OPTIMIZATION OF CRYSTALS FOR APPLICATIONS IN DUAL-READOUT CALORIMETRY

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on behalf of the Dream Collaboration

Dual Readout Method

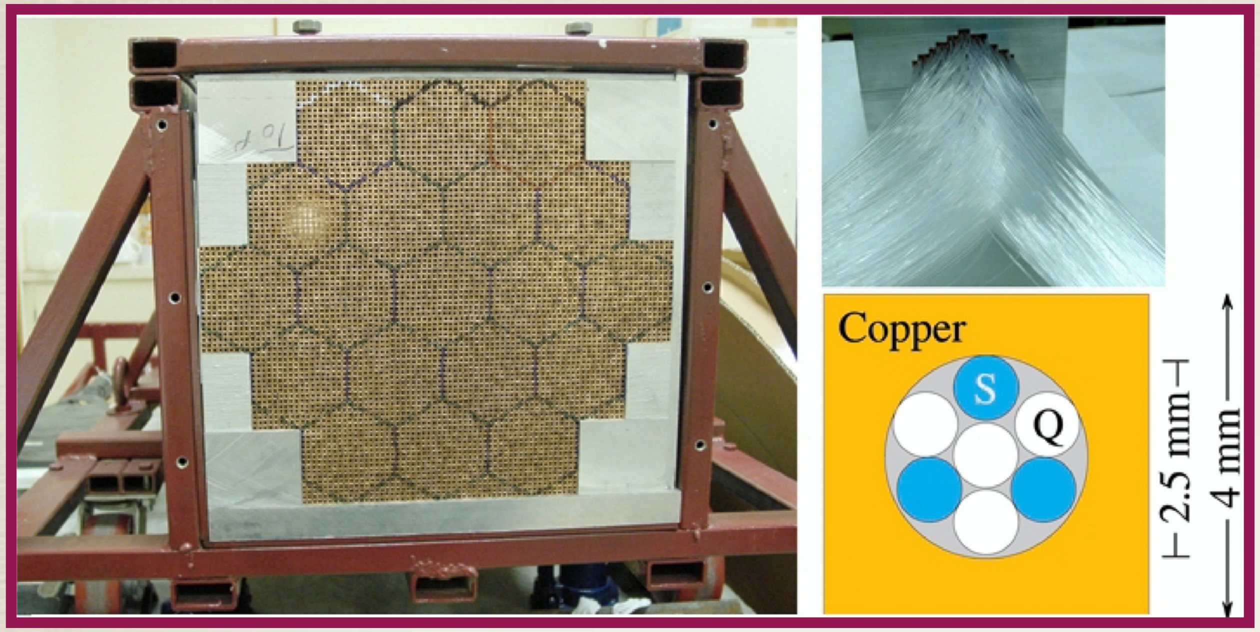
- Addresses the limiting factors of the resolution of hadron calorimetry with the aim of reaching the theoretical resolution limit (15%/√E) and in addition allows for
  - Calibration of an hadron calorimeter just with electrons
  - High resolution EM and HAD calorimetry
  - ILC/CLIC or Muon collider 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 (fem) of the hadron shower on event-by-event basis

Dual Readout Method

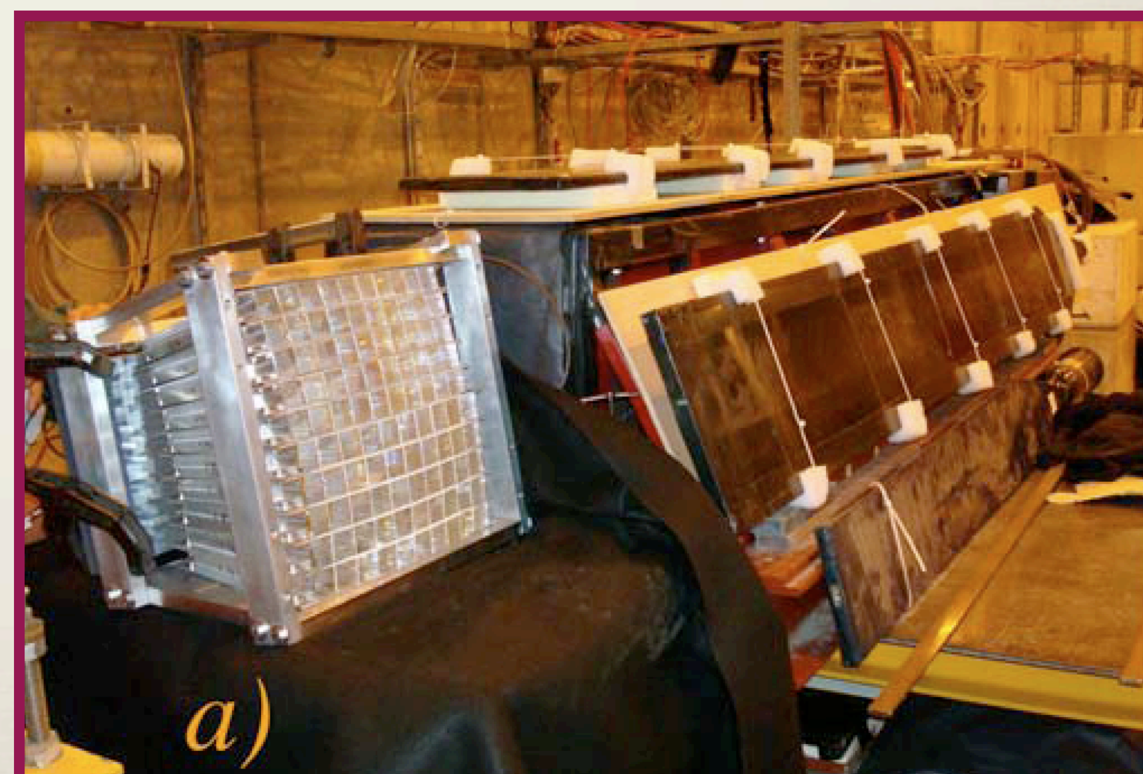


Quartz + scintillating fibers detector

- 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

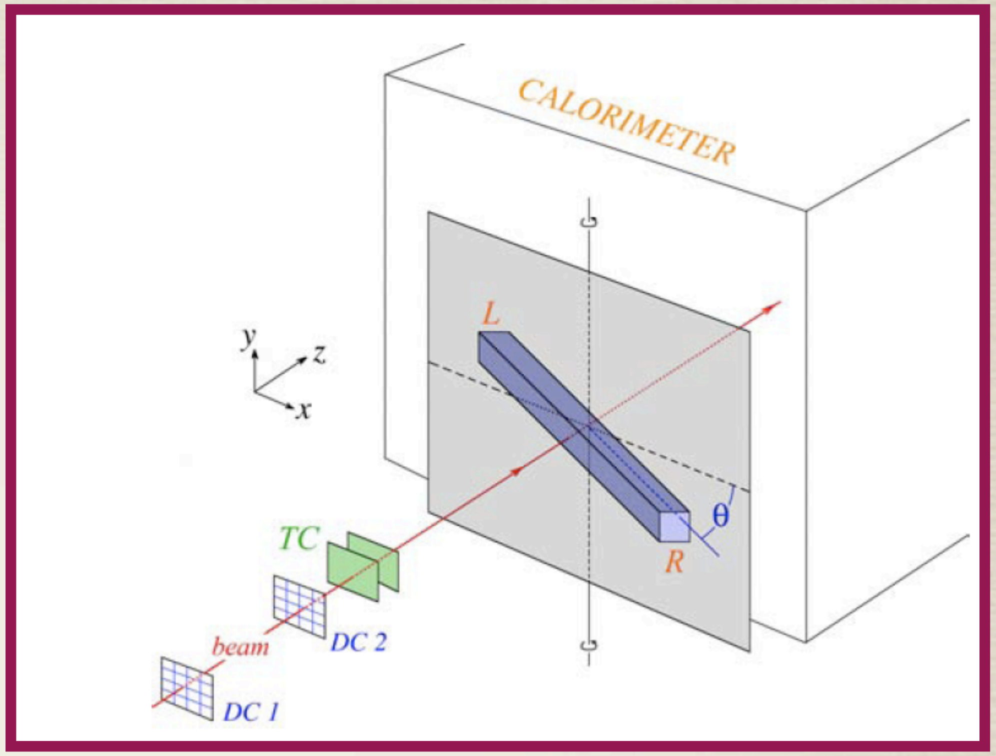
Crystal detector

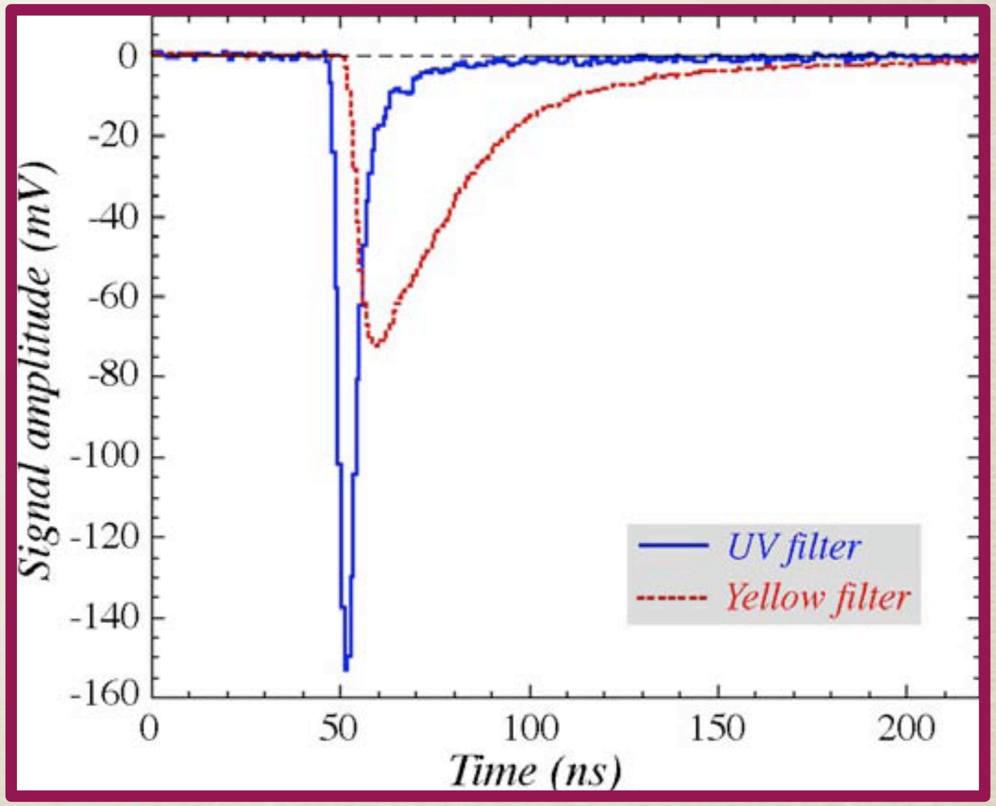
- C and S separated with different techniques (see later)
- optimal electromagnetic resolution
- hybrid system operated with a dual-readout technique allows to overcome e/h difference between the two types of detector and therefore maintain a good hadronic resolution (see **D. Pinci's** talk)



Čerenkov vs Scintillation

Properties	Čerenkov	Scintillation
Angular distribution	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
Time structure	Instantaneous, short signal duration (few ns)	Light emission is characterized by one or several time constants. Long tails are not unusual (slow component)
Optical spectra	λ^{-2} spectrum	Strongly dependent on the crystal type, usually concentrated in a (narrow) wavelength range
Polarization	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

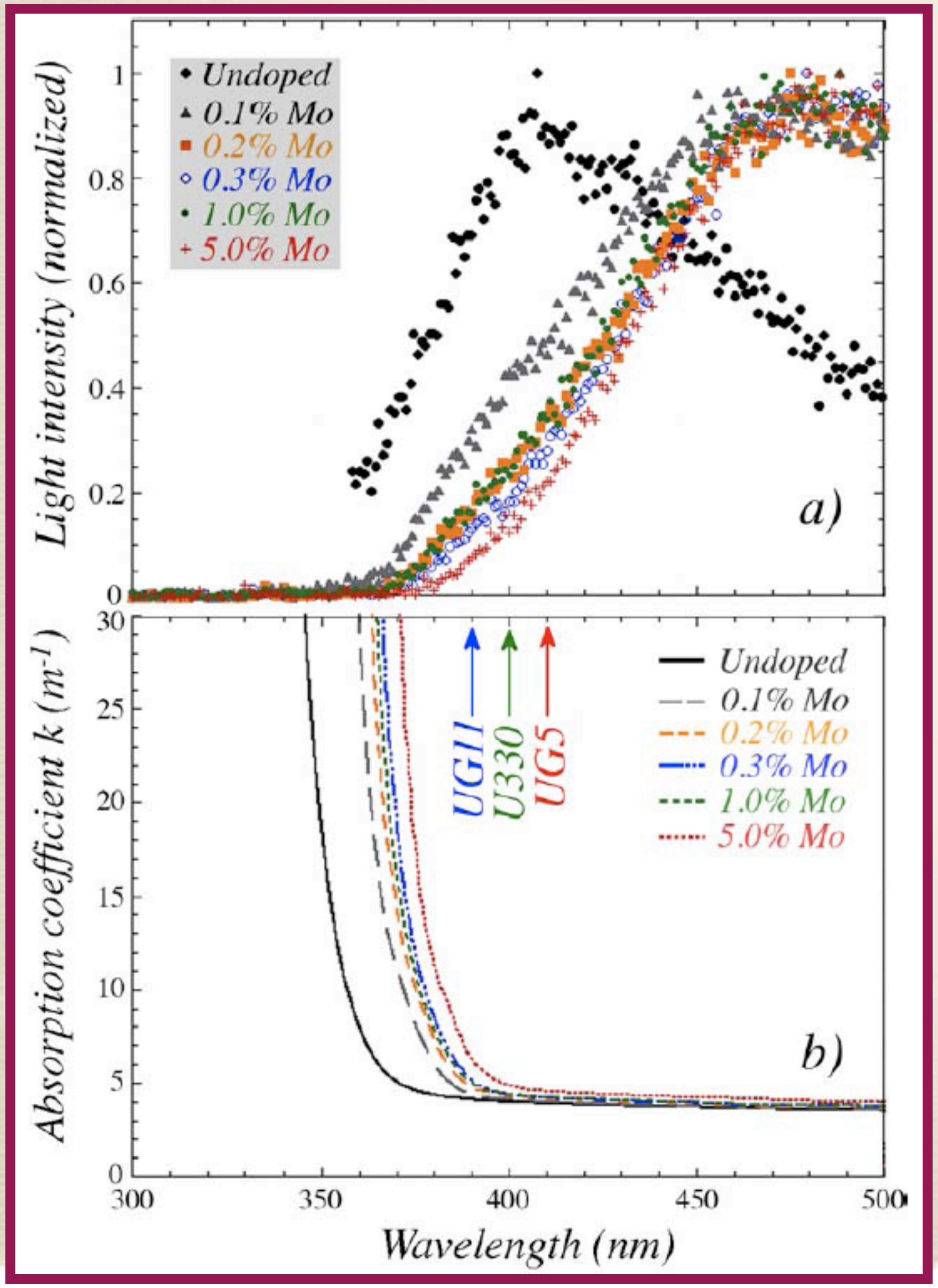
- PbWO4 crystals (N. Akchurin et al., NIM. A582 (2007), N. Akchurin et al., NIM A584 (2008), N. Akchurin et al., NIM A593 (2008))
- BGO (N. Akchurin et al., NIM. A598 (2009), N. Akchurin et al., NIM A598 (2009), N. Akchurin et al., NIM A 610 (2009))
- Doped PbWO4 crystals [Praseodymium, Molybdenum] (N. Akchurin et al., NIM A604 (2009))

Mo:PbW0$_4$ Crystals

CRYSTALS TESTED

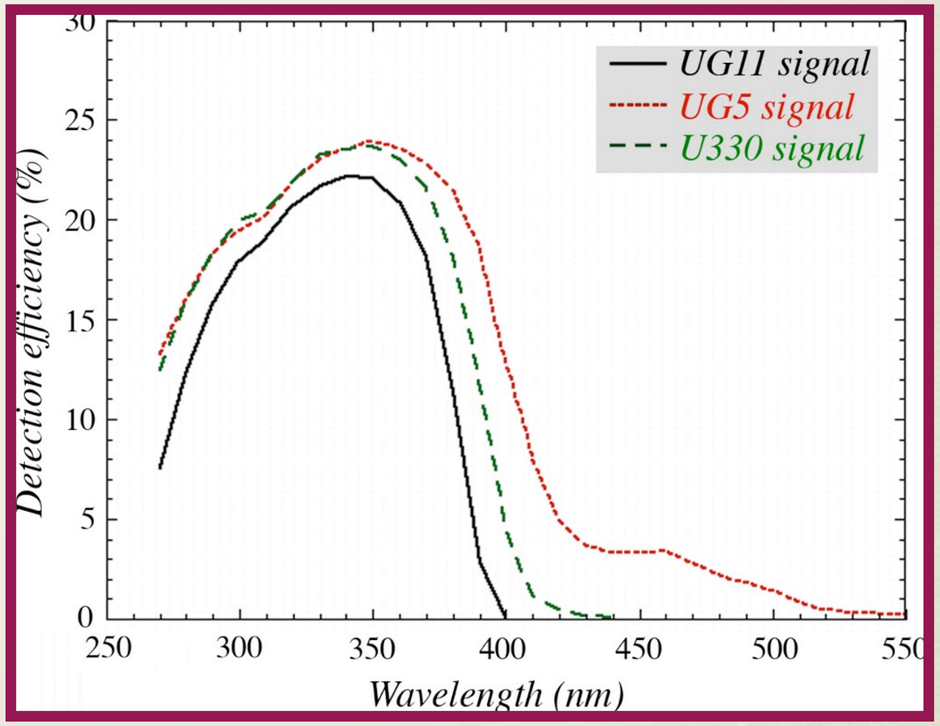
PbWO4 with 5 Mo dopant concentration

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



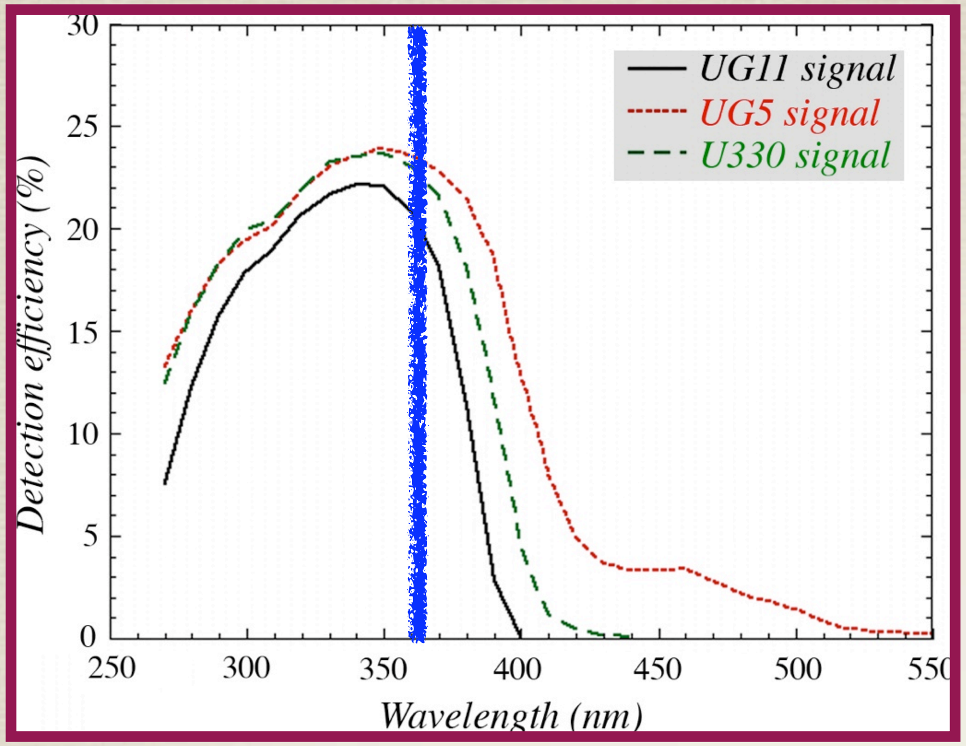
FILTERS

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

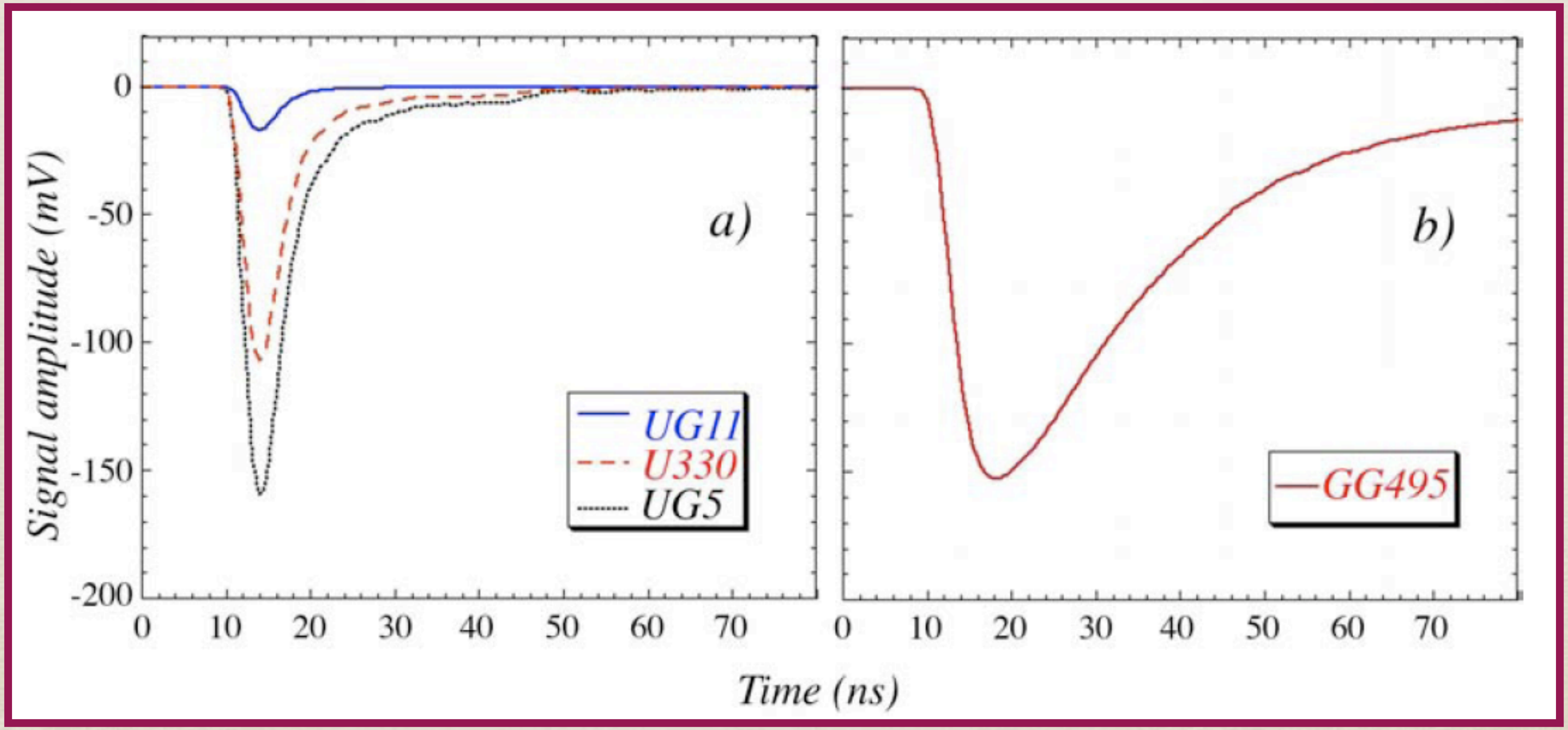


Detection efficiency of light exiting the crystal including optical transmission of the filter and the cookies and QE of the photocathode (Hamamatsu R8900U-100 SBA (36% QE))

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



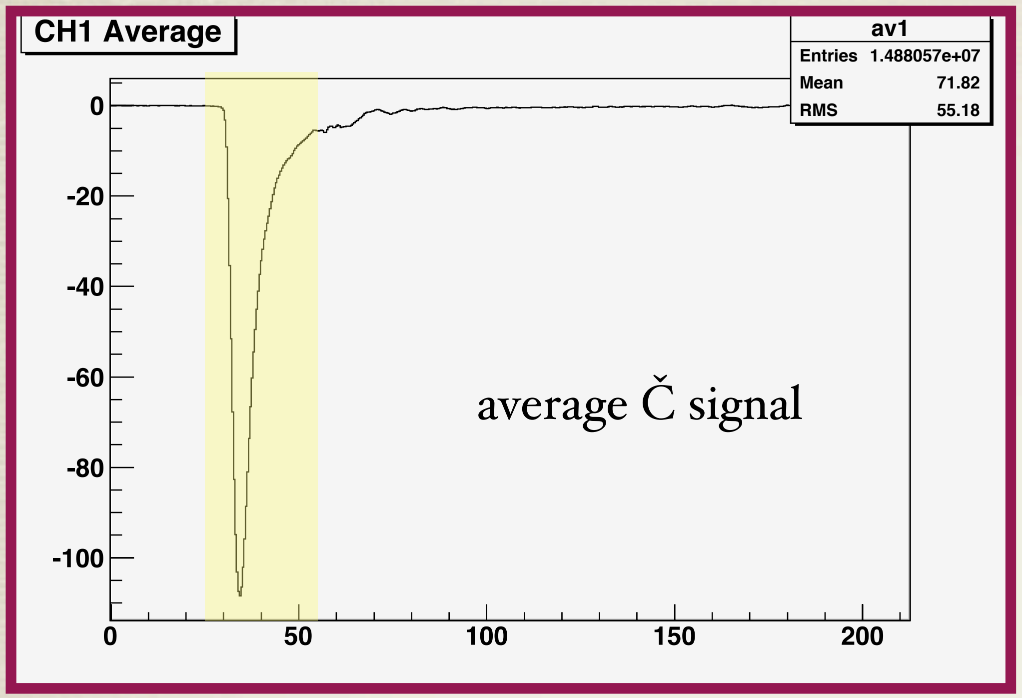
Crystals: what do we need?

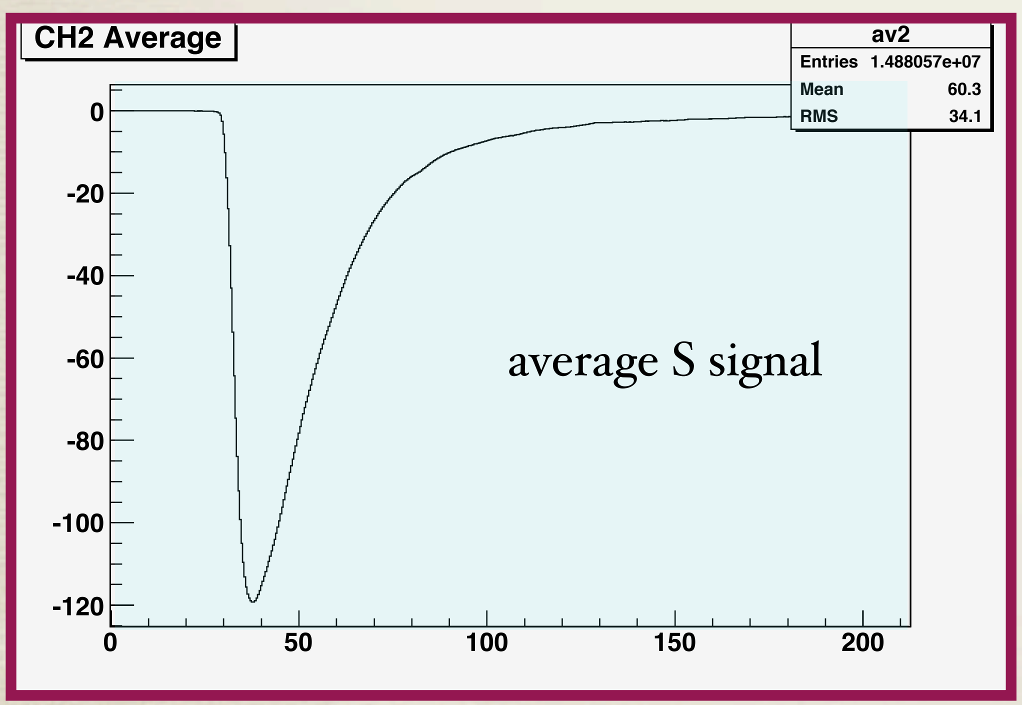
- Good Čerenkov vs Scintillation separation
- Response uniformity
- High light yield (to reduce contribution of p.e. fluctuation to the resolution)

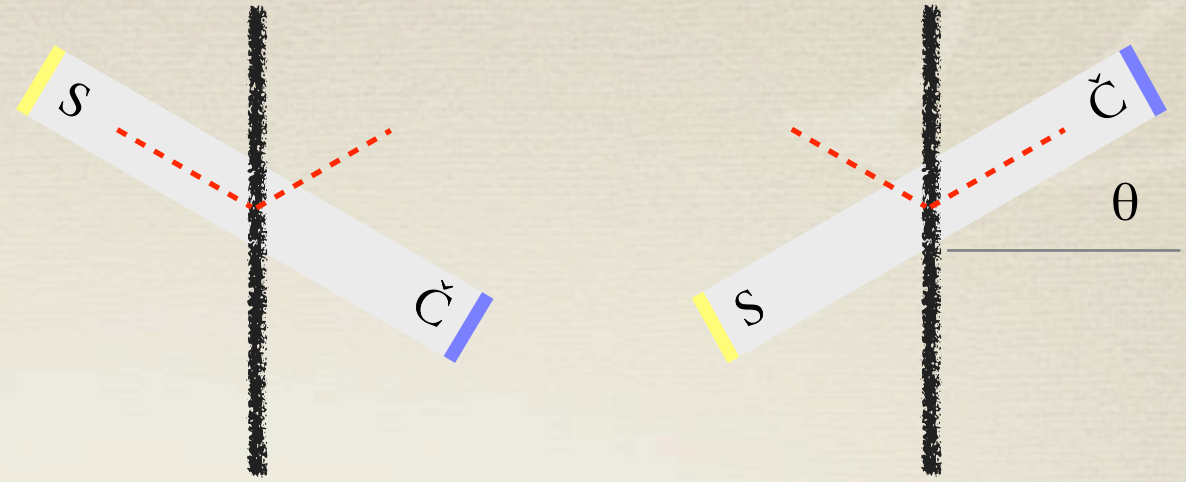
Figures of merit

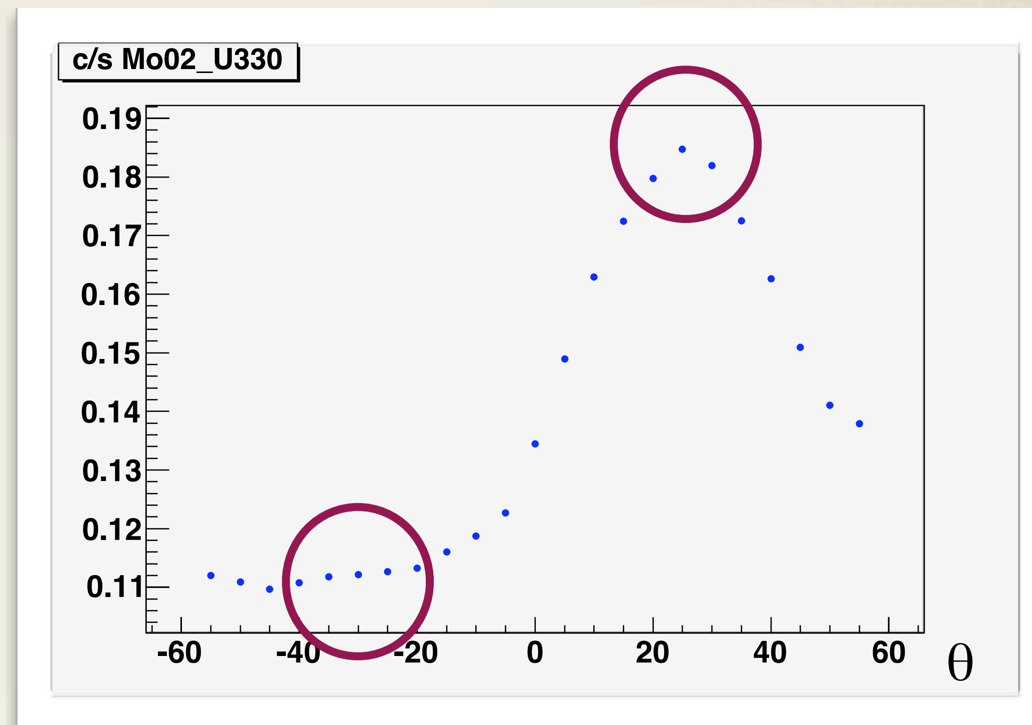
- C/S ratio (angular scan measurements)
- Light Attenuation (longitudinal scan measurements)
- Light yield measurements

C/S ratio



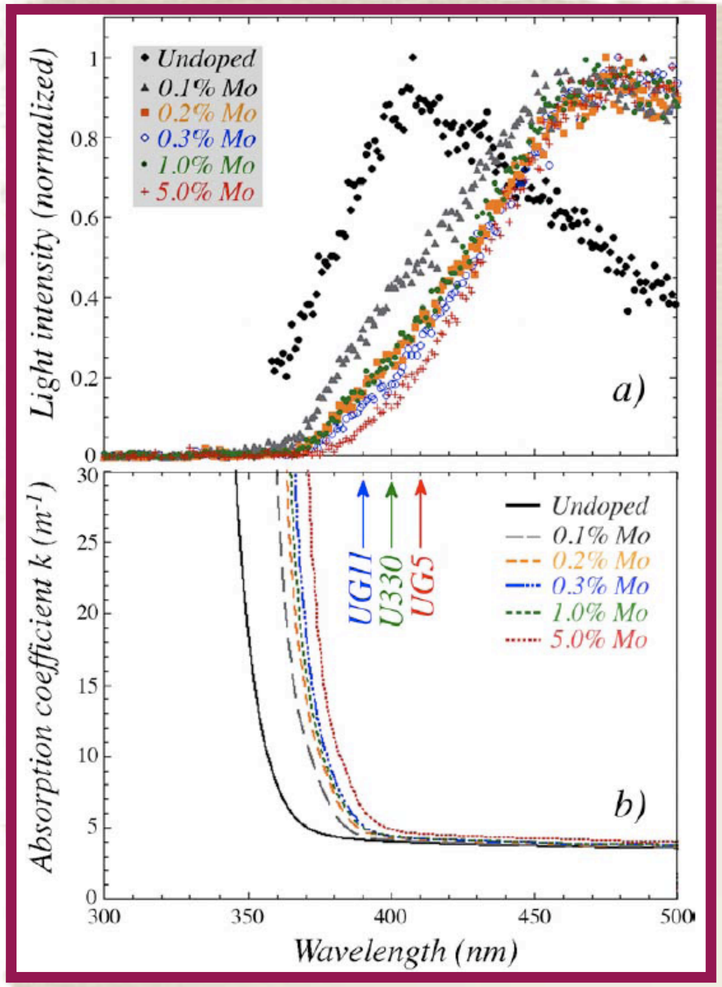




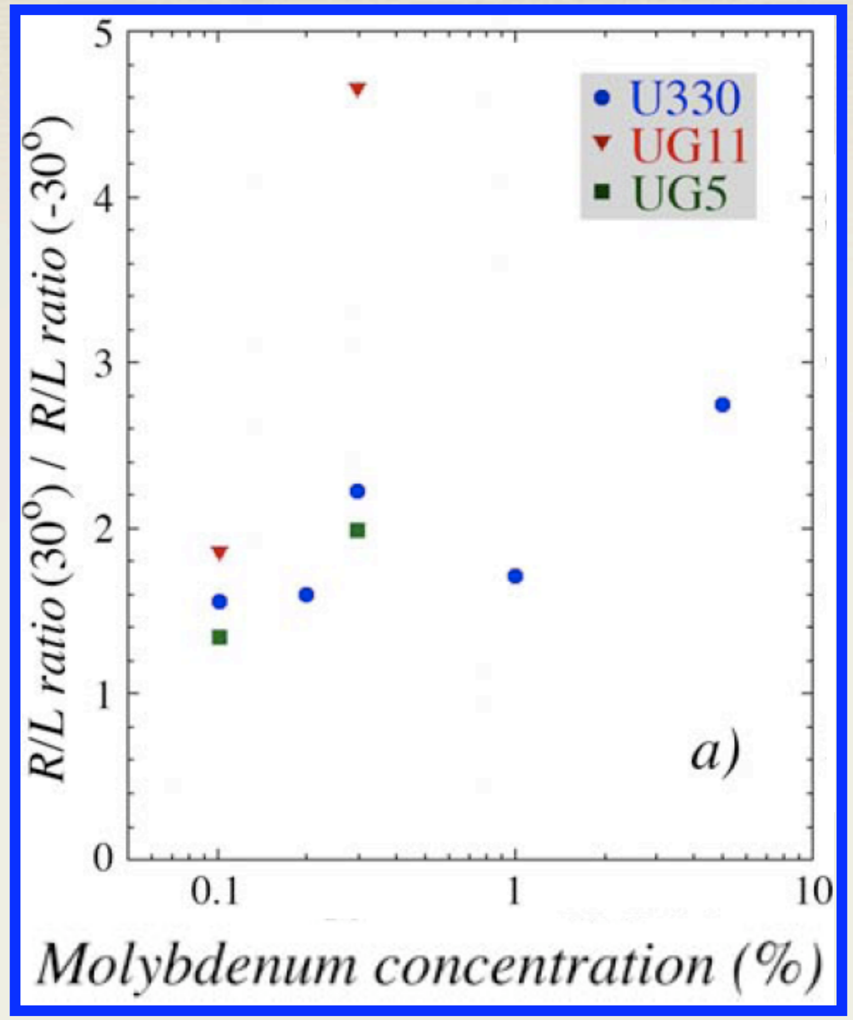


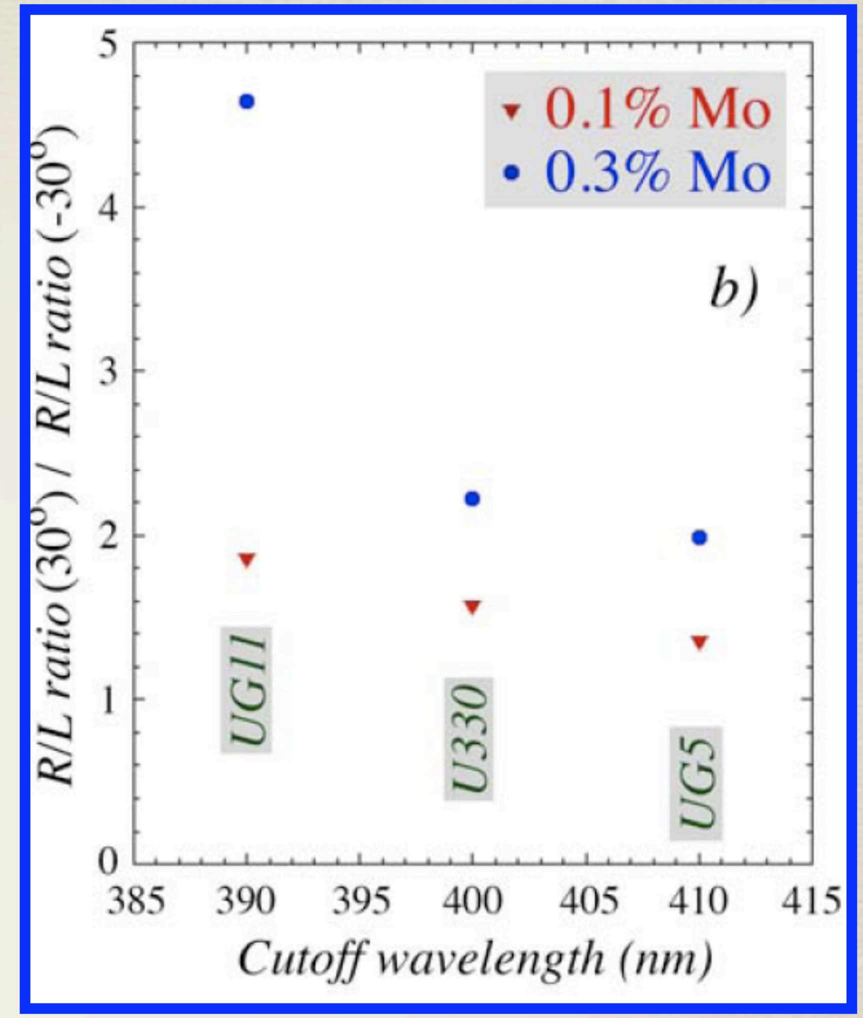
A figure of merit for separation power is the ratio of C/S at the Čerenkov angle and C/S at the anti-Čerenkov angle

$$\Pi = \frac{(C/S)|_{30^0}}{(C/S)|_{-30^0}}$$



C/S ratio: results





$$\Pi = \frac{(C/S)|_{30^0}}{(C/S)|_{-30^0}}$$

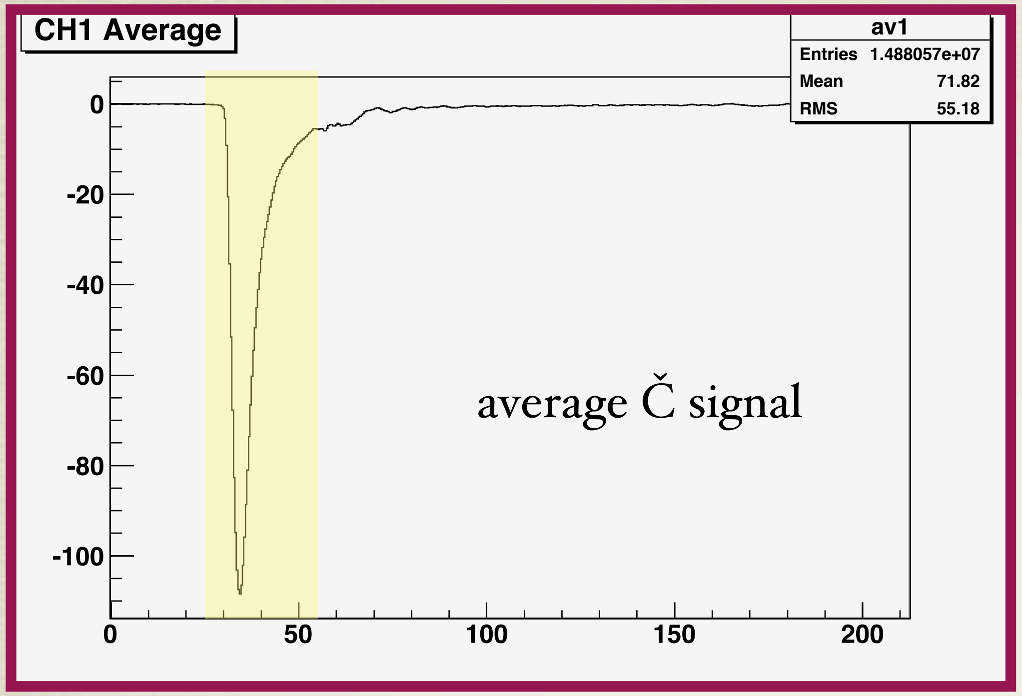
concentration effect

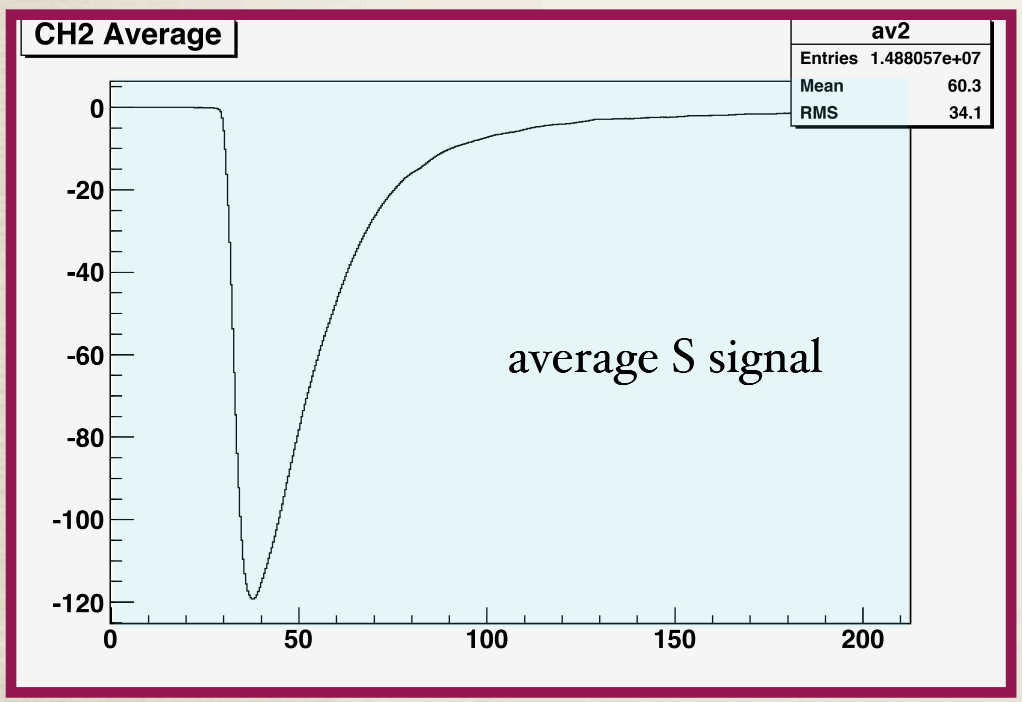
the lower the Mo concentration, the shorter the wavelength at which the scintillation emission starts: more contamination $\Rightarrow$ lower C/S ratio

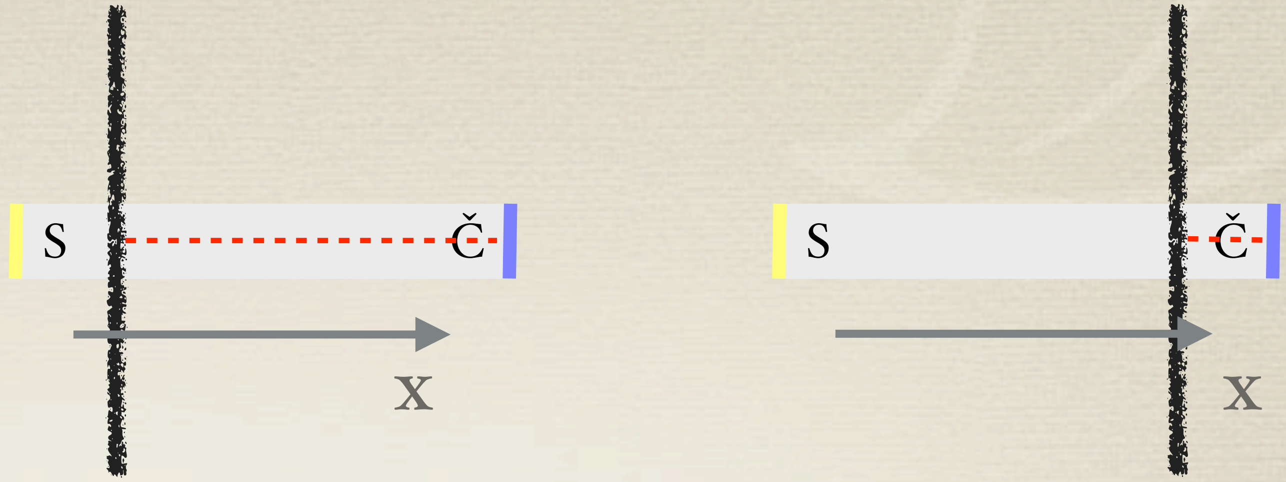
filter cut-off effect

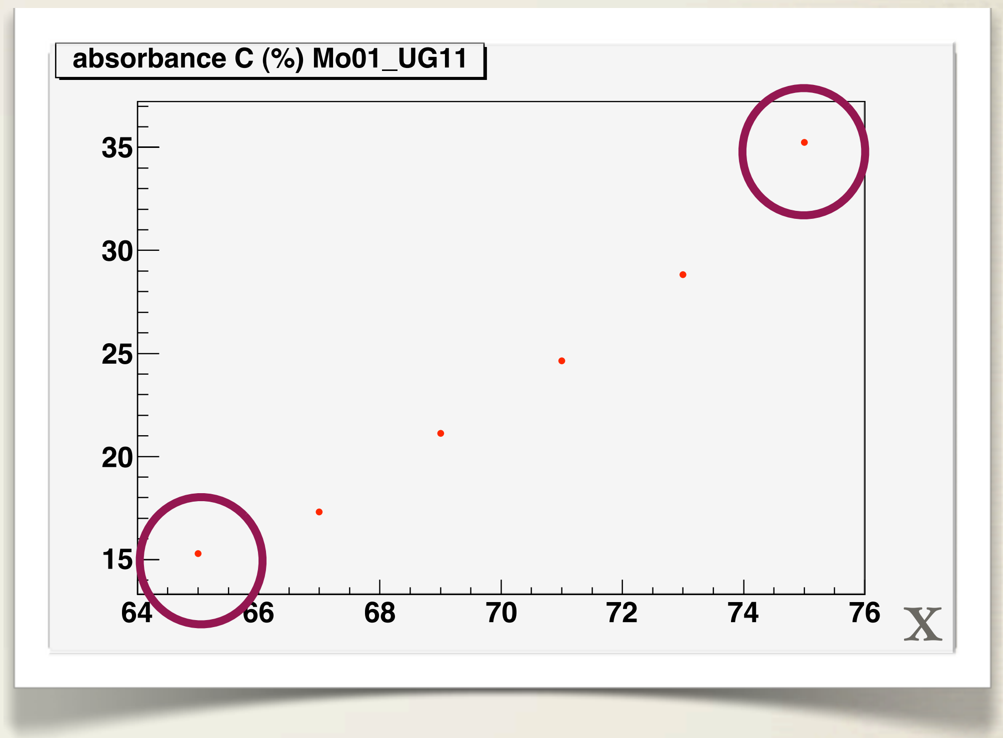
the lower the filter cut-off, the smaller the scintillation contamination, the larger the C/S ratio

Light Attenuation







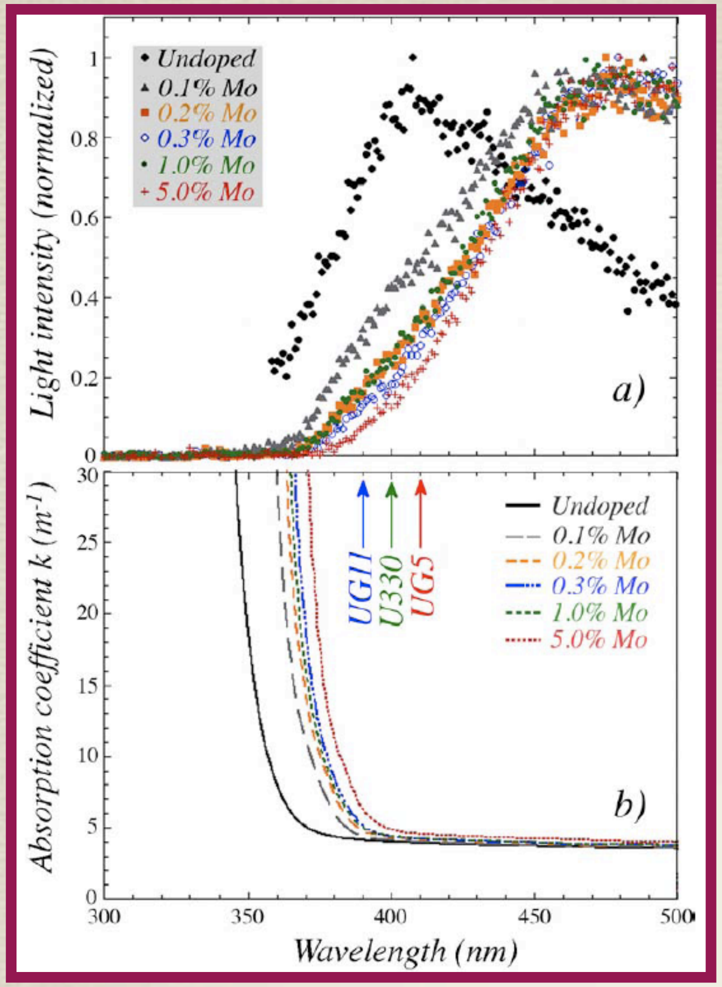


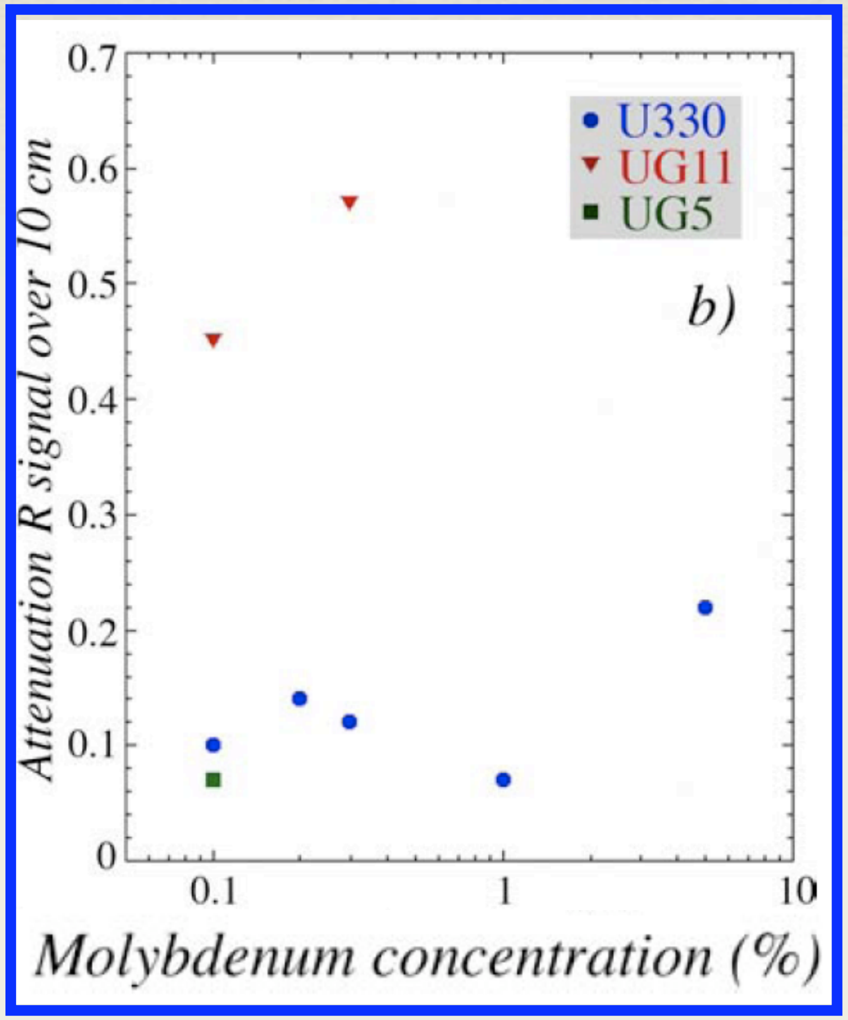
Signal loss (%) in 10 mm

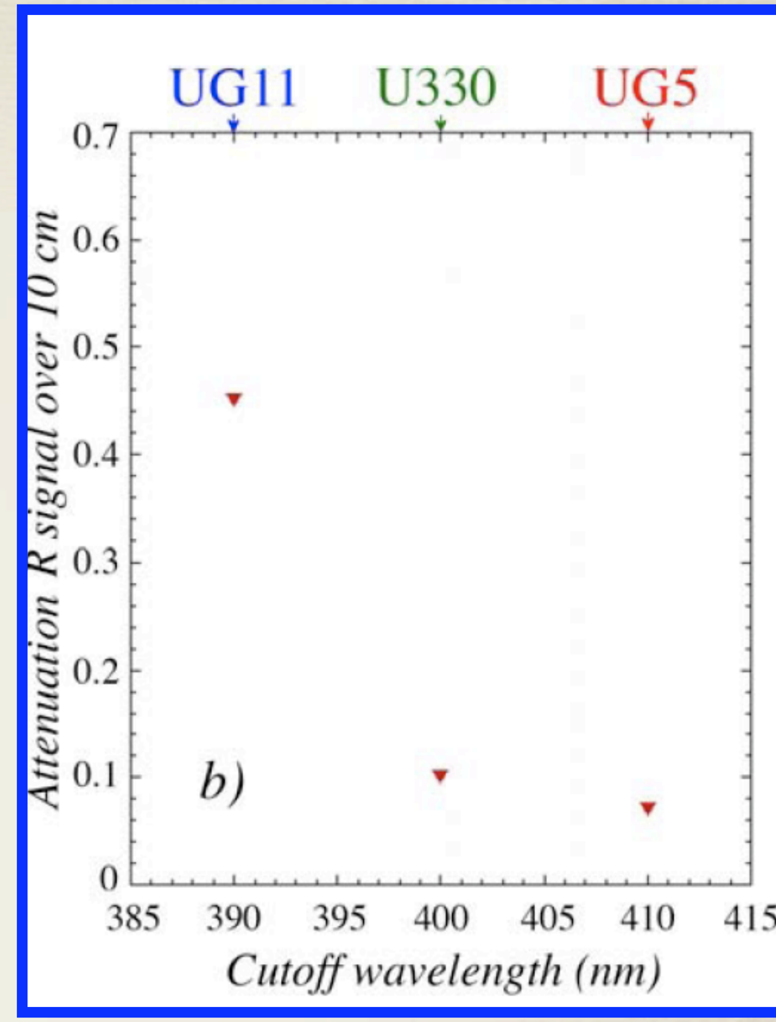
$$A = \frac{I(75) - I(65)}{I(75)}$$

- 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

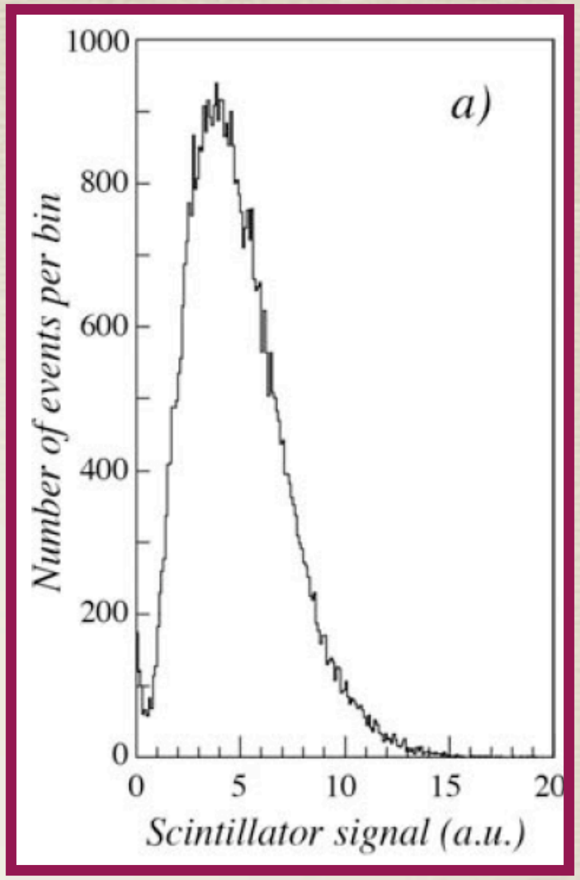
Čerenkov light yield

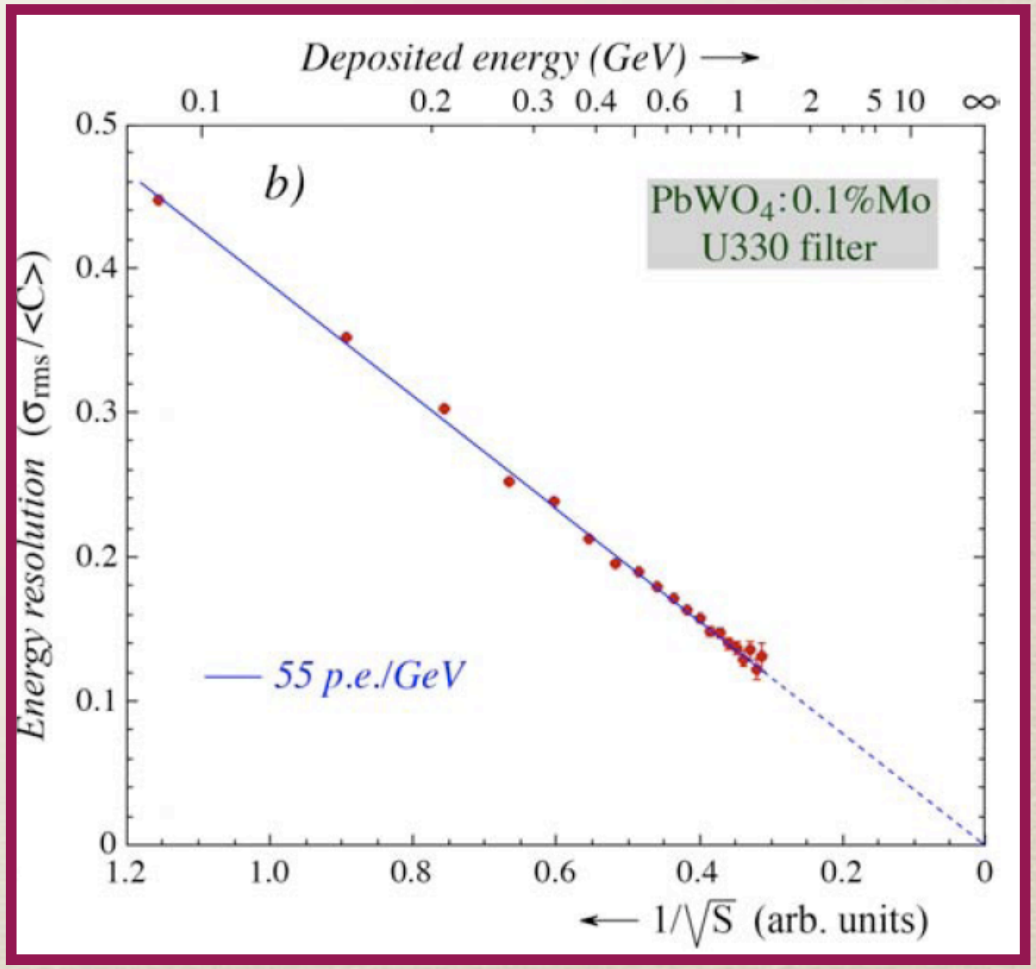
In order to measure the light yield we need to determine the energy deposited in the crystal

- 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

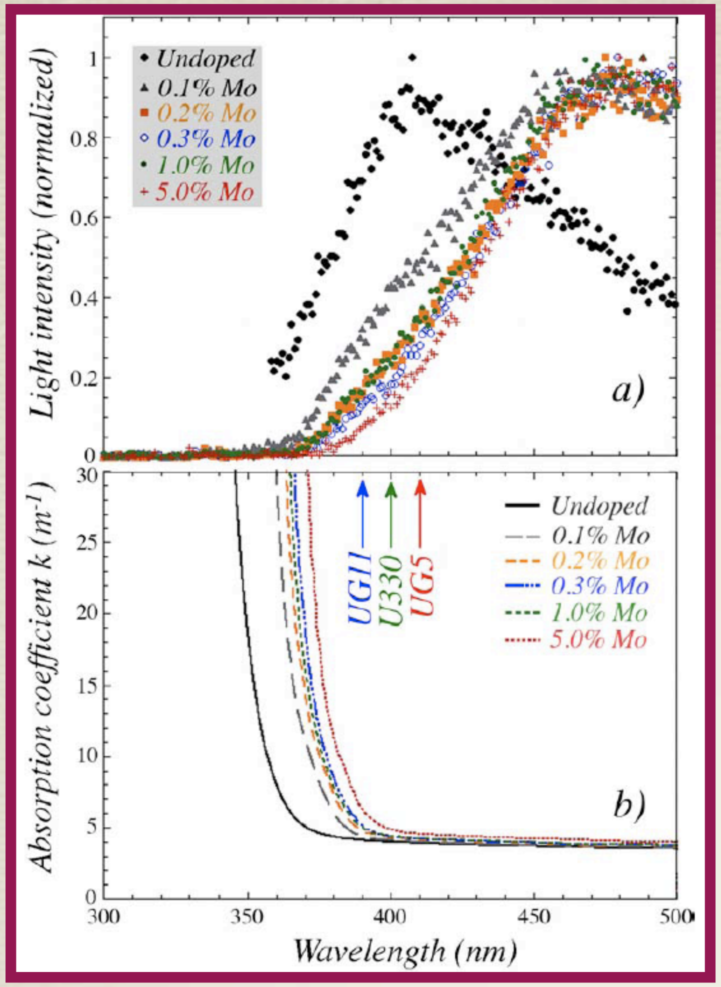
$$\frac{\sigma_c}{\mu_c} = p_0 + p_1 \frac{1}{\sqrt{S}} = \frac{1}{\sqrt{p.e.}}$$

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





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

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

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

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:PbWO4 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 wavelenghts and destroy or reflect the others

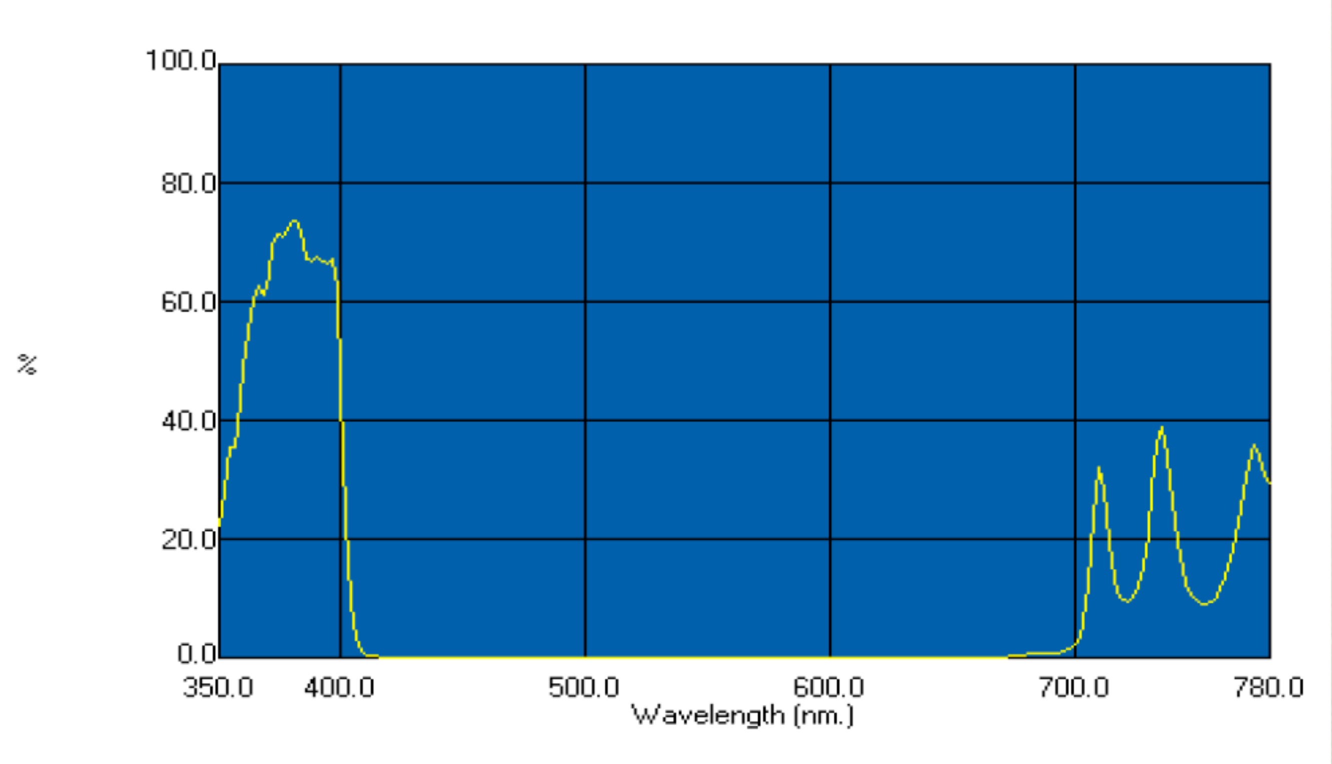
The filter can be customized and the transmission window can be finely tuned

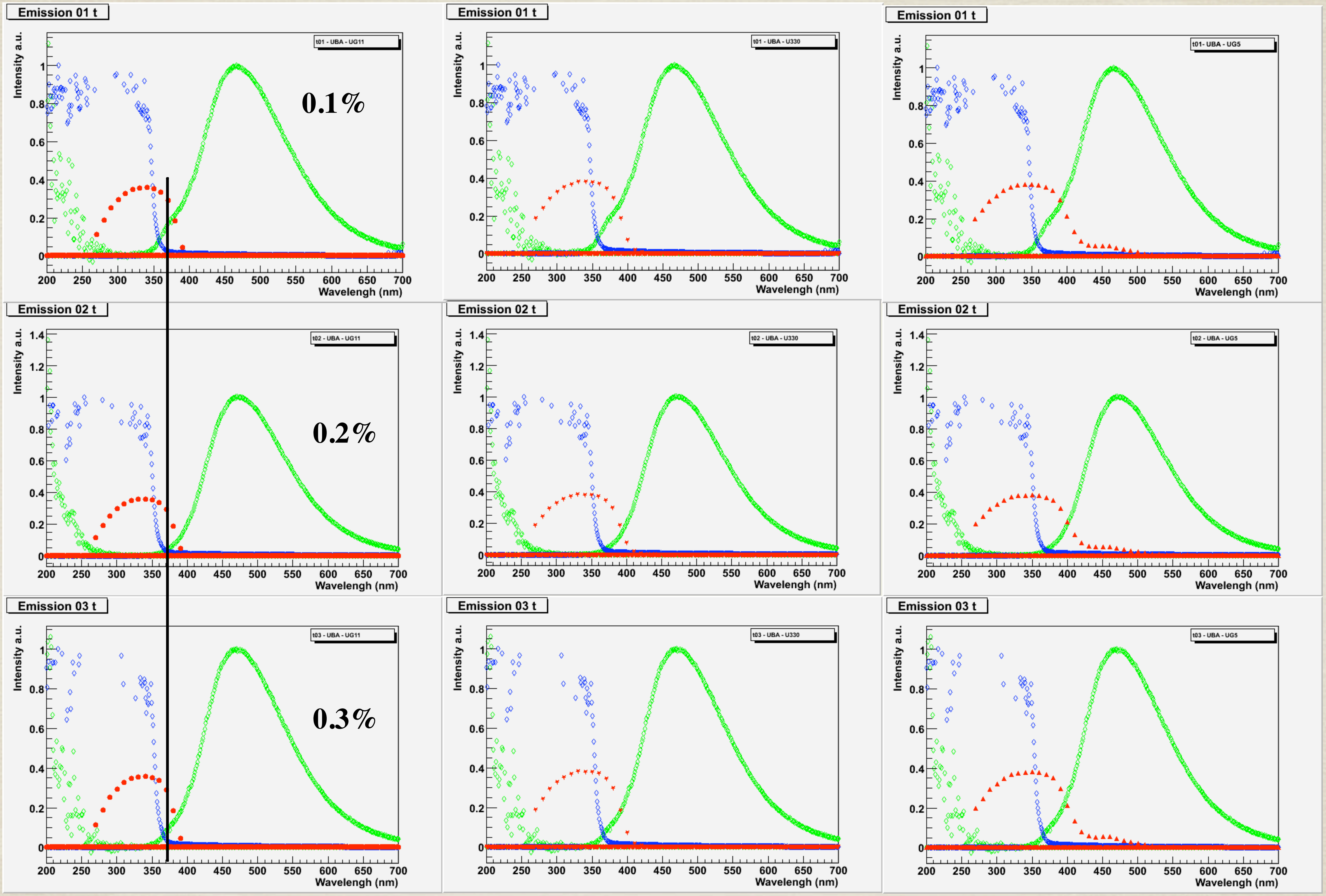
But the transmission depends on the incidence angle

Interference filter by ODL (Italy)

Transmission curve for normal incidence

For angles larger than 15^0 from the normal the transmission region shifts towards shorter w.l.





UG11 **U-330** **UG5**

BSO (bismuth silicate, $Bi_4Si_3O_{12}$)

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

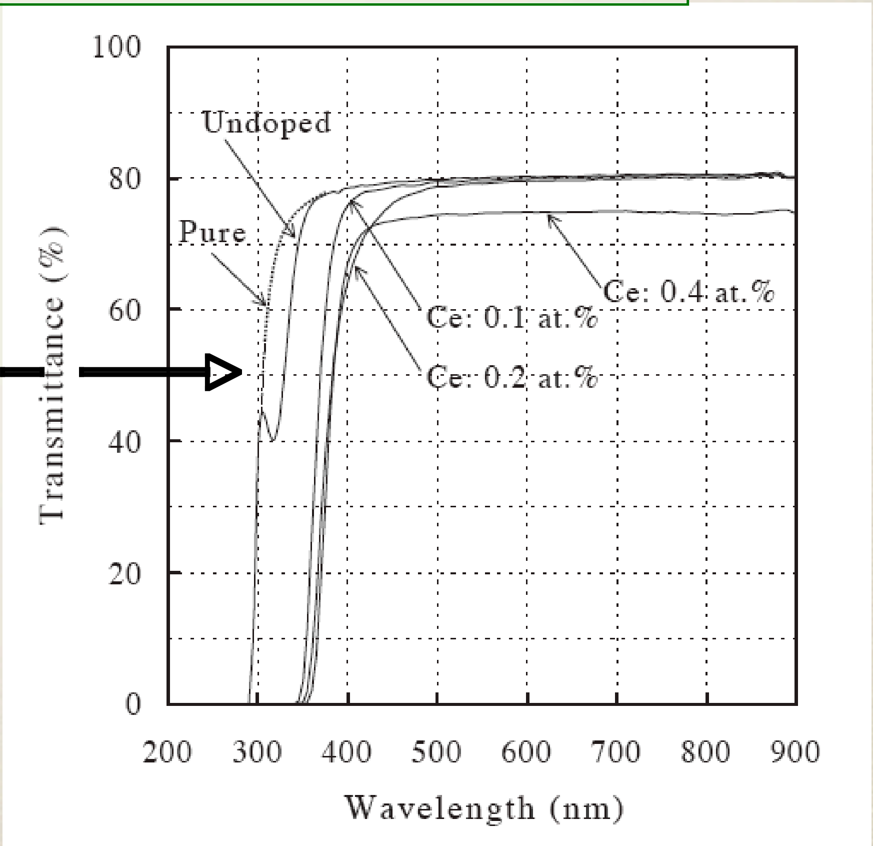
Kobayashi et al. Nim 205 (1983) 113-116

Property	BSO	BGO
Density(g/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(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 tranparency to Cherenkov light (absorption cutoff below 300 nm)

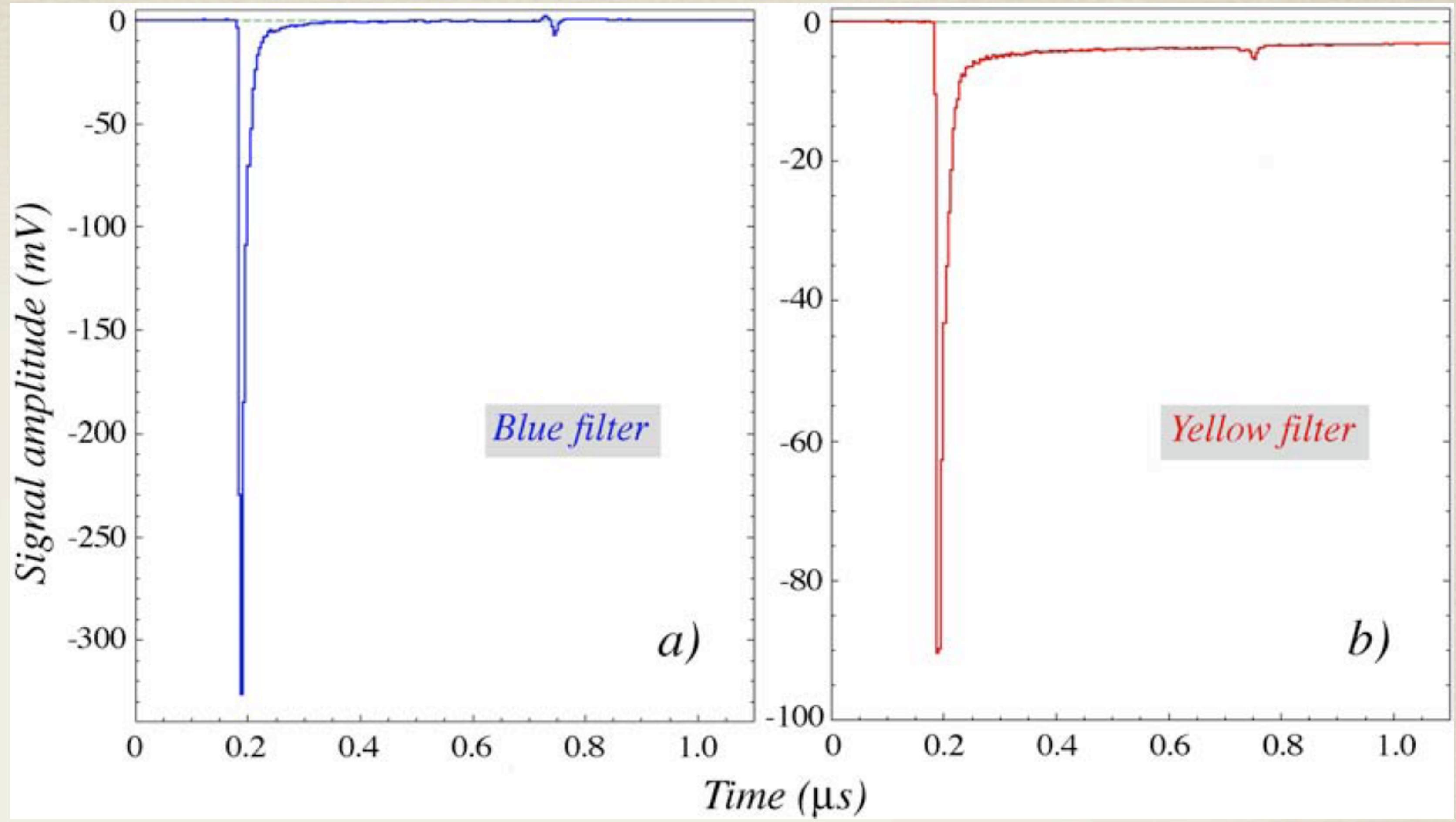
(doping to shorten the decay time would increase absorption)

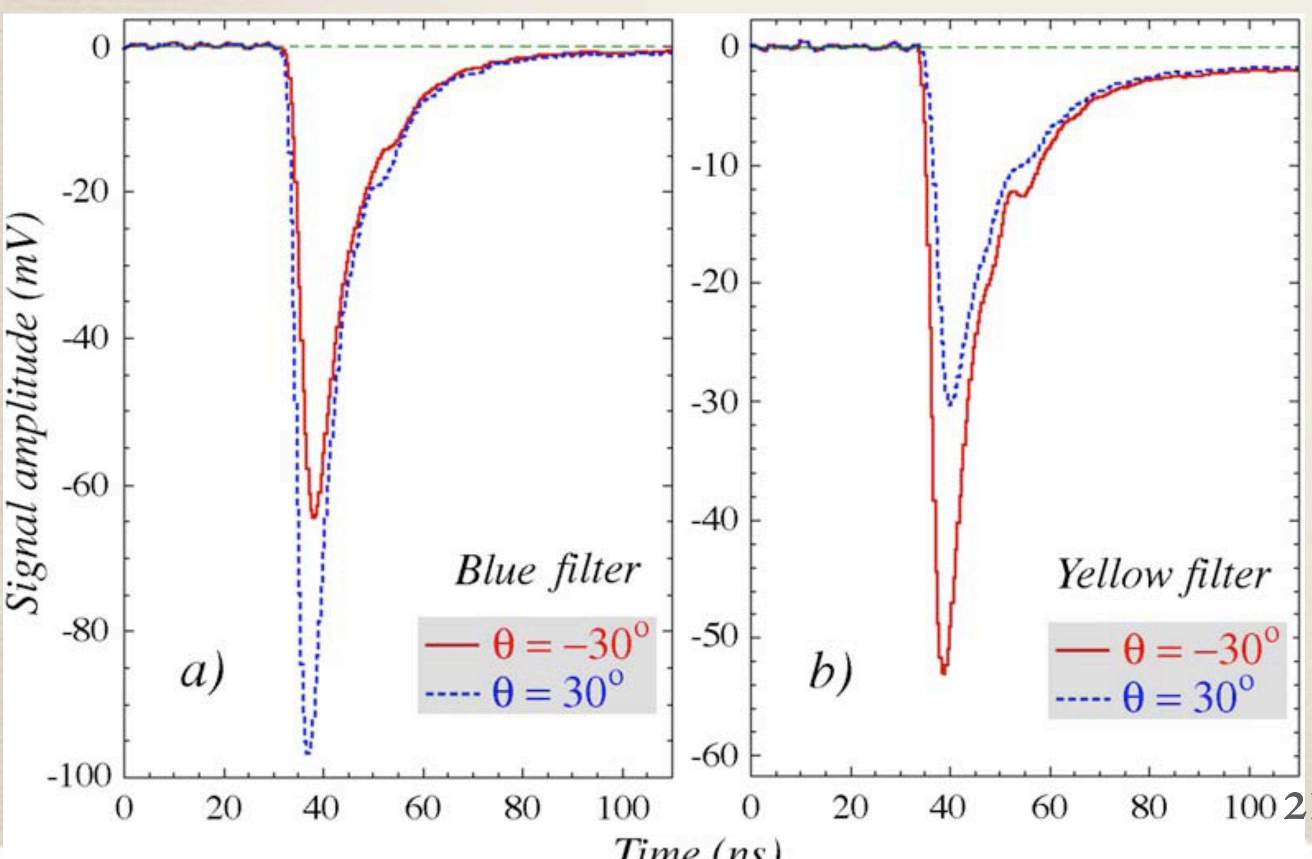


$PbWO_4$: Pr (0.5%): Time Spectra

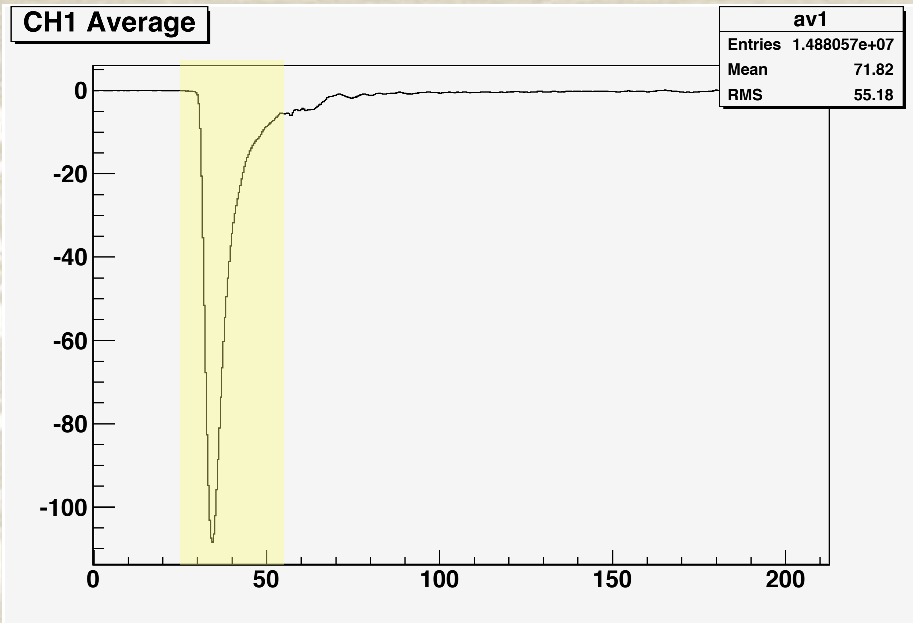
Very long tail (μs) on S side (not good for fast calorimeters)....

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

$$\frac{(C/S)|_{30^0}}{(C/S)|_{-30^0}}$$

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