Dual-Readout Calorimetry with Crystals

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On behalf of:
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Outline

i. General DRC principle of operation

ii. The DREAM hadronic calorimeter

iii. Homogeneous material as dual readout calorimeters: PWO and BGO

- Test set-up
- Data analysis
- Results

iv. Correlations between PWO/BGO and DREAM

v. Conclusion and future developments

General DRC equations

- The possibility of evaluating the em component (*f*) of a hadronic shower would allow to account for one of the main sources of the hadronic calorimeters response fluctuation;
- Suppose to have a Calorimeter equipped with two sensitive media (for example one sensitive to the Cherenkov light and a one to the Scintillation light) with different e/h;

$$C = [f + c(1-f)]\,E \text{ where } c = (h/e)_C$$
$$S = [f + s(1-f)]\,E \text{ where } s = (h/e)_S$$

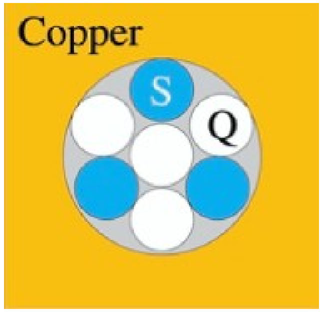
- It is possible to evaluate $f = \dfrac{c - s(C/S)}{(C/S)(1-s) - (1-c)}$ and $E = \dfrac{S - \lambda C}{1-\lambda}$
- Where $\lambda = \dfrac{1-s}{1-c}$ can easily be measured on beam of energy E_0:

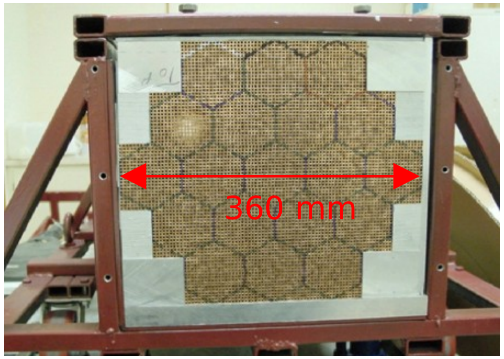
$$\lambda = \frac{E_0 - S}{E_0 - C}$$

- Or it can be extracted from a linear fit of C vs S $S = (1-\lambda)E_0 + \lambda C$

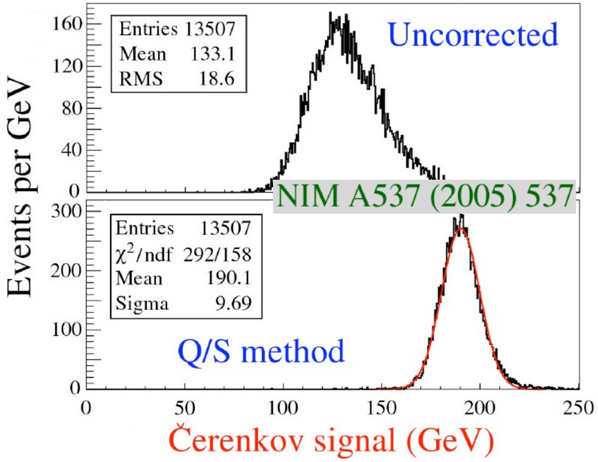
The DREAM DRC

- ✗ The Dual-REAdout Module (DREAM) scintillating (S) and in quartz (Q) fibers in copper absorber.





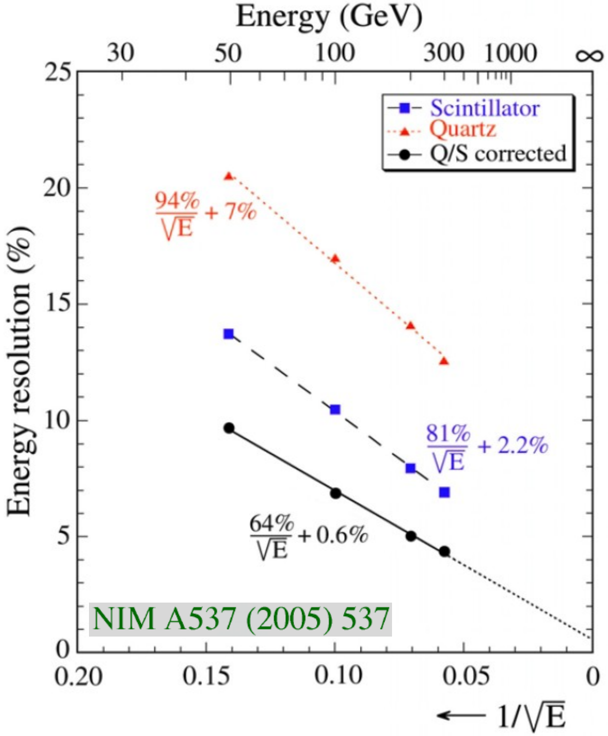
- ✗ The value of λ is: $\lambda = \frac{1-q}{1-c} = \frac{1-0.77}{1-0.2} \simeq 0.29$



Reduced response non linearities due to the unknown fluctuations of *f:*

Gaussian and symmetric measured Energy distribution

Perfect $E^{-½}$ scaling



A homogeneous material?

- The dominant limitation is the small number of Cherenkov photoelectrons (8 ph.e./GeV), arising from the very small sampling fraction → limited performance on em showers;
- DRC with a homogeneous material? This will largely increase the number of Cherenkov photoelectrons and improve performances on em showers;
- Separation of Scintillation and Cherenkov light components can be based on:

	Cherenkov	Scintillation
Time response	Prompt	Exponential decay
Light Spectrum	$\propto 1/\lambda^2$	Peak
Directionality	Cone: $\cos\theta_c = 1/\beta n$	Isotropic

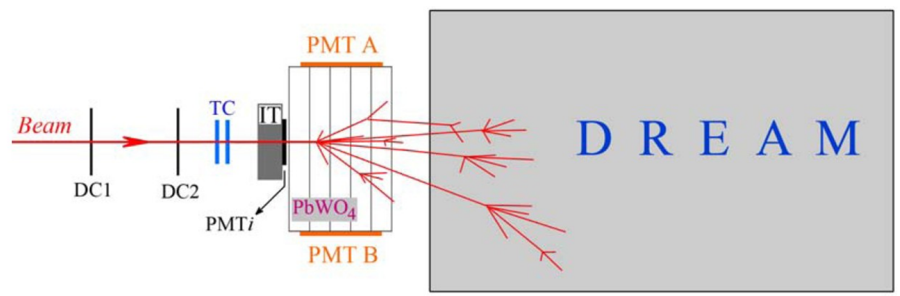
- Two different scintillating materials have been tested in on-beam tests carried out at the SPS in 2006 and 2007: PWO and BGO.

Crystal	LightYield % NaI(Tl)	Decay Time (ns)	Peak wavel.(nm)	Cutoff wavel.(nm)	Refr. Index	Density (g/cm³)
BGO	20	300	480	320	2.15	7.13
PWO	0.3	10	420	350	2.30	8.28

Experimental setup

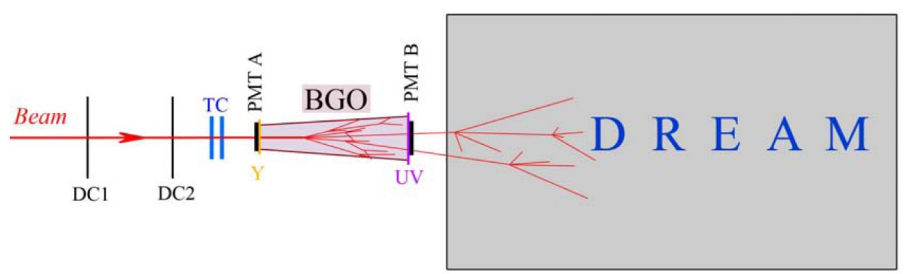
- The tested calorimeter systems consisted of two sections:
  - An electromagnetic section (ECAL) made by scintillating crystals
  - An hadronic section (HCAL) made by the DREAM calorimeter

PWO



- 19 (2.2 x 2.2 x 18 cm^2) crystals not optically isolated, orthogonal to the beam 12.4 X_0;
- Readout on the two lateral faces by means of low gain, fast and large sensitive area PMTs (XP4362B);

BGO

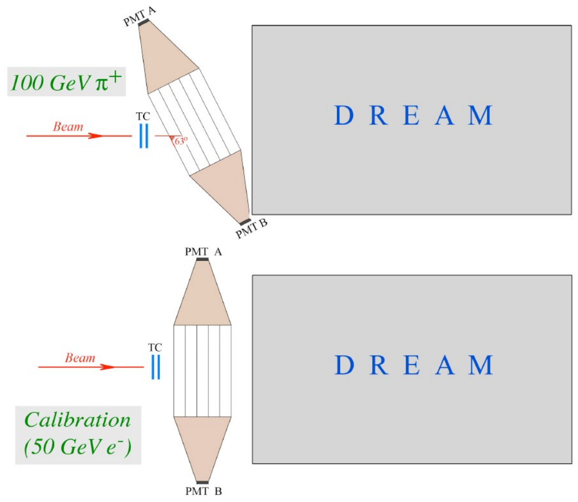


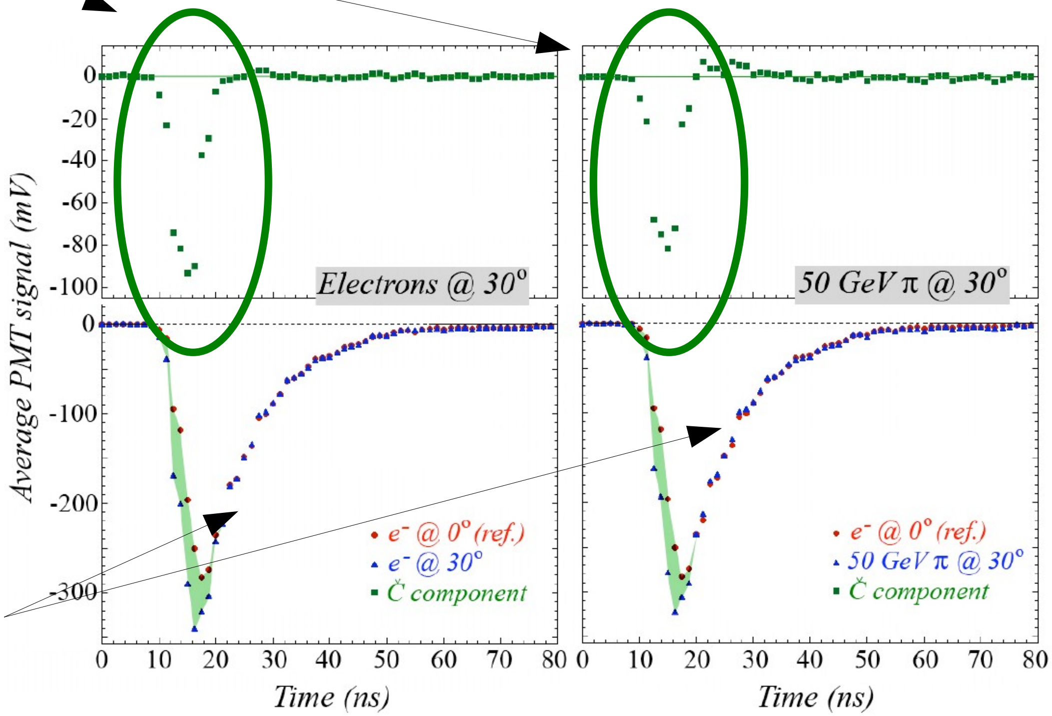
- A single tapered 24 cm long crystal (21 X_0) parallel to the beam;
- Equipped on both faces with an optical filter and a PMT:
  - Yellow filter on the small face;
  - Ultra-Violet filter on the large face;

- The PMT signal waveforms were acquired by means of 5 Gsample/s oscilloscope

PWO signal waveforms

- ✗ Signal waveforms acquired in different configurations allow to outline the presence of the prompt Cherenkov signals both for electrons and pions.



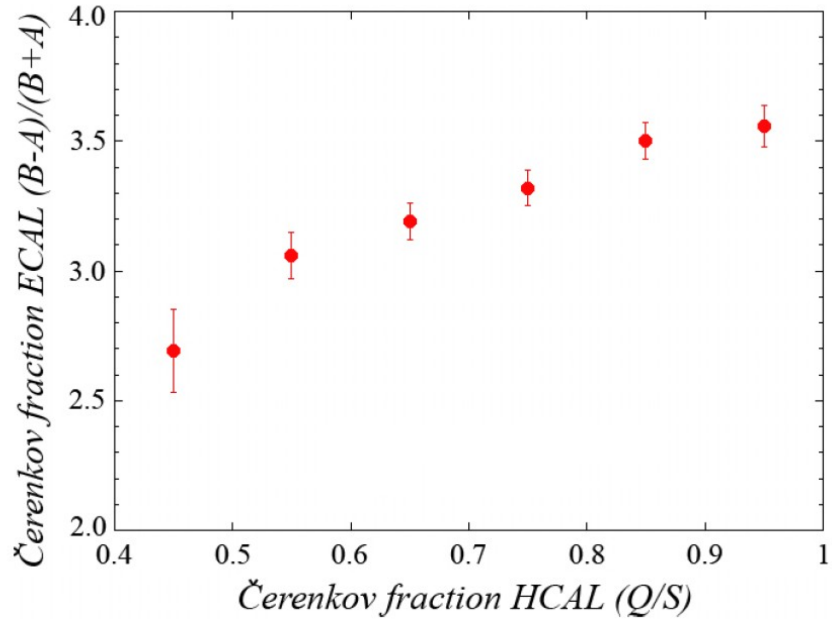


- ✗ The trailing edge (due to the scintillation light) is independent from the matrix position.

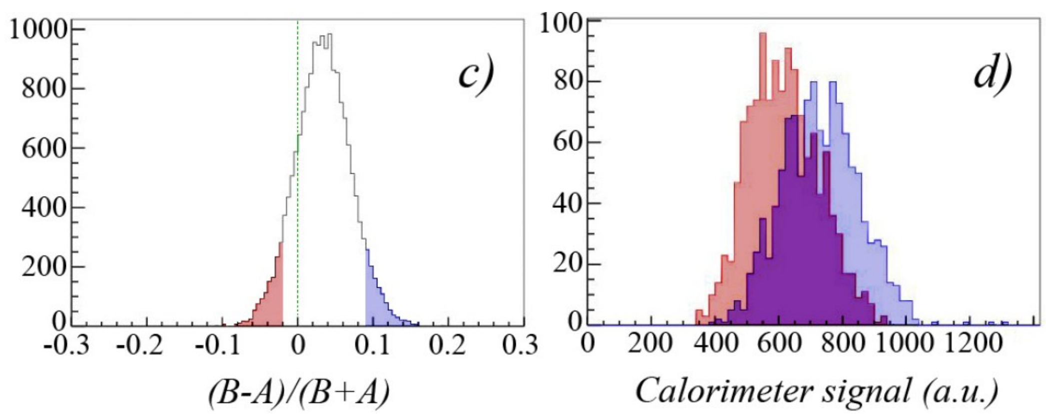
- ✗ With the tilted ECAL, the light-asymmetry (B-A)/(B+A) gives a measurement of the Cherenkov light ratio to the total signal which is a measurement of *f*;

PWO + DREAM

- ✗ EM showers produced late in a hadronic shower will be absorbed in HCAL;
- ✗ Correlation between *f* measured in ECAL and HCAL
- ✗ The Cherenkov component (i.e. *f*) measured in ECAL (B-A)/(B+A) results to be correlated with the same measurement performed in HCAL (Q/S);



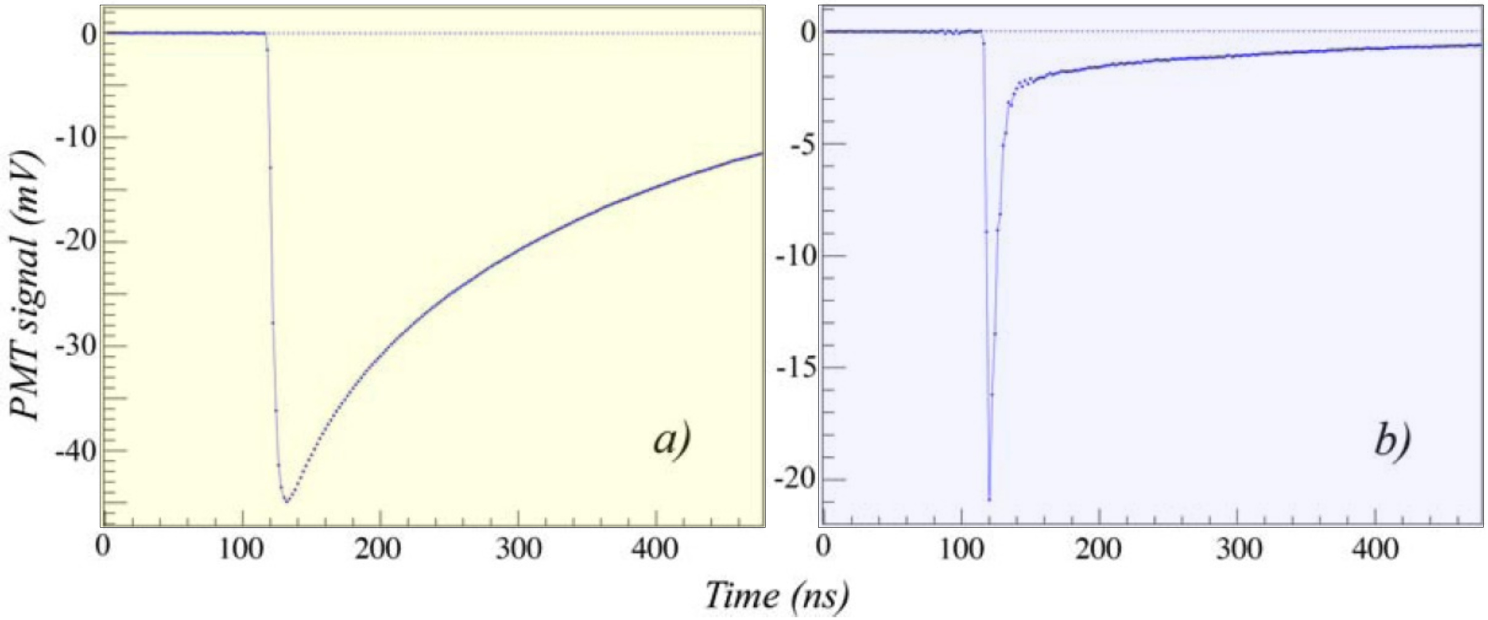
- ✗ Signals with different asymmetries measured in ECAL (i.e. different *f*) have a different total energy distribution in the Calorimeter.



- ✗ A PWO-based ECAL is able to give precious information on the em content of the shower and to allow to correct the HCAL response.

BGO signal waveforms

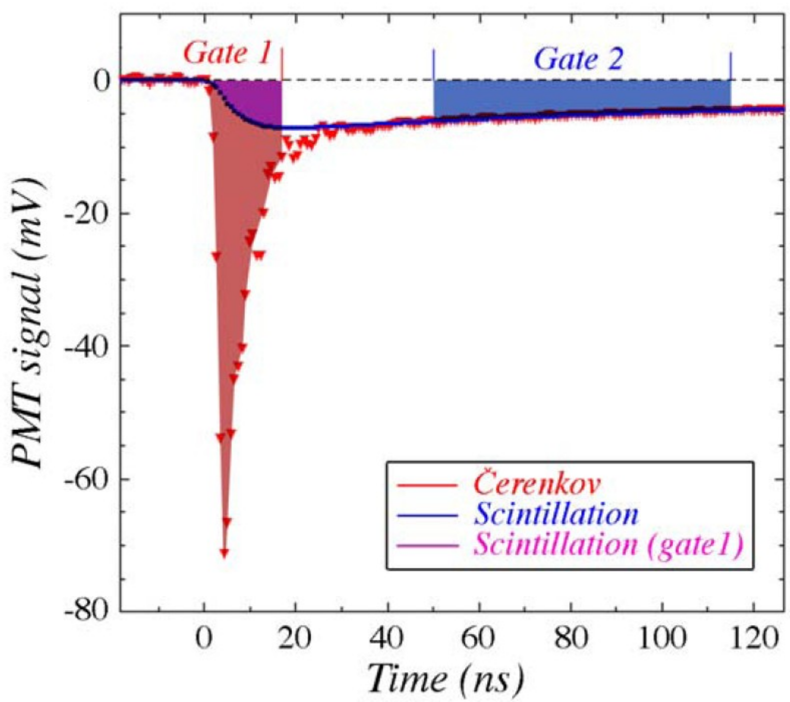
- The signal waveforms observed downstream of the two filters placed on the ends of the BGO crystal look very different:

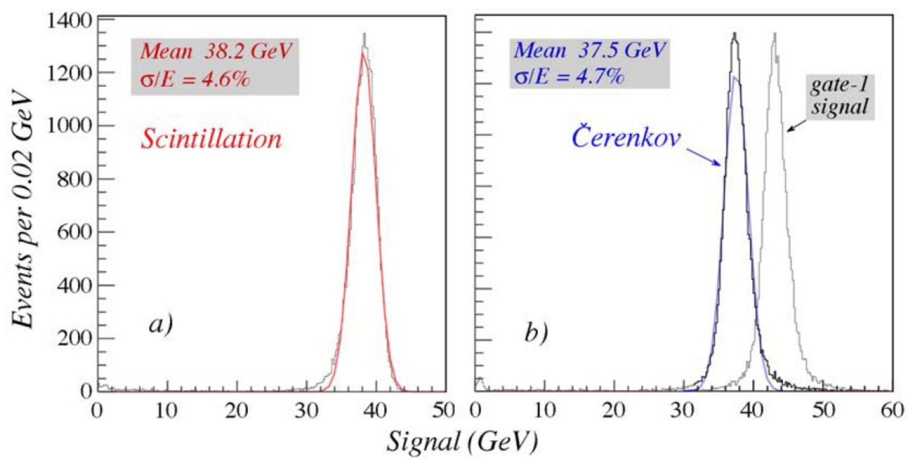


- The yellow filter is highly transparent to the BGO scintillation light (480 nm), which shows the expected 300 ns decay time;
- The UV filter (250 – 400 nm) allows the prompt Cherenkov light to pass, attenuating (but not completely cancelling) the slow scintillation component.

BGO: data analysis

- ✗ In order to extract information about the relative contribution of Cherenkov and Scintillation to the total light yield, the UV PMT signal waveforms have been analysed;
- ✗ An off-line integration of the charge Q1 collected in the first 16 ns of the pulse (Gate 1) and Q2 in the interval 50-115 ns (Gate 2) was performed;
- ✗ The use of information provided by the Yellow-filter side allowed to evaluate the shape of the scintillation signal and to evaluate its amount to the light in Q1 (15% of Q2);

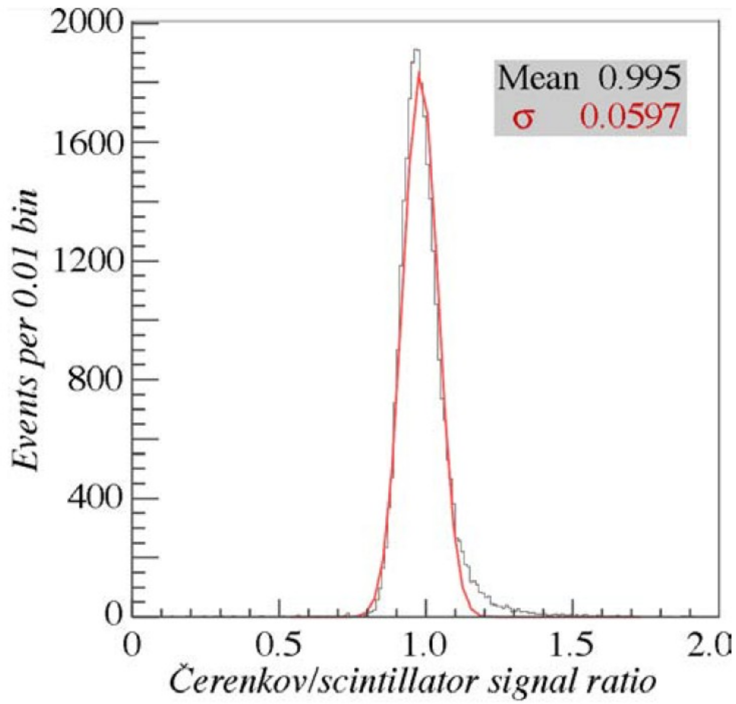




Once corrected for this effect Q1 and Q2 were calibrated to have C and S with distributions centred around 38 GeV in the run with 50 GeV electron beam (because of the lateral leakages).

BGO: photo-electron number

- ✗ The fluctuations of C (4.7%) and S (4.6%) depend both on the photo-electron statistics and on fluctuations in the showering process (lateral leakage and longitudinal development);
- ✗ The distribution of the ratio C/S may provide more information on the light yield.



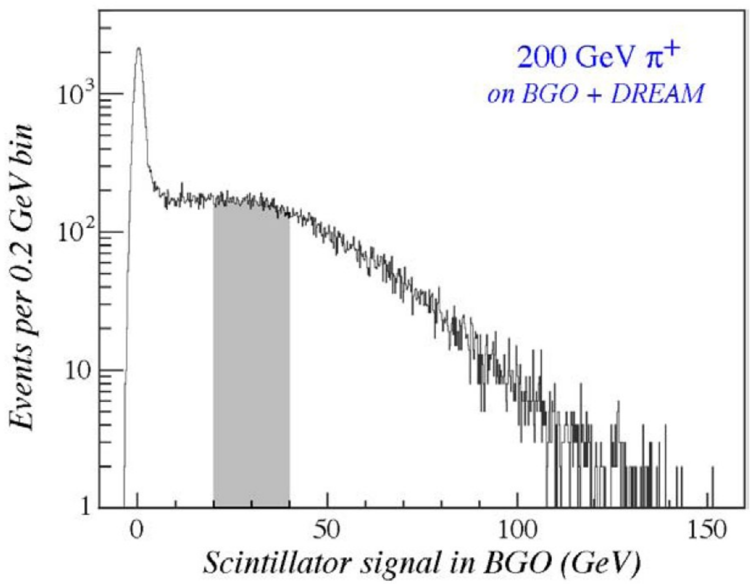
The C/S distribution has a σ/mean ratio of about 6%.

$$\frac{\sigma_{(C/S)}}{C/S} = \frac{\sigma_S}{S} \oplus \frac{\sigma_C}{C} \simeq \sqrt{2}\frac{\sigma_S}{S} = \sqrt{\frac{2}{N_{pe}}}$$

That implies a Cherenkov light yield of, at least, 15 photoelectrons per GeV.

BGO + DREAM: pion runs

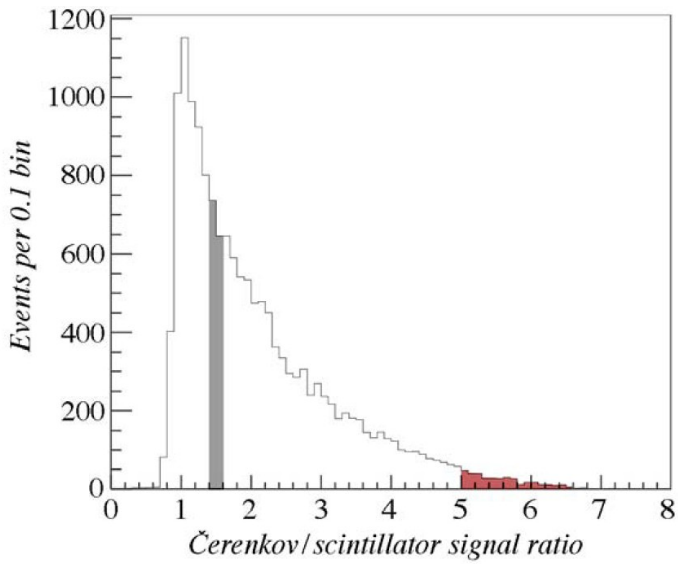
- In order to study the behaviour of the BGO crystal with hadrons, we switched to a 200 GeV π^+ beam;



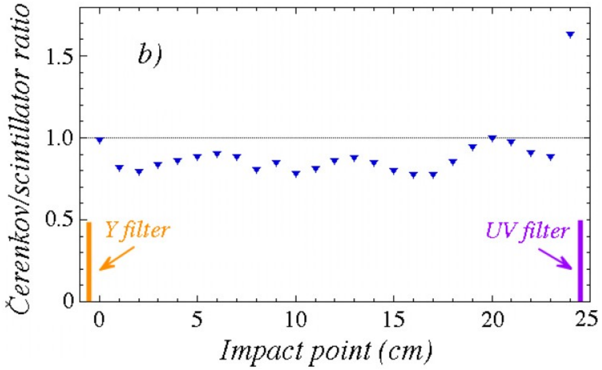
- From the analysis of S distribution in ECAL it is clearly visible:
  - A dominant peak containing the 50% of events in which the pion penetrate in the BGO crystal without starting a shower (mip peak) with an Energy released below 10 GeV;
  - A long tail of event with nuclear interactions with energy deposited up to more the 100 GeV;
- For further studies we concentrated on events with an Energy released ranging between 20 and 40 GeV;
- These events represent the 20% of the total and 40% of the non-mip events;

BGO: the ratio C/S

- The distribution of the C/S ratio can provide useful informations on the shower developing within the crystal.



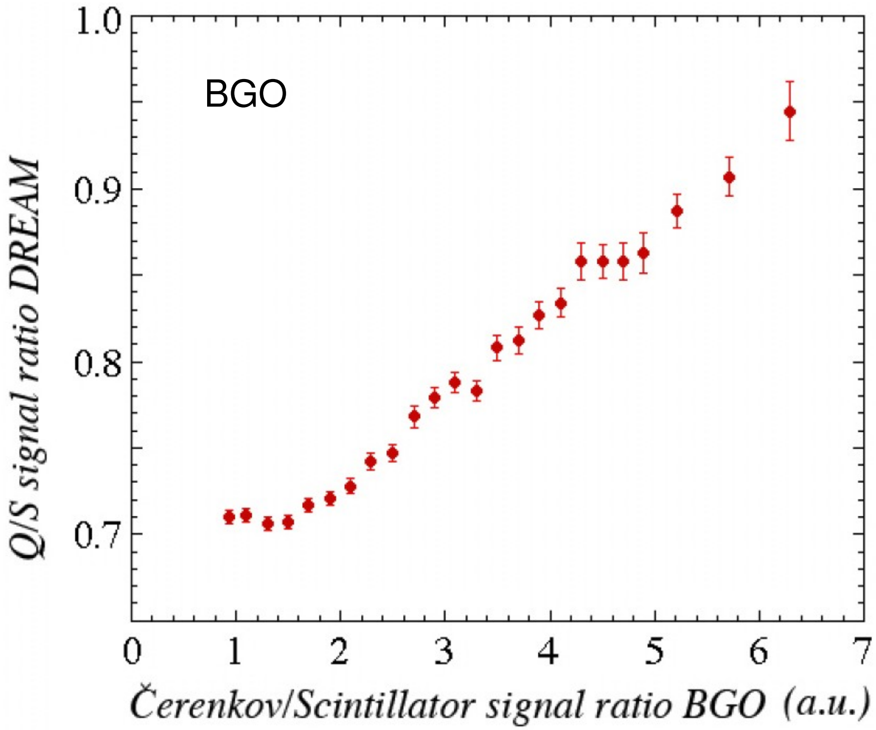
- While for electrons the C/S ratio distribution has a narrow gaussian shape (centred around 1.0) for pions it is completely asymmetric and it exhibits a long tail.
- The large excess of Cherenkov light produced in some event can be explained from the analysis of the behaviour of C/S as a function of the beam position in a longitudinal scan;



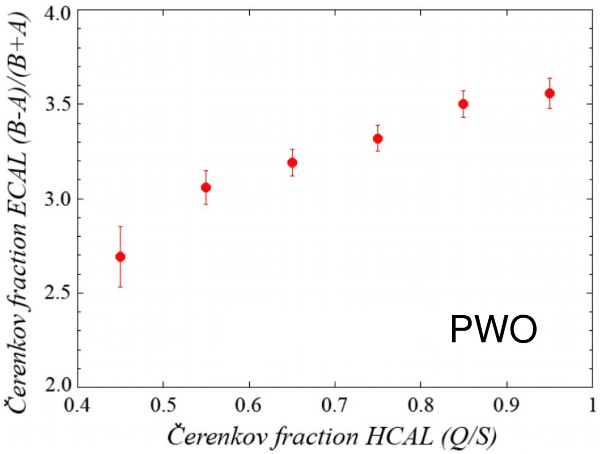
- For pions impinging the crystal close to the UV filter the C/S value is a factor 2 above the average;
- This can be due to Cherenkov light produced by fast particle in the filter itself and/or in the PMT window;
- When the em shower has its maximum on the filter/window a large amount of Cherenkov light (but no scintillation light) is produced.

BGO: the ratio C/S

- As already found for the PWO one could expect a correlation between the electromagnetic ratio measured in the two sections of the calorimeter system;

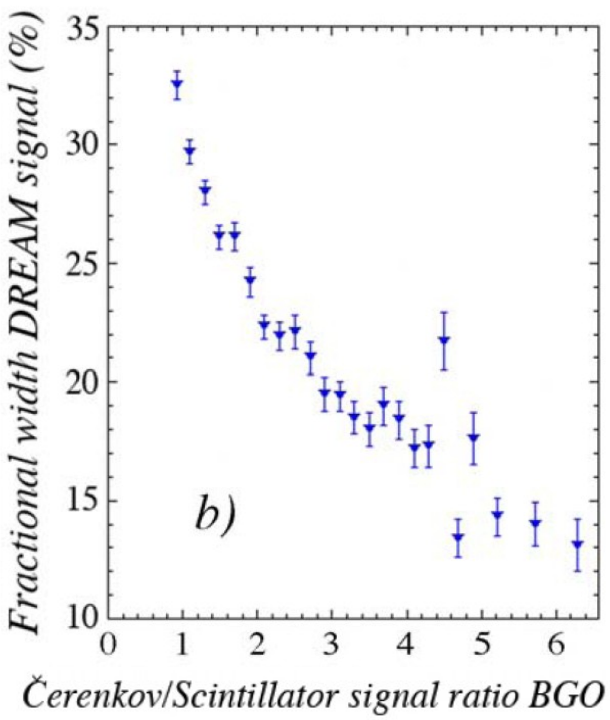


- A good correlation is found between C/S in BGO-ECAL and Q/S in DREAM-HCAL;
- The variable C/S in the BGO is able to measure the em component of the shower in the Calorimeter;
- C/S in the BGO resulted to be more sensitive than (A-B)/(A+B) in the PWO;

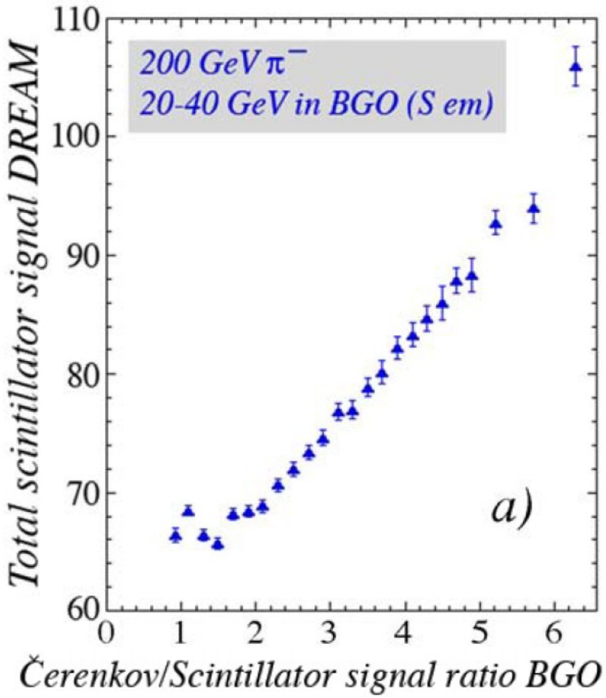


BGO: the ratio C/S

- ✗ The sensitivity of C/S to the shower *f* is confirmed also by studying the behaviour of the scintillating fibres in DREAM-HCAL;
- ✗ A high value of C/S means a large *f* that leads to:



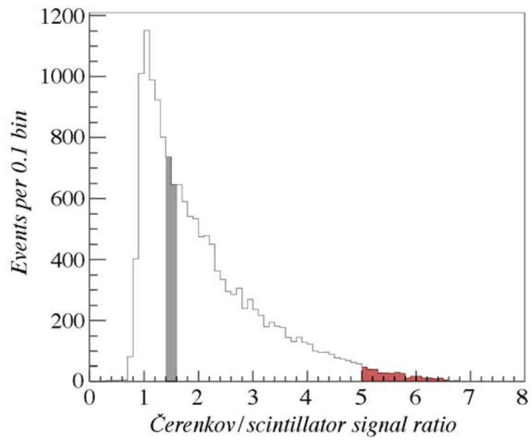
- ✗ Lower signal fractional fluctuations which are mainly induced (once the *f* fluctuations are corrected) by uncertainties of the invisible energy of the hadronic component

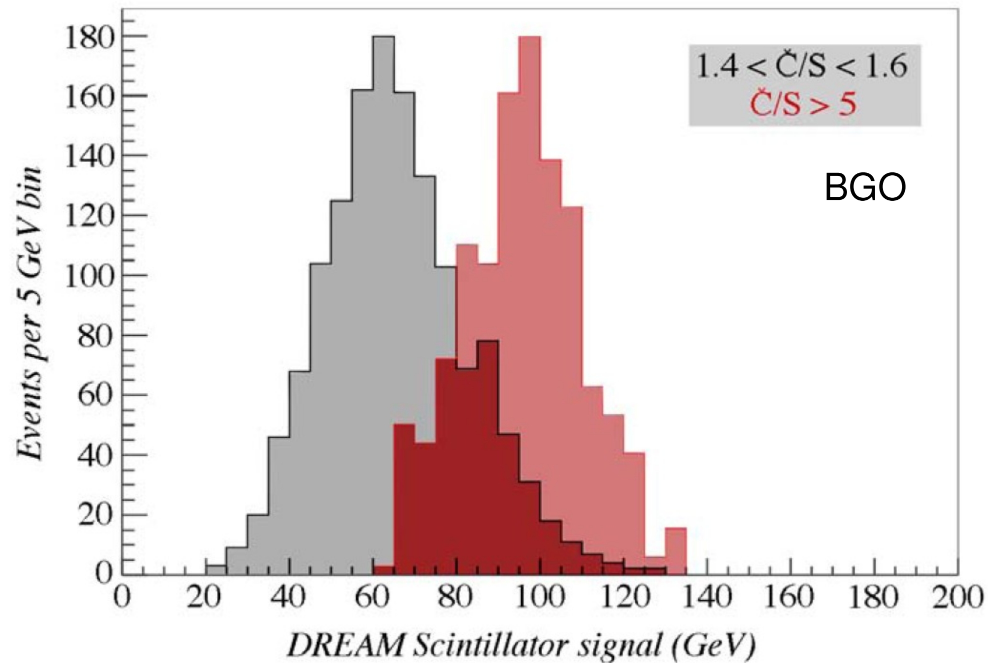


- ✗ a larger Scintillator signal in DREAM-HCAL

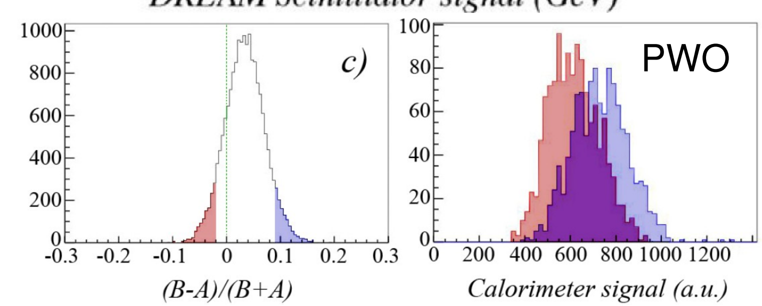
BGO: the C/S ratio

- The main results of the analysis are summarised in the plots below;
- By choosing different values of C/S in ECAL it is possible to select different “sub-distributions” in the HCAL-DREAM scintillator response that are narrower than the global one: DRC principle at work!





- This effect is more visible in the analysis performed on the BGO than in the PWO



Conclusion and future development

- Separation of Cherenkov and Scintillation components in homogeneous materials is possible;
- This allows to evaluate the electromagnetic fraction of a shower giving the possibility of reducing part of the fluctuations and non-linearities in measuring the Energy released by a hadron;
- The application of the Dual-Readout method on electromagnetic calorimeters can be exploited to improve the global ECAL+HCAL performance to electron and pion showers;
- A 100 BGO crystal matrix is being made-up and will be tested as an ECAL, followed by DREAM acting as an HCAL, on the SPS beam this summer .

System calibration

- Both the systems were calibrated by means of a 50 GeV electron beam;
- PWO:
  - In the configuration with the crystal orthogonal to the beam the amount of Cherenkov and Scintillation light reaching the two PMTs are the same;
  - Because the ECAL thickness was only 12.4 X_0, a longitudinal leakage is expected. On the basis of an EGS4 simulation it was calculated that on average only 35.8 GeV were deposited in the ECAL;
- BGO:
  - Since the BGO crystal thickness was 21 X_0, no significant longitudinal leakages are expected.
  - Of course lateral leakages in this case are important and, according to a simulation, 38.2 GeV are contained in the crystal
- DREAM:
  - Each single tower was calibrated, taking into account a simulated containment of 93 % (46.3 GeV)