Dual readout calorimetry (2)

Simulation studies of total absorption calorimeter

Development of heavy crystals and fibres for scintillation and cherenkov readout

Dual readout in the 4th concept

Outlook

Simulation studies of total absorption calorimeter

Courtesy: Adam Para et al. (Fermilab USA, Lecce It)

Limitations to traditional Hadron Calorimeters

- **Lost energy for jets**:
  - A fluctuating fraction of the hadron energy is lost to overcome nuclear binding energy

- **Fluctuations in f_{em}, combined with $e/h \neq 1$**

- **Hadron calorimeters are sampling calorimeters**
  - Sampling fluctuations (fluctuation of the energy sharing between passive and active materials)
  - Sampling fraction depend on the particle type and momentum

One expects to overcome most of these limitations in a fully active calorimeter with dual readout

High Resolution Jet Calorimeter: how to…

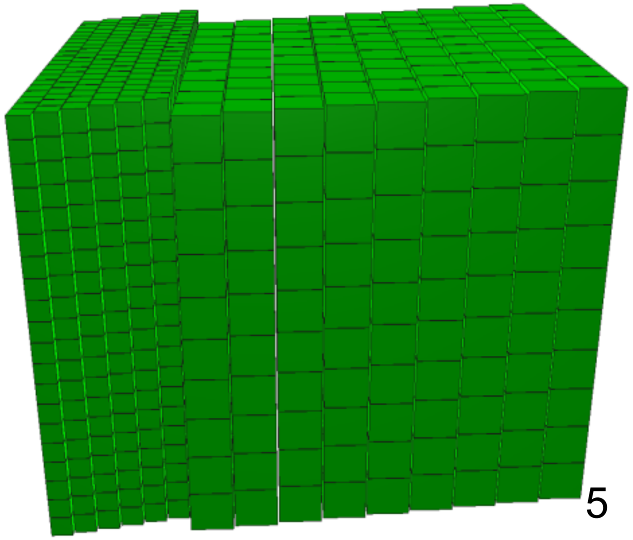
- **Homogeneous total absorption calorimeter** (SF = 1 for all particles and energies). This practically implies a light-collection based calorimeter.

- Correct on the shower-by-shower basis for f_{em} with $e/h \neq 1$ by **dual readout of Scintillation and Cherenkov light signals**.

- Need a calorimeter capable of performing required **topological measurements** for e/γ (position, direction, close showers separation)

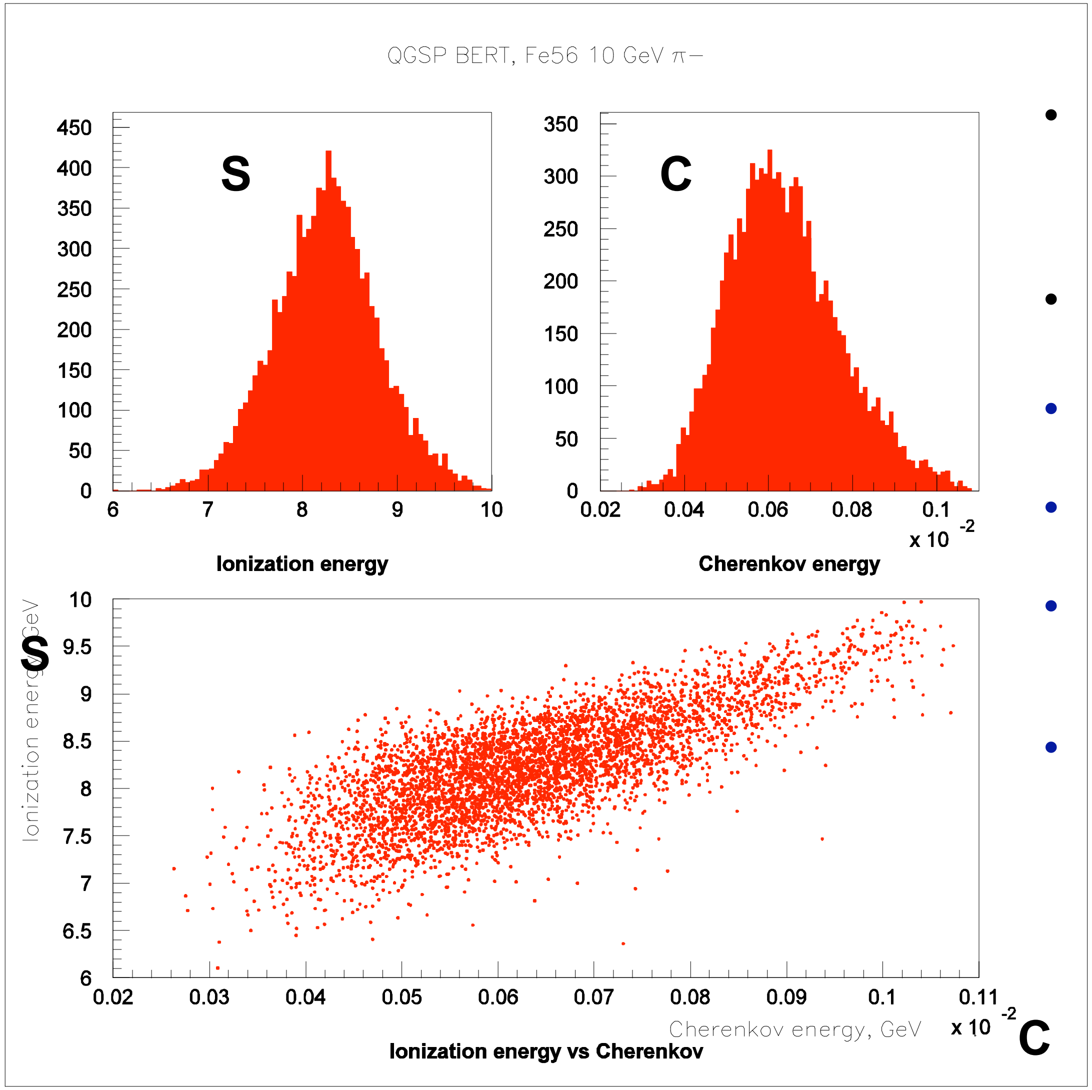
Proposed Design of a High Resolution Calorimeter

- Six layers of 5 x 5 x 5 cm^3 crystals (EM section): 108,000 crystals
- 3 embedded silicon pixel layers (e/γ position, direction)
- 9 layers of 10 x 10 x 10 cm^3 crystals (Hadronic section): 60,000 crystals
- 4 photodetectors per crystal. Half of the photodectors are 5x5 mm and have a low pass edge optical filters (Cherenkov)
  - No visible dead space.
  - Should not affect the energy resolution
  - 500,000 photodetectors
- Total volume of crystals ~ 80-100 m^3.



This type of detector was simulated
Full Geant4 + optical properties

Simulated raw data: example

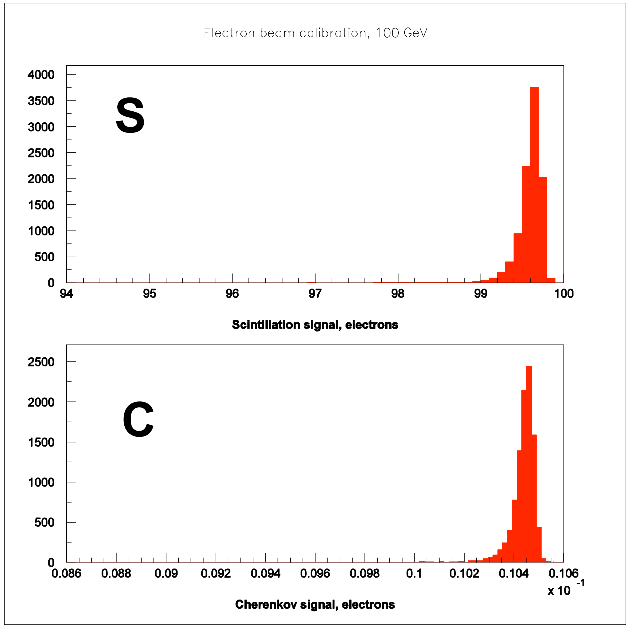


- Material: Fe56, n=1.65 (i.e. scintillating, transparent material with the absorption, radiation length and the nuclear properties of Fe56)
- 10 GeV negative pion beam

- Only ~80% of energy observed through ionization
- Cherenkov fluctuations much larger than the ionization
- Clear correlation of the total observed ionization and Cherenkov light
- Using the C-S correlation the energy resolution will be limited by the width of the scatter plot only

Step I: 100 GeV electron Beam Calibration ("test beam")

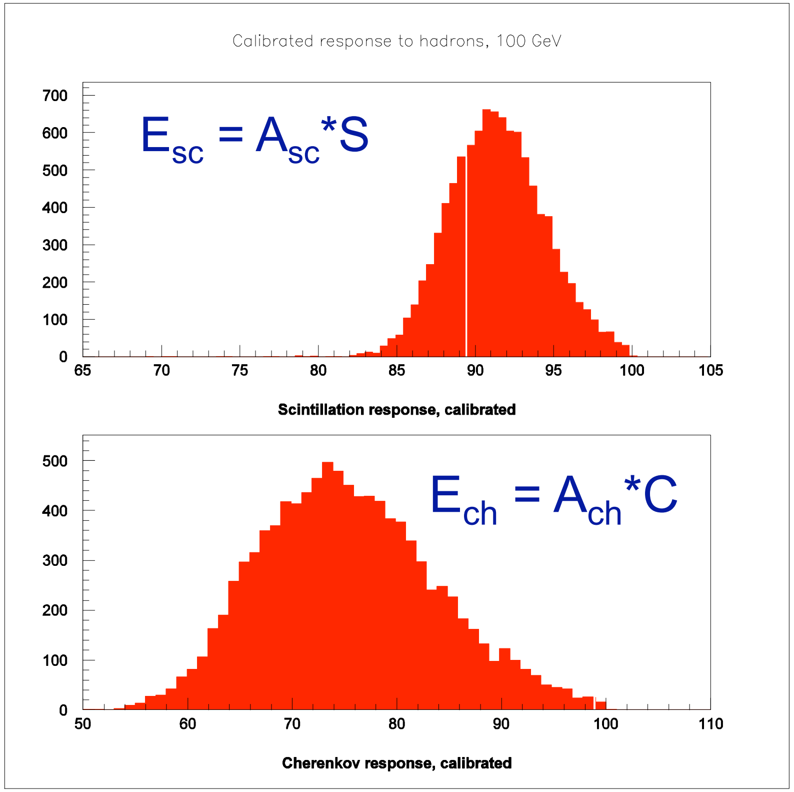
$E = A_{sc} \cdot S$ and $E = A_{ch} \cdot C$



pulseheight

- Collect the scintillation and Cherenkov light measured in some arbitrary units.
- Define the mean values of the distributions to correspond to 100 GeV (calibration beam energy)
- A_{sc}=100/<Scintillation>
- A_{ch}=100/<Cherenkov>

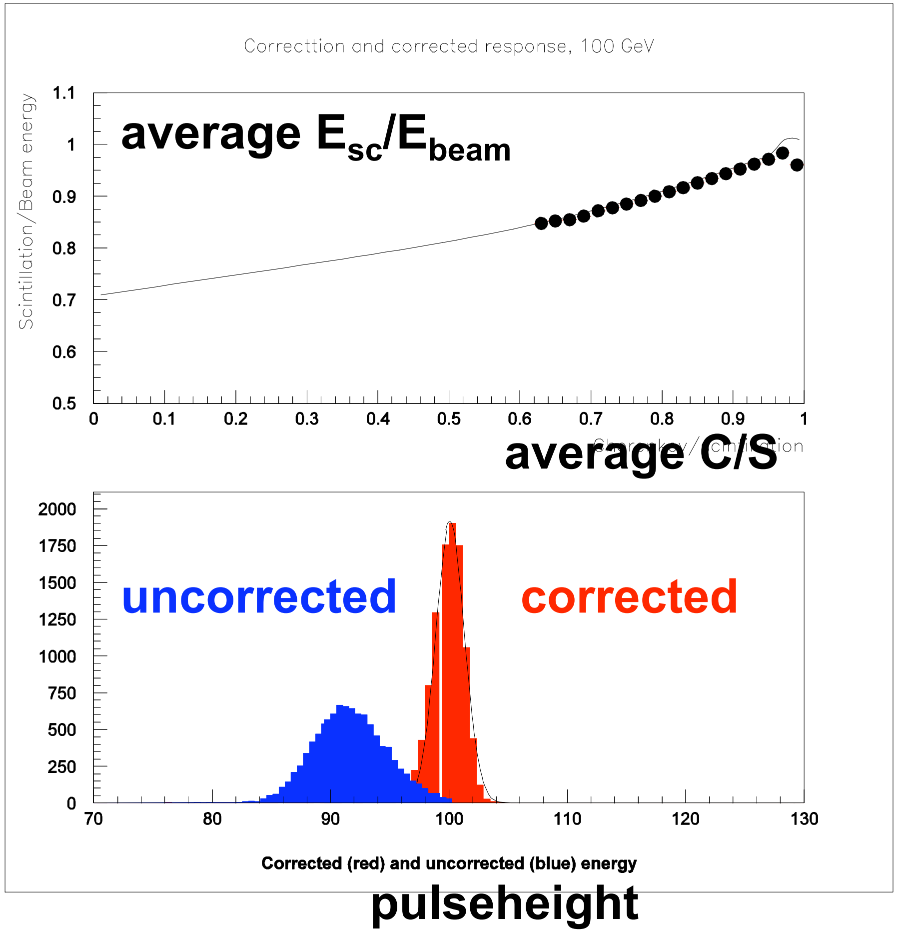
Step II:
simulate 100 GeV π- Beam



pulseheight

- Collect scintillation and Cherenkov light for 100 GeV π^- entering the detector
- Use absolute calibration determined with electrons
  - $E_{sc} = A_{sc}*S$
  - $E_{ch} = A_{ch}*C$

Step III: 100 GeV analysis

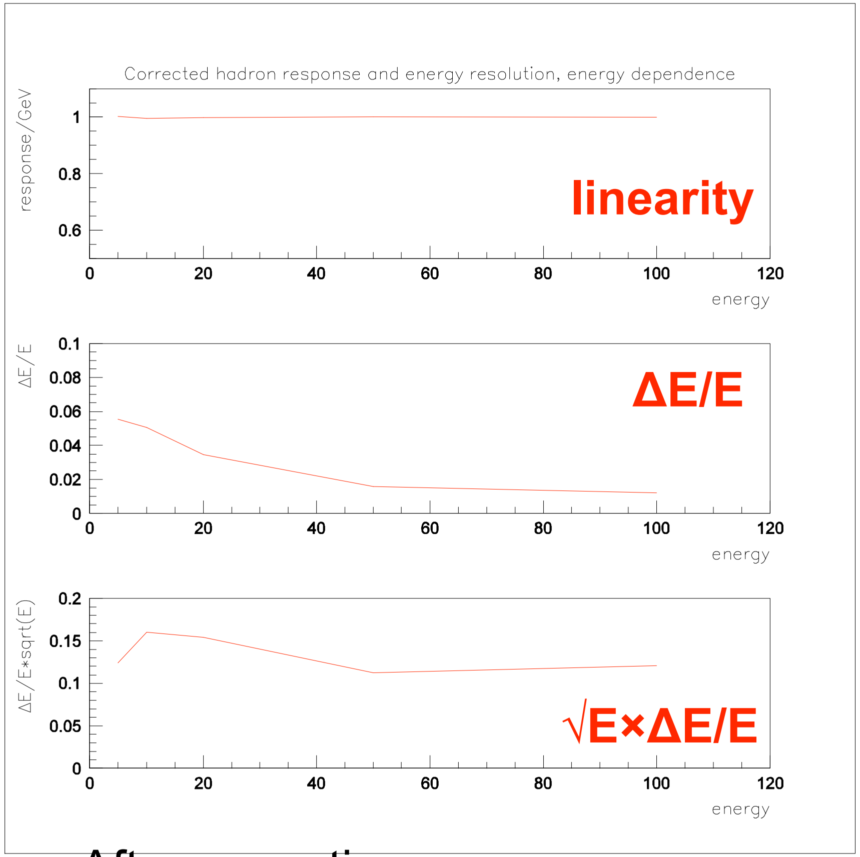


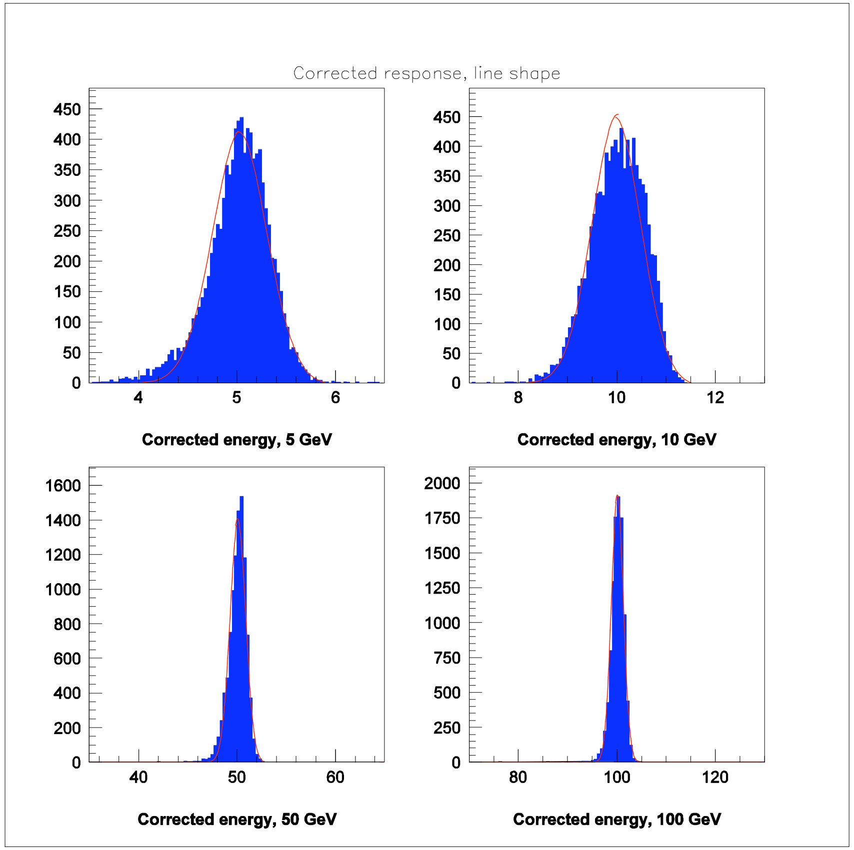
- Plot average S/E_{beam} as a function of C/S
- Fit some correction function *f*(C/S) (for example polynomial)
- Re-analyze the data:

$$E = A_{sc} * S/f(C/S)$$

- Observe:
  - Average corrected energy(red) ≈ Beam Energy (== $\pi/e \approx 1$)
  - Significantly improved resolution
  - Analysis does not require tuning or free parameters

Response and Resolution, Single Hadrons





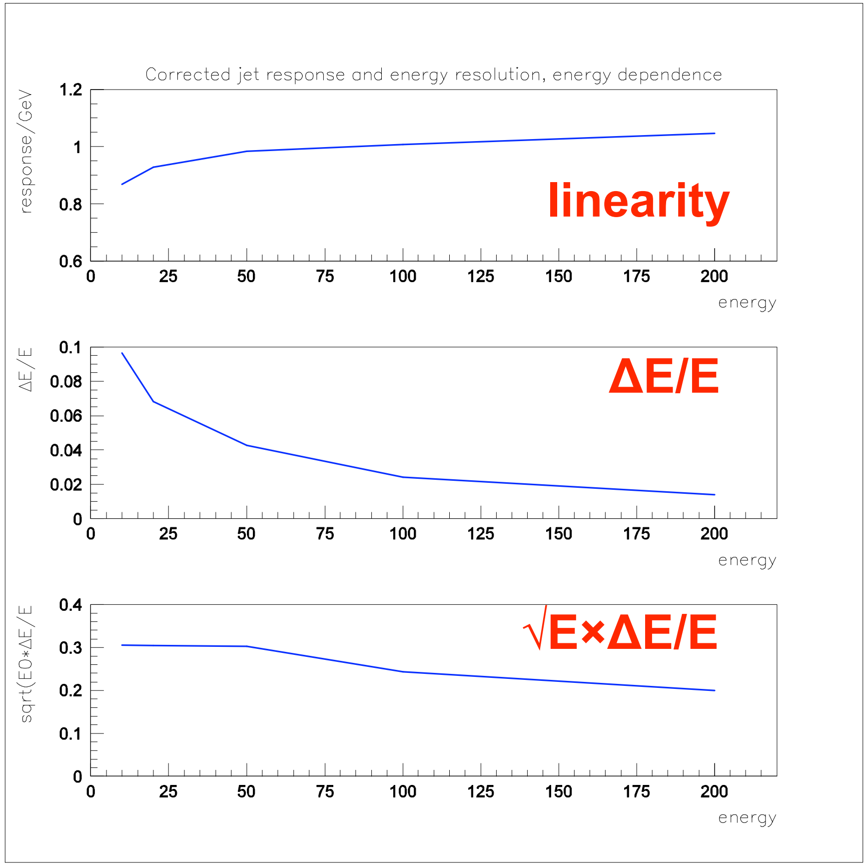
After correction:

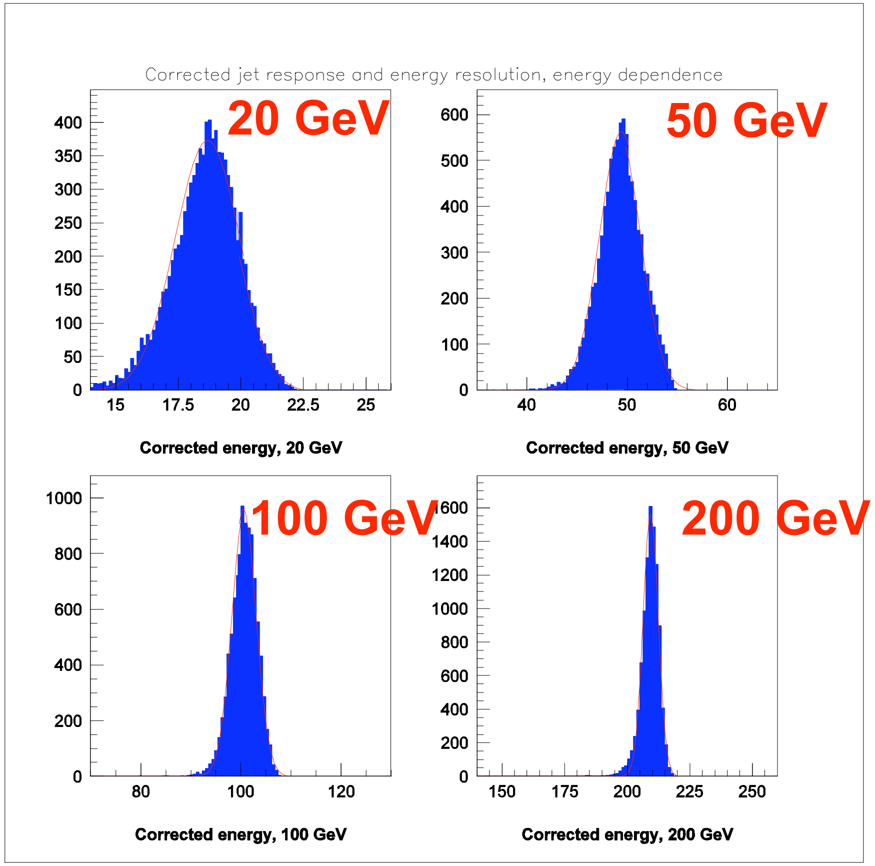
- good linearity of the corrected response
- good energy resolution ~ 0.12/√E
- no sign of a constant term up to 100 GeV
- Gaussian response function

Jets, Corrected Response

- Small non-linearity (~5%) for jets below 50 GeV
- Resolution <u>improves like 1/√E (or better)</u>
- ΔE/E ~ 0.22/√E

Gaussian response function.
No significant tails!





Lucie Linssen 23/7/2009

Conclusion of the simulation study

- Very high resolution jet calorimeters with the energy resolution of ~25%/sqrt(E) appears quite feasible with dual readout and fully active detectors
- Such a calorimeter requires development:
  - new heavy scintillating materials, which must be cheap
  - good photo-detector for scintillation and cherenkov light (cheap!)
  - full readout and engineering studies

This development represents a big challenge and will take several years.

Questions:

- How well can one measure? What are the systematic errors one can expect?
- Radial depth of the calorimeter
  - ~ at best density of 8 (kg/ℓ) for the crystal => at best ~6.6 for the HCAL
  - Compared to at best ~ 10.6 (kg/ℓ) for a W-Scint PFA-based HCAL

Measurements and development of heavy crystals for scintillation and cherenkov readout

DREAM with homogeneous materials?

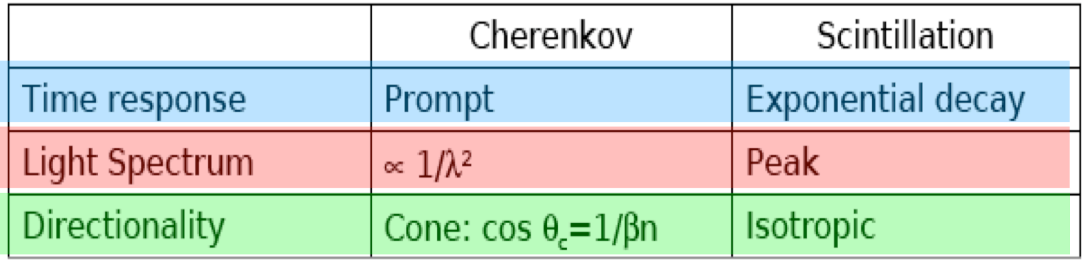
-->> Increase the number of Cherenkov photoelectrons

-->> Improve performances on em showers.

3 ways for ***Separation of Scintillation & Cherenkov light :***

- ***1) Time structure*** *of the signal*

  Signals read by fast electronic and separated offline event by event



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

- ***2) Spectral difference***

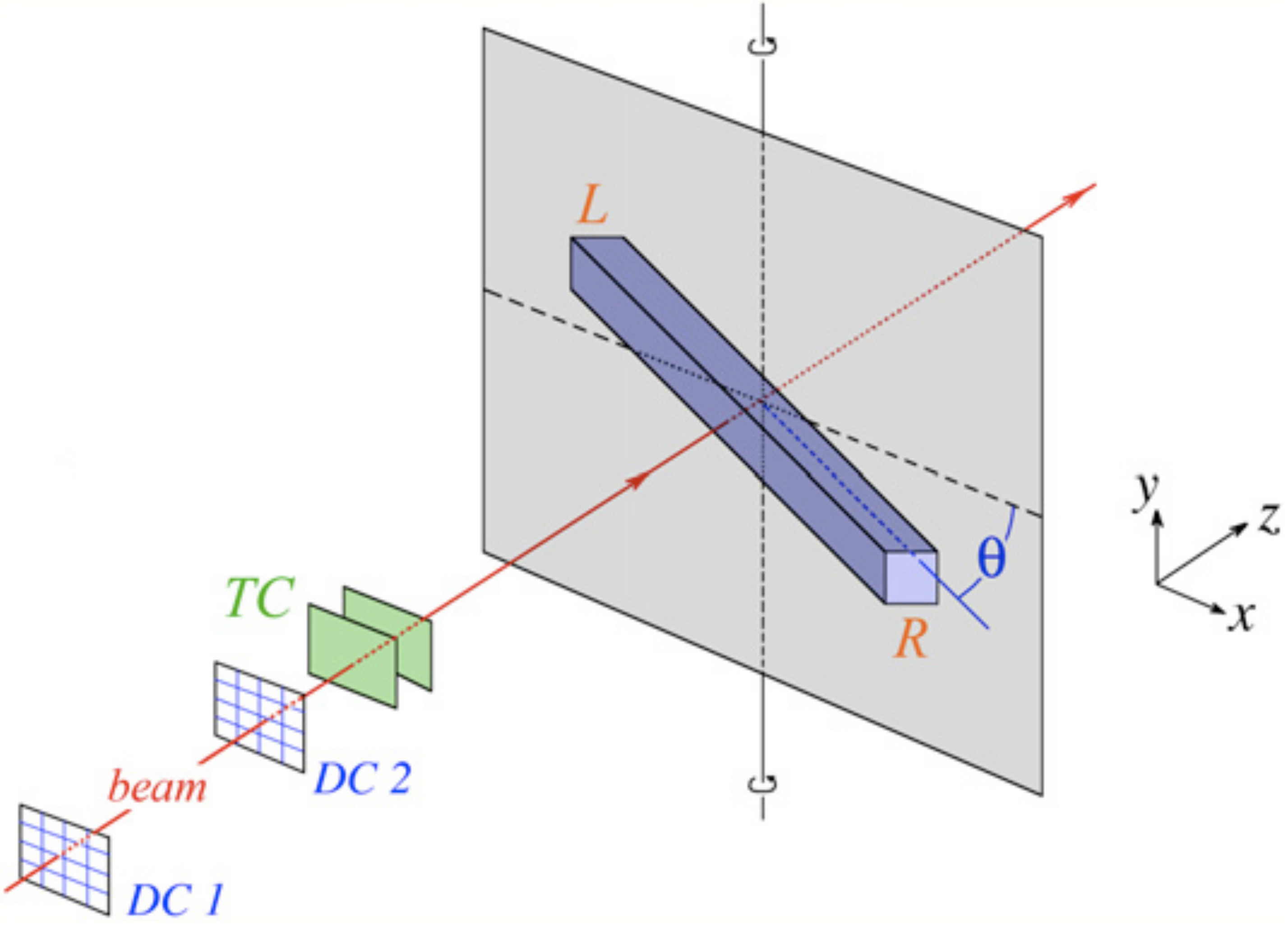
  Crystal equipped with 2 different optical filters, high-pass frequencies for Cherenkov, low pass for scintillation

- ***3) Directionality*** *of Cherenkov component*

  (not reliable for 4π calorimeter, used just to prove the existence of C light on the crystal)

  Crystal rotated wrt the beam and signals acquired in both ends

Courtesy: DREAM collab



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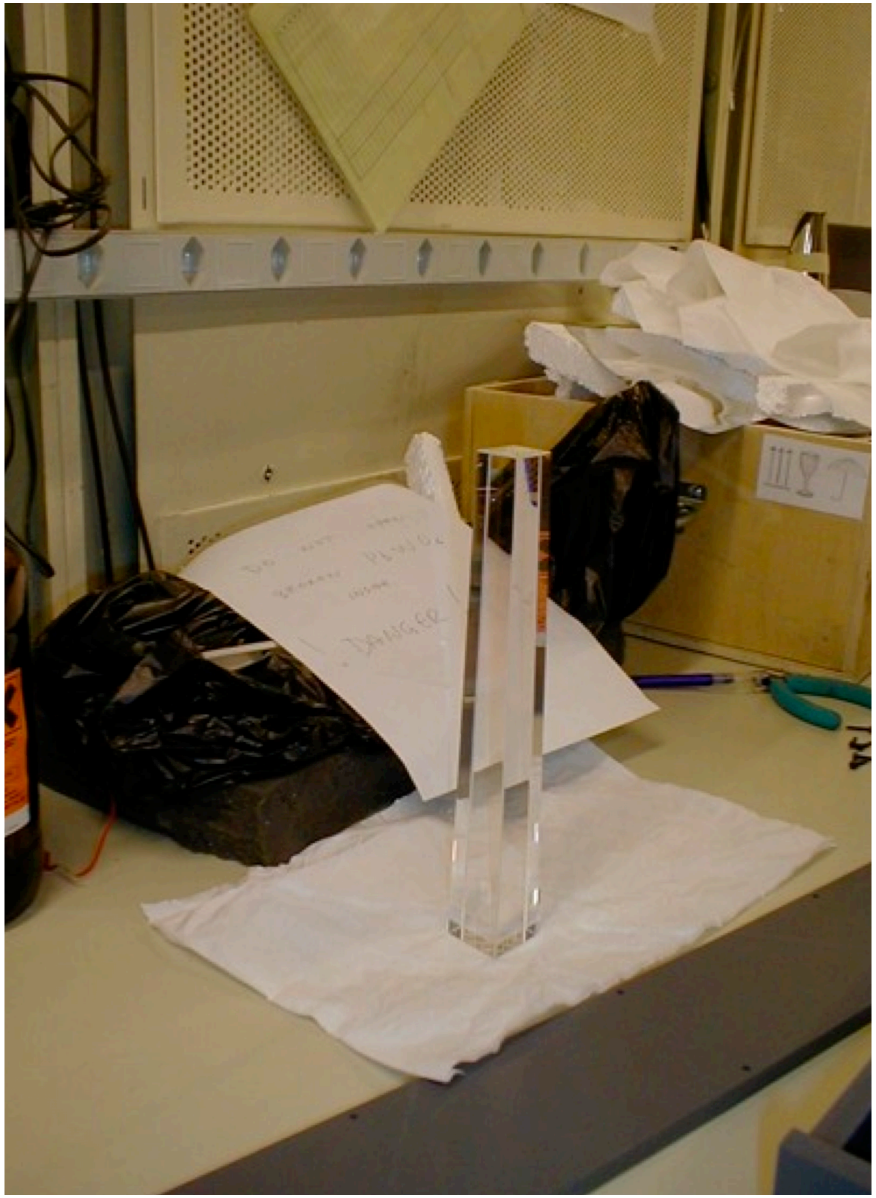
Dual readout of BGO and PBWO$_4$ crystals



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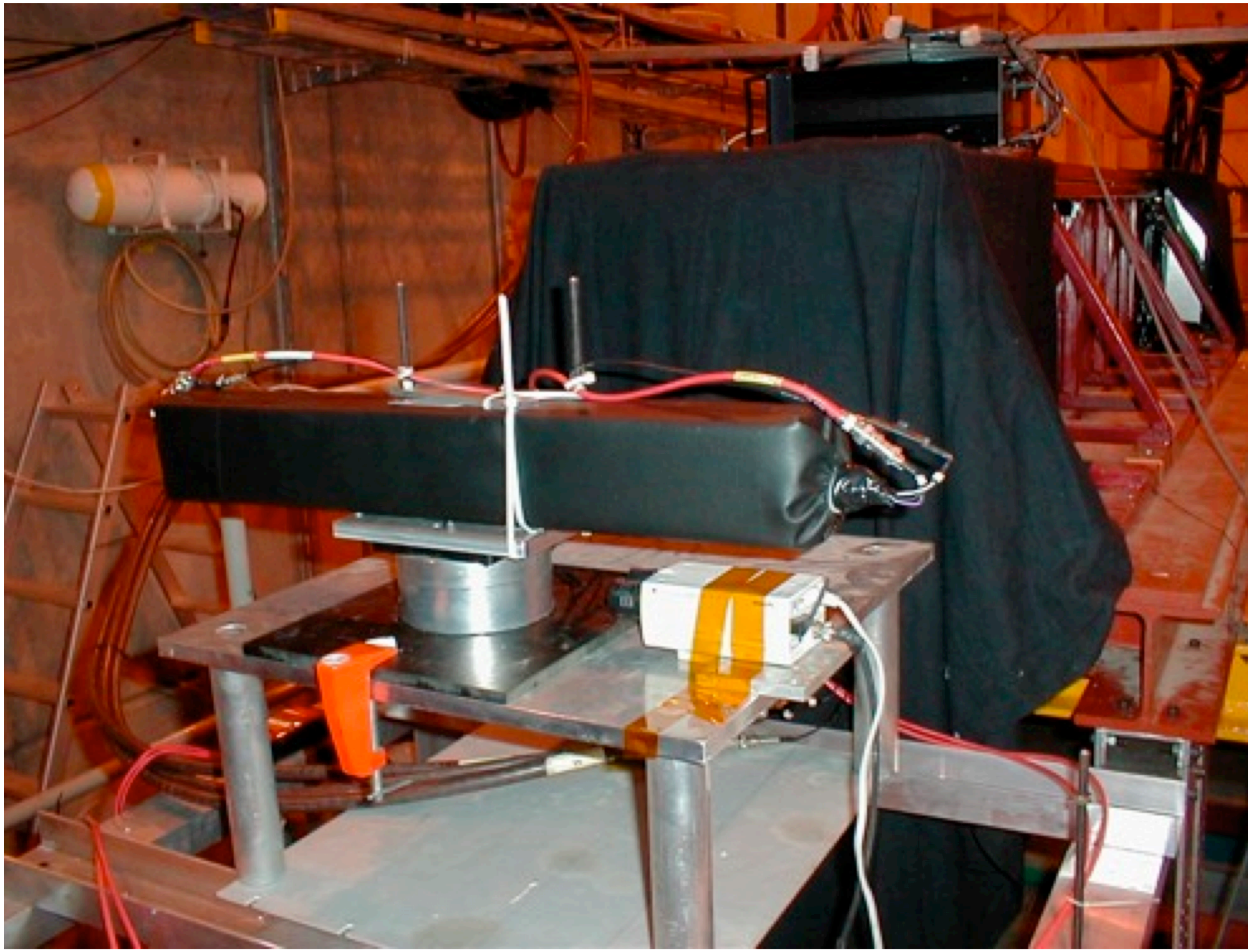
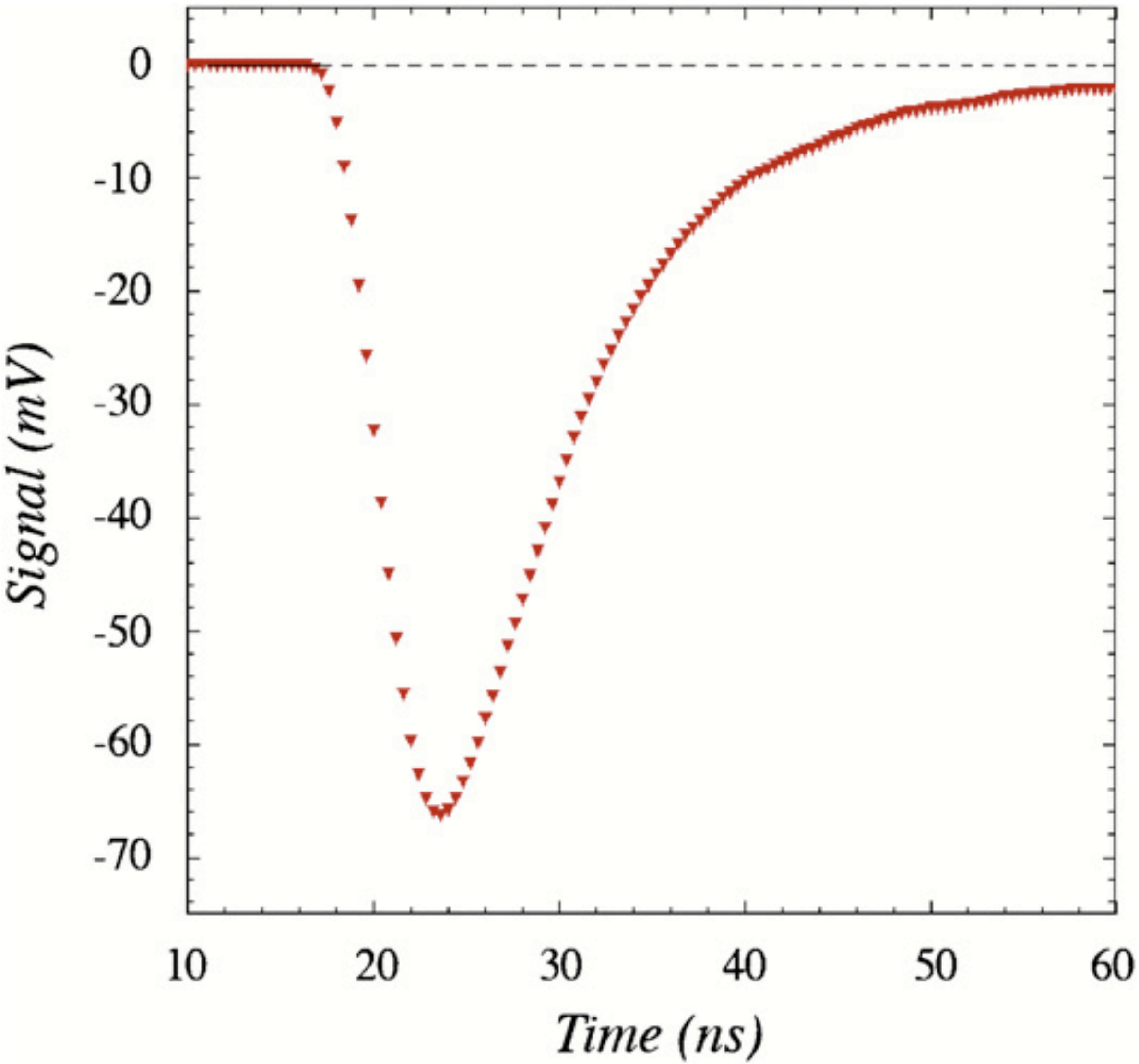
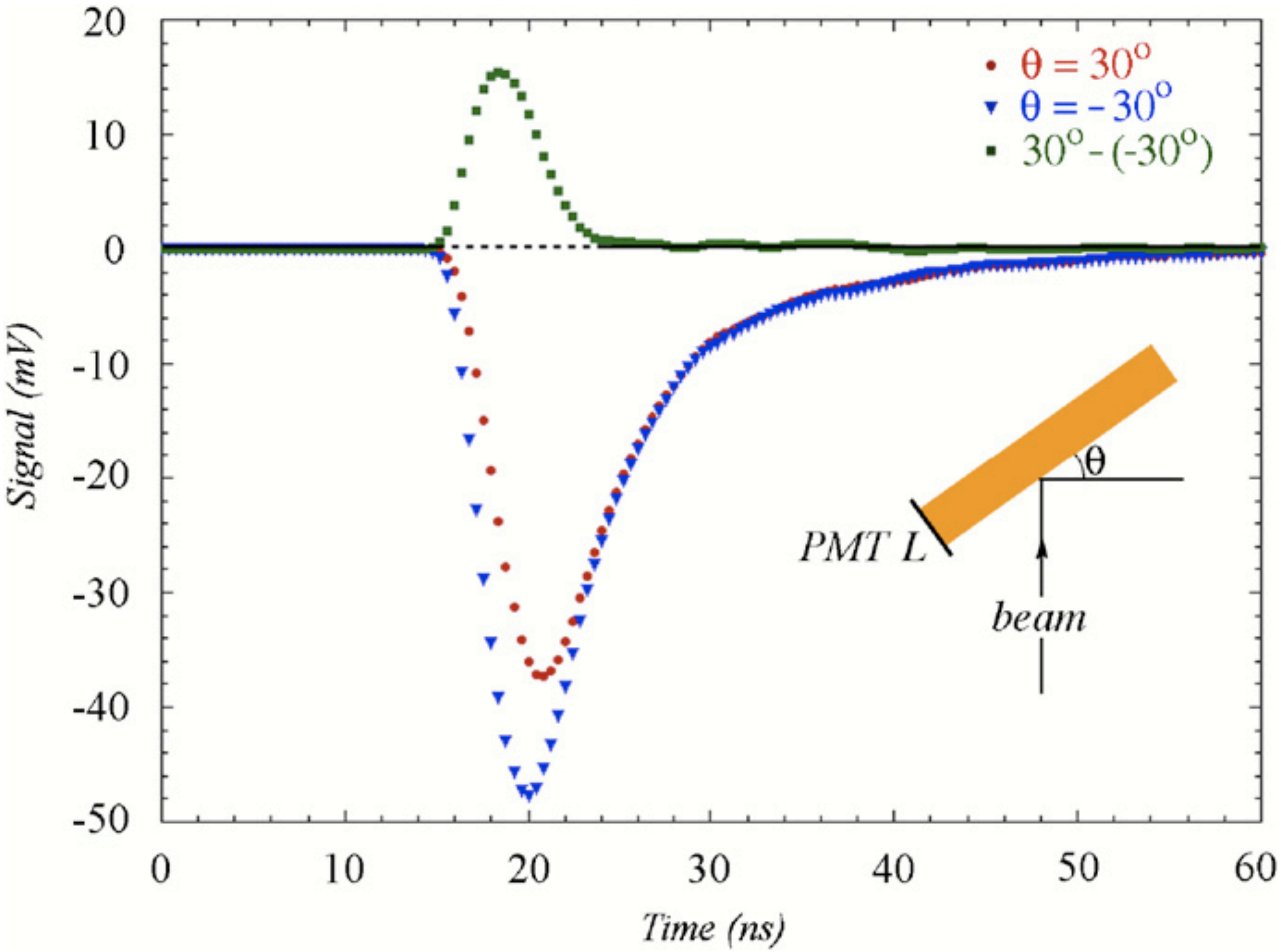
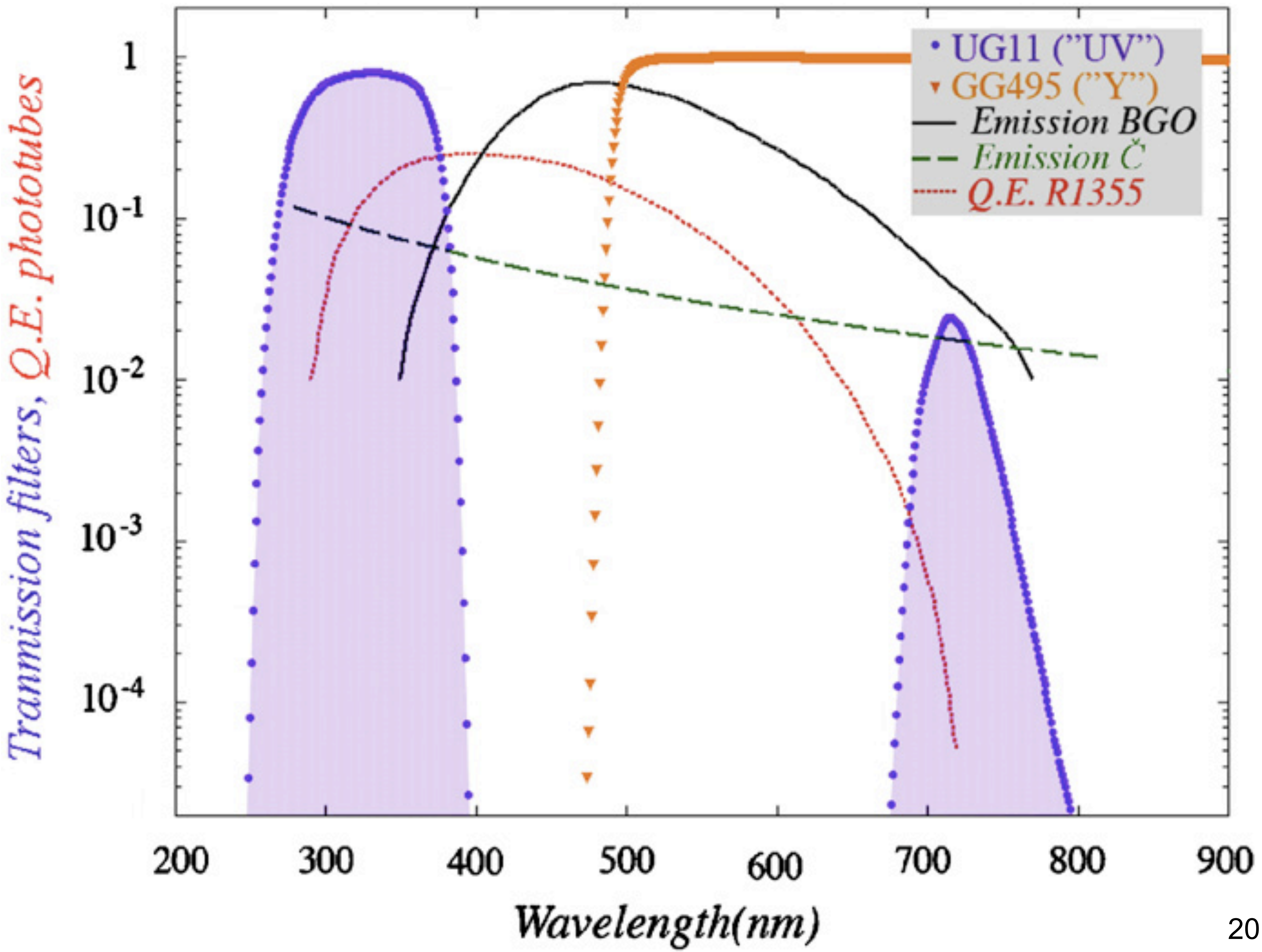


Average **time structure** of signals from 50 GeV electron showers in PbWO4 (lead-tungstenate) crystals (crystal orientation disfavours the detection of cherenkov light)



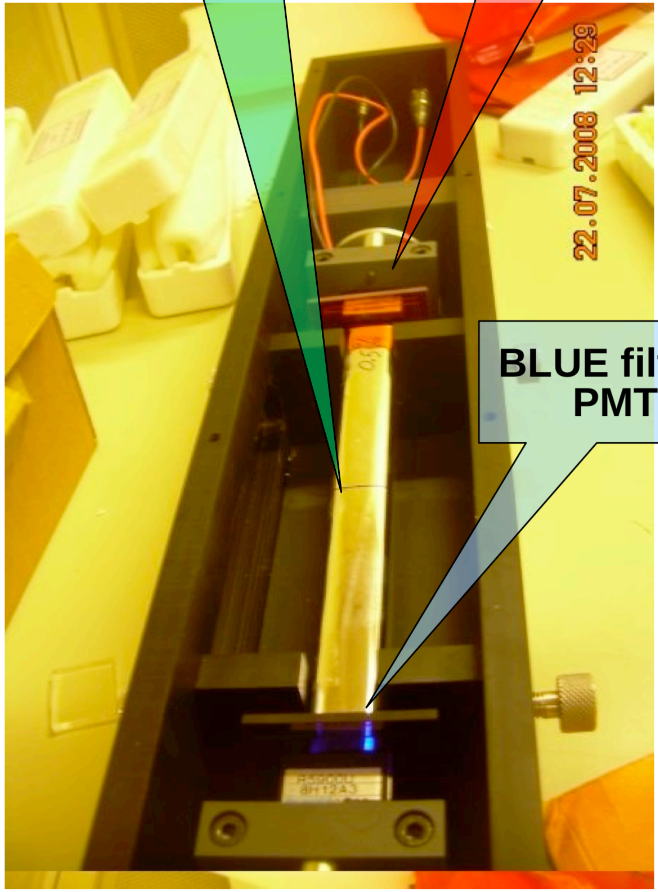
Time structure of signals from 50 GeV electron showers in PbWO4 (lead-tungstenate) crystals in Cherenkov-favoured and cherenkov-disfavoured orientation





• UG11 ("UV")
▾ GG495 ("Y")
Emission BGO
Emission Č
Q.E. R1355
Tranmission filters, Q.E. phototubes
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
200
300
400
500
600
700
800
900
Wavelength(nm)

2008 Test beam, single crystal

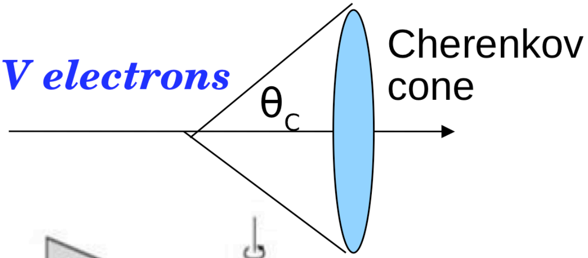


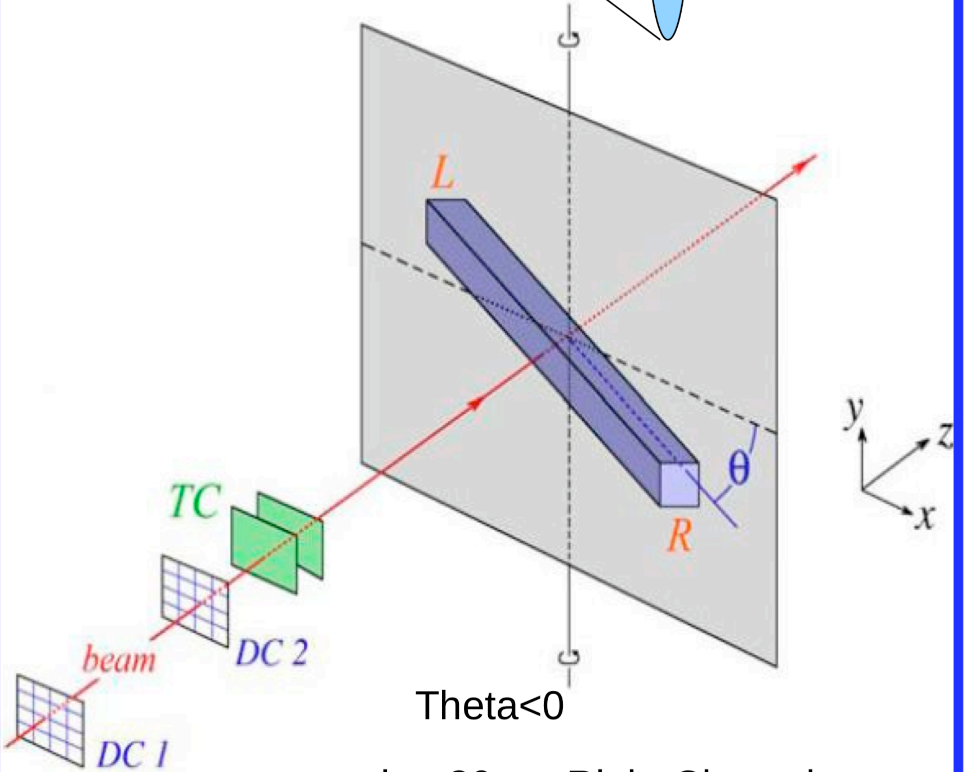
Crystal wrapped with maylar

RED filter + PMT red-extended

BLUE filter + PMT

Beam = 50 GeV electrons





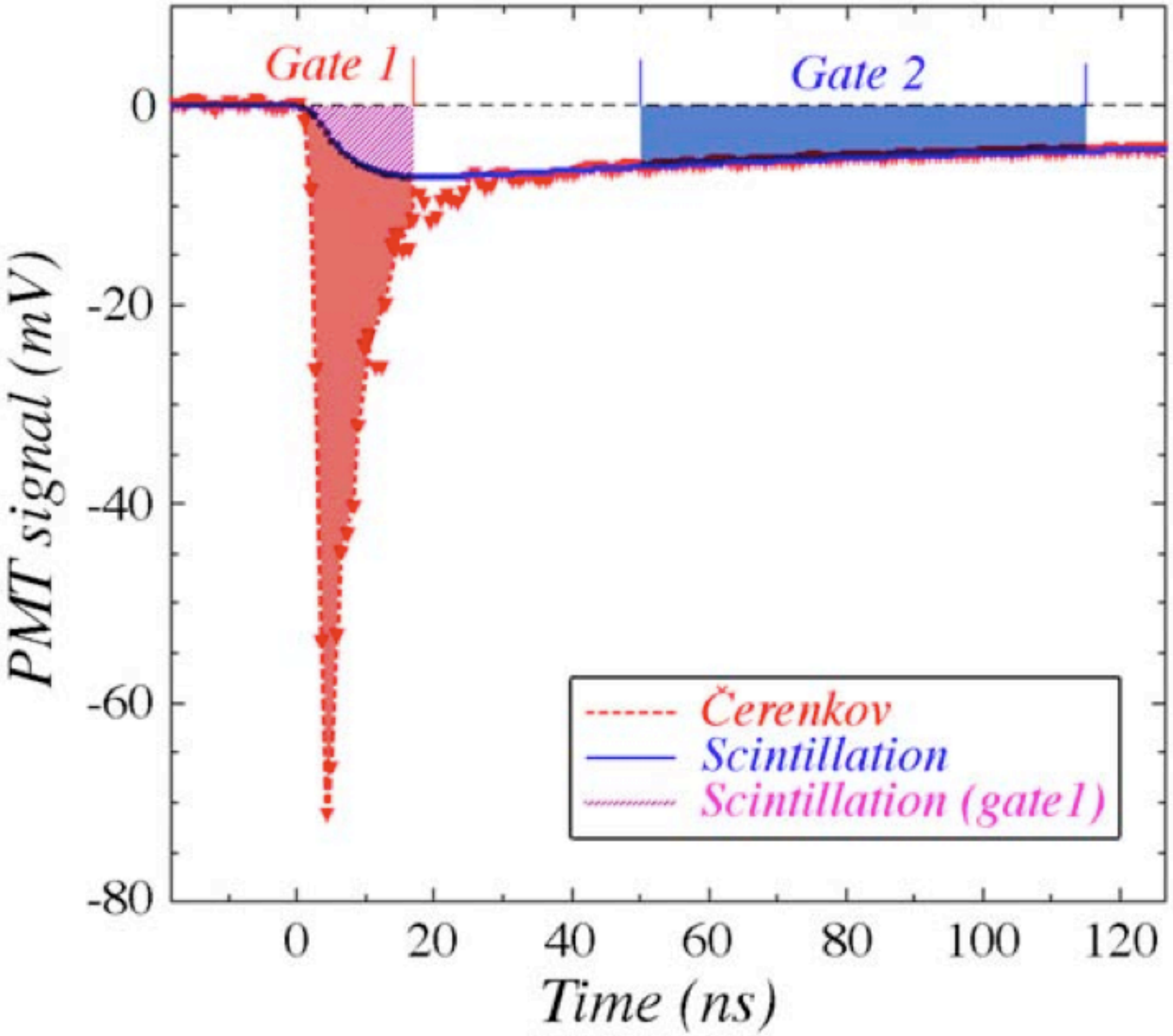
Theta<0

angle +30 --> Right Cherenkov
angle -30 --> Left Cherenkov

BGO crystal

Time structure

With use of:
- UV filter for C
- Yellow filter for S



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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

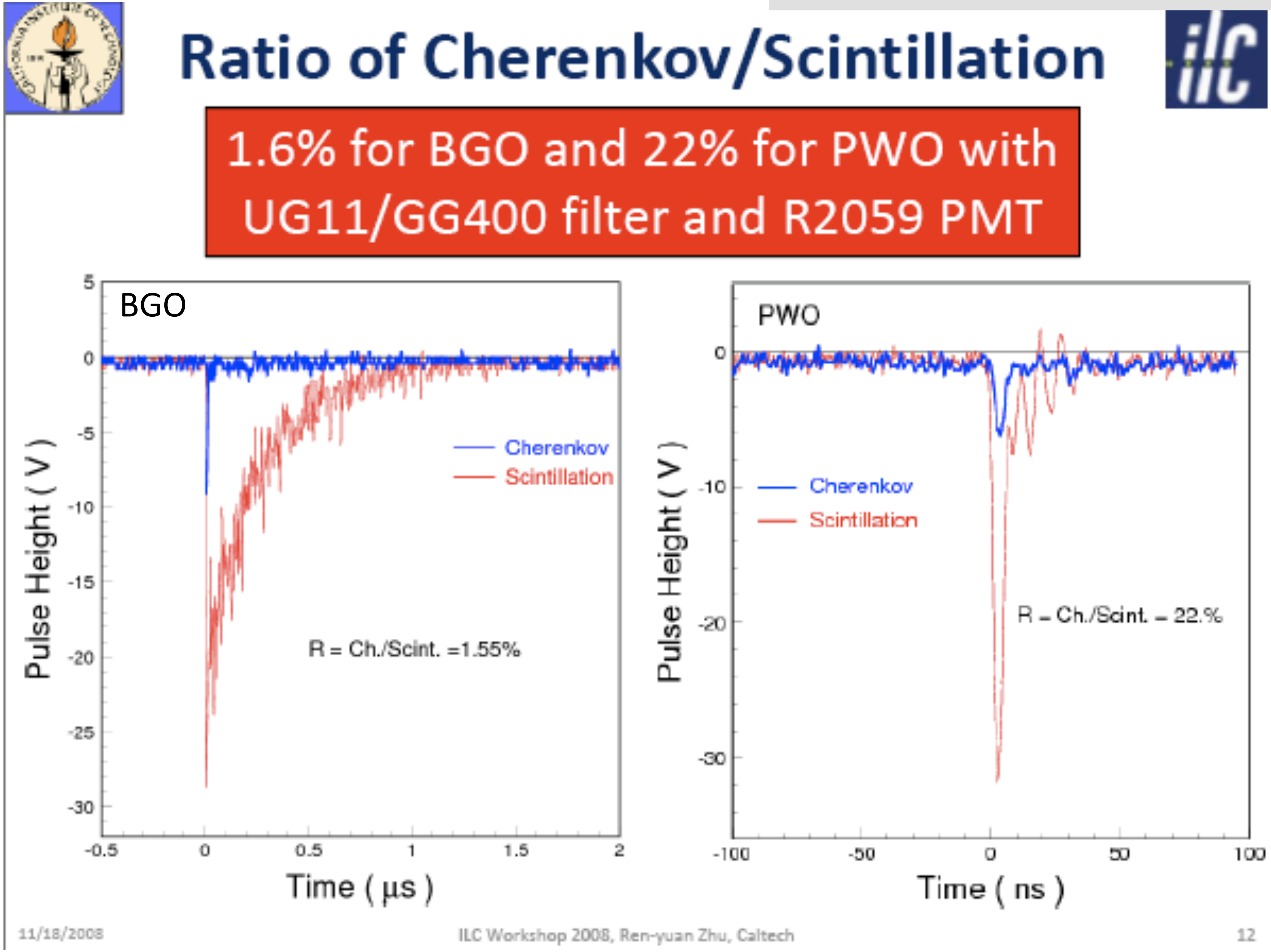
1) Move the scintillation wave length peak
in order to separate C and S through **emission spectrum**

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%)
Praseodymium (0.5%, 1%, 1.5%)

Ren-Yuan Zhu, crystal measurements

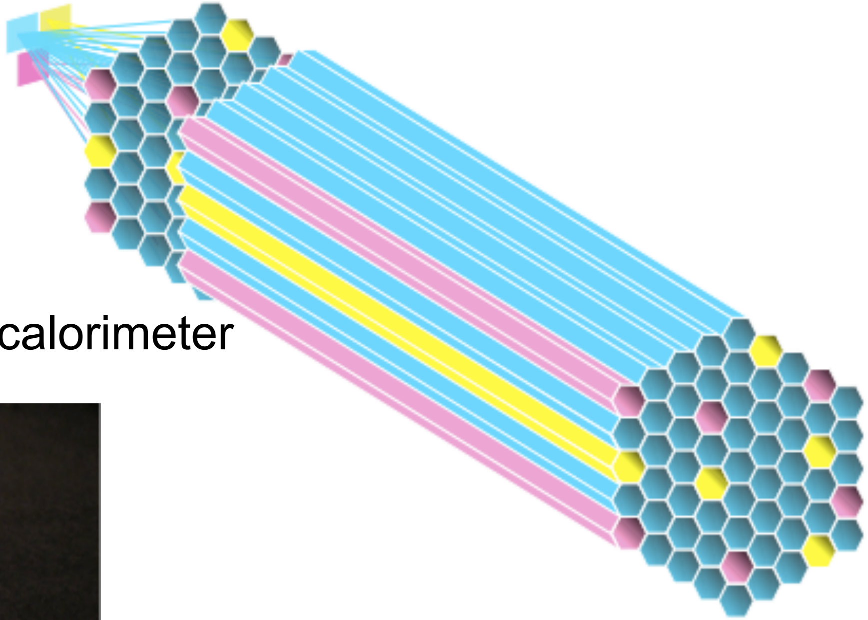


Ratio of Cherenkov/Scintillation

1.6% for BGO and 22% for PWO with UG11/GG400 filter and R2059 PMT

11/18/2008 ILC Workshop 2008, Ren-yuan Zhu, Caltech 12

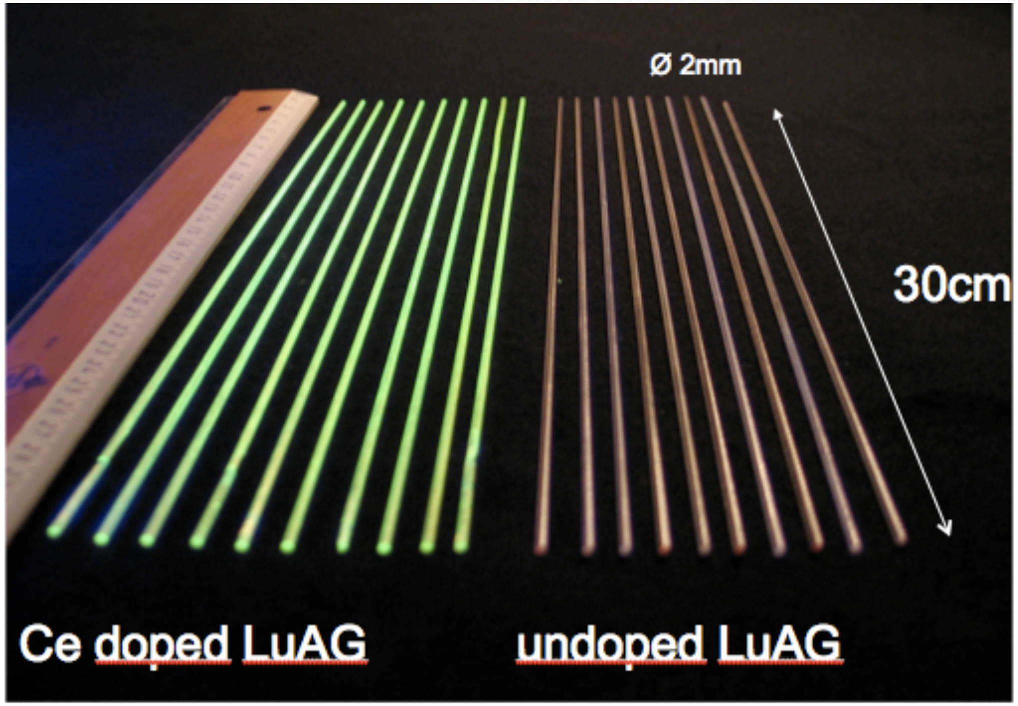
Fully active with crystal fibres?



Use 2 or 3 types of fibres

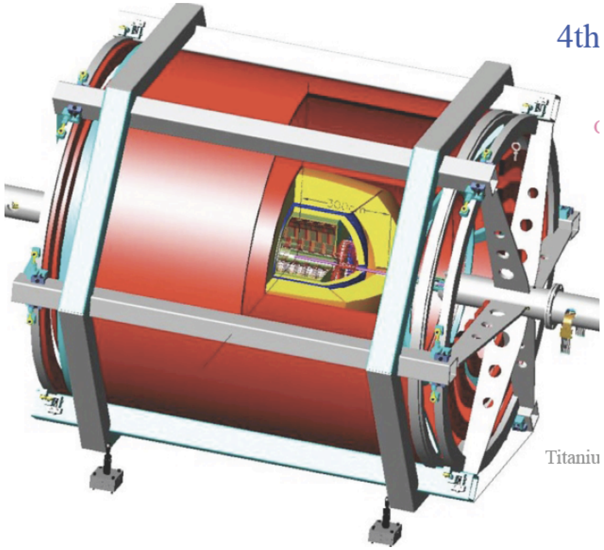
- Undoped => Cherenkov only
- Doped-1 => S + C
- (Neutron sensitive fibres)

Bundle those fibres together in fully active calorimeter



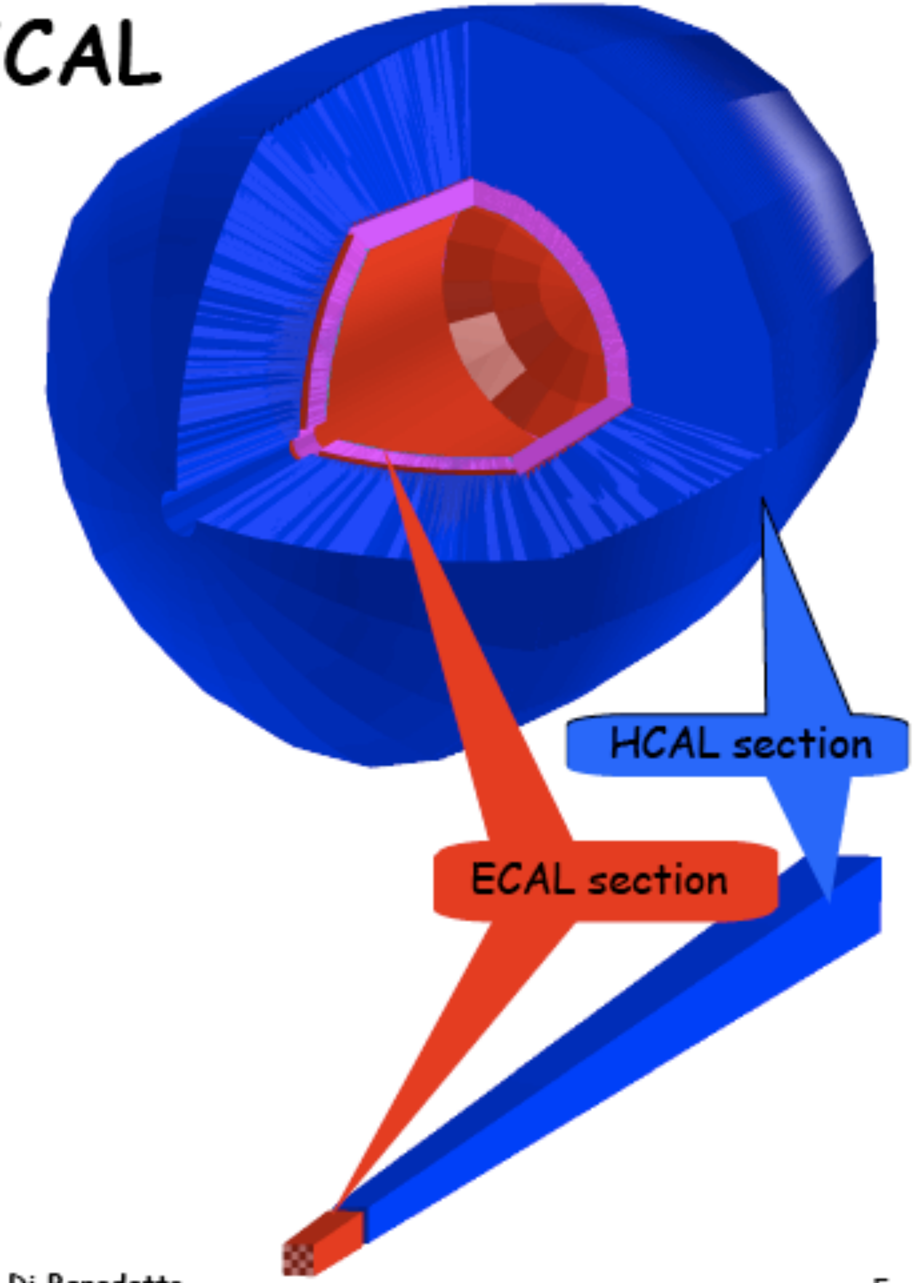
P. LeCoq, E. Auffray CERN

Dual readout in the 4th concept

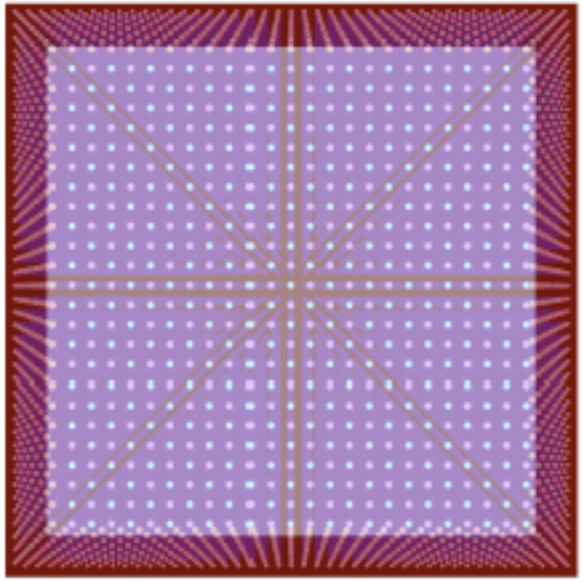


The 4th Concept HCAL

- Cu + scintillating fibers
  + Čerenkov fibers
- ~1.4° tower aperture angle
- ~ 7.3 λ_{int} depth
- Fully projective geometry
- Azimuth coverage
  down to ~2.8°
- Barrel: 16384 towers
- Endcaps: 7450 towers

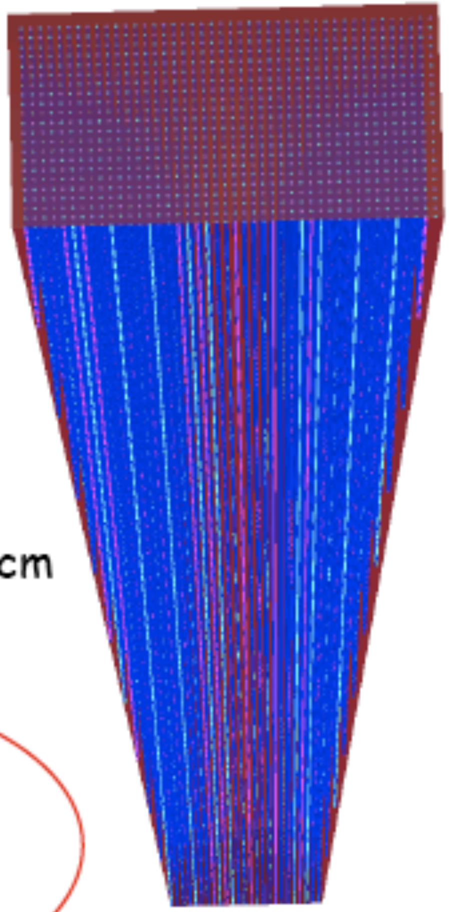


Hadronic Calorimeter Towers



Bottom view of single tower

Top tower size: ~ 8.1 × 8.1 cm^2



Prospective view of clipped tower

Quite the same absorber/fiber ratio as DREAM

- 500 µm radius plastic fibers
- Fiber stepping ~2 mm
- Number of fibers inside each tower: ~1600 equally subdivided between Scintillating and Čerenkov
- Each tower works as two independent towers in the same volume

Tower length: 150 cm

Dual Readout Fibers Calorimeter

Bottom tower size: ~4.4 × 4.4 cm^2

November 18th, 2008

LCWS08 V. Di Benedetto

Conclusions (1)

- Dual (triple) readout is a promising scheme

- First beam tests indicate:
  - Improved jet resolution capabilities
  - Good linearity
- Groups are becoming active in the field world-wide. Activities:
  - Proof-of-principle beam tests
  - Scintillation/Cherenkov materials studies
  - Photon detector studies
  - Simulations
- Fully active dual readout calorimeters are becoming an option thanks to recent technology advances:
  - Compact photon-detectors, compatible with strong magnetic fields (e.g. SiPM)
  - Development of crystals and fibres with high density

Conclusions (2)

- **Lots of work ahead**
  - Long-term core R&D of materials and light detectors
  - Work on a full engineering concept of a detector
  - Beam tests with small and large prototypes

- **Is this an option for a CLIC detector?**

My personal view:

A. Active/passive option with fibres without longitudinal segmentation:

⇒ systematic error issues may spoil most of the advantages one gets from the dual readout => so not too promising in my view

B. Fully active option with solid crystals:

⇒ Looks like an interesting option for particle physics in general. The limited density is a disadvantage for CLIC. Scintillation signal speed may not be a suitable S/C separation tool in the CLIC case.

C. Fully active option with metafibres:

⇒ …Readout scheme looks more of an issue than in the solid crystal case