DREAM*

towards high-resolution jet spectroscopy

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Outline:

- (Limitations of) calorimeter measurements in particle physics
- Dual-readout calorimetry
- Recent R&D results (DREAM = RD52)
- Future plans
- Conclusions

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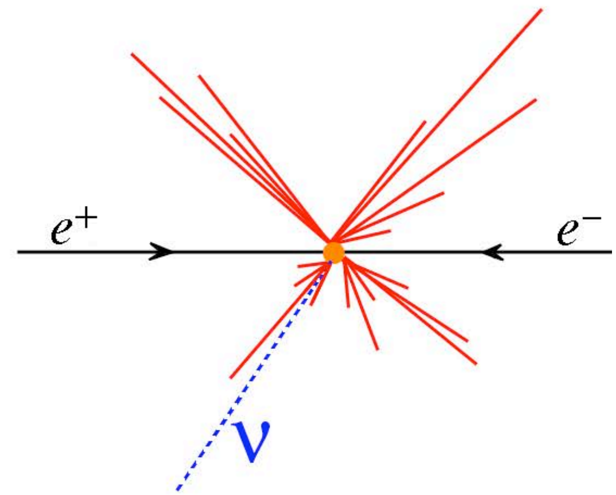
* *DREAM (RD52) Collaboration:*
Cagliari, Cosenza, Pavia, Pisa, Roma, Iowa State, TTU, Lisbon

Why calorimetry?

- Measure *charged + neutral* particles



- Obtain information on *energy flow*:
  Total (missing) transverse energy, jets, *etc*.

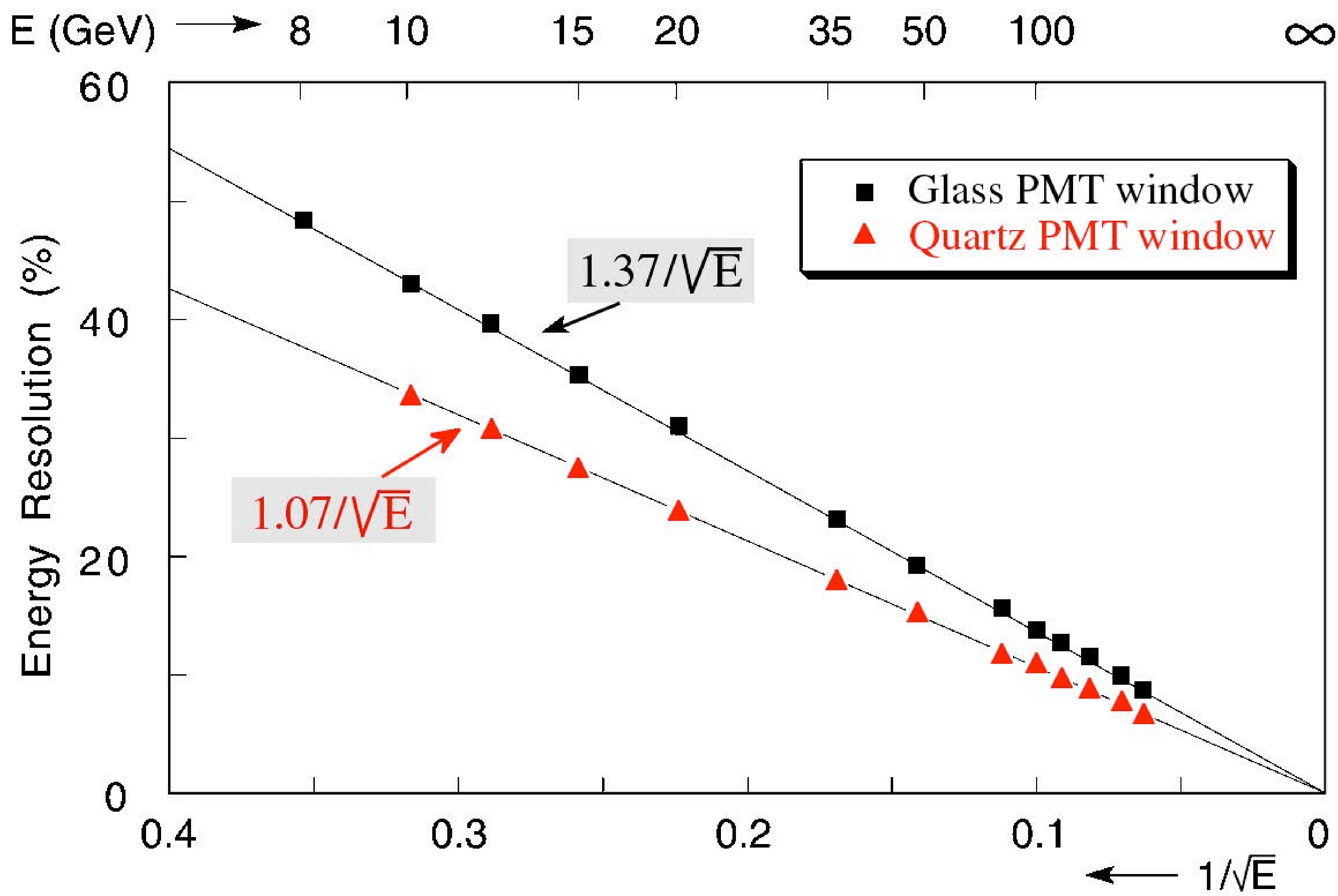
- Obtain information *fast*
  → recognize and select interesting events in real time *(trigger)*

- 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* $n \longrightarrow \sigma(E) \propto \sqrt{n}$

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

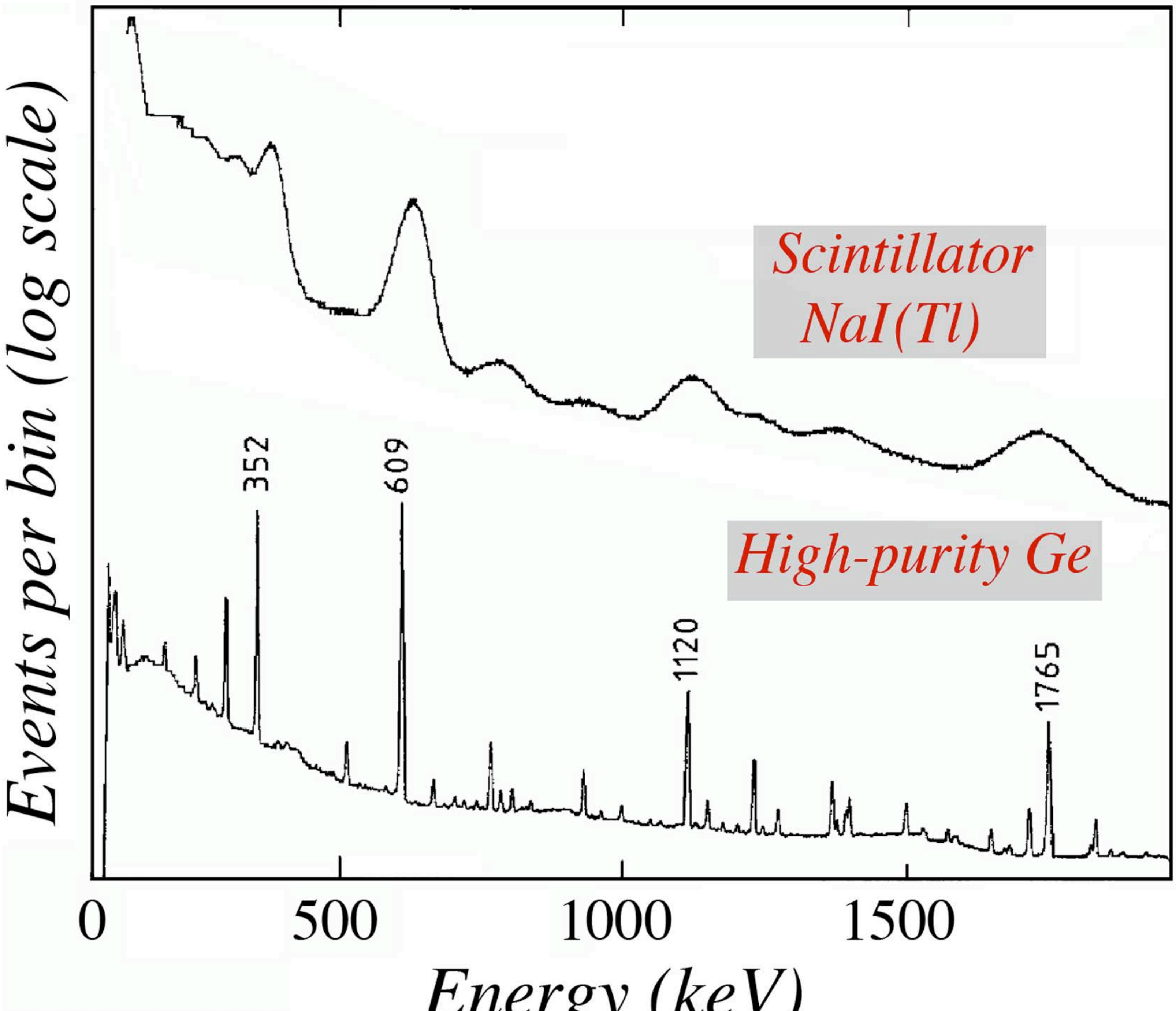
In an ideal calorimeter, resolution scales as $E^{-1/2}$



Important calorimeter features

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

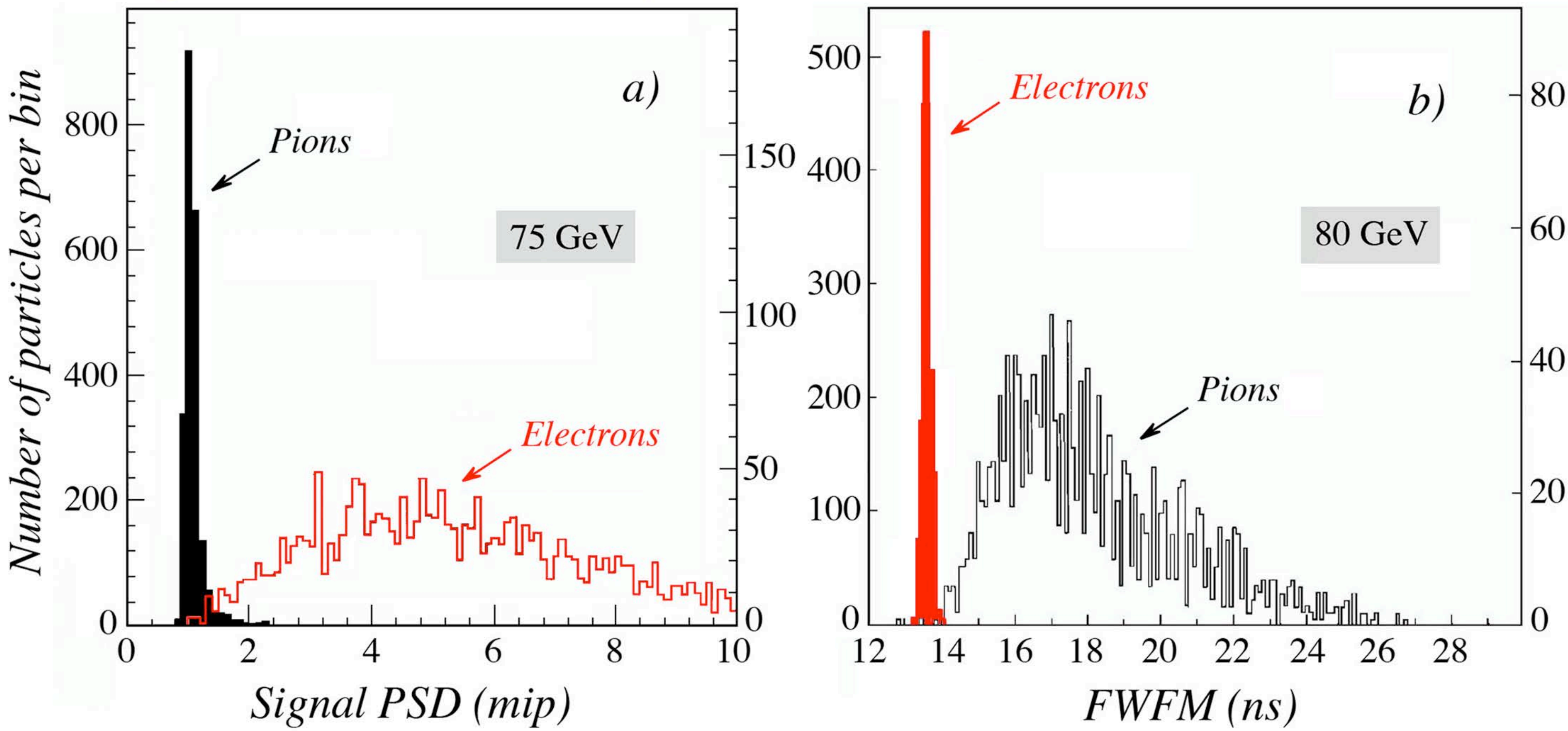
The importance of good energy resolution (1)



Particle identification with calorimeters

Using shower profile (pre-shower detector)

Using time structure of the signals

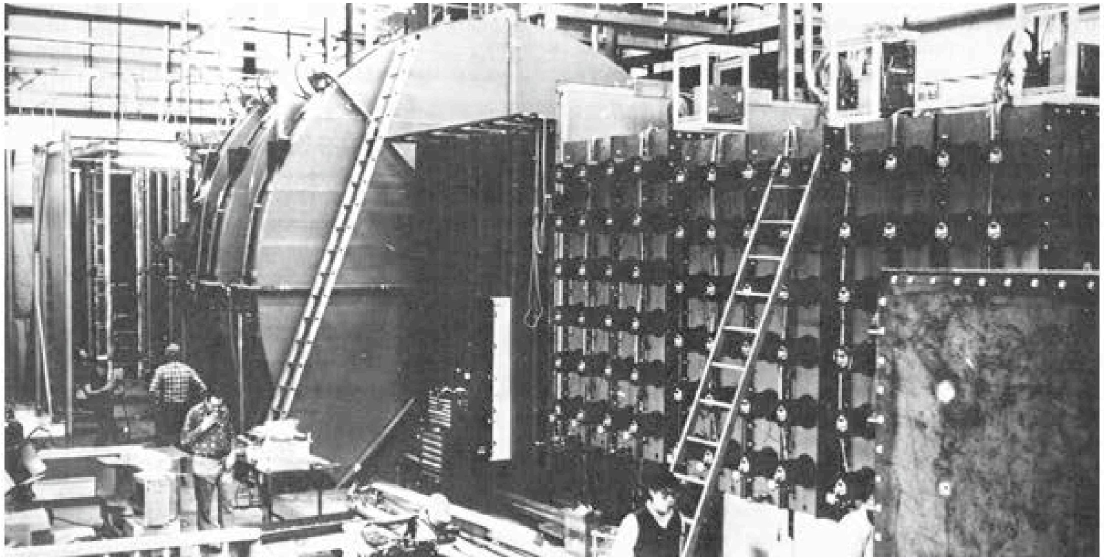


Whereas electromagnetic calorimeters (intended for e,γ detection) are typically very precise and very well understood instruments

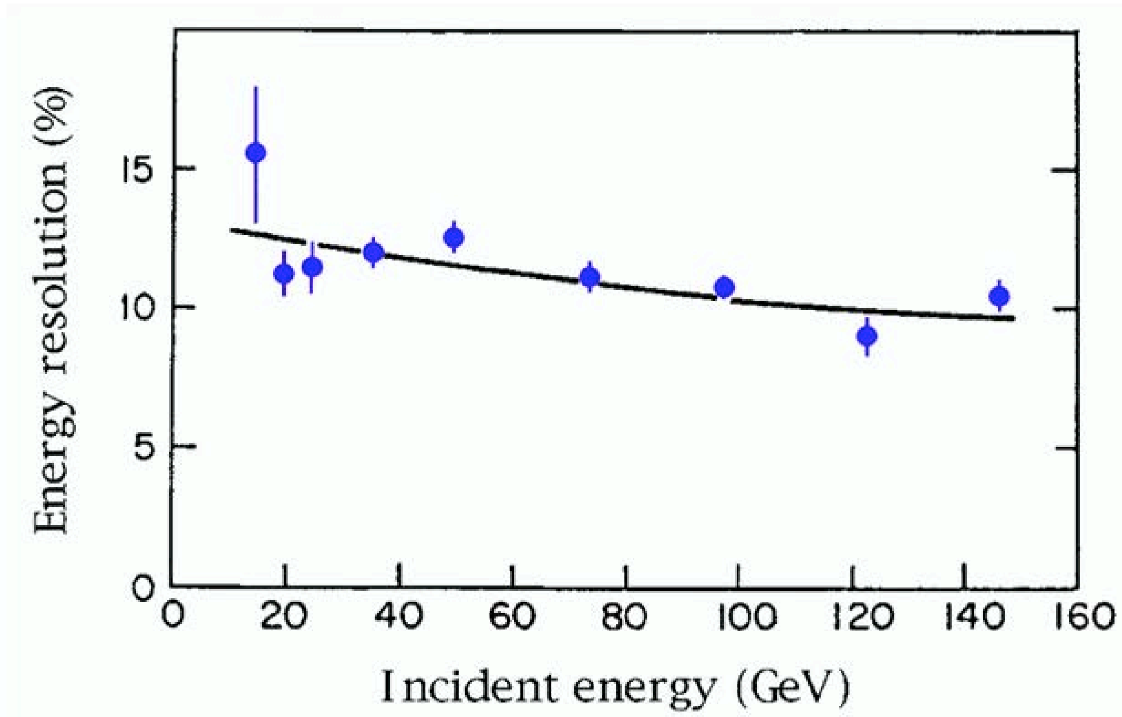
Hadron calorimeters are usually far from ideal

Energy resolution of a homogeneous hadron calorimeter

(60 tonnes of liquid scintillator)



From: NIM 125 (1975) 447



Hadron calorimetry in practice
Energy resolution for a non-compensating calorimeter

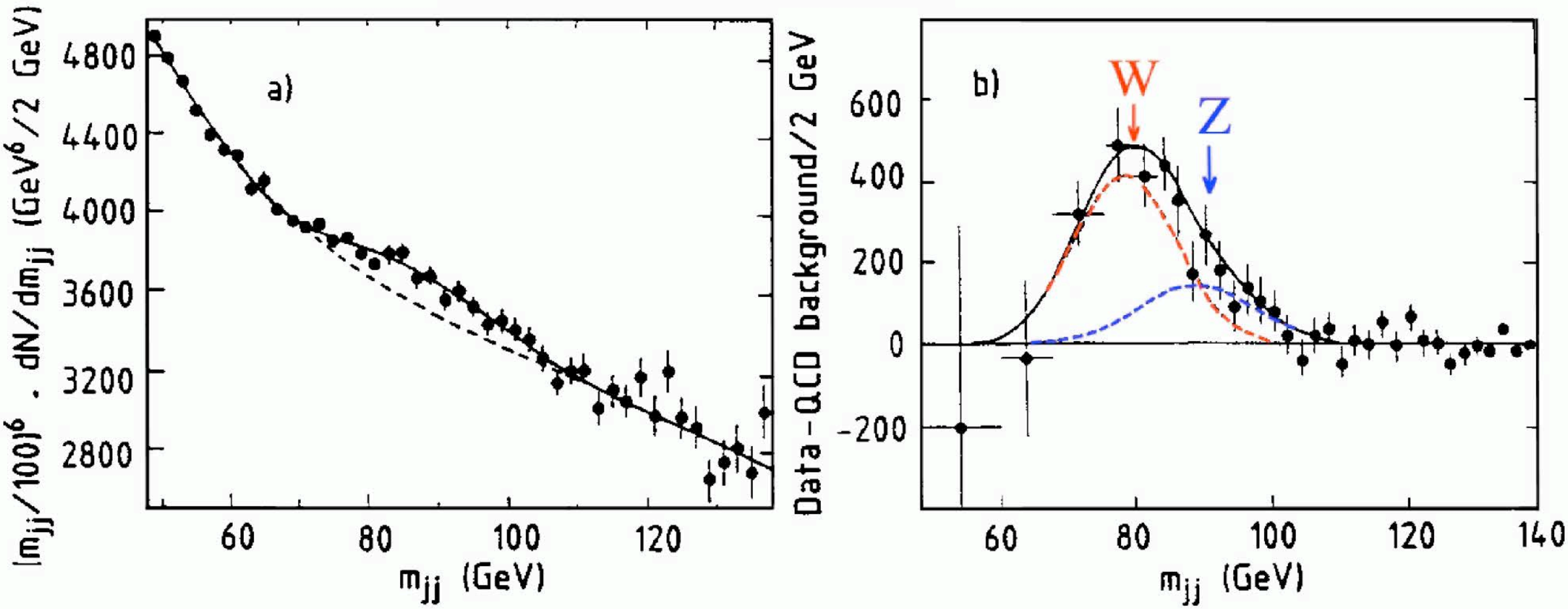
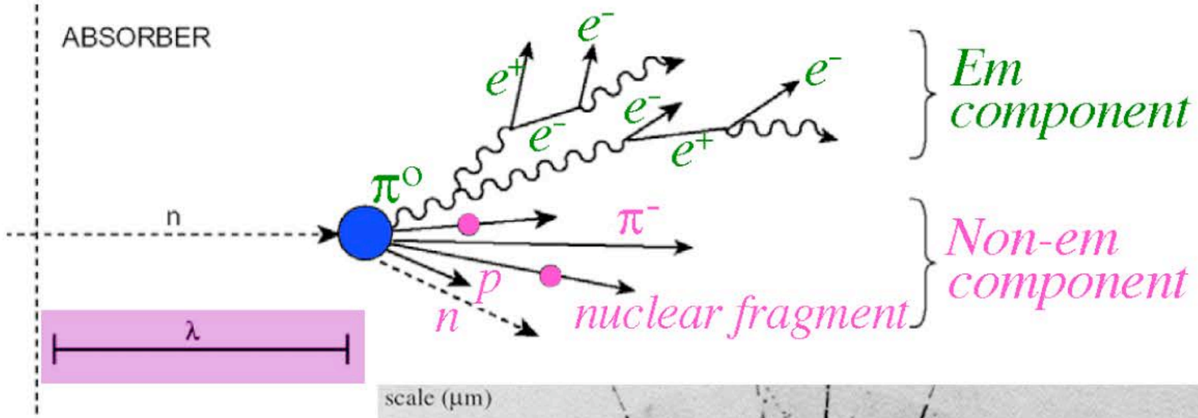


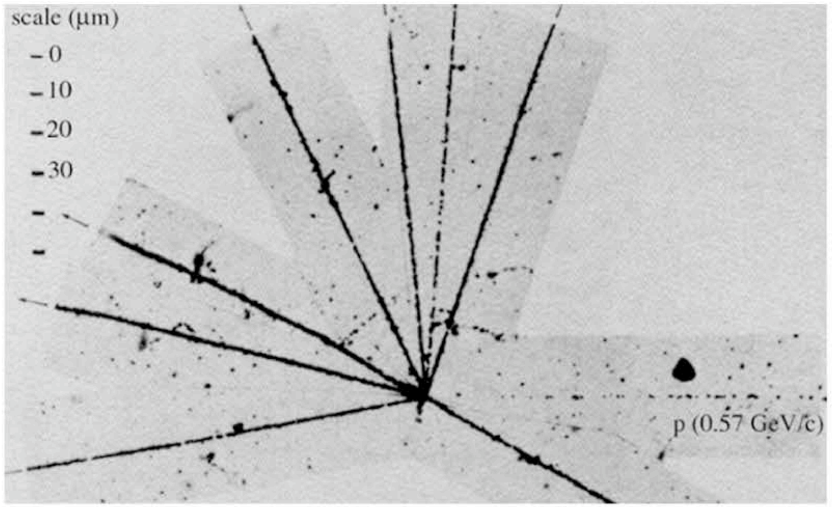
FIG. 7.50. Two-jet invariant mass distributions from the UA2 experiment [Alit 91]. Diagram a) shows the measured data points, together with the results of the best fits to the QCD background alone (*dashed curve*), or including the sum of two Gaussian functions describing $W, Z \to q\bar{q}$ decays.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

The physics of hadronic shower development

- *A hadronic shower consists of two components*



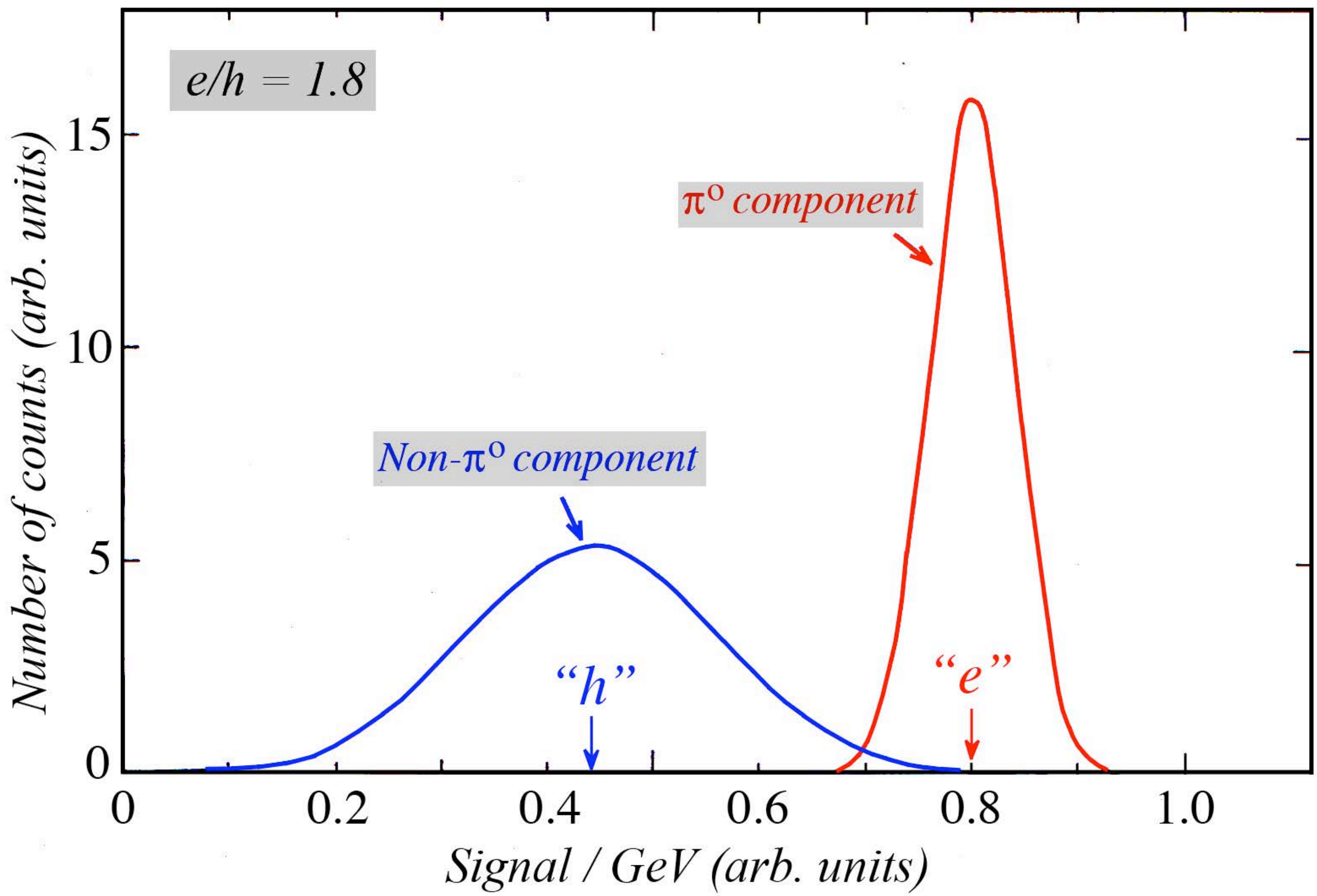
- *Electromagnetic component*
  - electrons, photons
  - neutral pions → 2 γ
- *Hadronic (non-em) component*
  - charged hadrons $\pi^{\pm}$, $K^{\pm}$ (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft γ's (15%)
  - break-up of nuclei *("invisible")* (40%)



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

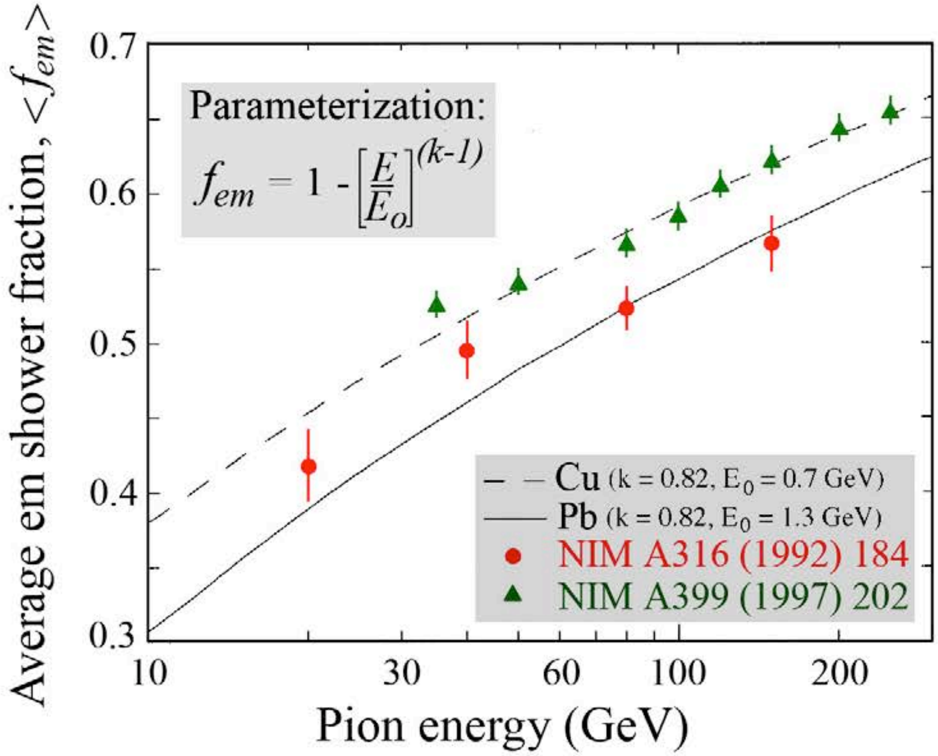
The calorimeter response to the two shower components is NOT the same

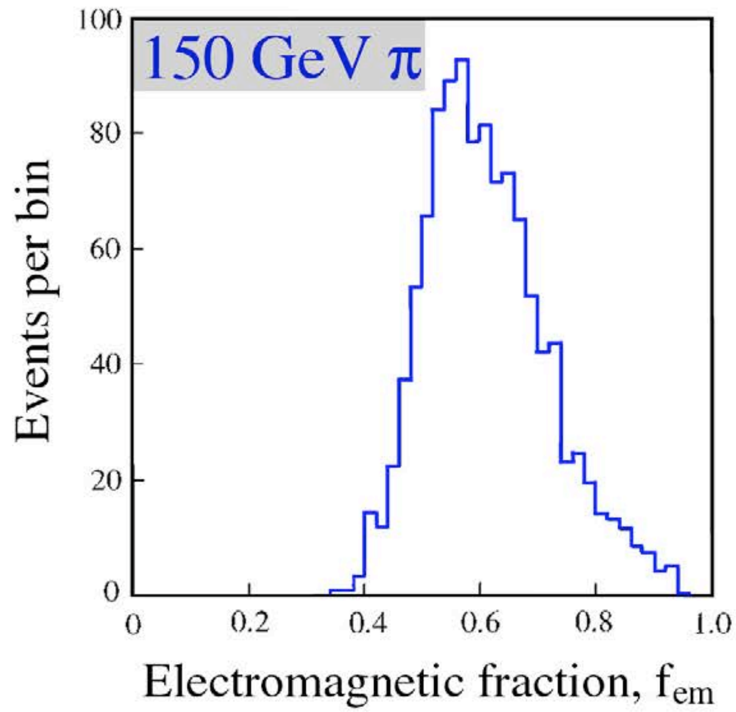
(mainly because of nuclear breakup energy losses in non-π^o component)



(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

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

Hadronic shower profiles: Fluctuations!

π^o *production may take place anywhere in the absorber*

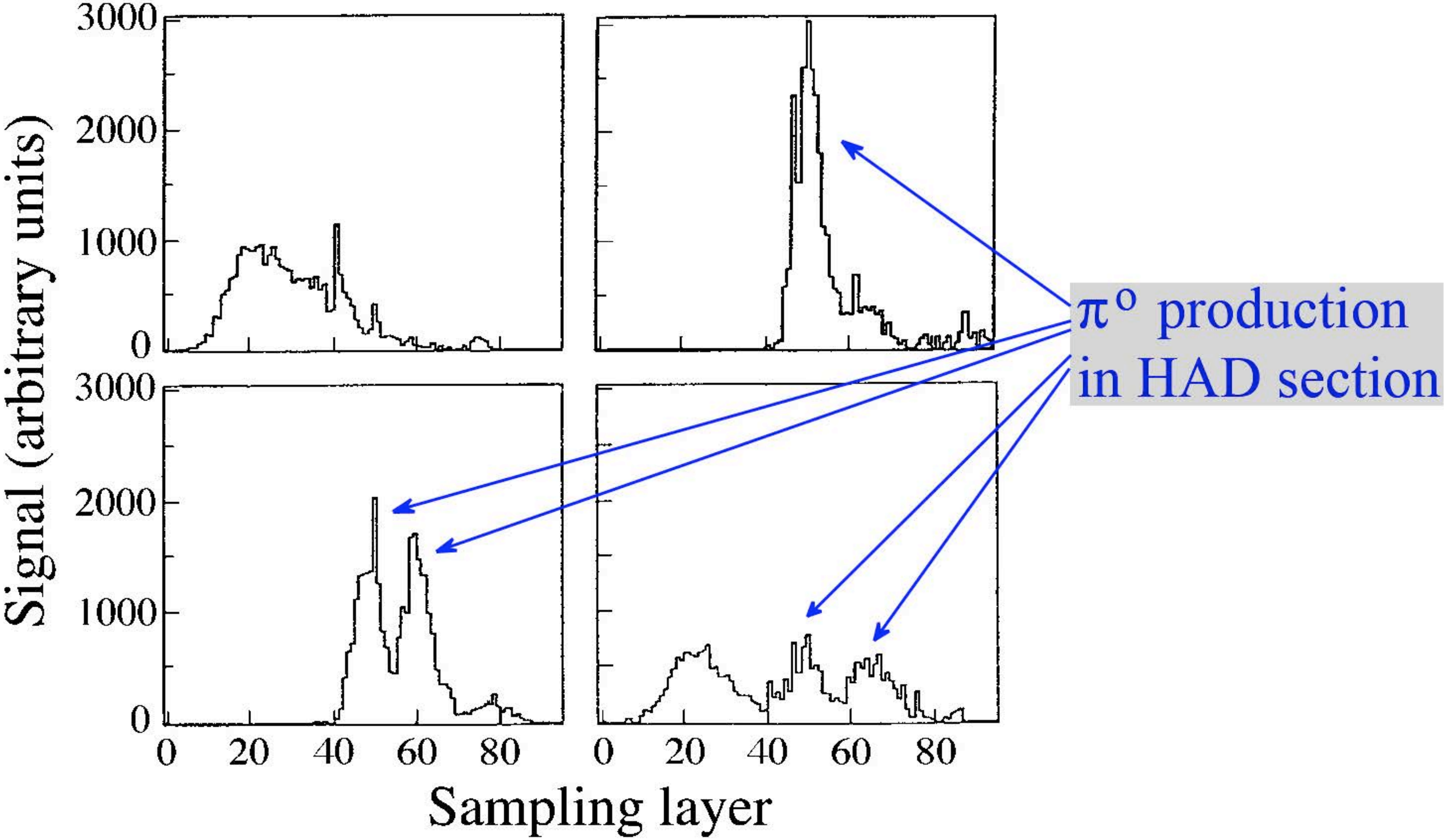


FIG. 2.35. Longitudinal profiles for 4 different showers induced by 270 GeV pions in a lead/iron/plastic-scintillator calorimeter. Data from [Gre 94].

Consequences for LHC calorimeters

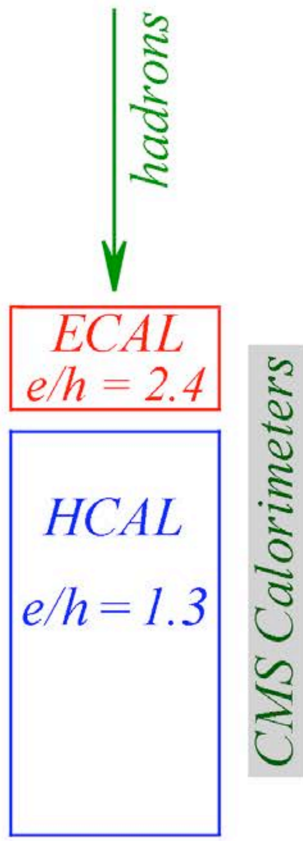
Hadronic response and signal linearity (CMS)

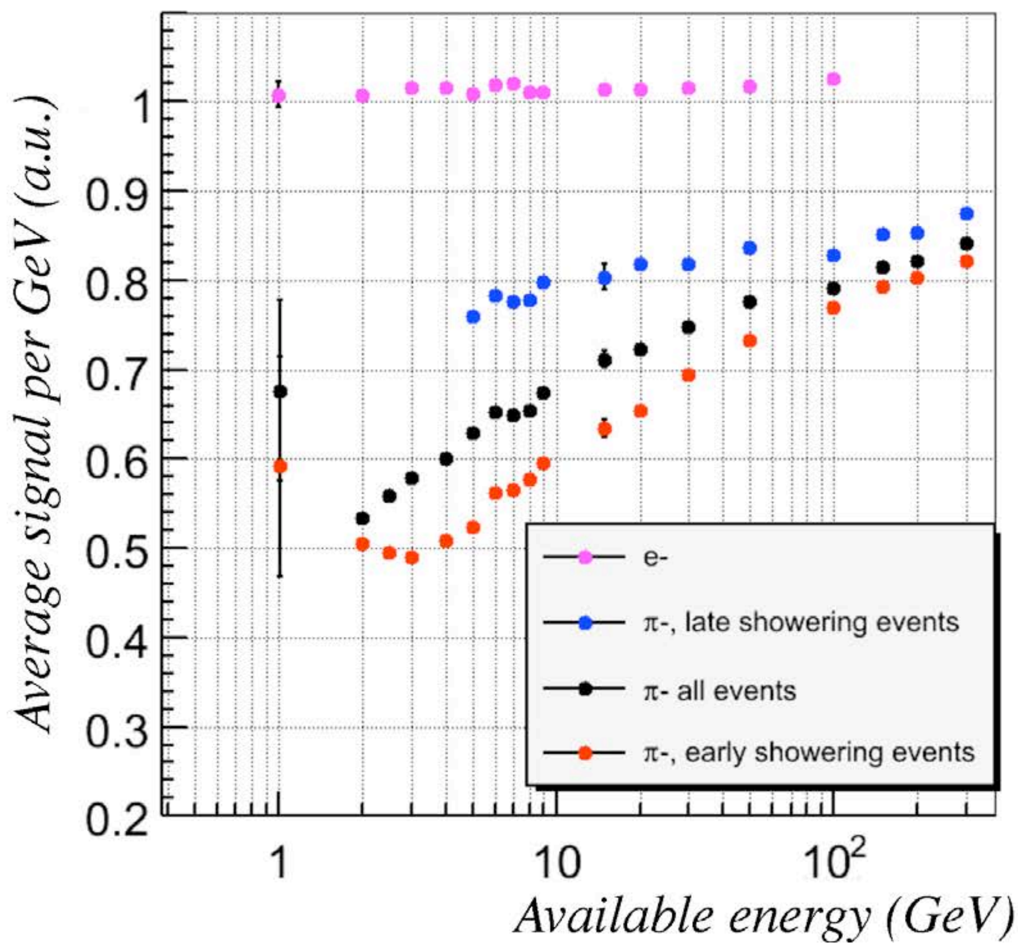
CMS pays a price for its focus on em energy resolution

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

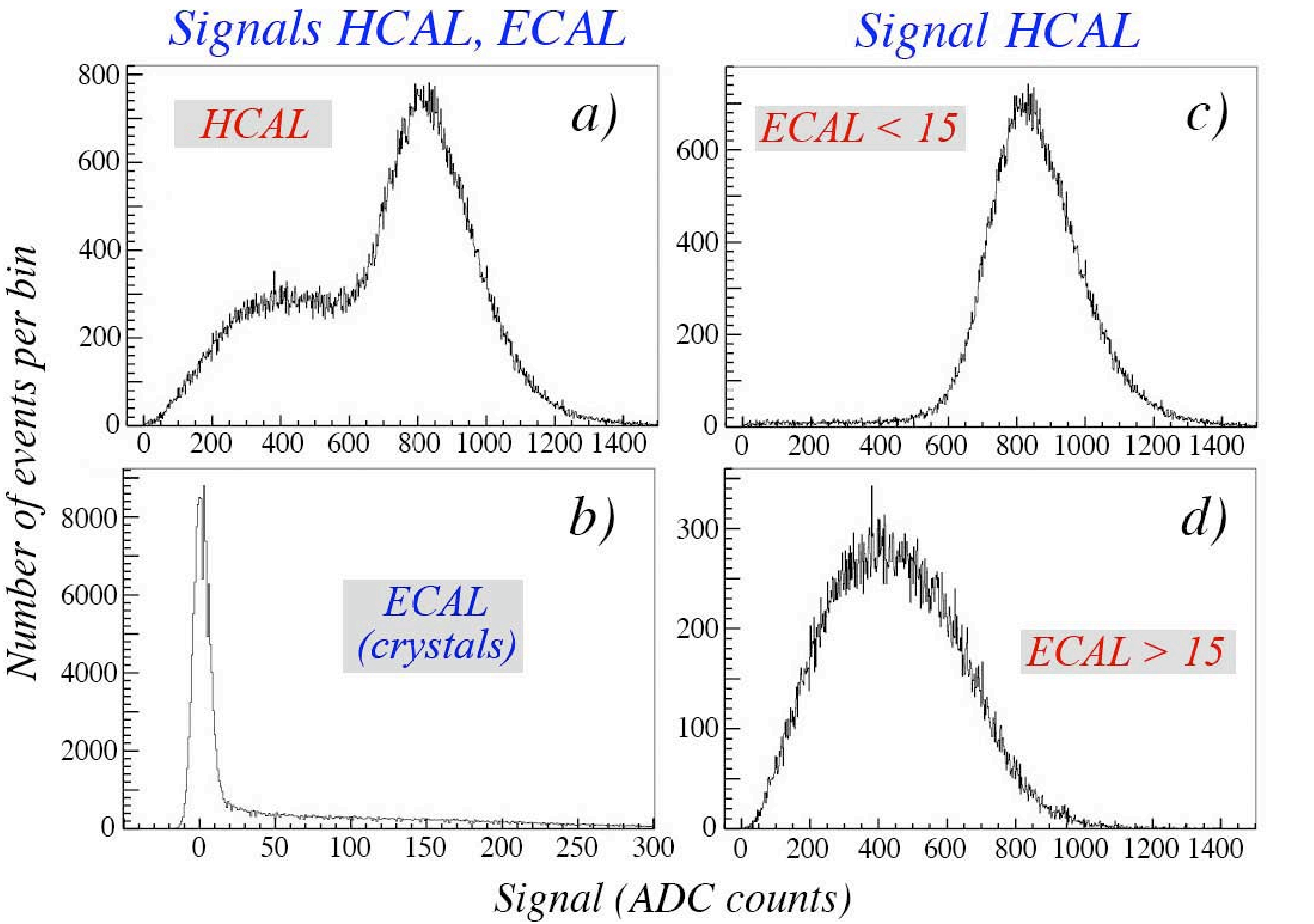
→ *Response depends strongly on starting point shower*

Data from: CMS note 2007/012





Pion signals in crystal ECAL + scintillator HCAL



The future of calorimetry

- *Hadronic calorimetry will become increasingly important, especially if a machine such as CLIC will ever be built. Jet spectroscopy will replace particle spectroscopy, e.g. to distinguish final-state W/Z bosons*

- *Different approaches are followed to develop calorimeter systems that are up to that task:*

  - *Compensating calorimeters*
    Proven technology, current holders of all performance records

  - *Dual-readout calorimeters*
    Try to improve on the performance of compensating calorimeters by eliminating the weak points of the latter
    Many experimental successes have been achieved, goals within reach

  - *Systems based on Particle Flow Analysis*
    Combine the information from a tracking system and a fine-grained calorimeter

Compensating calorimetry

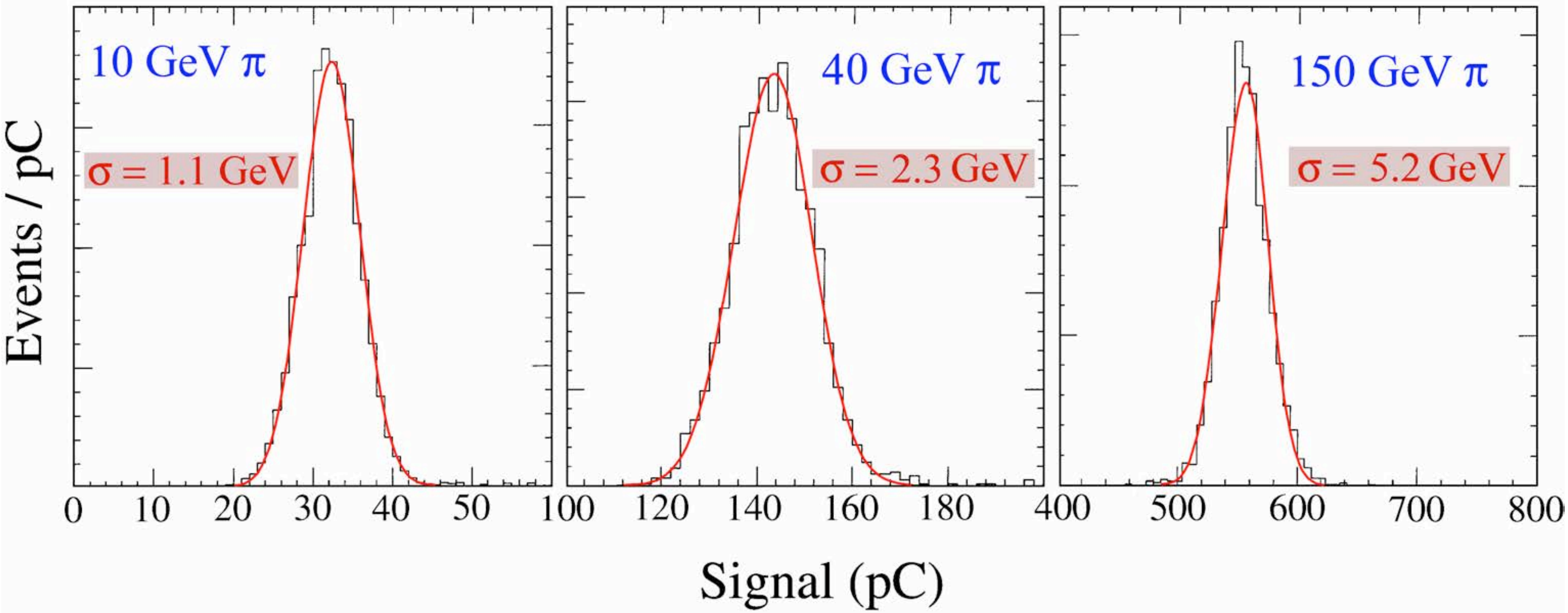
- *Reasons for poor hadronic performance of non-compensating calorimeters understood*

- *Compensation mechanisms fully understood*

  ^{238}*U absorber (fission* $\longrightarrow$ *compensation for invisible energy loss)*
  is neither needed nor sufficient

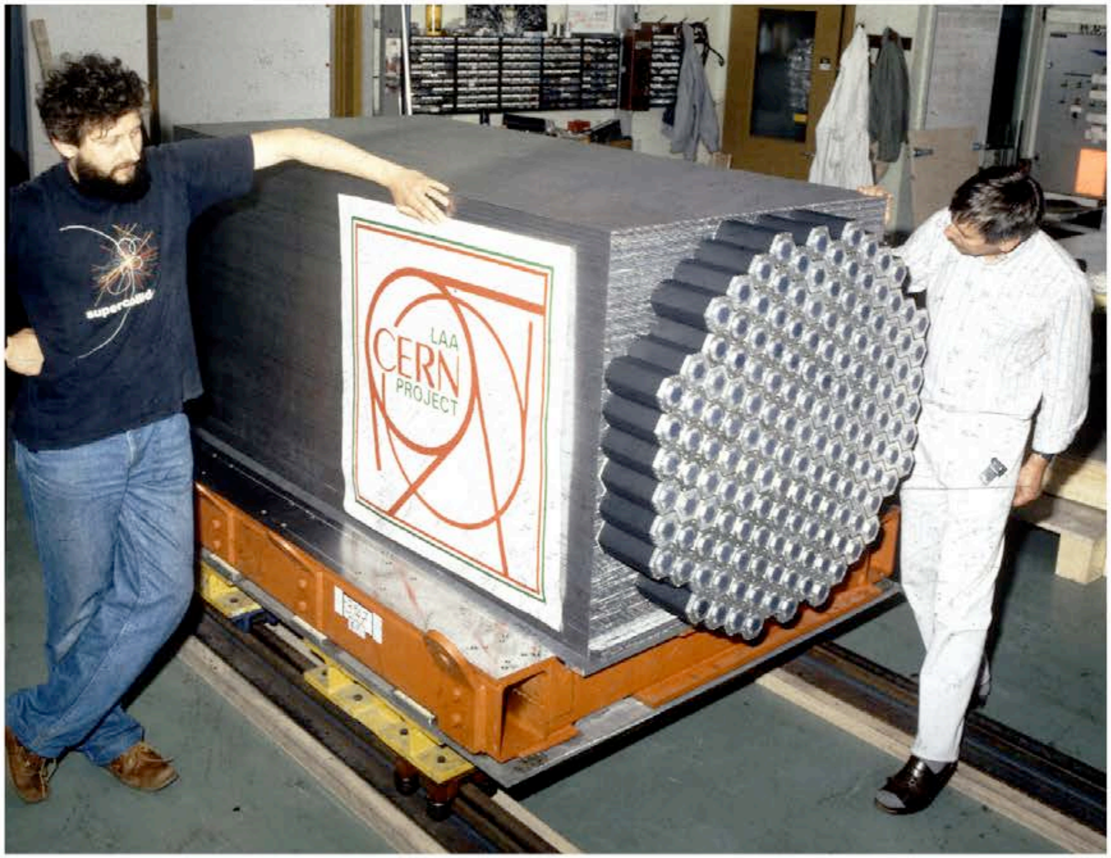
  Experimentally demonstrated with Pb/scintillator calorimeters (ZEUS, SPACAL)

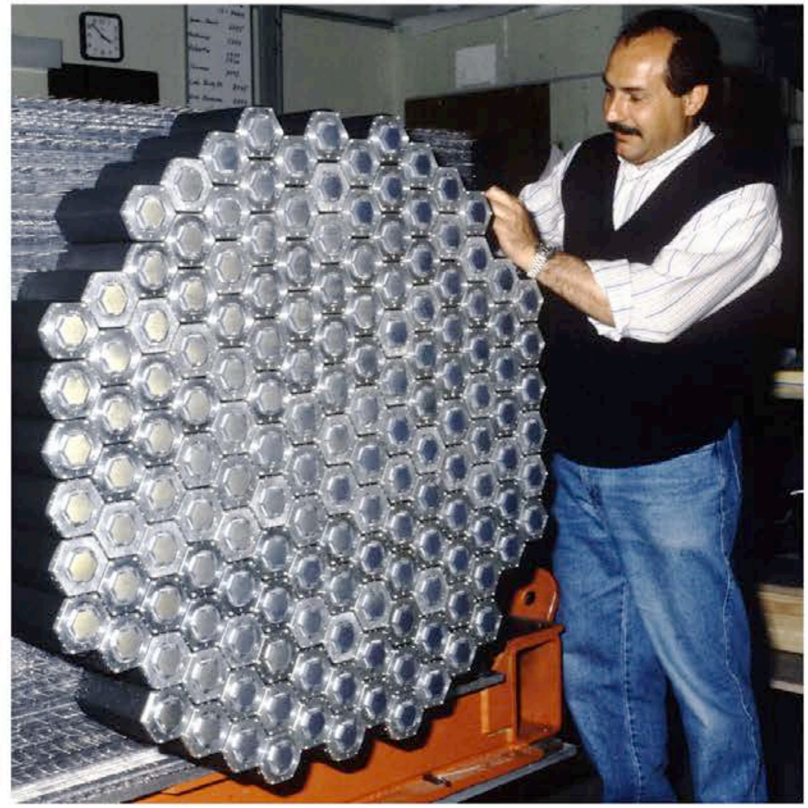
Hadronic signal distributions in a compensating calorimeter



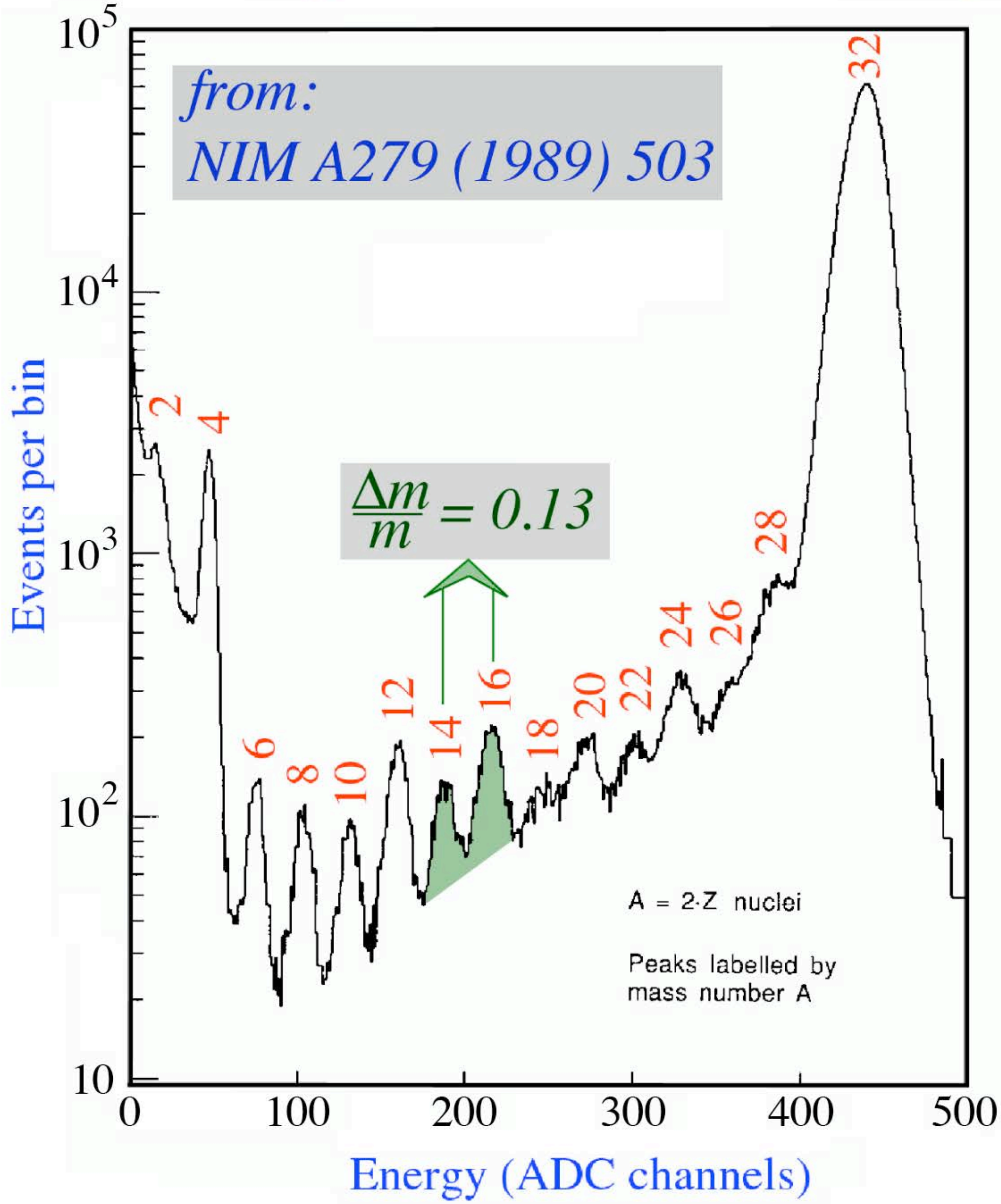
from: NIM A308 (1991) 481

SPACAL 1989





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

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)
  ⟶ *em energy resolution limited* (SPACAL: 13%/$\sqrt{E}$, ZEUS: 18%/$\sqrt{E}$)
- Compensation relies on detecting neutrons
  ⟶ Large *integration volume*
  ⟶ Long *integration time* (~50 ns)

Elements needed to improve the excellent ZEUS/SPACAL performance:

1) *Reduce the contribution of sampling fluctuations to energy resolution*
(THE limiting factor in SPACAL/ZEUS)

2) *Eliminate/reduce effects of fluctuations in "invisible energy"*
→ *calorimeter needs to be efficient in detecting the "nuclear" fraction of the non-em shower component*

3) *Eliminate the effects of fluctuations in the em shower fraction, f_{em}*
in a way that does NOT prevent 1), 2)

→ *Dual-Readout Calorimetry*

An attractive option for improving the quality of hadron calorimetry:

Use Čerenkov light!! *Why?*

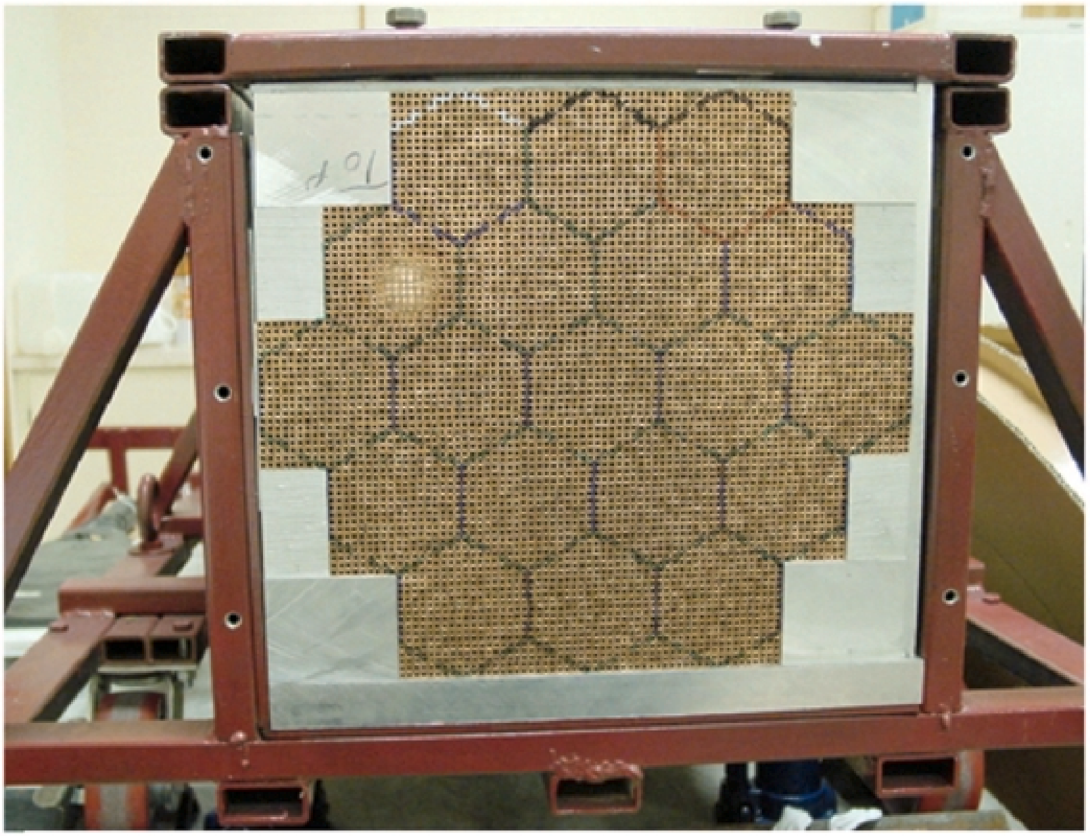
Hadron showers < *em* component (π^{o}) / *non-em* component (mainly soft *p*)

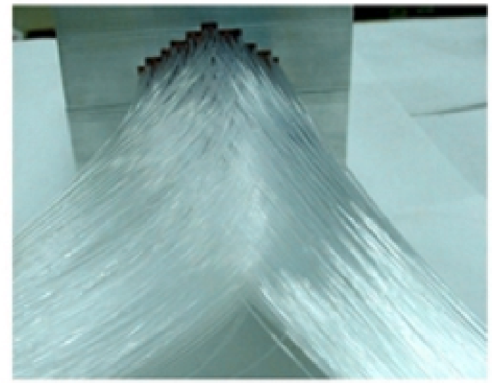
Calorimeter response to these components not the same *(e/h ≠ 1)*

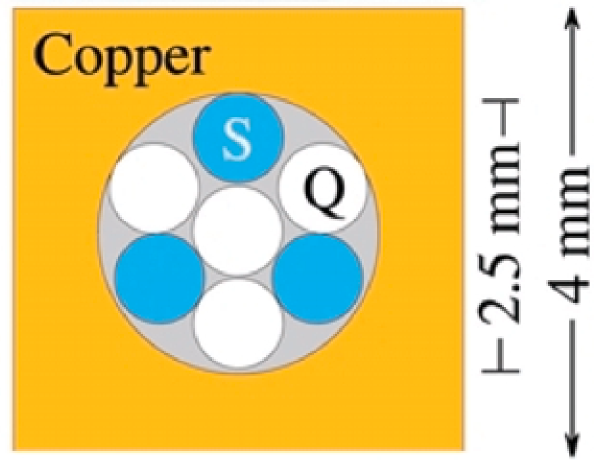
Čerenkov light almost exclusively produced by em component
(~80% of non-em energy deposited by non-relativistic particles)

➡ DREAM (Dual REAdout Method) principle:
Measure f_{em} *event by event by comparing Č and dE/dx signals*

DREAM: Structure

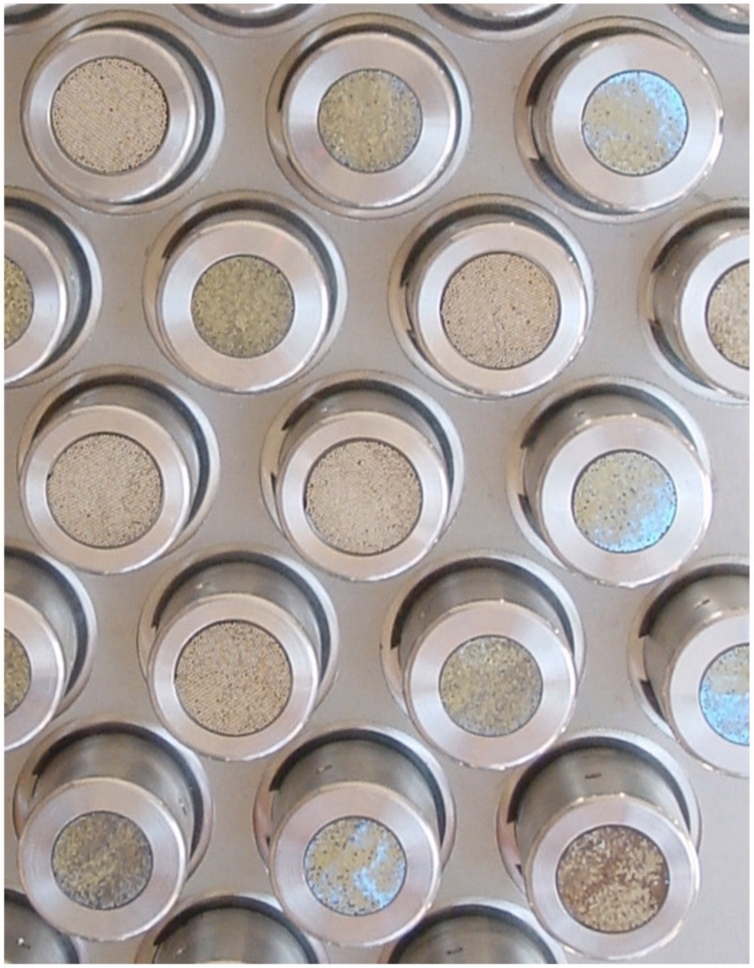


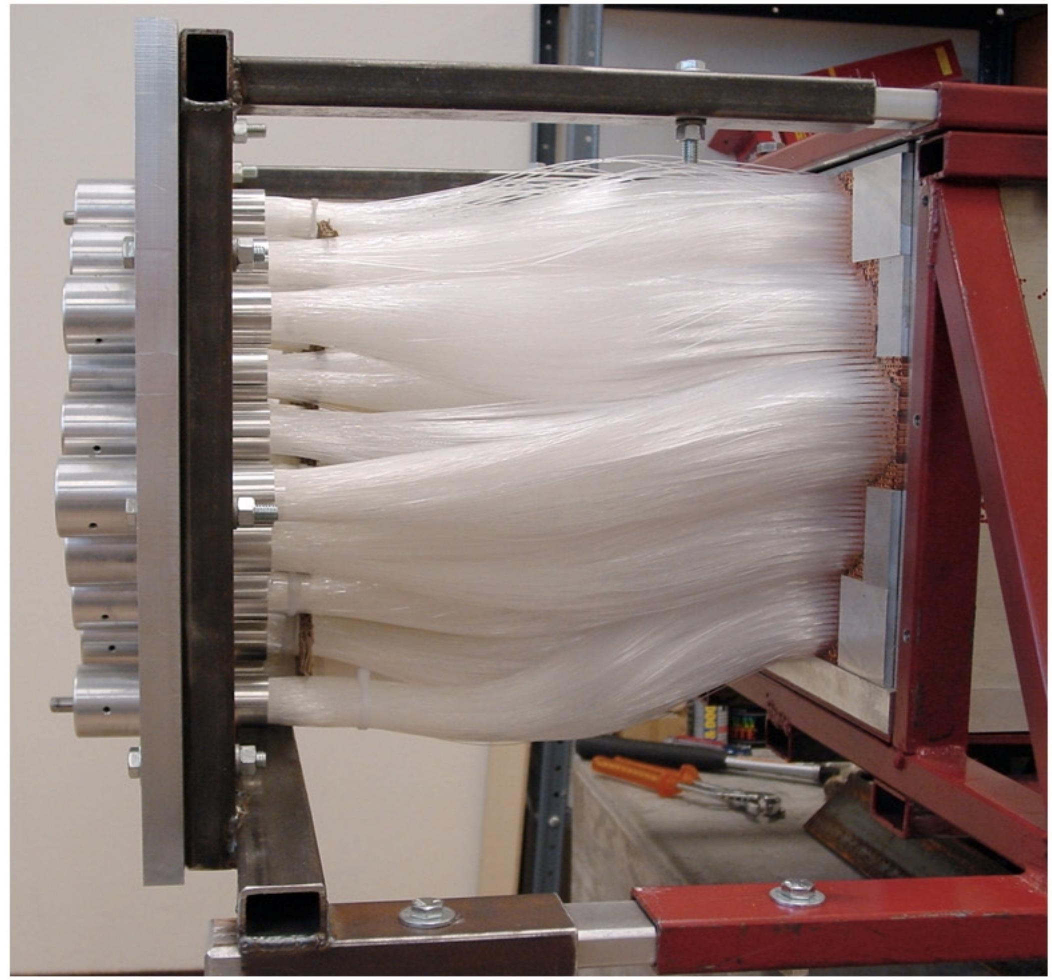


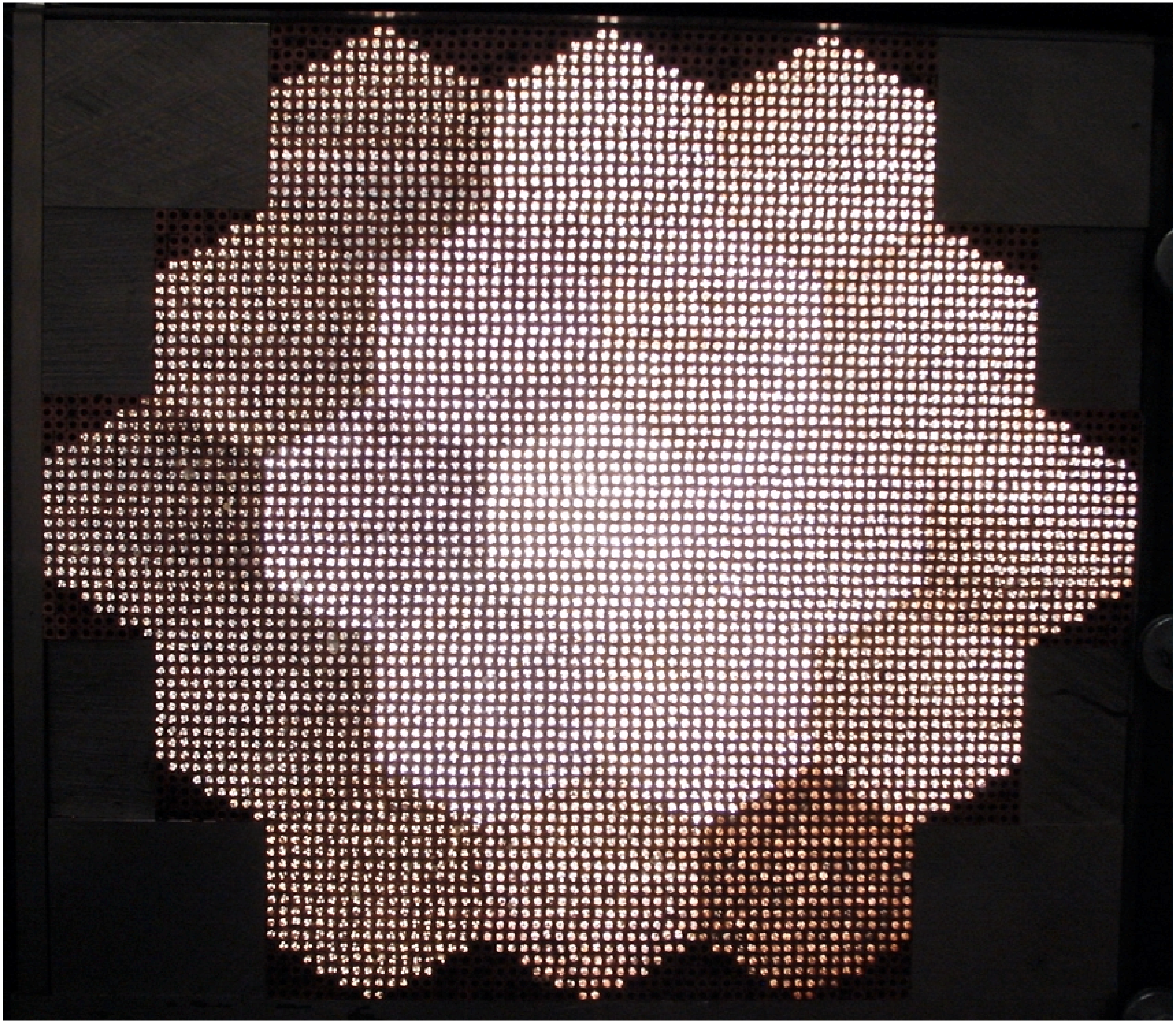


- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

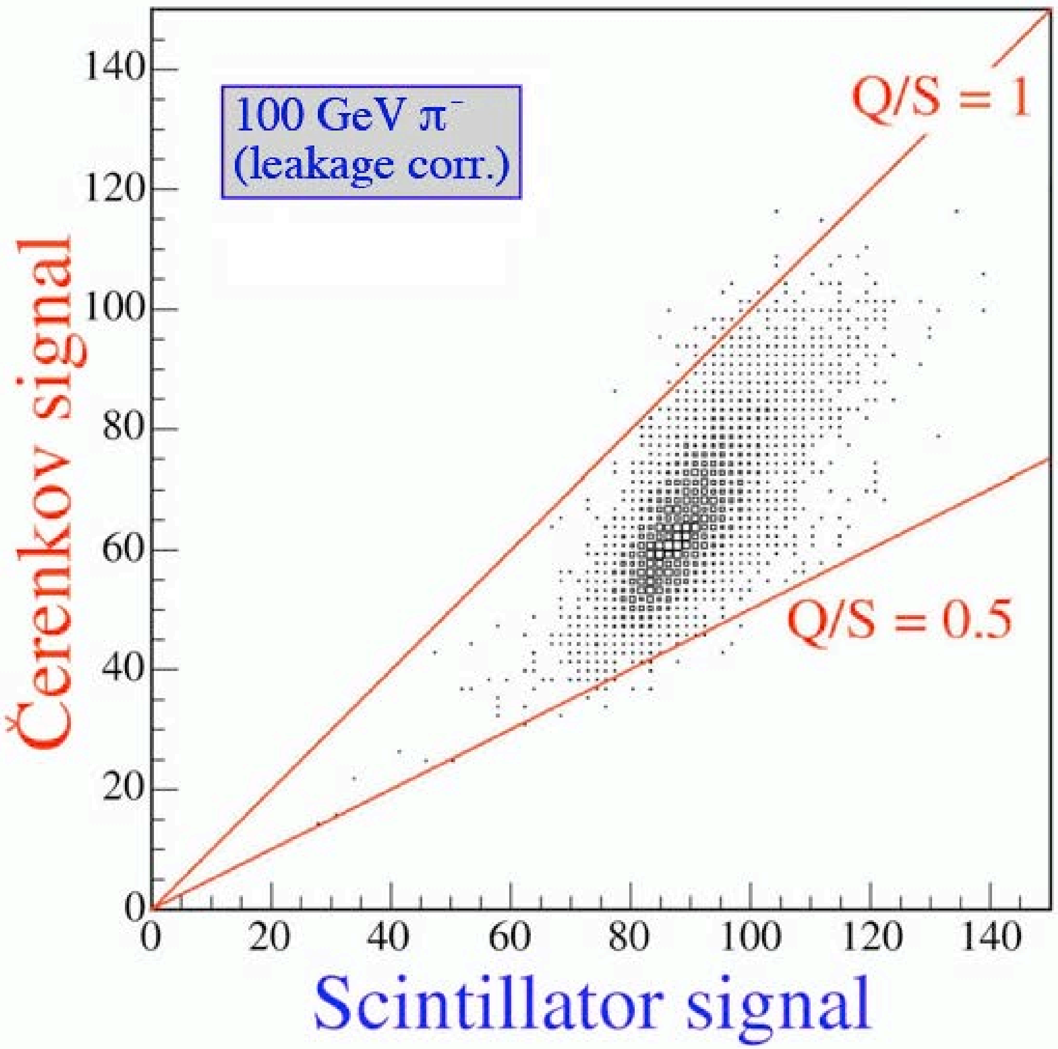
DREAM readout







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



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

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

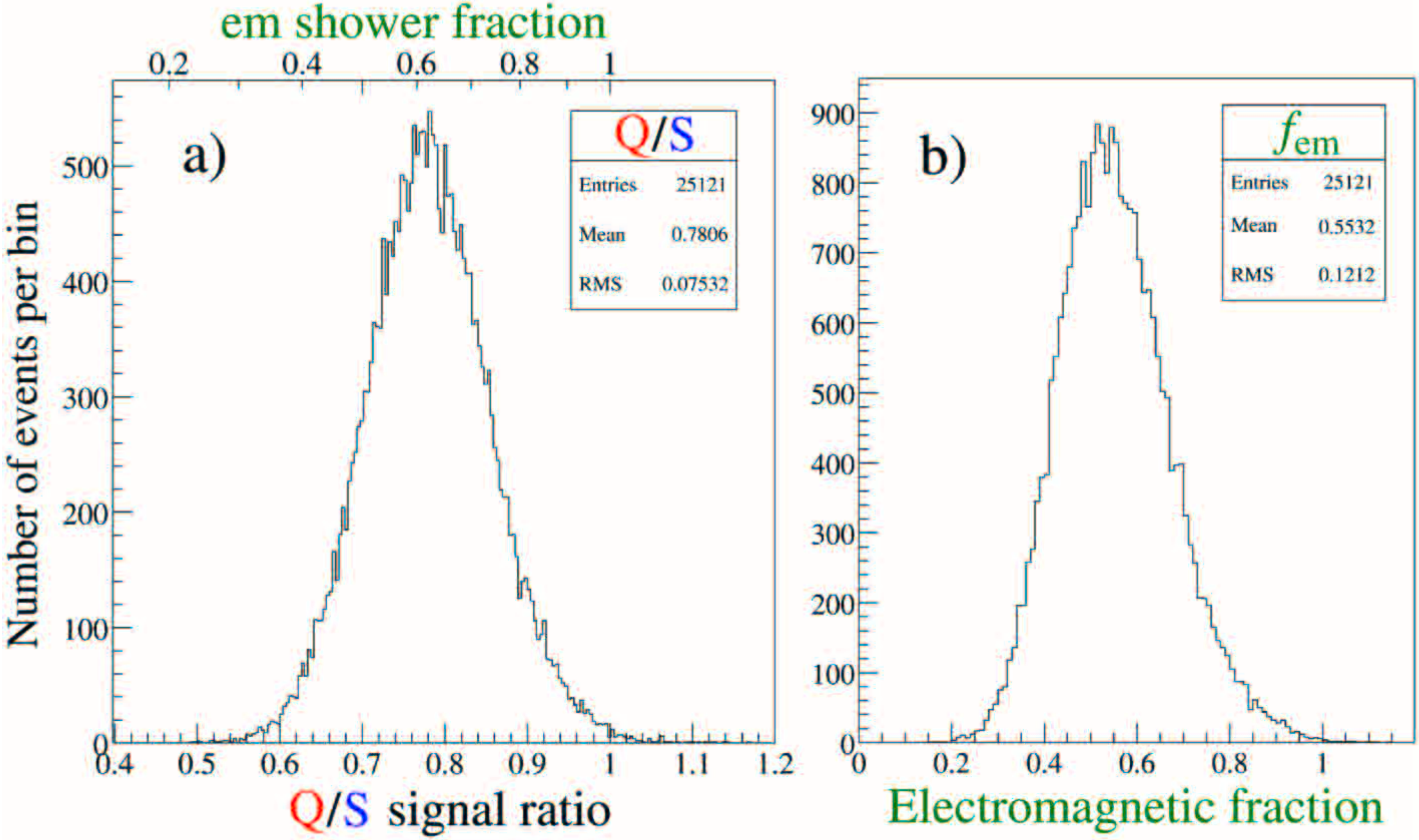
e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

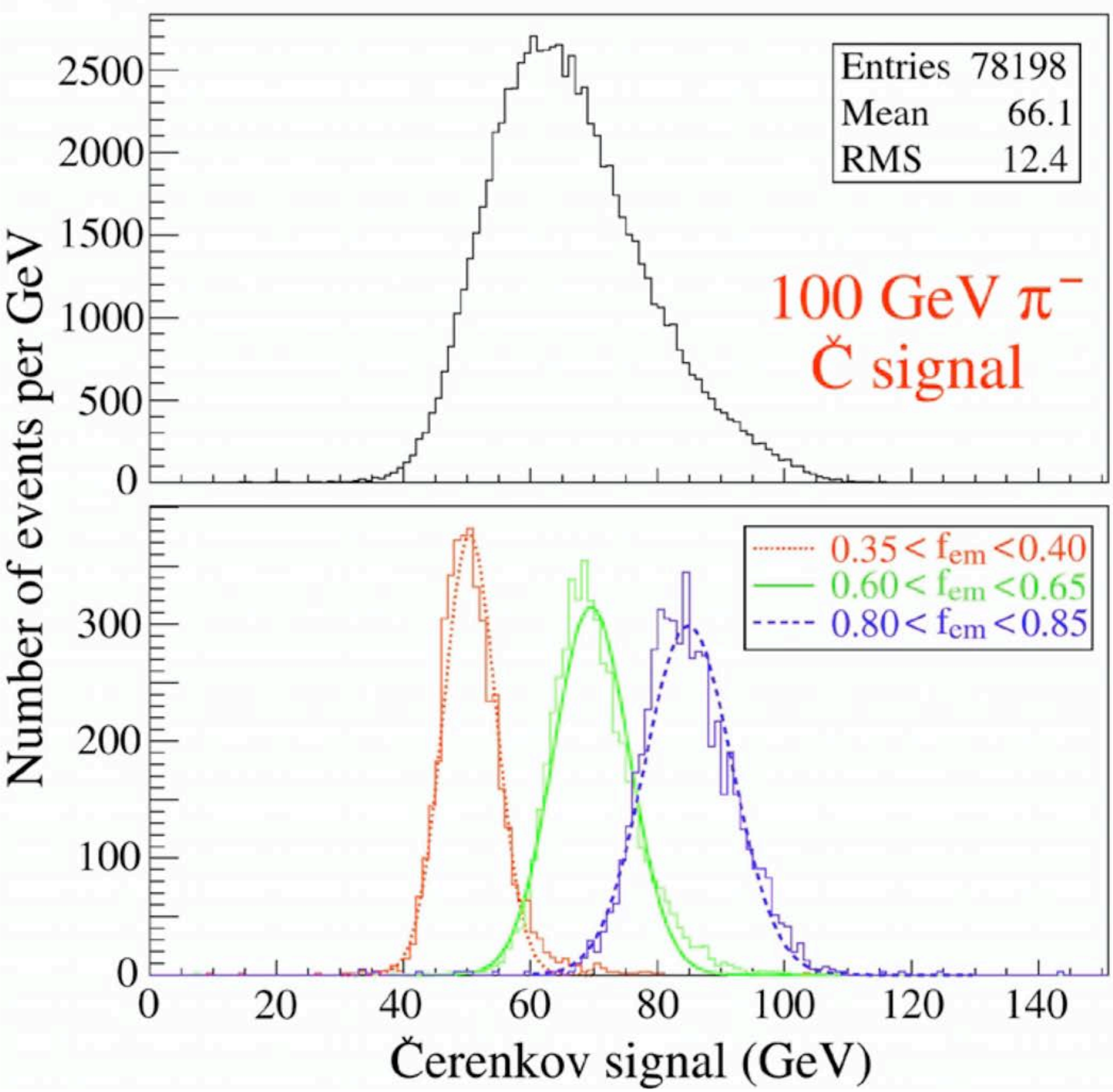
$$E = \frac{S - \chi Q}{1 - \chi}$$

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

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

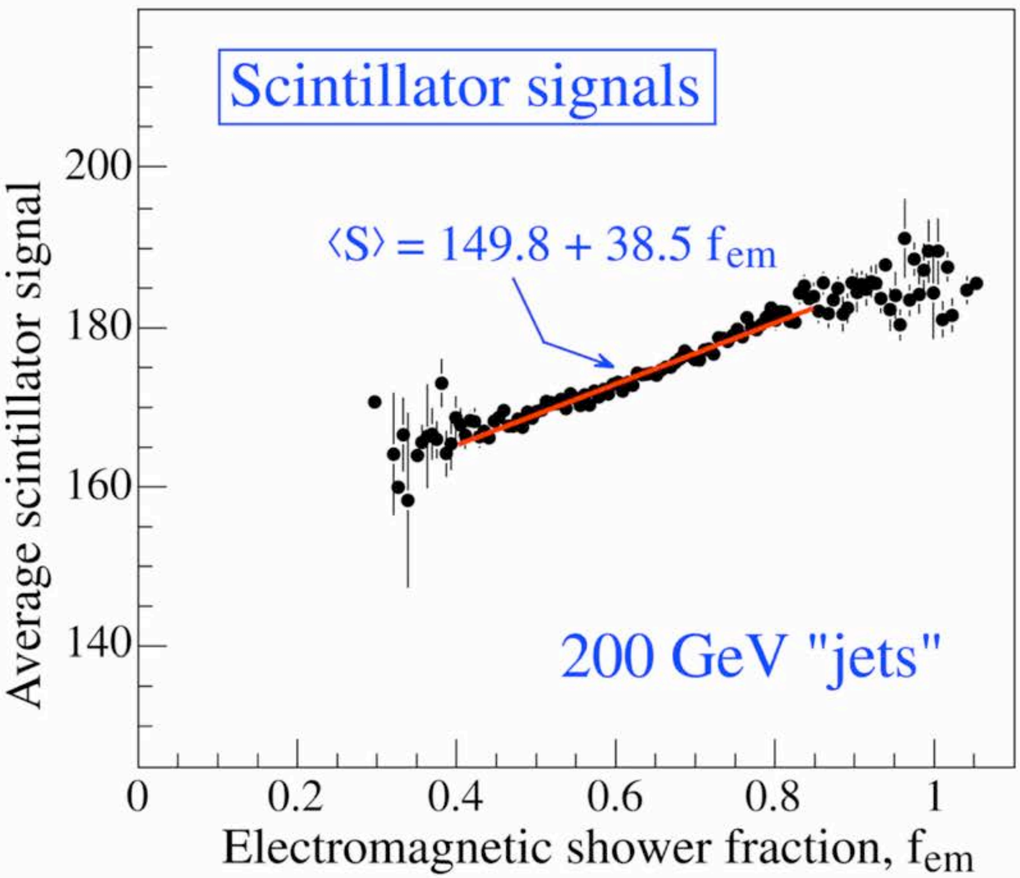


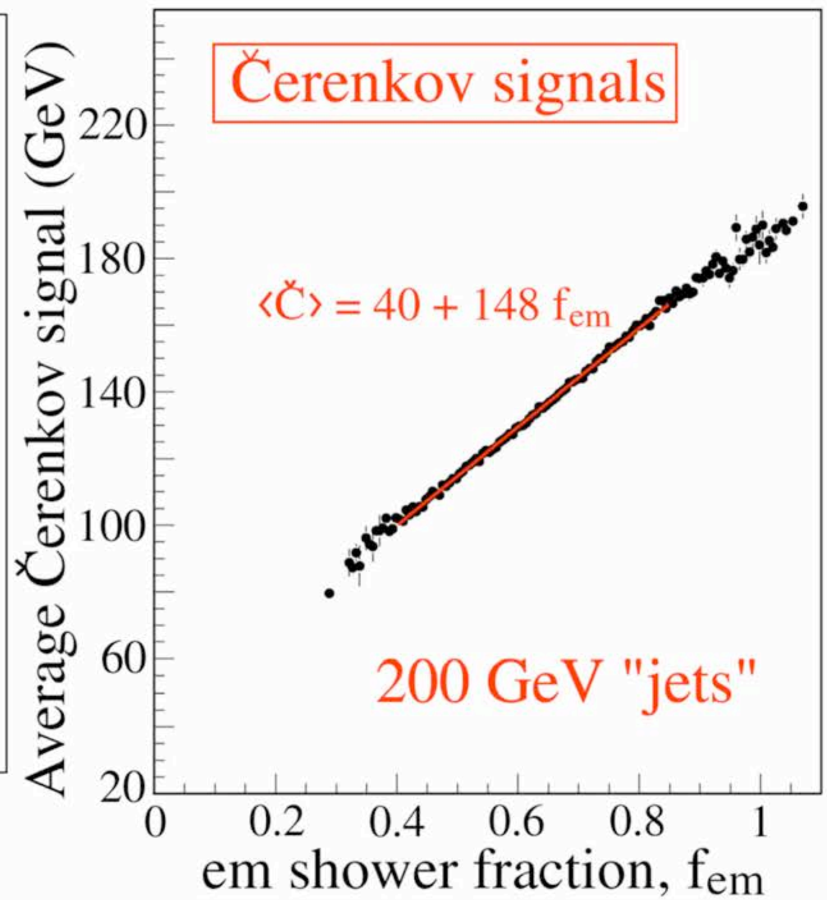
DREAM: Effect of event selection based on f_{em}



From:
NIM A537 (2005) 537

DREAM: Signal dependence on f_{em}



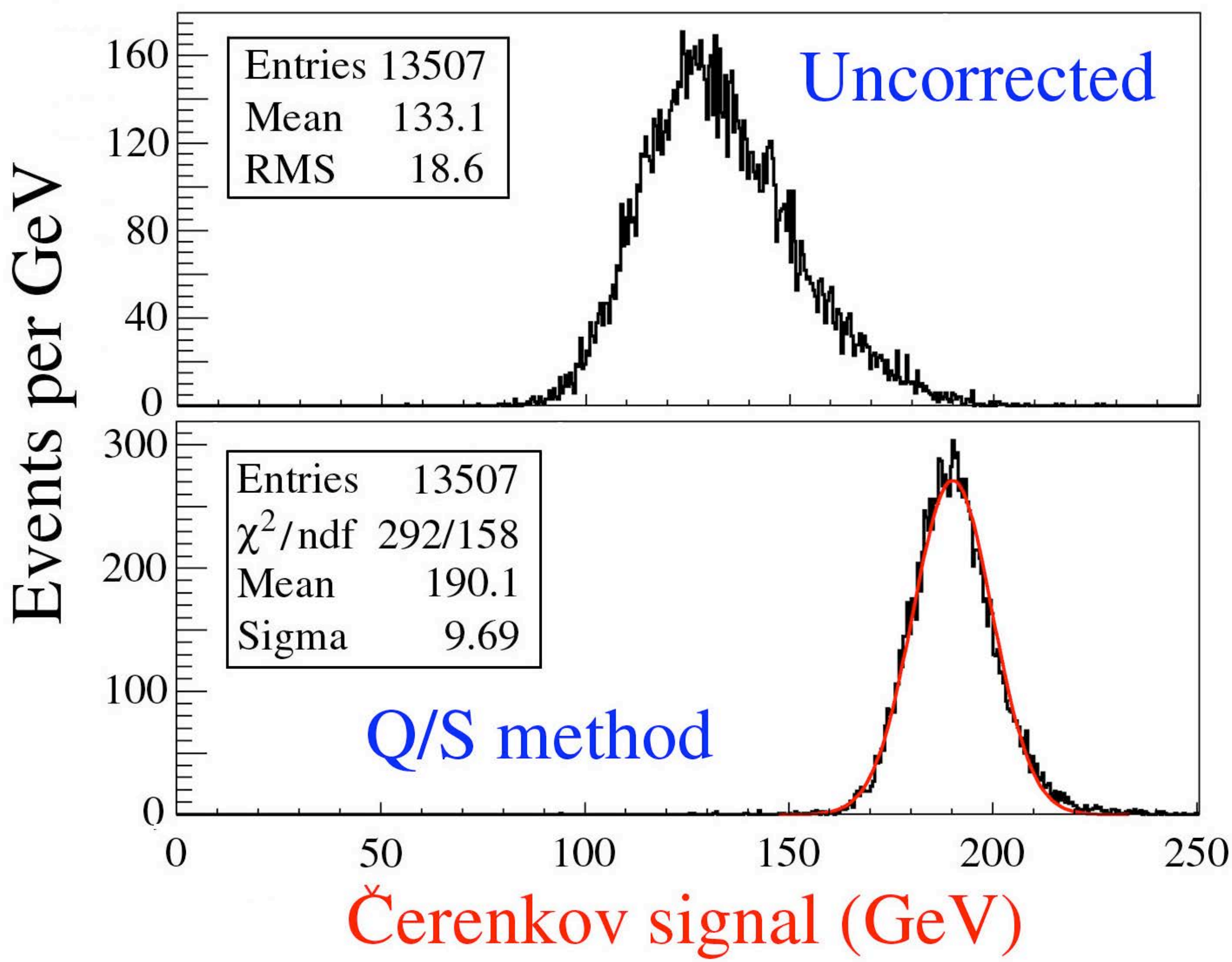


$$R(f_{\text{em}}) = p_0 + p_1 f_{\text{em}}$$ with $$\frac{p_1}{p_0} = e/h - 1$$

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

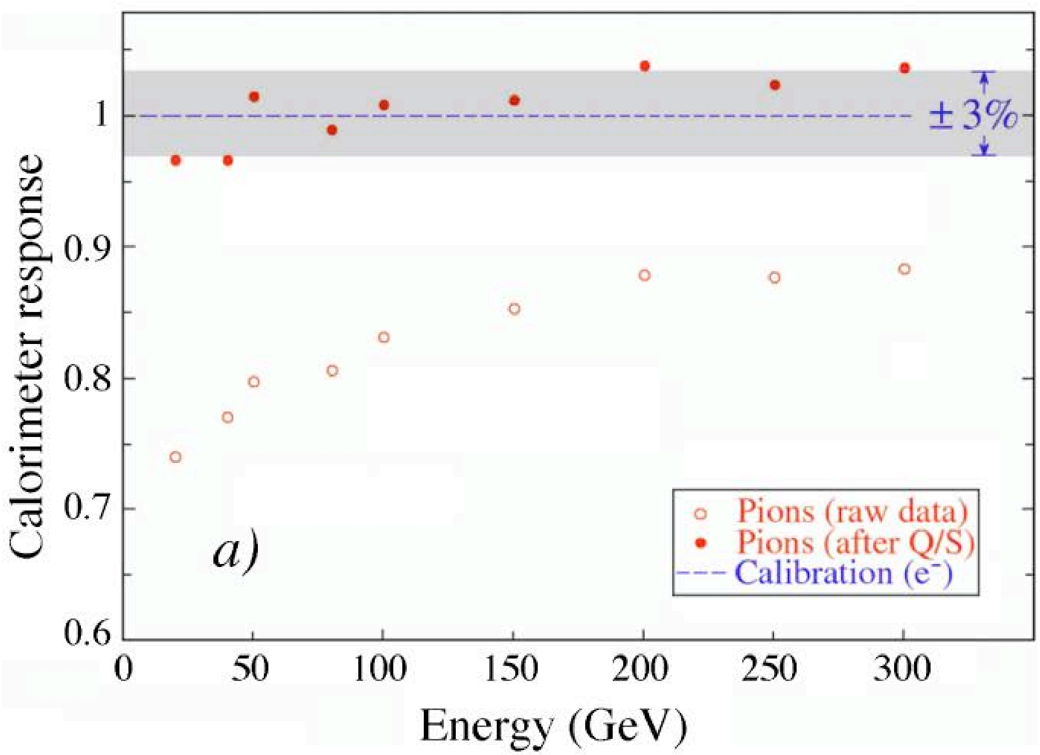
From:
NIM A537 (2005) 537

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



Effects of Q/S corrections on

hadronic signal linearity *and* *jet resolution*



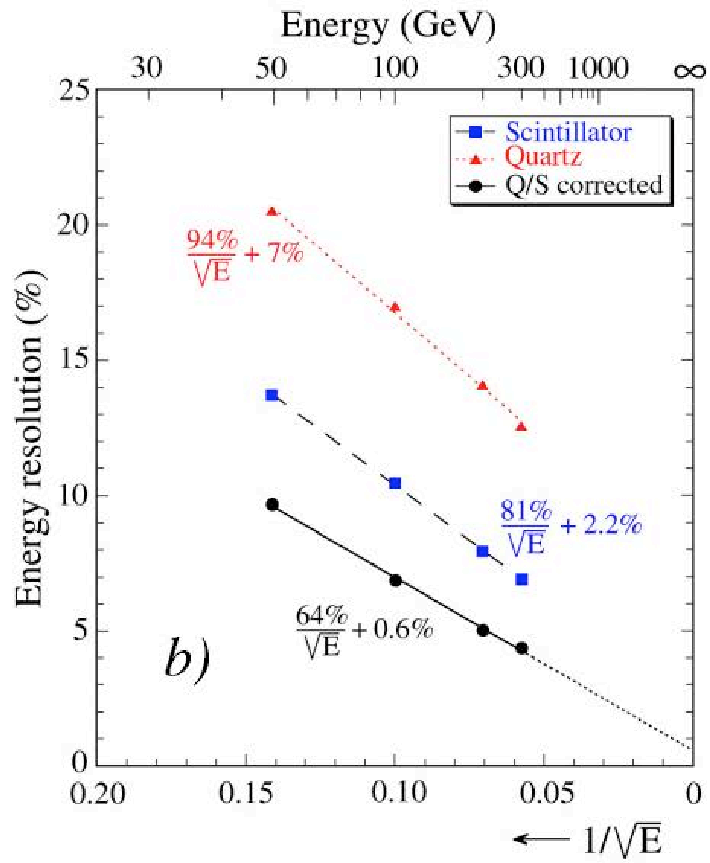


Figure 9: The scintillator response of the DREAM calorimeter to single pions (a) and the energy resolution for "jets" (b), before and after the dual-readout correction procedures were applied to the signals [5].

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

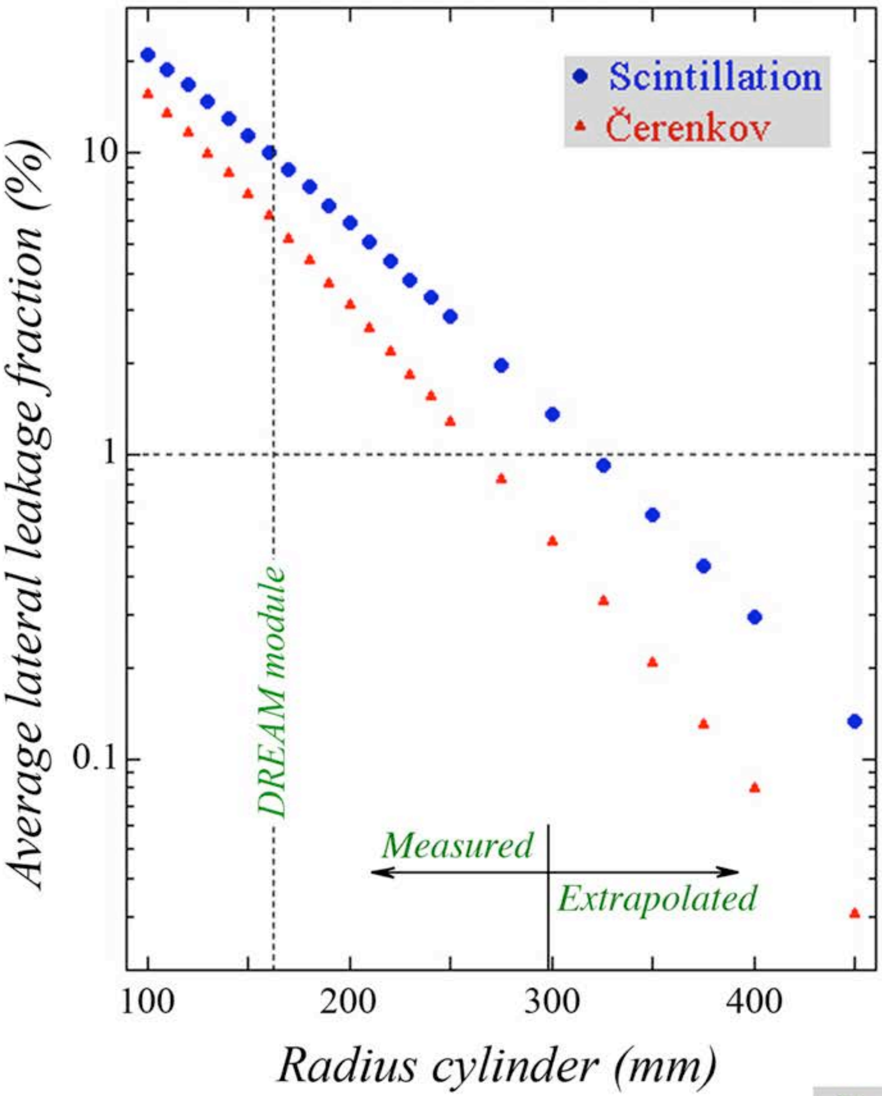
In other words:
The same advantages as intrinsically compensating calorimeters (e/h = 1)
WITHOUT the limitations (sampling fraction, integration volume, time)

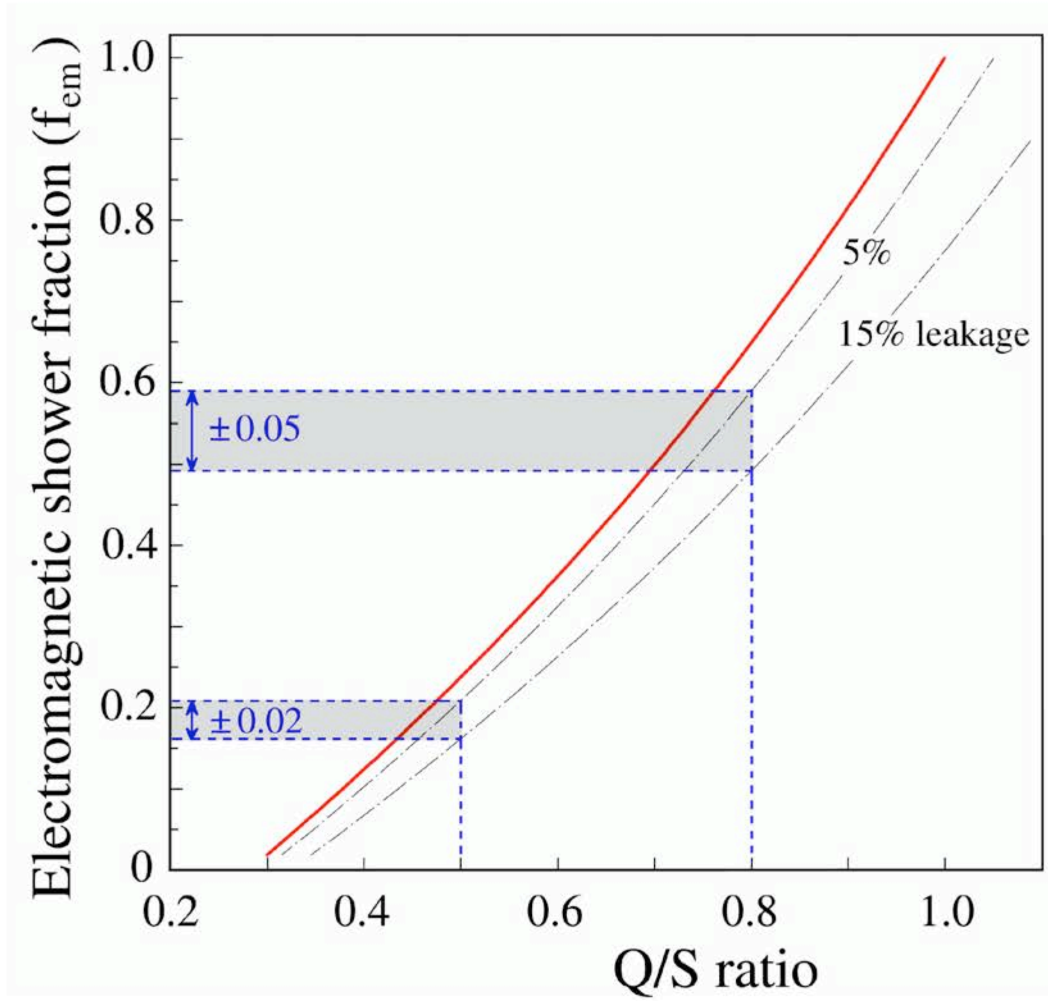
How to improve DREAM performance

- 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

Expected effect of full shower containment

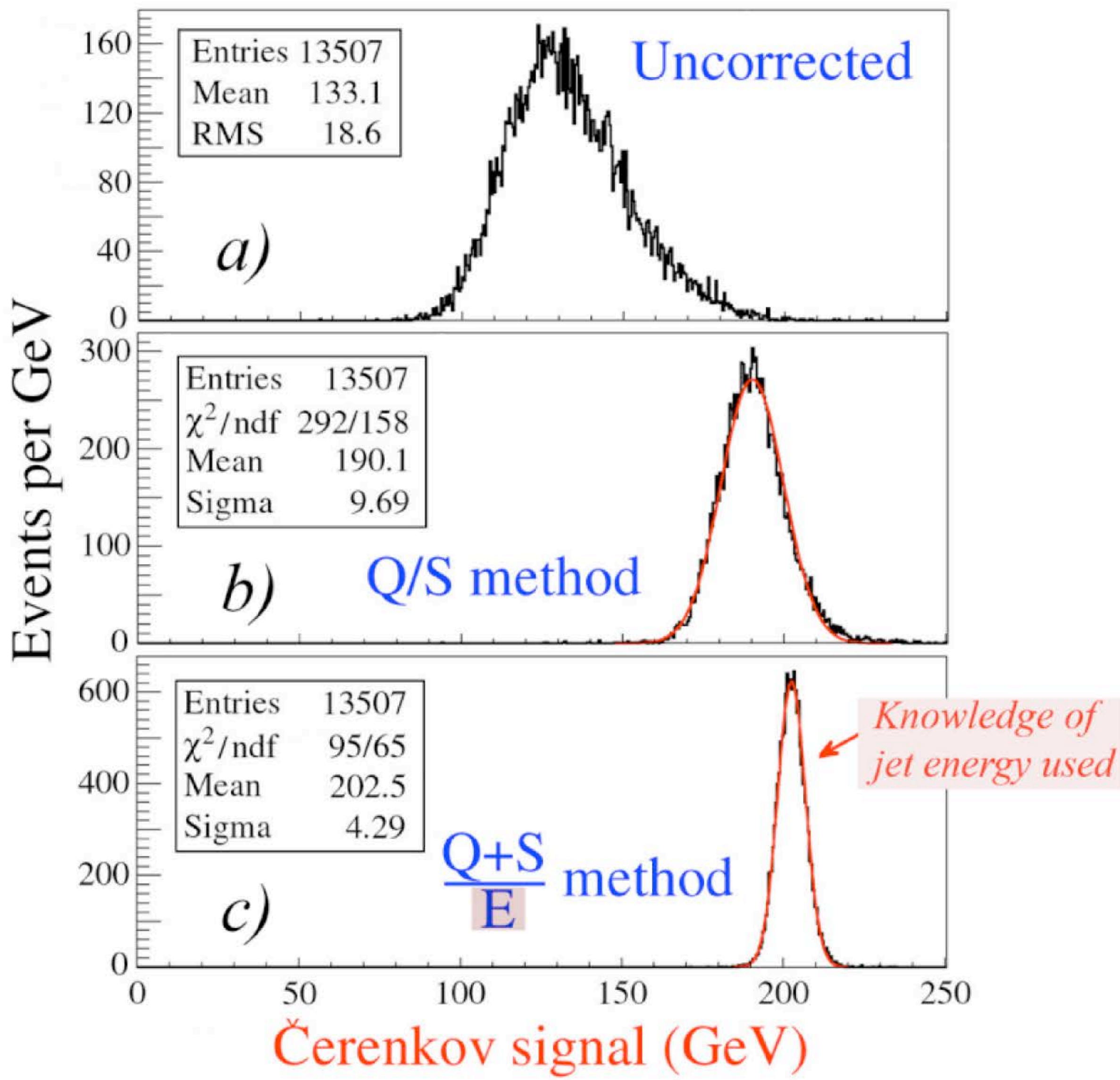


Figure 2: Čerenkov signal distributions for 200 GeV multi-particle events. Shown are the raw data (a), and the signal distributions obtained after application of the corrections based on the measured em shower content, with (c) or without (b) using knowledge about the total "jet" energy [5].

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

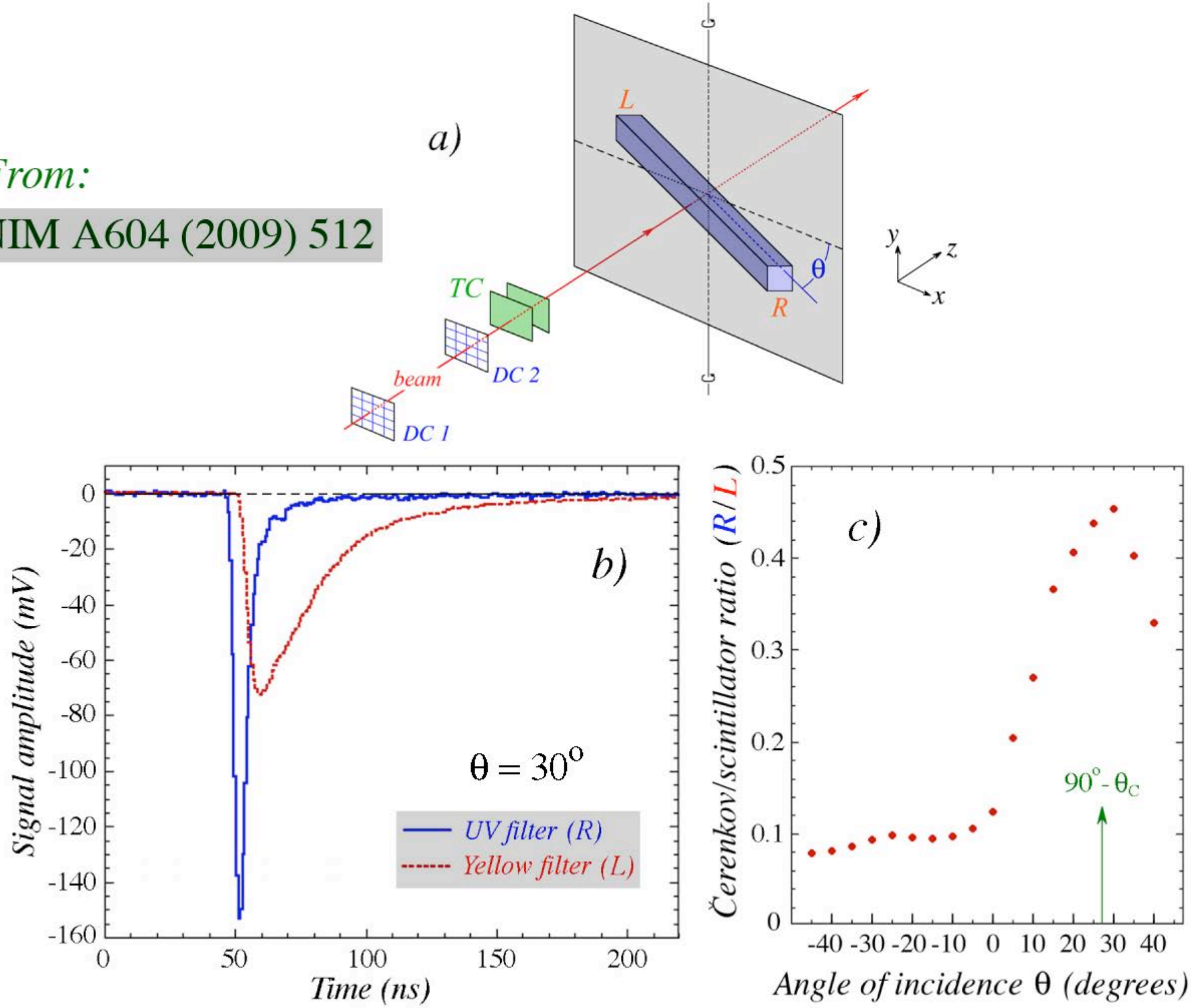
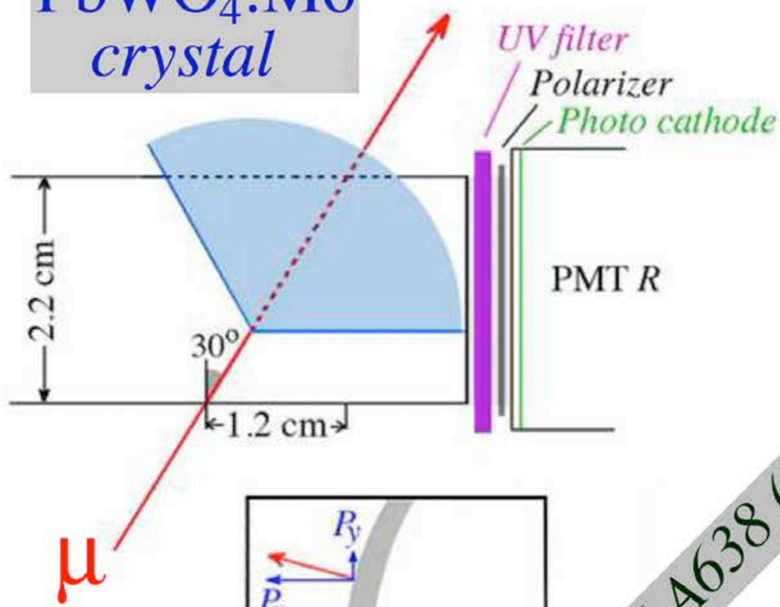


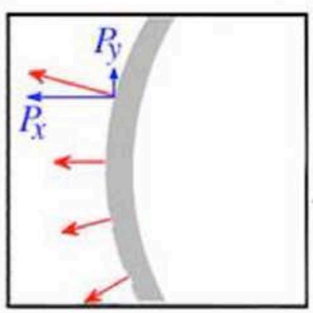
Figure 3: Unraveling of the signals from a Mo-doped $PbWO_4$ crystal into Čerenkov and scintillation components. The experimental setup is shown in diagram a. The two sides of the crystal were equipped with a UV filter (side R) and a yellow filter (side L), respectively. The signals from 50 GeV electrons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

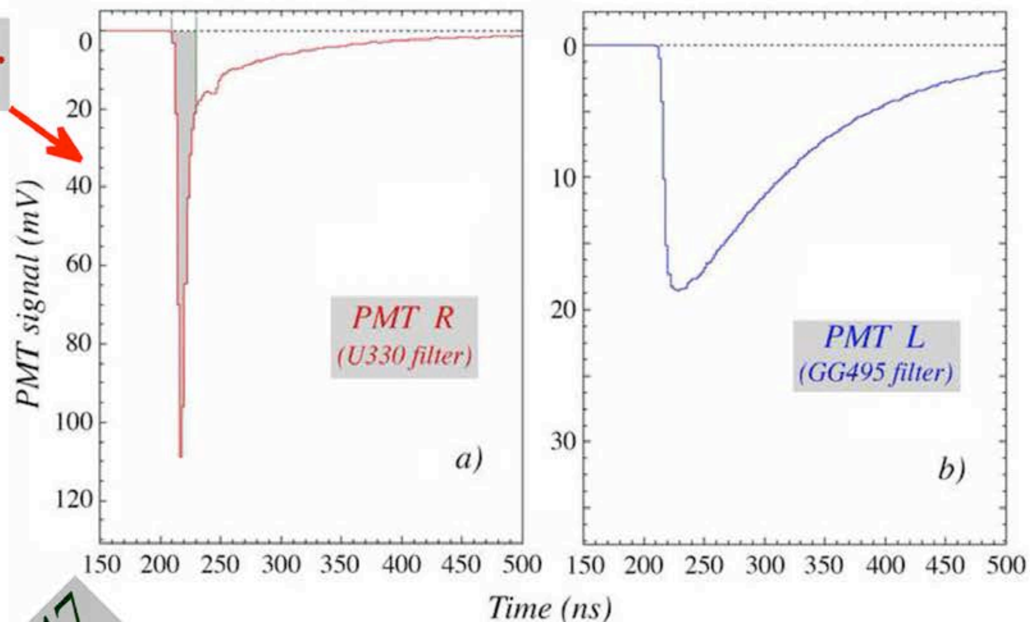
Separating the Čerenkov and scintillation components

Effects of the colored filter

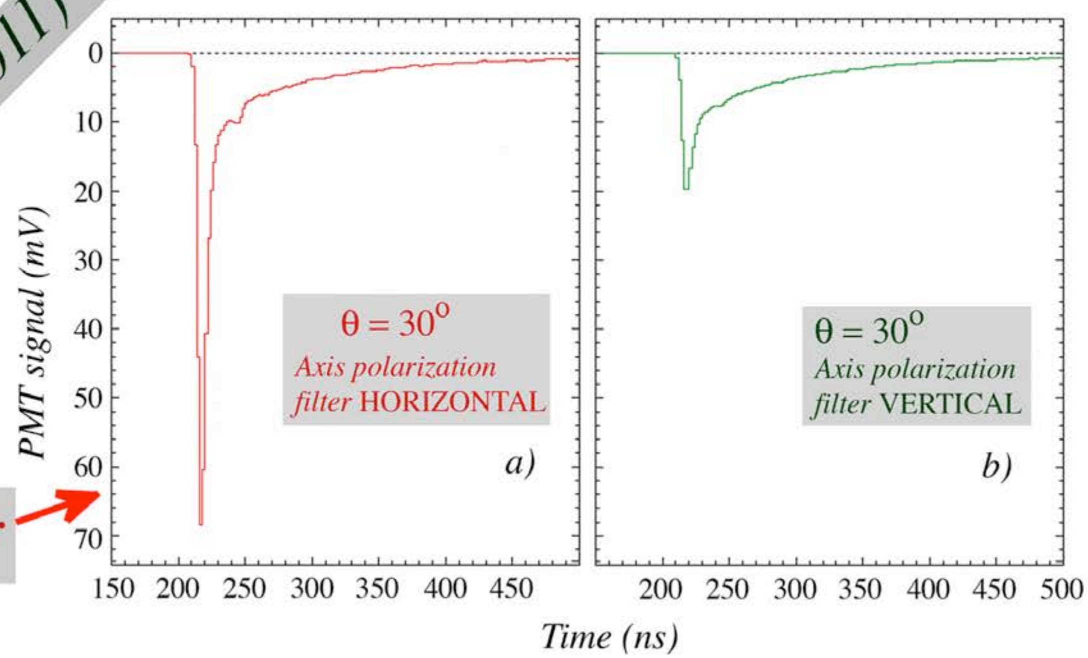
$PbWO_4$:Mo
crystal





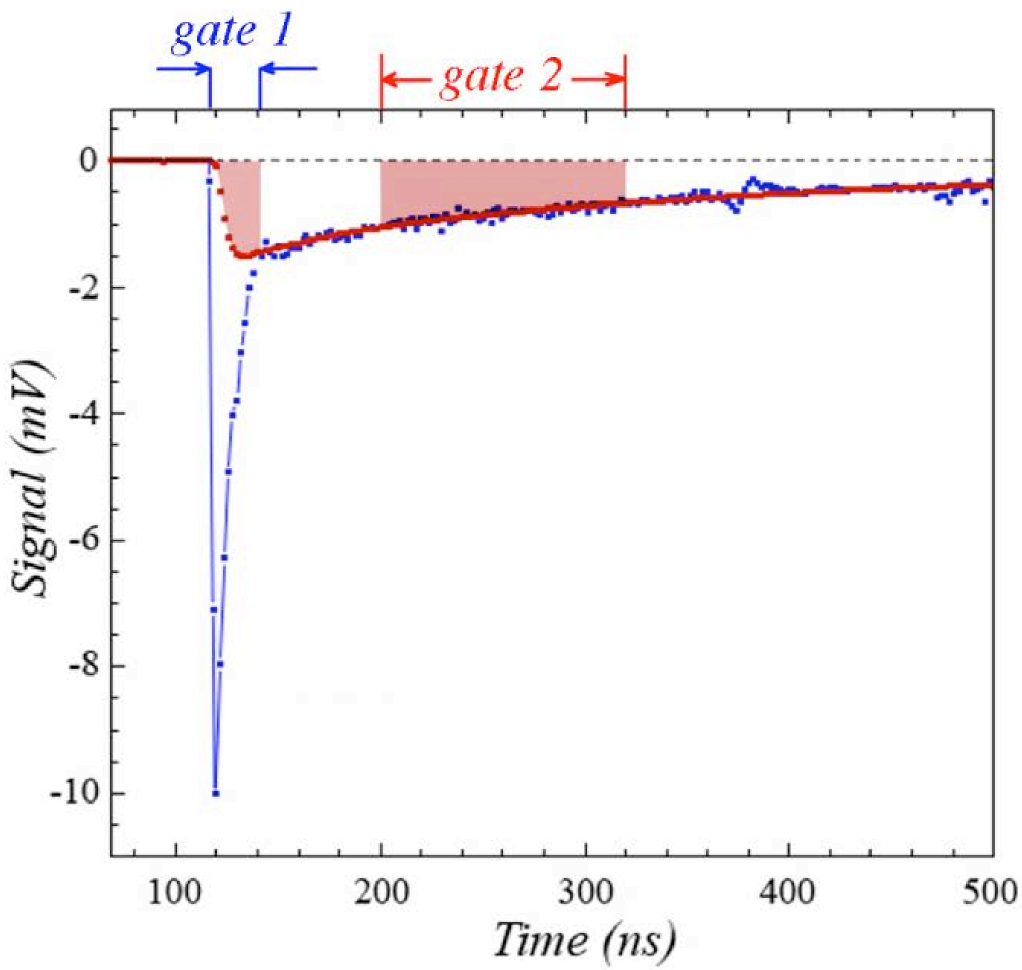


NIM A638 (2011) 47



Effects of the polarization filter

Čerenkov and Scintillator information from one signal !

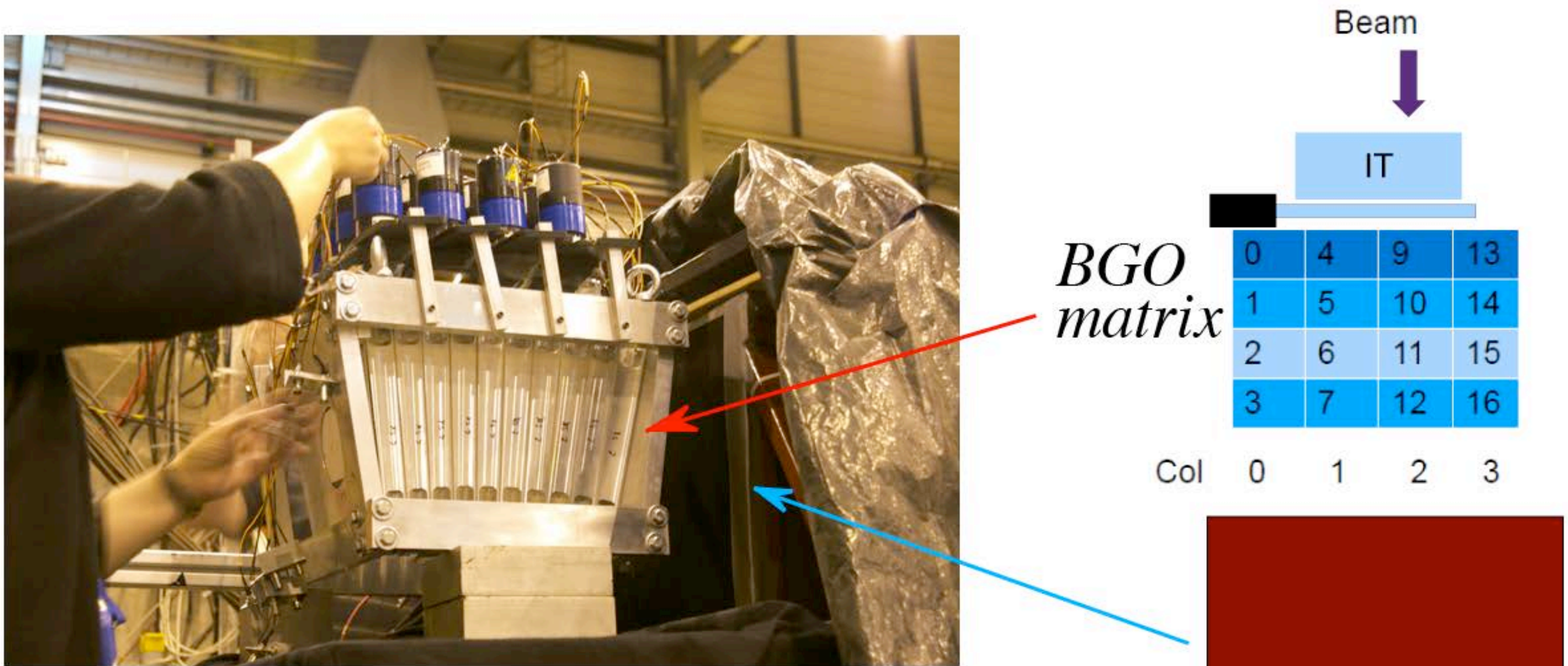


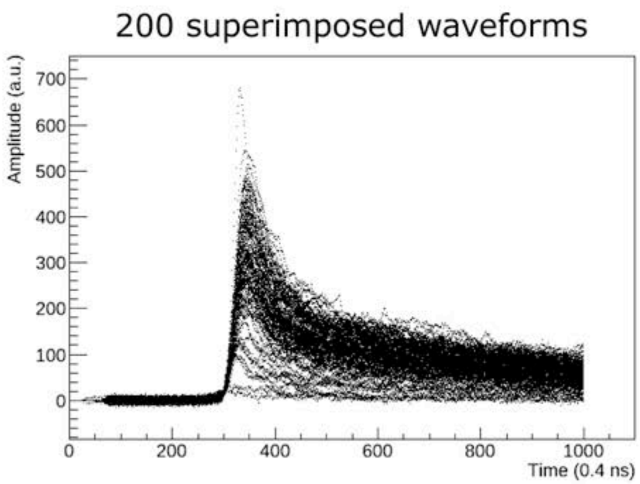
BGO crystal
UG 11 (UV) filter

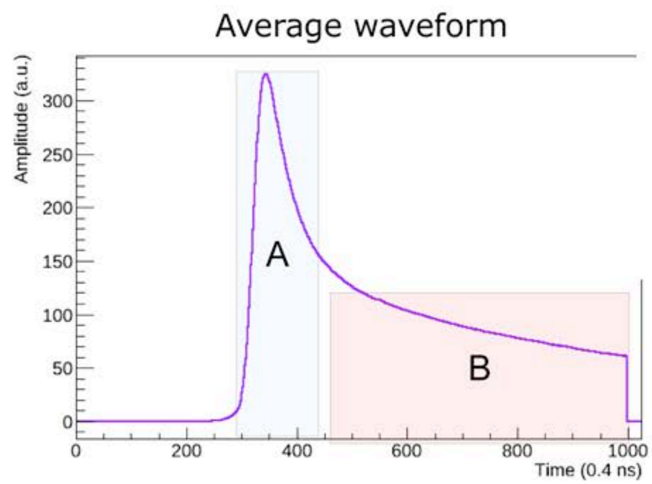
From:
NIM A595 (2008) 359

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)

Beam tests of em dual-readout BGO matrix



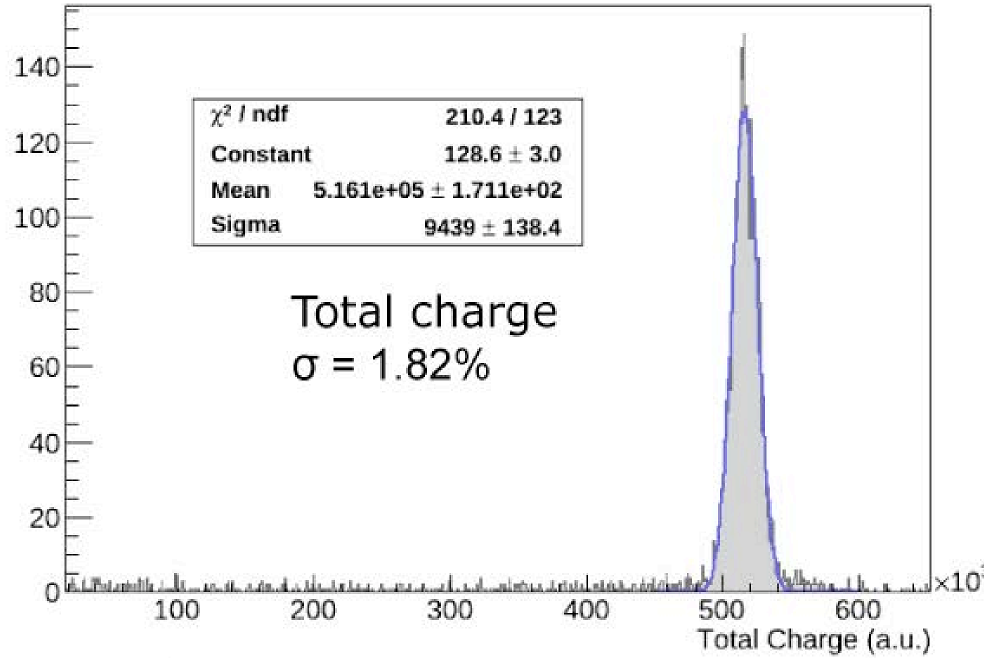


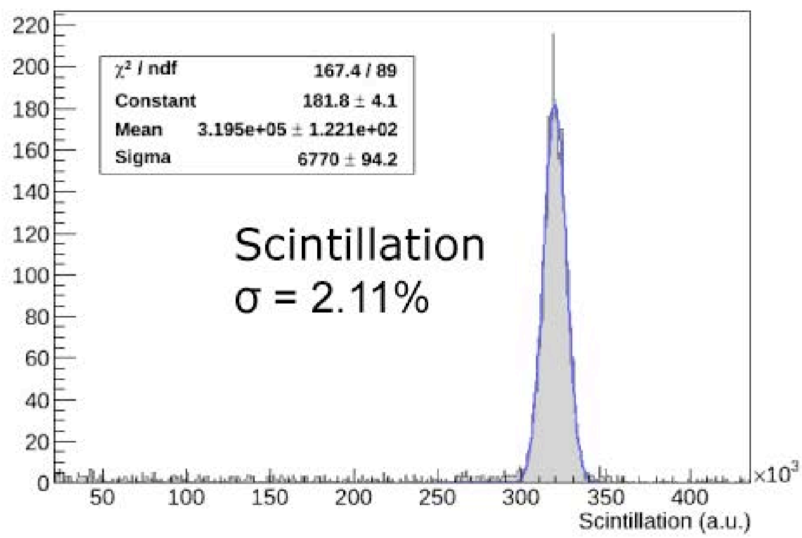


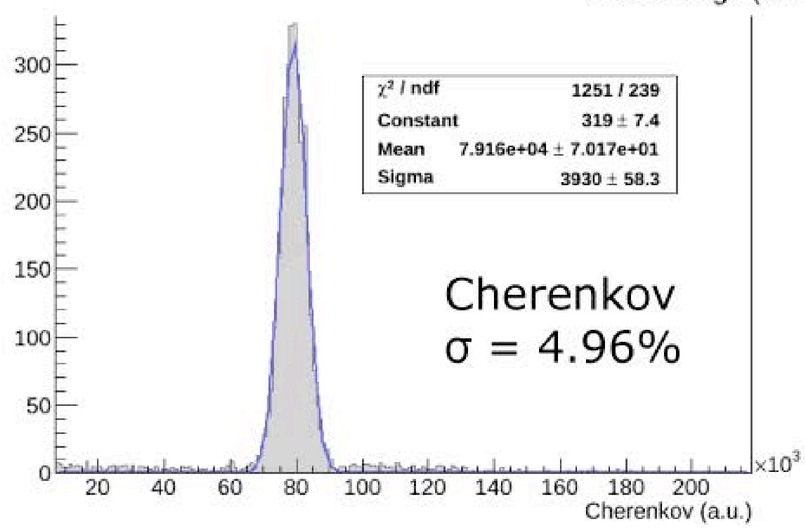
- The waveform is numerically integrated in two gates;
- S and C is evaluated from the two integrals as
  S = B; C = A − 0.35 x B;

Dual-Readout BGO calorimeter: Resolution for 100 GeV electrons

Signals decomposed into Scintillating and Čerenkov components on the basis of their time structure

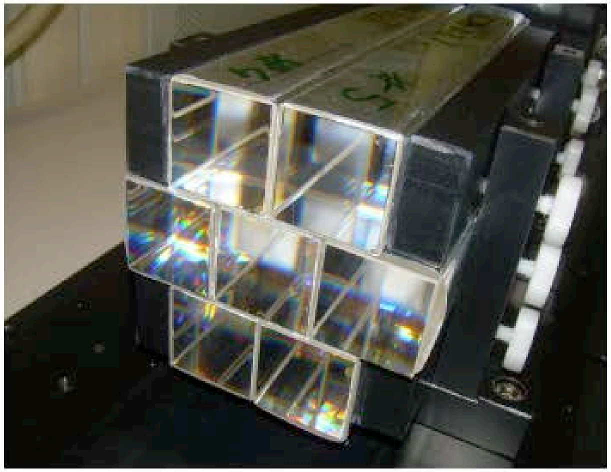




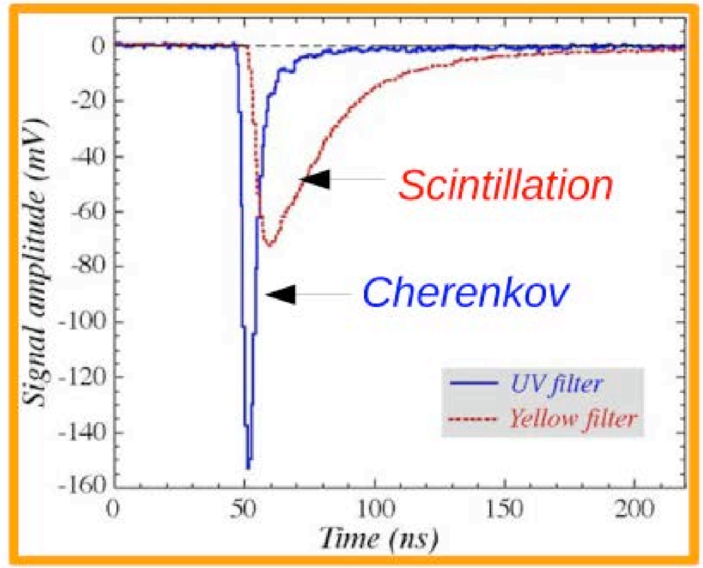


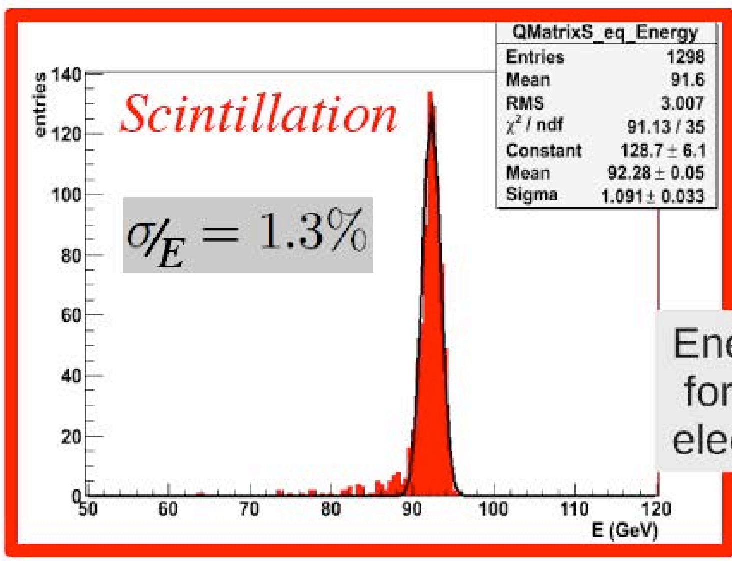
D. Pinci, IEEE, Valencia 2011

Dual-readout crystal calorimetry
S/C signal separation with filters

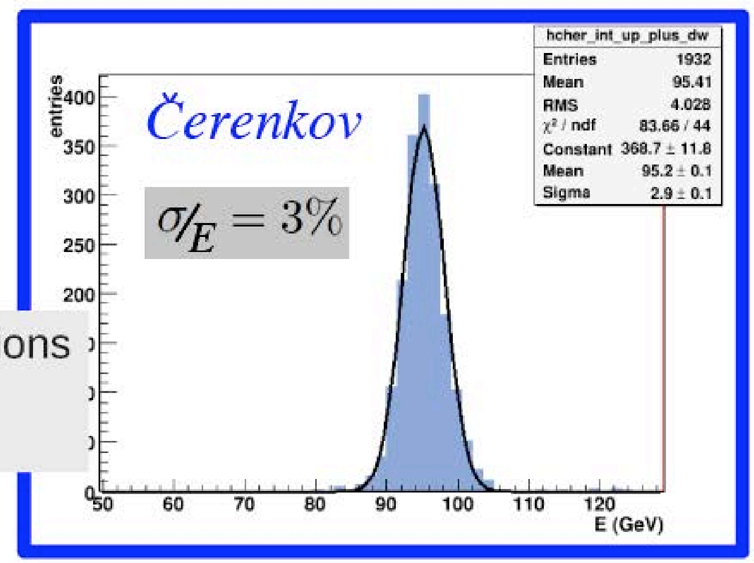


Mo-doped $PbWO_4$ crystal matrix
7 crystals, 3 x 3 x 20 cm^3





Energy distributions for 100 GeV electron beam



S. Franchino, IEEE, Valencia 2011

How to improve DREAM performance

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

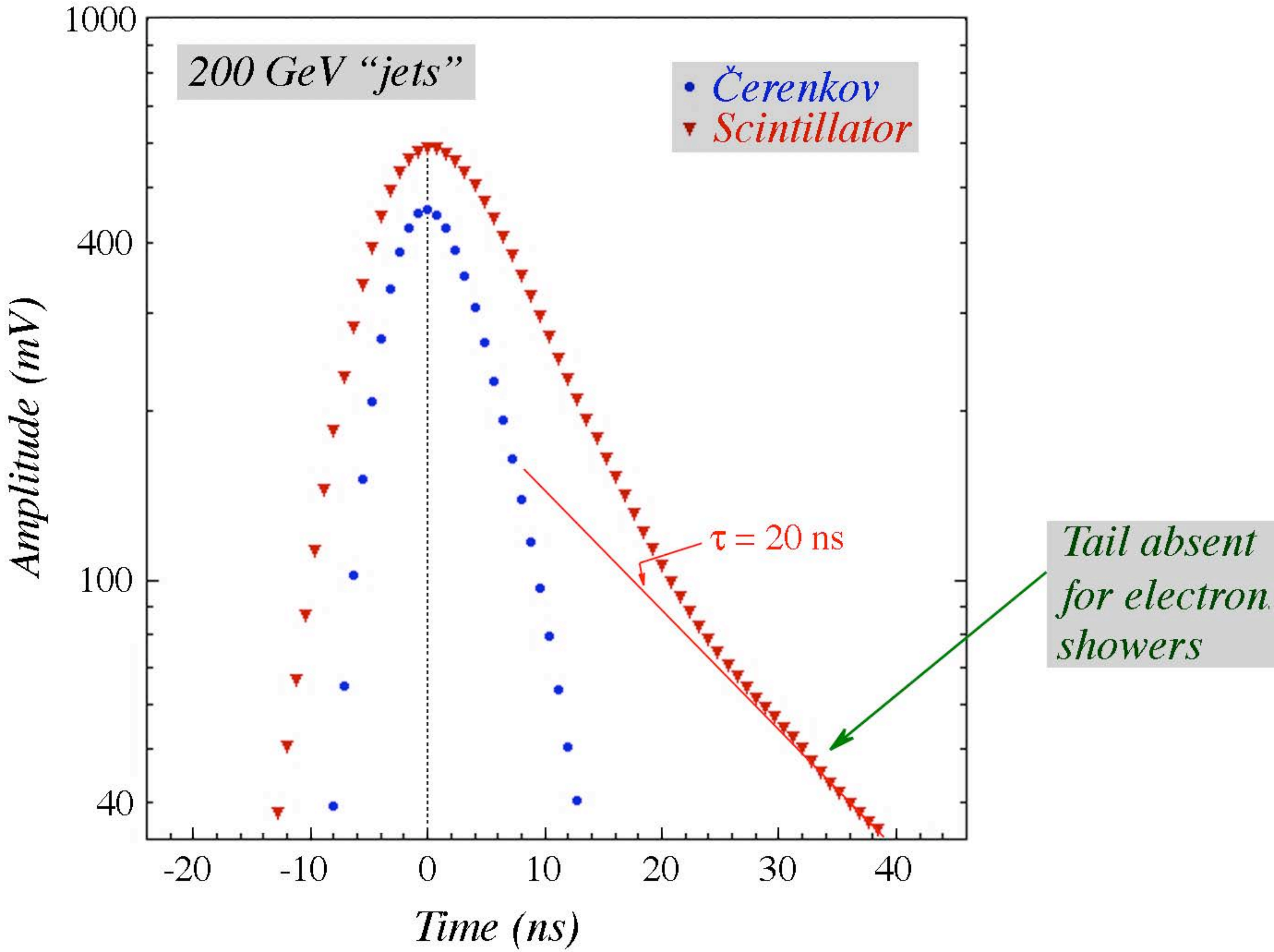
- *Increase Čerenkov light yield*
  DREAM: 8 p.e./GeV ⟶ fluctuations contribute 35%/$\sqrt{E}$

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

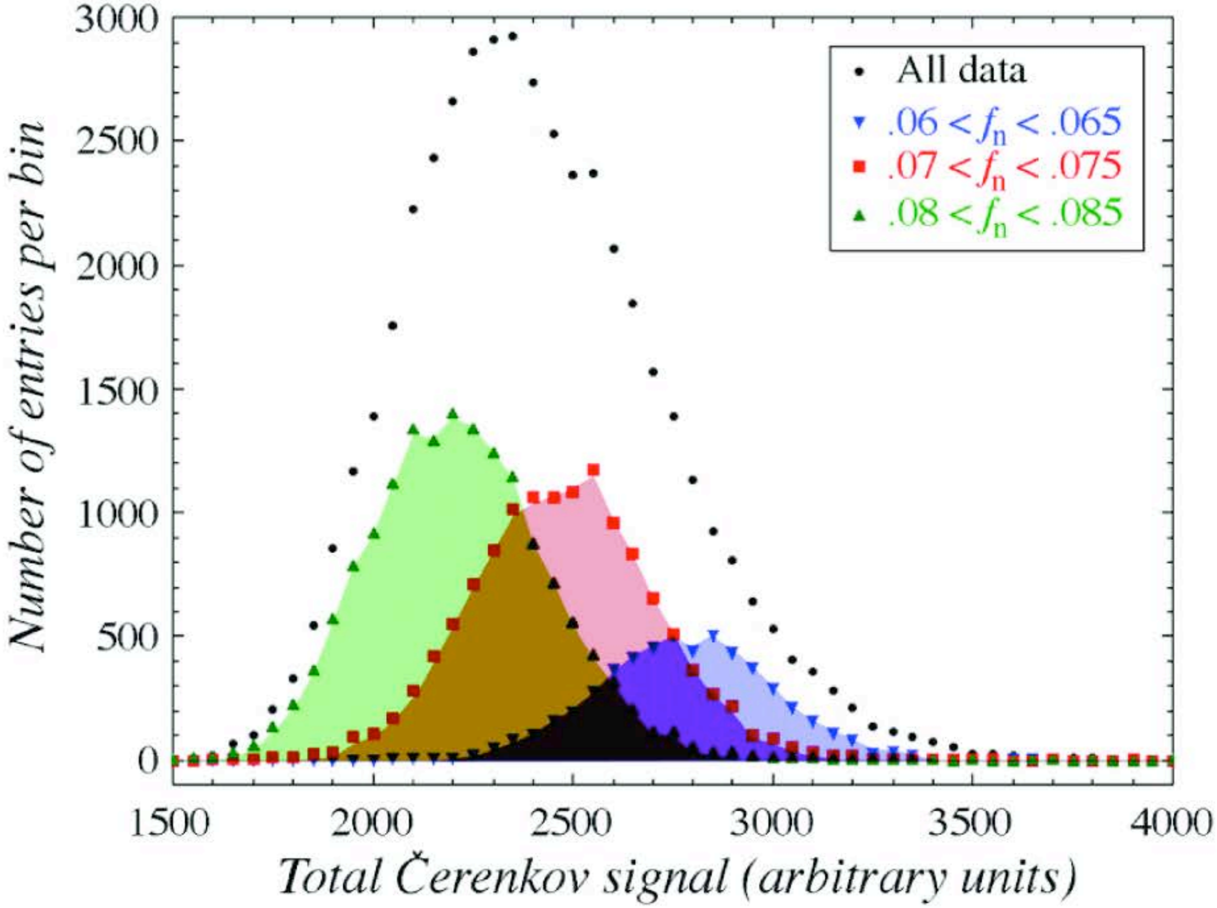
- For ultimate hadron calorimetry (15%/$\sqrt{E}$): *Measure E_{kin} (neutrons)*
  Is correlated to nuclear binding energy loss (invisible energy)

Can be inferred from the time structure of the signals

Time structure of the DREAM signals: the neutron tail



Probing the total signal distribution with the neutron fraction

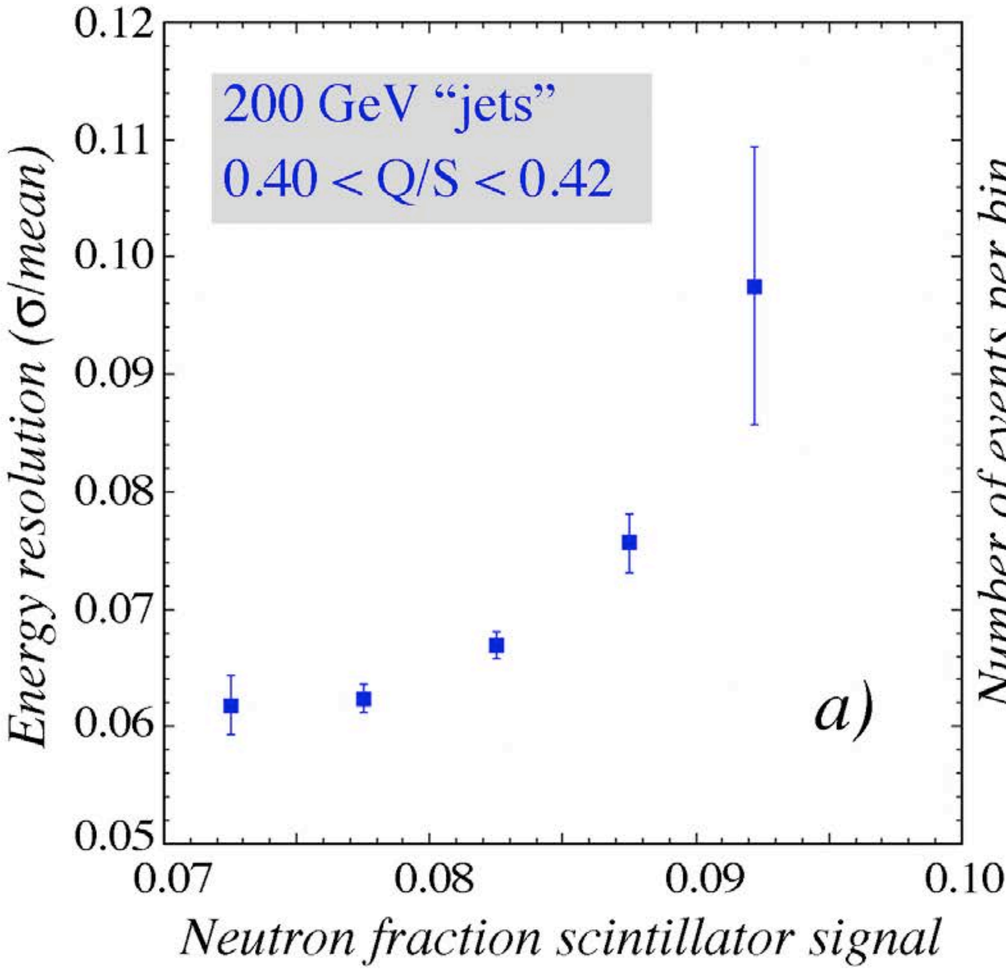


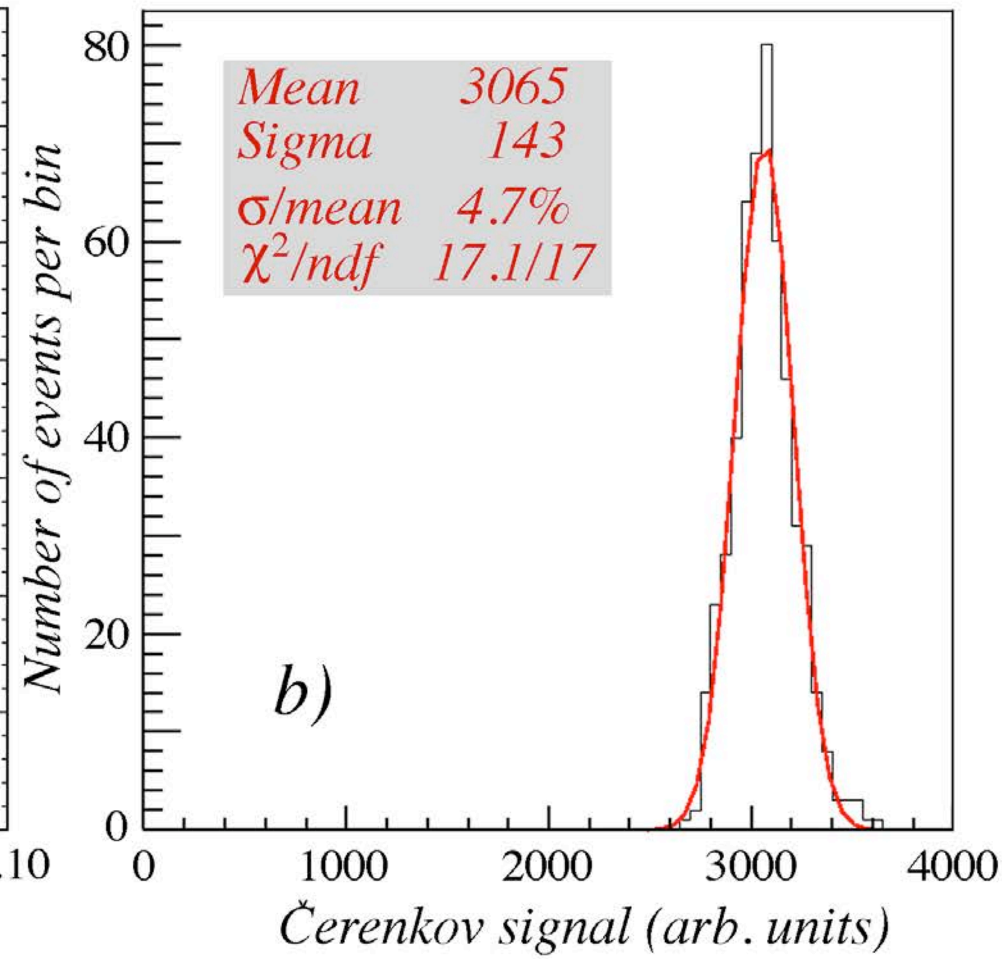
From:

NIM A598 (2009) 422

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 .

Neutron information is complementary to f_{em}





The follow-up: RD52

> 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

- Concentrate on fiber calorimetry.
  - *Shower containment >99% , i.e. mass ~ 5 tonnes*
    → *effects of leakage fluctuations negligible*
  - *Preferably copper absorber*

- Other design criteria:
  - *Čerenkov light yield in fiber detector > 100 p.e./GeV (em)*
  - *Sampling fluctuations fiber detector < 10%/√E (em)*
  - *Depth measurement of shower maximum for each event (attenuation!)*
  - *Time structure measured for every signal*

Fiber calorimeters vs crystals

Advantages crystals:

- No sampling fluctuations
- Some calibration problems characteristic for sampling calorimeters don't play a role

Disadvantages crystals:

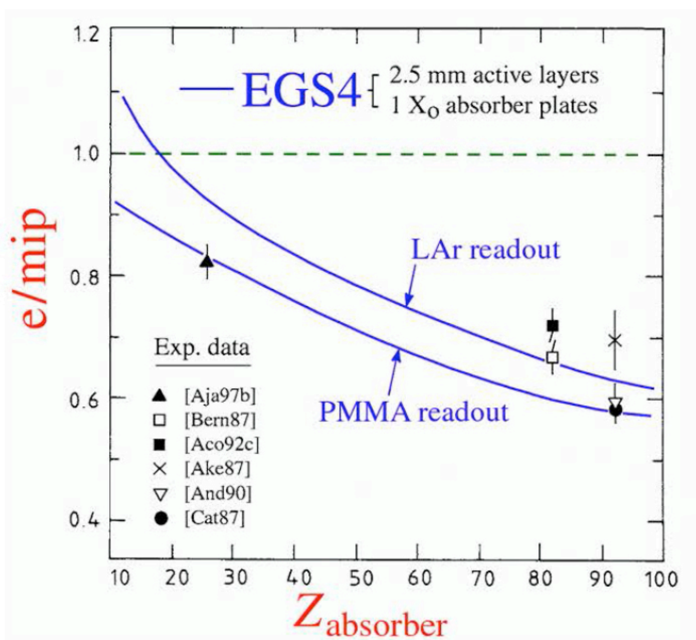
- No sensitivity to neutrons, and thus to invisible energy fluctuations
- Light attenuation (also very important!)
- Readout
- COST

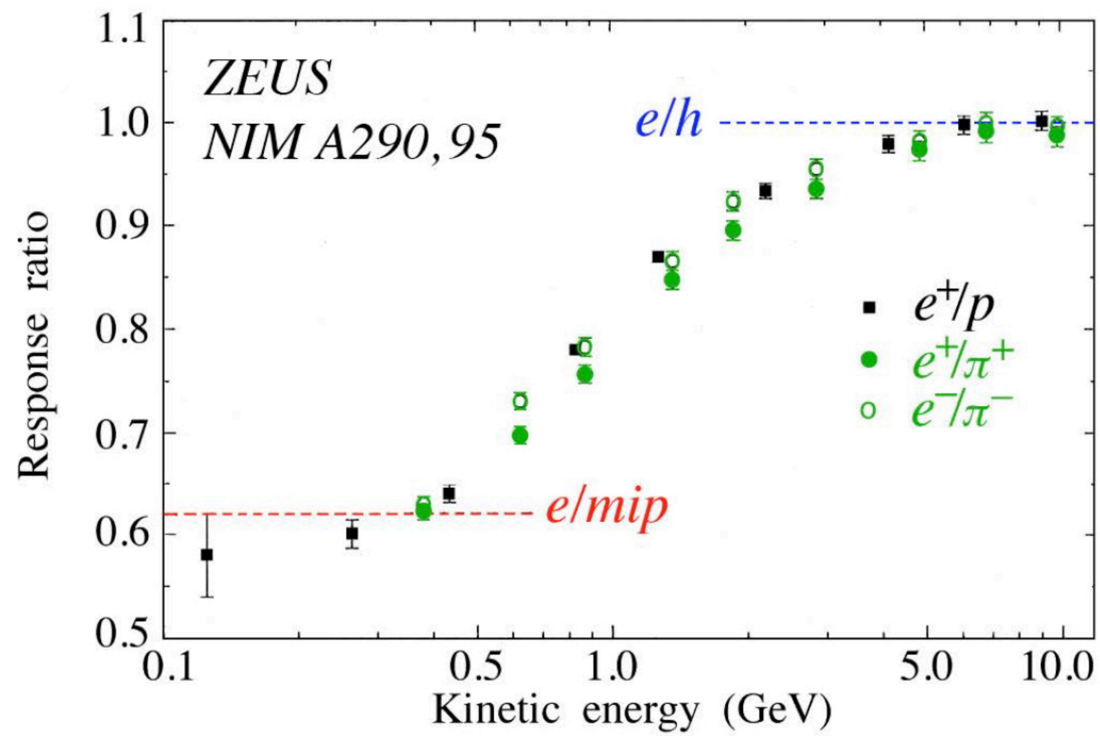
Absorber choice: Cu vs Pb

- *Detector mass:* $\lambda_{Cu} = 15.1\ cm$, $\lambda_{Pb} = 17.0\ cm$
  Mass $1\lambda^3$ *: Cu/Pb = 0.35 , mass detector Cu/Pb = 0.56*

- *e/mip* ⟶ *Čerenkov light yield Cu/Pb ~ 1.4*
  (Showers inefficiently sampled in calorimeters with high-Z absorber)

- *Non-linearity at low energy in calorimeters with high-Z absorber*
  Important for jet detection





Time structure signals

Fiber calorimeter: needed for

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

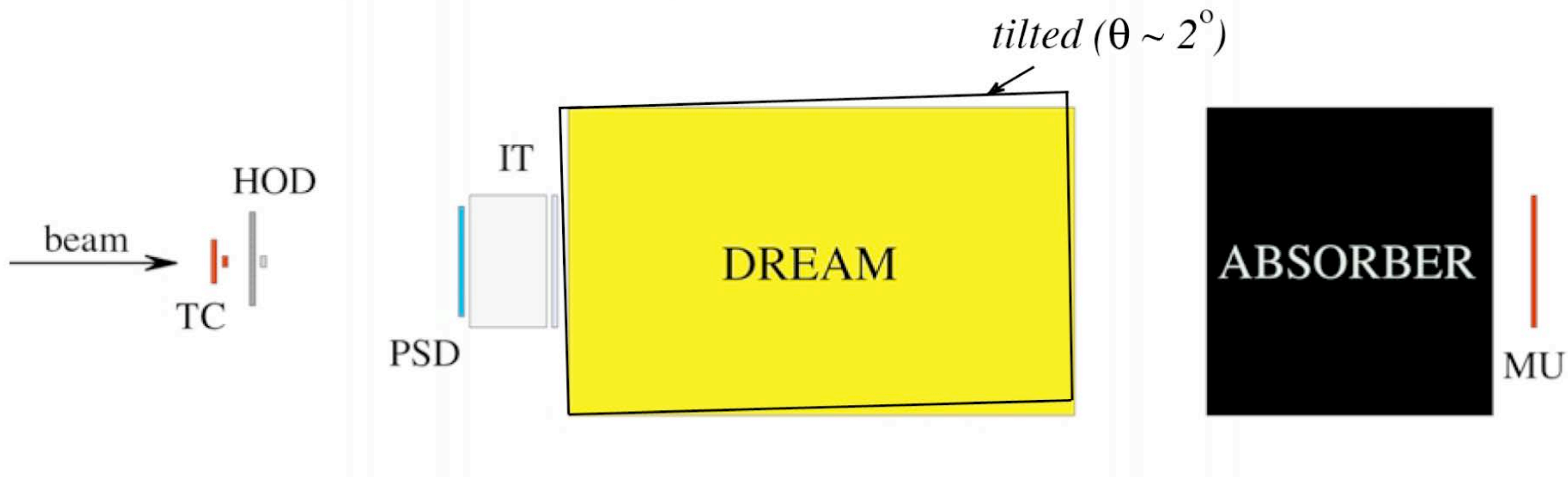
Crystals: needed to separate C and S signals

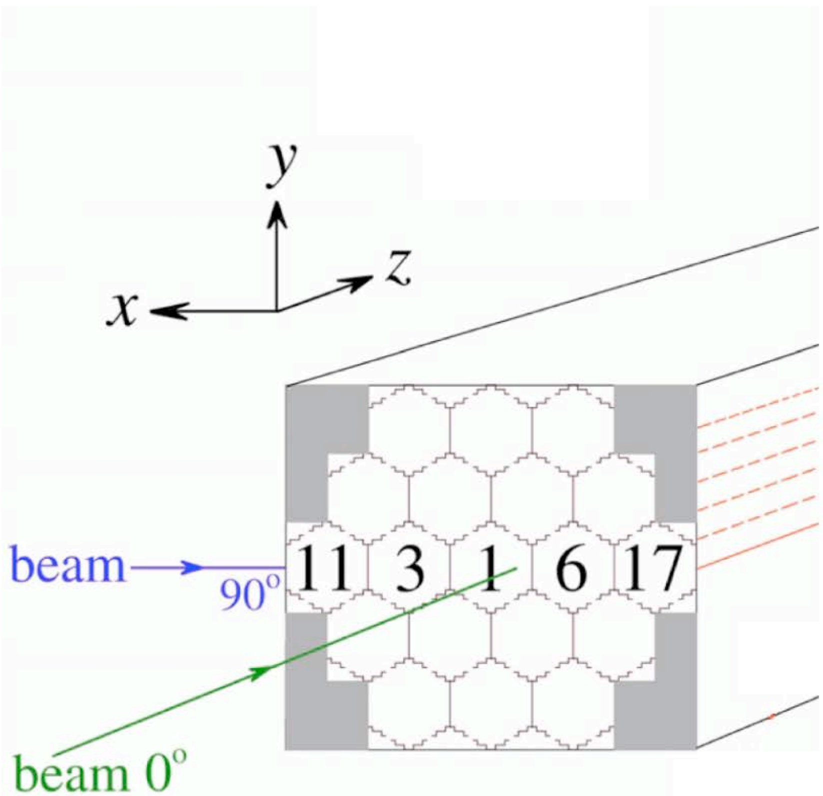
*We use a data acquisition system based on the DRS chip**
(Domino Ring Sampler) developed at PSI.
An array of 1024 switching capacitors samples the input signal,
at a frequency of 5 GHz (DRS-IV).
Read out by pipeline 12-bit ADC.

* *See* NIM A518 (2004) 407

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

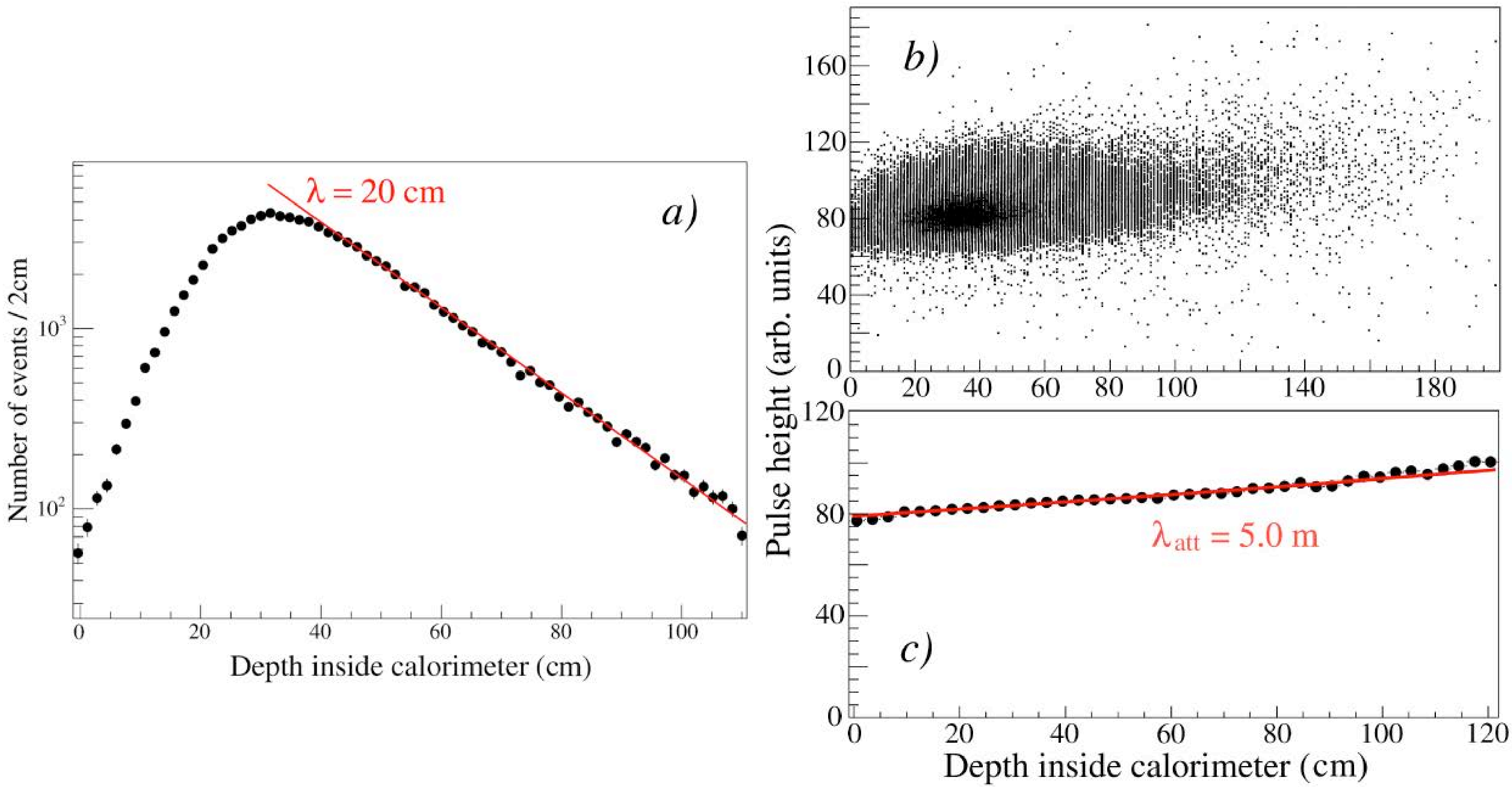


Figure 26: Distribution of the average depth at which the scintillation light is produced in the DREAM calorimeter by showering hadrons (a). Scatter plot showing the total scintillator signal versus the average depth of the light production (a) and the average size of the total scintillator signal as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

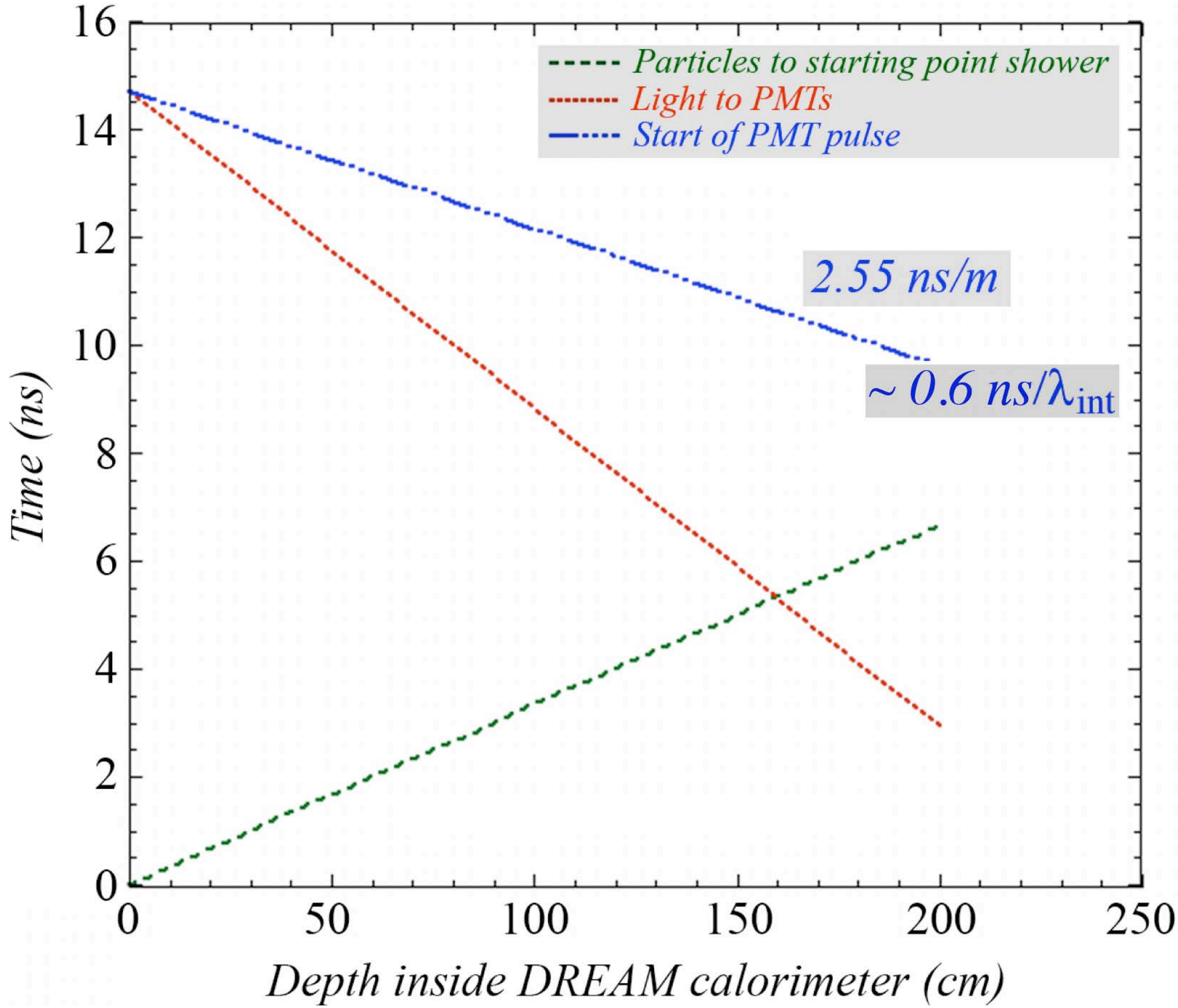
An alternative method to measure shower depth

Disadvantages of described method:

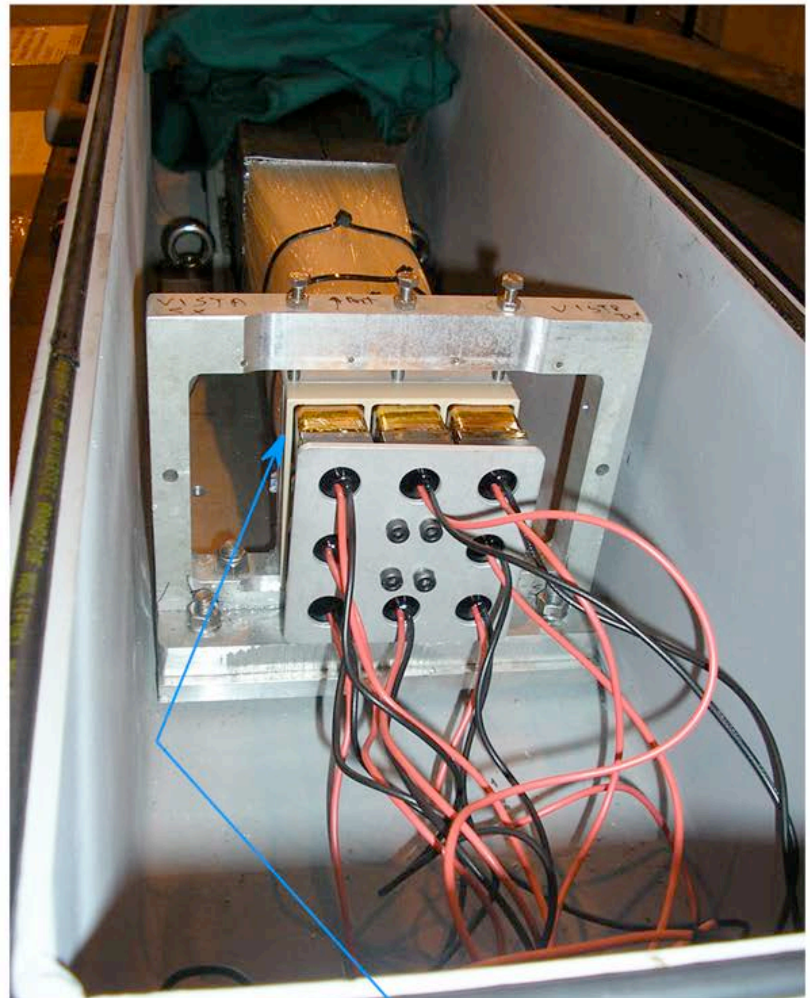
- *Does not work for neutral particles*
- *Does not work for jets*
- *Non-projective calorimeter impractical*

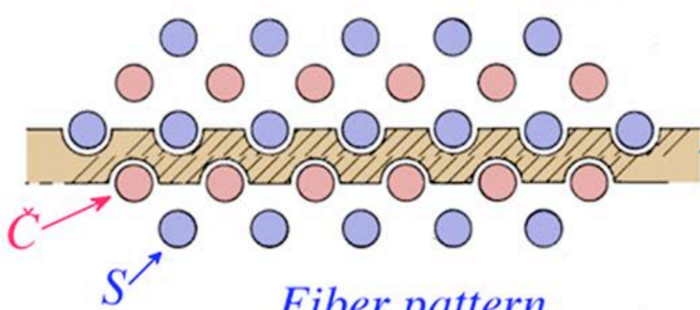
Alternative makes use of the fact that light in fibers travels at $v = c/n$, while particles producing the light travel at $v \sim c$

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



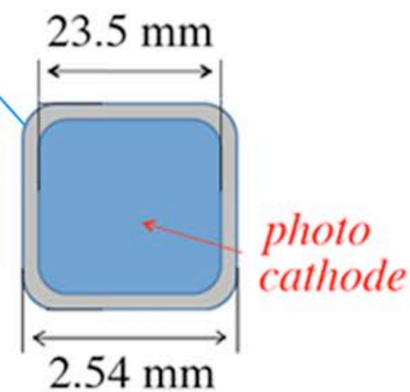
The first SuperDREAM module at H8





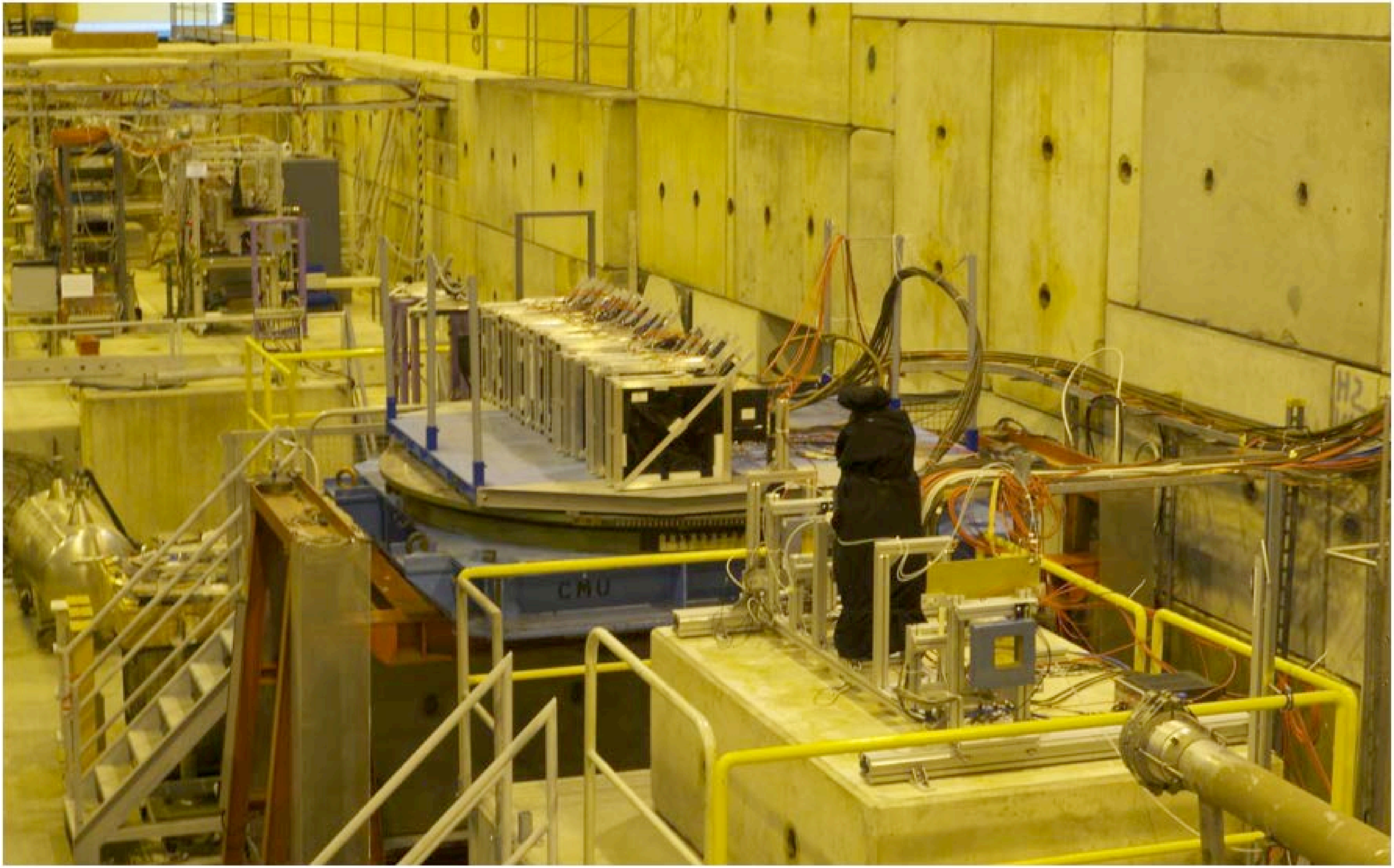
Fiber pattern

Hamamatsu R8900
pc: 85%!



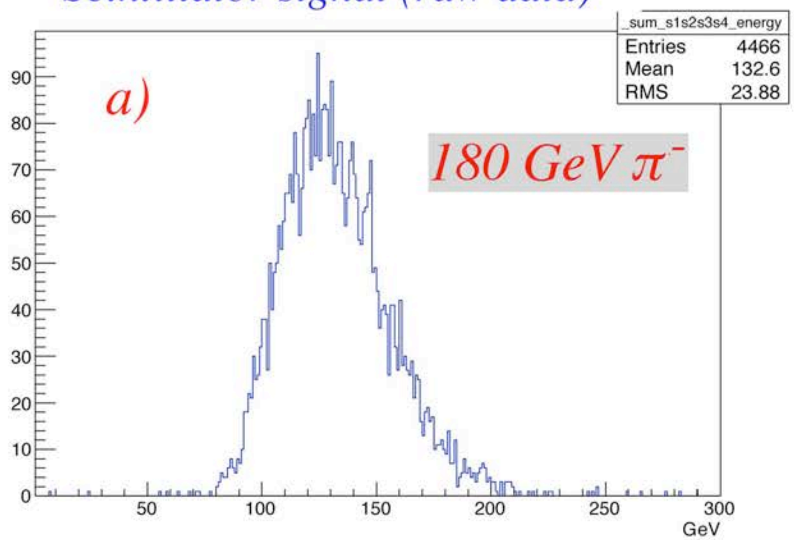
First hadrons in SuperDREAM (1 Pb module + n-shield)

Calibration of neutron shield (muon beam)

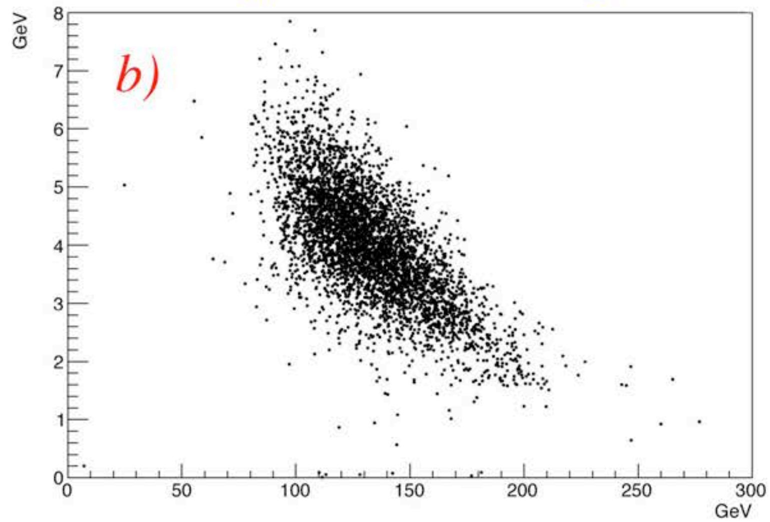


First results on pion detection in the new fiber calorimeter

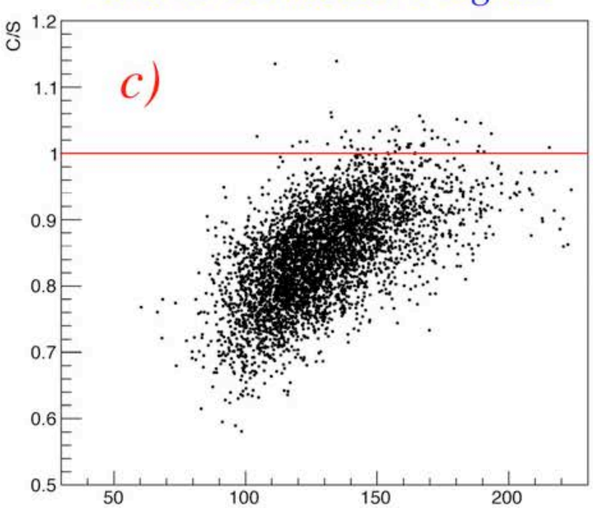
Scintillator signal (raw data)



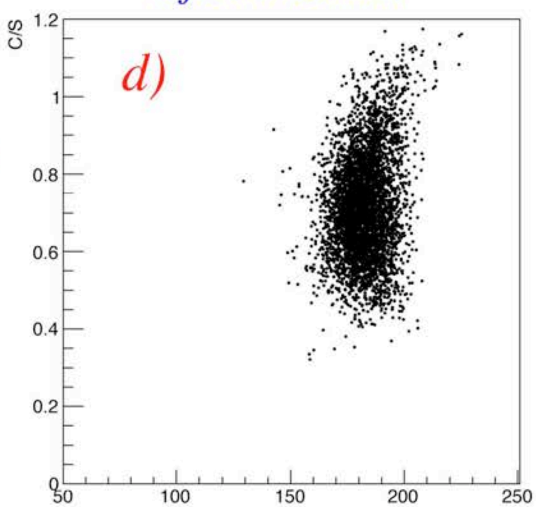
Leakage vs scintillator signals



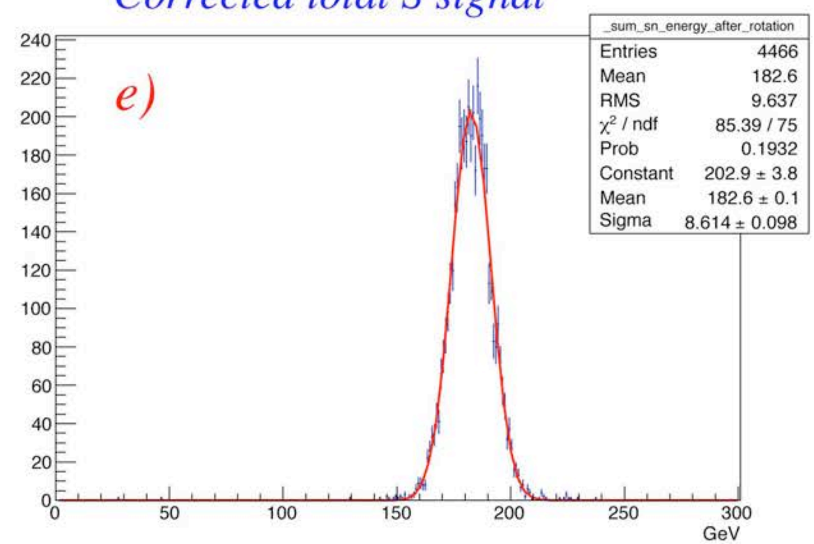
Č/S vs corrected S signal



After rotation

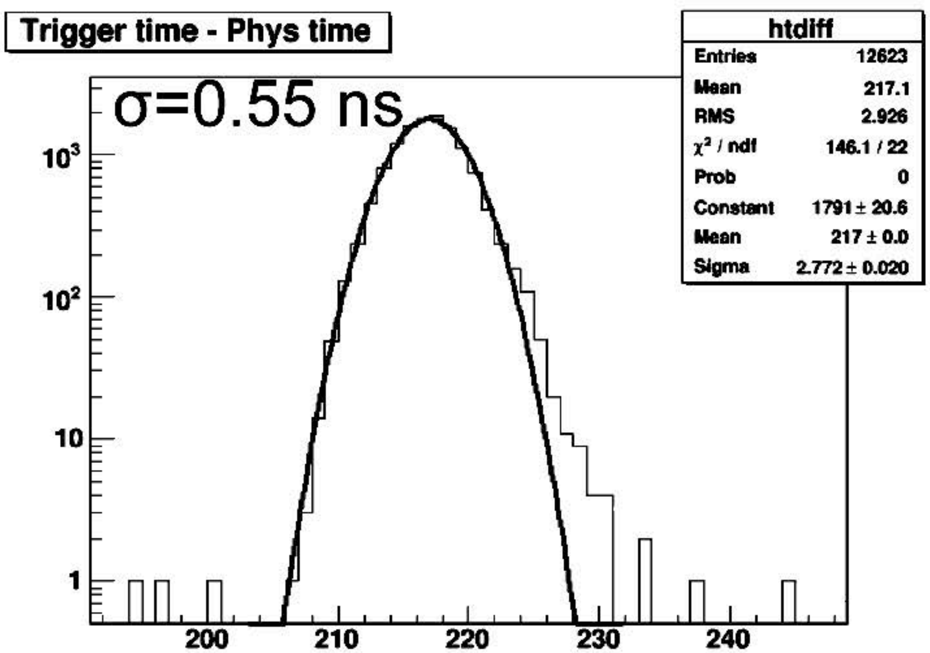


Corrected total S signal

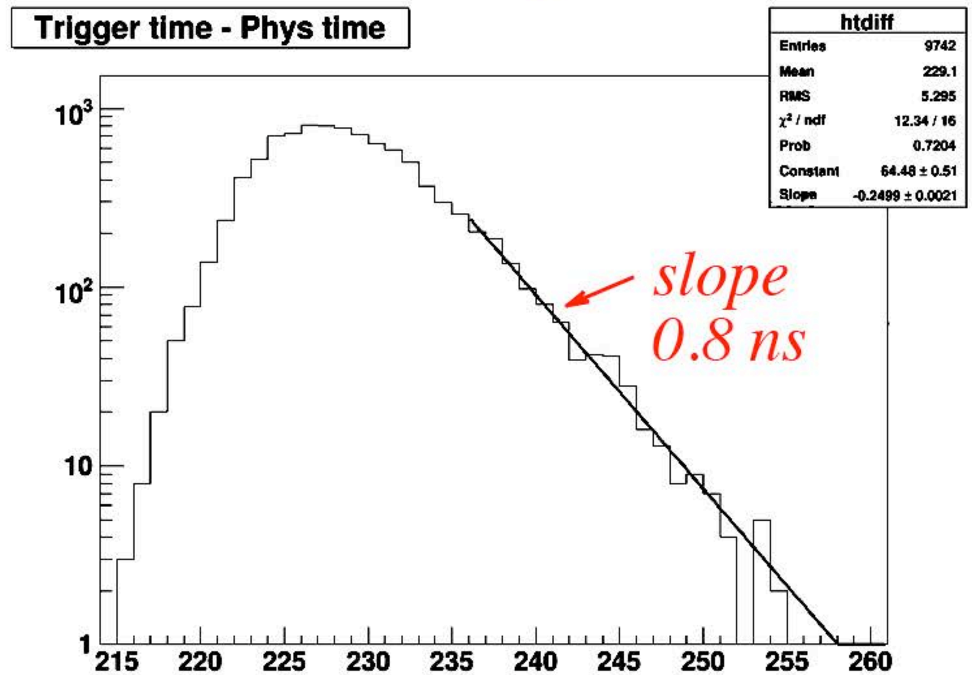


Measurement of the depth of the light production in module using the DRS timing

80 GeV electrons

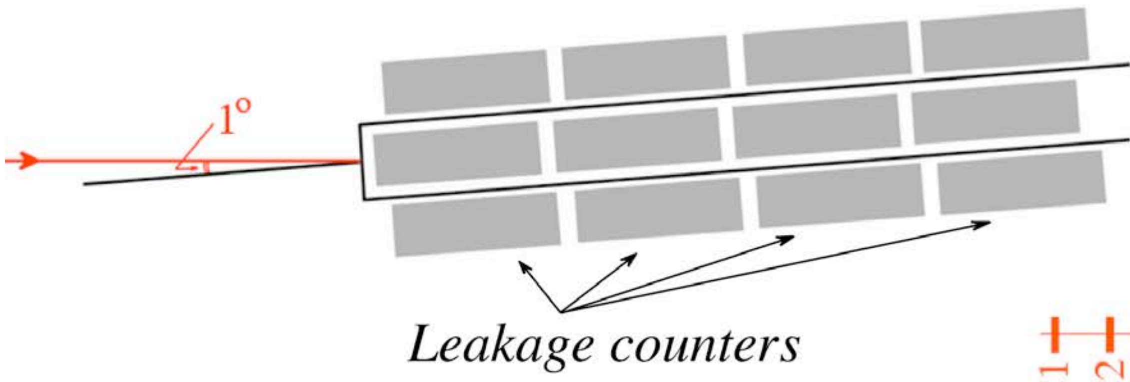


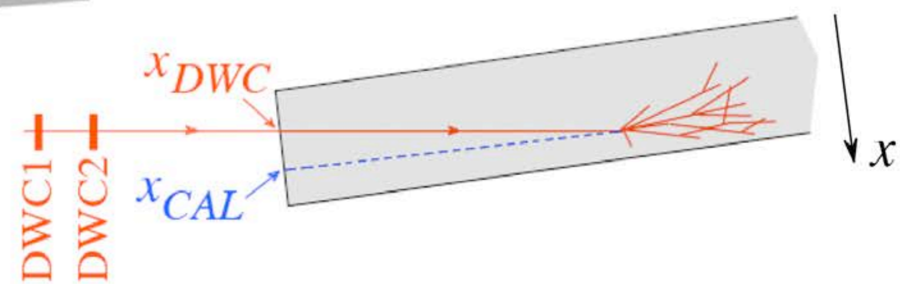
180 GeV pions

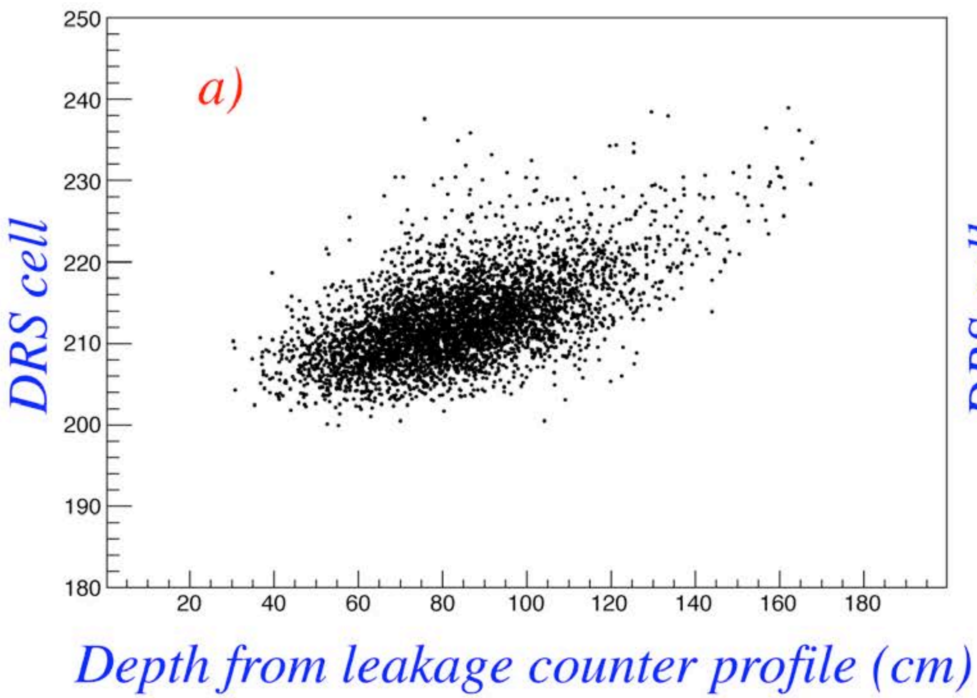


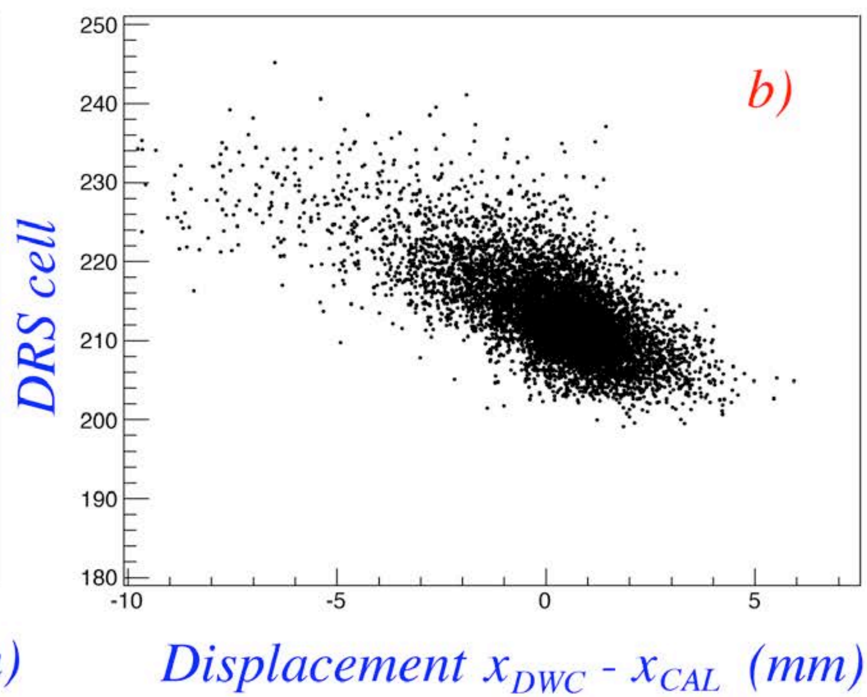
Start of calorimeter signal (in DRS cells = 0.2 ns)

Check that DRS time measures shower depth

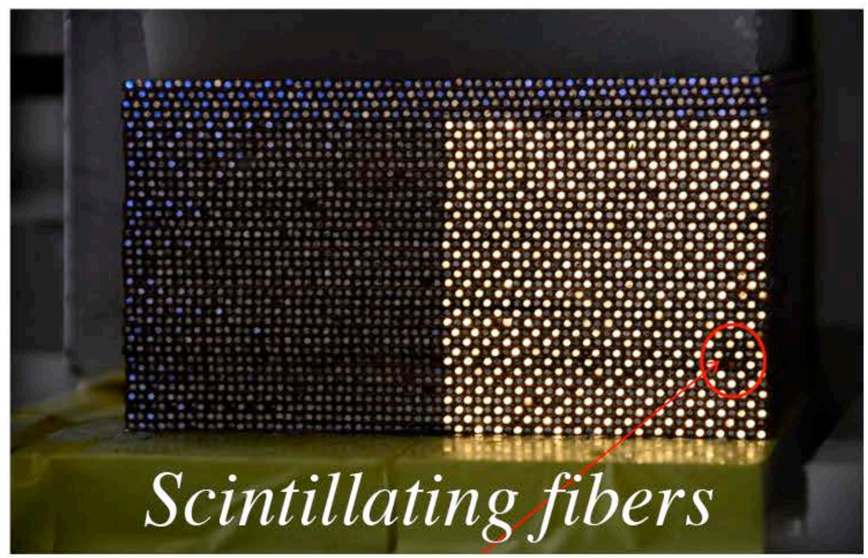




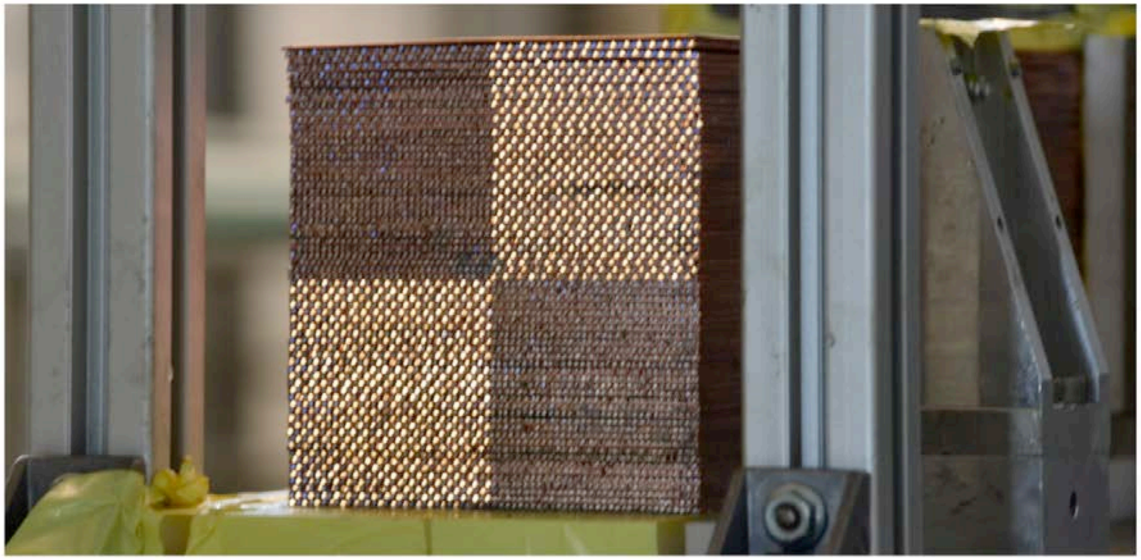




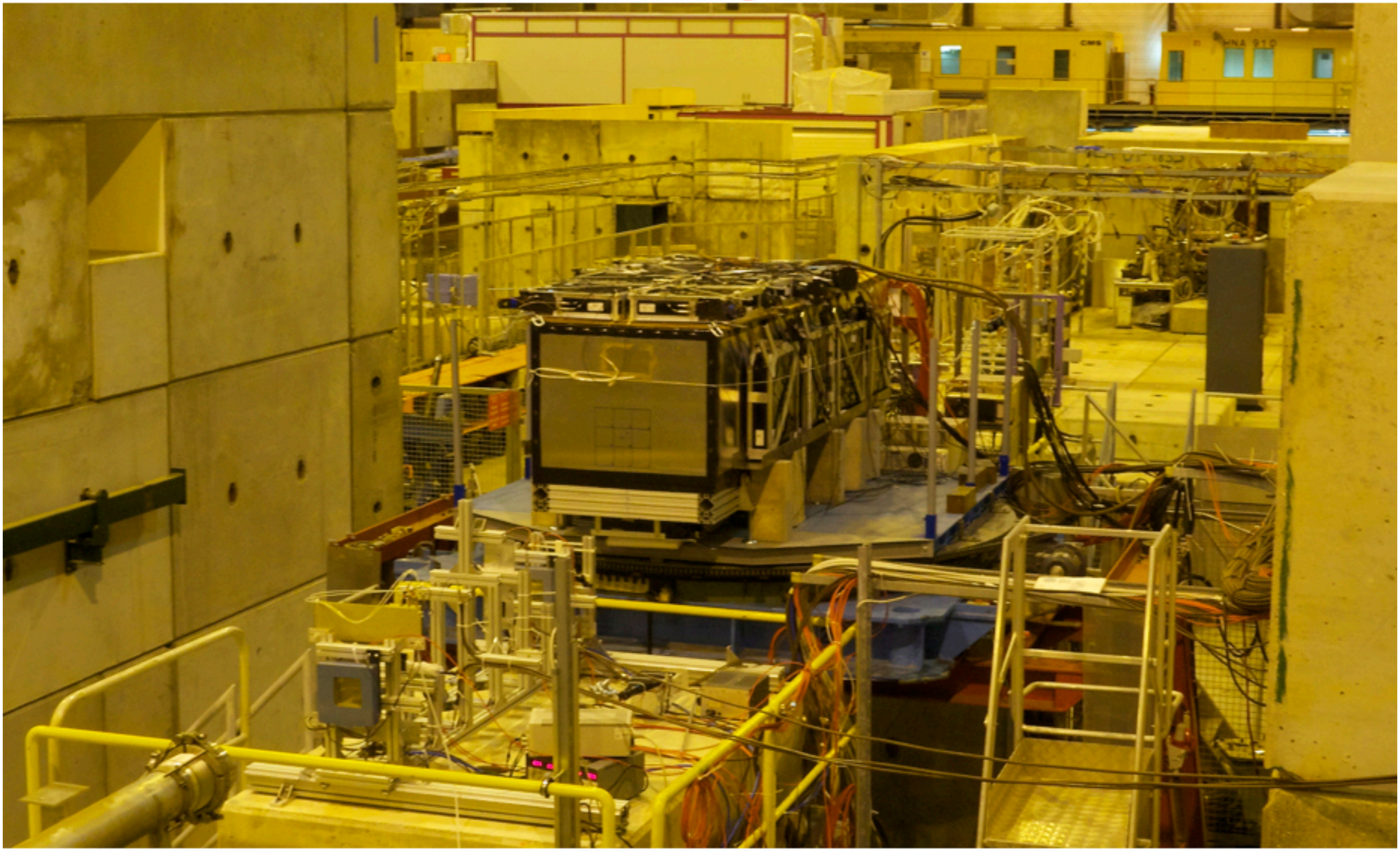
The first copper module



The first copper module

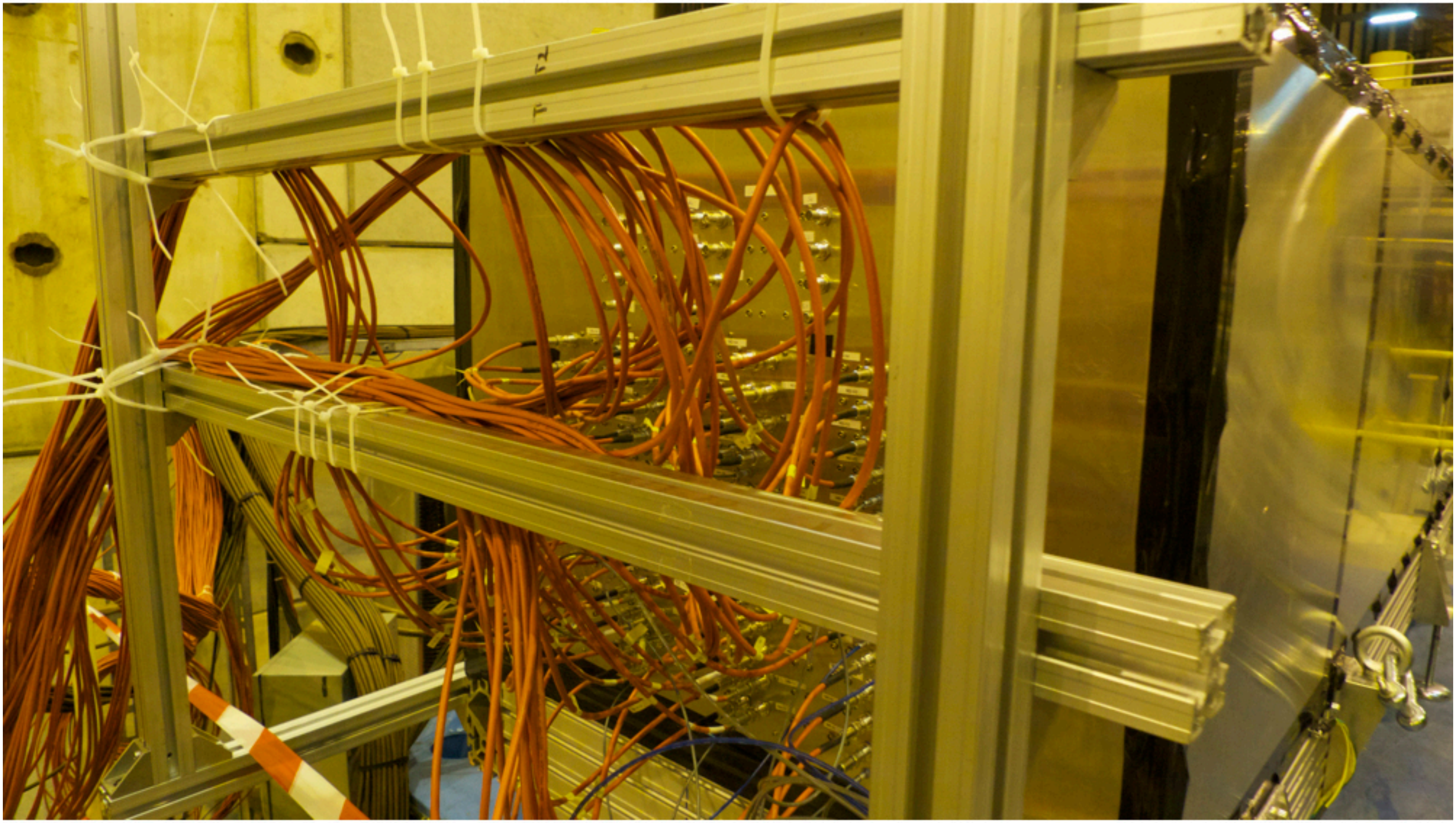


The new SuperDREAM fiber module tested at CERN (2 weeks ago)

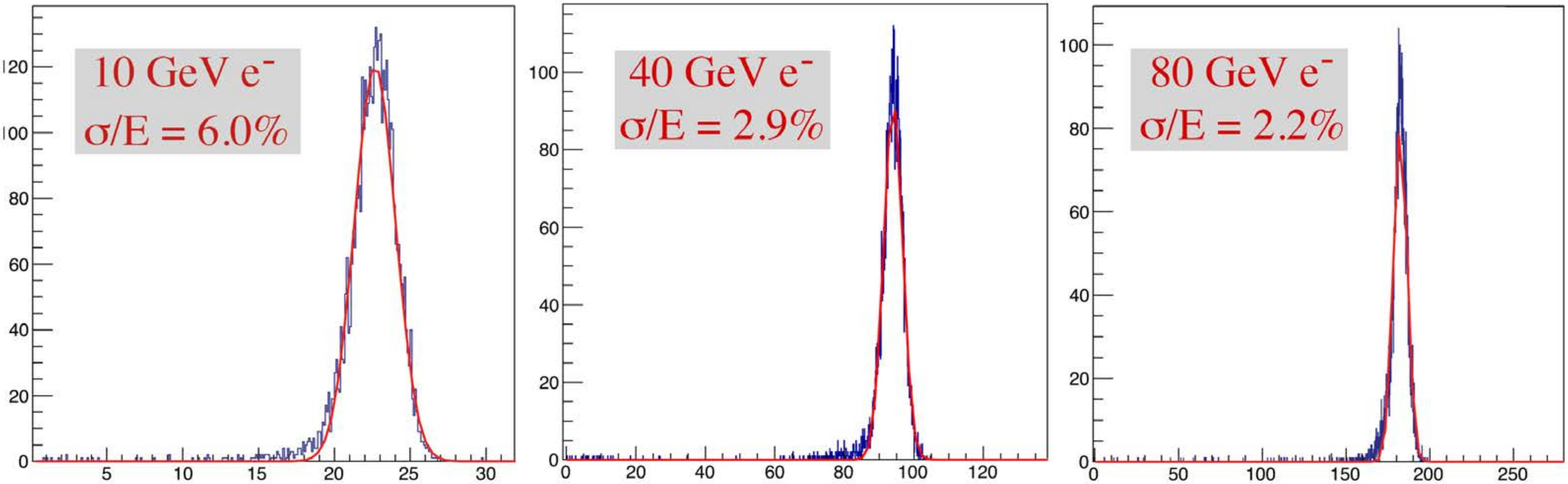


9 modules (36 towers, 72 signals), 1.4 tonnes Pb/fiber + 2 modules Cu/fiber
20 leakage modules (500 kg plastic scintillator)

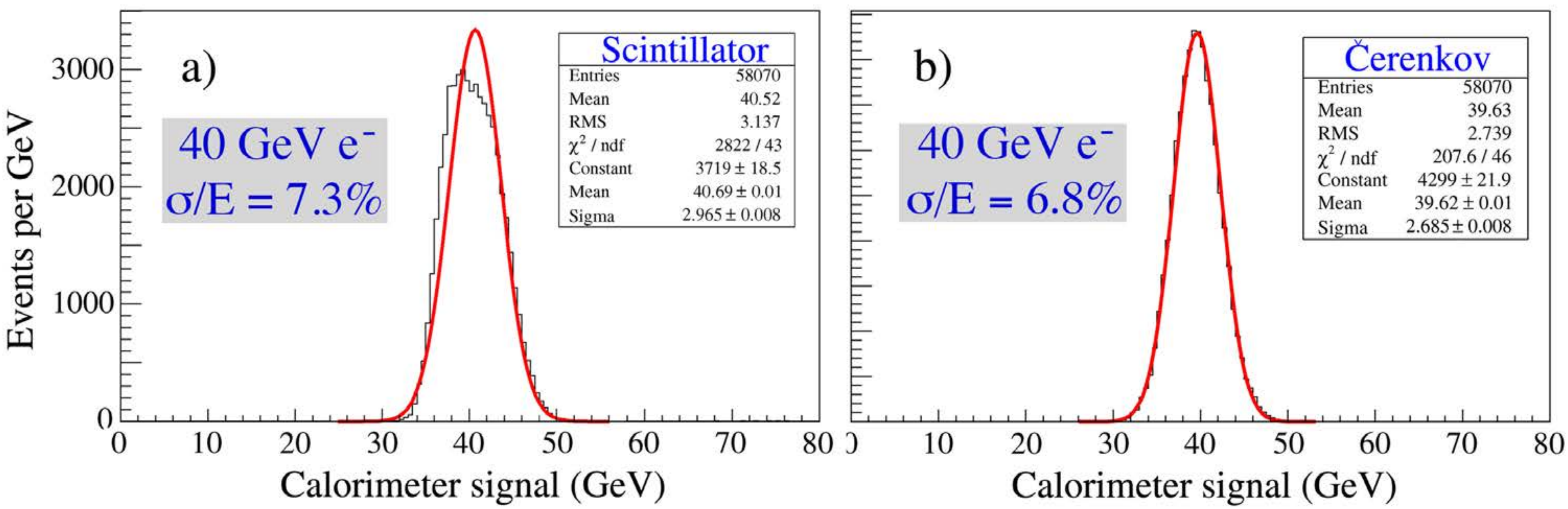
Rear side of the new SuperDREAM module



Electrons in new fiber calorimeter (on-line results, i.e. uncalibrated)



Compared with original DREAM results (NIM A536, 29)



Future research plans

Study issues related to implementing DREAM calorimeters in practice

- *Readout: Get rid of rear fiber forests (SiPM)*
- *Shorter effective interaction length (W?)*
- *Projective geometry*

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

Backup slides

Composition of the non-em shower component

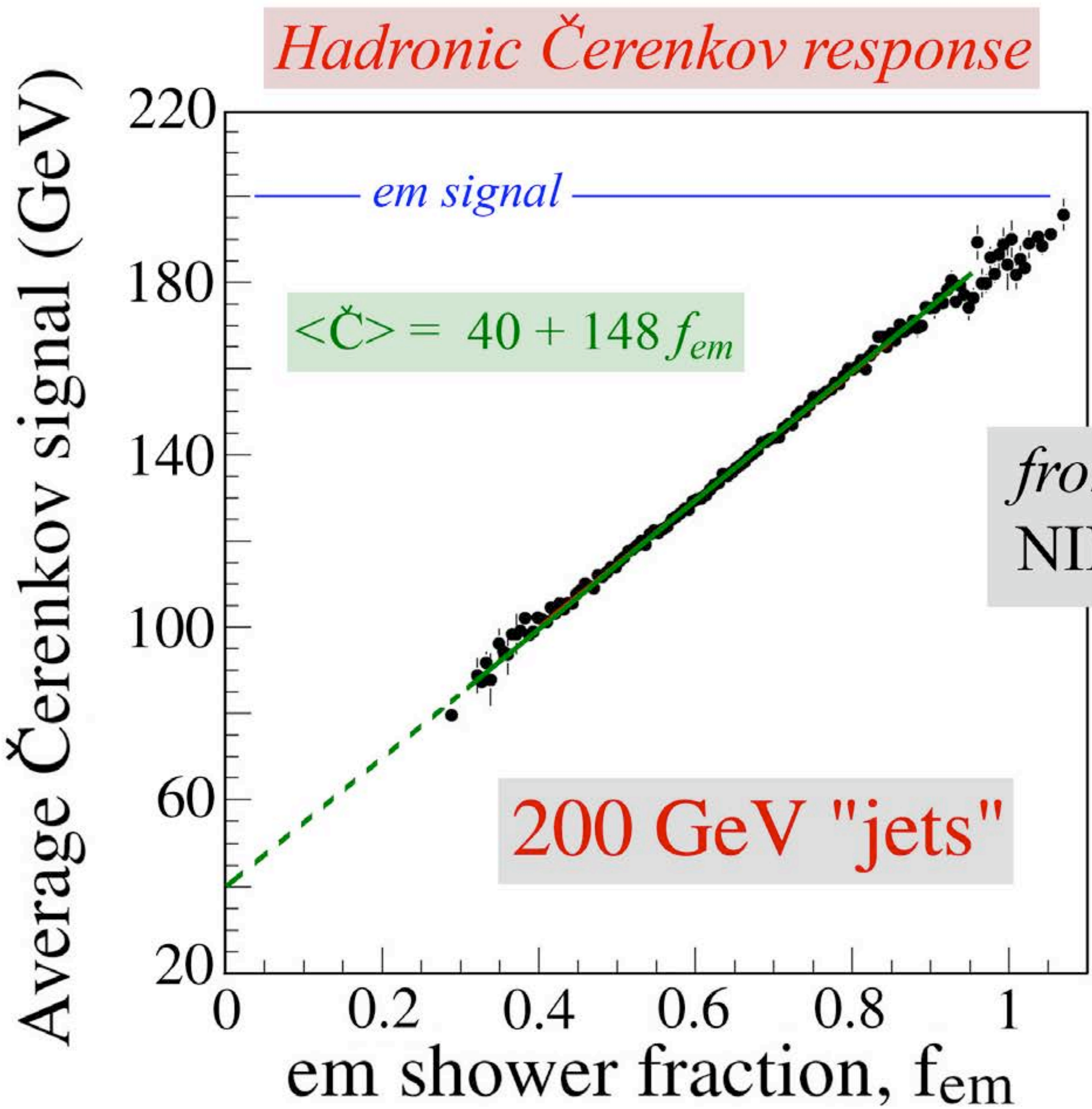
The non-electromagnetic shower component (1)

How do we know that protons dominate (~80%!) of the non-em signals?

1) Because of the small hadronic signals (i.e. large e/h values) of calorimeters that are blind to these protons.

In quartz-fiber calorimeters ($n = 1.46$), only particles with $\beta > 0.69$ emit Čerenkov light, i.e. $E_{kin} > 0.2$ MeV for electrons and > 350 MeV for protons

DREAM: Measure f_{em} event-by-event



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

from:
NIM A537 (2005) 537

$$f_{em} = 0 \longrightarrow R_h = 0.2\, R_{em}$$
$$< 0.2\, R_{mip}$$

The non-electromagnetic shower component (2)

How do we know that protons dominate (~80%!) of the non-em signals?

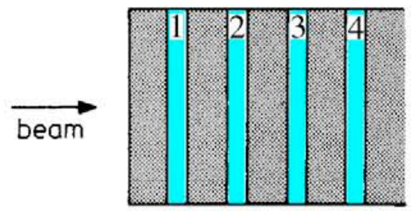
1) Because of the small hadronic signals (i.e. large e/h values) of calorimeters that are blind to these protons.

In quartz-fiber calorimeters ($n = 1.46$), only particles with $\beta > 0.69$ emit Čerenkov light, i.e. $E_{kin} > 0.2$ MeV for electrons and > 350 MeV for protons

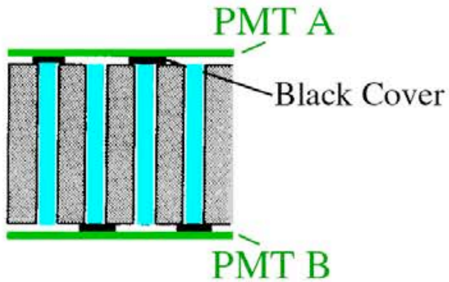
2) Because of the absence of correlations between the signals from adjacent active layers in fine-sampling hadron calorimeters

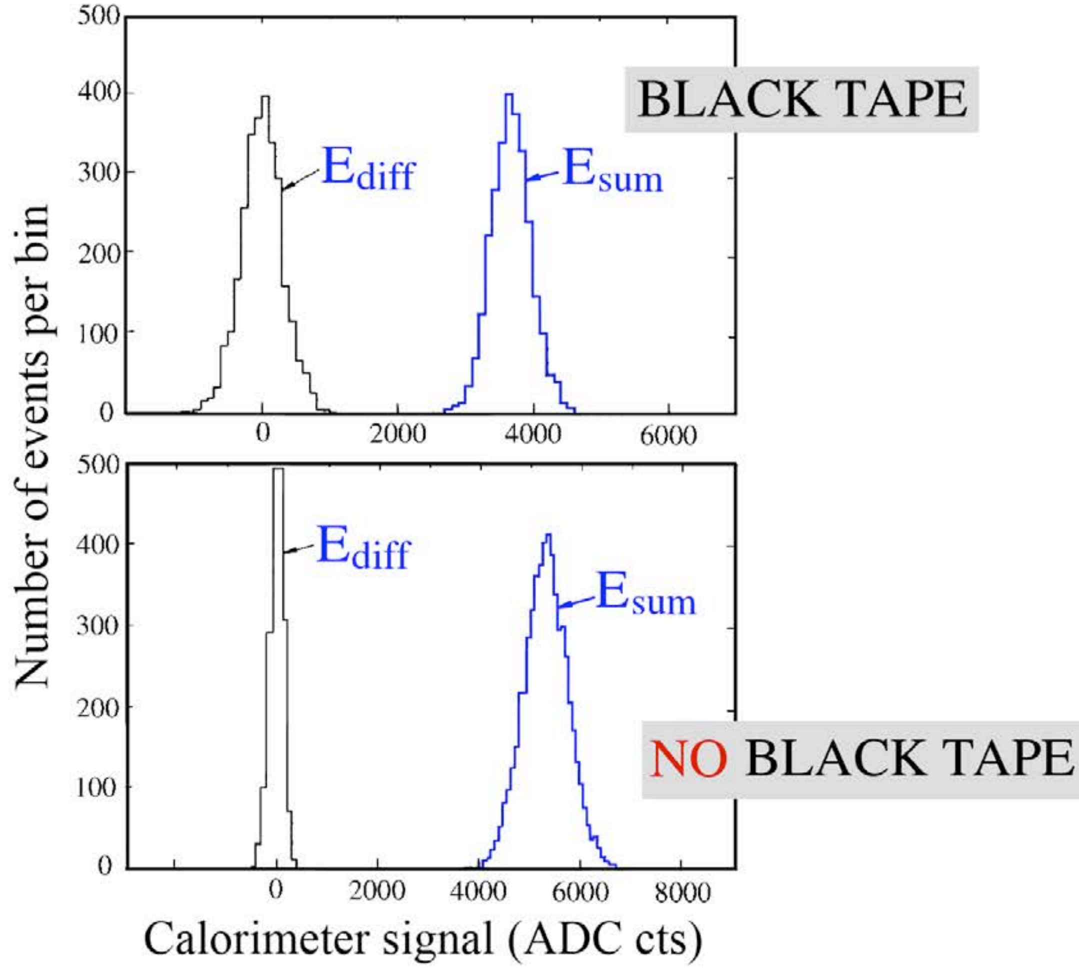
The calorimeter from the example had 0.06 λ_{int} thick sampling layers.
A mip would lose on average 12.7 MeV traversing these layers.

Correlations between signals from different sampling layers



$$E_a = E_1 + E_3 + \ldots$$
$$E_b = E_2 + E_4 + \ldots$$
$$E_{sum} = E_a + E_b$$
$$E_{diff} = E_a - E_b$$





Fluctuations (%)	*10 mm lead / 2.5 mm plastic* Electrons	Pions
σ_A, σ_B	36.0±1.0	60.5±1.0
σ_{sum}	24.5±1.0	43.5±1.0
σ_{diff}	25.8±1.0	42.3±1.0

from:
NIM A290 (1990) 335

The crucial elements of hadronic shower simulations (2)

Where do these protons come from?

1) Nuclear spallation.

Spallation protons typically carry ~ 100 MeV kinetic energy.
Their range is typically of the order of the thickness of sampling layers in hadron calorimeters.

2) Nuclear reactions induced by neutrons, e.g. (*n,p*) reactions

These protons have kinetic energies comparable to those of the (evaporation) neutrons that generated them (< 10 MeV)
These neutrons outnumber spallation protons by an order of magnitude

Measurements of neutron production in hadronic showers:
> 40 per GeV in some materials (NIM A252 (1986) 4)

About the contribution of relativistic hadrons to the signals

$$\text{D. Groom: } \langle f_{em} \rangle = 1 - \left[\frac{E}{E_0}\right]^{(k-1)}$$

with E_0 *= average shower energy needed for production of 1 secondary* π
varies from 0.7 GeV (Fe) - 1.3 GeV (Pb)

$k \sim 0.8$ *related to average multiplicity*

Example: High-energy hadron on Pb, 100 GeV non-em energy deposit
$\longrightarrow$ *100/1.3 = 77 secondairy/tertiary shower pions, kaons*

- *mips in Pb lose 218 MeV per* λ_{int} *through ionization*
  $\longrightarrow$ *77 mips lose in total 16.8 GeV*
- π*,K may lose a bit more, since* λ_{int} *defined for protons*
- *On the other hand, many soft* π*'s cause* Δ *resonance production, with cross sections much larger than the asymptotic one used for calculating* λ_{int} *(e.g.* $\pi^+ n \longrightarrow p\pi^o$*)*

$\longrightarrow$ *ionization loss* π*,K may account for ~20% of non-em E*

Naive expectations for hadron calorimeters

Average composition of non-em shower component:

- Pions, kaons,.... 20% (relativistic)
- Protons 25%
- Neutrons 15%
- Invisible 40%

		Exp. value
Cherenkov calorimeter:	$e/h = 1/0.2$	~ 5
Crystal calorimeter:	$e/h = 1/(0.2 + f_1 \cdot 0.25)$ with $f_1 < 1$	> 2
LAr calorimeter:	$e/h = \frac{e}{mip} / (0.2 + f_1 \cdot 0.25)$, $0.6 < \frac{e}{mip} < 1$	1.3-1.8*
Plastic-scint. calorimeter	$e/h = \frac{e}{mip} / (0.2 + f_1 \cdot 0.25 + f_2 \cdot 0.15)$ with $f_2 > 1$	< 1.5

Efficient neutron detection is very important for hadronic energy resolution because kinetic energy neutrons correlated with invisible energy

Compare intrinsic limits SPACAL, ZEUS, D0

* Except for uranium absorbers (fission energy)

Sampling considerations

Sampling fluctuations and the e.m. energy resolution

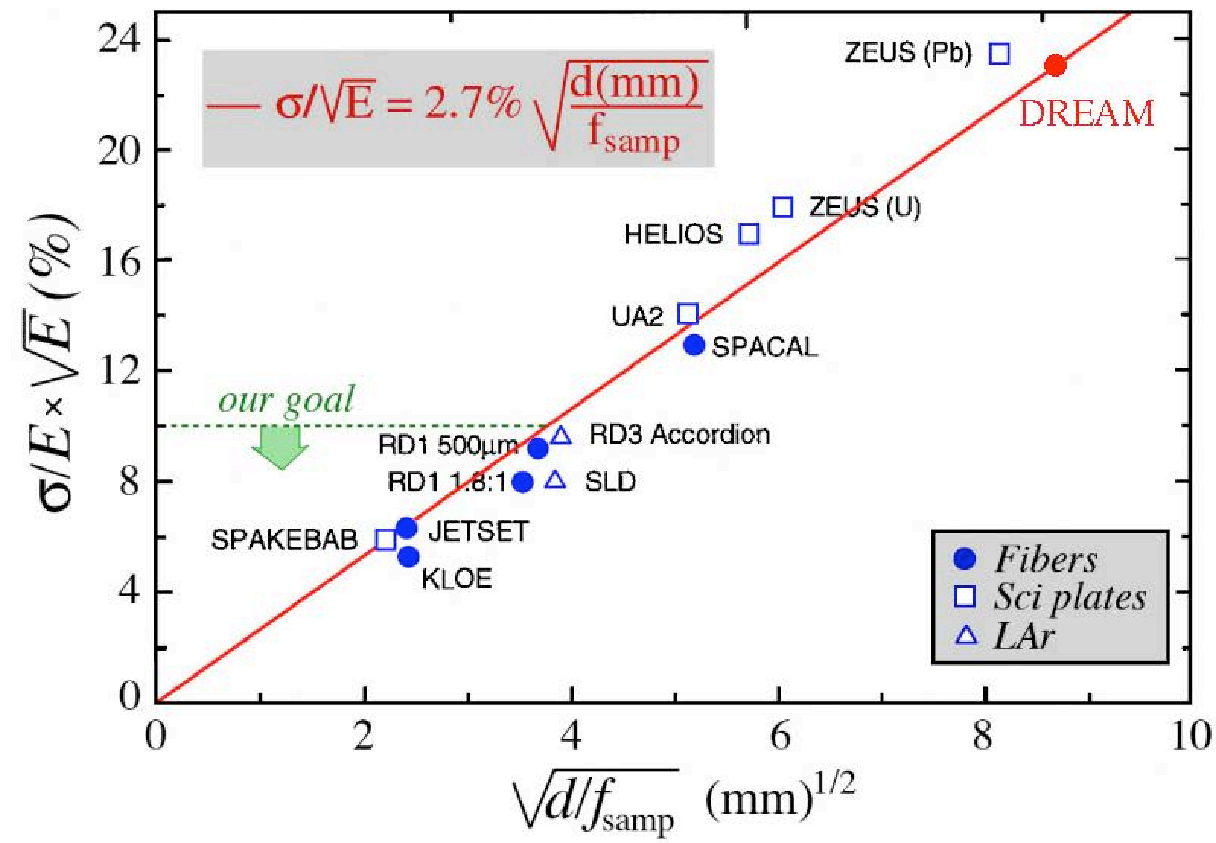


Figure 23: The em energy resolution of sampling calorimeters as a function of the parameter $(d/f_{\rm samp})^{1/2}$, in which d is the thickness of an active sampling layer (*e.g.* the diameter of a fiber or the thickness of a liquidargon gap), and $f_{\rm samp}$ the sampling fraction for mips [20].

Sampling fluctuations

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

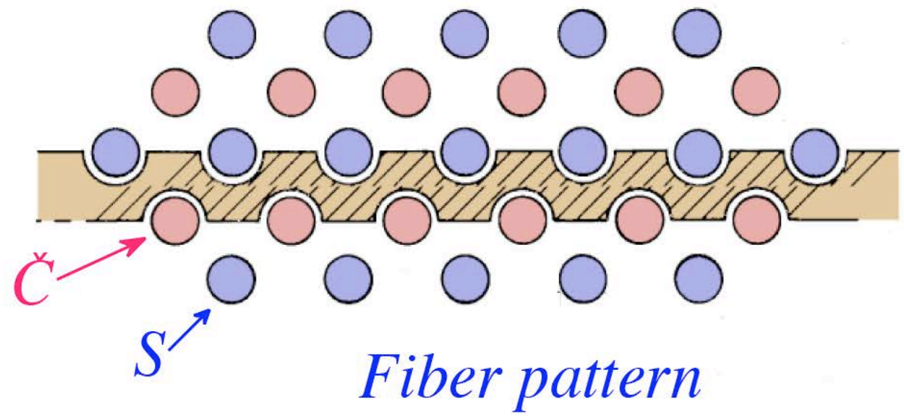
Decrease the sampling fluctuations as follows:

- *Embed fibers individually in metal structure, instead of bunches*
  Reduces to 15%/√E

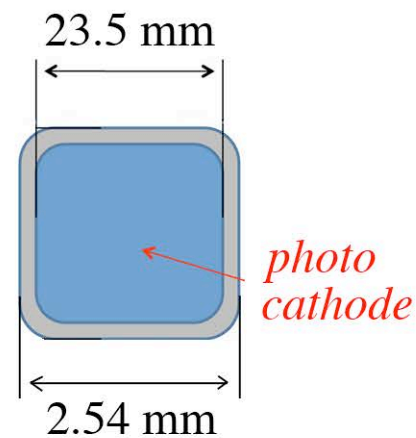
- *Increase the overall fiber filling fraction*
  (from 22% in original fiber module to 43%. PMTs should fit in "shadow")
  Reduces to 11%/√E

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

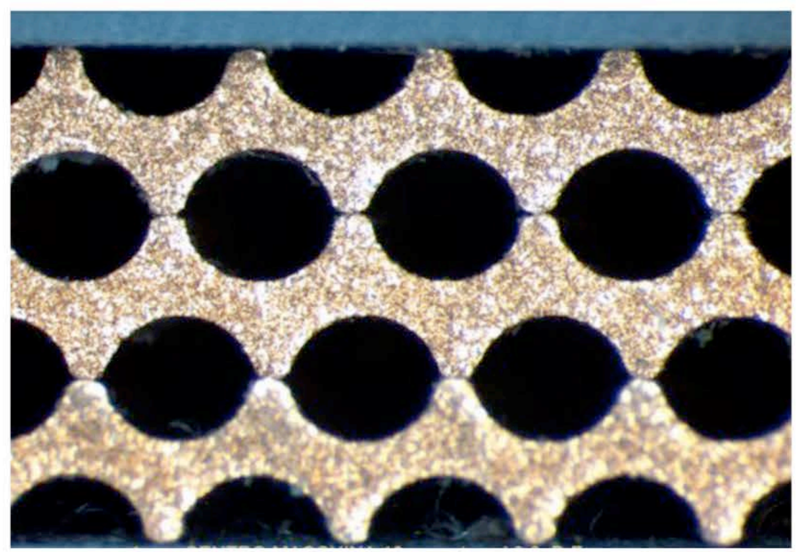
Learn from KLOE and SPACAL!



- 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)

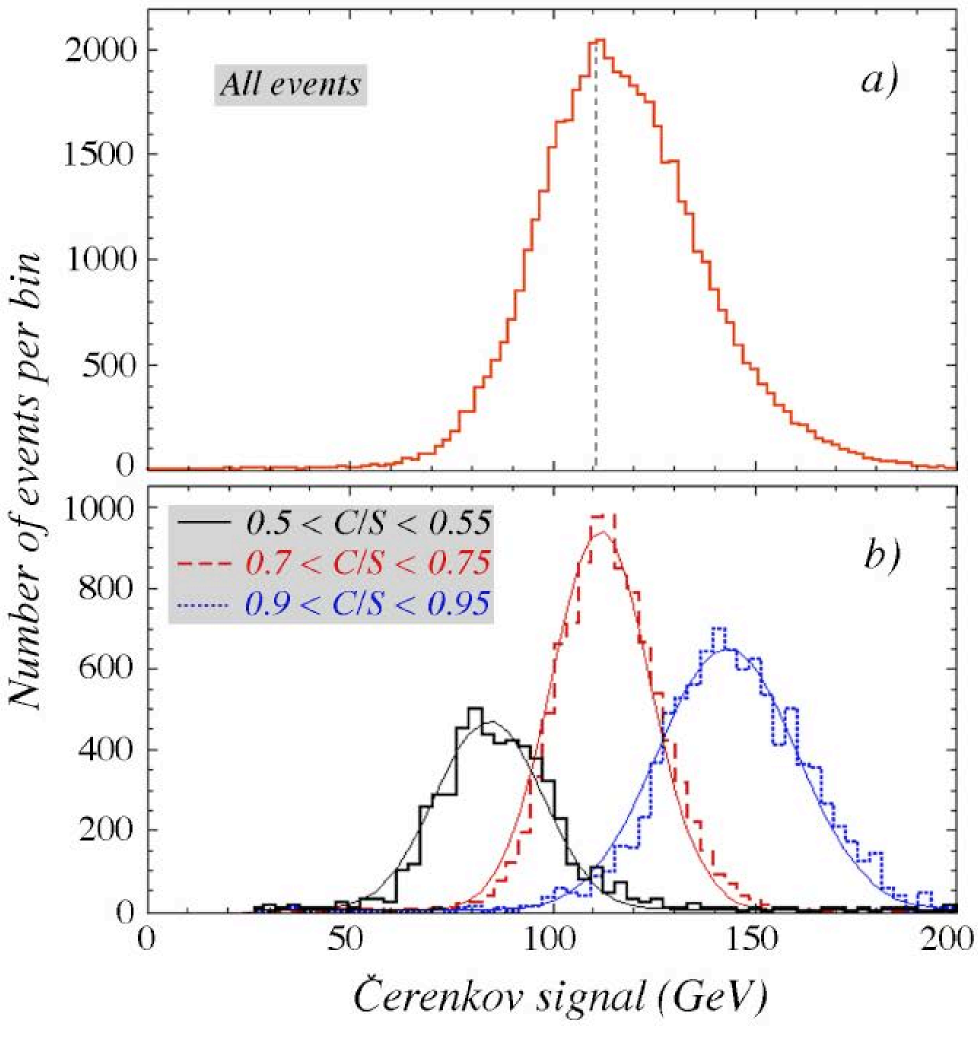
- *Increasing the (Čerenkov) sampling fraction* x 2

- *Using PMTs with a larger quantum efficiency* x 1.5

Expect to reach > 100 p.e./GeV

Miscellaneous DREAM results

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



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

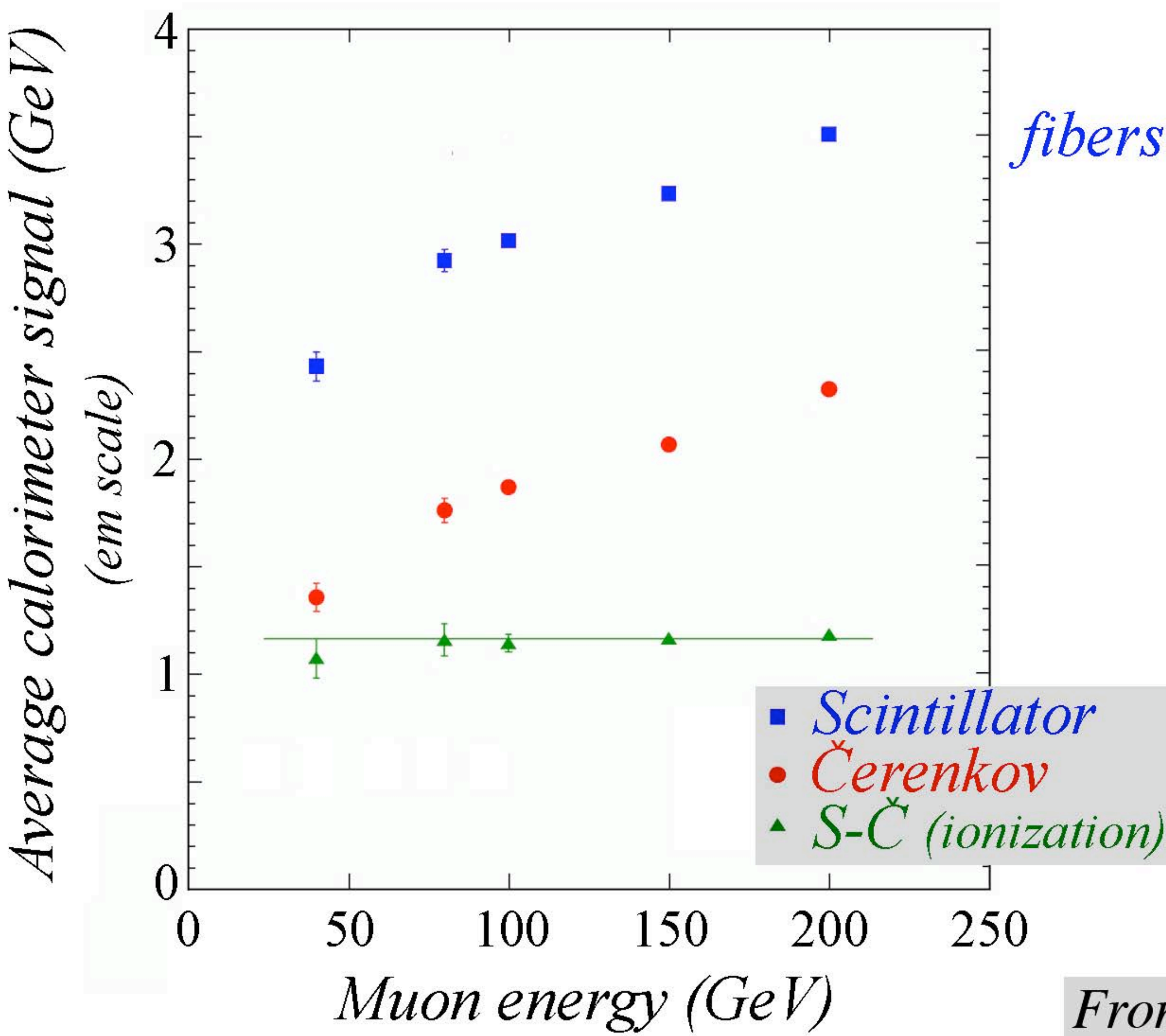
from

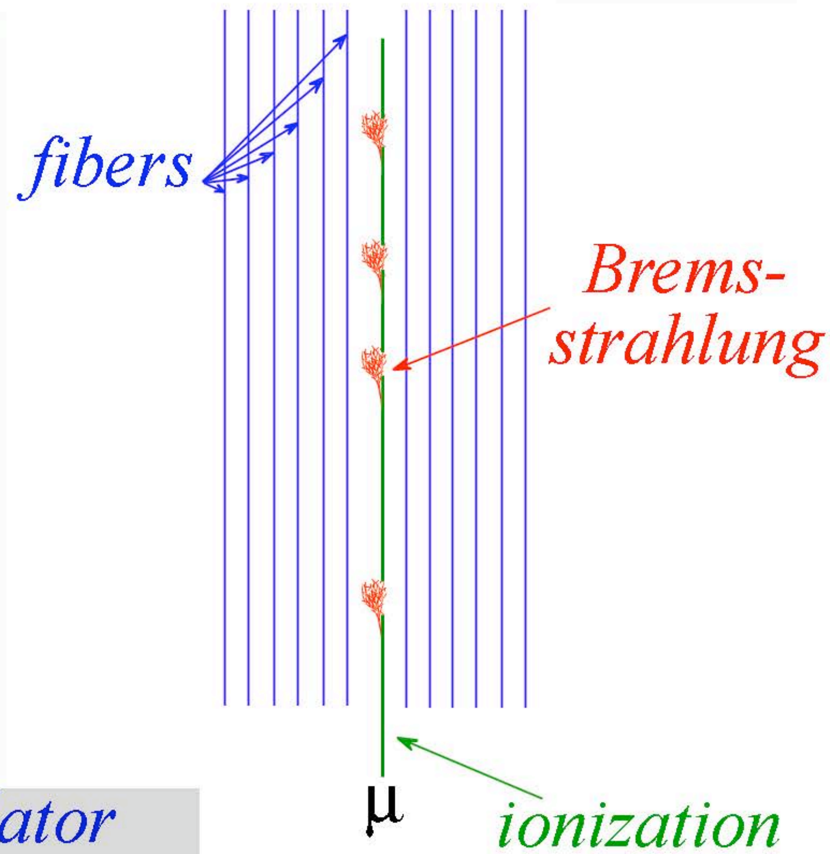
NIM A610 (2009) 488

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).

Calorimetric separation of ionization / radiation losses

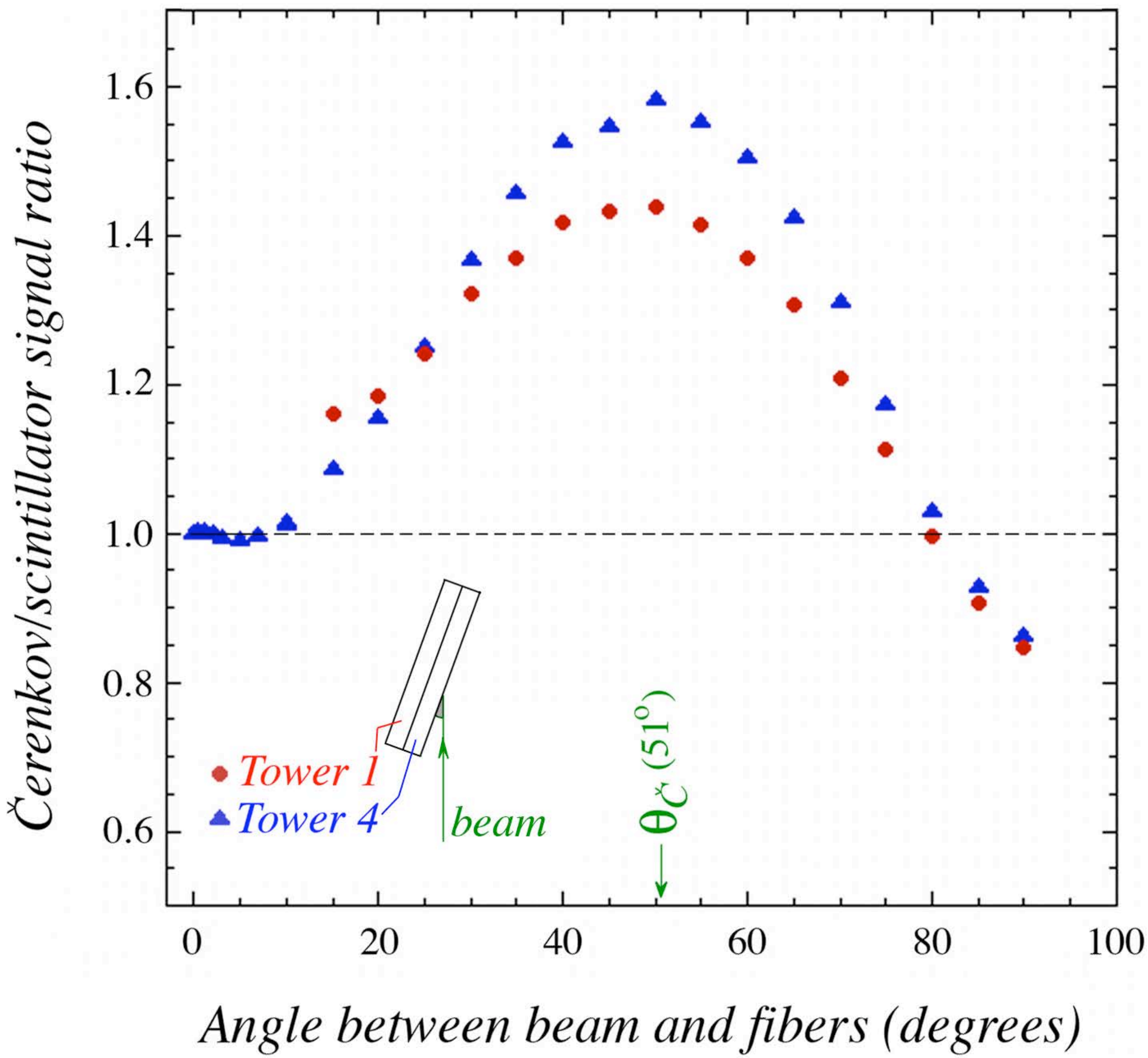
Muon signals in the DREAM calorimeter





From: NIM A533 (2004)305

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



P F A

Particle Flow Analysis

- *The basic idea*

  Combine the information of the tracker and the calorimeter system to determine the jet energy

  Momenta of charged jet fragments are determined with the tracker

  Energies of the neutral jet fragments come from the calorimeter

- *This principle has been used successfully to improve the hadronic performance of experiments with poor hadronic calorimetry*

  However, the improvements are fundamentally limited

  In particular, no one has ever come close to separating W/Z this way

- *The problem*

  The calorimeters do not know that the charged jet fragments have already been measured by the tracker. These fragments are also absorbed in the calorimeter. Confusion: Which part of the calorimeter signals comes from the neutral jet fragments?

- *Advocates of this method claim that a fine detector granularity will help solve this problem. Others believe it would only create more confusion.*

  Like with all other issues in calorimetry, this issue has to be settled by means of experiments, NOT by Monte Carlo simulations!!

A critical look at PFA

- *The fact that 65% of the jet energy is measured with excellent precision in the tracker is irrelevant*

In our detectors, the charged tracks are better measured than photon(s) which are themselves better measured than neutral hadron(s)

Resolution on the charged track(s)	$\Delta p/p$	$\sim qq\ 10^{-5}$
Resolution on the photon(s)	$\Delta E/E$	$\sim 12\%$
Resolution on the h°	$\Delta E/E$	$\sim 45\%$

$$\underset{\text{fraction}}{E_{jet}} = \underset{65\%}{E_{\text{charged tracks}}} + \underset{26\%}{E_{\gamma}} + \underset{9\%}{E_{h^0}}$$

From: J.C. Brient CALOR 08

What matters for the jet energy resolution are the fluctuations in this 65%.

In the absence of a calorimeter, one should therefore not expect to be able to measure jet energy resolutions better than 25–30% on the basis of tracker information alone, *at any energy*. And

From: NIM A495 (2002) 107

A critical look at PFA (2)

- *The crucial issue is if one can eliminate the contributions from showering charged hadrons in the calorimeter system, i.e. avoid double counting*

All claims in this respect are based on GEANT4 MC simulations, which

a) have never predicted anything correctly concerning hadron calorimetry

b) are especially wrong in predicting lateral shower shapes (too narrow)

and since the advocates still don't like the results (tails in distribitions), they

c) resort to phony statistics to make them look better

resolution over-emphasises the importance of these tails. In this paper, performance is quoted in terms of rms_{90}, which is defined as the rms in the smallest range of reconstructed energy which contains 90% of the events.

From:
NIM A611 (2009) 25

Even for a perfectly Gaussian distribution, $\mathrm{rms}_{90} \ll \sigma_{\mathrm{fit}}$

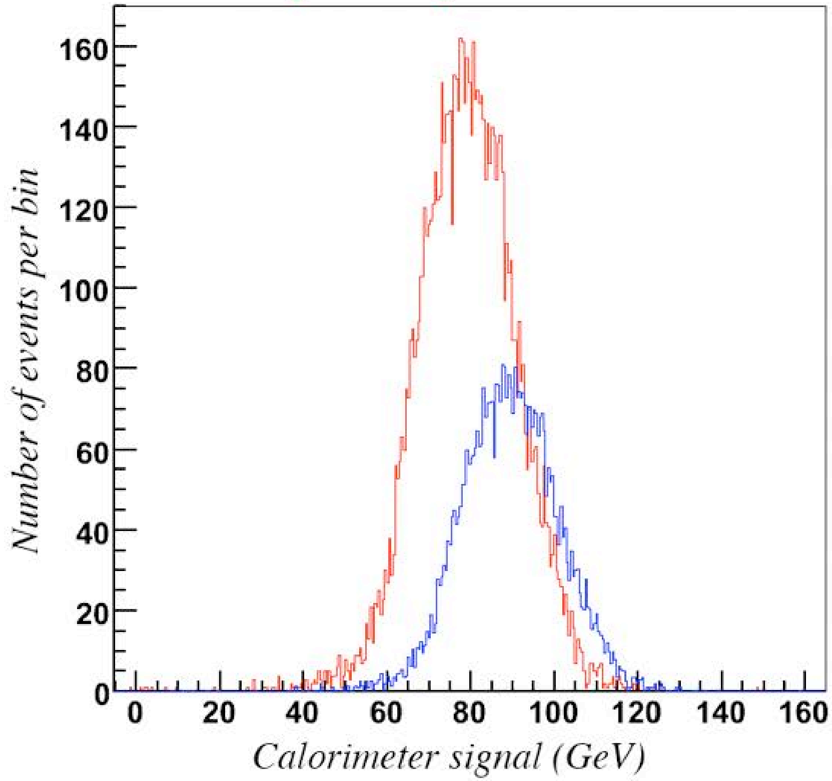
perform the first systematic study of the potential of high granularity PFlow calorimetry. For simulated events in the ILD detector concept, a jet energy resolution of $\sigma_E/E \lesssim 3.8\%$ is achieved for 40–400 GeV jets. This result, which demonstrates that high granularity PFlow calorimetry can meet the challenging

A critical look at PFA (3)

- *Testing claims of how well PFA algorithms are capable of avoiding double counting should be straightforward for the CALICE Collaboration, who have pursued this technique experimentally in the last 10 years*

A jet is a collection of particles, mainly pions and photons. If one has a data base of beam particles of different energies hitting the calorimeter system at different impact points, one could use these experimental data to construct the energy deposit profile for a given jet in many different ways. For each profile, one could apply one's favorite PFA algorithm to eliminate the contributions from charged hadrons and determine the remaining calorimeter energy, which could then be added to the (precisely known) energy of the charged hadrons to give the jet energy ➔ *Jet response function*

Example:
Jet response function CMS



A critical look at PFA (4)

- *Proposed PFA systems consist of millions of readout channels (fine granularity!)*
  Question: How does one want to calibrate these calorimeters?
  (cf. problems discussed earlier)
  Answer (CALICE): DIGITAL calorimetry (energy ∝ # of channels that fired)

This was tried and abandoned in 1983, for good reasons:
Particle density in the core of em showers is very high

→ *Non-linearity*

From: NIM 205 (1983) 113