0 (e.g. thickness ratio ~5/1 for lead/plastic-scintillator)

Uranium / gas (L3)



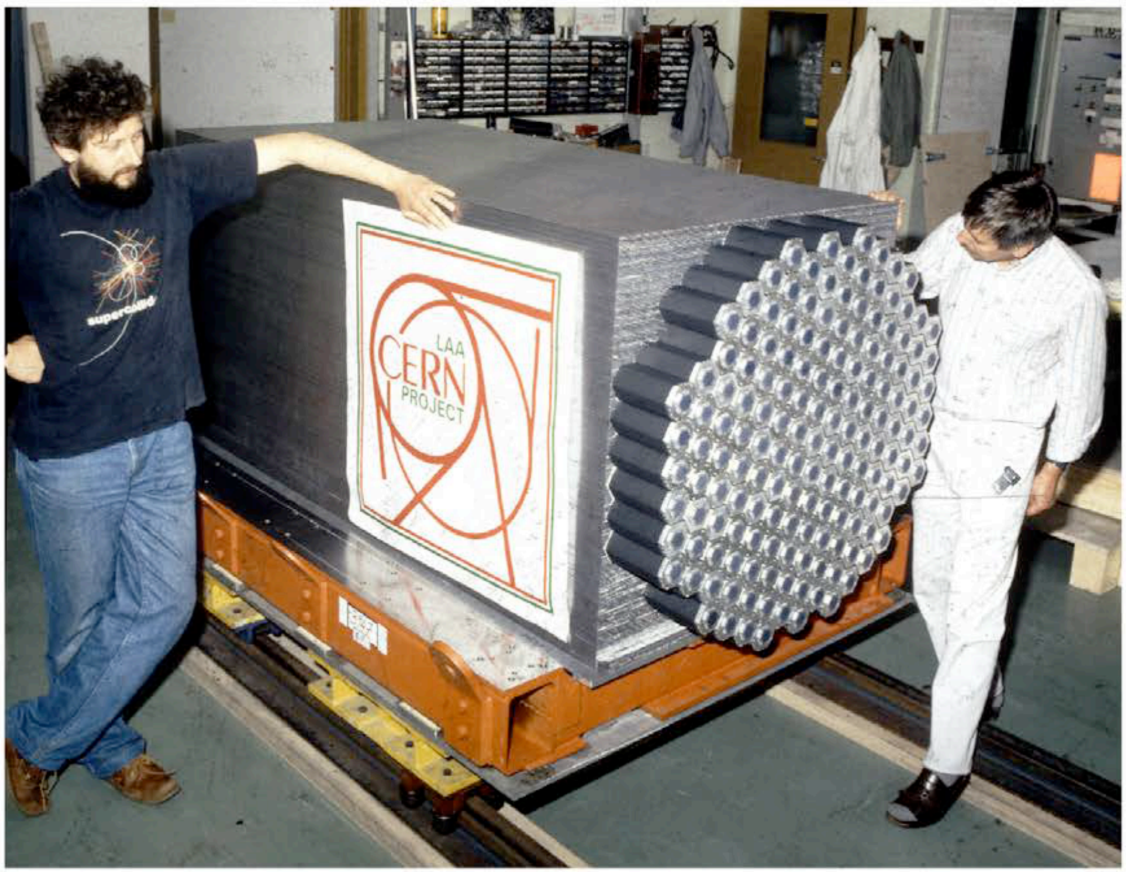
Pb/plastic-scintillator (KEK)

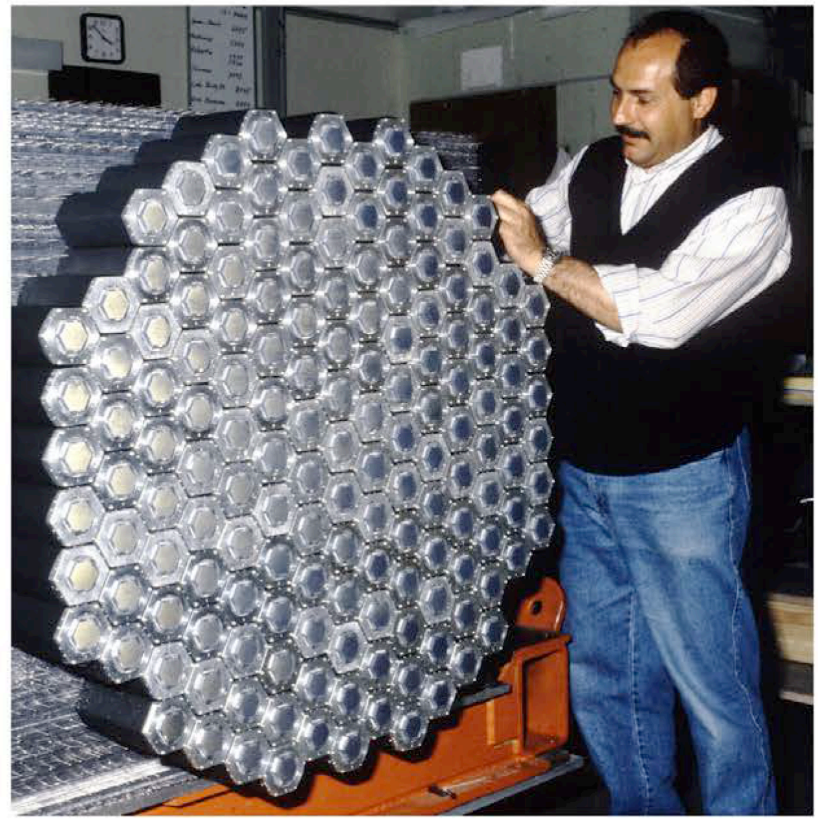


Compensation

Achieved by boosting the relative contribution of neutrons to the signals by means of the sampling fraction, to the point where e/h = 1

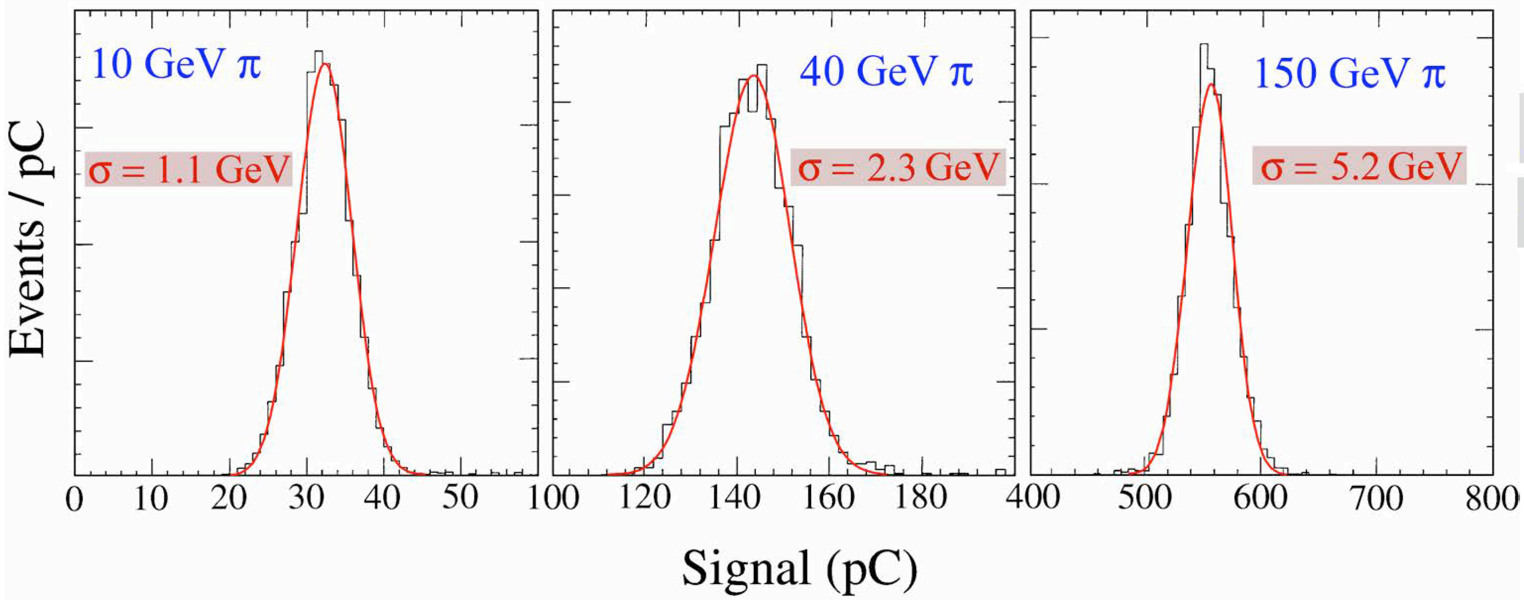
SPACAL 1989





Pb - plastic fibers
(4:1 volume ratio)

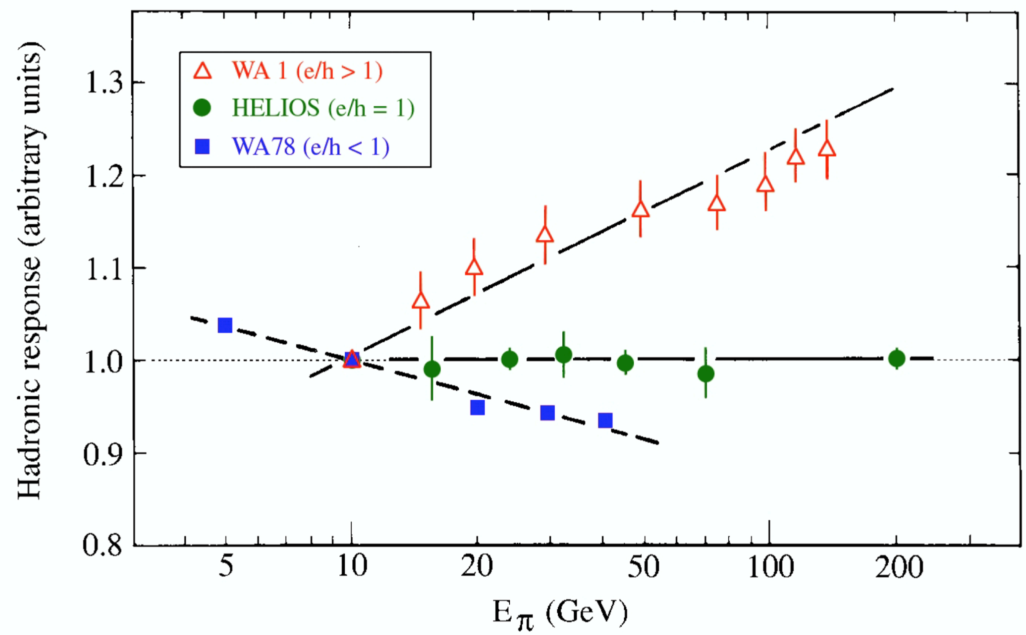
Hadronic signal distributions in a compensating calorimeter



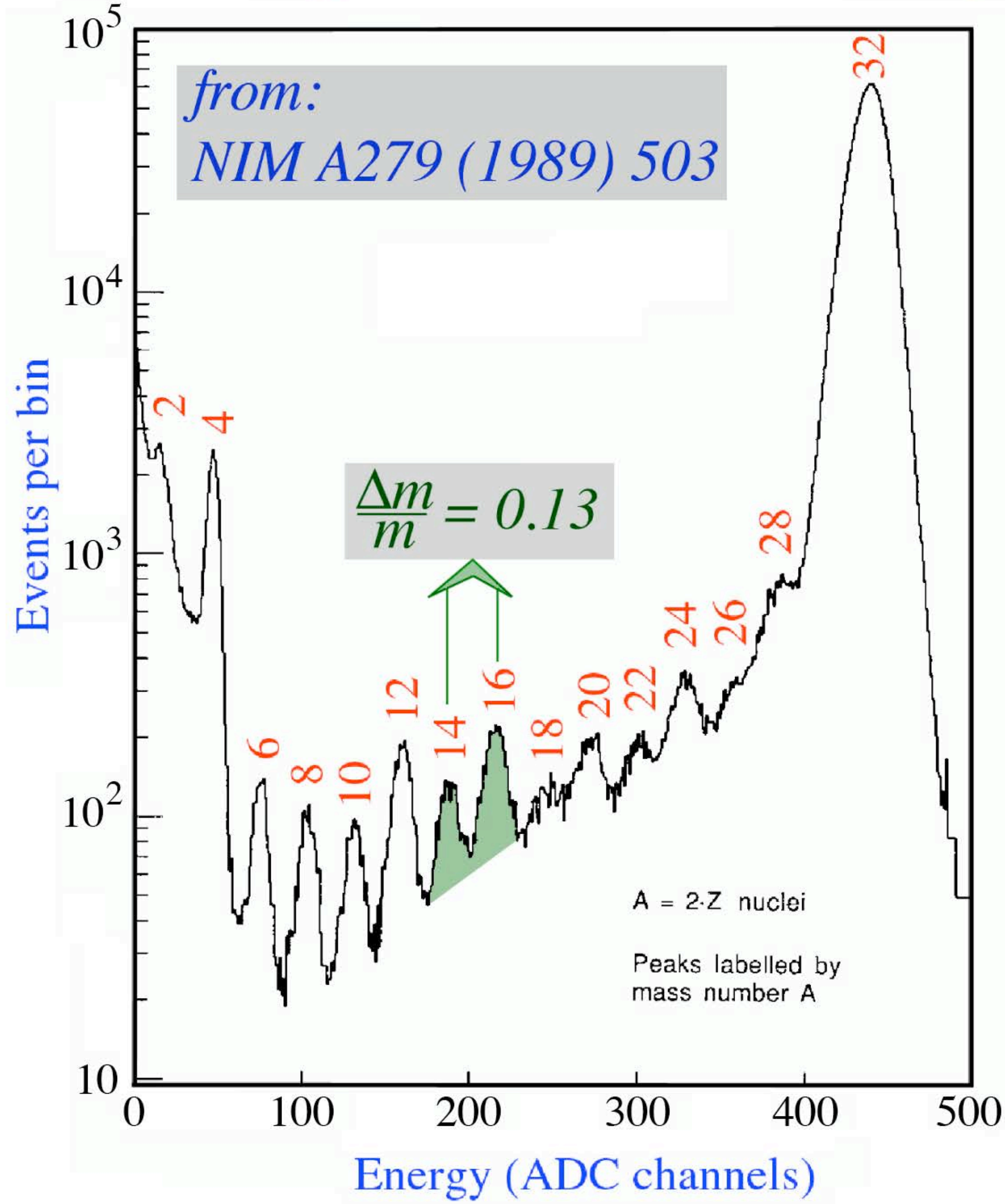
from:

NIM A308 (1991) 481

Hadronic signal (non-)linearity: Dependence on e/h



Hadron calorimetry in practice
Energy resolution in a compensating calorimeter



W/Z separation:

$\frac{\Delta m}{m} \sim 0.11$

The WA80 calorimeter as high-resolution spectrometer. Total energy measured with the calorimeter for minimum-bias events revealed the composition of the momentum-selected CERN heavy-ion beam

Methods to improve hadron calorimeter performance

1) Equalize the response to em and non-em shower components

e/h = 1 (compensation)

This can be achieved by exploiting a combination of 2 phenomena, which both only work in sampling calorimeters:

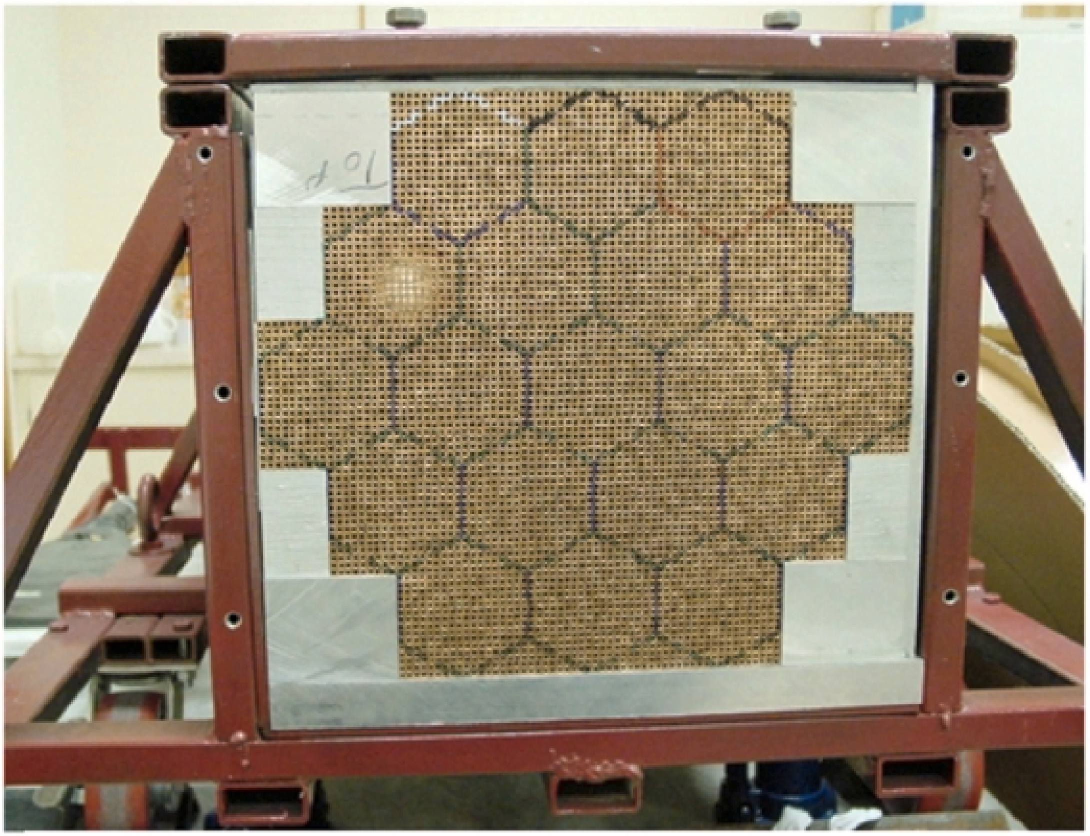
a) Suppression of em response for high-Z absorber material
b) Boosting the non-em response for hydrogenous active material

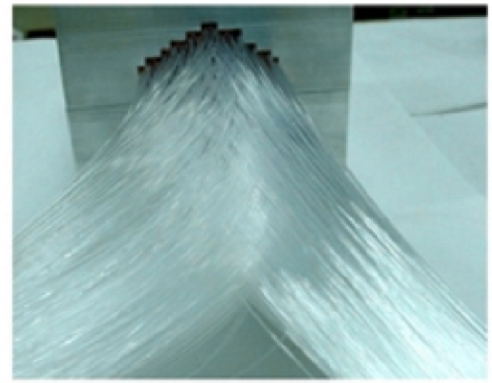
2) Dual-readout calorimetry:

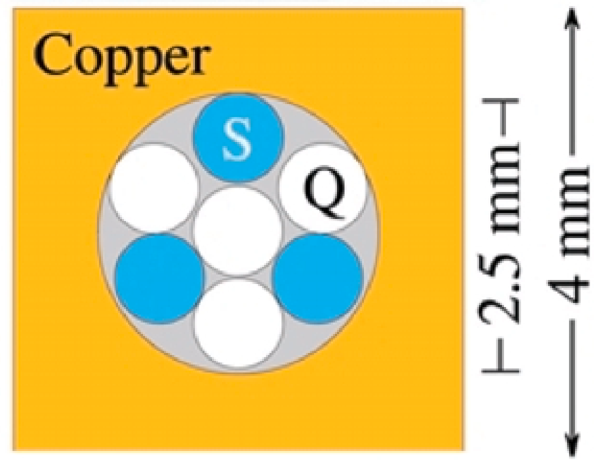
Determine em energy fraction (f_{em}) event by event
This makes it possible to eliminate effects of fluctuations in f_{em}

Measure both the Cherenkov light and the scintillation light produced in the shower development.
For all practical purposes, Cherenkov light is ONLY produced in the em shower component.

DREAM: Structure

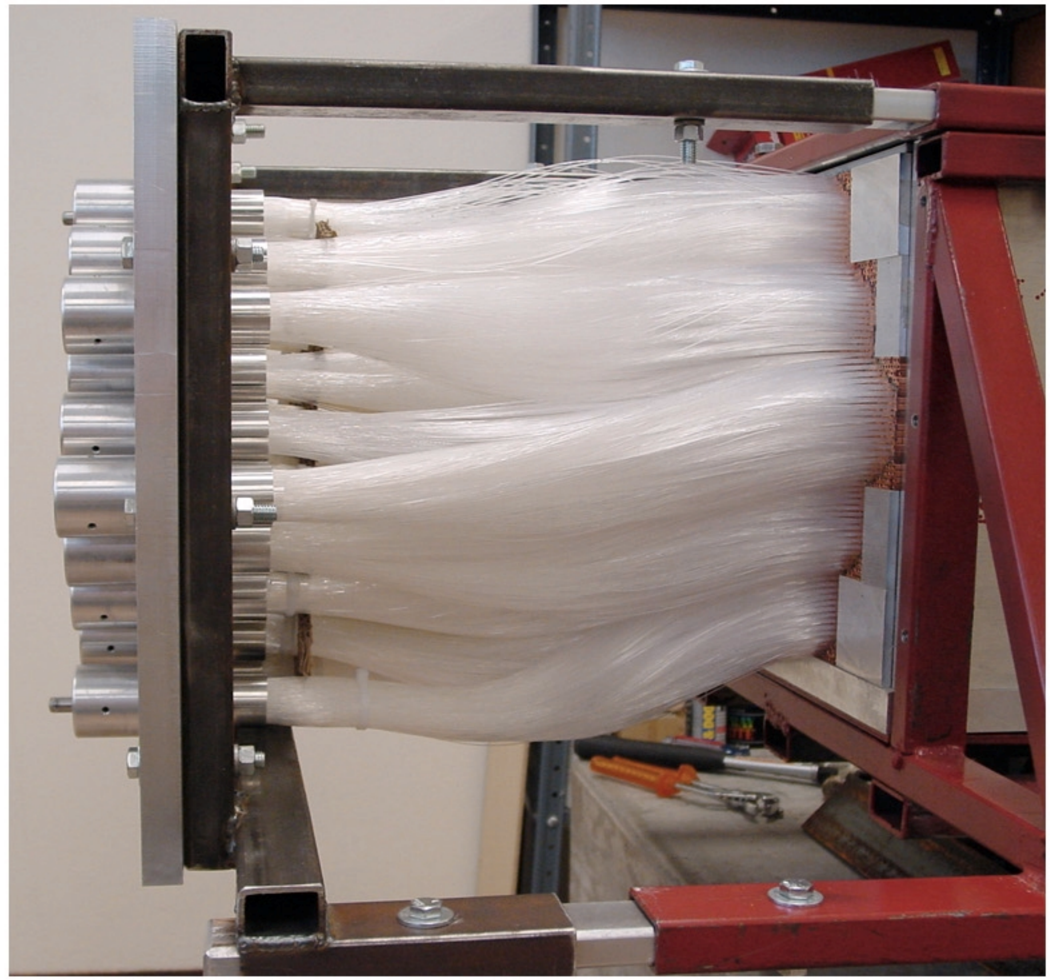


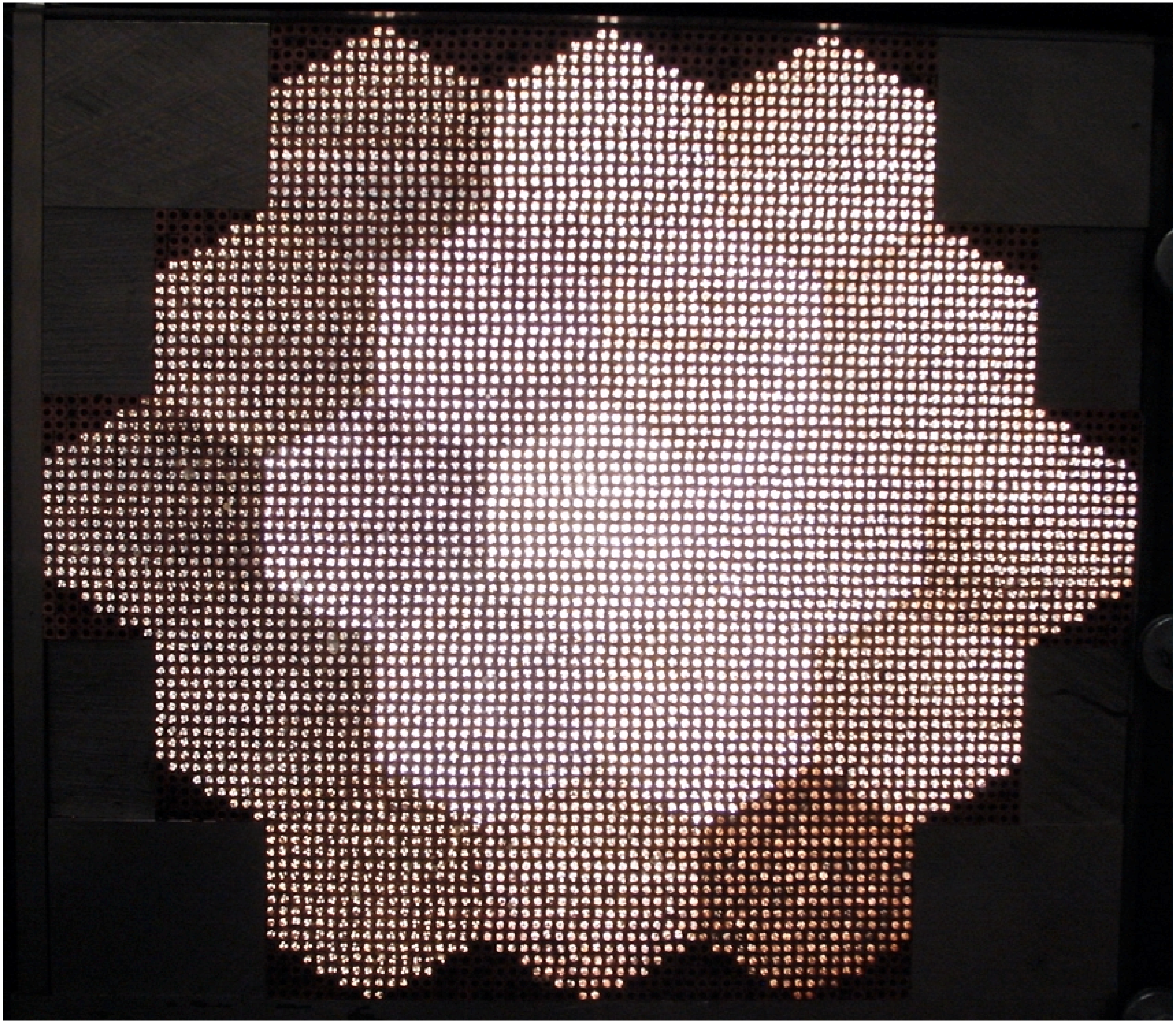




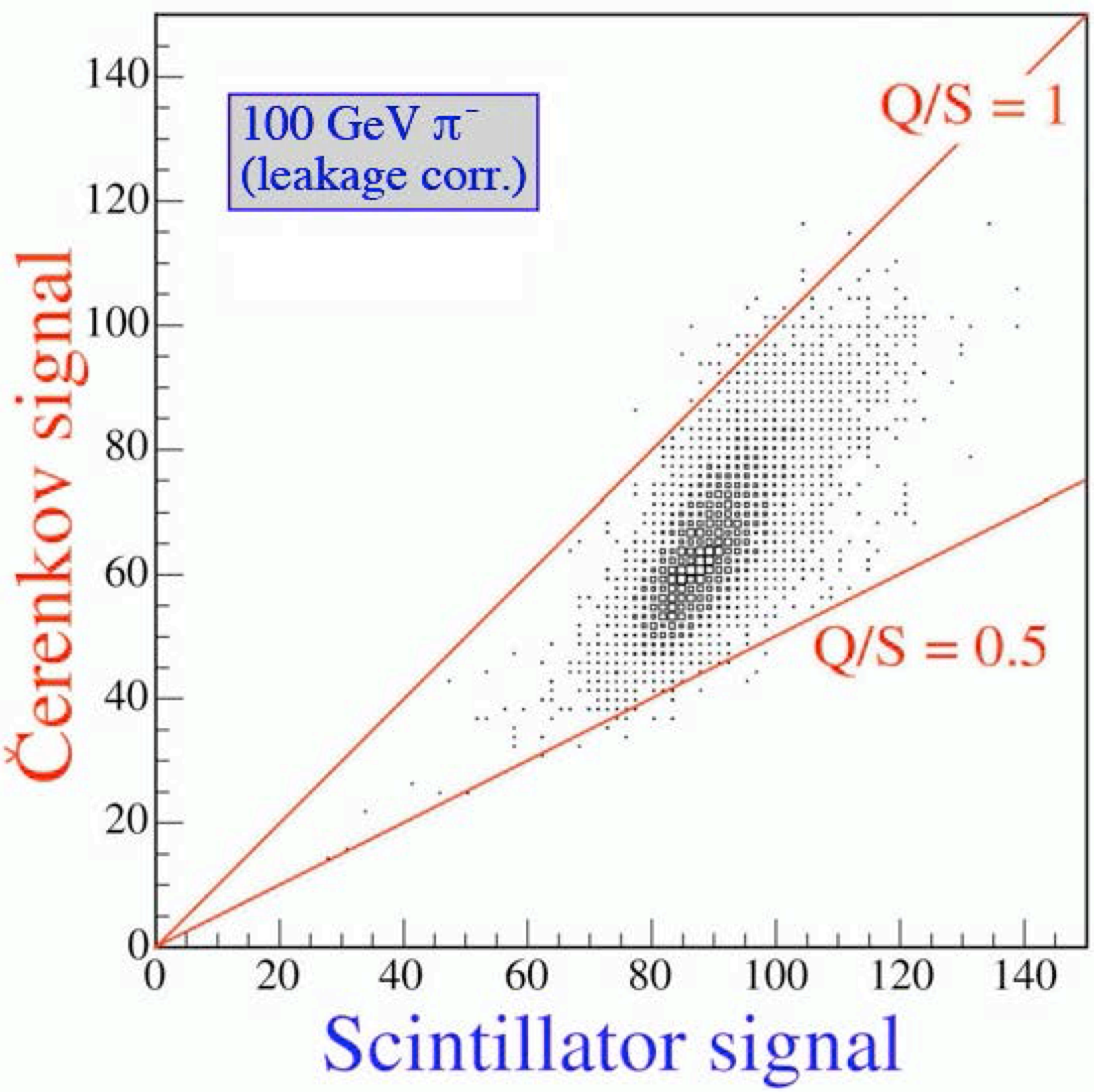
- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

DREAM readout





DREAM: How to determine f_{em} and E?



$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$

$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right]$$

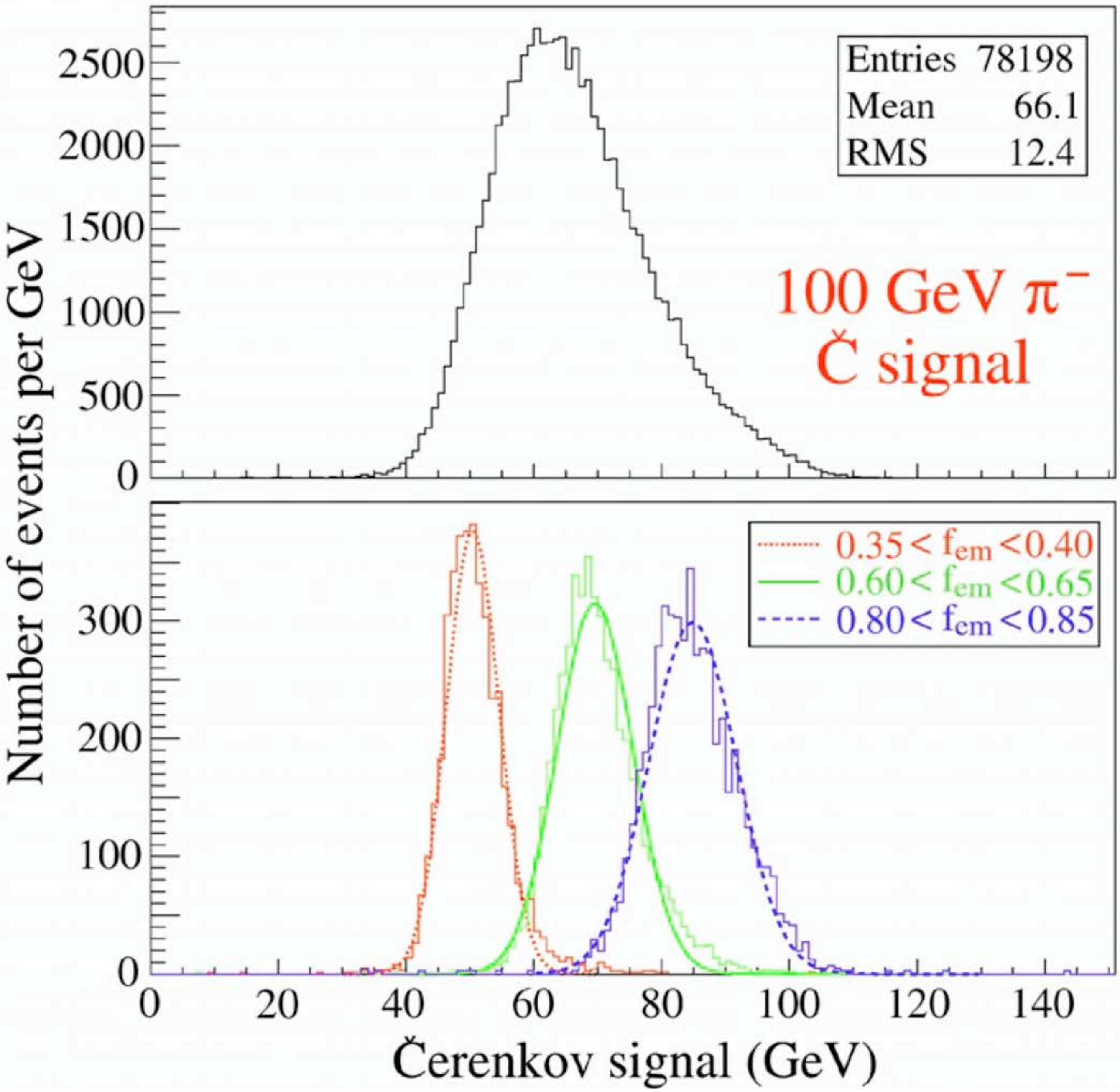
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

$$\frac{Q}{S} = \frac{f_{em} + 0.21\,(1 - f_{em})}{f_{em} + 0.77\,(1 - f_{em})}$$

$$E = \frac{S - \chi Q}{1 - \chi}$$

with $\chi = \dfrac{1 - (h/e)_S}{1 - (h/e)_Q}$

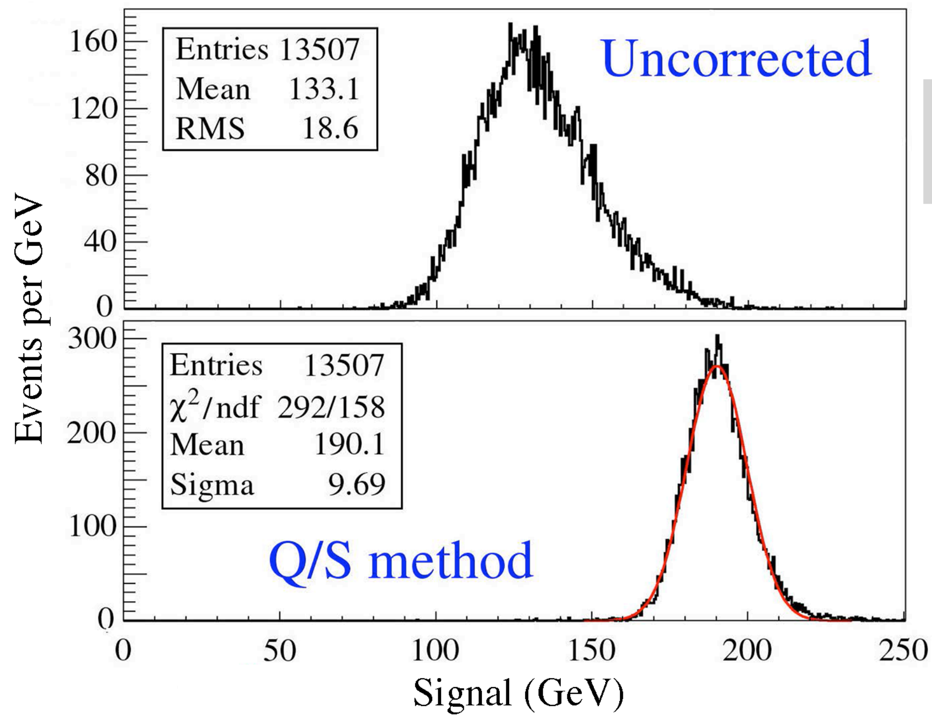
DREAM: Effect of event selection based on f_{em}



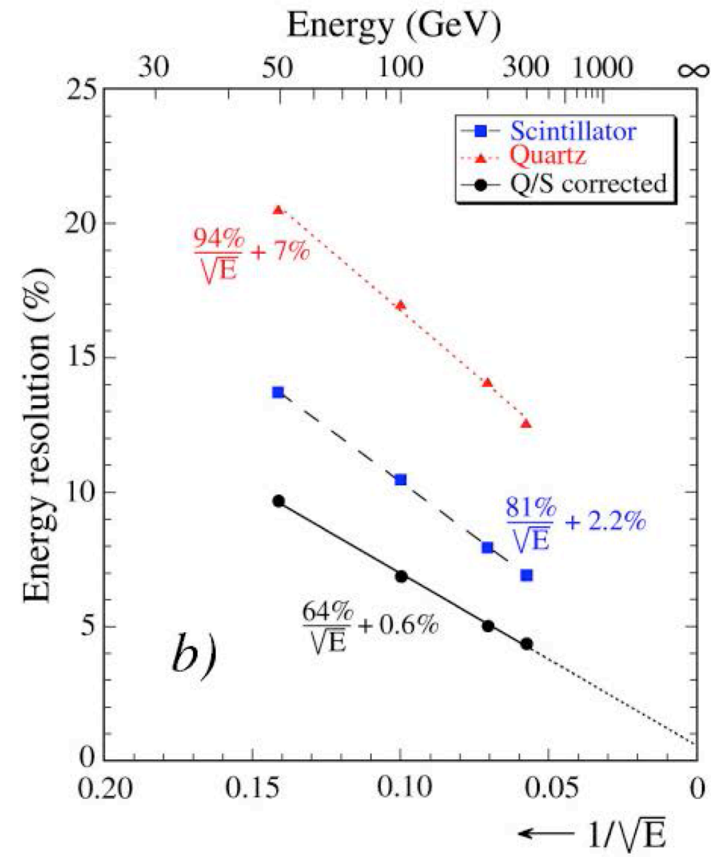
From:
NIM A537 (2005) 537

Effects of Q/S corrections on

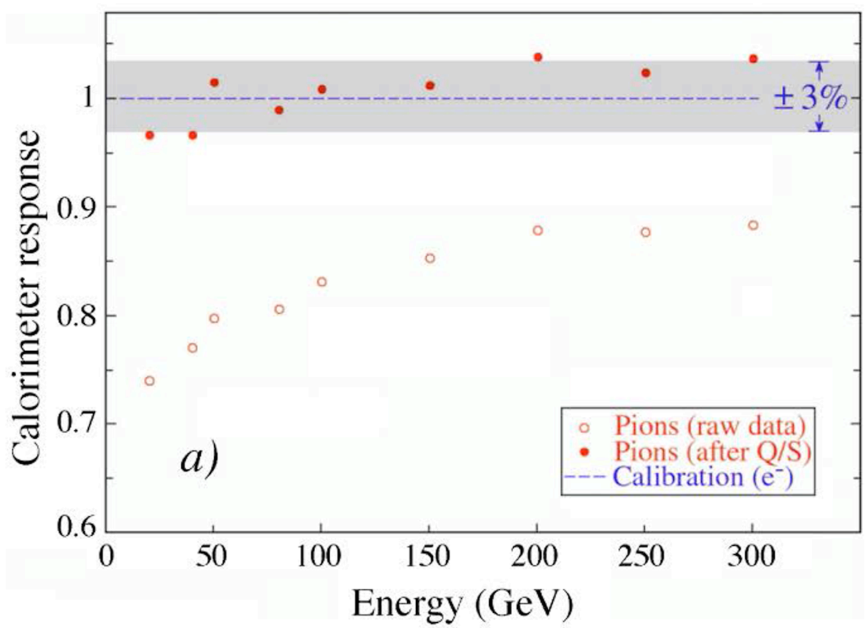
Calorimeter response function



jet energy resolution



hadronic signal linearity



Separation of PbWO4 :1%Mo signals into S, Č components

From:

NIM A604 (2009) 512

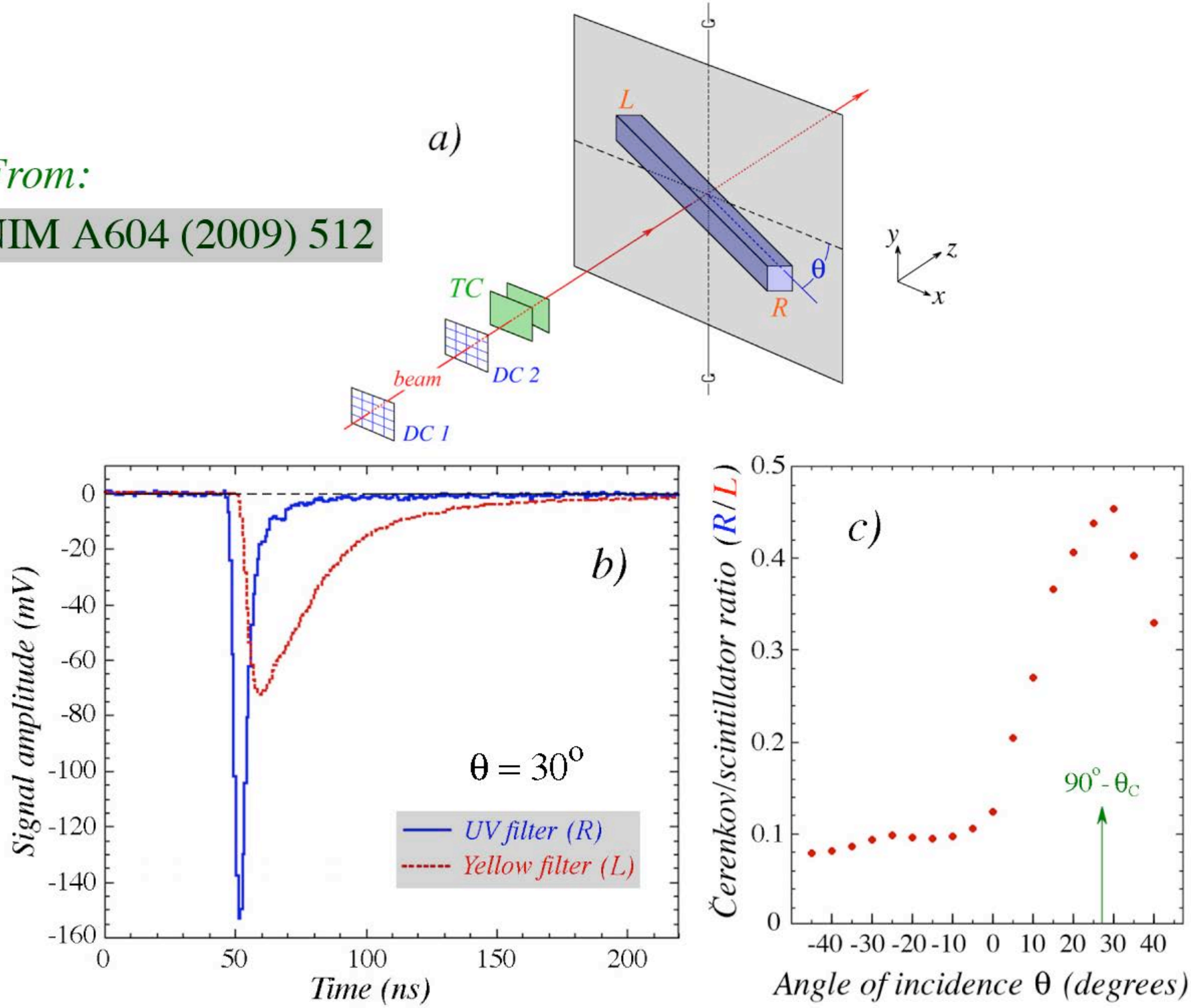
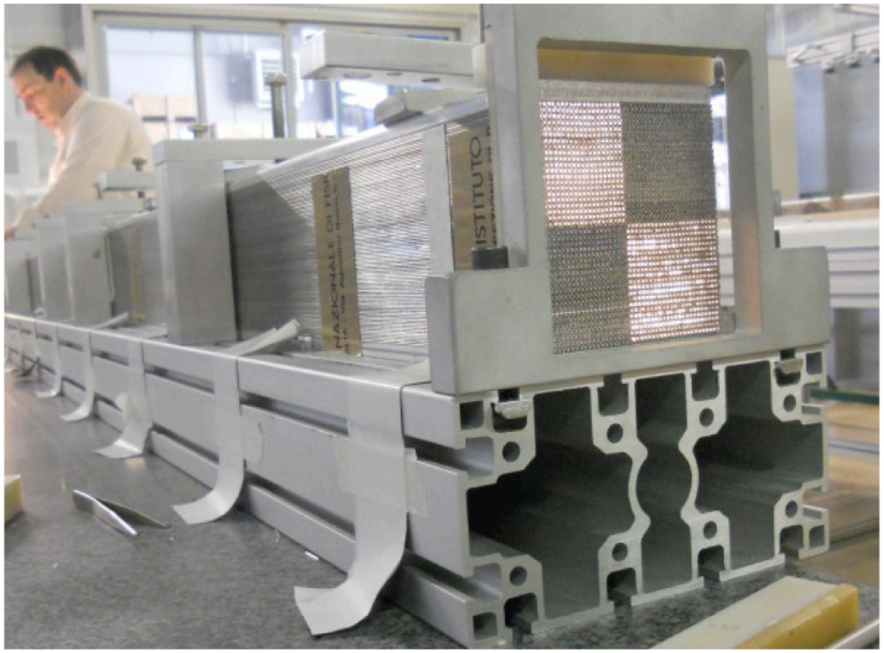
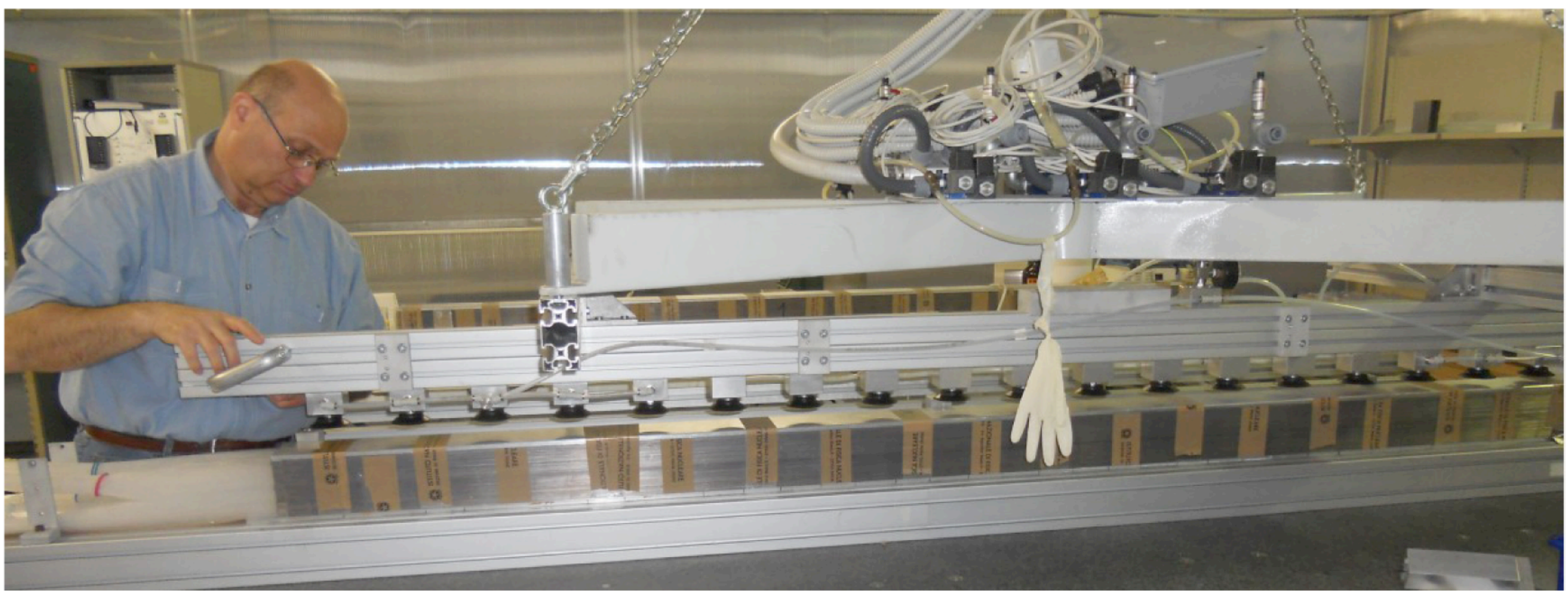


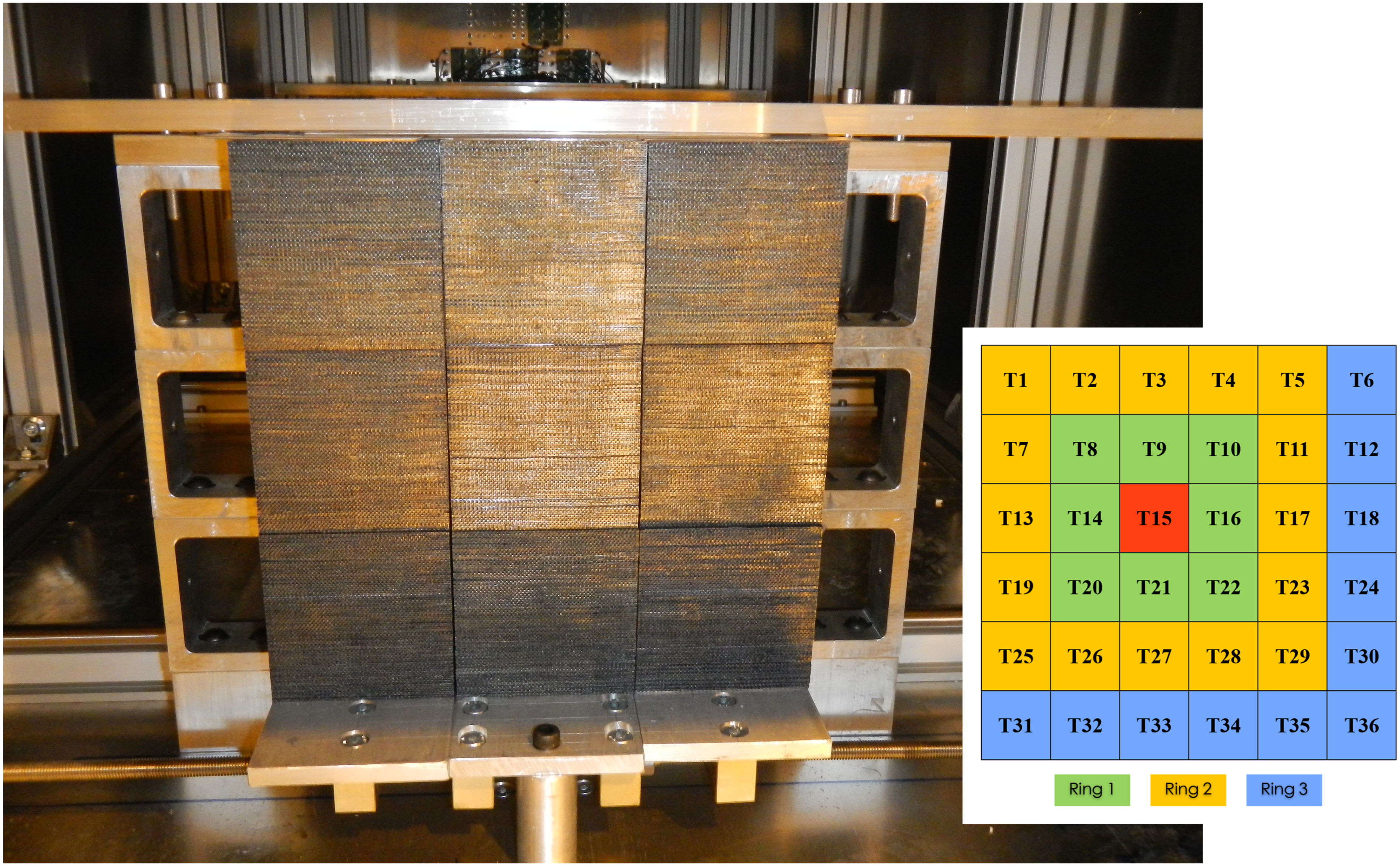
Figure 3: Unraveling of the signals from a Mo-doped $PbWO_4$ crystal into Čerenkov and scintillation components. The experimental setup is shown in diagram *a*. The two sides of the crystal were equipped with a UV filter (side *R*) and a yellow filter (side *L*), respectively. The signals from 50 GeV electrons traversing the crystal are shown in diagram *b*, and the angular dependence of the ratio of these two signals is shown in diagram *c* .

Production of Pb based SuperDREAM modules



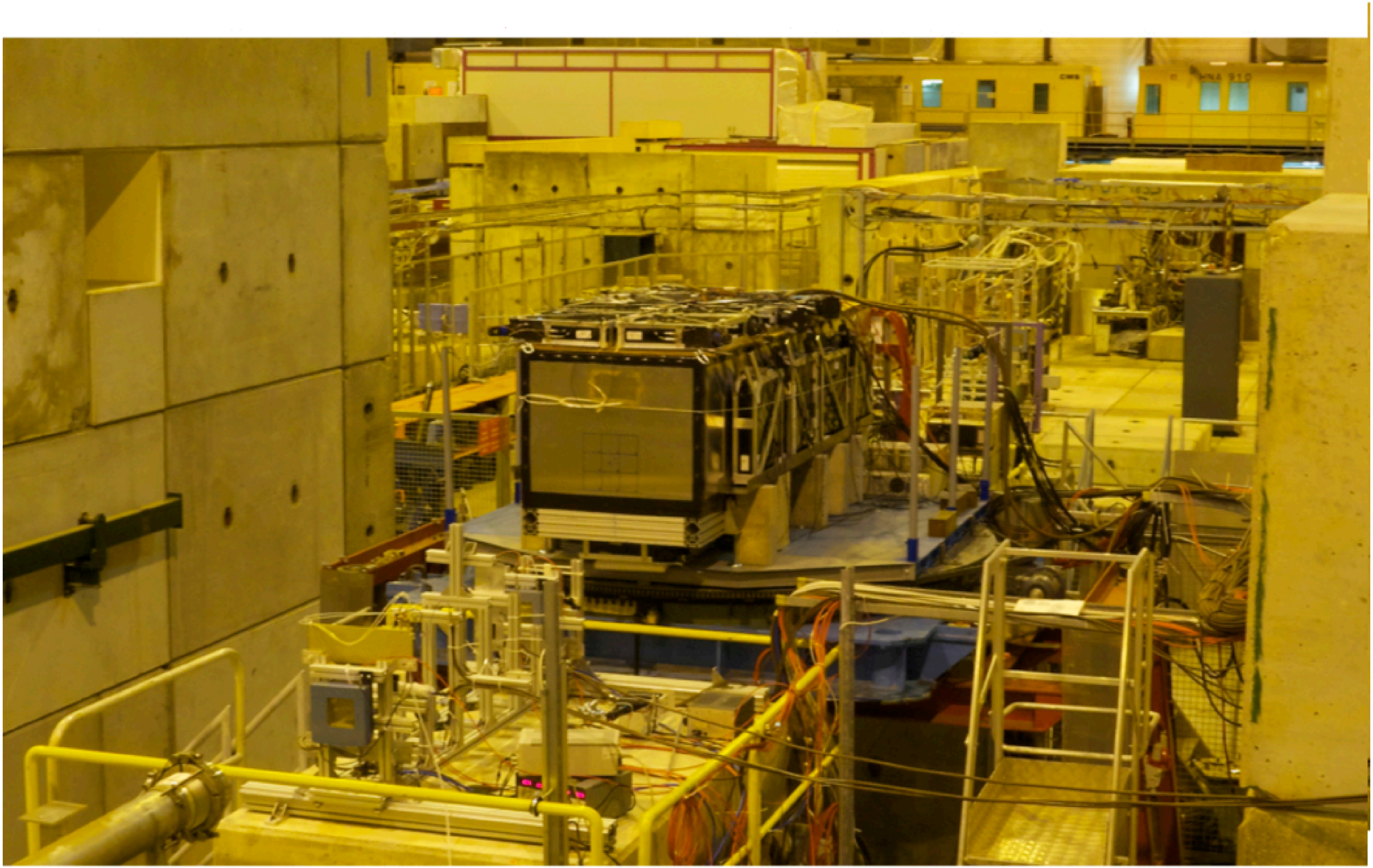


The Pb-fiber calorimeter

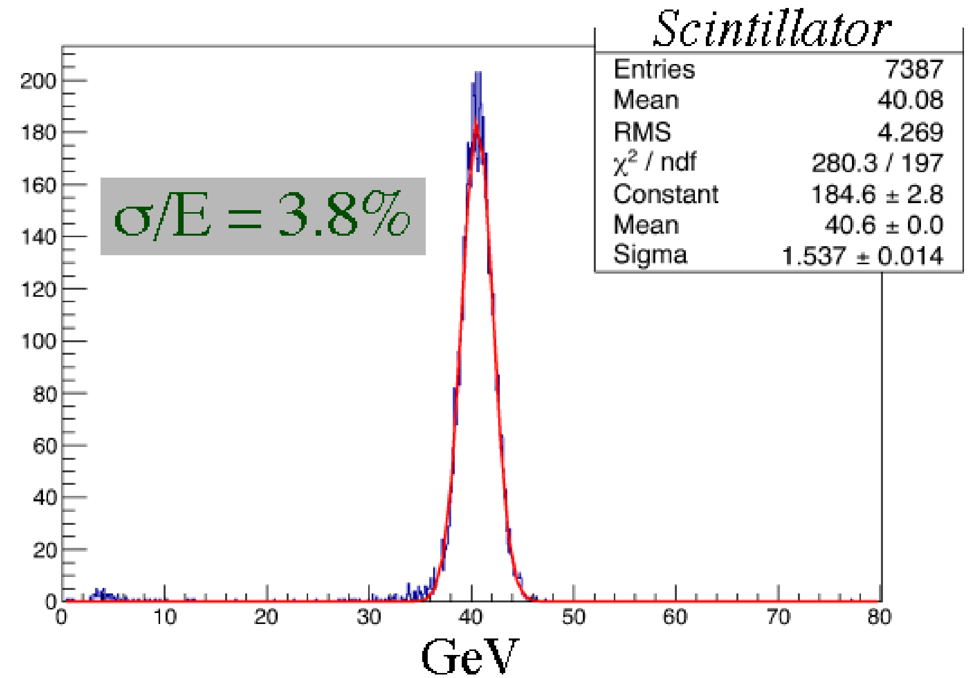


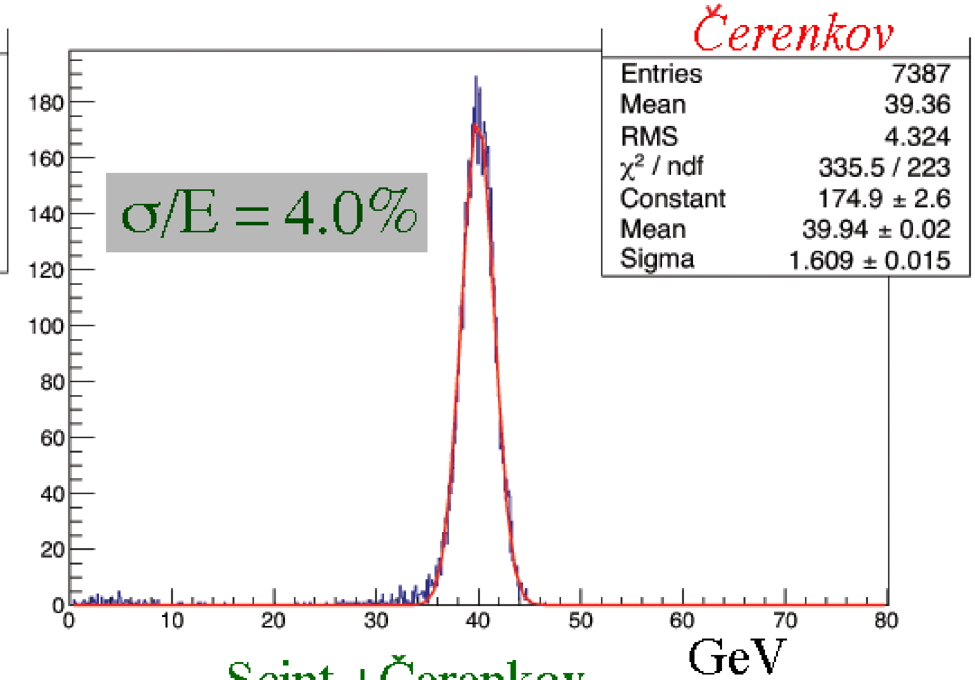
28 x 28 x 250 cm^3 , 1300 kg, 72 electronic channels

The RD52 test area in the H8 beam line

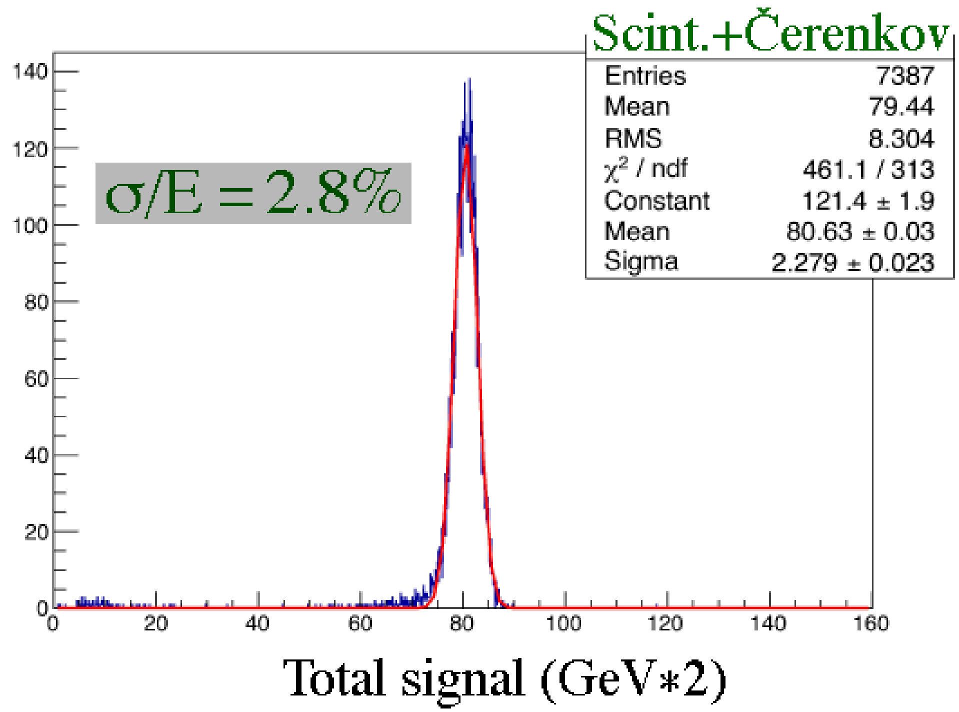


S and Č signals sample the showers independently
Resolution improves by combining





40 GeV electrons
Cu-fiber calorimeter



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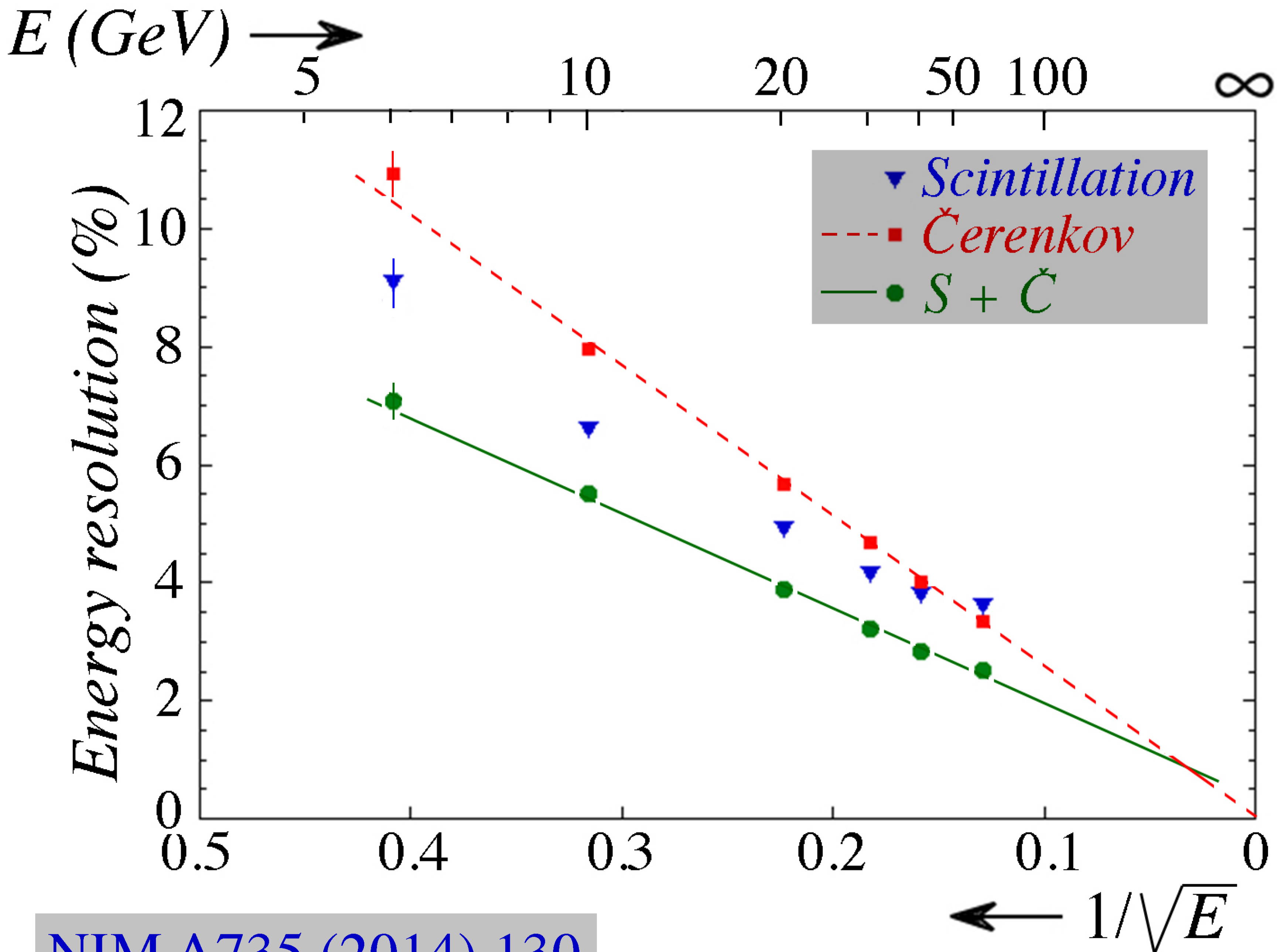
Combining signals from two fiber types improves resolution

→ Stochastic term dominates



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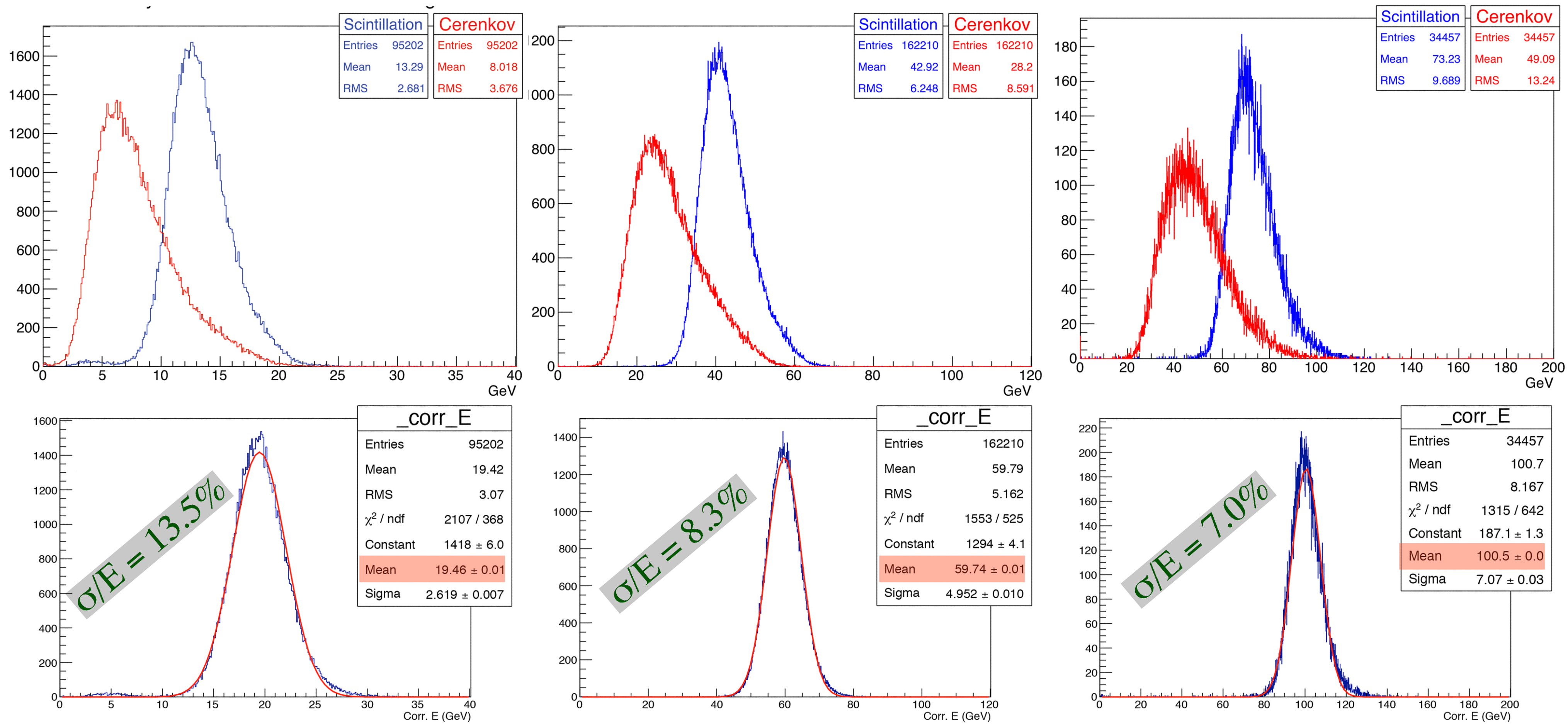
Hadron detection with a dual-readout calorimeter

$$E = \frac{S - \chi C}{1 - \chi} \quad \textit{with} \quad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C} = 0.45$$

20 GeV π^- | 60 GeV π^- | 100 GeV π^-



Calorimetric methods in

Dark Matter searches

The case for dark matter

Galactic rotation curves
+ Orbital velocities of galaxies in clusters
+ Cluster mass determination with gravitational lensing
+ Acoustic fluctuations in Cosmic Microwave Background Radiation
+ ....

indicate that there is ~5 times as much mass in the form of non-luminous (dark) matter as in the form of luminous (baryonic) matter

The nature of this dark matter is unknown.
Gravitationally bound → non-relativistic WIMPs are candidates (lightest SUSY particle, Kaluza-Klein particle, relic neutrinos,....)

Searches for WIMPs:
Direct: Measure nuclear recoil of collision with DM particle
Indirect: Look for decay or annihilation products from regions where large numbers of DM particles congregate (center of Sun, center of galaxy, dwarf galaxies)

Direct detection of WIMPs
through elastic scattering with detector nuclei

$$m_{det}\, v_{det} = M_{wimp}\, V_{wimp}$$

Assume $M_{wimp} \sim m_{det}$ *(50 - 150 proton masses in practice)*

$\longrightarrow$ $v_{det} \sim V_{wimp} \sim$ *600 km/s (escape velocity galaxy)*

The kinetic energy of the recoil nucleus is thus $1/2\, m_{det}\, v_{det}^2$

$$\sim 1/2 \times 100 \times 1.67\ 10^{-27} \times (6.\ 10^5)^2 = 3\ 10^{-14}\ J$$

that is 190 keV
(for $M_{wimp} = 100\ m_p$*)*

It is NOT EASY to detect particles with such small kinetic energies

Calorimetric detection of WIMPs through nuclear recoil

Calorimeters operating close to absolute zero temperature (~ 10 mK)

The material is superconducting ⟶ *target ≡ detector (very practical)*

A small local increase in temperature may make it normally conducting, causing a dramatic increase in the electric resistance

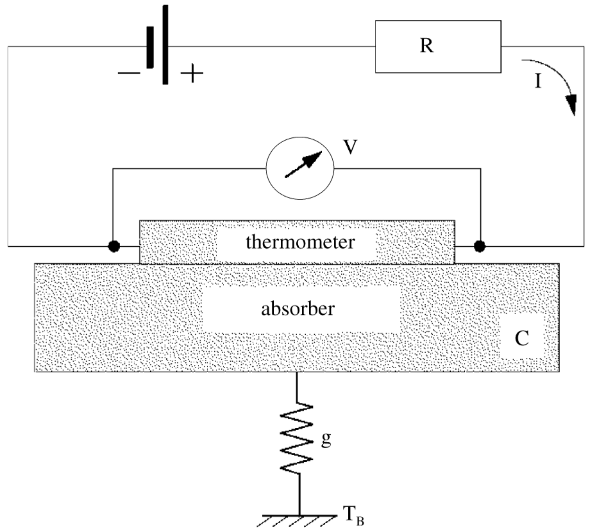
This is the operating principle of some of these "cryogenic calorimeters"

Collision WIMP-nucleus sets up vibrations in crystal (phonons)

These phonons travel to the surface and transfer their energy to Cooper pairs of electrons in the superconducting sensors, which increases T by a tiny little bit, but changes the electrical resistance by a lot.

The current flowing through the sensor changes dramatically and the current change can be transformed into an electric pulse (Transition Edge Sensors).

The principle of a cryogenic calorimeter



Several large-scale experiments are based on this principle, e.g.:
CDMS (Minnesota, USA), EDELWEISS (Modane, F.), CRESST (Gran Sasso)

Direct detection of recoil from WIMP-nucleon scattering

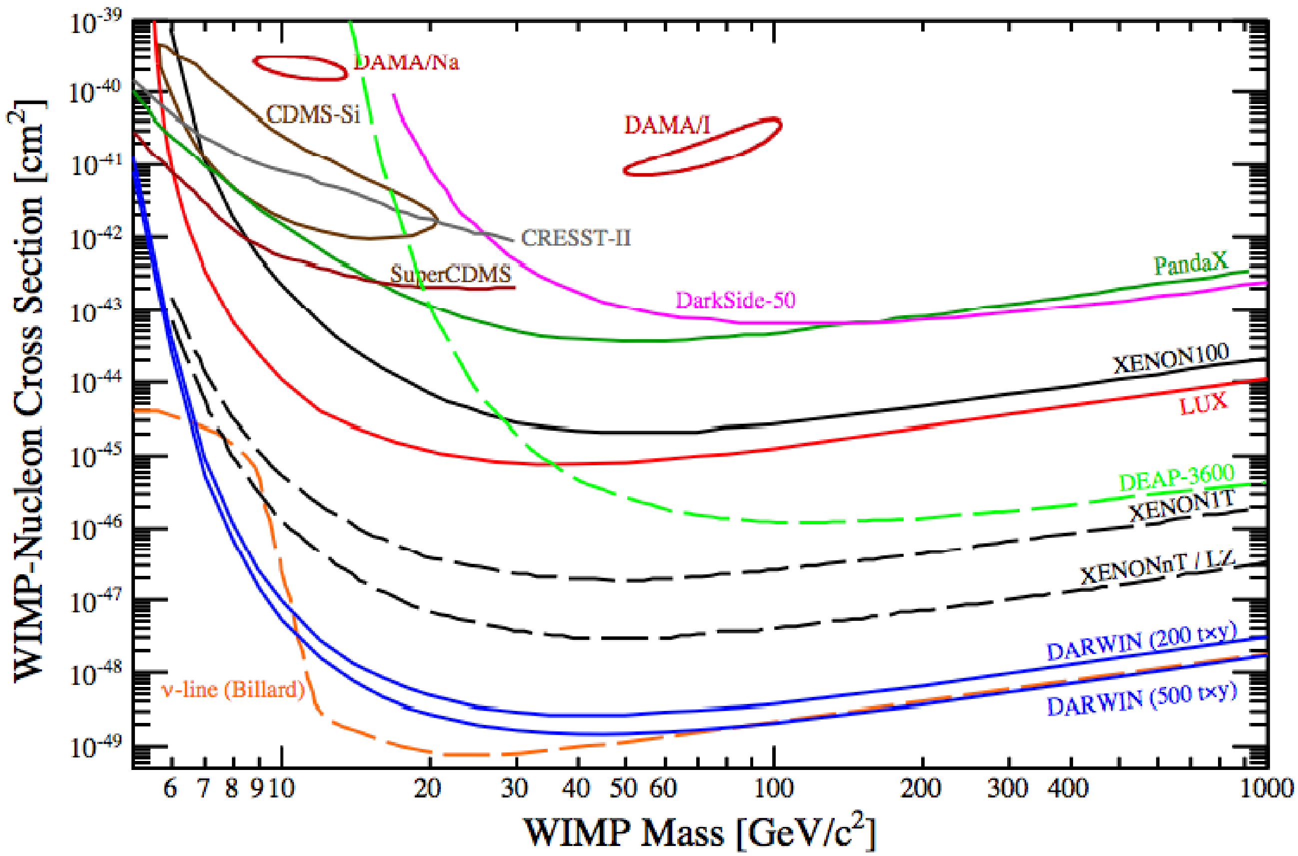


Figure 2 Spin-independent WIMP-nucleon scattering results: Existing upper limits from the CRESST-II [38], SuperCDMS [40], PandaX [50], DarkSide-50 [51], XENON100 [42], and LUX [41] experiments, along with projections for DEAP3600 [44], XENON1T [45], XENONnT [47], LZ [46], and DARWIN [49] are shown. DARWIN is designed to probe the entire parameter region for WIMP masses above ~6 GeV/c^2, until the neutrino background (ν-line) will start to dominate the recoil spectrum.

Indirect WIMP search

Excess of e^+ interpreted as the result of Dark Matter annihilation

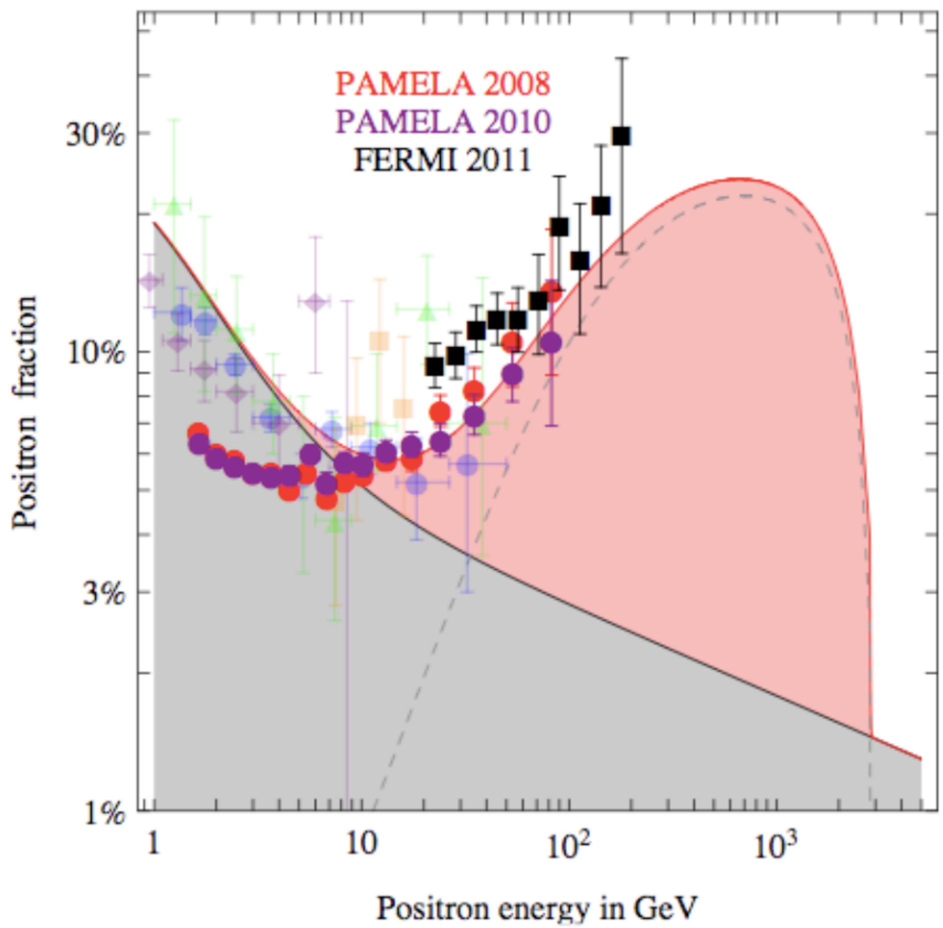


Figure 2. Figure and caption by M. Cirelli [12]: the positron fraction of charged cosmic ray data interpreted in terms of Dark Matter annihilations: the flux from the best fit DM candidate (a 3 TeV DM particle annihilating into $\tau^+\tau^-$ with a cross section of $2 \cdot 10^{22}$ cm^3s^{-1}) is the lower dashed line and is summed to the supposed background (solid black), giving the pink flux which fits the data.

Flyby anomalies

6 satellites have passed close the Earth on their way to the outer regions of the solar system:
Cassini, Rosetta, NEAR, Galileo I/II, MESSENGER
There is a small, unexplained change in the velocity in this process (~10^{-6})

One possible explanation is based on the (drag) effects of a dark matter halo surrounding the Earth

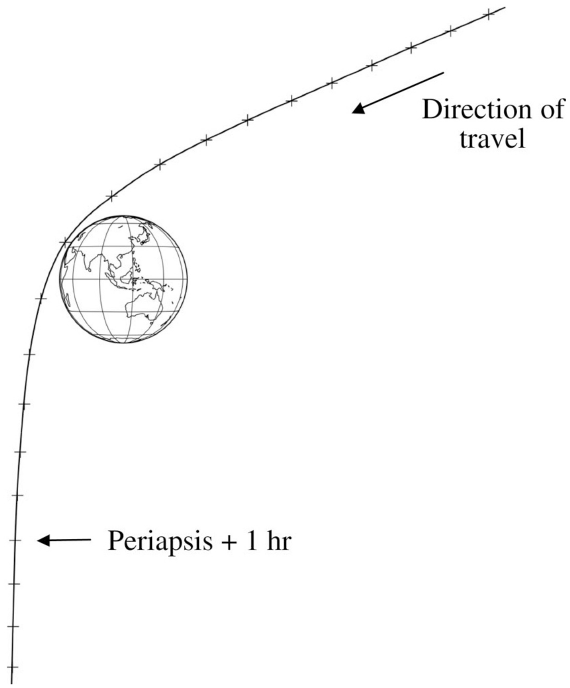


FIG. 1. Equatorial view of the NEAR flyby, the most asymmetrical flyby with respect to the Equator and the flyby with the largest energy change. The extent of the bending in the Earth's gravitational field, the geometry of the flyby and its time scale are illustrated. The tick marks are at 10-min intervals as measured from closest approach.

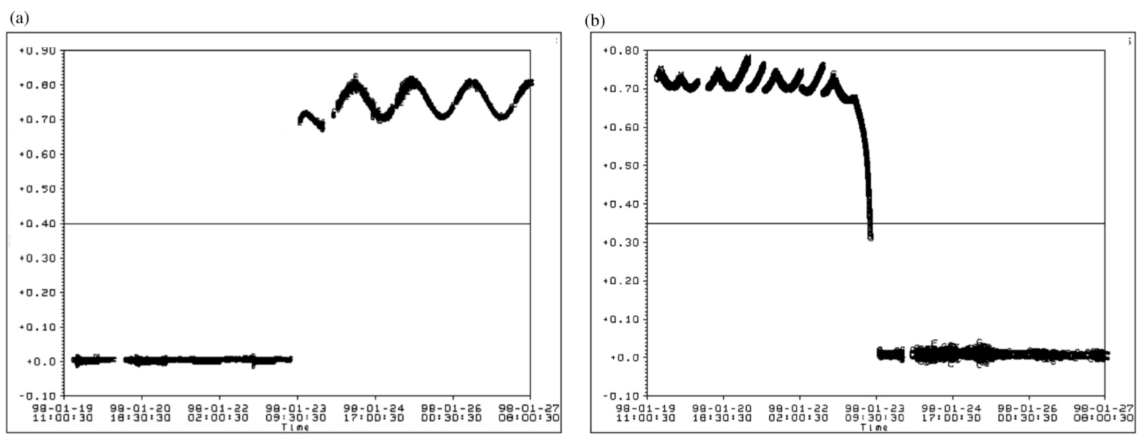


FIG. 2. *X*-band Doppler residuals in the sense observed Doppler frequency shift minus calculated Doppler frequency shift in units of Hz [10] from separately fitting (a) the pre- and (b) the postencounter data for the NEAR flyby. The residuals cluster on opposite sides of the respective fits and demonstrate the impossibility of fitting both pre- and postencounter data with a single fit. The difference in Doppler frequency shift is approximately 0.760 Hz, consistent with an increase of 13.5 mm/s in the V_∞ needed to fit both sides of the encounter.

Spacecraft calorimetry as a test of the dark matter scattering model for flyby anomalies

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Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA.

In previous papers we have shown that scattering of spacecraft nucleons from dark matter gravitationally bound to the earth gives a possible explanation of the flyby velocity anomalies. In addition to flyby velocity changes arising from the average over the scattering cross section of the collision-induced nucleon velocity change, there will be spacecraft temperature increases arising from the mean squared fluctuation of the collision-induced velocity change. We give here a quantitative treatment of this effect, and suggest that careful calorimetry on spacecraft traversing the region below 70,000 km where the flyby velocity changes take place could verify, or at a minimum place significant constraints, on the dark matter scattering model.

From: arXiv:0910.1564 [physics.space-ph]

Conclusions

- *Calorimetry is a very useful technique for measuring what is going on in a wide variety of physics processes*
- *The energy released or transferred in these processes varies by more than 20 orders of magnitude in the examples discussed today*
- *This range can be easily increased by many orders of magnitude if we include methods for studying global climate change*
- *This capability has been made possible by exploiting the features made available by our understanding of physics (phonons, Cherenkov photons, Cooper pairs, etc.)*
  This illustrates the fact that improvements in our understanding of nature and the technology needed to achieve these improvements go hand in hand