Some applications of Calorimetry

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- *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.

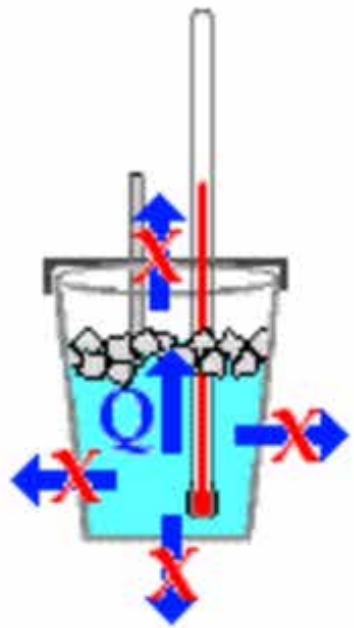
Units:

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

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

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

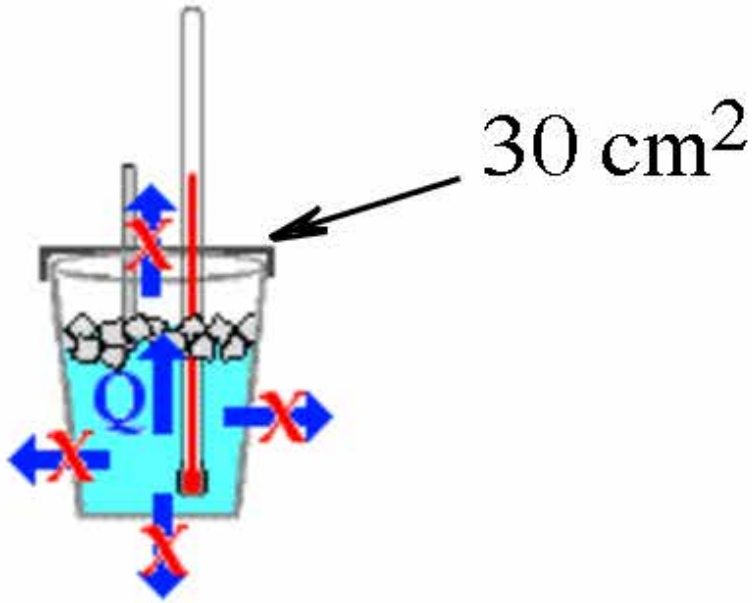
Coffee cup calorimetry



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

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

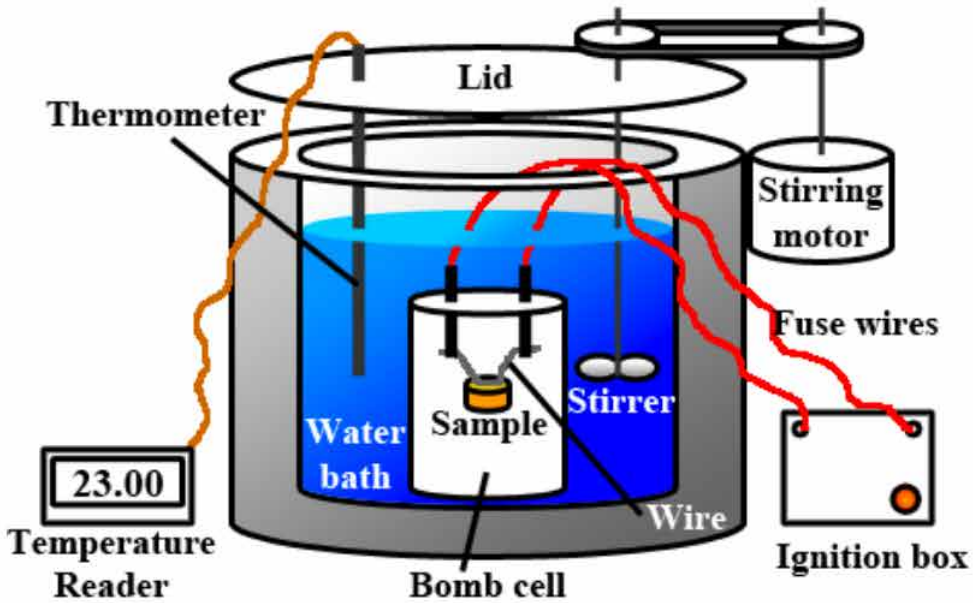
Coffee cup calorimetry (2)



Put coffee cup with 110 g of water @ 11° C in the Sun
After one hour, the temperature has risen to 38° 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

A more sophisticated version of the coffee cup calorimeter



Used to measure energy production in chemical reactions

(e.g. reactions used in conventional explosives)

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.

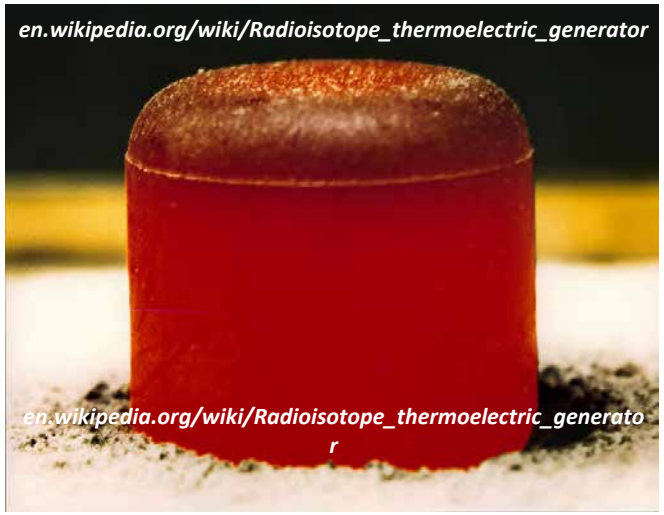
- Calorimetry assays are independent of sample geometry, nuclear material distribution in the sample, and matrix material composition
- Heat standards are directly traceable to National Standards and plutonium standards are not needed
- The assay is comparable to chemical assay in precision and accuracy 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

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



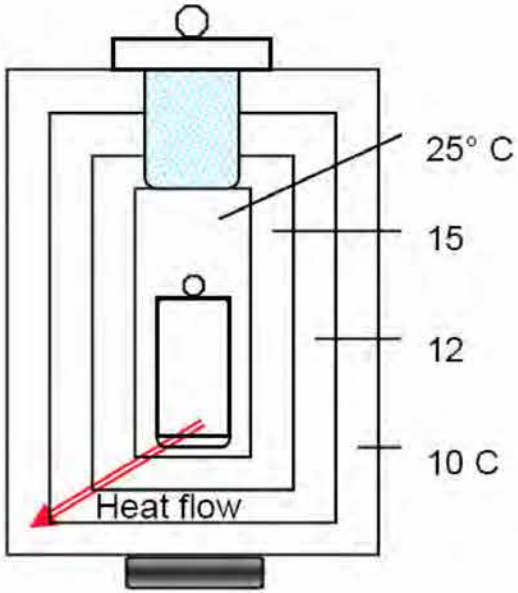
This is a photo of a ^{238}Pu fuel pellet of the type used in the NASA Cassini and Galileo probes; it produced 62 W of heat

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)

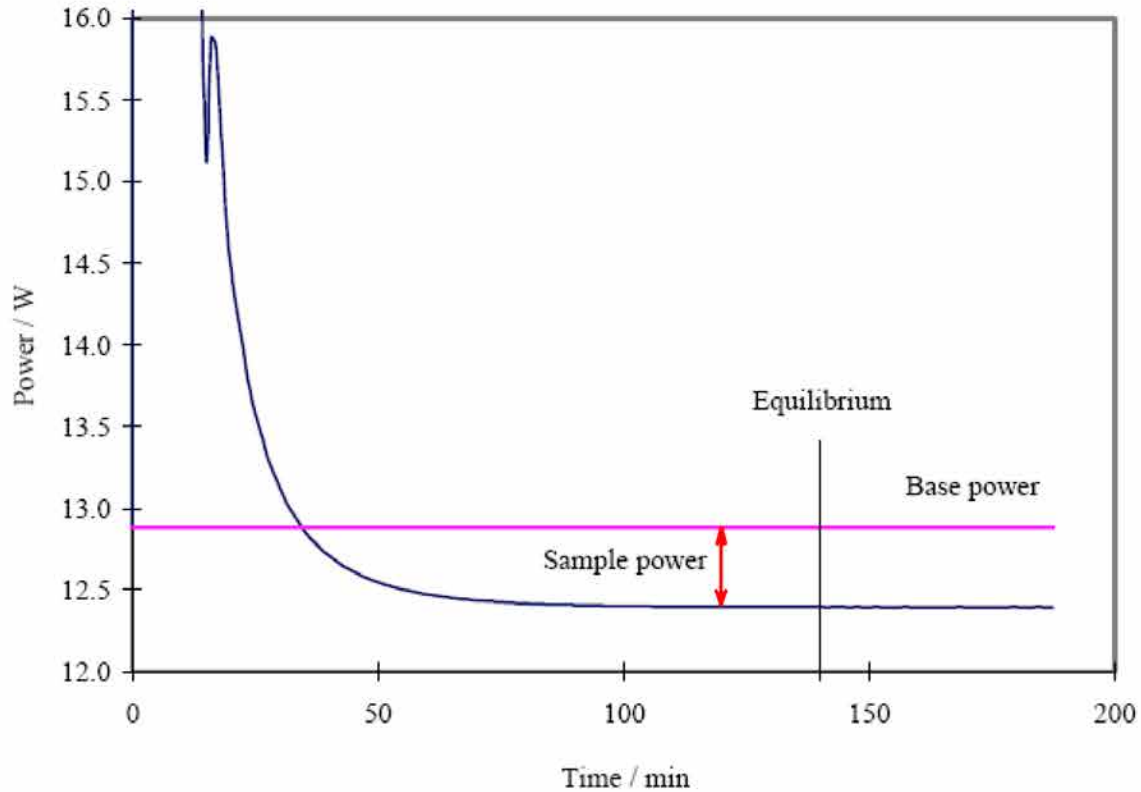
The Passive Gamma-Ray Signatures

Isotope	Energy (keV)	Activity (γ/g-s)	*Half life*
^{238}Pu	152.7	5.90×10^{6}	88 yr
	766.4	1.387×10^{5}	
^{239}Pu	129.3	1.436×10^{5}	24000 yr
	413.7	3.416×10^{4}	
^{240}Pu	45.2	3.80×10^{6}	6600 yr
	160.3	3.37×10^{4}	
	642.5	1.044×10^{3}	
^{241}Pu	148.6	7.15×10^{6}	14 yr
	208.0	2.041×10^{7}	
^{241}Am	59.5	4.54×10^{10}	432 yr
	125.3	5.16×10^{6}	

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

Plutonium Air-Flow Calorimeter

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

"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 $\lambda = 1/\tau = ln2/T_{1/2} = 0.693/(24000 \times 3.15\ 10^{7}) = 9.2\ 10^{-13}/s$

- 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 1.8 mW corresponds to 6.6 J/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 0.33 Gy/yr
  This is an order 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

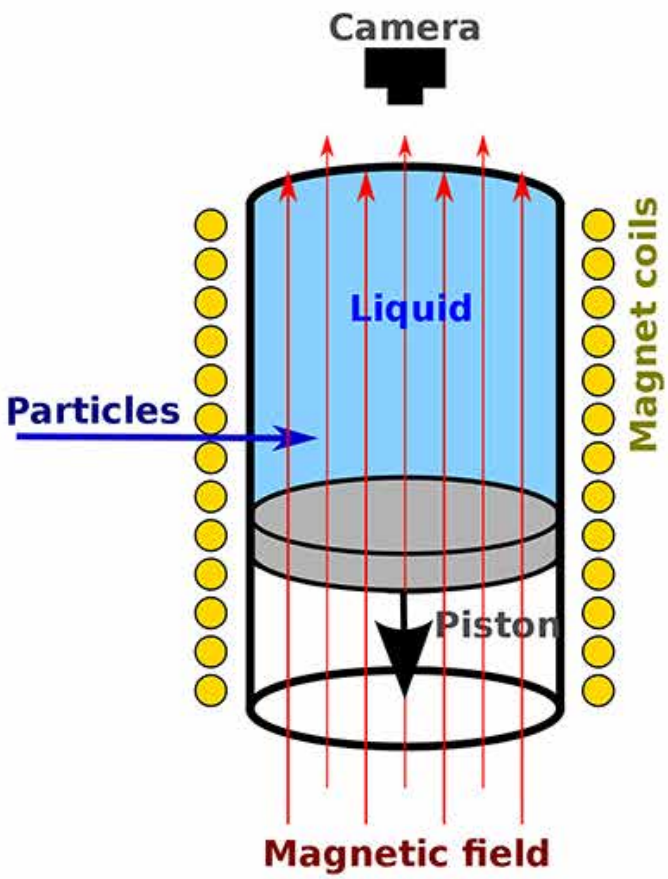
Local thermal effects in a particle detector

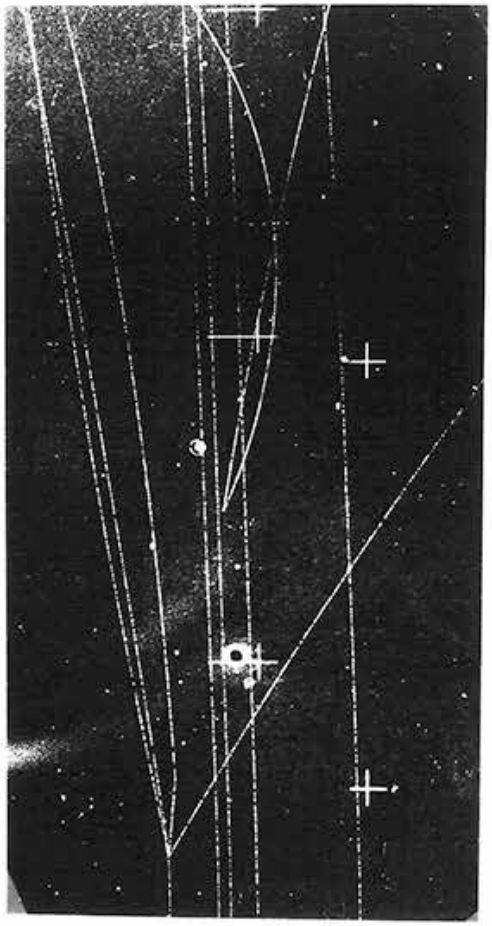
A passing charged particle heats the liquid along its track, causing it to boil. The trajectory of the particles is thus indicated by tracks of gas bubbles in this BUBBLE CHAMBER

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*

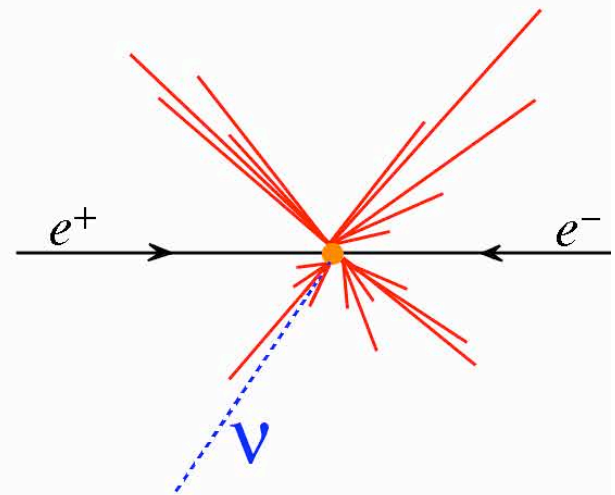
- *The segmentation of the instrumented volume makes it possible to determine the momentum vector of the particles.*

  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.*

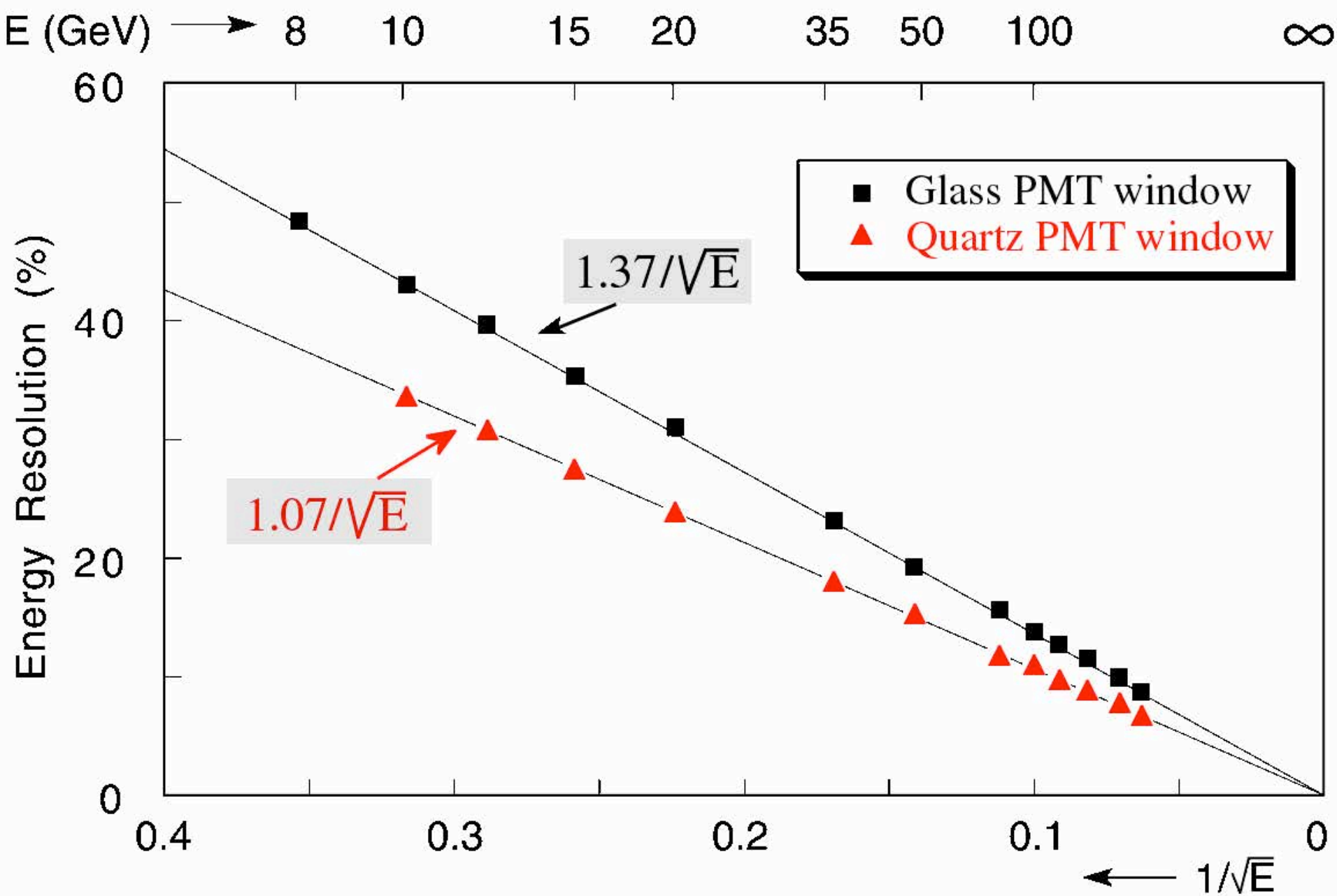
- Obtain information *fast*
  $\longrightarrow$ recognize and select interesting events in real time *(trigger)*

- Performance of calorimeters *improves with energy*
  ($\sim E^{-1/2}$ if statistical processes are the limiting factor)

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

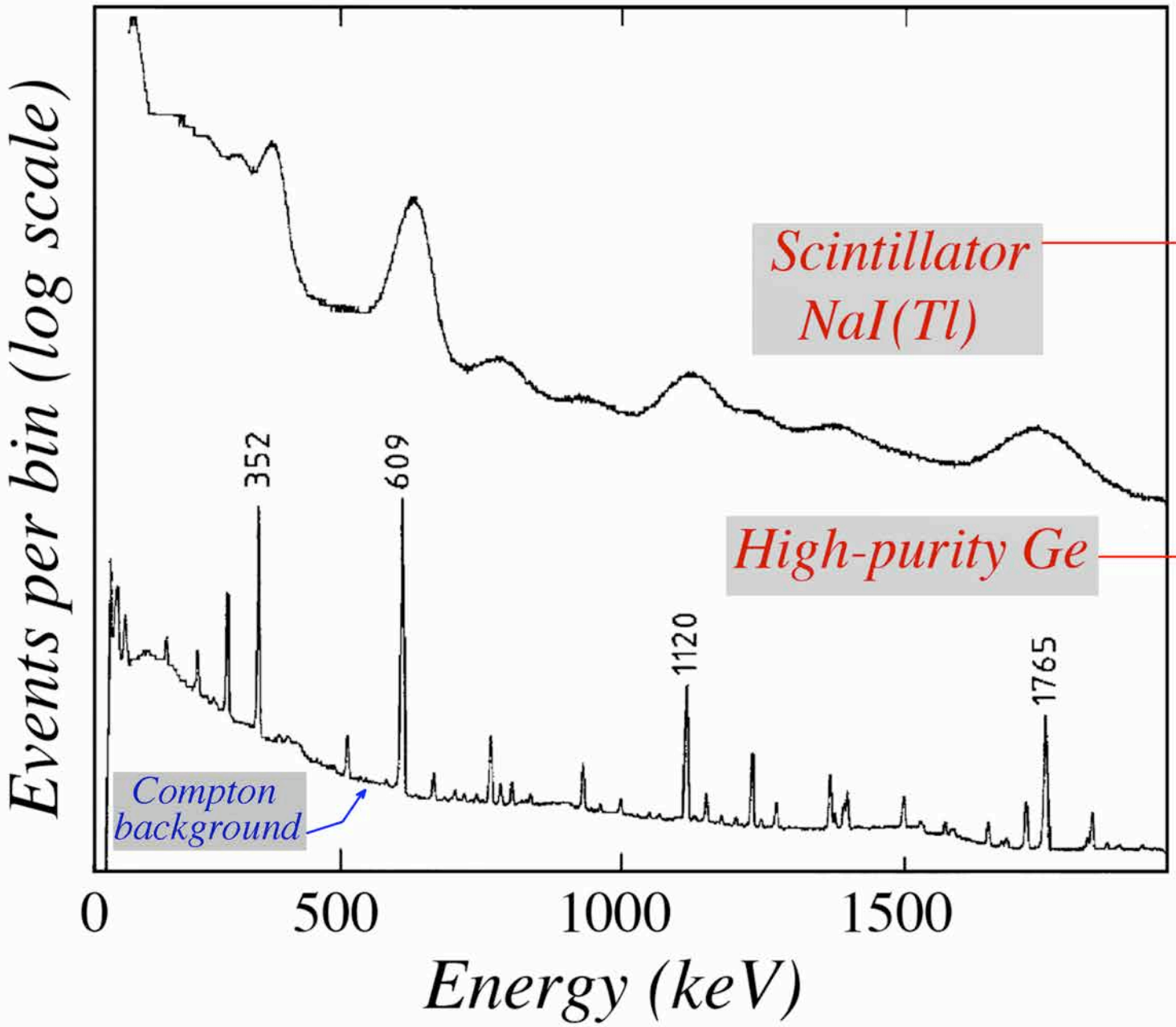
$$\longrightarrow \textit{energy resolution } \frac{\sigma(E)}{E} \propto 1/\sqrt{n} \propto 1/\sqrt{E}$$

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



Nuclear γ ray detectors

Energy resolution dominated by signal quantum fluctuations (?)

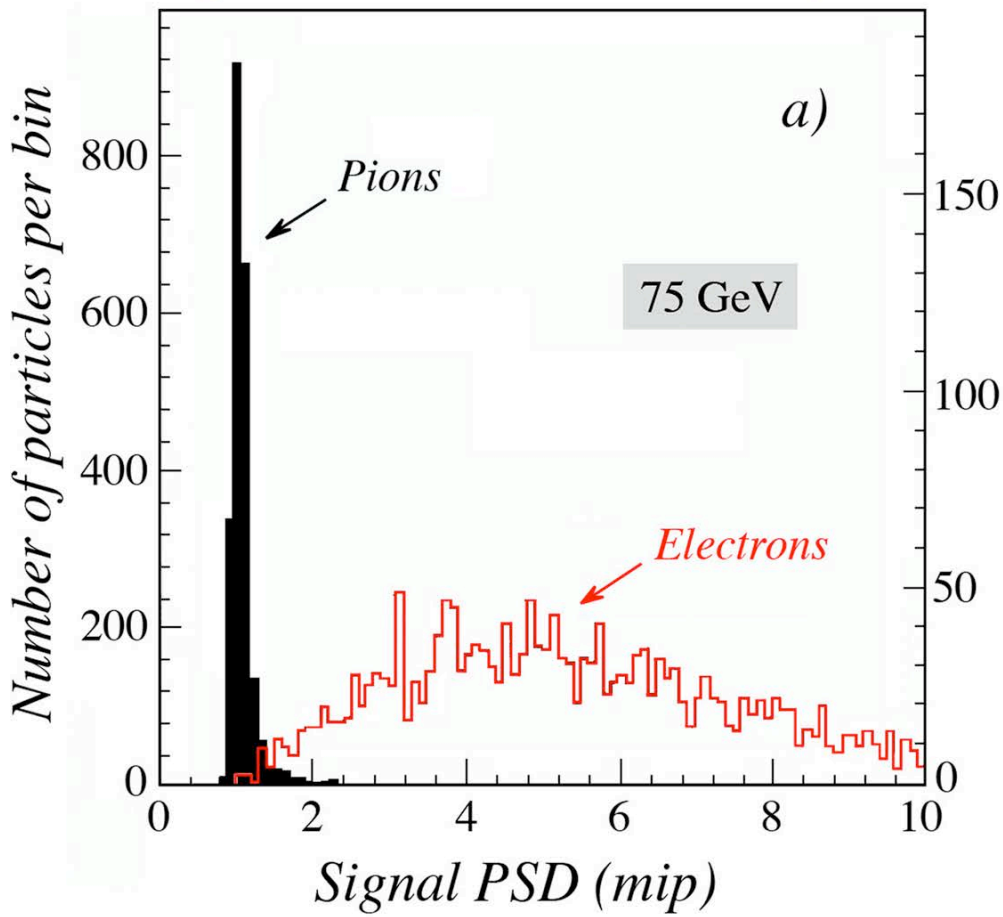


~100 eV per photon
10 000 photons/MeV

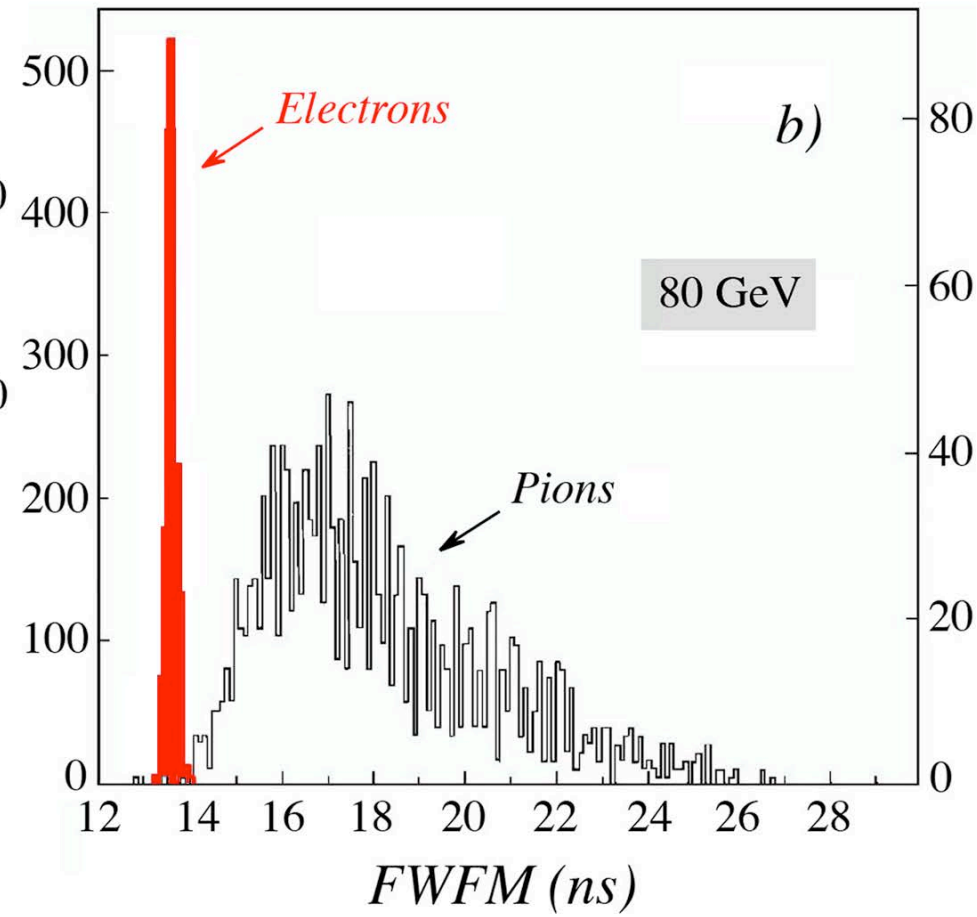
2.9 eV per $e^+ \cdot e^-$ pair
350 000 pairs/MeV
$\sigma/E \sim 0.2\%$

Particle identification with calorimeters

Using shower profile (pre-shower detector)



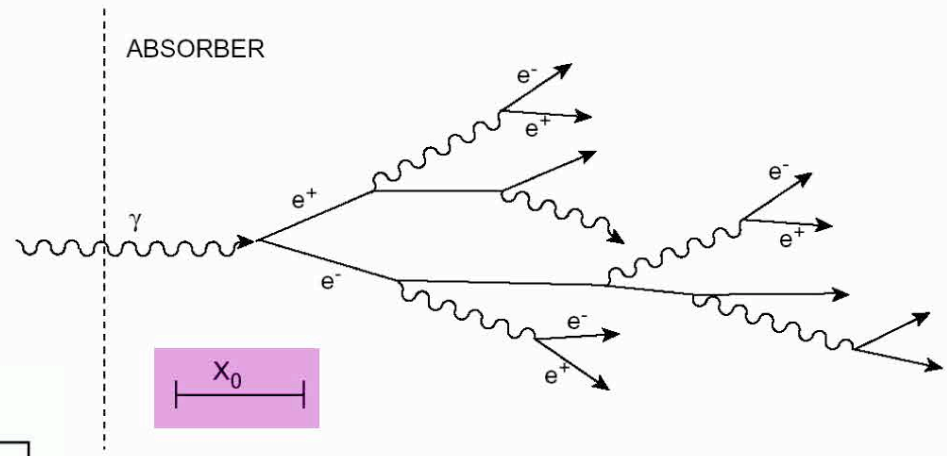
Using time structure of the signals

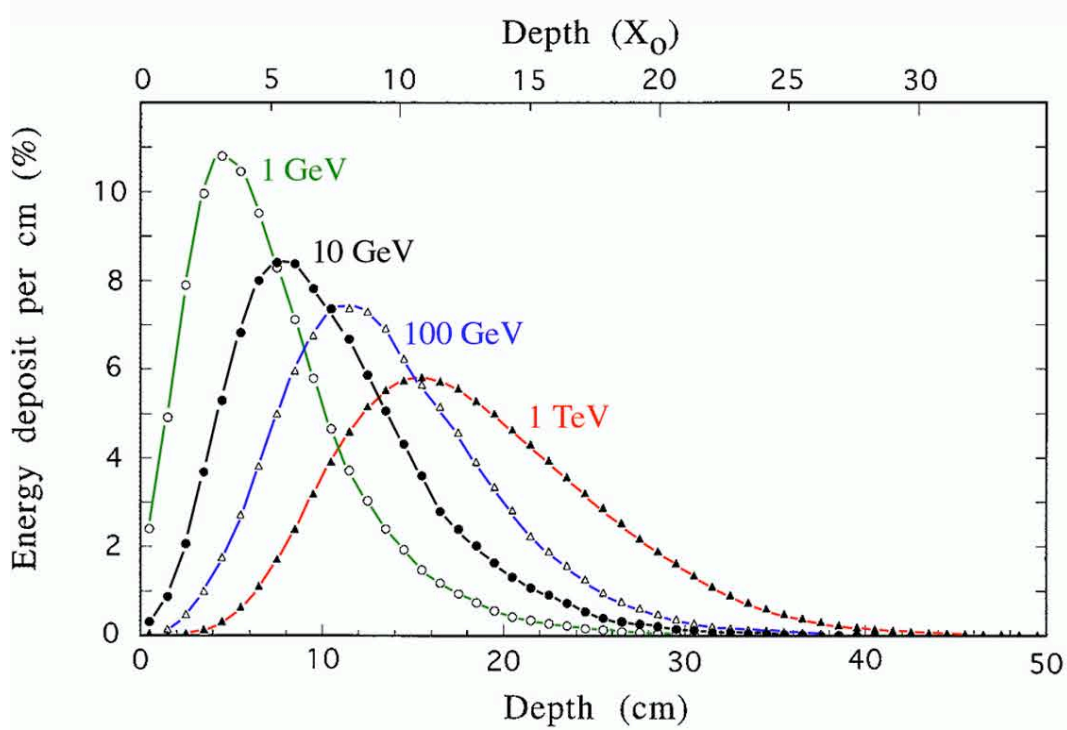


Calorimeters

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)

Calorimetry: Homogeneous calorimeters

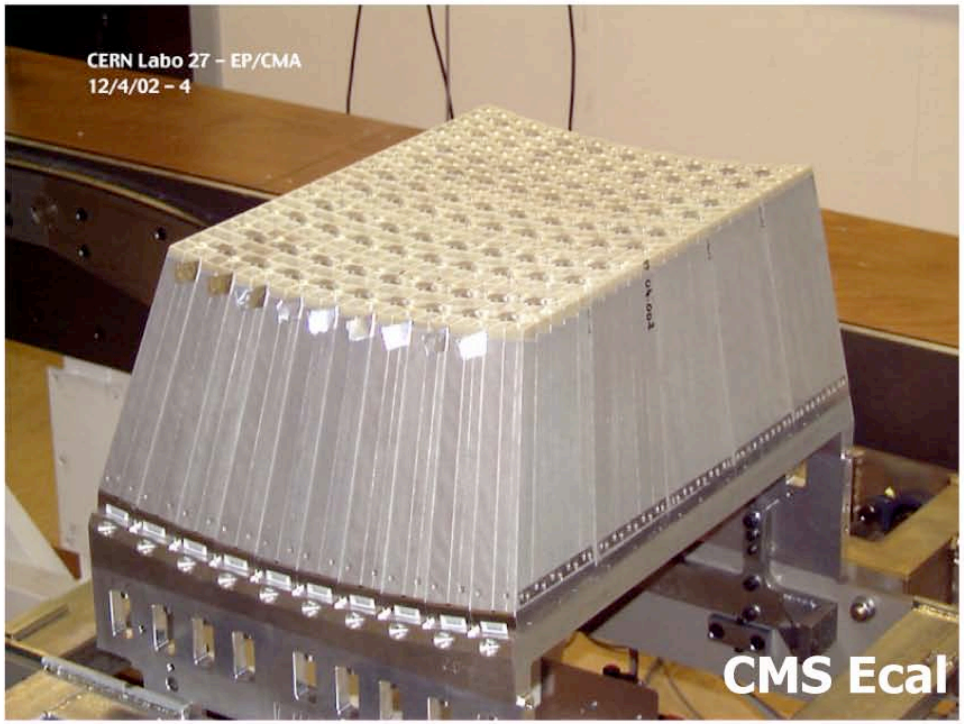
- *High-density crystals used as electromagnetic calorimeters*
  Example: CMS ECAL, $PbWO_4$. Density 8.3 g/cm^3, radiation length 8.9 mm.

- *Very good energy resolution*

- *Very expensive*

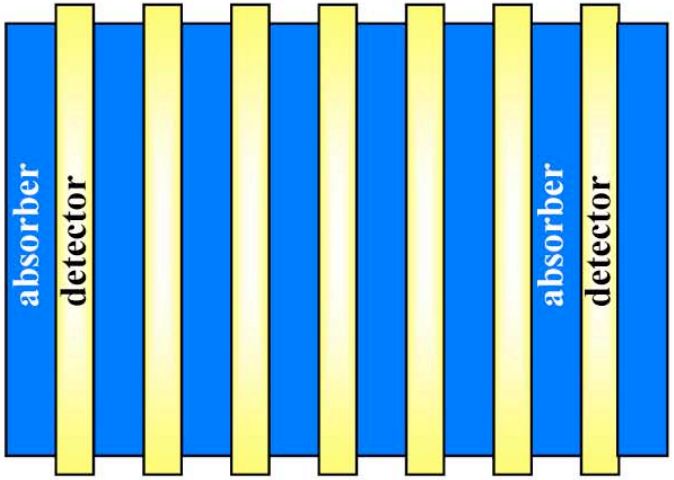
- *Radiation damage a problem*

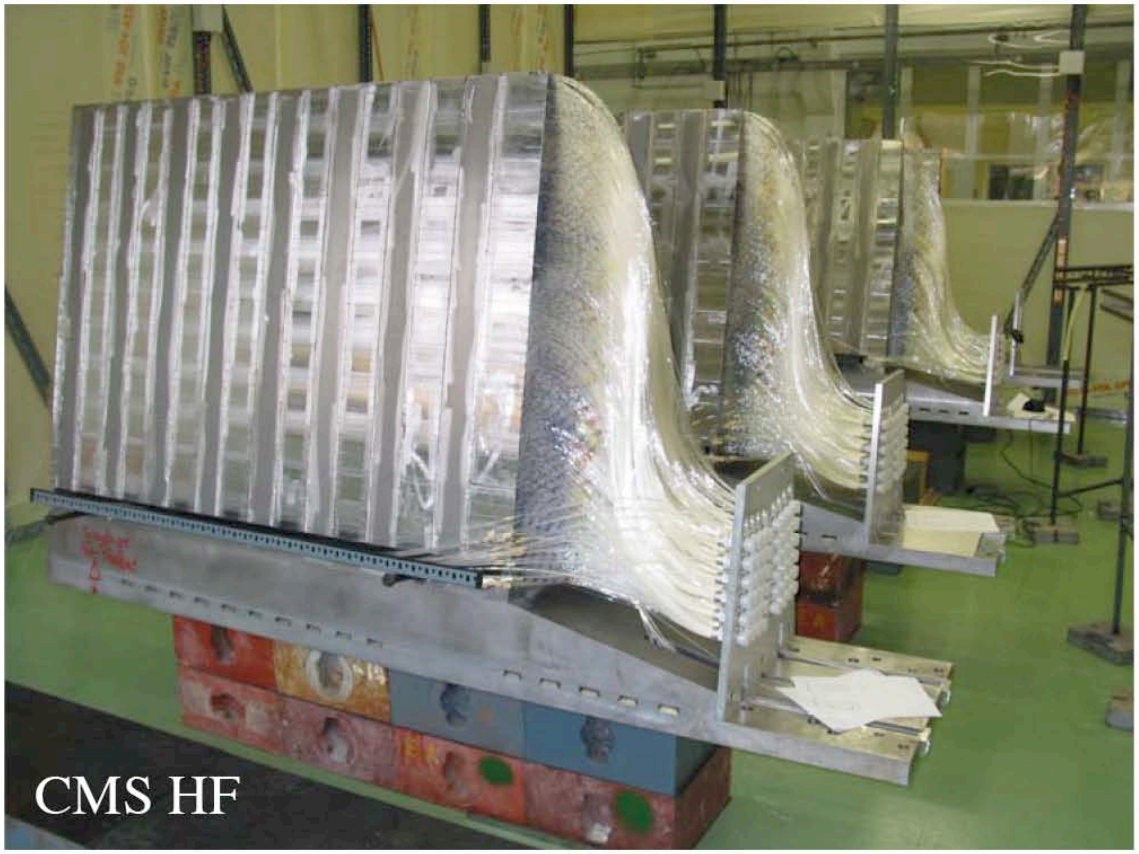
- *Other crystals:*
  NaI(Tl), CsI, BGO, BaF_2



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…*



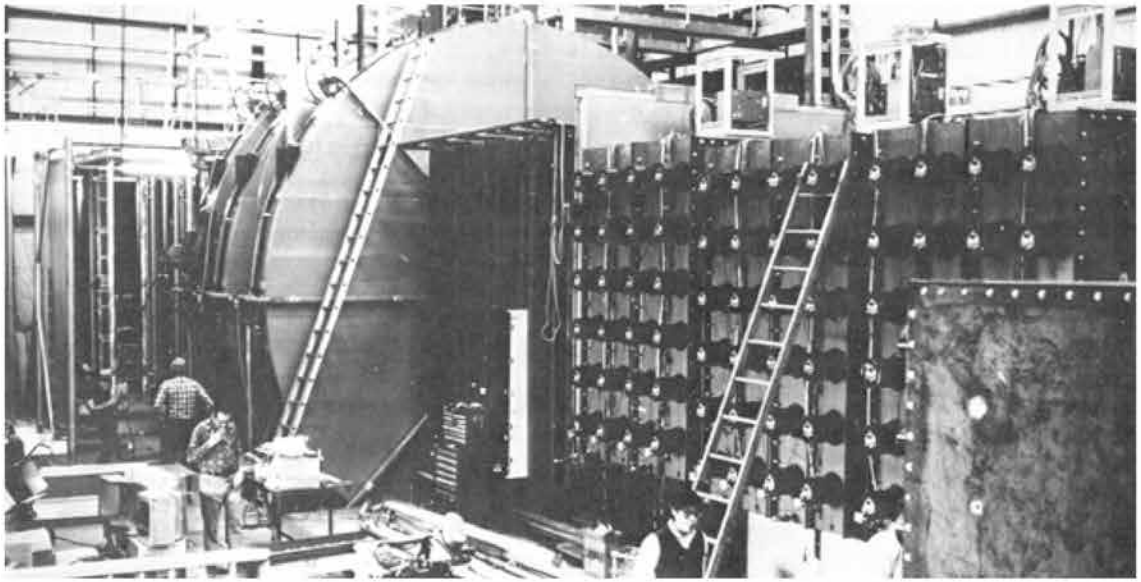


Whereas electromagnetic calorimeters (intended for e,γ detection) are typically very precise and very well understood instruments

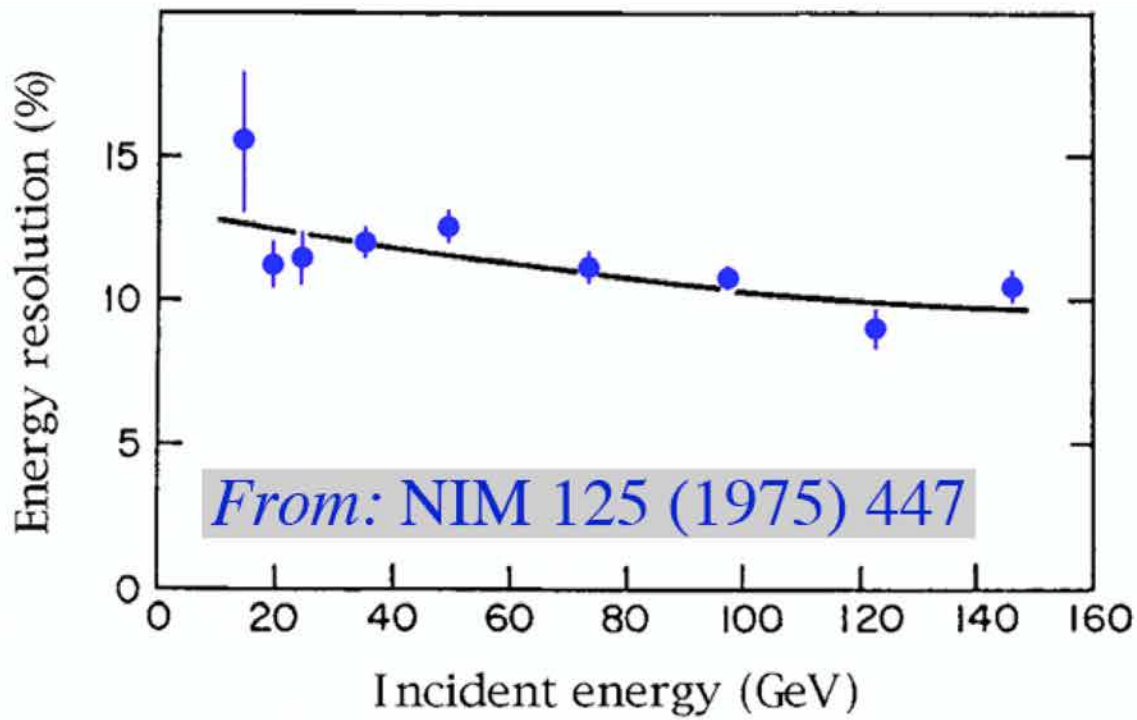
Hadron calorimeters are usually far from ideal

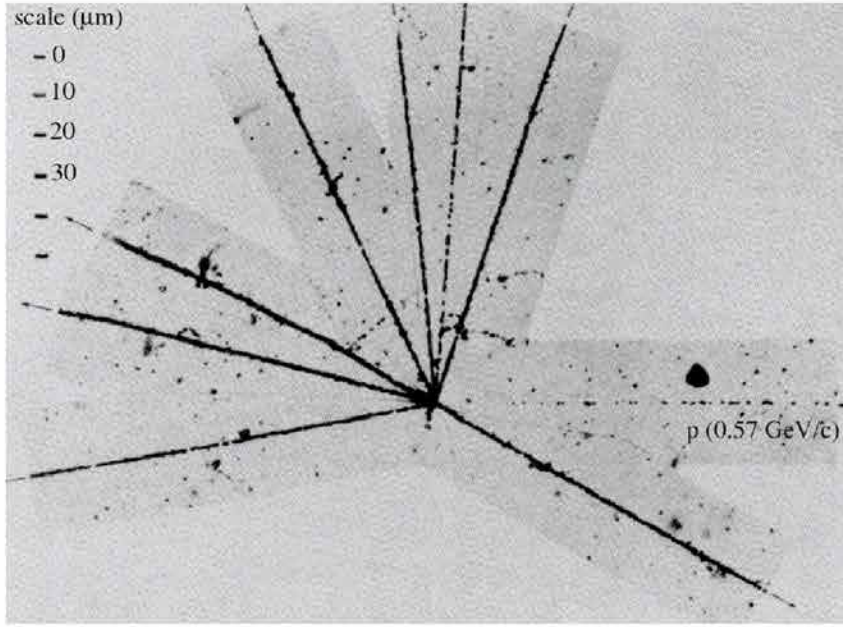
Energy resolution of a homogeneous hadron calorimeter

(60 tonnes of liquid scintillator)



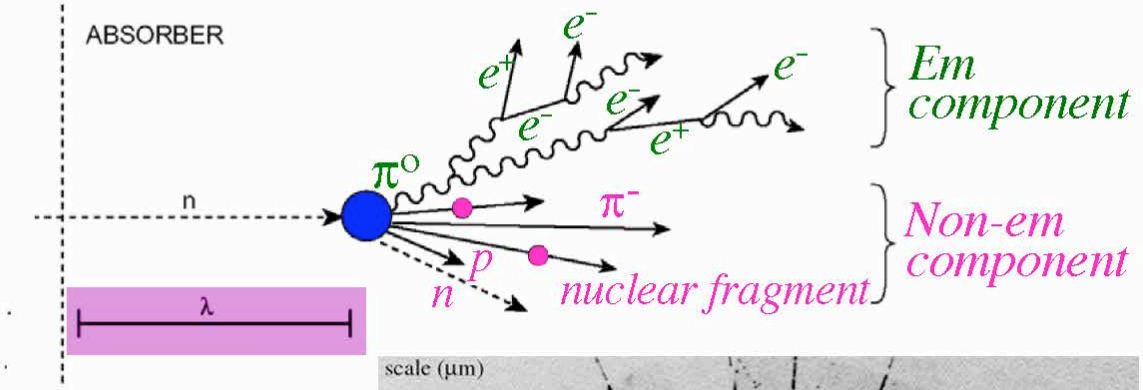
Statistical processes are NOT the limiting factor here. Resolution is limited by fluctuations in invisible energy losses in the non-em shower component, e.g. in nuclear interactions



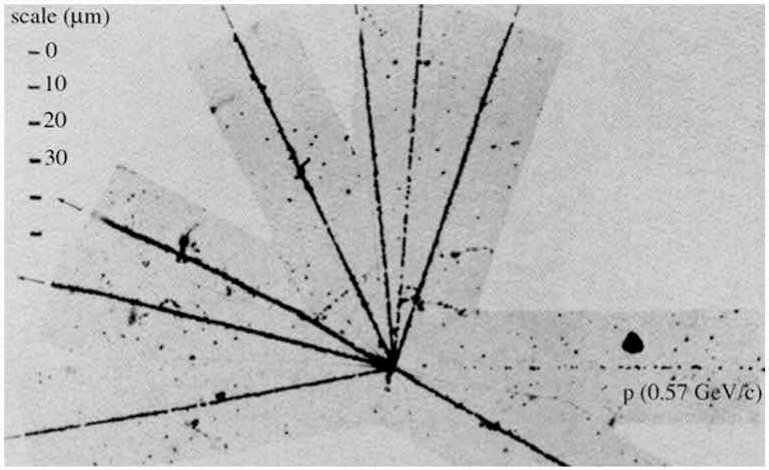


The physics of hadronic shower development

- *A hadronic shower consists of two components*



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

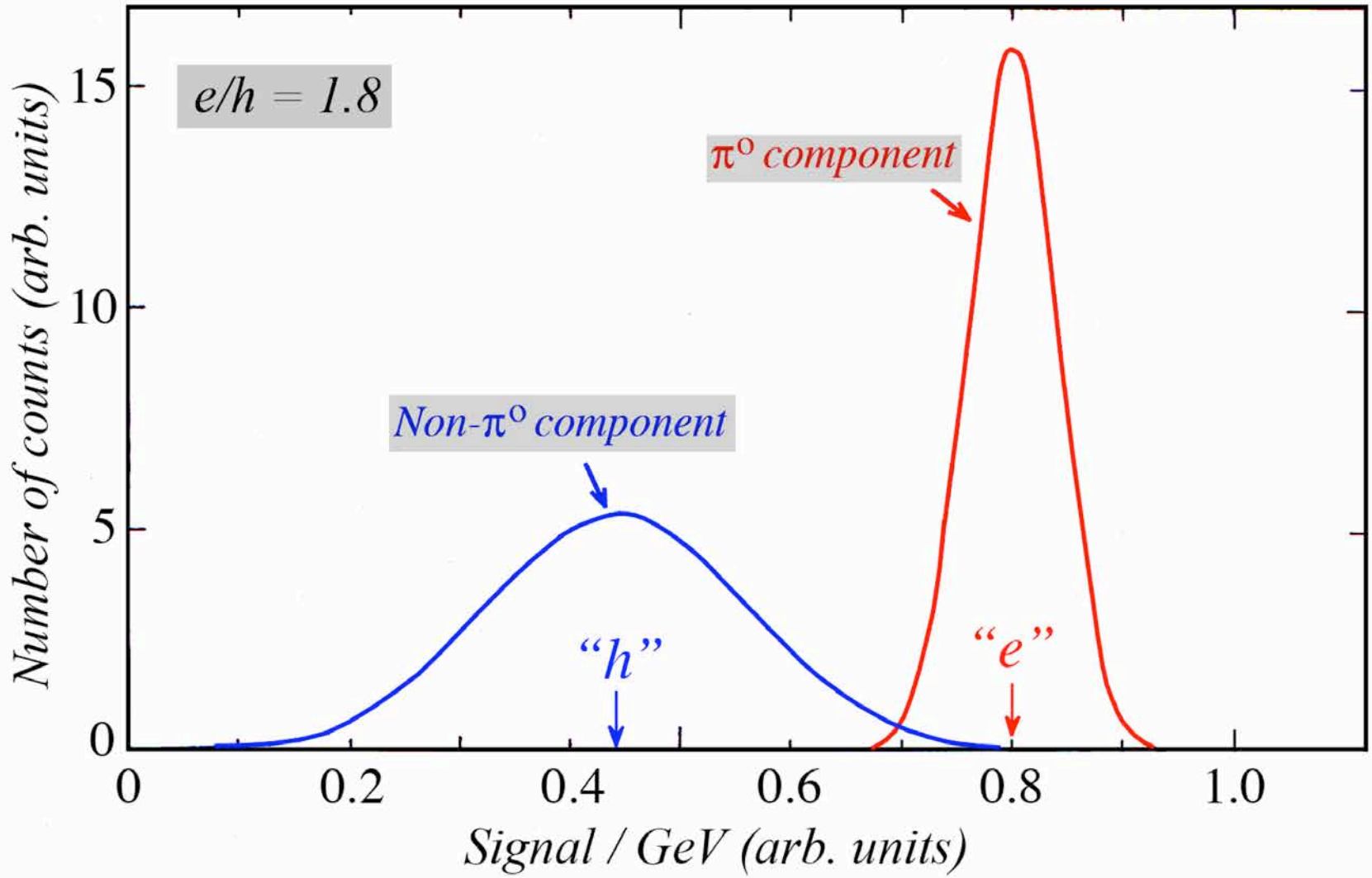


- *Important characteristics for hadron calorimetry:*
  - *Large, non-Gaussian fluctuations in* *energy sharing em/non-em*
  - *Large, non-Gaussian fluctuations in* *"invisible" energy losses*

(e.g. 100 GeV π: energy resolution ZEUS 3.5%, D0 7%)

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

(mainly because of nuclear breakup energy losses in non-π^o component)



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

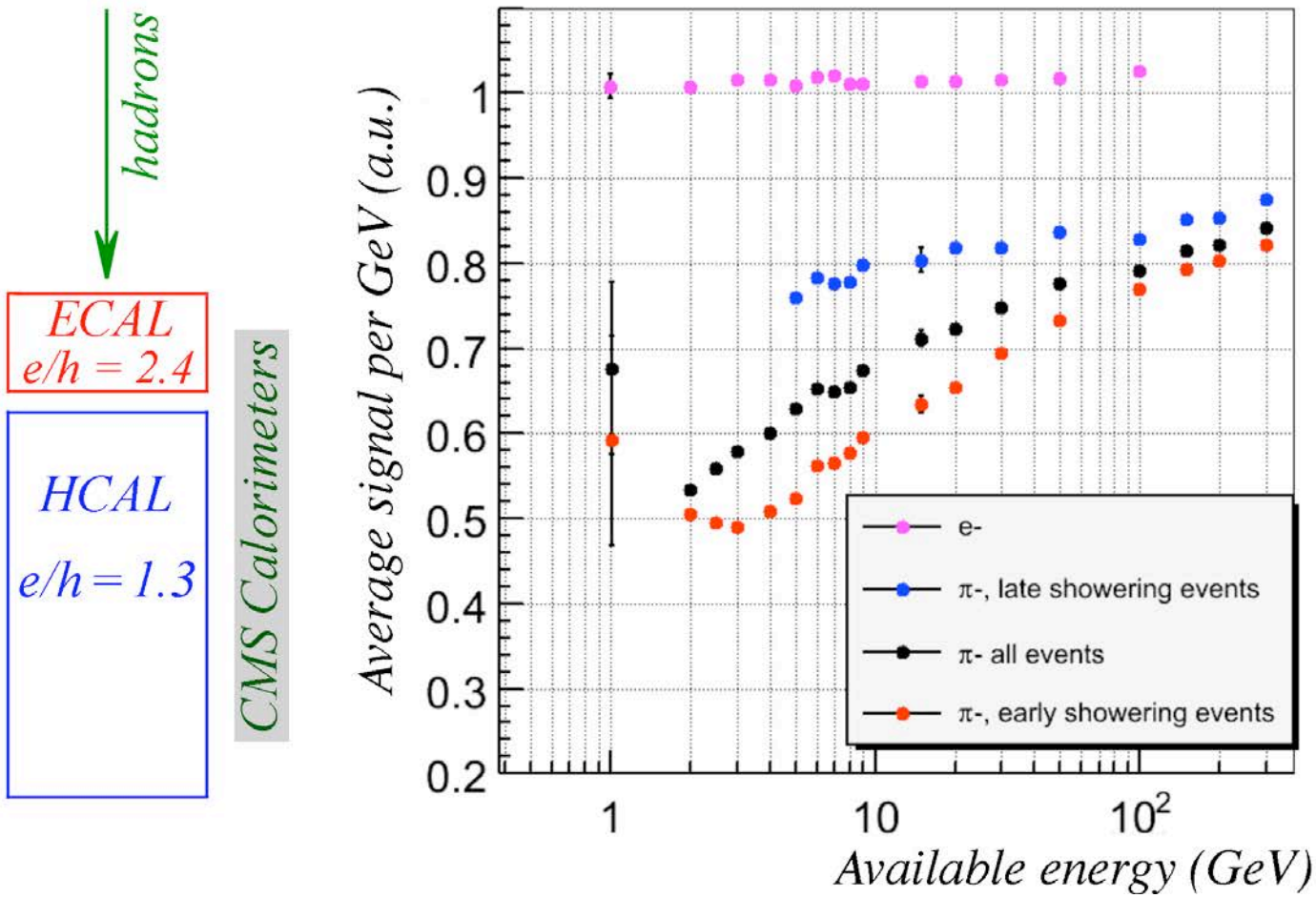
Consequences for LHC calorimeters

Hadronic response and signal linearity (CMS)

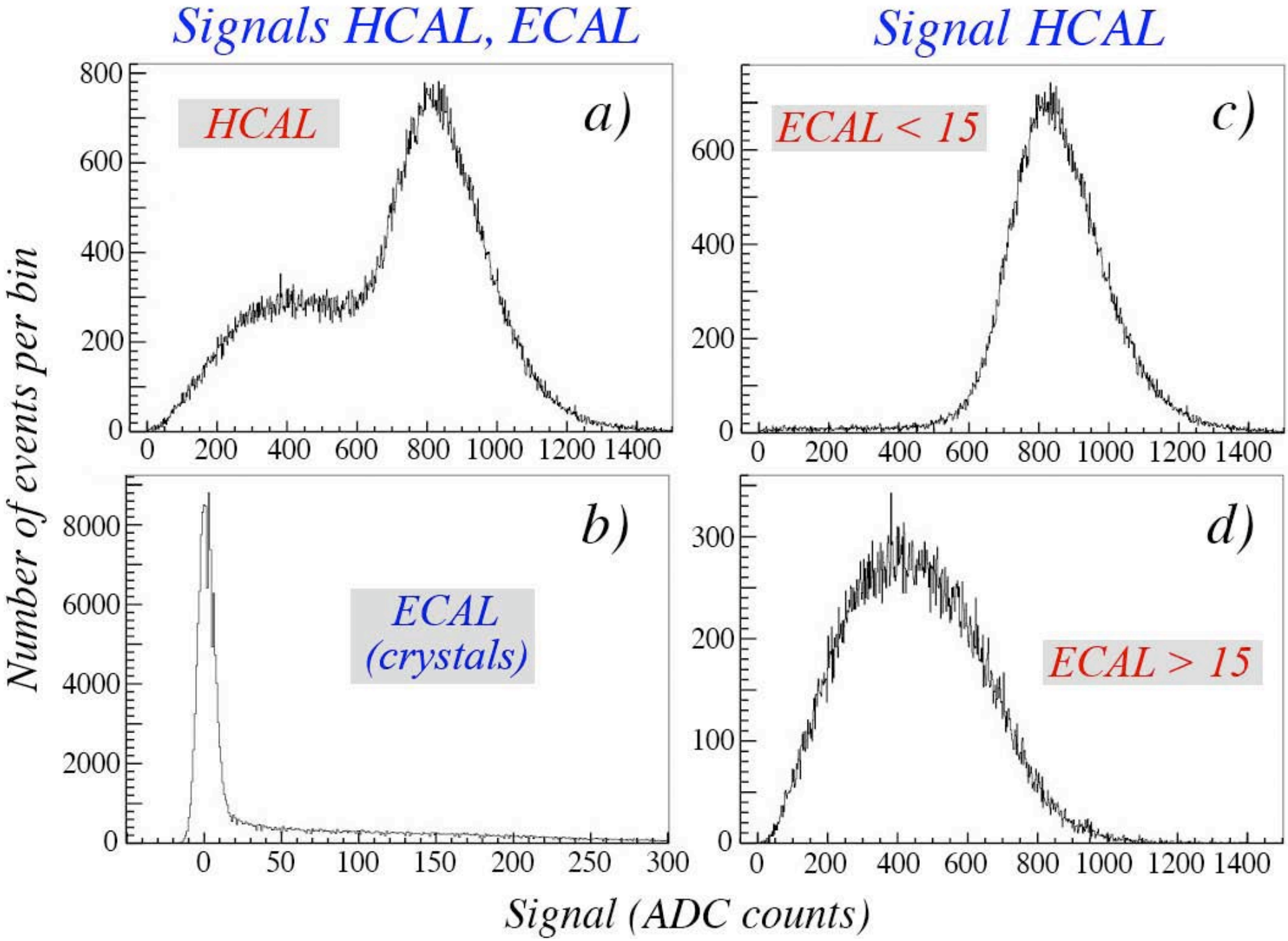
CMS pays a price for its focus on em energy resolution
ECAL has $e/h = 2.4$, while HCAL has $e/h = 1.3$

→ *Response depends strongly on starting point shower*

Data from: CMS note 2007/012



Pion signals in crystal ECAL + scintillator HCAL



Methods to improve hadron calorimeter performance

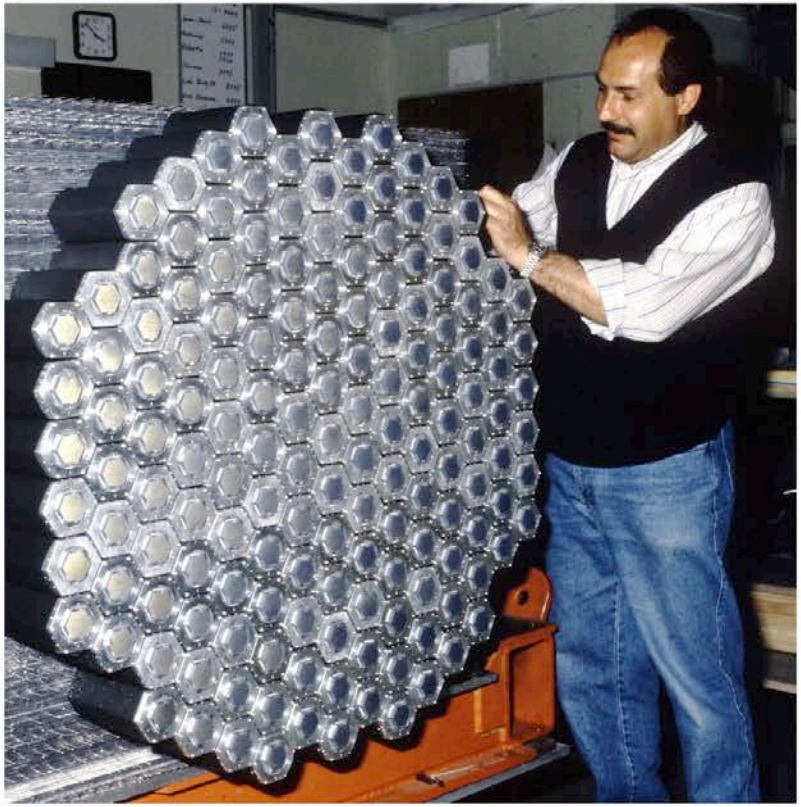
1) Equalize the response to em and non-em shower components

e/h = 1 (compensation)

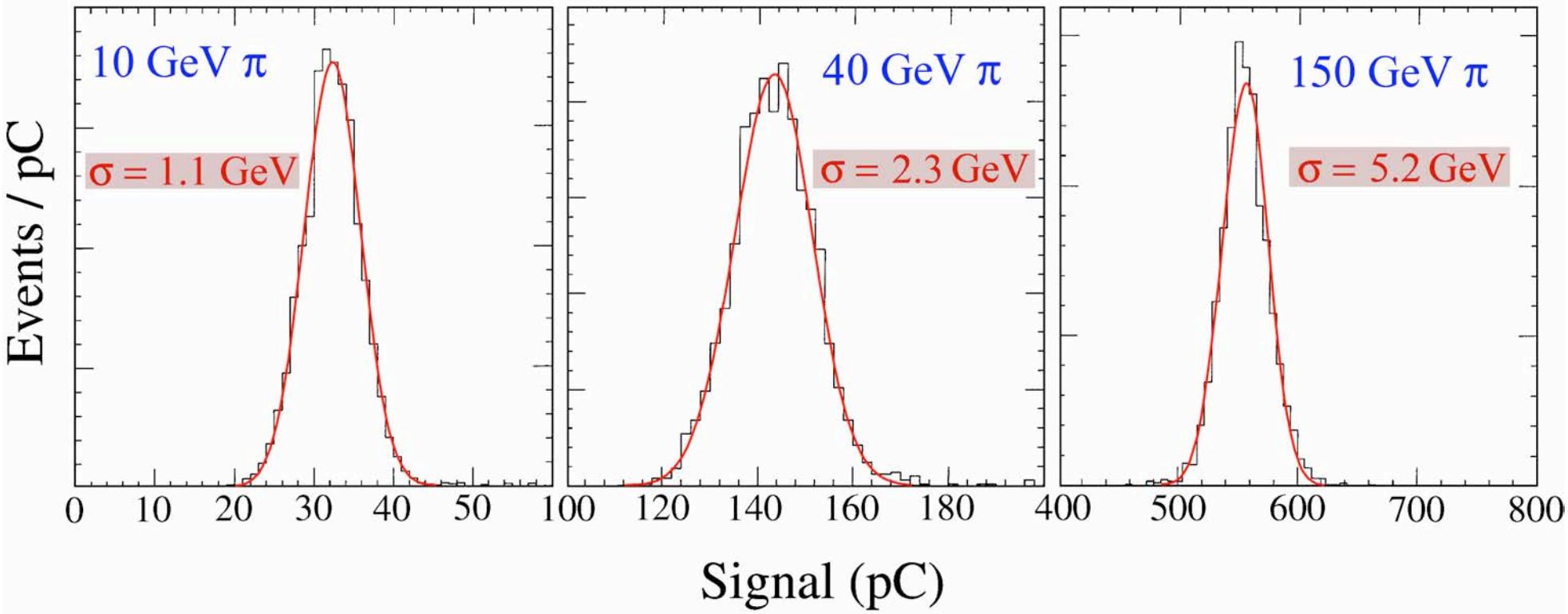
This can be achieved by exploiting a combination of 2 phenomena, which both only work in sampling calorimeters:

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

SPACAL 1989

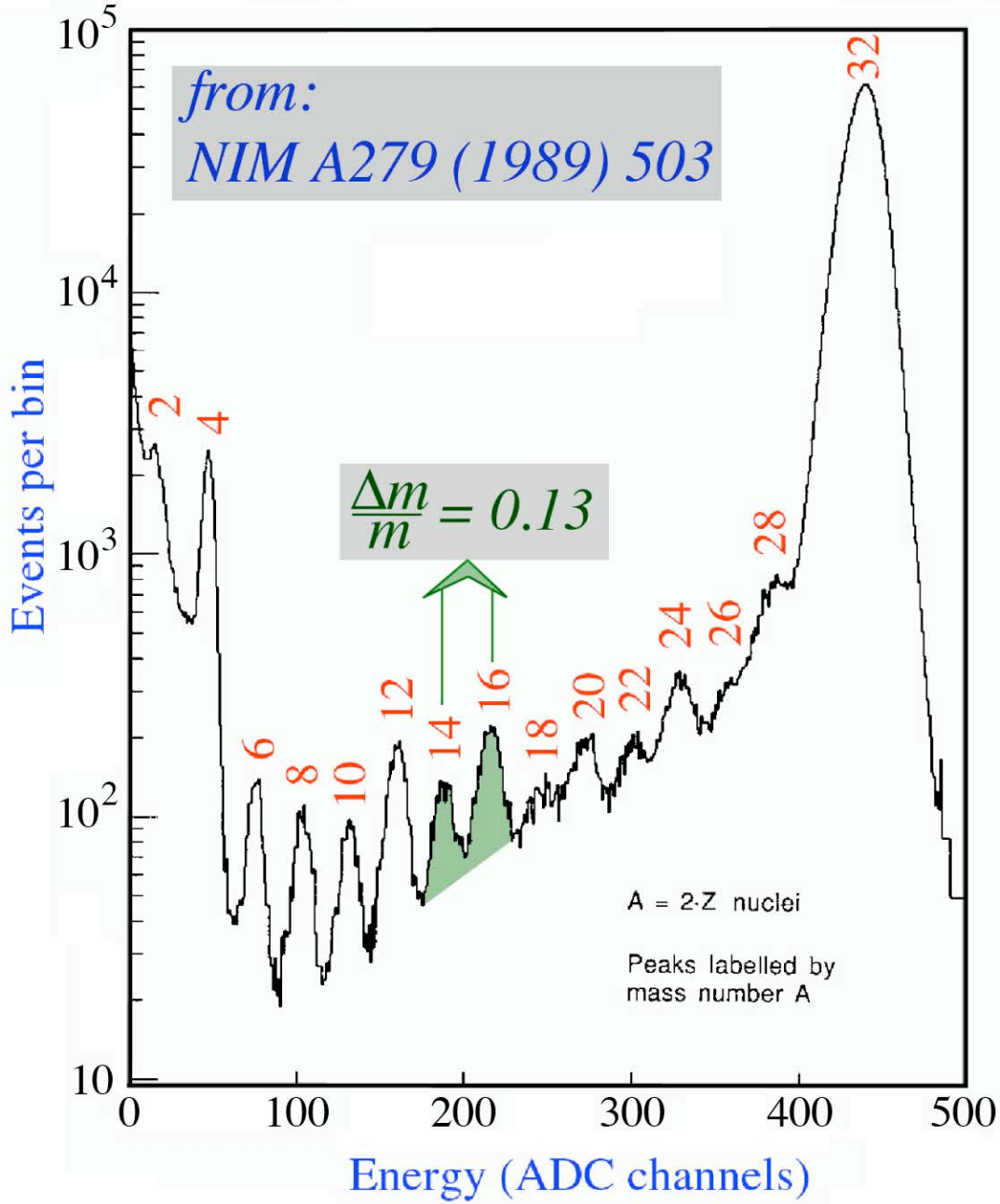


Hadronic signal distributions in a compensating calorimeter



from: NIM A308 (1991) 481

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

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

e/h = 1 (compensation)

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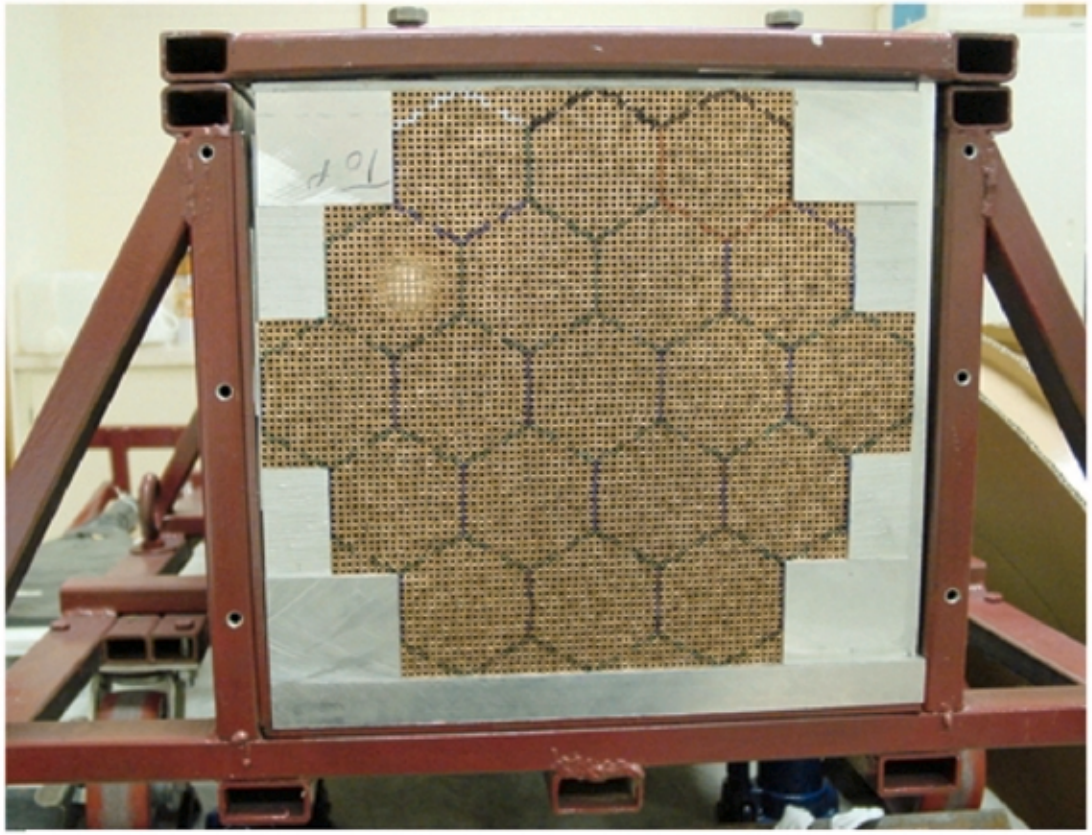
a) Suppression of em response for high-Z absorber material
b) Boosting the non-em response for hydrogenous active material

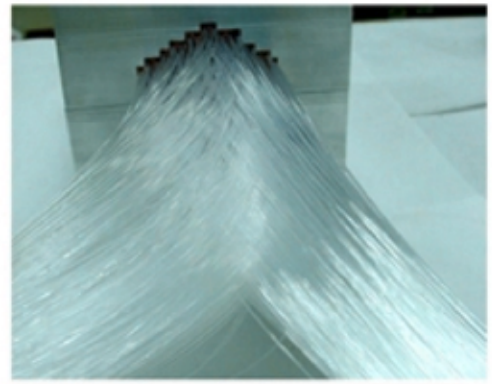
2) Dual-readout calorimetry:

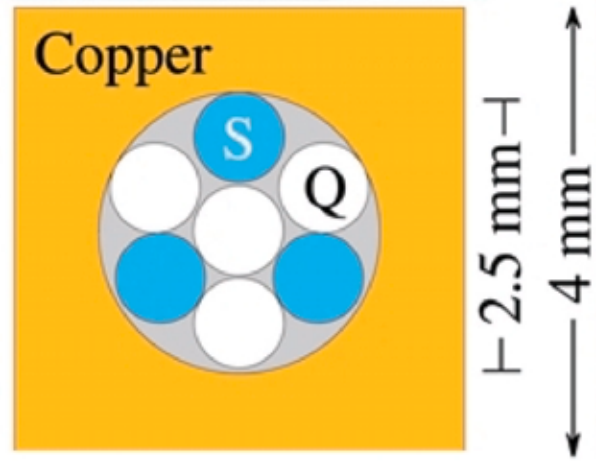
Determine em energy fraction (f_{em}) event by event
This makes it possible to eliminate effects of fluctuations in f_{em}

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

DREAM: Structure

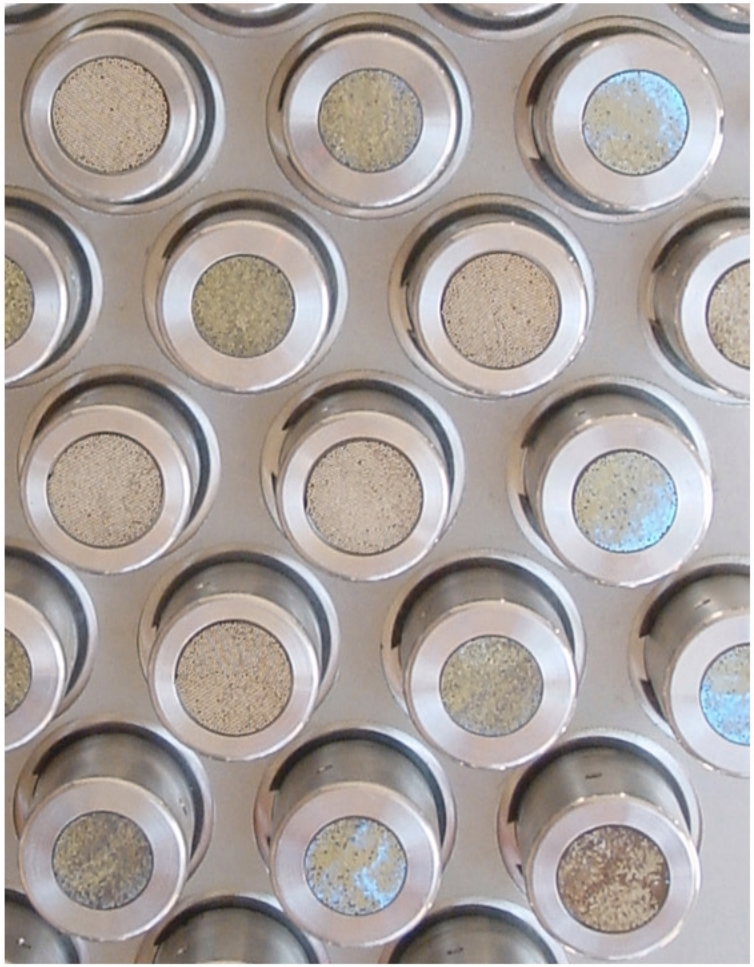


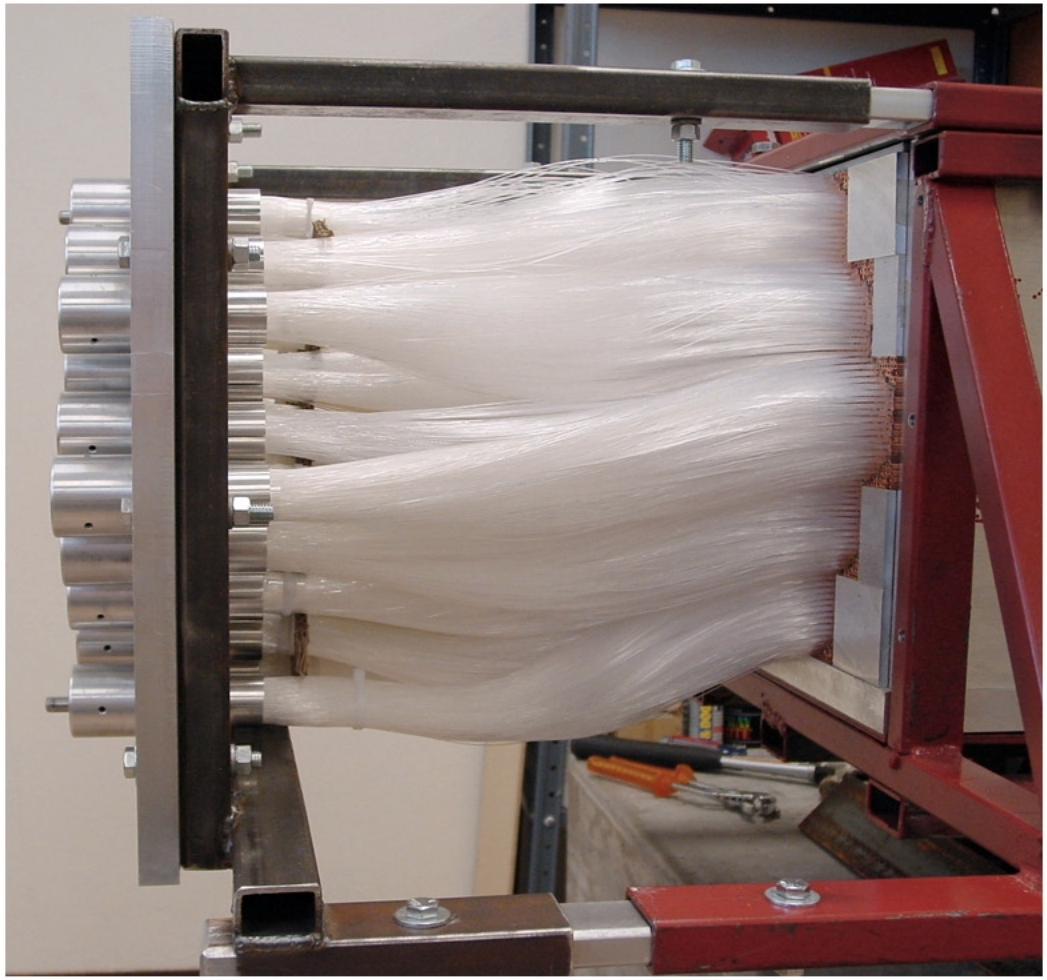


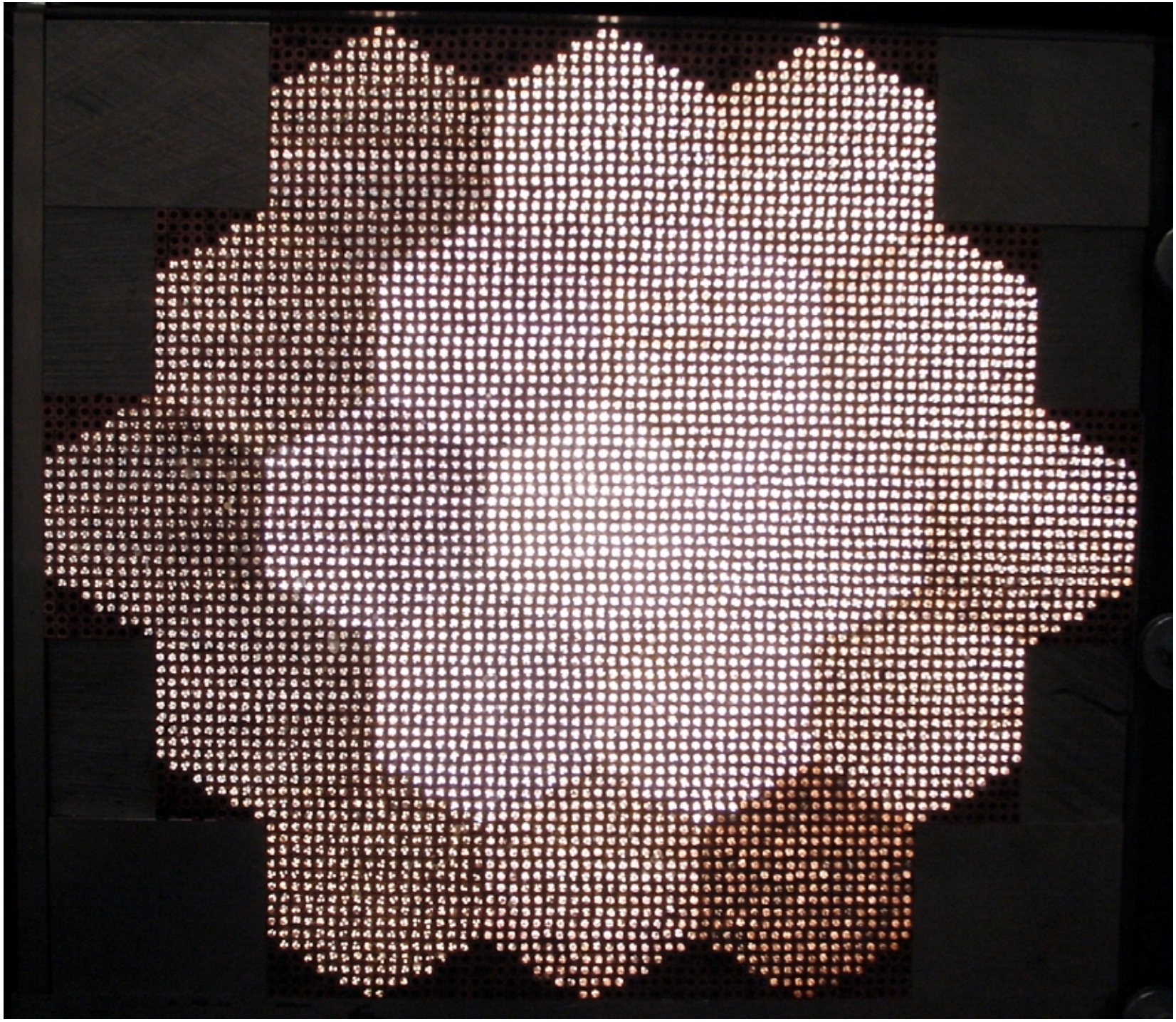


- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

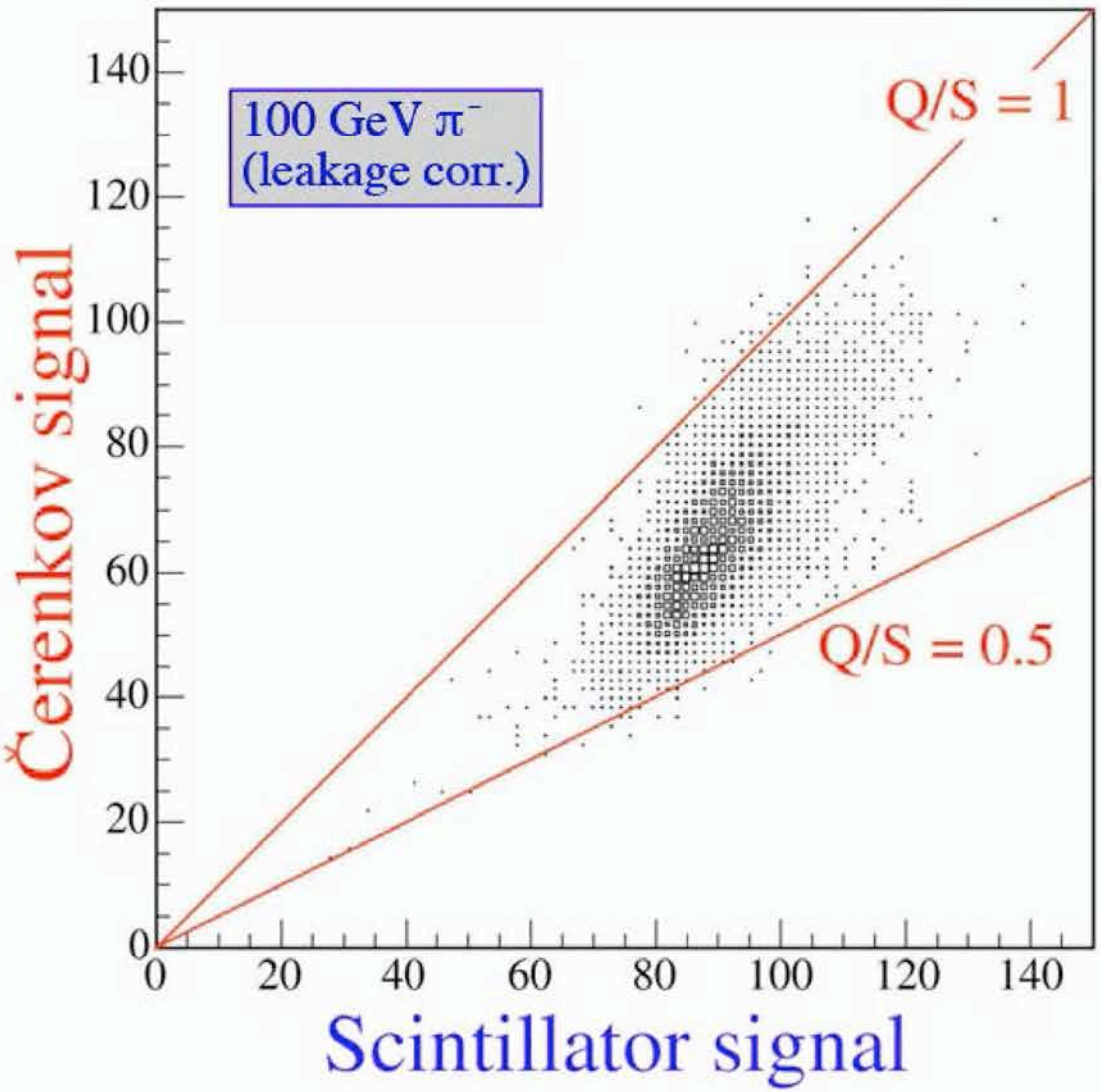
DREAM readout







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



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

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

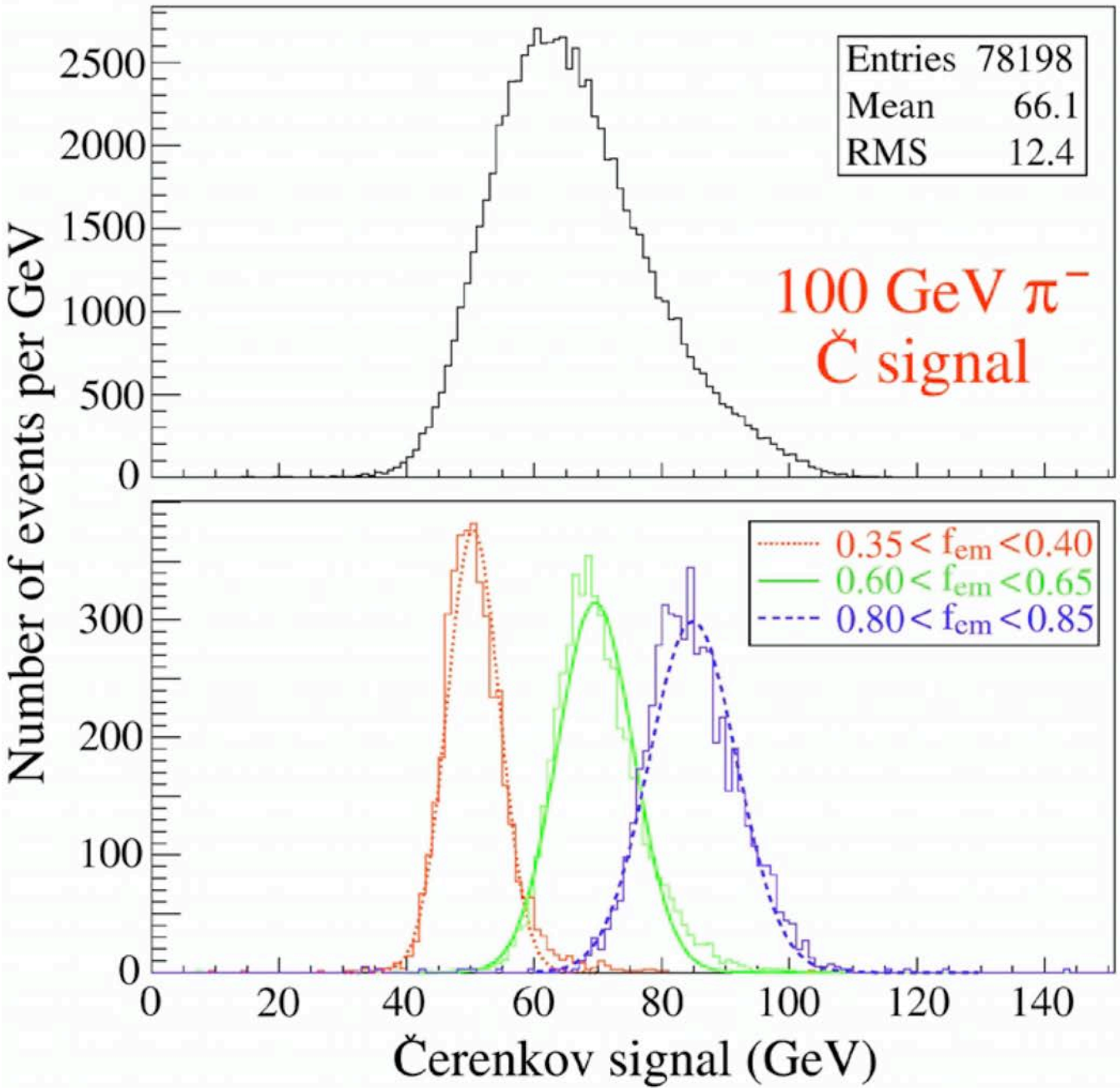
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

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

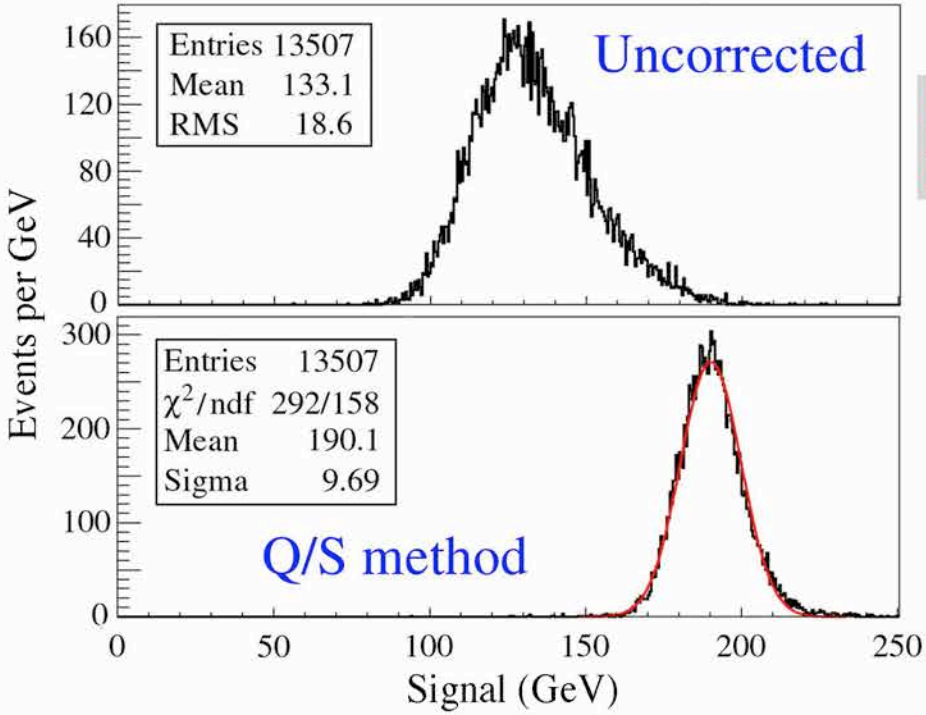
with $\chi = \dfrac{1-(h/e)_S}{1-(h/e)_Q}$

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



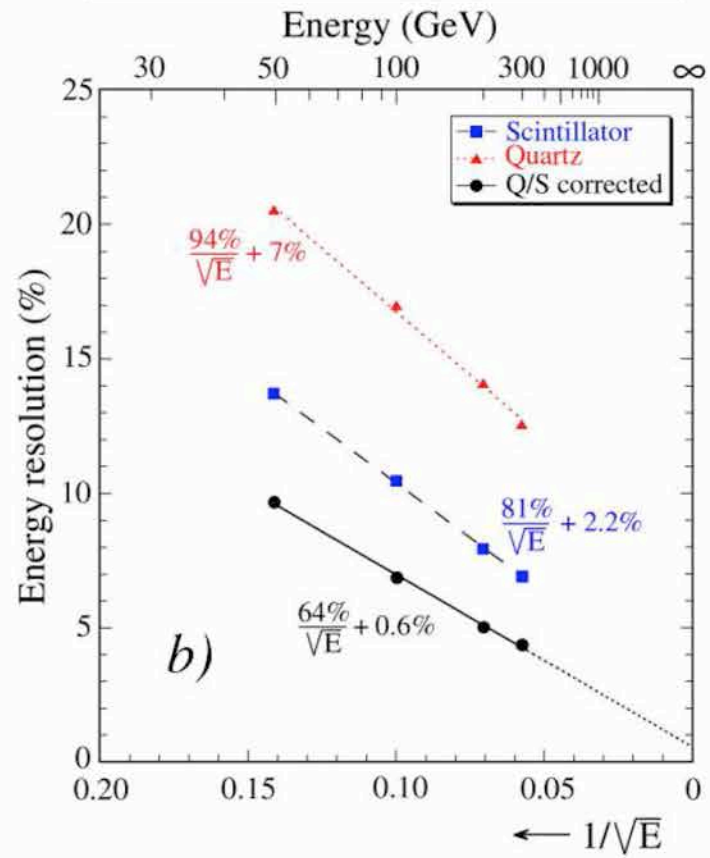
From:
NIM A537 (2005) 537

Effects of Q/S corrections on

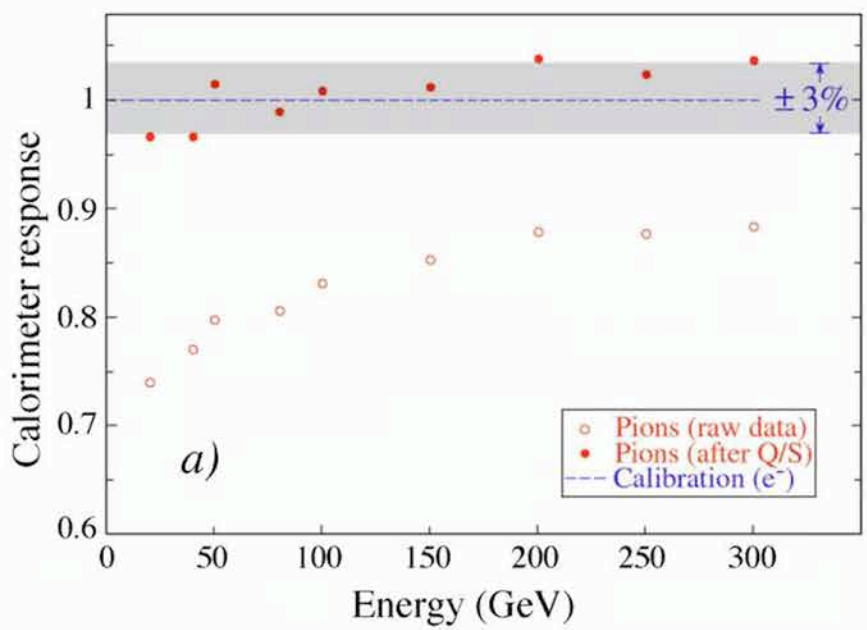


Calorimeter response function

jet energy resolution



hadronic signal linearity



Separation of $PbWO_4$:1%Mo signals into S, Č components

From:

NIM A604 (2009) 512

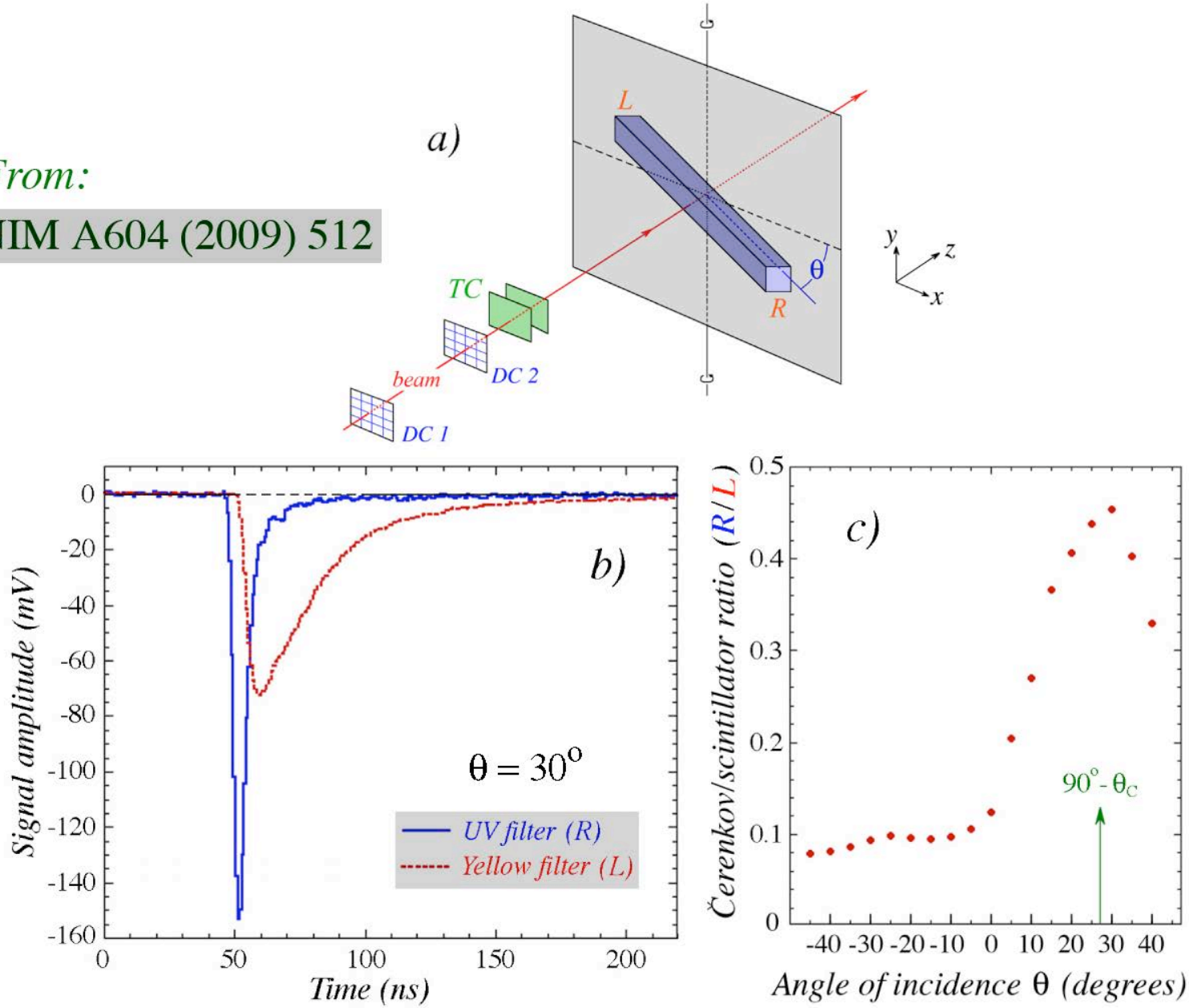
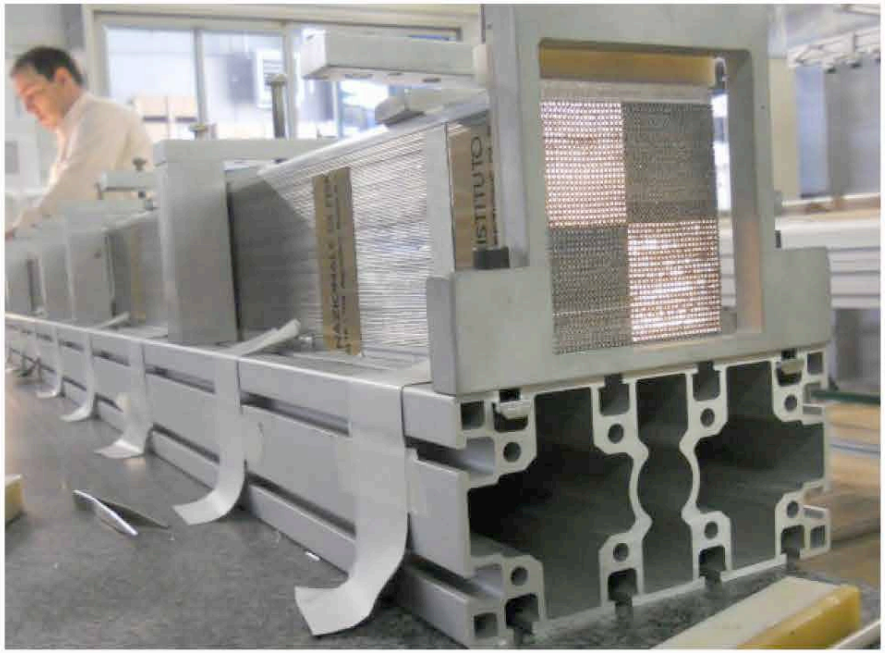
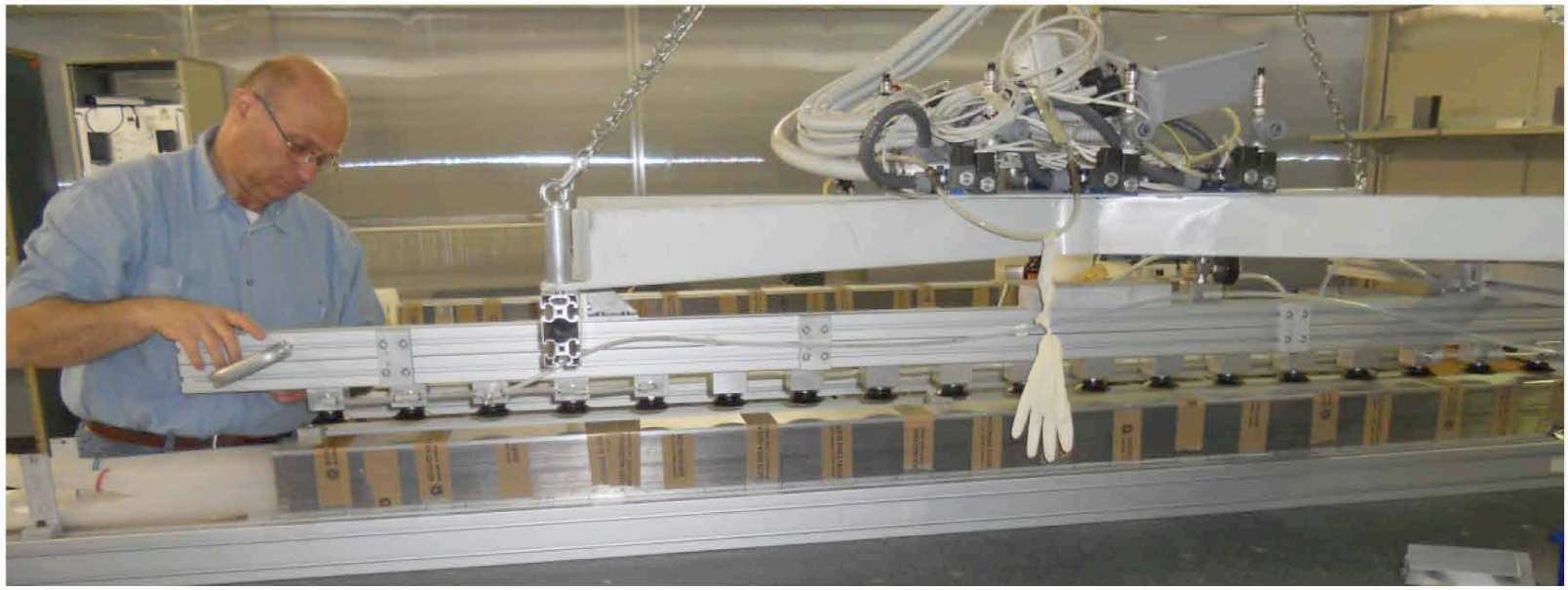


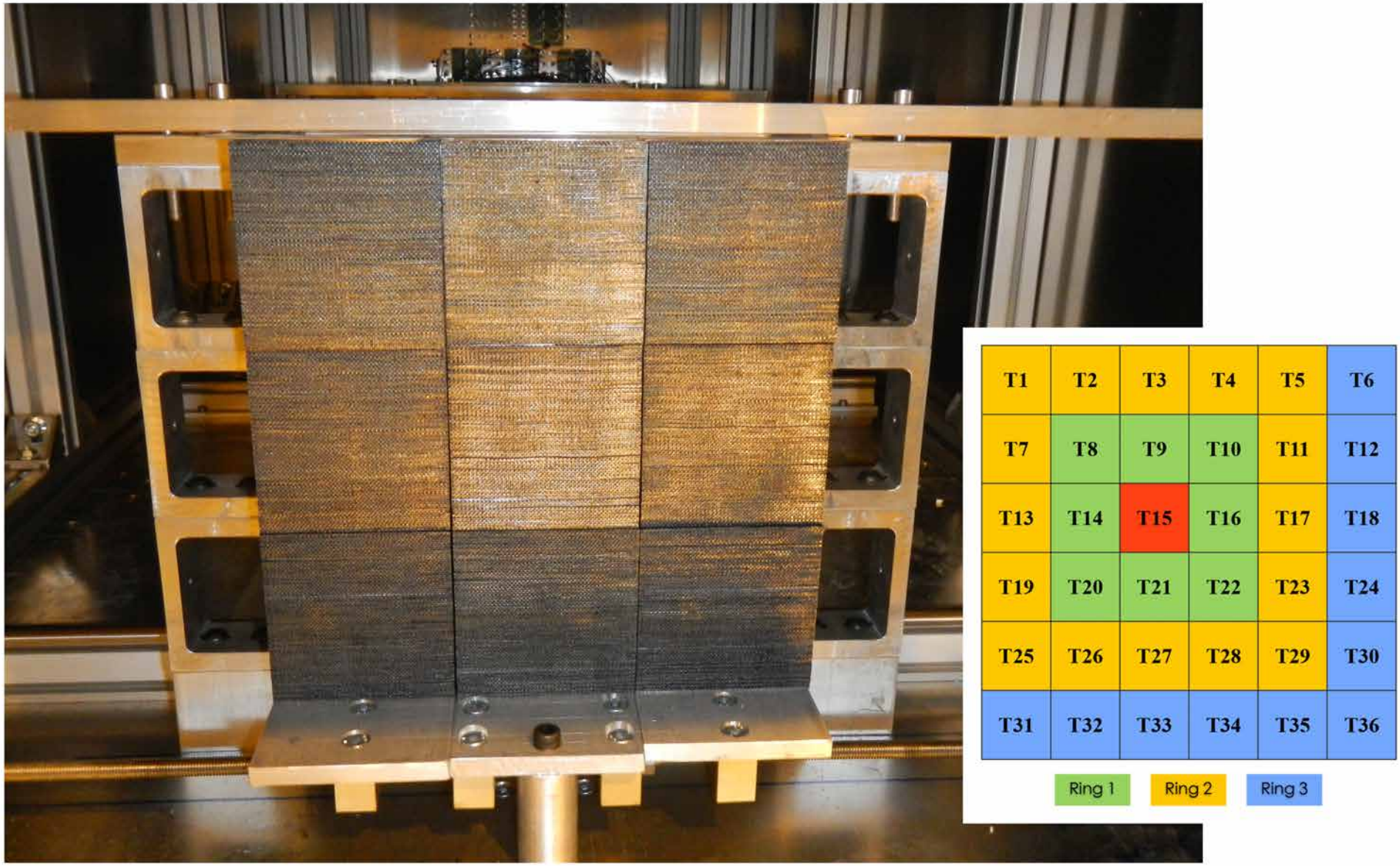
Figure 3: Unraveling of the signals from a Mo-doped $PbWO_4$ crystal into Čerenkov and scintillation components. The experimental setup is shown in diagram a. The two sides of the crystal were equipped with a UV filter (side R) and a yellow filter (side L), respectively. The signals from 50 GeV electrons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



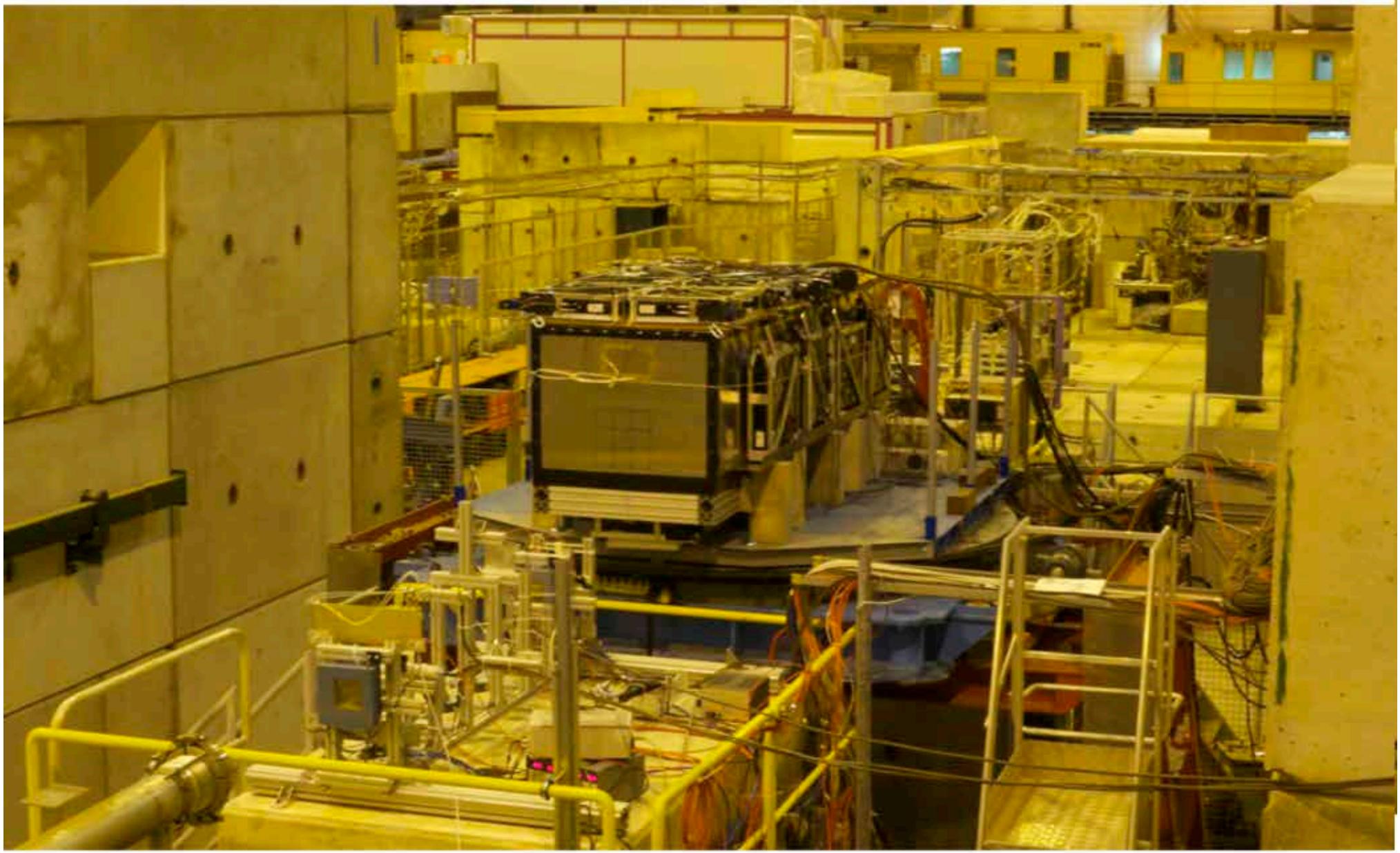


The Pb-fiber calorimeter

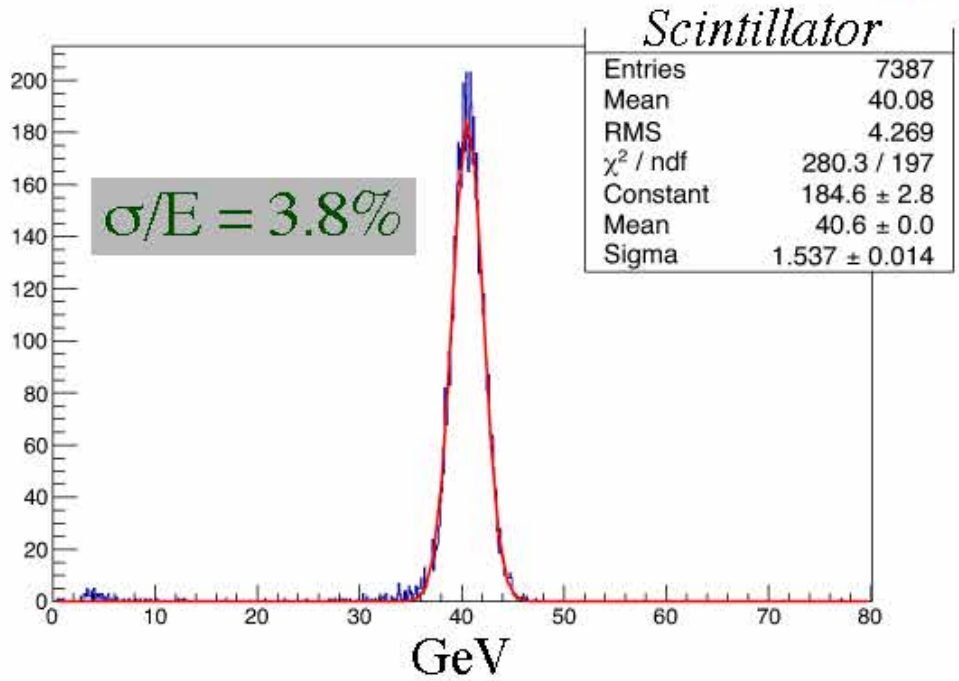


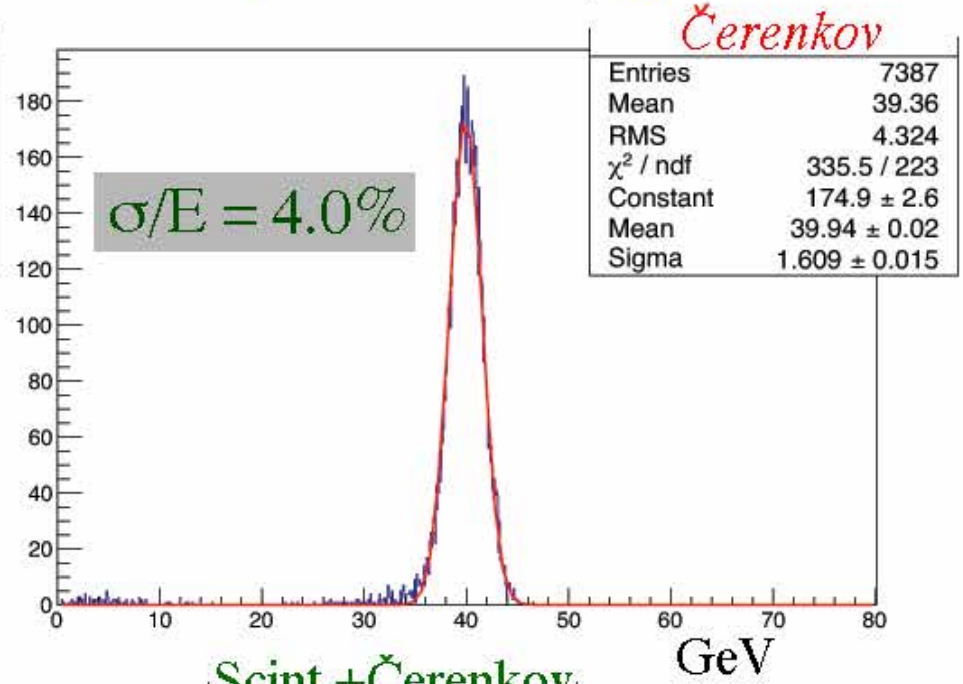
28 x 28 x 250 cm^3 , 1300 kg, 72 electronic channels

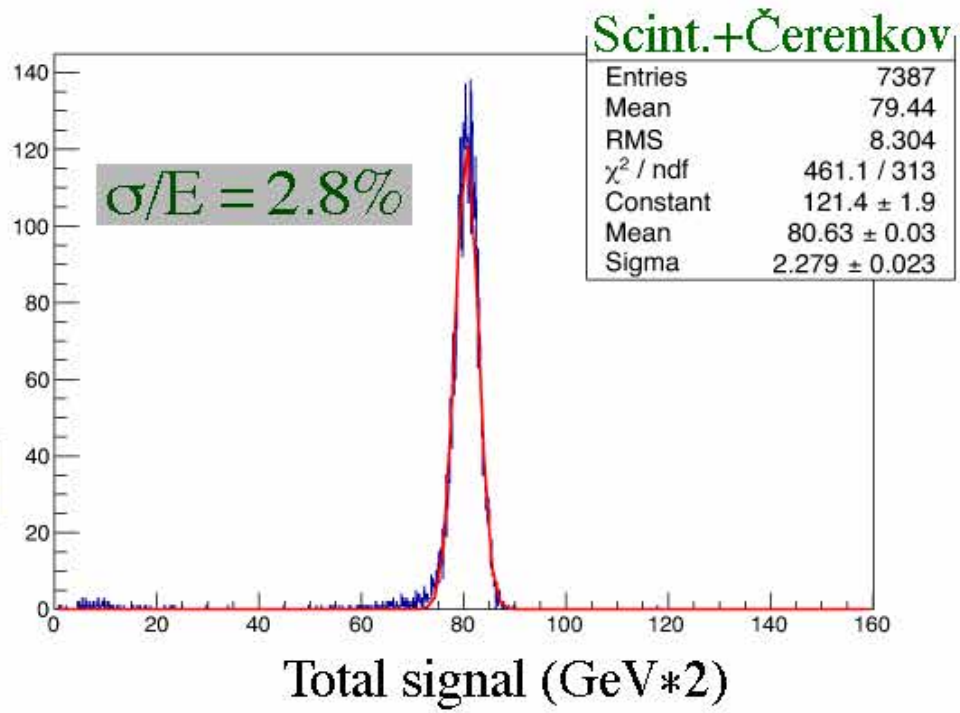
The RD52 test area in the H8 beam line



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





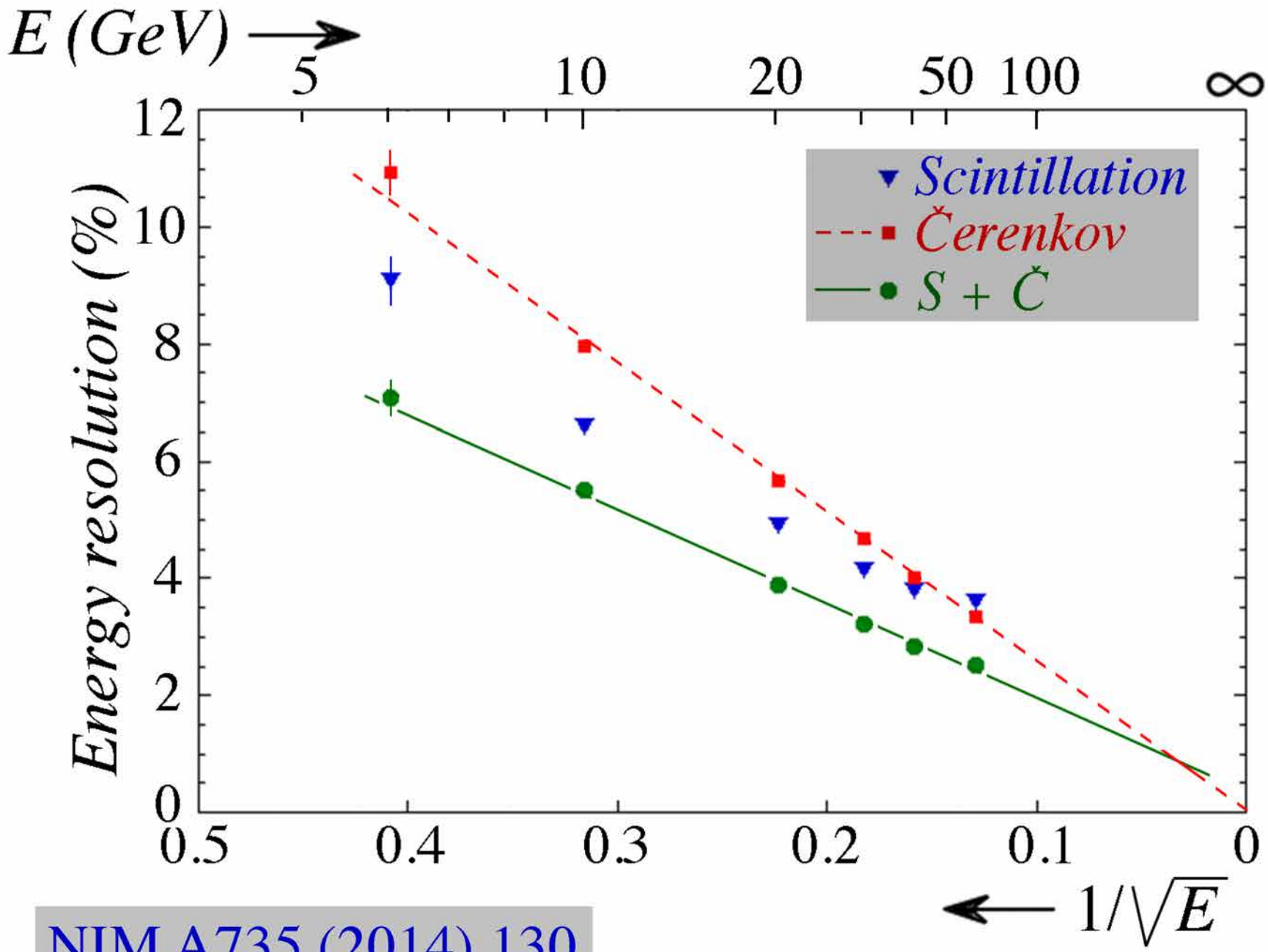


40 GeV electrons
Cu-fiber calorimeter

NIM A735 (2014) 130

Combining signals from two fiber types improves resolution

→ *Stochastic term dominates*

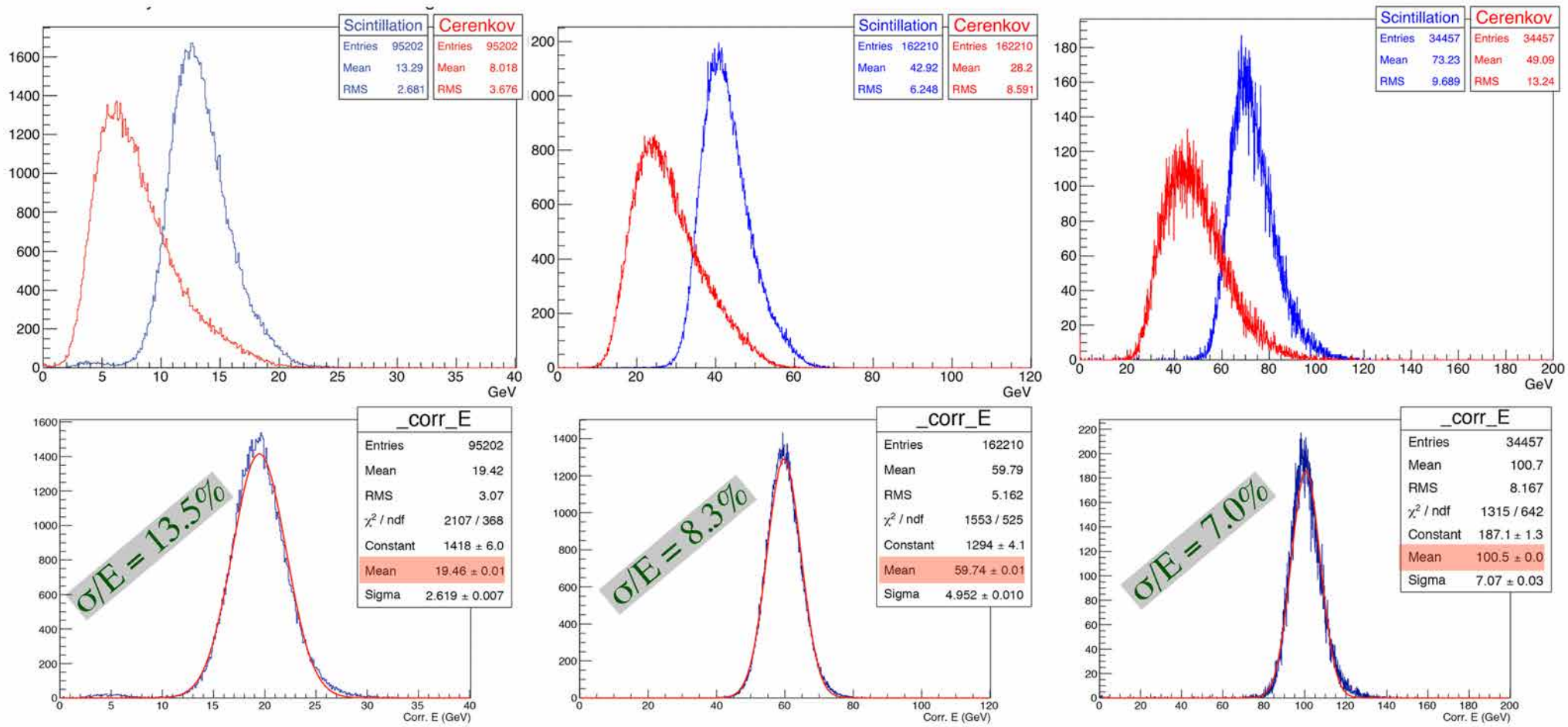


NIM A735 (2014) 130

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

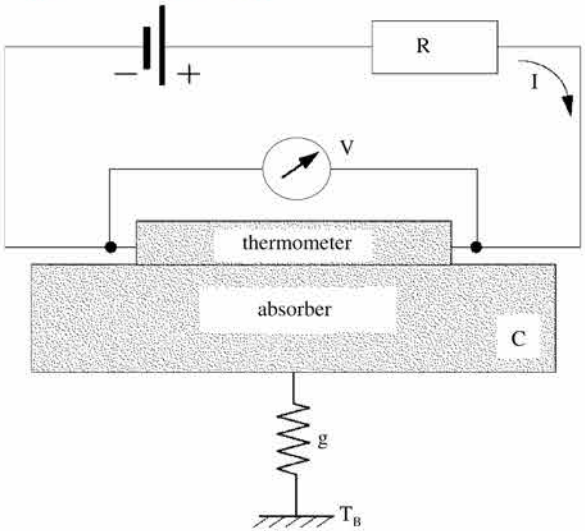
Calorimeters operating close to absolute zero temperature (~ 10 mK)

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"

The principle of a cryogenic calorimeter



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).

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

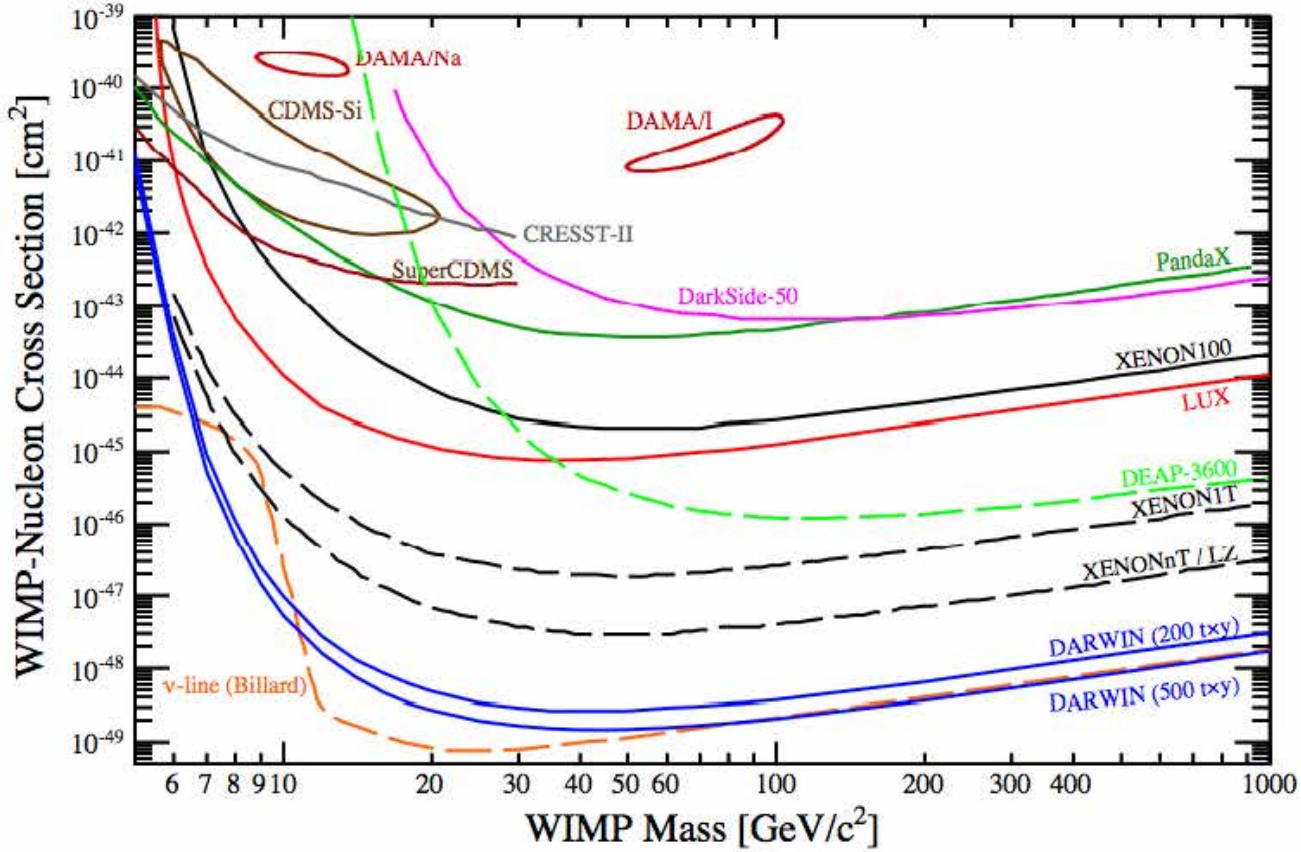


Figure 2 Spin-independent WIMP-nucleon scattering results: Existing upper limits from the CRESST-II [38], SuperCDMS [40], PandaX [50], DarkSide-50 [51], XENON100 [42], and LUX [41] experiments, along with projections for DEAP3600 [44], XENON1T [45], XENONnT [47], LZ [46], and DARWIN [49] are shown. DARWIN 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

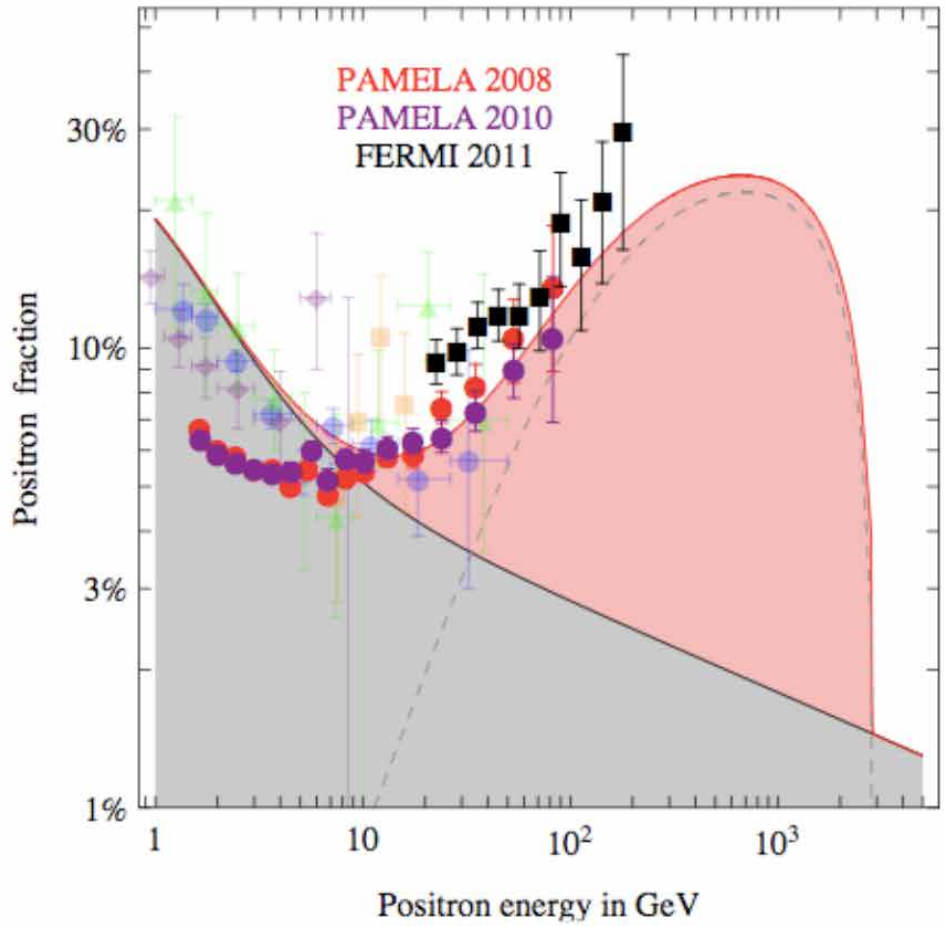


Figure 2. Figure and caption by M. Cirelli [12]: the positron fraction of charged cosmic ray data interpreted in terms of Dark Matter annihilations: the flux from the best fit DM candidate (a 3 TeV DM particle annihilating into $\tau^+\tau^-$ with a cross section of $2 \cdot 10^{22}$ cm^{3}s^{-1}) is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

Search for strongly interacting dark matter

In principle, it is not excluded that dark matter particles are subject to the strong interaction

In that case, one should not expect to detect them in Earth bound experiments (because of thermalization in the atmosphere)

Need experiments outside the Earth's atmosphere, e.g. the XQC experiment (cryogenic calorimeter launched with a rocket)

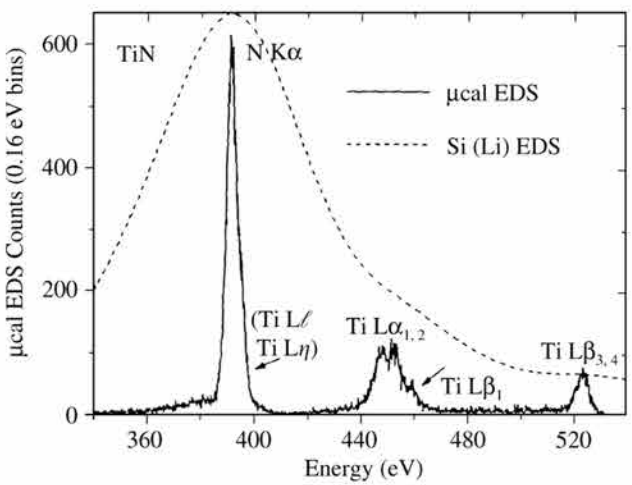


Fig. 2. TiN X-ray spectra obtained with a cryogenic microcalorimeter (solid line) from the NIST group (see text) and with a state-of-the-art Si(Li) solid-state device (dashed line) are compared. EDS stands for energy-dispersive spectrometer. TiN is an interconnect and diffusion barrier material used in semiconductor industy.

This detector was primarily intended for X-ray spectroscopy
It takes ~1 meV to produce one Cooper pair,
vs several eV for e^+e^- pair in semiconductor.
The resolution is thus MUCH better

In 90 seconds, this detector had collected so much data that strongly interacting particles ($\sigma \sim 1$ b) could be ruled out in the mass region $0.01 < M_{dm} < 10^5$ GeV/c²

Reminder: *energy resolution* $\frac{\sigma(E)}{E} \propto 1/\sqrt{n}$

Results from the X-ray Quantum Calorimetry experiment

PRD 76, 042007 (2007)

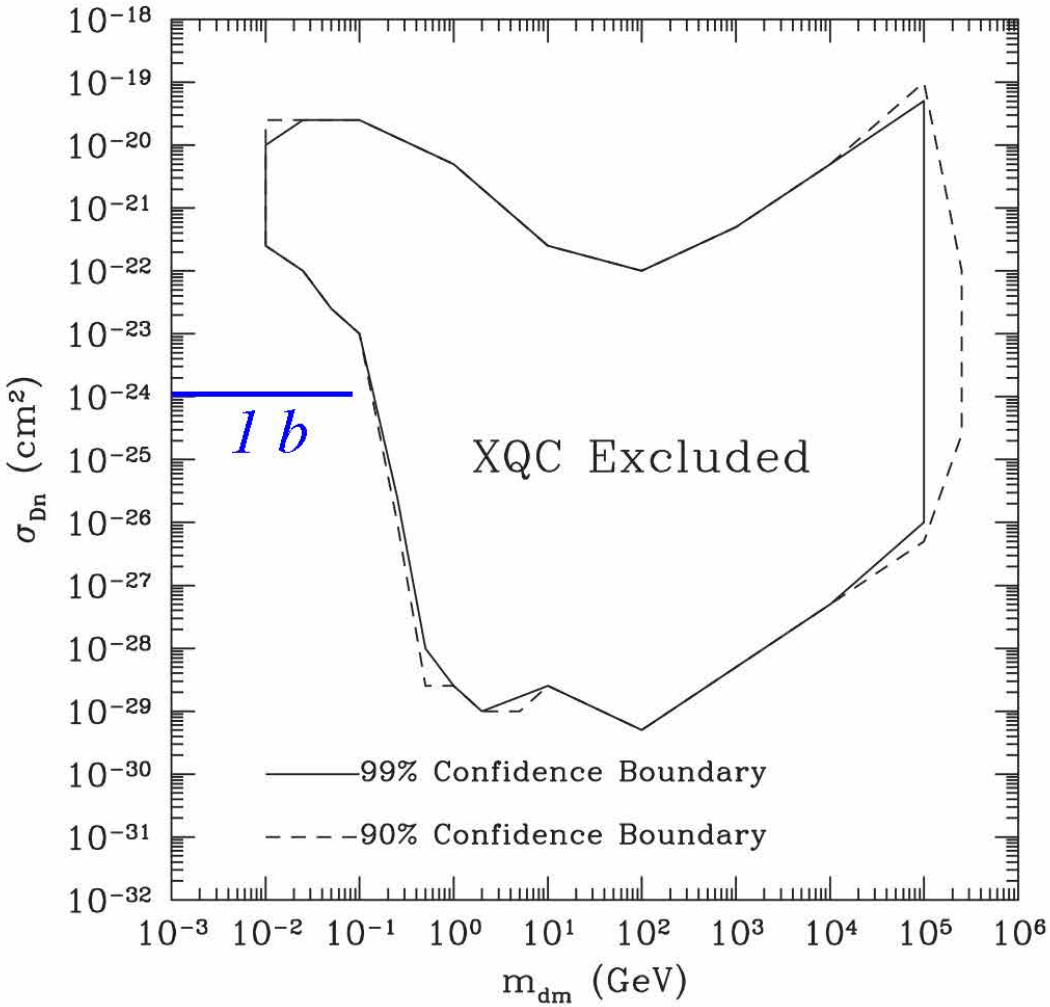


FIG. 7. The region of dark matter parameter space excluded by the XQC experiment; σ_{Dn} is the total cross section for scattering off a nucleon and m_{dm} is the mass of the dark matter particle. This exclusion region follows from the assumption that the local dark matter density is 0.3 GeV cm^{-3} and that all of the dark matter shares the same value of σ_{Dn}.

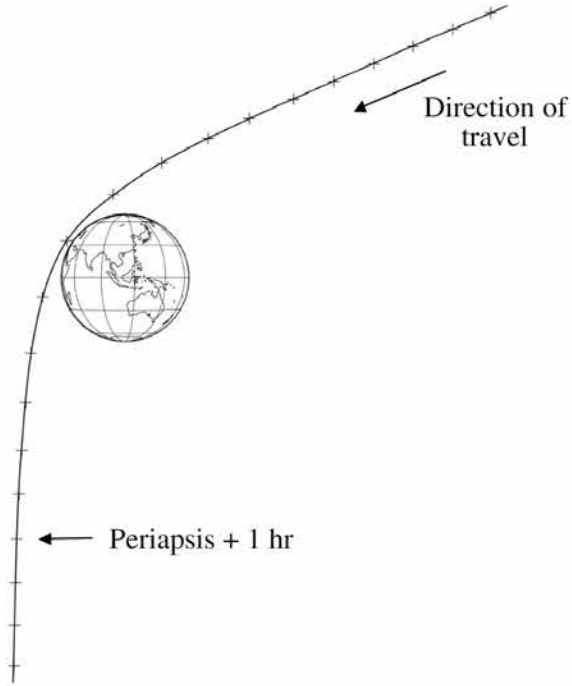


FIG. 1. Equatorial view of the NEAR flyby, the most asymmetrical flyby with respect to the Equator and the flyby with the largest energy change. The extent of the bending in the Earth's gravitational field, the geometry of the flyby and its time scale are illustrated. The tick marks are at 10-min intervals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

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

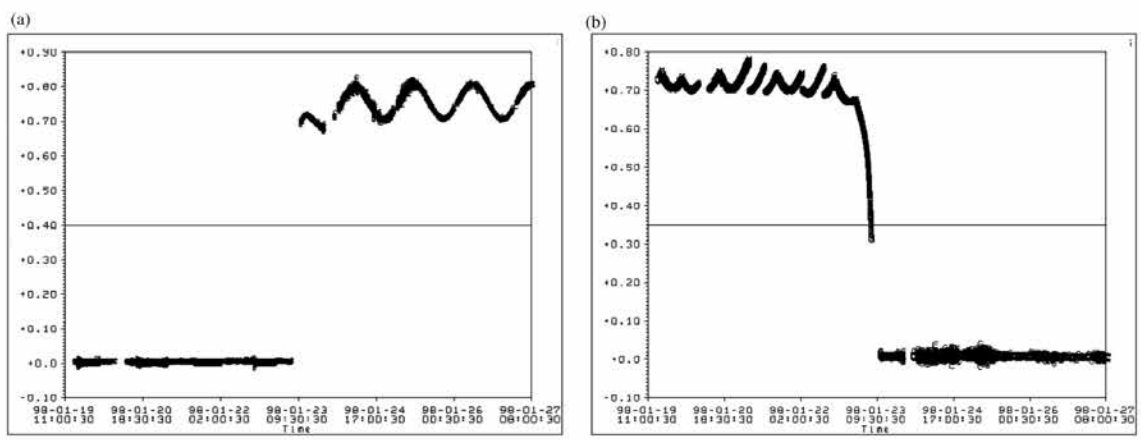


FIG. 2. X-band Doppler residuals in the sense observed Doppler frequency shift minus calculated Doppler frequency shift in units of Hz [10] from separately fitting (a) the pre- and (b) the postencounter data for the NEAR flyby. The residuals cluster on opposite sides of the respective fits and demonstrate 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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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