New Results from the DREAM project

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Outline

- The DREAM approach to precision hadron calorimetry and the basic performance of the first fiber calorimeter

- The extension of the DREAM approach to a homogeneous calorimeter :
  - results on single crystals (doped $PbWO_4$ crystals, BGO)
  - results on an hybrid calorimeter (fiber module + BGO matrix)

- Conclusions

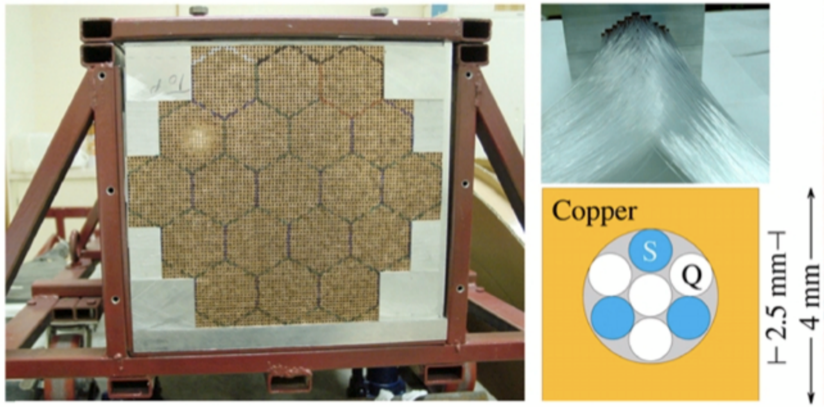
Dual REdAout Method

- Main limitations of the hadron calorimetry:
  - calorimeter response to em component and non-em component not the same
  - fluctuations of the electromagnetic fraction (f_{em}) large and non-poissonian

- Consequences:
  - hadronic signal non-linearity, no Gaussian response , poor hadronic energy resolution (with a deviation from $E^{-1/2}$)

- The DREAM approach :
  - Cerenkov light is almost exclusively produced by em component
  - A sampling calorimeter with two separate active materials (one sensitive to the Cerenkov and one to the Scintillation light) can measure event by event the f_{em} (by comparing the two signals) eliminating this source of fluctuations

Dual-REAdout Module Performance



Some characteristics:

5130 copper rods equipped with plastic scintillating (S) and undoped quartz (Q) fibers, grouped in 19 hexagonal towers each read-out by 2 PMTs

Depth 200 cm (10.0 λ_{int})

Effective radius 16.2 cm (0.81 λ_{int},8.0 ρ_M).

Dream equations:

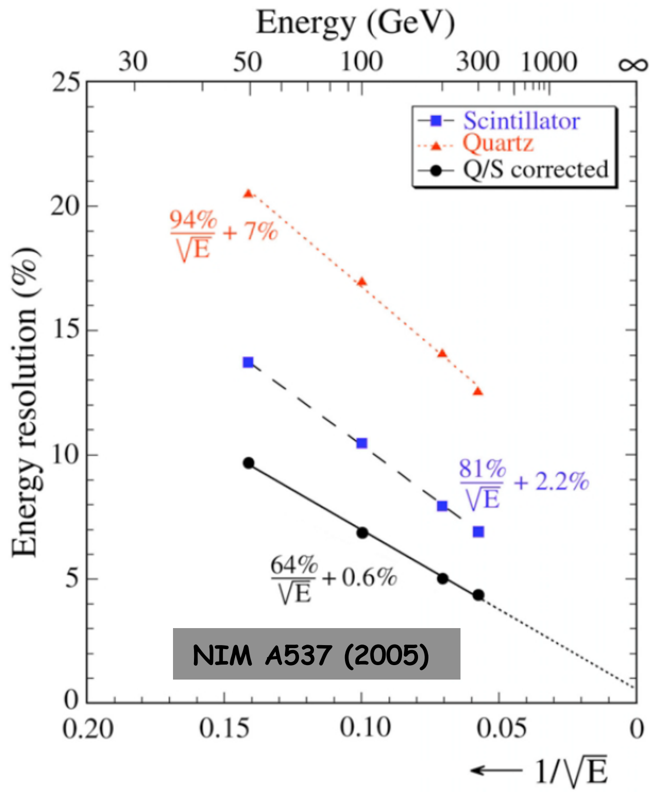
$$\begin{cases} S = E\left[f_{em} + \frac{1}{(e/h)_S}(1-f_{em})\right] \\ Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1-f_{em})\right] \end{cases}$$

$$\frac{Q}{S} = \frac{f_{em} + (e/h)_Q^{-1}(1-f_{em})}{f_{em} + (e/h)_S^{-1}(1-f_{em})}$$

$$E = \frac{S - \chi Q}{1-\chi} \quad with\ \chi = \frac{1-(e/h)_S^{-1}}{1-(e/h)_Q^{-1}} = \frac{1-(1.3)^{-1}}{1-(4.7)^{-1}} \approx 0.3$$

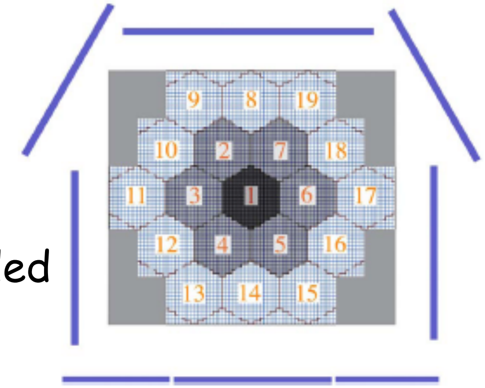
The results: reduced hadronic signal non-linearity, improved resolution, perfect $E^{-1/2}$ scaling

Resolution dominated by: Leakage fluctuations, sampling fluctuations, fluctuations in the Cerenkov light yield, fluctuations in invisible energy

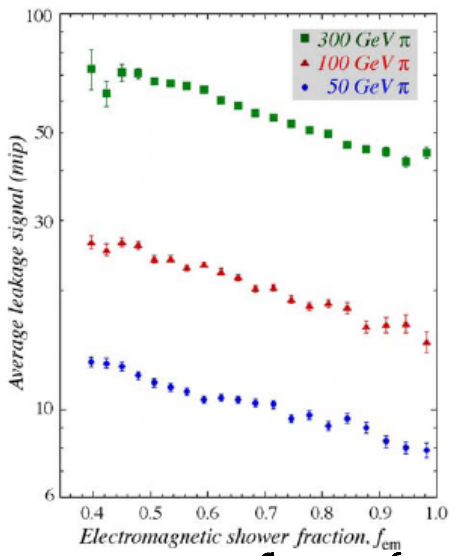


DREAM lateral leakage

Dream resolution limited by: fluctuations in side leakage
(at 100 GeV, the side leakage amounted to 9.7% on average, in the scintillator channel)



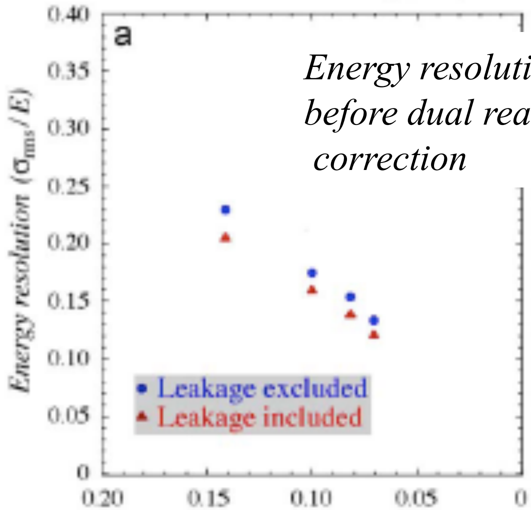
In the 2008 and 2009 CERN H4 beams tests, DREAM was surrounded by 7 plastic scintillator paddles to detect the lateral leakages



f_{em} computed using: $\dfrac{C_{DREAM}}{S_{DREAM}} = \dfrac{f_{em} + 0.21(1-f_{em})}{f_{em} + 0.77(1-f_{em})}$

Good anti-correlation found between the f_{em} and the leakage. The more the shower is electromagnetic the better it is contained. Moreover the f_{em} increases with the beam energy as expected.

Adding the leakage signals led to an improvement of the energy resolution of the scintillation signal at level of 10%



Homogeneous calorimetry

Dream resolution limited by : fluctuations in the Cerenkov light yield
(8 p.e./GeV ➔ fluctuation contribution 35%/√E)

Scintillating crystals are possible candidates for a homogeneous dual-readout calorimeter.
We need:

- Good Cerenkov vs Scintillation separation

	Cerenkov	Scintillation
Time response	Prompt (short signal duration, few ns)	Exponential decay (light emission characterized by one or several time constants)
Light Spectrum	$1/\lambda^2$	Peak (Strongly dependent on the crystal, usually concentrated in a narrow wavelength range)
Directionality	Cone: $\cos(\theta_C)=1/\beta n$	Isotropic

- Response uniformity (no light attenuation)
- High light yield (to reduce contributions to the resolution due to p.e. statistics)

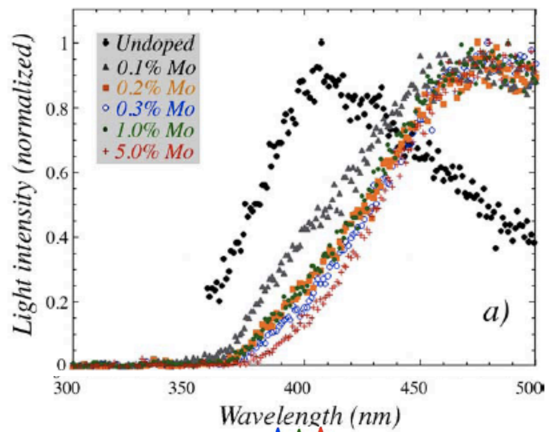
Different scintillating materials have been tested during the CERN H4 beam tests of 2006, 2007, 2008, 2009 : $PbWO_4$, Doped $PbWO_4$ (with Molybdenum) and BGO

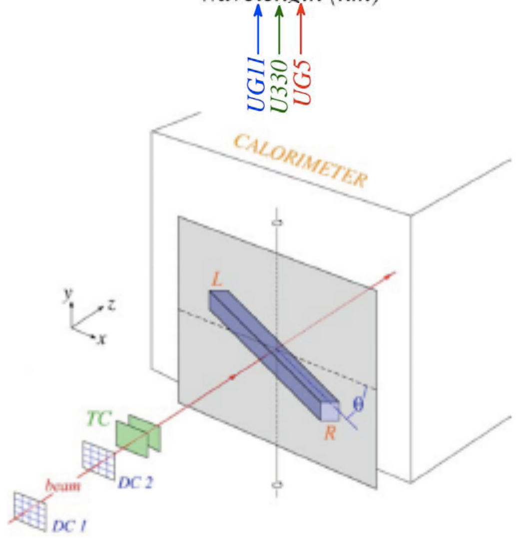
Mo-doped $PbWO_4$ single crystals

A significant fraction of signals in $PbWO_4$ is due to Cherenkov radiation (15% on average at room temperature), but it is hard distinguish the scintillation component from the Cherenkov one, since the $PbWO_4$ is a very fast scintillator with a blue dominated spectrum

2006 and 2007 CERN H4 beam tests:
NIM. A582 (2007), NIM A584 (2008),
NIM A593 (2008)

➔In the 2008 and 2009 tested $PbWO_4$ crystals doped with small fractions of impurities chosen such as to achieve a shift of the scintillation spectrum to longer wavelengths, and a longer decay time



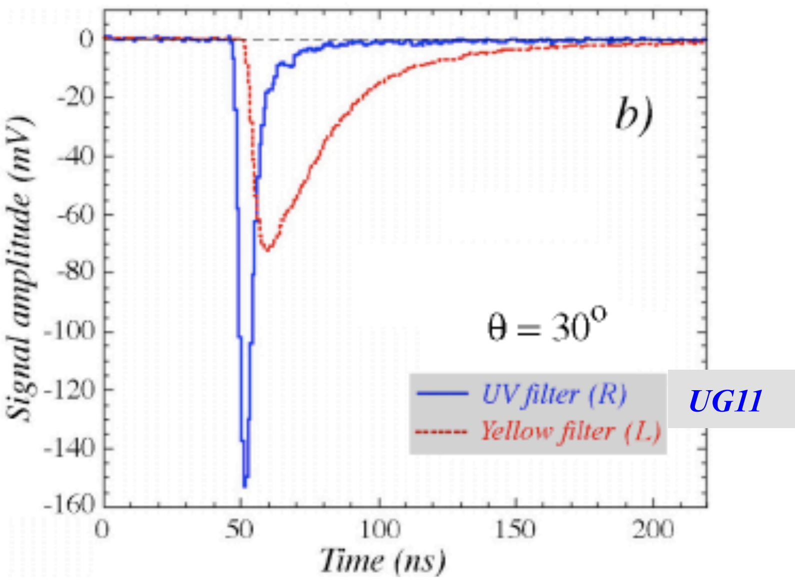


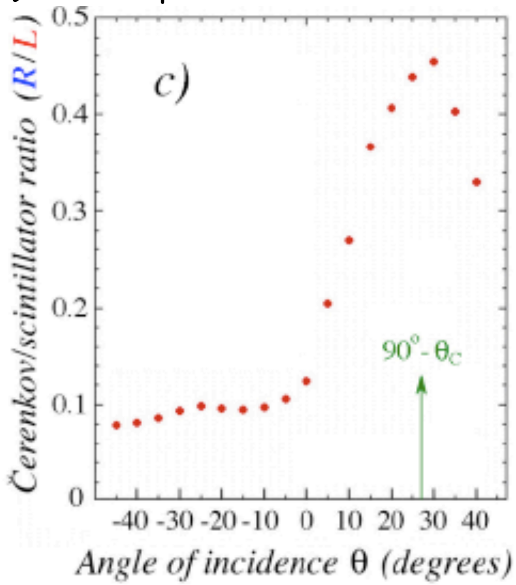
Mounted filters on the two ends of the crystal to generate signal dominated by scintillation light on one end and Cherenkov light on the other end:

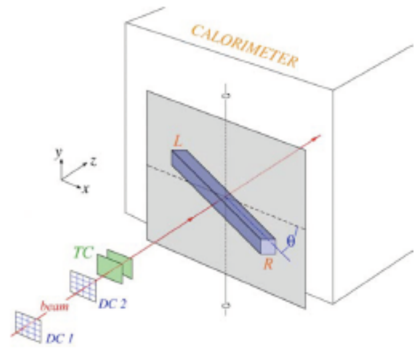
Scintillation side (L) : yellow filter (GG495) transmits light with λ>495 nm
Cerenkov side (R) : UV filters transmitted light with small λ, UG11 (λ<390nm), U330 (λ<400nm), UG5 (λ<410nm)

Mo-doped $PbWO_4$ single crystals

Mo-doped (1%) $PbWO_4$

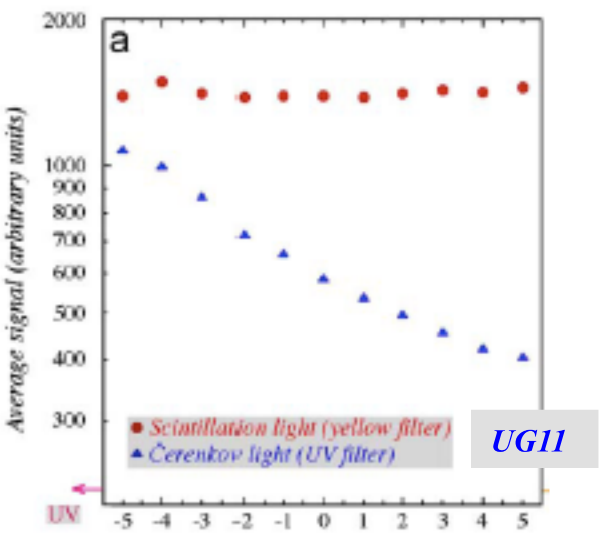






Good Cerenkov vs Scintillation separation

Mo-doped (1%) $PbWO_4$

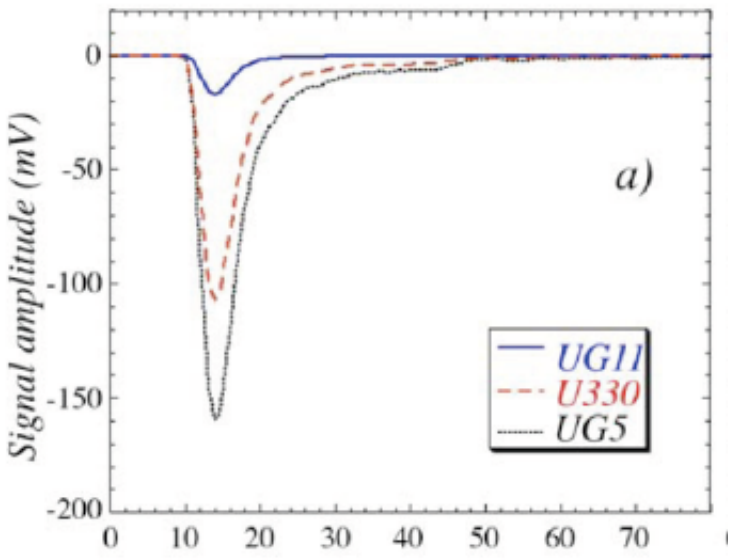


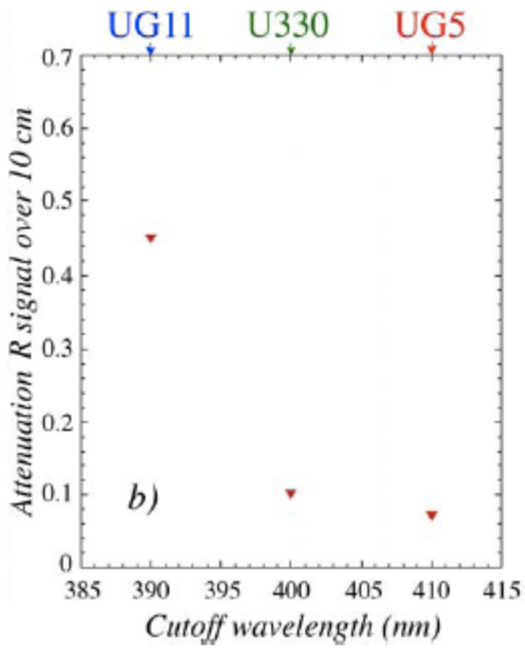
Test done on Mo doped (1%) $PbWO_4$ using UV filter (UG11) shows the Cerenkov component strongly attenuated

Tried to attenuate the effect:
- -by changing the doping level (no large improvement)
- -by using less restrictive filters for the Cerenkov component (UG330,UG5)

Mo-doped $PbWO_4$ single crystals

Mo-doped (0.3%) $PbWO_4$





By using a U330 or UG5 filter, less restrictive respect to the UG11 (that transmits very close to the UV absorption edge of the crystal), the Cerenkov light was increased by an order of magnitude while the attenuation was reduced to less than 10%

Also the light yield is increased using U330 or UG5 respect to UG11 (strongly increased transmission at 400ns, around the PMTs maximum sensitivity)

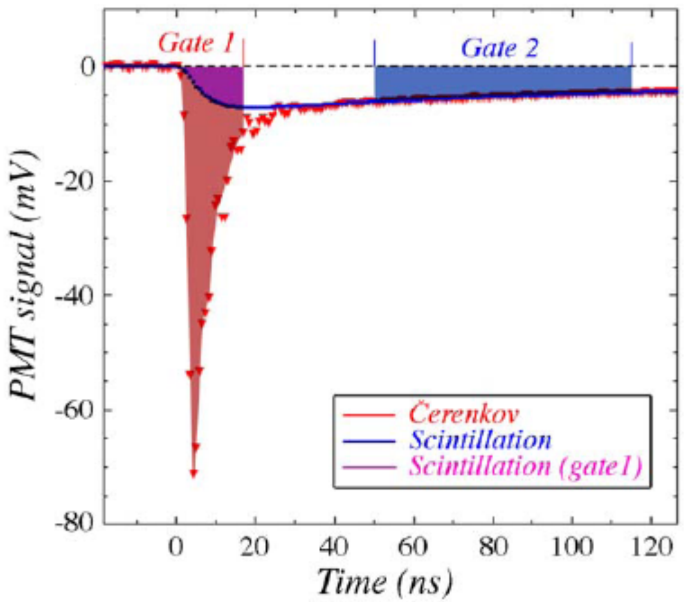
Similar results for different Molybdenum concentration between 0.1 and 1%

BGO single crystal

In BGO crystals, despite the fact the the Cerenkov radiation is less than 1% of the light produced, a good separation between Cerenkov and scintillation is obtained by means of filters due to the different spectral properties (scintillation light centered on 480 nm with a slow decay time of 300 ns)

2007 CERN H4 beam test:
NIM A593 (2008)

Typical signal generated by a beam of 50 GeV electrons in a BGO crystal equipped with UV filter (UG11)

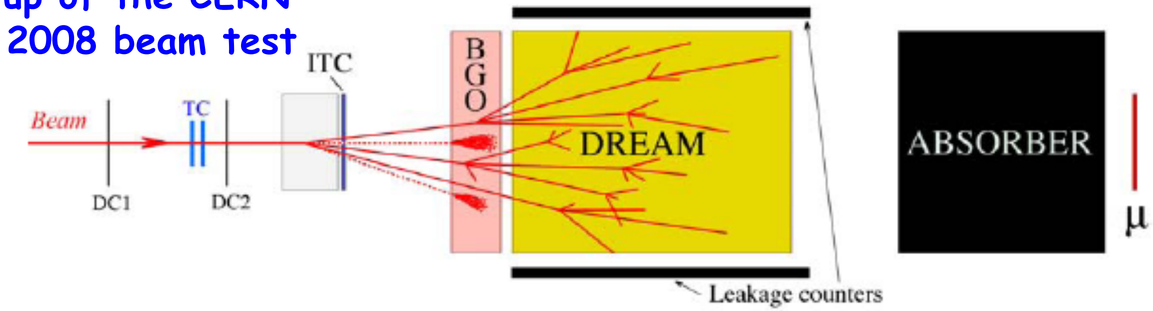


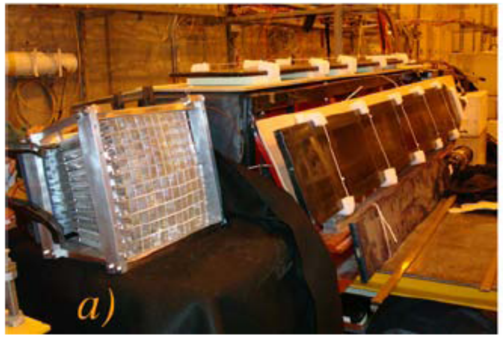
The Cerenkov and scintillation component can be measured from one signal

Scintillation component defined as the integral of the pulse over gate 2 (50-115 ns)
Cerenkov component defined as integral of the pulse over gate 1 (0-16 ns), subtracted by the scintillation contribute
(~20% of scintillation in gate 2)

Hybrid calorimeter system (BGO+fibers)

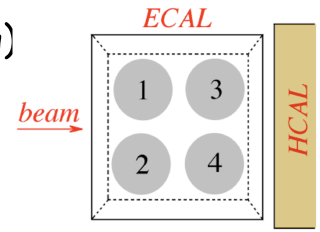
Setup of the CERN H4 2008 beam test



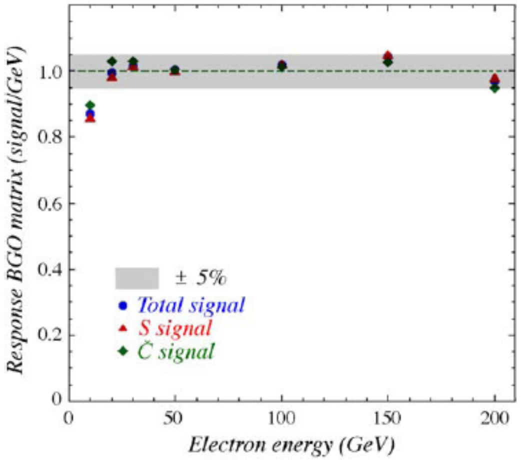


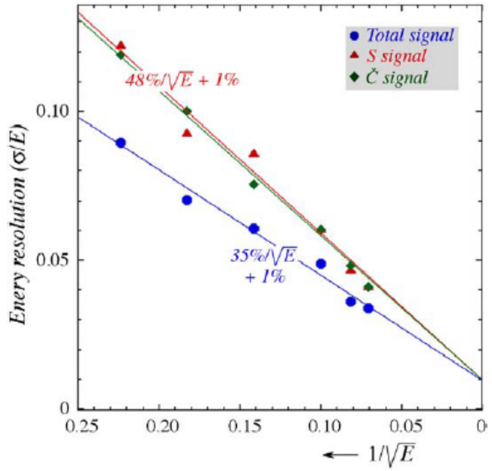
Electromagnetic calorimeter (matrix of BGO crystals) + Hadronic calorimeter (Dream fiber module)

100 BGO crystals tapered (small face: 2.4 x 2.4 cm^2, large face: 3.2 x3.2 cm^2, 24 cm long) perpendicular to the beam (25 X_0, 1.3 λ_{int}), read-out by 4 PMTs facing the small end face side of the crystals, equipped with UV filters (UG11), PMT signal waveforms acquired by means of 5 Gsample/s oscilloscope



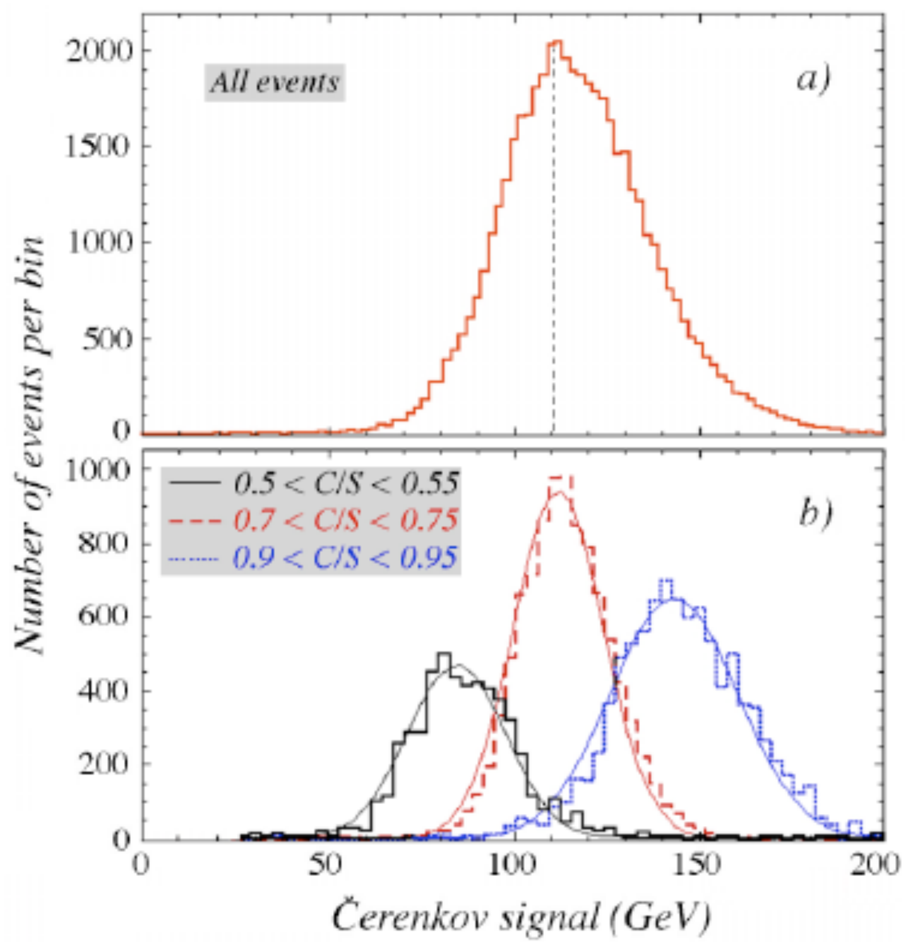
Linearity and resolution of the BGO matrix with electrons





Performances of BGO matrix far from ideal, but sufficient to reach the goal of the test:
verify if the DREAM principle works also in a hybrid calorimeter when on average most of the energy is deposited in the homogeneous section

The DREAM method is based on the correction of the energy by means of the f_{em} measurement obtained by comparing the C and the S signal.
In the Hybrid calorimeter at first step verified that C/S remains a good measurement of the em shower containment.



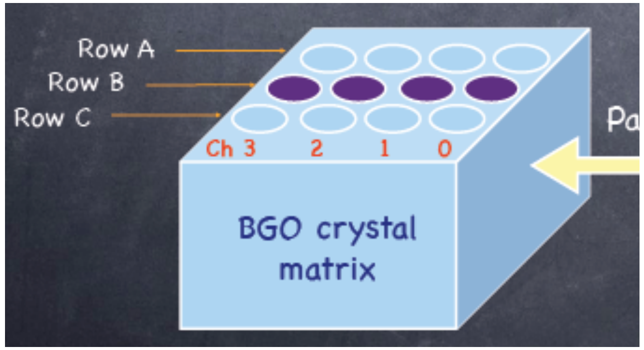
Cerenkov signal distribution in the hybrid calorimeter for 200 GeV jets (on average 50% of the energy deposited in the BGO):

Asymmetric (non- gaussian) shape, centred around 110 GeV

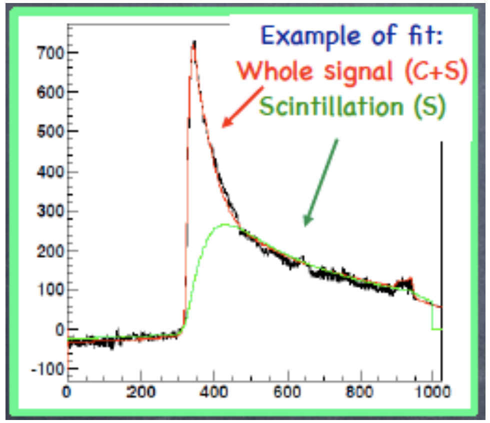
The total Cerenkov distribution is the superposition of many gaussian distributions with different C/S ratio
The DREAM principle works!

Hybrid calorimeter system: a second test

To improve the performances of the BGO calorimeter, in the 2009 beam test, tried a new setup:
matrix readout by 12 PMTs arranged in 3 rows of 4 PMTs, the 4 PMTs of the B row equipped by UV filters. PMT signal waveform acquired by means of several Domino Ring Samplers IV at 2Gs/s



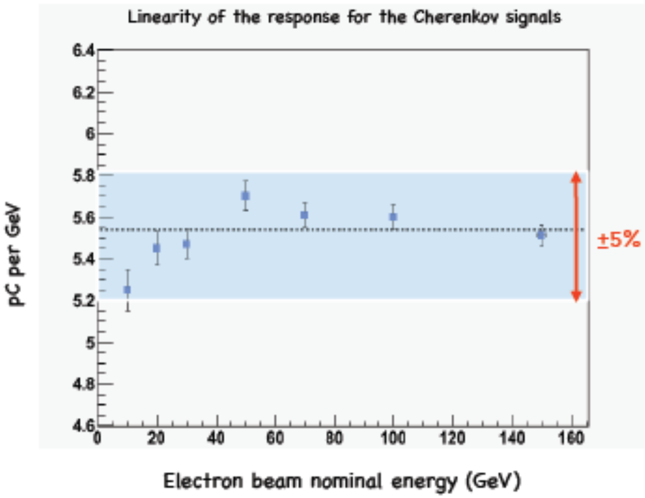
For the filtered PMTs of the row B a fit was performed event by event to extract the Cerenkov and the scintillation component.
For the other PMTs, the signal is only scintillation
The total value of S and C is the sum of 12 Si and 4 Ci

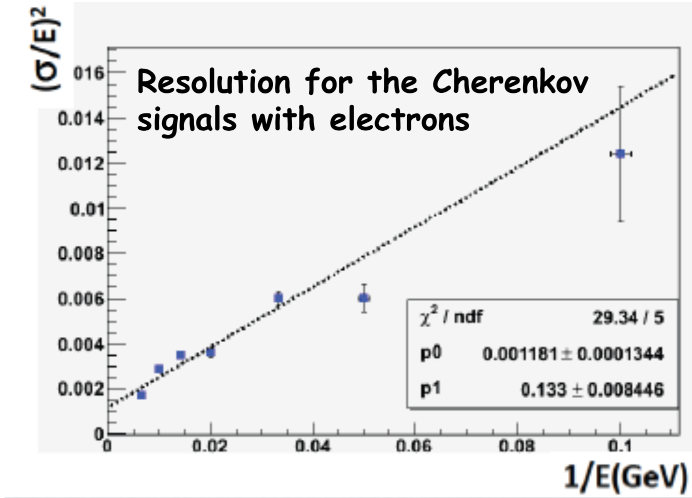


Improved performance respect to the previous system

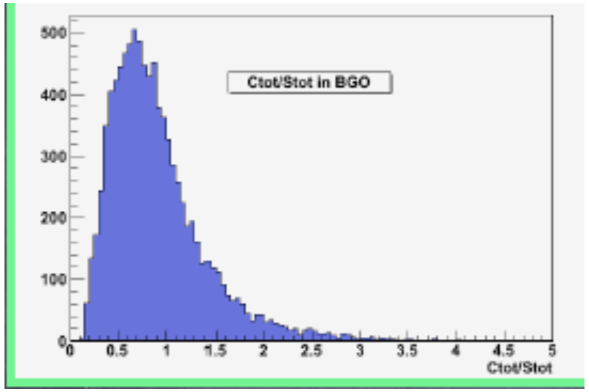
$$\text{Cherenkov}\ \frac{\sigma_E}{E} = \frac{36\%}{\sqrt{E}} \oplus 3\%$$

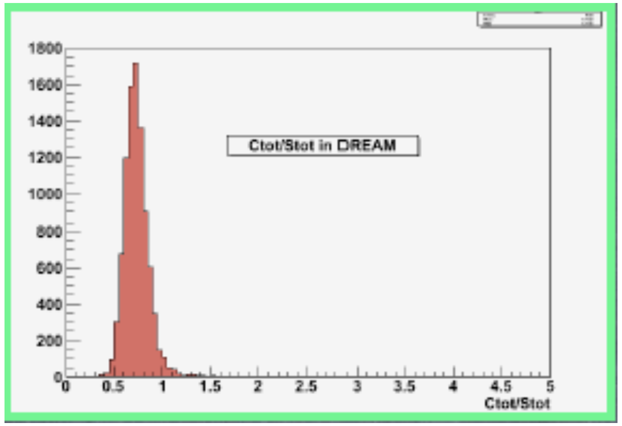
$$\text{Scintillation}\ \frac{\sigma_E}{E} = \frac{33\%}{\sqrt{E}} \oplus 1\%$$



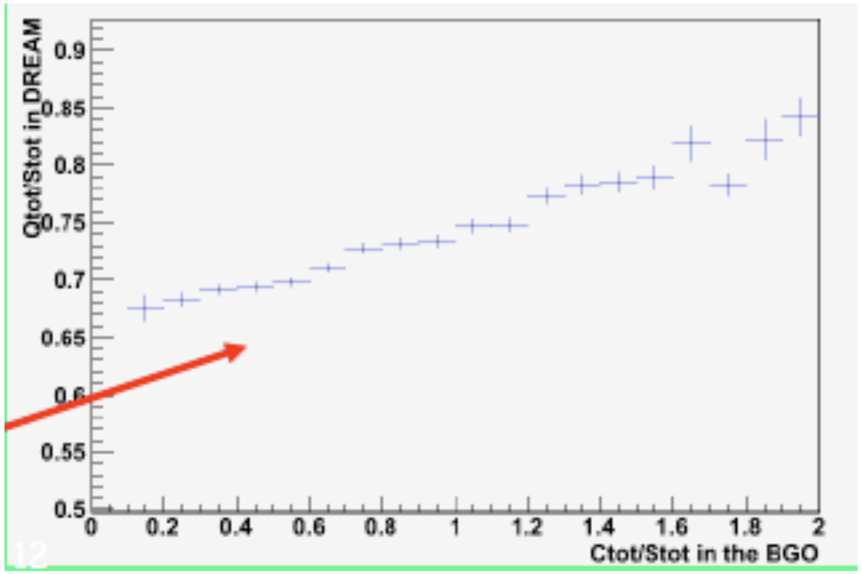


The results of this test confirm again that the ratio between the Cherenkov and the Scintillation signals is directly related to the f_{em} of the shower





C/S in BGO and
in the fiber module
for no-MIP event



Large fluctuations of the f_{em} in the first stages were found.

For showers developing late in the BGO matrix, one could expect some correlation between the e.m. fractions measured in the two sections.

The ratios between the scintillation and the Cherenkov signals in the two calorimeters show a good correlation

Conclusions

The DREAM approach foresees to improve the hadronic resolution by measuring f_{em} event by event (elimination of the fem fluctuations contribution)

The use of leakage counters makes a significant improvement in the energy resolution, demonstrating that a dominating limiting factor of DREAM fiber module is constituted by the side leakage

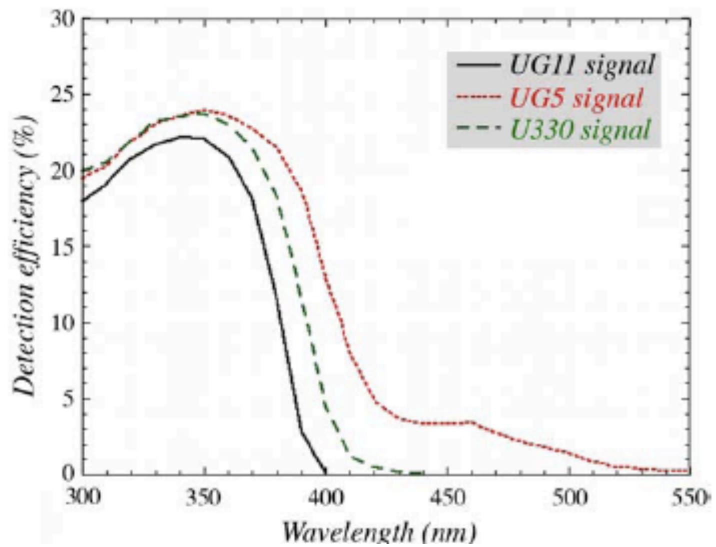
Because of the large fluctuations of the f_{em} in the first stages of the shower, a "standard" electromagnetic calorimeter would spoil the overall energy measurement.

A hydrid dual readout calorimeter was tested using a BGO matrix as electromagnetic section, since the separation of Cherenok and Scintillation components is possible also in a homogeneos materials. Although the non-perfect readout system adopted the Dream principle worked quite well

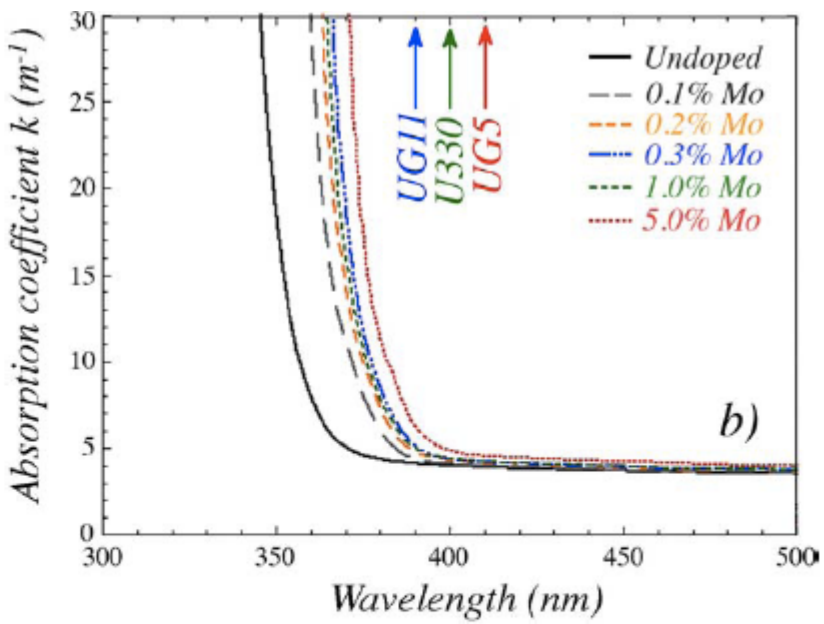
Next steps:
- Measurements with a better readout BGO section are foreseen for the beam test of this summer (detector completely covered with 16 filtered PMTs)
- Given the promising results of the tests on $PbWO_4$ crystals doped with Molybdenum and opportune filters a matrix made of 0.3%Mo:$PbWO_4$ crystals will be tested next summer

BACKUP SLIDES

Mo-doped $PbWO_4$ single crystals



Detection efficiency of the light exiting the PbWO4
(includes losses due to optical transmission trough filter and silicone cookies, the quantum Efficiency of the PMT's photocathode)



Absorption coefficient for $PbWO_4$