Dual readout calorimetry (1)

general introduction
DREAM fibre calorimeter tests

Lucie Linssen

Dual readout calorimetry research projects world-wide

(may be incomplete)

- DREAM collaboration (R.Wigmans et al.)
  - US and Italien institutions (USA:TTU, UCSD, ISU Italy: PV, RM1, CS, CG, PI)
  - Dual readout beam tests, materials studies
- 4th concept (J. Hauptmann, C. Gatto et al., partially overlapping with Dream)
  - EMsection + HCAL section of full concept, mainly simulation studies
- Fermilab (A. Para et al.)
  - Crystals, light detection (SiPM), concept study (simulation)
- CalTech (R-Y. Zu)
  - Properties of crystals
- CERN (P. Lecoq, E. Auffray-Hillemans)
  - Properties of: crystals, crystal fibres, metafibres
- ……..

Disclaimer: **all** material in the upcoming slides has been extracted from their work

ILC/CLIC calorimetry requirements

Requirements for ILC calorimetry are dominated by:

•High-precision jet reconstruction (mass reconstruction with jets)

•Mass reconstruction with leptons (incl. neutrinos)

•Good π^0 reconstruction (including 2γ vertexing)

Energy resolutions required (for ILC, with similar values for CLIC):

Electrons, photons: typically $\sigma_E/E = 15\%/\sqrt{E}$ quoted

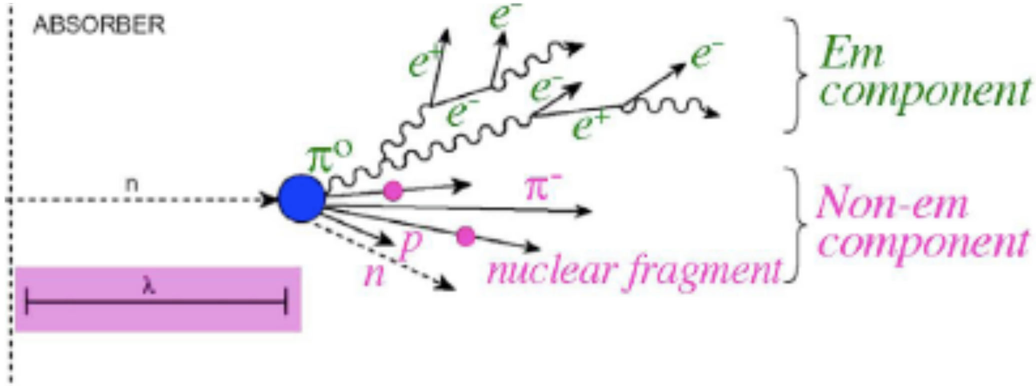
Single Hadrons: $\sigma_E/E = 60\%/\sqrt{E}$ ← actually, momentum resolution will be used instead

Jets: $\sigma_E/E = 30\%/\sqrt{E}$ (below 100 GeV), $\sigma_E/E = 3\text{-}4\%$ (above 100 GeV)

(with $\sigma_E/E = 60\%/\sqrt{E}$ => $\sigma_E/E = 30\%/\sqrt{E}$ giving factor 1/1.4 in luminosity for some crucial processes)

ILC jets go up to up to ~250 GeV in energy, CLIC jets up to ~700 GeV (tbc)

Why would we need an alternative method for calorimetry, e.g. dual readout ?



- Typically, calorimeters give a larger signal per unit deposited energy for the EM shower component (mostly initiated by $\pi^0 \rightarrow \gamma\gamma$) than for non-EM components: **e/h>1**

- There are **large fluctuations** in the intrinsic energy-sharing between the EM and non-EM component of the deposited energy. One cannot predict the fraction of electromagnetic energy $\mathbf{f_{em}}$ on an event-by-event basis.

What are the consequences of the above?

- Large event-by event fluctuations in the hadronic response
- Non-Gaussian shape of hadronic response
- Non-linearity of the hadronic response
- Deviations from the $1/\sqrt{E}$ behaviour for hadronic showers

Which methods are used to overcome these shortfalls?

- **Compensating calorimeters e/h=1**
  - This can be achieved with hydrogenous active medium (sensitive to soft neutrons, for example plastic scintillator).
  - This method requires a precisely tuned sampling fraction, requiring normally a large fraction of passive medium.

- **Offline re-calibration method**
  - Use average shower profile information to give a different weighting of the signals as a function of the shower depths. This method gives only limited results. Insufficient when excellent resolution is required.

- **Particle flow analysis**
  - Gives good simulation results (….not easy to do hardware test on a large scale). Intrinsically becomes more limited at higher energies.

Richard Wigmans

Dual (triple) readout method

Basic principle:

- Measure EM shower component separately
- Measure HAD shower component separately
- Measure Slow Neutron component separately

$\left.\begin{array}{l}\text{EM}\\\text{HAD}\end{array}\right\}$ **Dual**

$\left.\begin{array}{l}\text{EM}\\\text{HAD}\\\text{Slow Neutron}\end{array}\right\}$ **Triple**

EM-fraction=> electrons => highly relativistic => Cherenkov light emission as well as Scintillation signal

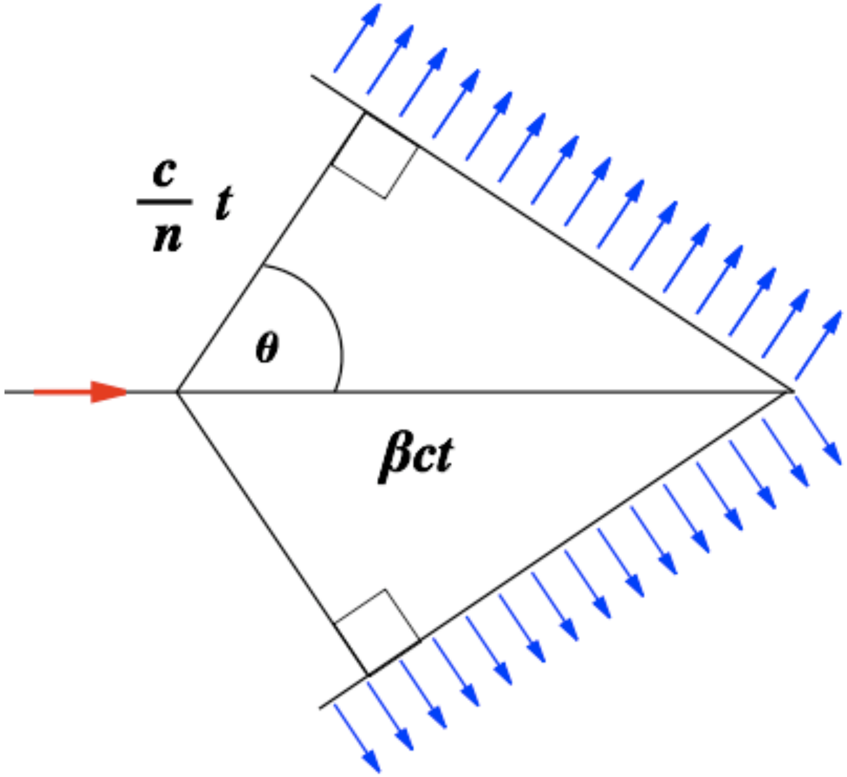
HAD-fraction=> “less” relativistic => Scintillation signal only

Slow neutrons => late fraction of the Scintillation signal

Cherenkov light light production

When a particle with velocity $v = \beta c$ enters a medium with refractive index n

If $\beta c > c/n$ the particle goes "too fast" and starts emitting light



Wave front at: $\cos\Theta = 1/n\beta$

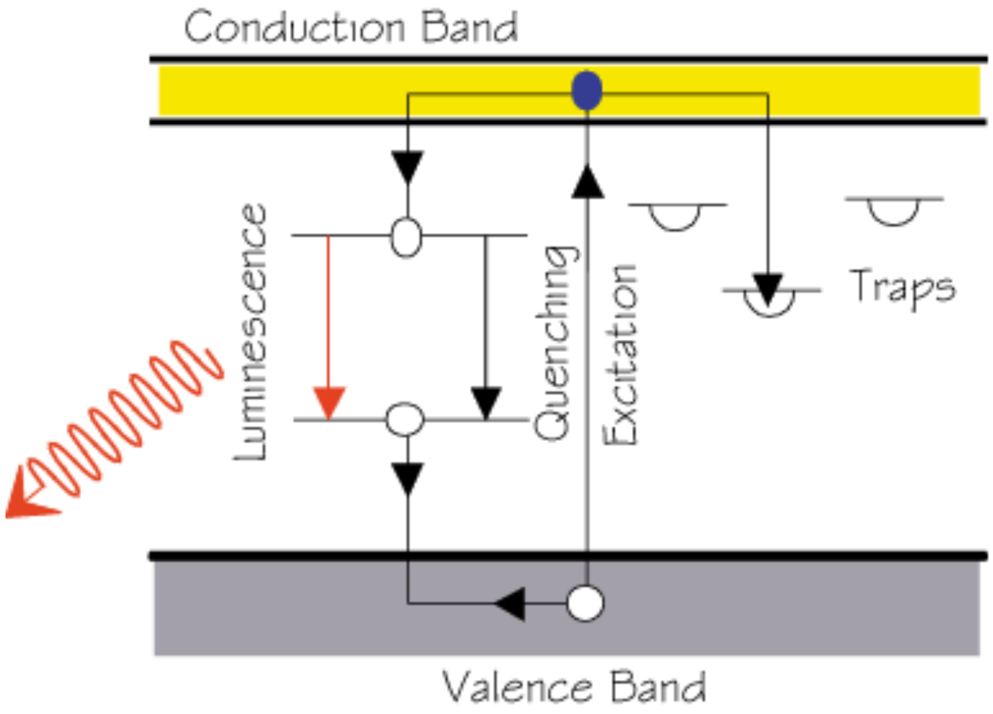
e.g: $n = 2.2 \Rightarrow \Theta = 63$ degrees

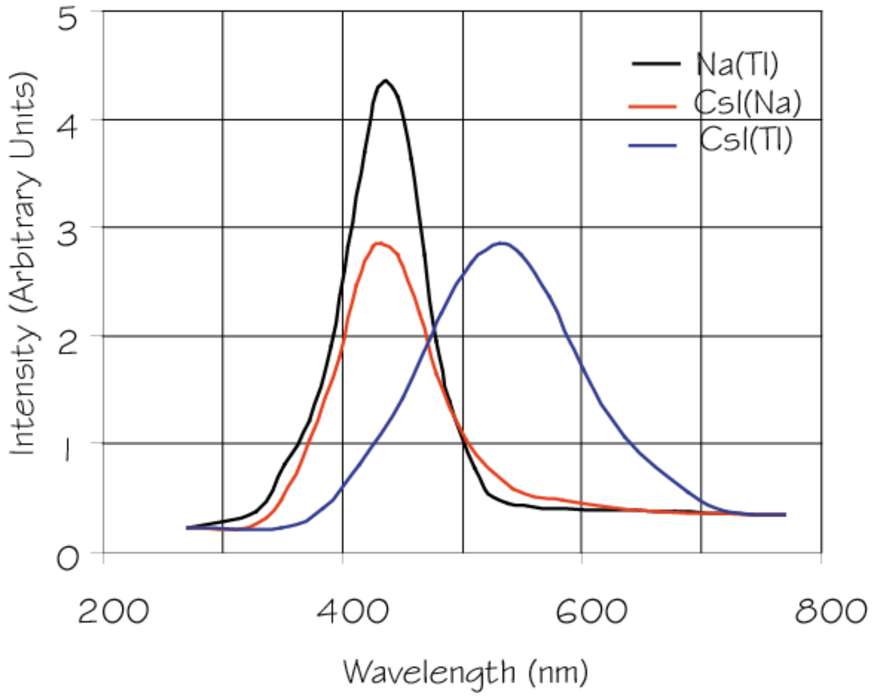
Threshold for the production of Cherenkov light: $v_{thr} = c/n$

Threshold energies for n=2.2:
Electrons 0.6 MeV
Pions 157 MeV
Protons 1.05 GeV

Scintillation light production

e.g. energy band in impurity activated crystal





Final wavelength depends on material properties (dopants) and can be engineered

Need to avoid overlaps between absorption and emission bands

Decay time of the scintillation signal is an important property

Final emitted light is isotropic (emitted in all directions)

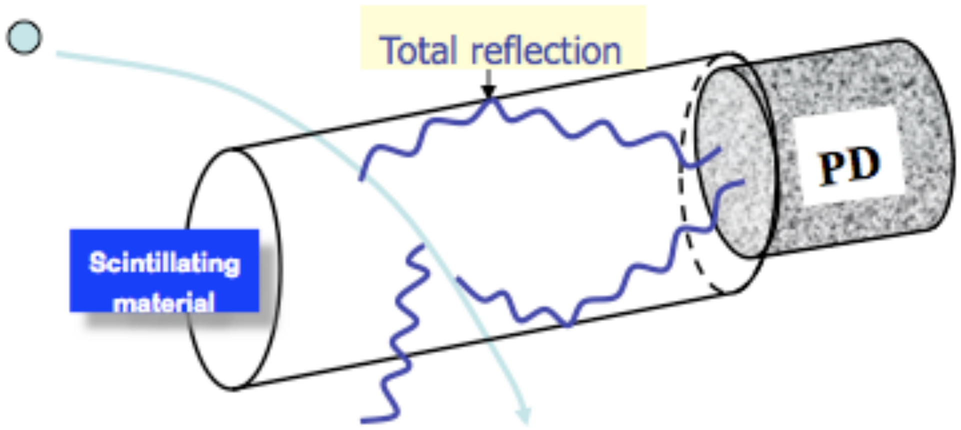
Some properties of crystal scintillators

Scintillator composition	Density (g/cm^3)	Index of refraction	Wavelength of max.Em. (nm)	Decay time Constant (µs)	Scinti Pulse height[1)]	Notes
NaI(Tl)	3.67	1.9	410	0.25	100	2)
CsI	4.51	1.8	310	0.01	6	3)
CsI(Tl)	4.51	1.8	565	1.0	45	3)
CaF_2(Eu)	3.19	1.4	435	0.9	50	
BaF_2	4.88	1.5	190/220 310	0,0006 0.63	5 15	
BGO	7.13	2.2	480	0.30	10	
$CdW0_4$	7.90	2.3	540	5.0	40	
$PbWO_4$	8.28	2.1	440	0.020	0.1	
CeF_3	6.16	1.7	300 340	0.005 0.020	5	
GSO	6.71	1.9	430	0.060	40	
LSO	7	1.8	420	0.040	75	
YAP	5.50	1.9	370	0.030	70	

1) Relative to NaI(Tl) in %; 2) Hygroscopic; 3) Water soluble

from C. D'Ambrosio, Academic Training, 2005

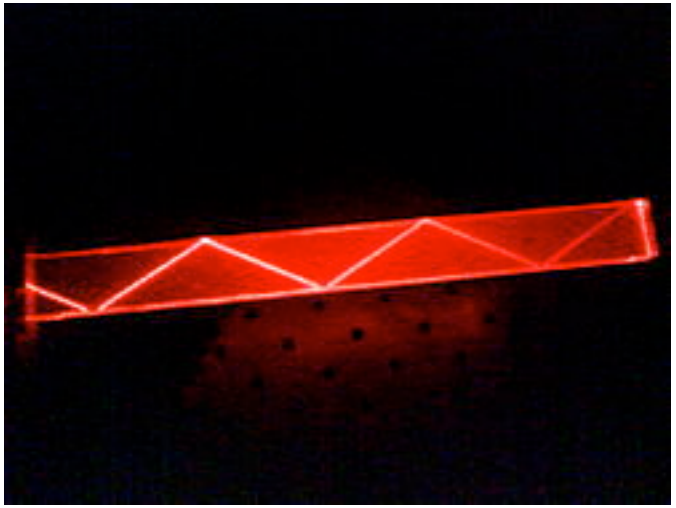
Detection of scintillation light



The photon-detector (PD) converts the light signal into an electronic signal.
The conversion factor (quantum-efficieny QE) is generally well below 1.
QE = #electrons / #photons (at the photocathode)

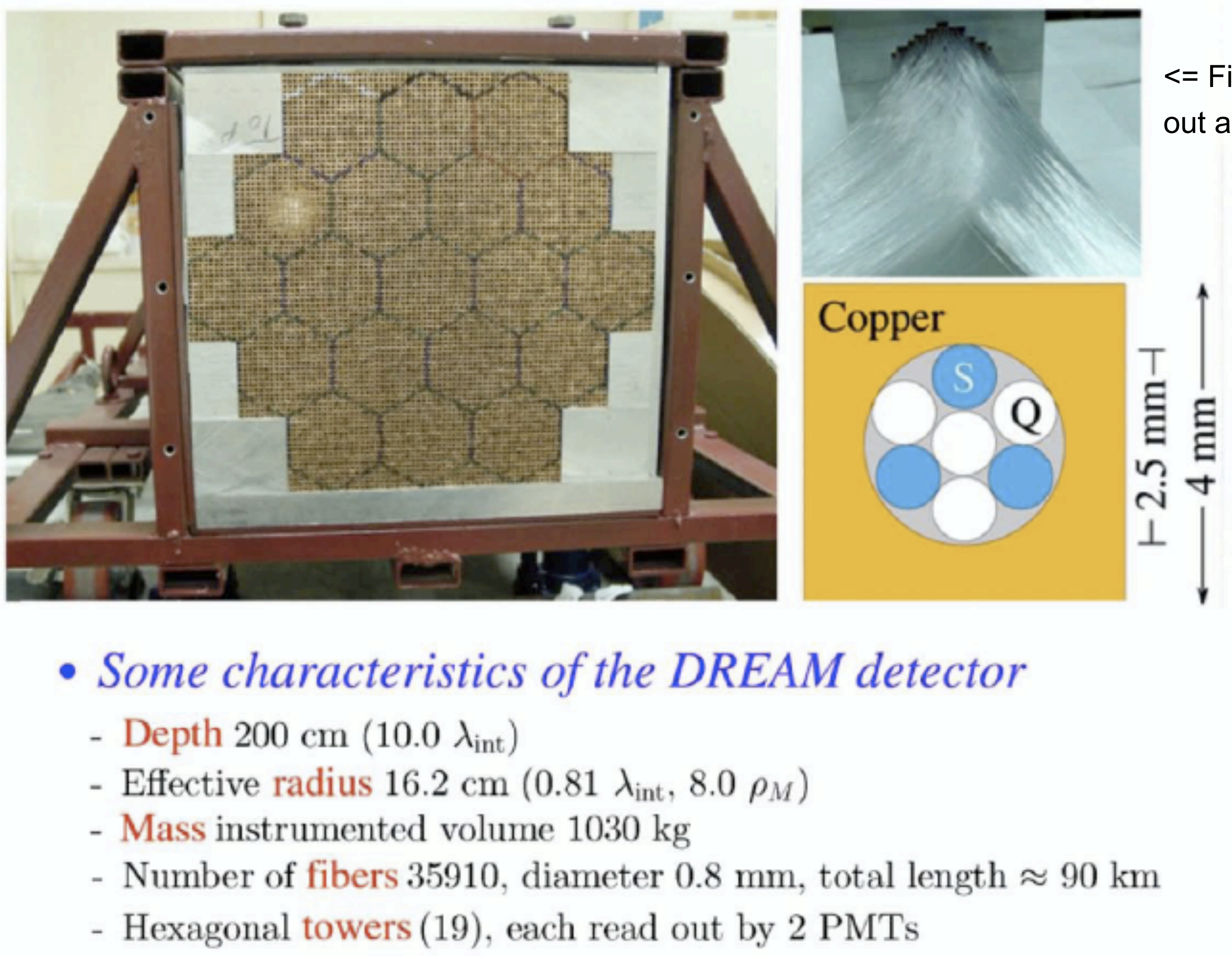
Total internal reflection depends on refractive indexes:
$\Theta_c = \arcsin(n_2/n_1)$
(with n_1 = refractive index of dense medium)
(Θ_c is measured with respect to the normal of the boundary)

Attenuation length L: $I = I_0 e^{-x/L}$


Total internal reflection in a block of PMMA

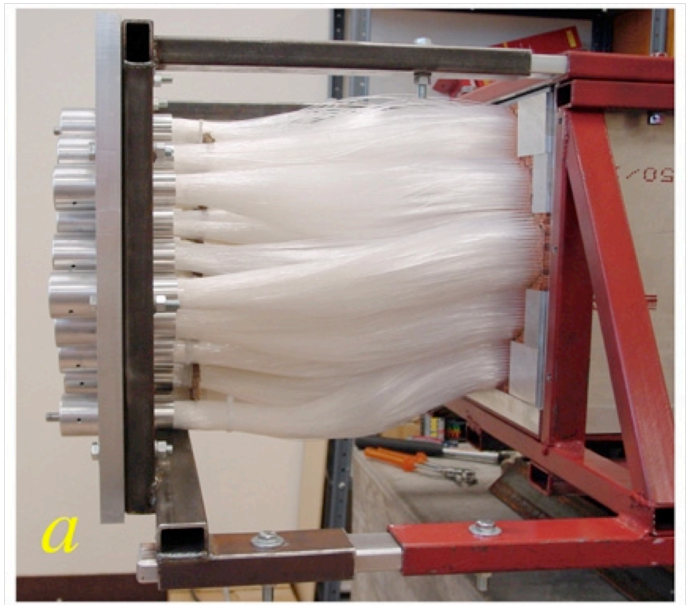
Dual (triple) readout method

Richard Wigmans

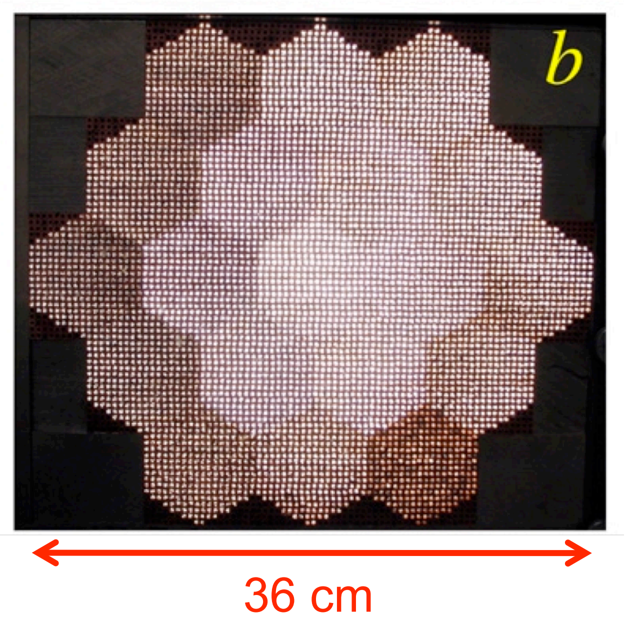


<= Fibres coming out at the back

- *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 ≈ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

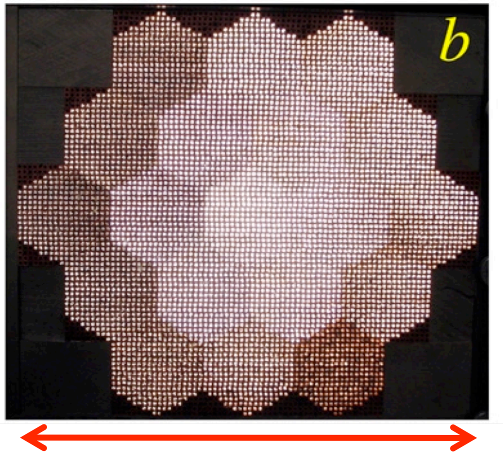


Rear side of the DREAM fibre-calorimeter Scintillation fibres and Cerenkov-fibres are separated from eachother for each of the 19 hexagonal cells



View of the front face of the calorimeter, while the fibre-bundles are illuminated from the back. One clearly sees the hexagonal organisation of the readout cells

A few more parameters of the **D**ual **REA**dout **M**odule calorimeter



36 cm

Radiation length X_0 = 20.1 mm

Moliere radius ρ_{mol} = 20.4 mm

Full detector is $8\rho_{mol}$ wide

Interaction length λ_{int} = 200 mm

Full detector is $10\lambda_{int}$ deep

Detector volume composition:

Copper 69.3%

Scint. Fibres: 9.4%

Cherenkov fibres: 12.6%

Air 8.7%

Sampling fraction: 2.1%

The detector was fully calibrated with 40 GeV electrons (reproducibility 2%)

Impact angle (2°, 0.7°) to avoid that single particles channel through fibres only

A few optical characteristics:

Fibres:

- Scintillating: SCSF-81J, Kurakay, Japan (plastic)
- Cherenkov
  - Polymer-clad fused-silica, Polymicro USA
  - Raytela PJR-FB750, Toray, Japan

Coupling to photomultiplier (1.5” Hamamatsu R-580) via air gap

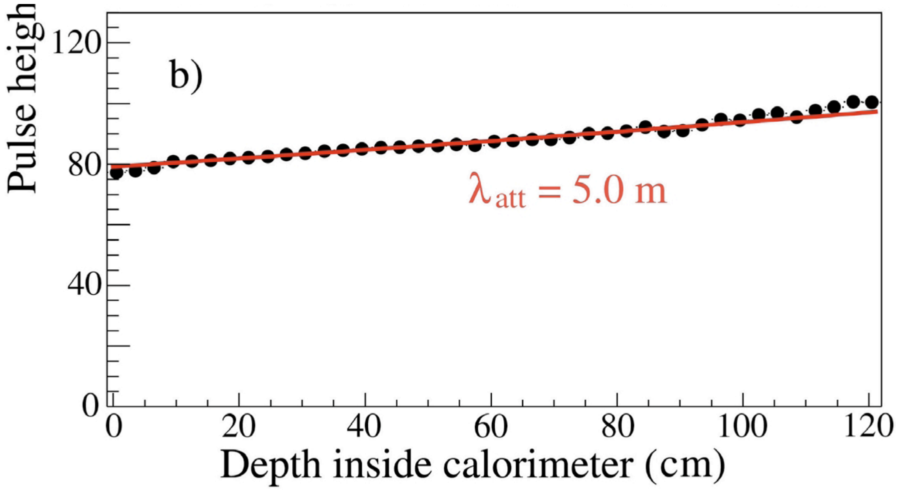
Yellow filter (7% at 425 nm, 90% at 550 nm) used for scintillating fibres

- The yellow filter cuts out the blue part of the scintillation spectrum (actually overlap between emission and absorption bands)
- The yellow filter improves the attenutation length of the scintillation fibres

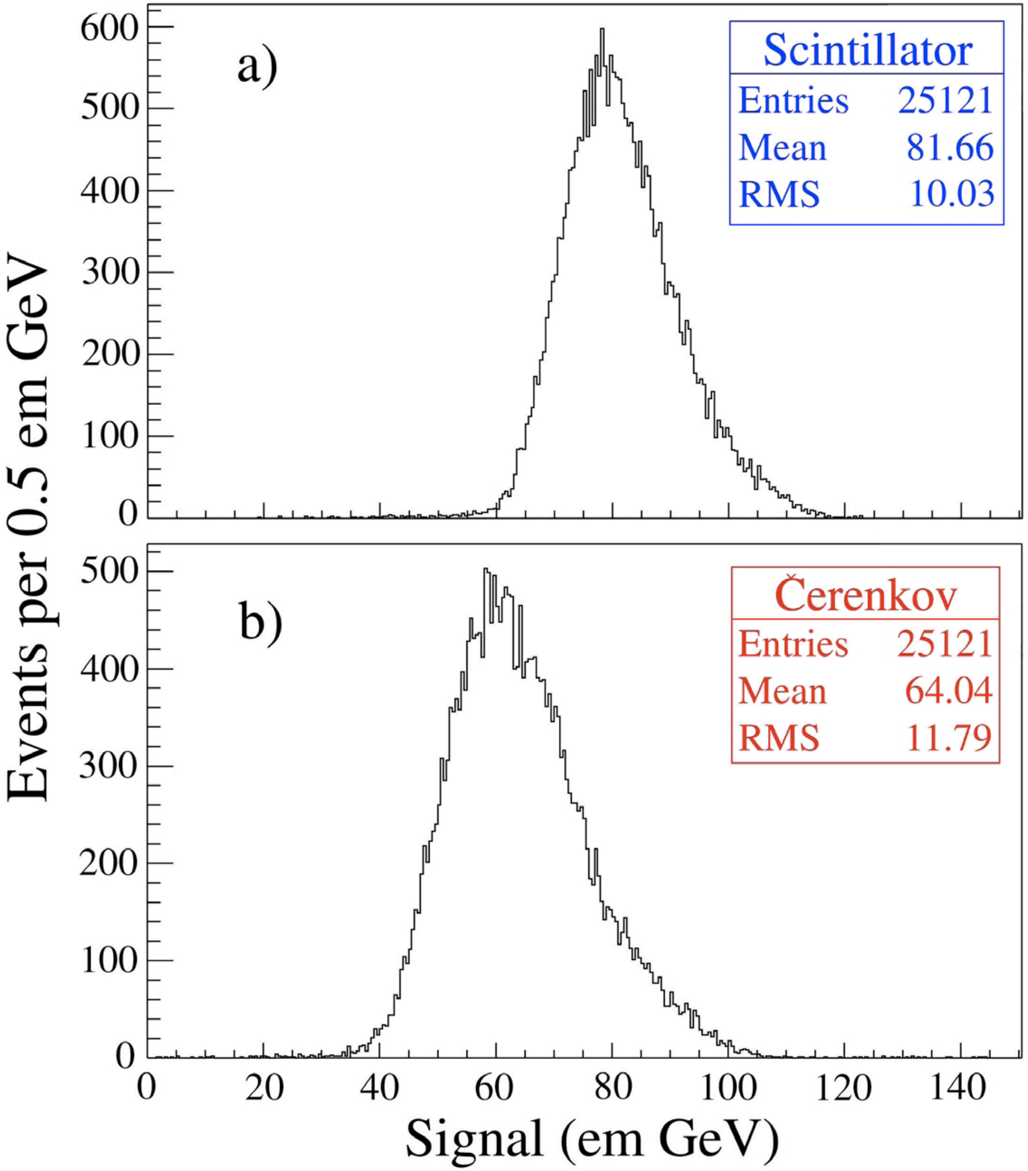
Effective attenuation lengths:

Cherenkov: λ_{att} = 15 m, 18 m

Scintillating: λ_{att} = 5 m



Raw signals from 100 GeV π^-



Scintillator only:

Asymmetric signal, large tails

σ_{RMS}/mean = 12.3%

Full signal is 82% of equivalent signal for 100 GeV electrons

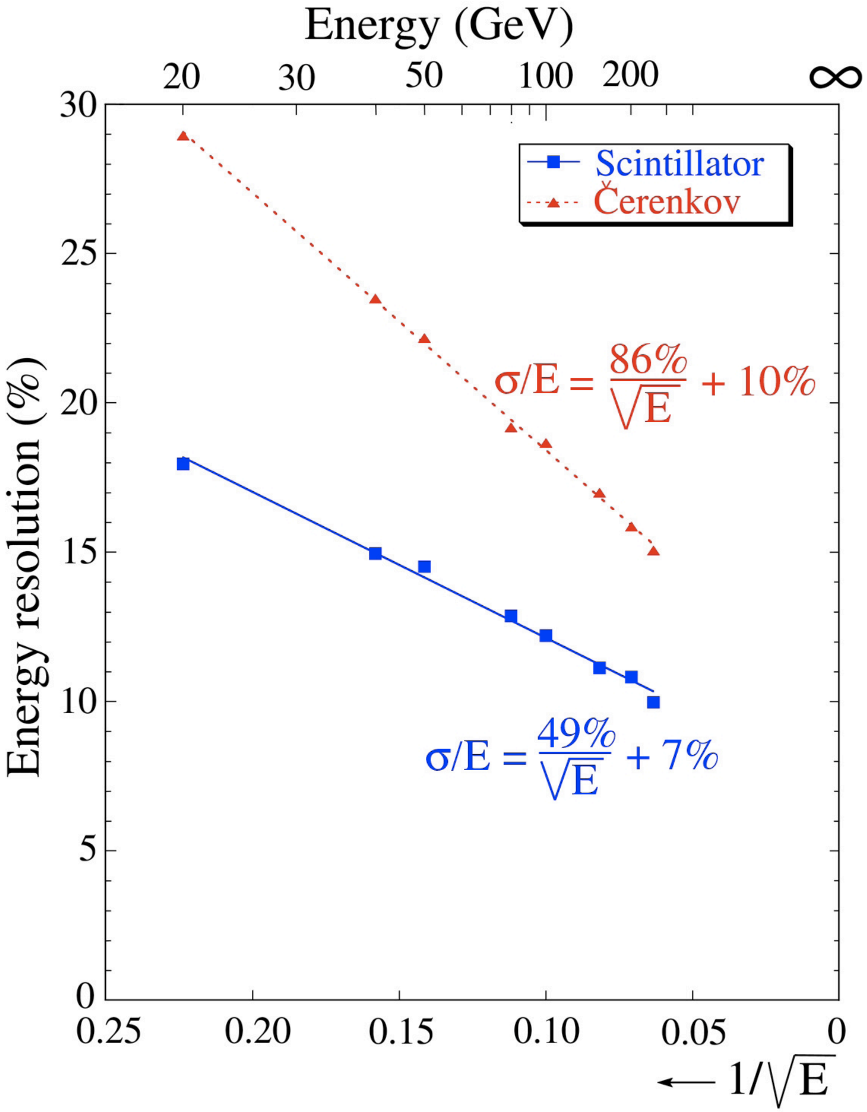
Cherenkov only:

Asymmetric signal, large tails

σ_{RMS}/mean = 19%

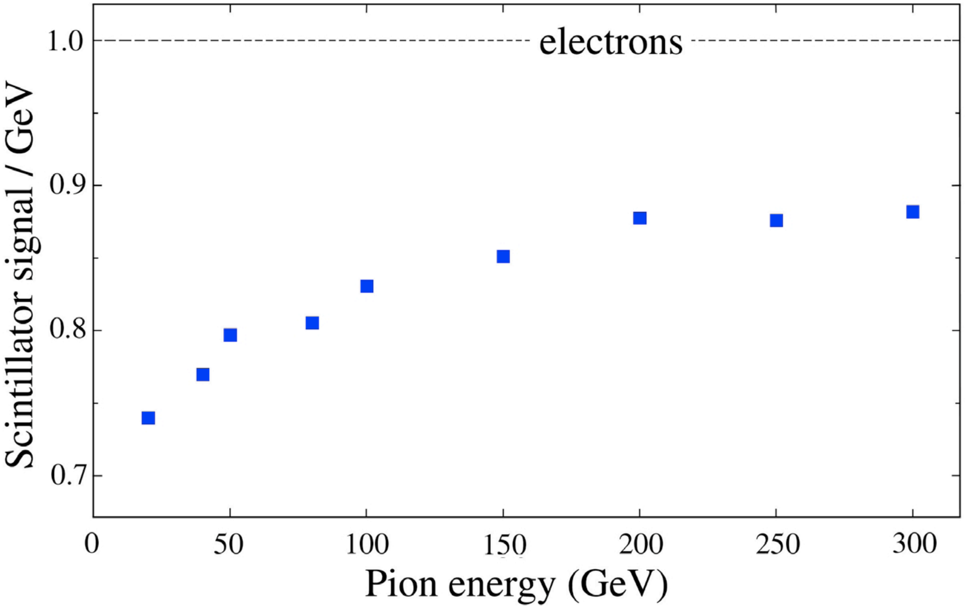
Full signal is 64% of equivalent signal for 100 GeV electrons

Energy resolution for raw Scintillator and Cherenkov signals



Energy resolution σ/E for raw Scintillator and Cherenkov signals for single pions is best described by a *linear* (not quadratic) sum of a stochastic term plus a constant term.

The energy-dependence of the response is non-linear



Response R of the calorimeter

$R = \text{signal}/E = f_{em} + (e/h)^{-1}(1-f_{em})$

f_{em} = electromagnetic fraction of the shower

e/h = ratio of detector response to EM and HAD components

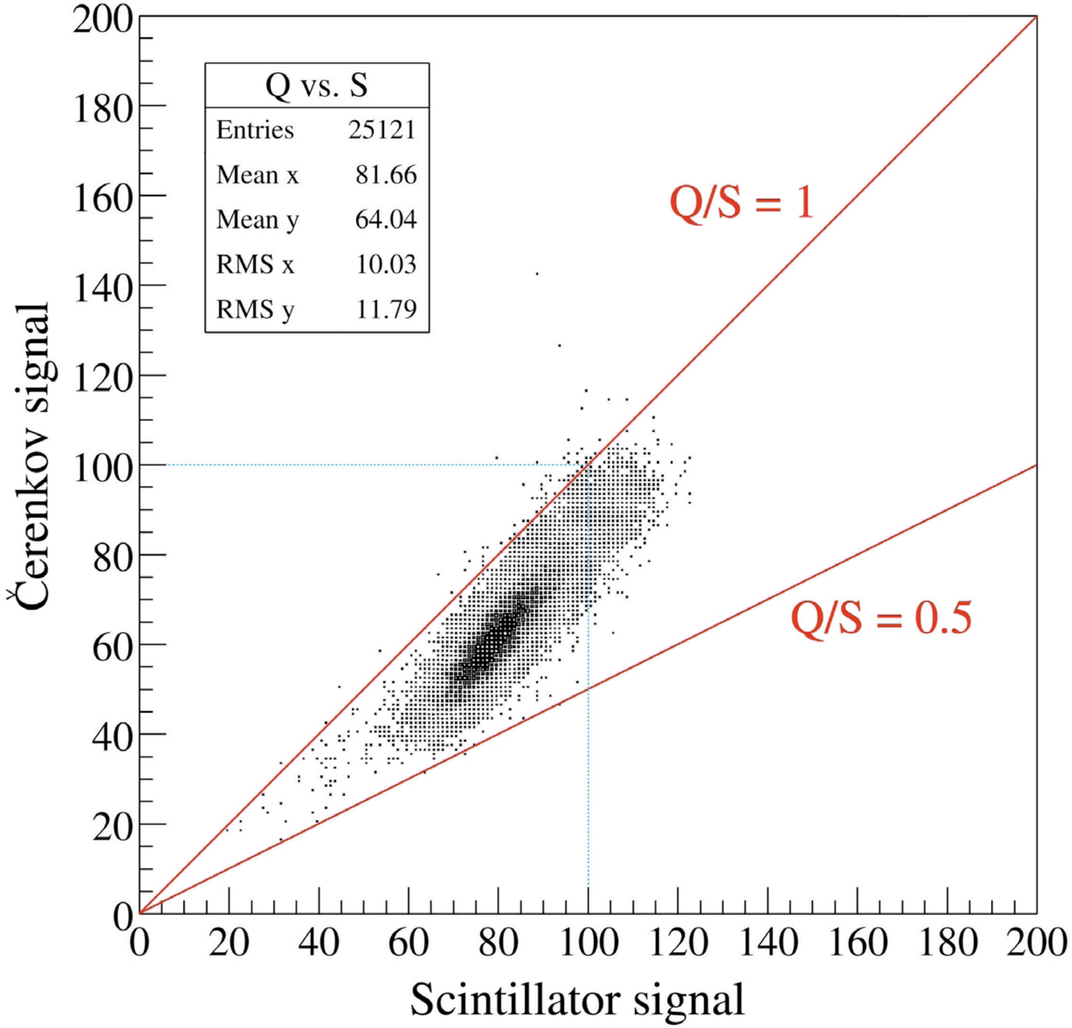
Typical values of e/h:

- Estimate for Copper/Plastic fibre: $e/h \approx 1.4$
- Estimate for Copper/Quartz fibre: $e/h \approx 5.0$

The poor hadronic energy resolution and non-linearity of the scintillation signal (and equally of the cherenkov signal) are caused by the fluctuations in f_{em}.

Moreover the average value of f_{em} depends on the energy (actually increases with energy).

How to measure the energy E using S (scintillator) and Q (Cherenkov) responses?



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

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

Constants $(h/e)_S$ and $(h/e)_Q$ do not depend on energy.

Once $(h/e)_S$ and $(h/e)_Q$ are known, we are left for each event with 2 equations and 2 unknows values (E and f_{em}) => problem solved!

However…… first we need to correct for a few instrumental effects:

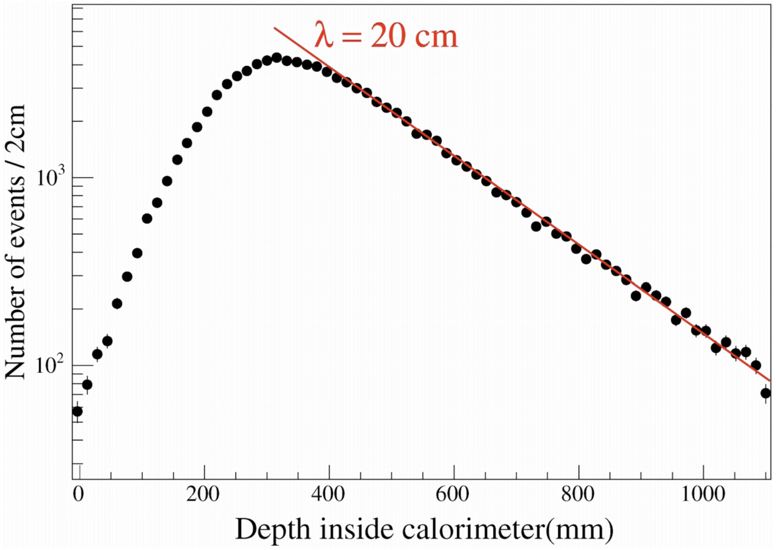
Attenuation of light in the scintillating fibres (λ_{att} = 5 m) :

Use the slightly tilted position of DREAM (2°, 0.7°) to determine the centre-of-gravity of the shower in z (depth).

This requires that you know the impact point!

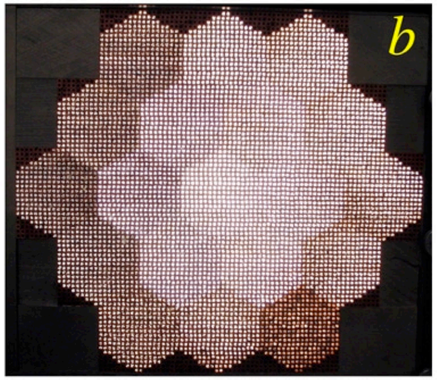
⇒ Remove all showers with centre-of-gravity beyond $5\lambda_{int}$ from the sample (5% of events)

⇒ Correct for the light attenuation (correction amounts to typically 2%)



Lateral shower leakage:

With an effective radius of $8\rho_{mol}$ the calorimeter is too small to contain full hadronic showers => count signals in the outer ring twice.



This is an ad-hoc solution, removing most of the lateral leakage effect, but not all (e.g. f_{em} depends on leakage)

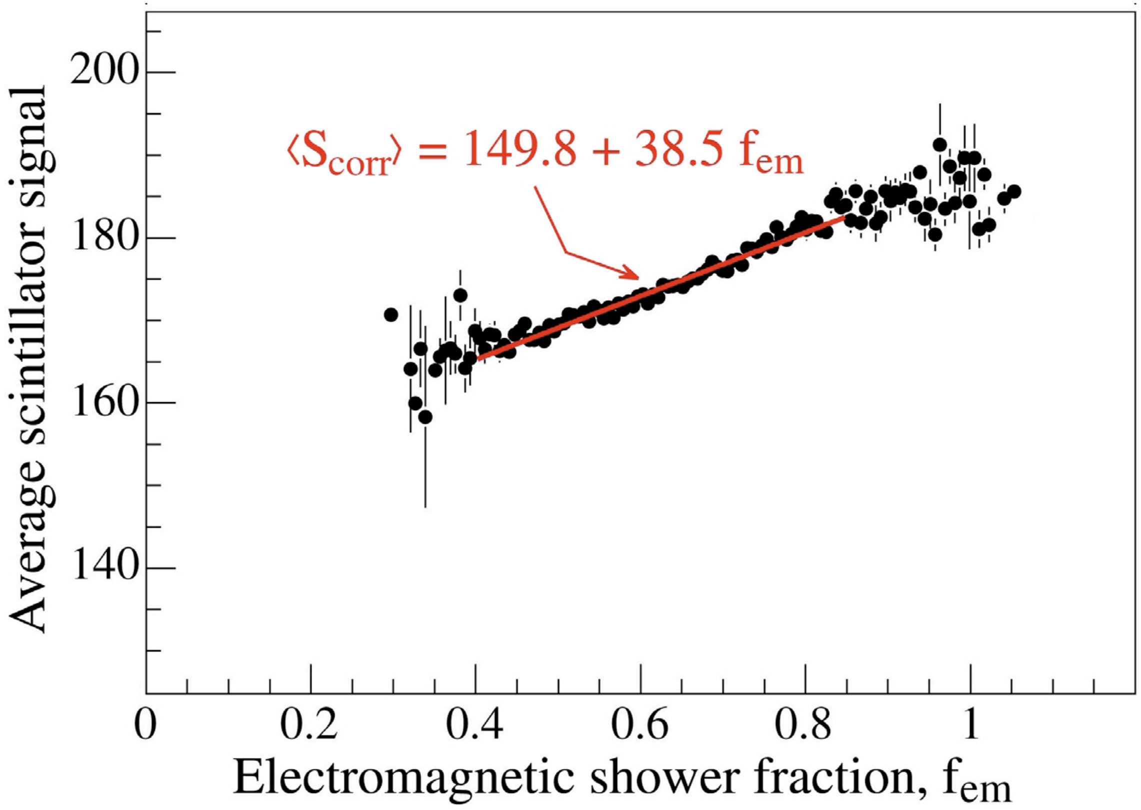
Unfortunately the lateral shower leakage is the real limiting factor for the DREAM module.

How to measure constants $(e/h)_S$ and $(e/h)_Q$?

Start with $(e/h)_S$:

- Use initial estimated values of $(e/h)_S$
- Use calibrated beam (E is known) => 200 GeV jets were used
- Use $R_S = S/E = f_{em} + (e/h)_S^{-1}(1-f_{em}) = f_{em}(1 - (e/h)_S^{-1}) + (e/h)_S^{-1}$

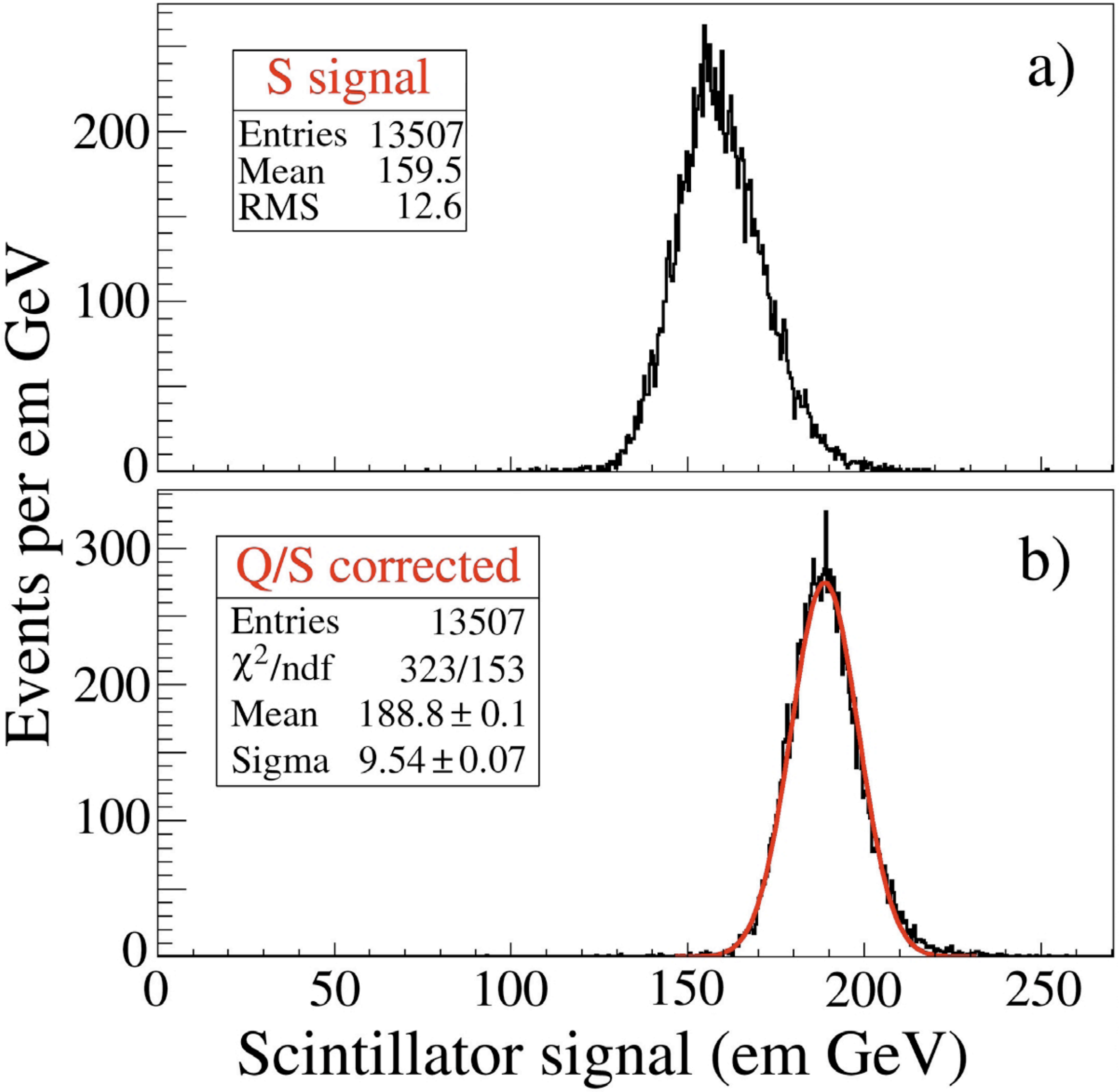
In an iterative procedure one finds that $(e/h)_S \approx 1.3$



Once the correction is applied, one finds a narrow Gaussian distribution for $R_S = S/E = f_{em} + (e/h)_S^{-1}(1-f_{em})$

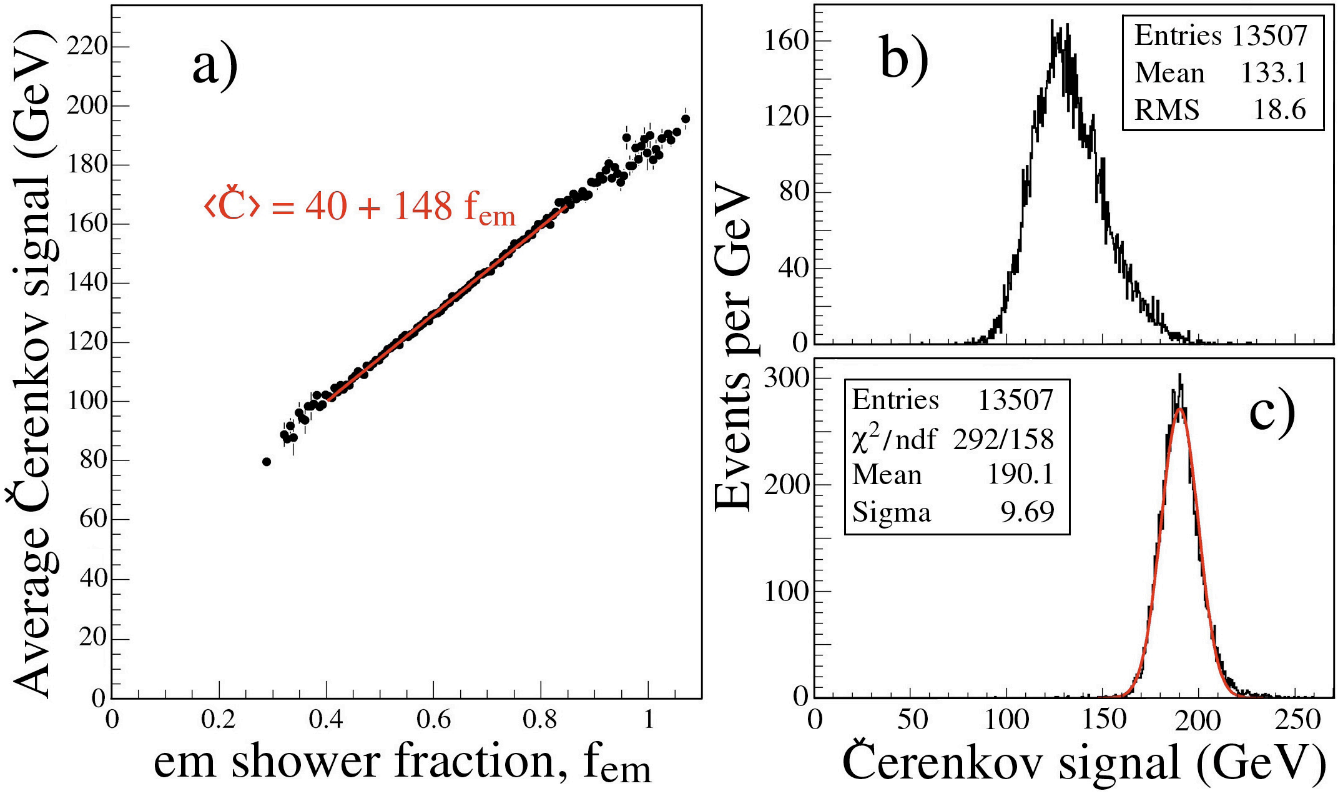
for 200 GeV jets

$\sigma/E = 5.1\%$



…. and similarly for $(e/h)_Q$:

One finds that $(e/h)_S \approx 4.7$

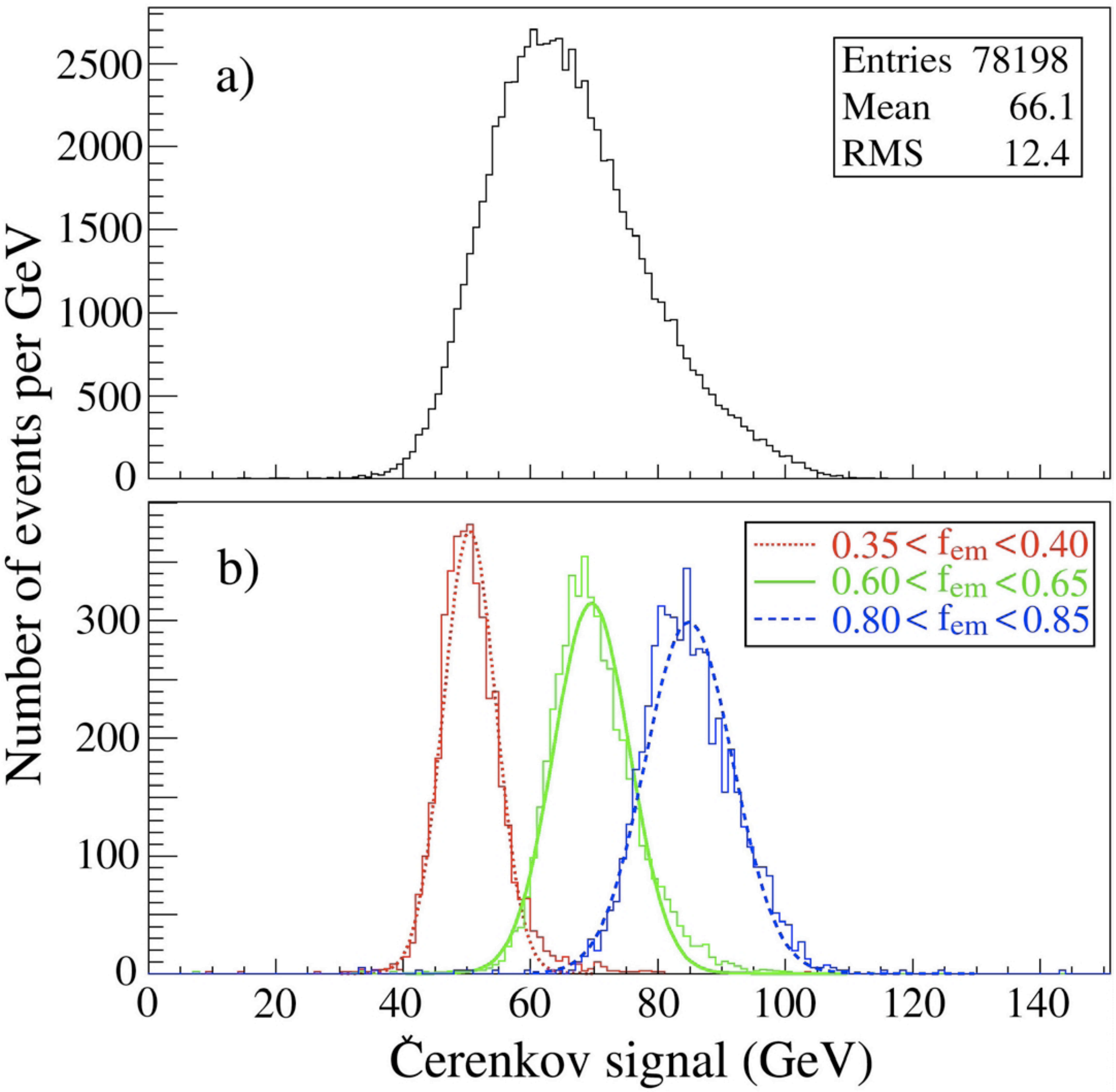


for 200 GeV jets

$\sigma/E = 5.1\%$

Once the correction is applied, one finds a narrow Gaussian distribution

for $R_Q = Q/E = f_{em} + (e/h)_Q^{-1}(1-f_{em})$



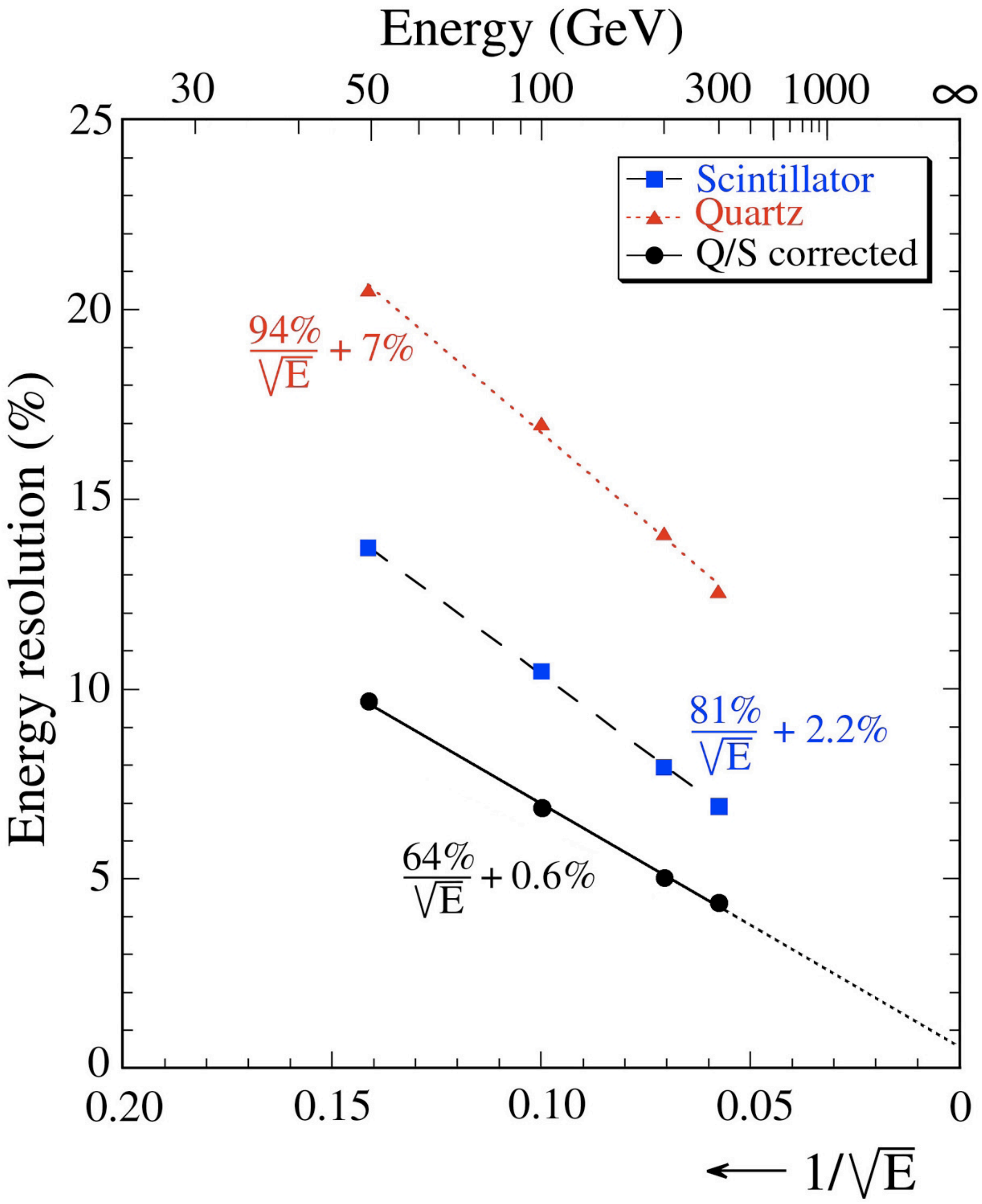
Raw Cherenkov signals from 100 GeV π^-

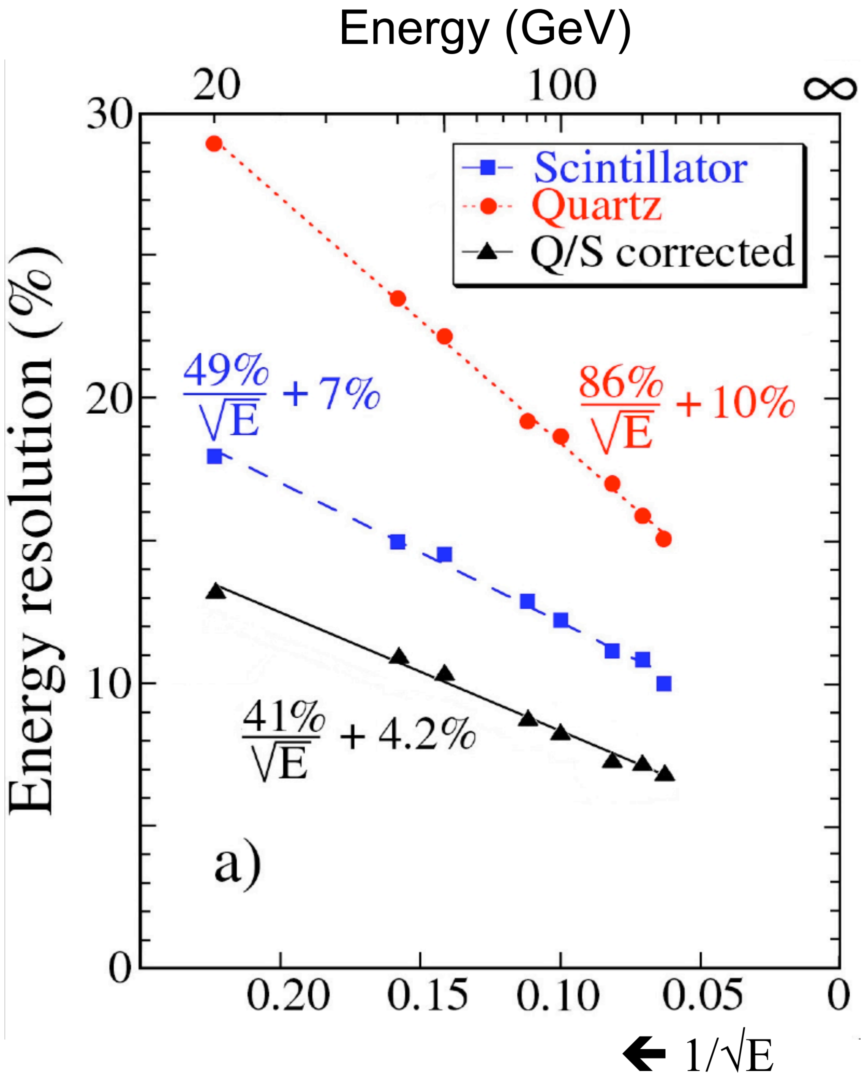
Raw Cherenkov signals from 100 GeV π^- for different bins in f_{em}

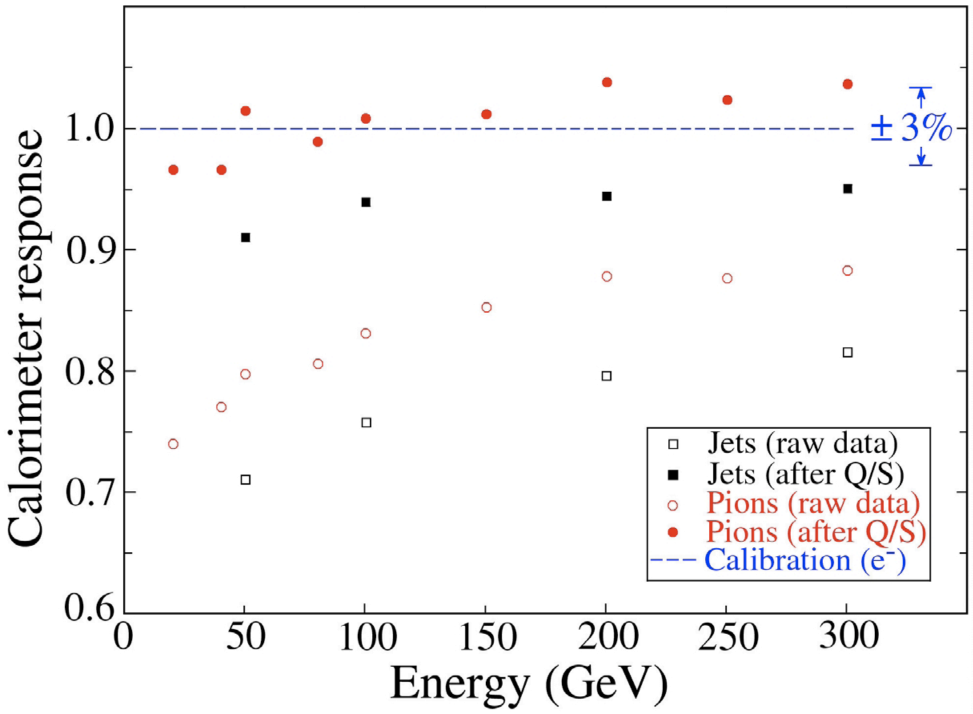
“jet” energy resolution, as measured with the DREAM module in a test beam.

The graph shows the energy resolution for the uncorrected scintillator and Cherenkov signals, and also for the Q/S corrected signal.

Unfortunately the ultimate resolution cannot be demonstrated with the DREAM module, because the module is too small ➔ too much lateral shower leakage







Energy resolution for Pions, linearity for Pions and Jets

Using an *ad-hoc correction* for shower leakage

Neutron component of the shower

Now that we have corrected the signal for the f_{em} and e/h, other effects become the dominating limits to the energy resolution.

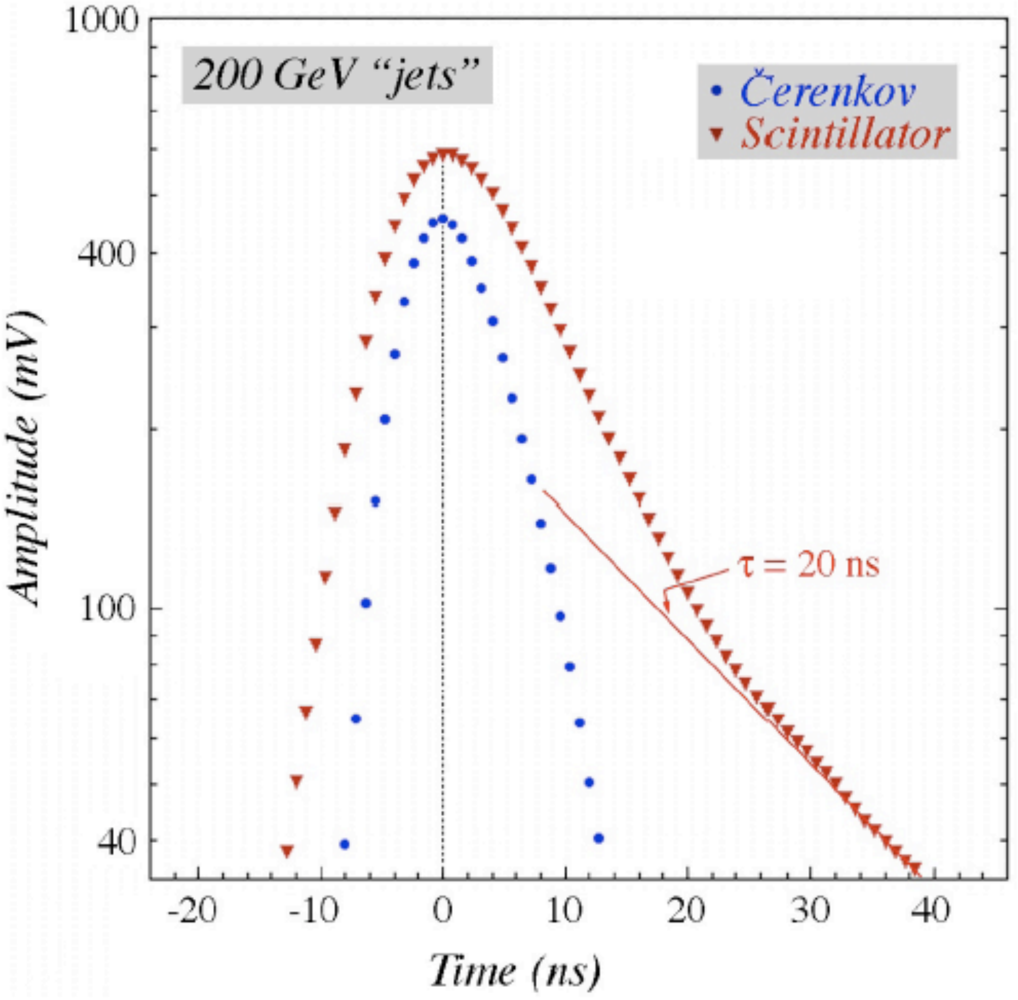
Some parts of the hadronic shower remain undetected.
A varying fraction of the shower energy is used to provide nuclear binding energy needed to release nucleons in nuclear reactions.
This fraction of the energy becomes “invisible”.
This can account for up to 40% of the non-EM shower fraction.

There is a correlation between this lost energy and the number of thermal neutrons released from the nuclei during the process.

These evaporation neutrons have typically E= 2-3 MeV.
Mean free path ~0.5 m
These neutrons are ultimately detected by the scintillator
This gives an expected time structure with a ~25 ns decay time on the scintillation signal.

Neutron component of the shower

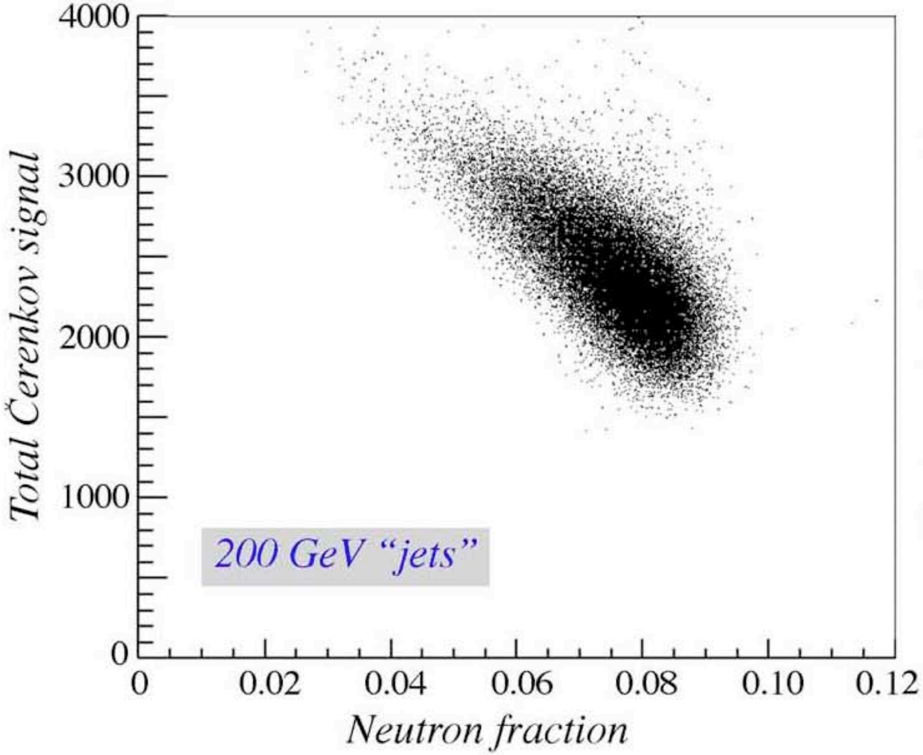
Richard Wigmans

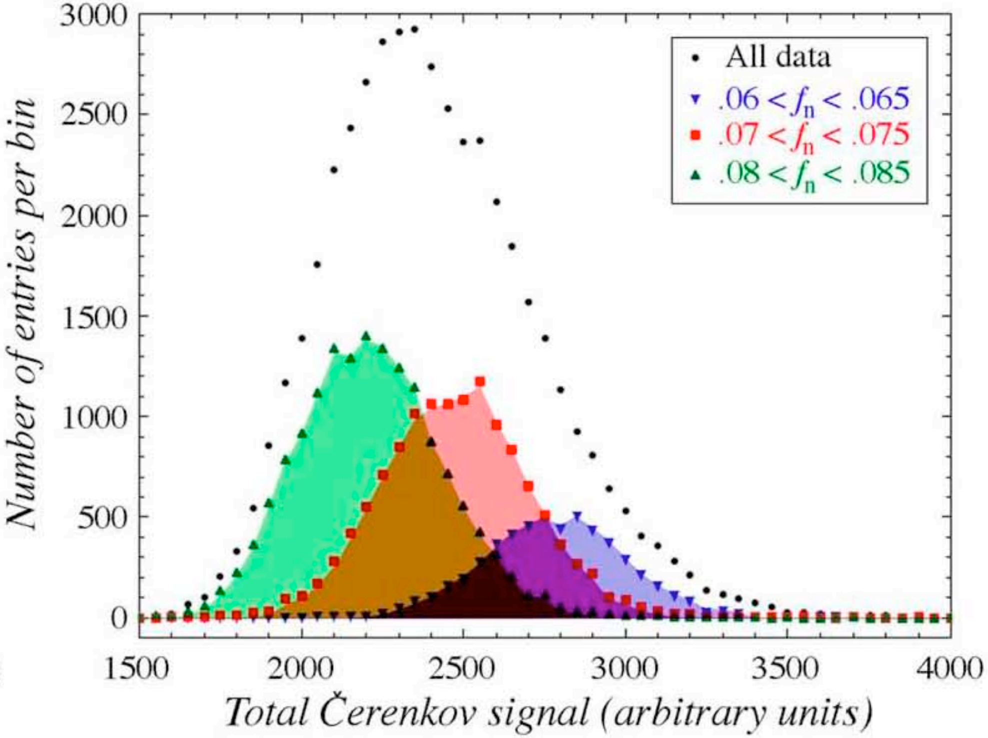


"neutron signal" defined simply as the integral of the Scintillation pulse over 20-40 ns

The slow neutrons can be seen from the time structure of the Scintillation signal

The neutron signal is anti-correlated with the electromagnetic fraction, therefore anti-correlated with the Cherenkov signal,





Using the information on the neutron fraction f_n, the resolution can be further improved

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

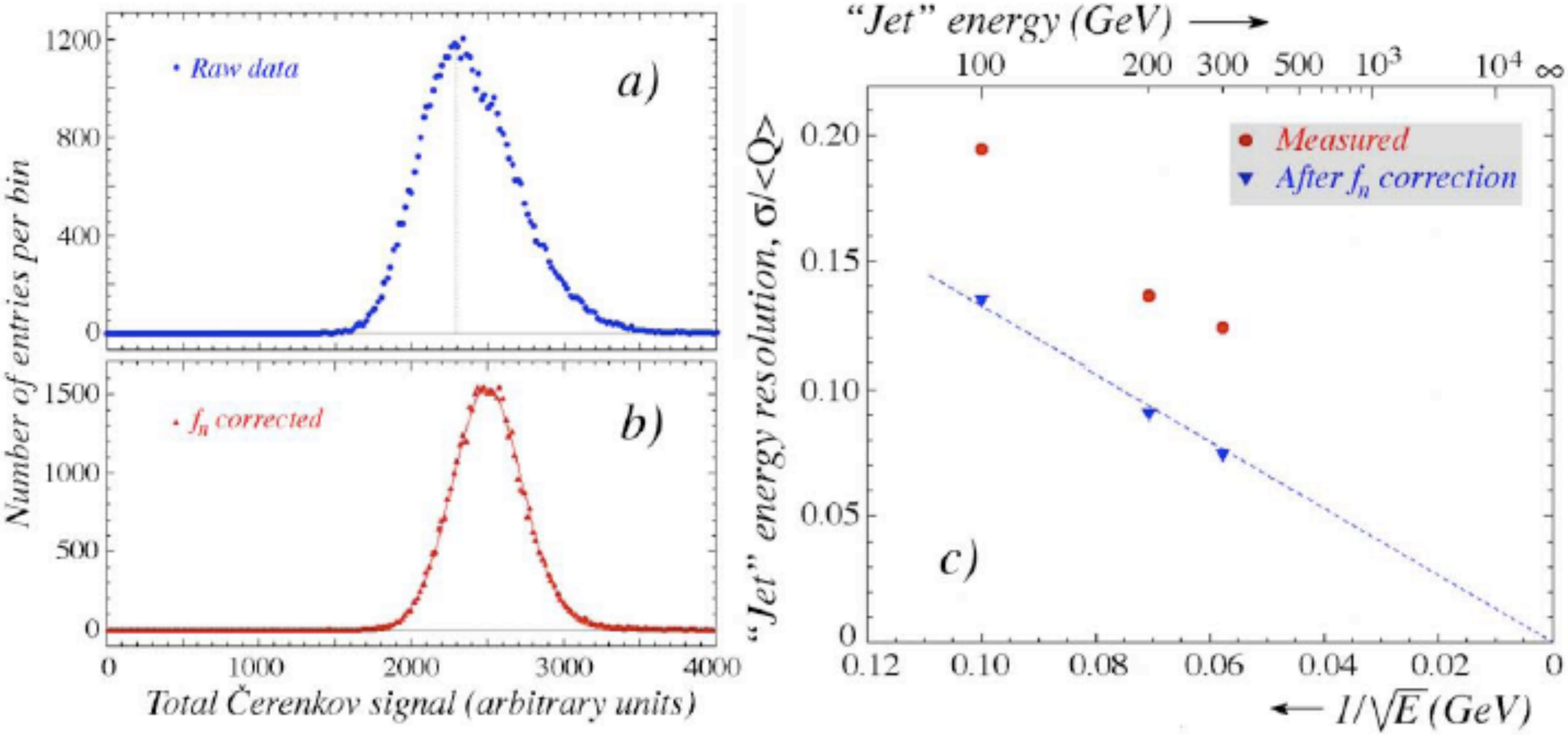


Figure 19: Distribution of the total Čerenkov signal for 200 GeV "jets" before (a) and after (b) applying the correction based on the measured value of f_n, described in the text. Relative width of the Čerenkov signal distribution for "jets" as a function of energy, before and after a correction that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

Summary of systematic effects of the DREAM-type calorimeter, using active and passive material, readout with scintillating fibres, no longitudinal segmentation:

5 m scintillating attenuation length requires average correction of 2% on hadronic shower. This requires knowledge of shower depth (obtained from impact point an few-degrees tilt). This correction cannot be applied conveniently in projective modules.

Signal height depends on initial impact point (in fibre or in Cu). In case beginning of shower is mainly in fiber => signal higher, effect is few %

In case of longitudinal leakage: large energy deposit in the fibre bundles behind: size of the effect is several %.

Fluctuations in sampling fraction due to the sharing of energy deposit between the passive and active material (this effect is “cured” by triple readout).

Number of photo-electrons for Cherenkov signal is ~8 p.e. per GeV => this gives a limit to the ultimate pion resolution of ~35%/√E

Next plans of the DREAM collaboration

Build a 5 times larger HCAL module

Similarly based on Cu + fibres

One fibre per hole. (half cherenkov / half scintillator)

Use different PM's with better light yield

Use plastic fibres for cherenkov to increase numerical aperture

Read out fine time structure for all fibres

Aluminise the front face of the fibres:

> Allows to see unreflected and reflected signal independently and therefore extract the depth of the signal

Optional EM crystal section

5000 kg detector, 600 km fibre. Time scale?

DREAM collaboration is principally interested in demonstrating the ultimate precision capability of the dual/triple readout technique (~25%/√E for jets)