Performance of a dual readout calorimeter with a BGO electromagnetic section

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on behalf of the Dream Collaboration

Thanks to D. Pinci for providing slides

Summary of the Dual Readout Method

The response R* of an hadronic calorimeter to an hadron shower with an energy release E_0, will depend on the electromagnetic fraction of the shower f as:

$$R^* = [ef + h(1 - f)]E_0$$

being e and h the calibration constants for a completely electromagnetic and a completely hadronic shower.

With an electron beam ($f = 1$) it is possible to measure the value of e and the above equation can be written:

$$R = [f + (h/e)(1 - f)]E_0$$

Even thought that (h/e) can be measured, if it is different from one, event by event the fluctuations of f represent one of the main limitation in a good measurement of the released Energy.

Summary of the Dual Readout Method

Suppose to have a calorimeter with two different sensitive media (C and S) with different *h/e* (*c* and *s)*

Their responses will be:

$$C = [f + c(1 - f)]E_0$$

$$S = [f + s(1 - f)]E_0$$

If *c* and *s* are known, event by event it will be possible to measure the electromagnetic fraction:

$$f = \frac{c - s(C/S)}{(C/S)(1 - s) - (1 - c)}$$

and thus the released energy, corrected for the fluctuations of *f,*

$$E_0 = \frac{C - \lambda S}{1 - \lambda} \qquad \text{where} \qquad \lambda = \frac{1 - c}{1 - s} \qquad \text{is a constant of the calorimeter}$$

The Dual Readout Module (DREAM)

DREAM is a sampling hadronic calorimeter, made of 19 towers;

The basic element is an extruded copper rod, 2m long and 4x4 mm^2 in cross-section. This rod has a central cylindric hole (diameter of 2.5 mm) that houses 7 optical fibers: 3 scintillating and 4 quartz for detecting Cherenkov light.
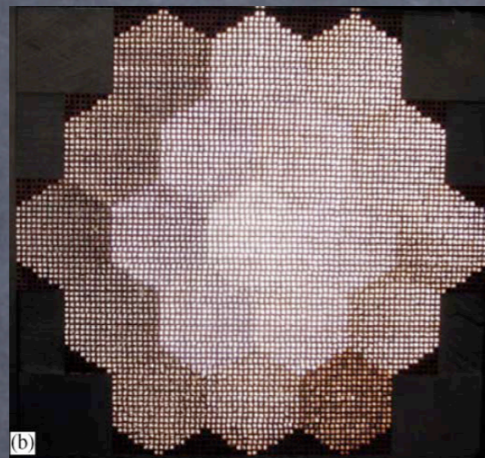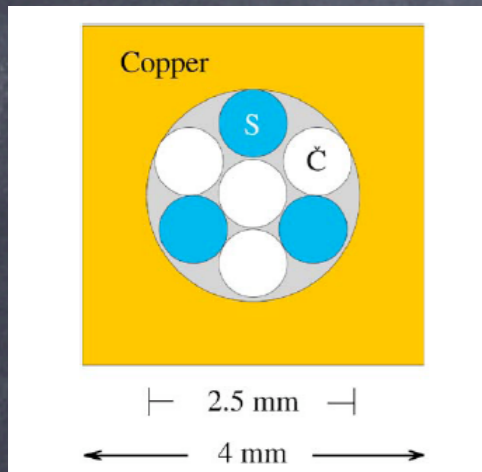

| scint. fibers/copper	e/h = 1.3	s = (e/h)$^{-1}$ = 0.77
quartz/copper	e/h = 4.7	c = (e/h)$^{-1}$ = 0.21

4
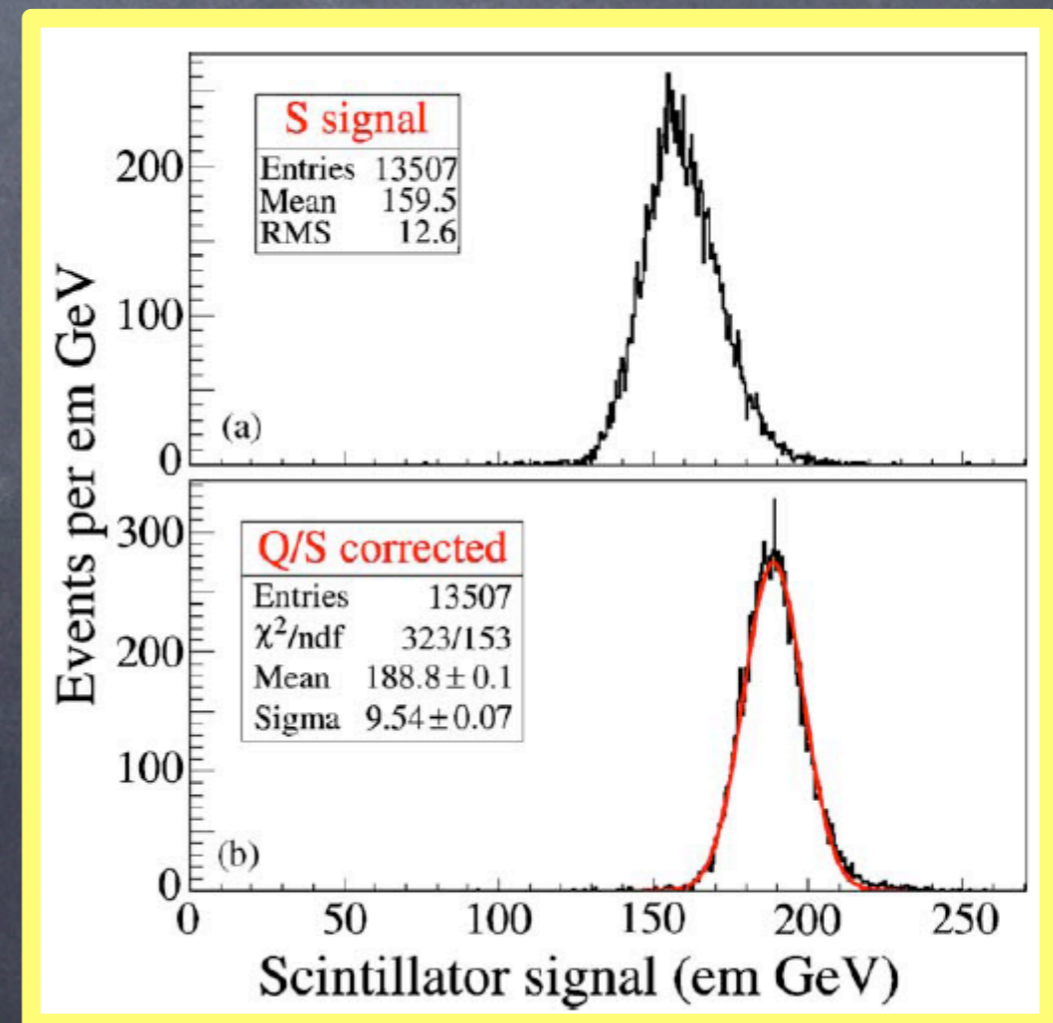
DREAM 2009: lateral leakages

Once the fluctuations of the e.m. fraction were successfully eliminated, the resolution of the detector turned out to be limited mainly by the uncertainties on the lateral leakages (5%÷10% measured for 100 GeV pions);

In the 2009 test beam DREAM was surrounded by 7 plastic scintillator paddles to detect the lateral leakages and to study their effects;
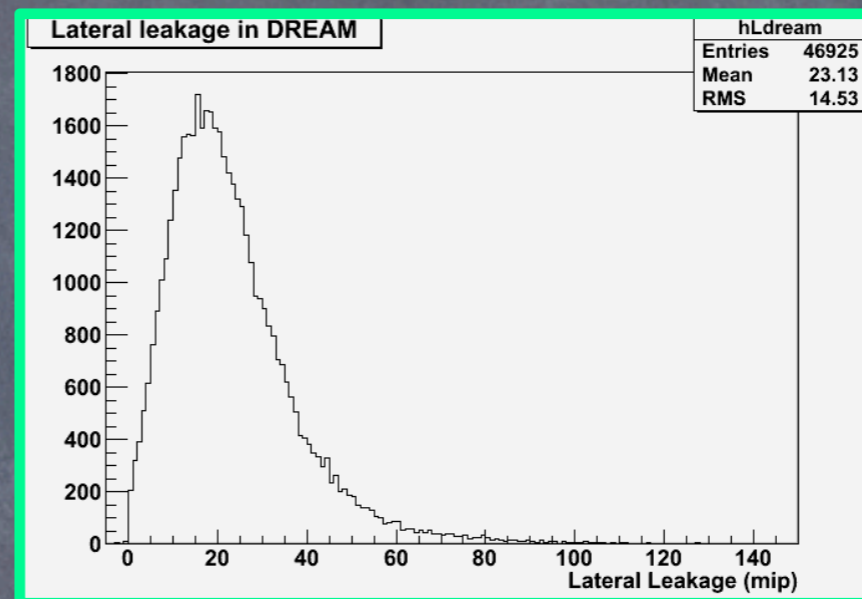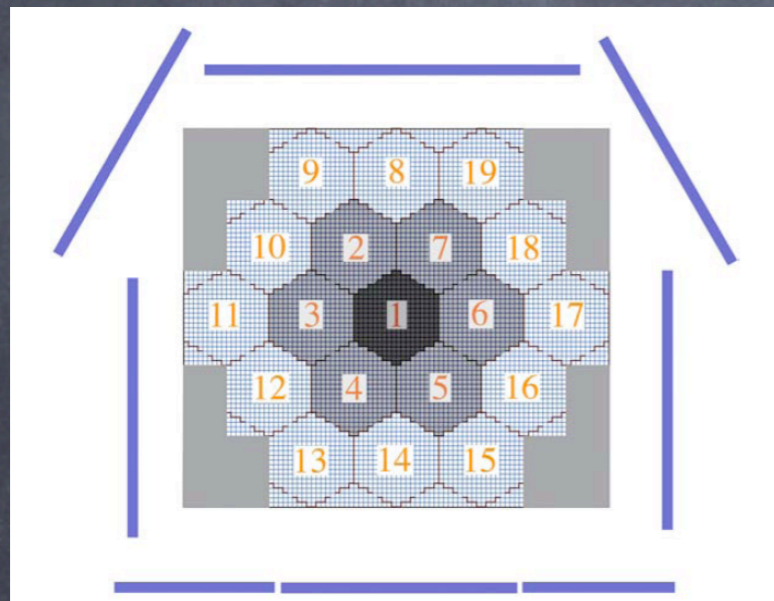
Distribution of the lateral leakage for 100 GeV pions
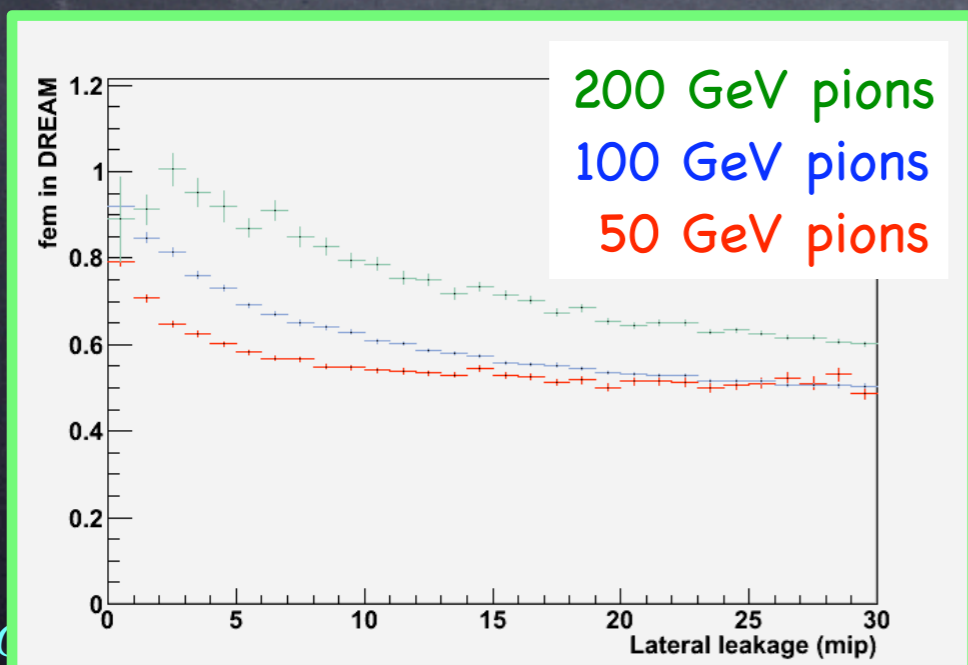
A good anti-correlation was found between the electromagnetic fraction measured in DREAM and the leakage measured by the external scintillators.
• The more the shower is electromagnetic the better it is contained.
• Moreover the e. m. fraction increases with the beam energy as expected.

DREAM 2009: lateral leakages

In the case of a leaking detector, supposing that mostly the hadronic part of the shower leaks, the responses of the two sensitive media will be:
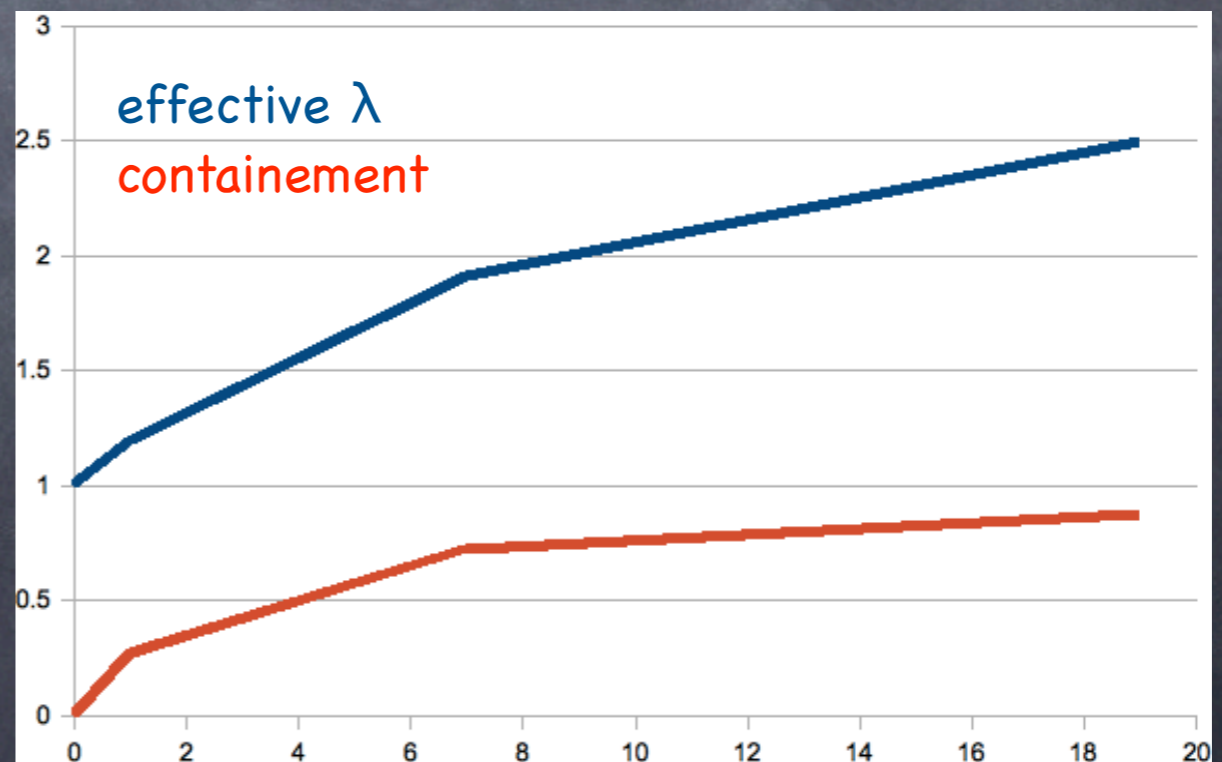
$$C = [f + c\alpha(1 - f)]E_0$$
$$S = [f + s\alpha(1 - f)]E_0$$

Where α is the contained fraction of the hadronic part. The Energy released will be:

$$E_0 = \frac{C - \hat{\lambda}S}{1 - \hat{\lambda}} \quad \text{with} \quad \hat{\lambda} = \frac{1 - \hat{c}}{1 - \hat{s}} \quad \text{where} \quad \hat{c} = \alpha c \quad \text{and} \quad \hat{s} = \alpha s$$

By exploiting the granularity of our detector we found the behavior of $\hat{\lambda}$ and of the containment α.

The containment of DREAM resulted to be 95% in good agreement with previous measurements.

effective λ

containement

A complete DR calorimetry system

In order to make up a complete Dual Readout calorimeter a 100 crystal BGO matrix was placed upstream of DREAM as the electromagnetic section.

The matrix was readout by 12 PMTs (Photonis 3392B) arranged in 3 rows of 4 PMTs .

Row A
Row B
Row C

Ch 3   2   1   0

BGO crystal matrix

Particle beam
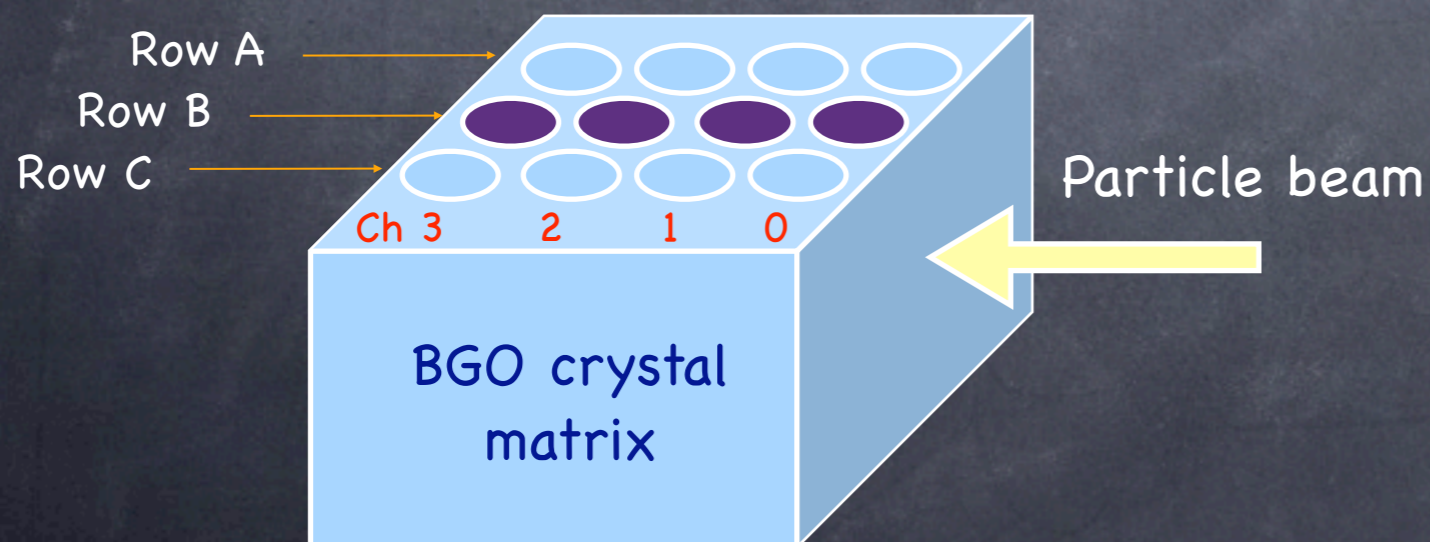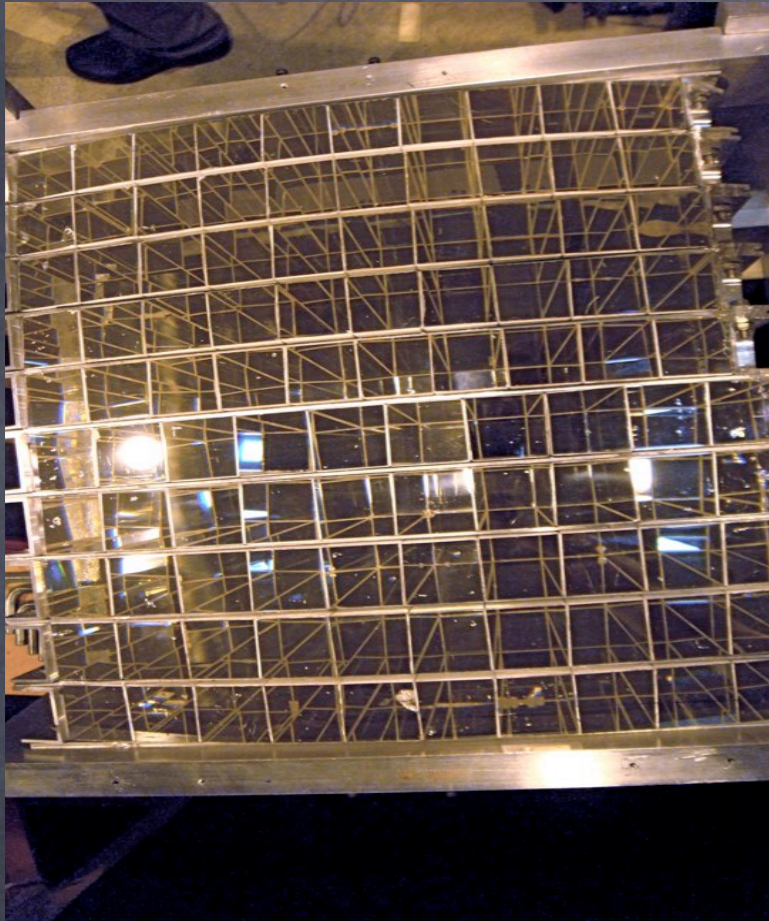
BGO readout

UV filters were placed upstream of the 4 PMTs of the central row (row B) in order to suppress the scintillation component of the signals.

UG11

Typical transparency window of the XP3392B
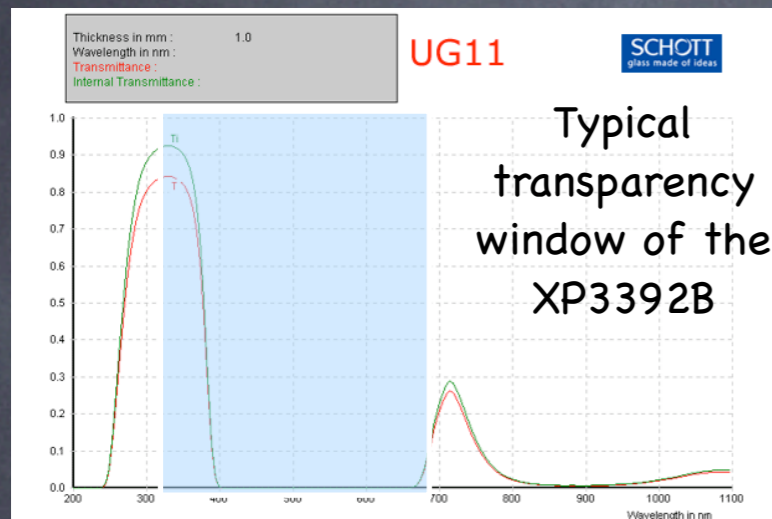
Event by event the waveforms of the PMT signals were recorded by means of several Domino Ring Samplers IV:
- developed at PSI;
- up to 6 Gs/s;
- intrinsic bandwidth for analog inputs above 900 MHz at -3dB;
- 1% of maximum analog differential output non-linearity

DRS (Row A)

DRS (Row B)

DRS (Row C)
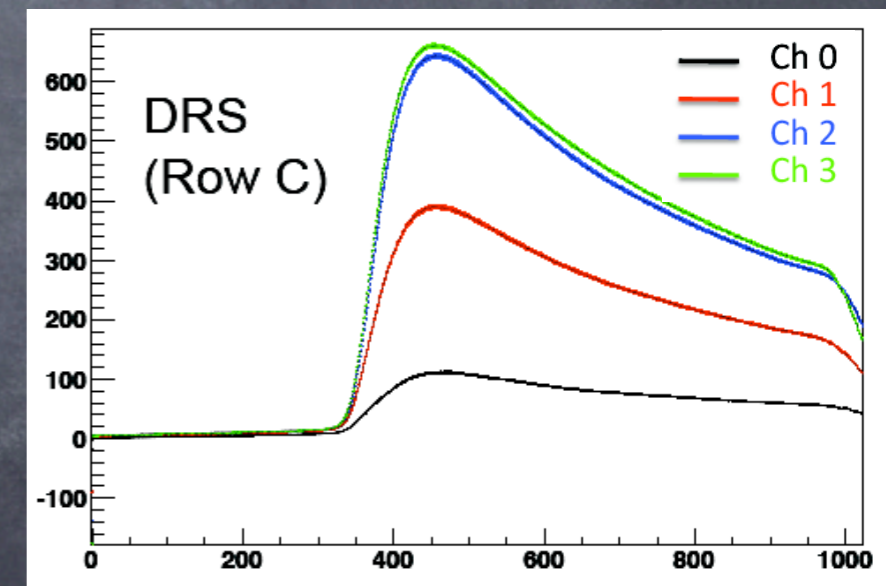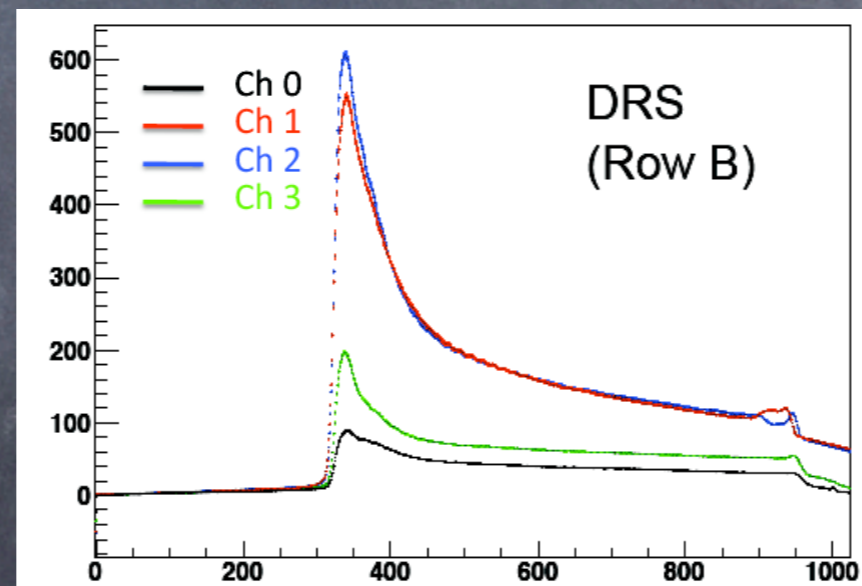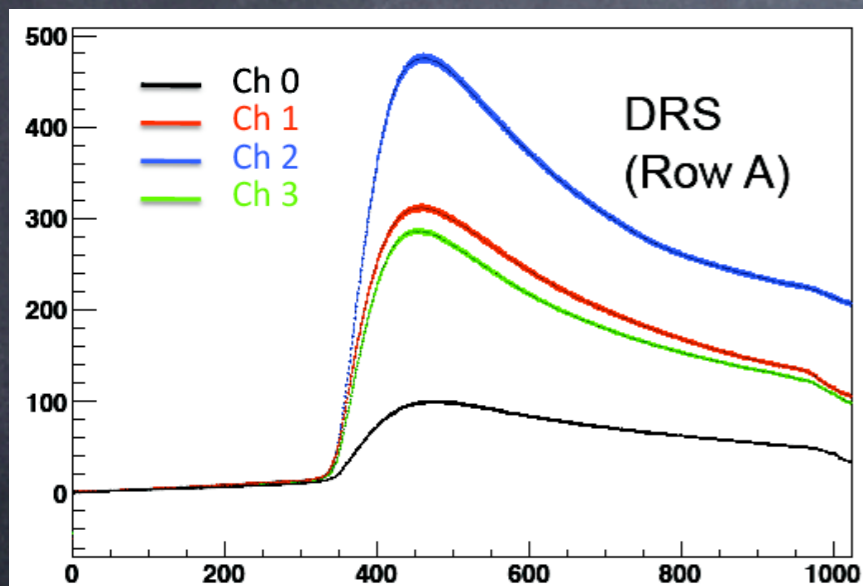
By working with 2 Gs/s it has been possible to record the long tail due to the scintillation of the BGO;

The PMTs of central row have an enhanced prompt peak due to the Cherenkov light.

C and S signals in the BGO

For filtered PMTs , in order to extract the content of C and S in the central PMT signals a fit was performed event by event on the acquired waveforms;

By summing the 12 S_i and the 4 C_i it is possible to obtain to total value of S and C for the event.

Example of fit:
Whole signal (C+S)
Scintillation (S)
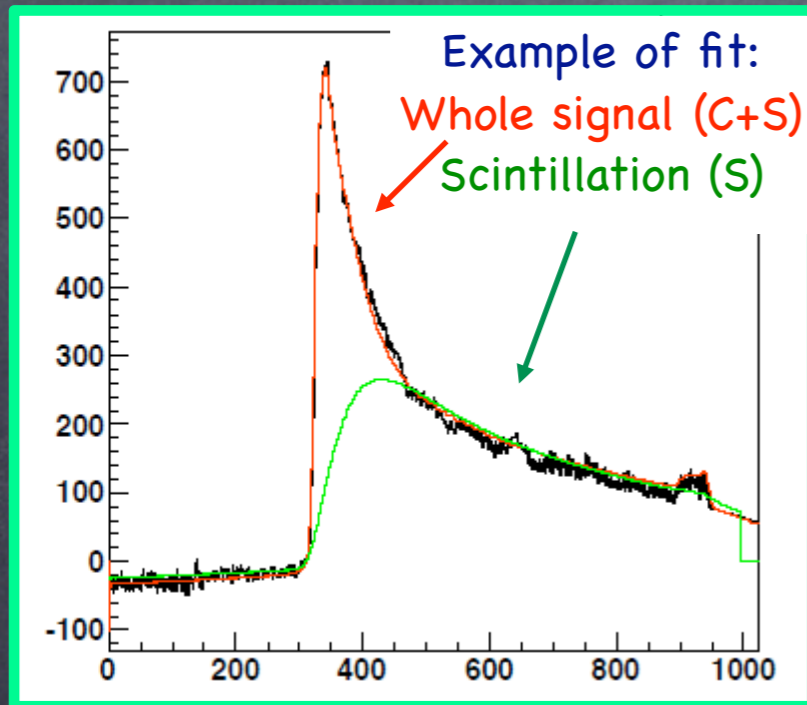
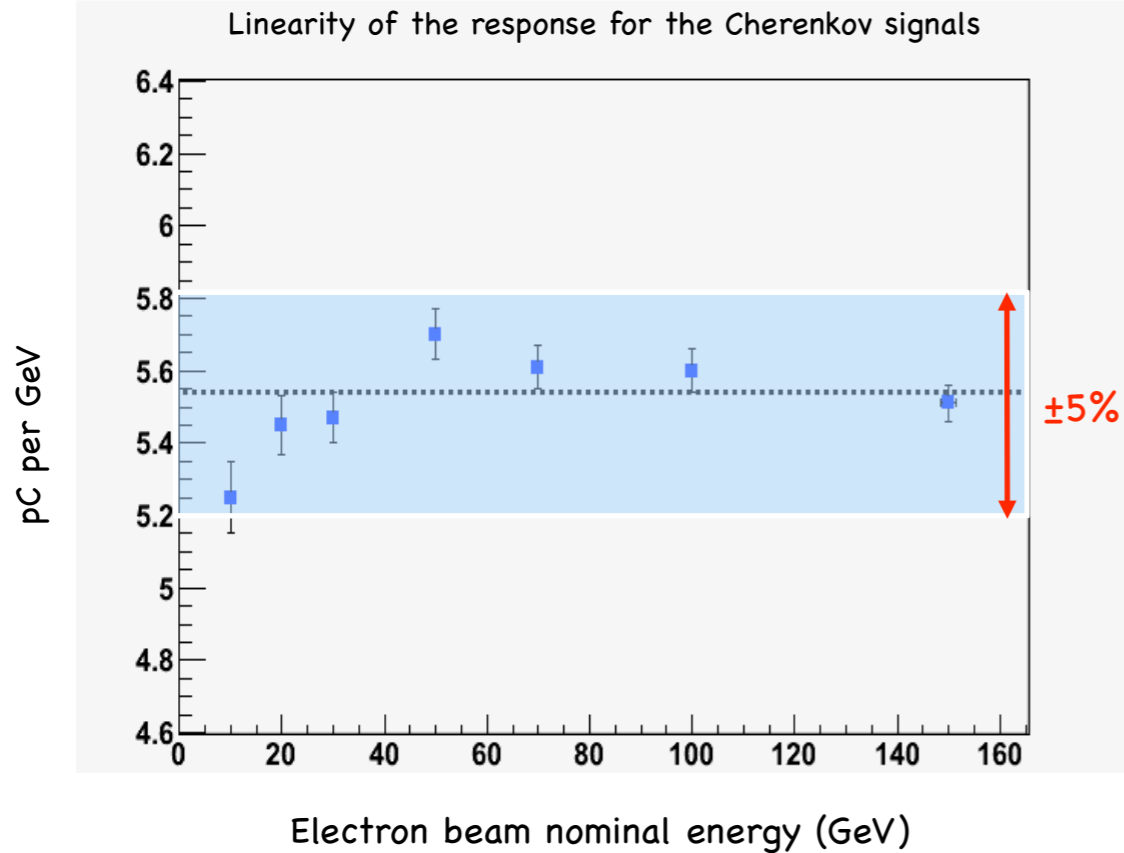Examples of spectra of the total Cherenkov charge for different electron beam energy
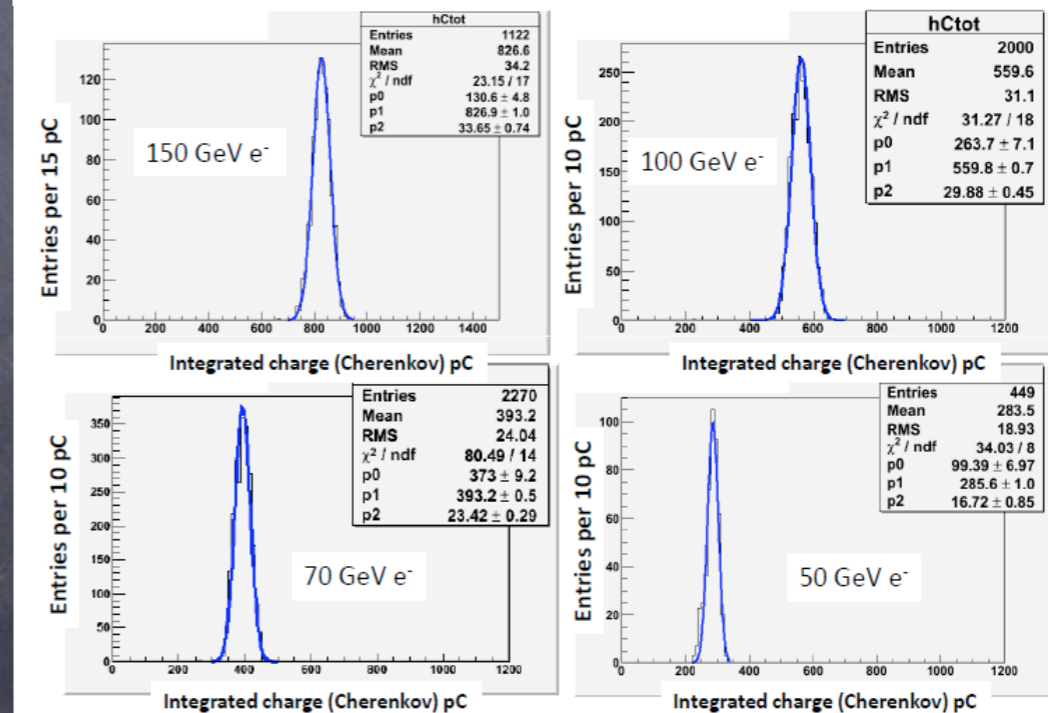
# C and S signals in the BGO

With the electrons we found:

Cherenkov (C) $\dfrac{\sigma_E}{E} = \dfrac{36\%}{\sqrt{E}} \oplus 3\%$

Scintillation (S) $\dfrac{\sigma_E}{E} = \dfrac{33\%}{\sqrt{E}} \oplus 1\%$
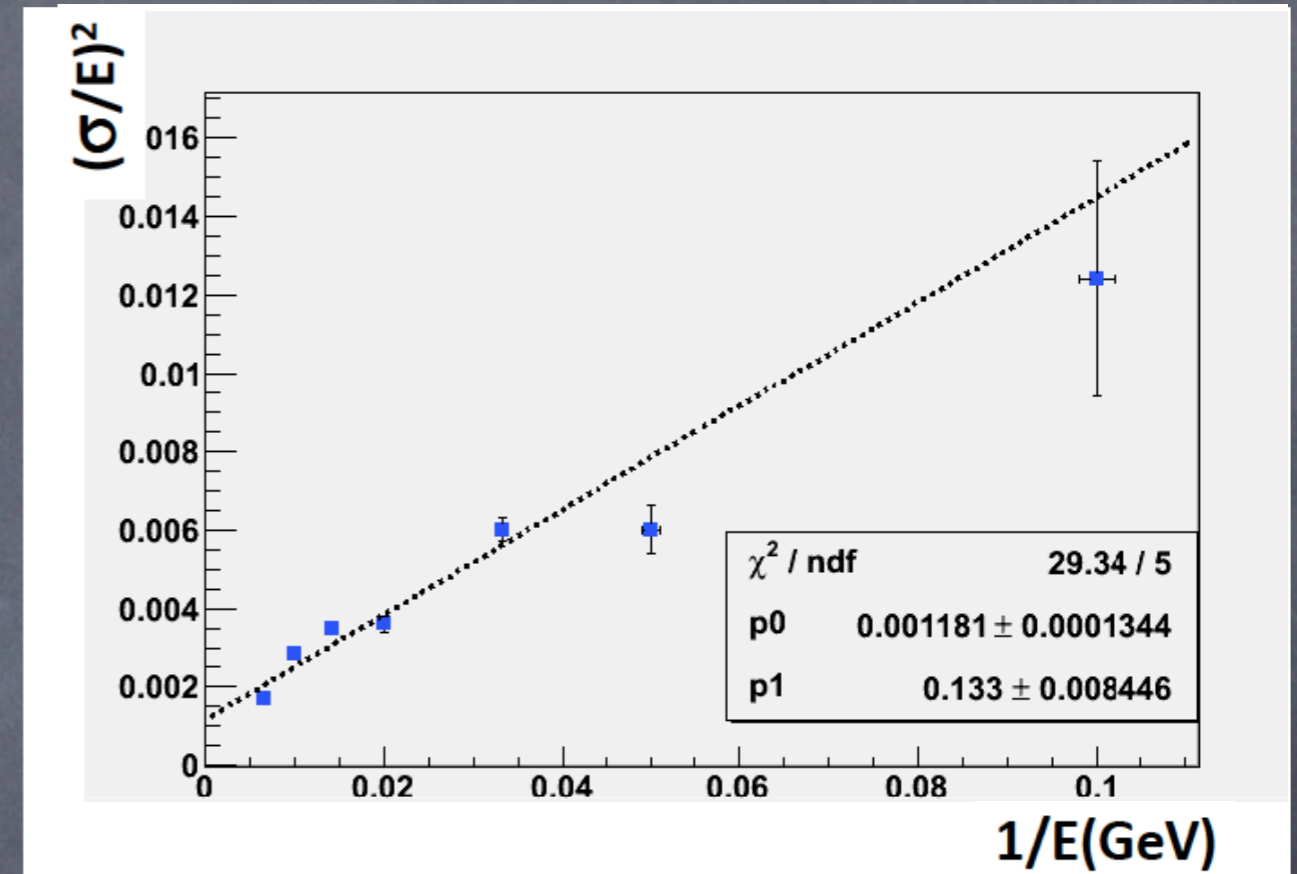
Linearity of the response for the Cherenkov signals

pC per GeV — Electron beam nominal energy (GeV)

±5%

$(\sigma/E)^2$ vs $1/E(GeV)$

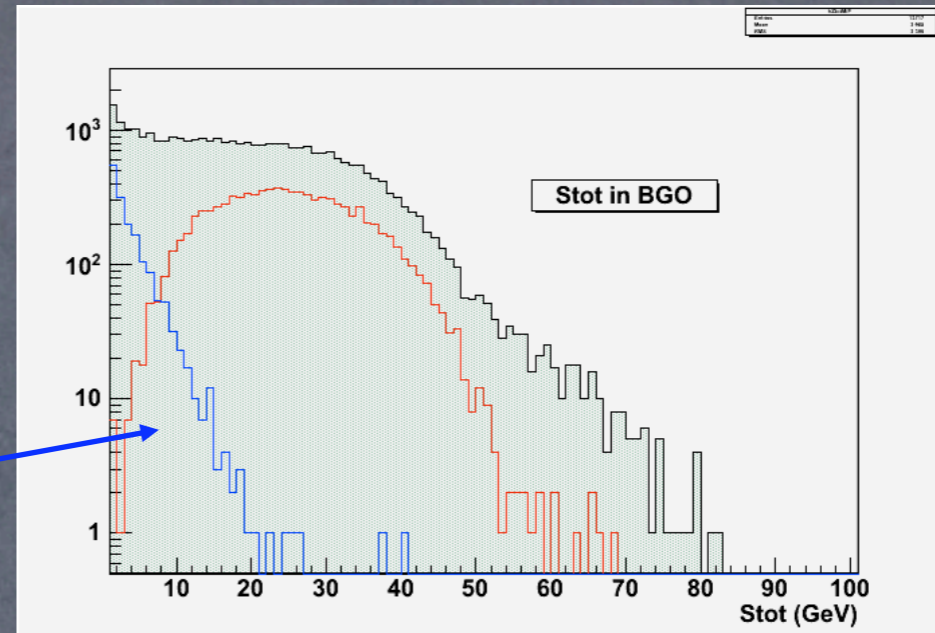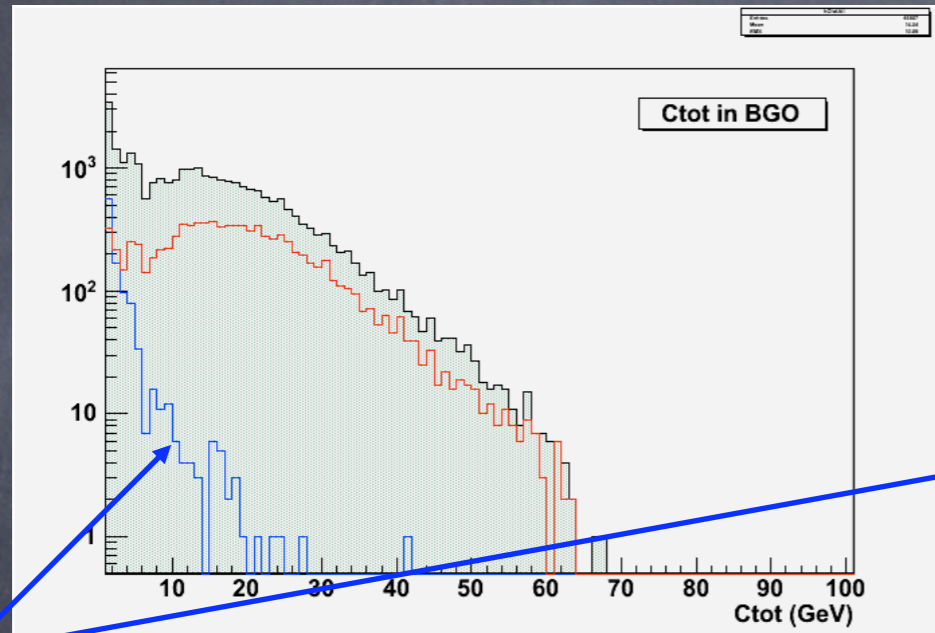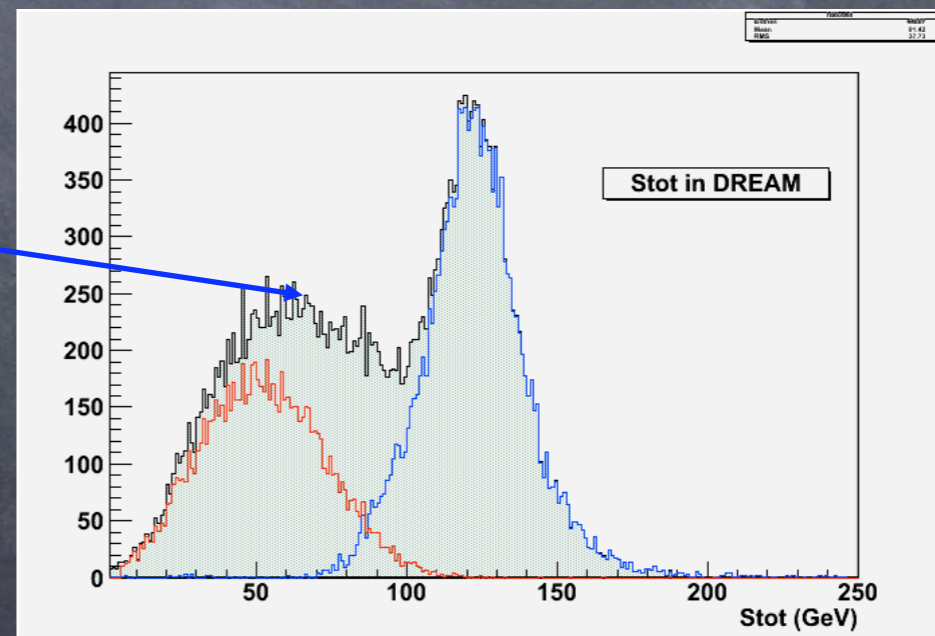| χ^2 / ndf	29.34 / 5
p0	0.001181 ± 0.0001344
p1	0.133 ± 0.008446

Pions on BGO+DREAM

After a suitable calibration with electrons we started to study the performance of the whole calorimeter with pion beams.
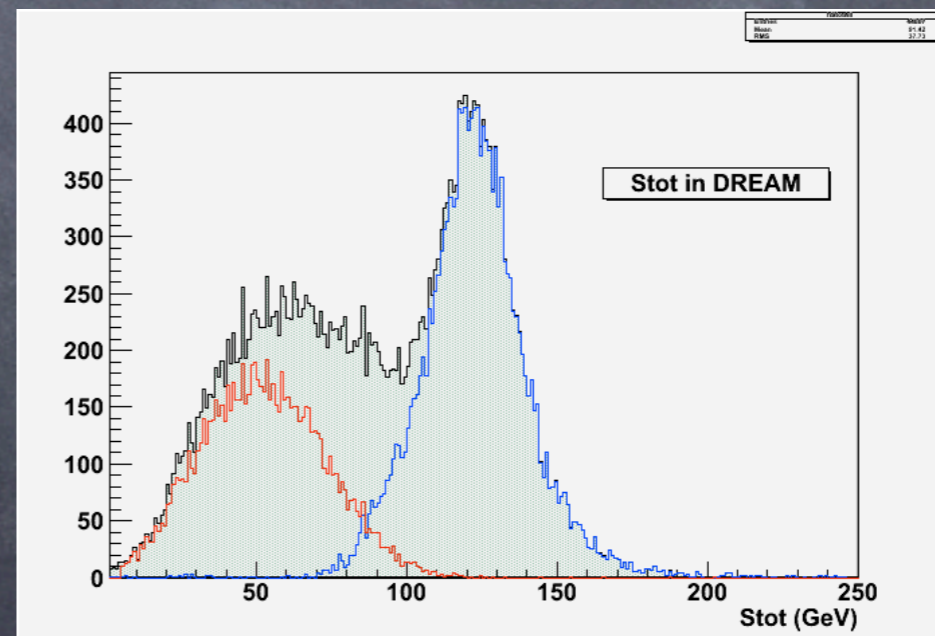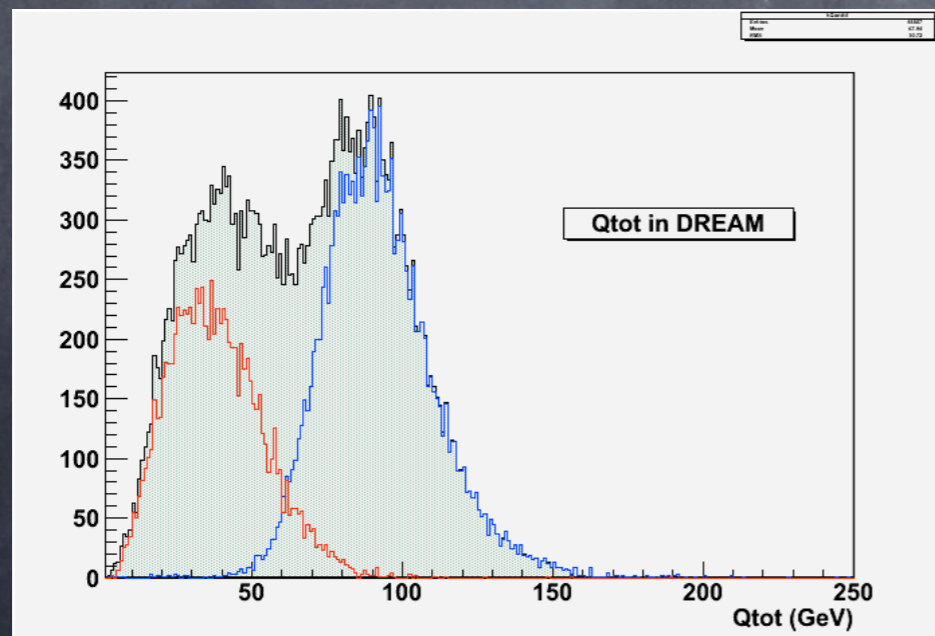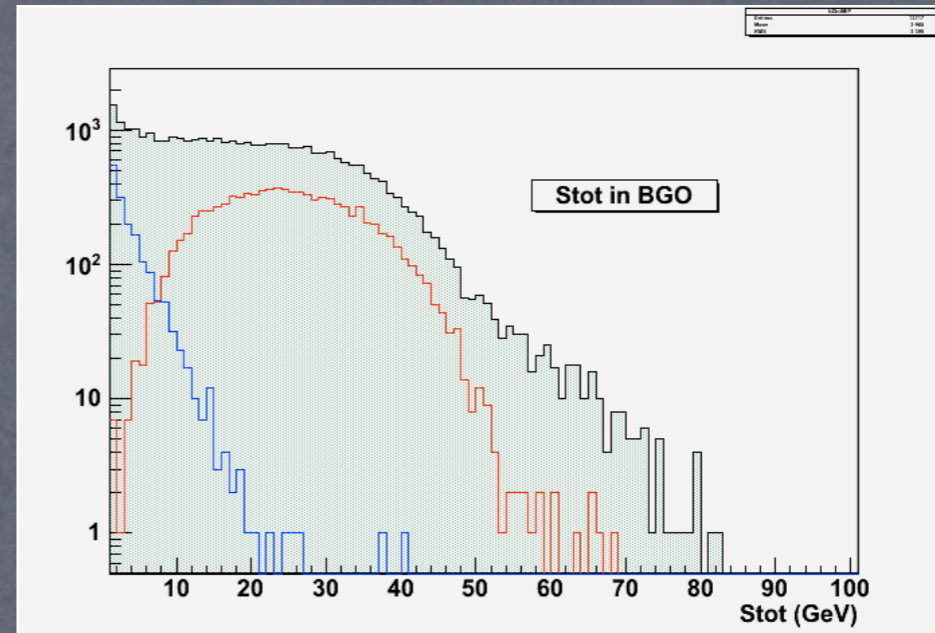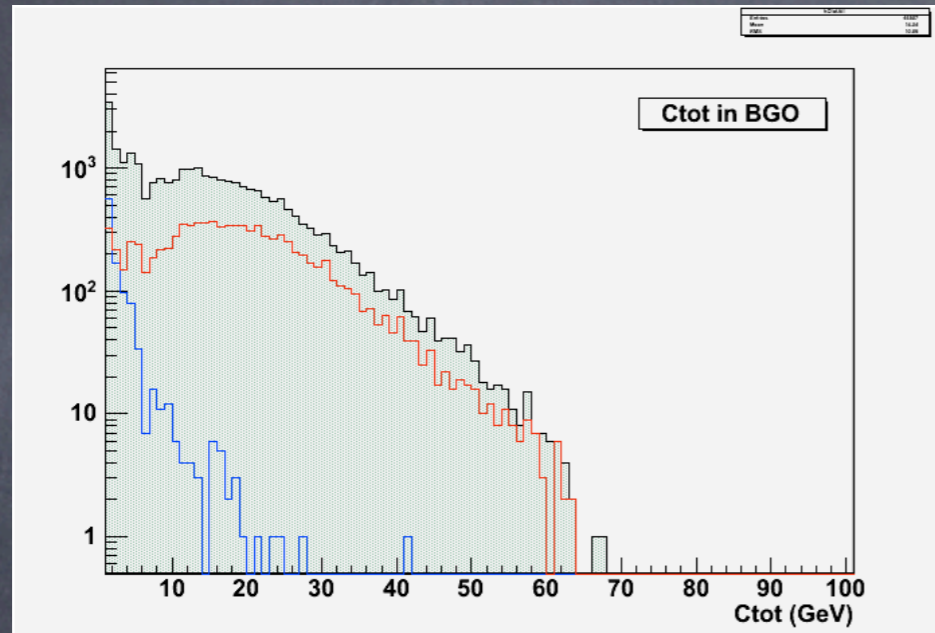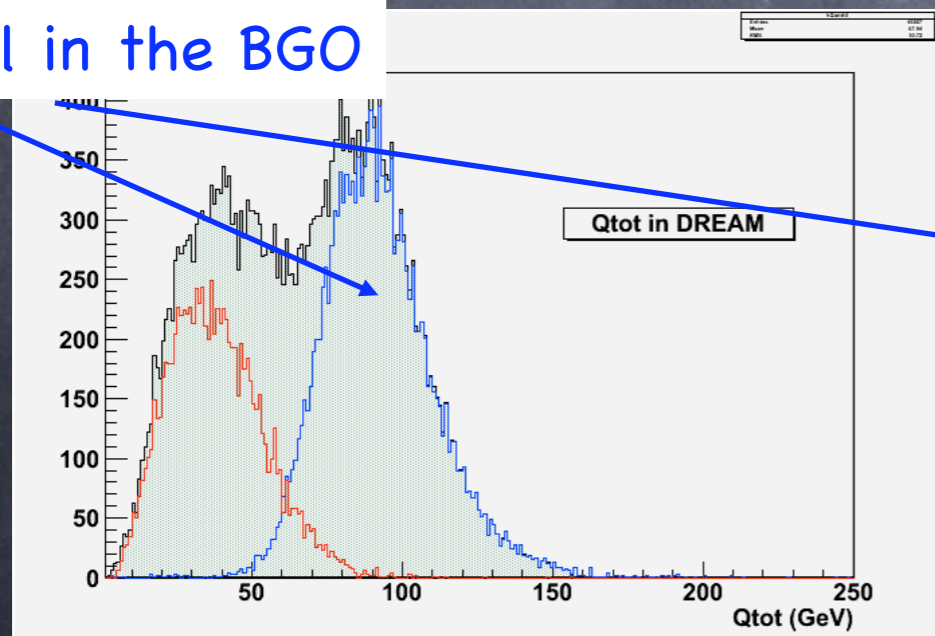
Pions on BGO+DREAM

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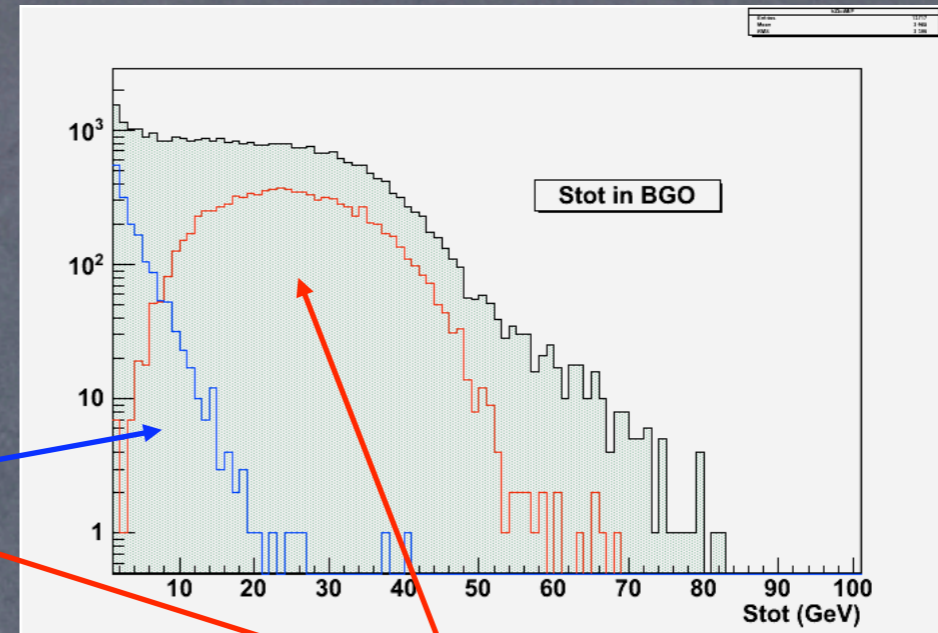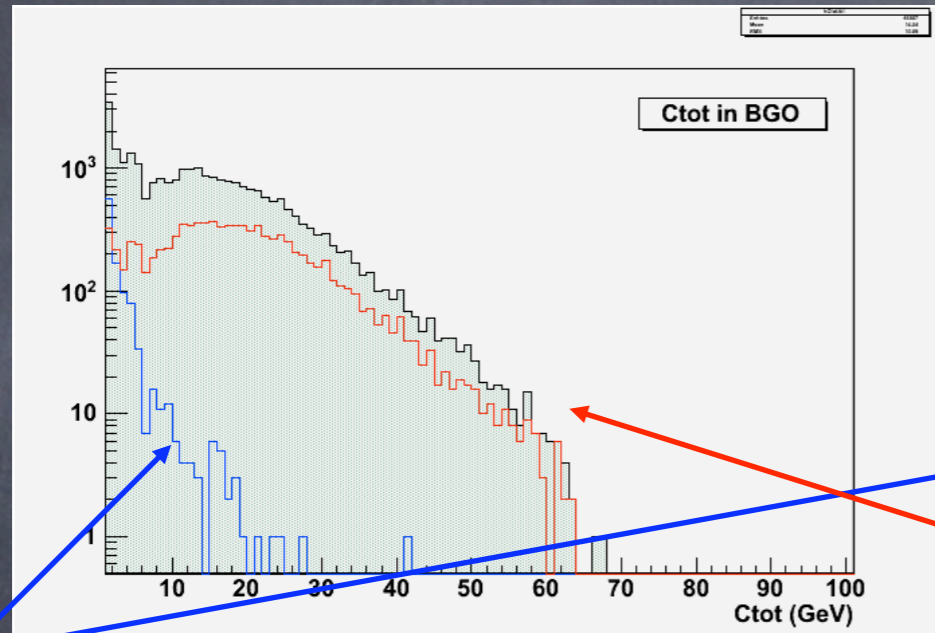

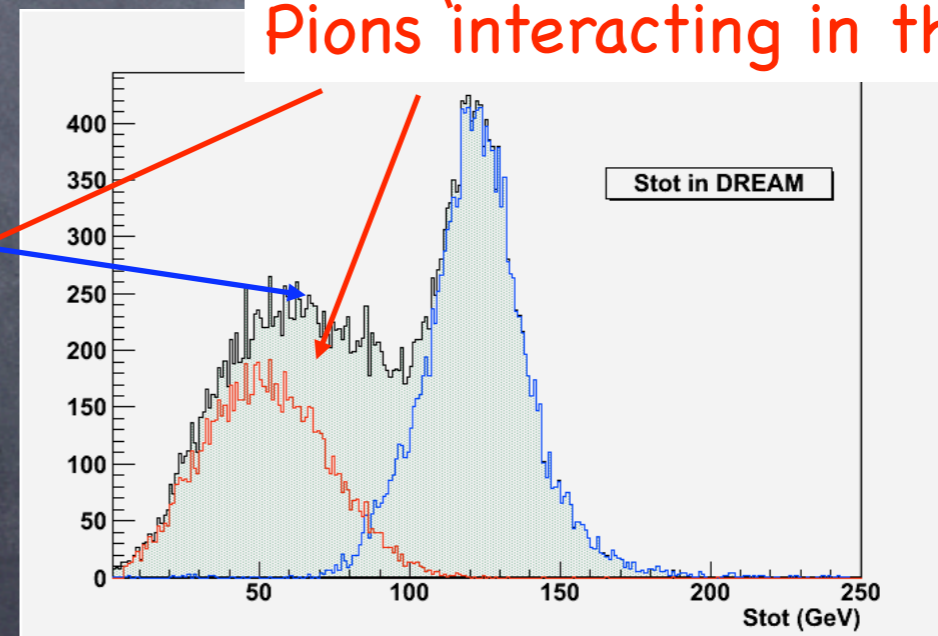Mip signal in the BGO

Pions on BGO+DREAM

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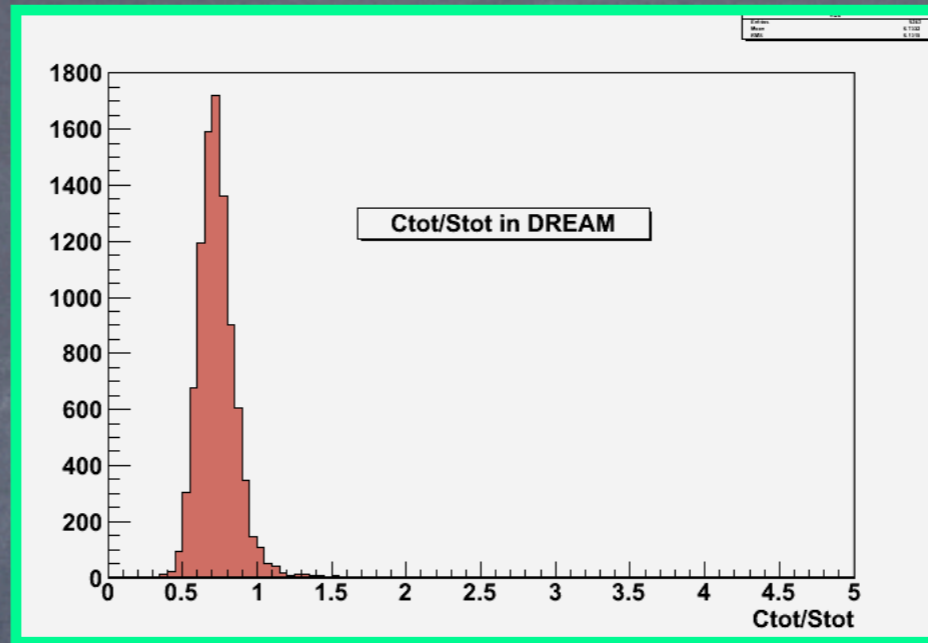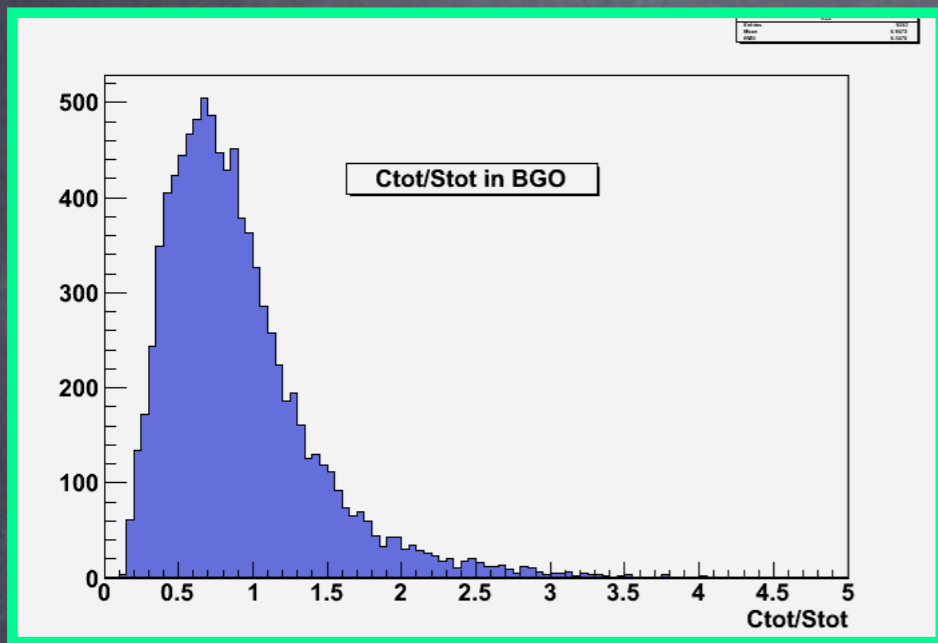

Mip signal in the BGO

Pions interacting in the BGO

The e. m. fractions

The ratio between the Cherenkov and the Scintillation signals is directly related to the e. m. fraction of the shower.


Ctot/Stot in BGO

Ctot/Stot in DREAM

Non-mip event

Large fluctuations of the e. m. fraction 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.


Q/S vs C/Z
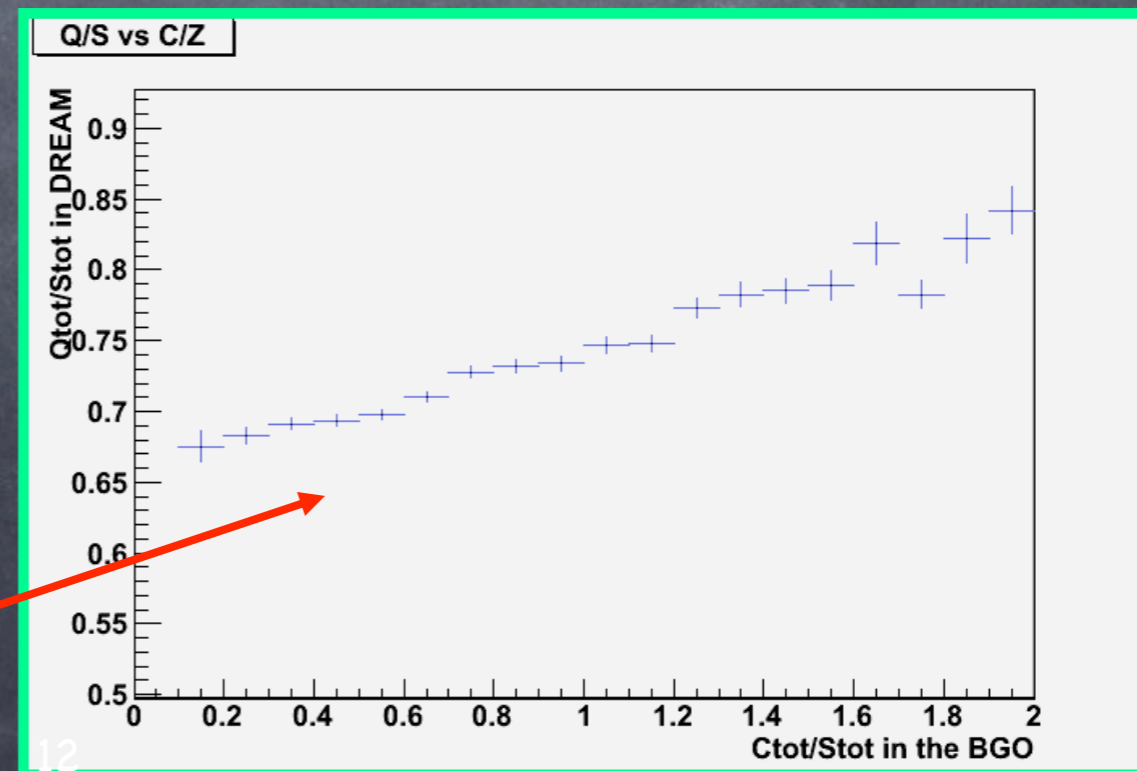
Exploiting the knowledge of the e.m. fraction

This plot shows the distribution of the Cherenkov signals in the whole system;
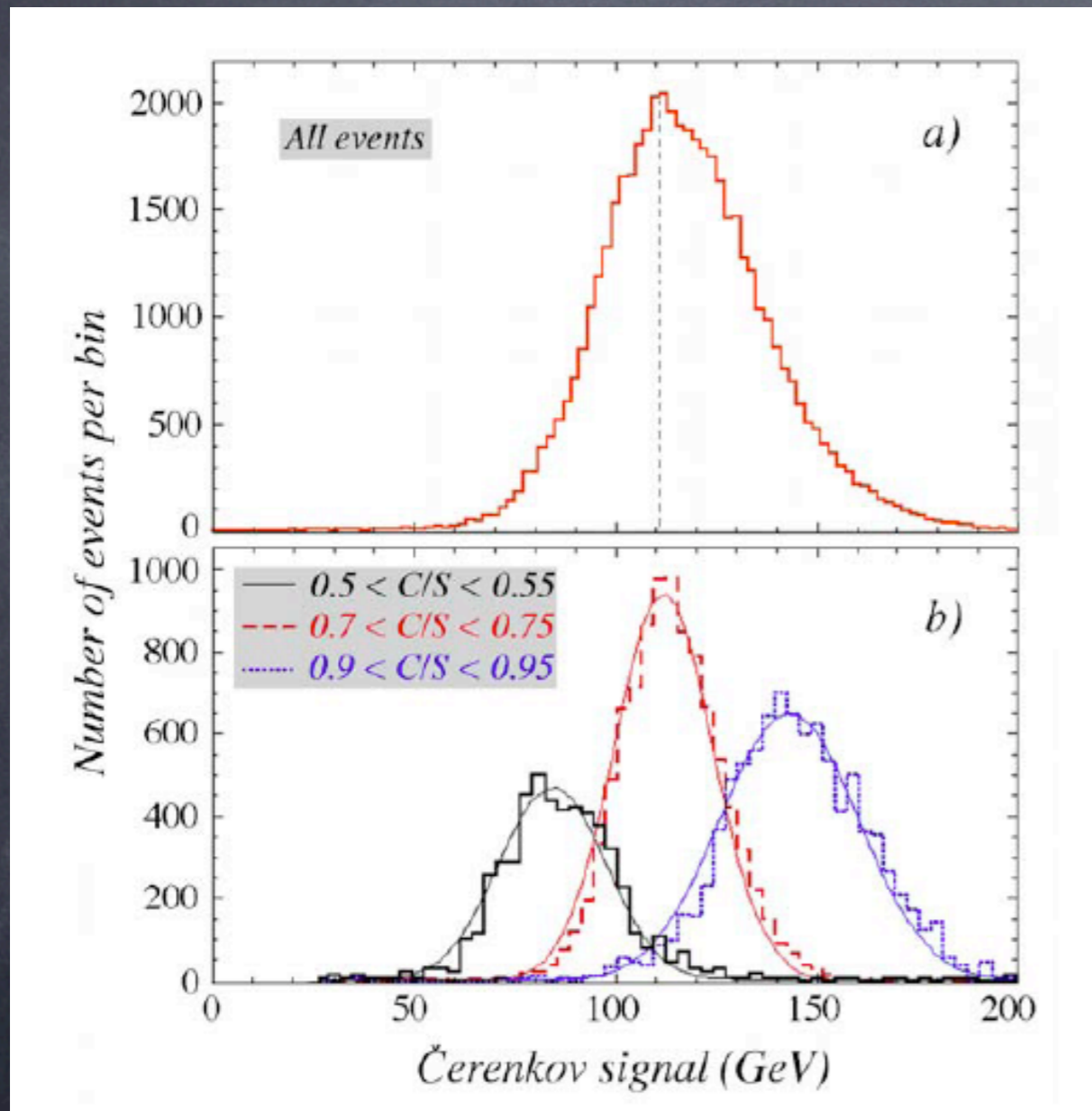
It appears to be large and asymmetric as it could be expected for an uncompensated hadronic calorimeter.

Once all events are subdivided in different sub-samples of C/S, it is possible to see that the overall asymmetric distribution is a superposition of several symmetric and more gaussian spectra.
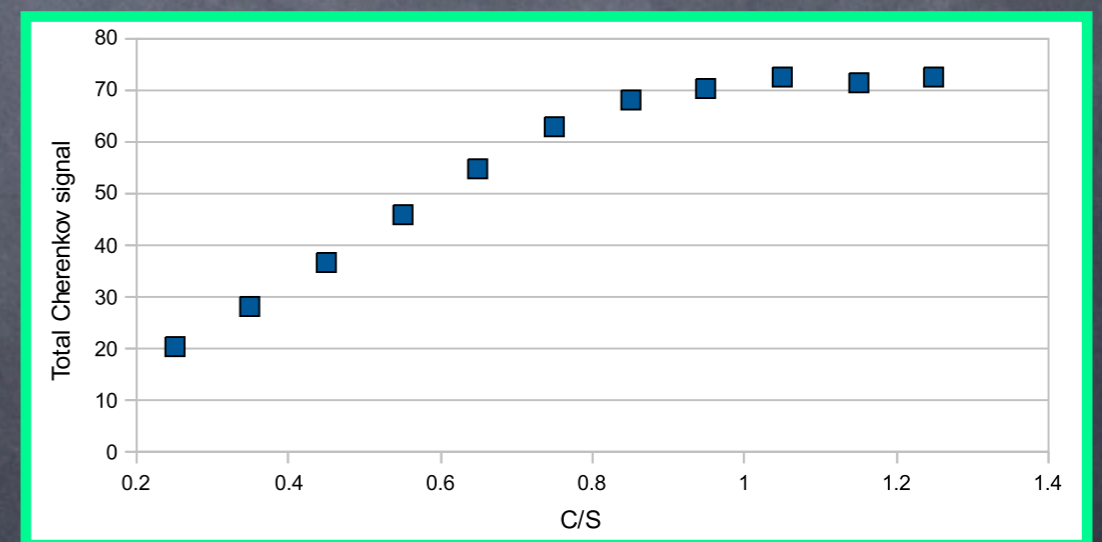
In general, the total Cherenkov signal (due to the e.m. fraction) increases with C/S.

The energy resolution

In both sections of the detector, the resolution on the energy measurement depends on the single resolutions on C and S and on the correlation between the two quantities

$$\frac{\sigma_{E_0}}{E_0} = \frac{\sqrt{\sigma_C^2 + \lambda^2 \sigma_S^2 - 2\rho\lambda\sigma_C\sigma_S}}{C - \lambda S}$$

The poor resolution on S and C in the BGO section makes the correlation in BGO very low: 0.45;

Although the lateral leakages the correlation in DREAM was measured to be 0.8 ÷ 0.9;
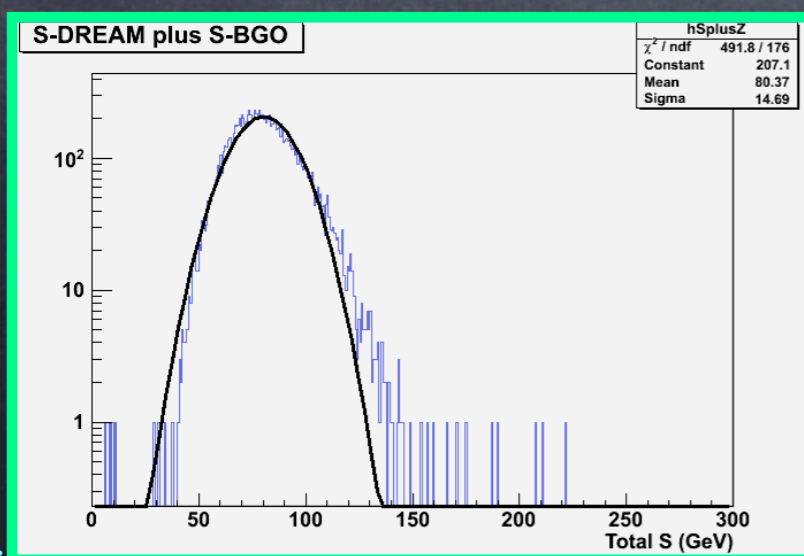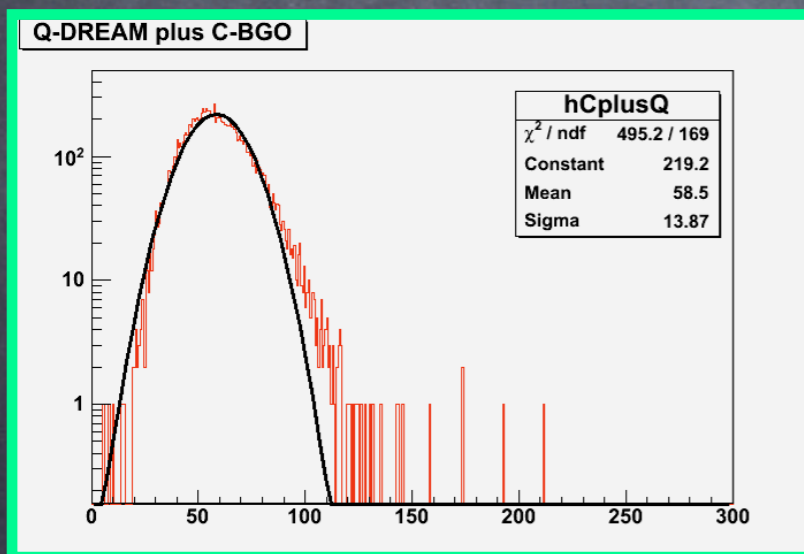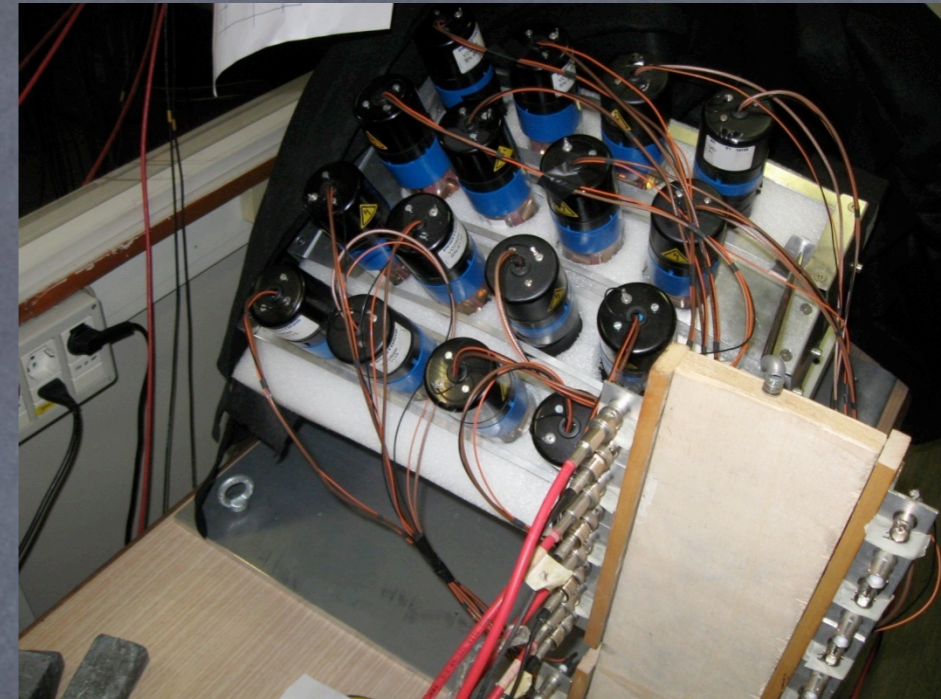

The distribution of the total energy has a symmetric and better gaussian shape, with respect to the total Cherenkov and Scintillation spectra that show both the typical response of a uncompensated calorimeter.
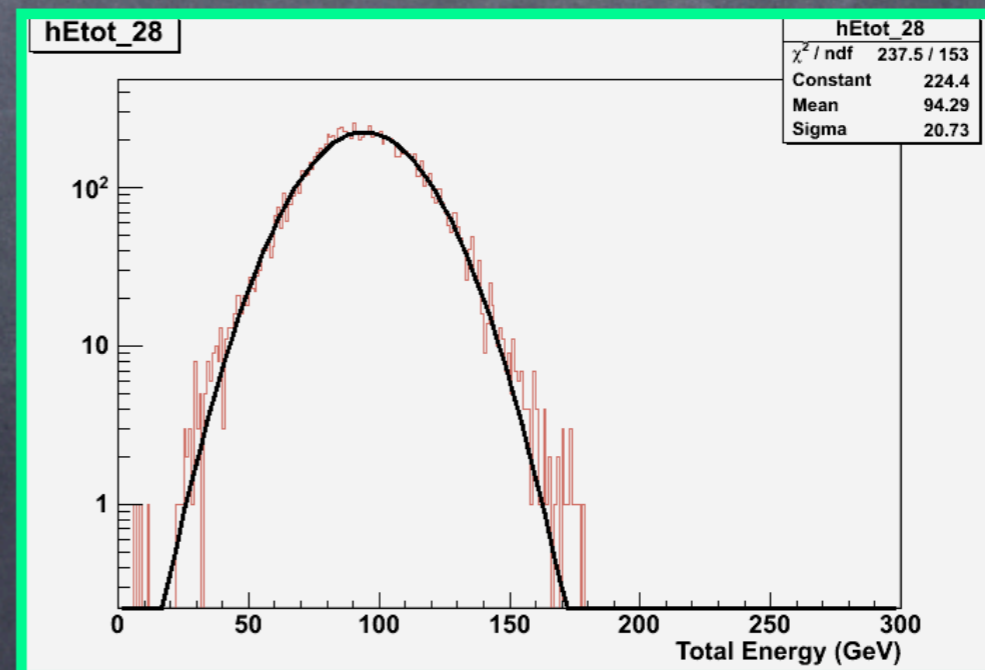
Next steps

In order to reach a better performance of the BGO matrix, we have set-up a detector completely covered with 16 filtered PMTs;
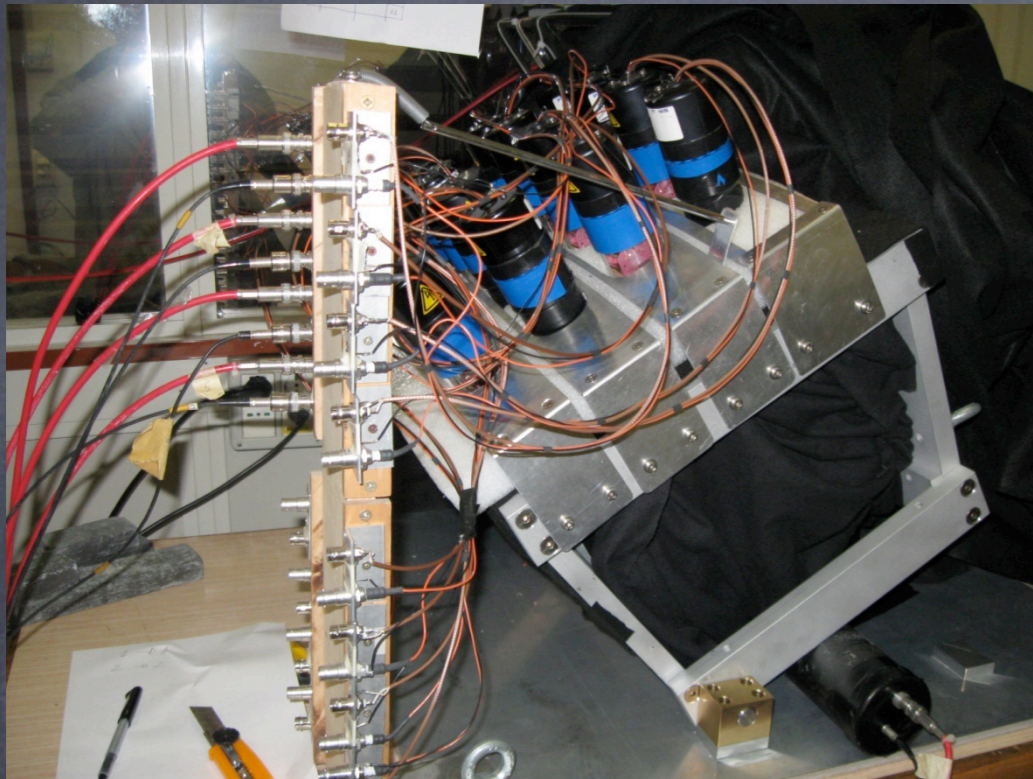
The detector is now under test with cosmic rays to get a good inter-calibration of the PMTs.

Scintillation tail
Cherenkov peak

Conclusion

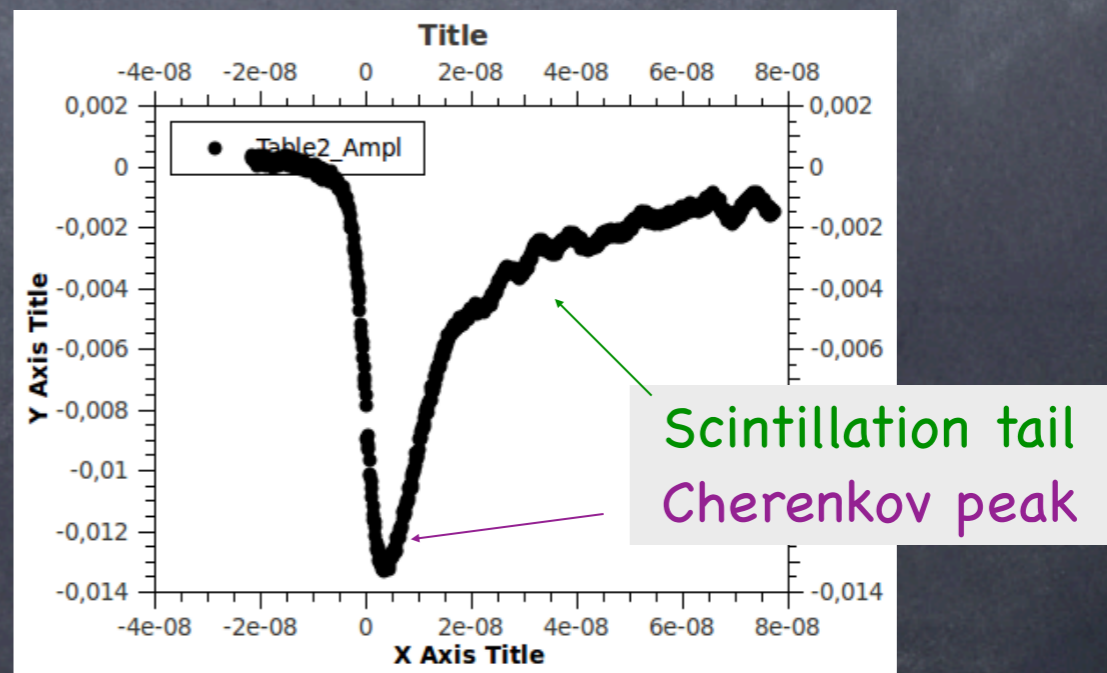Dual readout calorimetry has already shown to be able to evaluate the electromagnetic fraction of a hadronic shower event by event allowing to correct the response of a hadronic calorimeter;

Because of the large fluctuations of the e.m. fraction found already in the first stages of the shower, a "standard" electromagnetic calorimeter (needed to measure the energy of electron, photons, π^0...) would spoil the overall energy measurement;

A complete dual readout calorimeter, with a BGO based e.m. section, was built and tested;

Although the non-perfect readout system adopted (only 4 PMTs with filters) the DR principle worked quite well:

× A clear correlation between the e.m. fraction measured in the two sections was found;

× The energy measured by the complete system has a gaussian distribution and doesn't show the tail typical of a non-compensating calorimeter.
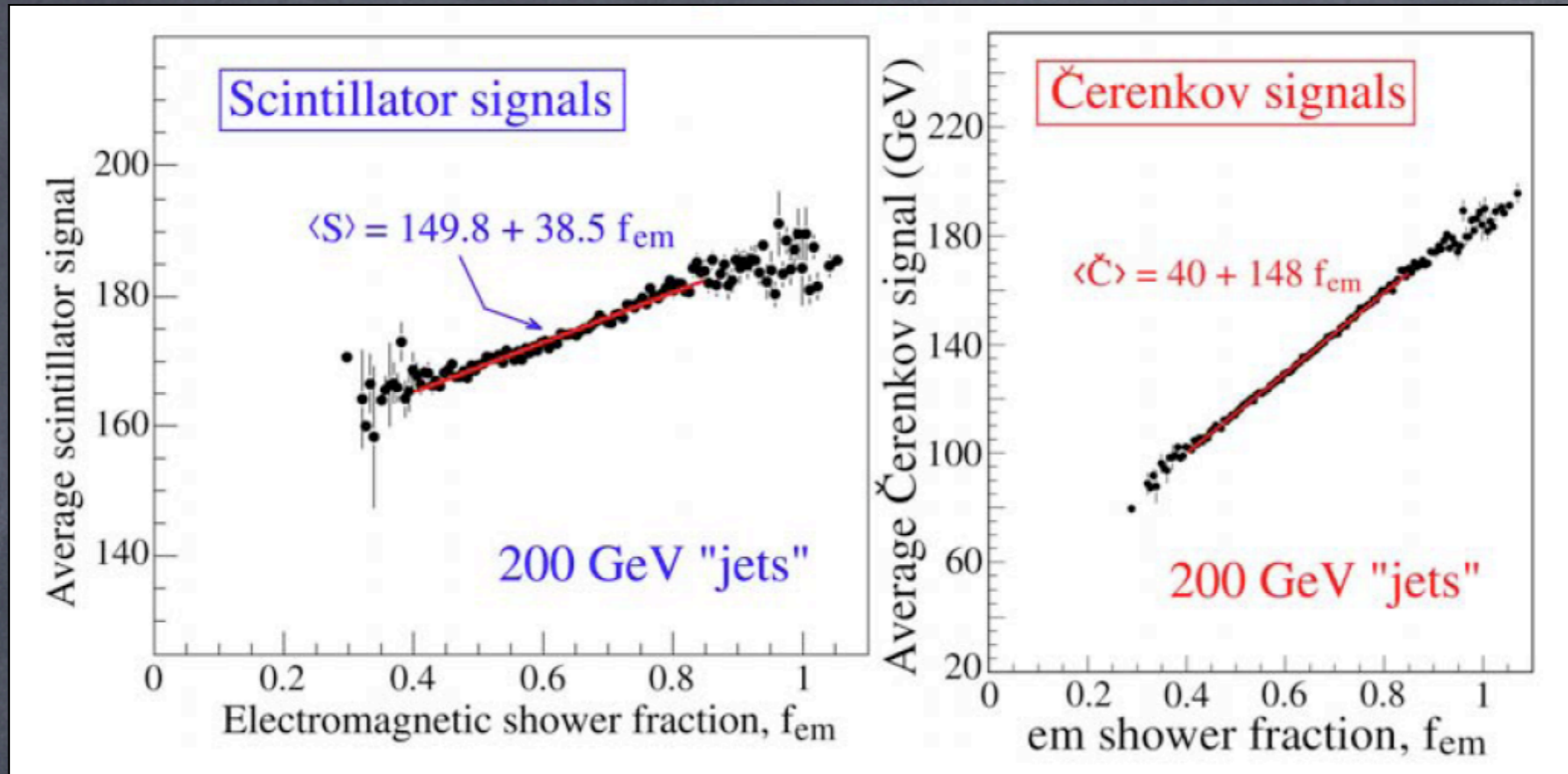
Tests with a better readout BGO section are foreseen for this summer ...

SPARE

Effect of selection based on f_{em}
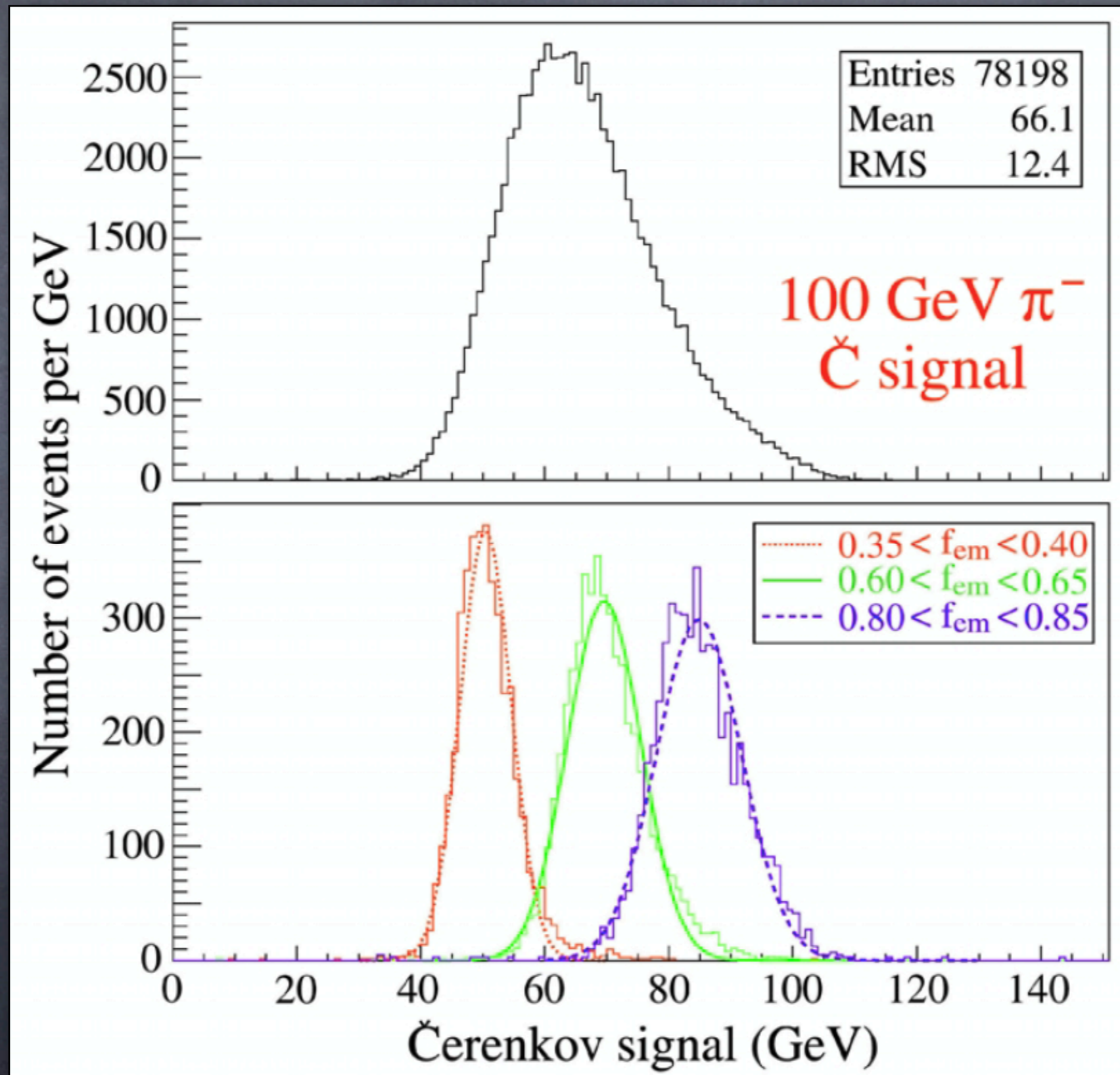
Finally a way to measure e/h

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

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

Dual-Readout Calorimetry in Practice

- The (energy-independent) Q/S method

  - Hadronic response (normalized to electrons)

$$\frac{Q}{S} = \frac{R_Q}{R_S} = \frac{f_{em} + 0.20(1 - f_{em})}{f_{em} + 0.77(1 - f_{em})}$$

  - Q/S response ratio related to f_{em} value $\rightarrow$ find f_{em} from Q/S

$$R(f_{em}) = f_{em} + \frac{1}{e/h}[1 - f_{em}], \qquad e/h = 1.3(S), 5(\check{C})$$

  - Correction to measured signals (regardless of energy)

$$S_{corr} = S_{meas}\left[\frac{1 + p_1/p_0}{1 + fem \cdot p_1/p_0}\right], \qquad with \qquad \frac{p_1}{p_0} = (e/h)_s - 1$$

$$Q_{corr} = Q_{meas}\left[\frac{1 + p_1/p_0}{1 + fem \cdot p_1/p_0}\right], \qquad with \qquad \frac{p_1}{p_0} = (e/h)_{\check{C}} - 1$$

39

20

Lateral leakages