Dual-Readout Calorimetry with Crystals

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on behalf of:

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Outline

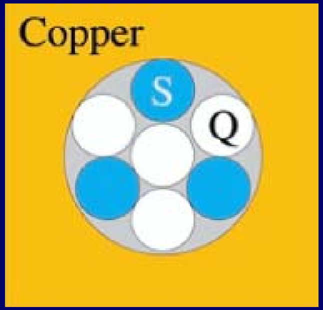
- The Dual-Readout Method: principle and results from the Cu-Scintillating/Quartz fibers calorimeter (DREAM)
- The Dual-Readout approach in a homogeneous material
- The 2006 CERN-H4 beam test: performance of
  - a single $PbWO_4$ crystal
  - a $PbWO_4$ crystal matrix
- Preliminary results on a BGO crystal from 2007 beam test
- Conclusions and outlook

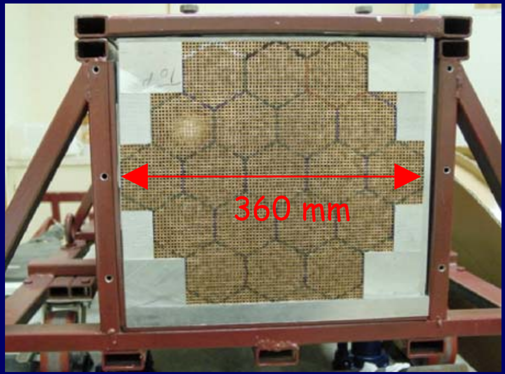
Why a Dual-Readout Calorimeter?

- Performances of hadronic calorimeters mainly limited by:
  - Different detector response to electromagnetic (em) and non-electromagnetic shower components (i.e. $e/h \neq 1$)
  - Fluctuations in the em fraction (f_{em}) are large and non-poissonian

- Consequences are:
  - hadronic signal non-linearity
  - poor hadronic energy resolution (with a deviation from $E^{-1/2}$ scaling at high energies)
  - Non-gaussian response function

- The <u>Dual-REAdout Method (DREAM)</u>, which allows to measure f_{em} event-by-event by comparing the total visible energy in scintillating and in quartz fibers, <u>eliminates this source of fluctuations</u>





DREAM Performance

N. Akchurin et al.,
NIM A537 (2005)

- DREAM equations:

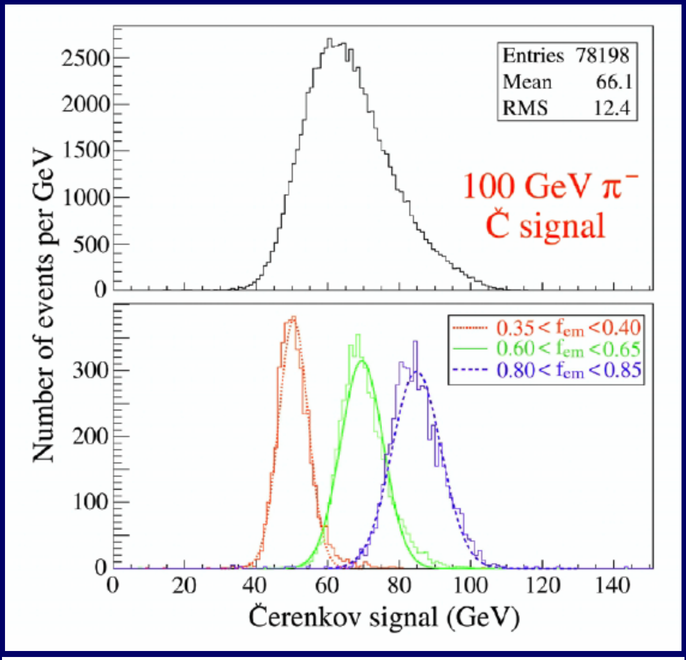
$$\begin{cases} S = E\left[f_{em} + (e/h|_S)^{-1}(1-f_{em})\right] \\ Q = E\left[f_{em} + (e/h|_Q)^{-1}(1-f_{em})\right] \end{cases}$$

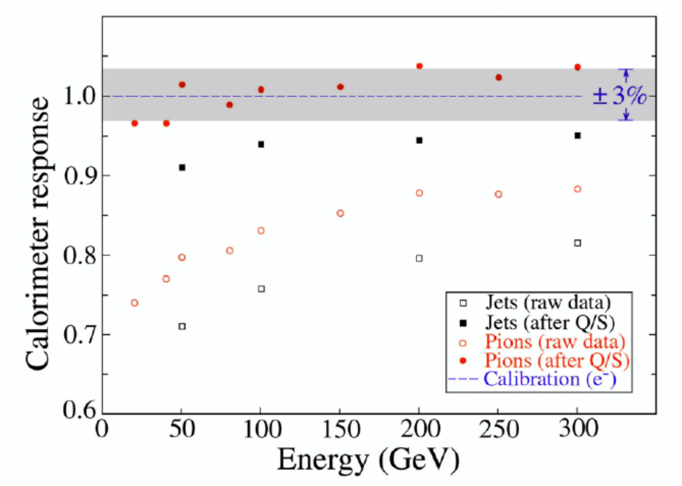
$$E = \frac{S - \chi Q}{1-\chi} \qquad \chi = \frac{1-(e/h|_S)^{-1}}{1-(e/h|_Q)^{-1}} \approx 0.29$$

- ➔ Improved resolution, perfect scaling with $E^{-1/2}$, reduced hadronic signal non-linearity!

- The dominant limitation is the small number of Čerenkov photoelectrons (8 ph.e./GeV), arising from the very small sampling fraction ➔ limited performance on em showers

- DREAM method with a homogeneous material? This will largely increase the number of Cerenkov photoelectrons and improve performances on em showers





Which Homogeneous Material?

- Scintillating crystals are possible candidates for a homogeneous materials to be used in a dual-readout calorimeter

- For the first tests we used $PbWO_4$, a well-know material (CMS, ALICE…) and "easily" available (thanks to ALICE collaboration)

Crystal	Light Yield (% NaI)	Decay Time (ns)	Peak wavel. (nm)	Cutoff Wavel. (nm)	Refr. Index	Density (g/cm^3)
$PbWO_4$	1.3	10	440	350	2.2	8.28

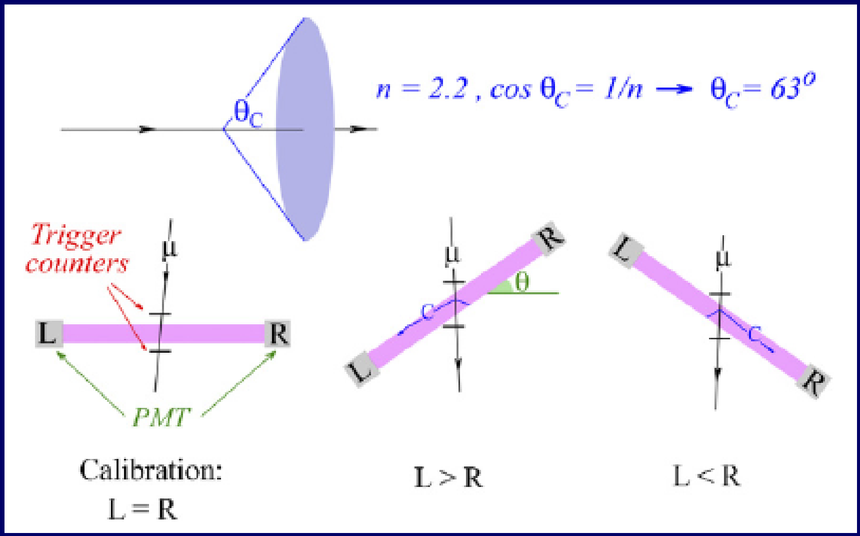
- Separation of scintillation and Čerenkov light components based on:

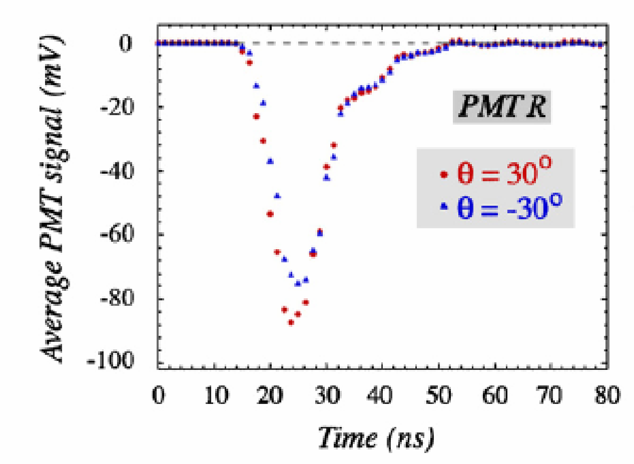
	Čerenkov	Scintillation
Time response	Prompt	Exponential decay
Light Spectrum	$\propto 1/\lambda^2$	Peak
Directionality	Cone: $\cos\theta_c = 1/\beta n$	Isotropic
Polarization	Yes	No

Results from a single $PbWO_4$ crystal

- The contribution of Čerenkov light to signals from $PbWO_4$ crystal has been first evaluated with a single crystal with photomultiplier (PM) readout on each side, and acquired with fast digitizers and charge integrating ADCs
- We tilt the crystal to increase Čerenkov light collection on one side with respect to the other
- If ε_x is the fraction of Čerenkov light in the signal recorded on PM on side x (the same scintillating light is seen on both sides), the left-right signal asymmetry α is defined as

$$\alpha = \frac{R-L}{R+L} = \frac{\varepsilon_R - \varepsilon_L}{2+\varepsilon_R+\varepsilon_L}$$

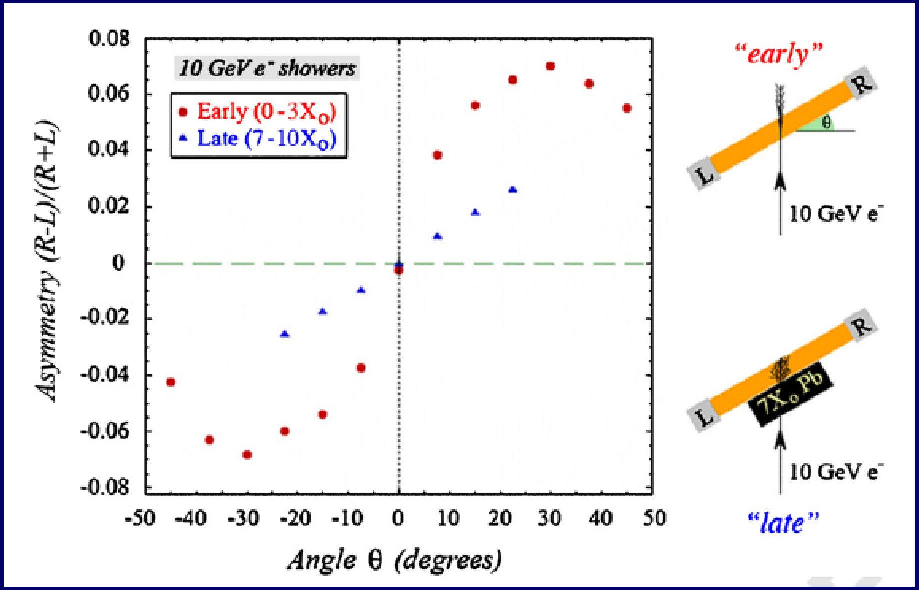


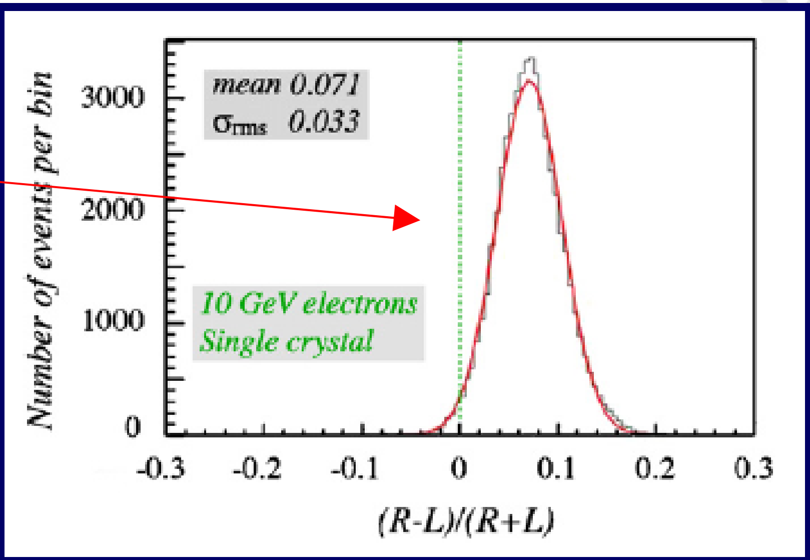


N. Akchurin et al., NIM in publication

Left-Right Asymmetry

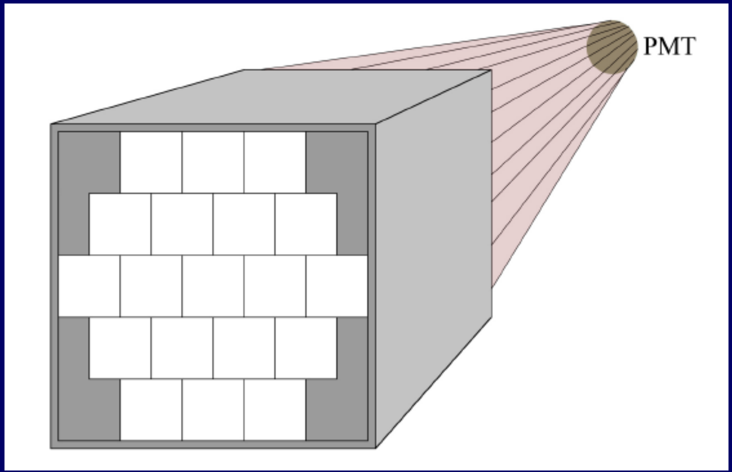
- Čerenkov contribution is clearly visible and, for 10 GeV electrons, has a maximum value of ~15% for θ close to 90 - θ_c = 27°
- "Late" showers shows smaller asymmetry due to the increase of the isotropic component (low energy electrons from Compton or Photoelectric effect)
- The asymmetry reported is the mean value of the α distribution, which, at 30 ° has an RMS of 0.033, resulting in a Čerenkov fraction in the signal of 15 ± 6 %
- This large uncertainty is <u>dominated by photoelectron statistics</u>

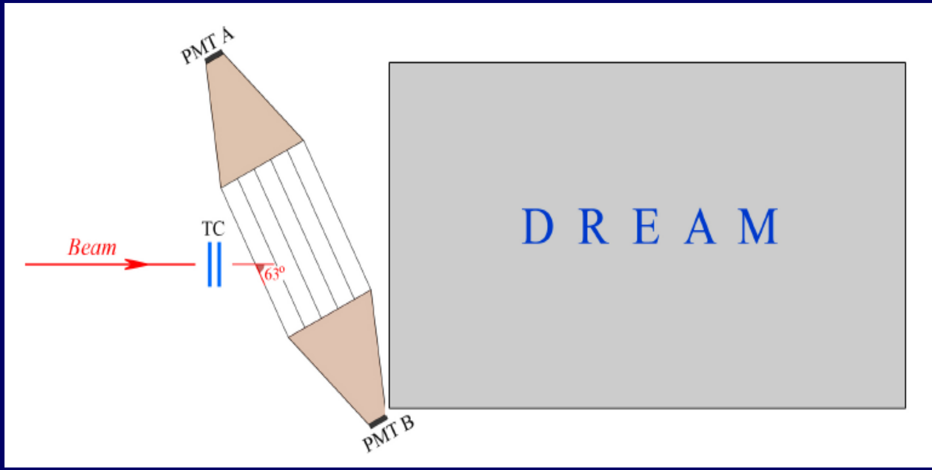




The $PbWO_4$ Crystal ECAL

- 19 $PbWO_4$ crystal, 18 cm long, 2.2 cm x 2.2 cm in cross section, were arranged in a matrix and readout by two R5900U 10-stage Hamamatsu photomultiplier through mylar cone-shaped air light-guides
- $X_0(PbWO_4)$= 8.9 mm, so the effective ECAL length is 12.4 X_0 (important leakages)
- PMs signals were equalized with 50 GeV electrons entering the matrix perpendicular to crystal axis
- DREAM towers were also calibrated with 50 GeV electrons
- To measure the Čerenkov light production by means of the L-R asymmetry method, ECAL was tilted at an angle $90-\theta_c = 27°$ and we took data with a 50 GeV π^+ beam



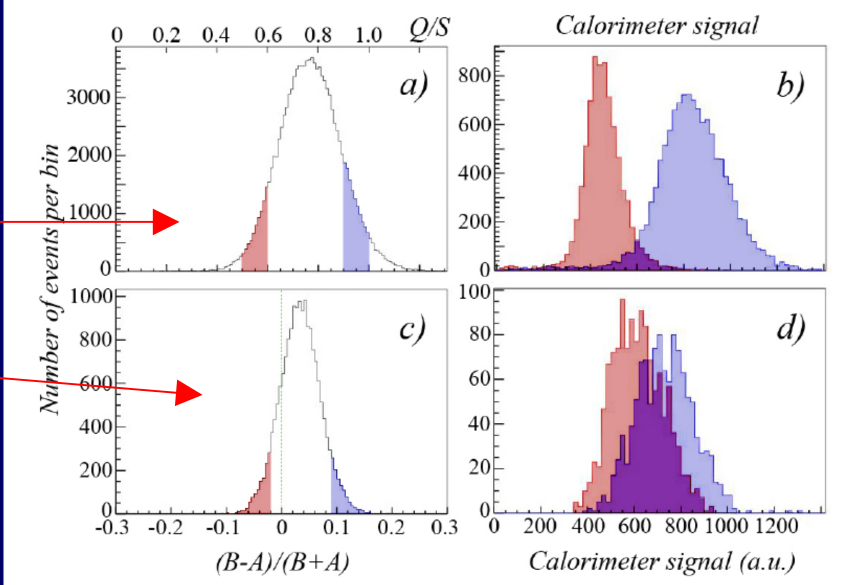


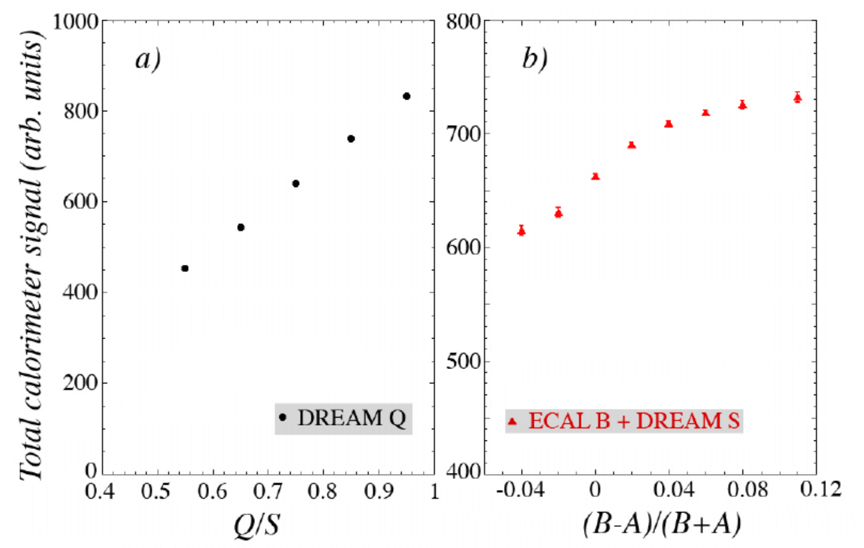
$PbWO_4$ ECAL + DREAM: Results

- When the shower develops entirely in DREAM, signals with different f_{em} (measured from Q/S) have a different total energy distribution in the calorimeter

- For the $PbWO_4$ matrix results are qualitatively similar: signals with different asymmetries measured in ECAL (i.e. different fem) have a different total energy distribution in the calorimeter

- This is the proof of principle that the DREAM method works on $PbWO_4$, however with some limitations:
  - Signals in DREAM Q have a step increase w.r.t. $PbWO_4$ thanks to the large e/h for Cu/Quartz
  - Measurement of Cerenkov component by means of asymmetry is not an optimal method:
    - Asymmetry is very small in general
    - Fully-contained showers have an asymmetry smaller than minimum ionizing particles





Choosing other Homogeneous Materials

For an efficient separation of the scintillation and the Cerenkov component one should consider:

	Čerenkov	Scintillation
Time response	Prompt	Exponential decay
Light Spectrum	$\propto 1/\lambda^2$	Peak
Directionality	Cone: $\cos\theta_c=1/\beta n$	Isotropic
Polarization	Yes	No

- Time response: Cerenkov is prompt ➔ "slow" scintillator ($\tau \approx 50 \div 200$ns)
- Light Spectrum: Cerenkov emission spectrum is λ^{-2}, but it is hard to collect light below 300 nm, so one would like to have a scintillator which emits only above ~400 nm
- Transmittance: to efficiently collect the short wavelength part of the Cerenkov spectrum the crystal should have an excellent transmittance in the near-UV (300nm $\div$ 400nm)
- Light yield: scintillation and Cerenkov signals should be comparable, calorimeter resolution is dominated by the statistical fluctuations on the smallest signal component

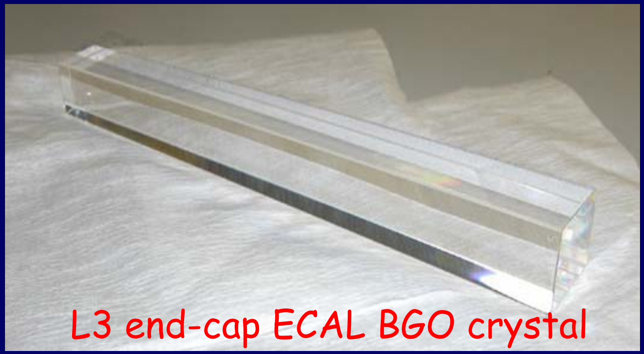
BGO

Crystal	Light Yield	Decay Time (ns)	Peak wavel. (nm)	Cutoff Wavel. (nm)	Refr. Index	Density (g/cm^3)
BGO	20	300	480	320	2.15	7.13
PWO	1.3	6	440	350	2.30	8.28
LYSO	75	41	420	400	1.81	7.10

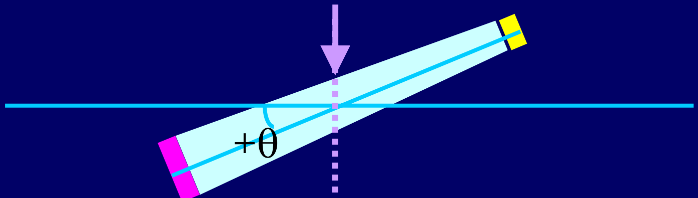
- Light emission peaks at 480nm, green
- It is transparent down to 320nm
- It has a "long" decay time
- It is "easily" available for tests (L3 ECAL)

- Single BGO crystal with photomultiplier readout on both sides exposed to electron and pion beams

- Both crystal end were equipped with a different optical filter to select the scintillation component (S) on one side (yellow, Schott GG495) and the Cerenkov component (C) on the other (UV, Schott UG11) → estimate of f_{em}



L3 end-cap ECAL BGO crystal



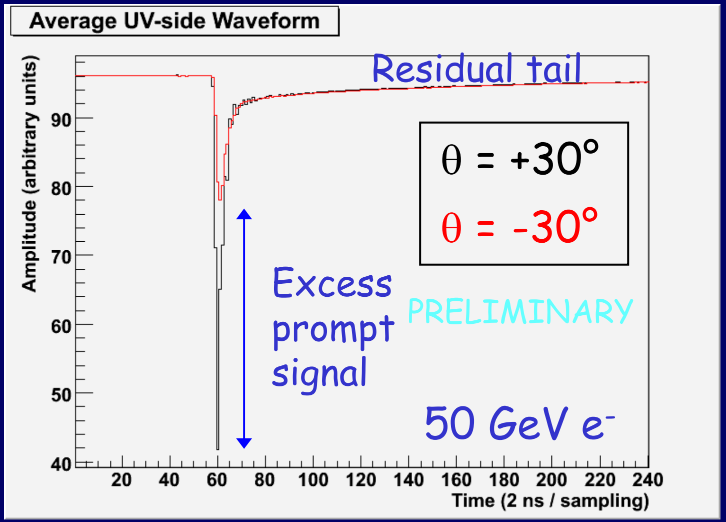
Preliminary BGO Results

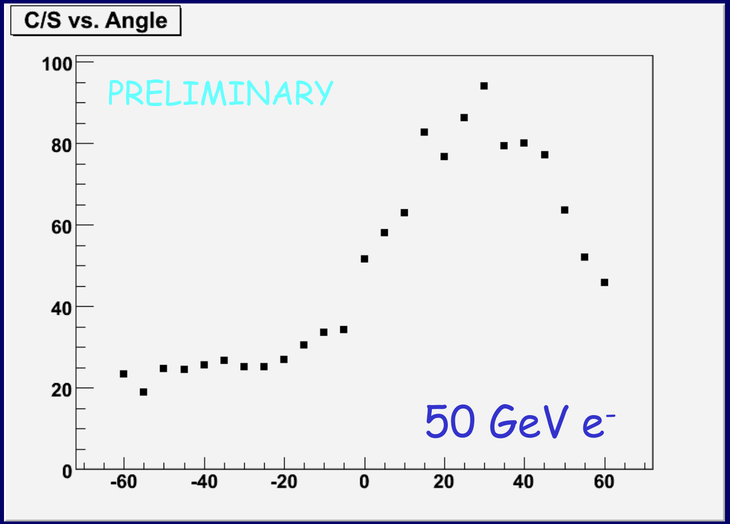
- There is a clear evidence of an excess of prompt light production at +30° with respect to -30° from the average waveforms recorded

- A residual scintillation tail exists below the prompt peak → easily measure C and S using only the information from the "UV" side and by exploiting the different time characteristics

- Average C/S has been measured for various crystal orientations with respect to the beam line: there is a clear increase of C/S at angles where the Cerenkov light can easily reach the photomultiplier on the "UV" side, indicating that the separation of the two light components has been efficiently performed

- Photoelectron statistics is still the limiting factor for this single crystal measurement



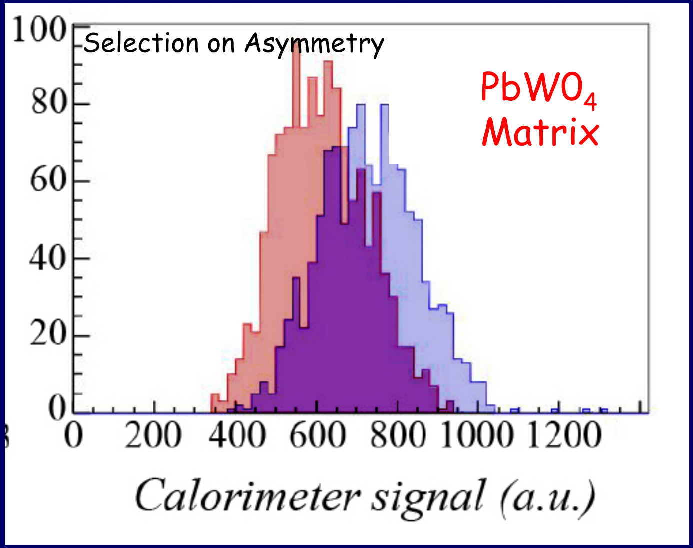


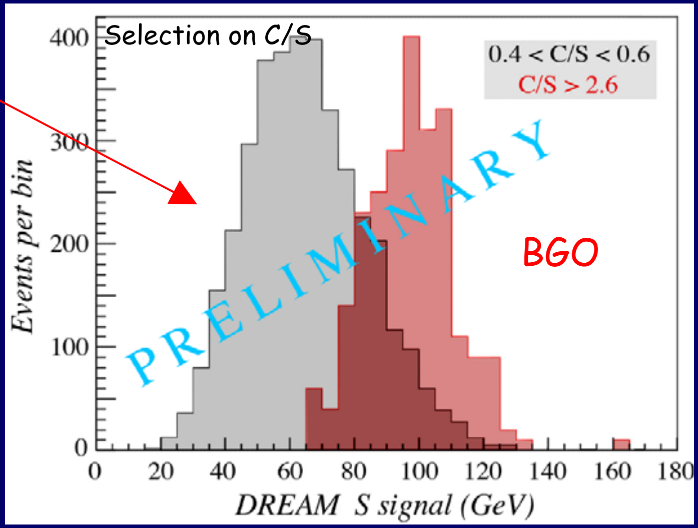
Preliminary BGO + DREAM

- A single-crystal ECAL was obtained by carefully aligning the BGO crystal with the beam axis. This crystal was positioned in front of DREAM, acting as an HCAL. Beam was 200 GeV π^+

- We found a very clear separation of the total calorimeter signal by selecting two intervals of C/S (measured in BGO), enhanced with respect to what was obtained with the $PbWO_4$ matrix

- On the basis of this promising result we are now planning to perform the same measurement on a new ECAL made of a matrix of BGO crystal, positioned in front of DREAM acting as an HCAL





Conclusions and Outlook

- Separation of Cerenkov and scintillation components in homogeneous materials is possible
- The application of the Dual-Readout method on electromagnetic calorimeters can be used to improve the global ECAL+HCAL performance to electron and pion showers
- Other homogeneous materials like BGO have been tested to improve Cerenkov/scintillator separation in a homogeneous material, and preliminary results are very promising
- 2008 DREAM beam test program foreseen the construction and test of a BGO matrix acting as an ECAL, followed by DREAM acting as an HCAL