Dual-Readout Calorimetry

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University of Stockholm, March 19, 2009

Outline:

- (Limitations of) scientific measurements
- (Limitations of) calorimeter measurements in particle physics
- Dual-readout calorimetry
- Recent R&D results (DREAM)

Measurements and progress in science

Progress in scientific understanding has gone hand in hand with the quality of measurements that could be performed

- *Biology/medicine:*

  Invention of microscope → Breakthrough in understanding of the functioning of living organisms

- *Astronomy:*

  Telescopes have improved understanding of our place in space & time

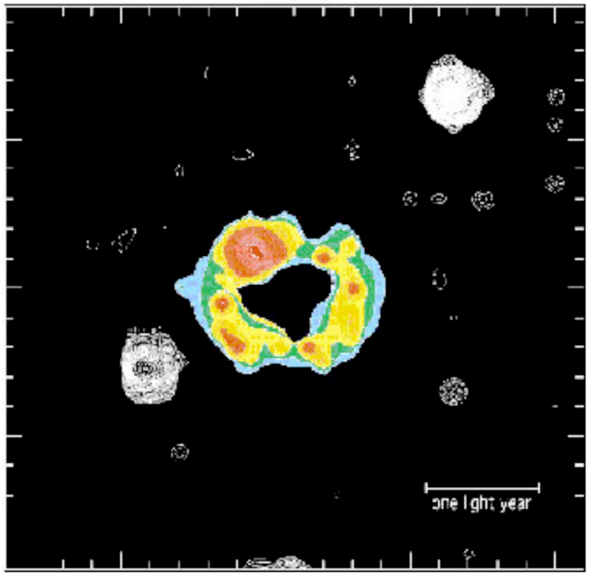
- *(Sub)atomic structure:*

  Understanding driven by quality of particle accelerators

  $\lambda = h/p$ → for studying structure at the level of 10^{-15} m (size proton) one needs a probe with $p \sim 10^{-19}$ kg.m/s, *i.e.* ~ 100 MeV/c

Sometimes, further progress is limited by external factors, not by the intrinsic quality of the instruments

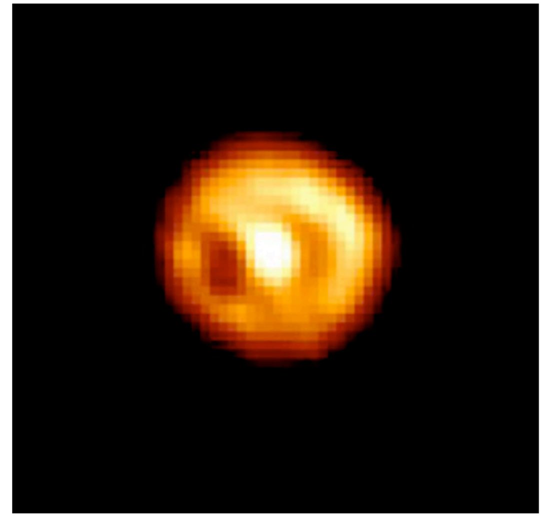
The limiting effects of atmospheric turbulence

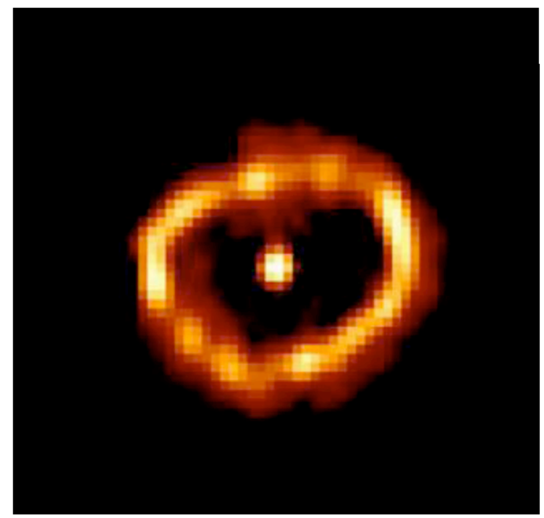


SN 1987a

Ground-based observations (Cerro Tololo, Chile)

Hubble Space Telescope





Nova Cygni 1992

Optical interferometry in Paranal (Chile)

Credit: Gerhard Hüdepohl

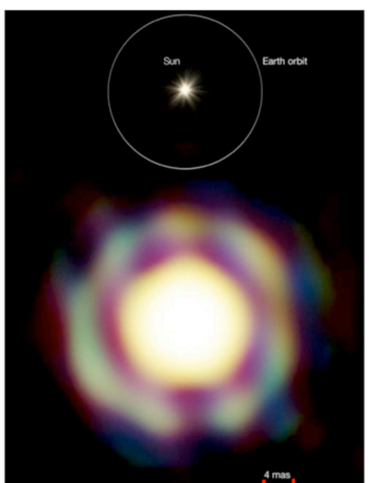
The VLT and VISTA

ESO Press Photo 04c/07 (17 January 2007)

Photograph: Y. Beletsky

Shooting a Laser at the Galactic Centre

ESO Press Photo 33b/07 (2 August 2007)



0.004”

Rayleigh’s criterion

$$\theta_{lim} = 1.22\,\frac{\lambda}{D}$$

$$e.g.\ \lambda = 500\ \text{nm}$$
$$D = 10\ \text{m}$$

$$\rightarrow \theta_{lim} = 6\cdot 10^{-8}\ \text{rad} \sim 0.012''$$

Calorimeters

- *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 detector is instrumented such as to provide signals that make it possible to determine the particle's 4-vector*
- *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, ...*

Calorimetry: Homogeneous calorimeters

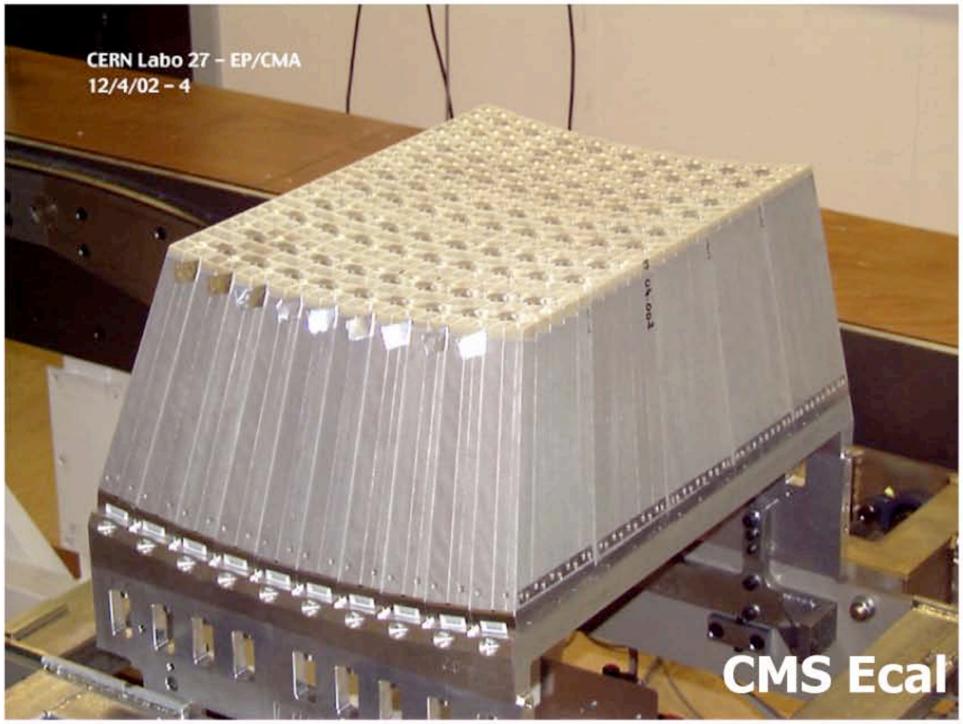
- *High-density crystals used as electromagnetic calorimeters*
  Example: CMS ECAL, $PbWO_4$. Density 8.3 g/cm^3, radiation length 8.9 mm.

- *Very good energy resolution*

- *Very expensive*

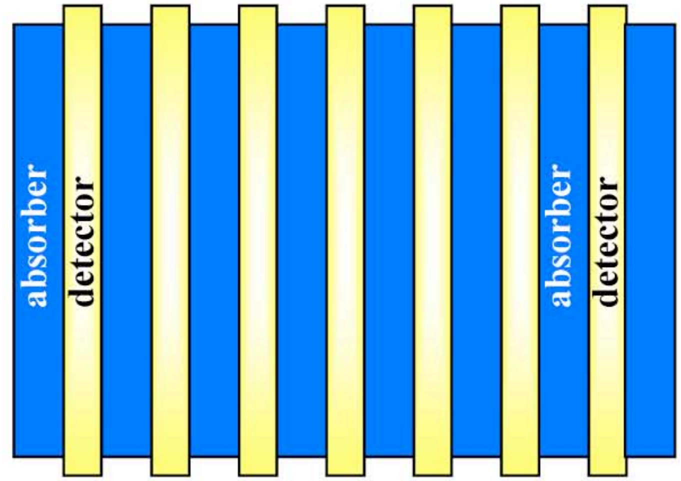
- *Radiation damage a problem*

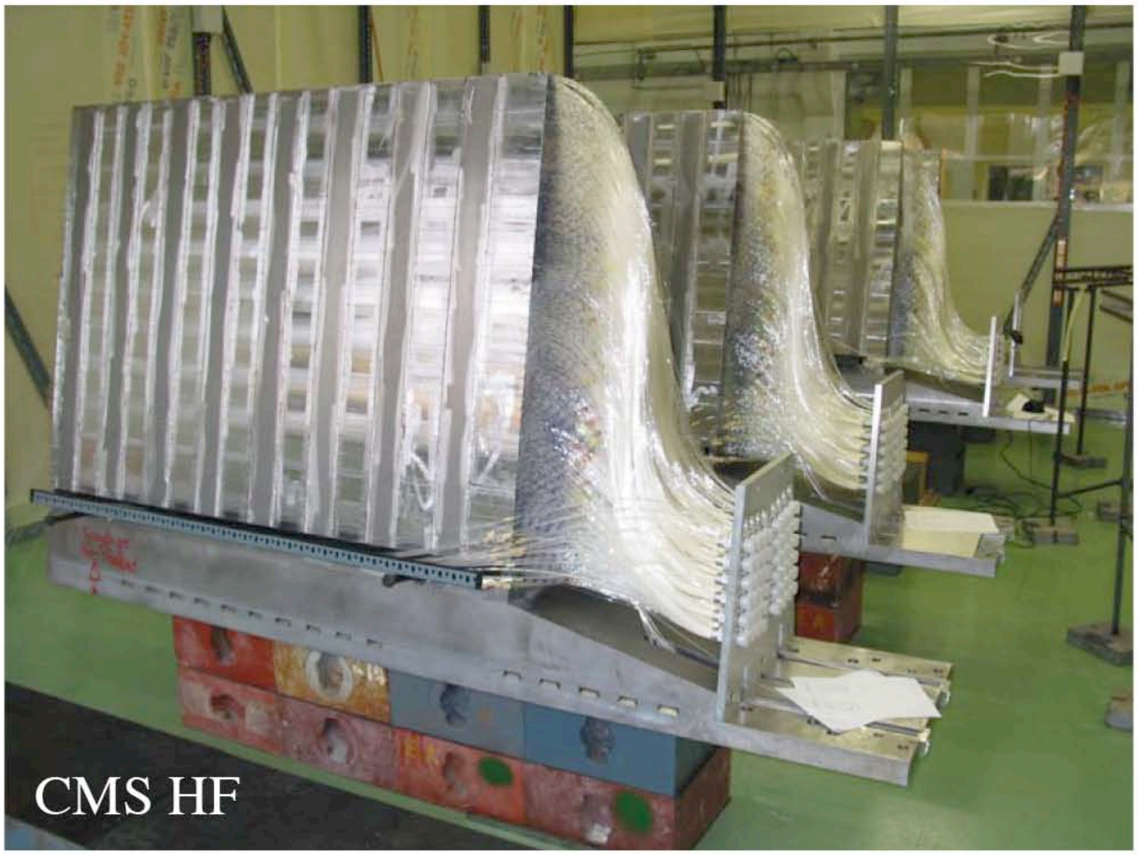
- *Other crystals:*
  NaI(Tl), CsI, BGO, BaF_2



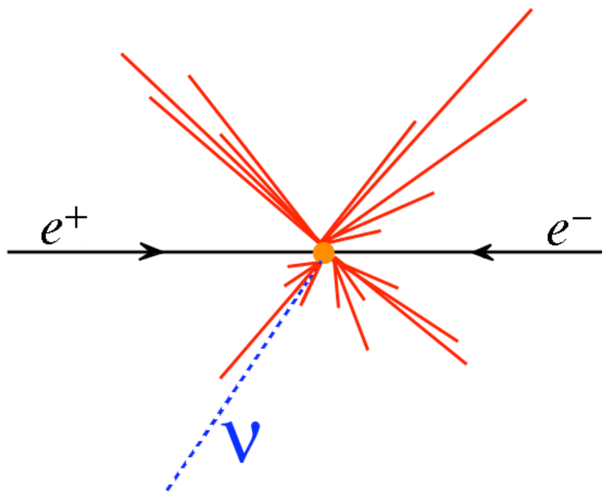
Calorimetry: Sampling calorimeters

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





Why calorimetry?

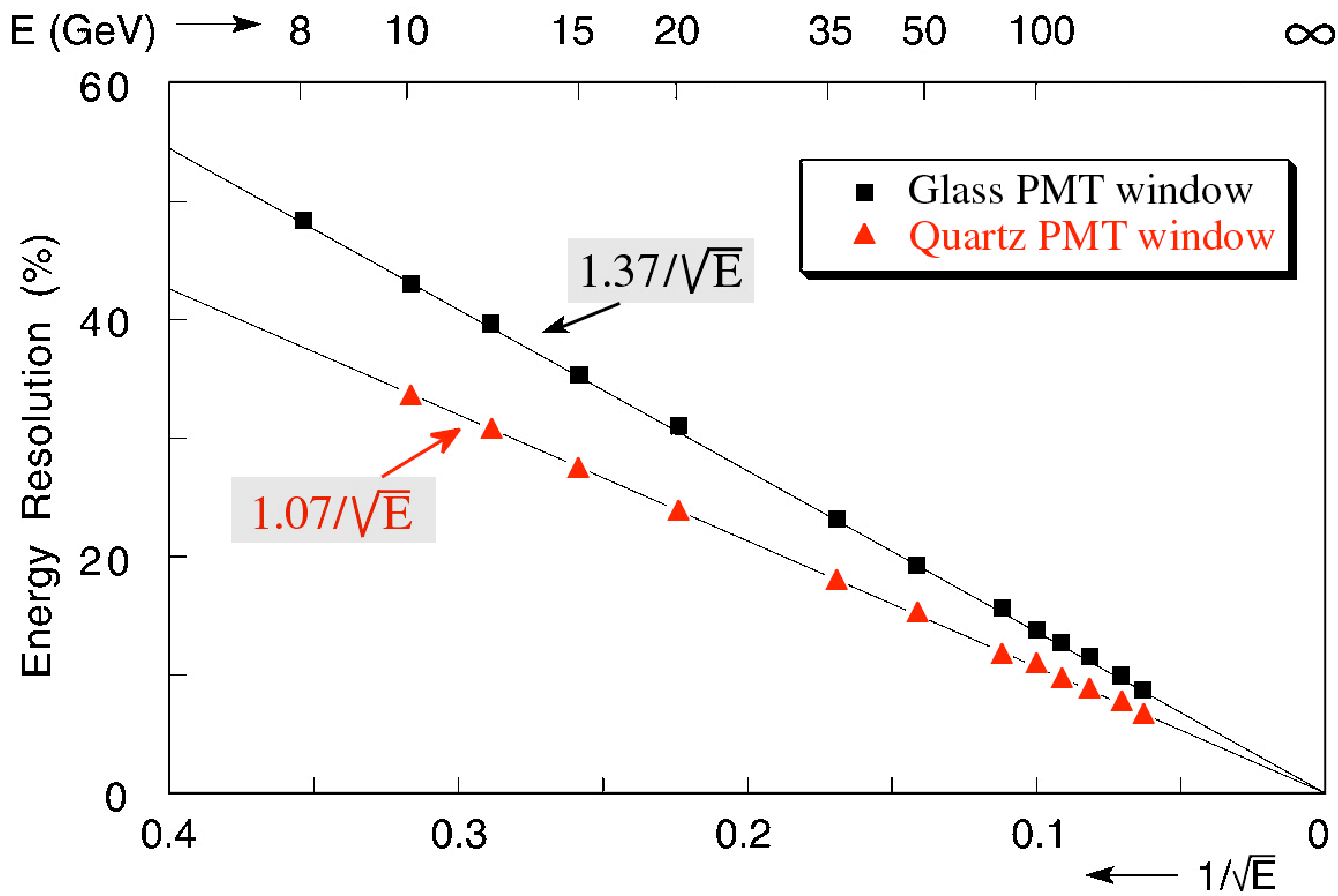


- Measure *charged + neutral* particles
- Obtain information on *energy flow*: Total (missing) transverse energy, jets, *etc*.
- Obtain information *fast*
  → recognize and select interesting events in real time *(trigger)*
- Performance of calorimeters *improves with energy* ($\sim E^{-1/2}$ if statistical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

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

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

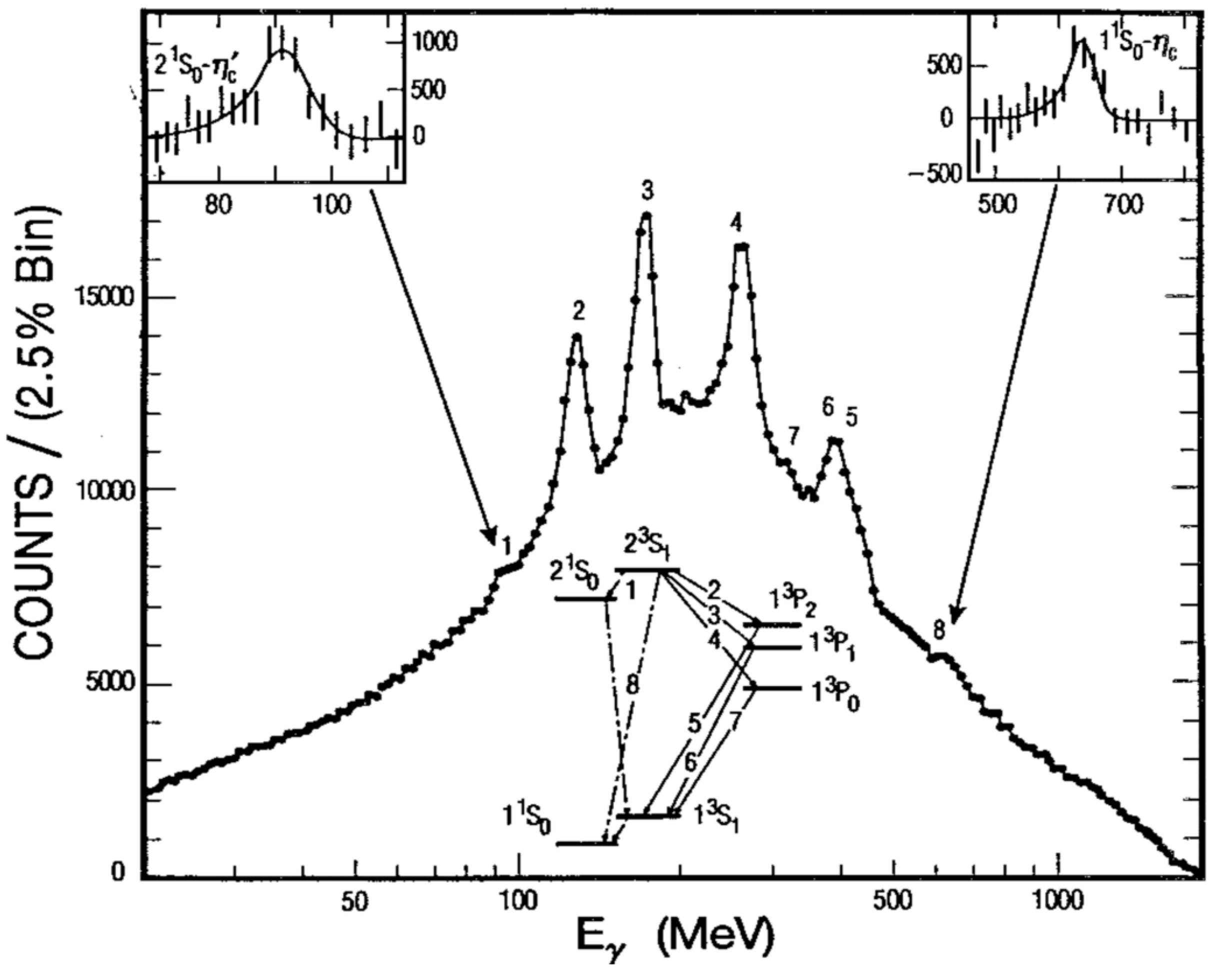
In an ideal calorimeter, resolution scales as $E^{-1/2}$



Important calorimeter features

- Energy resolution
- Position resolution (need 4-vectors for physics)
- Signal speed
- Particle ID capability

The importance of (electromagnetic) energy resolution



Charmonium spectroscopy (SPEAR)

The importance of (hadronic) energy resolution

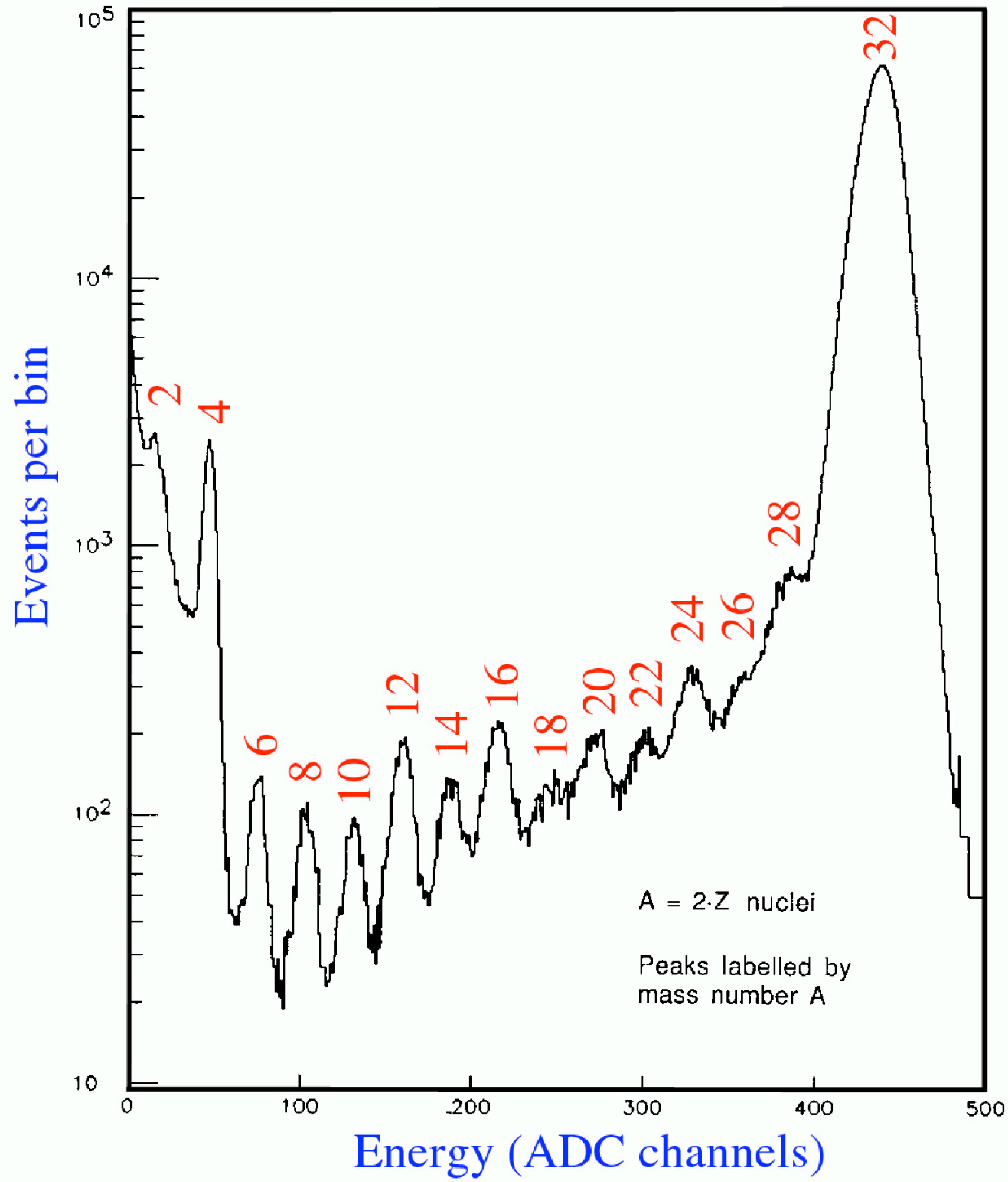


FIG. 7.51. The WA80 calorimeter as a high-resolution spectrometer. Total energy measured with the calorimeter for minimum-bias events revealed the composition of the momentum-selected CERN heavy-ion beam [You 89].

The importance of (hadronic) energy resolution (2)

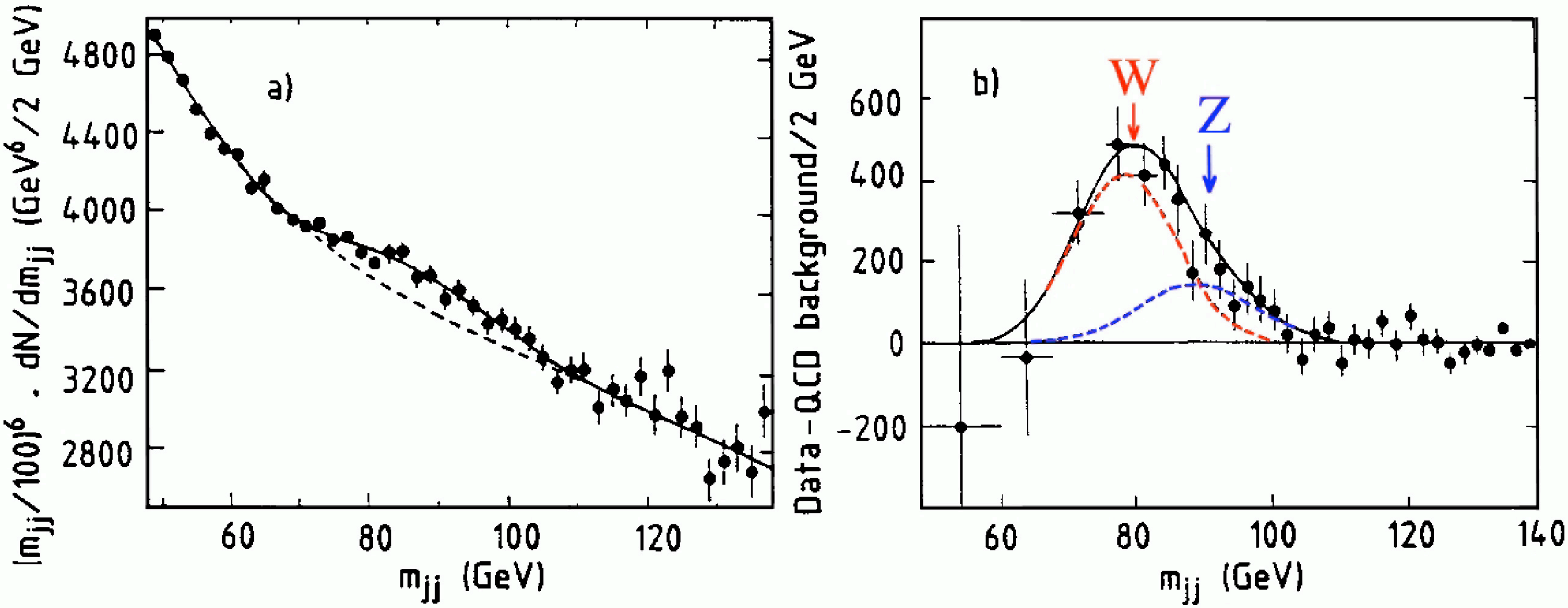


FIG. 7.50. Two-jet invariant mass distributions from the UA2 experiment [Alit 91]. Diagram *a*) shows the measured data points, together with the results of the best fits to the QCD background alone (*dashed curve*), or including the sum of two Gaussian functions describing $W, Z \rightarrow q\bar{q}$ decays. Diagram *b*) shows the same data after subtracting the QCD background. The data are compatible with peaks at $m_W = 80$ GeV and $m_Z = 90$ GeV. The measured width of the bump, or rather the standard deviation of the mass distribution, was 8 GeV, of which 5 GeV could be attributed to non-ideal calorimeter performance [Jen 88].

Particle identification with calorimeters

e/π separation using time structure signals

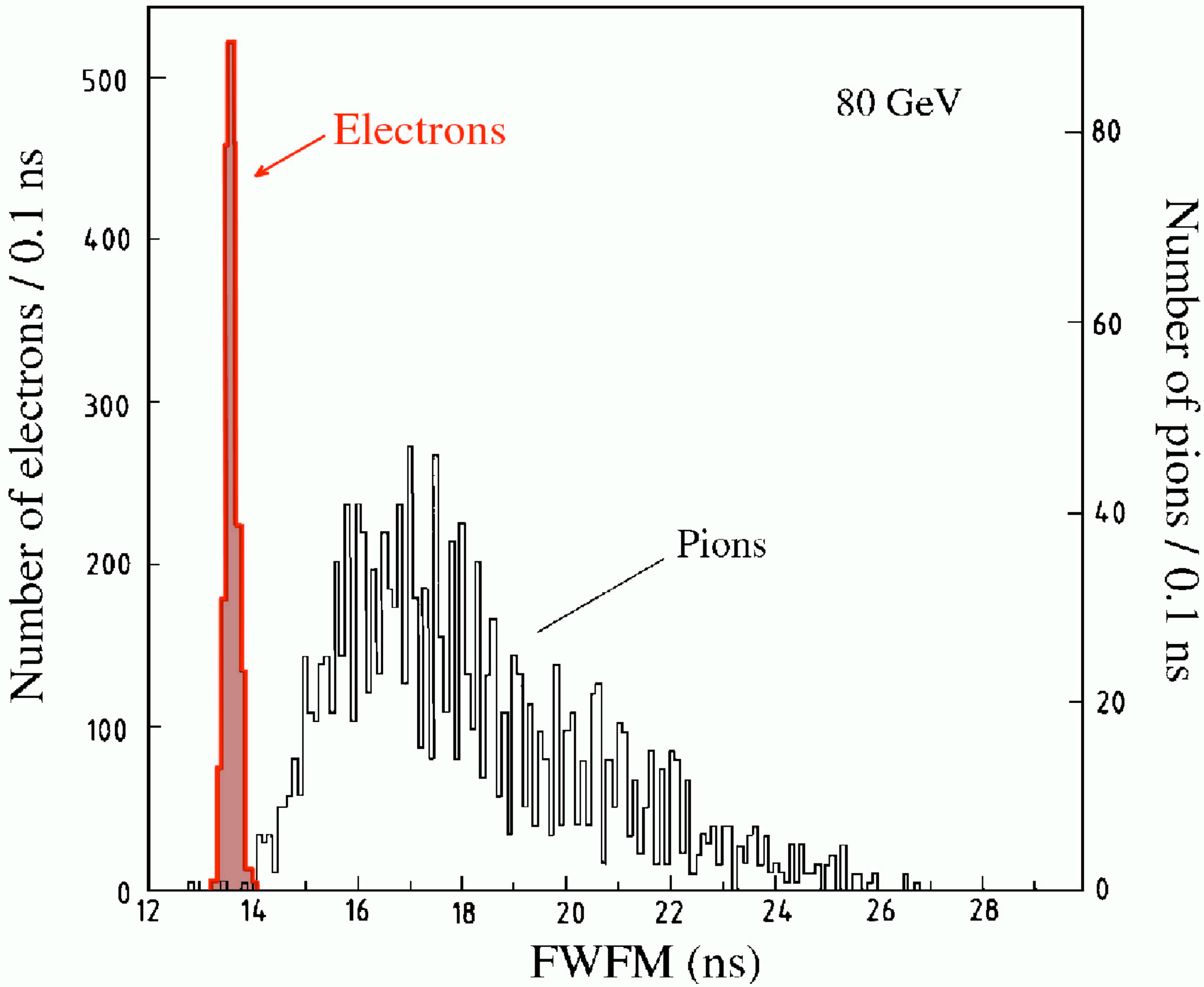


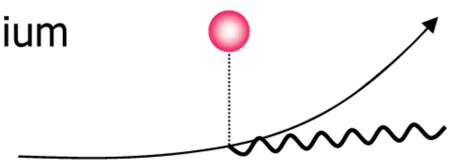
FIG. 7.33. The distribution of the full width at one-fifth maximum (FWFM) for 80 GeV electron and pion signals in SPACAL [Aco 91a].

Calorimeters

Electromagnetic shower development

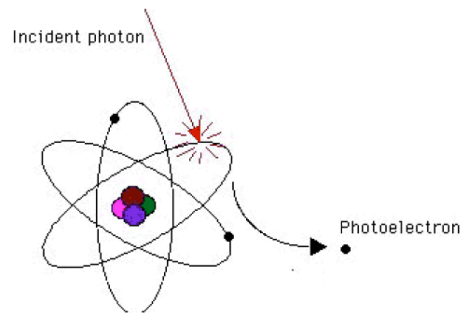
Processes that play a role in total absorption of high-energy particles are more complicated than just ionization of the traversed material

- *Electrons: "bremsstrahlung". Photons: Compton effect, pair production*
  - Radiation of real photons in the Coulomb field of the nuclei of the medium
    - Any deflection of the electron from its original trajectory accompanied by radiation of photons and deceleration of electrons



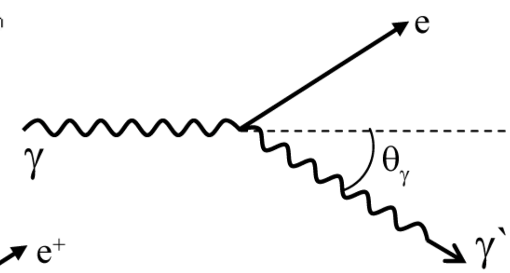
  - Photo-electric effect

$$\sigma_{ph-el} \propto Z^5 \frac{1}{\varepsilon} \qquad \varepsilon = \frac{E_\gamma}{m_e c^2}$$



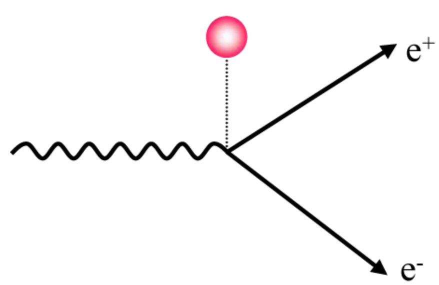
  - Compton scattering: $\gamma + e \rightarrow \gamma' + e'$

$$\sigma_c \propto \frac{\ln \varepsilon}{\varepsilon}$$



  - Pair production: γ + nucleus $\rightarrow e^+ e^-$ + nucleus
    - Process independent of energy
    - Dominates at high energies

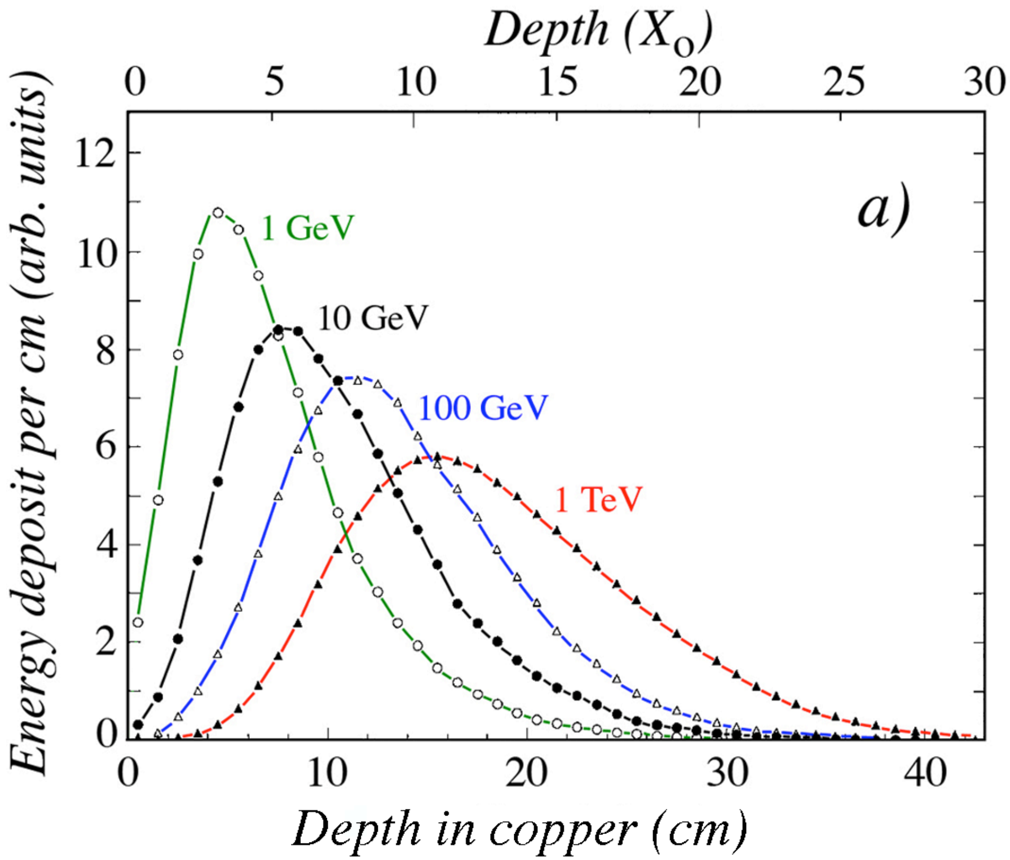
$$\sigma_{pair} \propto Z^2$$

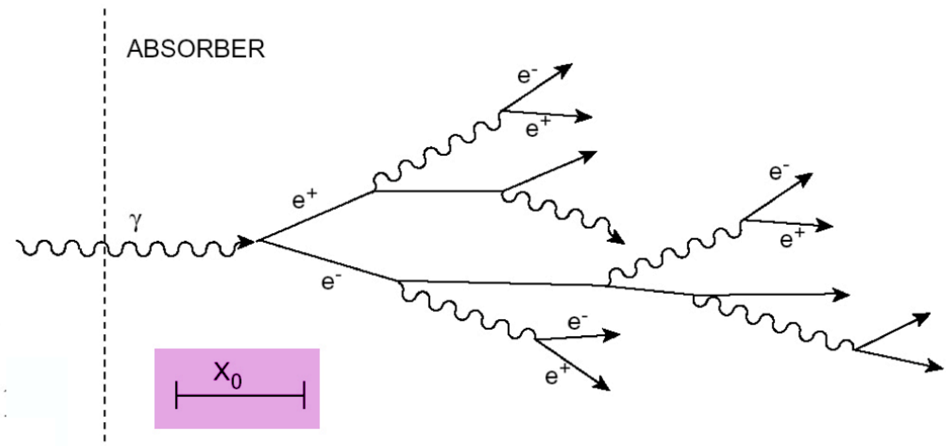


Calorimeters

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.





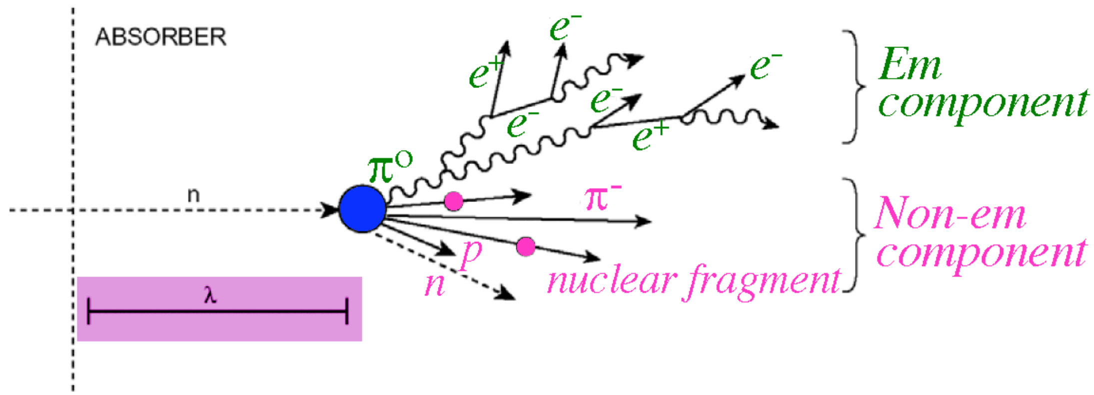
The shower development is governed by the "radiation length" X_o, which is typically ~ 1 cm

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

Calorimeters

Hadronic shower development

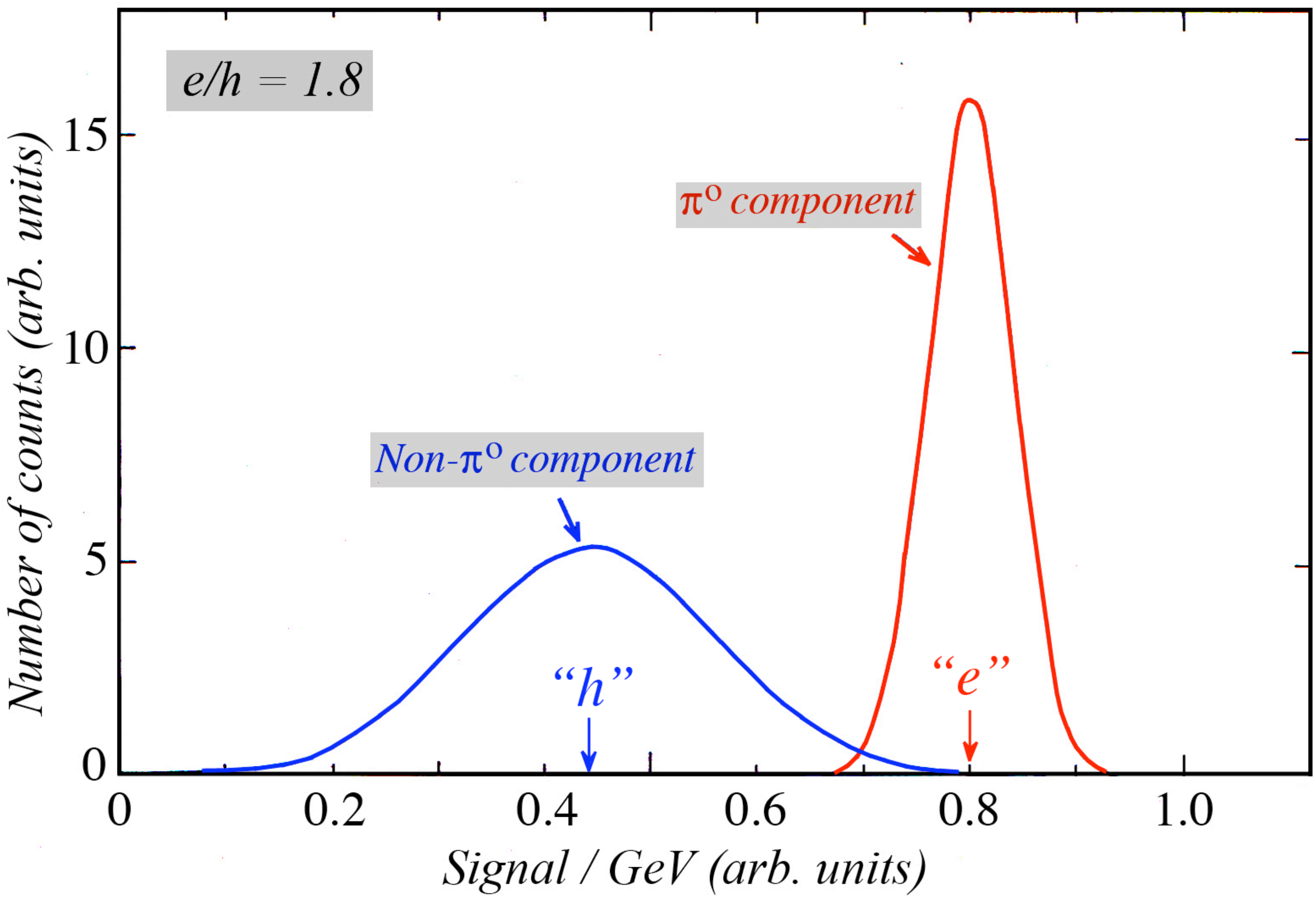
- *There are many more processes involved in hadronic shower development. Also, some fraction of the energy is deposited through electromagnetic cascades*
- *A hadronic shower consists of two components*
  - *Electromagnetic component*
    - electrons, photons
    - neutral pions $\rightarrow 2\,\gamma$
  - *Hadronic (non-em) component*
    - charged hadrons $\pi^{\pm}$,$K^{\pm}$
    - nuclear fragments, p
    - neutrons, neutrino's, soft γ's
    - break-up of nuclei (*"invisible"*)



- *Hadronic shower development governed by nuclear interaction length λ*
  λ is typically $\gg X_o$, ~20 cm ⟶ it takes tonnes to contain hadronic showers
- *Hadronic showers are characterized by very large fluctuations*
- *Calorimetric techniques are destructive, but work for charged + neutral particles*
  - Charged particles: complementary information to momentum measurement
  - Neutral particles: only way to obtain kinematic information

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

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



Hadronic shower profiles: Fluctuations!

π^o production may take place anywhere in the absorber

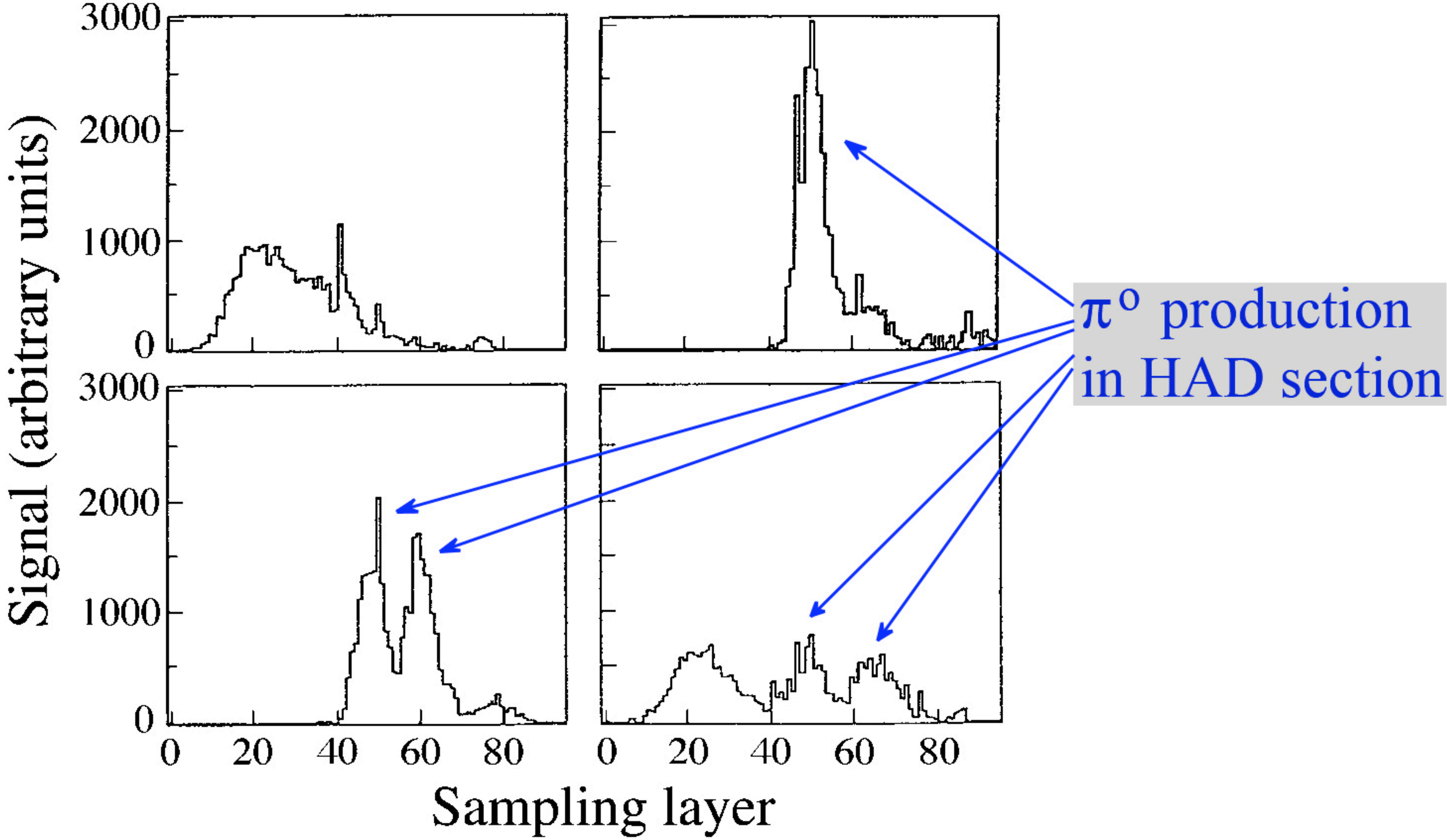
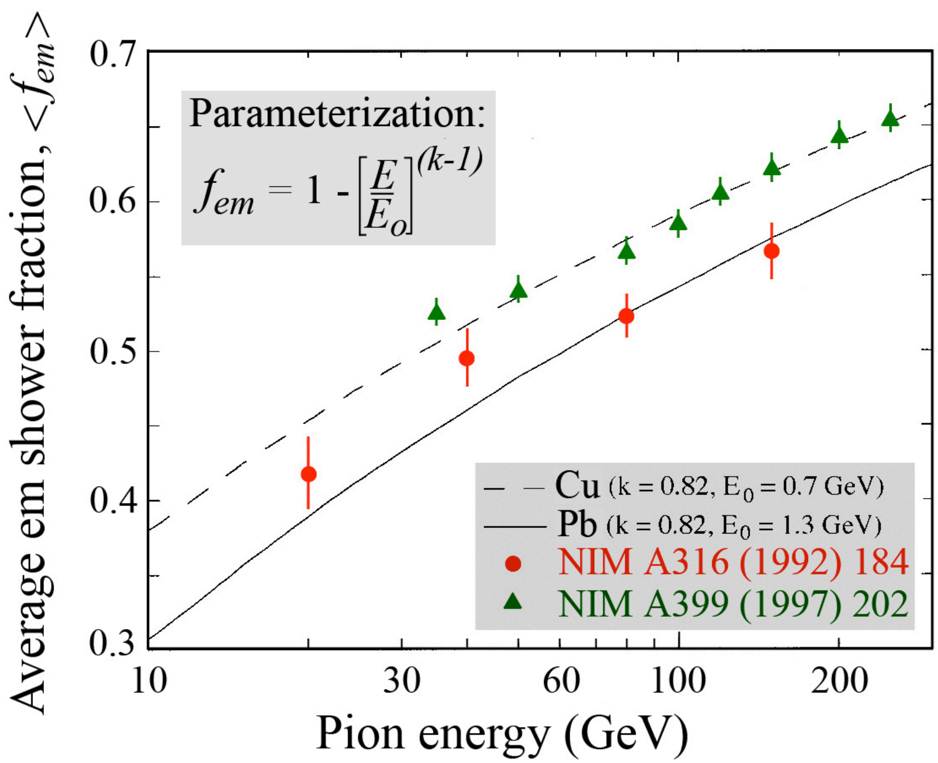


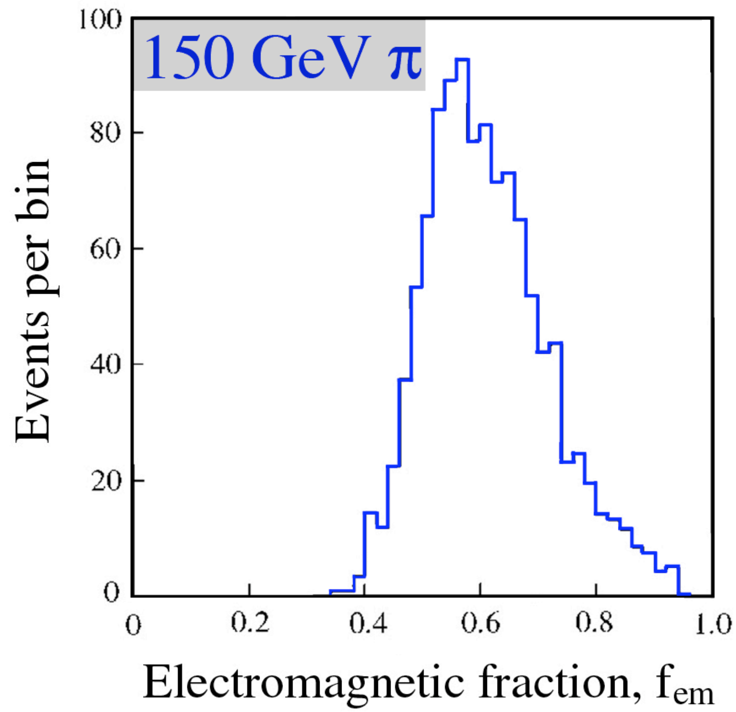
FIG. 2.35. Longitudinal profiles for 4 different showers induced by 270 GeV pions in a lead/iron/plastic-scintillator calorimeter. Data from [Gre 94].

(Fluctuations in) the electromagnetic shower fraction, f_{em}

i.e. the fraction of the shower energy deposited by π^os



The em fraction is, on average,
large and energy dependent



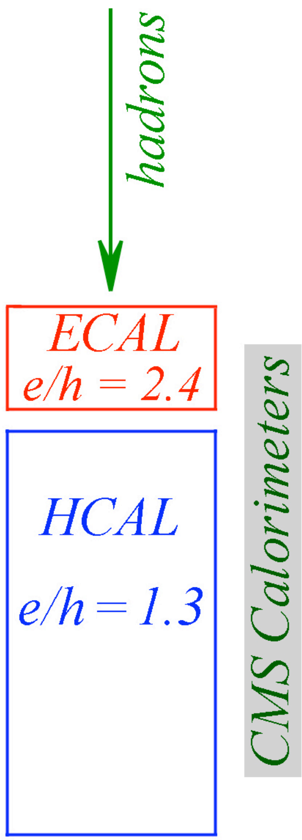
Fluctuations in f_{em} are
large and non-Poissonian

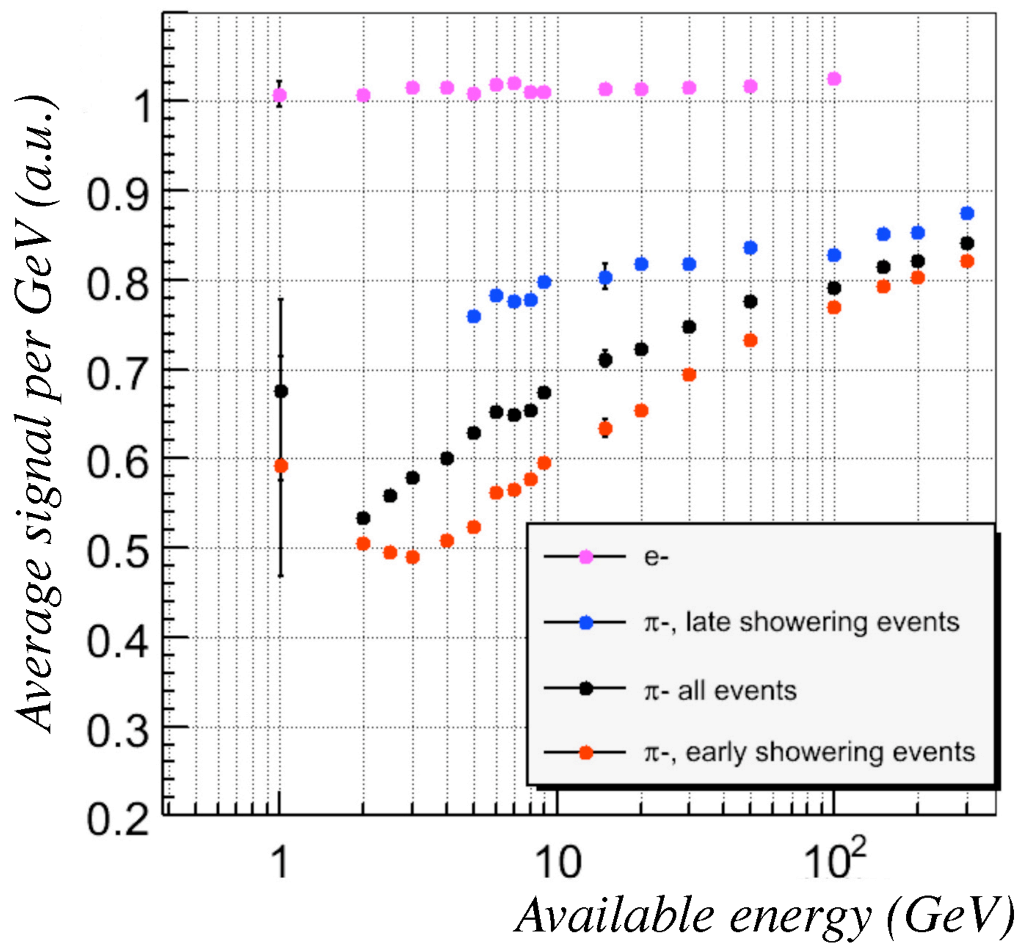
Consequences for LHC calorimeters

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 $e/h = 1.3$

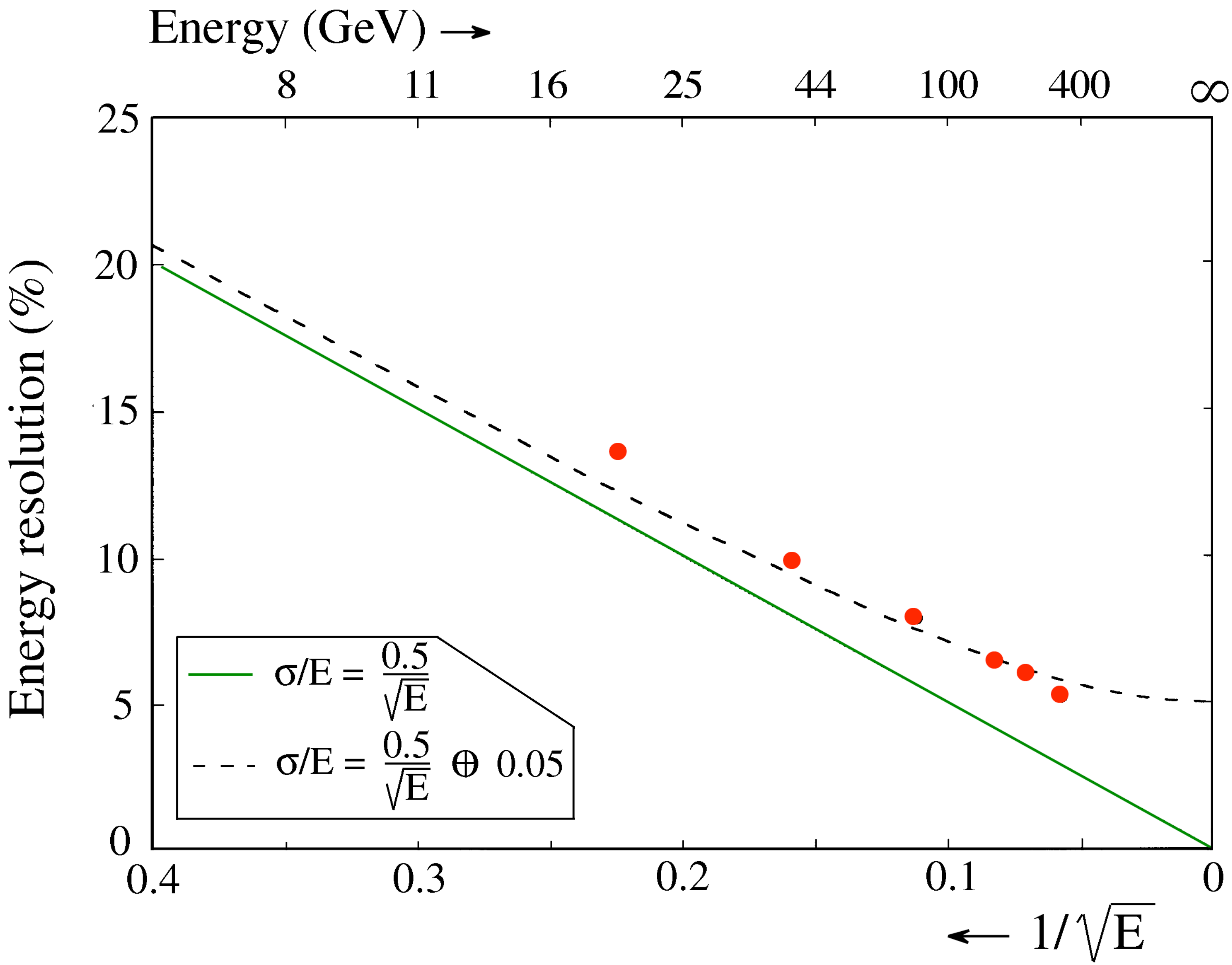
→ *Response depends strongly on starting point shower*





Consequences for LHC calorimeters

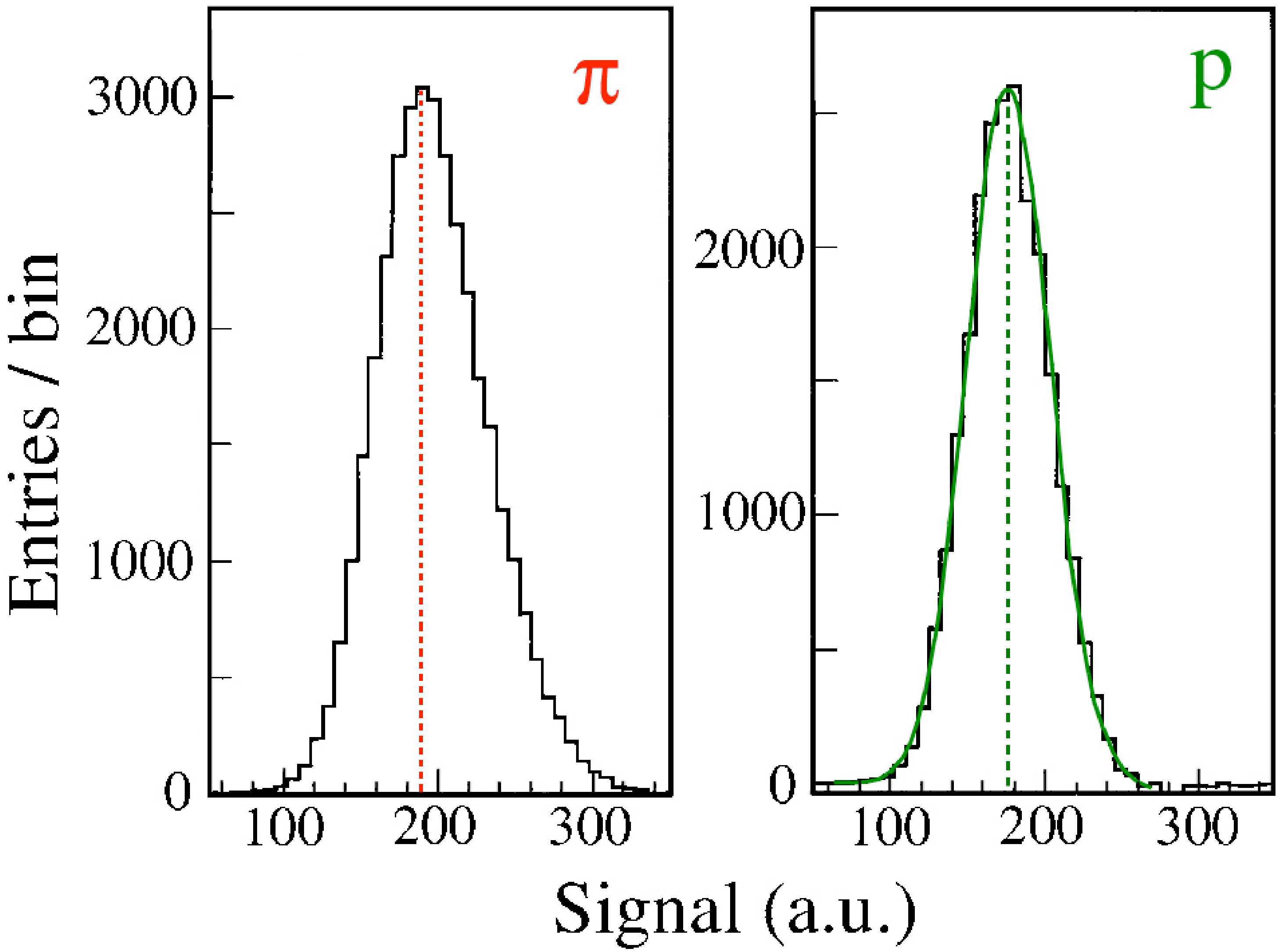
Hadronic energy resolution (ATLAS): no $E^{-1/2}$ scaling



Consequences for LHC calorimeters

Different response functions for (300 GeV) p, π

CMS



Important calorimeter features

- Energy resolution
- Position resolution (need 4-vectors for physics)
- Signal speed
- Particle ID capability

but also

- *Gaussian response function* (avoid bias for steeply falling distributions)
- *Signal linearity*, or at least
- Well known relationship between signal & energy *(reliable calibration)*

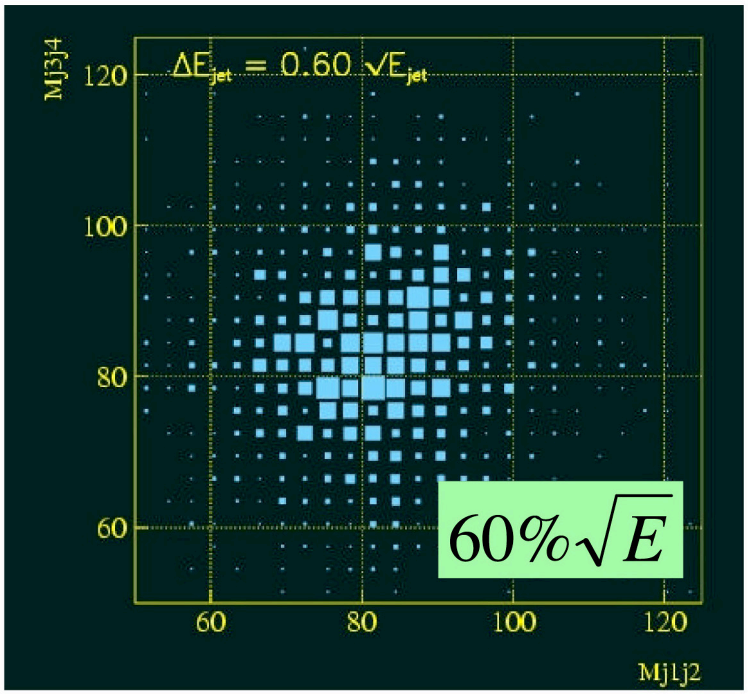
Most hadron calorimeters fall short in this respect

Design goal ILC/CLIC: separate W,Z $\rightarrow q\bar{q}$

- *Hadronic energy resolution very important for this multi-jet spectroscopy.*

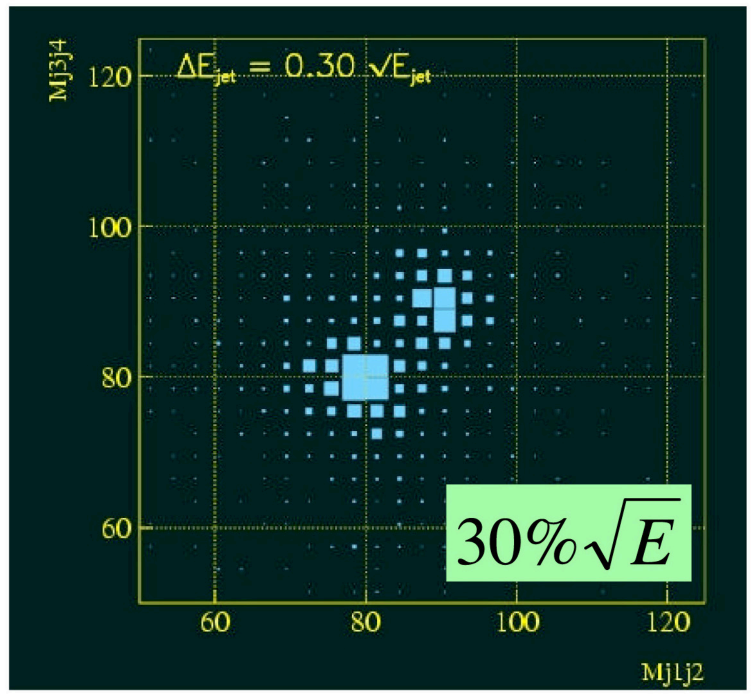
LEP-like detector

M_{jj}



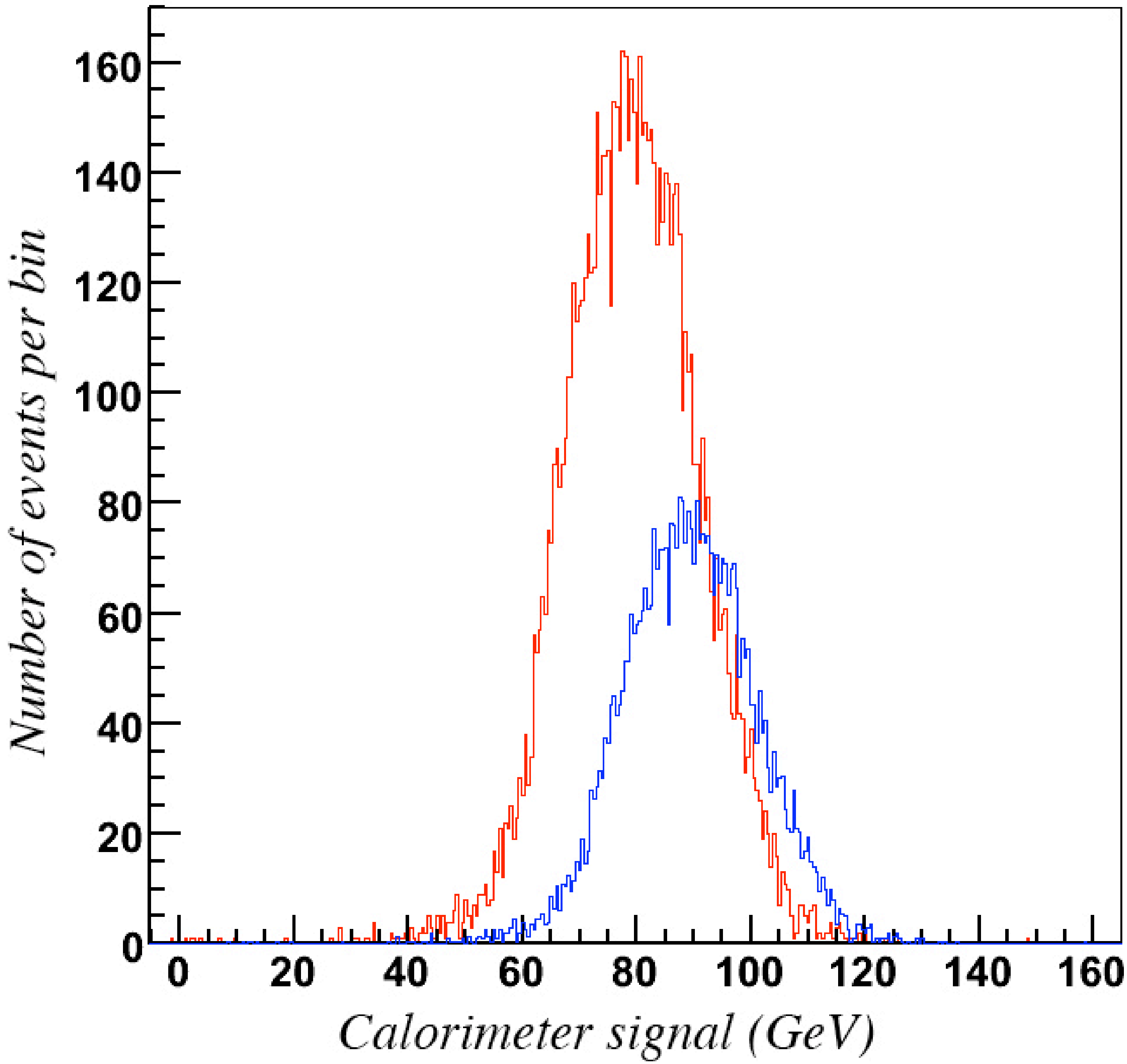
M_{jj}

LC design goal



- *No kinematic constraints as in LEP (beamstrahlung)*

Hadron Detection in CMS



Fluctuations in the em shower component (f_{em})

- *Why are these important ?*
  - Electromagnetic calorimeter response ≠ non-em response *($e/h \neq 1$)*
  - Event-to-event fluctuations are large and *non-Gaussian*
  - *$\langle f_{em} \rangle$ depends on* shower *energy* and *age*

- *Cause of all common problems in hadron calorimeters*
  - *Energy scale* different from electrons, in energy-dependent way
  - Hadronic *non-linearity*
  - *Non-Gaussian* response function
  - Poor energy *resolution*
  - *Calibration* of the sections of a longitudinally segmented detector

Recent results from the DREAM * *project*

* DREAM is a collaboration of US and Italian institutions
TTU, UCSD, ISU (USA), PV, RM1, CS, CG, PI (I)

An attractive option for improving the quality of hadron calorimetry:

Use Čerenkov light!! *Why?*

Hadron showers < *em* component (π^o) / *non-em* component (mainly soft *p*)

Calorimeter response to these components not the same *(e/h ≠ 1)*

Čerenkov light almost exclusively produced by em component *
(~80% of non-em energy deposited by non-relativistic particles)

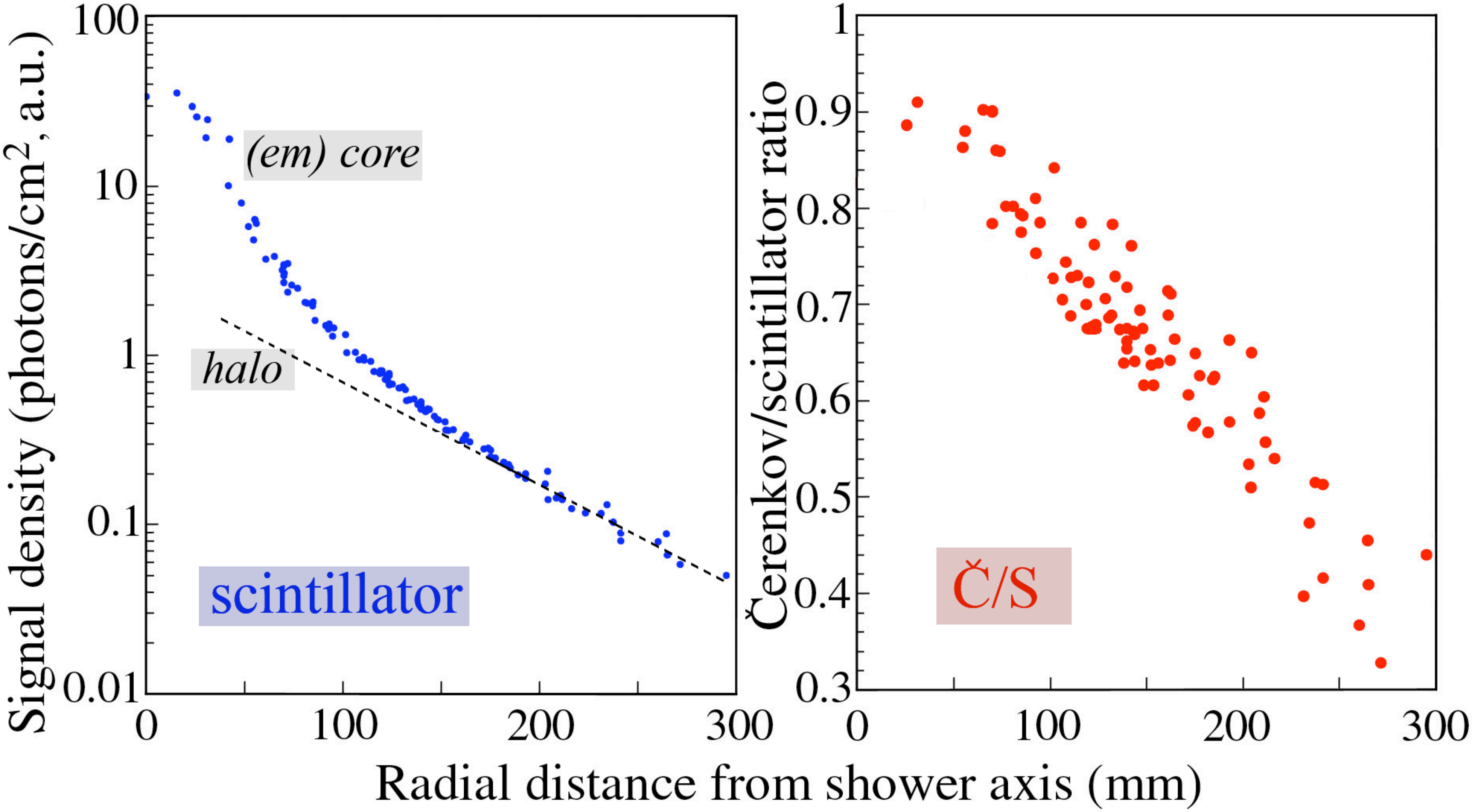
➡ DREAM (Dual READout Method) principle:

Measure f_{em} event by event by comparing Č and dE/dx signals

* How do we know this?

- CMS HF: *e/h* ~ 5
- Lateral profiles of hadronic showers

Radial hadron shower profiles (DREAM)



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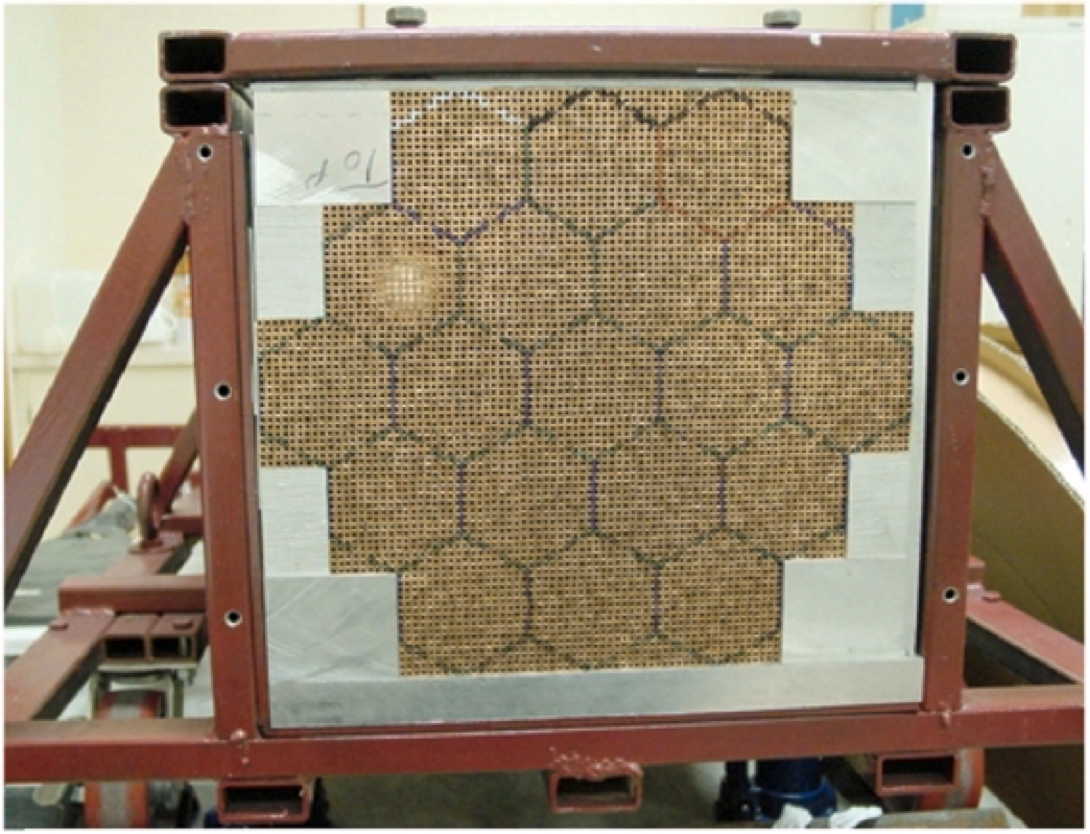
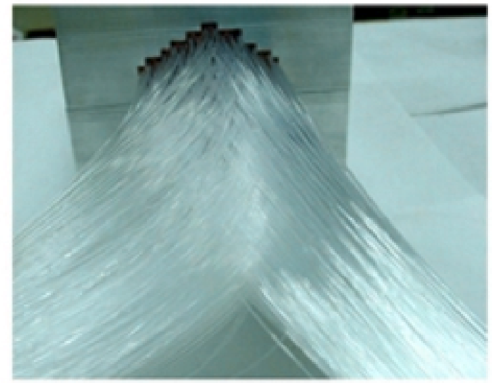
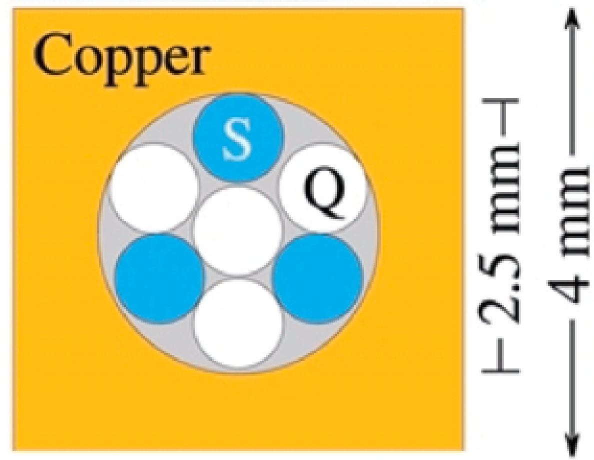
NIM A584 (2008) 273

DREAM: Structure

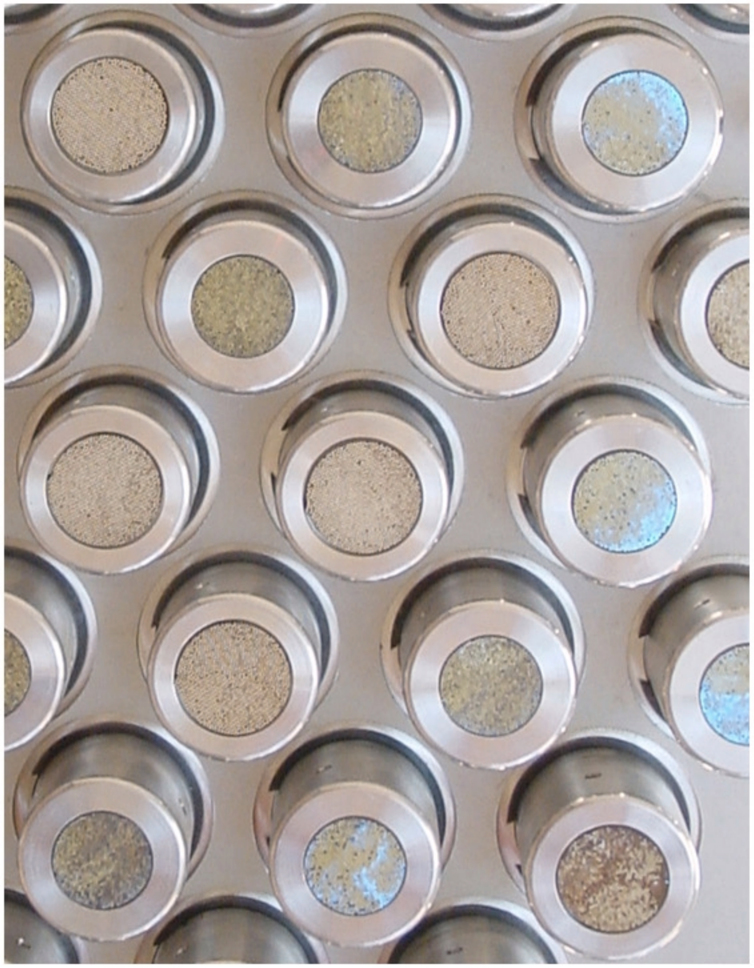


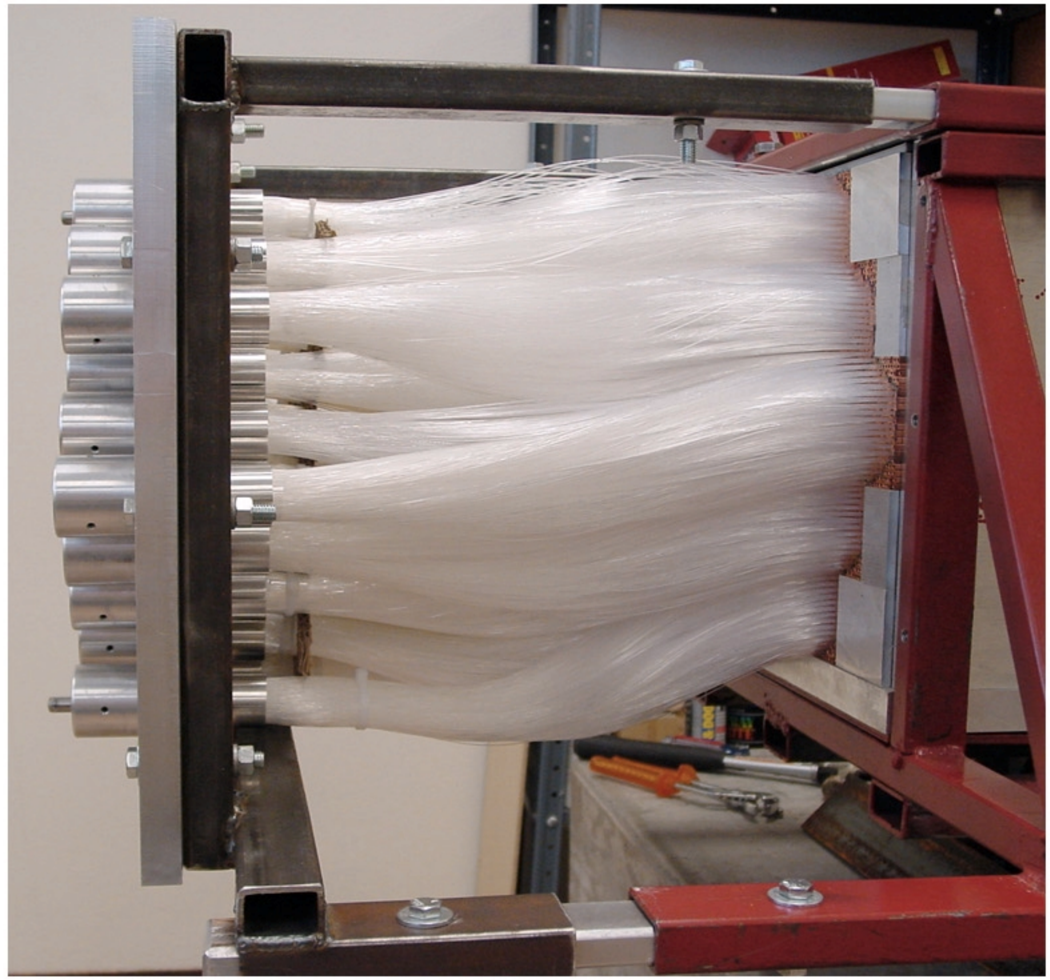


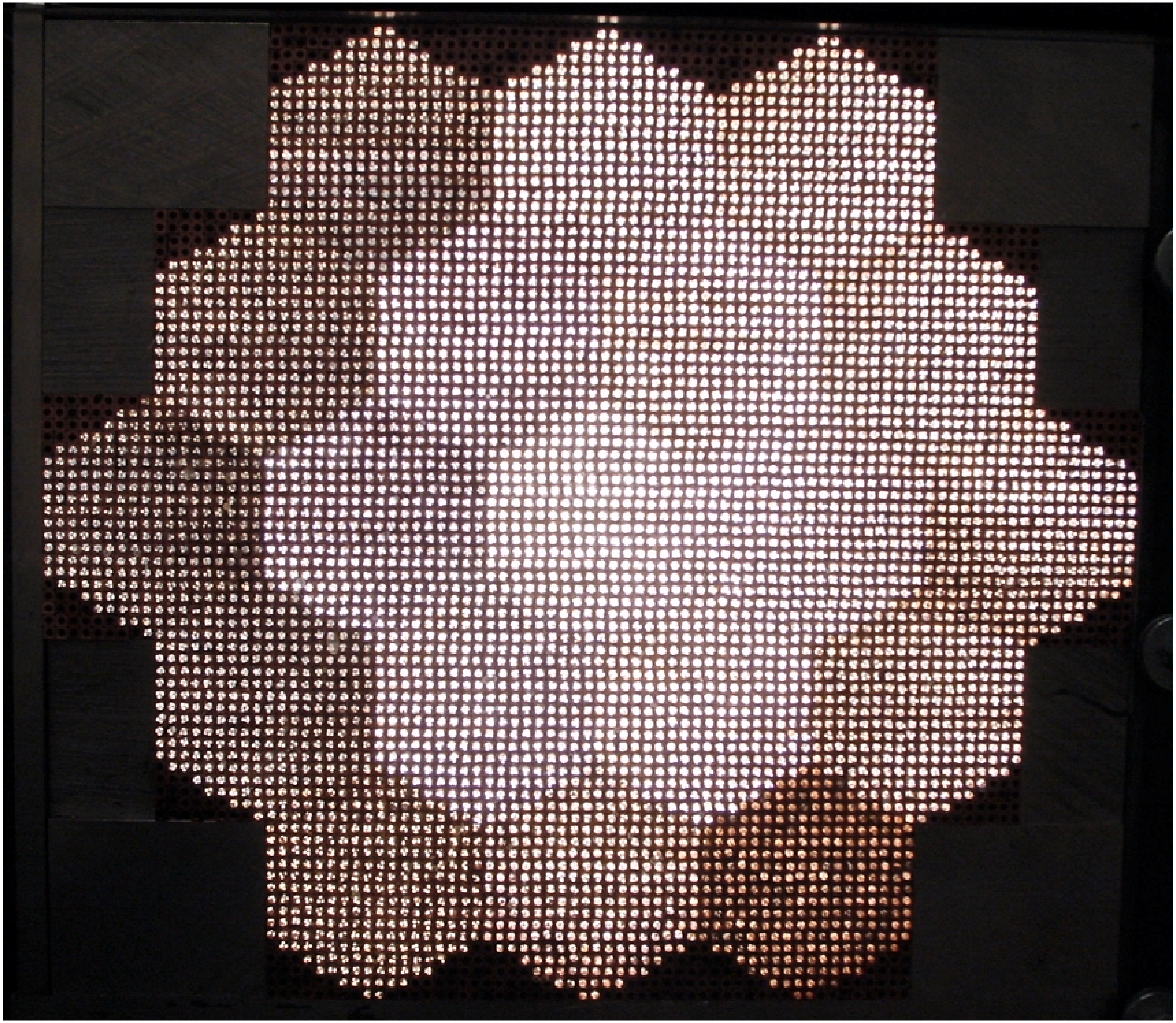


- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

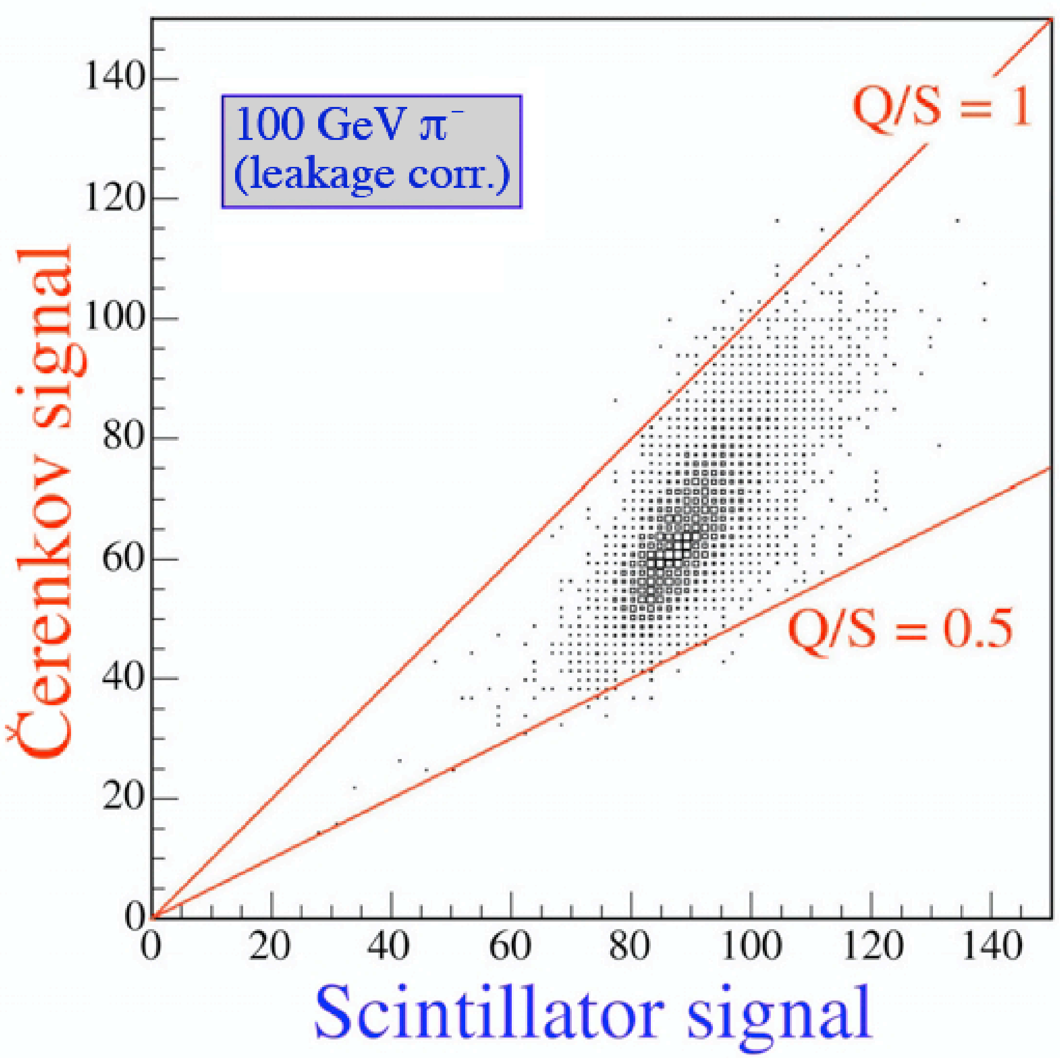
DREAM readout







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



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

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

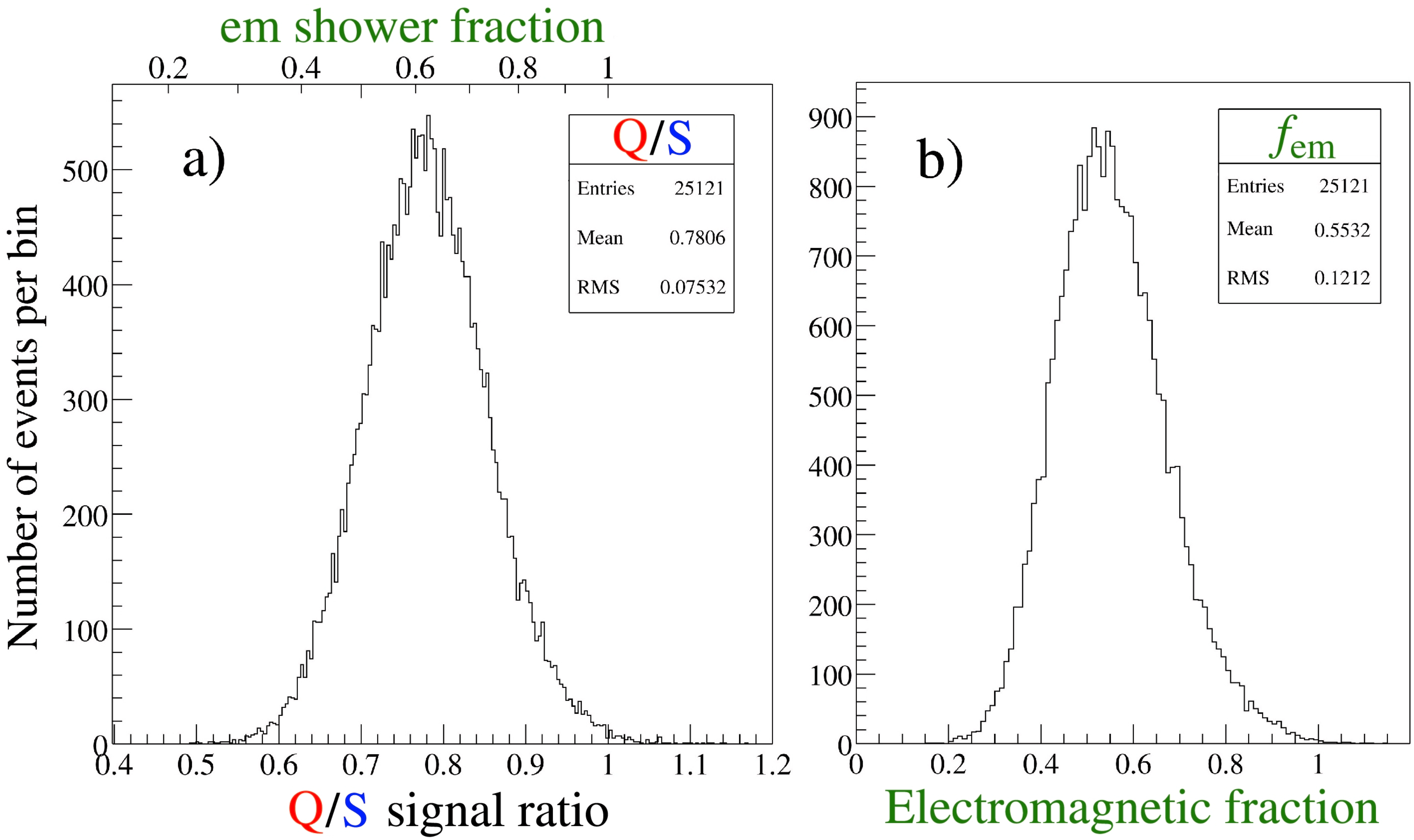
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

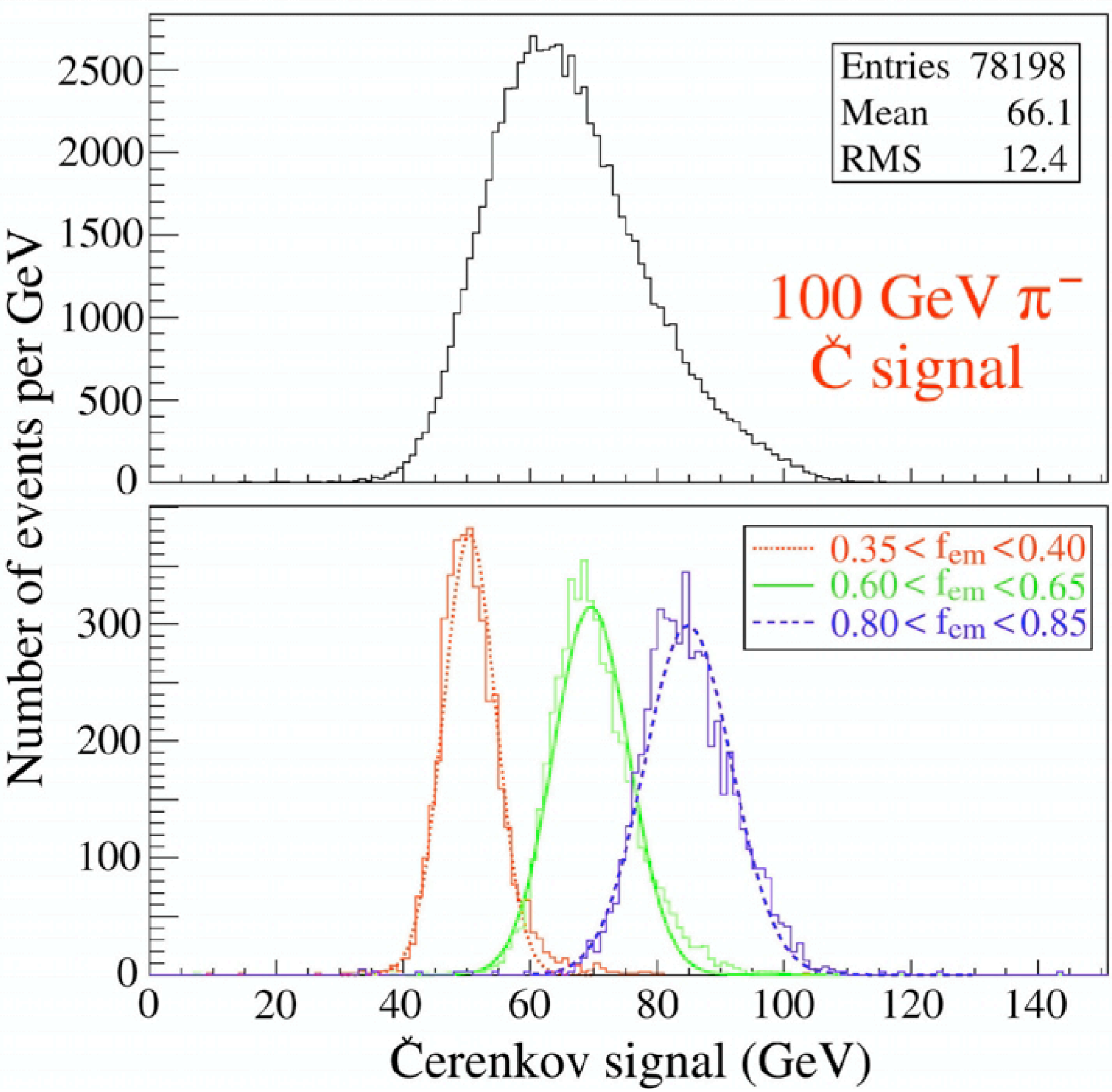
$$E = \frac{S - \chi Q}{1 - \chi}$$

with $\chi = \dfrac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

DREAM: relationship between Q/S ratio and f_{em}



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



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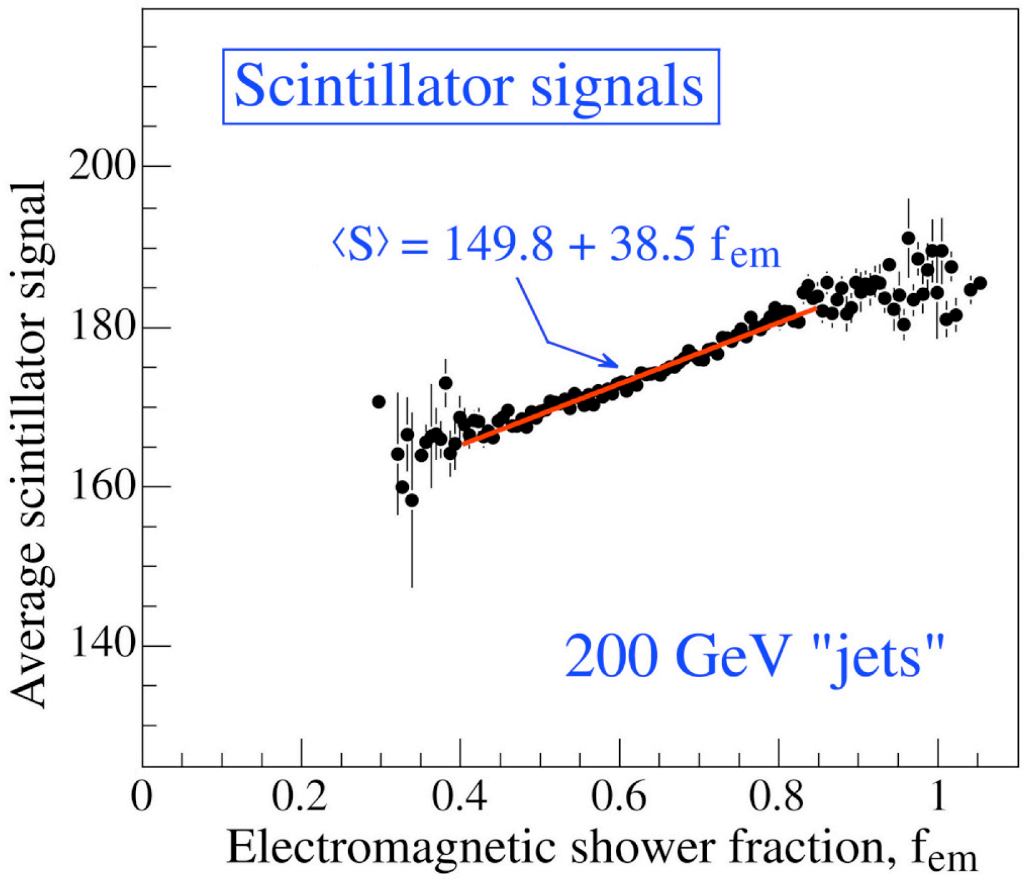
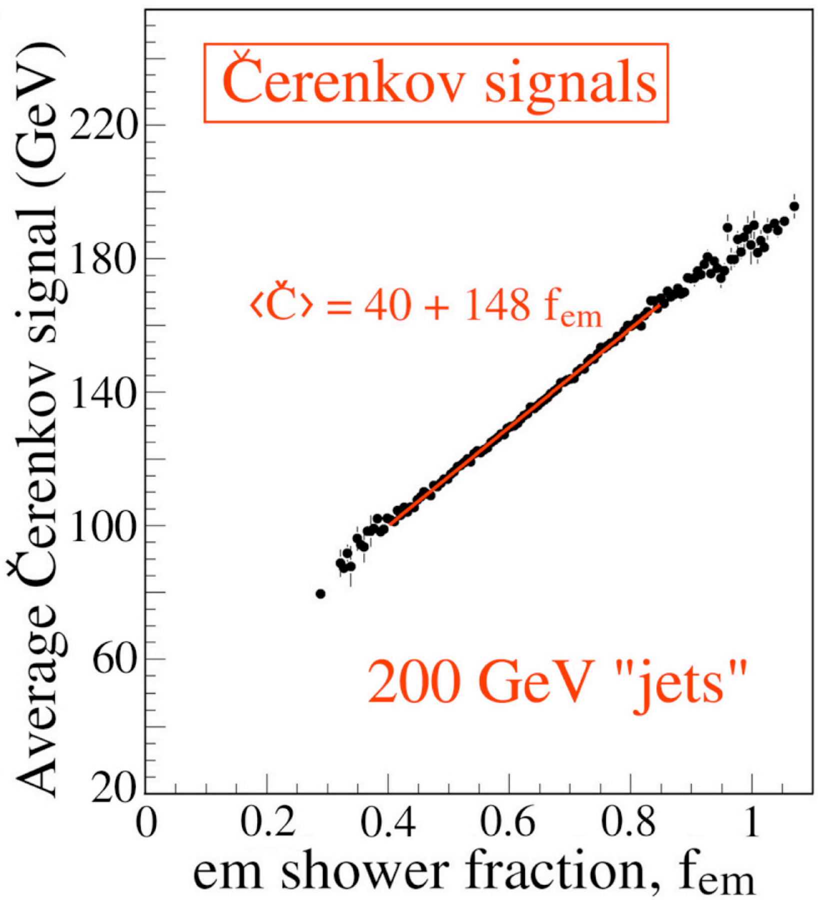
NIM A537 (2005) 537

DREAM: Signal dependence on f_{em}





$$R(f_{\text{em}}) = p_0 + p_1 \, f_{\text{em}}$$ with $$\frac{p_1}{p_0} = e/h - 1$$

Cu/scintillator e/h = 1.3

Cu/quartz e/h = 4.7

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Effects of Q/S corrections on

hadronic signal linearity and jet resolution

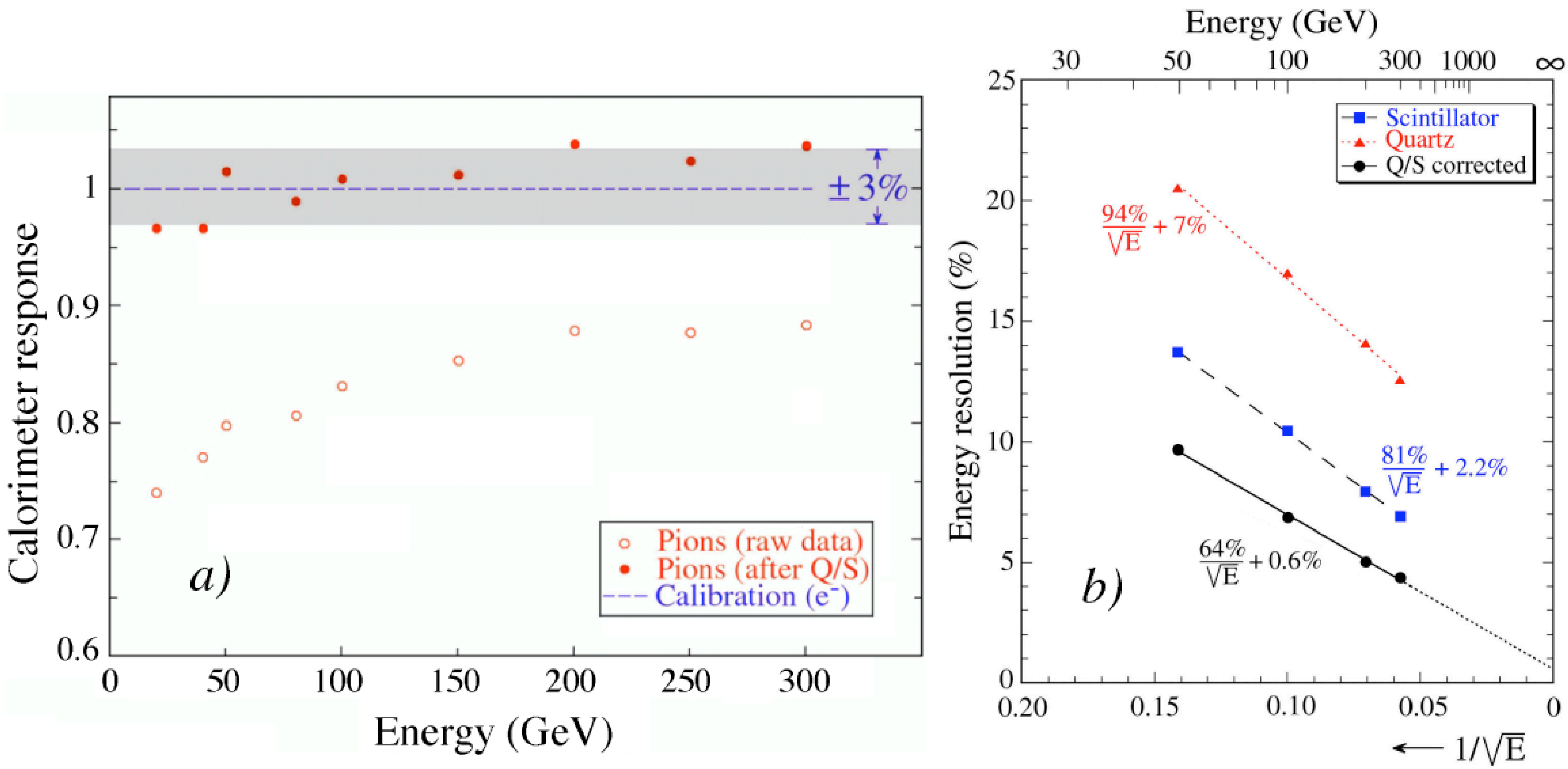
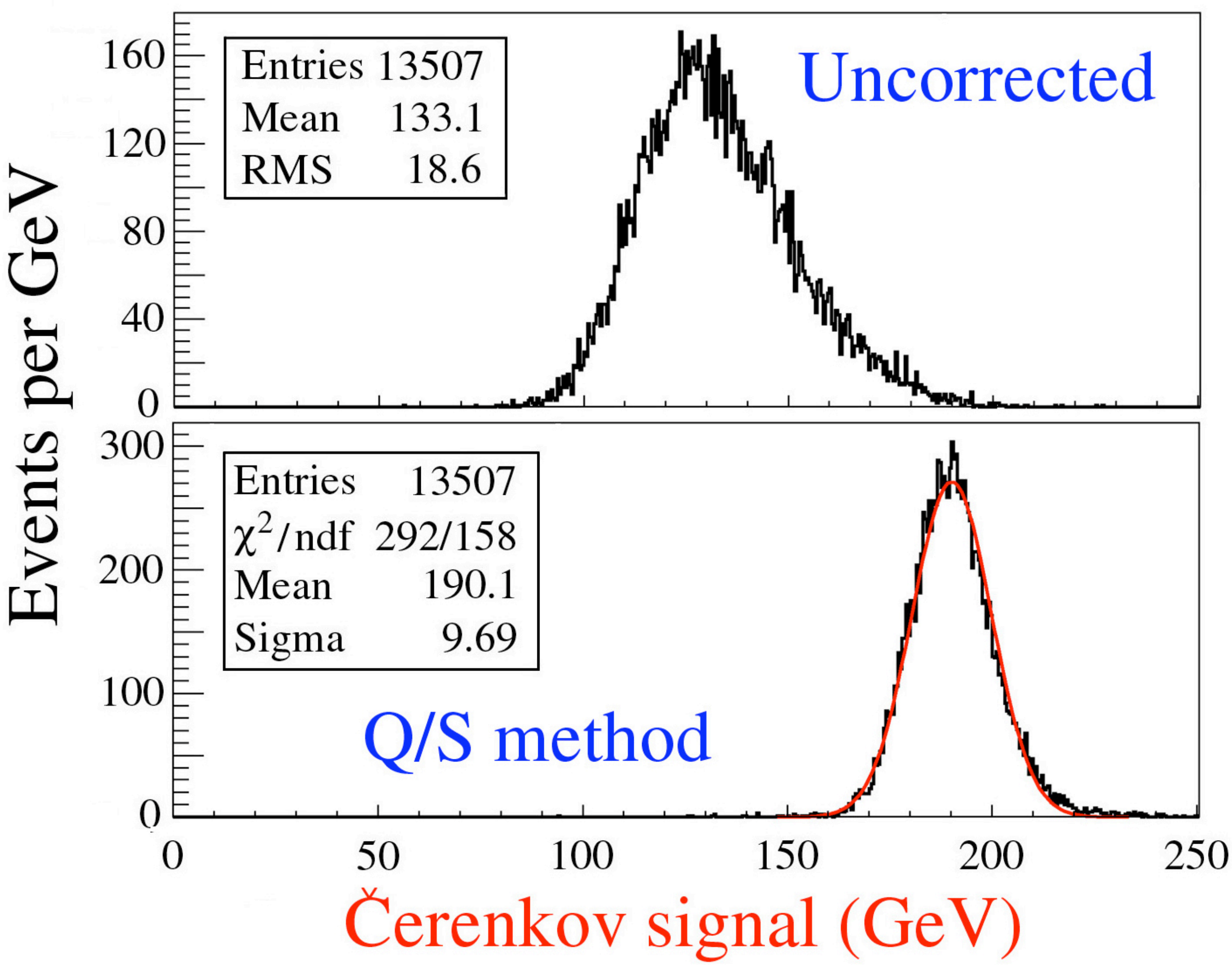


Figure 9: The scintillator response of the DREAM calorimeter to single pions (a) and the energy resolution for "jets" (b), before and after the dual-readout correction procedures were applied to the signals [5].

DREAM: Effect of corrections (200 GeV "jets")



CONCLUSIONS
from tests

- DREAM offers a powerful technique to *improve* hadronic calorimeter performance:
  - Correct hadronic energy reconstruction, *in an instrument calibrated with electrons!*
  - Linearity for hadrons and jets
  - Gaussian response functions
  - Energy resolution scales with $1/\sqrt{E}$
  - $\sigma/E < 5\%$ for high-energy "jets", in a detector with a mass of only 1 ton!
    dominated by fluctuations in shower leakage

- These, and many other, experimental results are described in 3 papers:

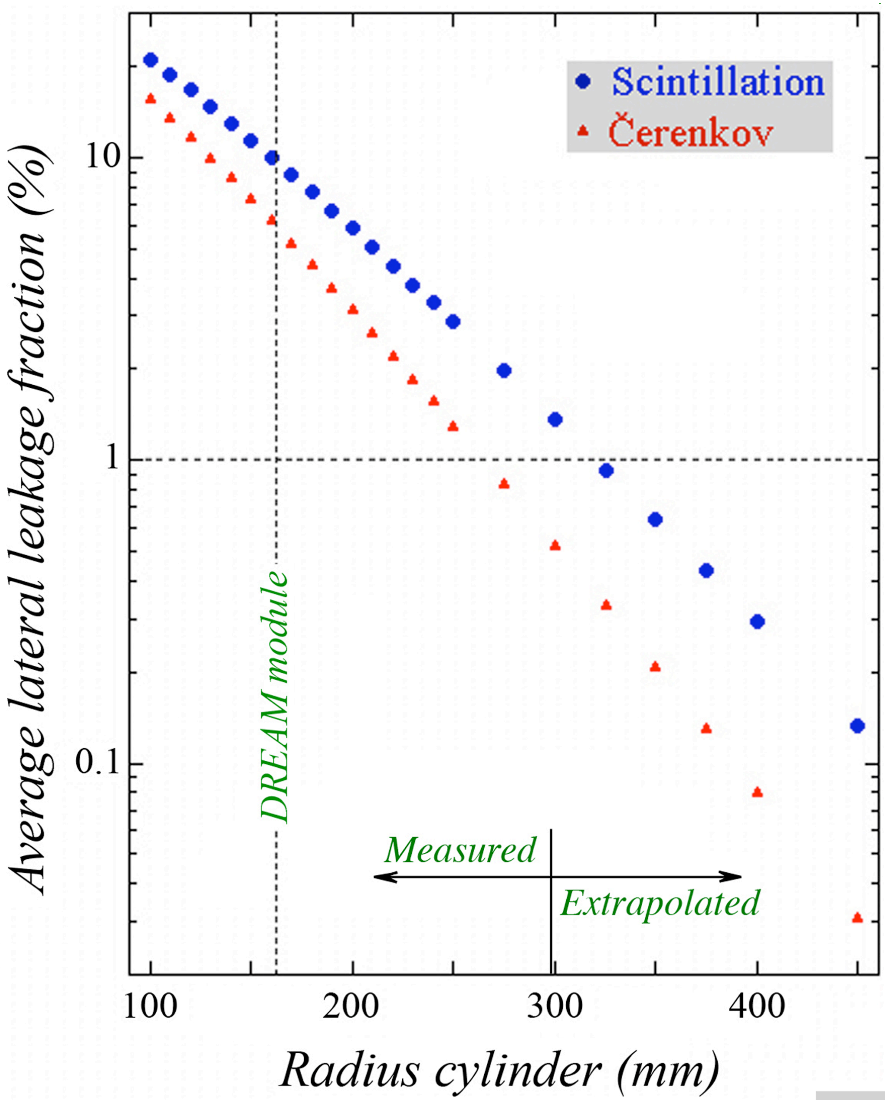
Hadrons & jets:	Nucl. Instr. & Meth. A537 (2005) 537
Electrons:	Nucl. Instr. & Meth. A536 (2005) 29
Muons:	Nucl. Instr. & Meth. A533 (2004) 305

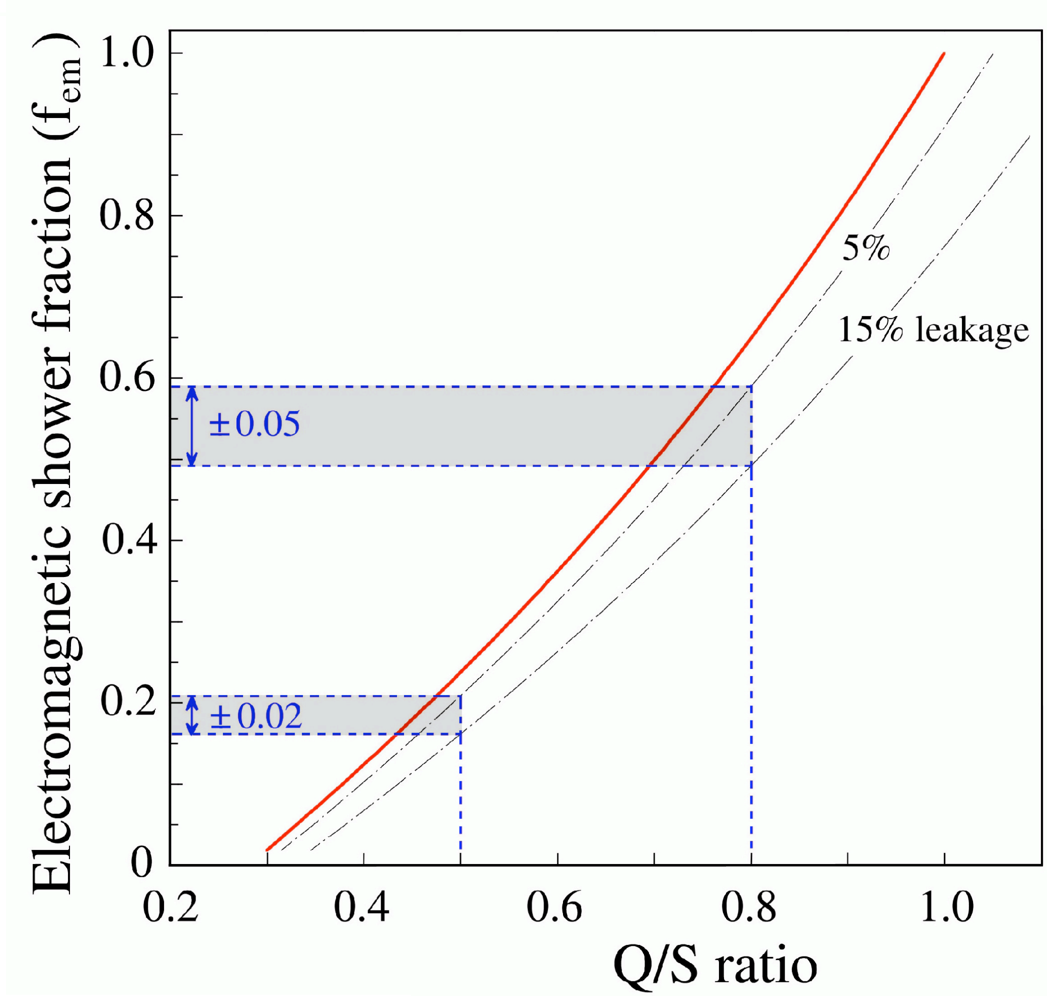
How to improve DREAM performance

- Build a larger detector ⟶ *reduce effects side leakage*

DREAM: The importance of leakage and its fluctuations

Lateral shower containment (π)





From:
NIM A584 (2008) 273

How to improve DREAM performance ?

- Build a larger detector ⟶ *reduce effects side leakage*

- *Increase Čerenkov light yield*

  DREAM: 8 p.e./GeV ⟶ fluctuations contribute 35%/$\sqrt{E}$

  No reason why DREAM principle is limited to fiber calorimeters

Homogeneous detector ?!

⟶ *Need to separate the light into its Č, S components*

Čerenkov component in light from $PbWO_4$ crystals?

- Light yield typically ~10 p.e./MeV (dependent on T, readout)
- Lead glass: 500 - 1000 p.e./GeV from Čerenkov effect (3 - 5%/$\sqrt{E}$)

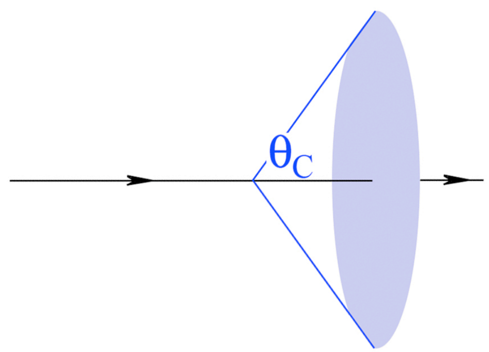
  ⟶ *Expect substantial Č component in $PbWO_4$ signals*

- *How to detect / isolate Čerenkov component?*

  - *Directionality of Čerenkov component*
  - *Time structure of the signals*
  - *Spectral differences*

Experimental setup Čerenkov measurements

(directionality)



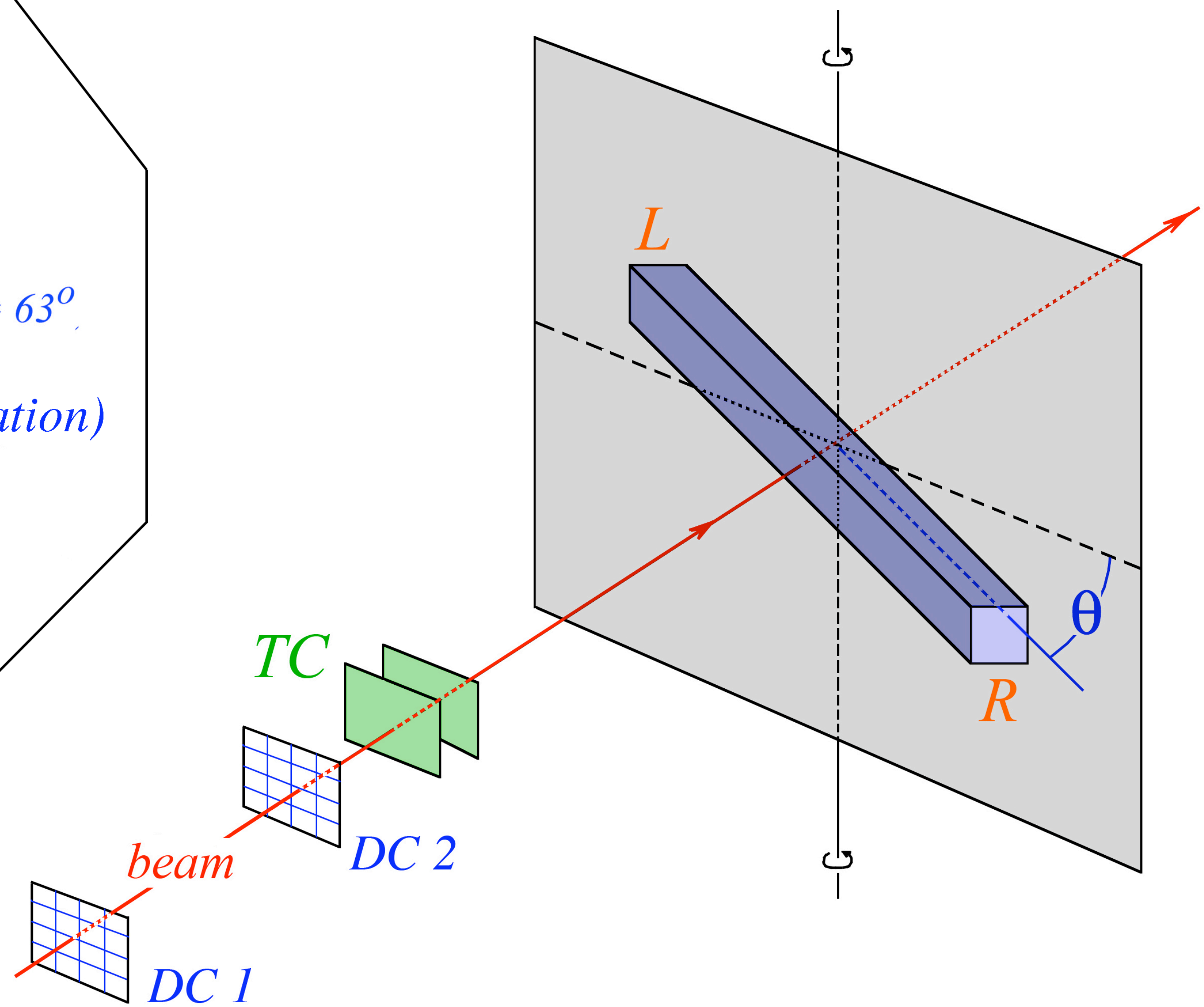
$n = 2.2$, $\cos\theta_C = 1/n \longrightarrow \theta_C = 63^o$

$\theta = 0 \longrightarrow L = R$ *(calibration)*

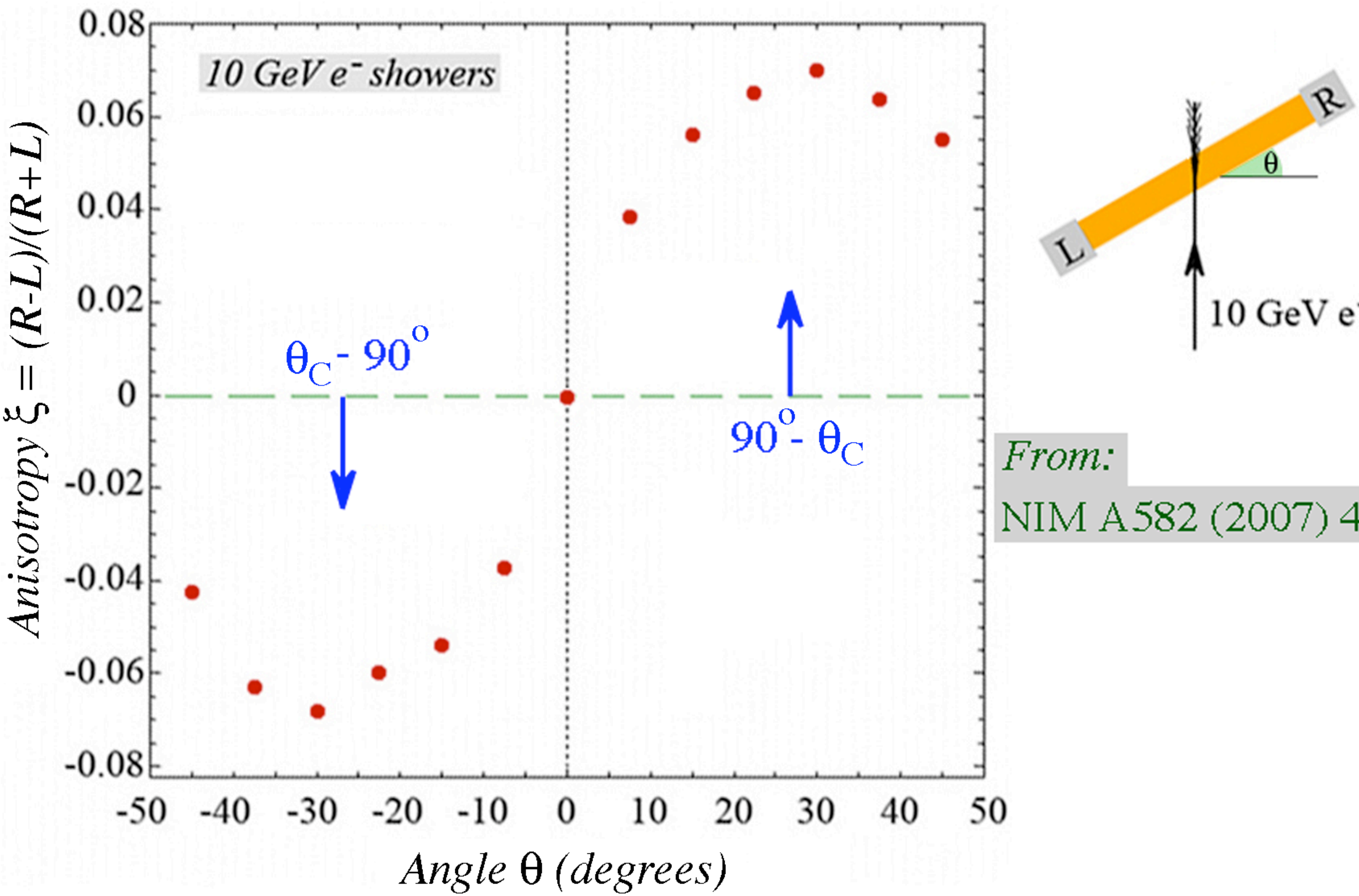
$\theta < 0 \longrightarrow L > R$

$\theta > 0 \longrightarrow L < R$

Measure $\frac{L-R}{L+R}(\theta)$



Experimental results $PbWO_4$: Directionality



From:
NIM A582 (2007) 474

Experimental results $PbWO_4$: *Time structure of the signals*

The importance of time resolution for the $PbWO_4$ signals (0.4 ns sampling oscilloscope)

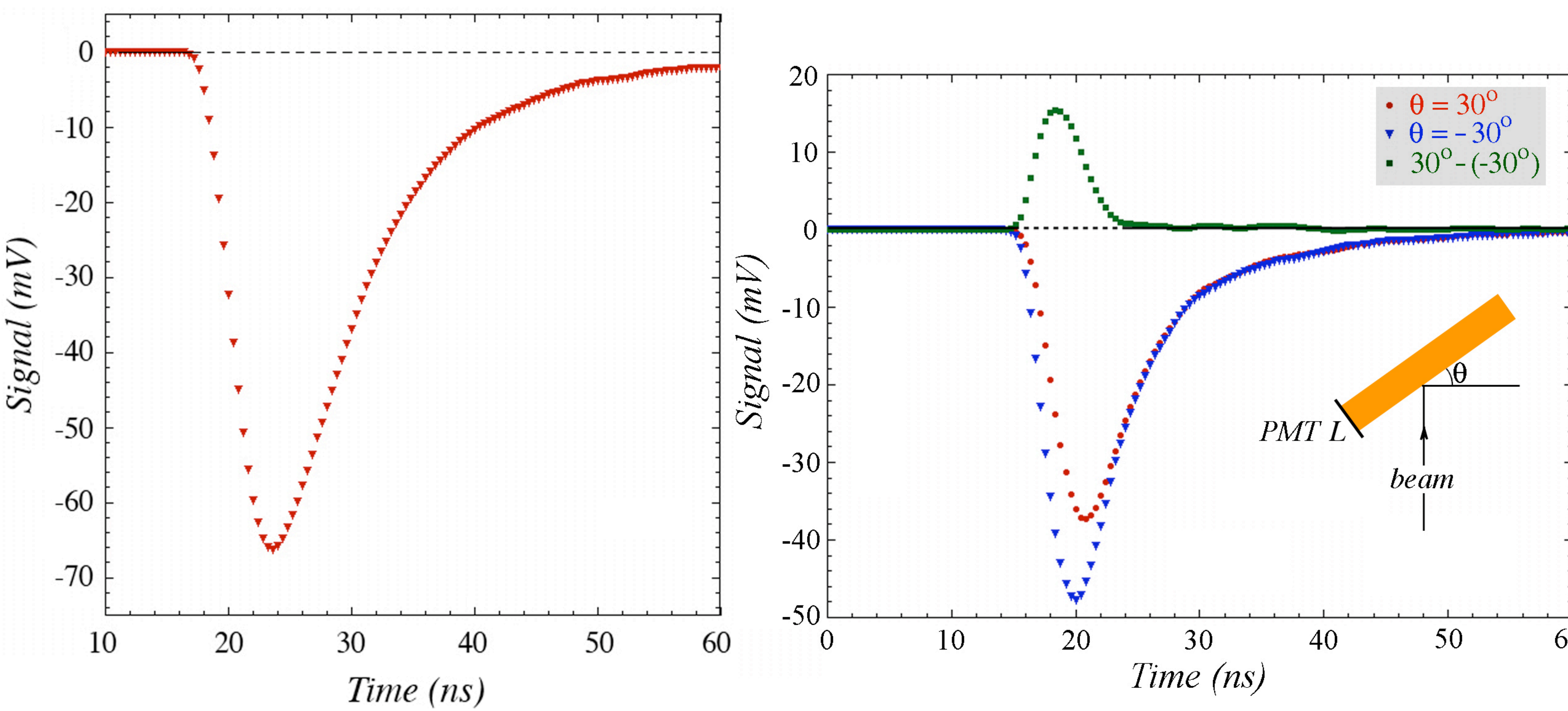
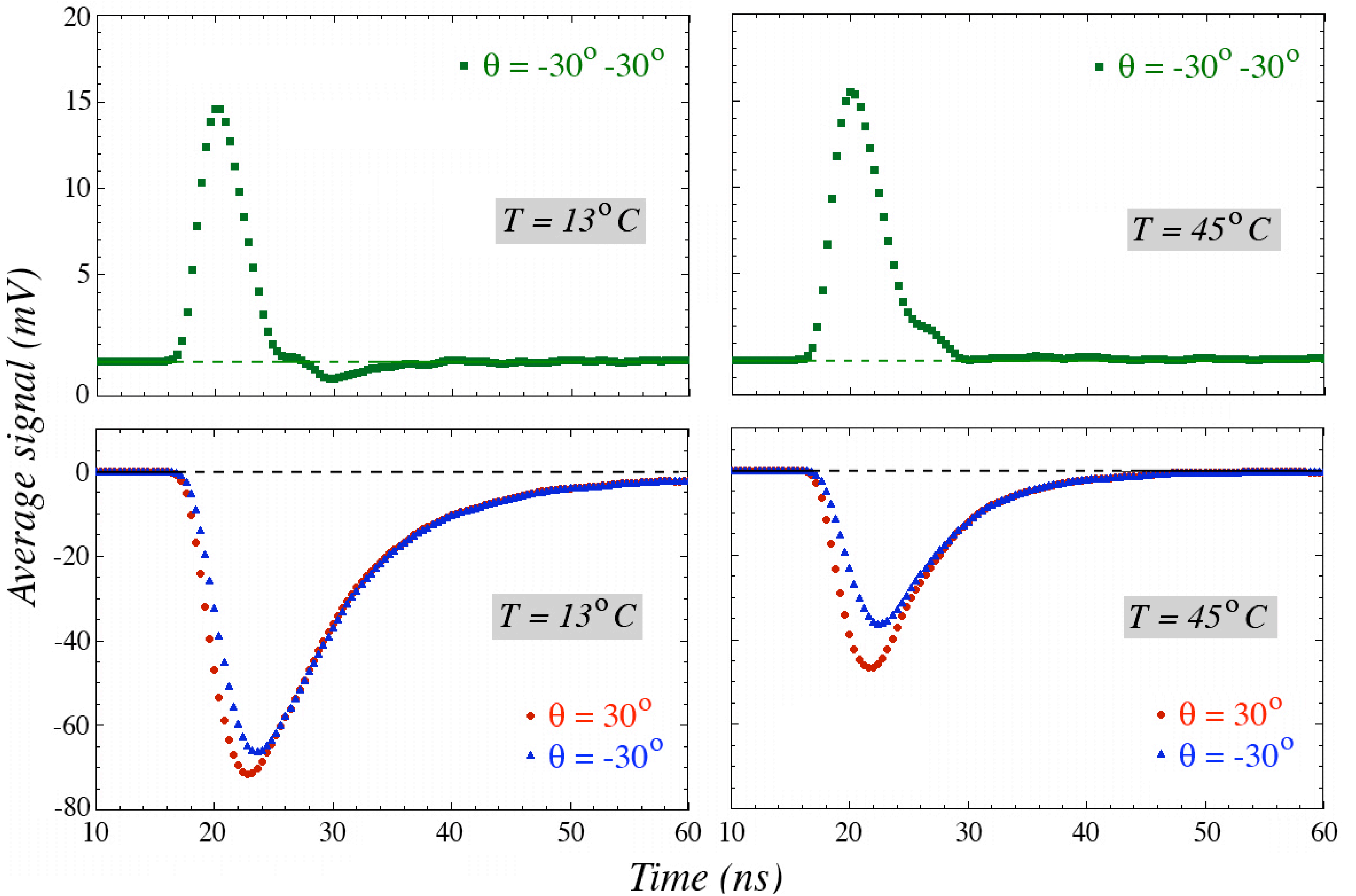


Figure 12: Average time structure of the signals measured with the PMT reading out one end (L) of a $PbWO_4$ crystal traversed by 10 GeV electrons, for two different orientations of the crystal, and the difference between these two time distributions. At $\theta = -30°$, Čerenkov light contributes to the signals, at $\theta = 30°$, it does not [14, 15]. When the crystal was read out from the other side, the prompt excess signal was detected for $\theta = 30°$, and was absent for $\theta = -30°$ [15].

Temperature effects on the $PbWO_4$ signals



A new crystal: BGO!!

Disadvantage compared to $PbWO_4$:

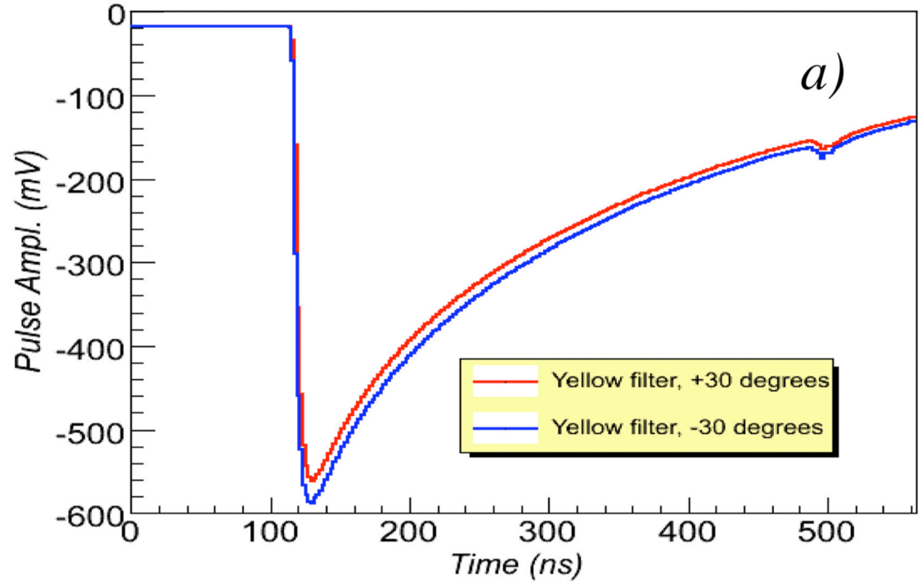
A much brighter scintillator, Č/S factor 100 smaller

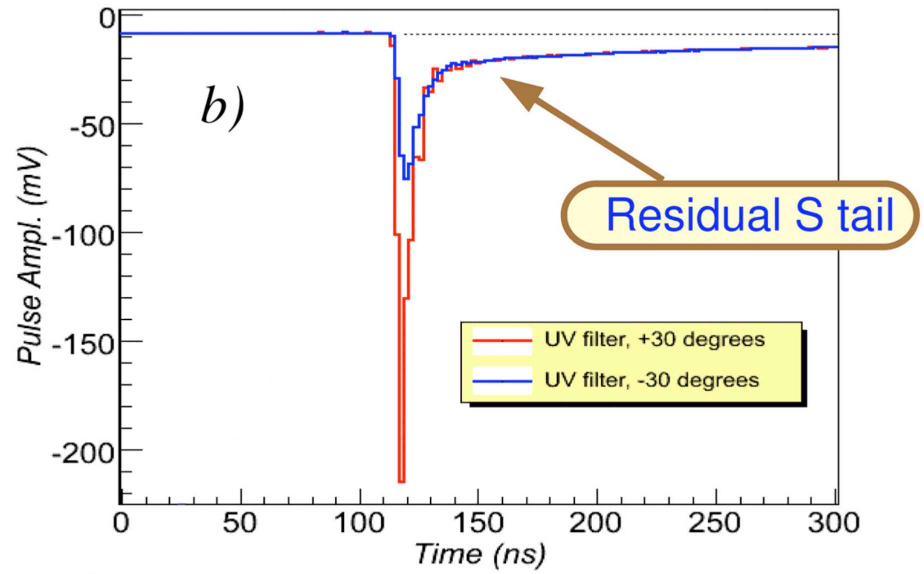
Advantages:

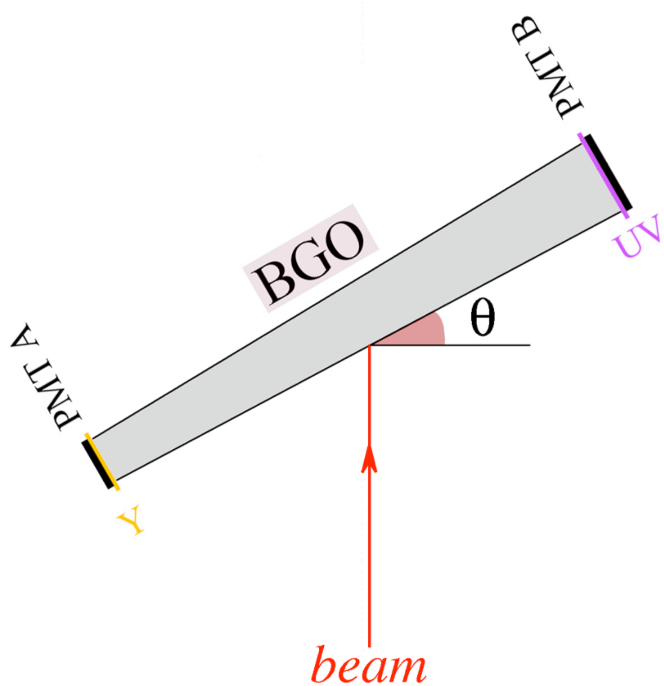
- *Scintillation spectrum peaks at 480 nm* $\longrightarrow$ *use filters*
- *Decay time scintillaton 300 ns (very different from prompt)*

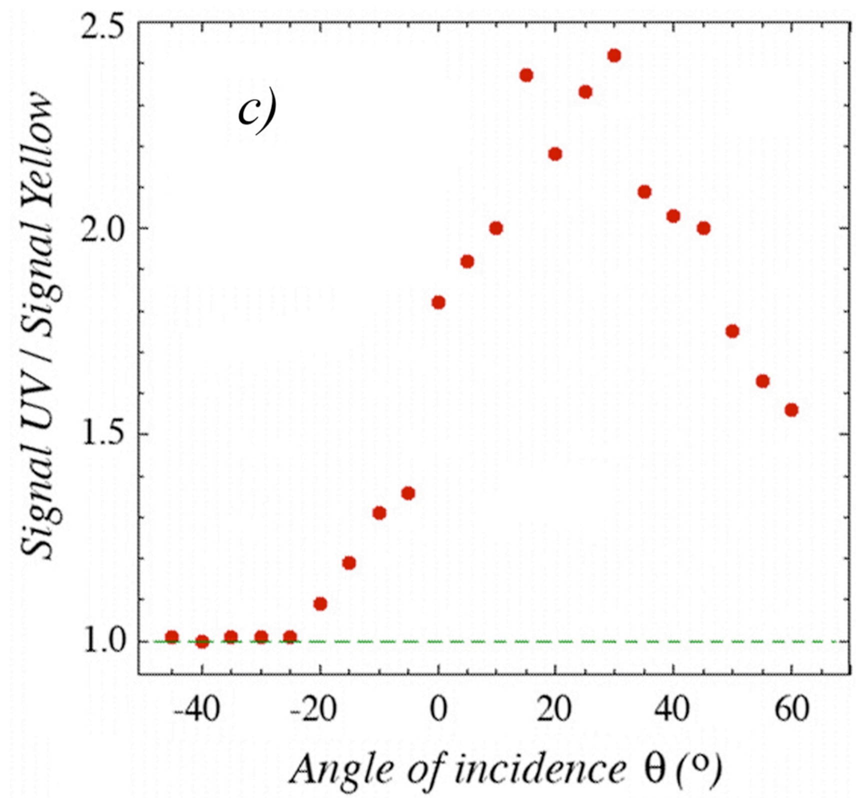
$\longrightarrow$ *More (and better) options to isolate Čerenkov signal*

The Čerenkov component in BGO signals









Čerenkov and Scintillator information from one signal !

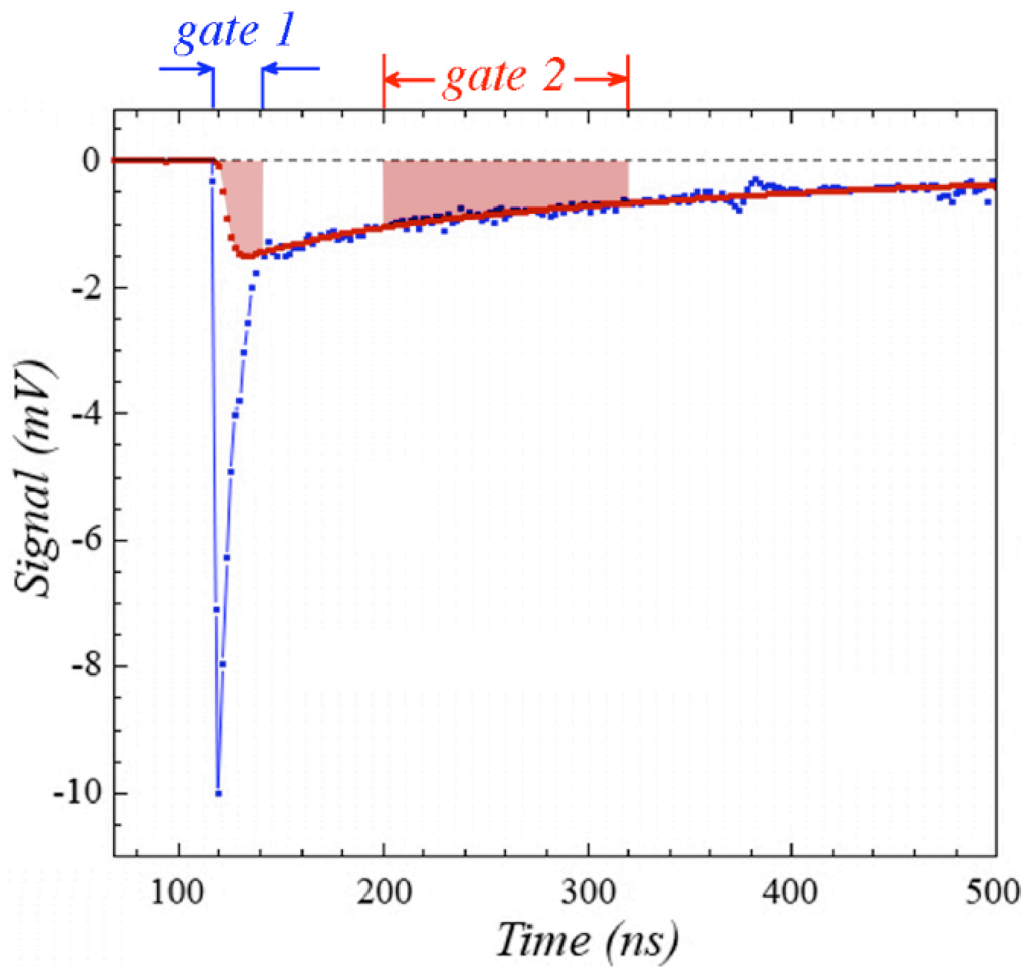


Figure 14: The time structure of a typical shower signal measured in the BGO em calorimeter equipped with a UV filter. These signals were measured with a sampling oscilloscope, which took a sample every 0.8 ns. The UV BGO signals were used to measure the relative contributions of scintillation light (gate 2) and Čerenkov light (gate 1) [15].

Test setup hybrid calorimeter system (BGO + fibers)

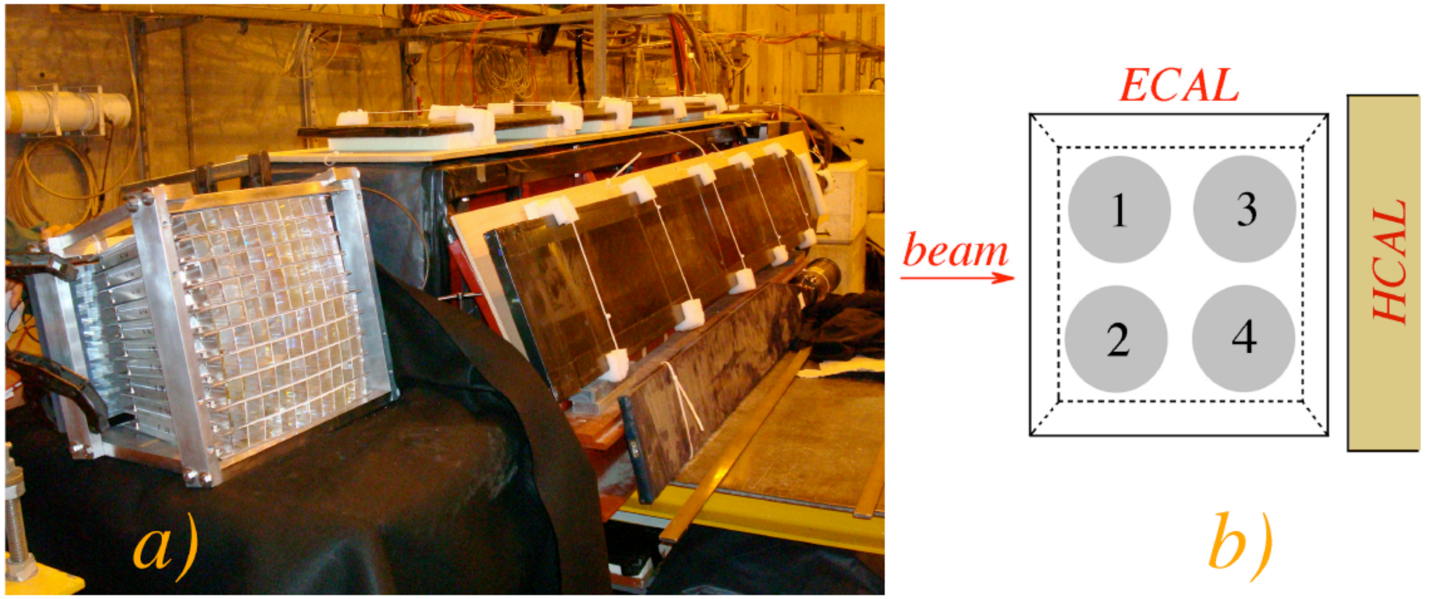


Figure 15: The calorimeter during installation in the H4 test beam, which runs from the bottom left corner to the top right corner in this picture. The 100-crystal BGO matrix is located upstream of the fiber calorimeter, and is read out by 4 PMTs on the left (small end face) side.

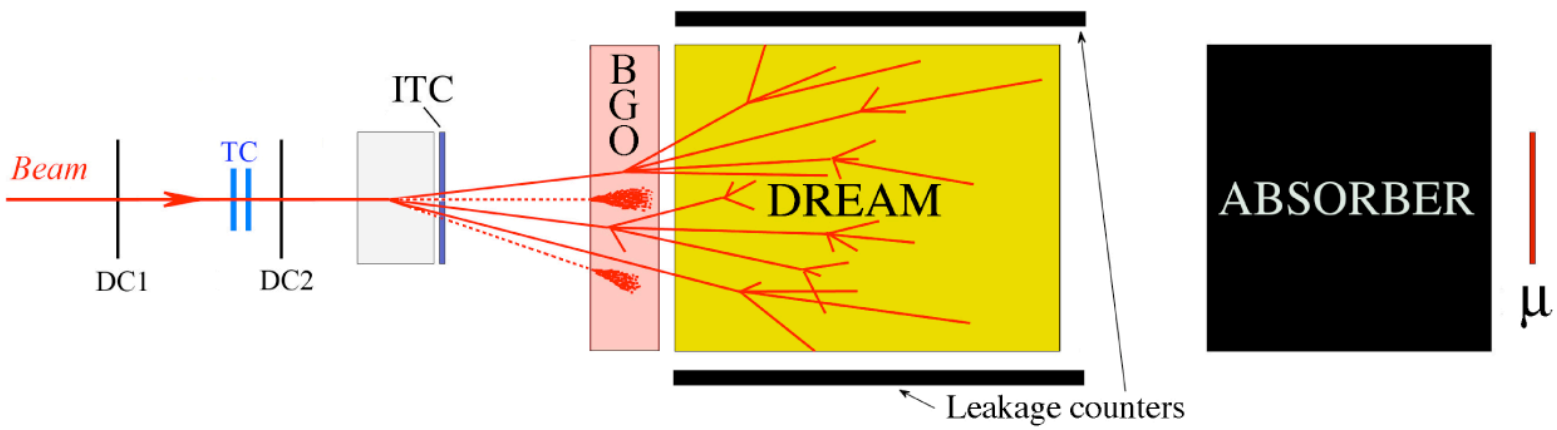
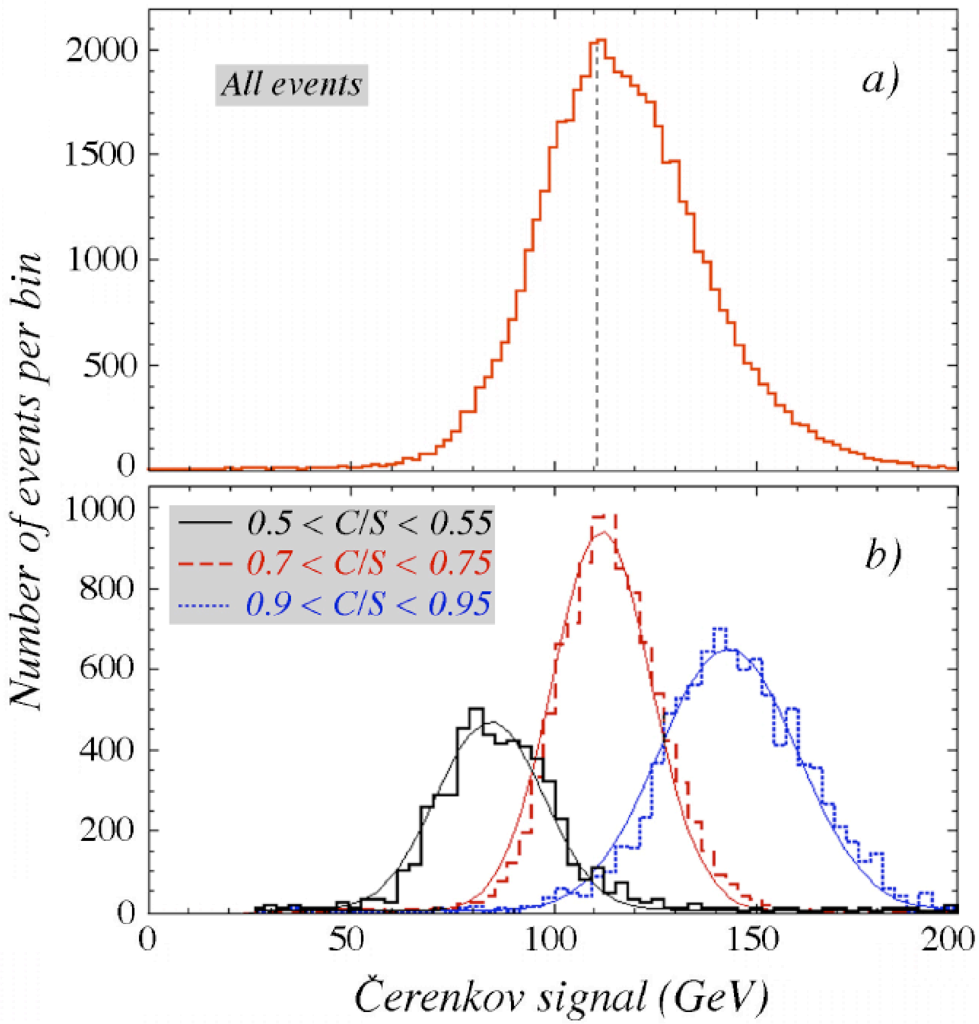


Figure 16: Schematic of the experimental setup in the beam line in which the hybrid calorimeter system was tested (see text for details). Also shown is the occurrence and development of a multi-particle event ("jet") originating in the upstream target [17].

Čerenkov/scintillator ratio also measures f_{em} for jets in hybrid!



On average, ~50% of the "jet" energy deposited in BGO matrix

Figure 17: The Čerenkov signal distribution for 200 GeV "jet" events detected in the BGO + fiber calorimeter system (a) together with the distributions for subsets of events selected on the basis of the ratio of the total Čerenkov and scintillation signals in this detector combination (b) [17].

First results of new, dedicated DREAM crystals

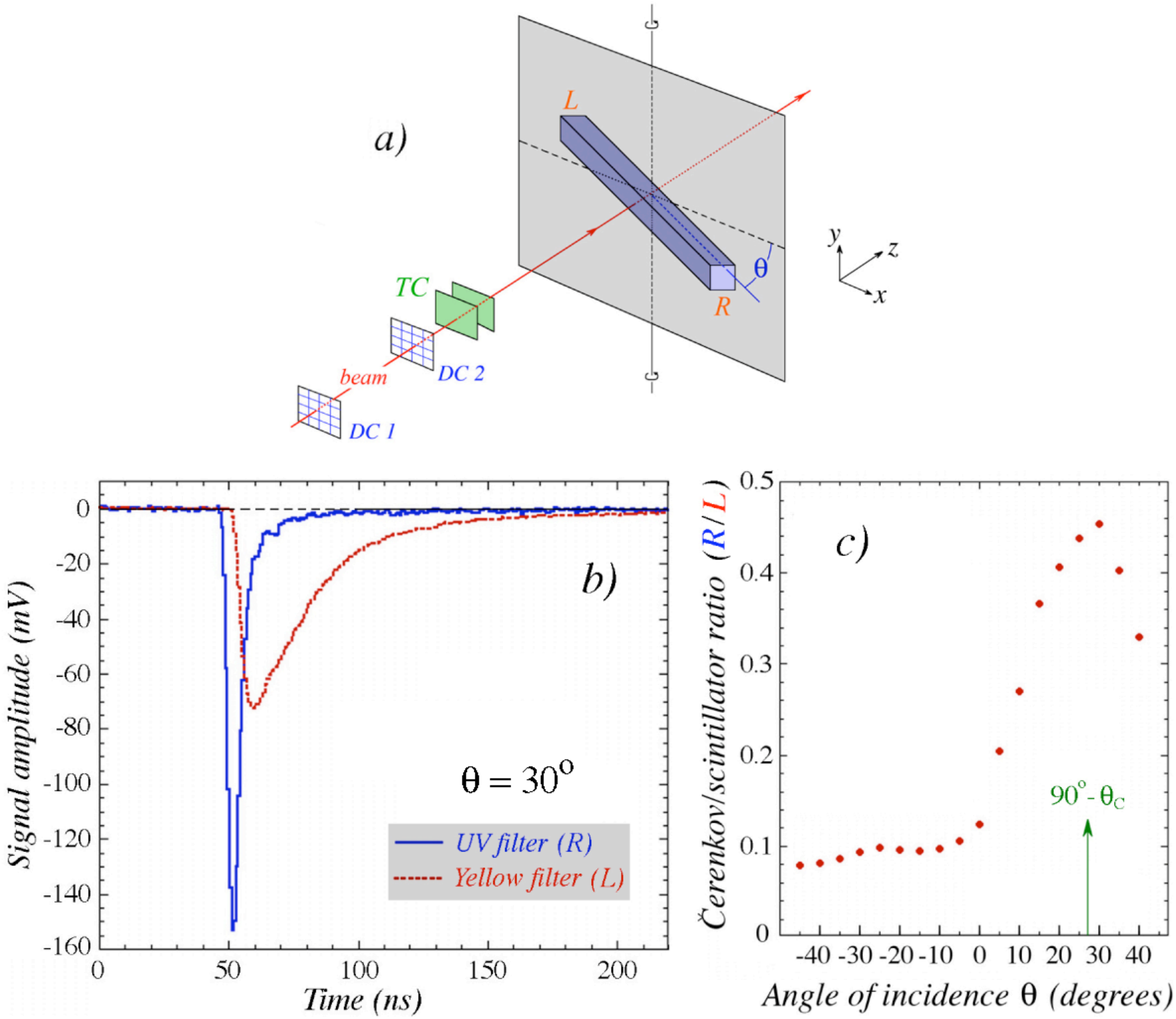


Figure 3: Unraveling of the signals from a Mo-doped $PbWO_4$ crystal into Čerenkov and scintillation components. The experimental setup is shown in diagram *a*. The two sides of the crystal were equipped with a UV filter (side *R*) and a yellow filter (side *L*), respectively. The signals from 50 GeV 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* [6].

How to improve DREAM performance

- Build a larger detector ⟶ *reduce effects side leakage*

- *Increase Čerenkov light yield*

  DREAM: 8 p.e./GeV ⟶ fluctuations contribute $35\%/\sqrt{E}$

  No reason why DREAM principle is limited to fiber calorimeters

  Homogeneous detector ?!

  ⟶ *Need to separate the light into its Č, S components*

- For ultimate hadron calorimetry ($15\%/\sqrt{E}$): *Measure E_{kin} (neutrons)*

  Is correlated to nuclear binding energy loss (invisible energy)

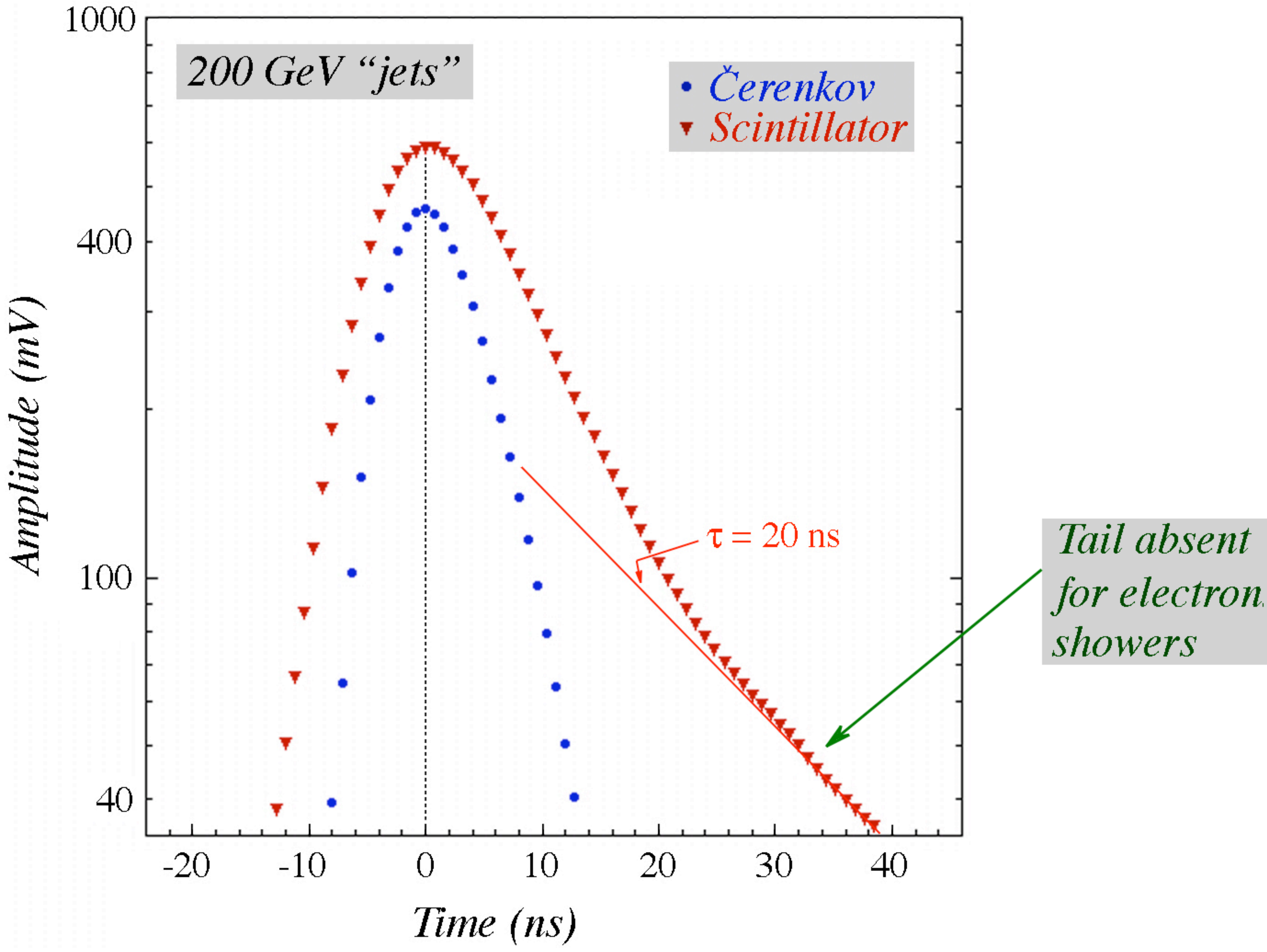
Can be inferred from the time structure of the signals

Neutron contribution to calorimeter signals

What to expect?

- > 95% of neutrons produced in *nuclear deexcitation*: $\langle E_n \rangle \sim 3$ MeV
- These neutrons lose their energy predominantly through *elastic scattering*
- Energy loss in elastic scattering ~ A^{-1} ⟶ *free protons dominate this process*
- Density of free protons in DREAM (plastic fibers): $8 \cdot 10^{21}$ p/cm^3
- Cross section for elastic *n-p* scattering: 2.2 b (3 MeV) ⟶ 12 b (0.1 MeV)
- Mean free path between elastic *n-p* scattering events: 56 cm ⟶ 10 cm
- Average *time* between subsequent *n-p* scattering events: 23 ns
  (independent of E_n ⟶ expect exponential tail in time structure signals)
- Neutrons lose on average *50%* of their kinetic energy in elastic *n-p* scattering
  ⟶ *$E_{kin}(n)$ reduced to e^{-1} in 33 ns* if other processes are negligible
- Other processes through which neutrons may lose energy:
  Elastic scattering off C,Si,Cu, inelastic scattering ⟶ *expect $\tau_n \sim 25$ ns*

Time structure of the DREAM signals: the neutron tail



The em and neutron signal fractions are anti-correlated

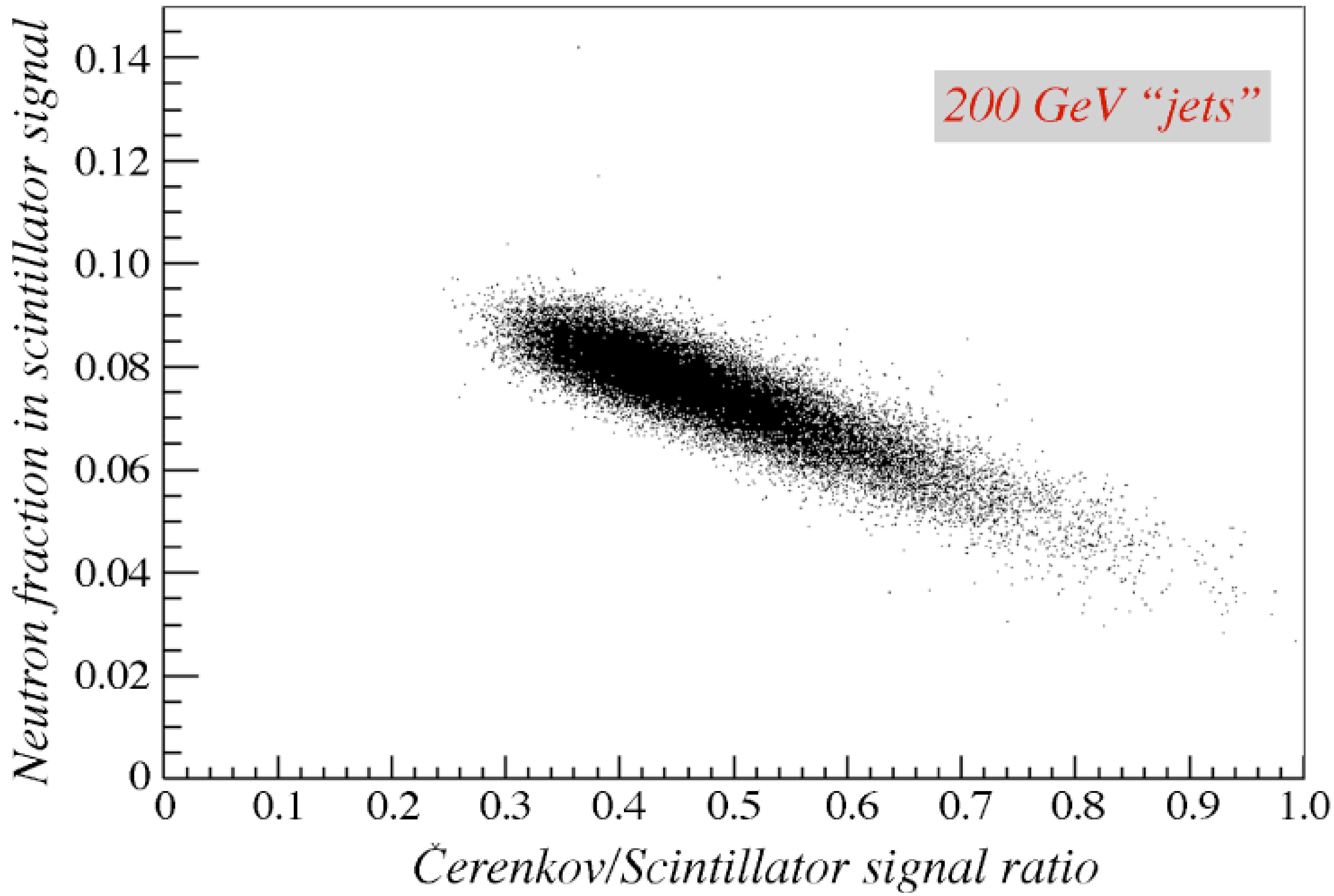


Figure 4: Scatter plot of the fraction of the scintillation light contained in the (20 ns) exponentional tail versus the Čerenkov/scintillation signal ratio measured in these events [9].

Probing the total signal distribution with the neutron fraction

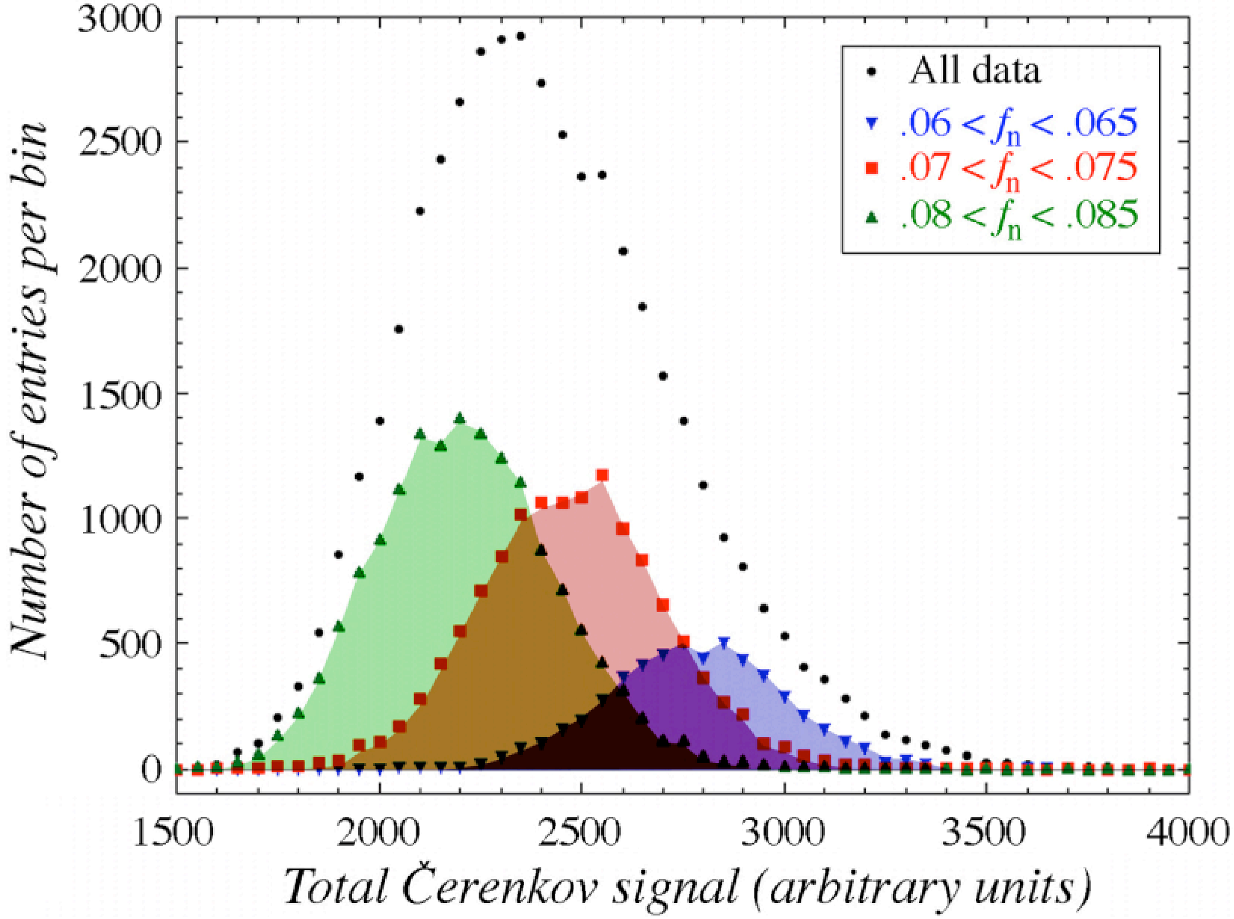


Figure 18: Distribution of the total Čerenkov signal for 200 GeV "jets" and the distributions for three subsets of events selected on the basis of the fractional contribution of neutrons to the scintillator signal [9].

Neutron information can be used to improve the response function and the energy resolution

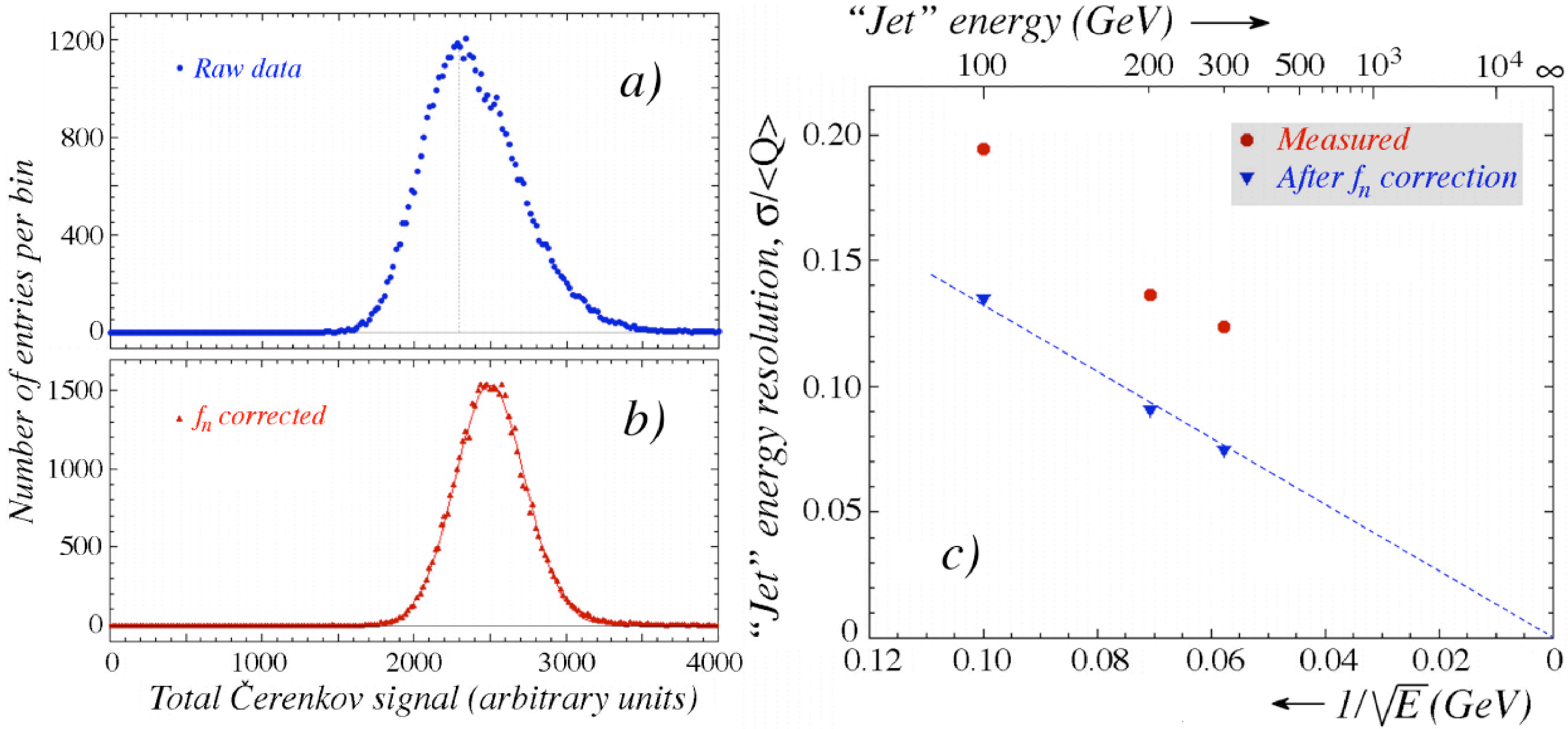
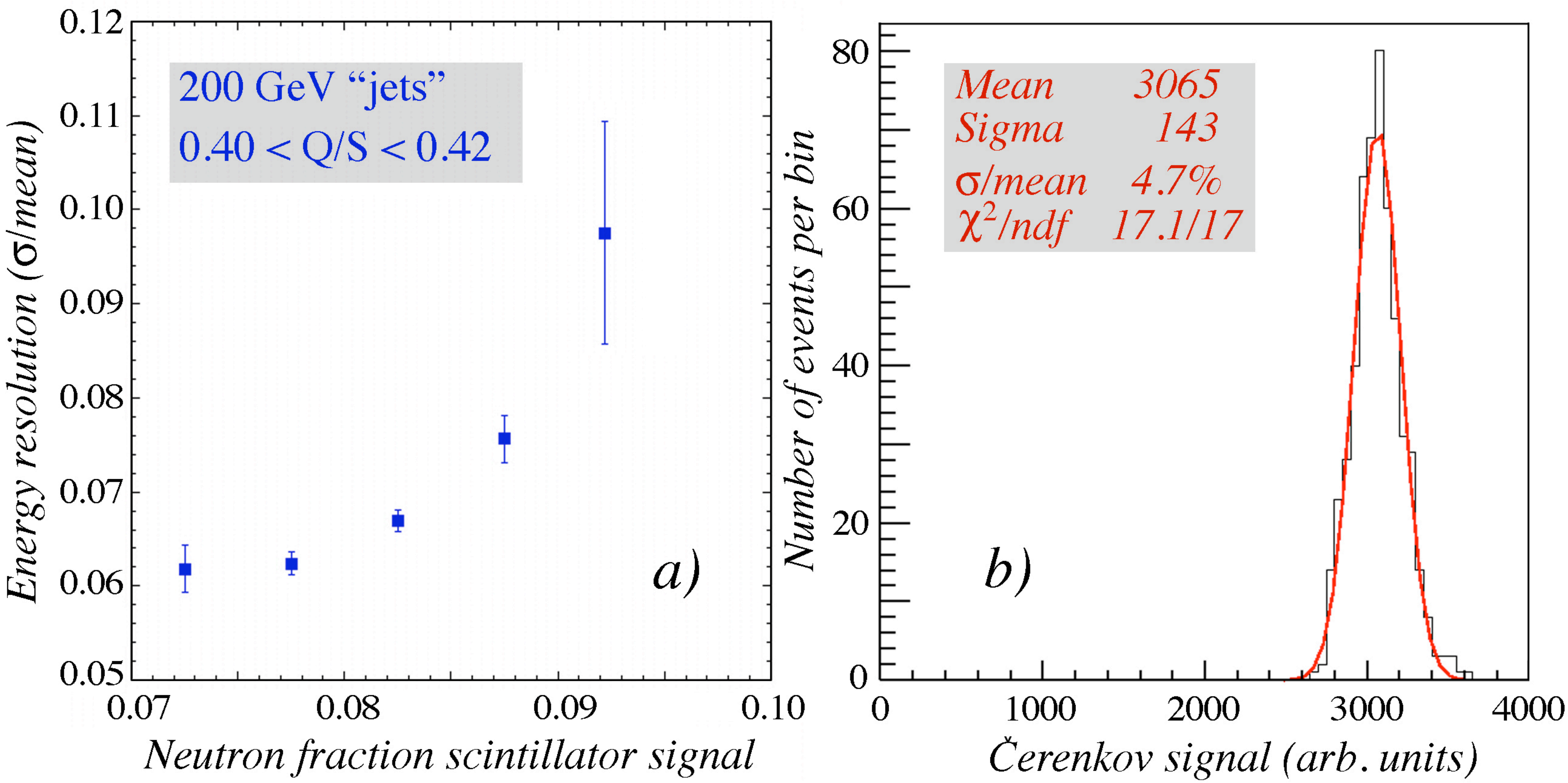


Figure 19: Distribution of the total Čerenkov signal for 200 GeV "jets" before (a) and after (b) applying the correction based on the measured value of f_n, described in the text. Relative width of the Čerenkov signal distribution for "jets" as a function of energy, before and after a correction that was applied on the basis of the relative contribution of neutrons to the scintillator signals (c) [9].

Neutron information is complementary to f_{em}



Plans for the Future

DREAM road map:

Eliminate the dominating sources of fluctuations one after the other

- Fluctuations in the em shower fraction √
- Fluctuations in Čerenkov light yield
- Sampling fluctuations
- Fluctuations in invisible energy √

Develop dedicated crystal(s) (Čerenkov light yield, Sampling fluctuations)
in progress

Then build a full-scale prototype calorimeter

Proposals to funding agencies submitted

Conclusions (R&D)

- The DREAM approach combines the advantages of compensating calorimetry with a reasonable amount of design flexibility
- The dominating factors that limited the hadronic resolution of compensating calorimeters (ZEUS, SPACAL) to 30 - 35%/$\sqrt{E}$ can be eliminated
- The theoretical resolution limit for hadron calorimeters (15%/$\sqrt{E}$) seems within reach
- The DREAM project holds the promise of high-quality calorimetry for *all* types of particles, with an instrument that can be calibrated with electrons

How about Compensating Calorimeters?

- $e/h = 1.0$ can be achieved by design.

- Use hydrogenous readout, to boost response to shower neutrons

- Has been demonstrated for U/plastic and Pb/plastic calorimeters
  Energy resolution 30-35%/$\sqrt{E}$

Pros & Cons of Compensating Calorimeters

Pros

- Same *energy scale* for electrons, hadrons and jets. No ifs, ands or buts.
- *Calibrate* with electrons and you are done.
- Excellent hadronic *energy resolution* (SPACAL: 30%/$\sqrt{E}$).
- *Linearity,* Gaussian *response function* and all that good stuff.
- Compensation fully understood.
  We know how to build these things, even though GEANT doesn't

Cons

- Small sampling fraction (2.4% in Pb/plastic)
  $\longrightarrow$ *em energy resolution limited* to 10-15%/$\sqrt{E}$
- Compensation relies on detecting neutrons
  $\longrightarrow$ Large *integration volume*
  $\longrightarrow$ Long *integration time* (~50 ns)

Benchmark data for hadronic Monte Carlo

Test of π^0 production modelling

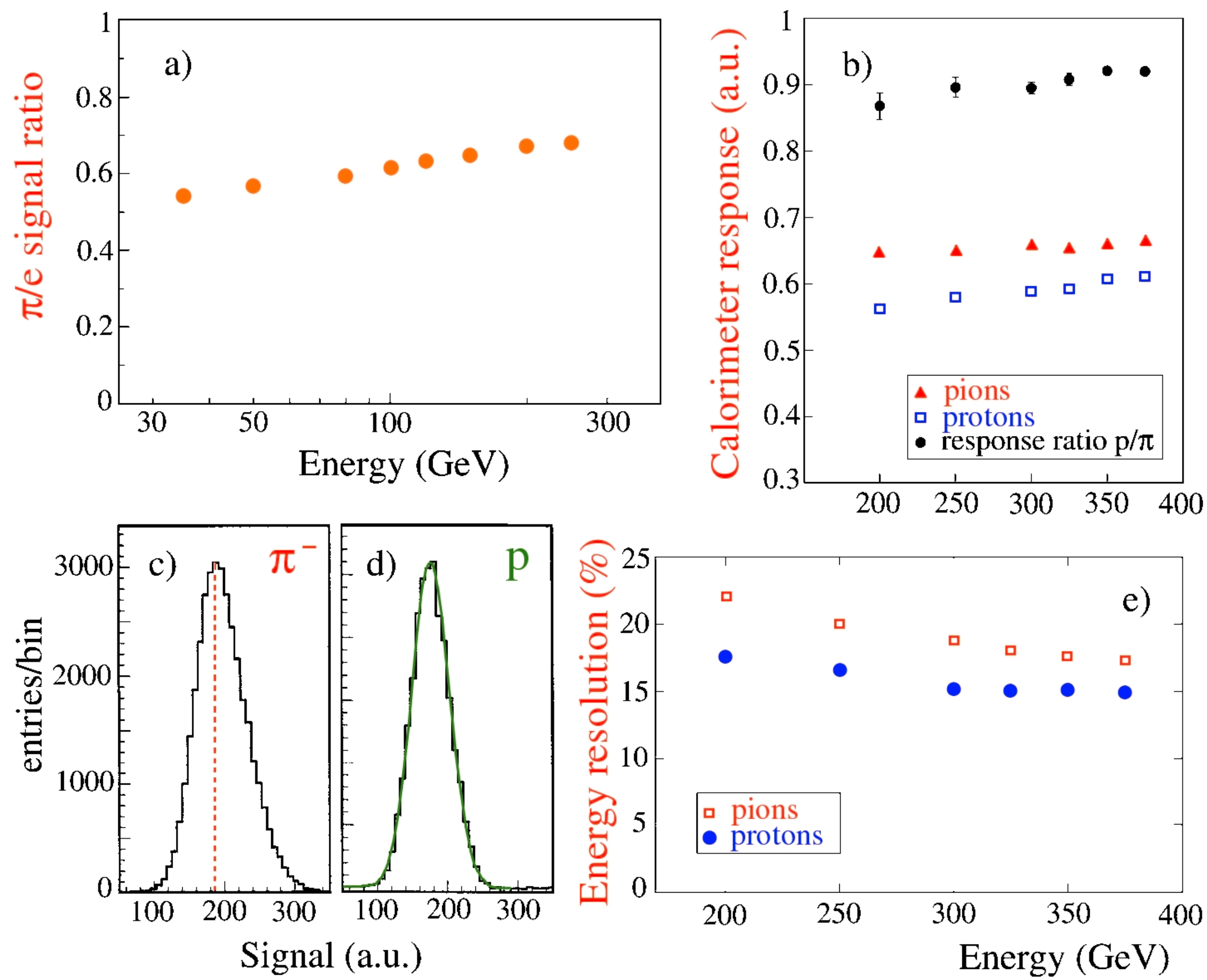


FIG. 8.27. Calorimeter benchmark data for testing the correct implementation of π^0 production in Monte Carlo simulations of hadronic shower development. Experimental data from a copper/quartz-fiber calorimeter, showing the π/e signal ratio as a function of energy (a), the response to protons and pions, as well as the ratio of these responses, as a function of energy (b), the response functions to 300 GeV pions (c) and protons (d), and the energy resolutions for pions and protons as a function of energy (e) [Akc 97].

Benchmark data for hadronic Monte Carlo

Test of description neutron effects

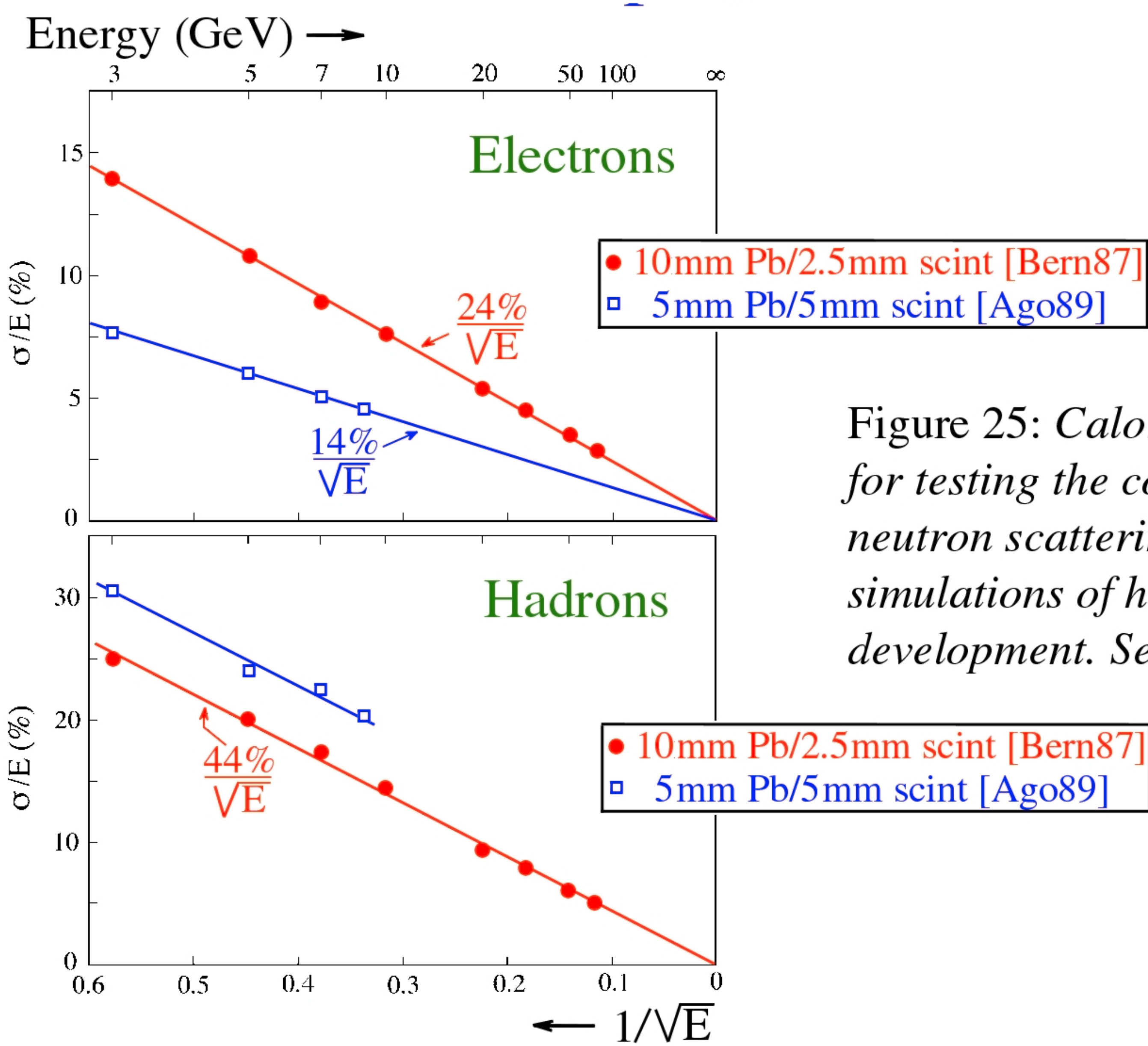


Figure 25: *Calorimeter benchmark data for testing the correct implementation of neutron scattering data in Monte Carlo simulations of hadronic shower development. See text for details.*