

# OPTIMIZATION OF CRYSTALS FOR APPLICATIONS IN DUAL-READOUT CALORIMETRY

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on behalf of the Dream Collaboration



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# Dual Readout Method

- ◆ Addresses the limiting factors of the resolution of hadron calorimetry with the aim of reaching the theoretical resolution limit ( $15\%/ \sqrt{E}$ ) and in addition allows for
  - ◆ Calibration of an hadron calorimeter just with electrons
  - ◆ High resolution EM and HAD calorimetry
  - ◆ ILC/CLIC or Muon collider physics requirements
- ◆ The Dual-Readout technique is based on the simultaneous measurement of
  - ◆ **Čerenkov light** (only produced by relativistic particles, dominated by electromagnetic hadron shower component)
  - ◆ **Scintillation** ( a measure of  $dE/dx$ )

on an **event-by-event** basis



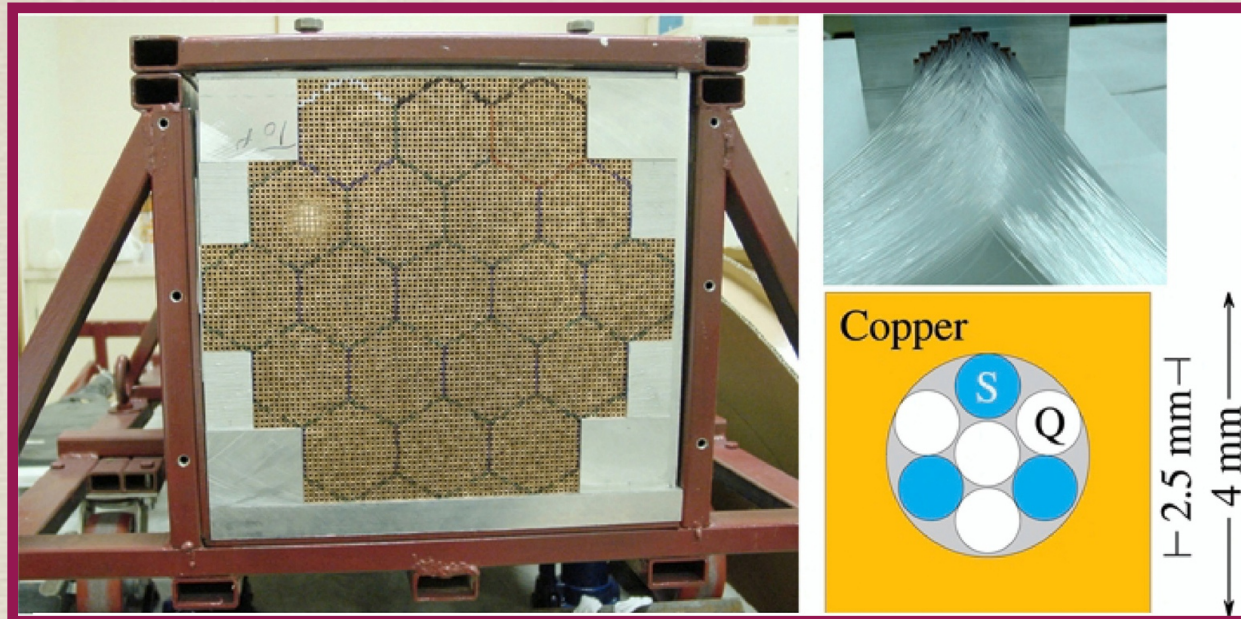
Measurement of the electromagnetic fraction ( $f_{em}$ ) of the hadron shower on event-by-event basis



# Dual Readout Method

## Quartz + scintillating fibers detector

- C and S separated by construction
- feasible technique for an hadronic calorimeter or an EM+HAD integrated calorimeter
- neutron fraction measurement capability (see **J. Hauptman's** talk)
- limited electromagnetic resolution due to sampling fraction



## Crystal detector

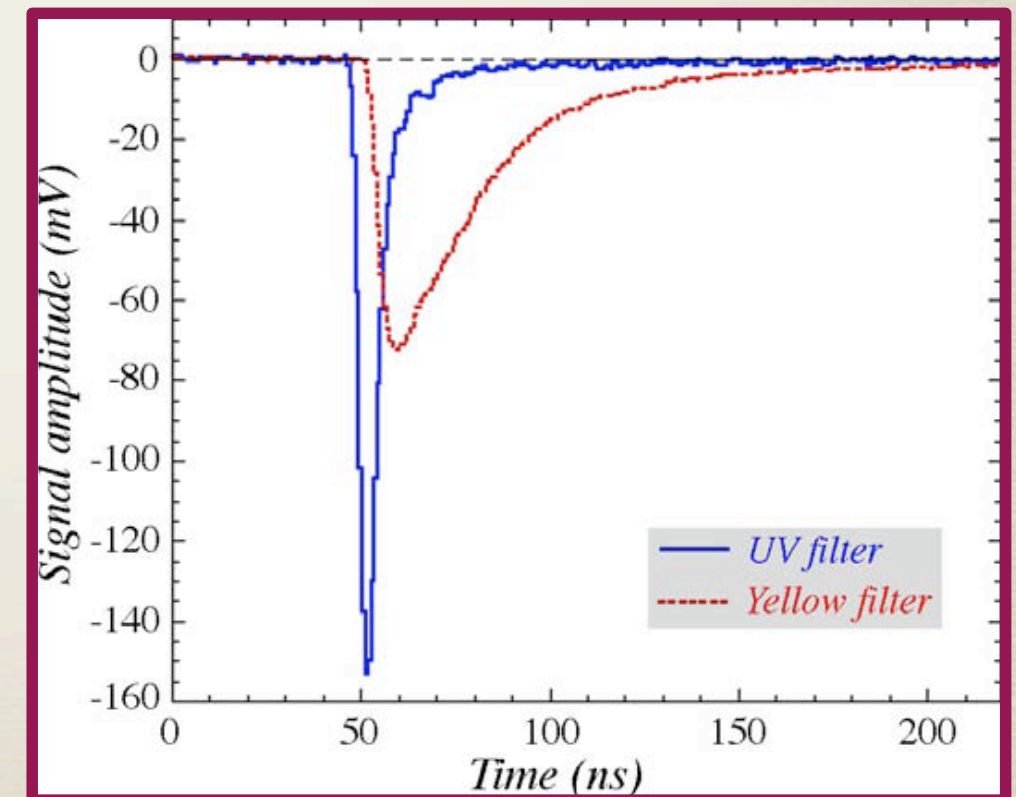
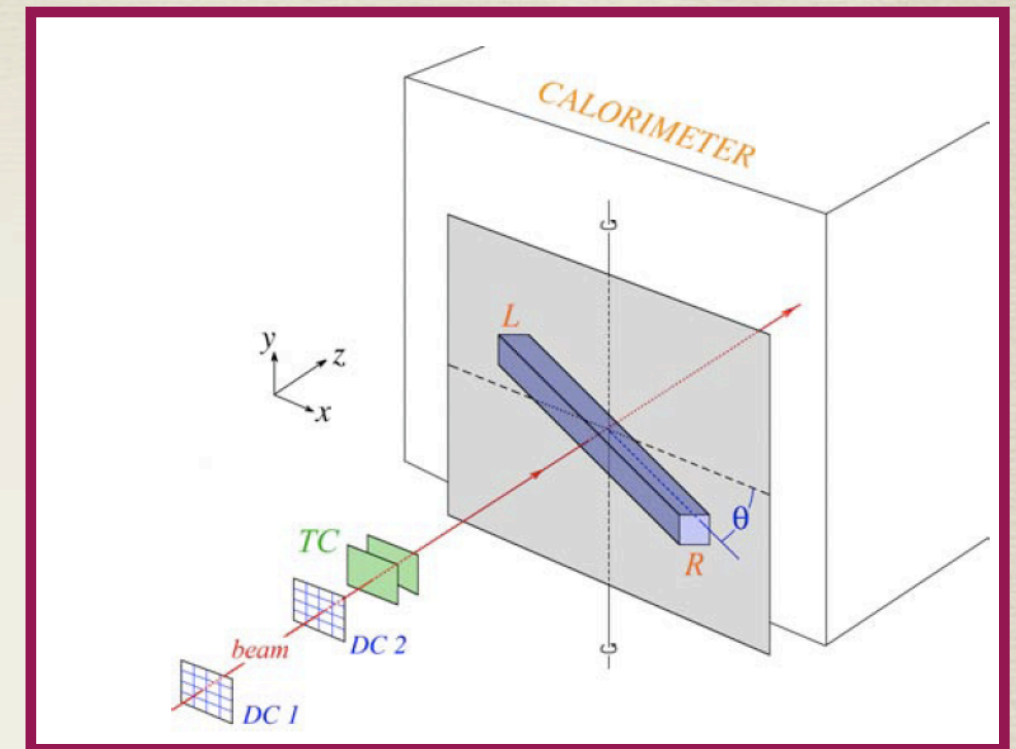
- C and S separated with different techniques (see later)
- optimal electromagnetic resolution
- hybrid system operated with a dual-readout technique allows to overcome e/h difference between the two types of detector and therefore maintain a good hadronic resolution (see **D. Pinci's** talk)





# Čerenkov vs Scintillation

Properties	Čerenkov	Scintillation
<b>Angular distribution</b>	Light emitted at a characteristic angle by the shower particles that generate it $\cos\theta = 1/(n\beta)$	Light emission is isotropic: excited molecules have no memory of the direction of the particle that excited them
<b>Time structure</b>	Instantaneous, short signal duration (few ns)	Light emission is characterized by one or several time constants. Long tails are not unusual (slow component)
<b>Optical spectra</b>	$\lambda^{-2}$ spectrum	Strongly dependent on the crystal type, usually concentrated in a (narrow) wavelength range
<b>Polarization</b>	polarized	not polarized





# Crystals: what do we need?

- Good Čerenkov vs Scintillation separation
- Response uniformity (no light attenuation)
- High light yield (to reduce contributions to the resolution due to p.e. statistics)

## Test performed so far

- **PbWO<sub>4</sub> crystals** (N. Akchurin et al., NIM. A582 (2007), N. Akchurin et al., NIM A584 (2008), N. Akchurin et al., NIM A593 (2008) )
- **BGO** (N. Akchurin et al., NIM. A598 (2009), N. Akchurin et al., NIM A598 (2009), N. Akchurin et al., NIM A 610 (2009) )
- **Doped PbWO<sub>4</sub> crystals** [Praseodymium, Molybdenum] (N. Akchurin et al., NIM A604 (2009))



## CRYSTALS TESTED

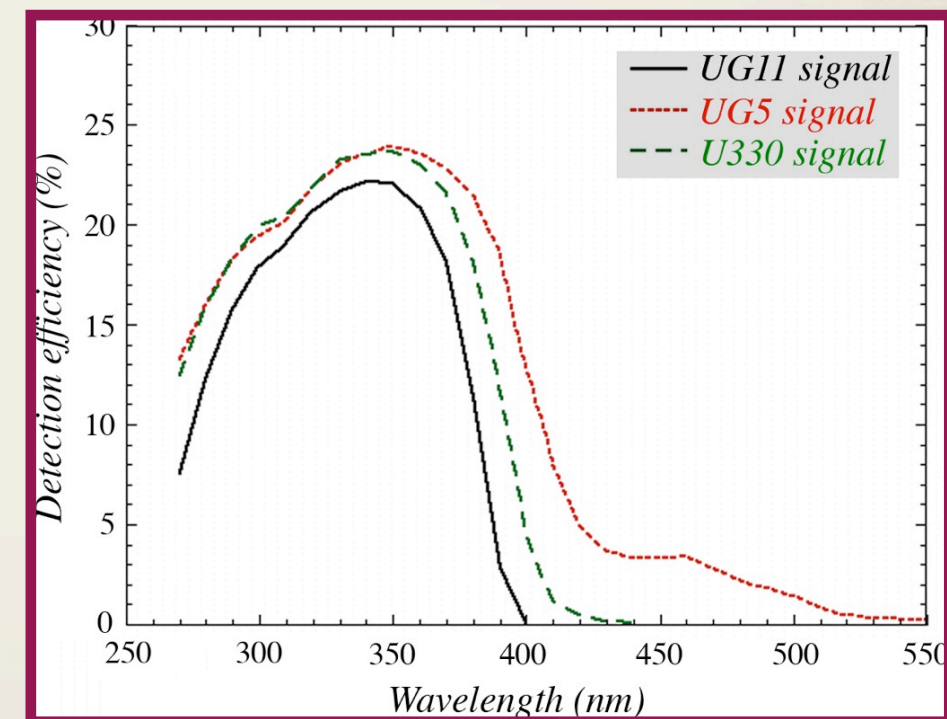
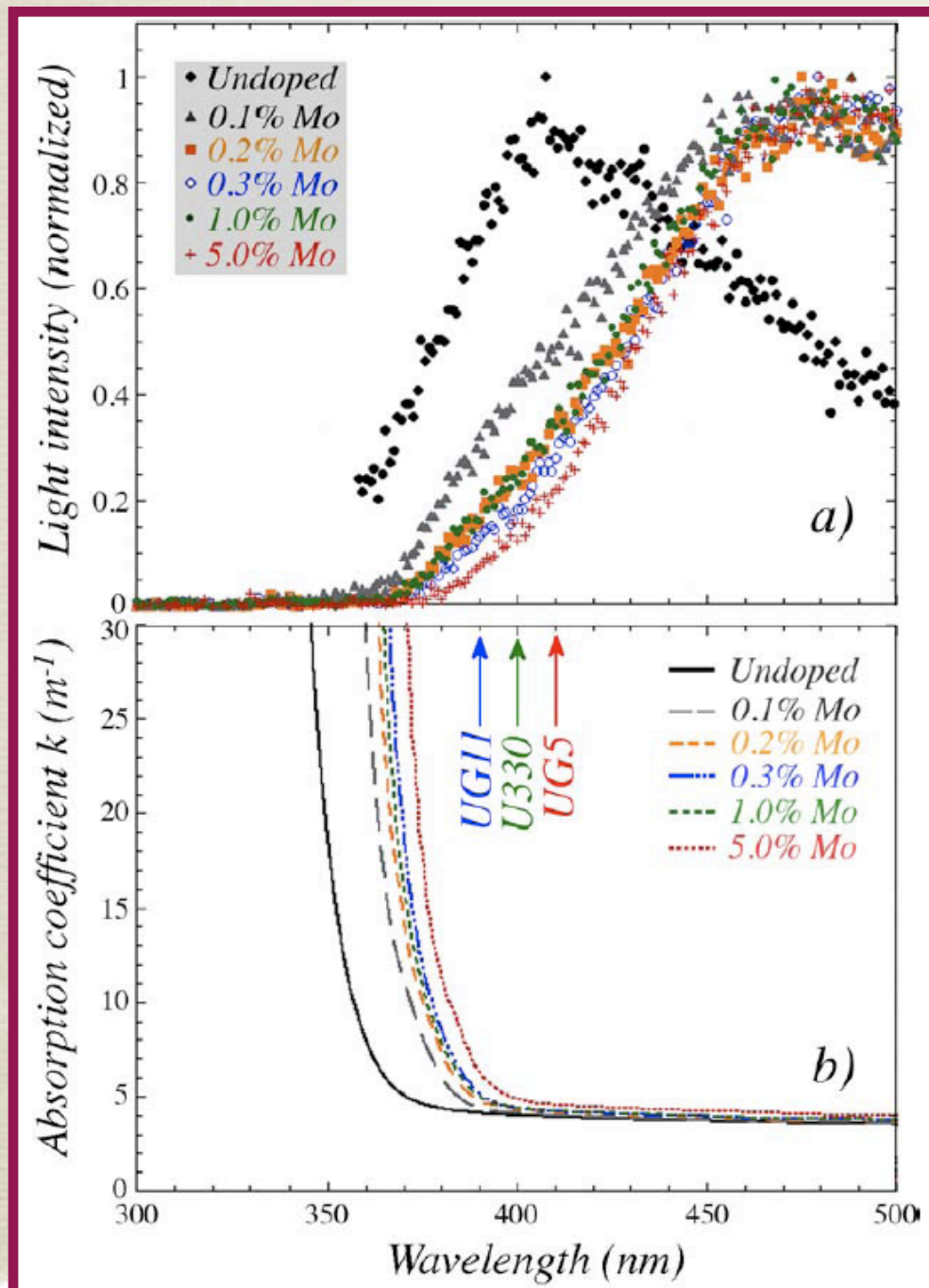
PbWO<sub>4</sub> with 5 Mo dopant concentration

- \* 0.1%, 0.2%, 0.3%
- \* 1%, 5%
- \* produced for TB2008
- \* *N. Akchurin et al, NIM A604 (2009)*

## Mo:PbWO<sub>4</sub> Crystals

### FILTERS

- \* Scintillation side: GG495 (yellow)
- \* Čerenkov side:
  - \* UG11 (cutoff 390 nm)
  - \* U330 (cutoff 400 nm)
  - \* UG5 (cutoff 420 nm)

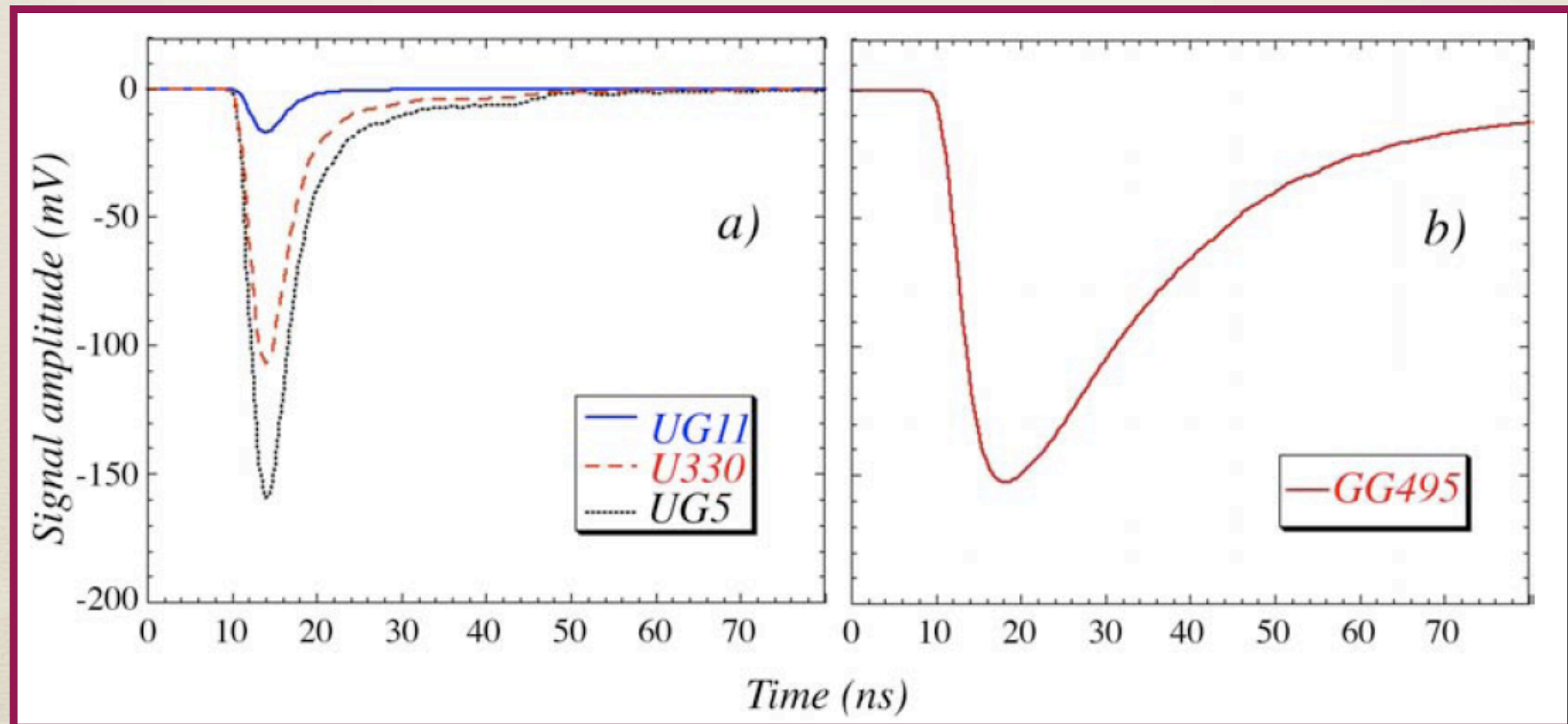
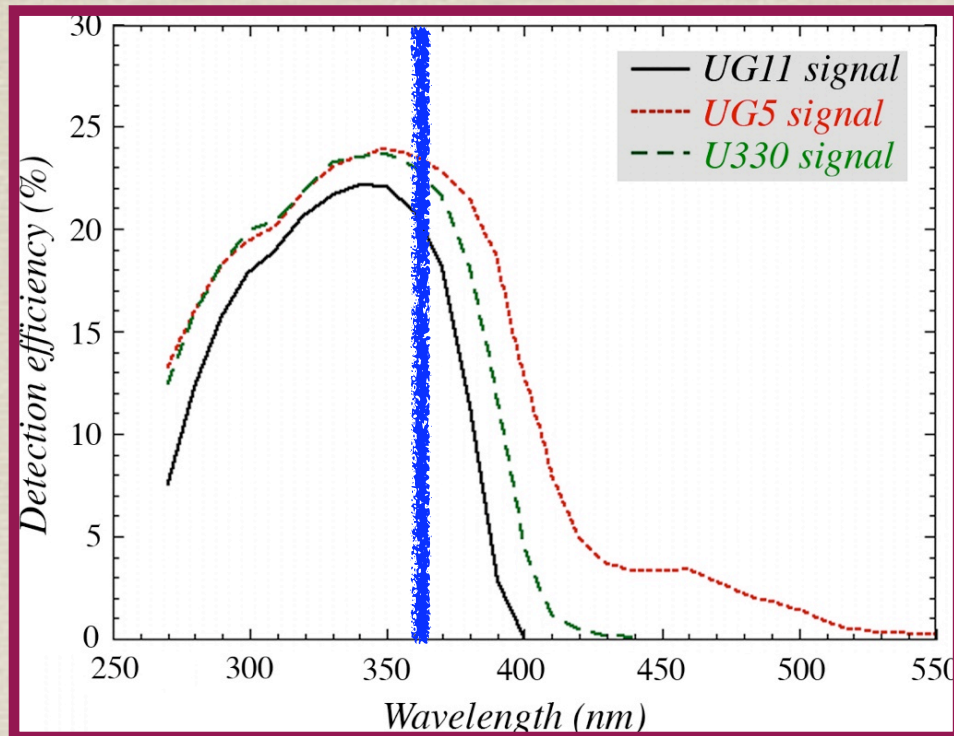


Detection efficiency of light exiting the crystal including optical transmission of the filter and the cookies and QE of the photocathode (Hamamatsu R8900U-100 SBA (36% QE))



# Signal time structure

- Mo 0.3% crystal oriented at 30°
- Signal in the UV region filtered by UG11 filter is really marginal: region close to the absorption edge extremely critical





# Crystals: what do we need?

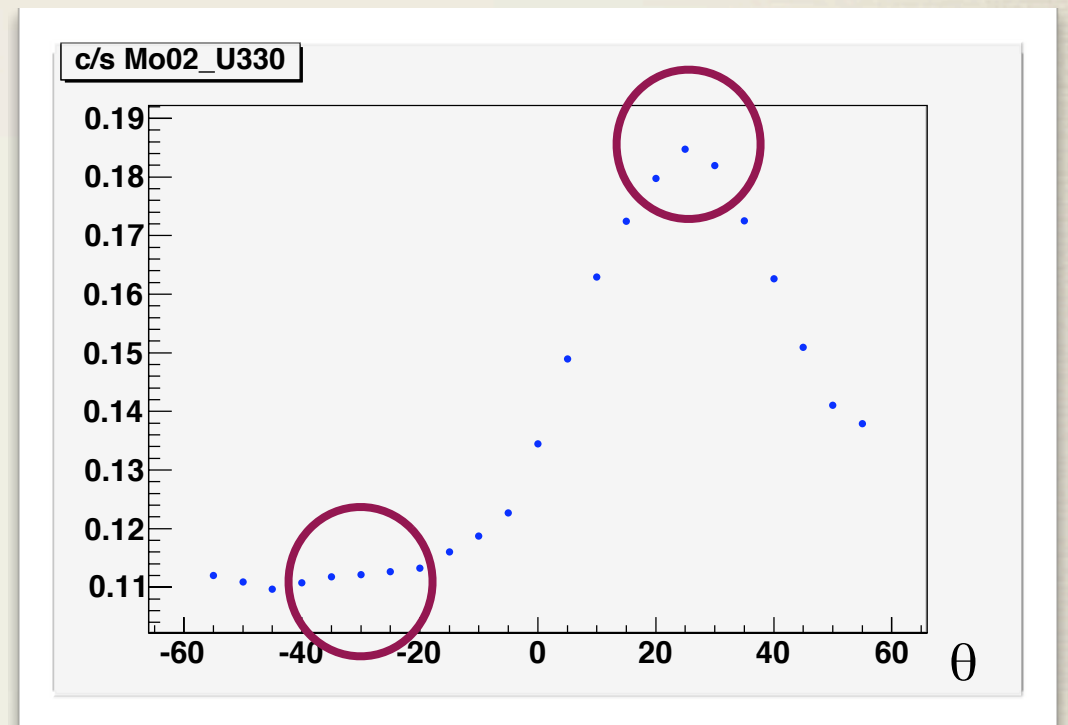
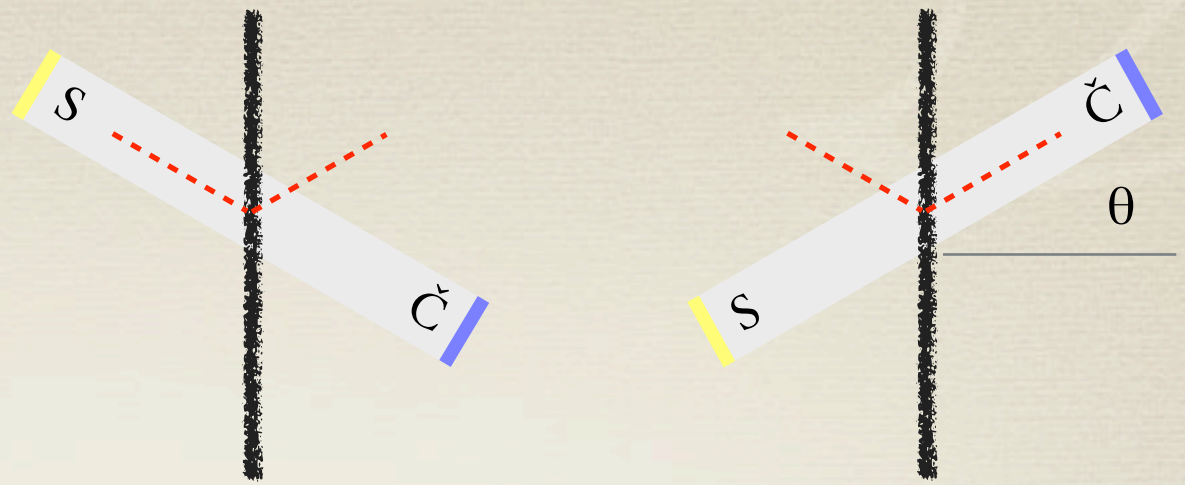
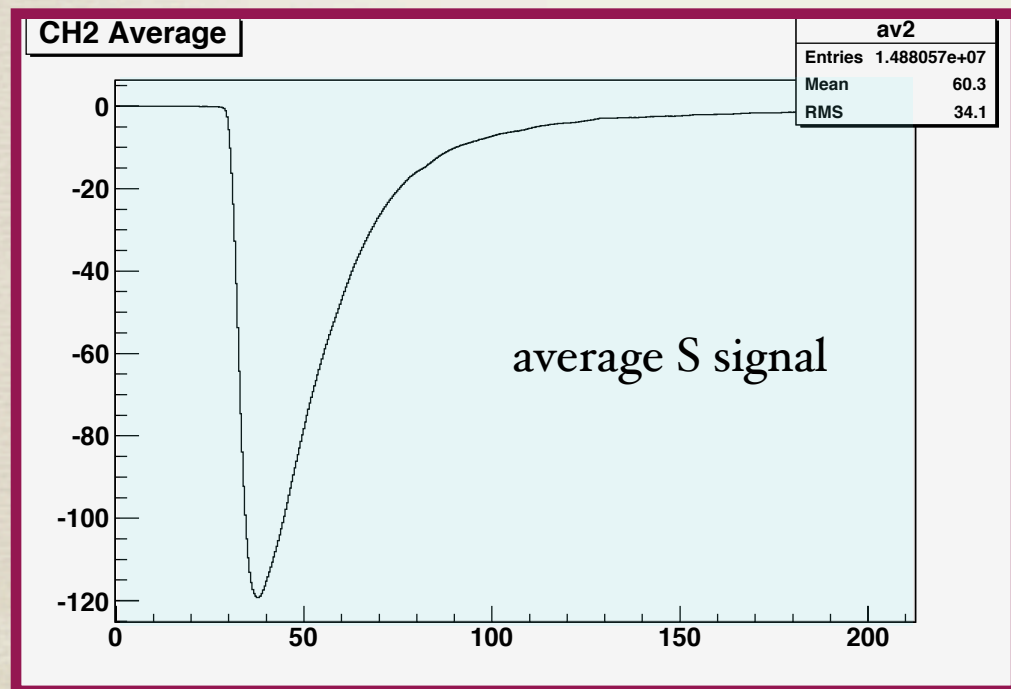
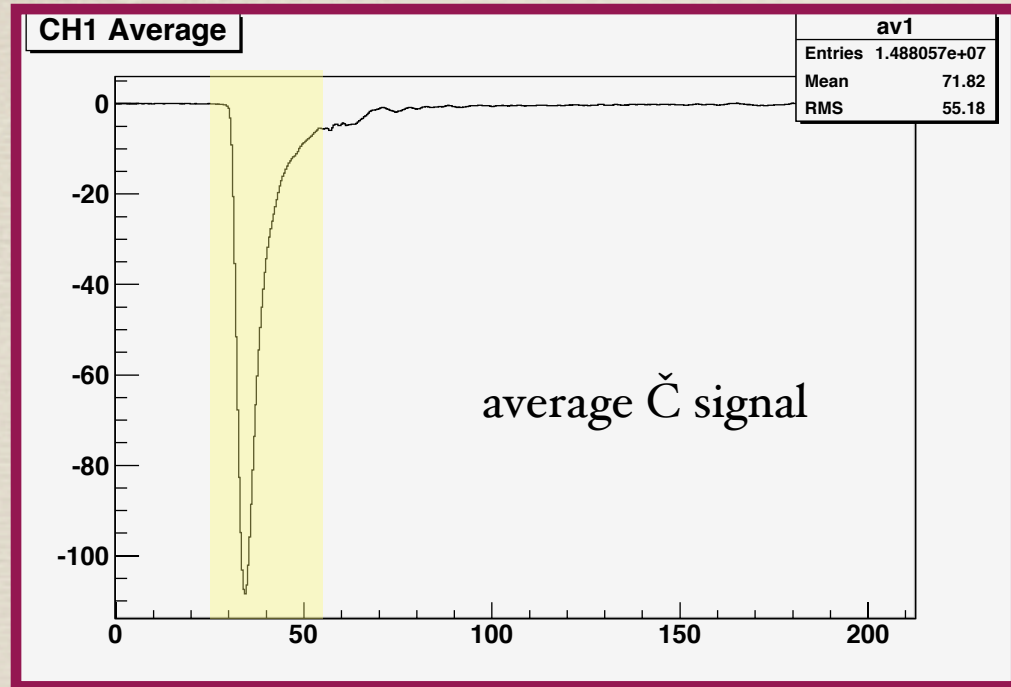
- Good Čerenkov vs Scintillation separation
- Response uniformity
- High light yield (to reduce contribution of p.e. fluctuation to the resolution)

## Figures of merit

- C/S ratio (angular scan measurements)
- Light Attenuation (longitudinal scan measurements)
- Light yield measurements



# C/S ratio

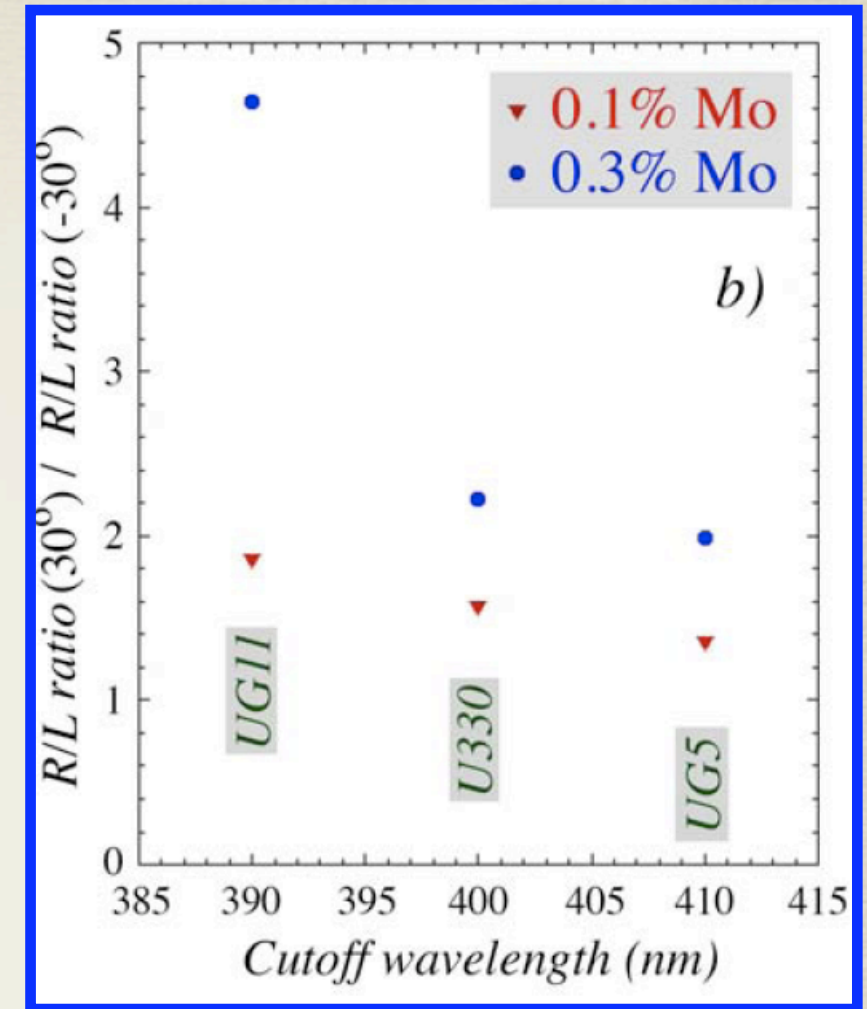
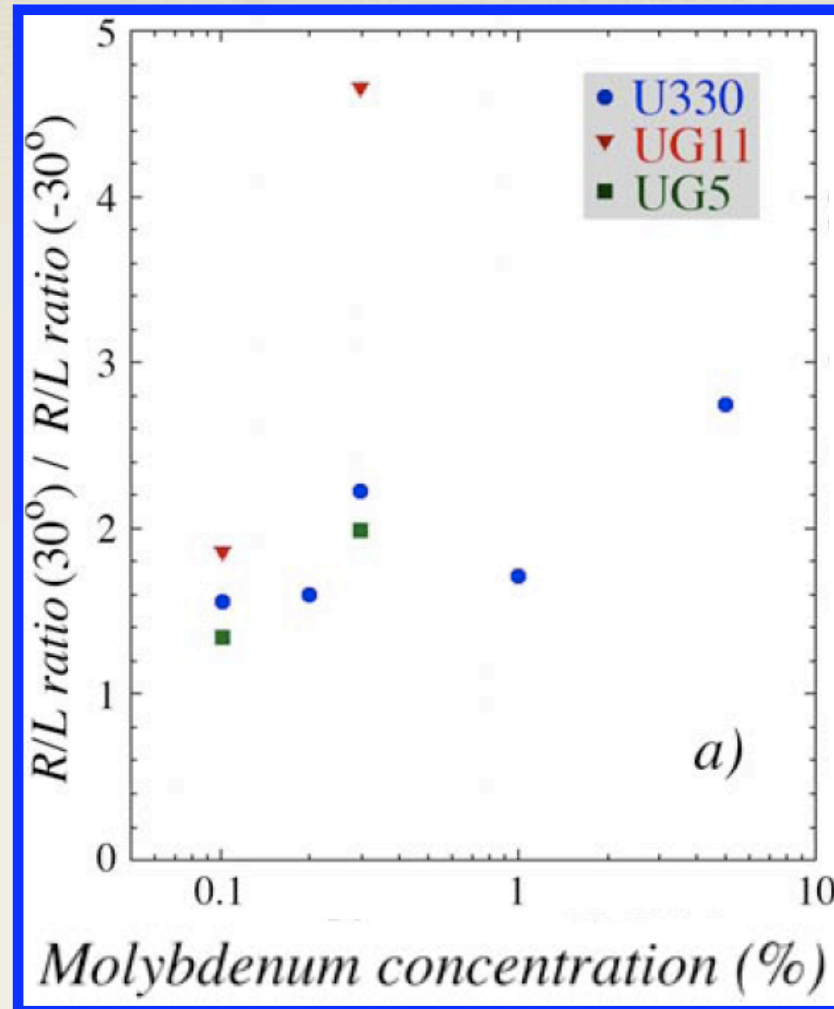
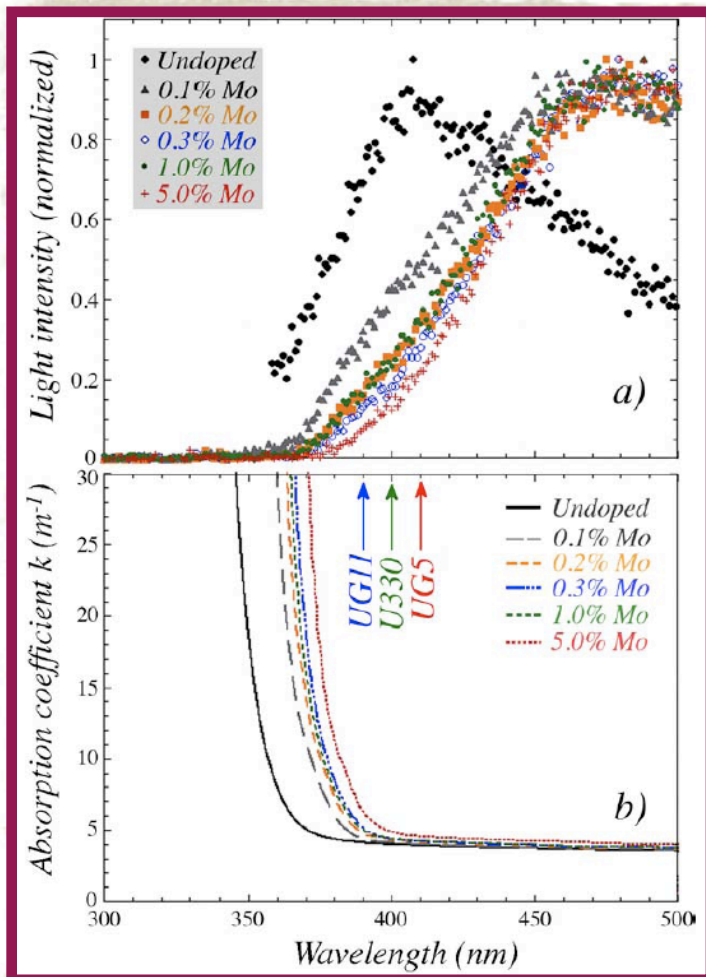


A figure of merit for separation power is the ratio of C/S at the Čerenkov angle and C/S at the anti-Čerenkov angle

$$\Pi = \frac{(C/S)|_{30^{\circ}}}{(C/S)|_{-30^{\circ}}}$$



# C/S ratio: results



$$\Pi = \frac{(C/S)|_{30^\circ}}{(C/S)|_{-30^\circ}}$$

## concentration effect

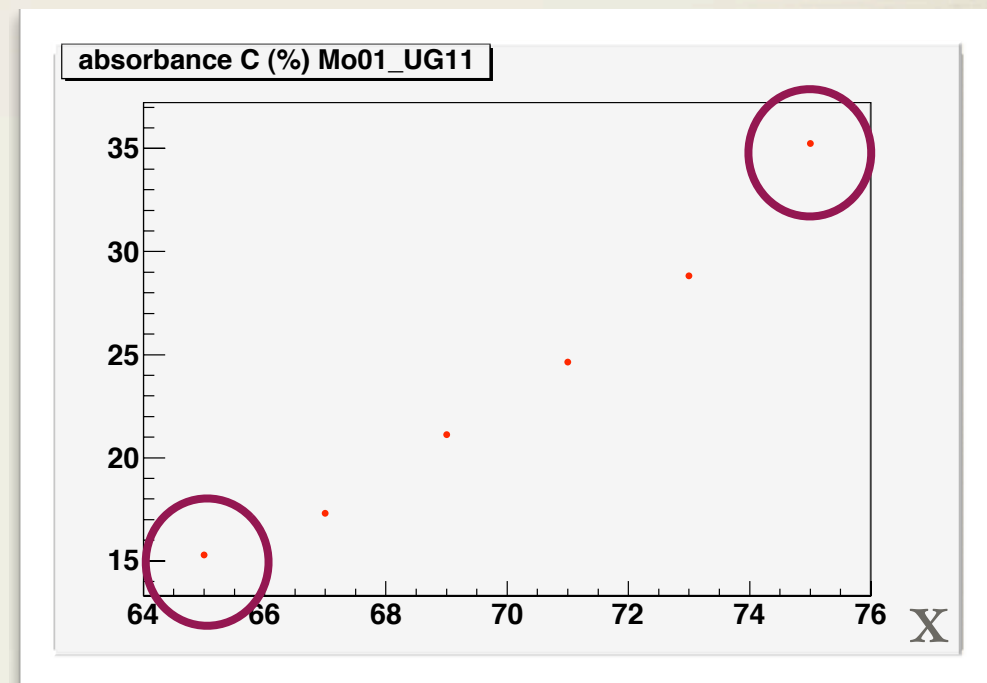
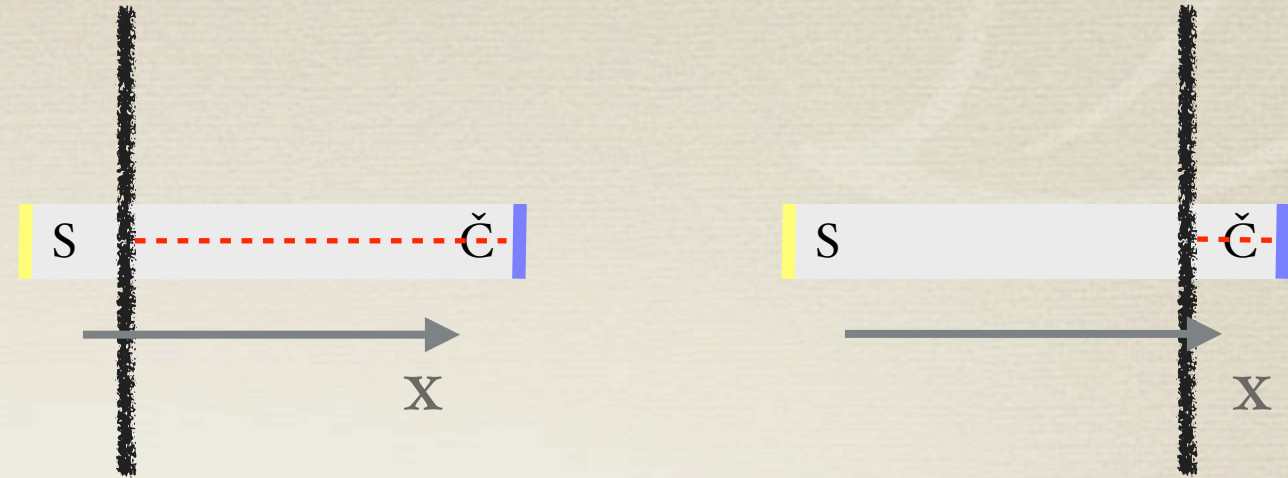
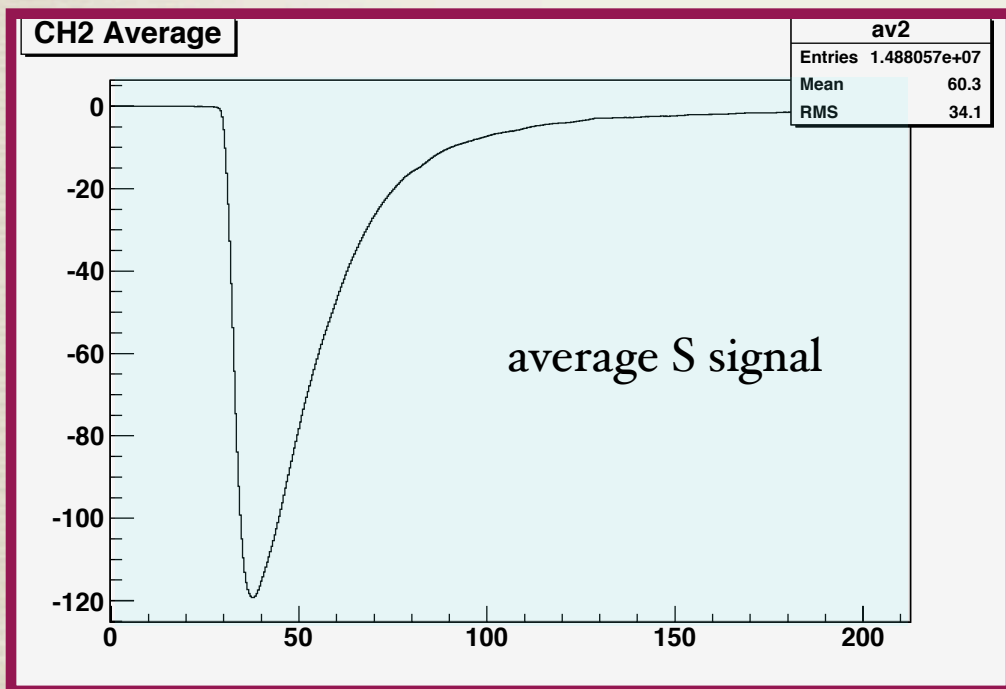
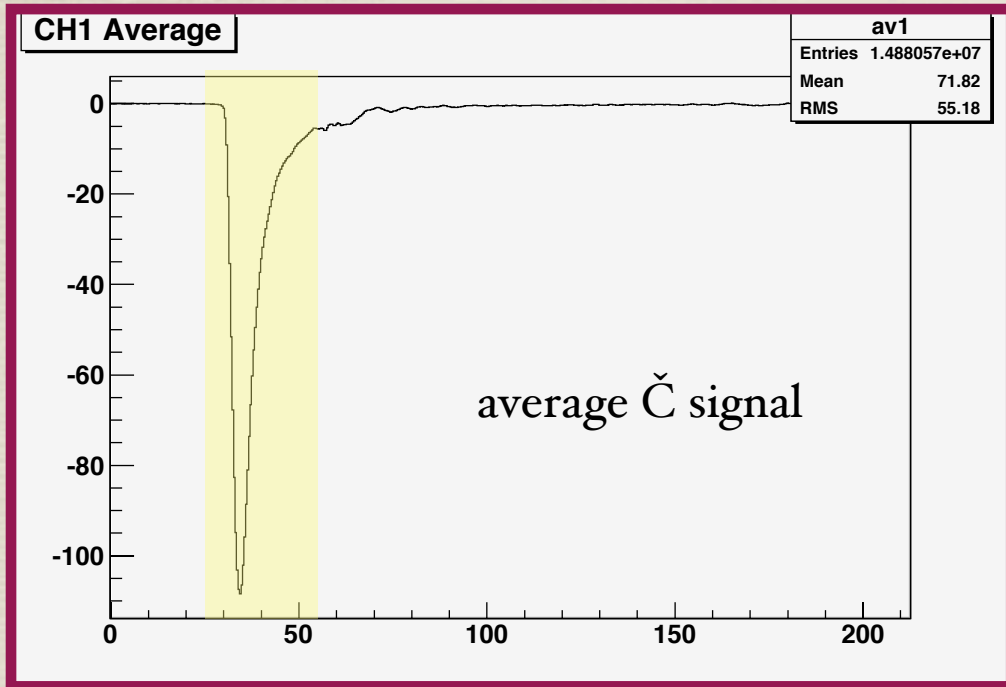
the lower the Mo concentration, the shorter the wavelength at which the scintillation emission starts: more contamination  $\Rightarrow$  lower C/S ratio

## filter cut-off effect

the lower the filter cut-off, the smaller the scintillation contamination, the larger the C/S ratio



# Light Attenuation



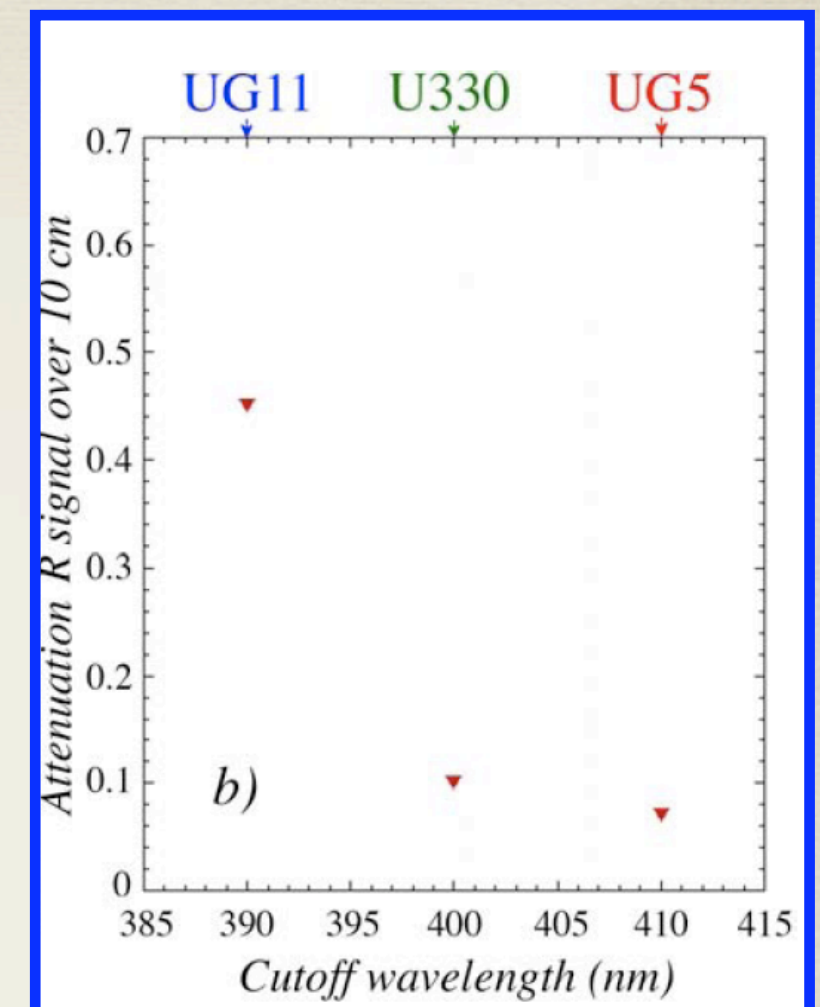
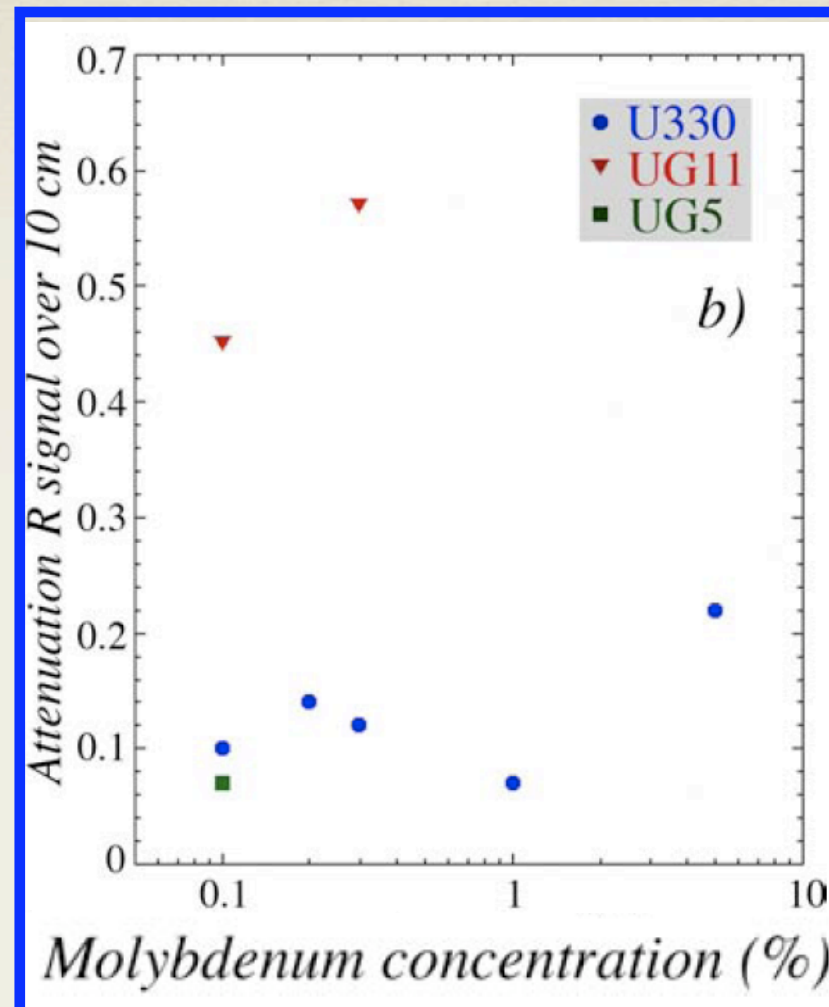
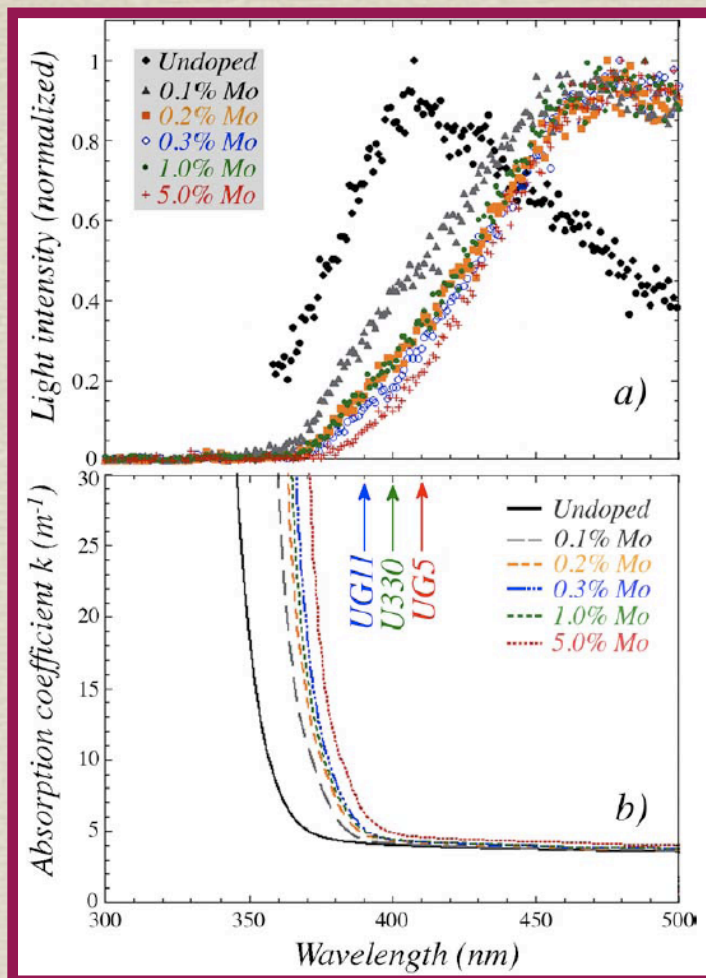
Signal loss (%) in 10 mm

$$A = \frac{I(75) - I(65)}{I(75)}$$

- Shown results are for Čerenkov signal
- Scintillation attenuation negligible



# Light attenuation: results



$$A = \frac{I(75) - I(65)}{I(75)}$$

concentration effect  
 the smaller the Mo concentration, the lower the self-absorption edge, the smaller the effect on light attenuation

filter cut-off effect  
 the lower the filter cut-off, the smaller the Čerenkov signal integration window, the larger the light attenuation effect



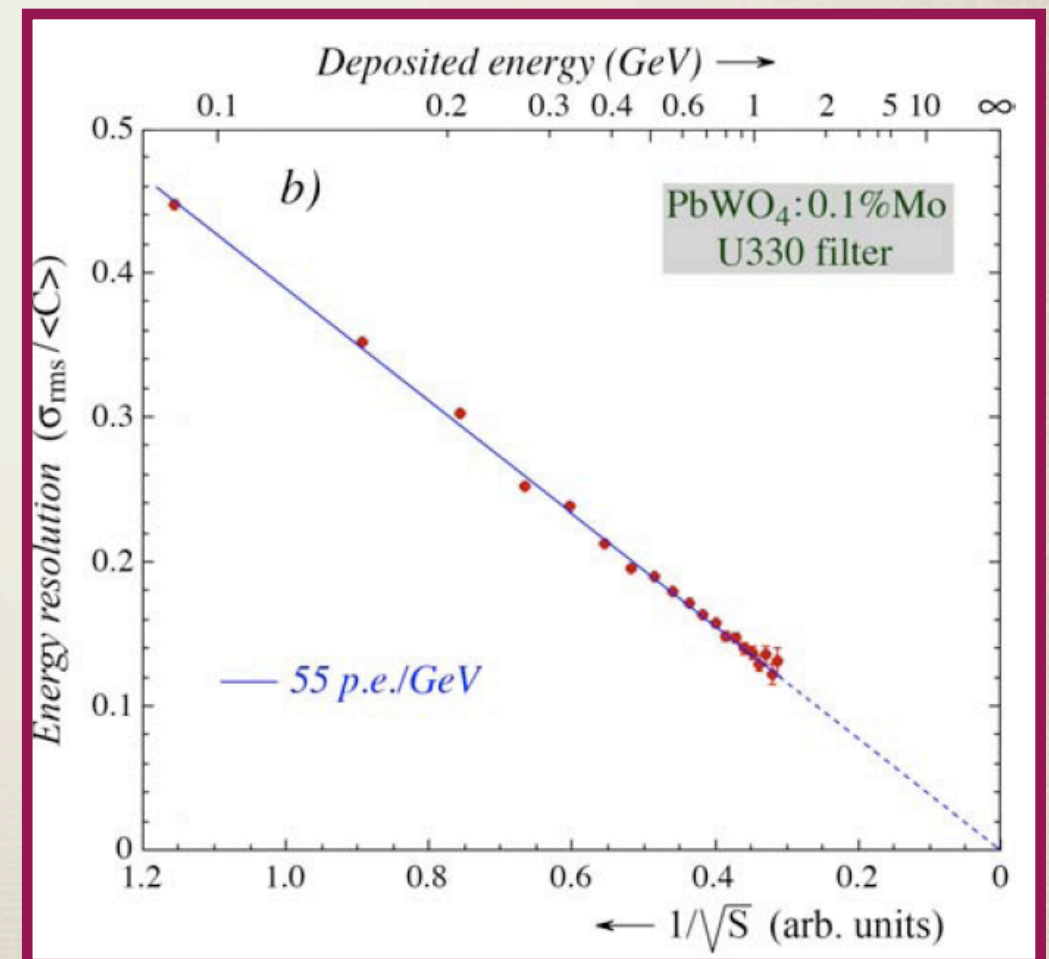
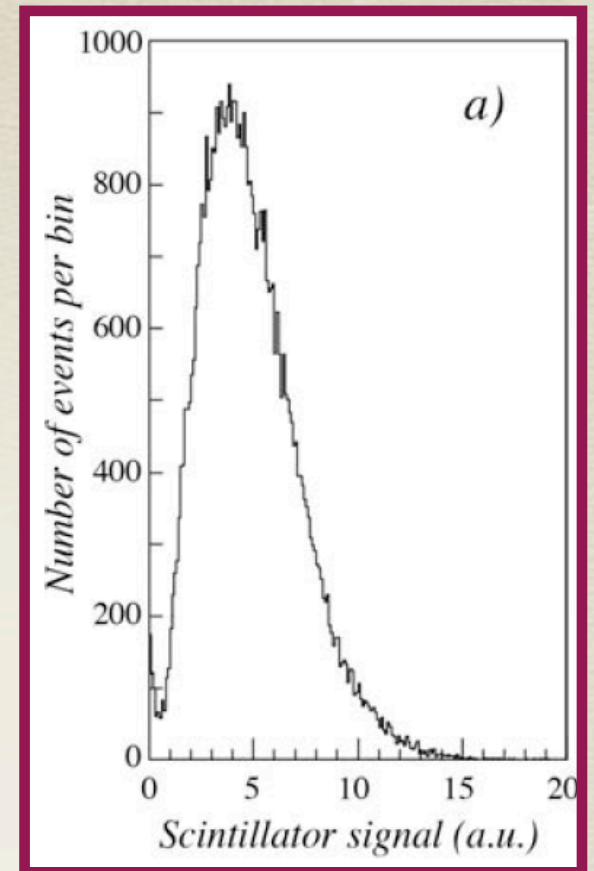
# Čerenkov light yield

In order to measure the light yield we need to determine the energy deposited in the crystal

- No ADC readout: event-by-event integration of the time structure of the signal generates an “*ADC-equivalent*” distribution
- The integrated scintillation signal provides a calibration for deposited energy
- From MC simulation the average deposited energy is 0.578 GeV

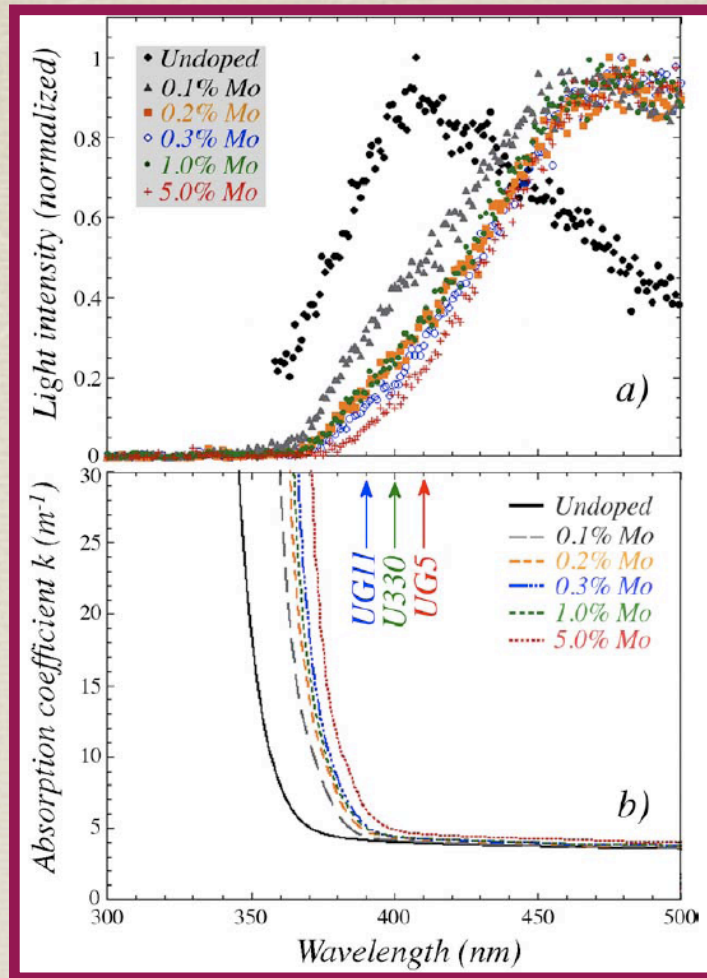
$$\frac{\sigma_c}{\mu_c} = p_0 + p_1 \frac{1}{\sqrt{S}} = \frac{1}{\sqrt{p.e.}}$$

$$p.e. = \frac{1}{0.578 \left( \frac{\sigma_c}{\mu_c} \right)^2}$$





# Čerenkov light yield: results



## filter cut-off effect

the lower the filter cut-off, the smaller the Čerenkov signal integration window, the smaller the light yield

## concentration effect

the smaller the Mo concentration, the lower the self-absorption edge, the larger the Čerenkov signal integration window, the larger the light yield

	UG11	U330	UG5
<b>0.1</b>	5	62	
<b>0.2</b>		57	
<b>0.3</b>	6	55	65
<b>1</b>		58	
<b>5</b>		38	



# Conclusions

LY

	UG11	U330	UG5
0.1	5	62	
0.2		57	
0.3	6	55	65
1		58	
5		38	

Att

	UG11	U330	UG5
0.1	0.55	0.13	0.12
0.2		0.15	
0.3	0.45	0.10	
1		0.08	
5		0.23	

C/S

	UG11	U330	UG5
0.1	4.7	2.3	2.1
0.2		1.7	
0.3	1.8	1.5	
1		1.8	
5		3.0	

- LY and attenuation performances tends to disfavor the UG11 filter which would be on the contrary the best choice for C/S
- U330 and UG5 filters give comparable results
- High Mo concentrations (5%) give the worst performances in almost any respect
- 0.1% - 1% Mo concentrations seem to be adequate for dual-readout technique purposes
  - 0.3% seems to be optimal
  - a matrix made of 0.3%Mo:PbWO<sub>4</sub> crystals will be tested next summer



# Optimization of Crystals for Applications in Dual-Readout Calorimetry

Submitted to NIM A

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# BACKUP SLIDES



# Interference filters

**Dichroic (interference) filters** made by depositing on the glass a series of coatings

They use interference to select the desired wavelengths and destroy or reflect the others

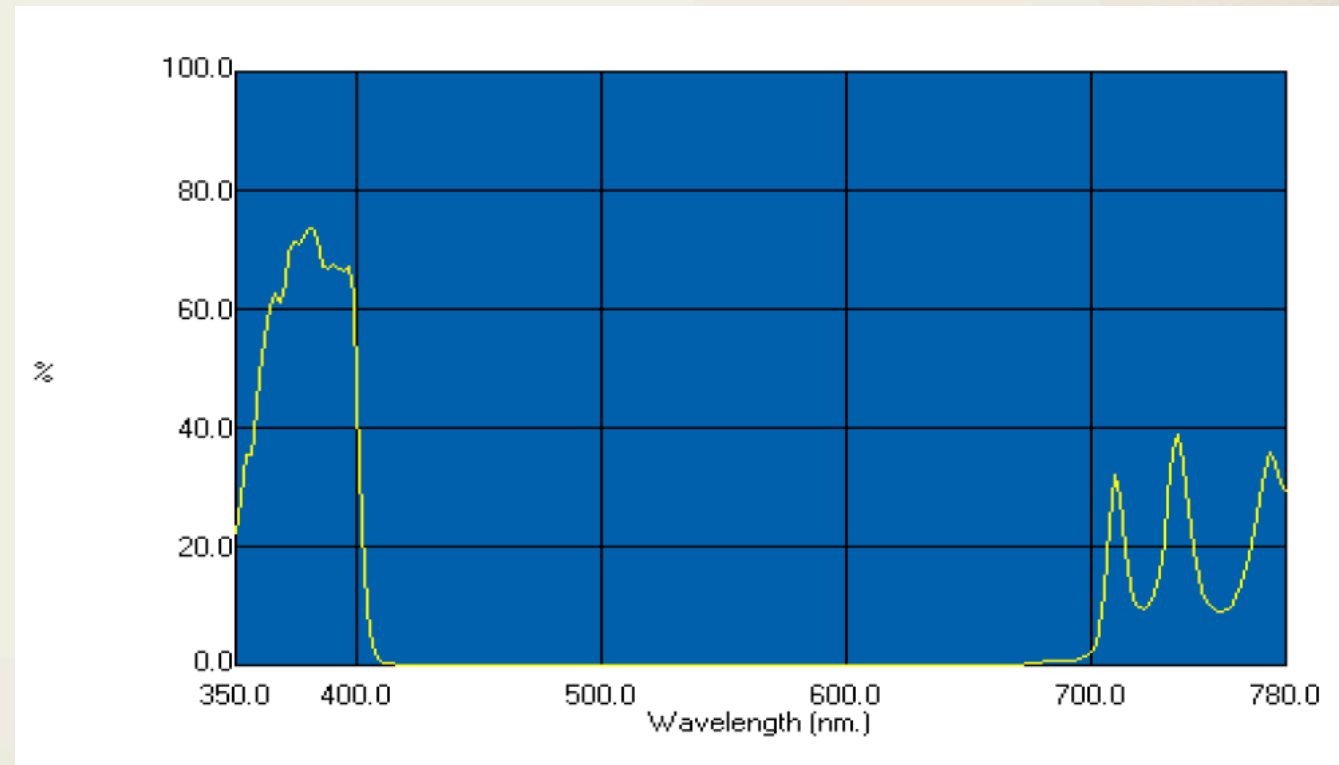
The filter can be customized and the transmission window can be finely tuned

**But the transmission depends on the incidence angle**

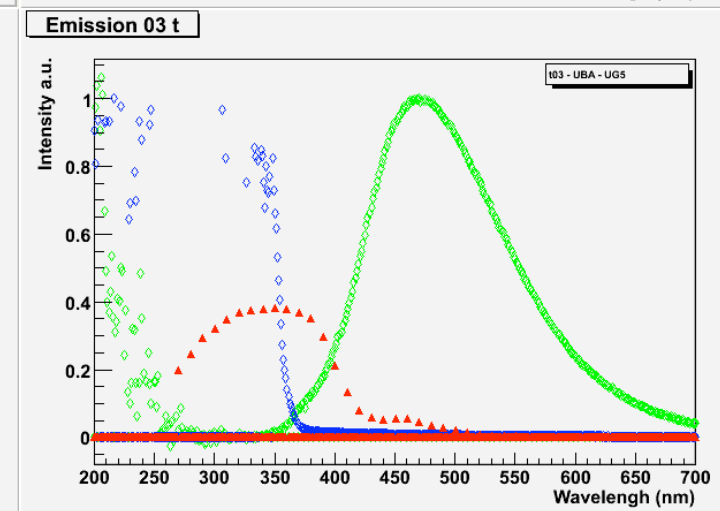
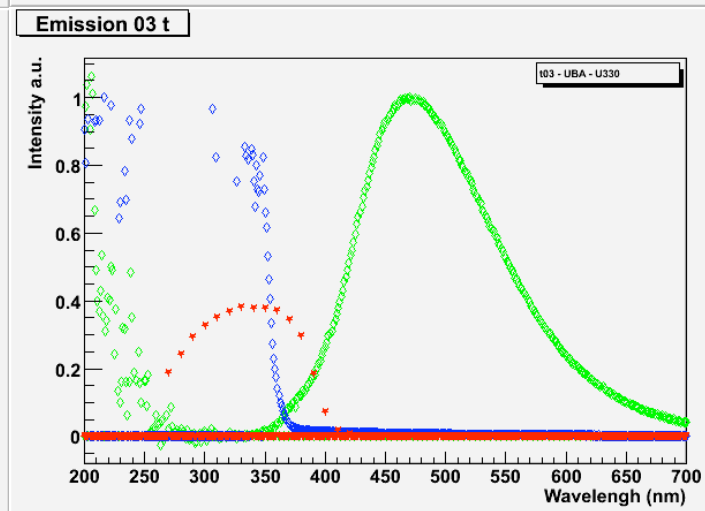
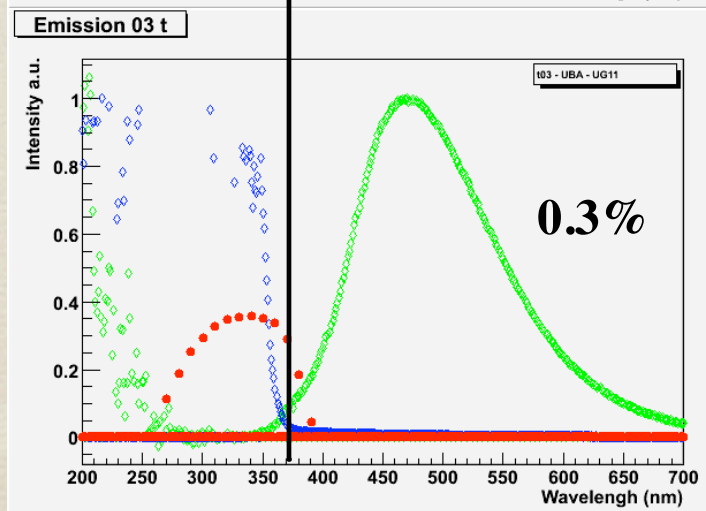
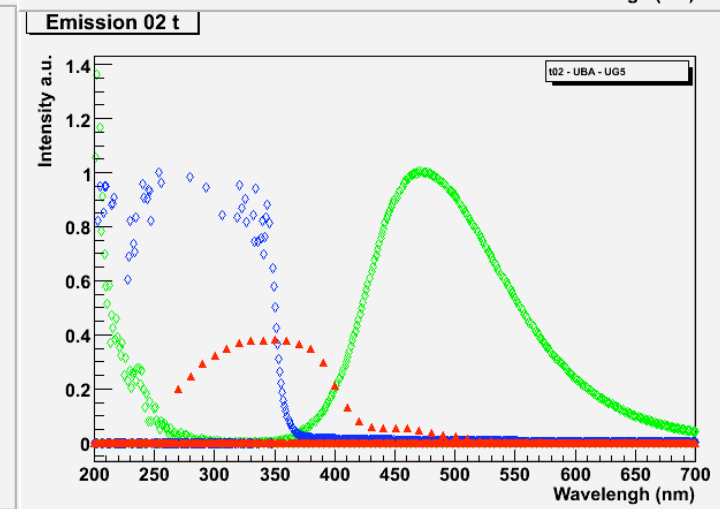
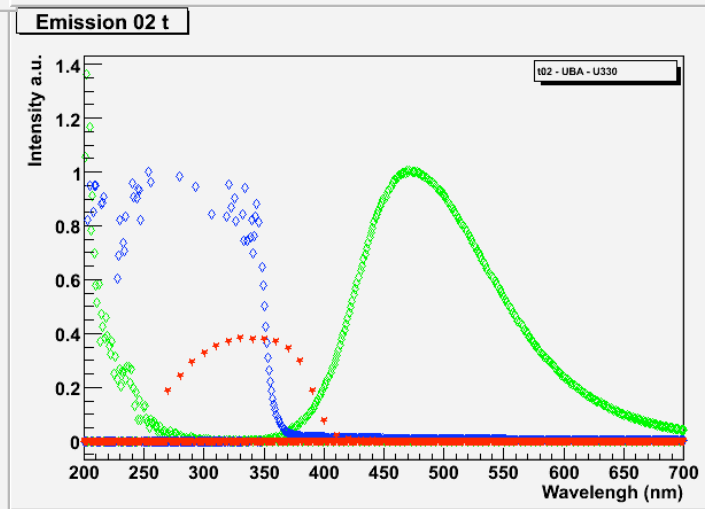
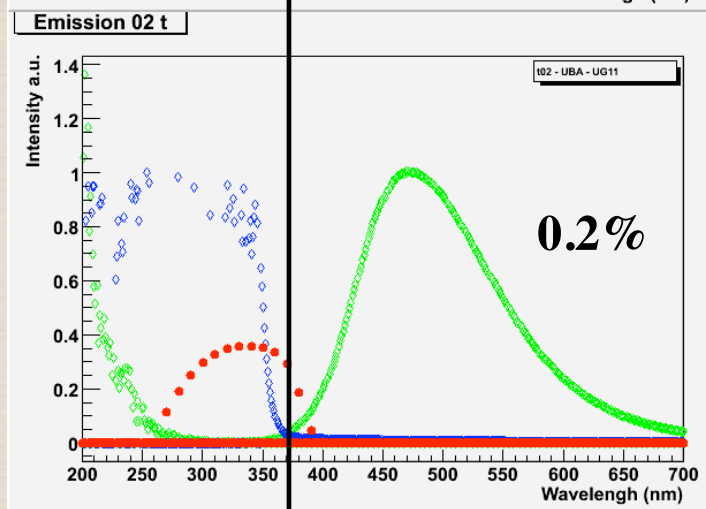
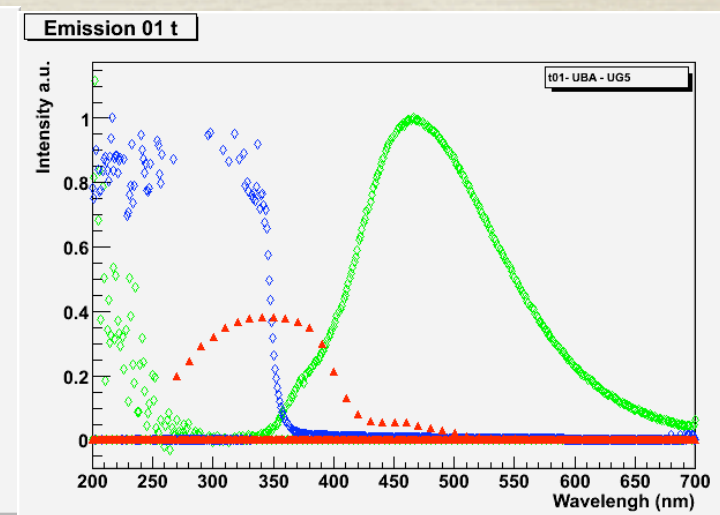
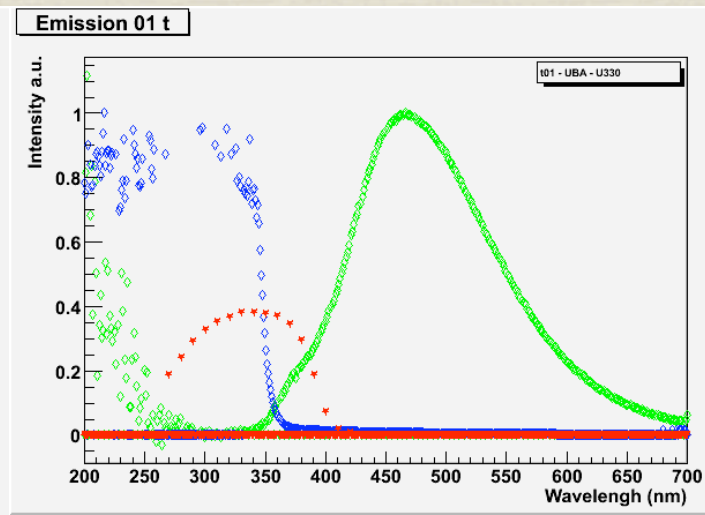
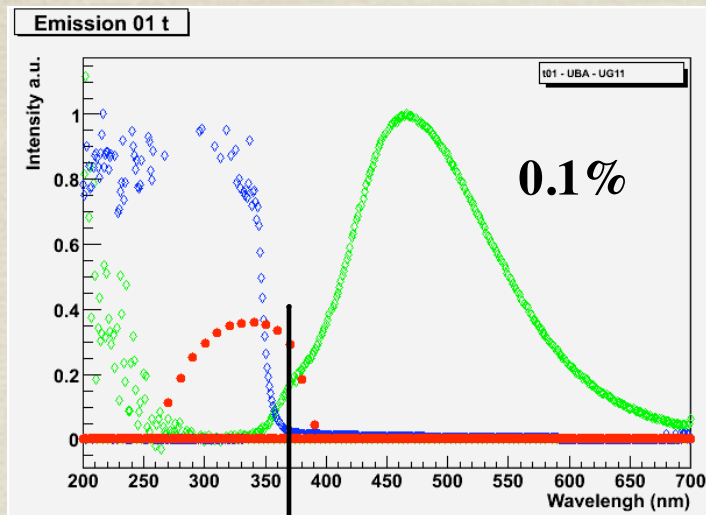
Interference filter by  
ODL (Italy)

Transmission curve  
for normal incidence

For angles larger than  $15^\circ$   
from the normal the  
transmission region  
shifts towards shorter w.l.







**UG11**

**U-330**

**UG5**



## BSO (bismuth silicate, $\text{Bi}_4\text{Si}_3\text{O}_{12}$ )

Same as BGO, with Si in place of Ge. Developed to increase rad hardness and decrease costs

Ishii et al., Optical Materials 19, (2002) 2001-212

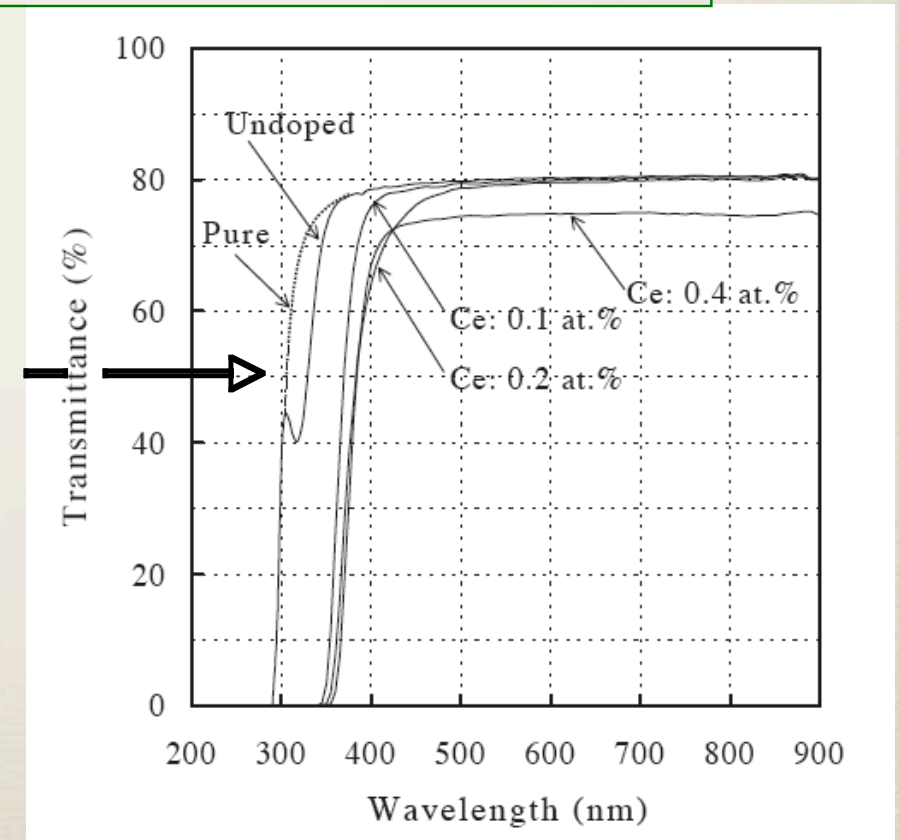
Harada et al., Jpn.J. Appl.Phys.Vol.40 (2001) 1360-1366

Kobayashi et al. Nim 205 (1983) 113-116

<u>Property</u>	<u>BSO</u>	<u>BGO</u>
Density( $\text{g}/\text{cm}^3$ )	6.80	7.13
Peak emission (nm)	480	480
Relative LY	20	100
Refractive index	2.06	2.15
Decay constants (ns)	2.4 (6%), 26(12%), 99(82%)	5.2 (2%), 45(9%), 279(89%)
$d(\text{LY})/dT(\%K)$	-2	-1.5

Similar to BGO.

Main differences: smaller LY (20% of BGO), shorter decay time of scintillating light (dominating 100 ns), and slightly better transparency to Cherenkov light (absorption cutoff below 300 nm) (doping to shorten the decay time would increase absorption)

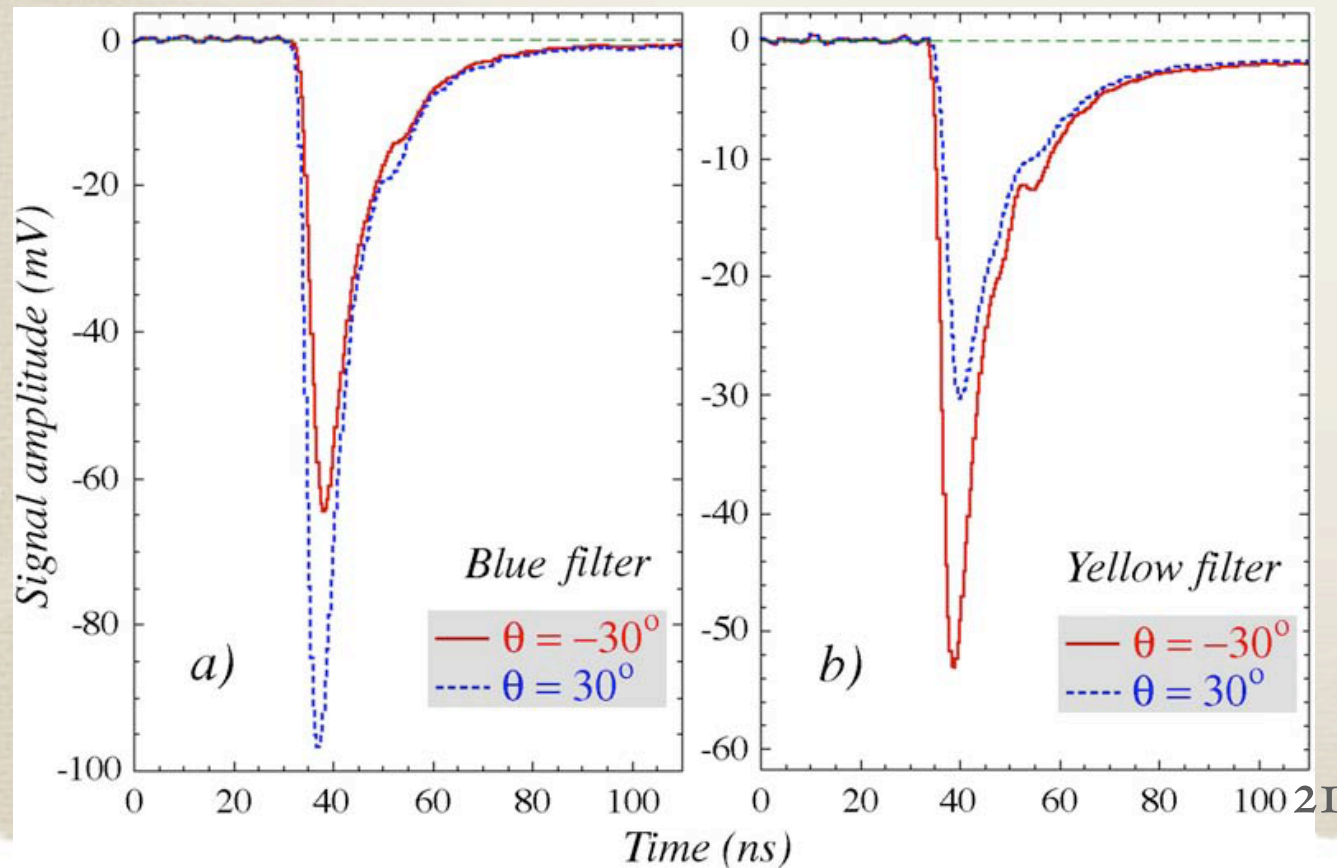
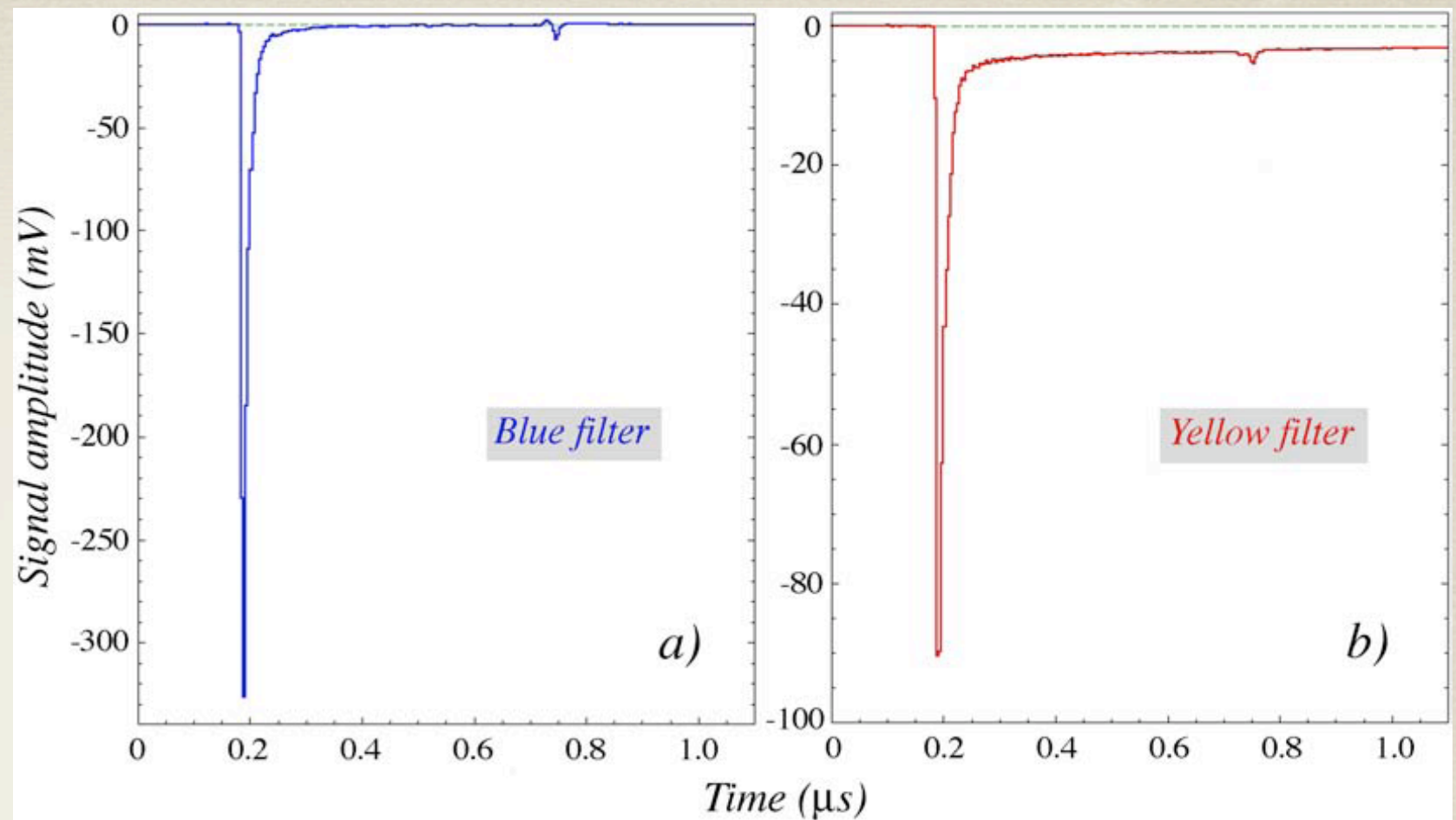




# PbWO<sub>4</sub>: Pr (0.5%): Time Spectra

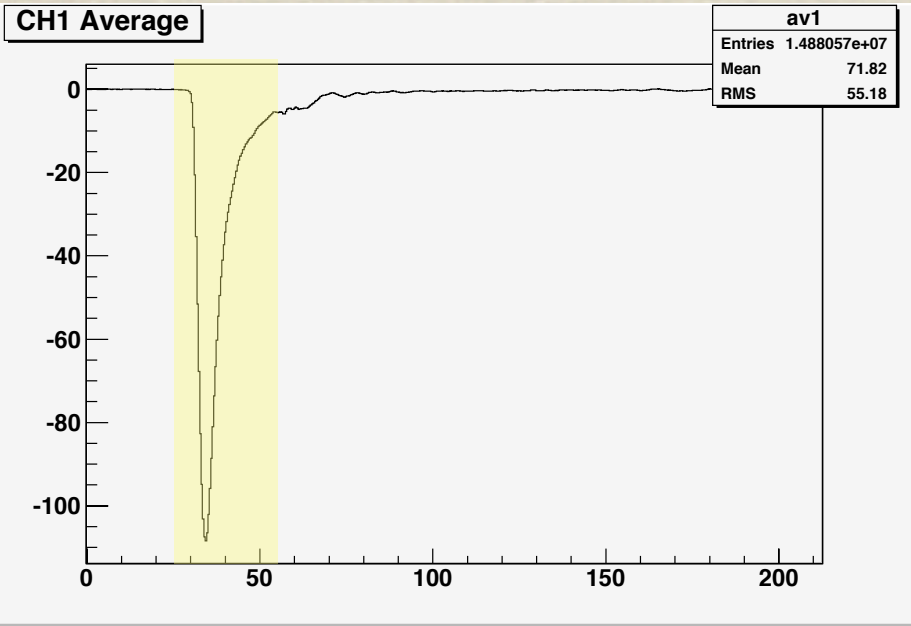
Very long tail ( $\mu\text{s}$ ) on S side (not good for fast calorimeters)....

Prompt peak also on the Yellow filter!



- \*Contamination of Cherenkov in the Scintillation signal
- \*Prompt peak at anti-cherenkov angle
- \*it shows a dependence of the rotation angle





# C/S ratio: results (II)

integration window effect

the smaller the integration window, the smaller the scintillation contamination

an optimization of the separation power is possible

$$\frac{(C/S)|_{30^\circ}}{(C/S)|_{-30^\circ}}$$

$$\frac{\int_{t_0}^t C}{\int_{t_0}^{t_{max}} C}$$

