DREAM

Dual-Readout calorimetry for high-quality energy measurements

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DOE review, 12/9/2010

Mission statement

DREAM is a *generic* detector R&D project
not linked to any experiment

Goal: Investigate + eliminate the factors that prevent us from measuring hadrons and jets with similar precision as electrons, photons

The importance of (hadronic) energy resolution

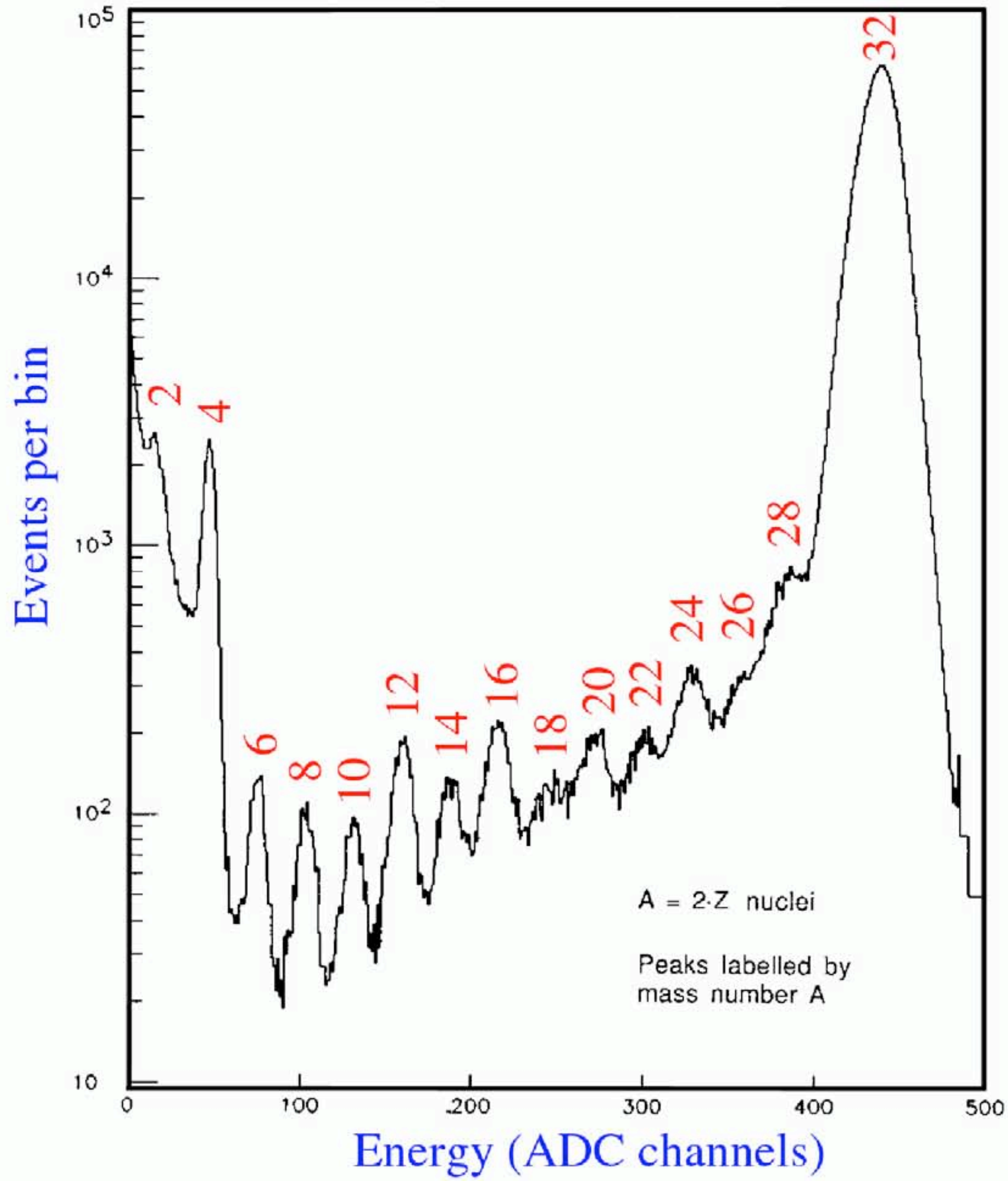


FIG. 7.51. The WA80 calorimeter as a high-resolution spectrometer. Total energy measured with the calorimeter for minimum-bias events revealed the composition of the momentum-selected CERN heavy-ion beam [You 89].

The importance of (hadronic) energy resolution (2)

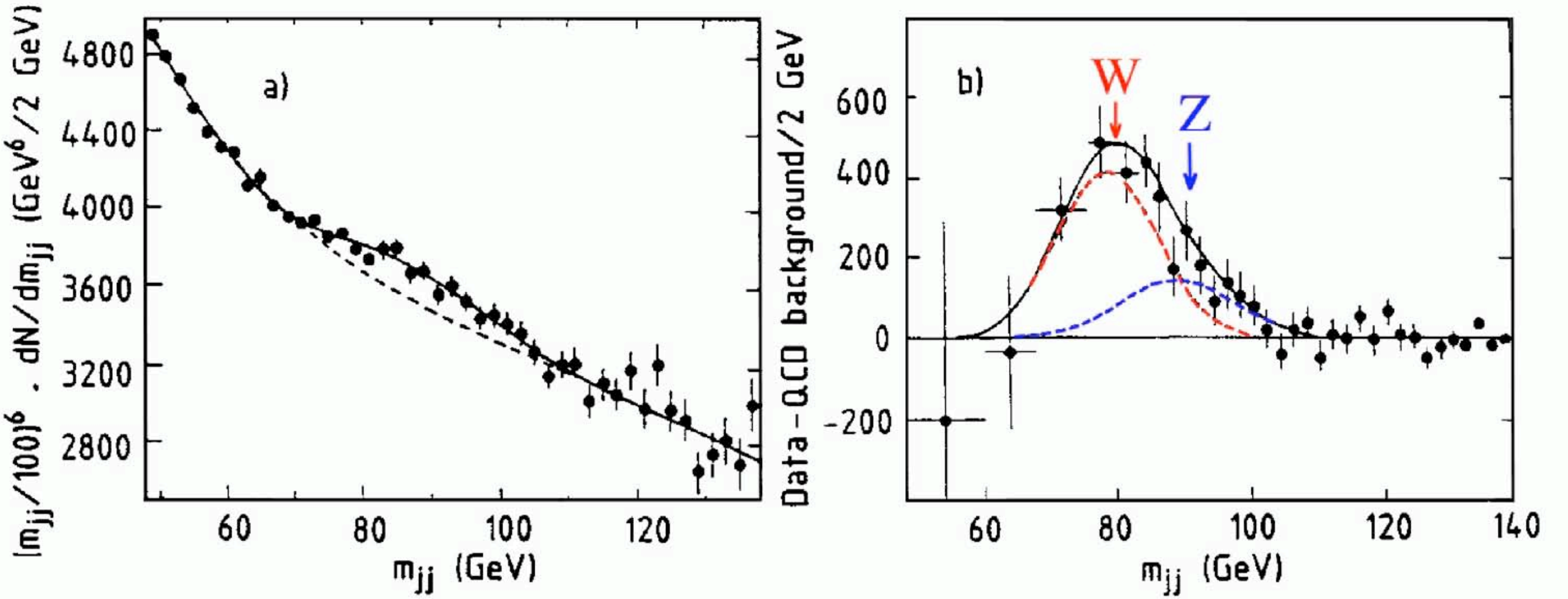
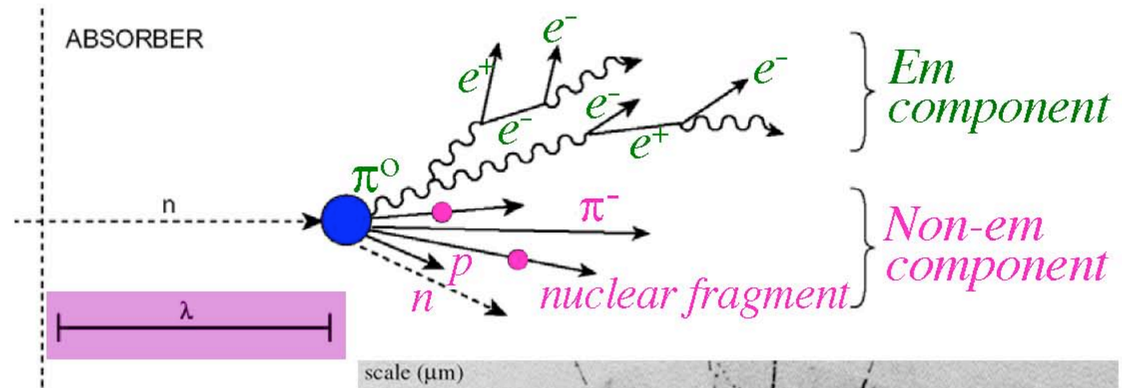


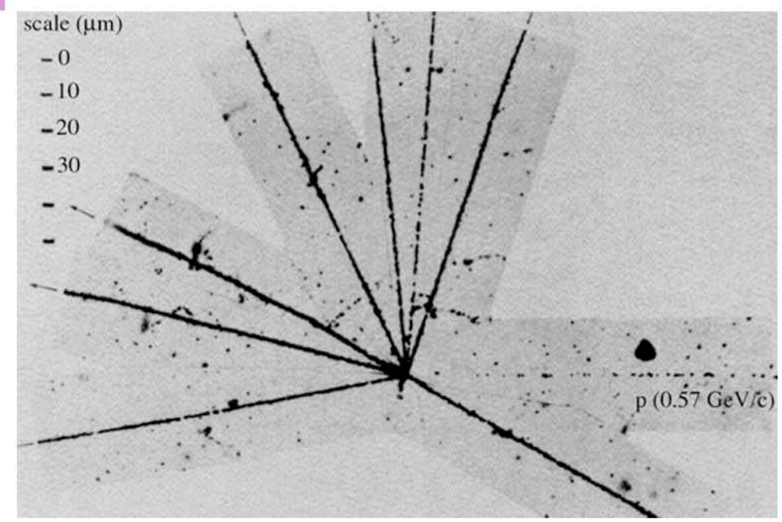
FIG. 7.50. Two-jet invariant mass distributions from the UA2 experiment [Alit 91]. Diagram a) shows the measured data points, together with the results of the best fits to the QCD background alone (*dashed curve*), or including the sum of two Gaussian functions describing $W, Z \to q\bar{q}$ decays. 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].

Hadronic Shower Development

- *A hadronic shower consists of two components*



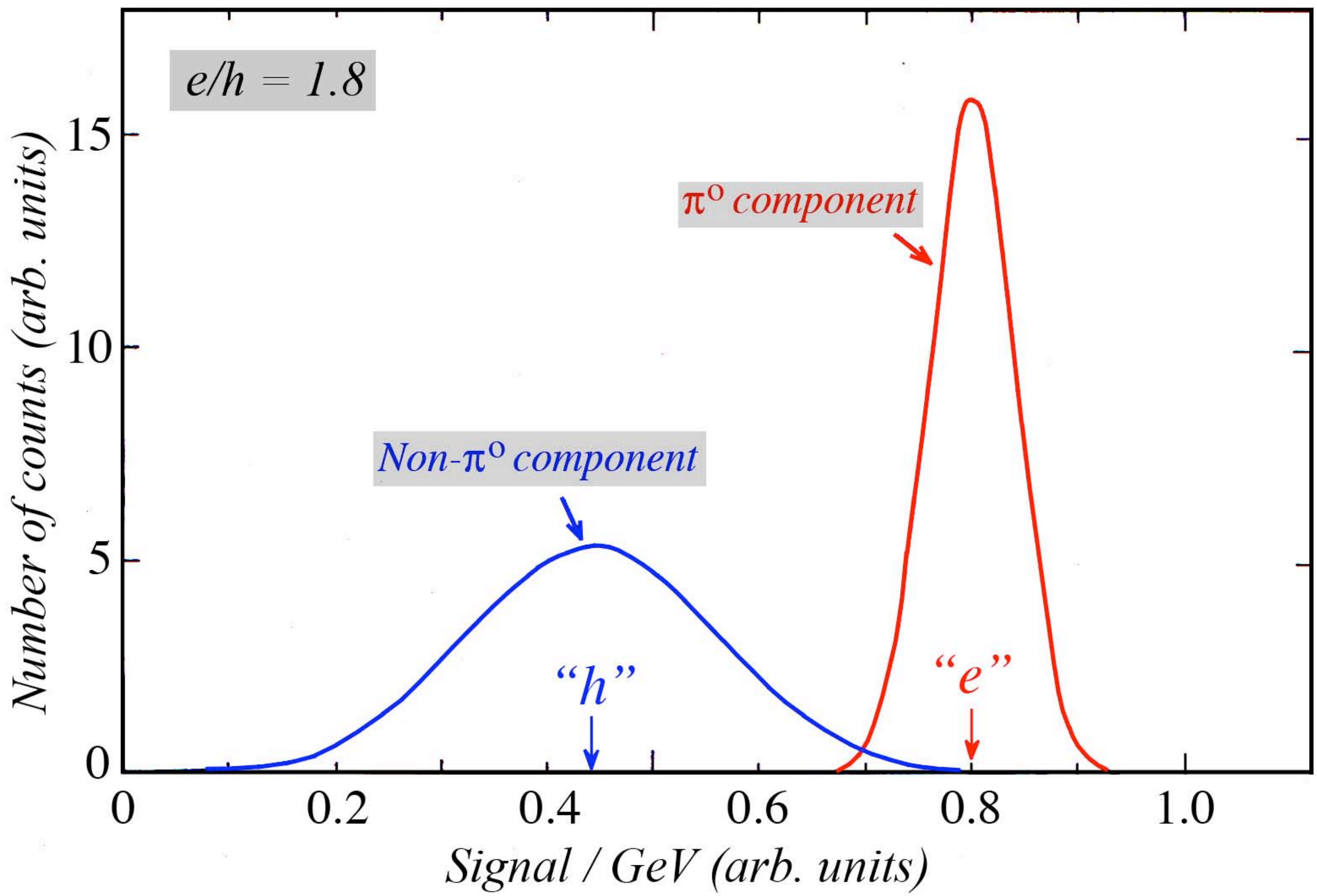
  - *Electromagnetic component*
    - electrons, photons
    - neutral pions → 2 γ
  - *Hadronic (non-em) component*
    - charged hadrons $\pi^\pm$, $K^\pm$ (20%)
    - nuclear fragments, p (25%)
    - neutrons, neutrino's, soft γ's (15%)
    - break-up of nuclei *("invisible")* (40%)



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

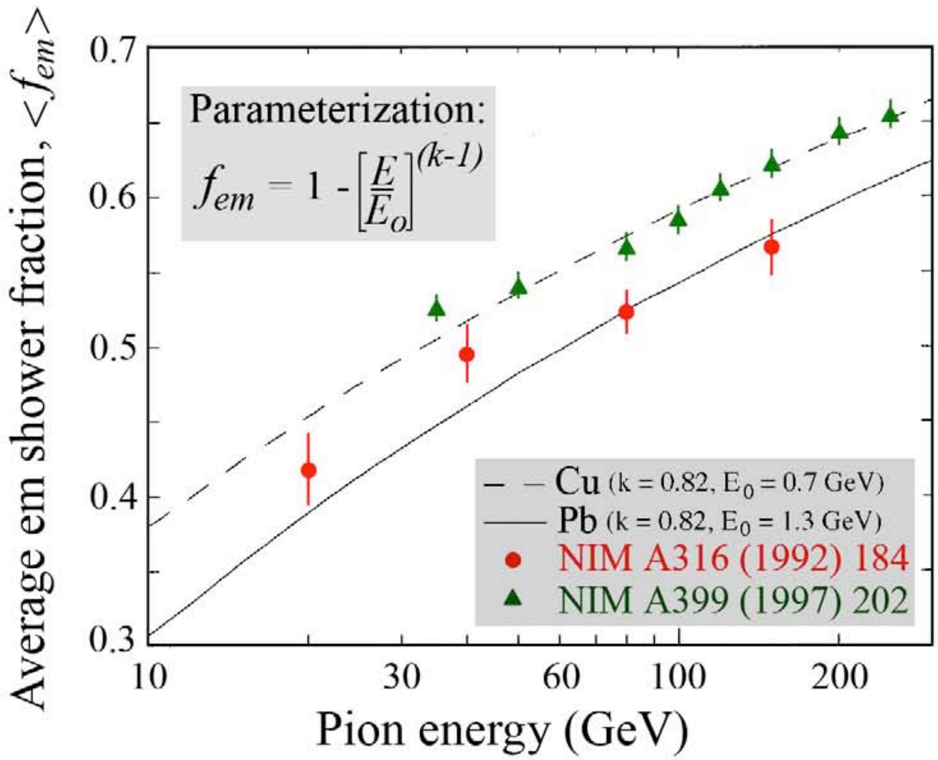
The calorimeter response to the two shower components is NOT the same

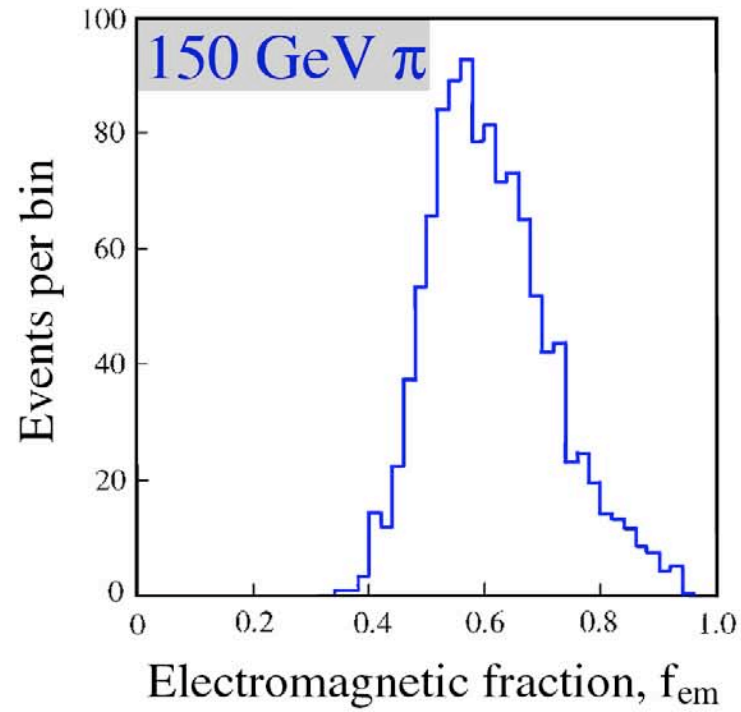
(mainly because of nuclear breakup energy losses in non-π^o component)



(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*

Hadronic shower profiles: Fluctuations!

π^o production may take place anywhere in the absorber

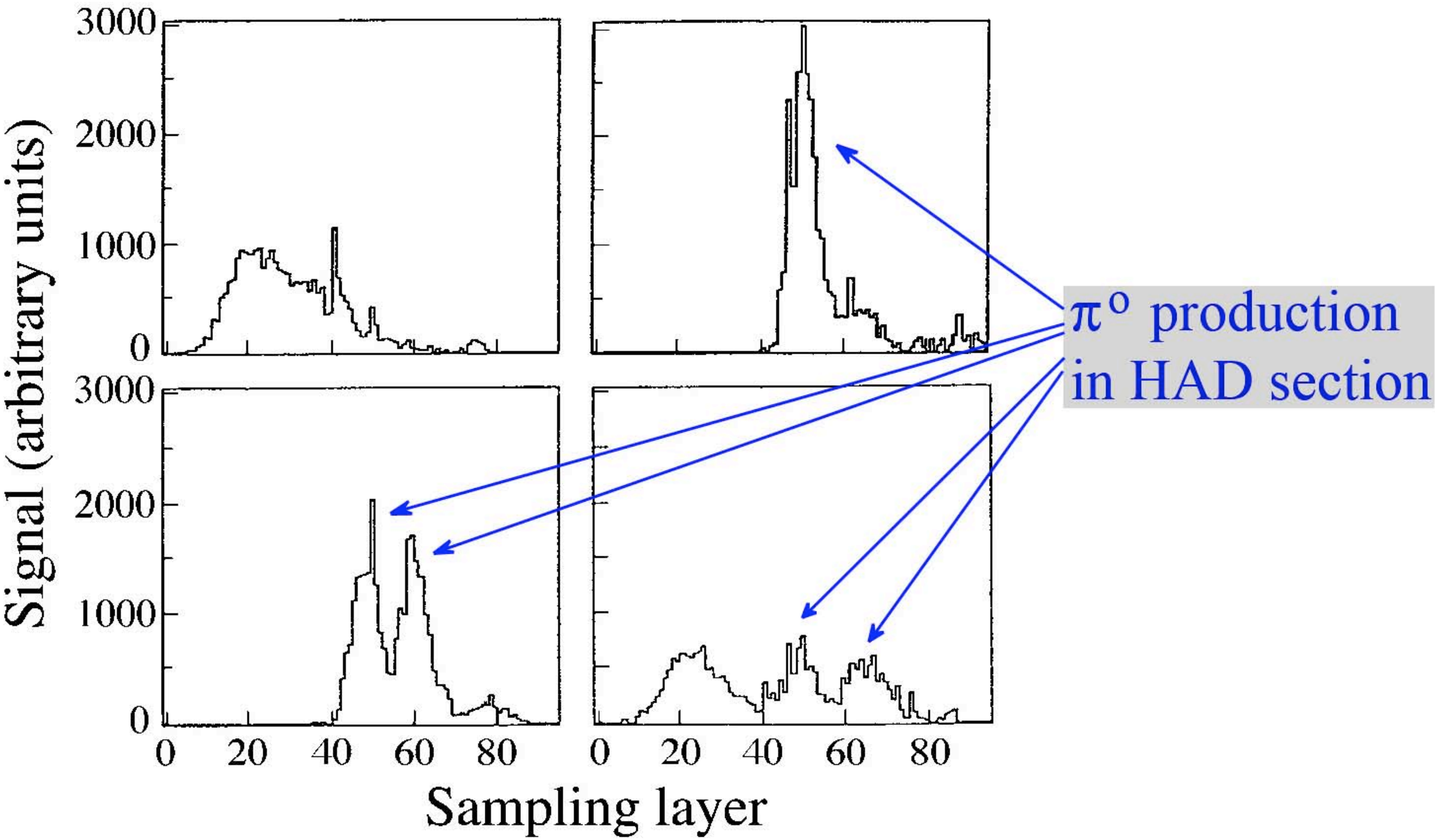


FIG. 2.35. Longitudinal profiles for 4 different showers induced by 270 GeV pions in a lead/iron/plastic-scintillator calorimeter. Data from [Gre 94].

Fluctuations in the 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*

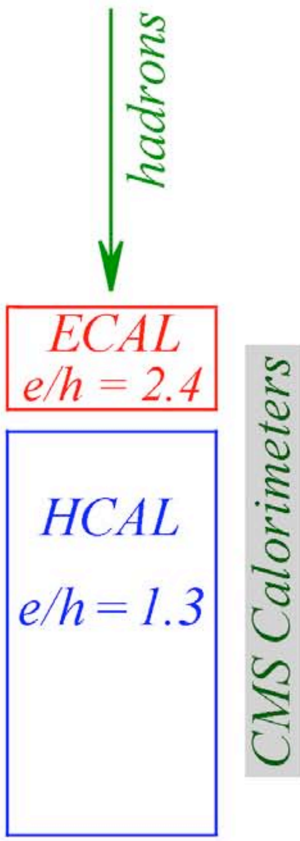
- *Cause of all common problems in hadron calorimeters*
  - *Energy scale* different from electrons, in energy-dependent way
  - Hadronic *non-linearity*
  - *Non-Gaussian* response function
  - Poor energy *resolution*
  - *Calibration* of the sections of a longitudinally segmented detector

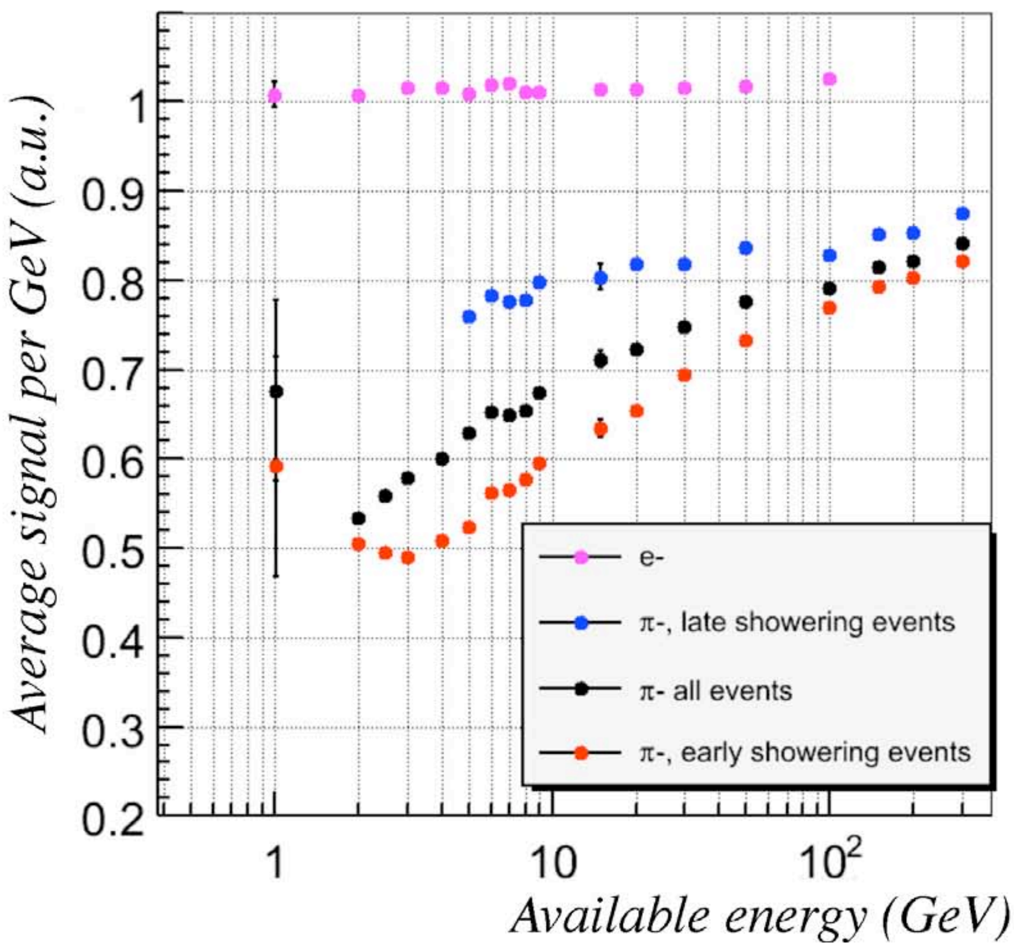
Consequences for LHC calorimeters

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 $e/h = 1.3$

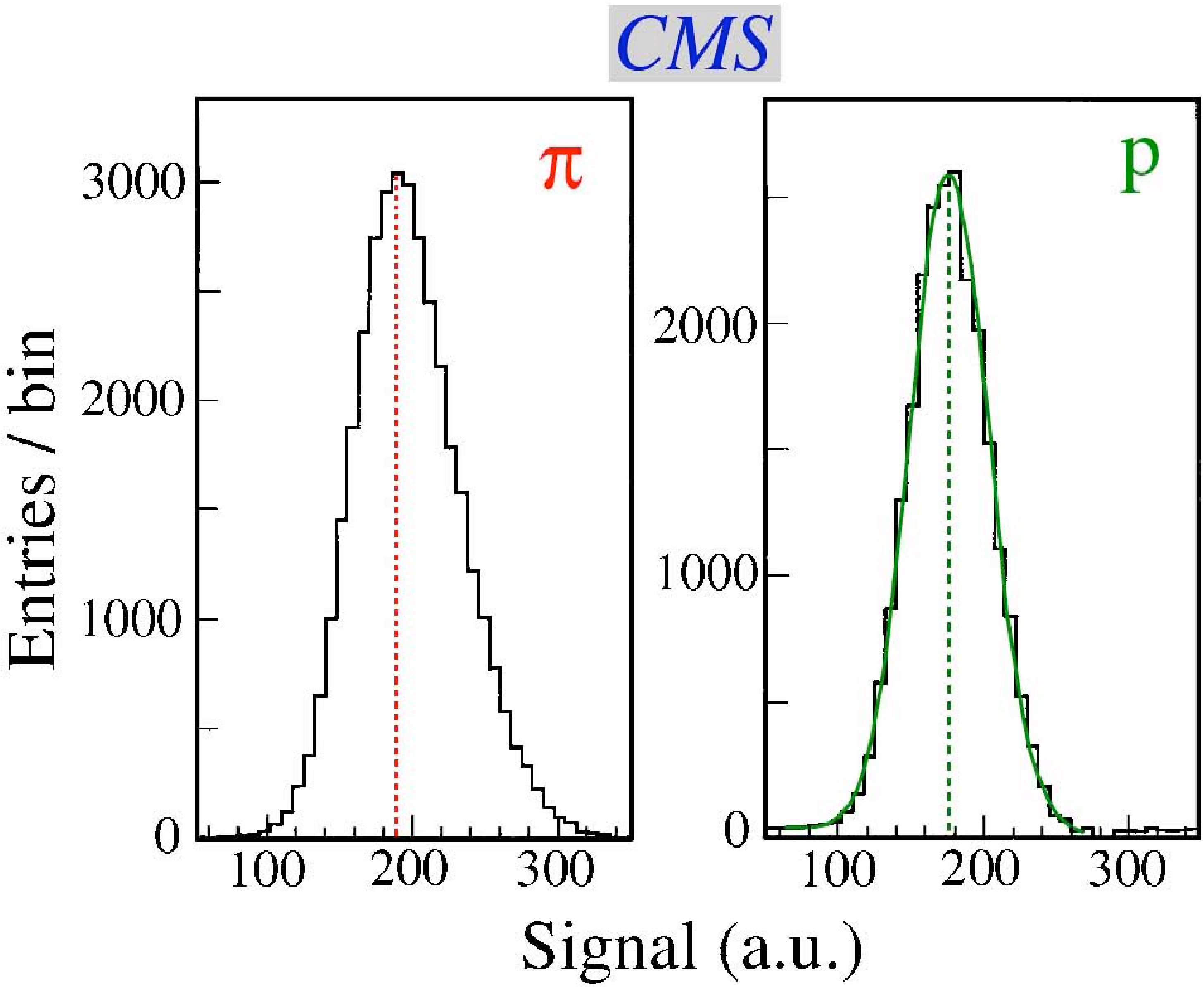
→ *Response depends strongly on starting point shower*





Consequences for LHC calorimeters

Different response functions for (300 GeV) p, π



The Dual-Readout Approach

to Hadron Calorimetry

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 *($e/h \neq 1$)*

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

A brief history of Dual-Readout calorimetry

- *Inspired by results of CMS HF prototype studies (1995)*

  e/h ~ 5 ⟶ only electromagnetic shower component in Č signals

- *Idea for Dual-Readout calorimetry first proposed at CALOR VII (1997)*

  Measure dE/dx and Č light simultaneously

  ⟶ determine em shower fraction event by event

- *2000: First experimental tests in ACCESS (PeV cosmic ray detector for ISS)*

  How to do a reasonable energy measurement of PeV ions in a $1 - 2\lambda_{\text{int}}$ deep calorimeter?

  - Energy resolution dominated by *leakage fluctuations* → need event-to-event leakage information
  - *Hypothesis*: Leakage correlated with π^0 production in calorimeter.
  - Compare signals from scintillating fibers/quartz fibers for same events:

  Q/S is indeed a measure for leakage, can be used to improve E resolution

- *2002: Since method works already so well for very thin devices, we built a 1-tonne calorimeter to explore its potential: DREAM*

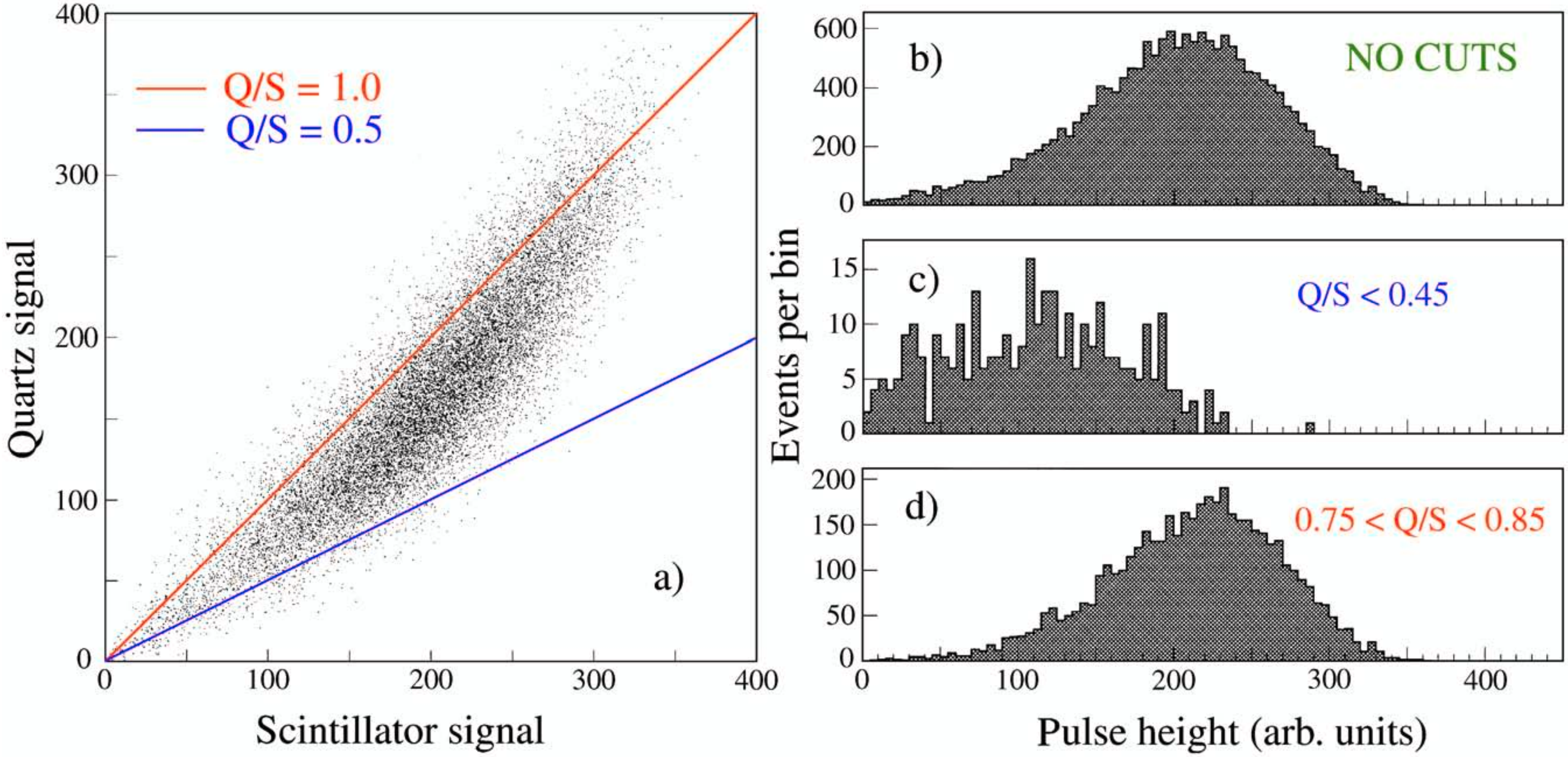
  Composition detector:

  Cu : scintillator : Čerenkov fibers : air = 69.3 : 9.4 : 12.6 : 8.7

  Filling fraction (active material/absorber) = 31.7%

  Fiducial mass = 1030 kg

ACCESS: Proof of principle



A brief history of Dual-Readout calorimetry (2)

- *2004: Inspired by excellent results of dual-readout calorimeter prototype*

  the DREAM Collaboration is formed

- *2006: First tests of crystal calorimeters based on dual-readout*

  PbWO4, BGO and BSO results generate interest from crystal community

  → *Spin-off projects (e.g. FNAL / Caltech)*

- *2008: Proposal for SuperDREAM submitted to DOE, CERN, INFN*

  DOE accepts and funds DREAM as separate TTU task

  INFN accepts proposal and makes funds available for SuperDREAM construction in Italy

- *2010: CERN SPSC accepts DREAM as an official CERN supported project and makes resources available*

  First SuperDREAM module tested at CERN SPS

The DREAM Collaboration

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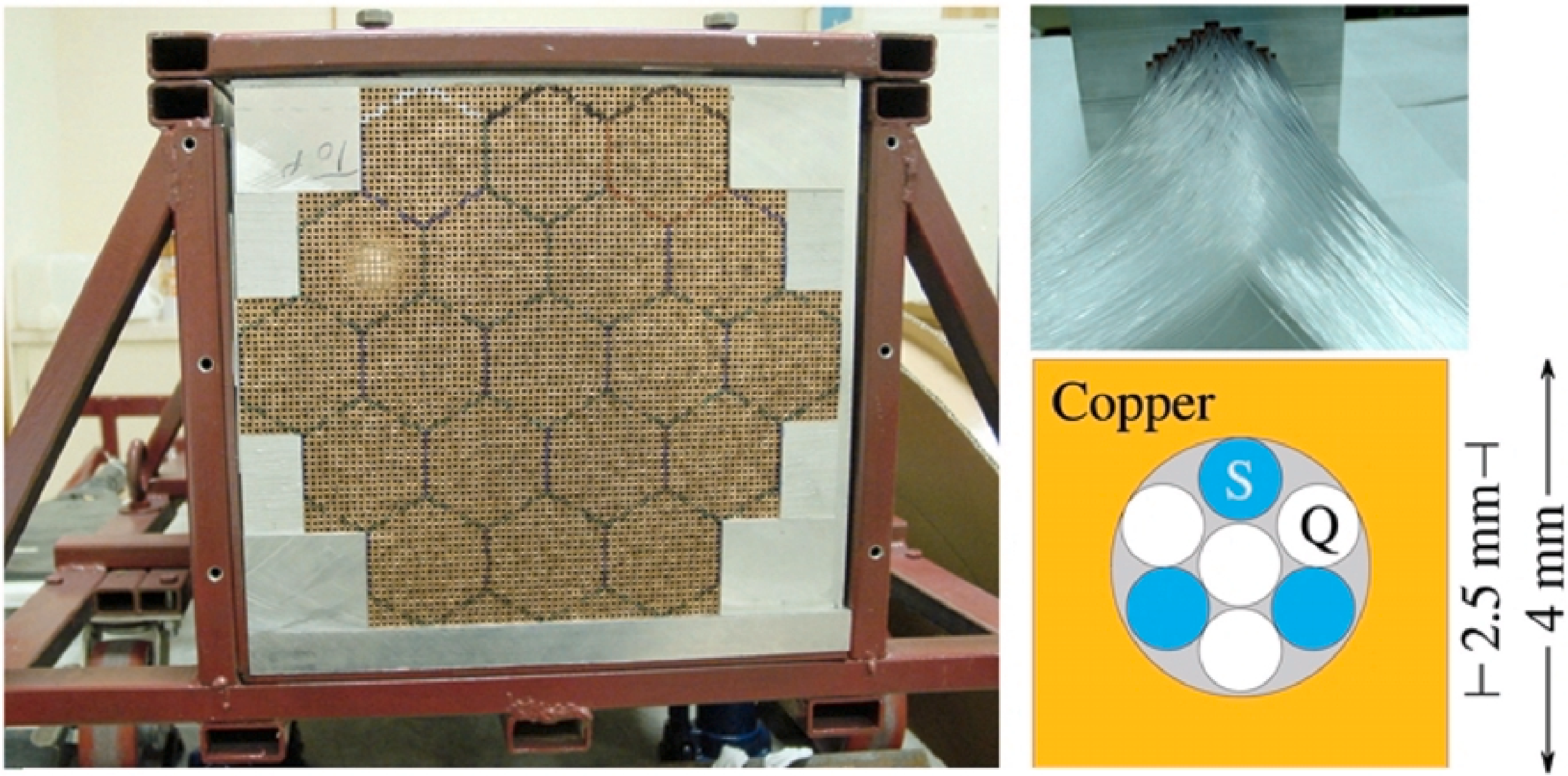
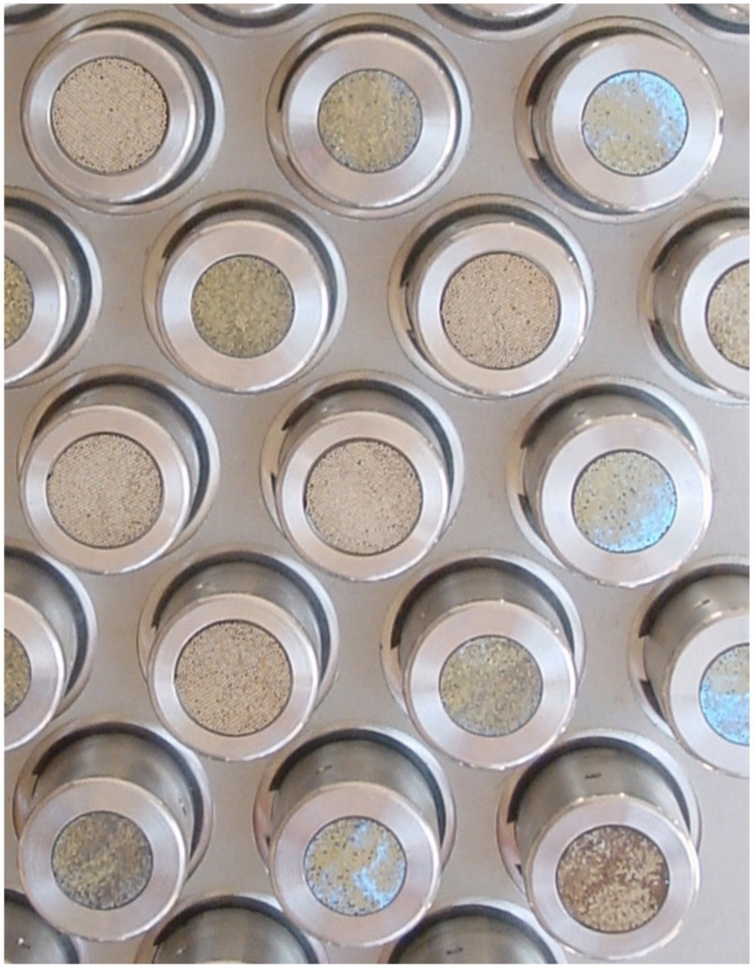
What have we learned in 7 years R&D?

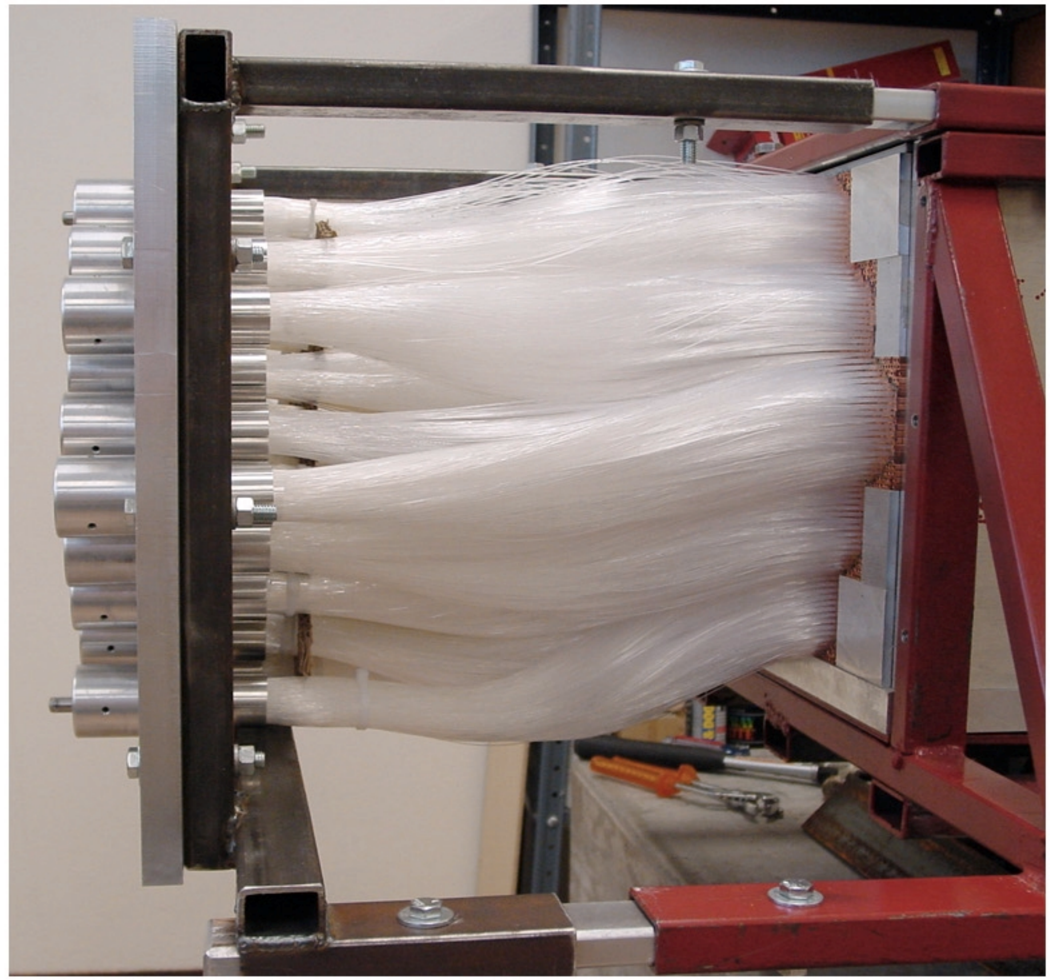
DREAM: Structure

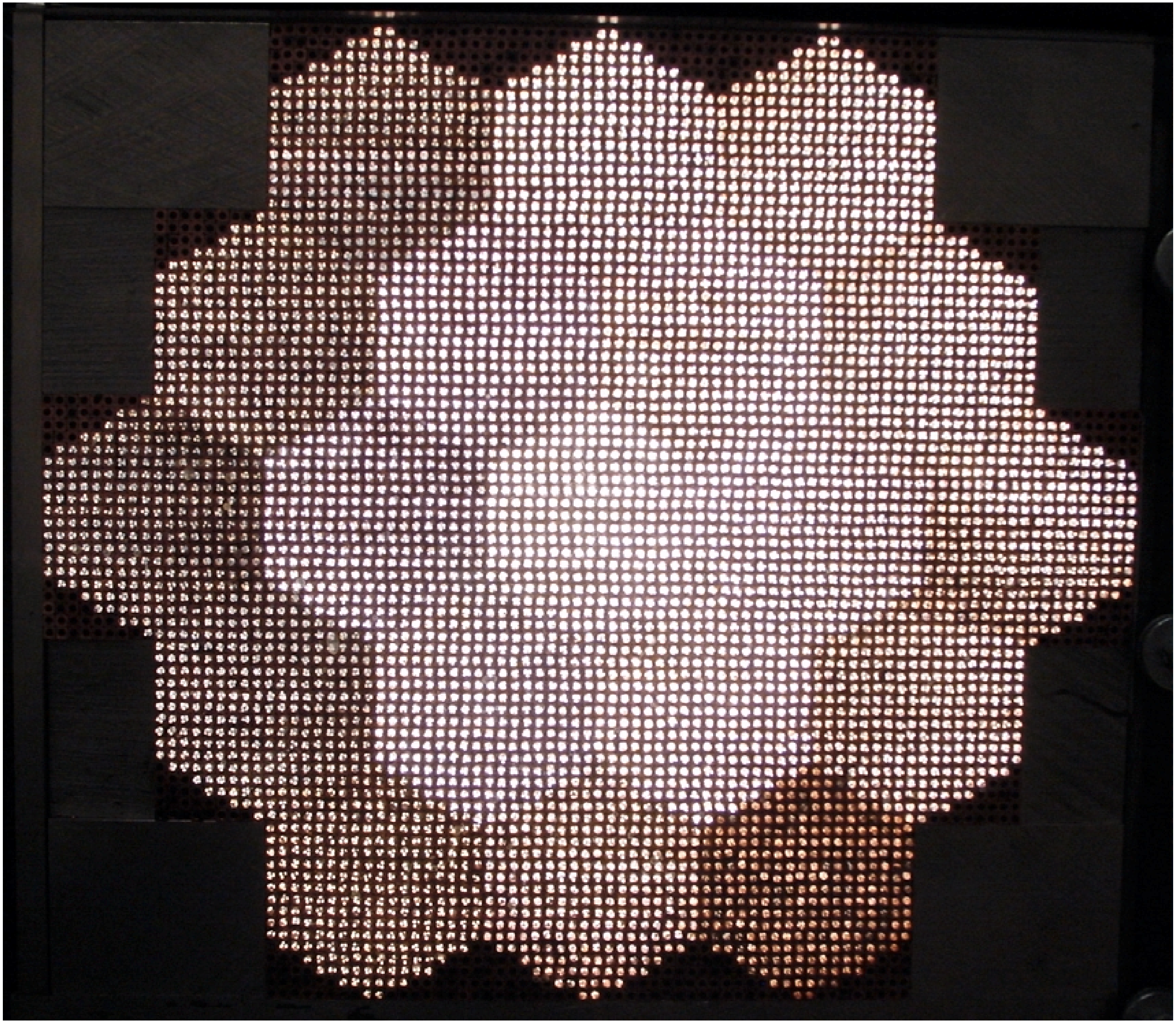


- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

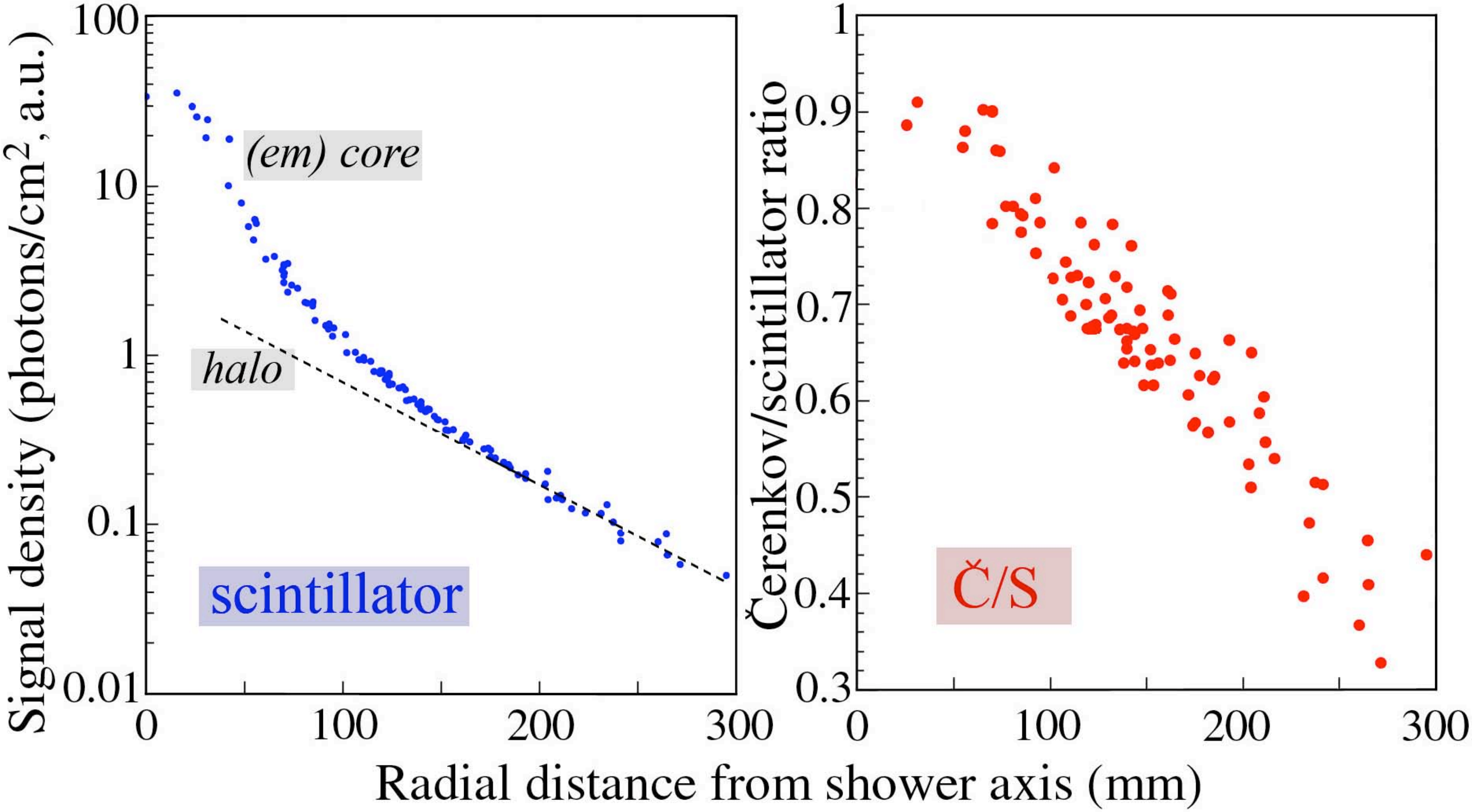
DREAM readout





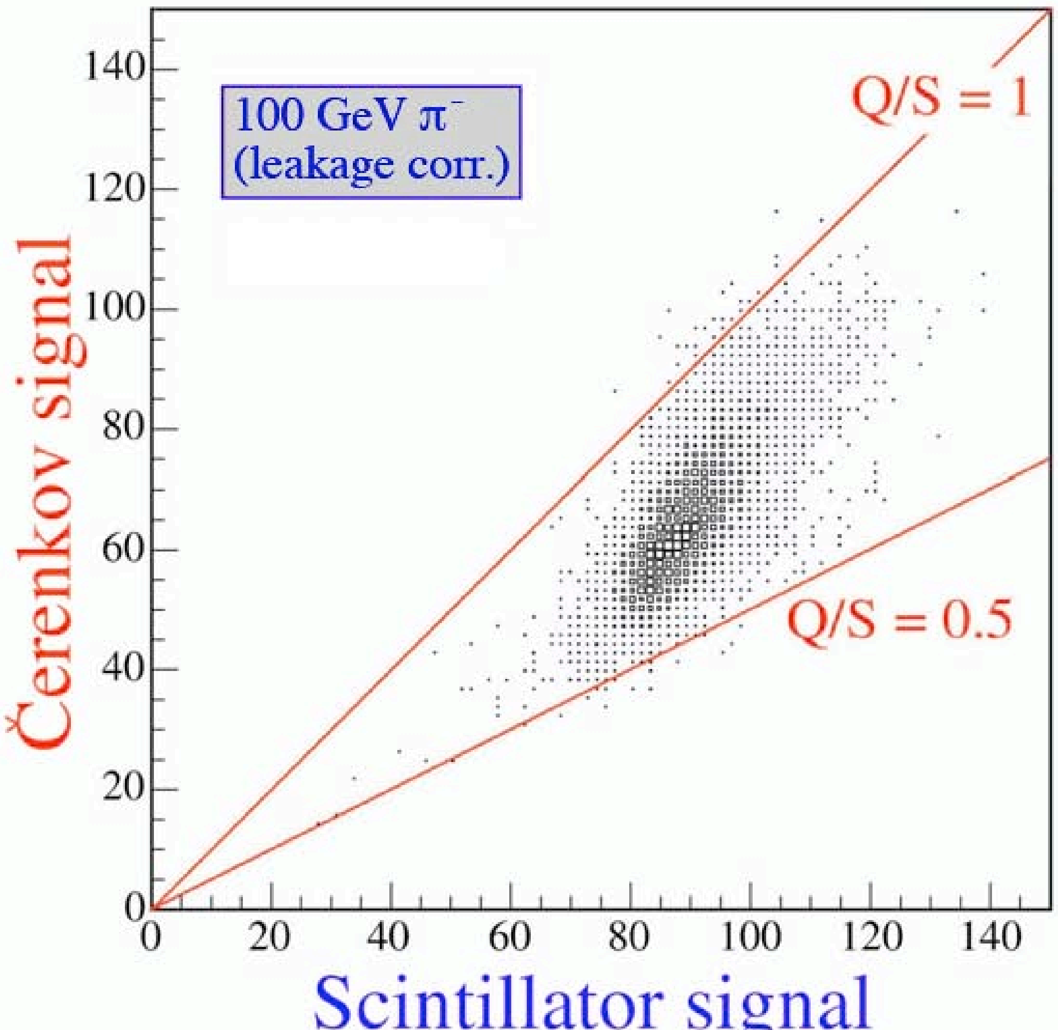


Radial hadron shower profiles (DREAM)



From:
NIM A584 (2008) 273

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



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

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

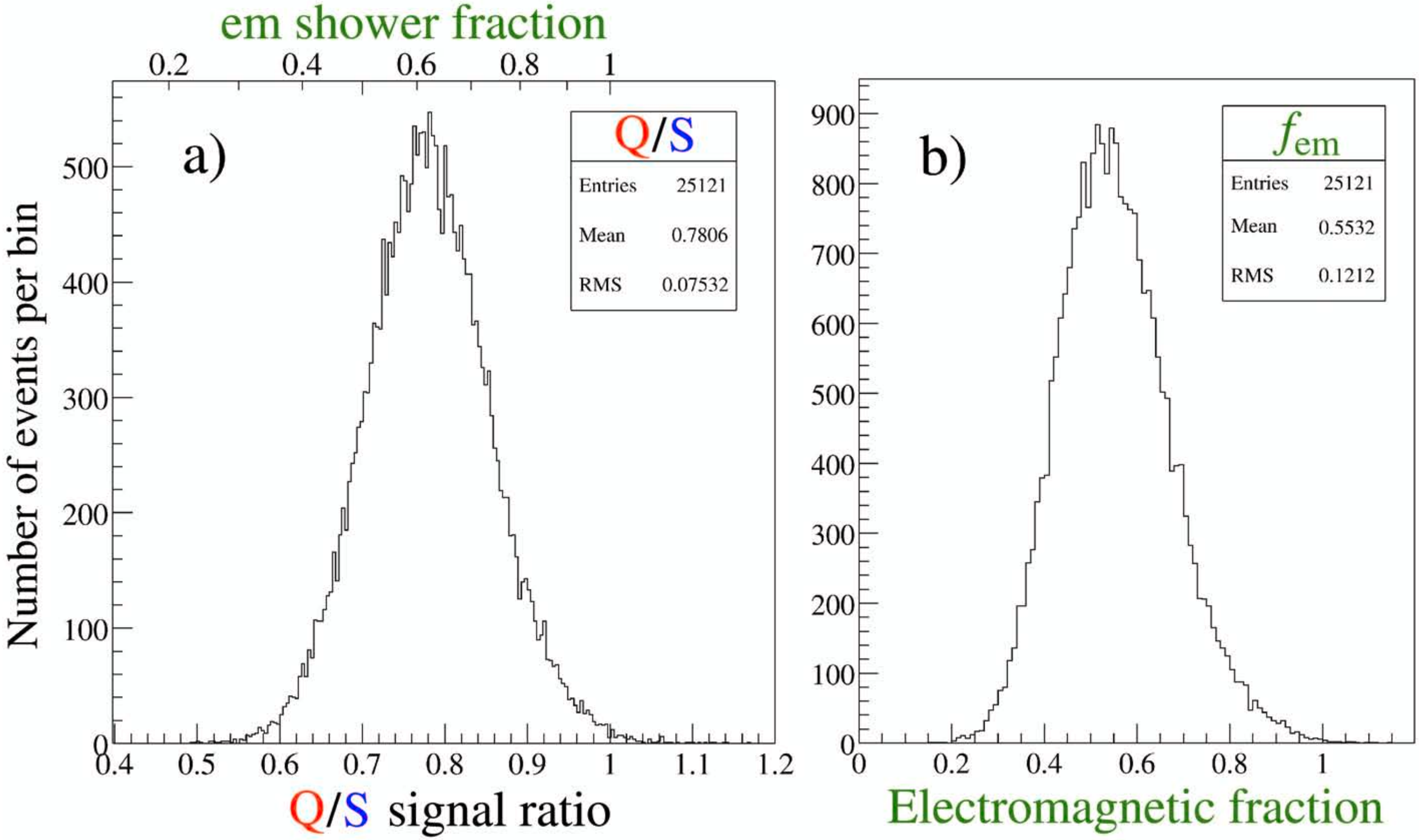
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

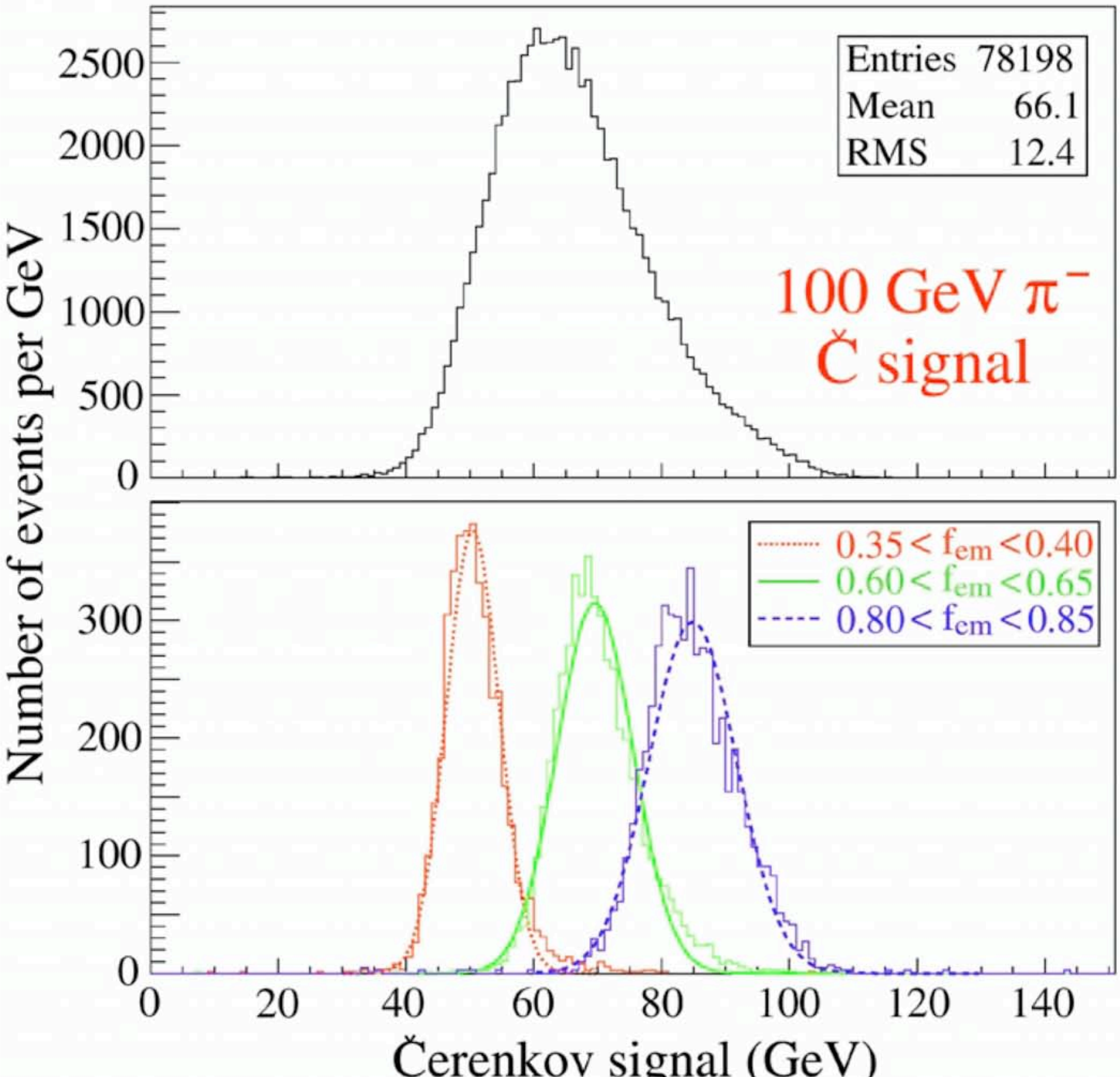
$$E = \frac{S - \chi Q}{1 - \chi}$$

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

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

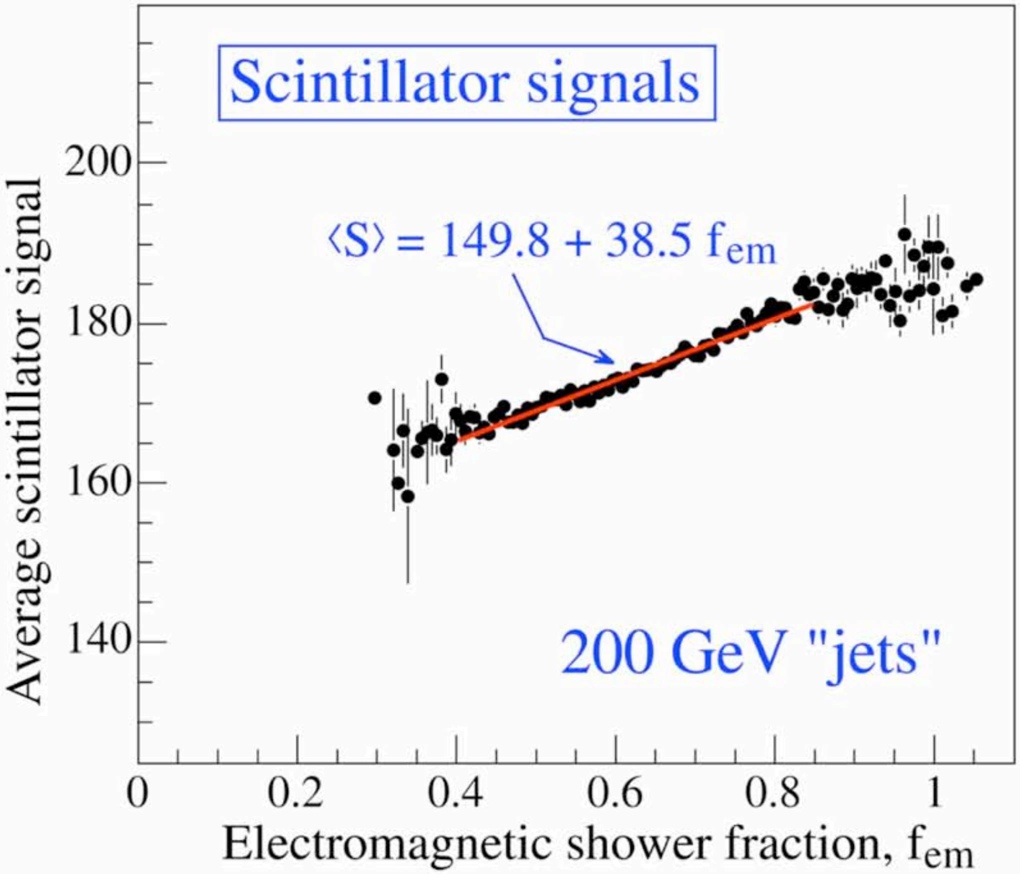


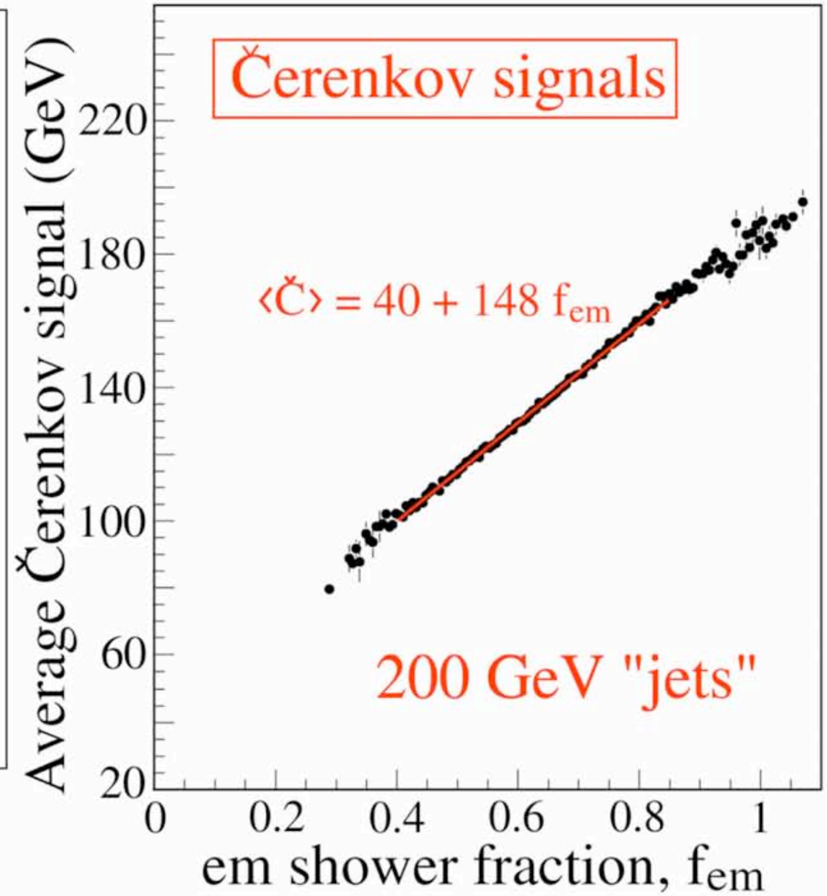
DREAM: Effect of event selection based on f_{em}



From:
NIM A537 (2005) 537

DREAM: Signal dependence on f_{em}



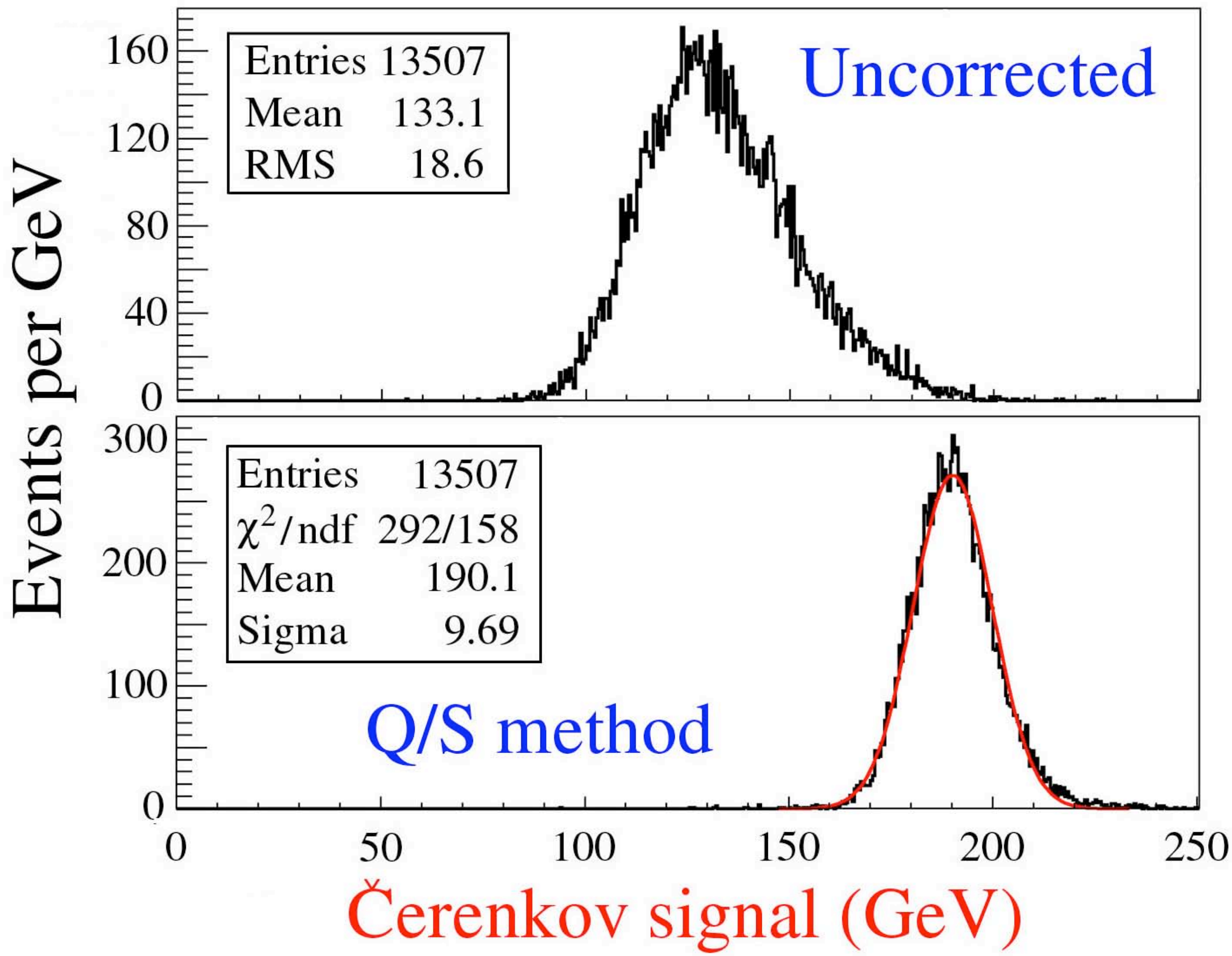


$$R(f_{em}) = p_0 + p_1 f_{em}$$ with $$\frac{p_1}{p_0} = e/h - 1$$

Cu/scintillator $e/h = 1.3$ Cu/quartz $e/h = 4.7$

From:
NIM A537 (2005) 537

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



Effects of Q/S corrections on

hadronic signal linearity and jet resolution

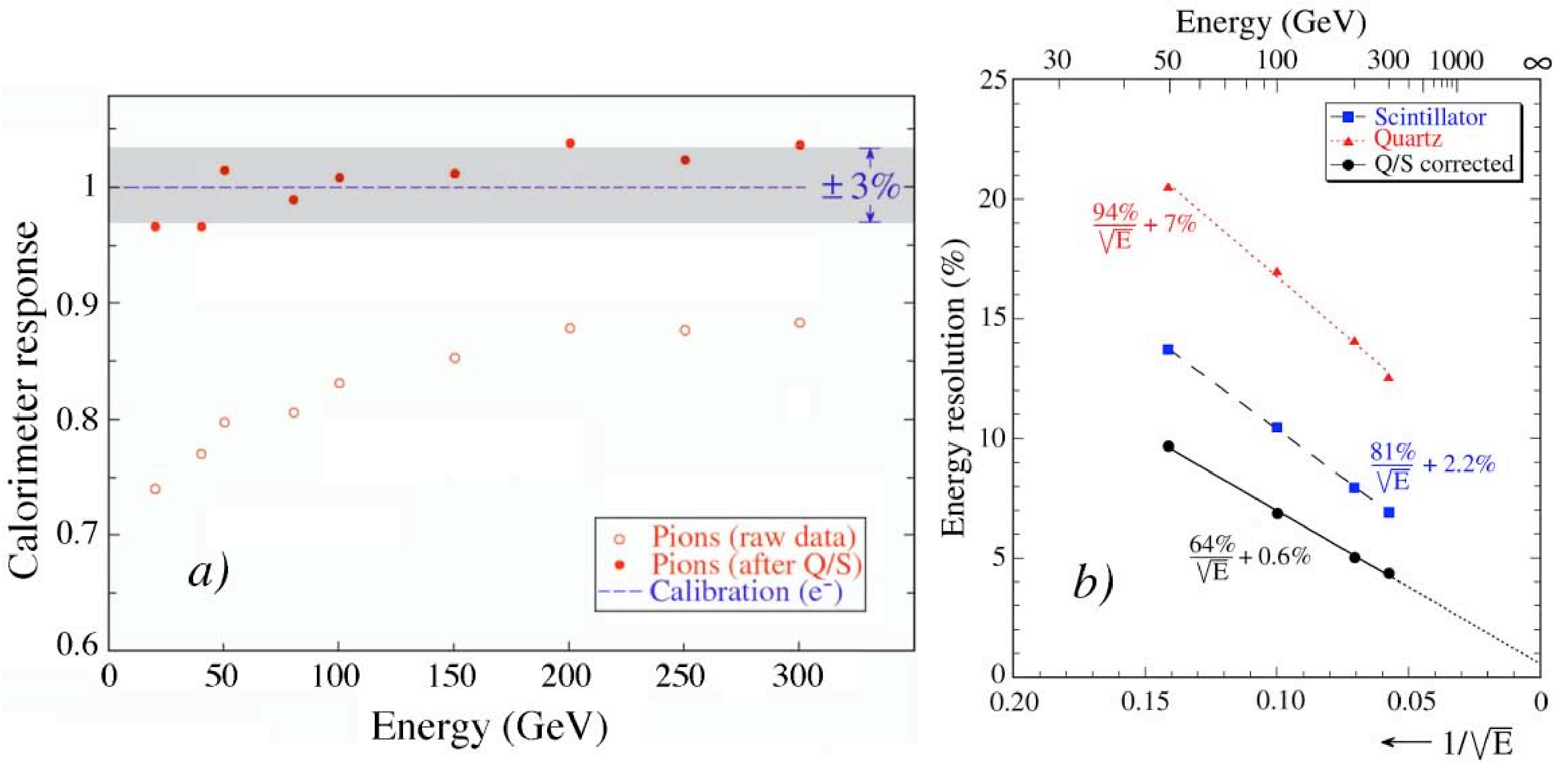


Figure 9: The scintillator response of the DREAM calorimeter to single pions (a) and the energy resolution for "jets" (b), before and after the dual-readout correction procedures were applied to the signals [5].

CONCLUSIONS
from tests of fiber prototype

- 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:

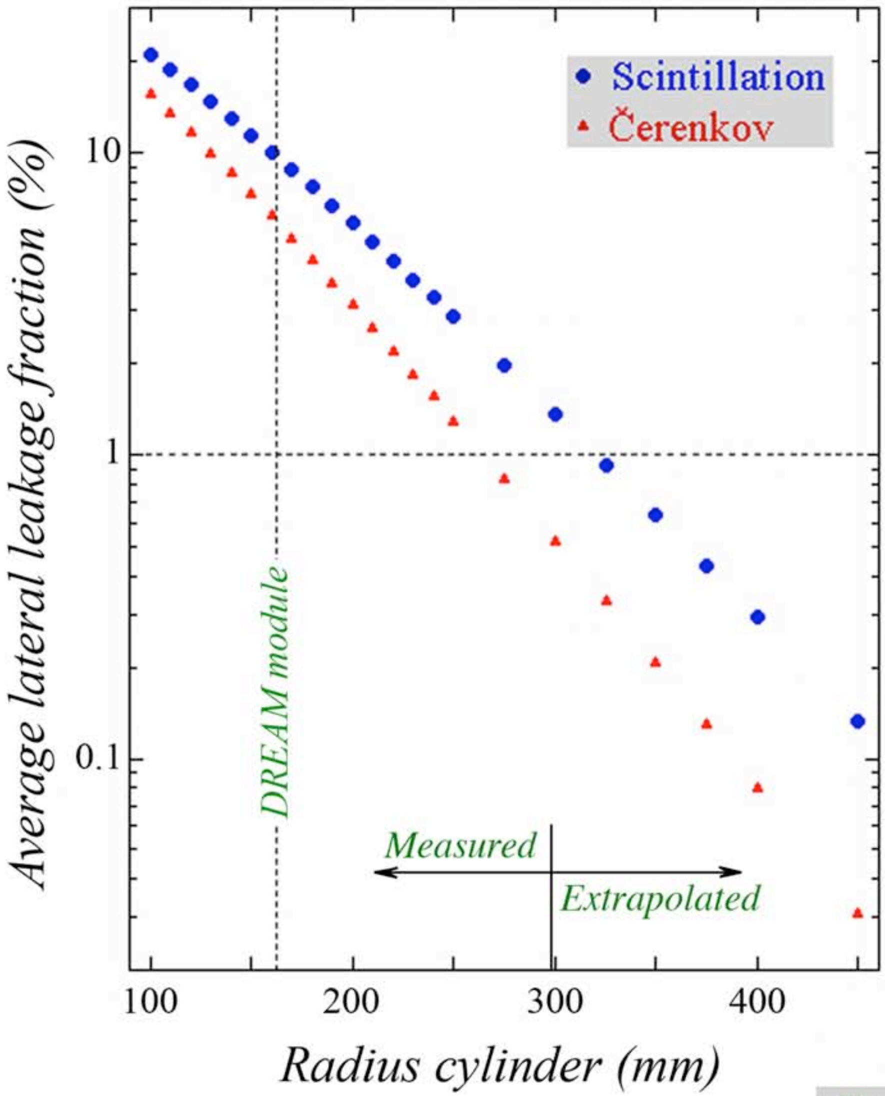
Hadrons & jets:	Nucl. Instr. & Meth. A537 (2005) 537
Electrons:	Nucl. Instr. & Meth. A536 (2005) 29
Muons:	Nucl. Instr. & Meth. A533 (2004) 305

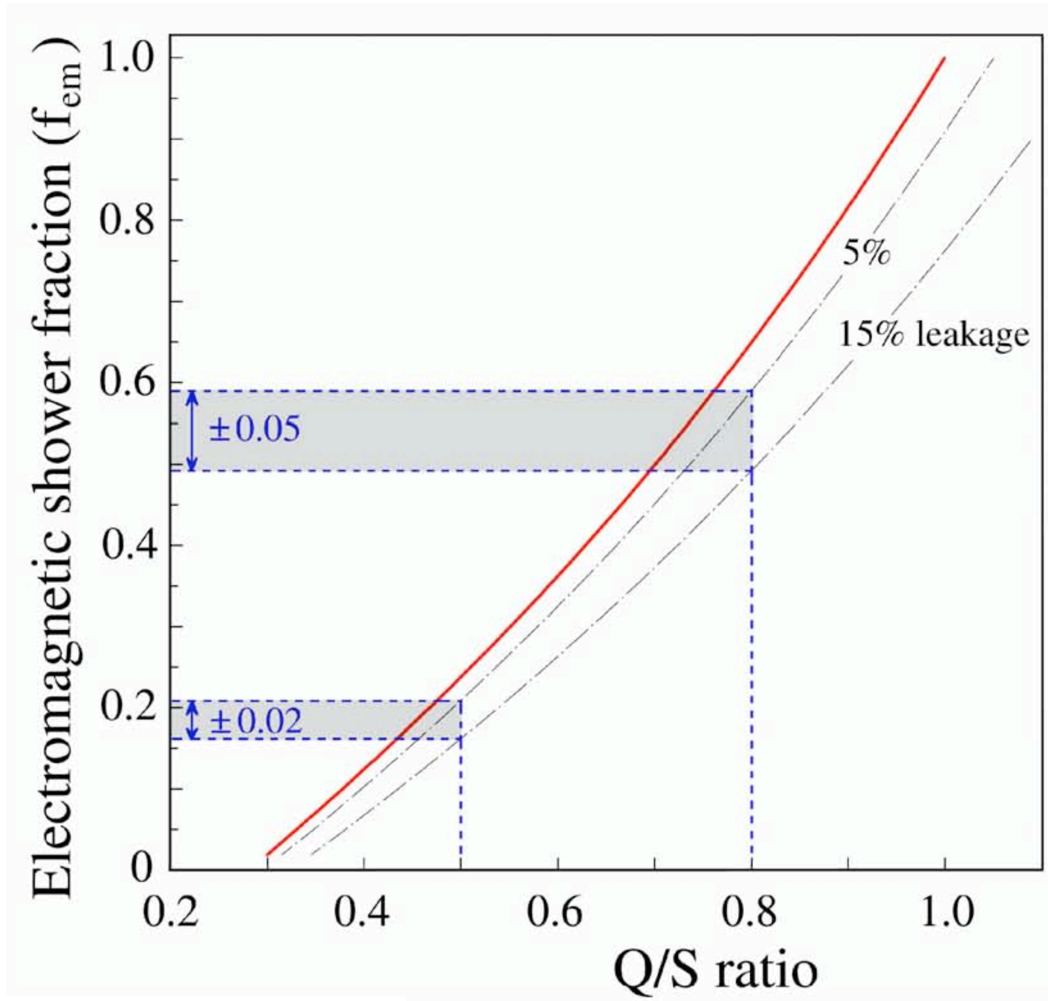
How to improve DREAM performance

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

DREAM: The importance of leakage and its fluctuations

Lateral shower containment (π)





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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 $35\%/\sqrt{E}$

- *Reduce sampling fluctuations*

  These contributed $\sim 40\%/\sqrt{E}$ to hadronic resolution in DREAM

Homogeneous calorimeters (crystals)

- No reason why DREAM principle should be limited to fiber calorimeters
- *Crystals* have the potential to solve light yield + sampling fluctuations problem
- HOWEVER: *Need to separate the light into its Č, S components*

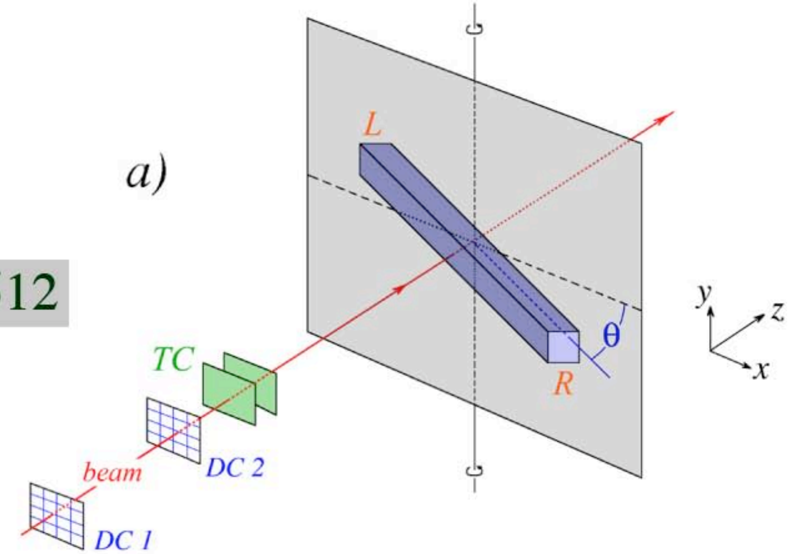
OPTIONS:

1) Directionality. S light is isotropic, Č light directional
2) Time structure. Č light is prompt, S light has decay constant(s)
3) Spectral characteristics. Č light λ^{-2} , S light depends on scintillator
4) Polarization. Č light polarized, S light not.

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

From:

NIM A604 (2009) 512



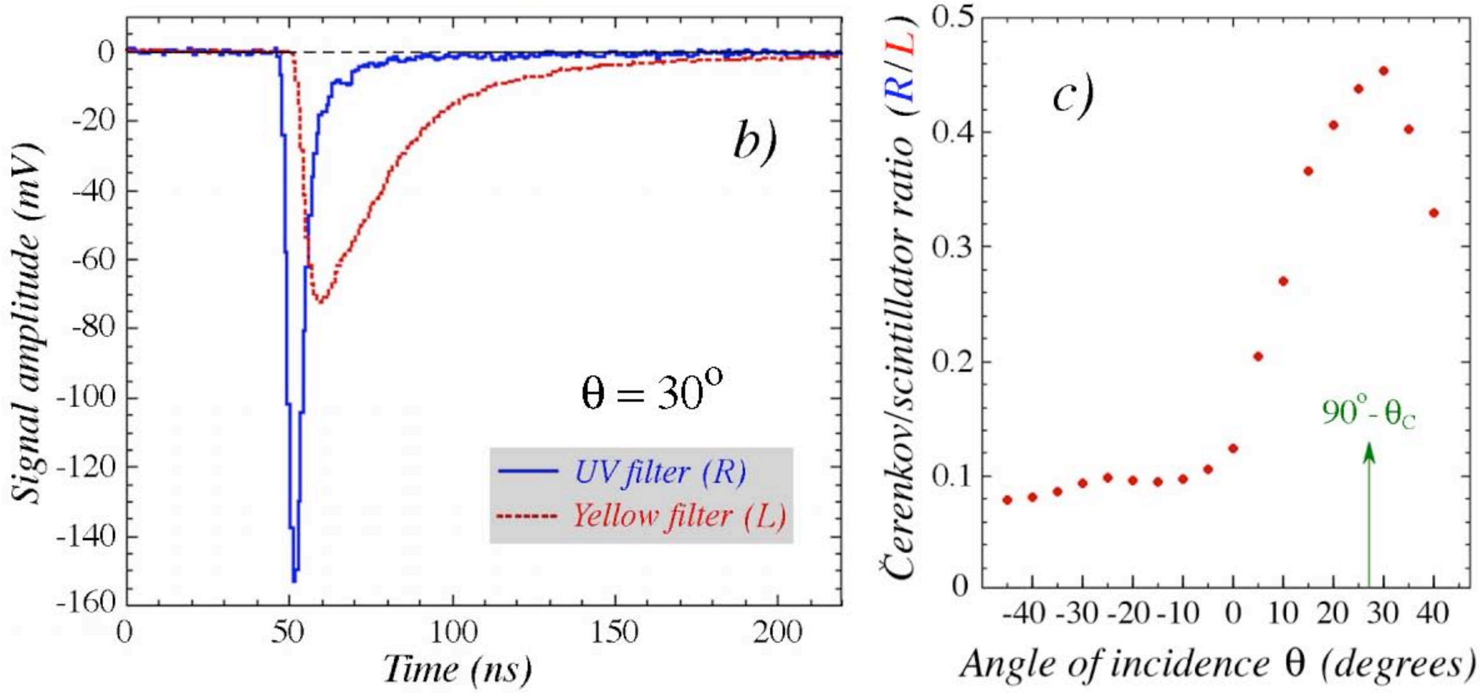
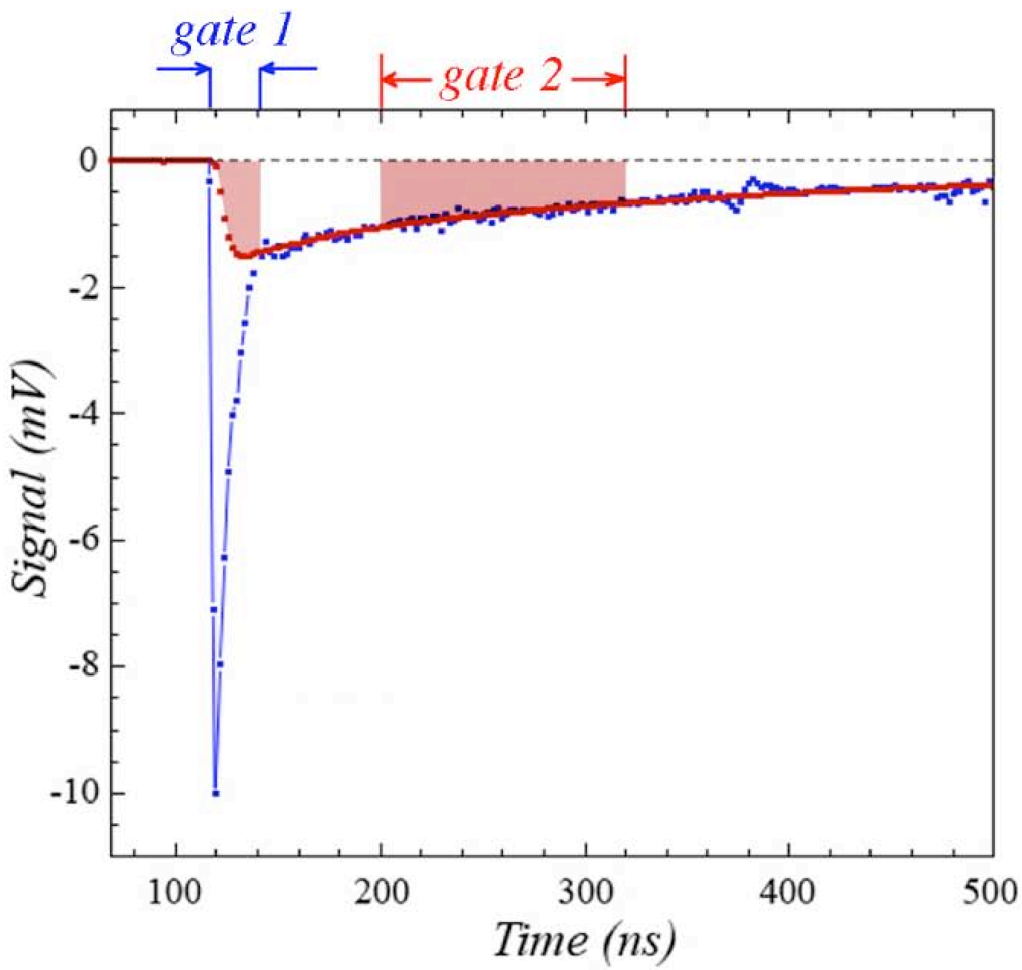


Figure 3: Unraveling of the signals from a Mo-doped $PbWO_4$ crystal into Čerenkov and scintillation components. The experimental setup is shown in diagram *a*. The two sides of the crystal were equipped with a UV filter (side *R*) and a yellow filter (side *L*), respectively. The signals from 50 GeV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

Čerenkov and Scintillator information from one signal !

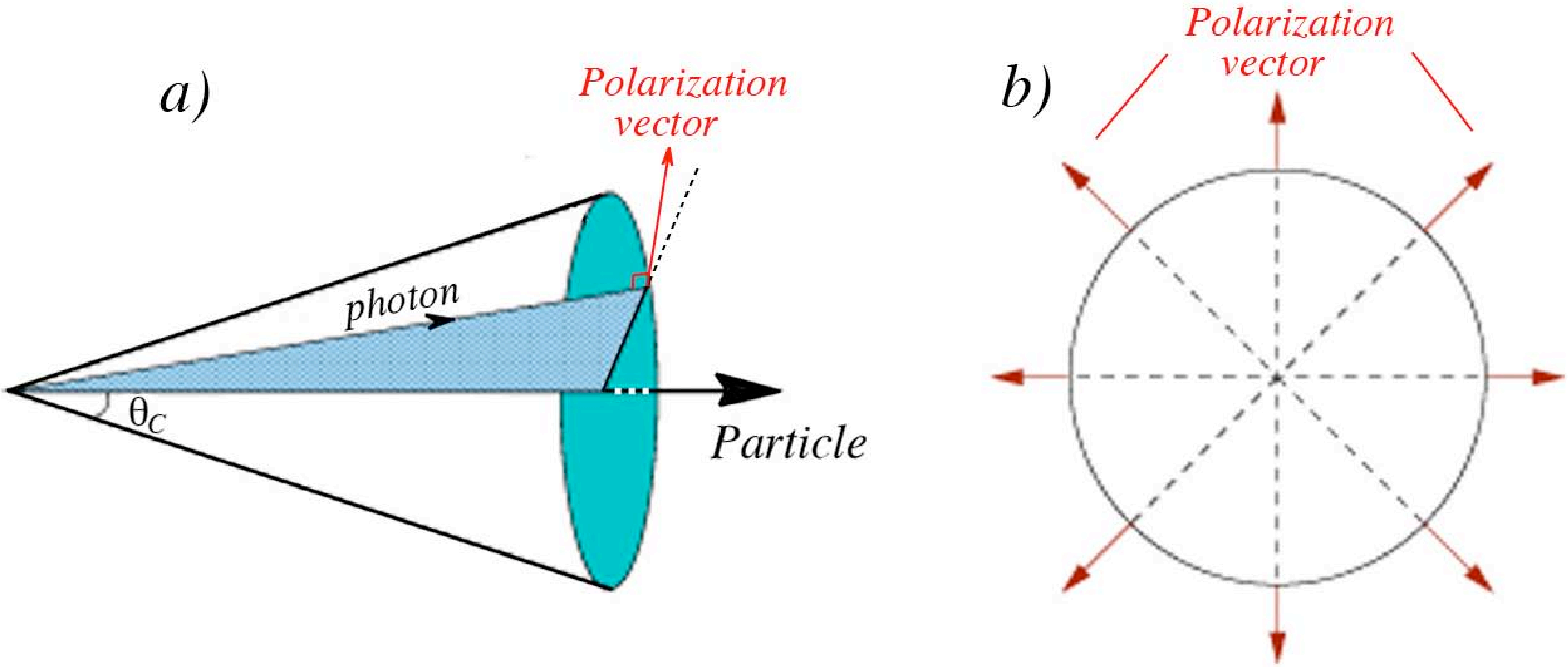


BGO crystal
UG 11 (UV) filter

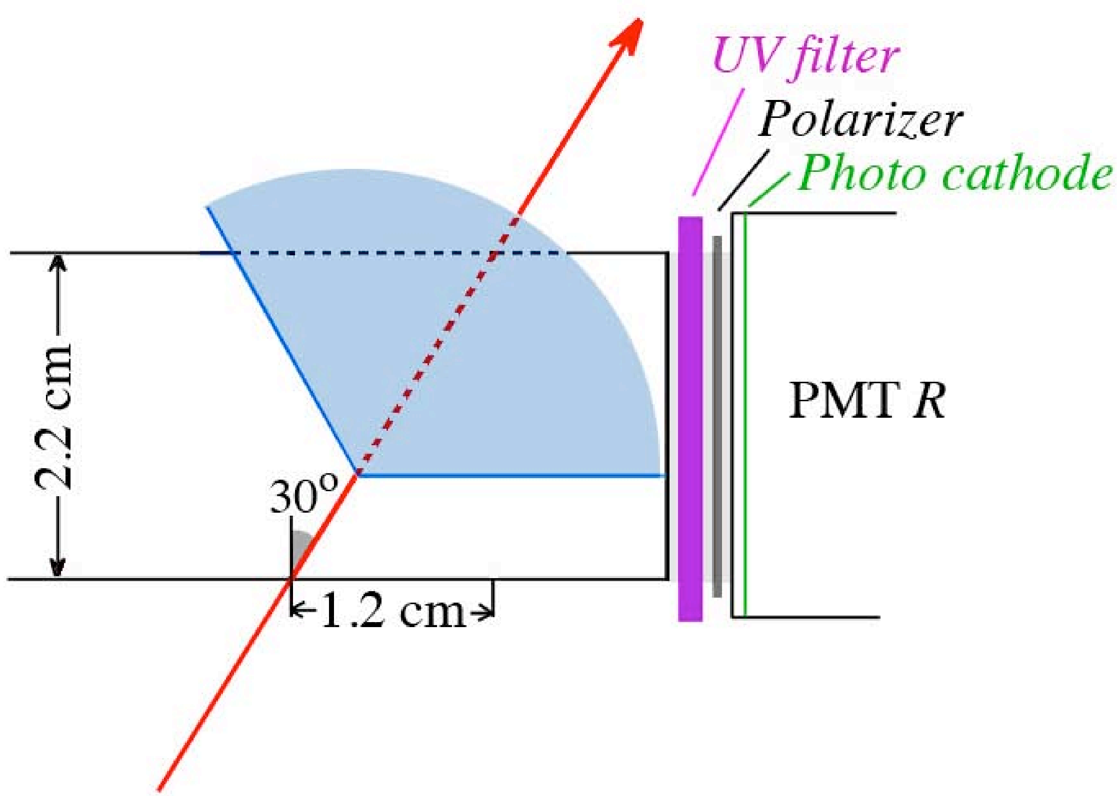
From:
NIM A595 (2008) 359

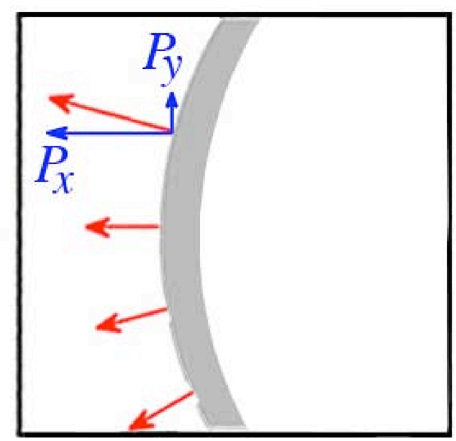
Figure 14: The time structure of a typical shower signal measured in the BGO em calorimeter equipped with a UV filter. These signals were measured with a sampling oscilloscope, which took a sample every 0.8 ns. The UV BGO signals were used to measure the relative contributions of scintillation light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

Polarization of Čerenkov light

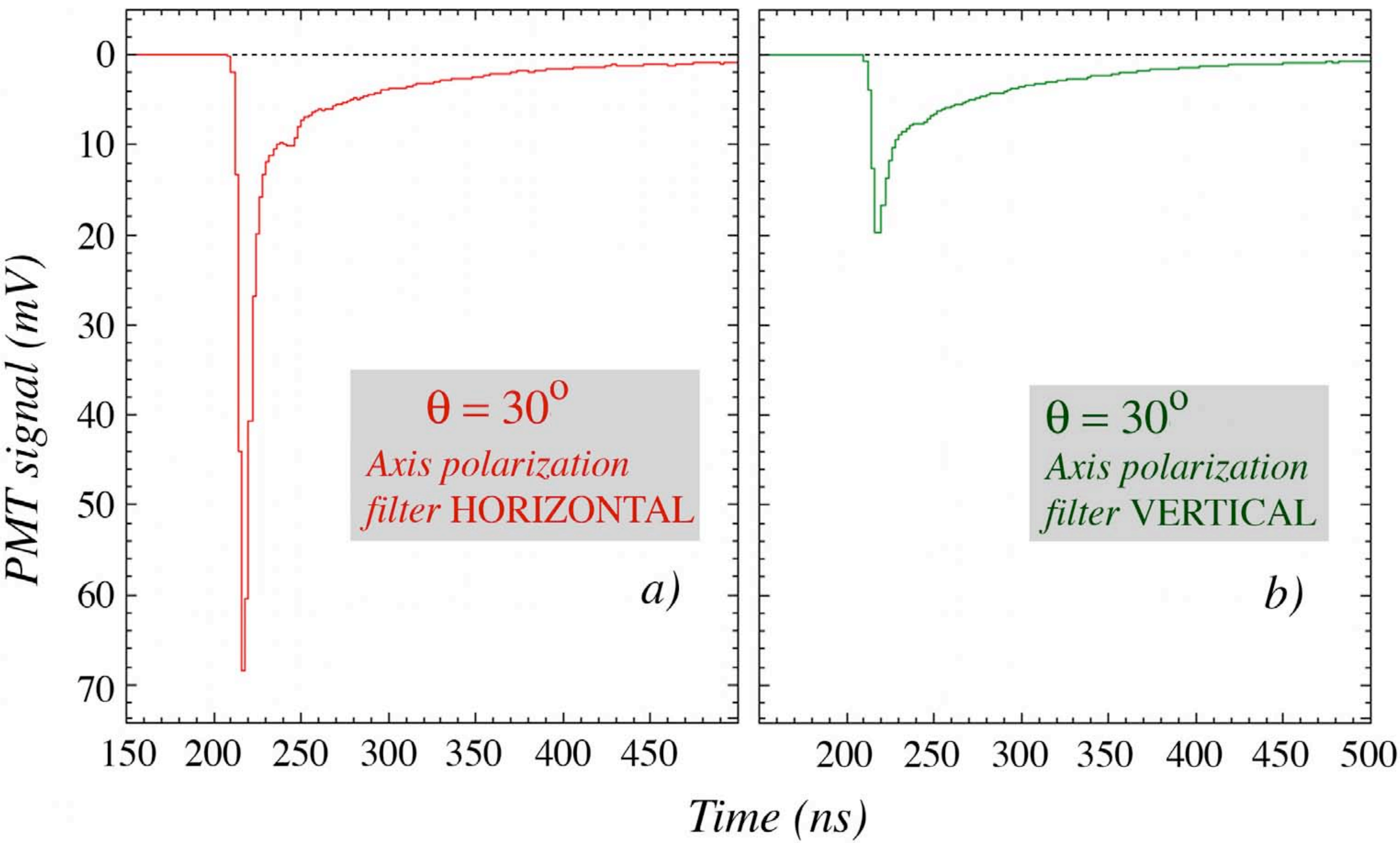


Polarization of Čerenkov light in crystal

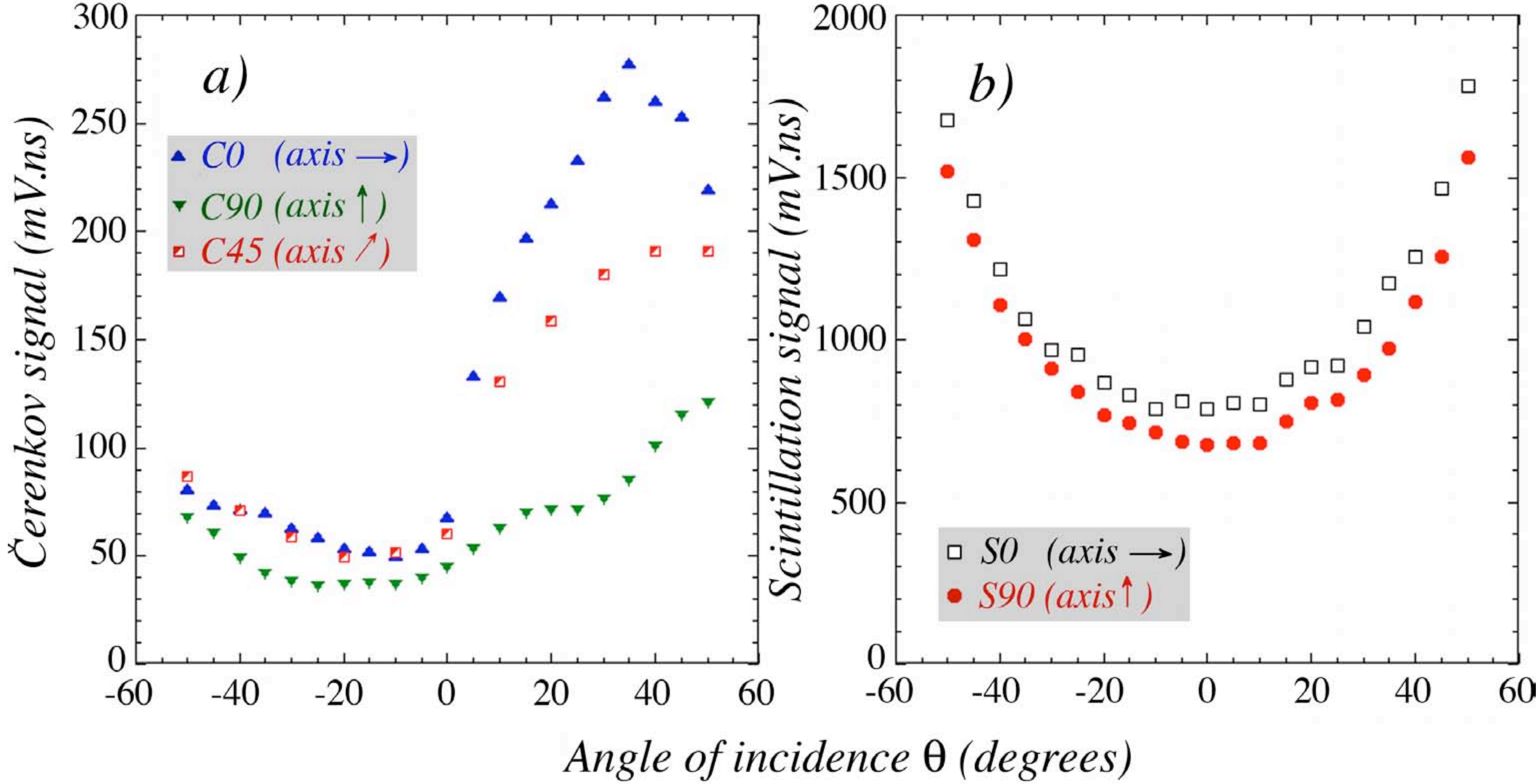




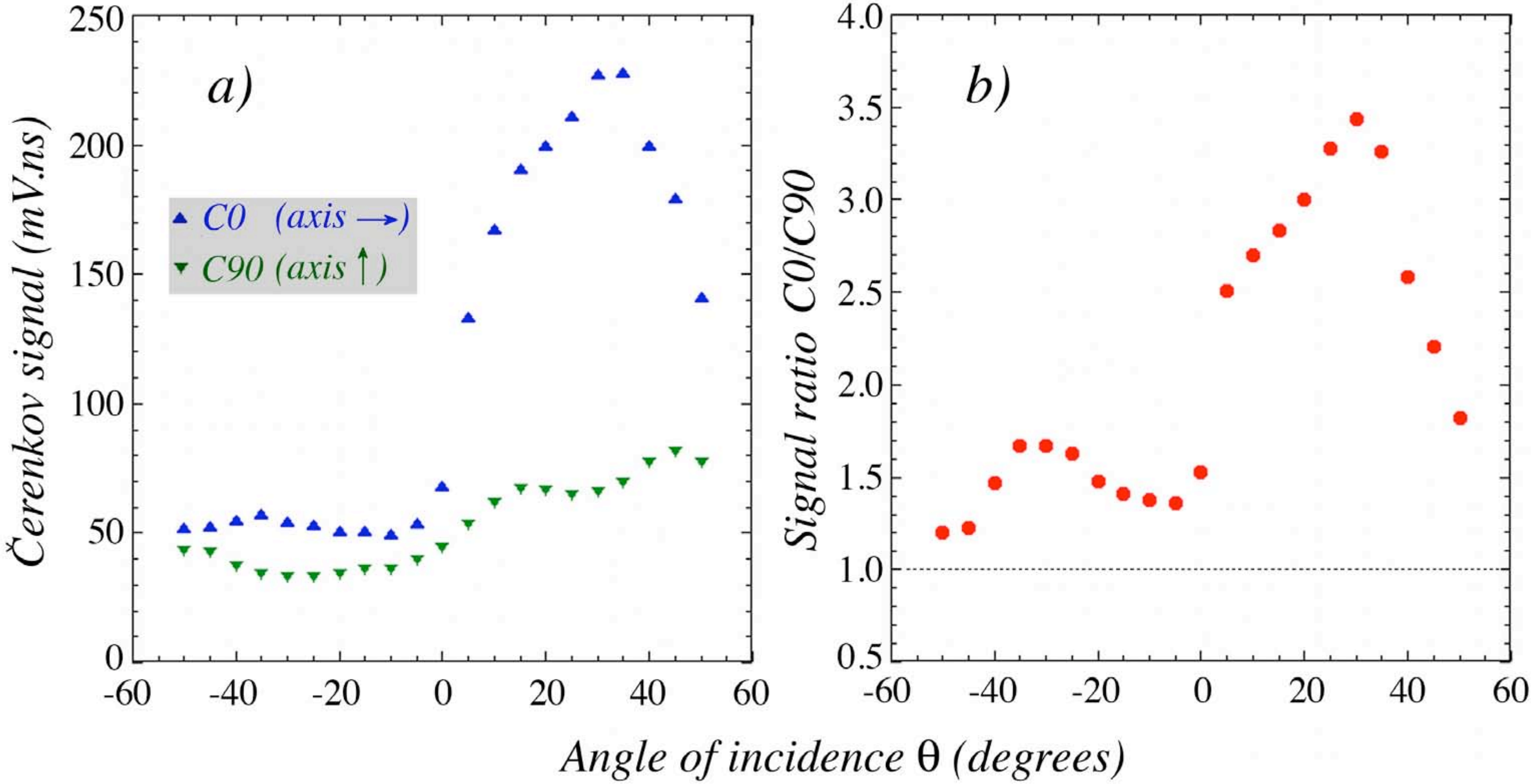
Time structure of polarized crystal (BSO) signals



Angular dependence of polarization crystal signals



Also reflected Čerenkov light is polarized



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.

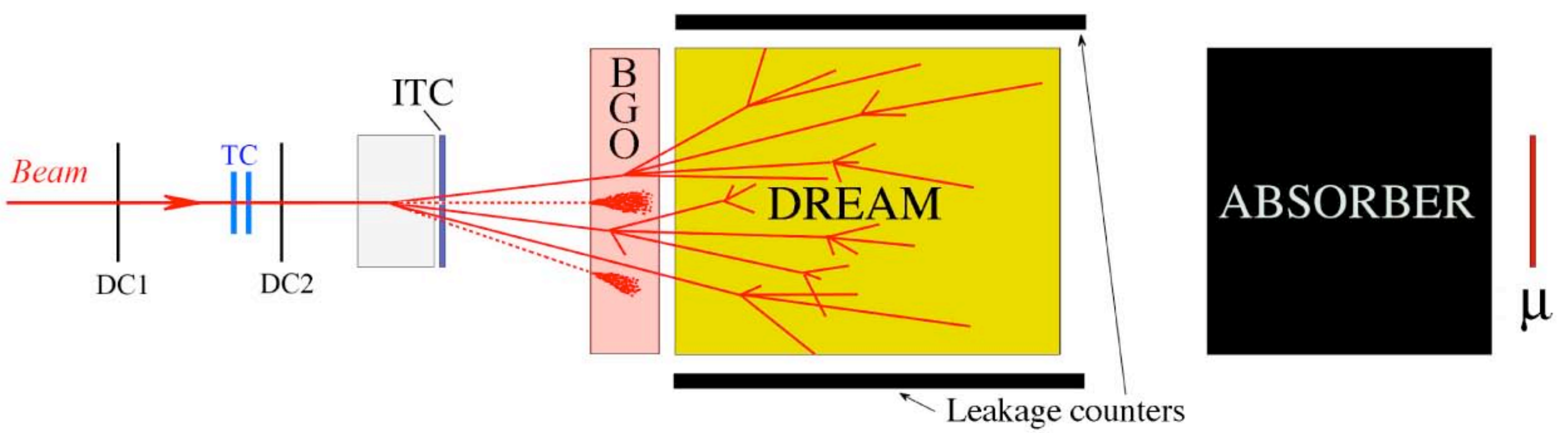


Figure 16: Schematic of the experimental setup in the beam line in which the hybrid calorimeter system was tested (see text for details). Also shown is the occurrence and development of a multi-particle event ("jet") originating in the upstream target [17].

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

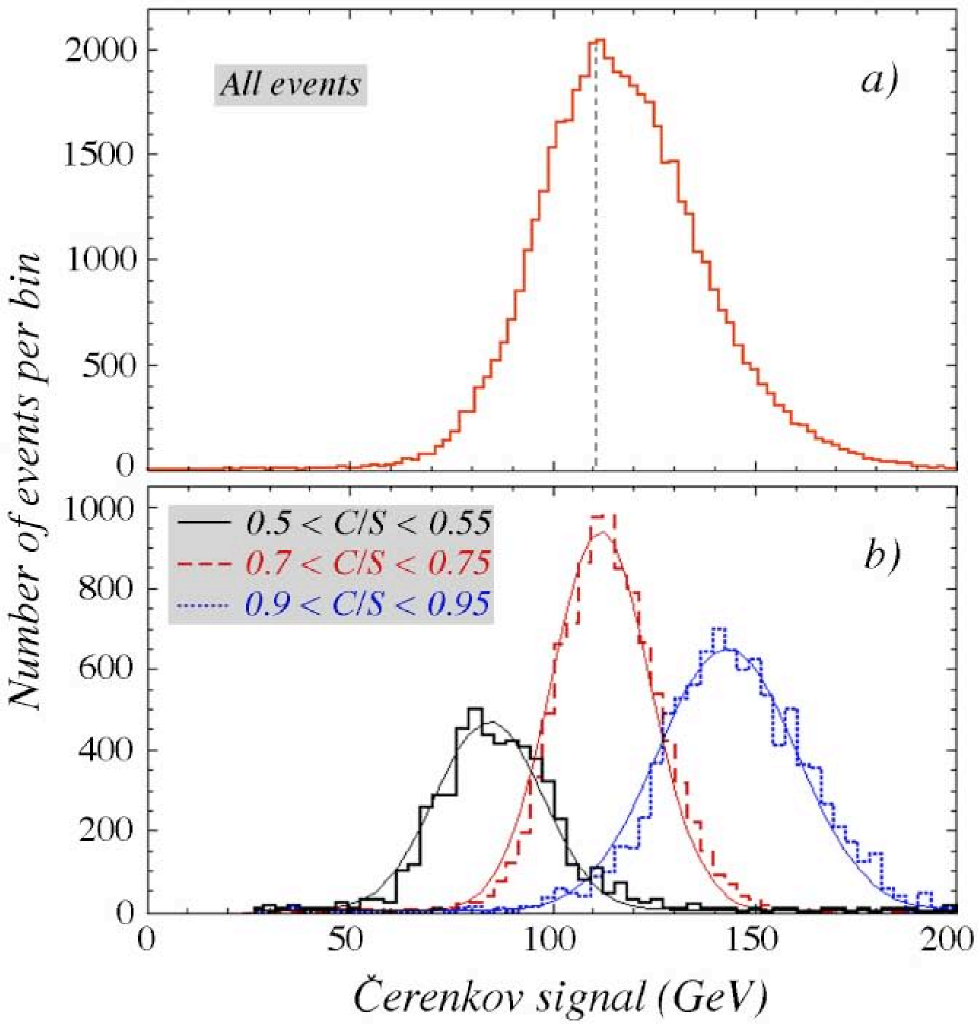


Figure 17: The Čerenkov signal distribution for 200 GeV "jet" events detected in the BGO + fiber calorimeter system (a) together with the distributions for subsets of events selected on the basis of the ratio of the total Čerenkov and scintillation signals in this detector combination (b).

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

from

NIM A610 (2009) 488

How to improve DREAM performance

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

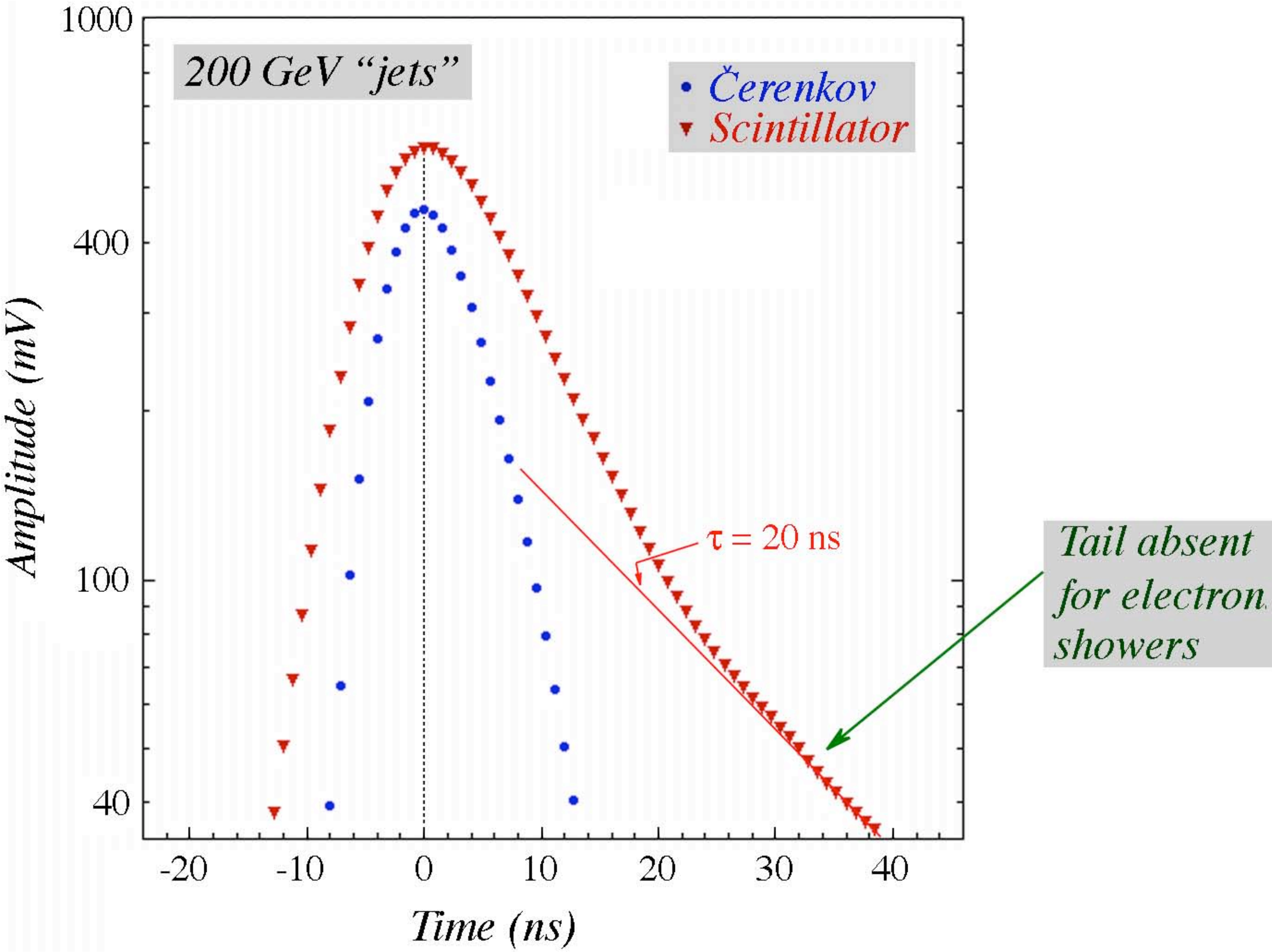
- *Increase Čerenkov light yield*
  DREAM: 8 p.e./GeV ⟶ fluctuations contribute $35\%/\sqrt{E}$

- *Reduce sampling fluctuations*
  These contributed ~ $40\%/\sqrt{E}$ to hadronic resolution in DREAM

- 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

Time structure of the DREAM signals: the neutron tail



The em and neutron signal fractions are anti-correlated

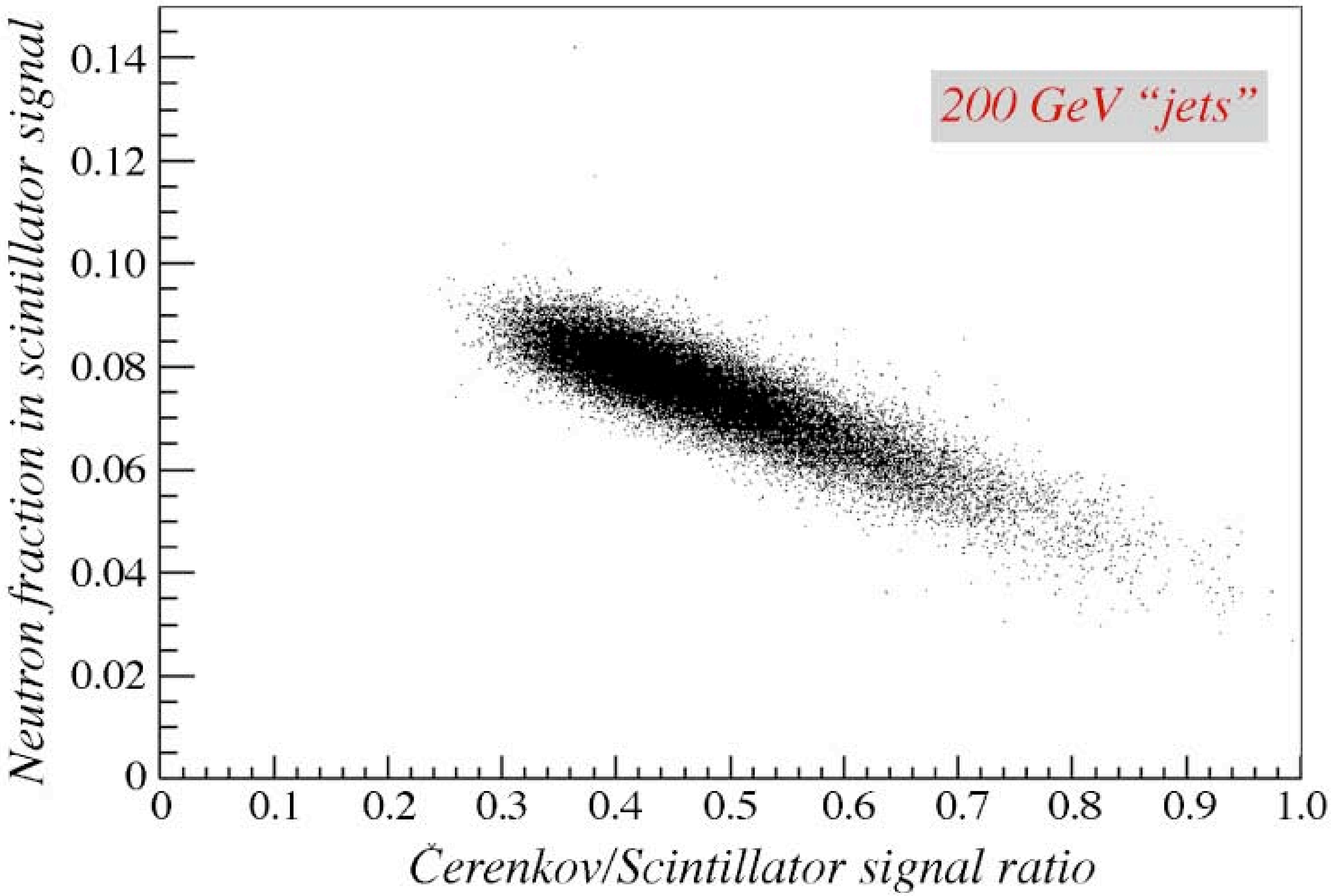


Figure 4: Scatter plot of the fraction of the scintillation light contained in the (20 ns) exponentional tail versus the Čerenkov/scintillation signal ratio measured in these events [9].

Probing the total signal distribution with the neutron fraction

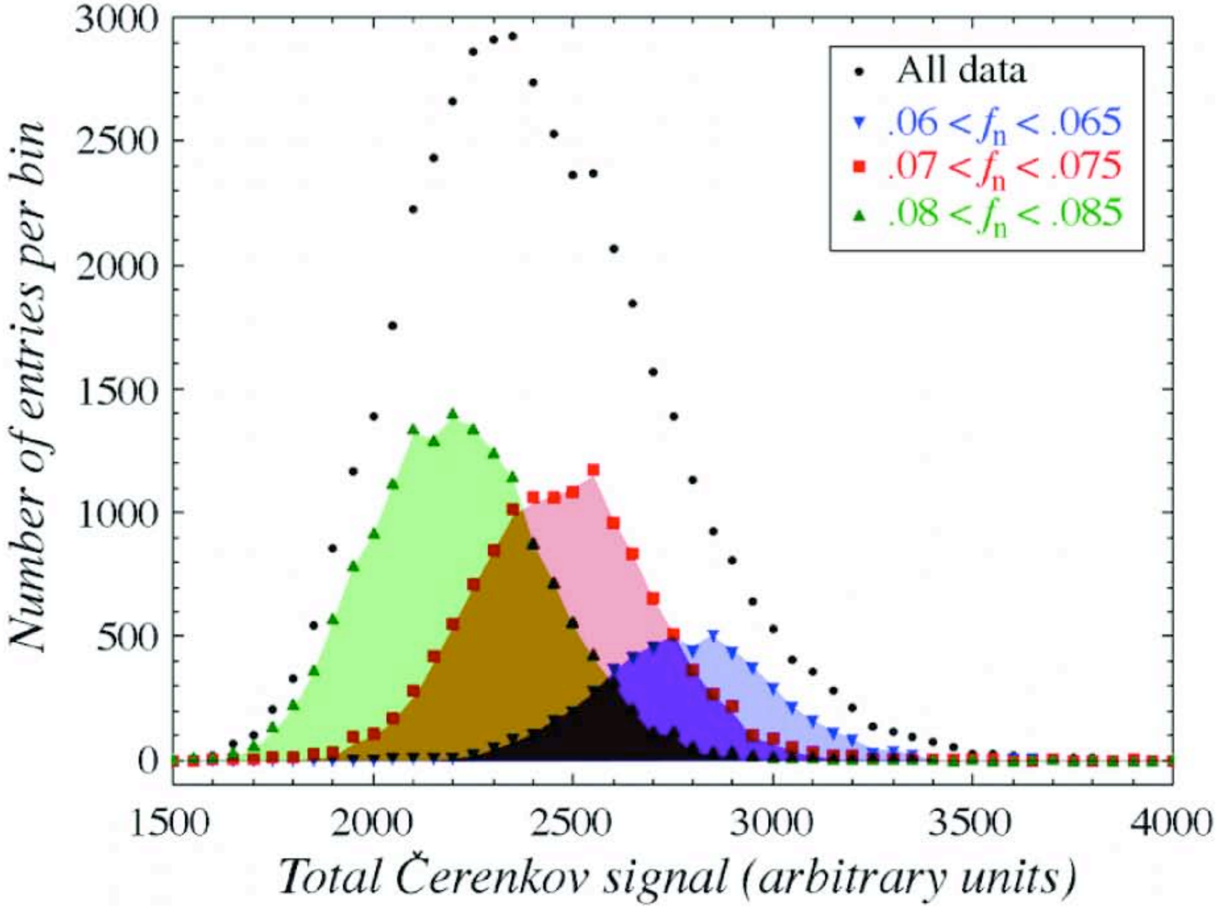


Figure 18: Distribution of the total Čerenkov signal for 200 GeV "jets" and the distributions for three subsets of events selected on the basis of the fractional contribution of neutrons to the scintillator signal .

From:

NIM A598 (2009) 422

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

From: NIM A598 (2009) 422

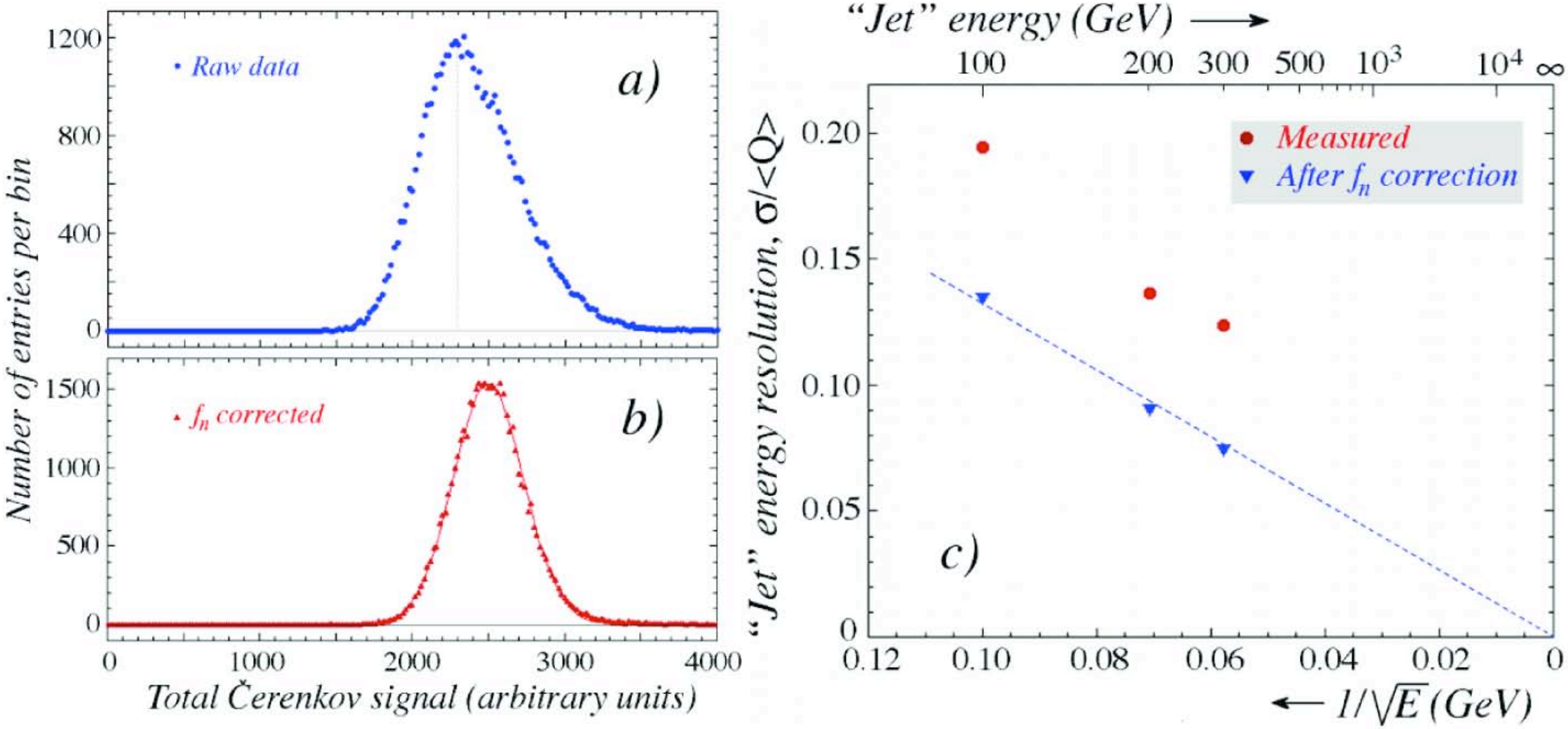
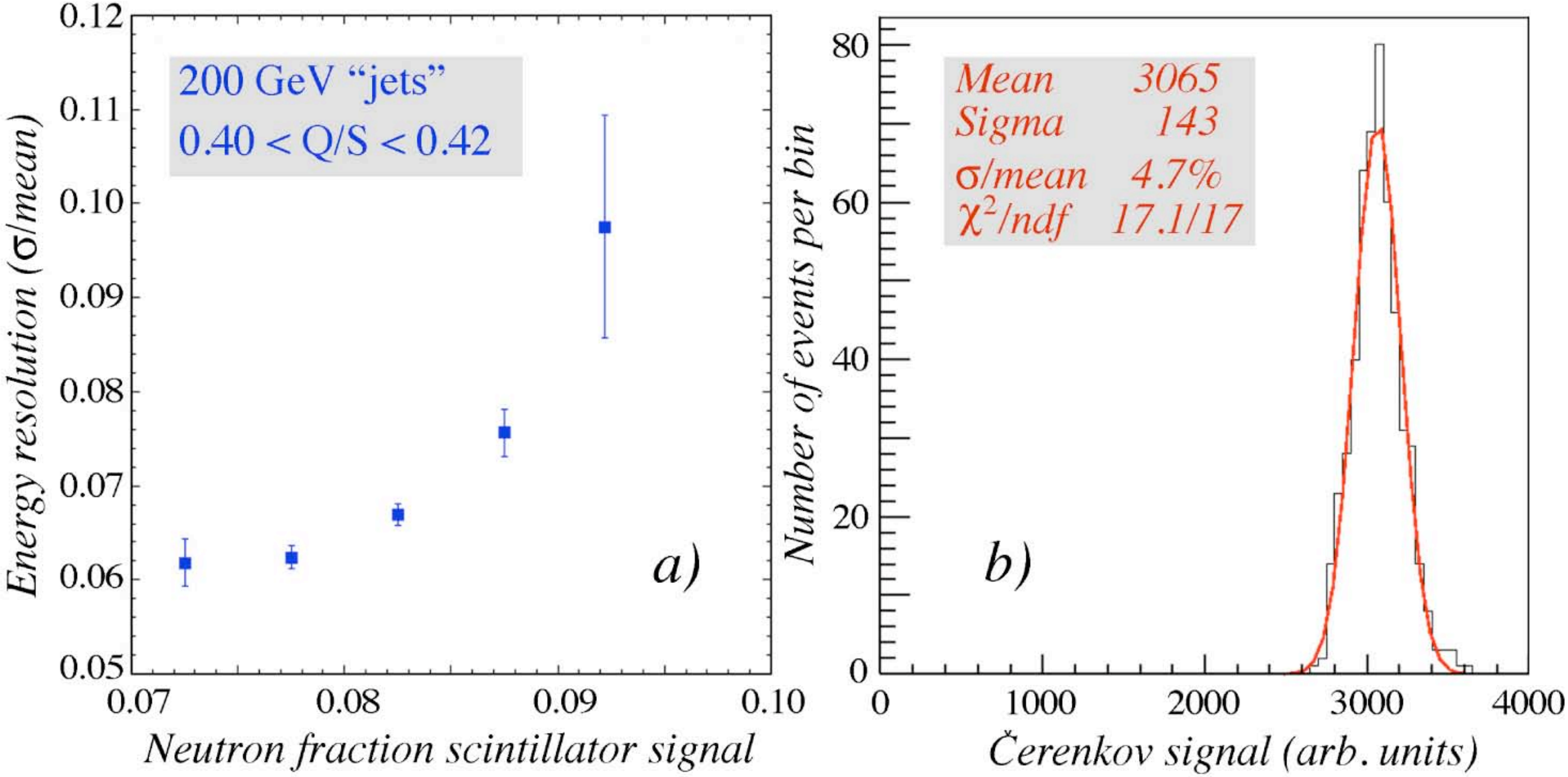


Figure 19: Distribution of the total Čerenkov signal for 200 GeV "jets" before (a) and after (b) applying the correction based on the measured value of f_n, described in the text. Relative width of the Čerenkov signal distribution for "jets" as a function of energy, before and after a correction that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

Neutron information is complementary to f_{em}



from: NIM A598 (2009) 422

Future research plans

> We have now reached the point where we believe that we have all the ingredients in hand to build the perfect calorimeter system, or at least a calorimeter system that meets and exceeds the performance requirements of experiments at the ILC and CLIC. We propose to prove this statement by building and testing such a detector.

(from proposal to funding agencies)

Crucial aspects of proposal

- Build two detectors, and test these separately and together
  - *Fiber calorimeter, 5 tonnes* ⟵ (FIRST PRIORITY)
  - *Dedicated dual-readout crystal matrix (em section)*
- Shower containment >99% ⟶ *effects of leakage fluctuations negligible*
- Other design criteria:
  - *Čerenkov light yield in fiber detector > 100 p.e./GeV (em)*
  - *Sampling fluctuations fiber detector < 10%/$\sqrt{E}$ (em)*
  - *Depth measurement of shower maximum for each event (attenuation!)*
  - *Time structure measured for every signal*

Sampling considerations

Sampling fluctuations and the e.m. energy resolution

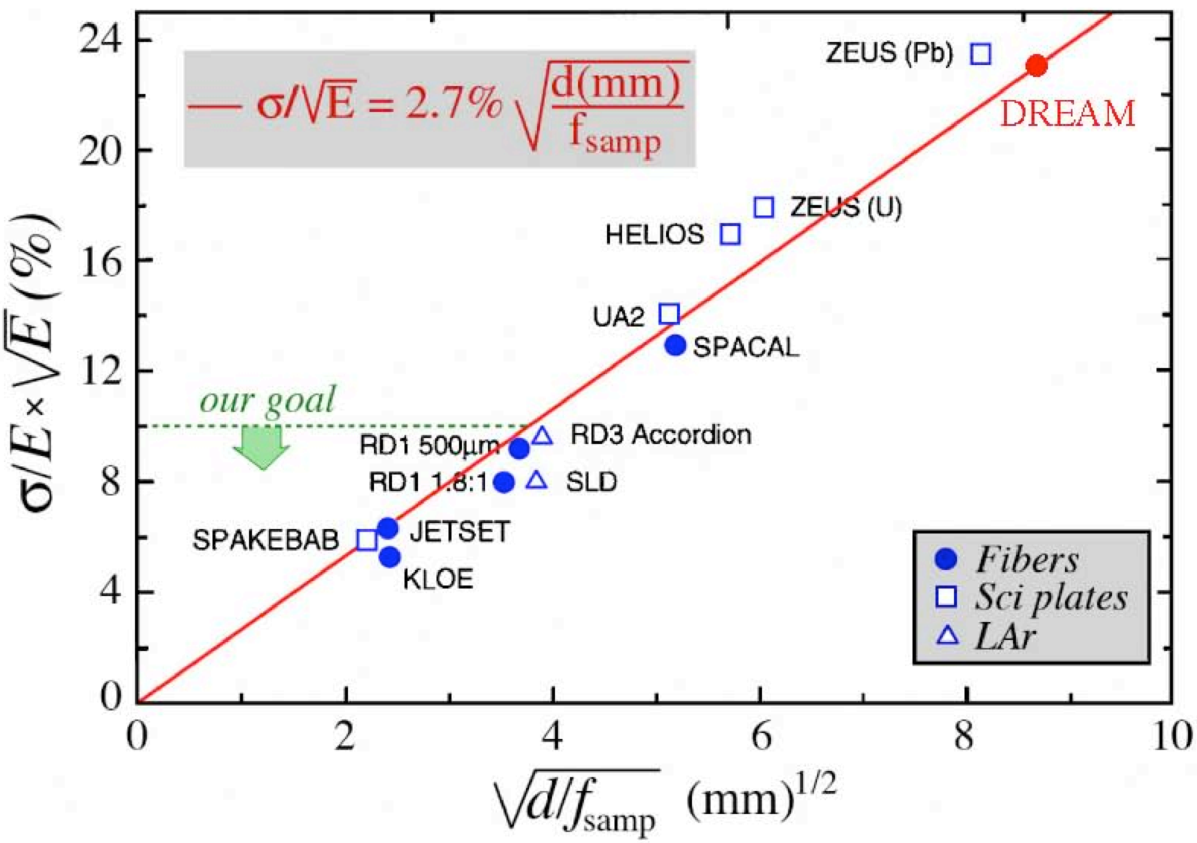


Figure 23: The em energy resolution of sampling calorimeters as a function of the parameter $(d/f_{\mathrm{samp}})^{1/2}$, in which d is the thickness of an active sampling layer (*e.g.* the diameter of a fiber or the thickness of a liquidargon gap), and f_{samp} the sampling fraction for mips [20].

Sampling fluctuations

DREAM fiber module: 21%/√E (em), twice as large for hadrons

Decrease the sampling fluctuations as follows:

- *Embed fibers individually in metal structure, instead of bunches*

  Reduces to 15%/√E

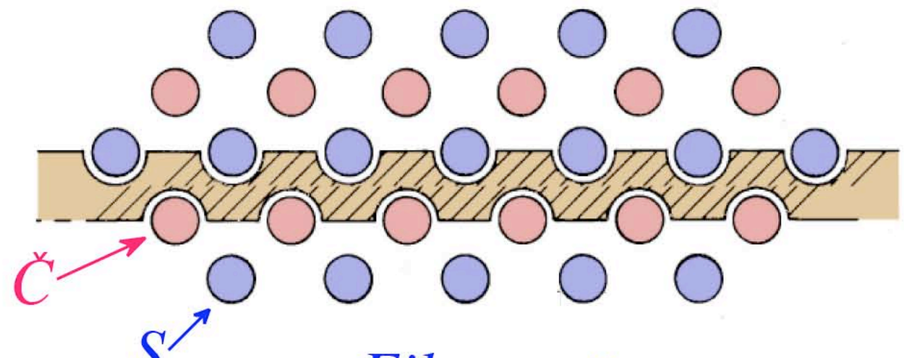
- *Increase the overall fiber filling fraction*

  (from 22% in original fiber module to 43%. PMTs should fit in "shadow")

  Reduces to 11%/√E

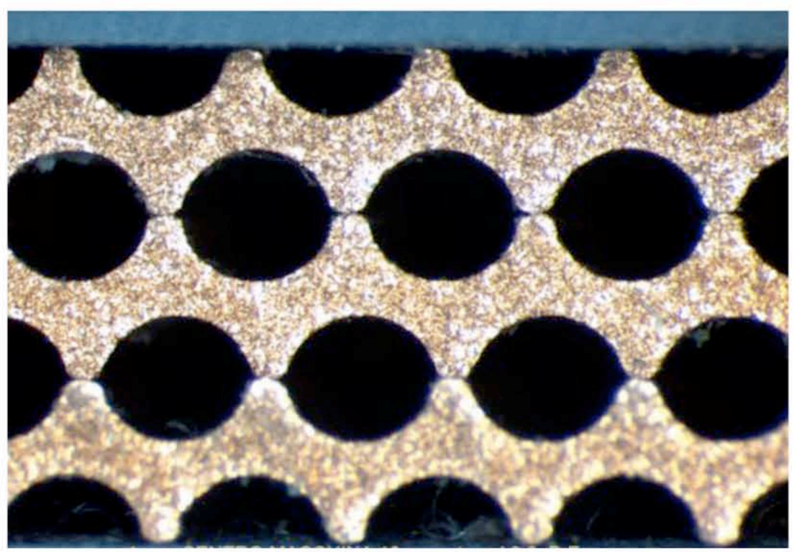
Combine C + S signals for em showers: 8%/√E

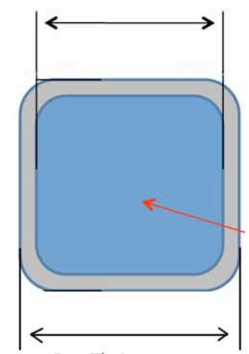
Learn from KLOE and SPACAL!



Fiber pattern

- *interaction length 25 cm*
- *Moliere radius 2.6 cm*
- *10 λ deep*
- *radiation length 2.8 cm*





Hamamatsu R8900
pc: 85%!

(Čerenkov) light yield

Čerenkov light yield in fiber calorimeter

In original DREAM module:

8 photoelectrons/GeV for quartz fibers (N.A. = 0.33)

18 photoelectrons/GeV for plastic fibers (N.A. = 0.50)

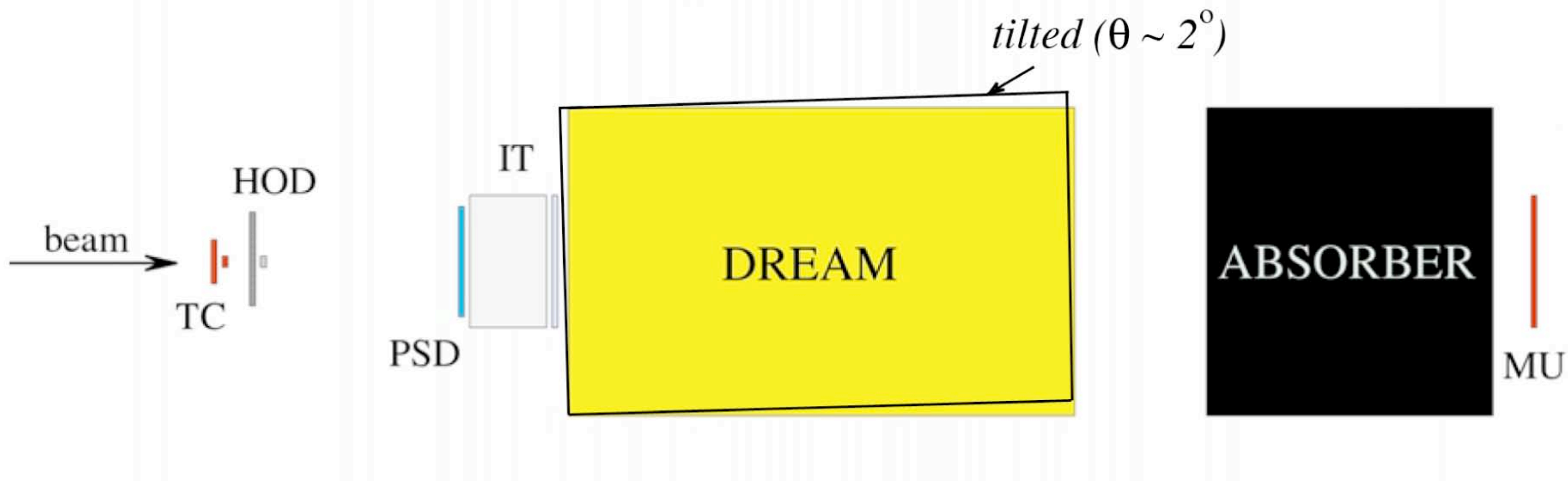
Increase by:

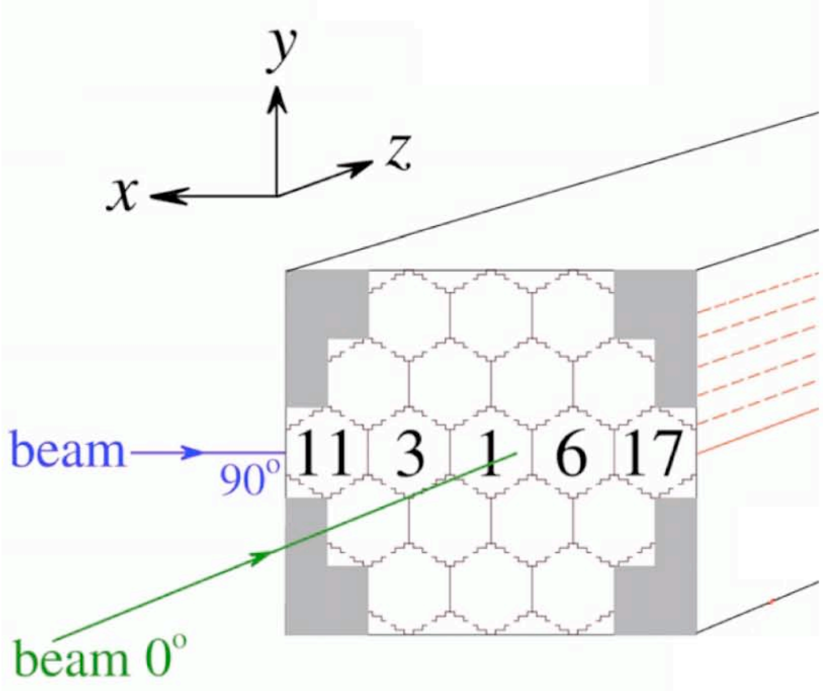
- *Using fibers with larger* *numerical aperture* x 2
  (multi-clad plastic, NA=0.72)
- *Increasing the (Čerenkov)* *sampling fraction* x 2
- *Using PMTs with a larger* *quantum efficiency* x 1.5

Expect to reach > 100 p.e./GeV

Light attenuation

Experimental setup for DREAM beam tests





$\theta = 2^{o}$: *The deeper the light is produced, the more the center-of-gravity of the shower shifts to Tower 6*

$$z = \frac{x_{hod} - x_{cal}}{\sin \theta}$$

Importance of measuring the depth of the shower maximum event by event

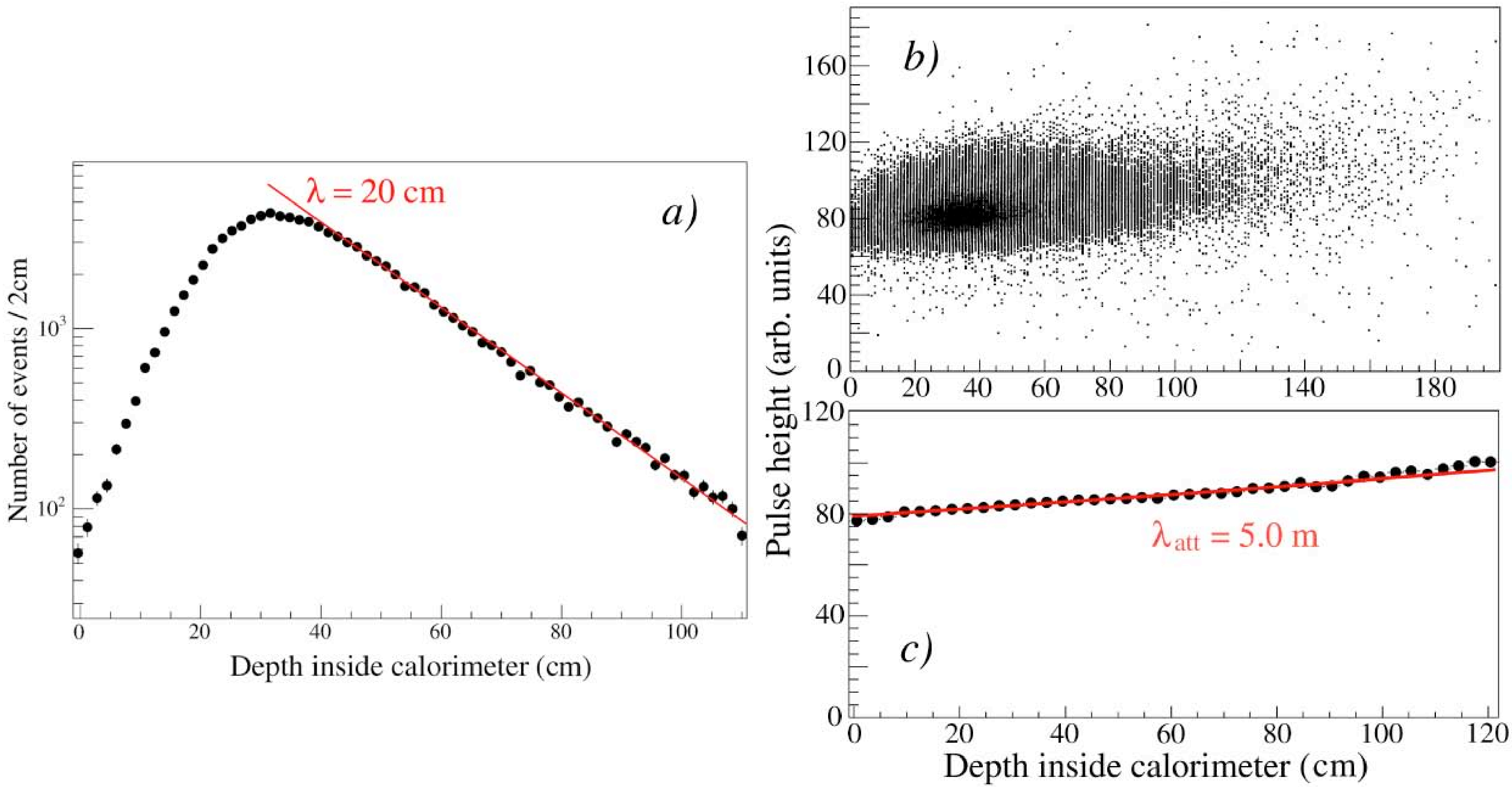


Figure 26: Distribution of the average depth at which the scintillation light is produced in the DREAM calorimeter by showering hadrons (a). Scatter plot showing the total scintillator signal versus the average depth of the light production (a) and the average size of the total scintillator signal as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

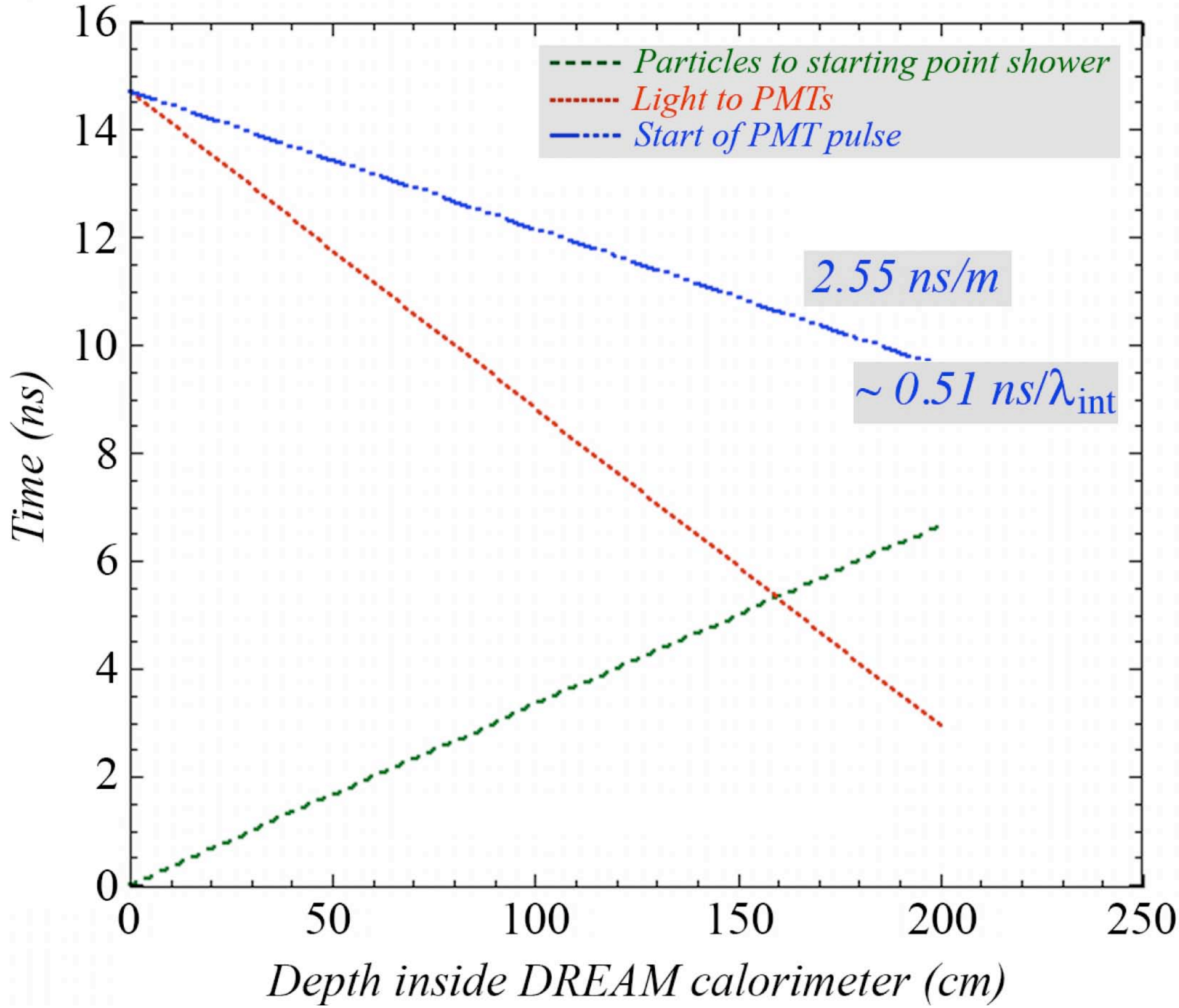
An alternative method to measure shower depth

Disadvantages of described method:

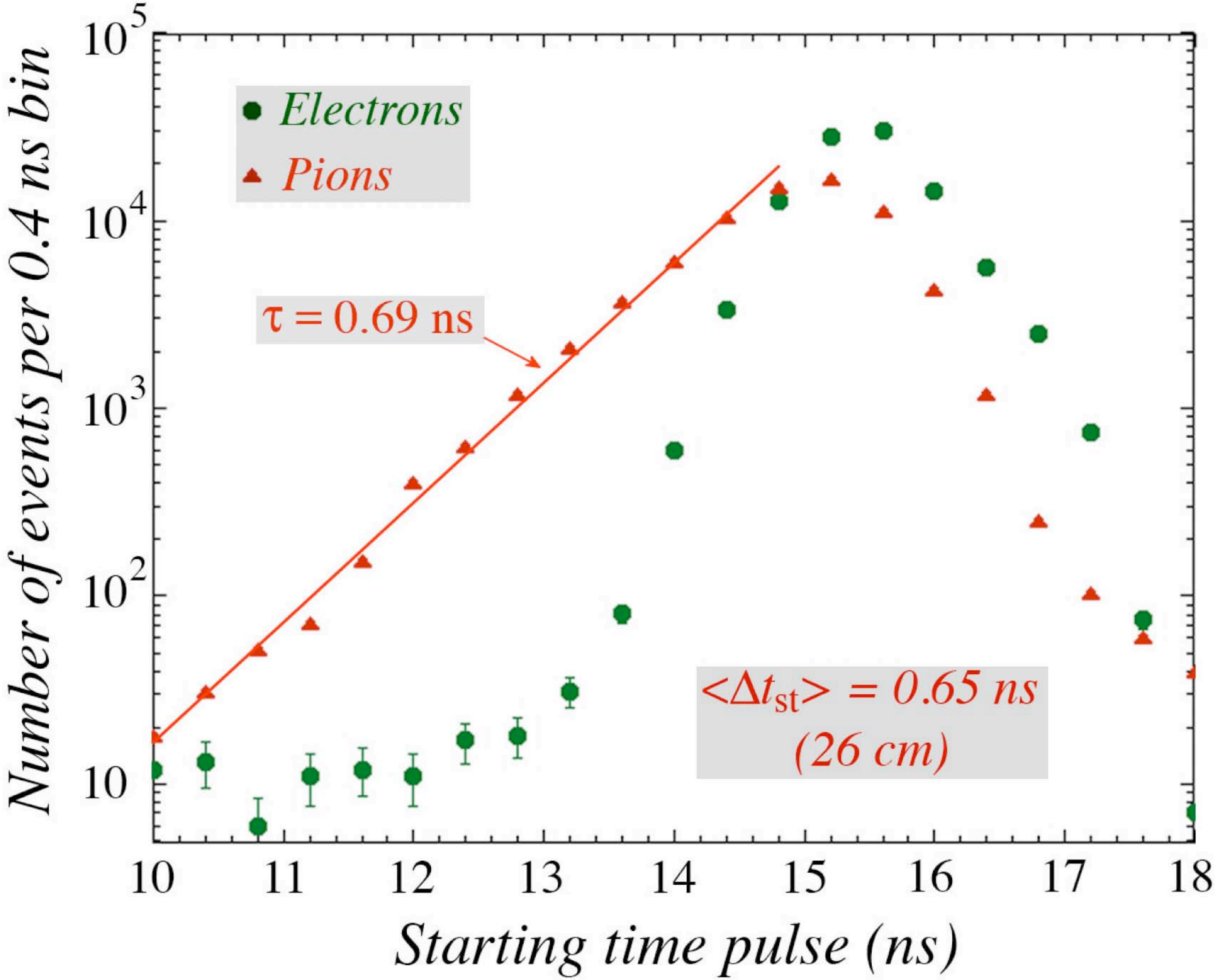
- *Does not work for neutral particles*
- *Does not work for jets*
- *Non-projective calorimeter impractical*

Alternative makes use of the fact that light in fibers travels at $v = c/n$, while particles producing the light travel at $v \sim c$

Depth of the light production and the starting point of the PMT signals



Precise measurement of starting point signal gives depth of the light production!!



Time structure signals

Fiber calorimeter: needed for

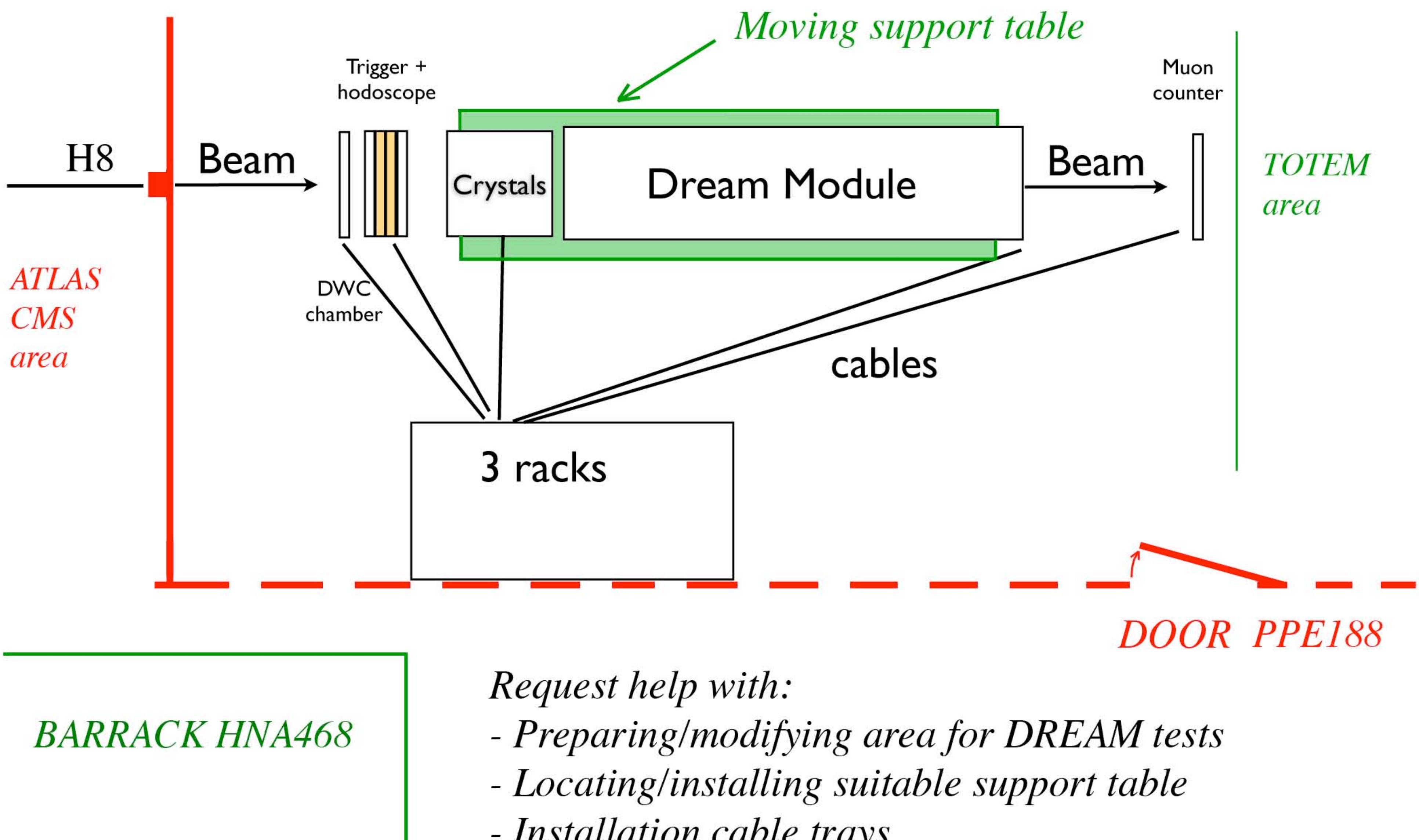
- *precision measurement of start time signals*
- *neutron tail of S signals*

Crystals: needed to separate C and S signals

*We plan to use a data acquisition system based on the DRS chip**
(Domino Ring Sampler) developed at PSI.
An array of 1024 switching capacitors samples the input signal, at a frequency of 2 GHz (DRS-IV).
Read out by pipeline 12-bit ADC.

* *See* NIM A518 (2004) 407

DREAM in H8C

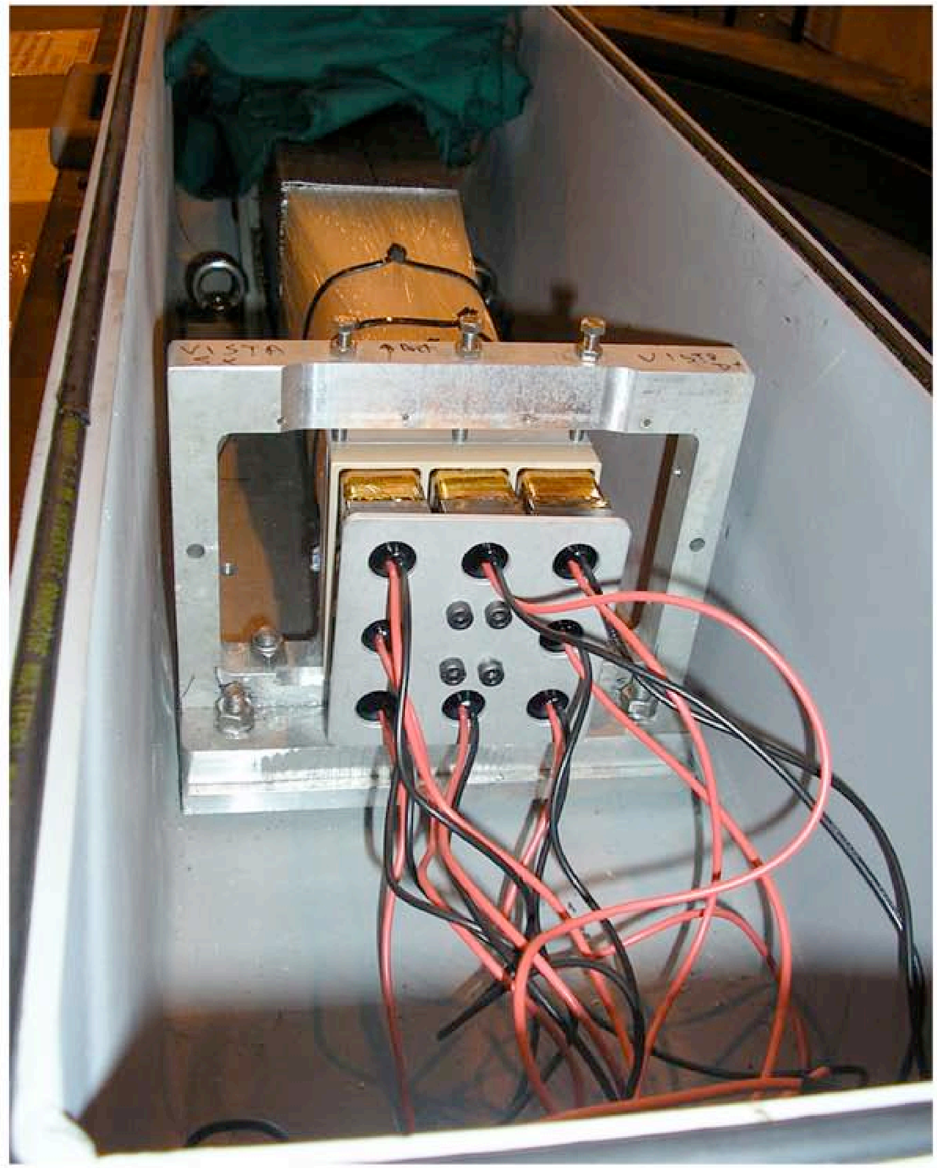


Request help with:

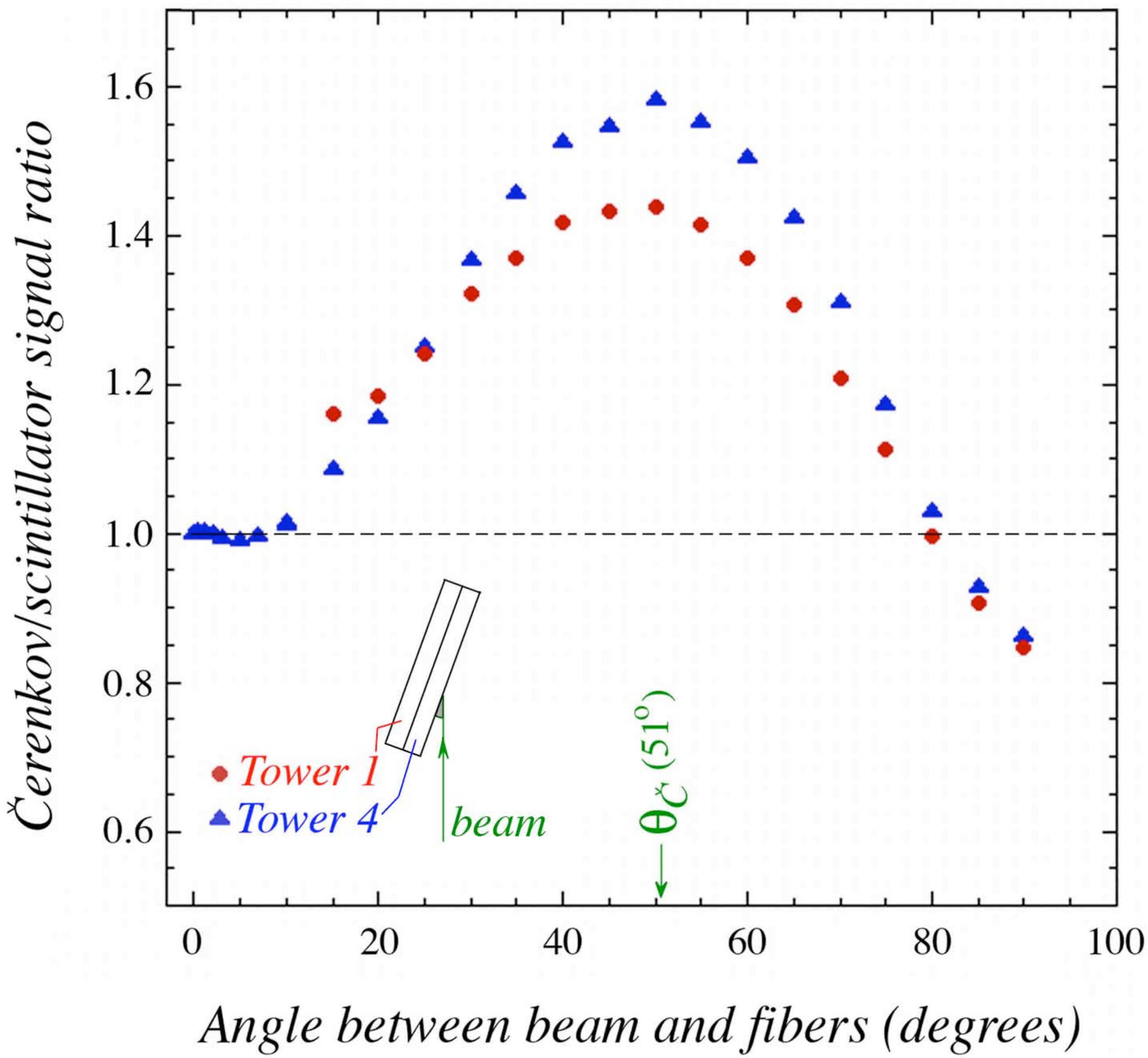
- *Preparing/modifying area for DREAM tests*
- *Locating/installing suitable support table*
- *Installation cable trays*
- *Re-installation of H8 low-energy option*

Estimate: 2 technician-months per year (average)

The first SuperDREAM module at H8



Angular dependence of the Č/S signal ratio in fiber calorimeter



Plans for 2011

- *We hope to build 10 additional SuperDREAM modules*
  RW will spend most of 2011 in Pisa to oversee this process

- *Will construct large system of leakage counters (n detection)*
  to be integrated with SuperDREAM (Iowa State Univ., CERN)

- *Have requested 6 weeks of beam in H8 (CERN SPS)*
  Plan to optimize beam quality, particle tracking system,
  DAQ systems (incl. DRS readout) and test SuperDREAM

Summary

- 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