D R E A M *
towards high-resolution jet spectroscopy

Richard Wigmans

(Texas Tech University)

Fermilab, 11/11/11 at 11am

Outline:

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

---

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

Why calorimetry?

- Measure *charged + neutral* particles

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

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

- Performance of calorimeters *improves with energy*
  ($\sim E^{-1/2}$ if statistical processes are the limiting factor)
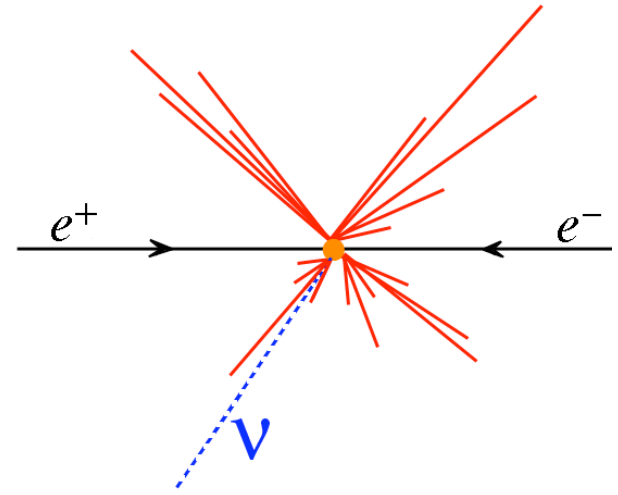
If $E \propto$ signal, i.e. $E \propto$ # signal quanta $n \longrightarrow \sigma(E) \propto \sqrt{n}$

$\longrightarrow$ *energy resolution $\dfrac{\sigma(E)}{E} \propto 1/\sqrt{n} \propto 1/\sqrt{E}$*
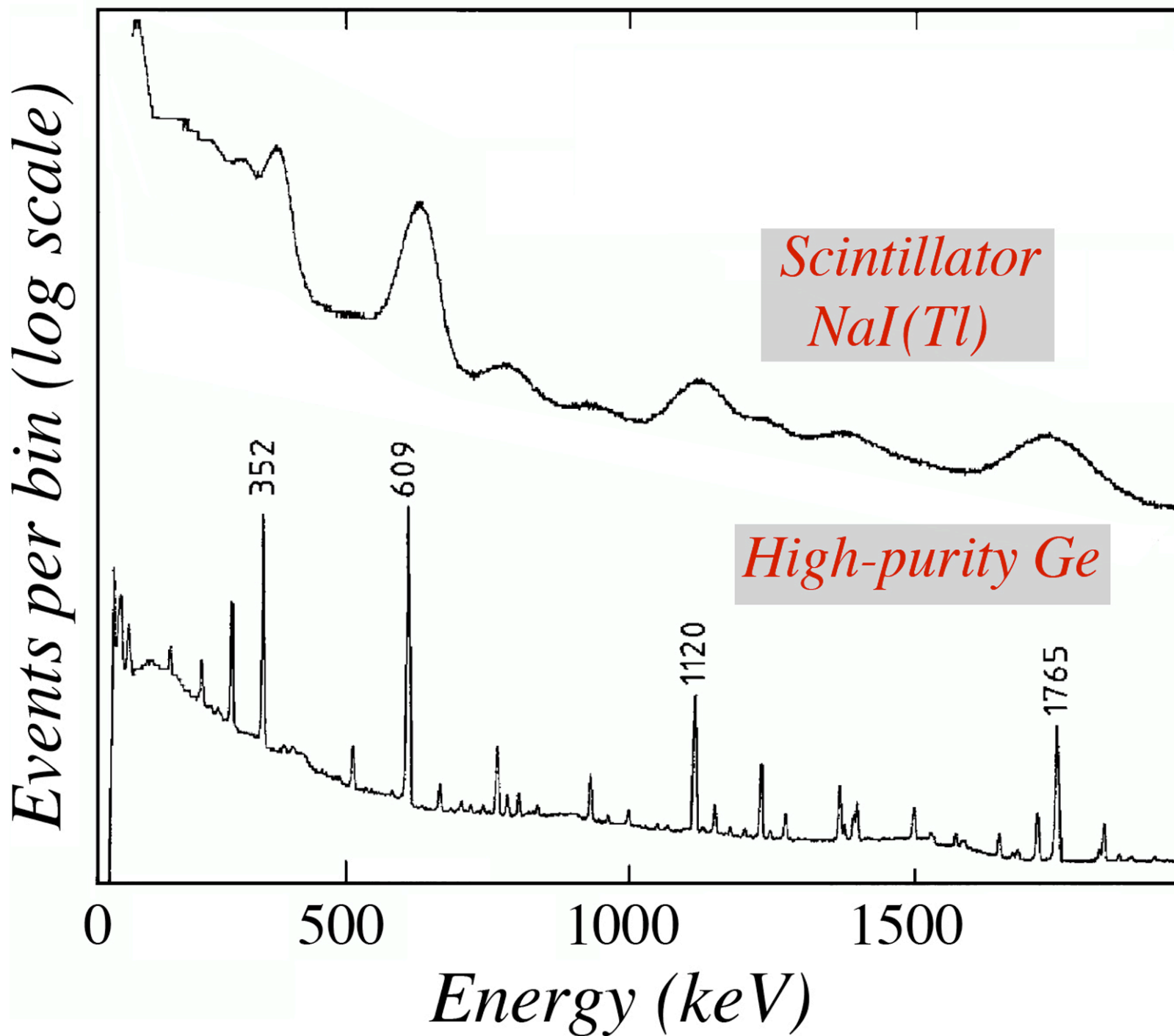
In an ideal calorimeter, resolution scales as $E^{-1/2}$
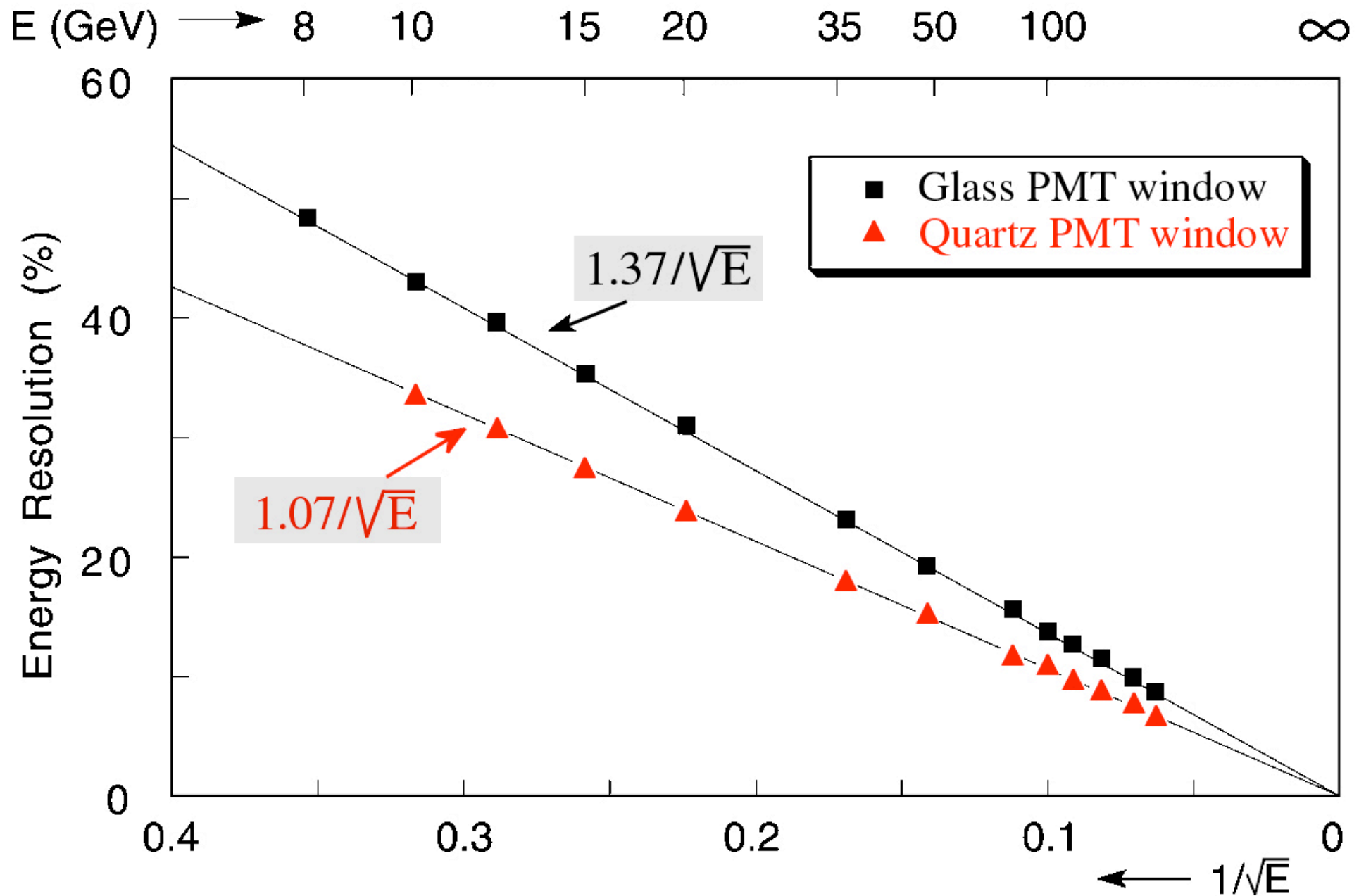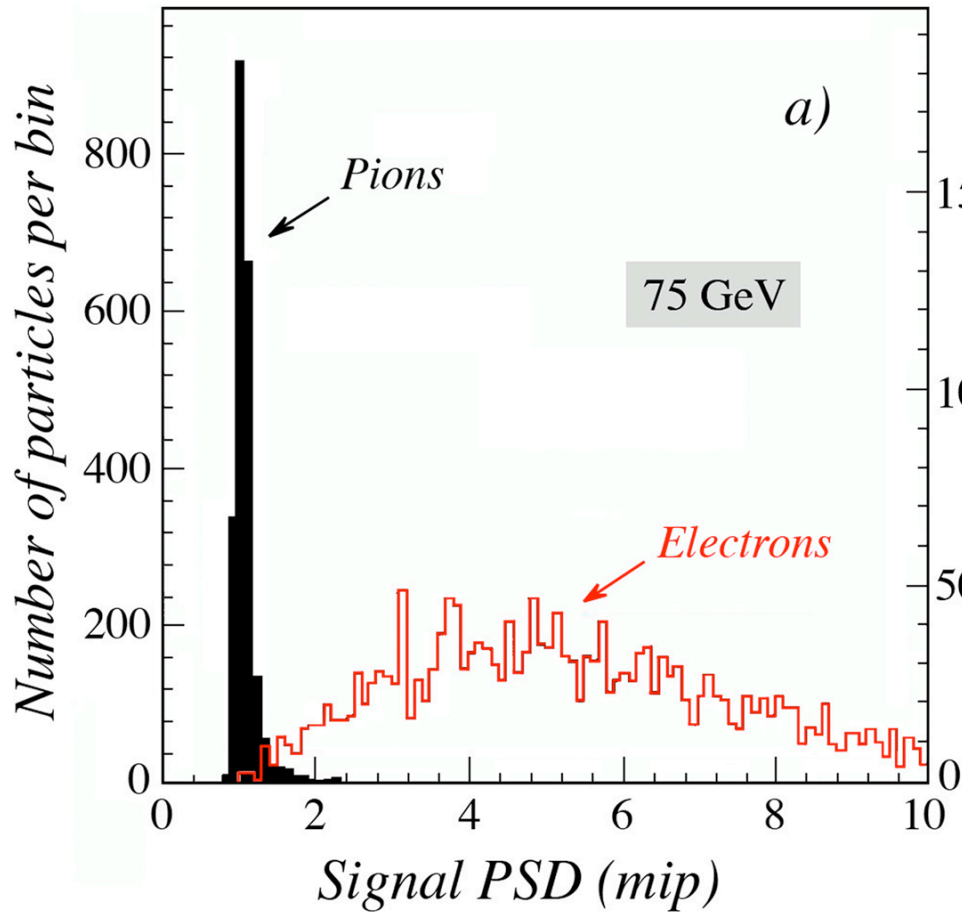
Important calorimeter features

- Energy resolution
- Position resolution (need 4-vectors for physics)
- Signal speed
- Particle ID capability
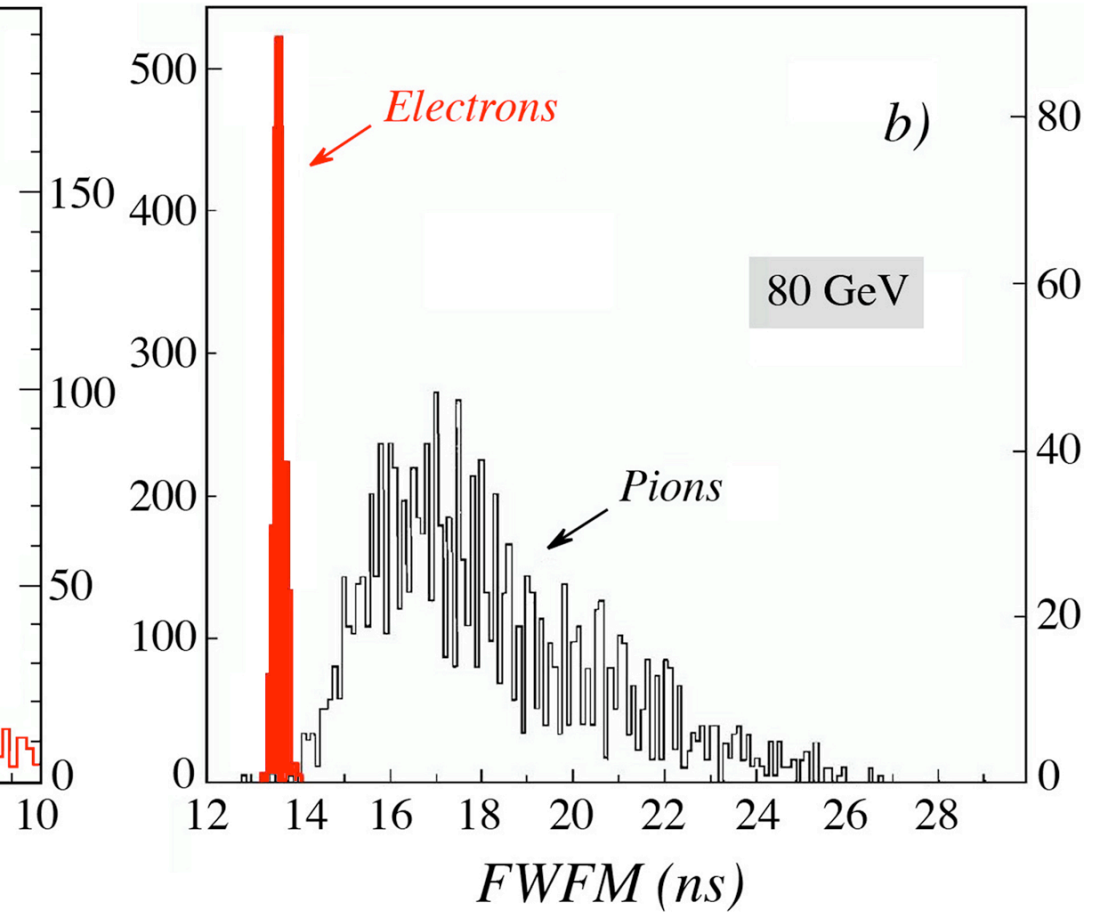
The importance of good energy resolution (1)

Particle identification with calorimeters

Using shower profile (pre-shower detector)
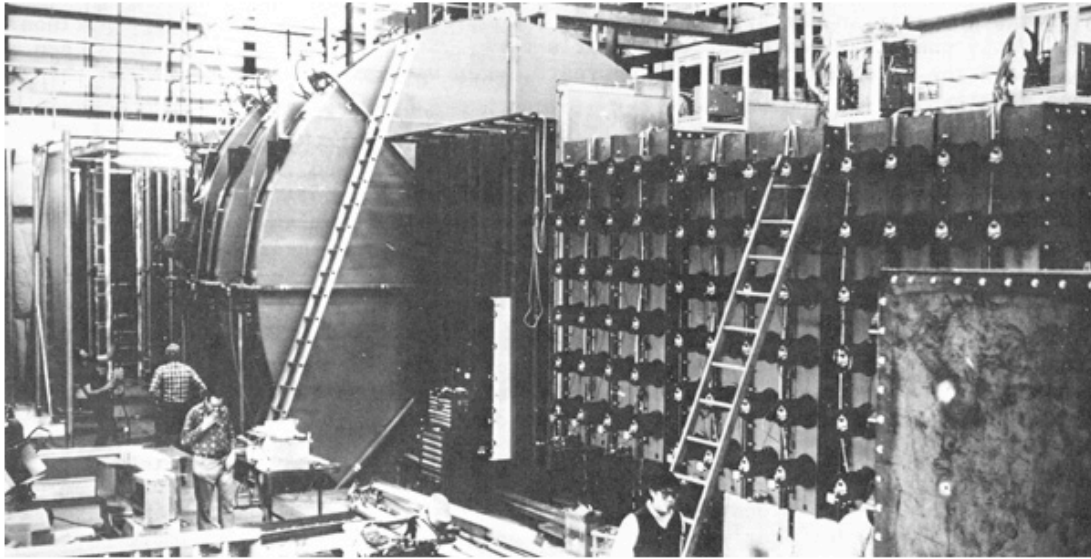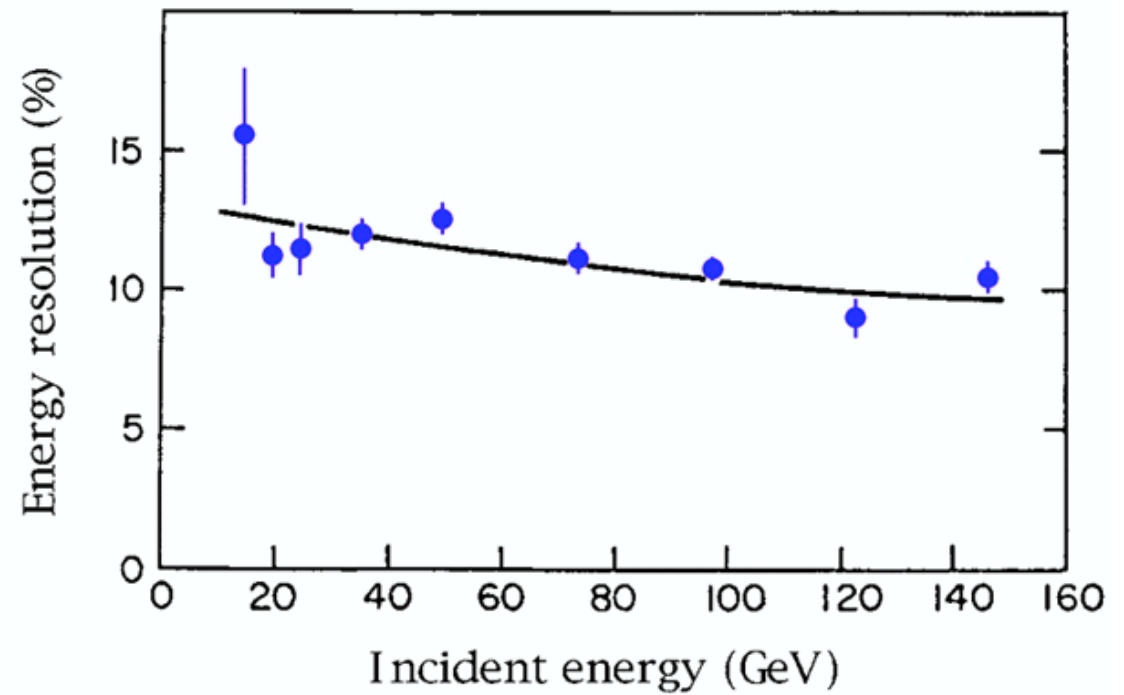
Using time structure of the signals

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)
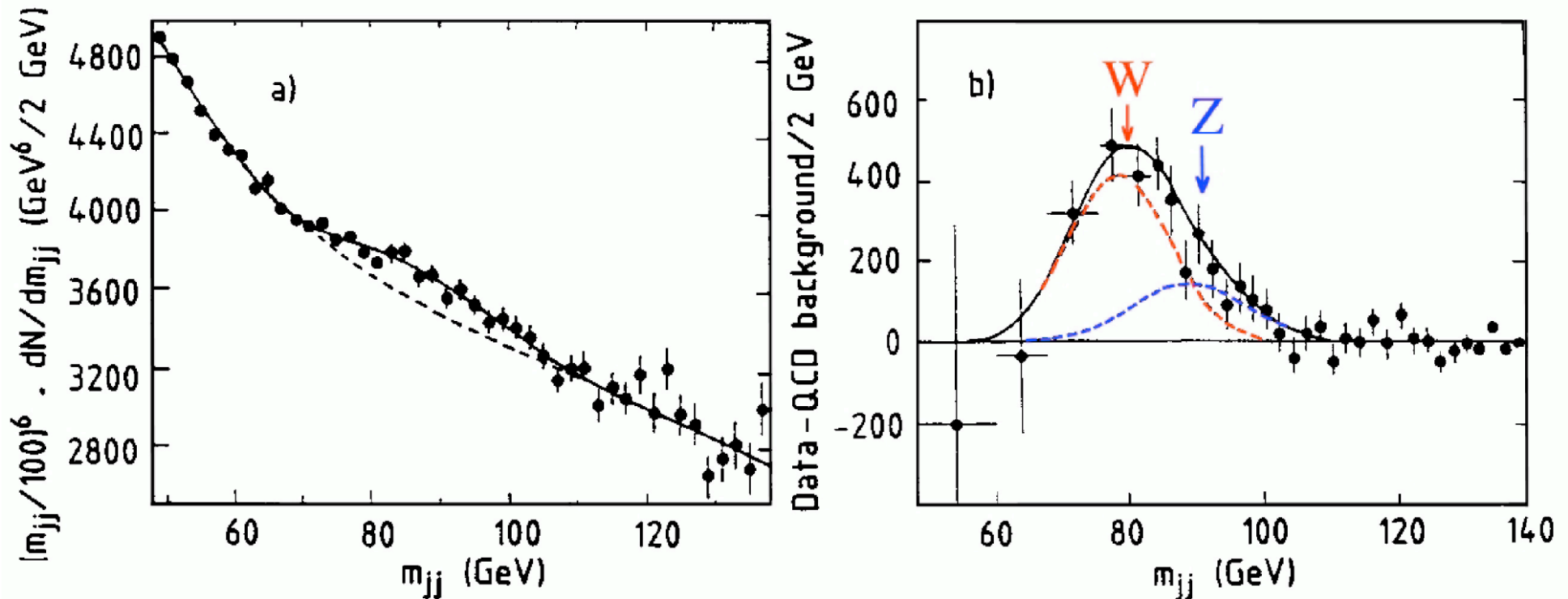

From: NIM 125 (1975) 447

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].
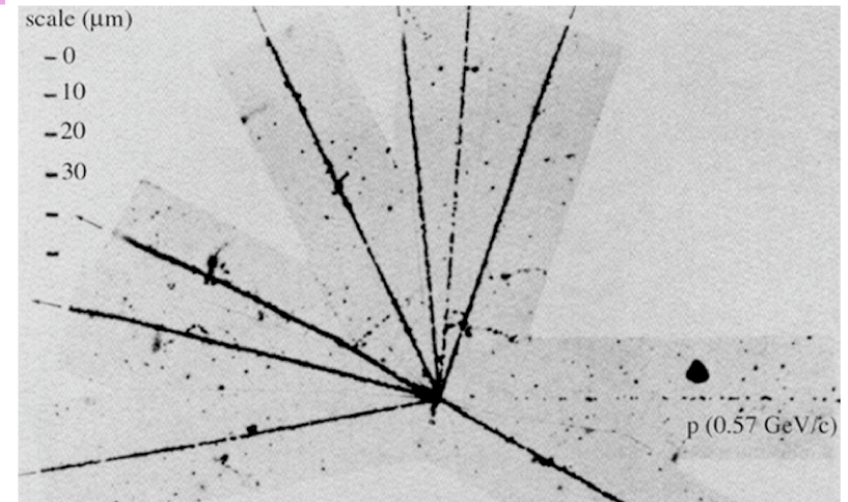
The physics of hadronic shower development

- *A hadronic shower consists of two components*

- **Electromagnetic component**
  - electrons, photons
  - neutral pions $\to 2\,\gamma$

- *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%)
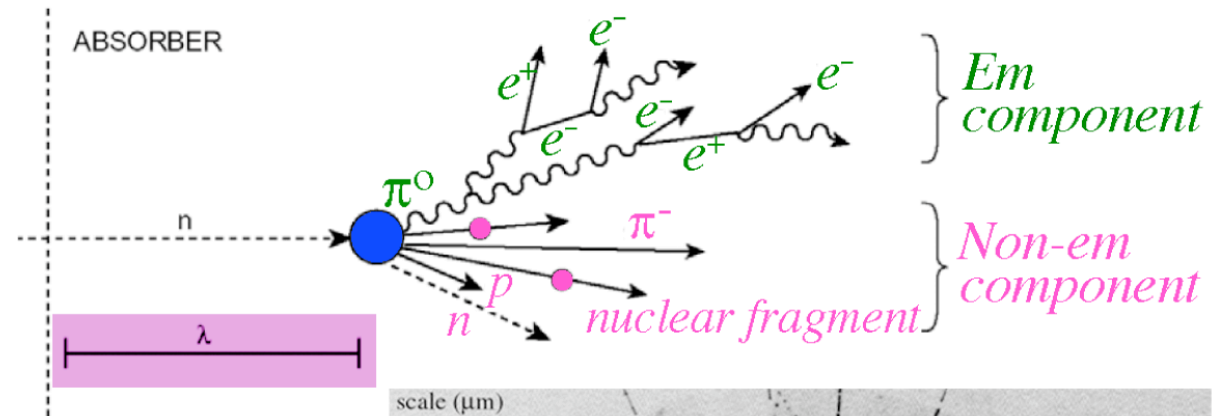
- *Important characteristics for hadron calorimetry:*

  - *Large, non-Gaussian fluctuations in* energy sharing em/non-em

  - *Large, non-Gaussian fluctuations in* "invisible" energy losses

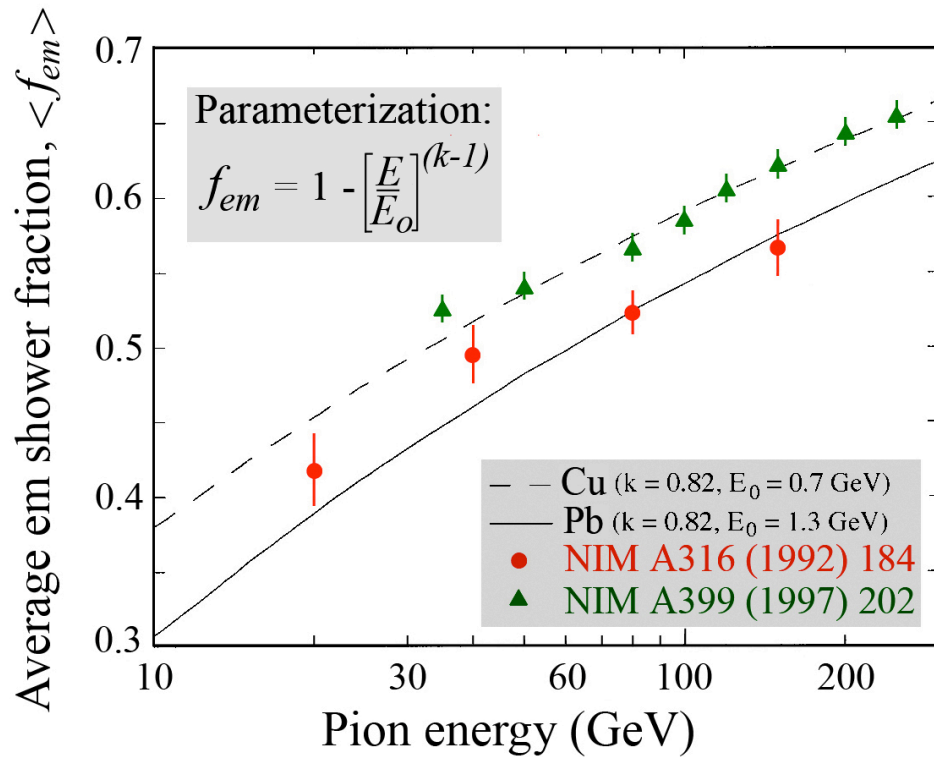*The calorimeter response to the two shower components is NOT the same*

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

$e/h = 1.8$

π^o component

Non-π^o component

"h"

"e"

Number of counts (arb. units)

Signal / GeV (arb. units)
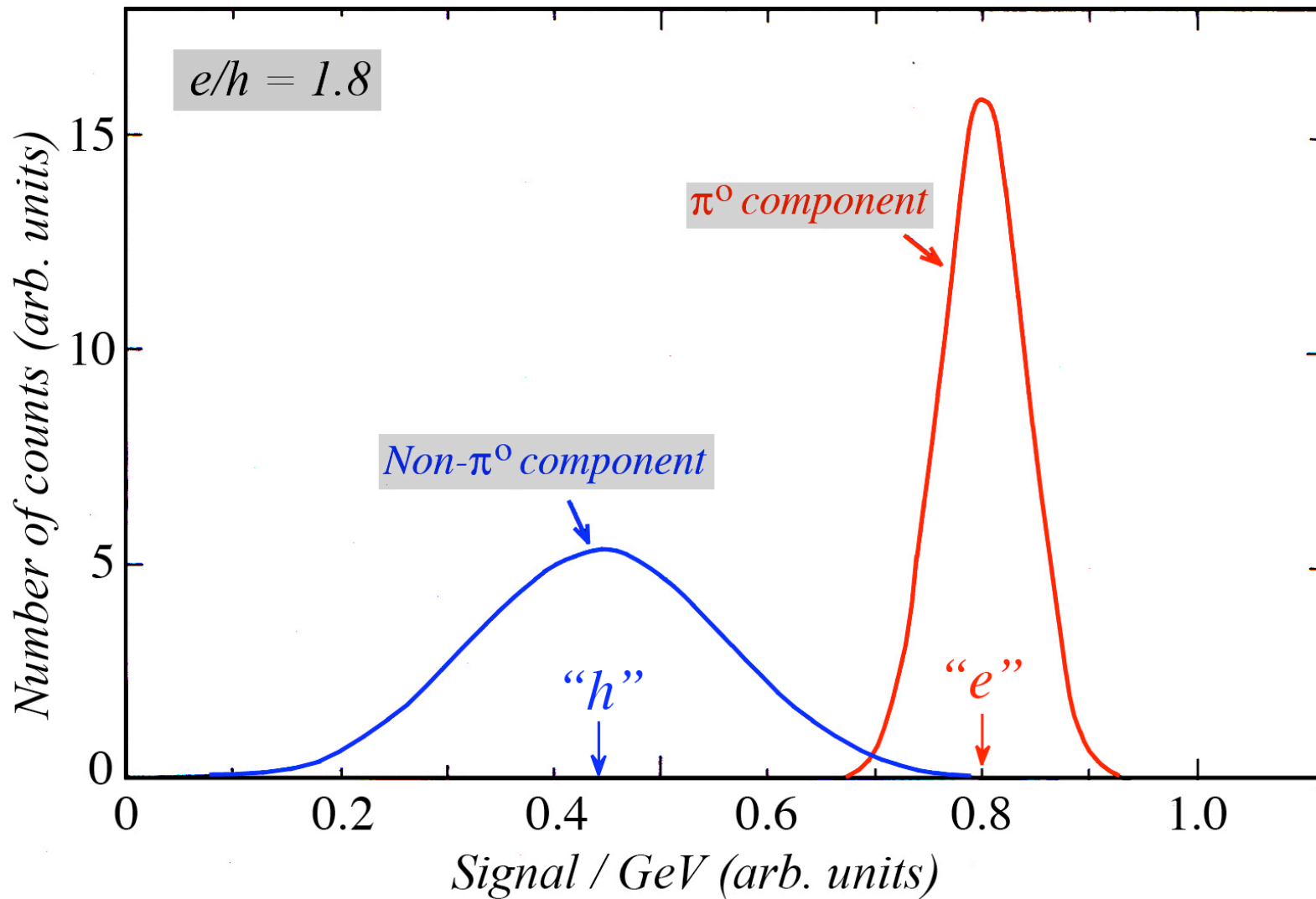
(Fluctuations in) the electromagnetic shower fraction, f_{em}

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

Parameterization:

$$f_{em} = 1 - \left[\frac{E}{E_o}\right]^{(k-1)}$$

- - Cu ($k = 0.82$, $E_0 = 0.7$ GeV)
— Pb ($k = 0.82$, $E_0 = 1.3$ GeV)
● NIM A316 (1992) 184
▲ NIM A399 (1997) 202

150 GeV π

The em fraction is, on average, *large and energy dependent*
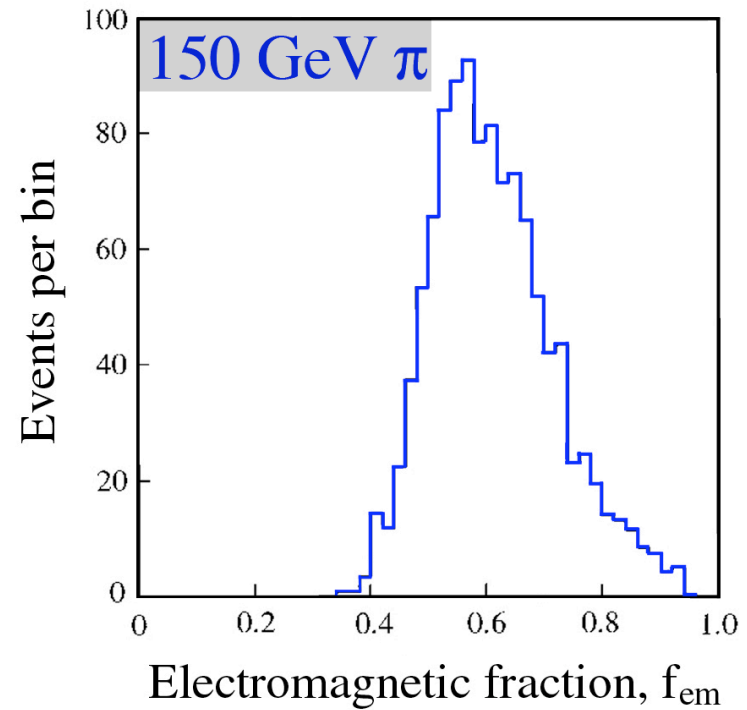
Fluctuations in f_{em} are *large and non-Poissonian*

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

- *Why are these important ?*
  - Electromagnetic calorimeter response ≠ non-em response *(e/h ≠ 1)*
  - Event-to-event fluctuations are large and *non-Gaussian*
  - *<f_{em}> 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!

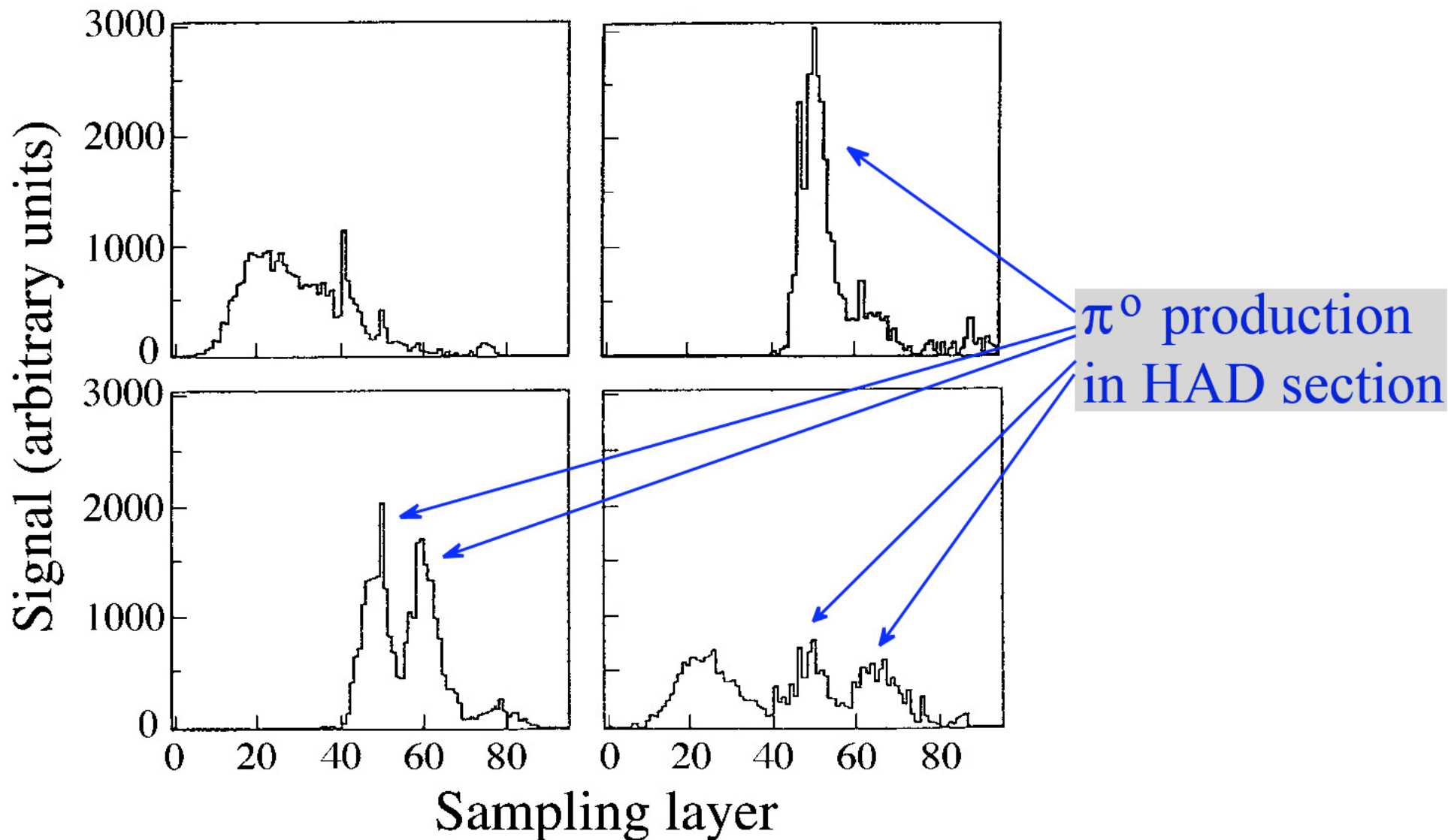## π⁰ production may take place anywhere in the absorber

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].
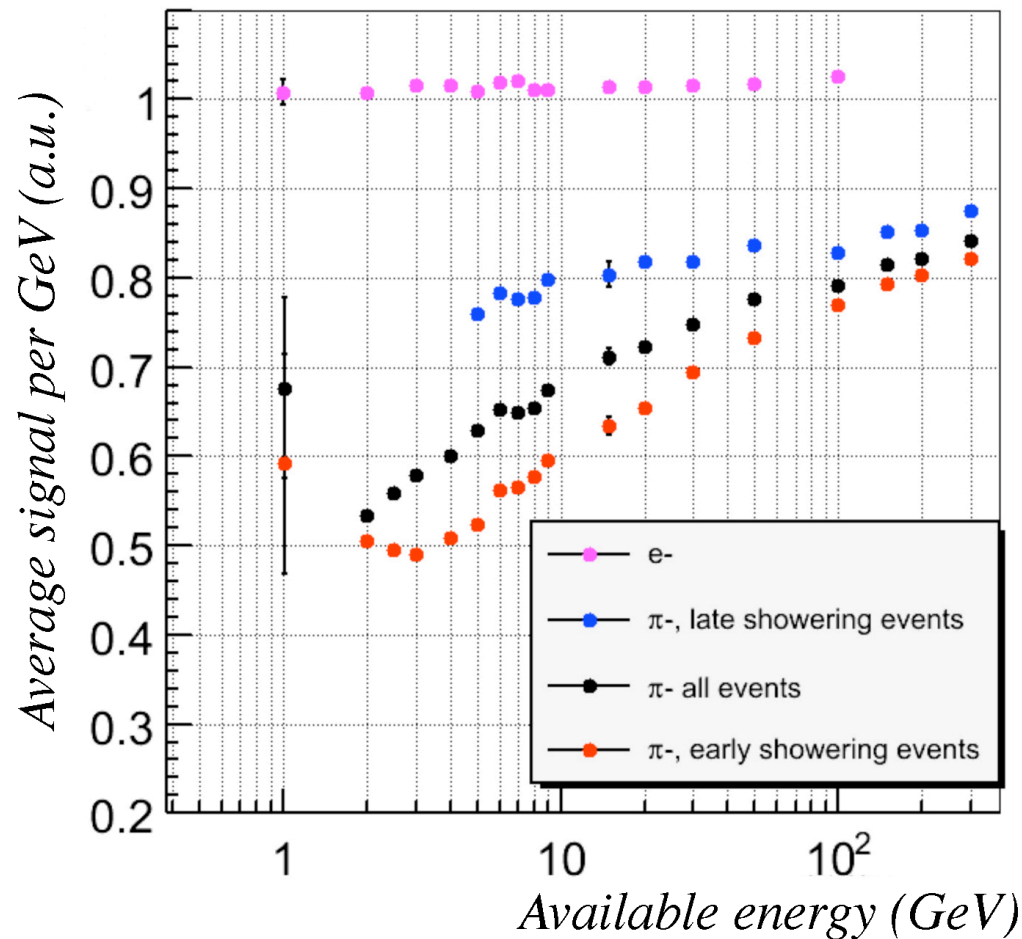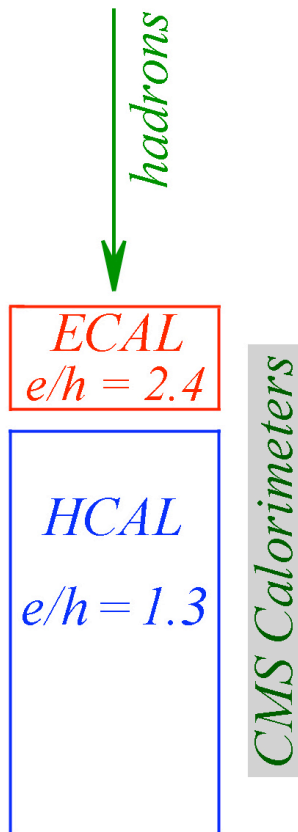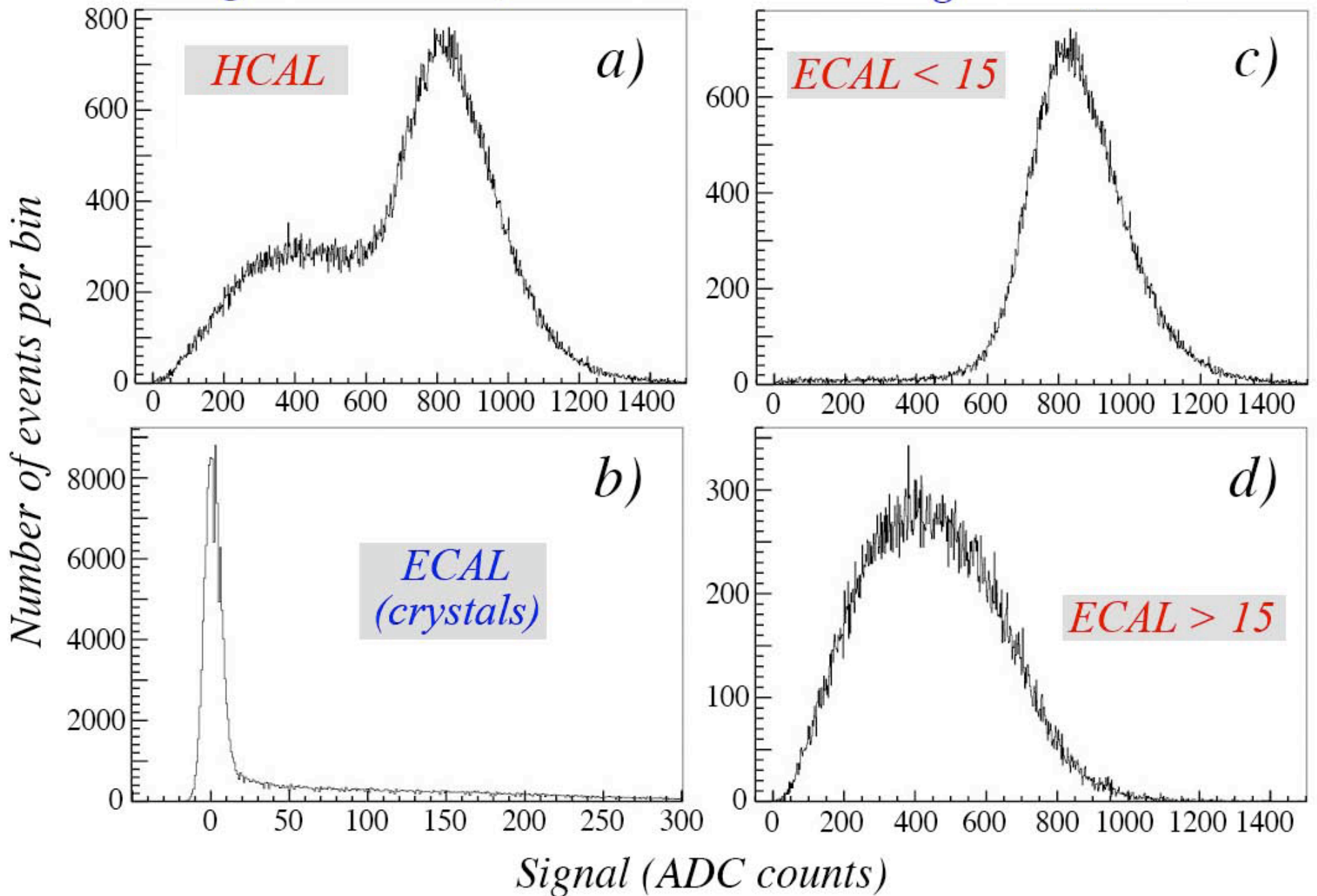
Pion signals in crystal ECAL + scintillator HCAL

Signals HCAL, ECAL

Signal 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

10 GeV π

σ = 1.1 GeV

40 GeV π

σ = 2.3 GeV

150 GeV π

σ = 5.2 GeV

Events / pC

Signal (pC)
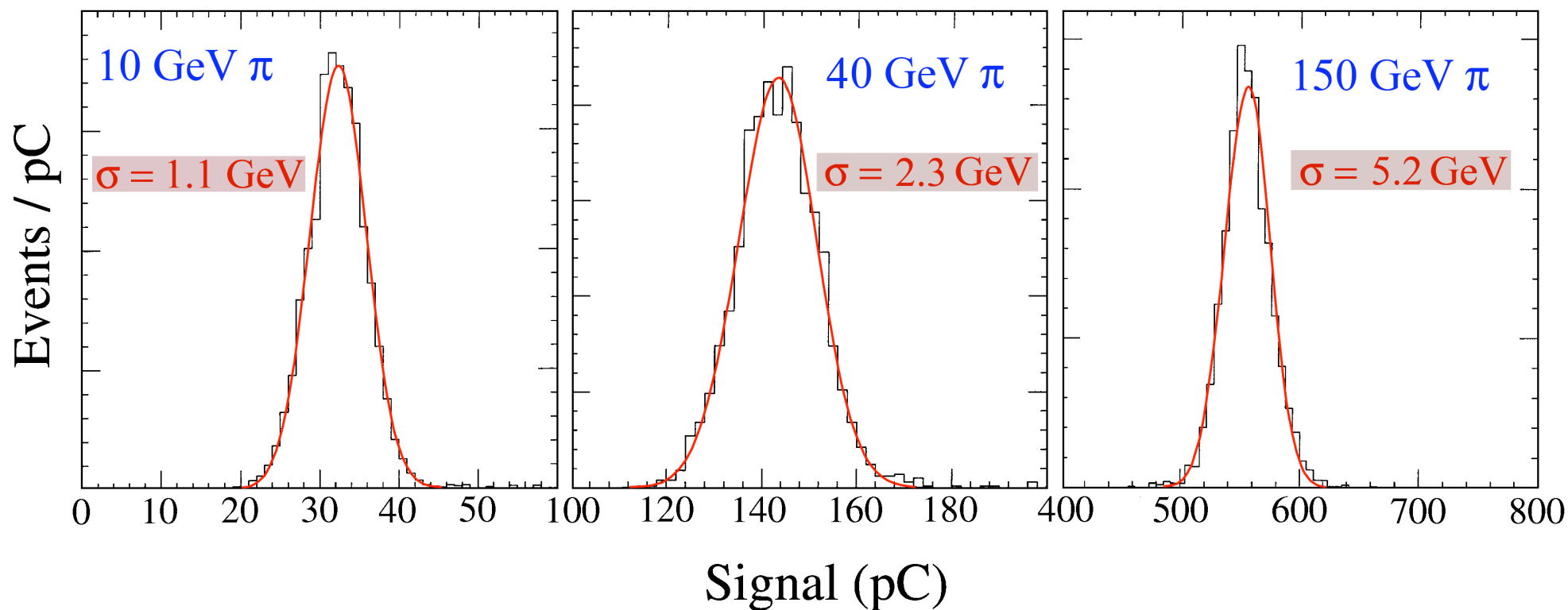
from: NIM A308 (1991) 481

SPACAL 1989
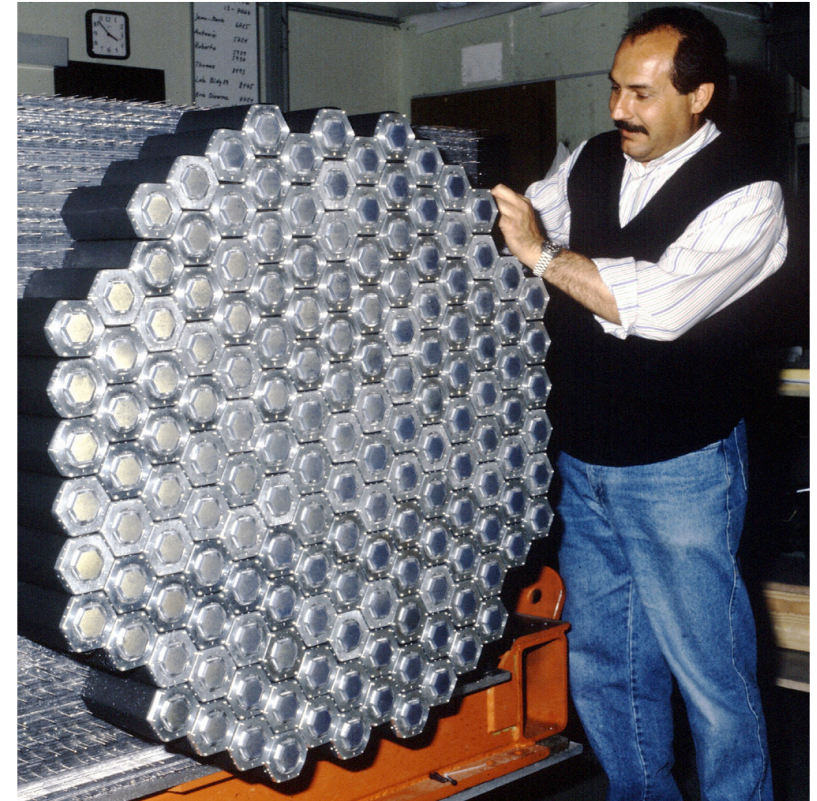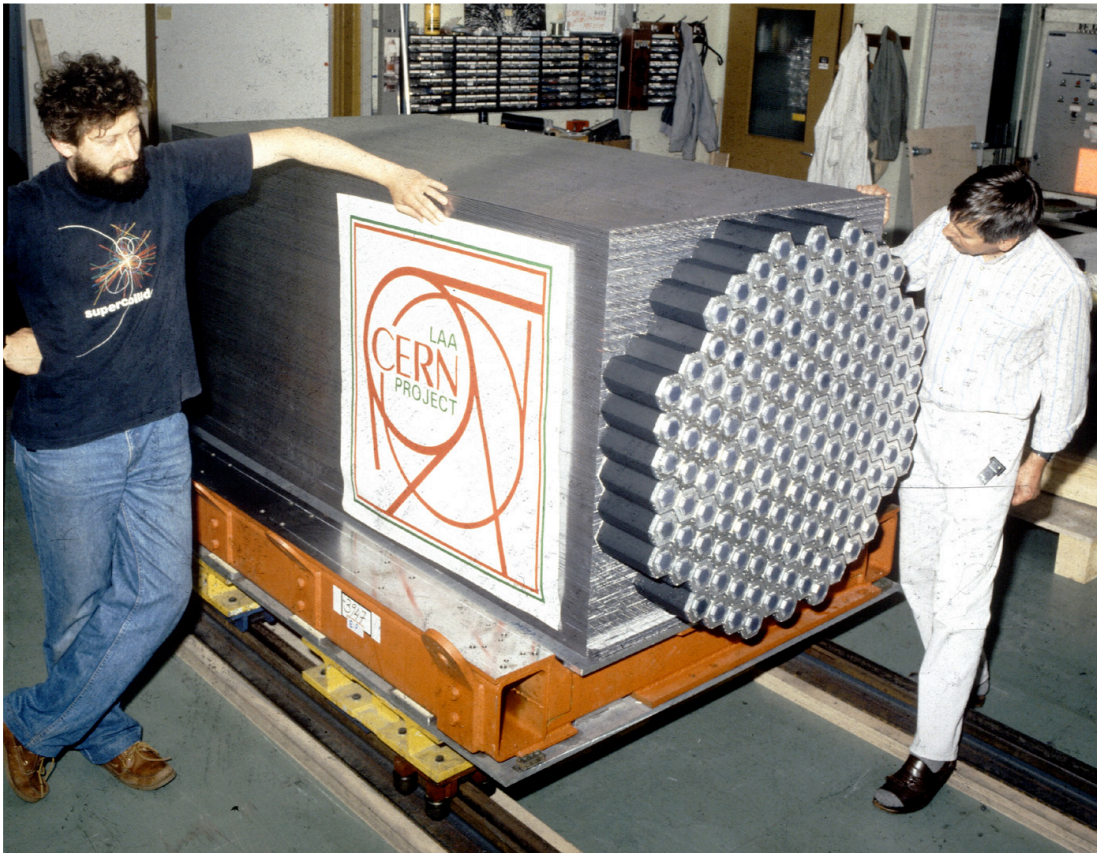
Hadron calorimetry in practice
Energy resolution in a *compensating* calorimeter

from:
NIM A279 (1989) 503

$$\frac{\Delta m}{m} = 0.13$$

Peaks labelled by mass number A

A = 2·Z nuclei

Events per bin

Energy (ADC channels)
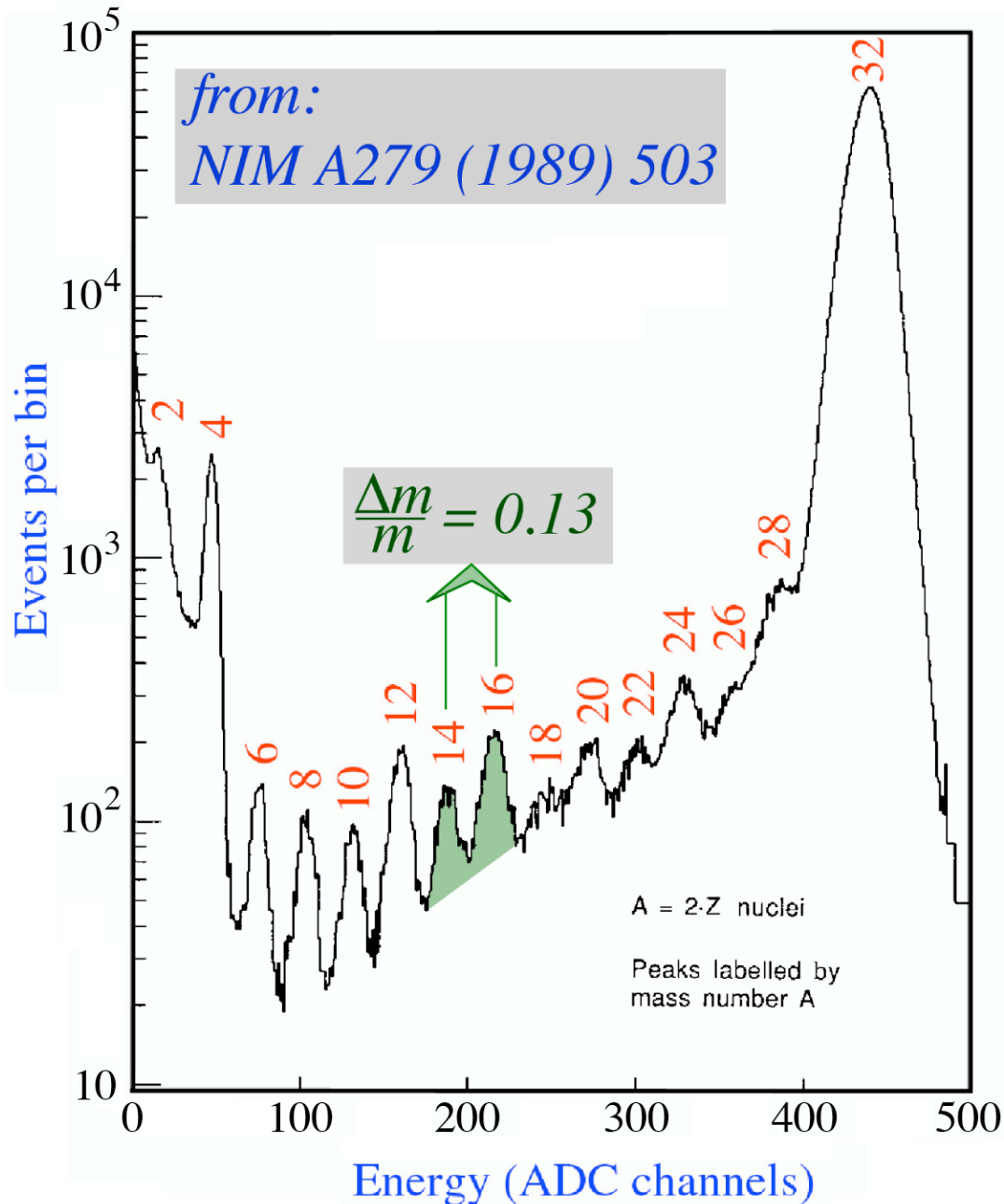
W/Z separation:
$$\frac{\Delta m}{m} \sim 0.11$$

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)
  $\longrightarrow$ *em energy resolution limited* (SPACAL: $13\%/\sqrt{E}$, ZEUS: $18\%/\sqrt{E}$)

- Compensation relies on detecting neutrons
  $\longrightarrow$ Large *integration volume*
  $\longrightarrow$ 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 $\Big\langle$ *em* component (π^0)
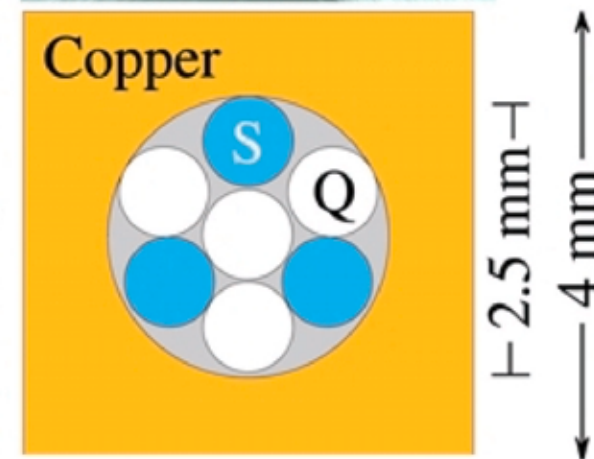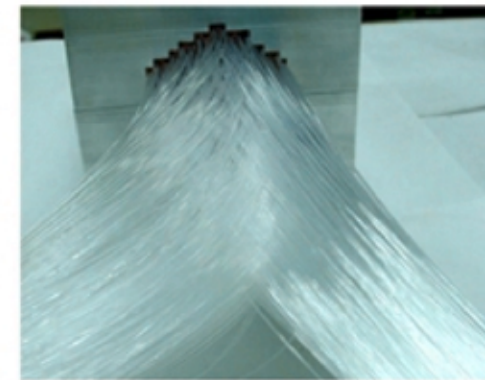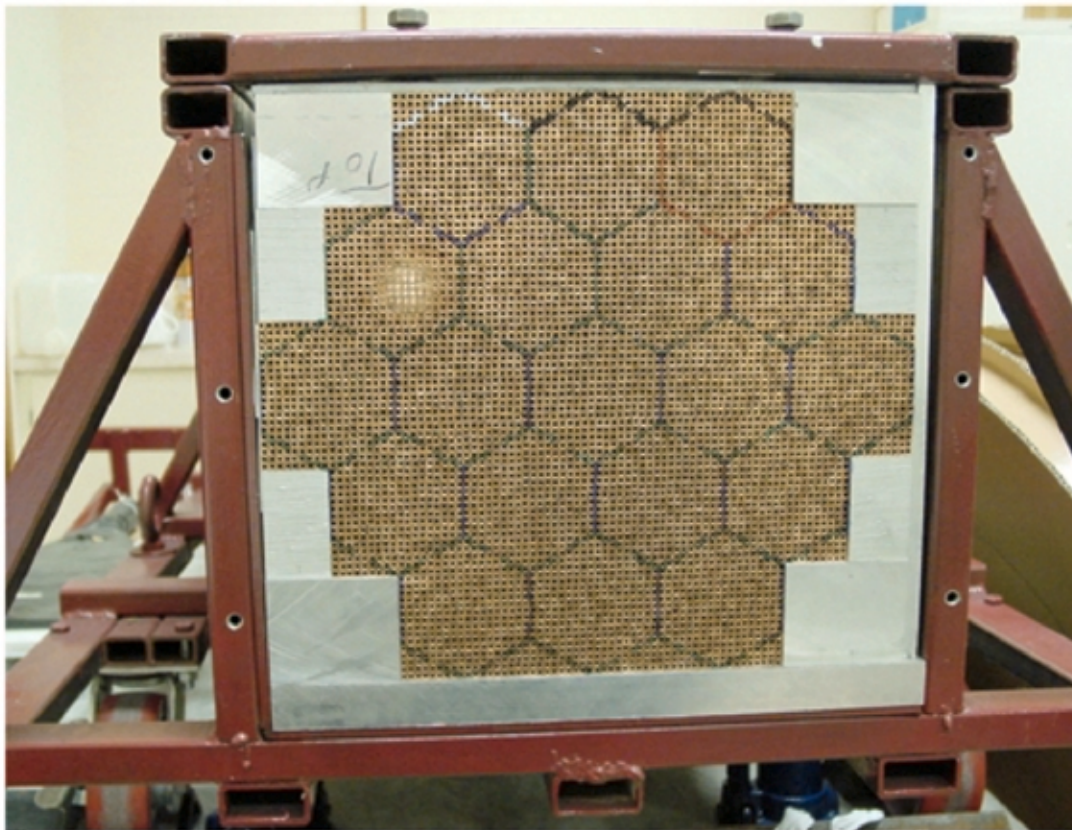*non-em* component (mainly soft p)

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
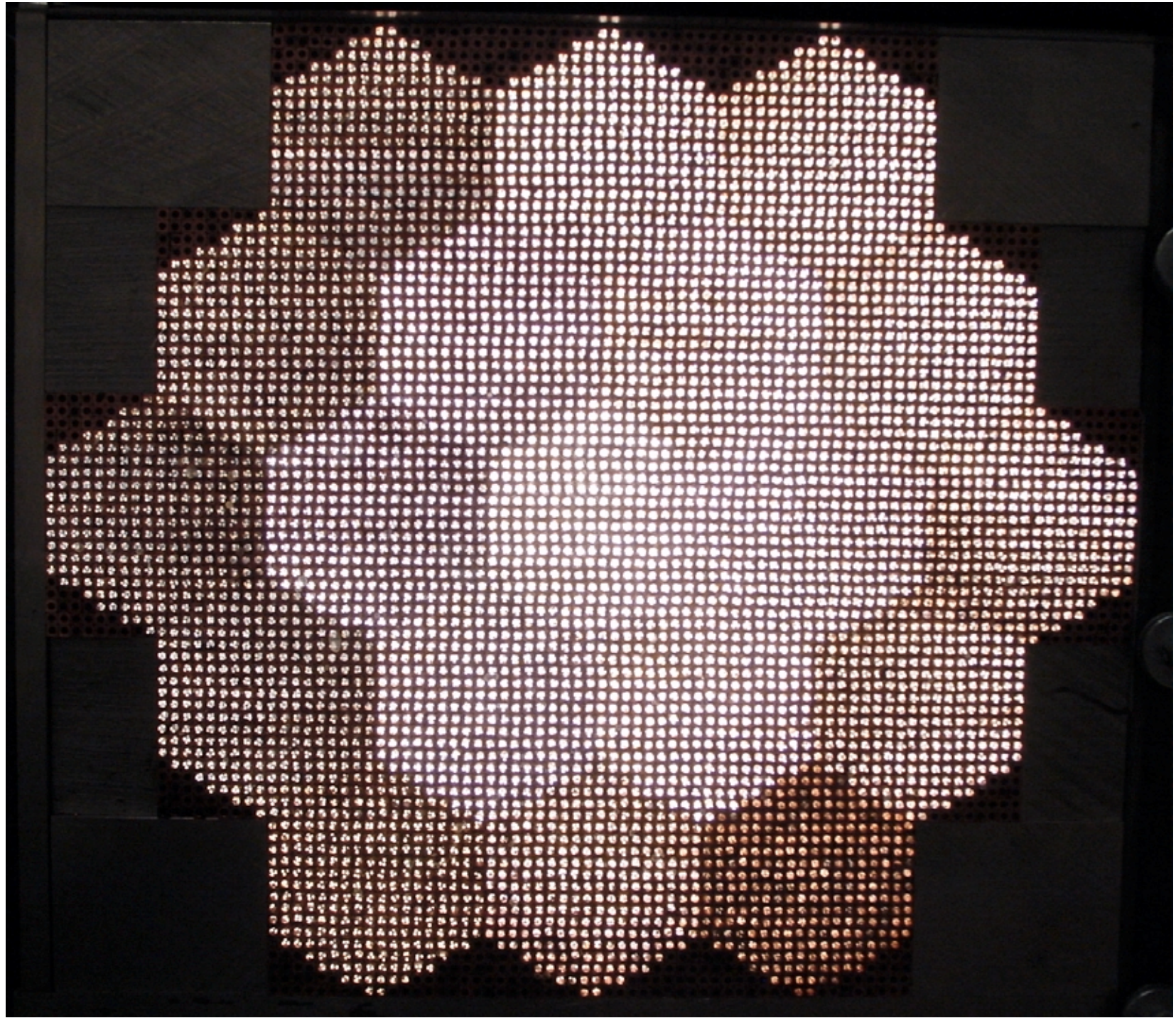
DREAM: Structure

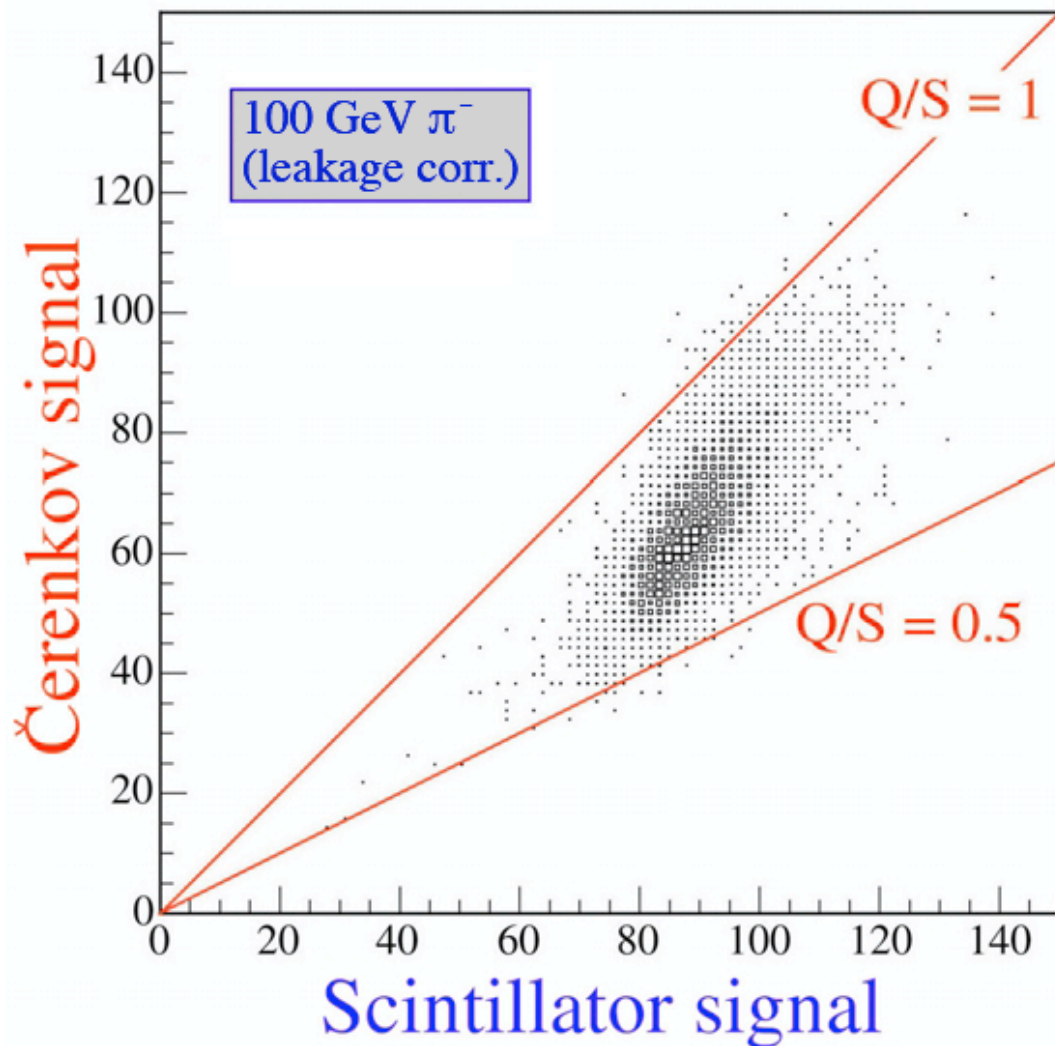

- *Some characteristics of the DREAM detector*
  - **Depth** 200 cm (10.0 λ_{int})
  - Effective **radius** 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - **Mass** instrumented volume 1030 kg
  - Number of **fibers** 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal **towers** (19), each read out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

DREAM readout

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

100 GeV π^-
(leakage corr.)

$Q/S = 1$

$Q/S = 0.5$

Čerenkov signal

Scintillator signal

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

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

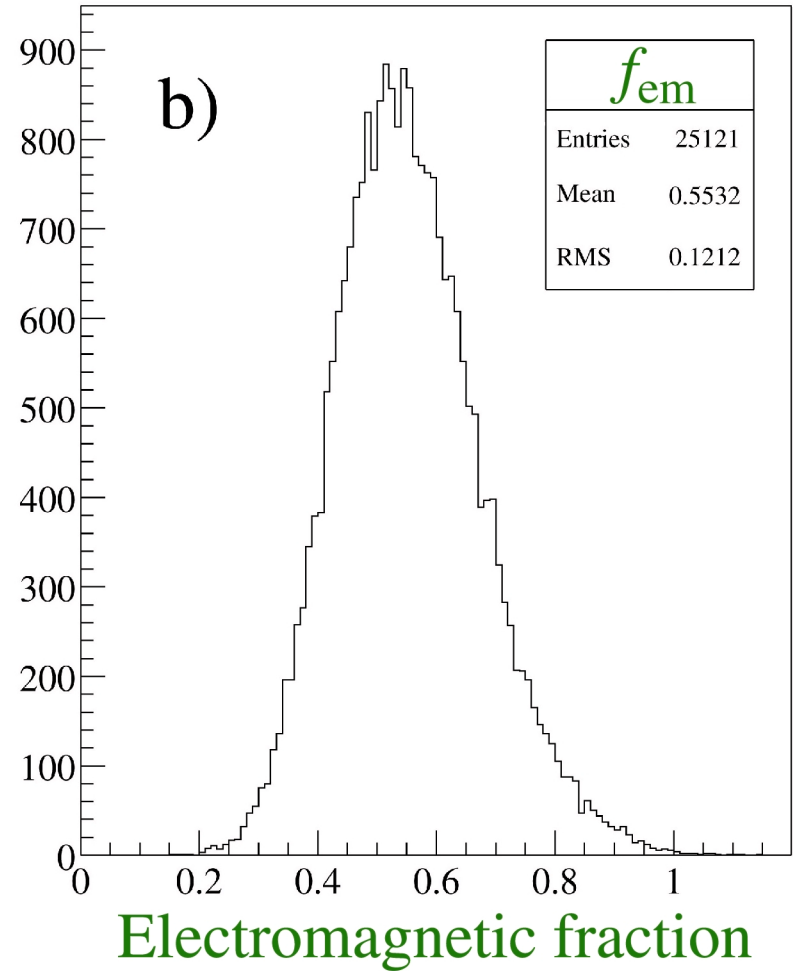$e.g.$ If $\quad e/h = 1.3\ (S),\ 4.7\ (Q)$

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

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

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

DREAM: relationship between Q/S ratio and f_{em}
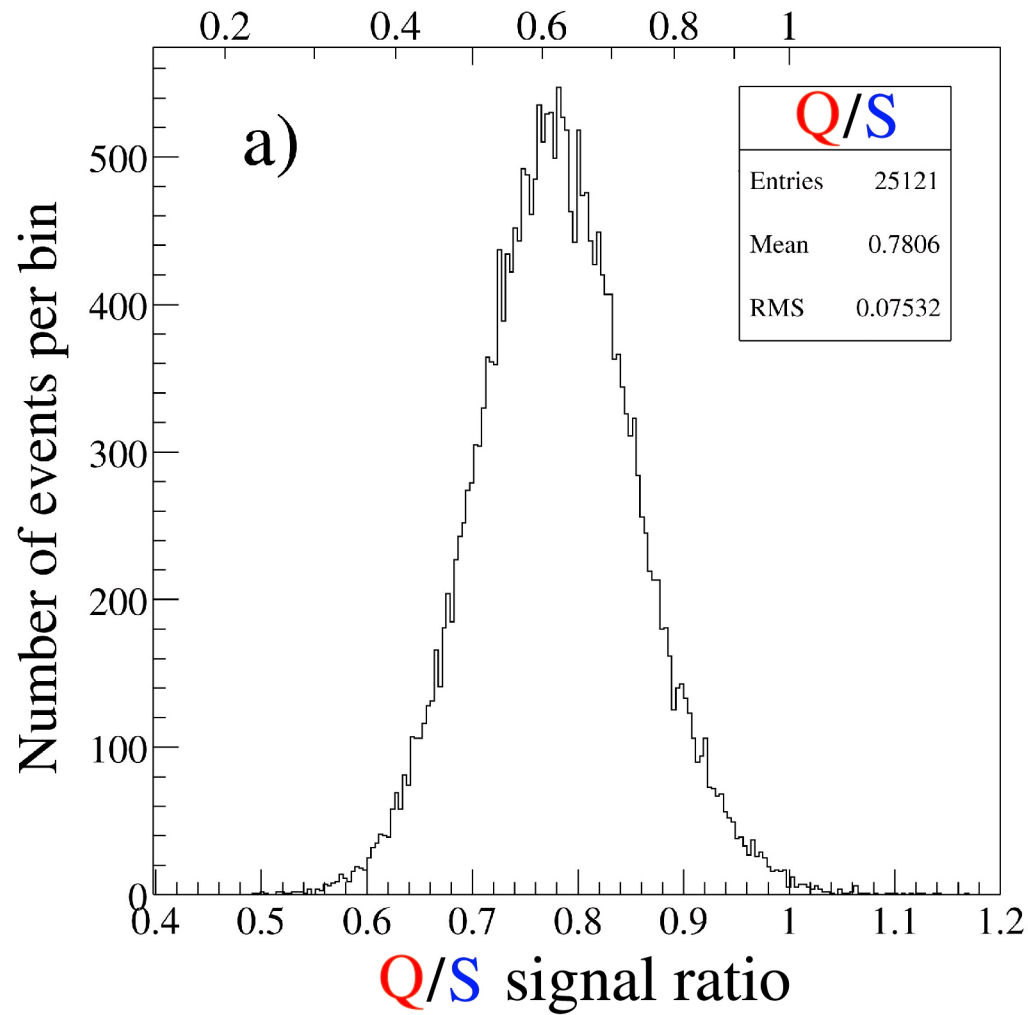
DREAM: Effect of event selection based on f_{em}

Entries 78198
Mean 66.1
RMS 12.4

100 GeV π^-
Č signal

Number of events per GeV

0.35 < f_{em} < 0.40
0.60 < f_{em} < 0.65
0.80 < f_{cm} < 0.85

Čerenkov signal (GeV)

From:
NIM A537 (2005) 537

DREAM: Signal dependence on f_{em}

Scintillator signals

$\langle S \rangle = 149.8 + 38.5\, f_{em}$

200 GeV "jets"

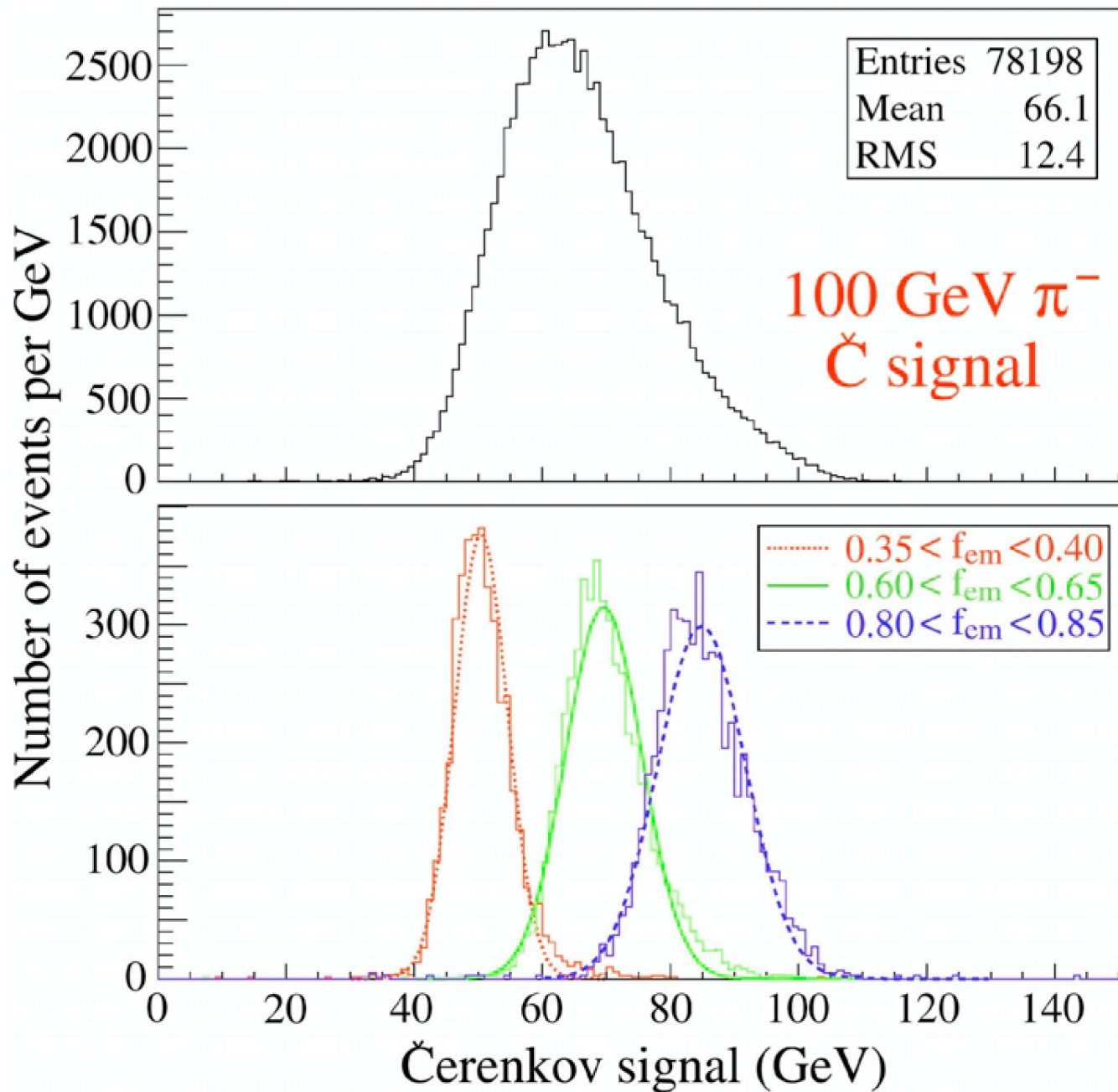Average scintillator signal

Electromagnetic shower fraction, f_{em}

Čerenkov signals

$\langle \check{C} \rangle = 40 + 148\, f_{em}$

200 GeV "jets"

Average Čerenkov signal (GeV)

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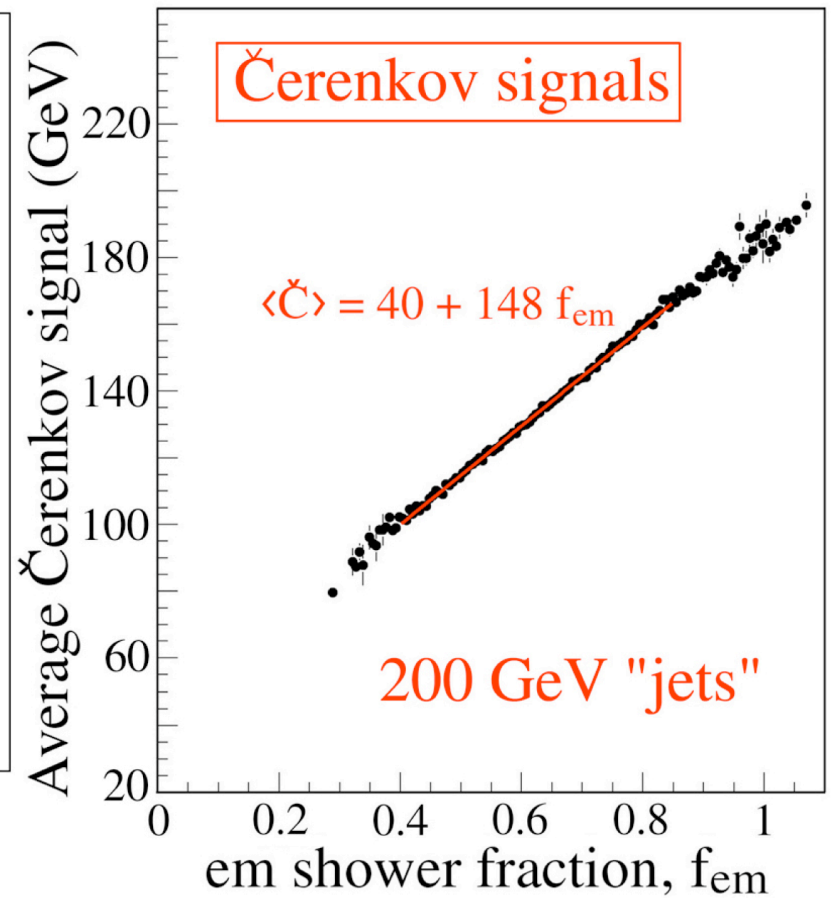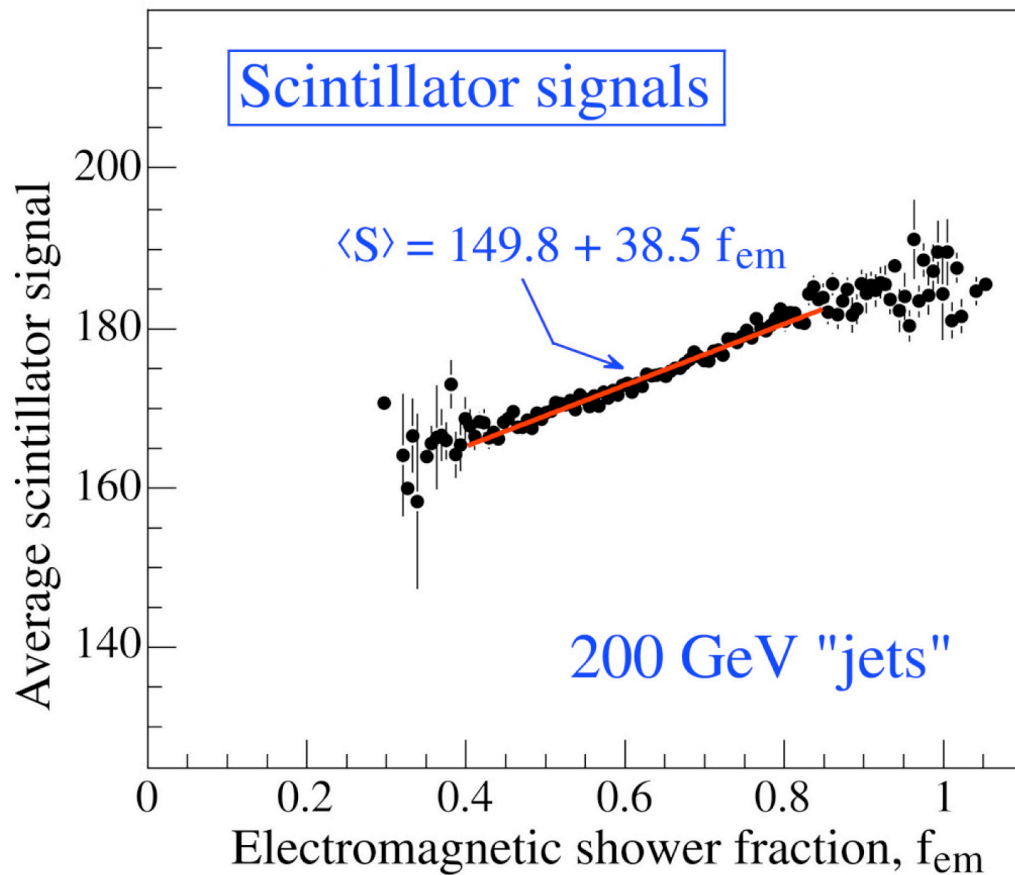
$$R(f_{em}) = p_0 + p_1\, f_{em} \quad \text{with} \quad \frac{p_1}{p_0} = e/h - 1$$

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

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

Uncorrected

Entries 13507
Mean 133.1
RMS 18.6

Q/S method

Entries 13507
χ^2/ndf 292/158
Mean 190.1
Sigma 9.69

Events per GeV

Čerenkov signal (GeV)
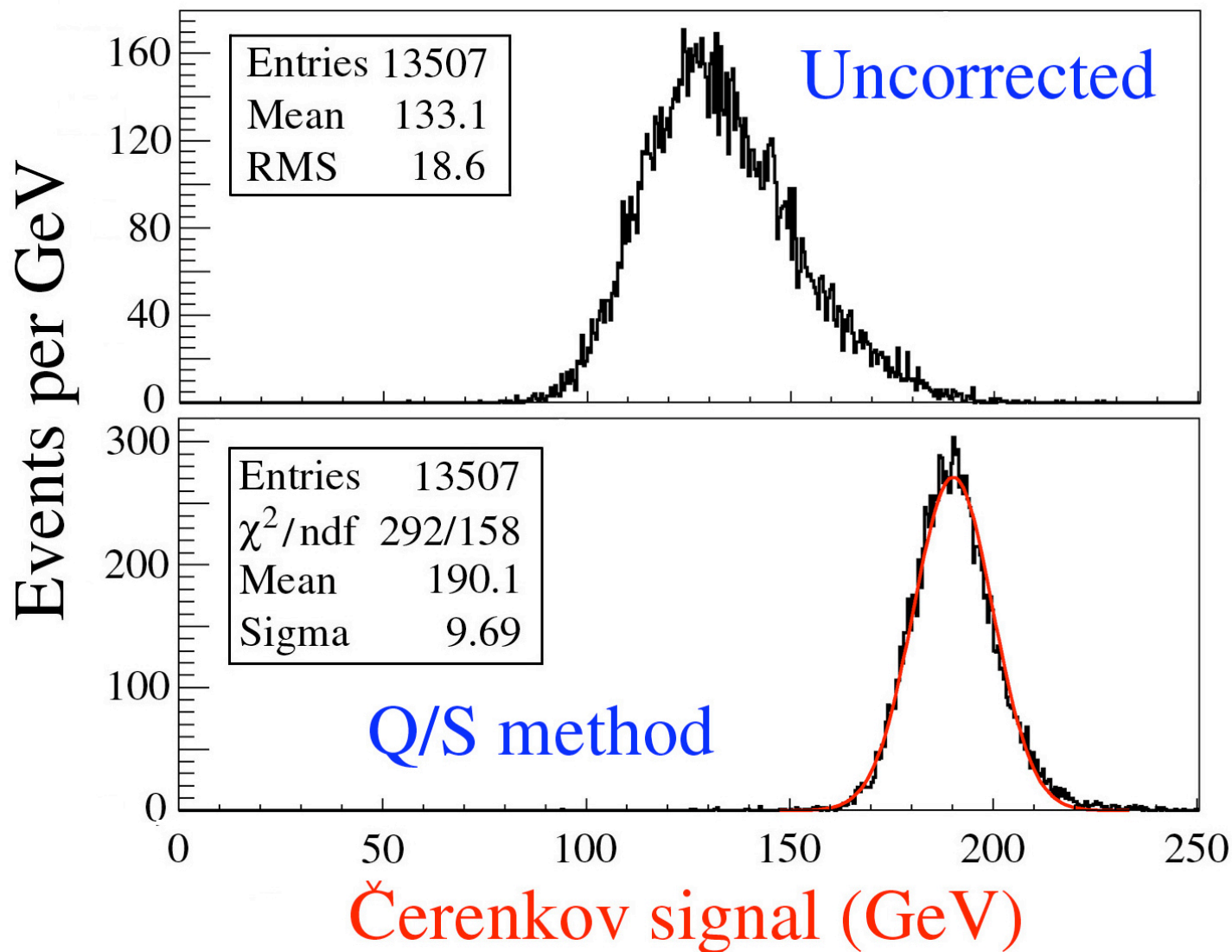
Effects of Q/S corrections on

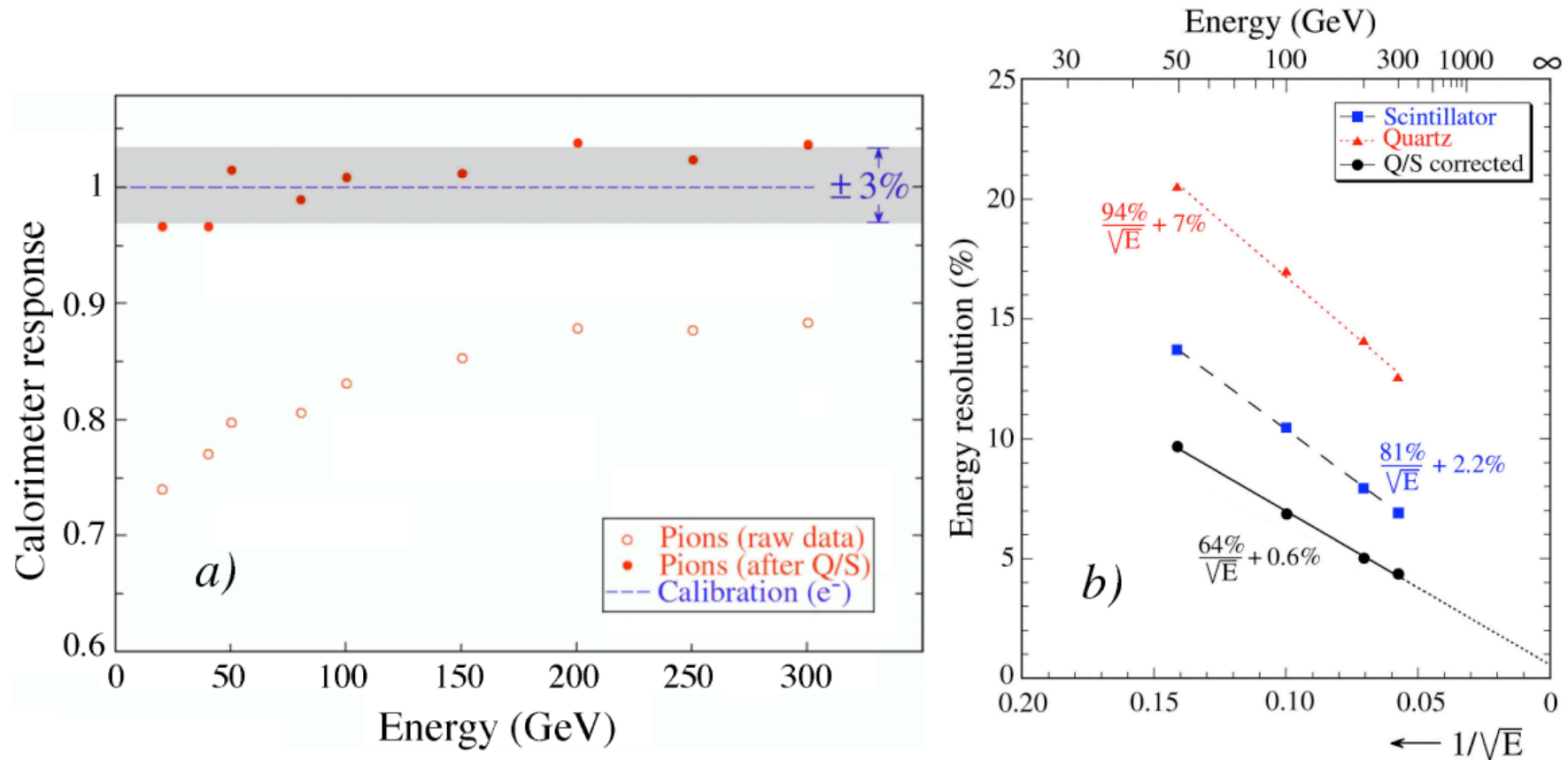## *hadronic signal linearity* *and* *jet resolution*

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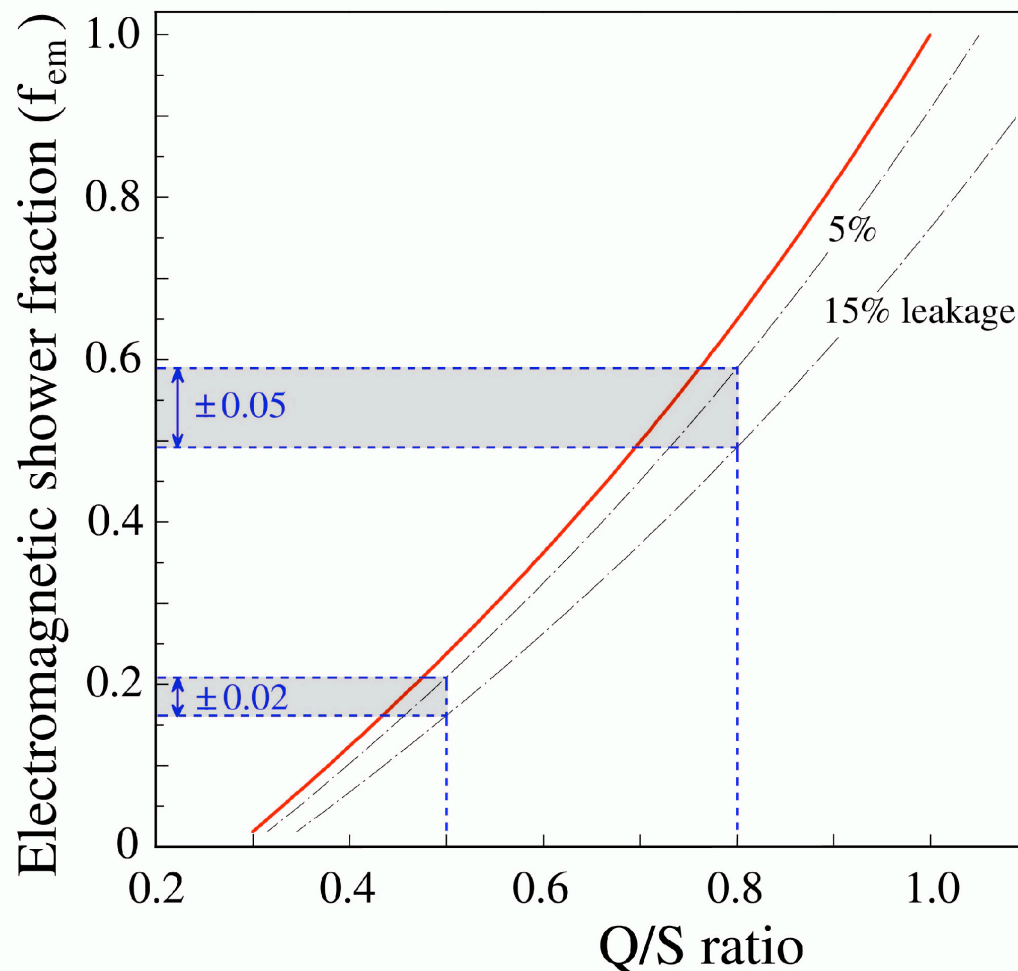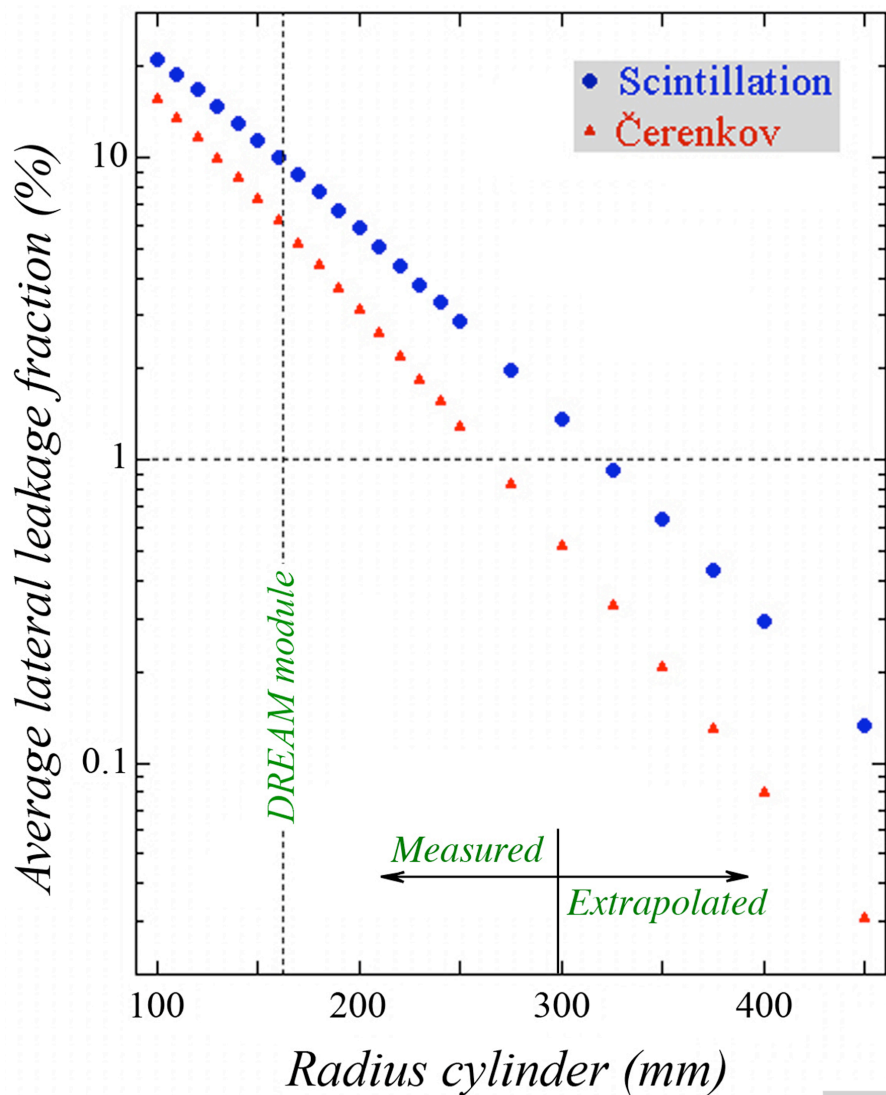*The same advantages as intrinsically compensating calorimeters (e/h = 1)*
WITHOUT the limitations (sampling fraction, integration volume, time)

How to improve DREAM performance

- Build a larger detector $\longrightarrow$ *reduce effects side leakage*

DREAM: The importance of leakage and its fluctuations

Lateral shower containment (π)

From:
NIM A584 (2008) 273

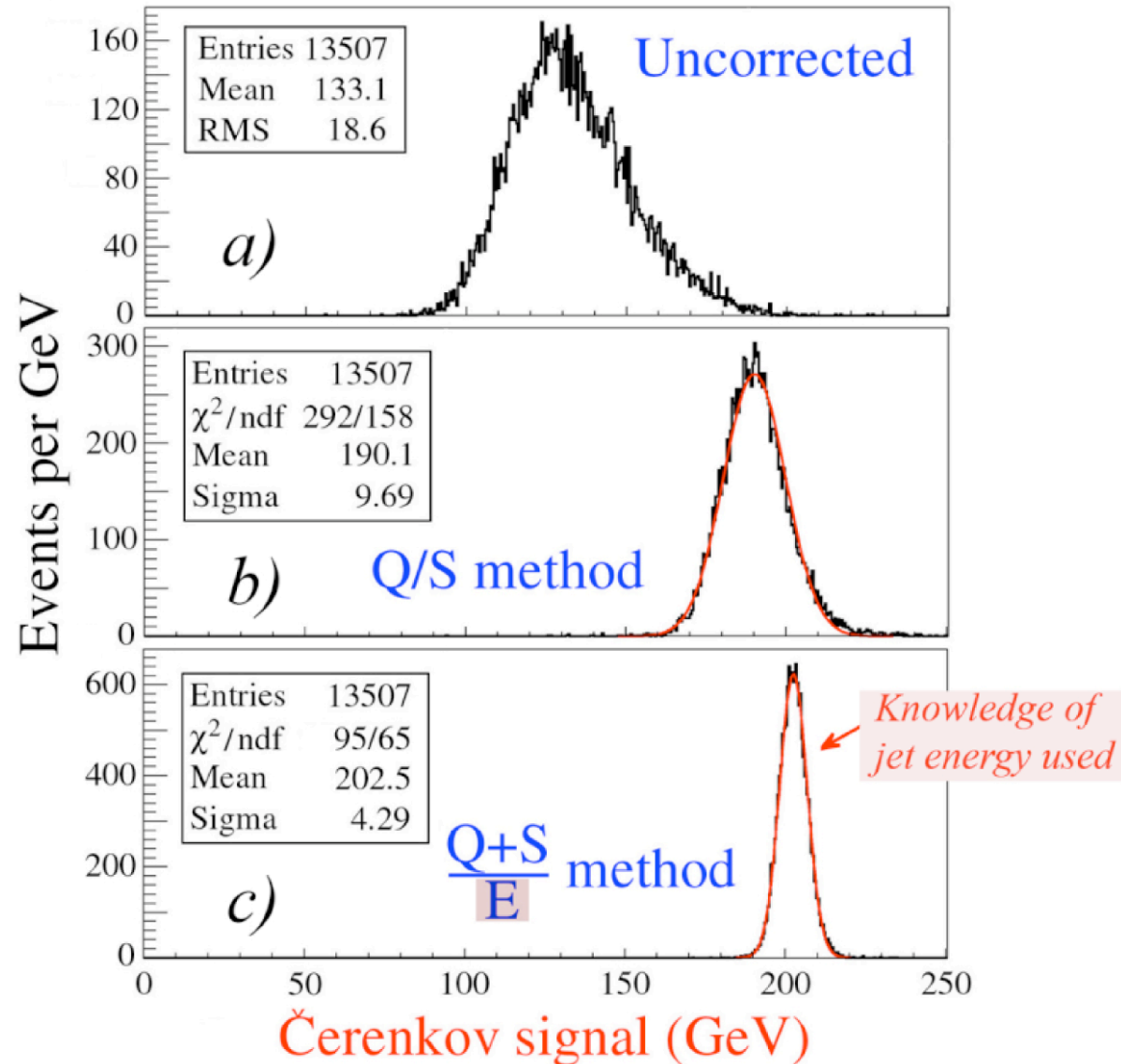# *Expected effect of full shower containment*

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 $\longrightarrow$ *reduce effects side leakage*

- *Increase Čerenkov light yield*
  DREAM: 8 p.e./GeV $\longrightarrow$ 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.

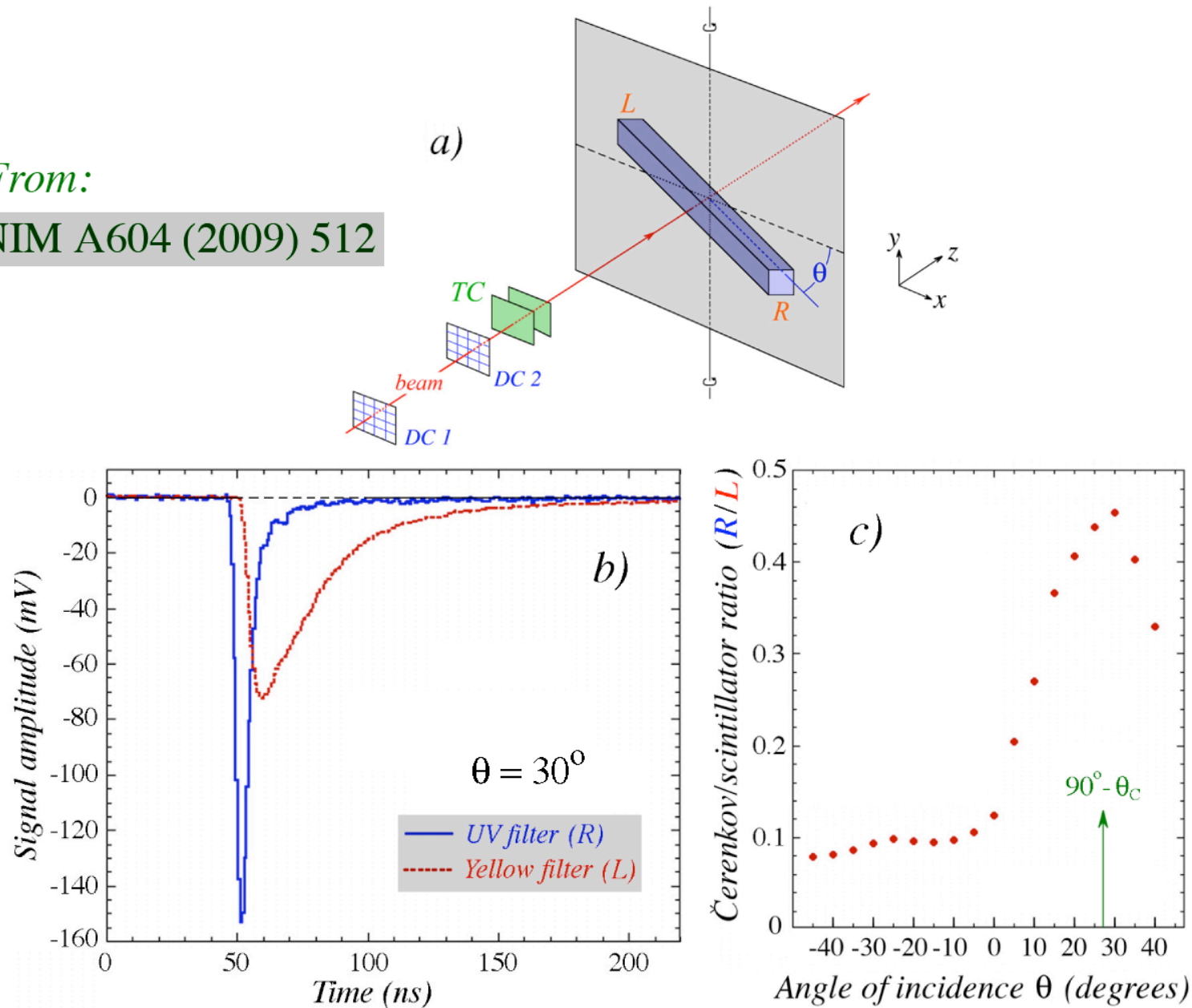# Separation of PbWO4 :1%Mo signals into S, Č components

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*

μ
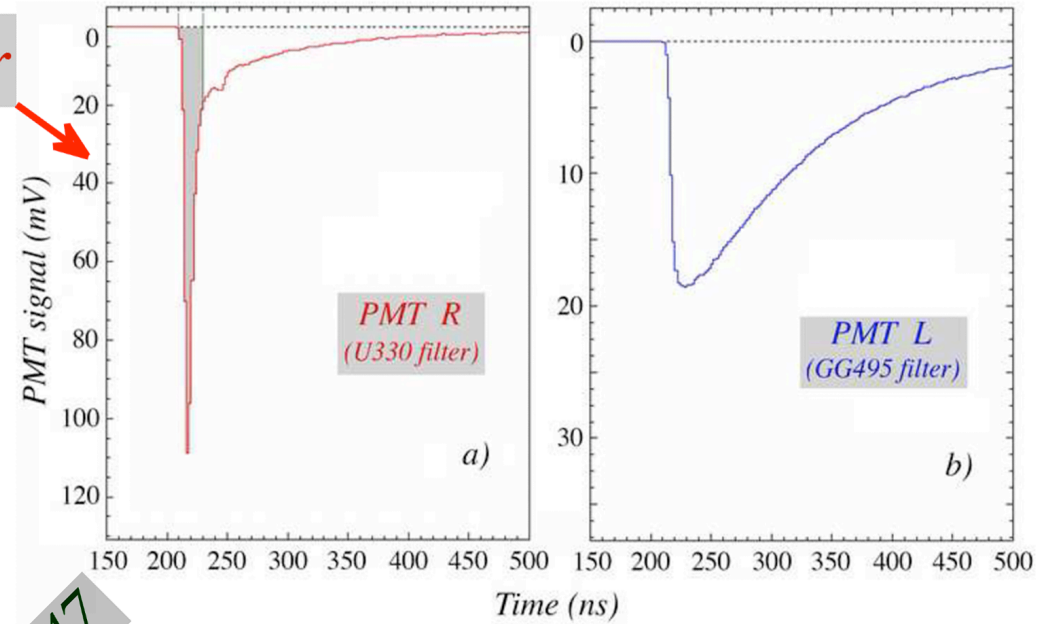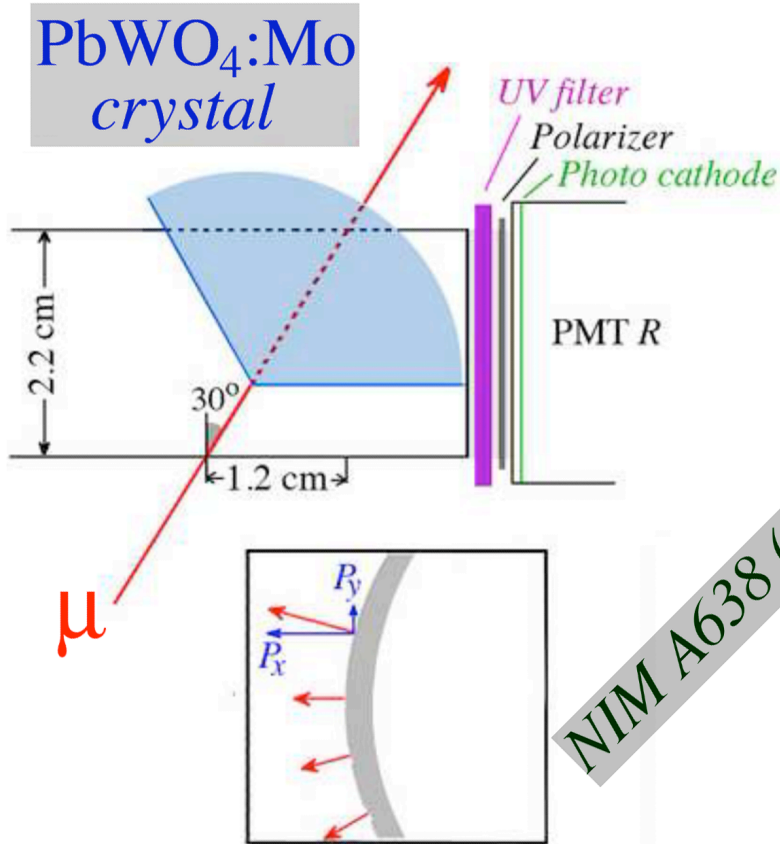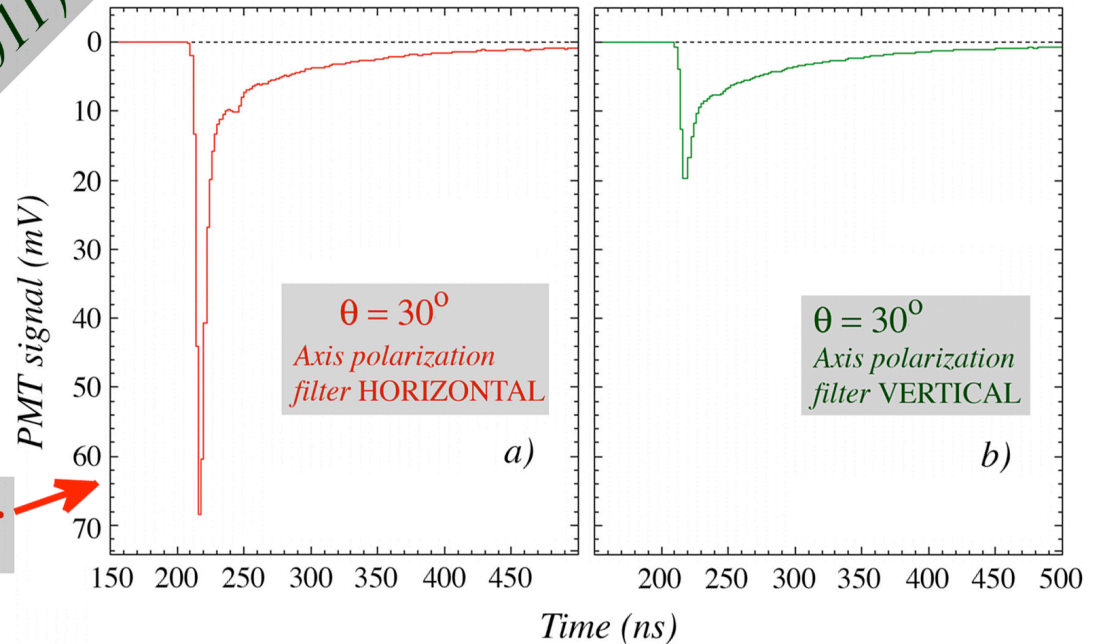
Effects of the polarization filter

NIM A638 (2011) 47

Čerenkov *and* Scintillator *information from one signal !*
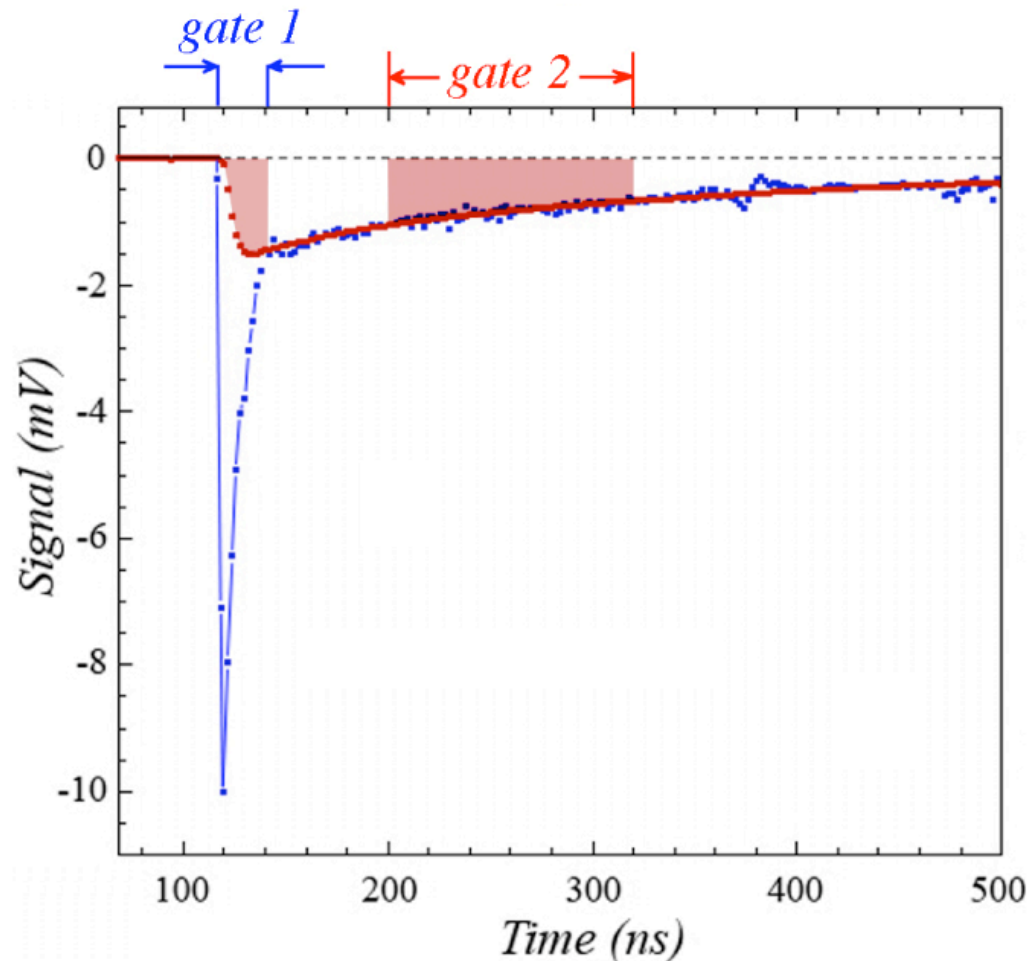
BGO crystal
UG 11 (UV) filter

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
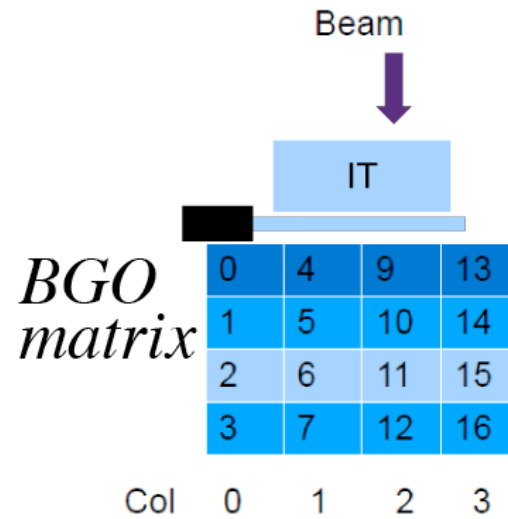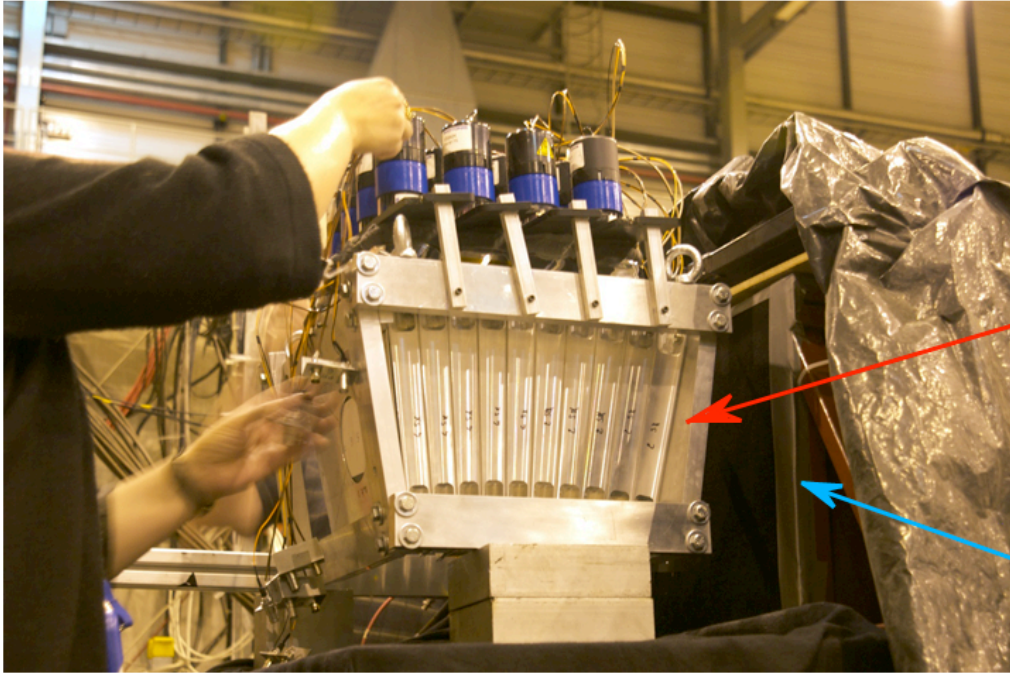
200 superimposed waveforms
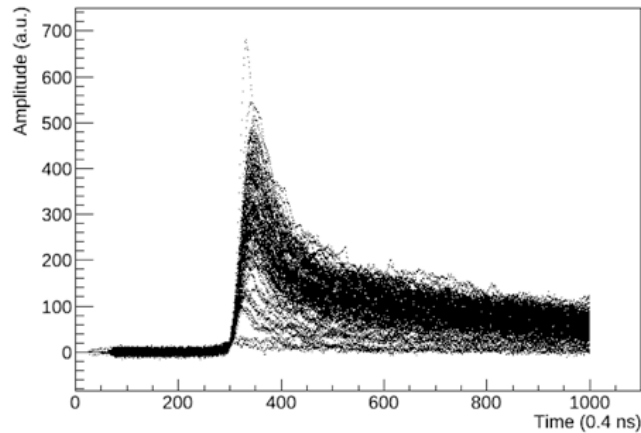
Average waveform
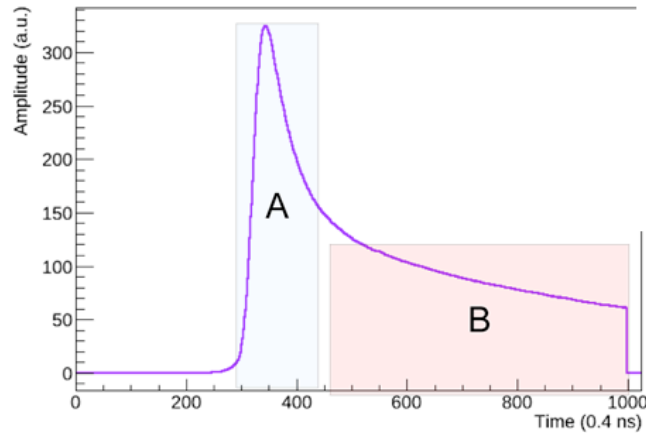
- The waveform is numerically integrated in two gates;

- S and C is evaluated from the two integrals as
  S = B;   C = A − 0.35 × B;

Dual-Readout BGO calorimeter: Resolution for 100 GeV electrons

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

Total charge
σ = 1.82%

χ² / ndf	210.4 / 123
Constant	128.6 ± 3.0
Mean	5.161e+05 ± 1.711e+02
Sigma	9439 ± 138.4

Scintillation
σ = 2.11%

χ² / ndf	167.4 / 89
Constant	181.8 ± 4.1
Mean	3.195e+05 ± 1.221e+02
Sigma	6770 ± 94.2

Cherenkov
σ = 4.96%

χ² / ndf	1251 / 239
Constant	319 ± 7.4
Mean	7.916e+04 ± 7.017e+01
Sigma	3930 ± 58.3

D. Pinci, IEEE, Valencia 2011
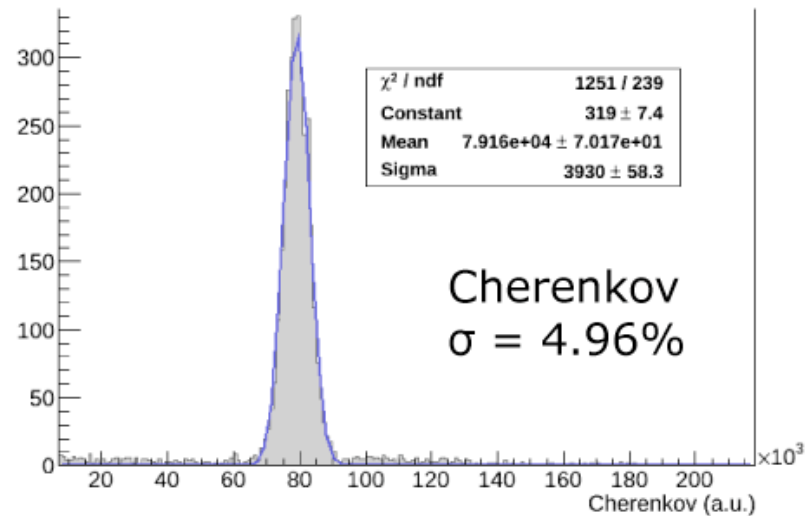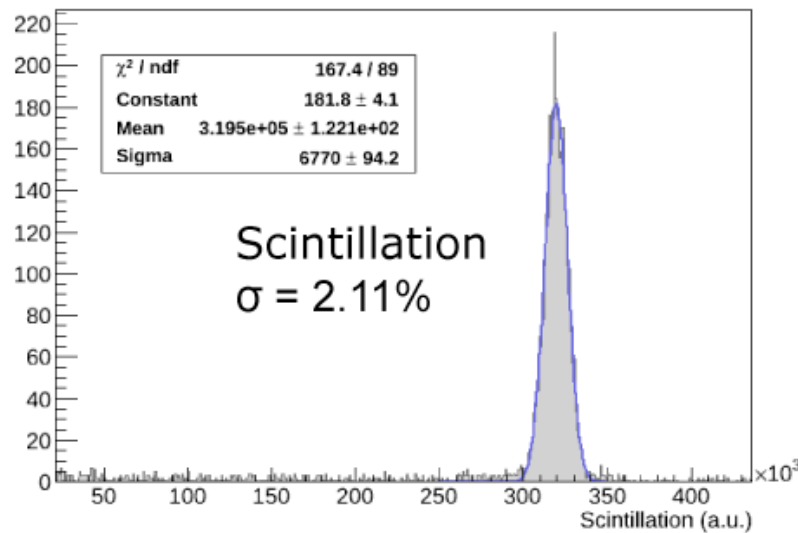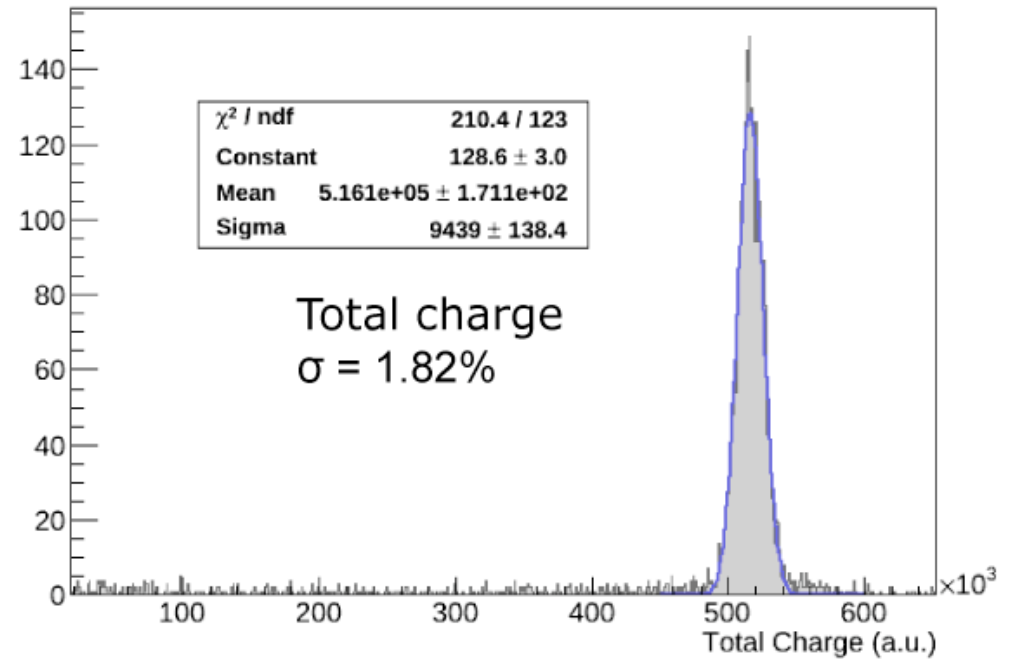
Dual-readout crystal calorimetry
S/C signal separation with filters
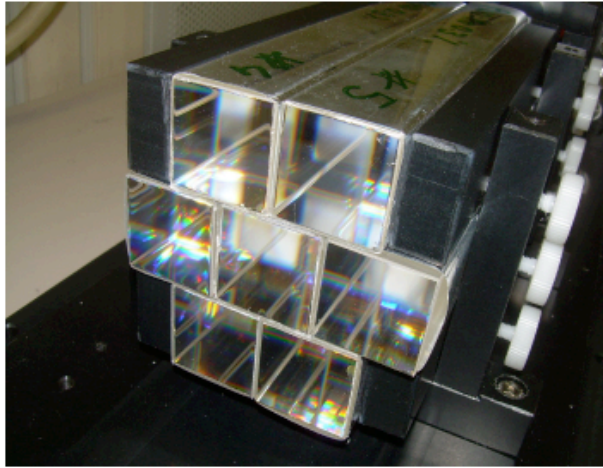
Mo-doped PbWO₄ crystal matrix
7 crystals, 3 x 3 x 20 cm³

Scintillation

Cherenkov

— UV filter
---- Yellow filter

Scintillation

$\sigma/E = 1.3\%$

QMatrixS_eq_Energy	
Entries	1298
Mean	91.6
RMS	3.007
χ^2 / ndf	91.13 / 35
Constant	128.7 ± 6.1
Mean	92.28 ± 0.05
Sigma	1.091 ± 0.033

Čerenkov

$\sigma/E = 3\%$

hcher_int_up_plus_dw	
Entries	1932
Mean	95.41
RMS	4.028
χ^2 / ndf	83.66 / 44
Constant	368.7 ± 11.8
Mean	95.2 ± 0.1
Sigma	2.9 ± 0.1
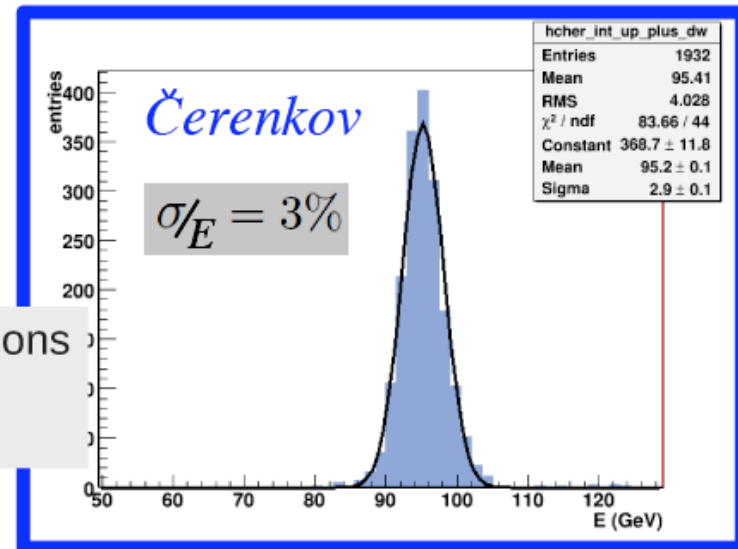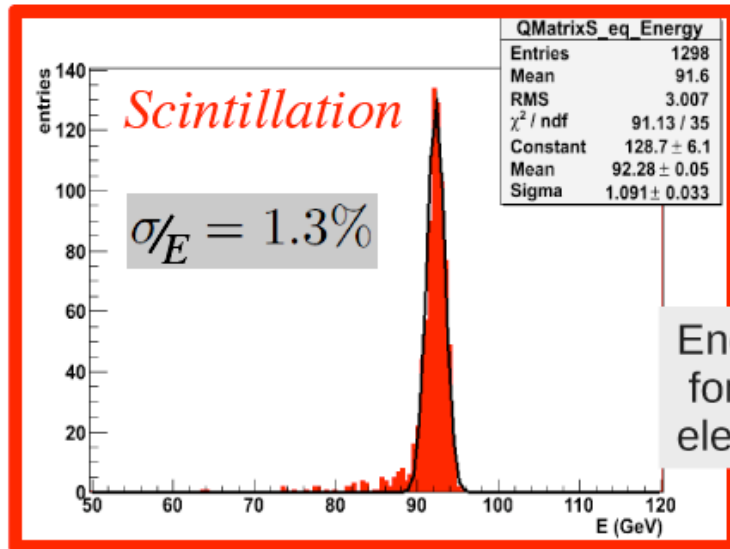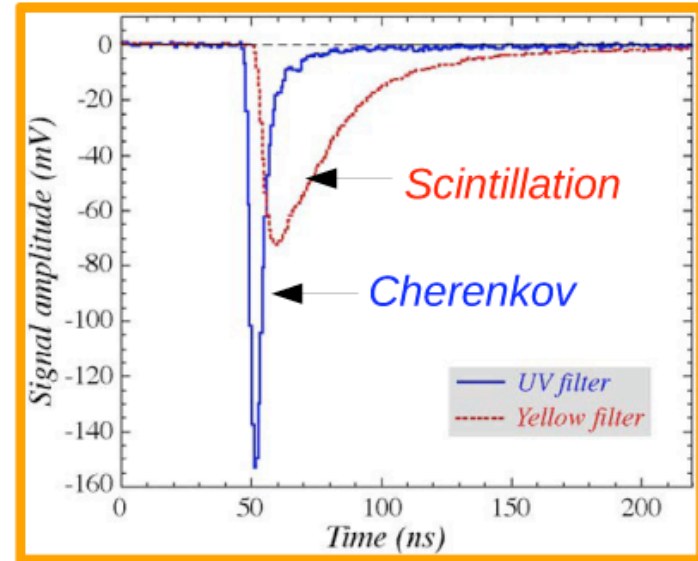
Energy distributions
for 100 GeV
electron beam

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

- 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

200 GeV "jets"

- • Čerenkov
- ▼ Scintillator

$\tau = 20$ ns

Tail absent for electron showers
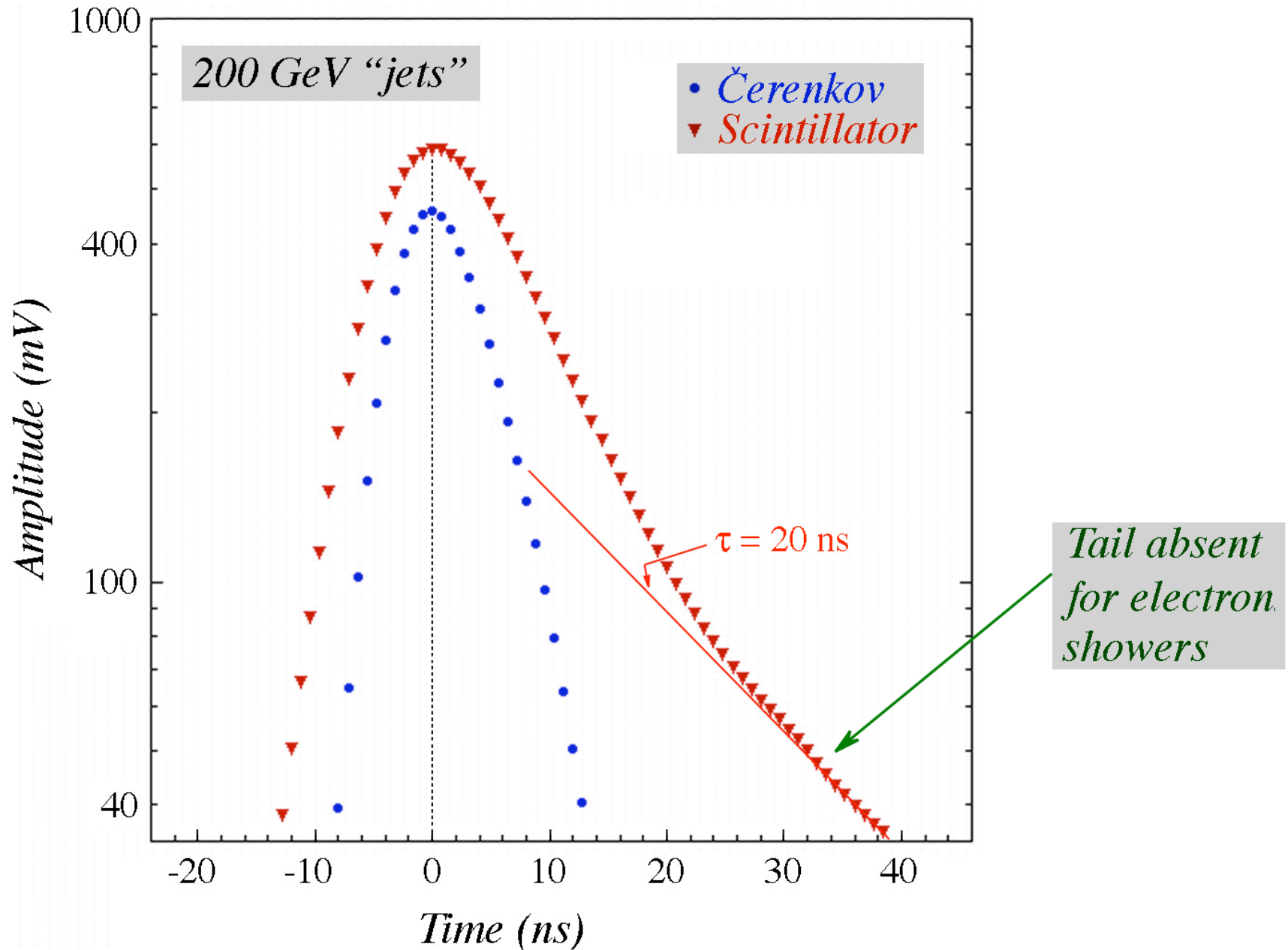
Probing the total signal distribution with the neutron fraction
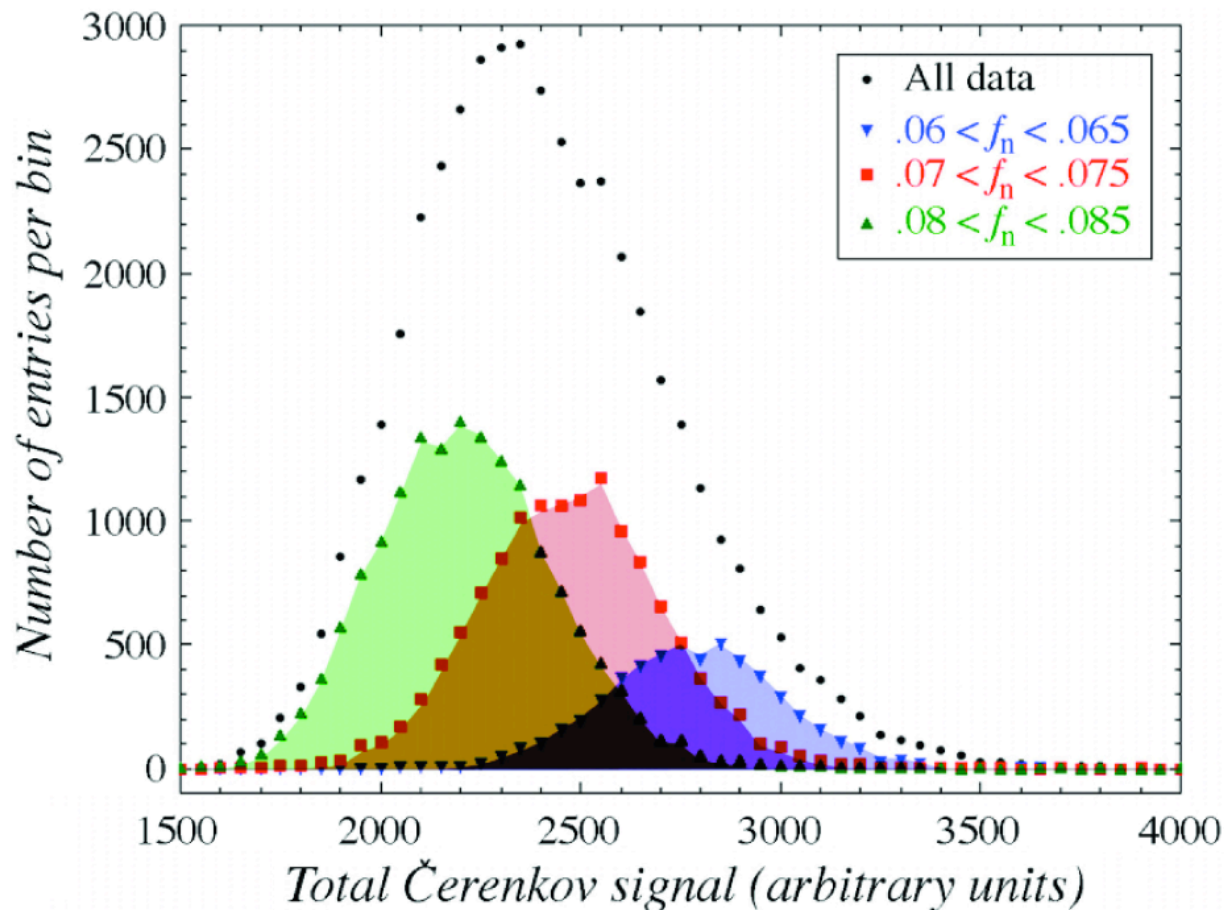
From:

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}

a) 200 GeV "jets" $0.40 < Q/S < 0.42$. Energy resolution (σ/mean) versus Neutron fraction scintillator signal.

b) Mean 3065, Sigma 143, σ/mean 4.7%, χ^2/ndf 17.1/17. Number of events per bin versus Čerenkov signal (arb. units).
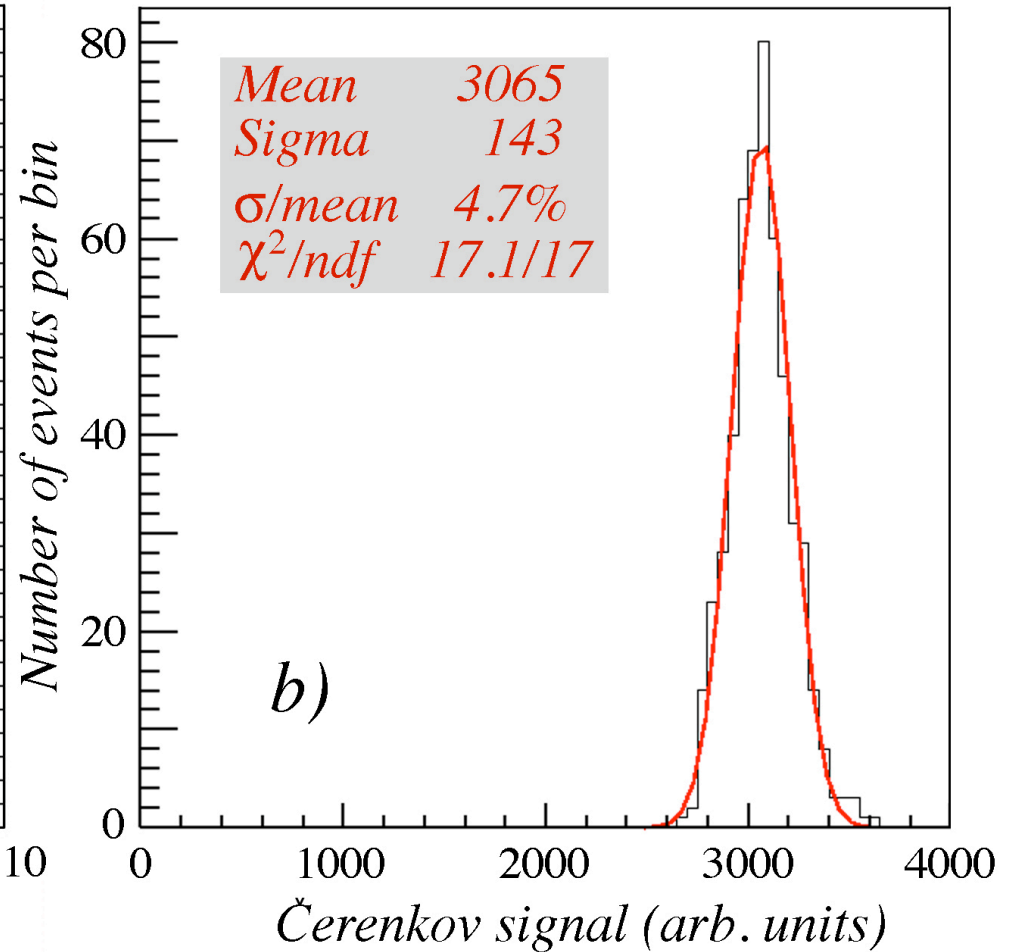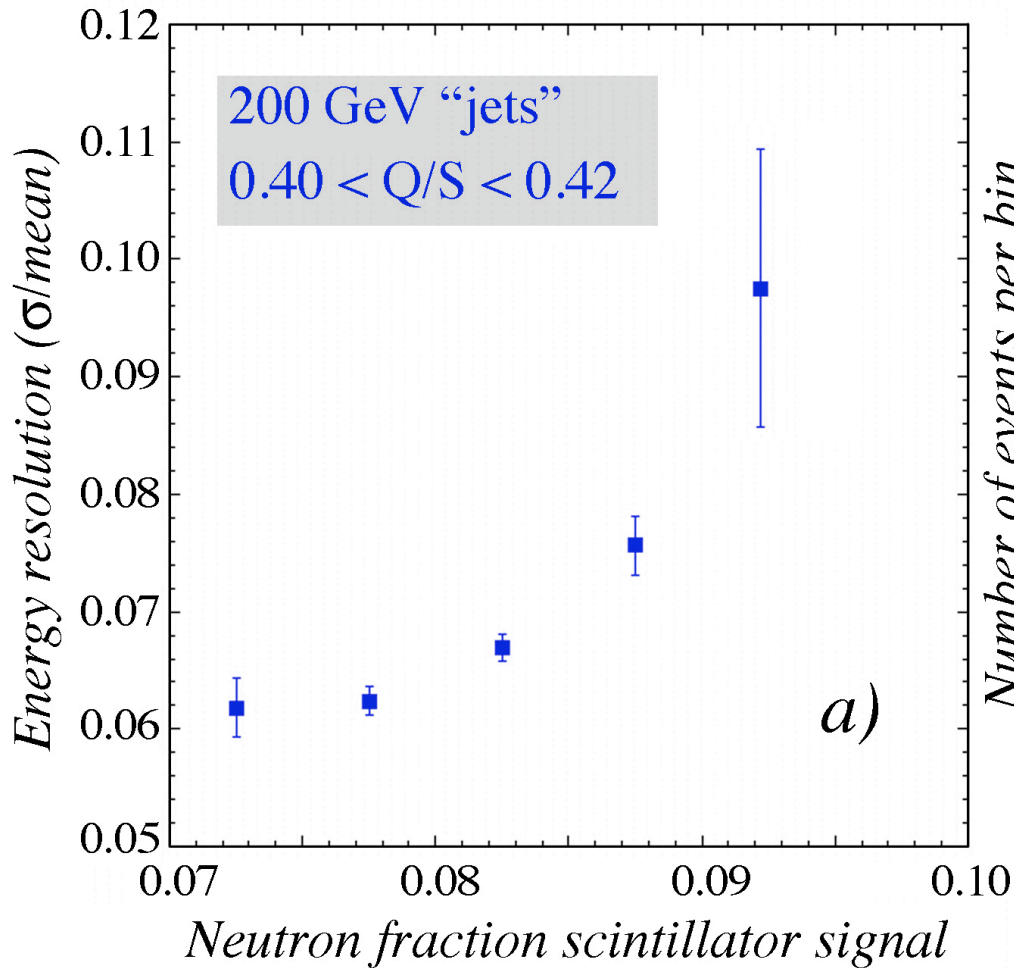
Future research plans

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

- 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 (1)

Elements needed for high-resolution calorimetry:

- *Elimination of contributions of fluctuations in em shower fraction*
  Intrinsic compensation (e/h = 1) or dual-readout

- *Minimization of contributions of fluctuations in visible energy*
  Efficient detection of "nuclear" shower component
  (e.g., energy resolution ZEUS much better than D0)

- *Limit contribution of stochastic fluctuations*
  These are THE limiting factor for em energy resolution

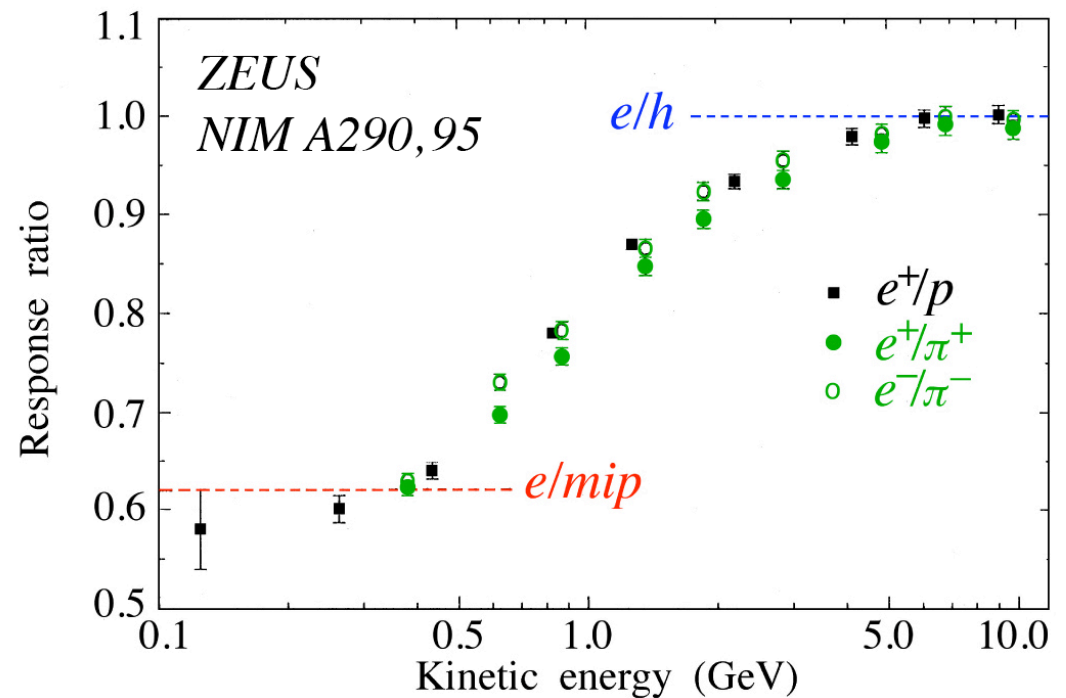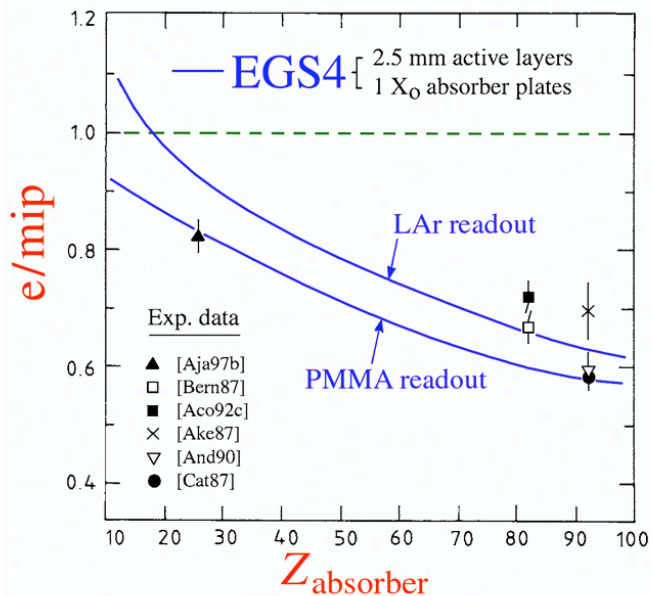# Fiber calorimeters vs crystals (2)

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

- e/mip $\longrightarrow$ 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

ZEUS
NIM A290,95

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

tilted (θ ~ 2°)

beam → HOD TC IT PSD DREAM ABSORBER MU
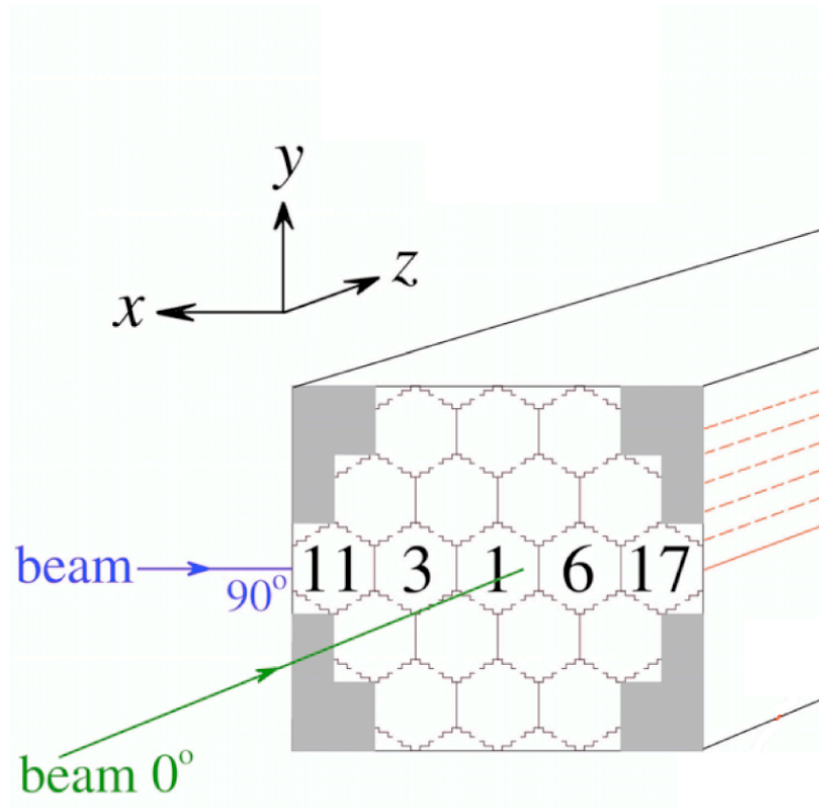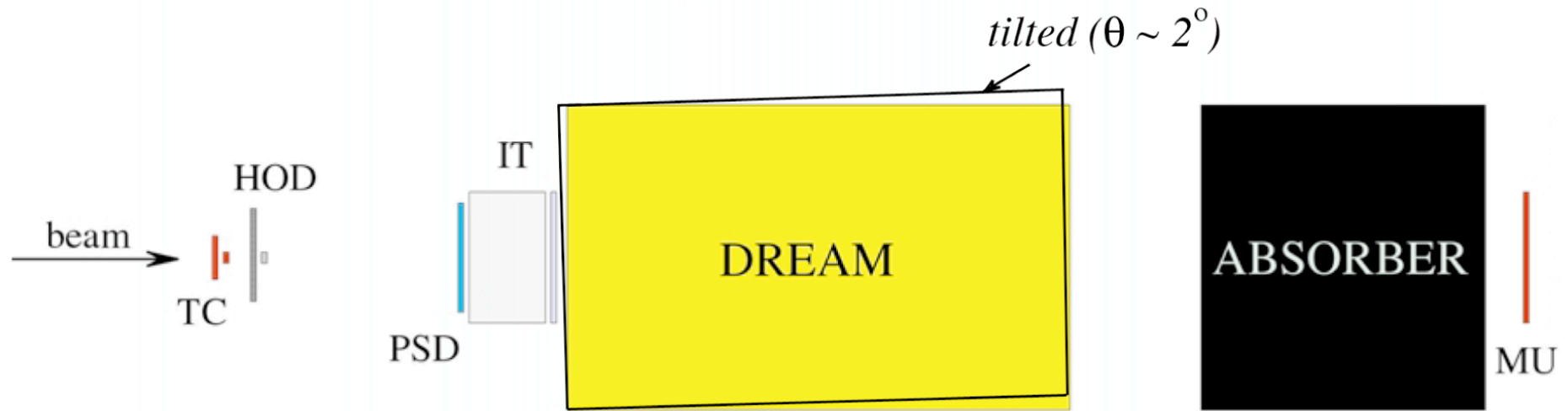
θ = 2°: *The deeper the light is produced, the more the center-of-gravity of the shower shifts to Tower 6*

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

beam → 90° | 11 3 1 6 17

beam 0°

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

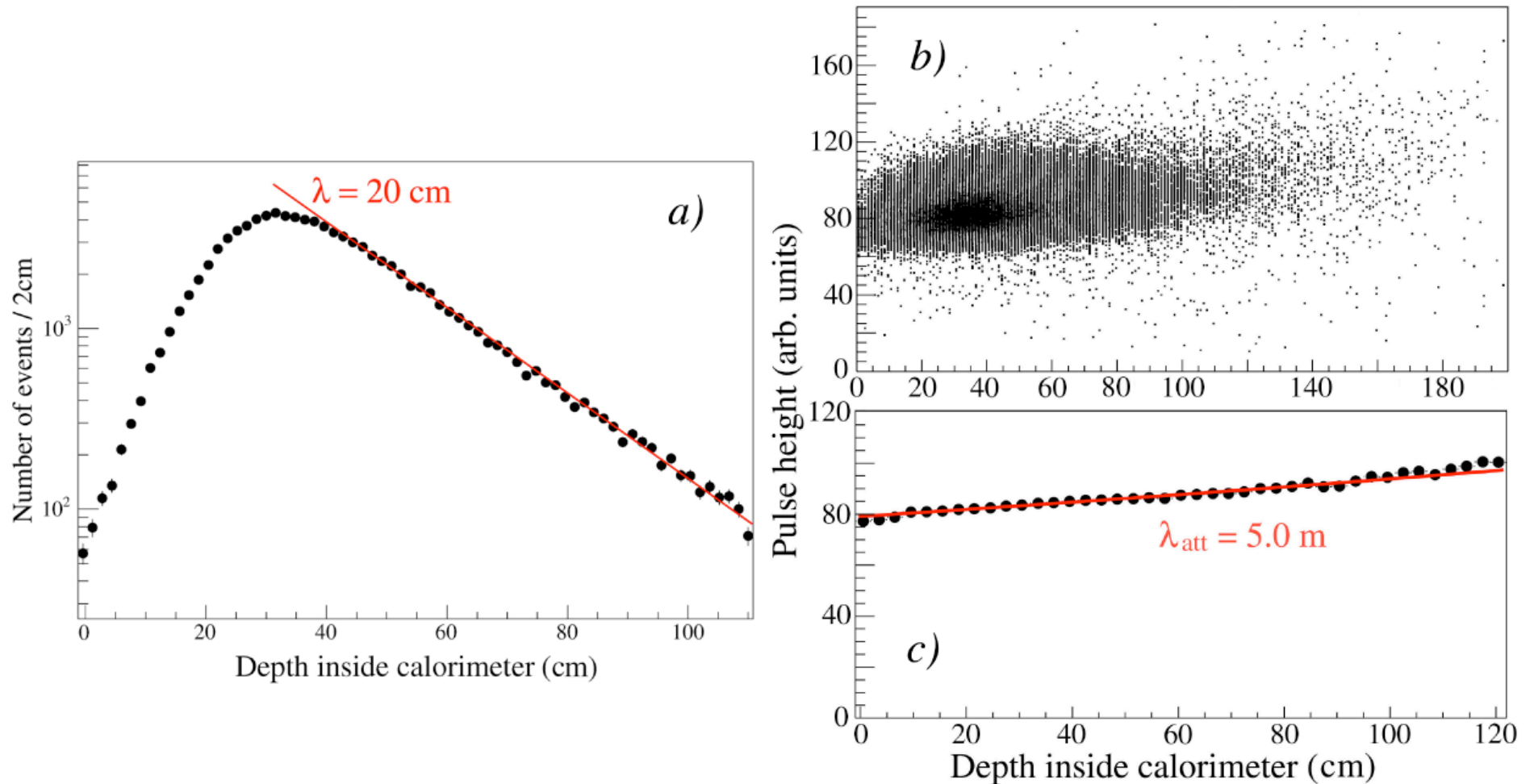**Figure 26:** Distribution of the average depth at which the scintillation light is produced in the DREAM calorimeter by showering hadrons (*a*). Scatter plot showing the total scintillator signal versus the average depth of the light production (*a*) and the average size of the total scintillator signal 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
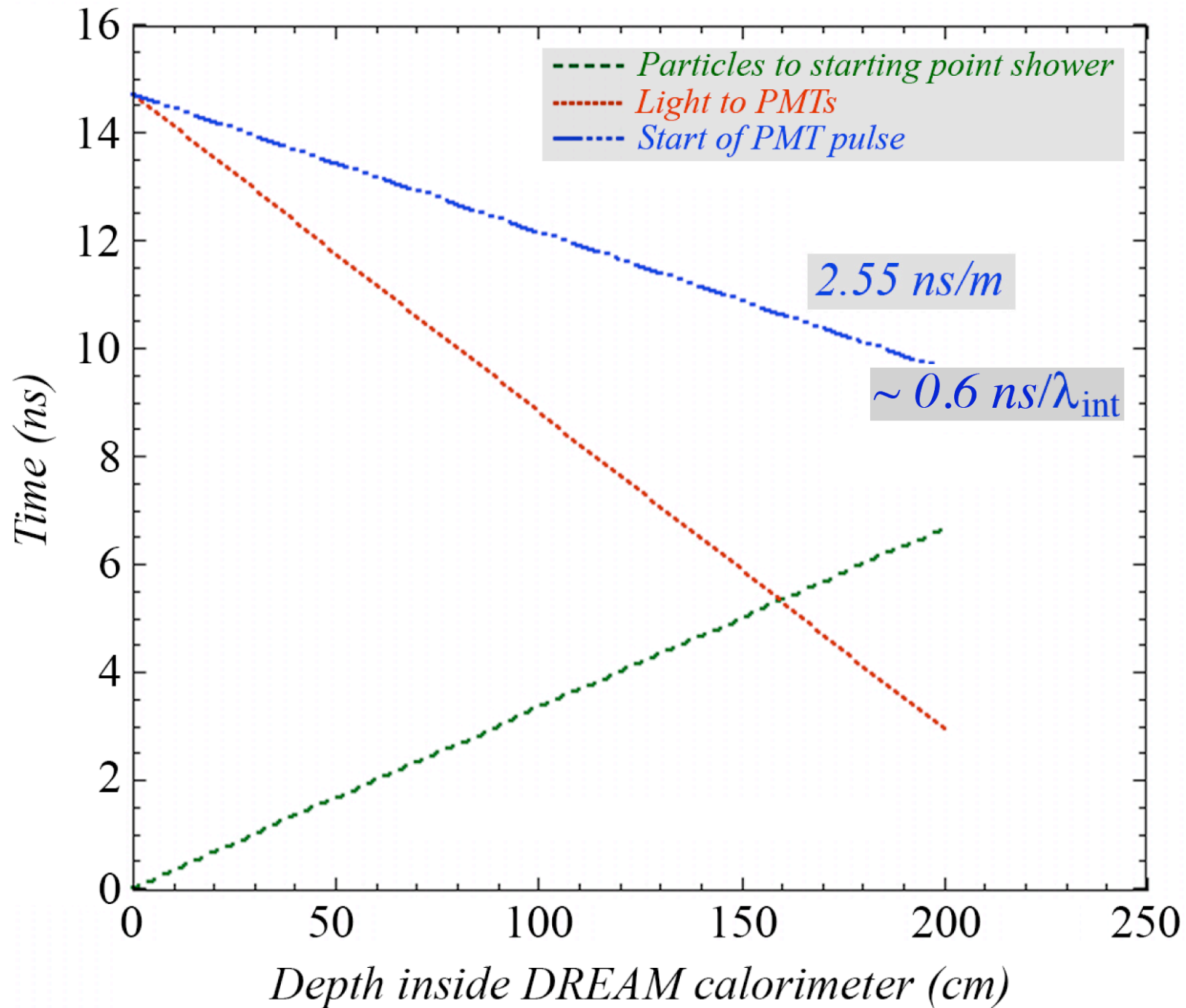
The first SuperDREAM module at H8

Fiber pattern

Č

S

Hamamatsu R8900
pc: 85%!

23.5 mm

2.54 mm

photo cathode
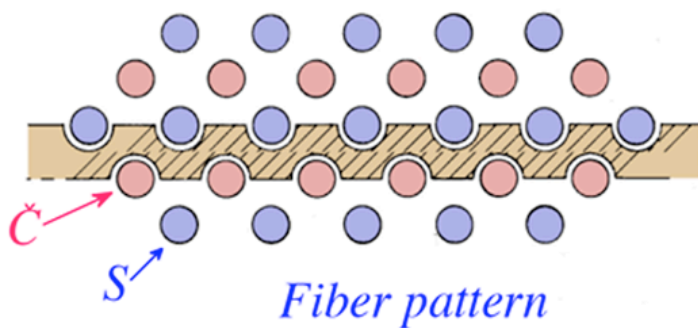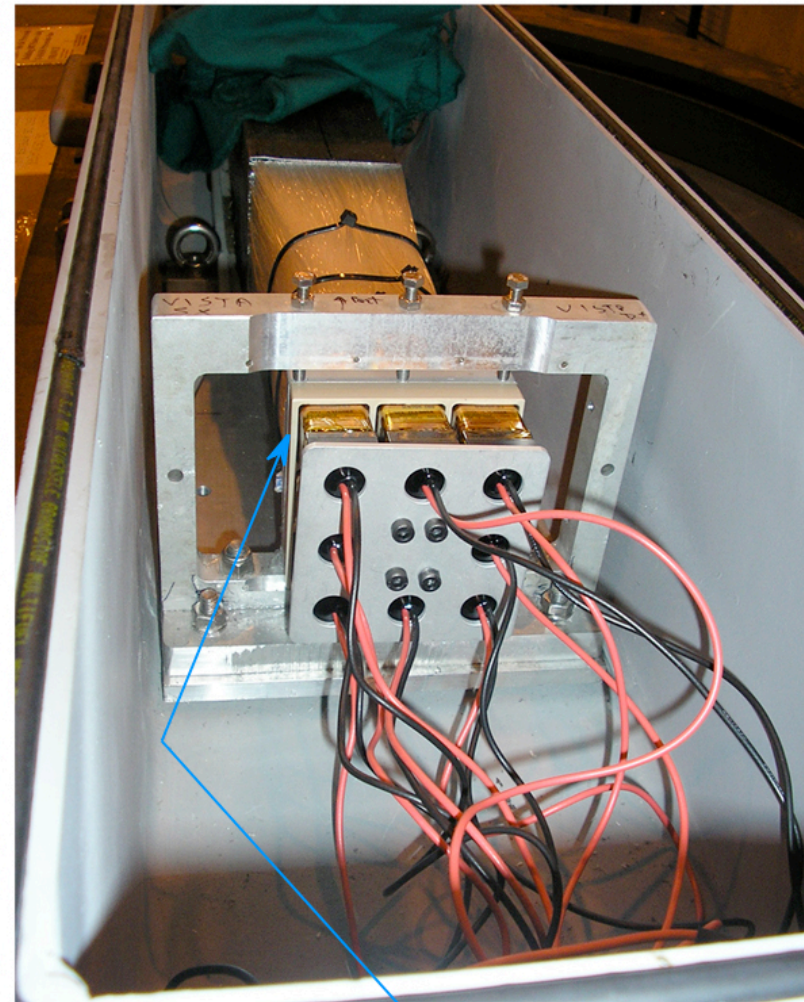
New fiber module

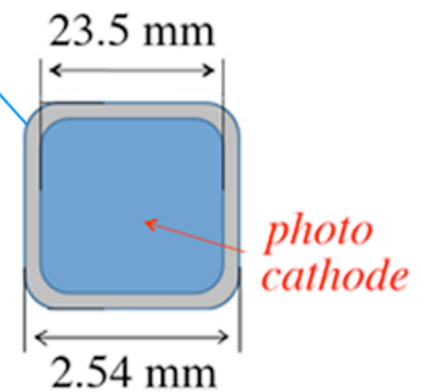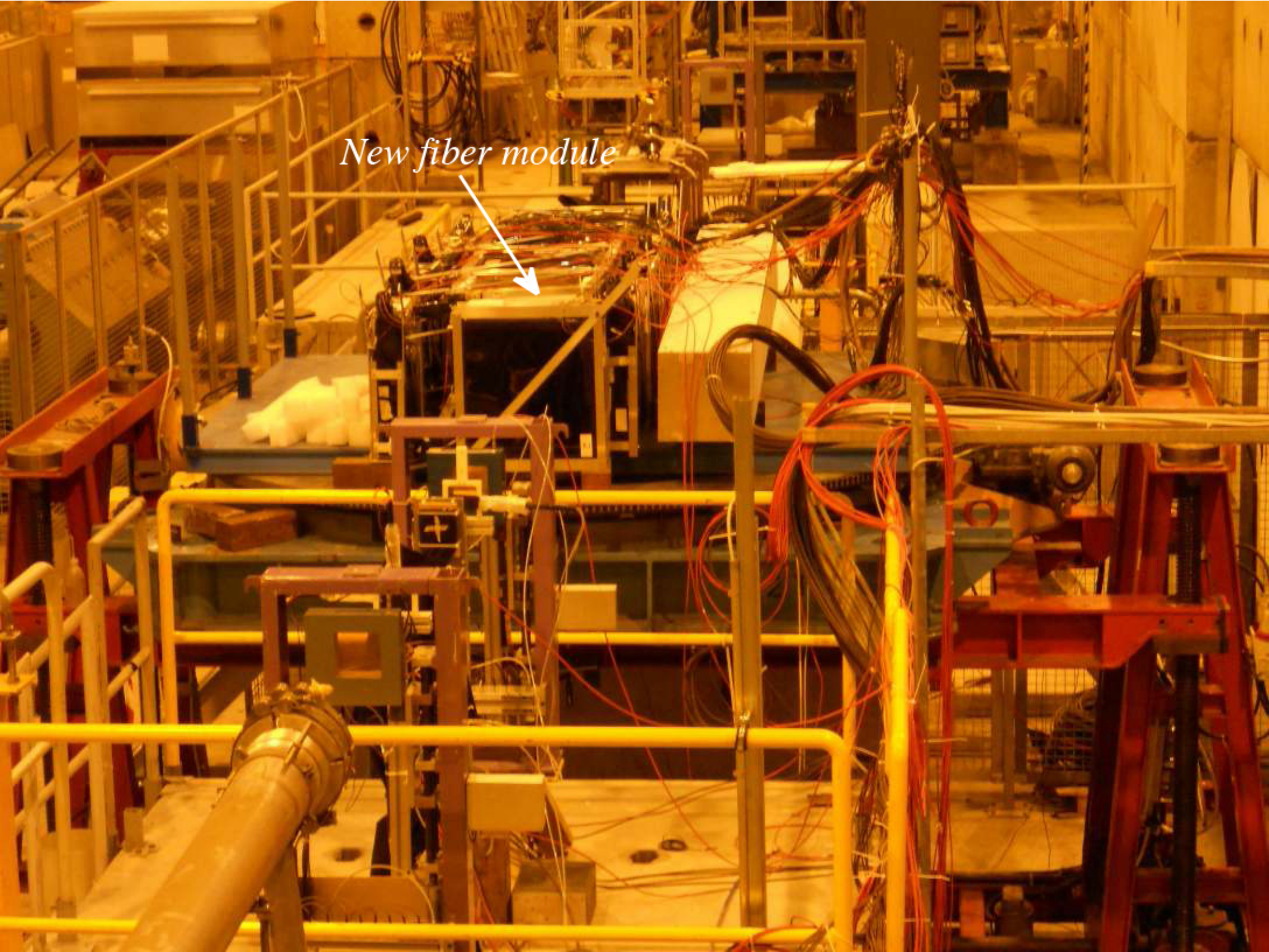# *Measurement of the depth of the light production in module using the DRS timing*

80 GeV electrons

Trigger time - Phys time

σ=0.55 ns
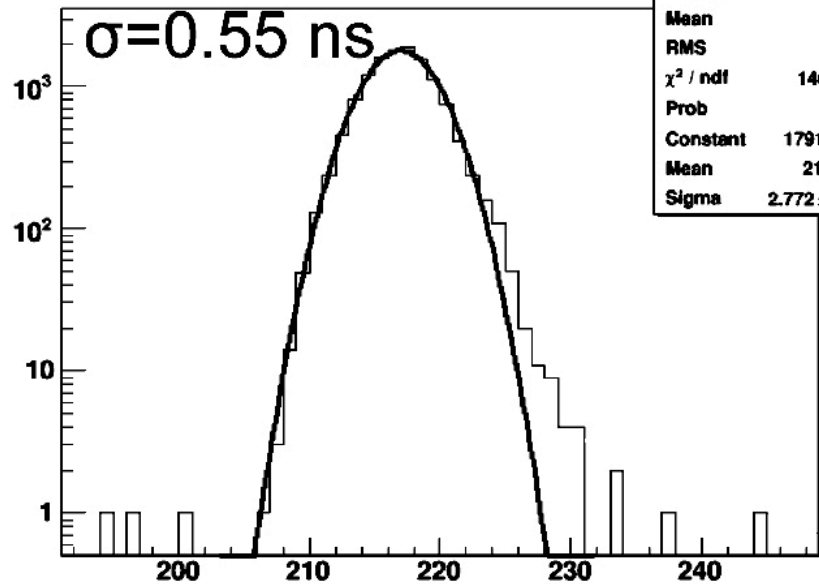
htdiff	
Entries	12623
Mean	217.1
RMS	2.926
χ^2 / ndf	146.1 / 22
Prob	0
Constant	1791 ± 20.6
Mean	217 ± 0.0
Sigma	2.772 ± 0.020

180 GeV pions

Trigger time - Phys time
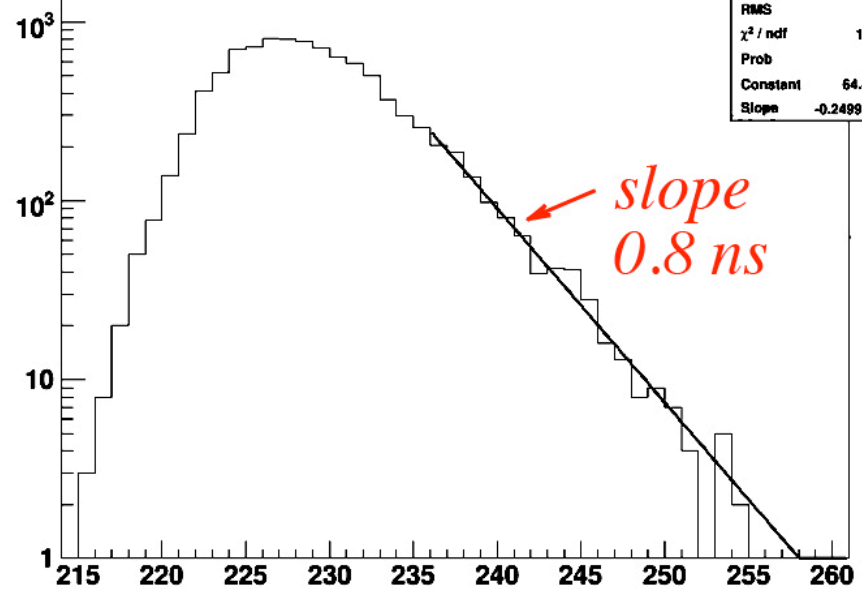
htdiff	
Entries	9742
Mean	229.1
RMS	5.295
χ^2 / ndf	12.34 / 16
Prob	0.7204
Constant	64.48 ± 0.51
Slope	-0.2499 ± 0.0021

slope 0.8 ns

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

Check that DRS time measures shower depth

Leakage counters

x_{DWC}

x_{CAL}

DWC1

DWC2

x

a)

DRS cell
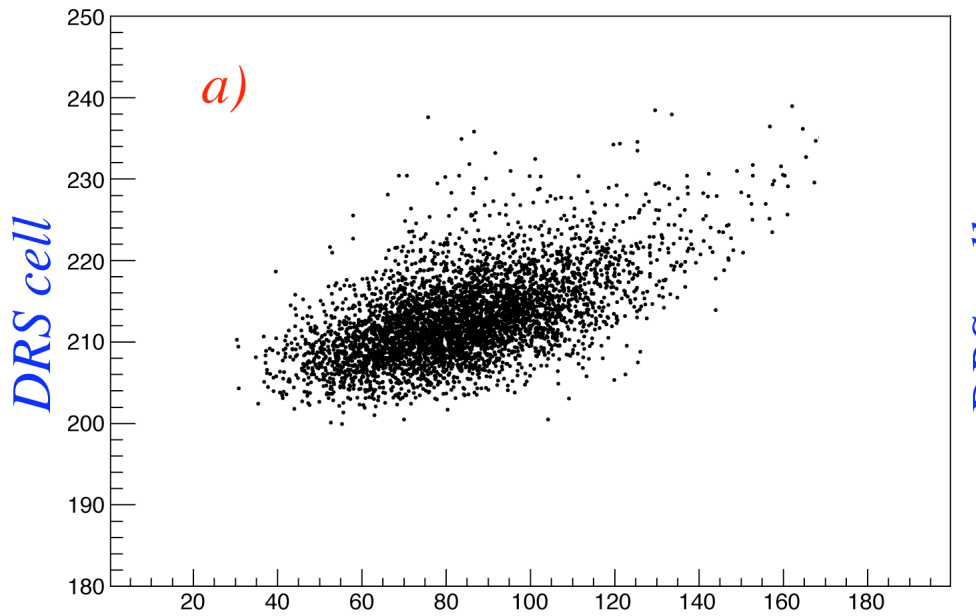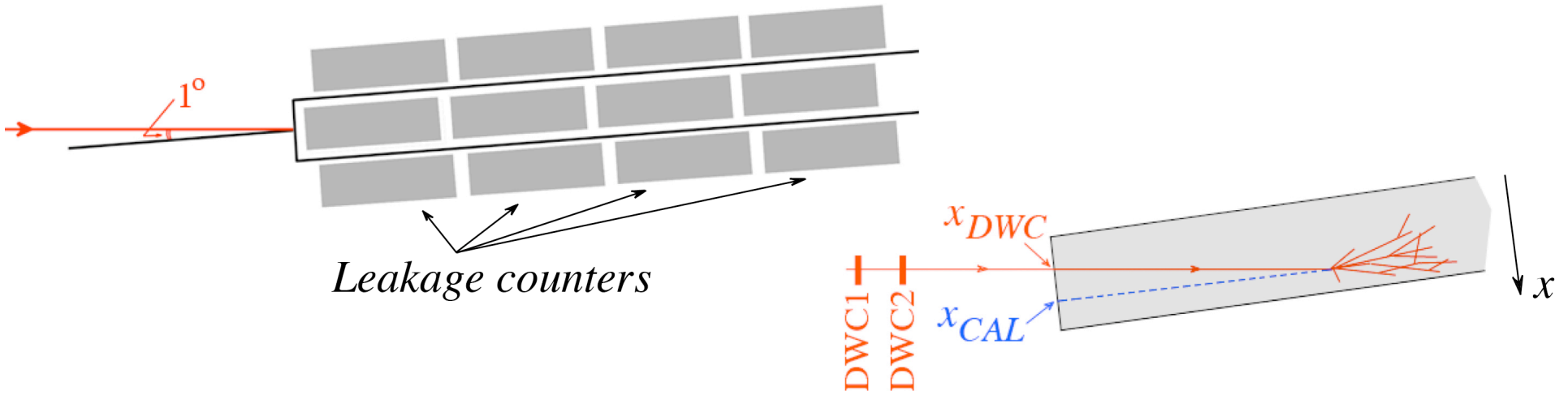
Depth from leakage counter profile (cm)

b)

DRS cell
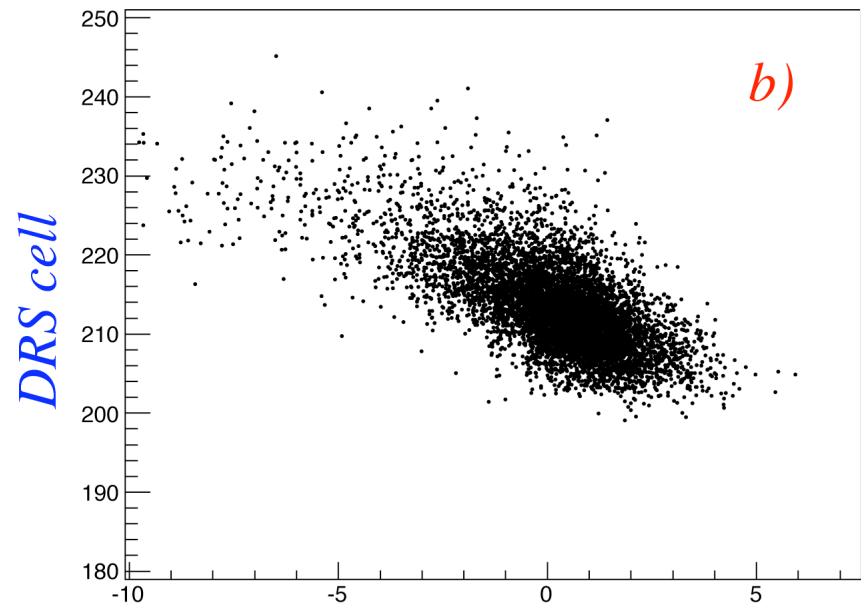
Displacement $x_{DWC} - x_{CAL}$ (mm)

First results on electron detection in new fiber calorimeter
(data taken last week!)

Electron resolution Čerenkov channel

DREAM (NIM A536, 29)

SuperDREAM (raw data)
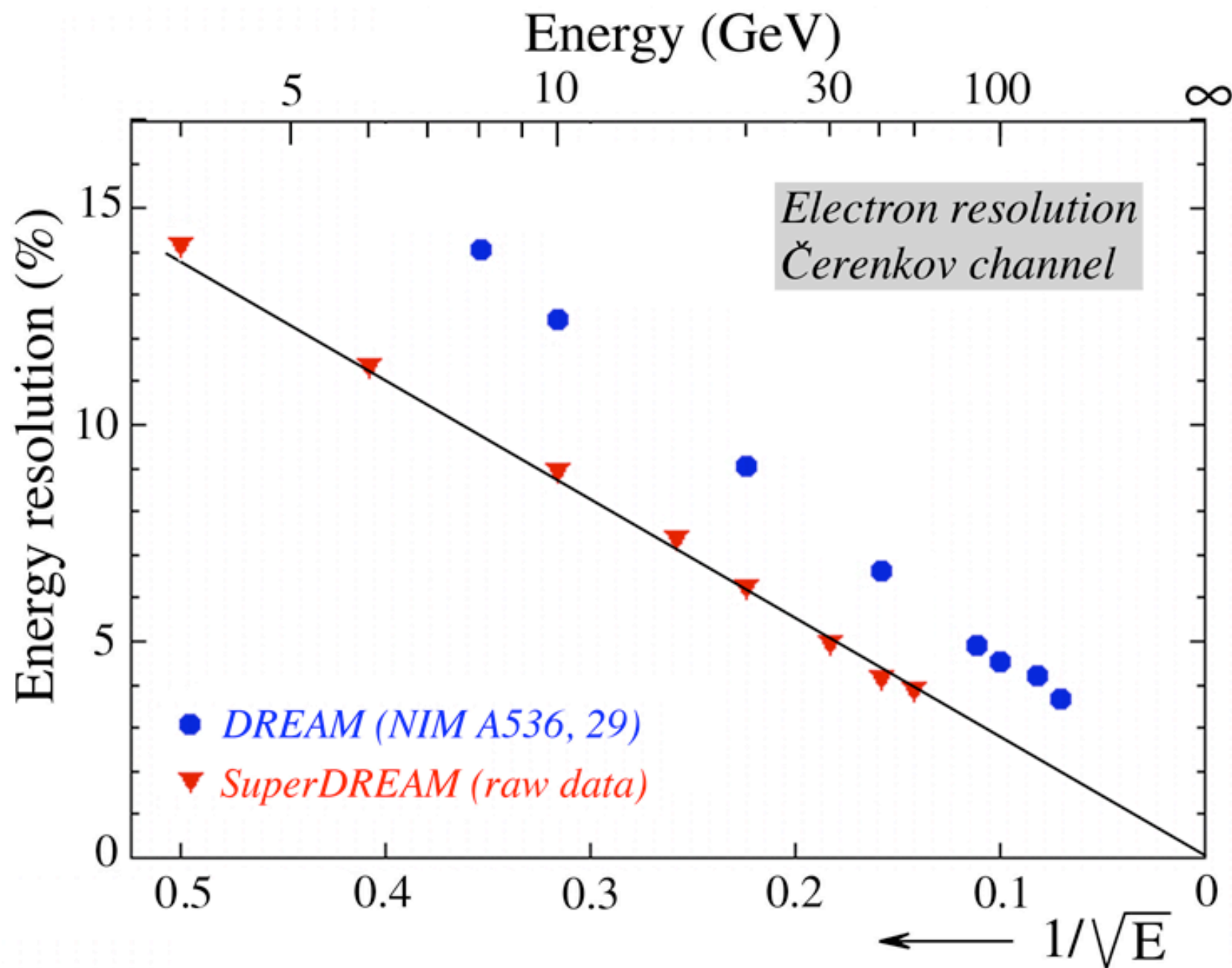
First results on pion detection in the new fiber calorimeter

Scintillator signal (raw data)

a)

180 GeV π^-

_sum_s1s2s3s4_energy	
Entries	4466
Mean	132.6
RMS	23.88
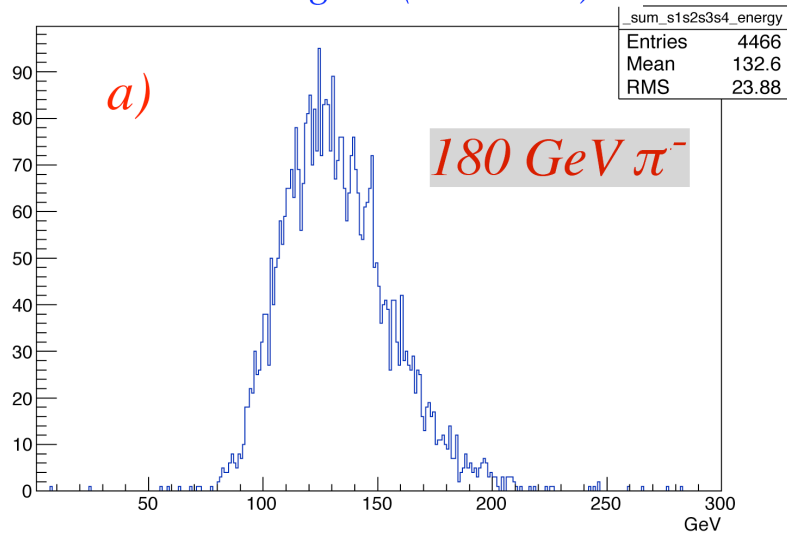
Leakage vs scintillator signals

b)
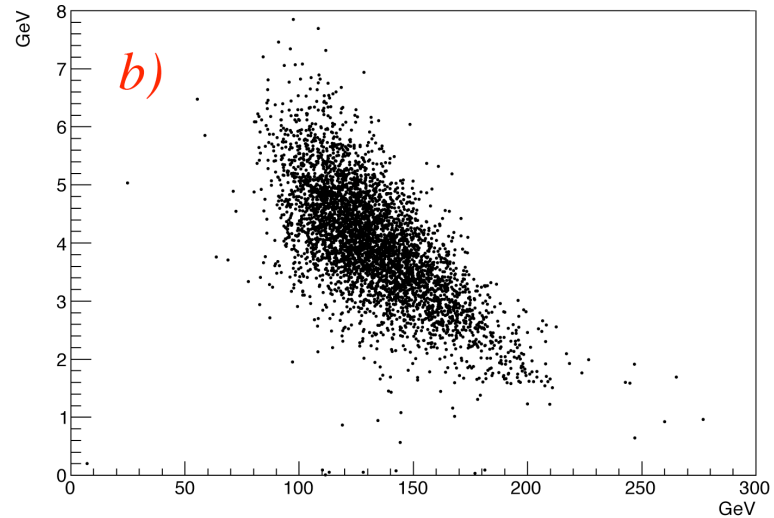
Č/S vs corrected S signal

c)

After rotation

d)
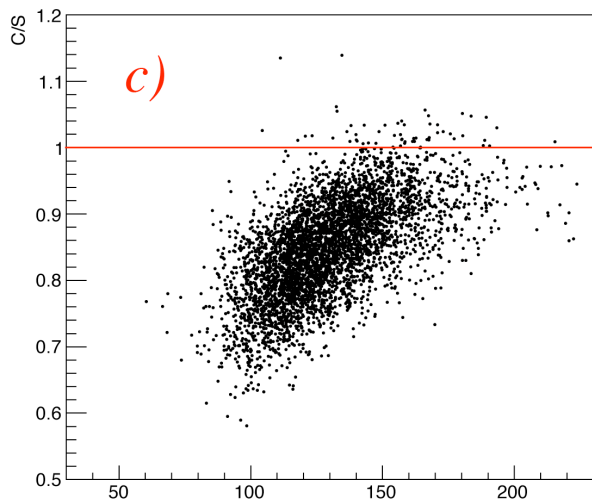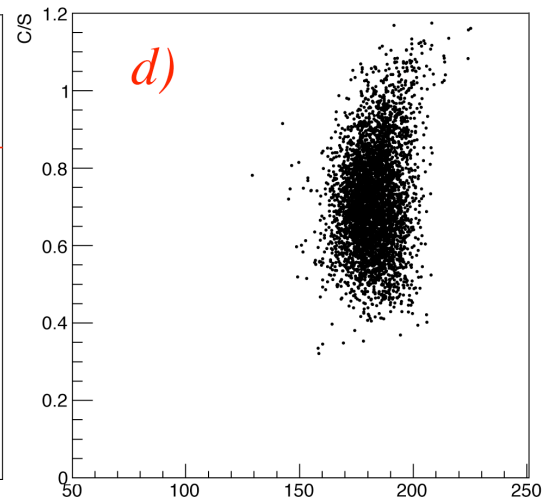
Corrected total S signal

e)

_sum_sn_energy_after_rotation	
Entries	4466
Mean	182.6
RMS	9.637
χ^2 / ndf	85.39 / 75
Prob	0.1932
Constant	202.9 ± 3.8
Mean	182.6 ± 0.1
Sigma	8.614 ± 0.098
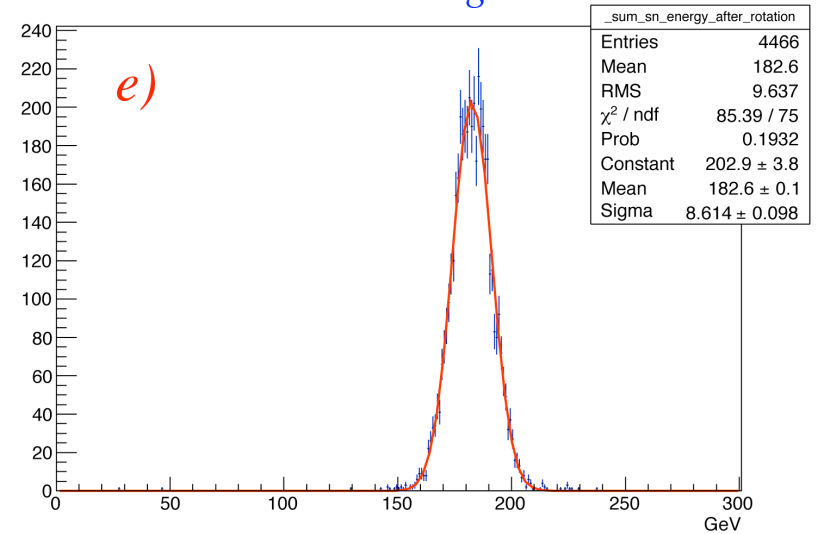
Conclusions (R&D)

- 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

Hadronic Čerenkov response

$\langle \check{C} \rangle = 40 + 148\, f_{em}$

em signal

200 GeV "jets"

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

from:
NIM A537 (2005) 537

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

Average Čerenkov signal (GeV)
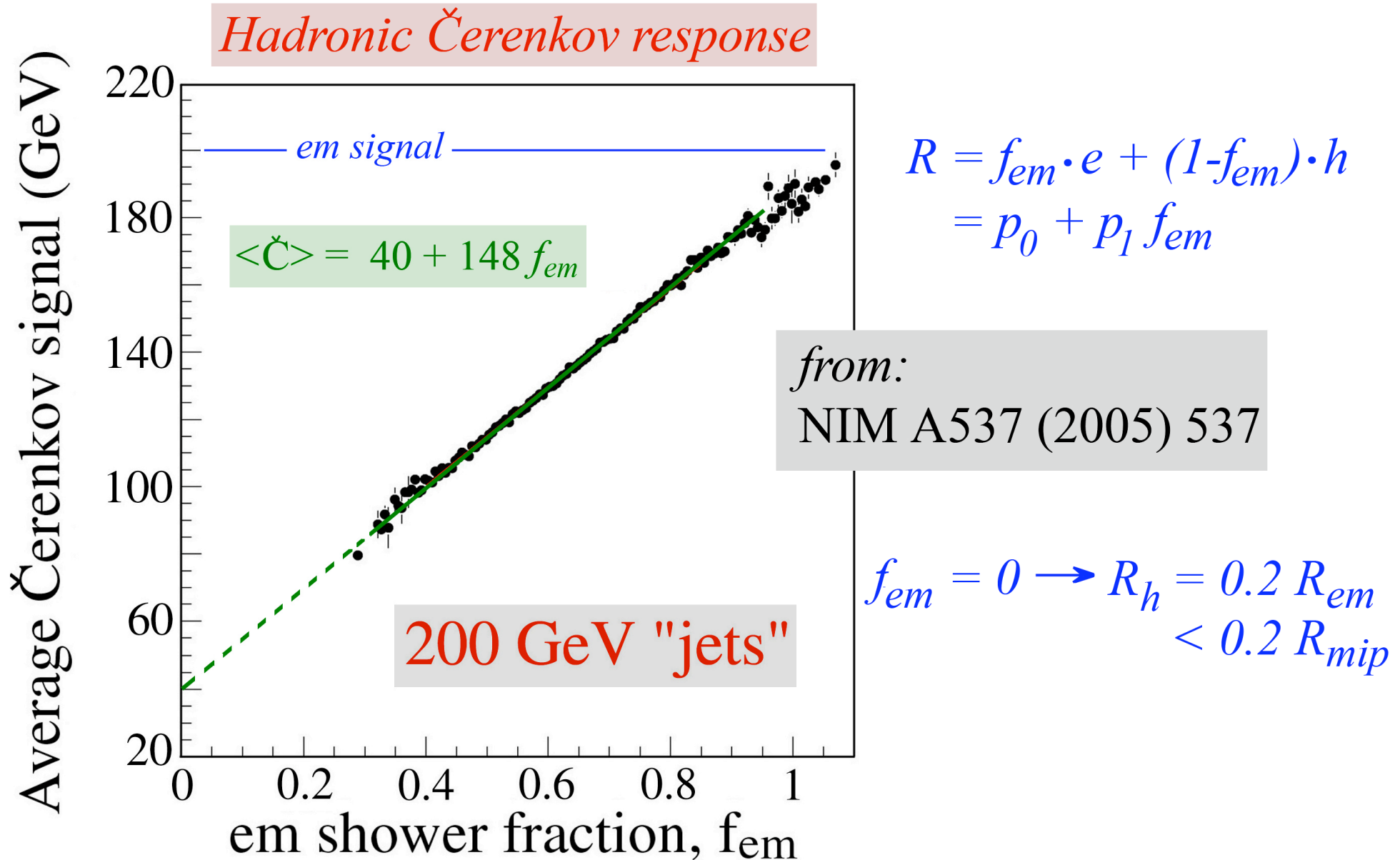
em shower fraction, f_{em}

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

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

beam

PMT A
Black Cover
PMT B

BLACK TAPE

E_{diff} E_{sum}

E_{diff}

E_{sum}

NO BLACK TAPE

Number of events per bin

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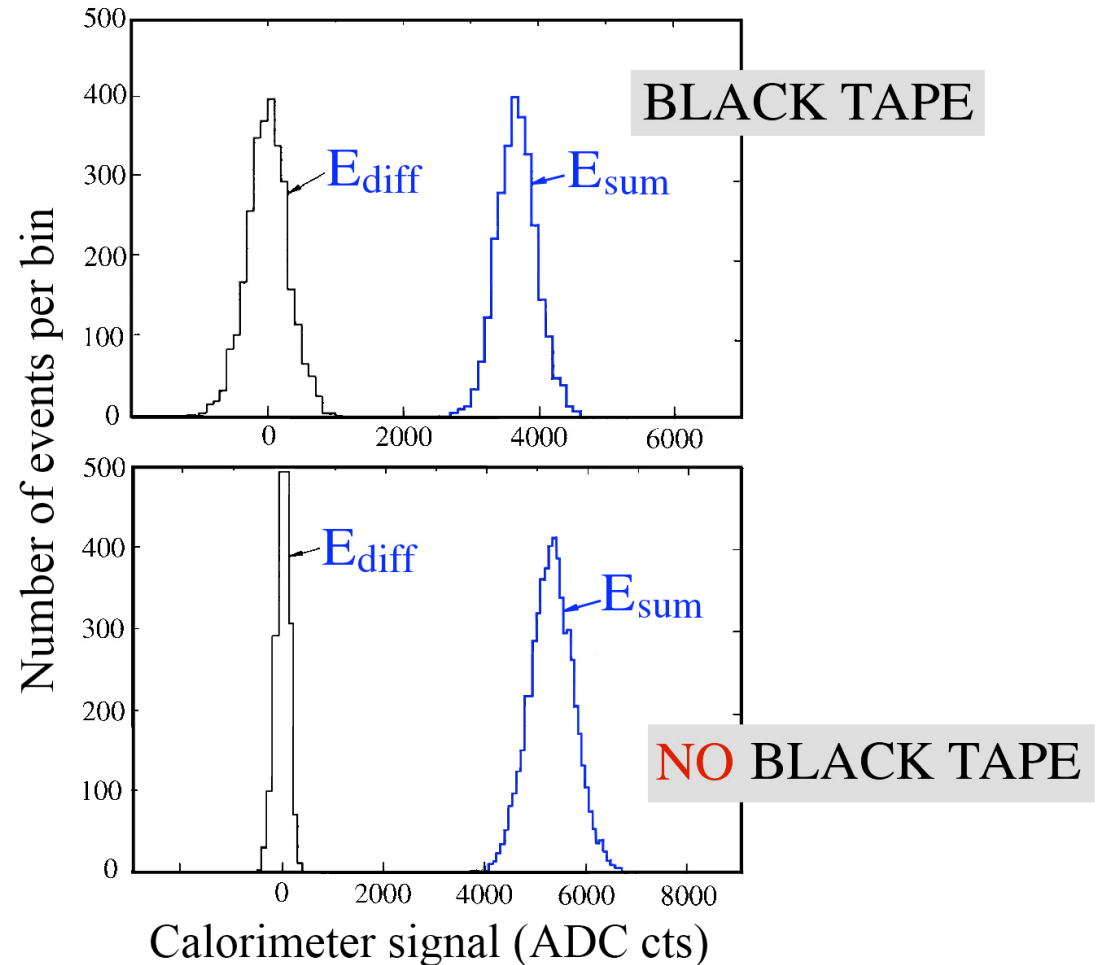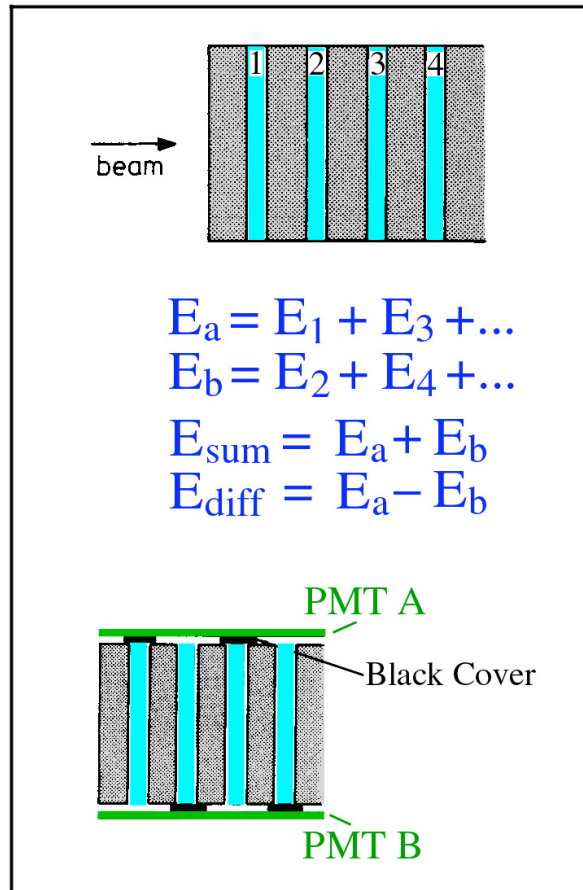
Fluctuations (%)	10 mm lead / 2.5 mm plastic	
	Electrons	Pions
σ_A, σ_B	36.0±1.0	60.5±1.0
σ_{sum}	24.5±1.0	43.5±1.0
σ_{diff}	25.8±1.0	42.3±1.0

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

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

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:	$e/h = \dfrac{e}{mip} / (0.2 + f_1 \cdot 0.25)$, $0.6 < \dfrac{e}{mip} < 1$	1.3-1.8*
Plastic-scint. calorimeter	$e/h = \dfrac{e}{mip} / (0.2 + f_1 \cdot 0.25 + f_2 \cdot 0.15)$ 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

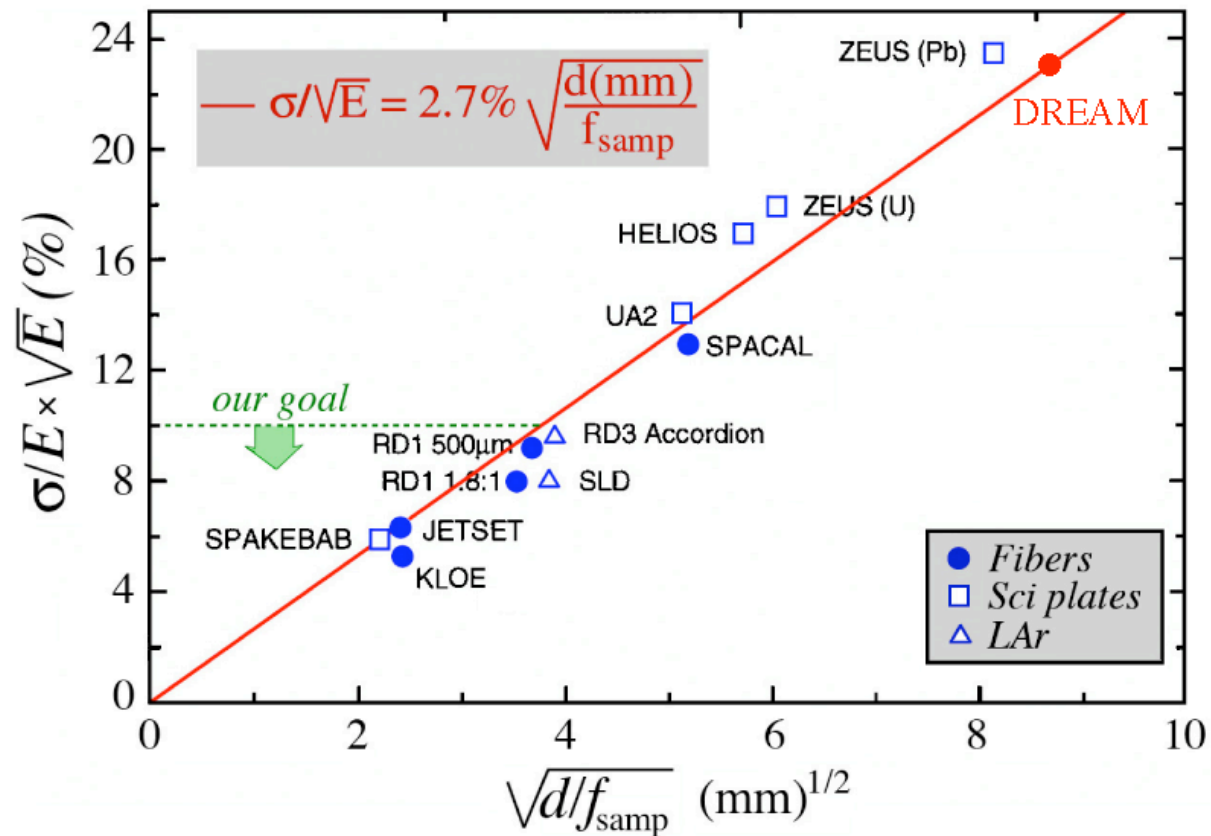# Sampling fluctuations and the e.m. energy resolution

Figure 23: The em energy resolution of sampling calorimeters as a function of the parameter $(d/f_{\mathrm{samp}})^{1/2}$, 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:

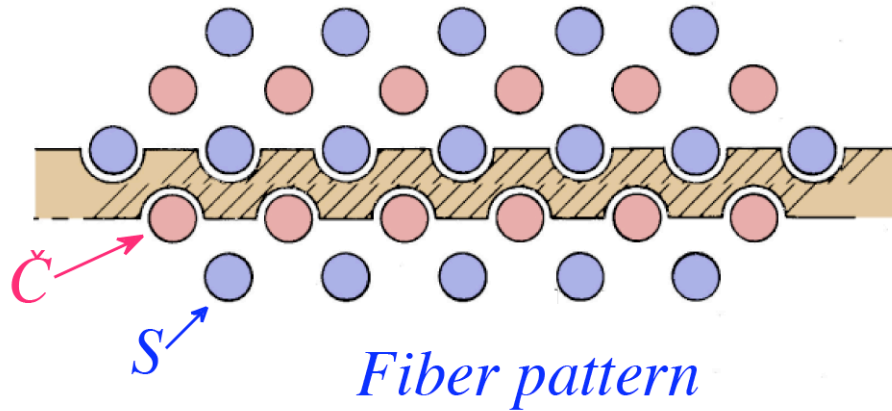- Embed fibers individually in metal structure, instead of bunches
  Reduces to 15%/√E

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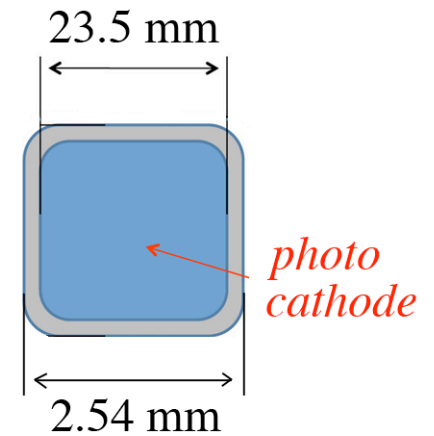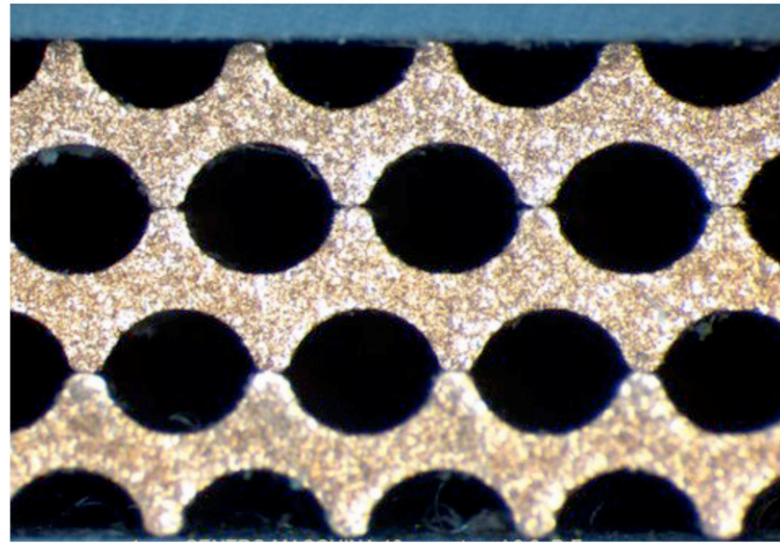 (from 22% in original fiber module to 43%. PMTs should fit in "shadow")
  Reduces to 11%/√E

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

Learn from KLOE and SPACAL!

Fiber pattern

Č
S

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

23.5 mm

2.54 mm

photo cathode

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)
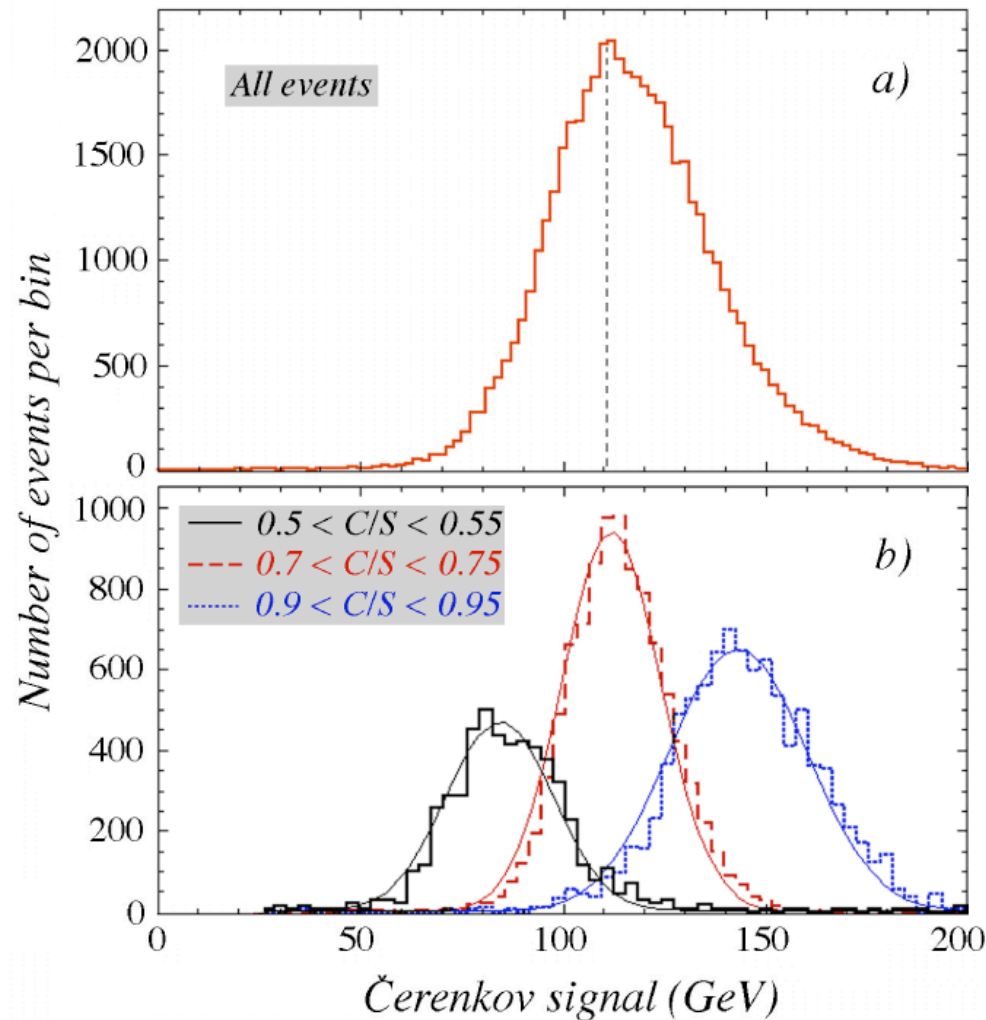
Increase by:

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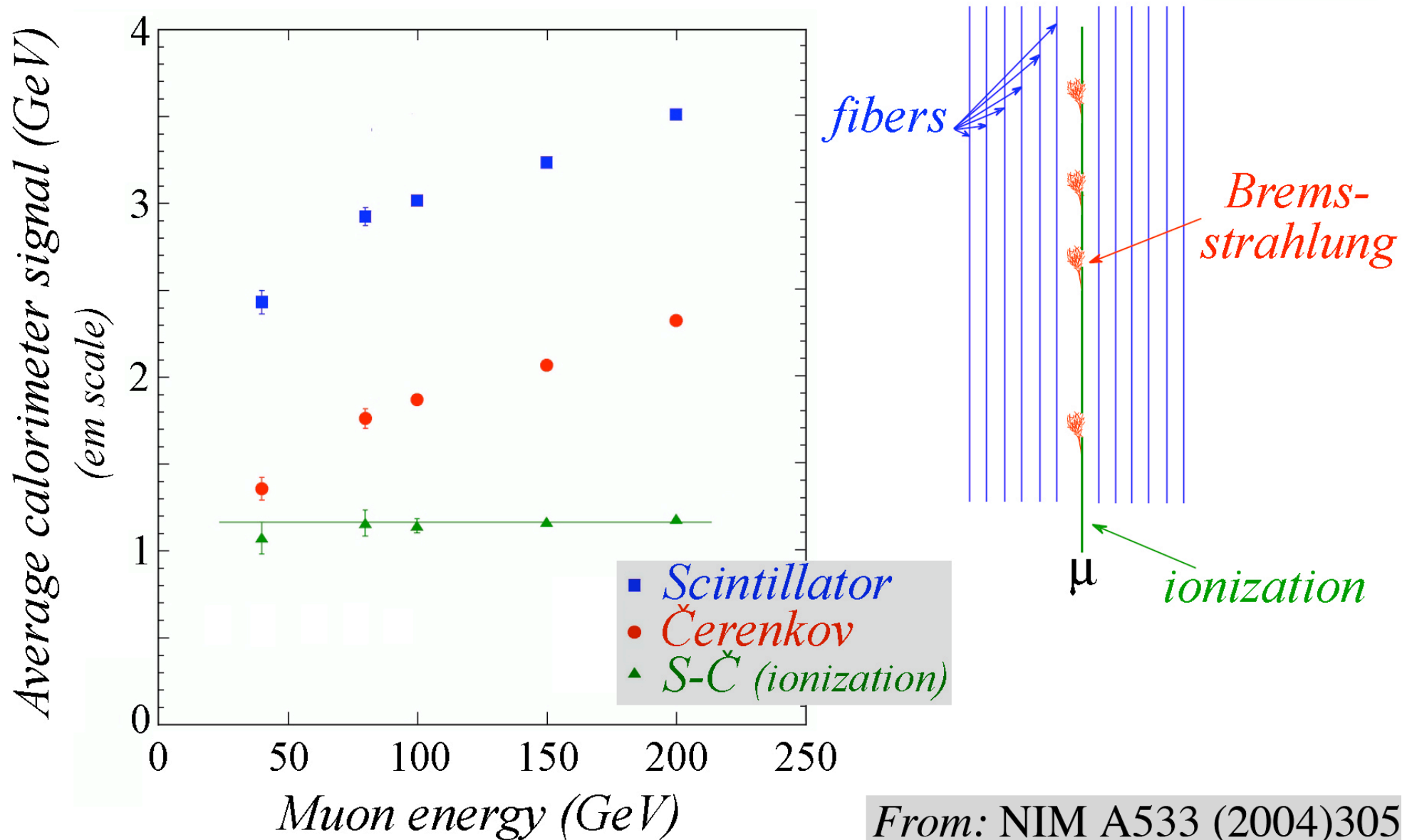
Angular dependence of the Č/S signal ratio in fiber calorimeter