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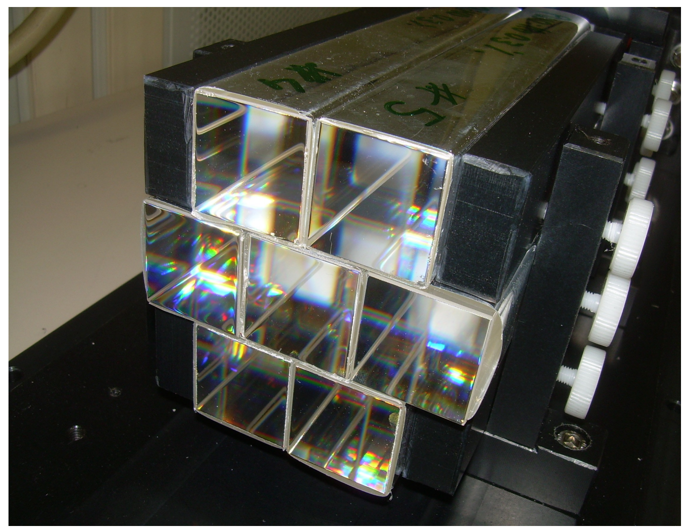
Workshop On Room-Temperature Semiconductor X-Ray And Gamma-Ray Detectors
23-29 October 2011, Valencia, Spain

Dual-Readout Calorimetry with a Mo-Doped $PbWO_4$ Electromagnetic Section



Silvia Franchino,

Università and INFN Pavia
On behalf of the DREAM collaboration
Cagliari- Cosenza - Iowa State - Pavia- Pisa - Roma1 - Texas Tech

Istituto Nazionale di Fisica Nucleare

Outline

- Introduction to Dual Readout Calorimetry
- Dual Readout with crystals
- Doping of $PbWO_4$ crystals
- Mo-doped $PbWO_4$ matrix results (test beams 2010, 2011)
  - Time spectra
  - Energy distributions
  - Energy resolutions
  - Linearity
- Conclusions

The Dual Readout Method

- Addresses the limiting factors of the resolution of hadron calorimetry with the aim of reaching the theoretical resolution limit (15%/√E)

- Performances of hadronic calorimeters limited by:
  - Different response to electromagnetic (em) and non electromagnetic (non-em) hadron shower components
  - Fluctuations on the em component

- The Dual-Readout technique is based on the simultaneous measurement, event by event, of
  - **Čerenkov light (C)** only produced by relativistic particles, dominated by em
  - **Scintillation (S)** a measure of dE/dx
  - **C/S** correlated to electromagnetic fraction of hadron shower (f_{em})

⬇

Measurement of the electromagnetic fraction (f_{em}) of the hadron shower on event-by-event basis

The Dual Readout Method

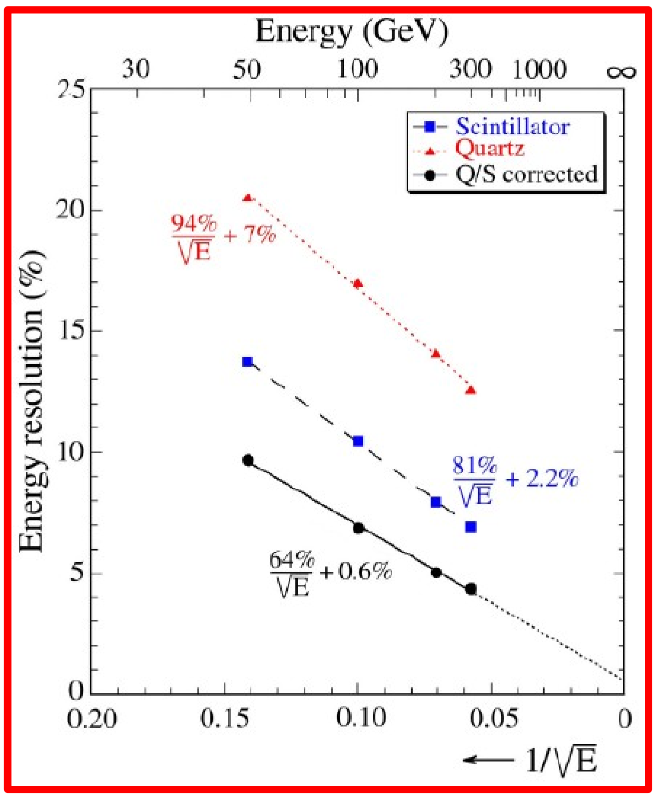
Response of each active media for hadronic showers:

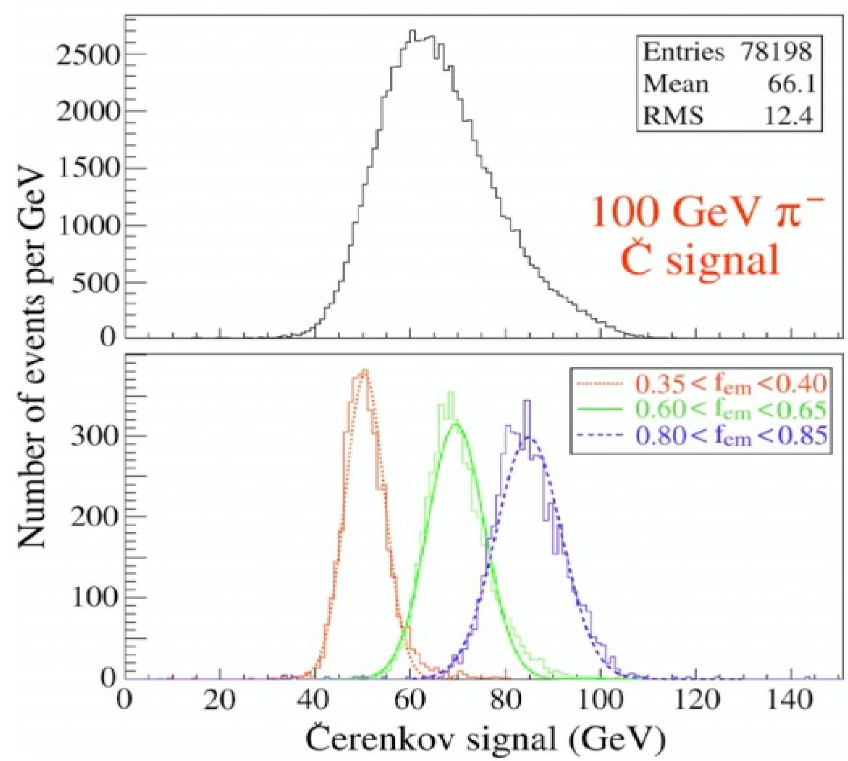
$$R(f_{em}) = f_{em} + \frac{1}{e/h}(1 - f_{em})$$

from the ratio of the signals in quartz (Q) and scintillating fibers (S)

$$\frac{Q}{S} = \frac{f_{em} + 0.21\,(1 - f_{em})}{f_{em} + 0.77\,(1 - f_{em})}$$

(0.21 and 0.77 are h/e for S and Q fibers)





f_{em} is measured event-by-event and energy is corrected

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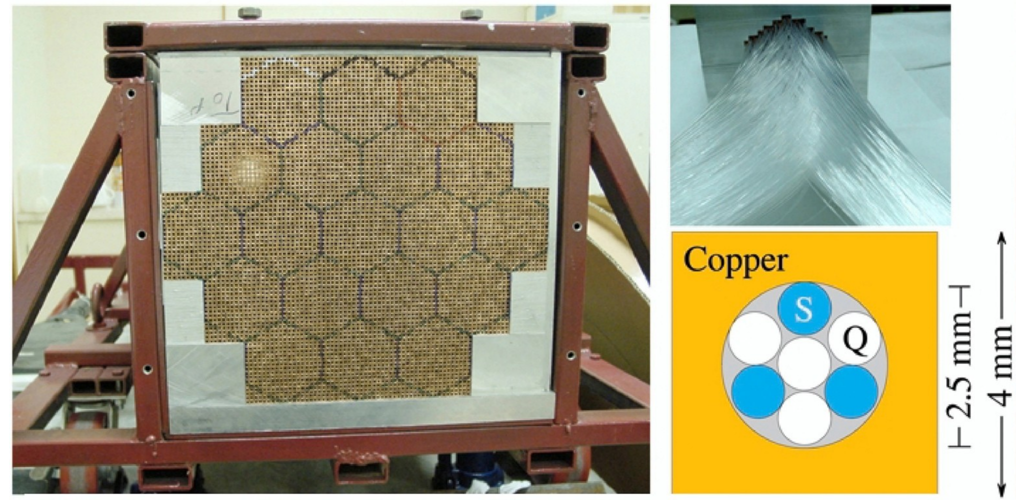
The DREAM project - Fibers

From 2003:

- tested the first DREAM prototype: copper embedded with two different types of fibers: quartz for Cherenkov and plastic for scintillation.
- 2m in depth (10 λ_{int}), radius ~16 cm
- C and S separated by construction
- 2.6% sampling fraction – > limited em resolution
- limited Cherenkov light yeld (8 p.e./GeV)



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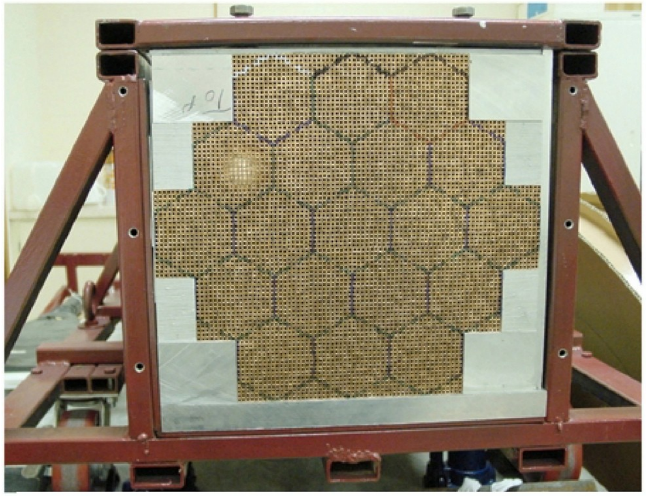
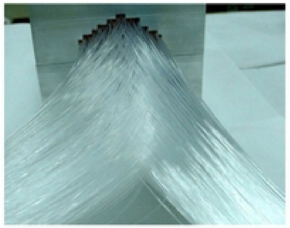
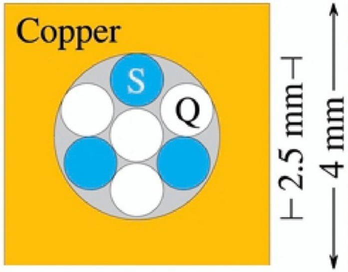
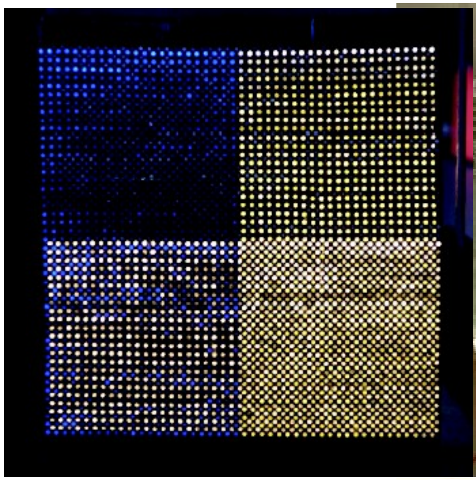






Future plans: NewDream

- **full containment detector** with
  - improved sampling fraction (5%)
  - improved sampling frequency (one fiber per each hole of passive material)
- two modules already built and tested in 2010 and 2011: Pb, 2.5m long, 92*92 mm^2.
- analysis and further construction is ongoing



The DREAM project - Crystals

- C and S separated with different techniques
- Optimal em resolution
- Increased Cherenkov light yield
- Eliminated sampling fluctuations
- Hybrid system operated with a dual-readout technique allows to overcome e/h difference between the two types of detector and therefore maintain a good hadronic resolution

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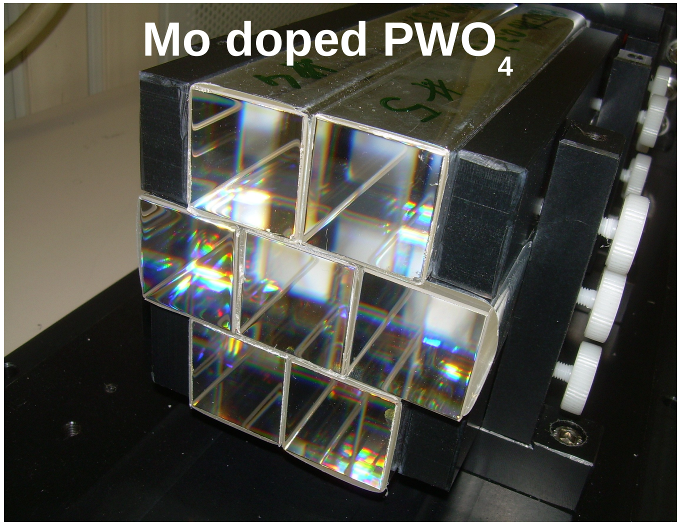
Crystals tested so far (since 2007):

- **$PbWO_4$** Single Crystal + Matrix
- **BGO** Single Crystal + Matrix See next talk D.Pinci
- **BSO** Single Crystal
- **Doped $PbWO_4$** with different % of Pr and Mo
- **Mo-doped $PbWO_4$ matrix** See next slides



Dual readout with crystals

Since 2007 extensive studies were performed at the H4 and H8 of SPS to extend the Dual Readout technique to crystals

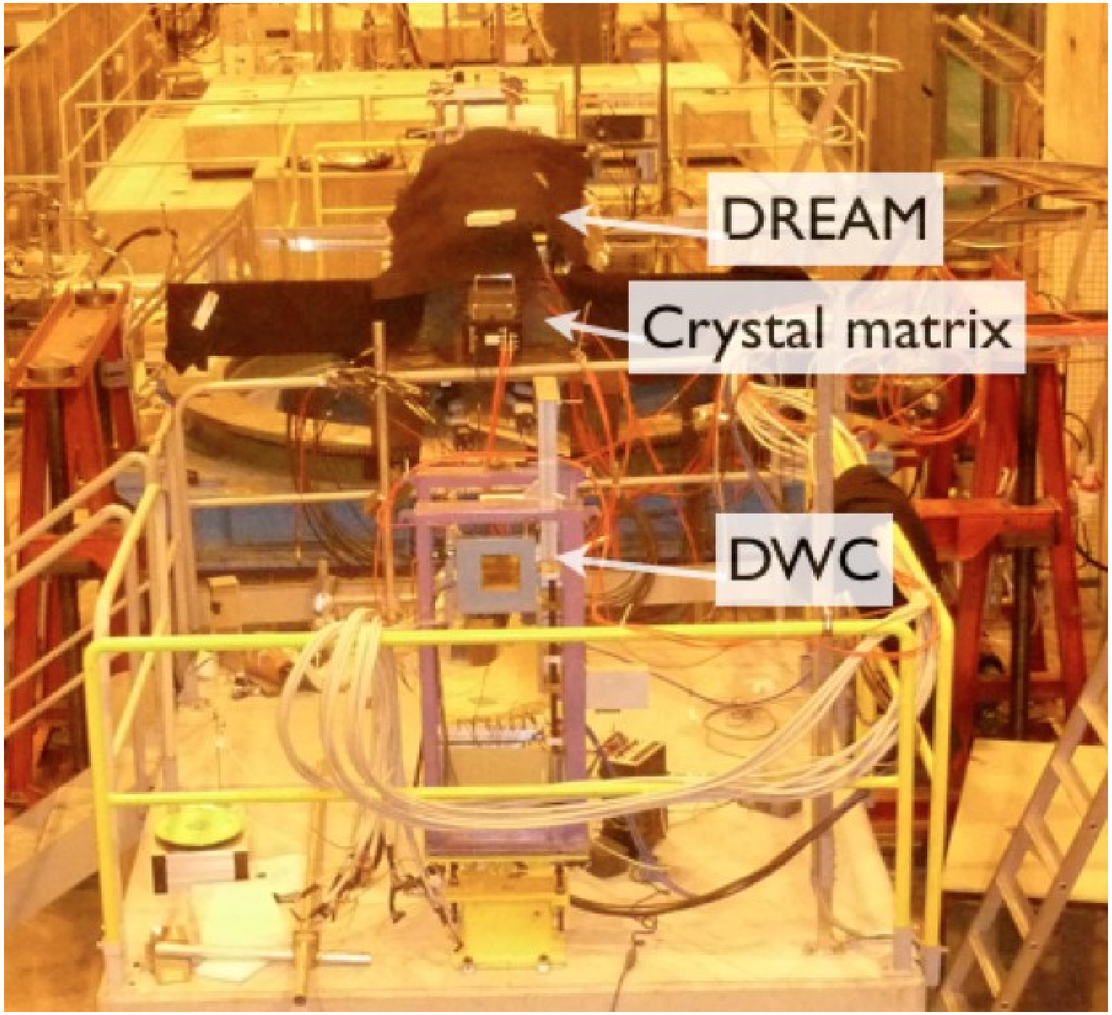
$PbWO_4$
NIM A582 (2007)
NIM A584 (2008)
NIM A593 (2008)

BGO
NIM A598 (2009)
NIM A598 (2009)
NIM A 610 (2009)

Pr, Mo doped $PbWO_4$
NIM A604 (2009)
NIM A621 (2010)

BGO-BSO comparison
NIM A640 (2011)

Polarization
NIM A 638 (2011)



DREAM with homogeneous materials?

4 ways to separate Scintillation from Cherenkov light :

1) Time structure of the signal

Signals read by fast electronic (DRS) and separated offline event by event.
C fast pulses, S long tail

	Cherenkov	Scintillation
Time response	Prompt	Exponential decay
Light Spectrum	$\propto 1/\lambda^2$	Peak
Directionality	Cone: $\cos\theta_c=1/\beta n$	Isotropic
Polarization	Polarized	Not polarized

2) Spectral difference

Crystal equipped with 2 different optical filters, high-pass frequencies for C, low pass for S

3) Directionality of Cherenkov light

(not reliable for 4π calorimeter, used just to prove the existence of C light in crystals). Crystal rotated wrt the beam and signals acquired in both ends

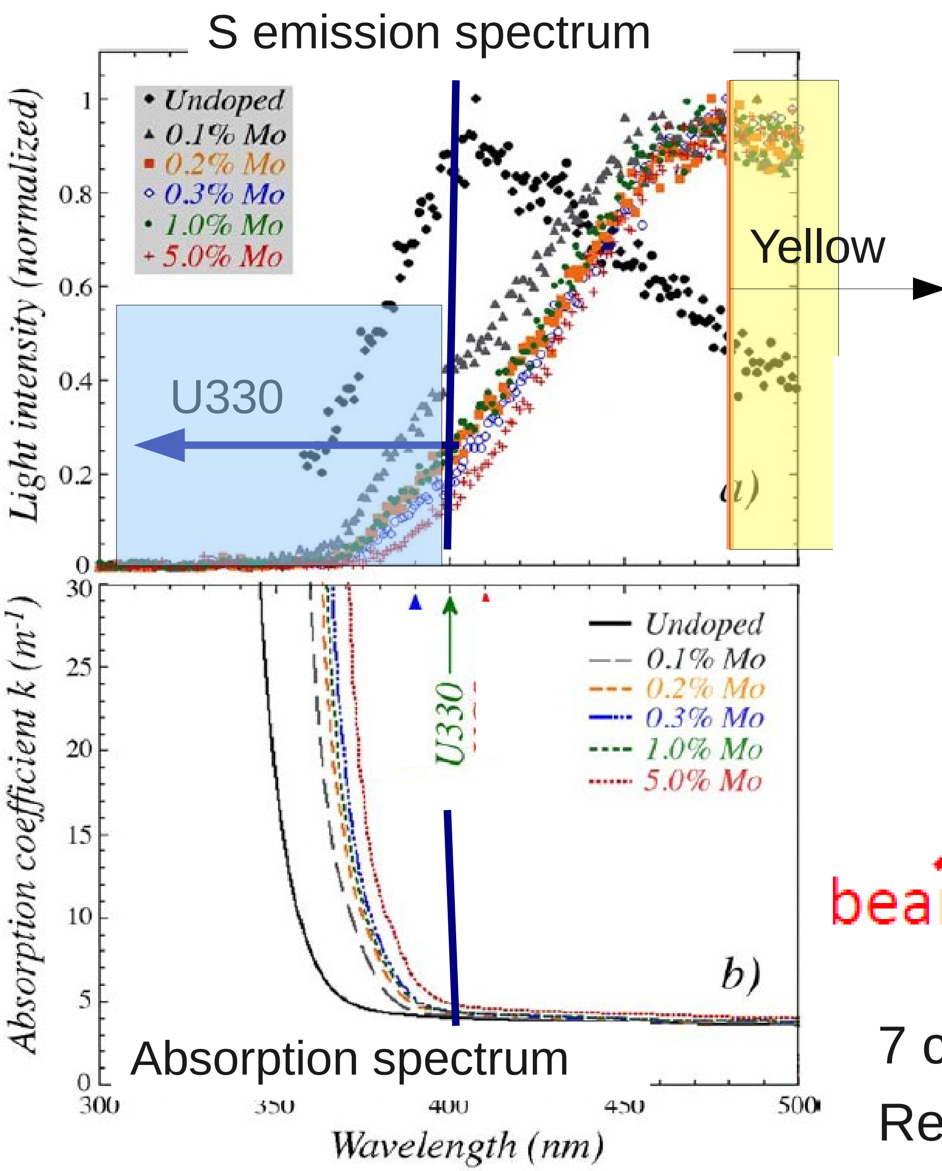
4) Polarization of Cherenkov light

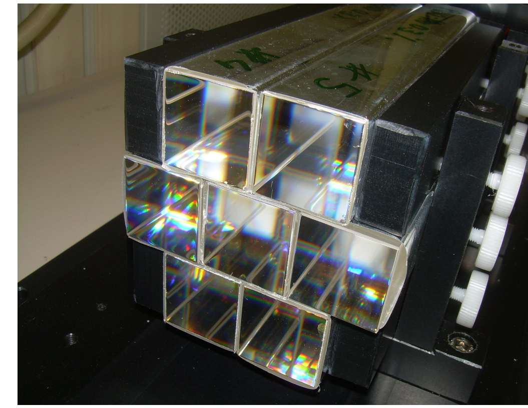
Crystals equipped with polarized filters

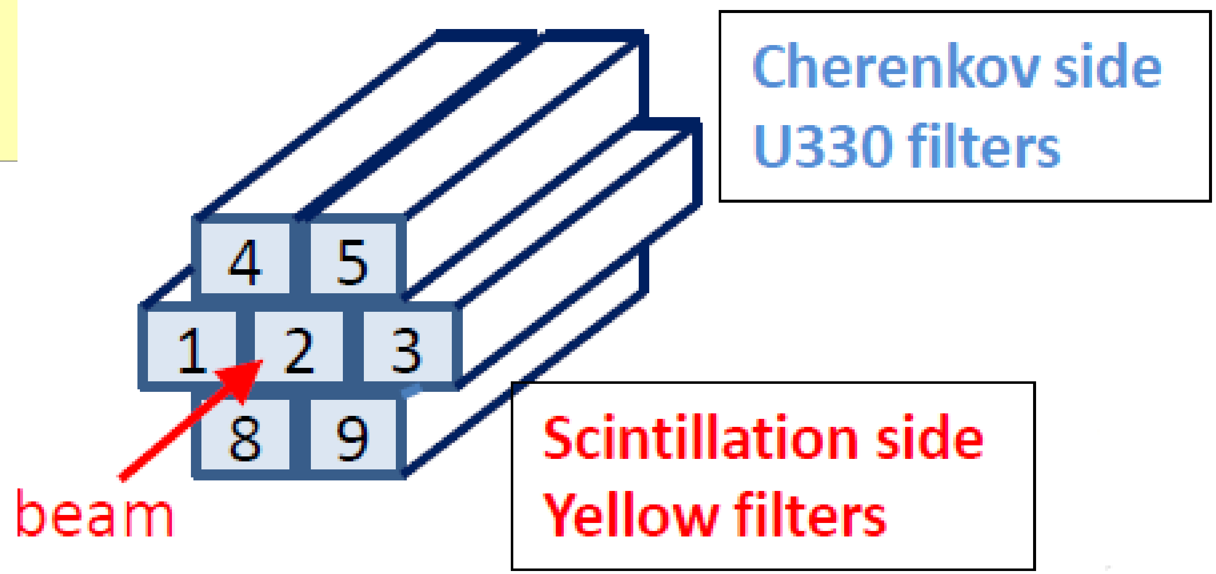
Time structure and spectral difference were used for the $PbWO_4$ matrix analysis

0.3% Mo-doped $PbWO_4$ crystal matrix

Matrix tested at the H8 SPS beam line in October 2010 and July 2011
(more tests foreseen for next week)







7 crystals 3*3*10 cm^3 (22.5 X_0, 1.1λ_{int}, 1.36ρ_M)

Readout with fast electronic Domino Ring Sampler

See tomorrow M.Cascella talk on DRS

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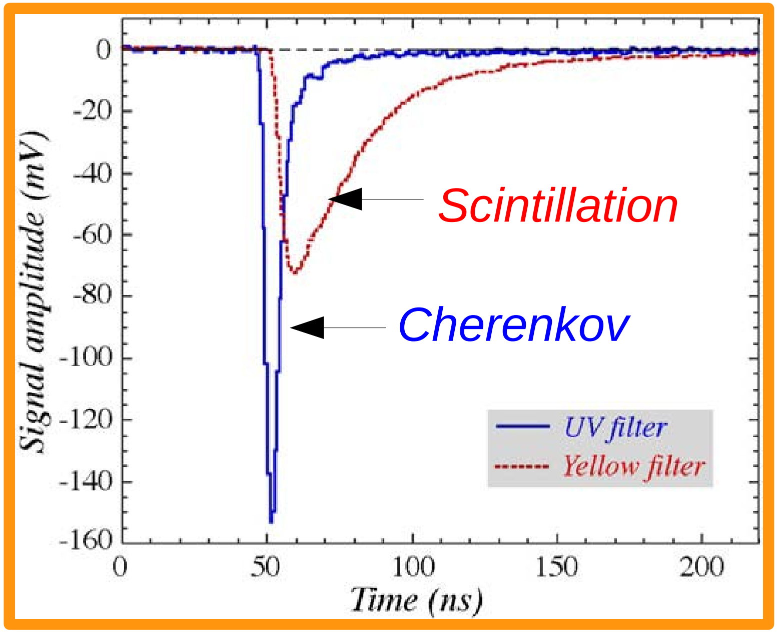
S and C distributions



Average time distribution from the DRS readout

good separation of C and S as results of UV and Yellow filters
(pulse shape of one crystal)

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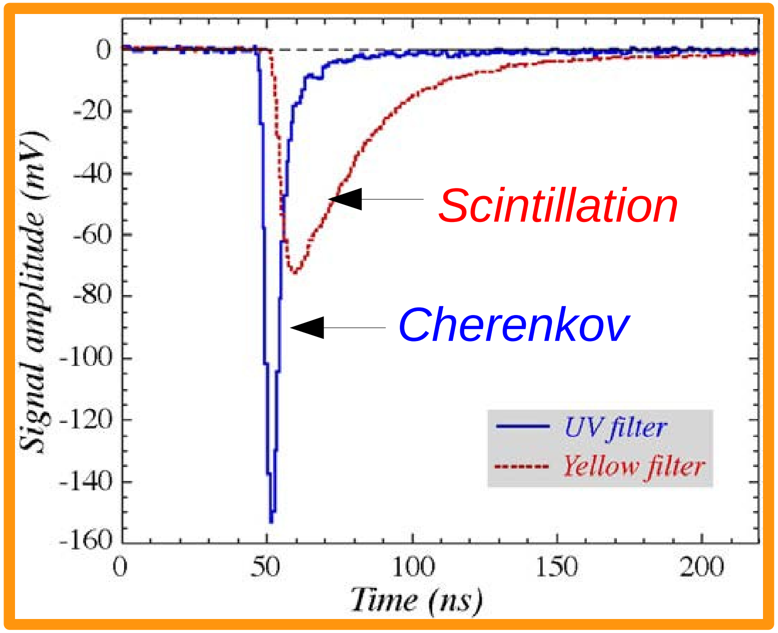
S and C distributions



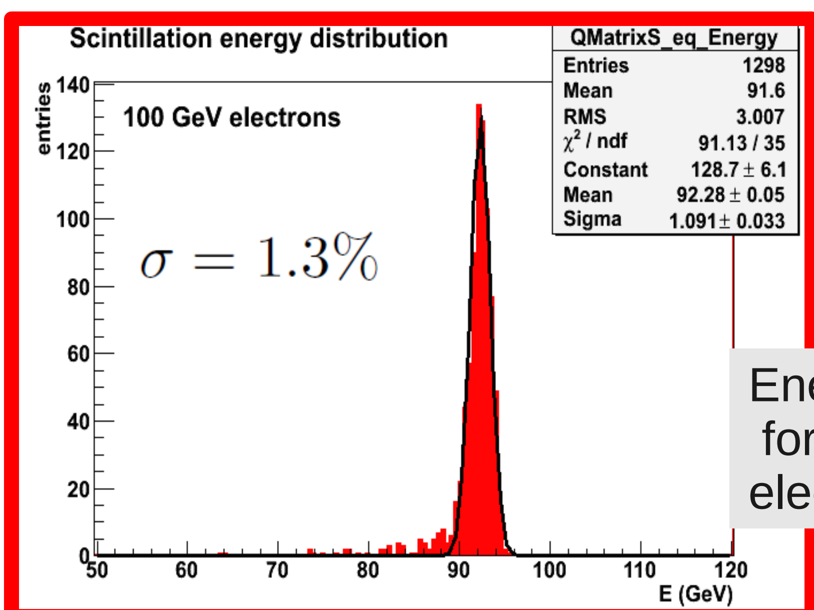
Average time distribution from the DRS readout

good separation of C and S as results of UV and Yellow filters

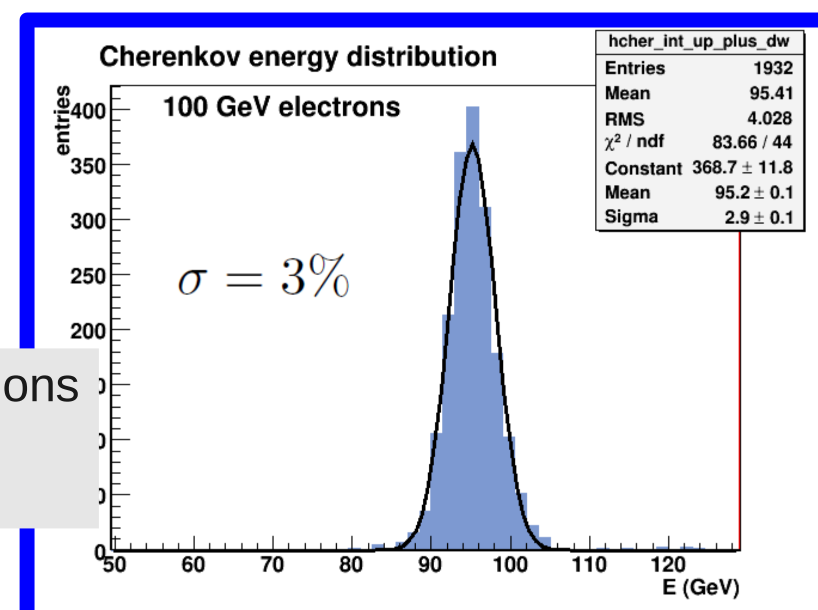
(pulse shape of one crystal)

Energy distributions: integral of the pulse shapes coming from different filters, event by event.

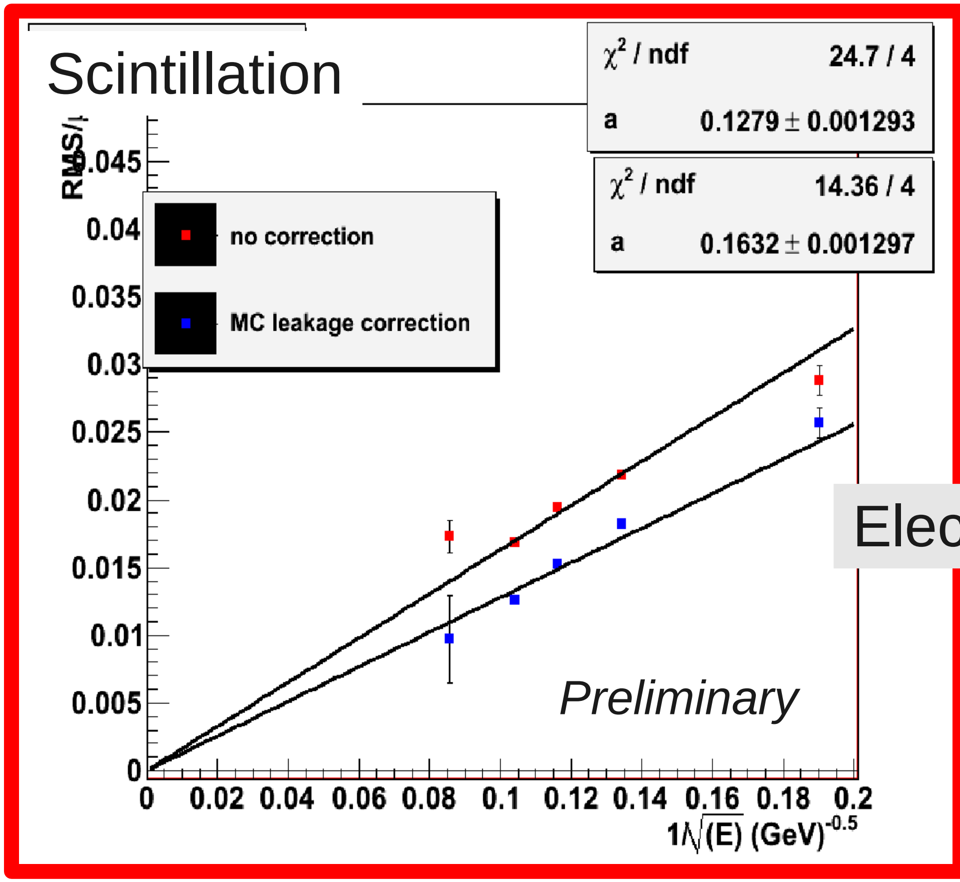
- sum over all the 7 crystals of the matrix
- C distribution is the sum of pulse shapes from both sides of the matrix equipped with UV filters (configuration tested in 2011)



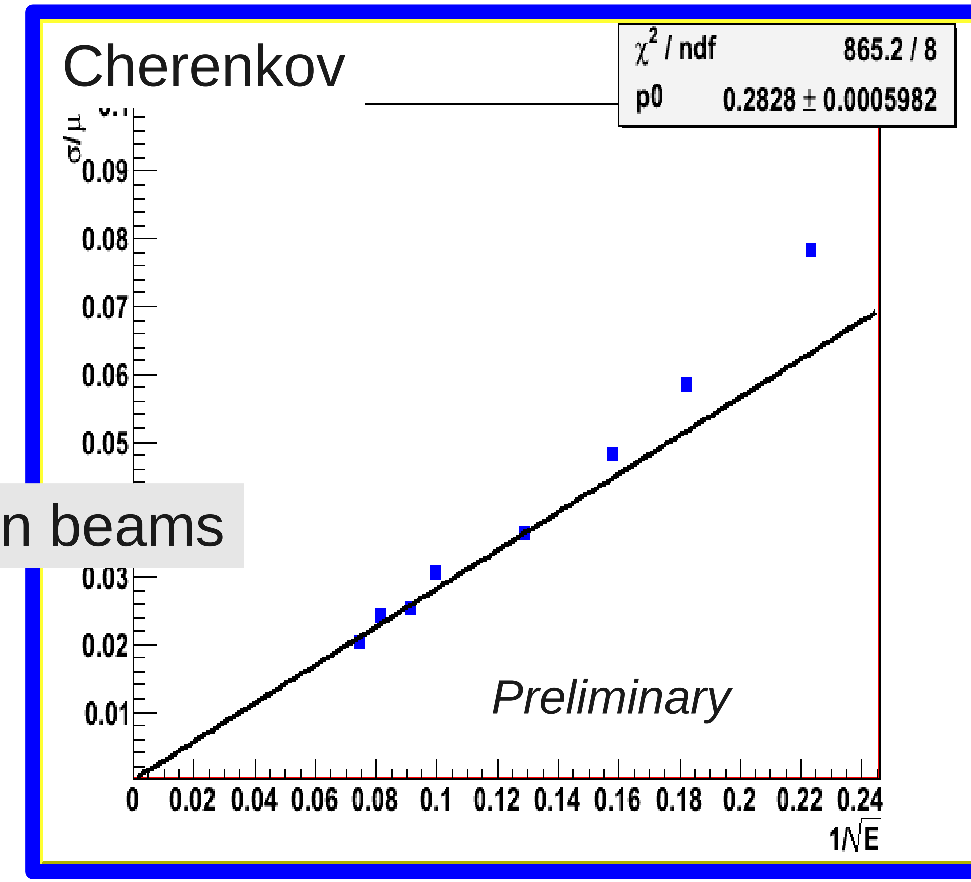
Energy distributions for 100 GeV electron beam



S and C energy resolution



Electron beams



Longitudinal leakage corrected through MC simulation

At low energies some discrepancy from linearity due to DRS baseline fluctuations (work in progress in order to understand them another test beam on next week)

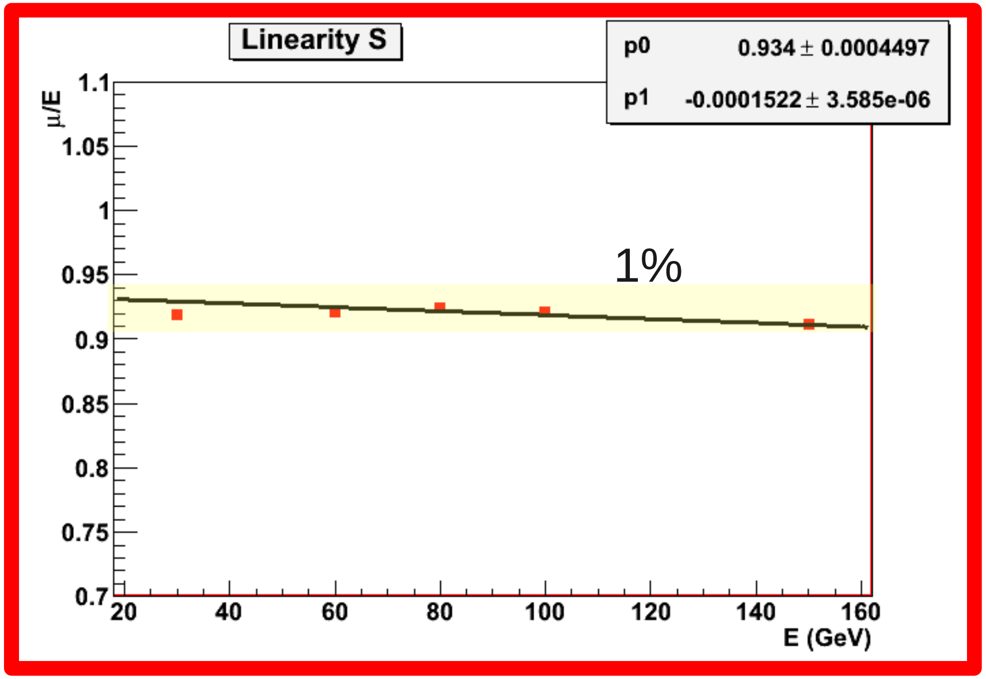
$$\frac{\sigma}{E}(S) = \frac{16.3\%}{\sqrt{E}}$$

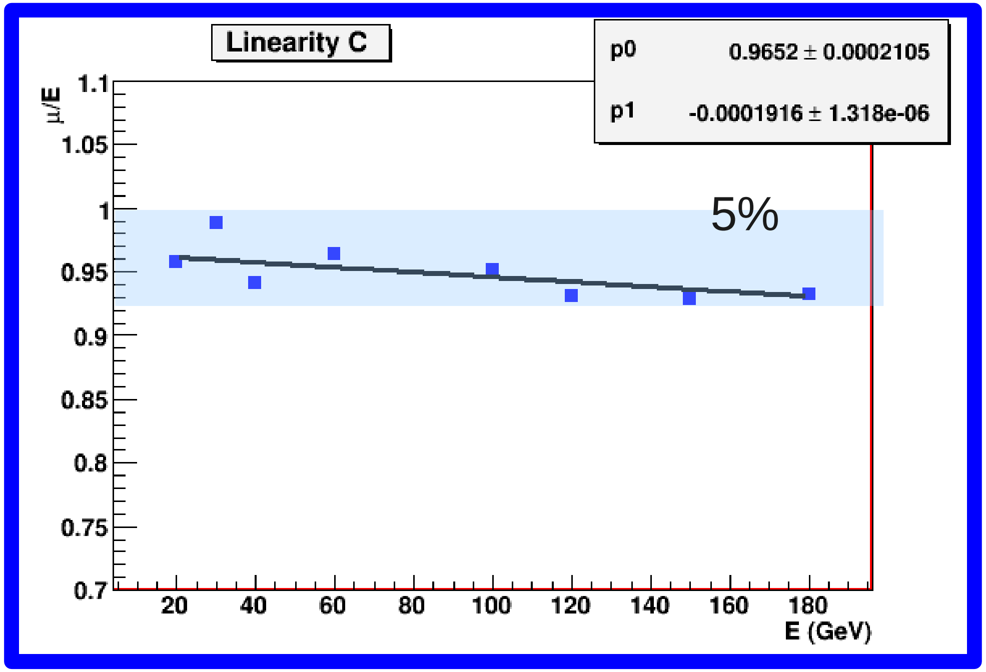
$$\frac{\sigma}{E}(Scorr) = \frac{12.8\%}{\sqrt{E}}$$

$$\frac{\sigma}{E}(C) = \frac{28.3\%}{\sqrt{E}}$$

S and C linearity

Signal response as a function of electron beam energy





Good S linearity (less than 1%)

5% linearity for Cherenkov.
Probably due to Intrinsic absorption of UV light
and DRS fluctuations

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Conclusions

- After tests of the first Dual Readout fiber calorimeter, the DREAM collaboration has extensively studied the Dual Readout in crystals.

- The separation of Cherenkov and Scintillation light can be achieved with several techniques based on the peculiar features of the Cherenkov radiation.

- The possibility to separate the Scintillation/Cherenkov components in crystals allows to extend the dual-readout also in e.m. crystals calorimeters.

- The tested matrix of 0.3% Mo-doped $PbWO_4$ crystal seems to be very promising and show good resolutions on both scintillation and Cherenkov lights
  - working in progress in data analysis
  - Another testbeam foreseen on next week, optimization of readout electronic

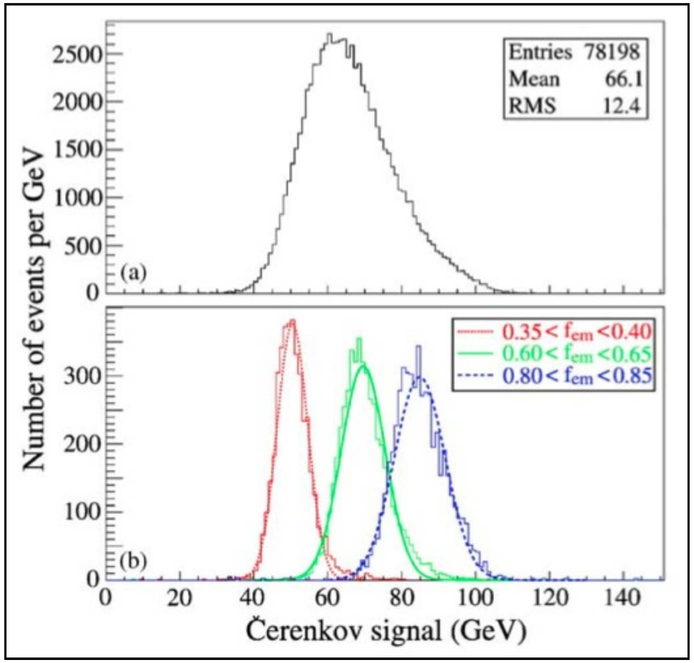
- Work on the extension of the dual readout to both e.m. and hadronic sections is in progress. Once the full containment fibre calorimeter will be ready, we will test it with the $PbWO_4$ matrix in front.

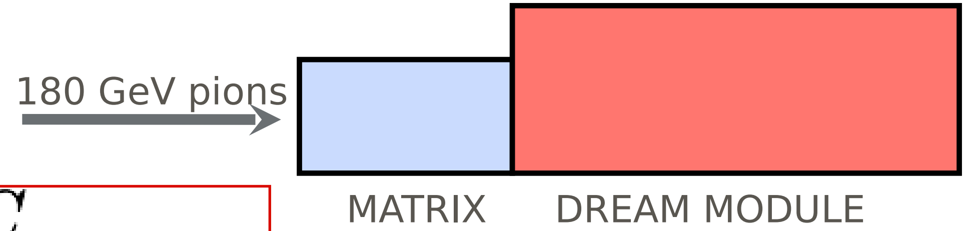
The end

BACKUP

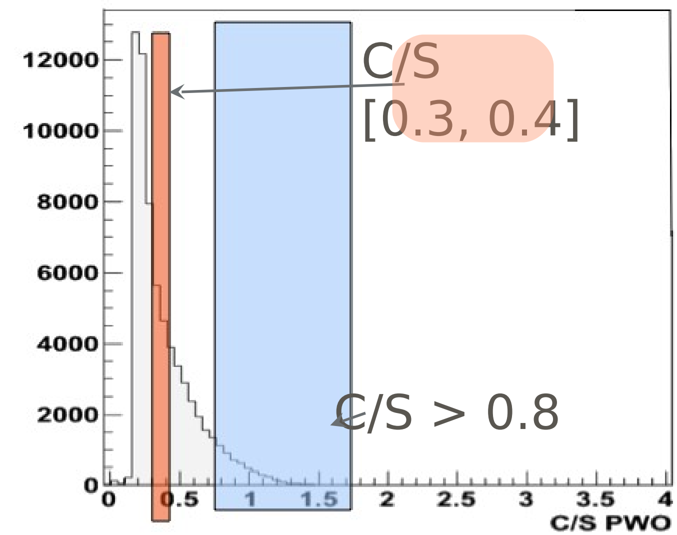
Preliminary results on the hybrid detector

Dual-readout method with DREAM in stand-alone mode



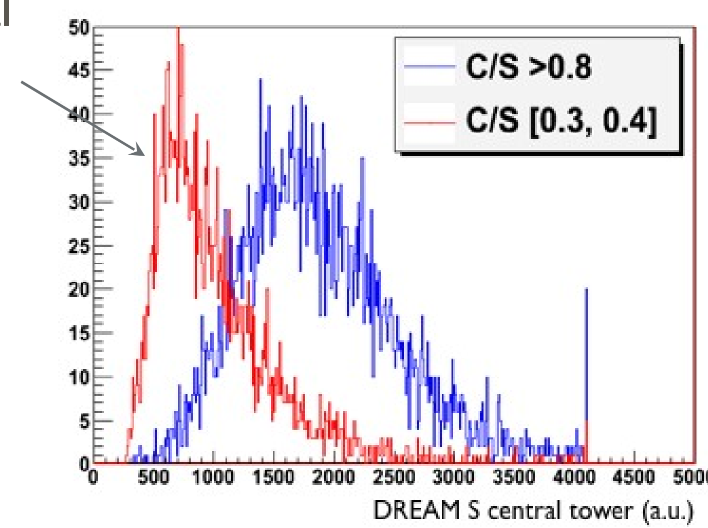


$$\frac{C}{S} \rightarrow f_{em}$$



selected two event samples with different C/S ratio in the central crystal of the matrix.

S signal in the central tower of DREAM.



As the C/S value increases, the average value of the subsample distribution of the S signal in DREAM increases.

➔ **The C/S of the crystal matrix is a good measurement of the em fraction.**

Why to dope $PbWO_4$ crystals?

BGO compared to $PbWO_4$:

Crystal	LightYield % NaI(Tl)	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	0.3	10	420	350	2.30	8.28

Disadvantages: Much brighter --> Cherenkov is a rare process --> C/S factor 100 smaller
Advantages: --> S spectrum peak at 480 nm --> allows the use of filters
--> S decay time 300 ns (very different from prompt C signal)

New Doped Crystals: to combine the advantages of BGO with the much higher C fraction of $PbWO_4$

GOALS

1) Move the scintillation wave length peak
in order to separate C and S through **emission spectrum**

2) Increase the decay time
in order to separate C and S through the **time structure**

We have tested $PbWO_4$ crystals doped with* **Molybdenum** (1%, 5%)

(*) Thanks to our crystal experts from Milano-Bicocca University (Italy) , Institute of Physics Prague (Czech Rep), Institute for Nuclear Problems Minsk Belarus

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