The DREAM project

towards the ultimate in calorimetry

Richard Wigmans[*]

(Texas Tech University)

Frontier Detectors for Frontier Physics
Elba, May 26, 2009

Outline:

- Why Dual-readout calorimetry?
- Recent R&D results
- Plans for the future

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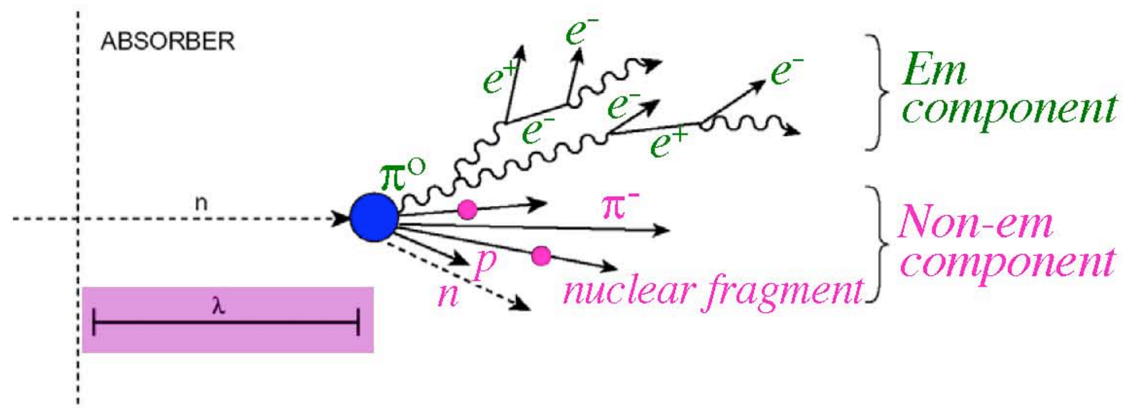
[*] *Representing the DREAM Collaboration*

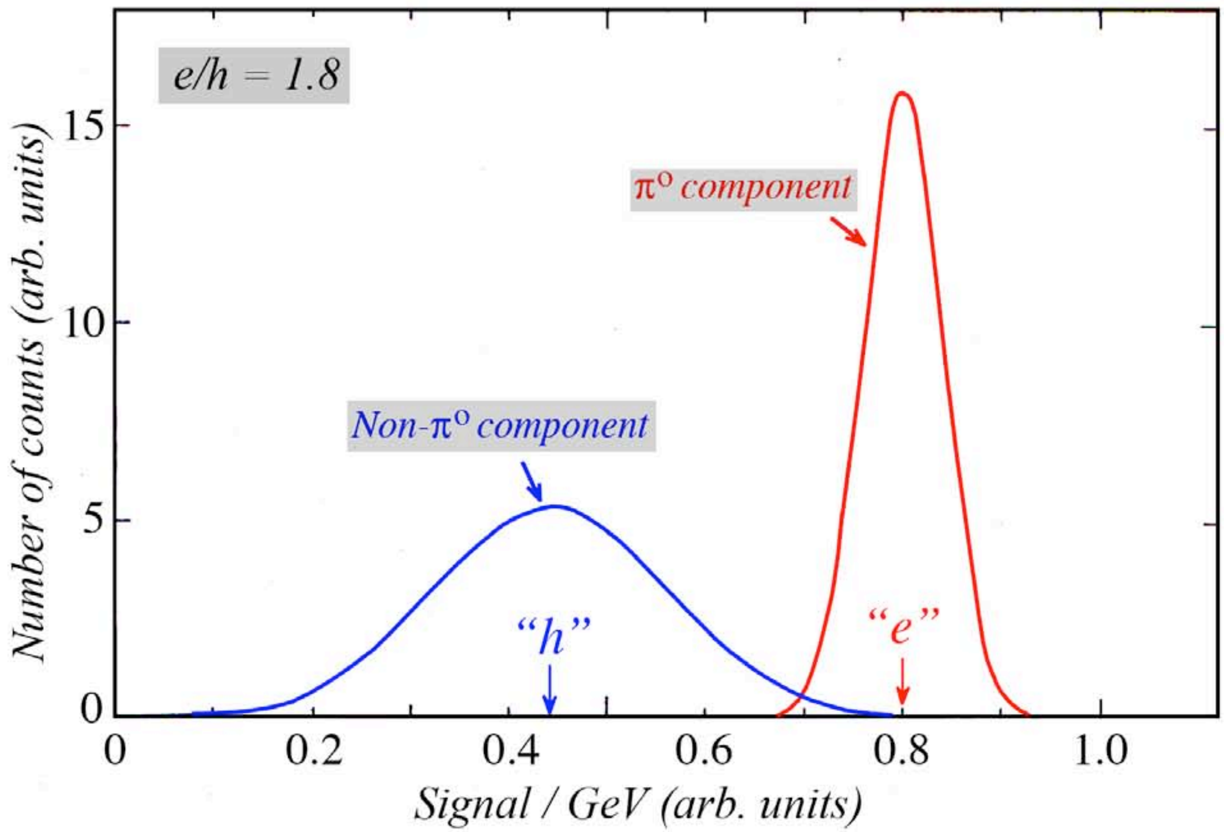
Hadronic shower development
the fundamental problems

- *A hadronic shower consists of two components*
  - *Electromagnetic component*
    - electrons, photons
    - neutral pions → 2 γ
  - *Hadronic (non-em) component*
    - charged hadrons $\pi^{\pm}$, $K^{\pm}$
    - nuclear fragments, p
    - neutrons, neutrino's, soft γ's
    - break-up of nuclei *("invisible")*



- *The calorimeter response to these two components is typically very different*
- *Hadronic showers are characterized by very large fluctuations*
  e.g. in the energy sharing between these two components

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



π^o component

Response (e): same as to electrons

Width response function: sampling fluctuations, # of signal quanta

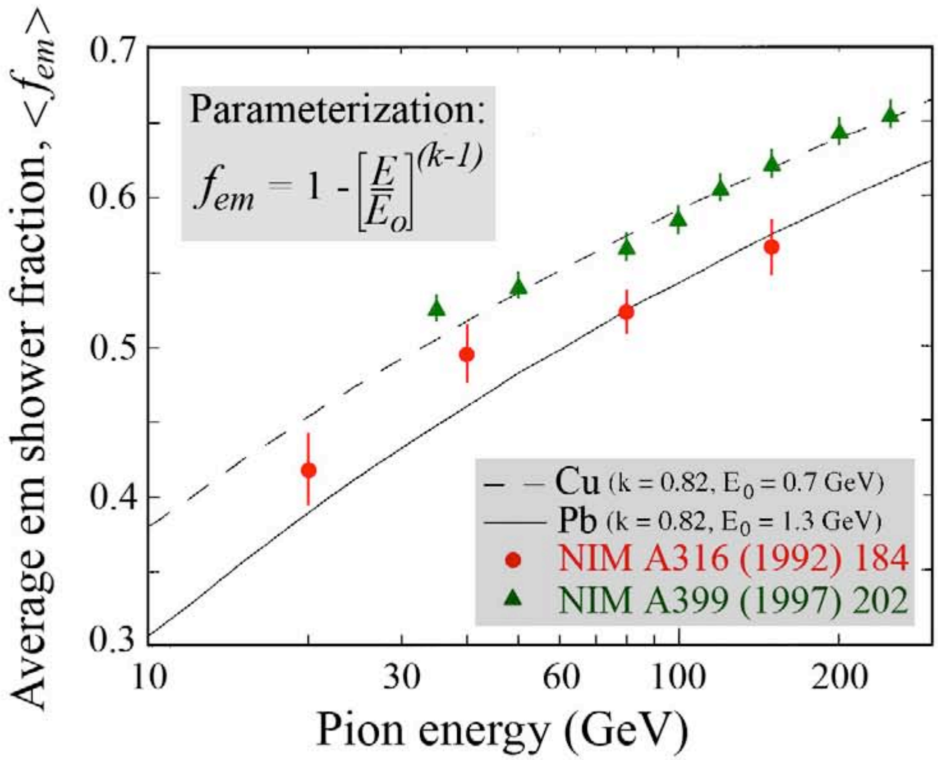
Non-π^o component

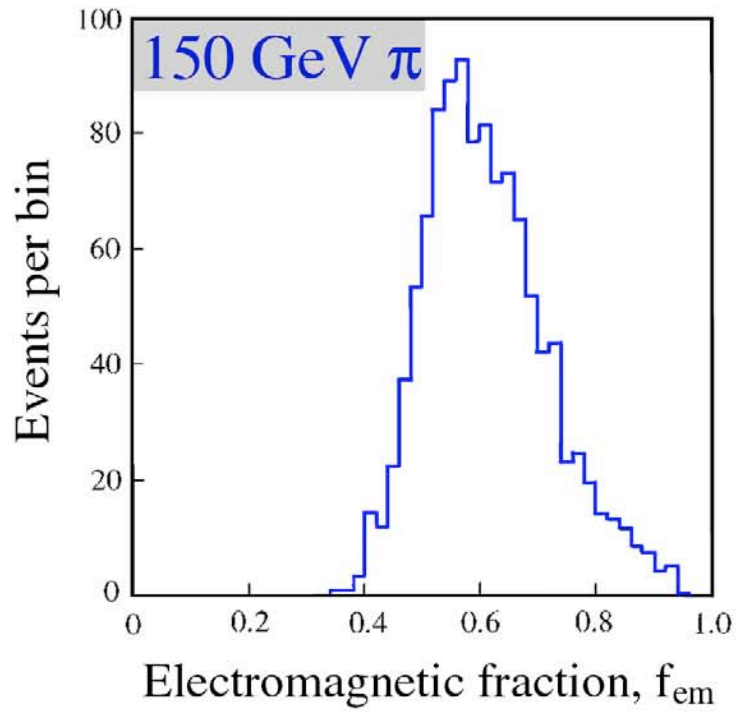
Response (h): Typically smaller than e, due to nuclear binding energy losses

Width response function: Larger, mainly due to large fluctuations in "invisible energy"

(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*

Characteristics of 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, ISU (USA), PV, RM1, CS, CG, PI (I)

An attractive option for improving the quality of hadron calorimetry:

Use Čerenkov light!!   Why?

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

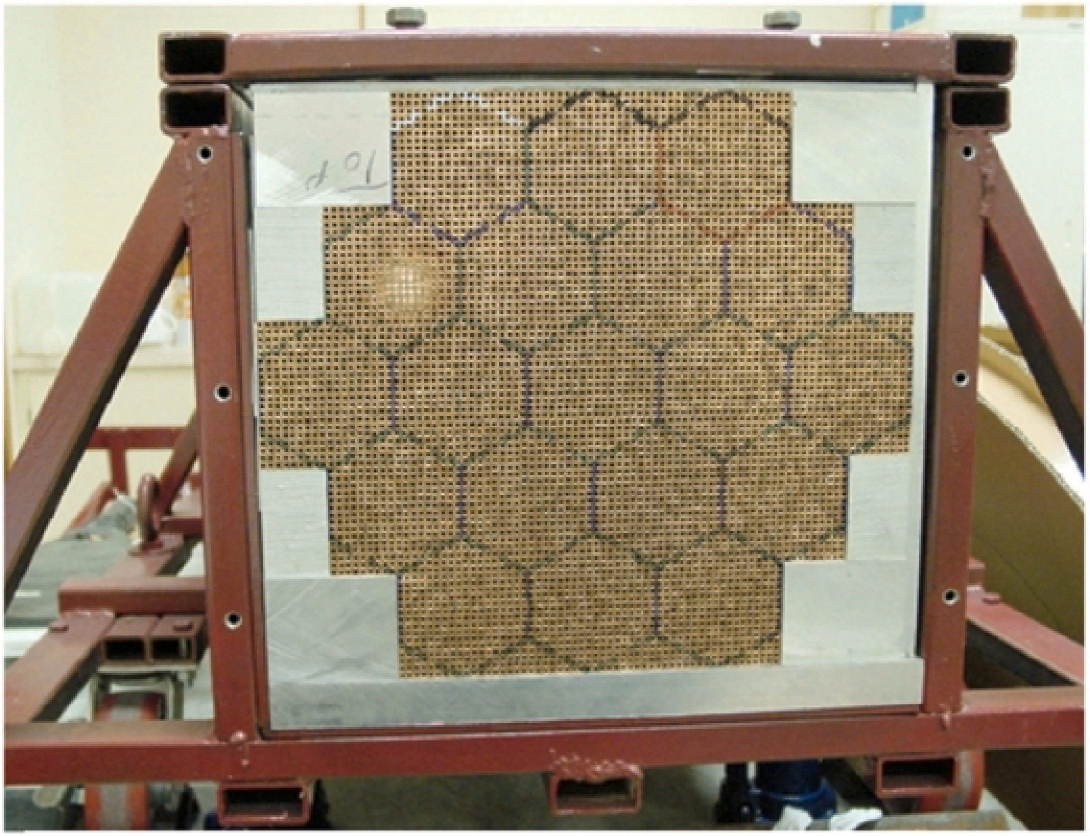
➡ DREAM (Dual REAdout Method) principle:

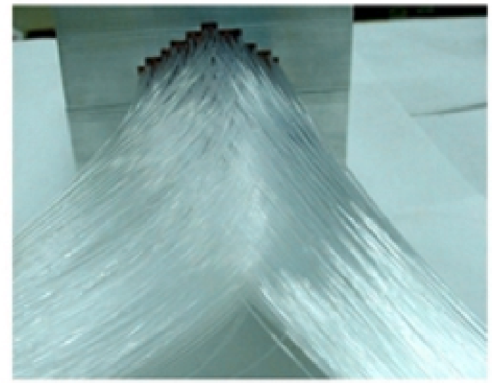
Measure f_{em} event by event by comparing Č and dE/dx signals

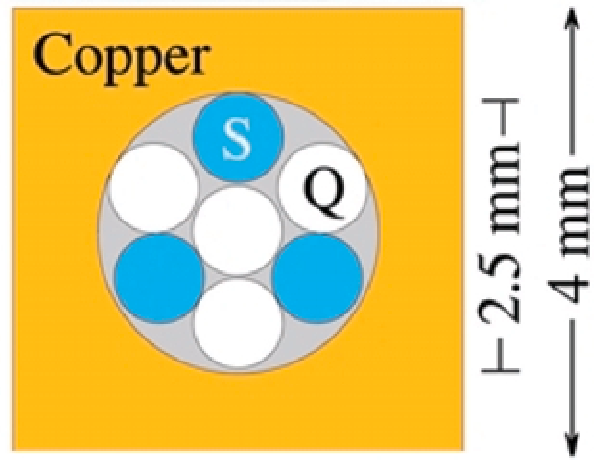
* How do we know this?

- CMS HF: $e/h \sim 5$
- Lateral profiles of hadronic showers

DREAM: Structure

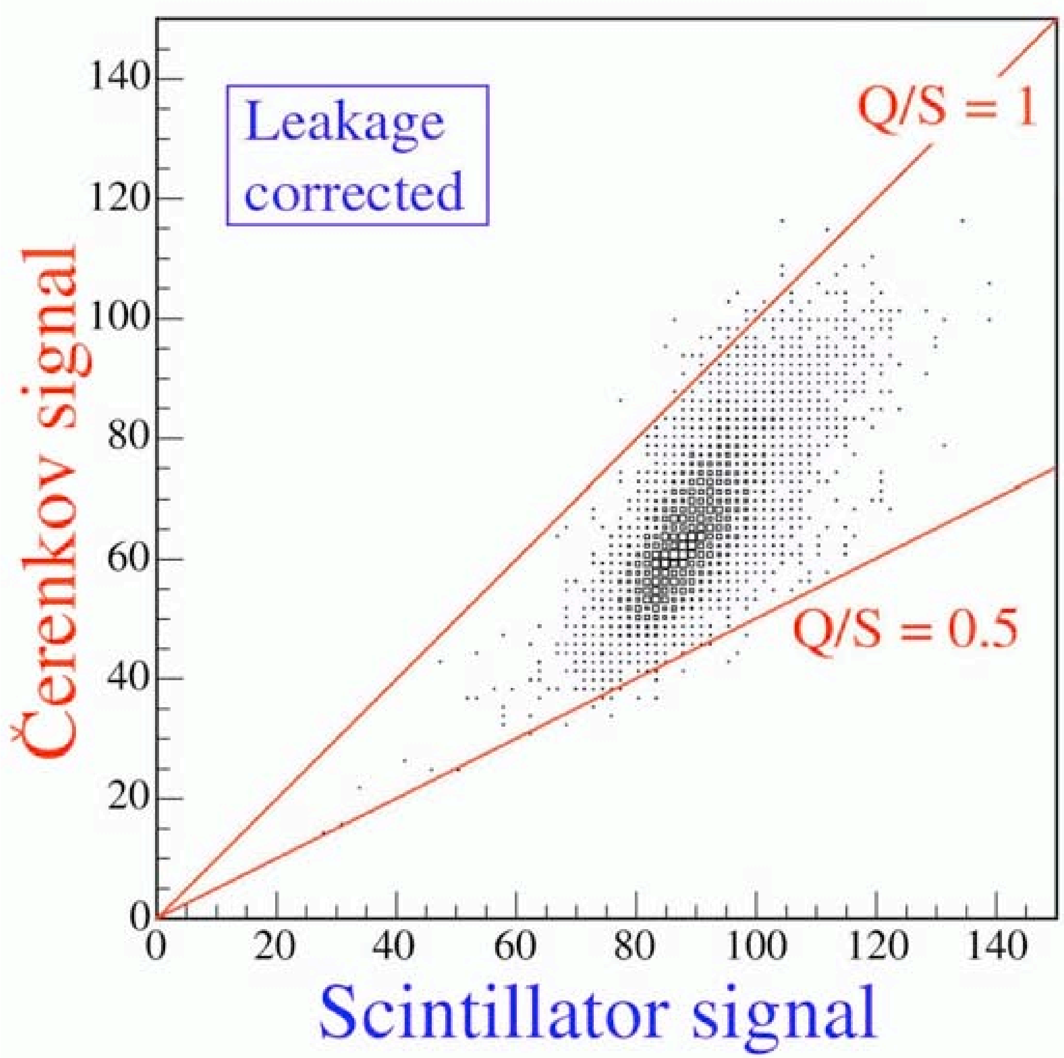






- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

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



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

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

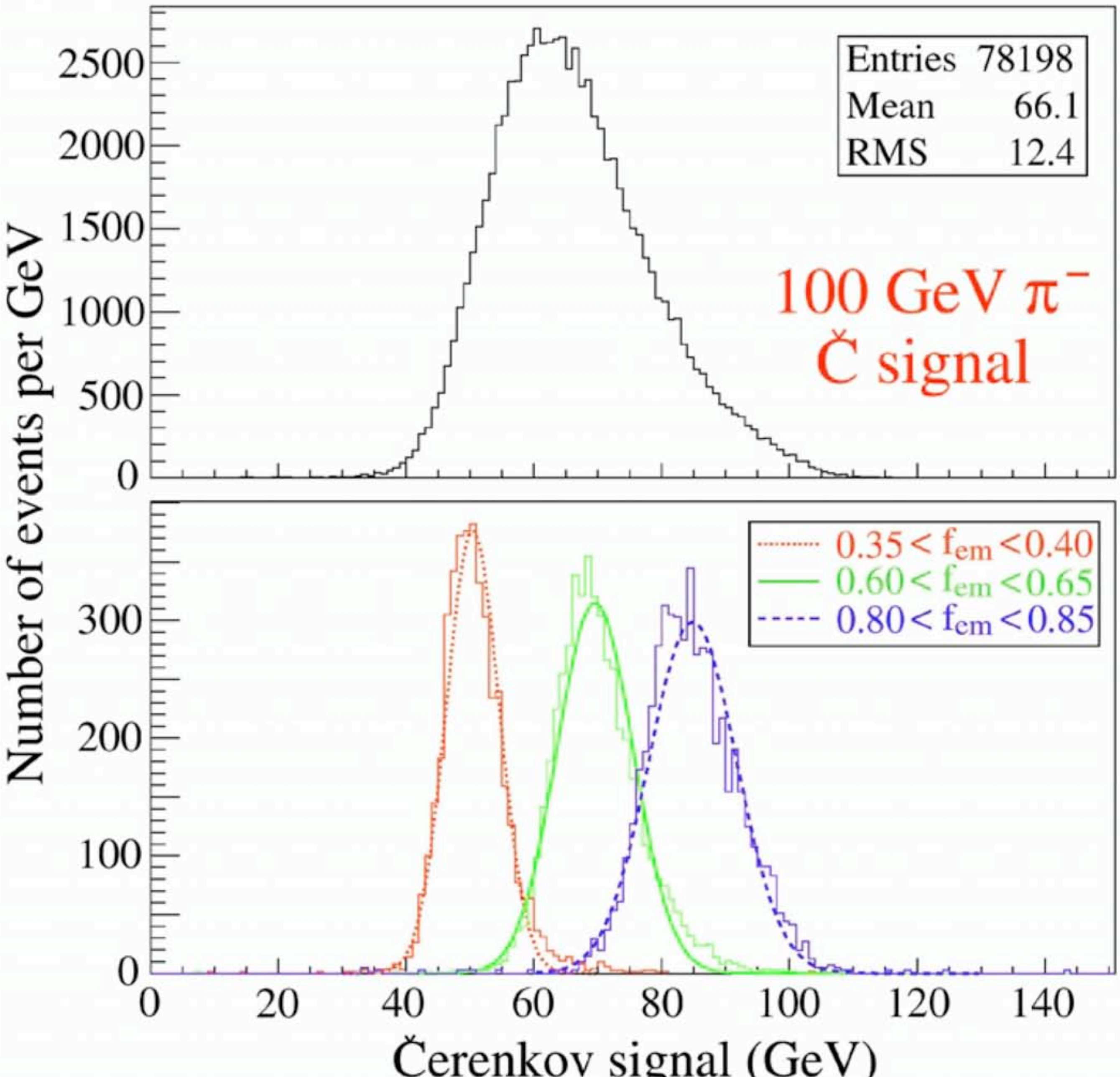
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

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

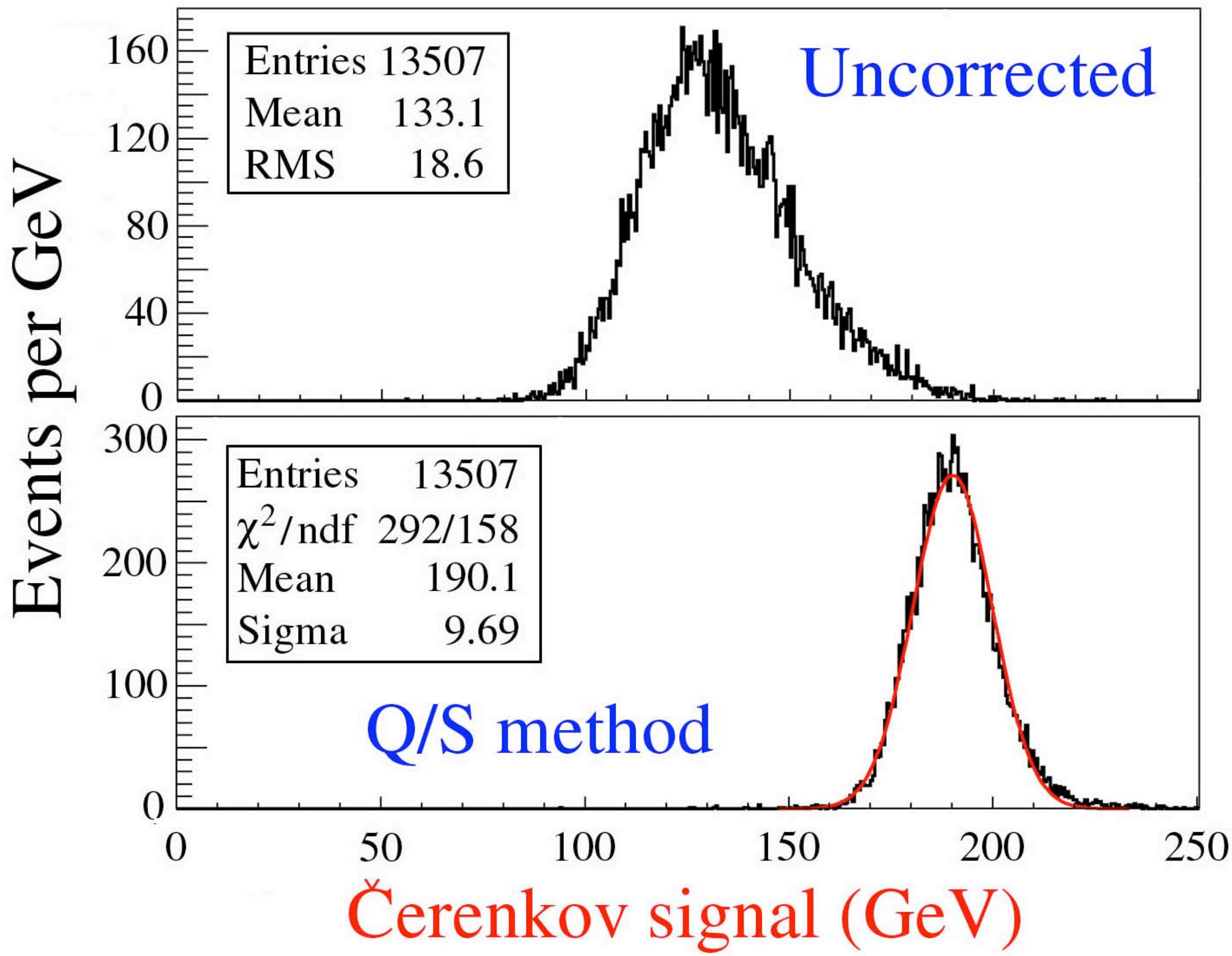
with $\chi = \dfrac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

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



From:
NIM A537 (2005) 537

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



Effects of Q/S corrections on

hadronic signal linearity and jet resolution

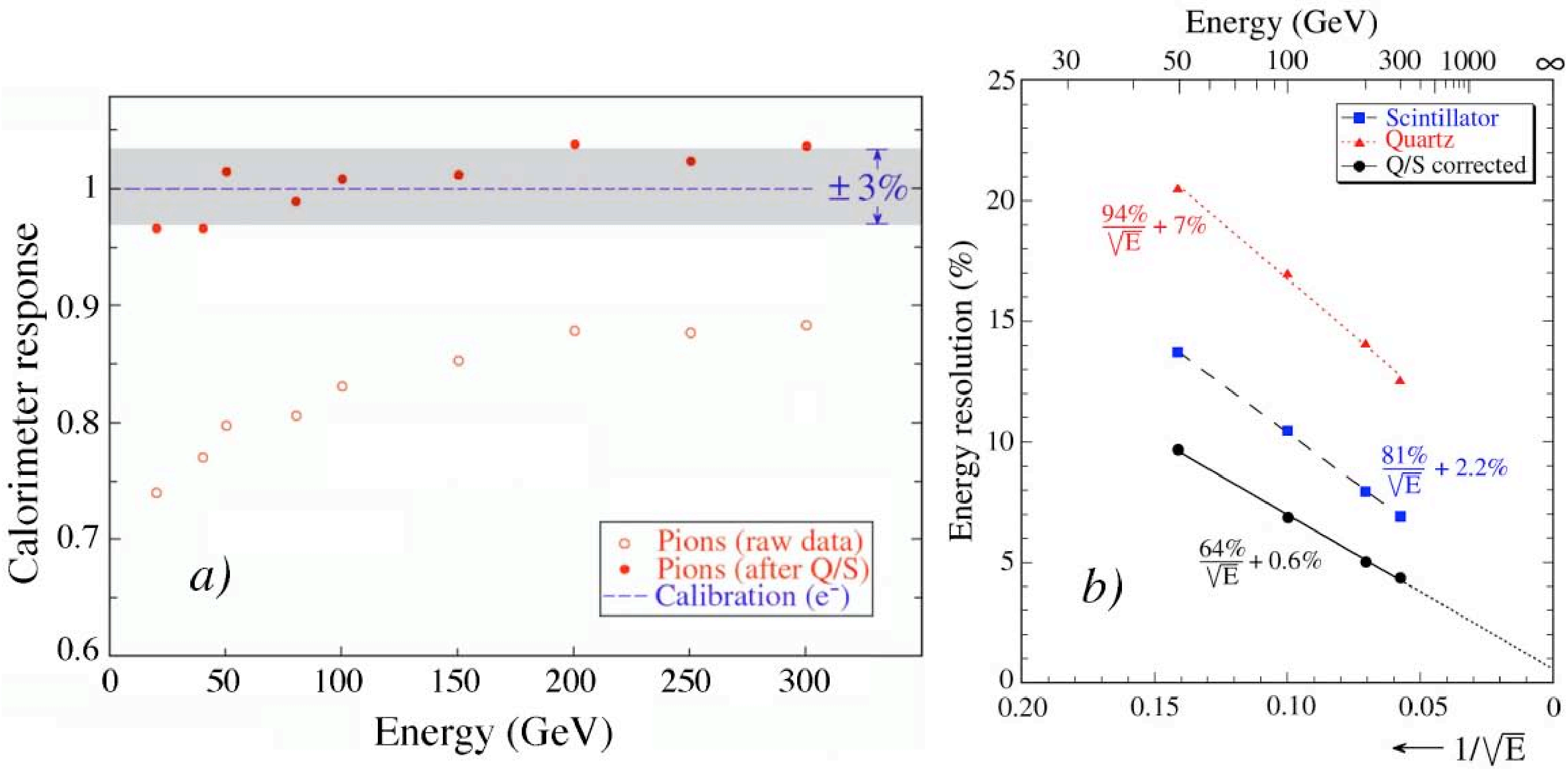


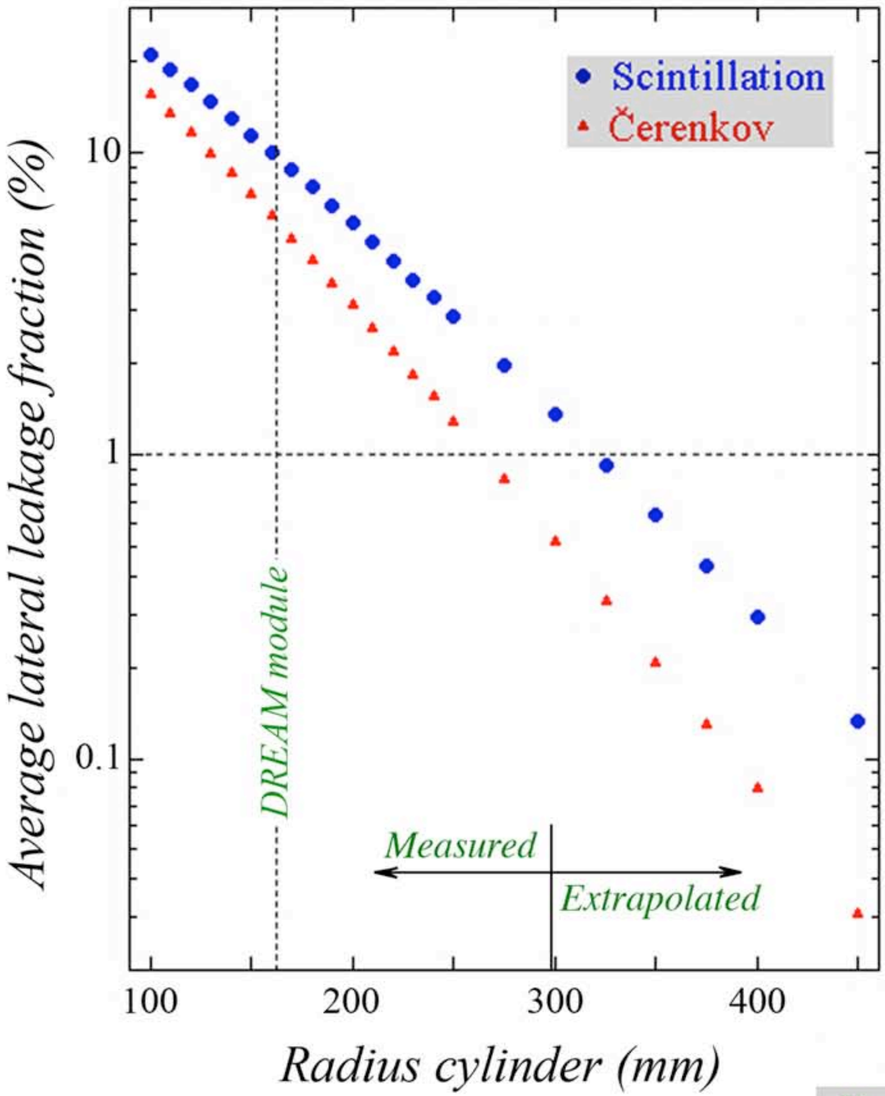
Figure 9: The scintillator response of the DREAM calorimeter to single pions (a) and the energy resolution for "jets" (b), before and after the dual-readout correction procedures were applied to the signals [5].

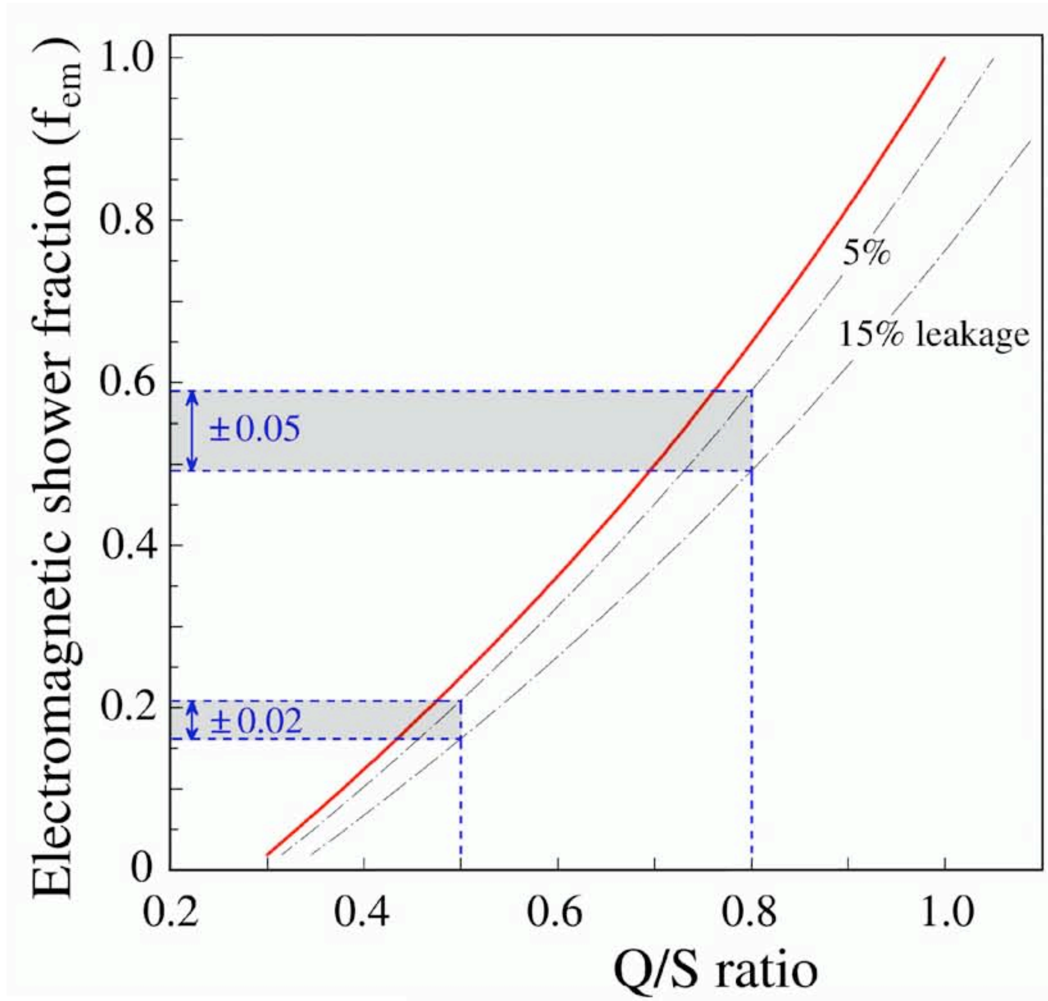
How to improve DREAM performance

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

DREAM: The importance of leakage and its fluctuations

Lateral shower containment (π)





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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

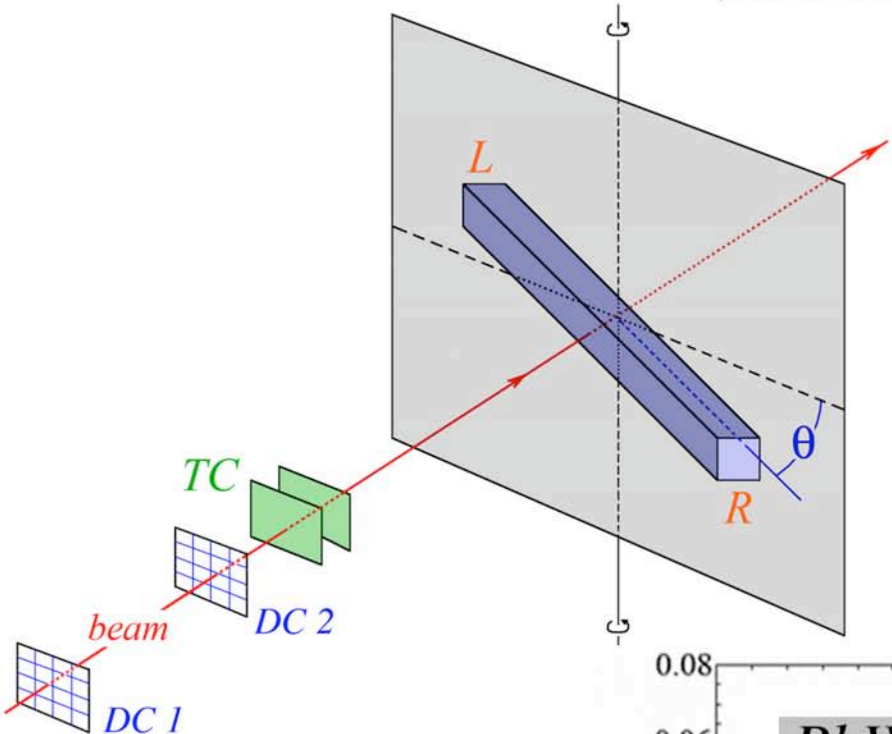
  Homogeneous detector ?! (would also eliminate sampling fluctuations)

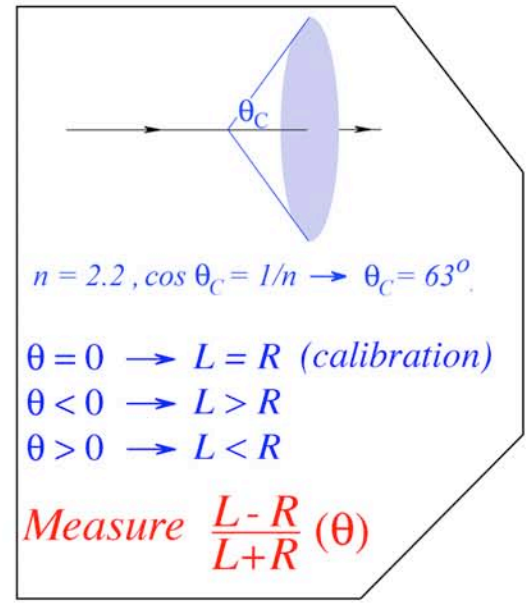
  ⟶ *Need to separate the light into its Č, S components*

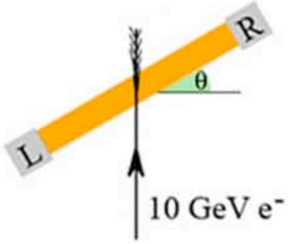
How to detect / isolate Čerenkov component?

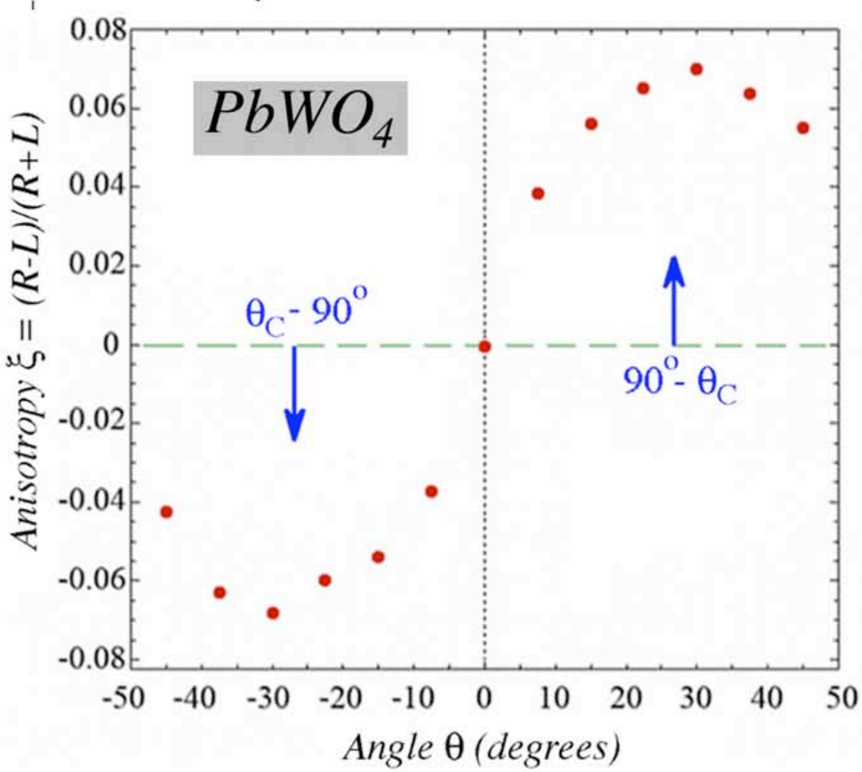
- *Directionality of Čerenkov component*
- *Time structure of the signals*
- *Spectral differences*

Experimental setup Čerenkov measurements
(directionality)









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

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

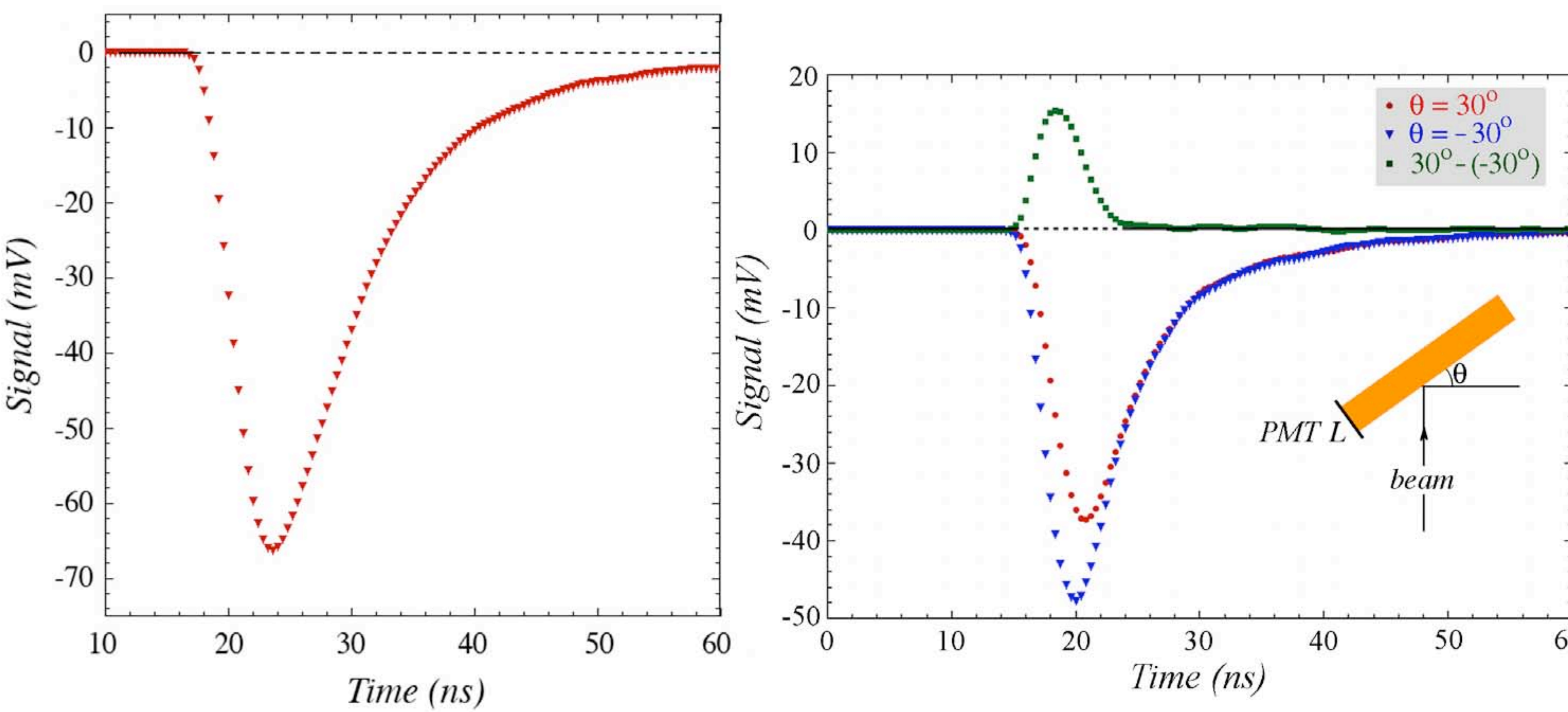


Figure 12: Average time structure of the signals measured with the PMT reading out one end (L) of a $PbWO_4$ crystal traversed by 10 GeV electrons, for two different orientations of the crystal, and the difference between these two time distributions. At $\theta = -30°$, Čerenkov light contributes to 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].

Čerenkov and Scintillator information from one signal !

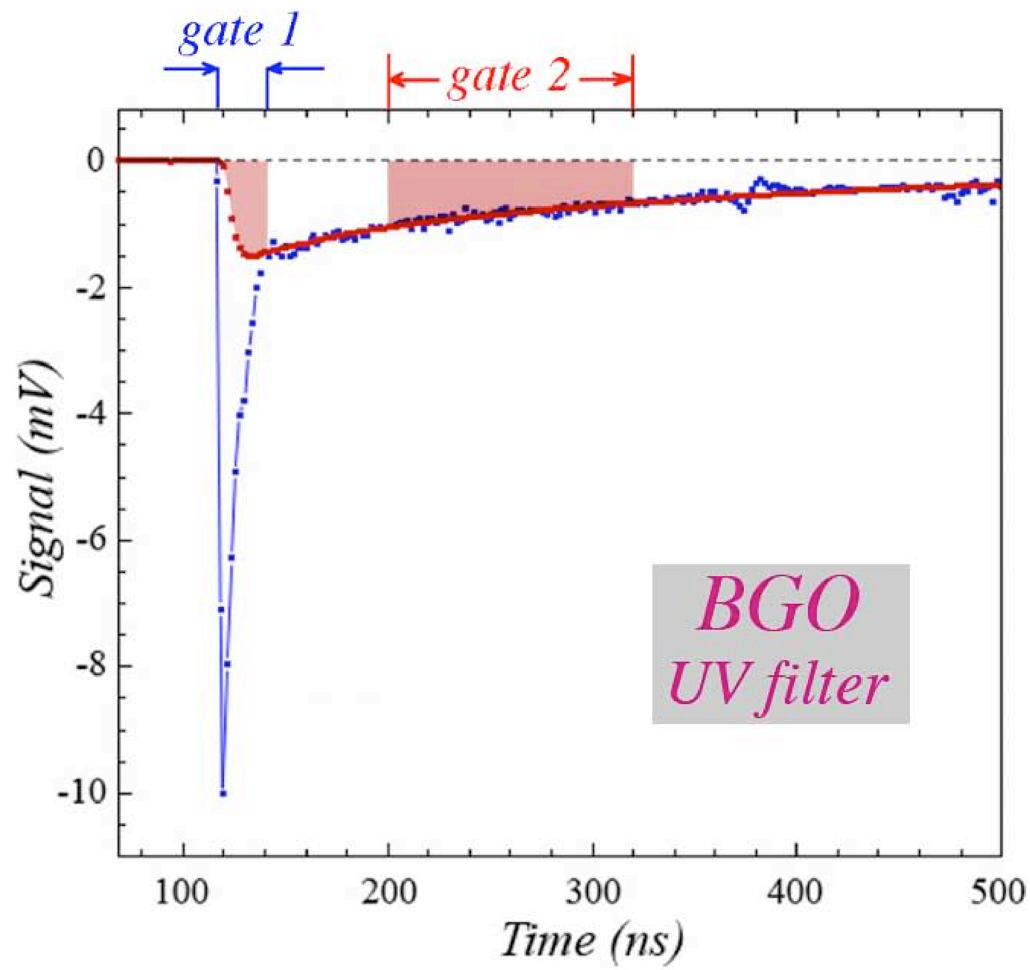


Figure 14: The time structure of a typical shower signal measured in the BGO em calorimeter equipped with a UV filter. These signals were measured with a sampling oscilloscope, which took a sample every 0.8 ns. The UV BGO signals were used to measure the relative contributions of scintillation light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

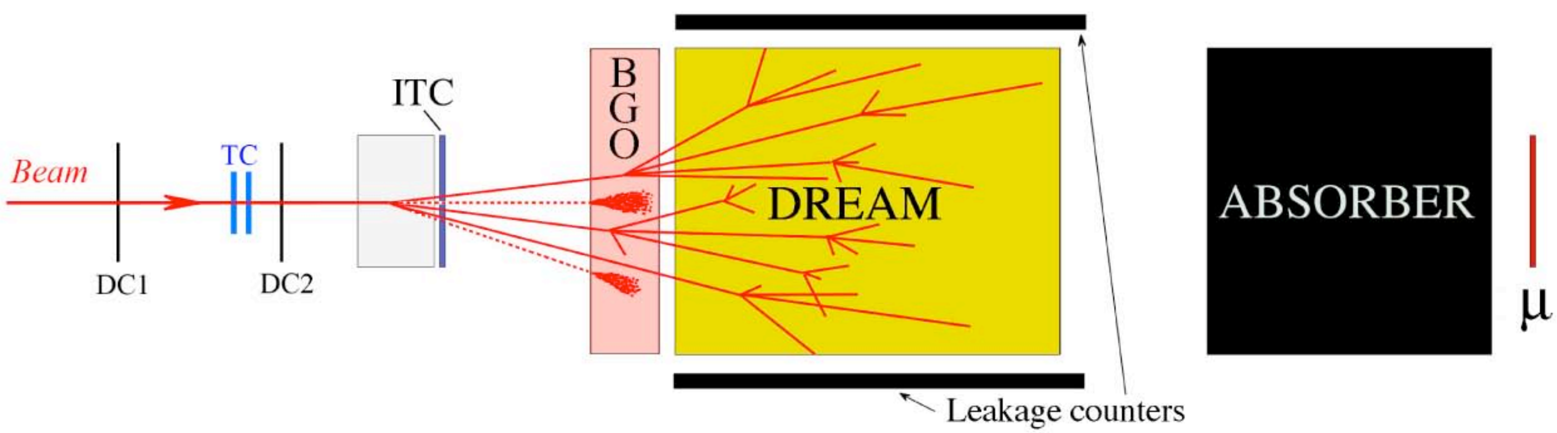
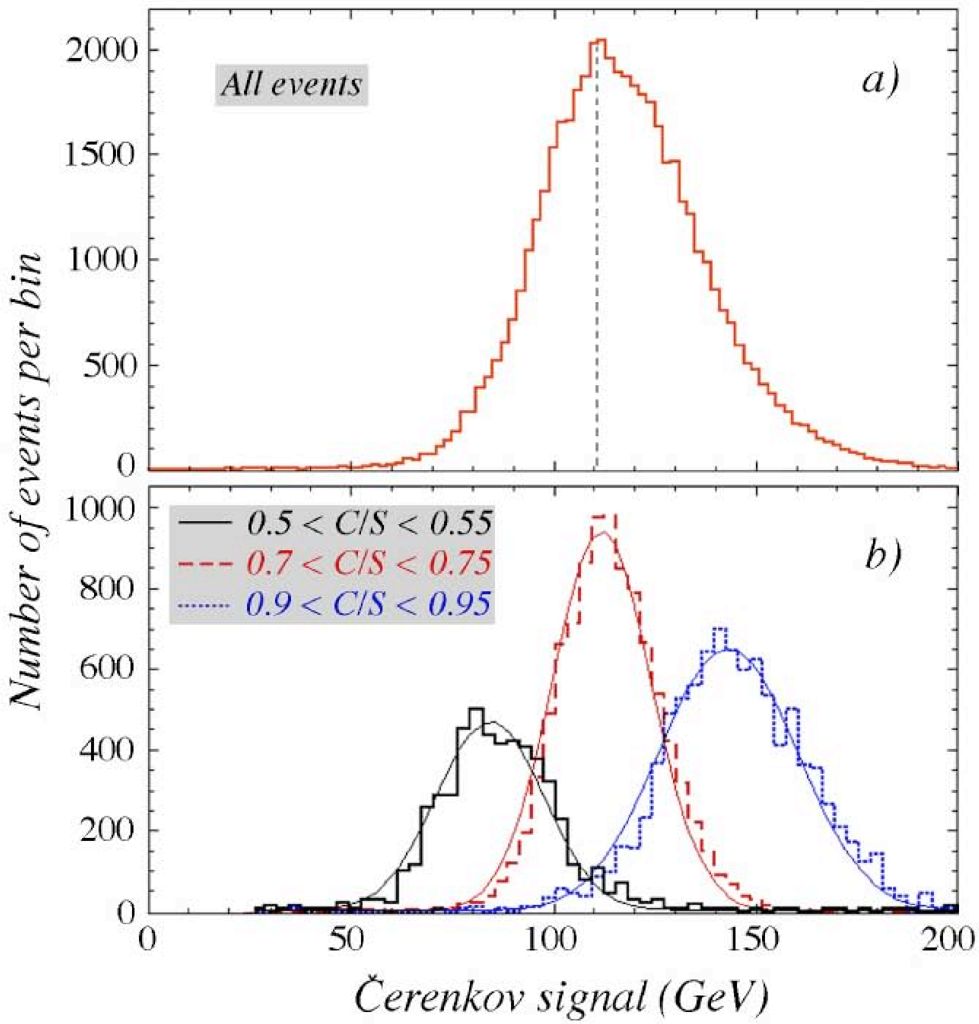


Figure 16: Schematic of the experimental setup in the beam line in which the hybrid calorimeter system was tested (see text for details). Also shown is the occurrence and development of a multi-particle event ("jet") originating in the upstream target [17].

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



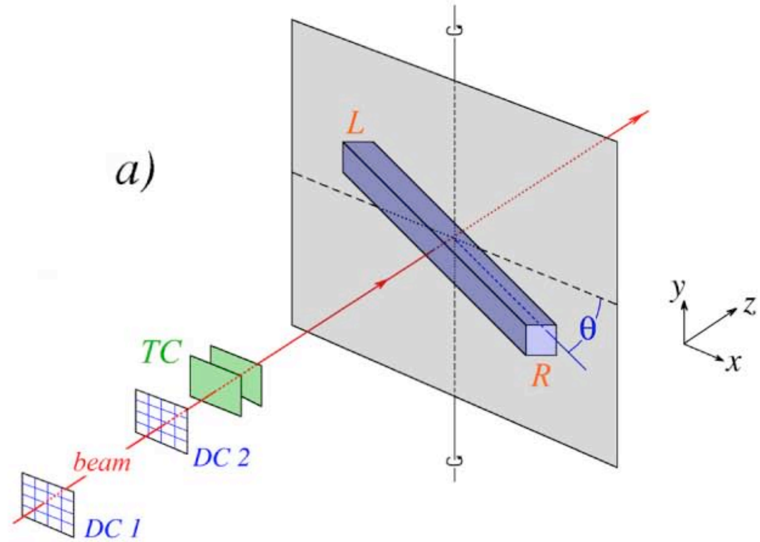
On average,
~50% of the "jet" energy
deposited in BGO matrix

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

$PbWO_4$:1%Mo

See poster G. Gaudio



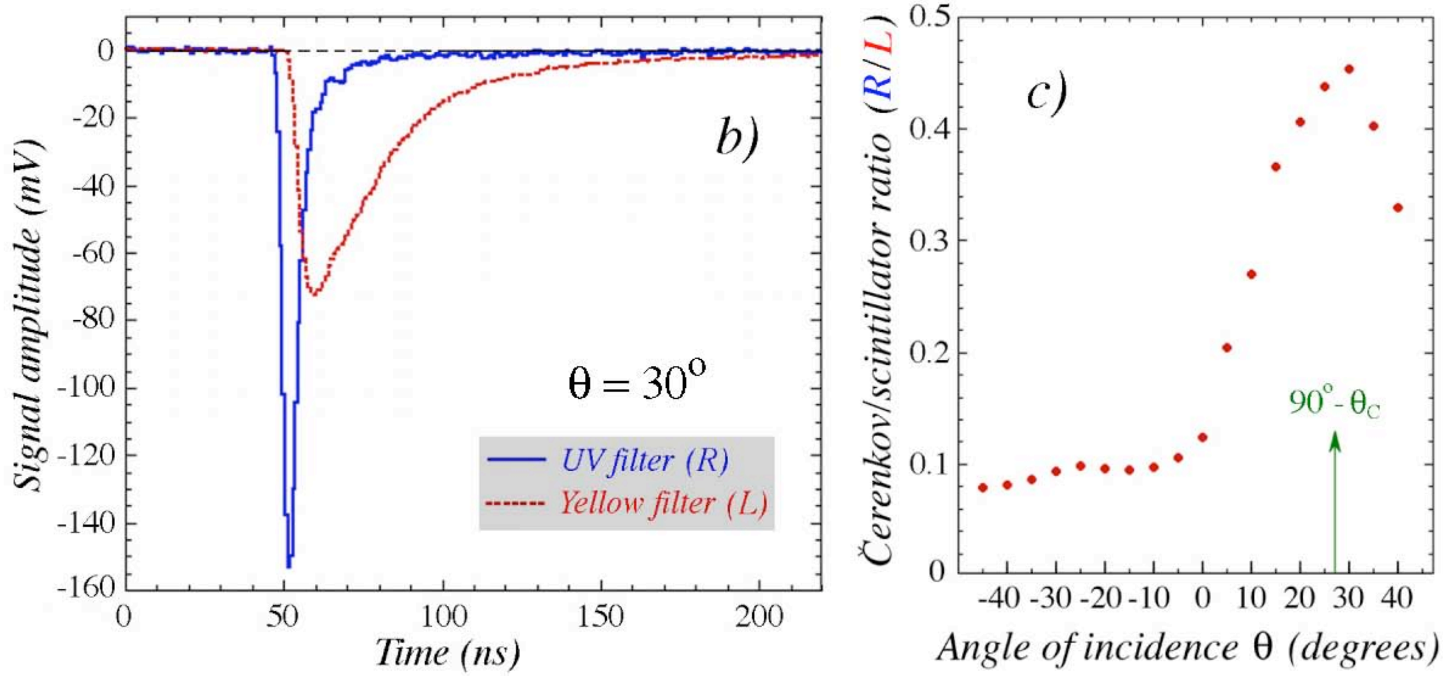


Figure 3: Unraveling of the signals from a Mo-doped $PbWO_4$ crystal into Čerenkov and scintillation components. The experimental setup is shown in diagram a. The two sides of the crystal were equipped with a UV filter (side R) and a yellow filter (side L), respectively. The signals from 50 GeV electrons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

  ⟶ *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 $\sim A^{-1} \longrightarrow$ *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) $\longrightarrow$ 12 b (0.1 MeV)
- Mean free path between elastic *n-p* scattering events: 56 cm $\longrightarrow$ 10 cm
- Average *time* between subsequent *n-p* scattering events: 23 ns
  (independent of E_n $\longrightarrow$ expect exponential tail in time structure signals)
- Neutrons lose on average *50%* of their kinetic energy in elastic *n-p* scattering
  $\longrightarrow$ *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 $\longrightarrow$ *expect $\tau_n \sim 25$ ns*

Time structure of the DREAM signals: the neutron tail (anti-correlated with f_{em})

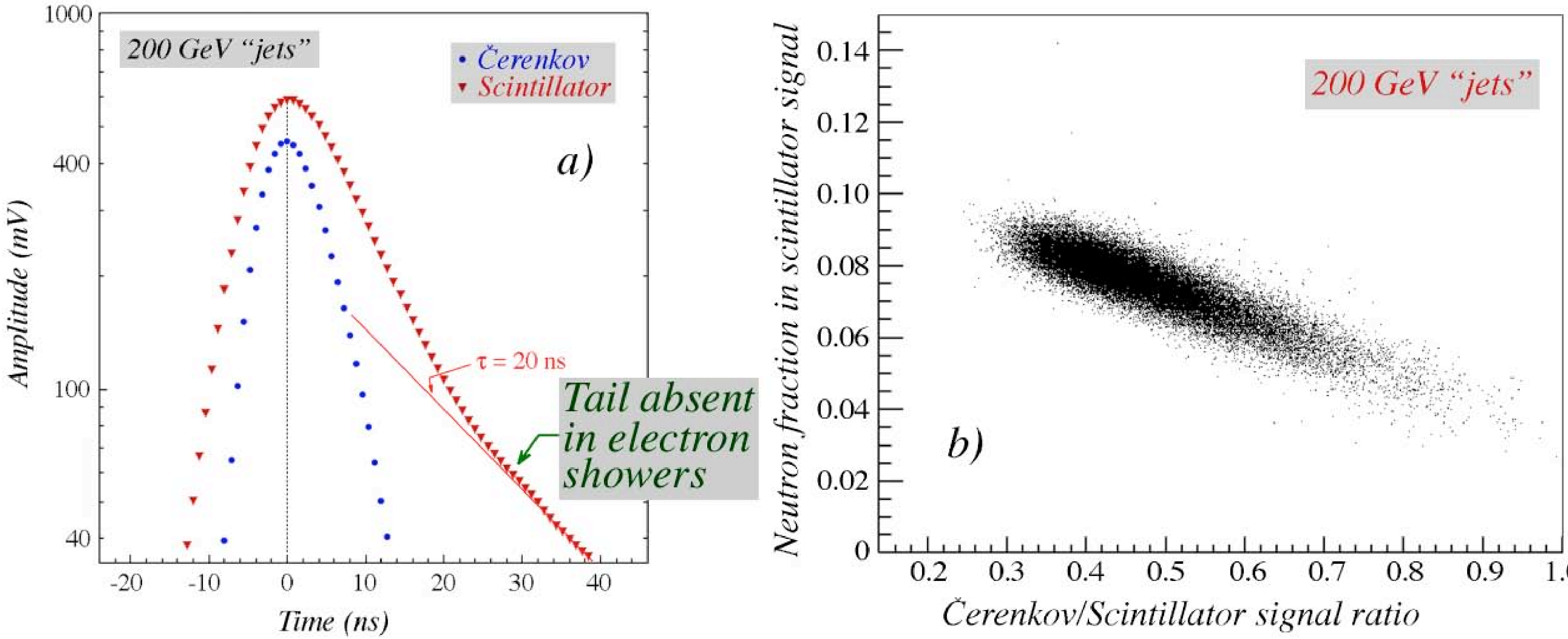


Figure 4: The average time structure of the Čerenkov and scintillation signals recorded for 200 GeV "jets" in the fiber calorimeter (a). Scatter plot of the fraction of the scintillation light contained in the (20 ns) exponentional tail versus the Čerenkov/scintillation signal ratio measured in these events (b) [9].

Probing the total signal distribution with the neutron fraction

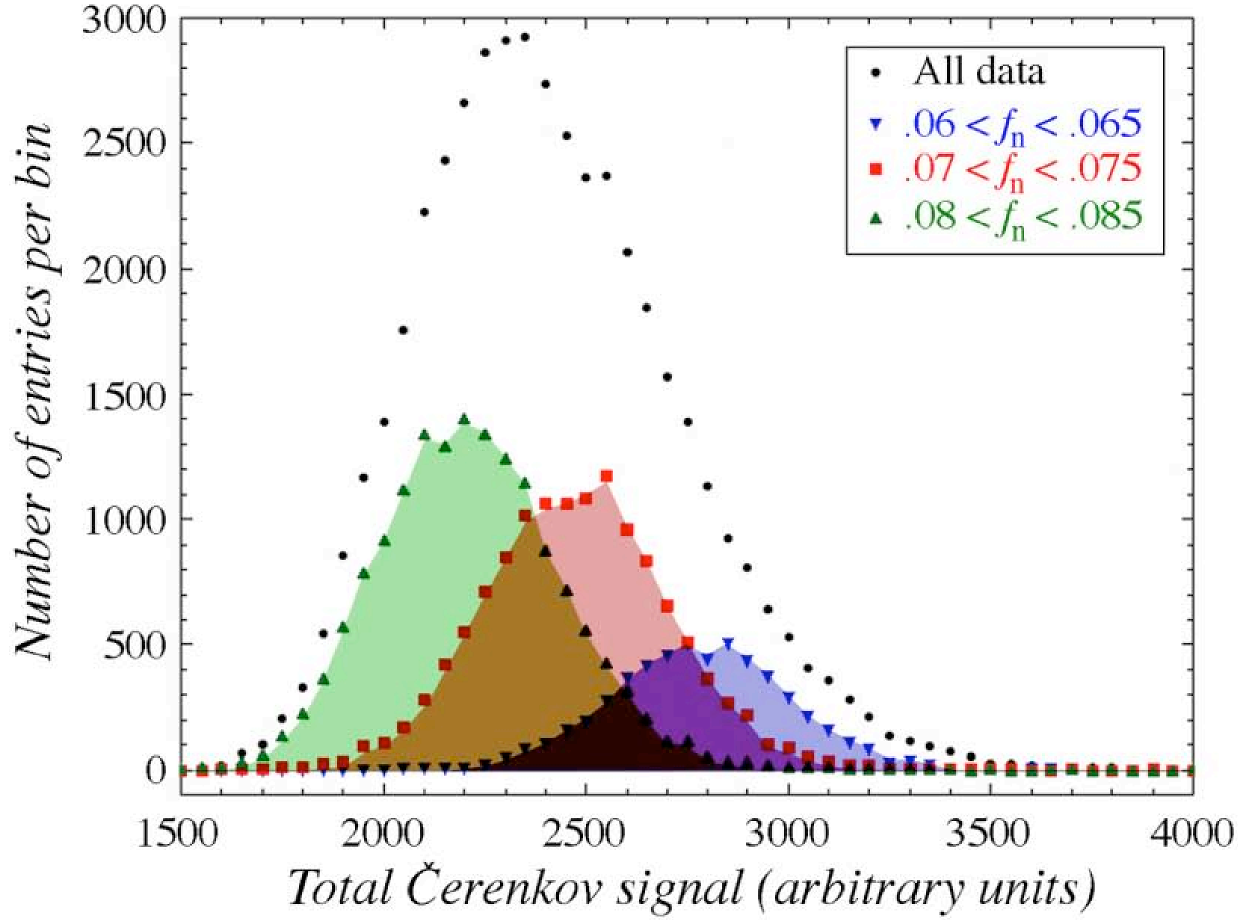


Figure 18: Distribution of the total Čerenkov signal for 200 GeV "jets" and the distributions for three subsets of events selected on the basis of the fractional contribution of neutrons to the scintillator signal [9].

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

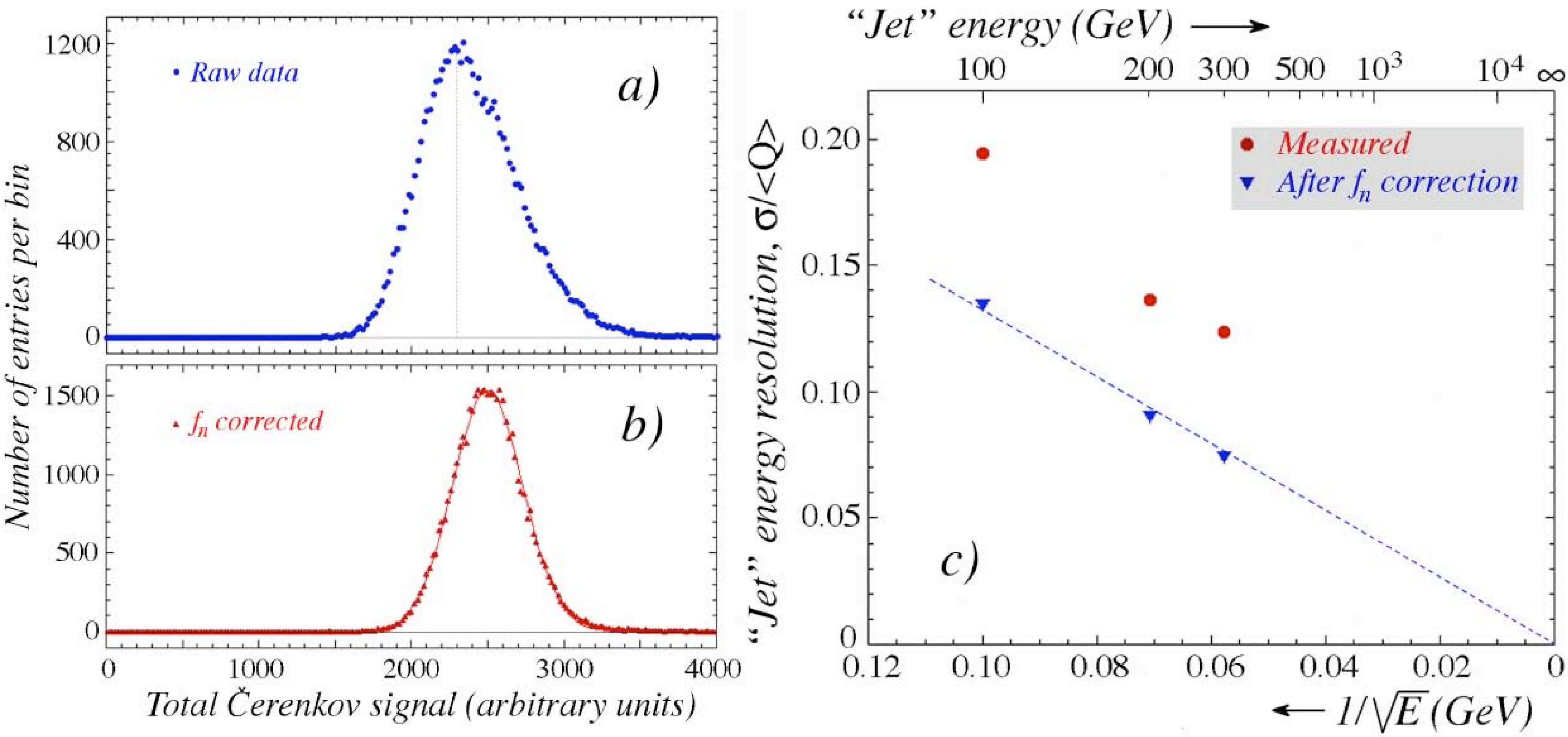
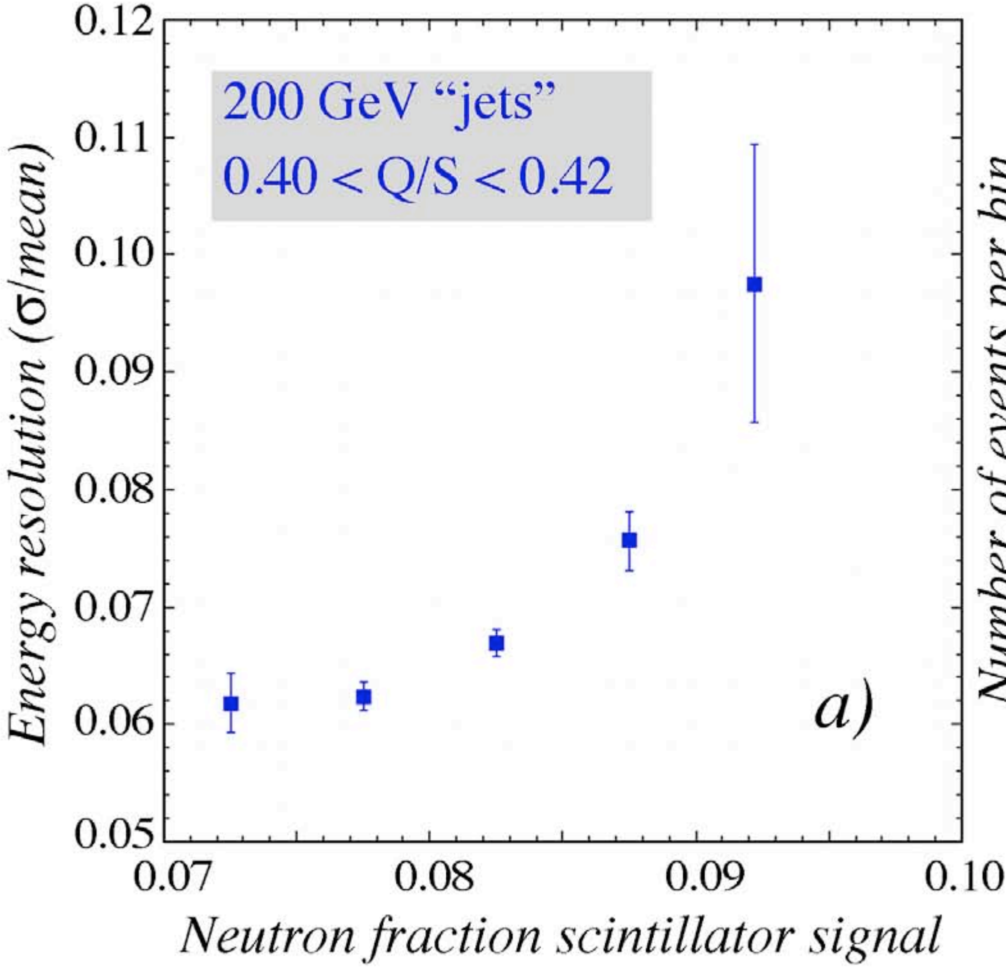
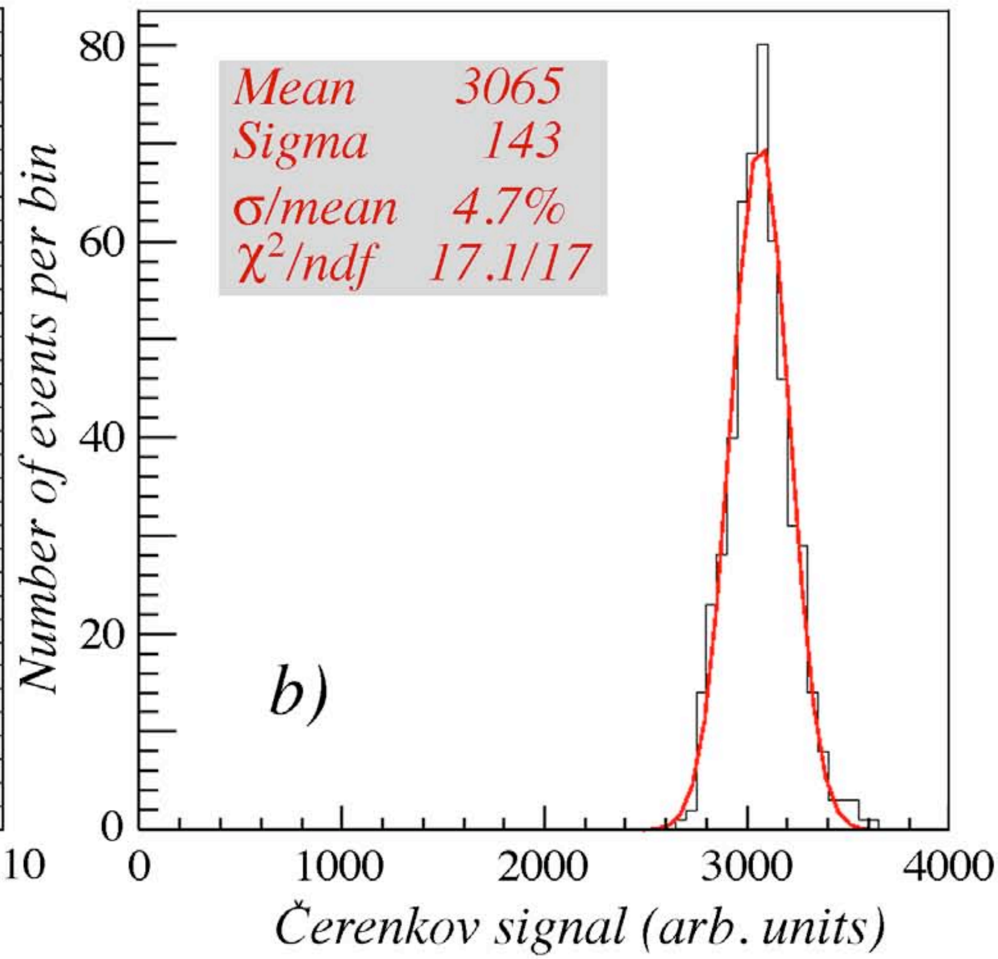


Figure 19: Distribution of the total Čerenkov signal for 200 GeV "jets" before (a) and after (b) applying the correction based on the measured value of f_n, described in the text. Relative width of the Čerenkov signal distribution for "jets" as a function of energy, before and after a correction that 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 √

(Čerenkov light yield and sampling fluctuations:) *Develop dedicated crystal(s)*
in progress

Then build a full-scale prototype calorimeter
Proposals to funding agencies submitted

Elements of the proposed detector

- *Hadronic shower containment > 99% at all energies (leakage fluctuations < 0.01E)*
- *Maximized fiber packing, photocathode area*
- *Fibers individually embedded in absorber*
- *Čerenkov fibers with large numerical aperture*
- *Upstream end of Čerenkov fibers aluminized (for depth determination of light production → eliminate attenuation effects)*
- *Time structure measured for all signals*
- *Optional em crystal section*

Fiber detector:

Total instrumented mass: 5000 kg

Total fiber length: 600 km

Readout channels (S+Č): 122

Expected resolution for hadrons. jets (stand-alone): < 0.25 $E^{-1/2}$

Expected resolution for electrons, photons (stand-alone): < 0.10 $E^{-1/2}$

Structure of proposed fiber calorimeter

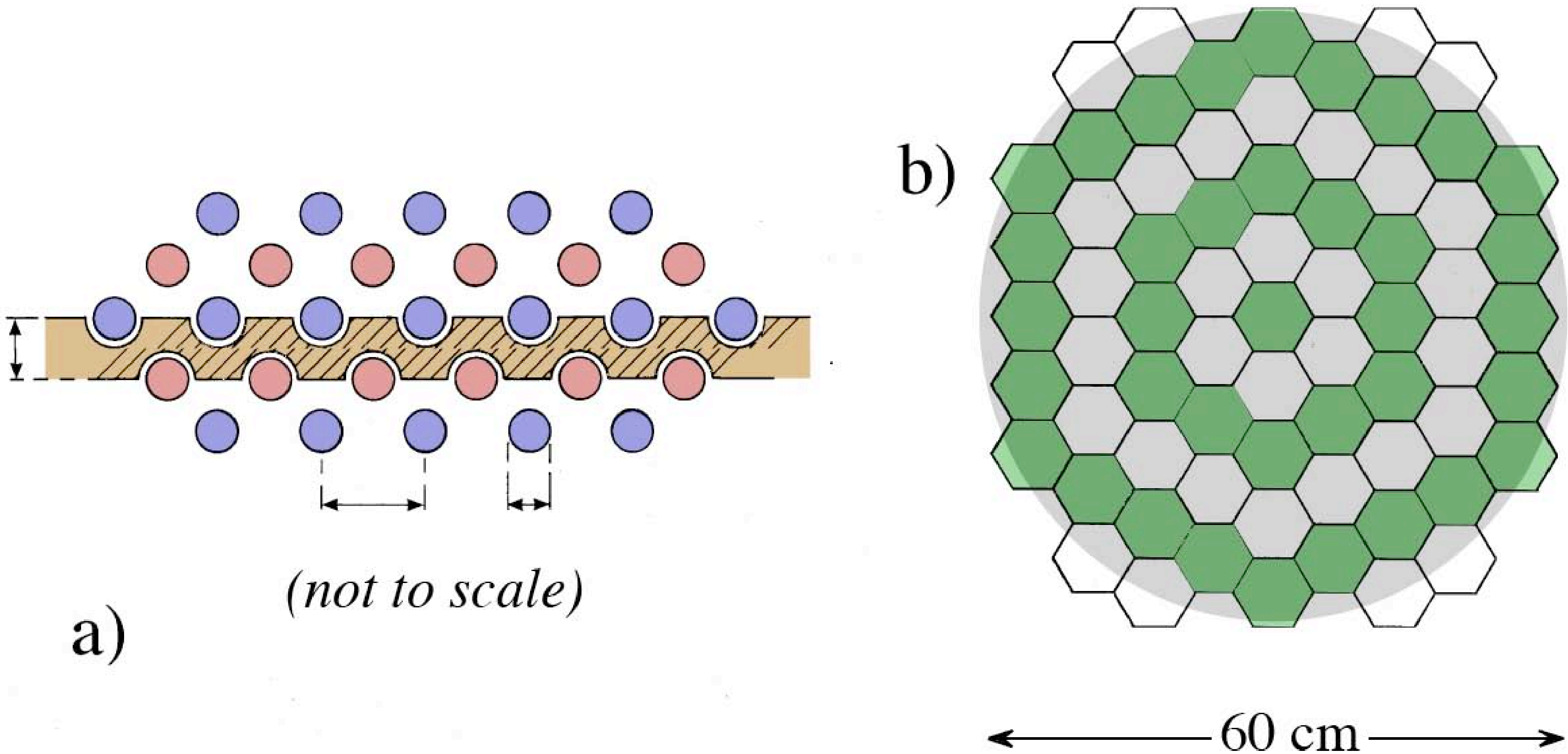


Figure 25: The pattern according to which the two types of fibers will be distributed inside the detector volume (a) and the tower structure of the proposed fiber calorimeter (b).

Design goal proposed fiber calorimeter

(light yield, sampling fluctuations)

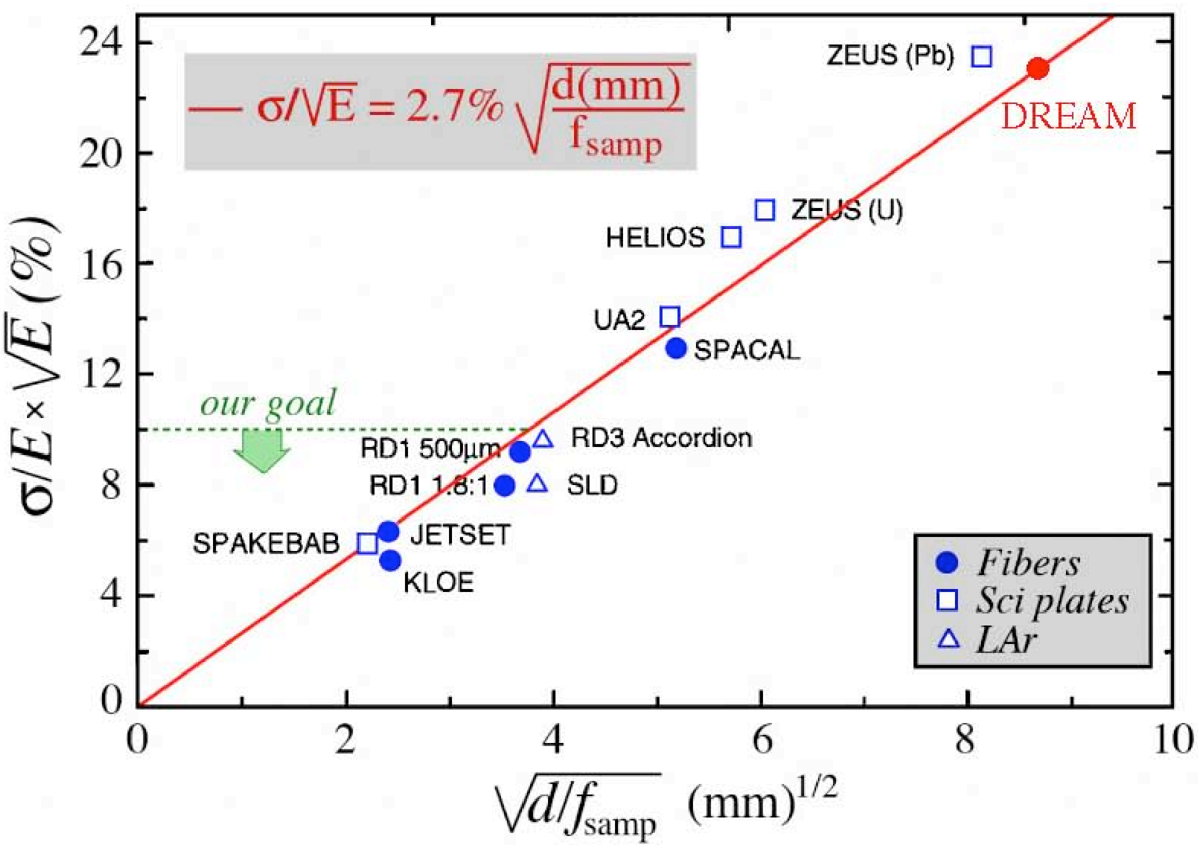


Figure 23: The em energy resolution of sampling calorimeters as a function of the parameter $(d/f_{\mathrm{samp}})^{1/2}$, in which d is the thickness of an active sampling layer (*e.g.* the diameter of a fiber or the thickness of a liquidargon gap), and f_{samp} the sampling fraction for mips [20].

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

Hadronic shower profiles: Fluctuations!

π^o production may take place anywhere in the absorber

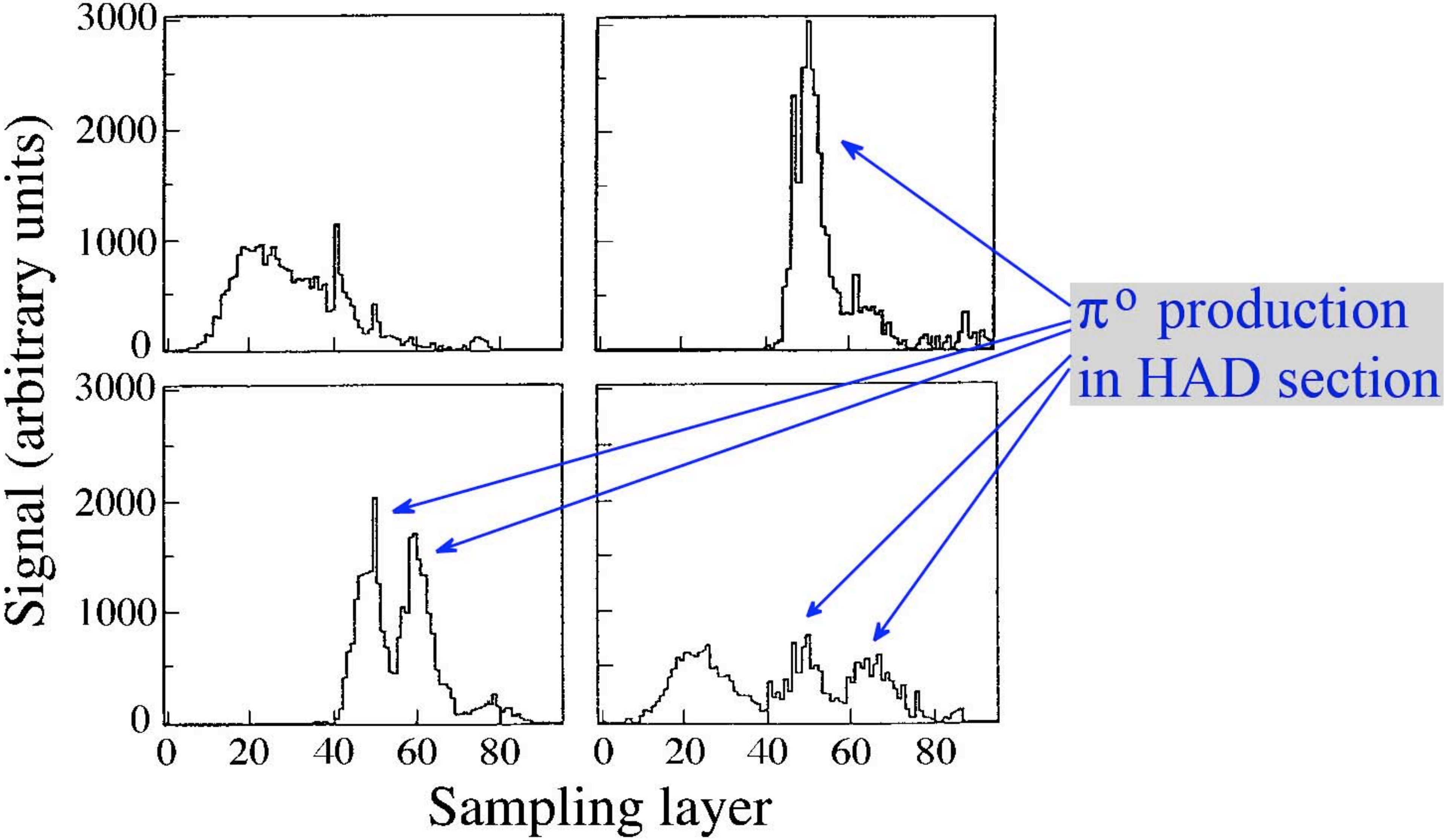
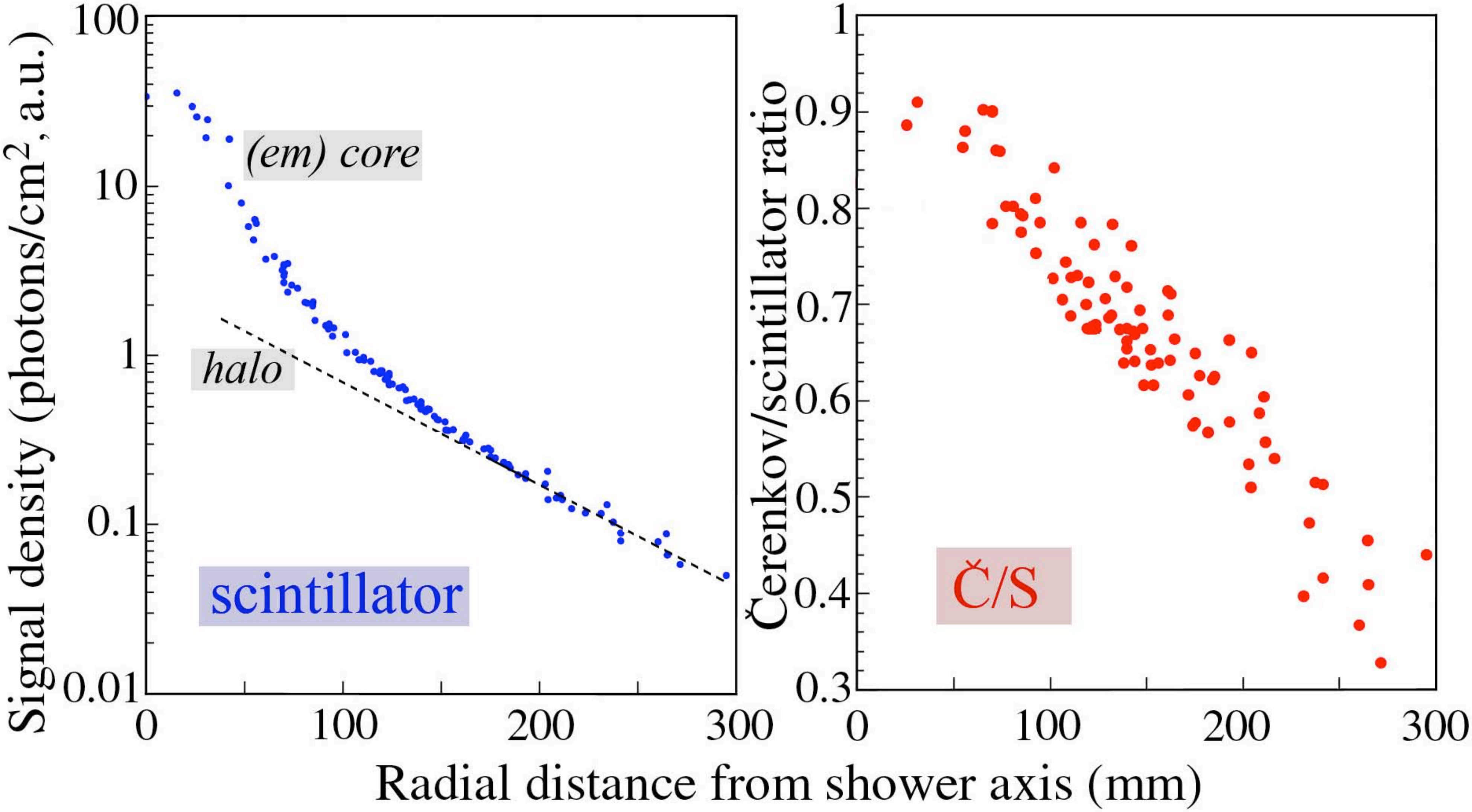


FIG. 2.35. Longitudinal profiles for 4 different showers induced by 270 GeV pions in a lead/iron/plastic-scintillator calorimeter. Data from [Gre 94].

Radial hadron shower profiles (DREAM)



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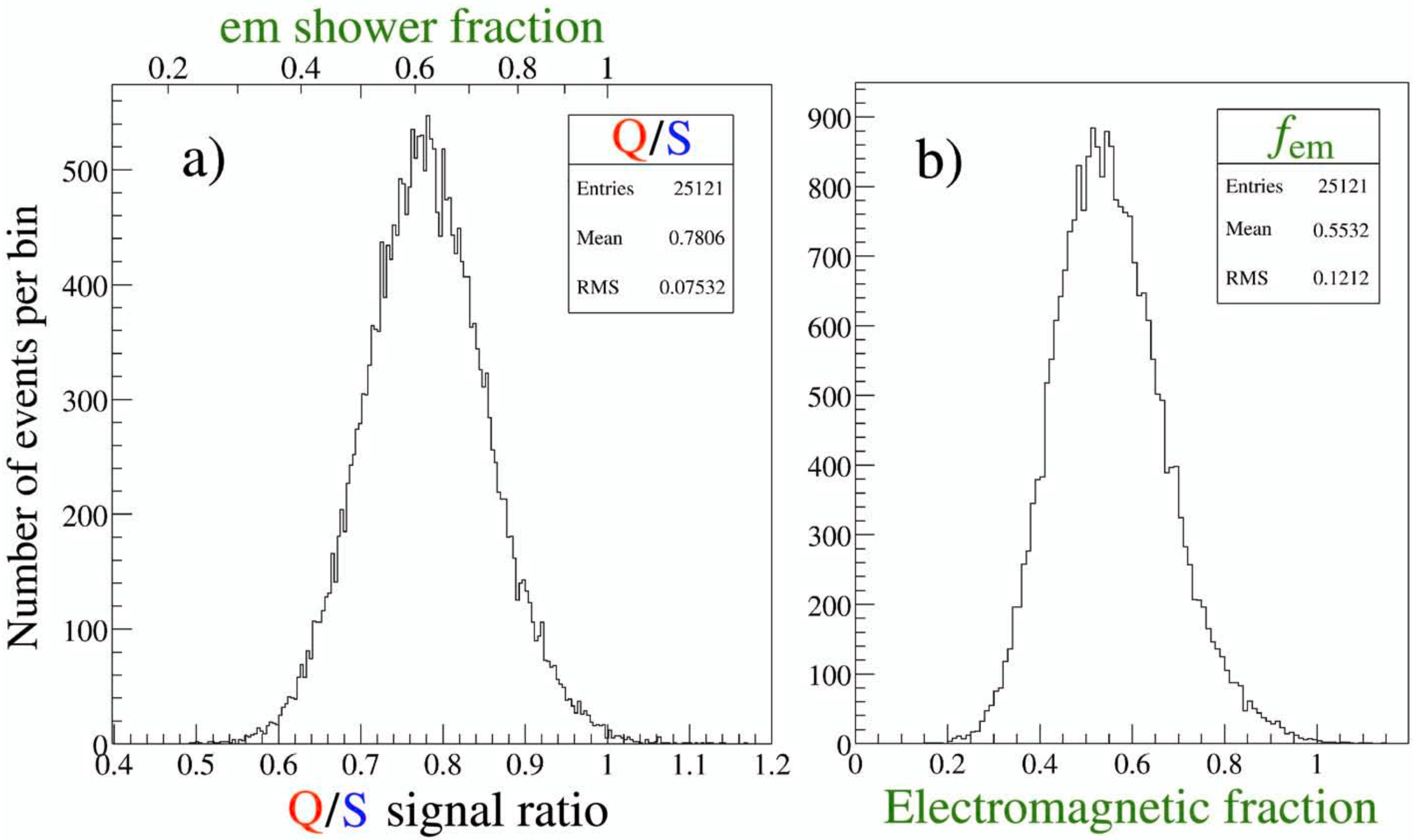
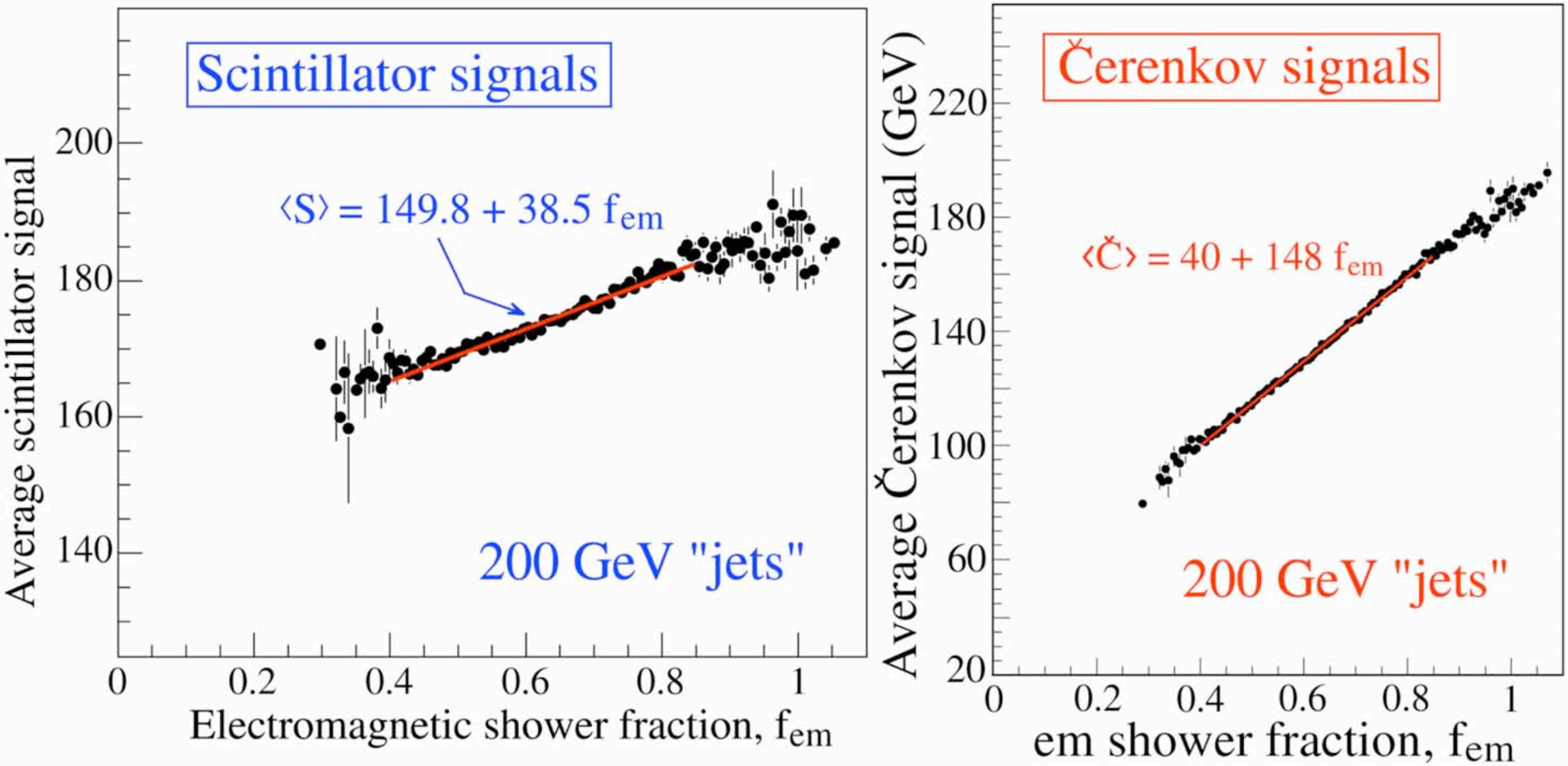
DREAM: relationship between Q/S ratio and f_{em}



DREAM: Signal dependence on f_{em}



$$R(f_{\mathrm{em}}) = p_0 + p_1 f_{\mathrm{em}}$$ 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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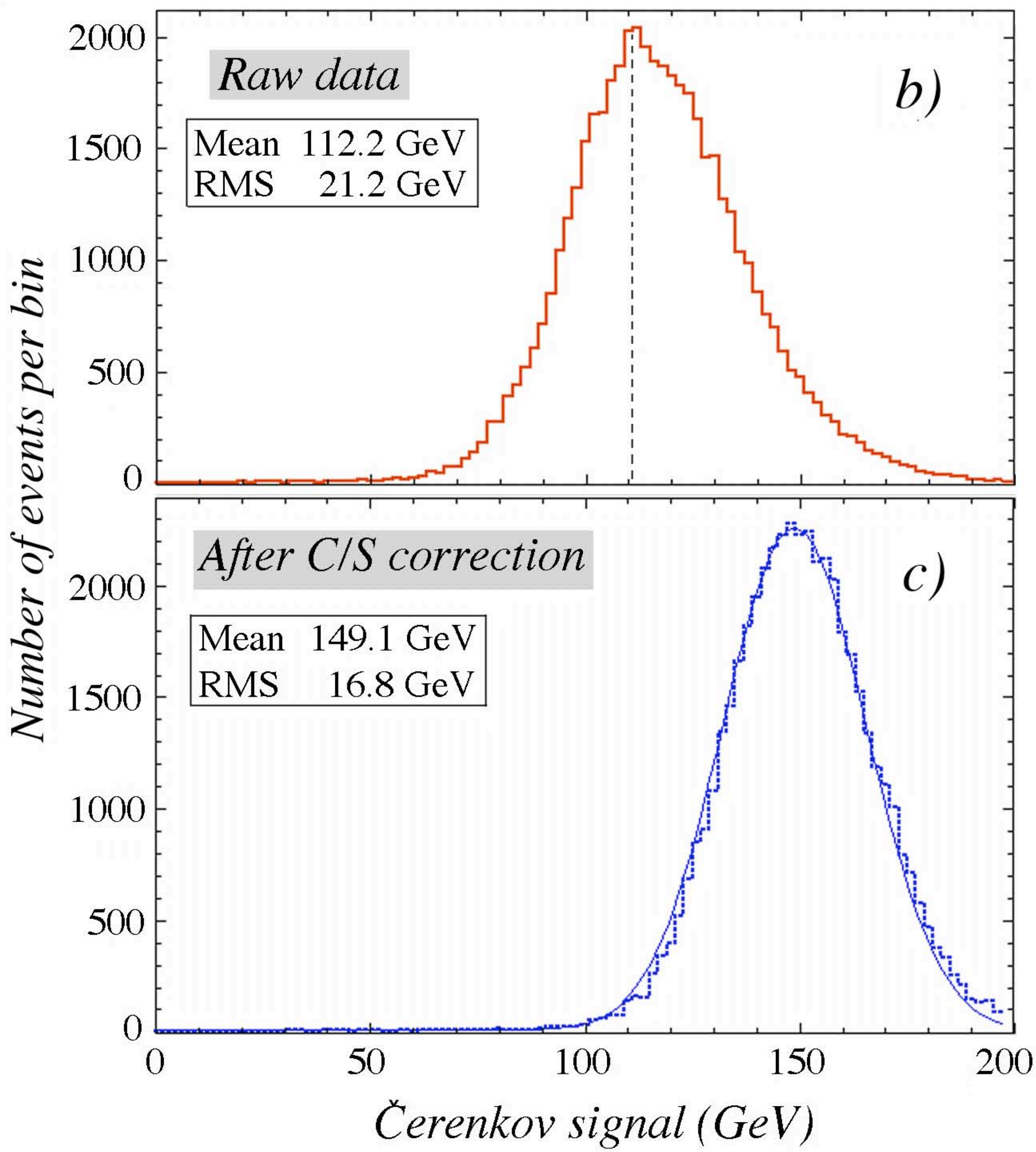
NIM A537 (2005) 537

Improvement response function hybrid calorimeter system



Effects of light attenuation on the fiber response

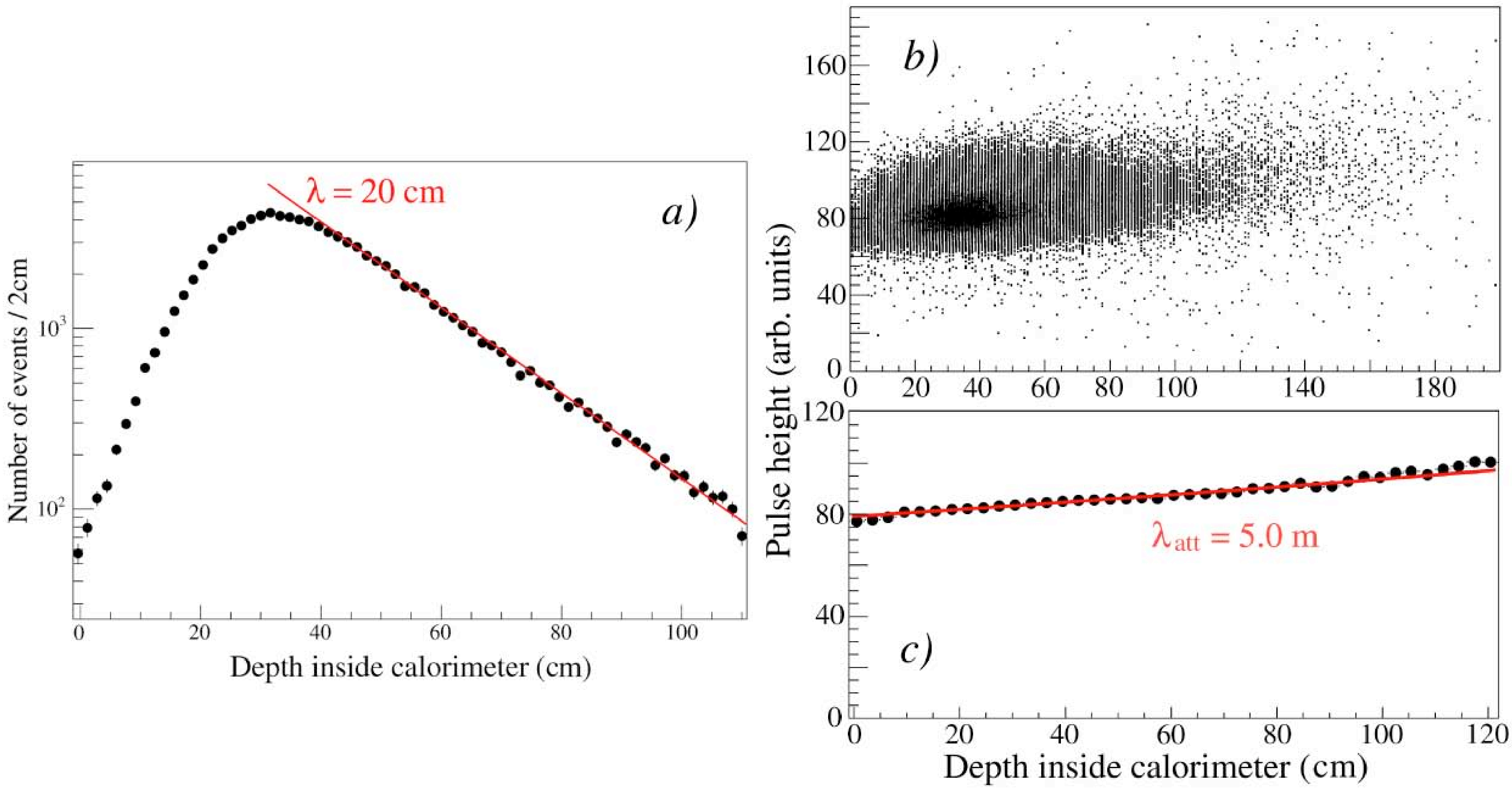


Figure 26: Distribution of the average depth at which the scintillation light is produced in the DREAM calorimeter by showering hadrons (a). Scatter plot showing the total scintillator signal versus the average depth of the light production (a) and the average size of the total scintillator signal as a function of that depth (b), for events induced by 100 GeV π^- mesons. [5].