Review of past DREAM work on dual-readout crystals

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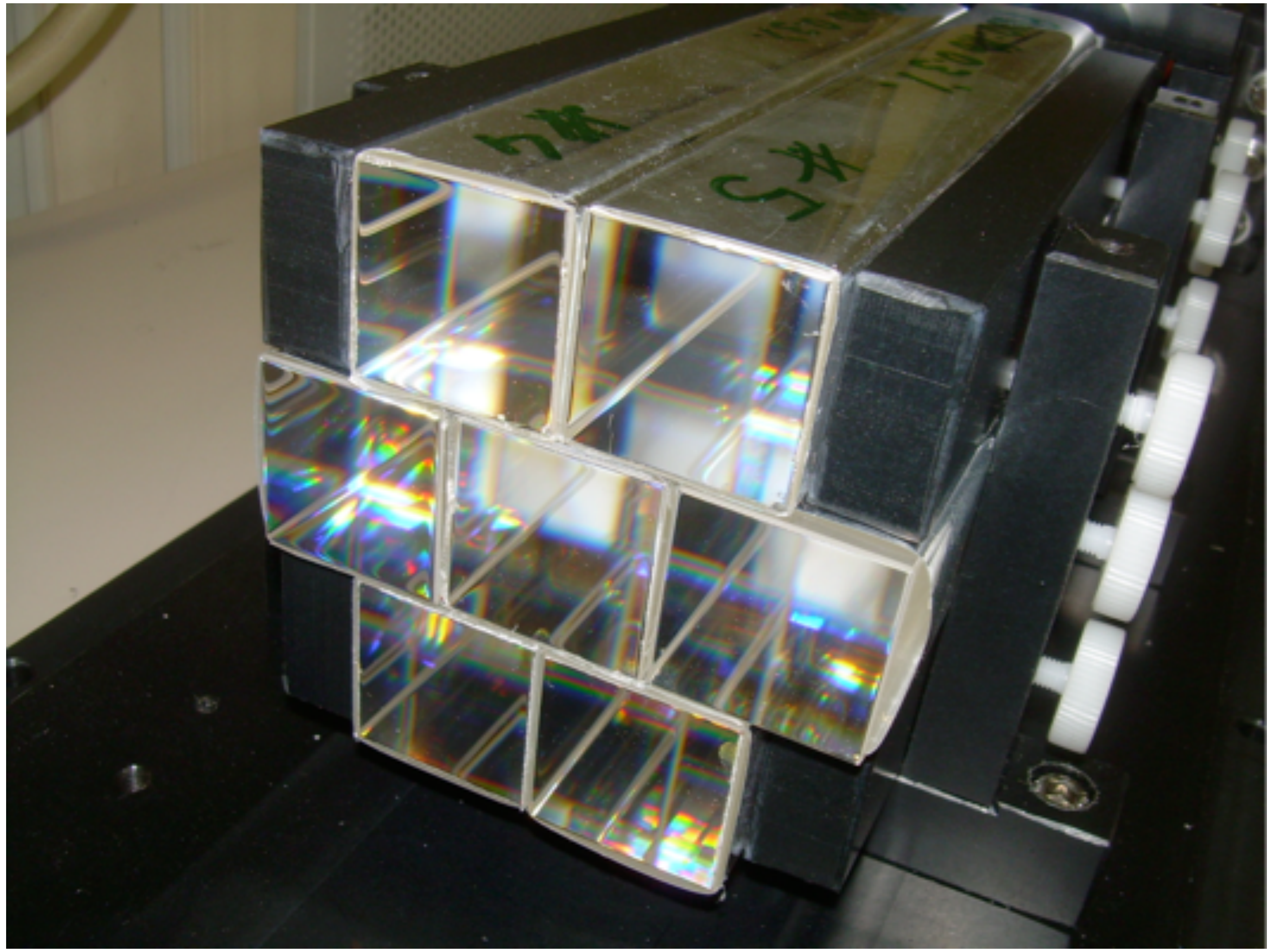
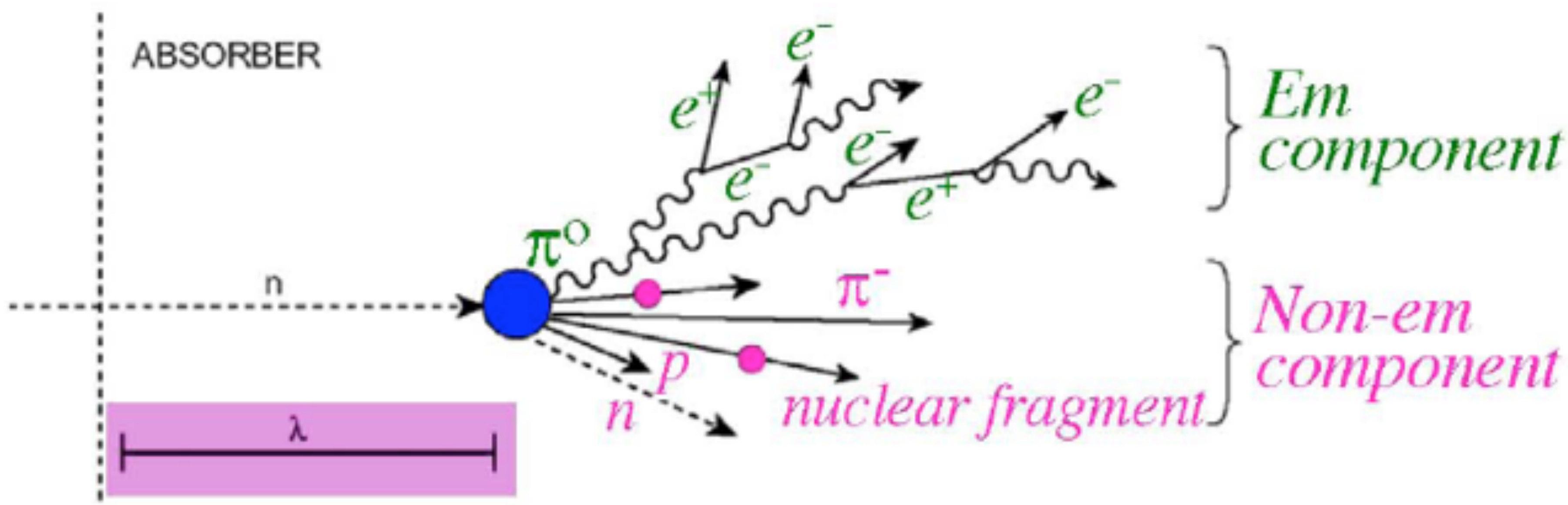


Dual-readout in a nutshell

electrons positrons, photons, π^0



Charged hadrons (π,k…), nuclear fragments, neutrons, neutrinos, breakup of nuclei (invisible energy)

Cherenkov light (C)	only produced by relativistic particles, dominated by electromagnetic shower component
Scintillation light (S)	measure dE/dx

Measure the electromagnetic fraction event by event to equalize the response off-line

- **Compensation** achieved without construction constraints
- **Calibration** of a hadron calorimeter just with electrons
- **High resolution** EM and HAD calorimetry

Dual-readout in a nutshell

Simultaneous measurement on event-by-event basis of em fraction of hadron showers

$$S = [\ f_{em} + (h/e)_s \times (1 - f_{em})\ ] \times E$$
$$C = [\ f_{em} + (h/e)_c \times (1 - f_{em})\ ] \times E$$

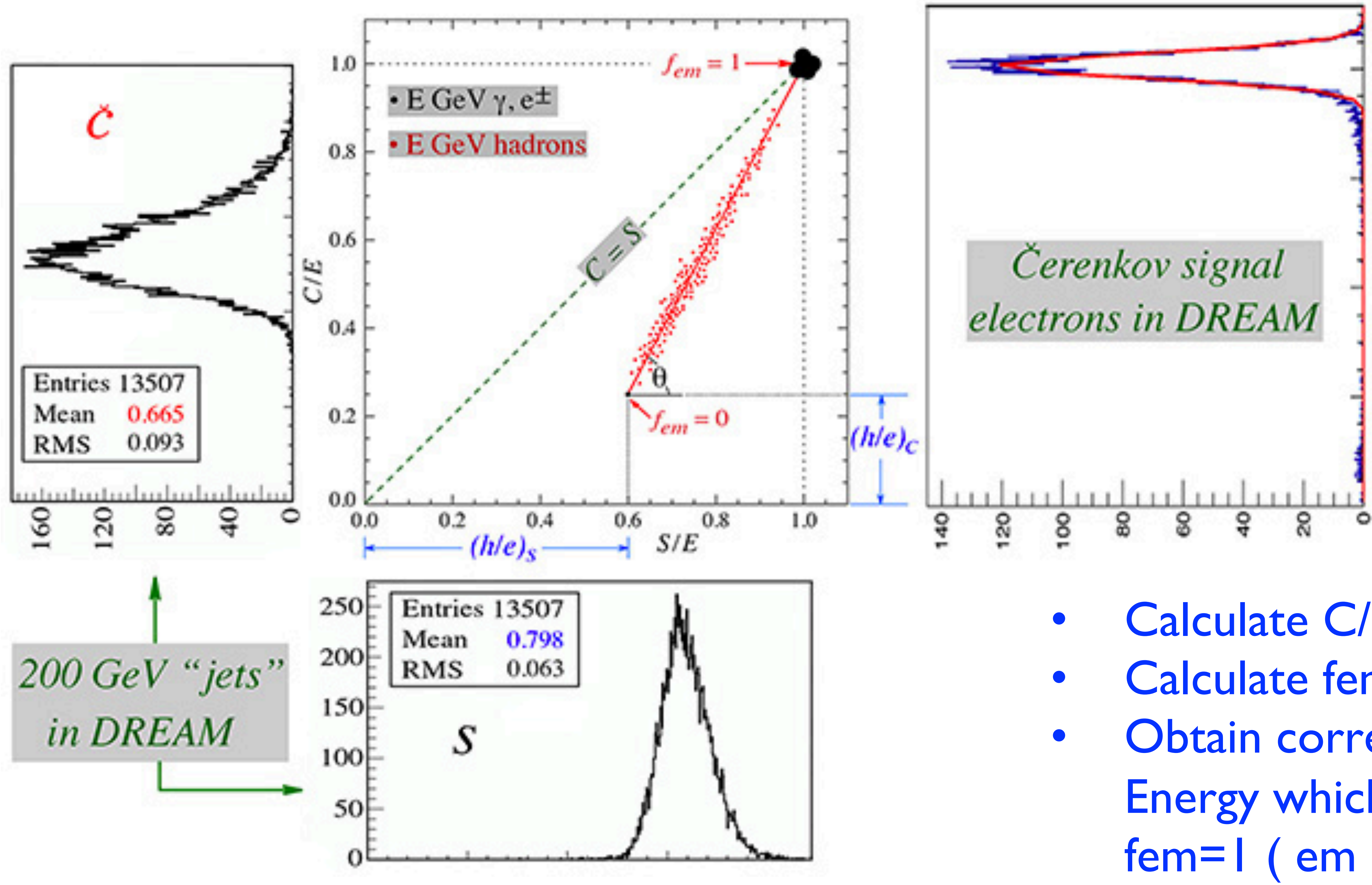
$$cotg\,\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

e/h ratios (c = $(h/e)_c$ and s = $(h/e)_s$ for either Cherenkov or scintillation structure) can be measured

Θ and χ are independent of both energy and particle type

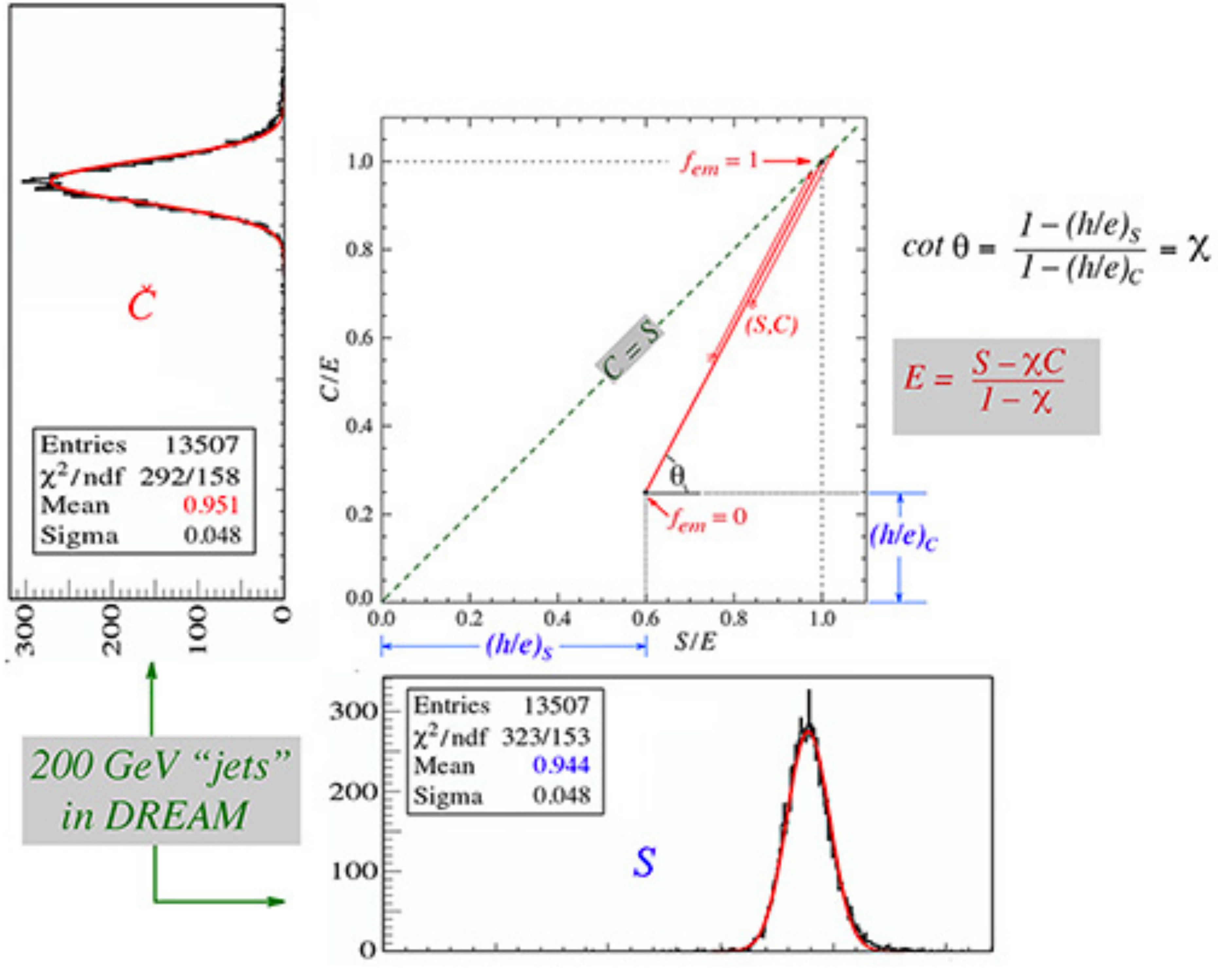
It is possible to evaluate $$f = \frac{c - s(C/S)}{(C/S)(1-s) - (1-c)}$$ and $$E = \frac{S - \chi C}{1 - \chi}$$

Before Correction



- Calculate C/S ratio event-by-event
- Calculate fem
- Obtain corrected C and S and Energy which one would obtain if fem=1 (em scale calibration)

Dual-Readout approach at work



$$\cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

$$E = \frac{S-\chi C}{1-\chi}$$

Motivation for Crystal calorimeters

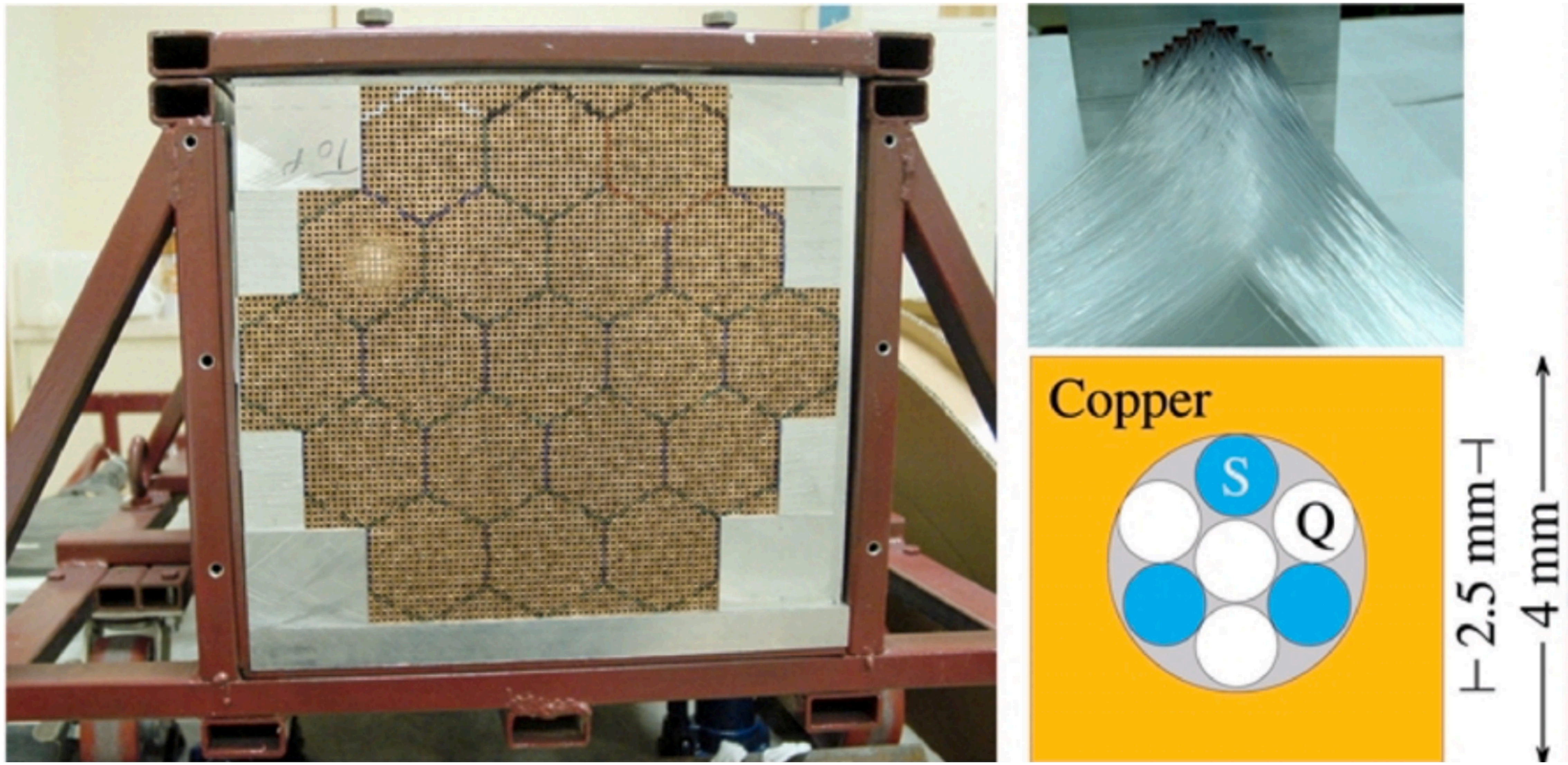
Original DREAM module showed a quite low Cherenkov photostatistic

8p.e./GeV

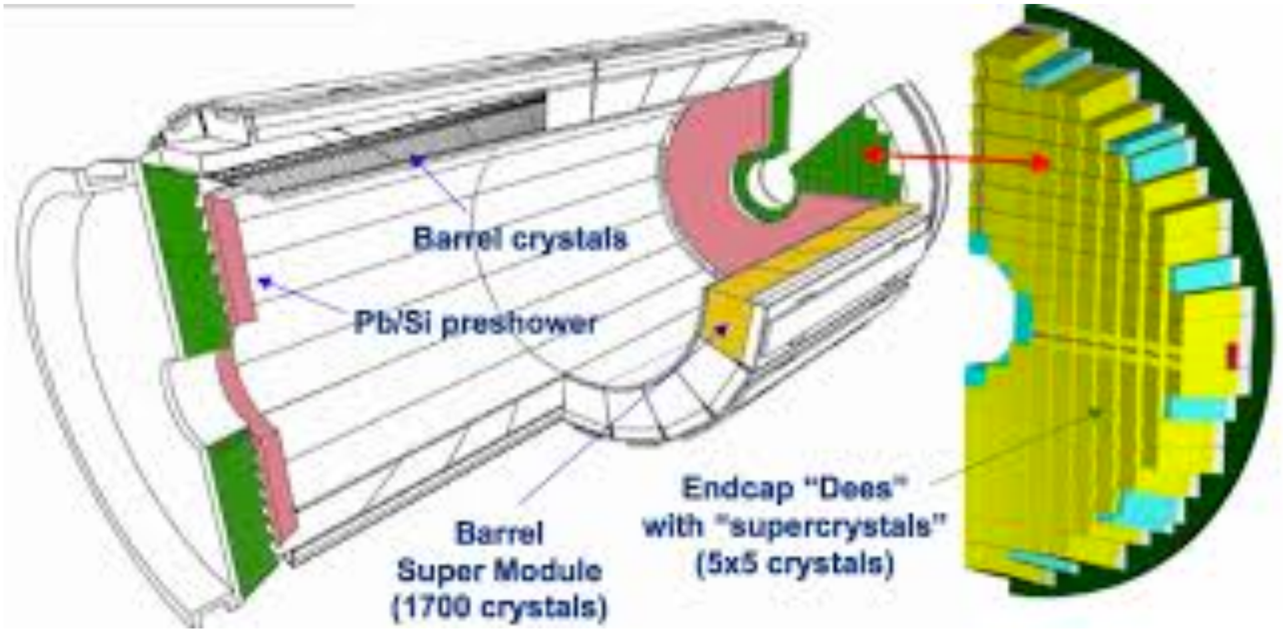
Fluctuation in the number of photoelectrons contribute as

$$\sim \frac{35\%}{\sqrt{E}}$$

Need to increase Cherenkov light yield especially for electromagnetic perfomance



Motivation for Crystal calorimeters



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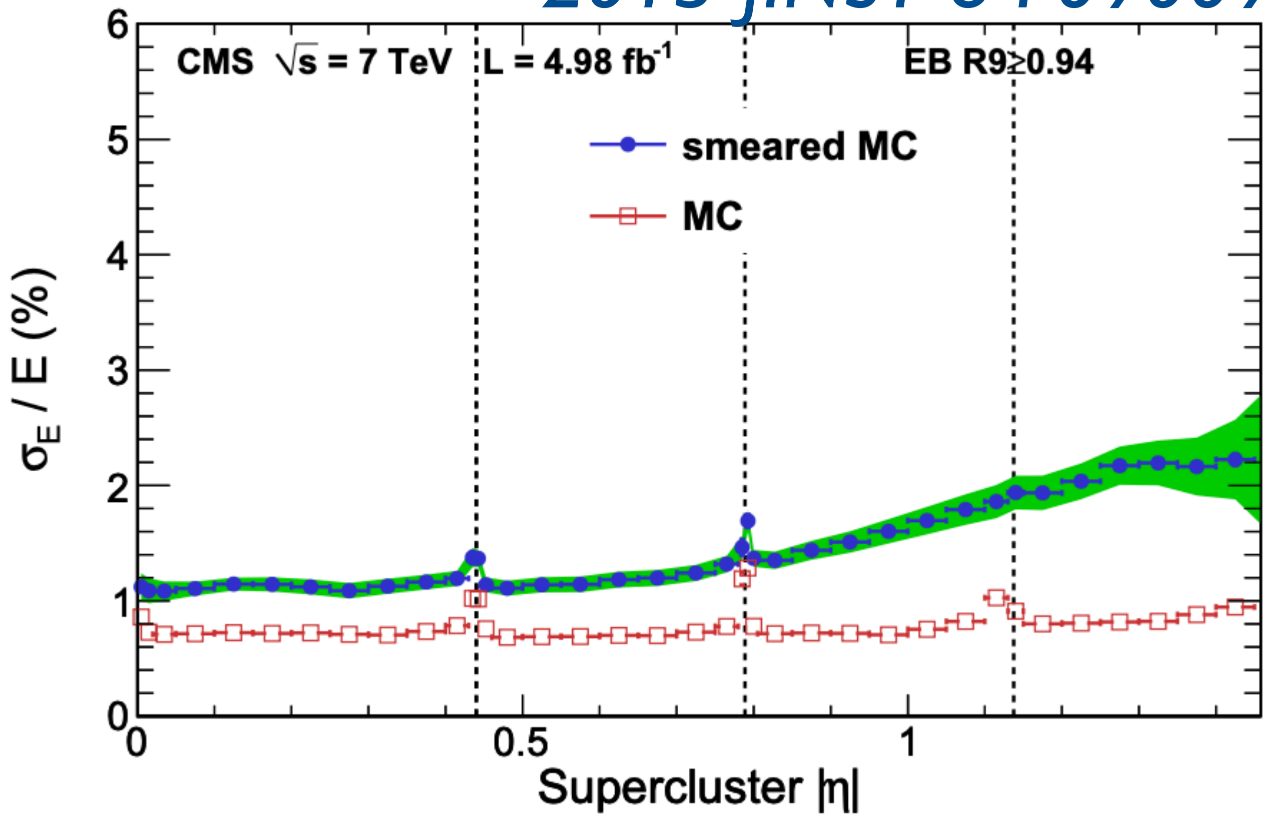


Crystal calorimeters can achieve excellent electromagnetic resolution.

High density scintillating crystals widely used in particle physics experiment: ensure excellent energy resolution for electromagnetic showers

Drawbacks of Crystal Calorimeters

Calorimeters with a crystal EM compartment usually have a poor had. resolution due to

- fluctuation of the starting point of the hadronic shower in the EM section
- different response to the em and non-em (e/h) components of the shower in the two calorimeters

Dual readout applied to an hybrid system:

Measuring f_{em} on an event-by-event basis allows to correct for such fluctuations and allows to eliminate the main reasons for poor hadronic resolution

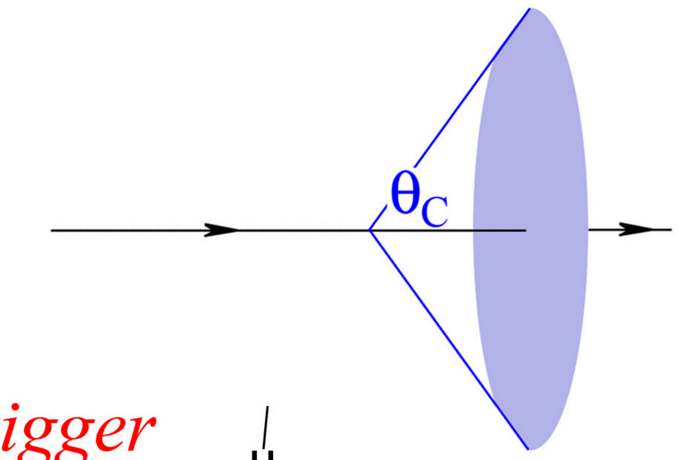
Separation of Cherenkov and scintillation light in homogeneous media is required

Cherenkov to scintillation separation

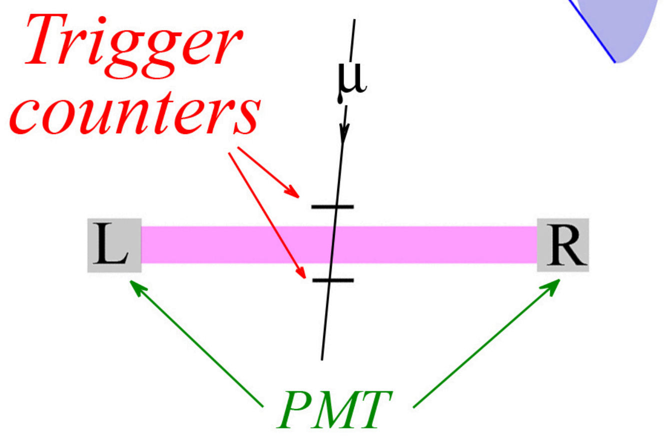
Properties	Čerenkov	Scintillation
Angular distribution	Light emitted at a characteristic angle by the shower particles that generate it $\cos\theta = 1/(n\beta)$	Light emission is isotropic: excited molecules have no memory of the direction of the particle that excited them
Time structure	Instantaneous,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

C to S separation: directionality

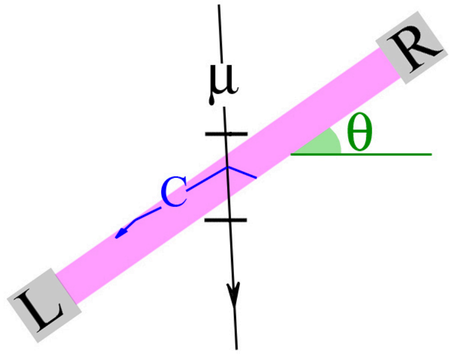
Properties	**Čerenkov**	**Scintillation**
Angular distribution	Light emitted at a characteristic angle by the shower particles that generate it $\cos\theta = 1/(n\beta)$	Light emission is isotropic: excited molecules have no memory of the direction of the particle that excited them



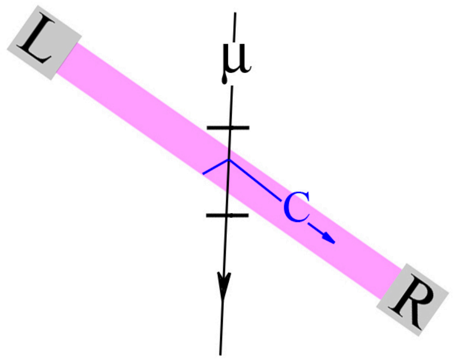
$n = 2.2$, $\cos\theta_C = 1/n \longrightarrow \theta_C = 63^o$



Calibration:
L = R



L > R



L < R

ONLY FOR:
Proof of concept
Evaluation of C content

Not intended for real experiment

C to S separation: directionality

Asymmetry: Cherenkov light only detected in downstream PMT

$$\alpha = \frac{R-L}{R+L}$$

Fraction of Cherenkov light to the total (downstream) PMTs signal

$$f_C = \frac{2\alpha}{1+\alpha}$$

PbWO4 crystal was studied

15% of the emitted light is due to Cherenkov

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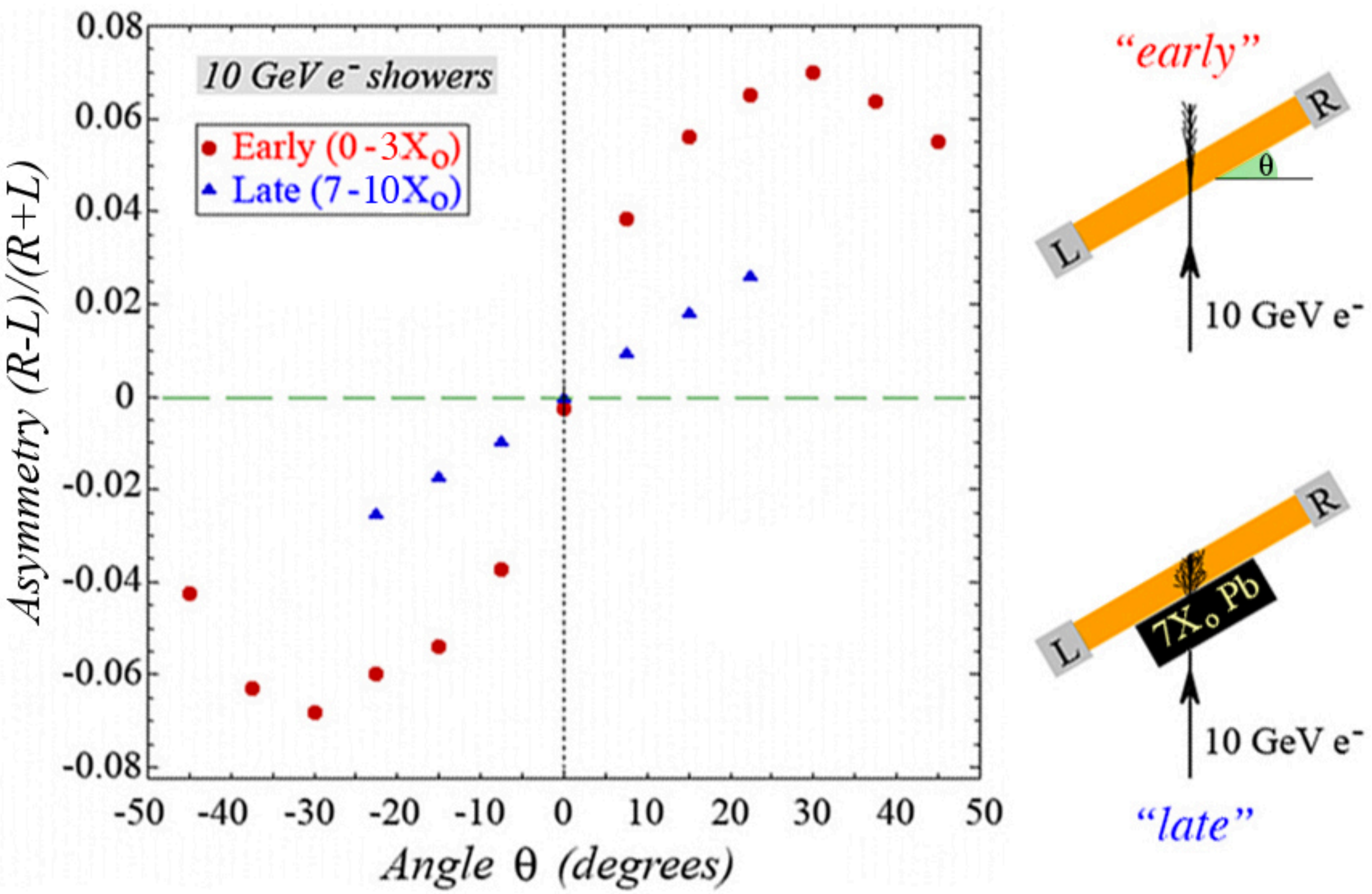

C to S separation: optical spectra

Properties	Čerenkov	Scintillation
Optical spectra	$\frac{dN_C}{d\lambda} = \frac{k}{\lambda^2}$	Strongly dependent on the crystal type, usually concentrated in a (narrow) wavelength range

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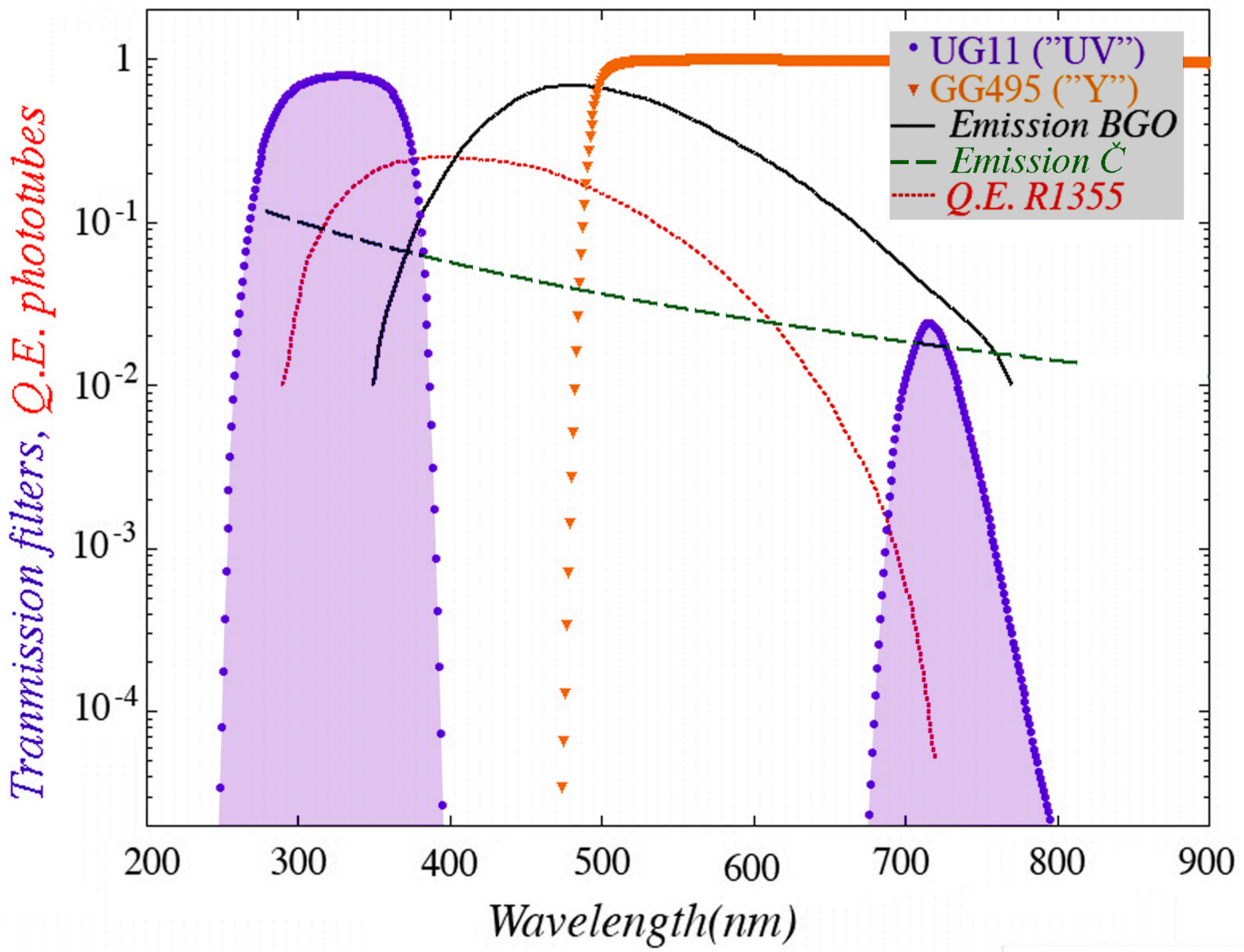
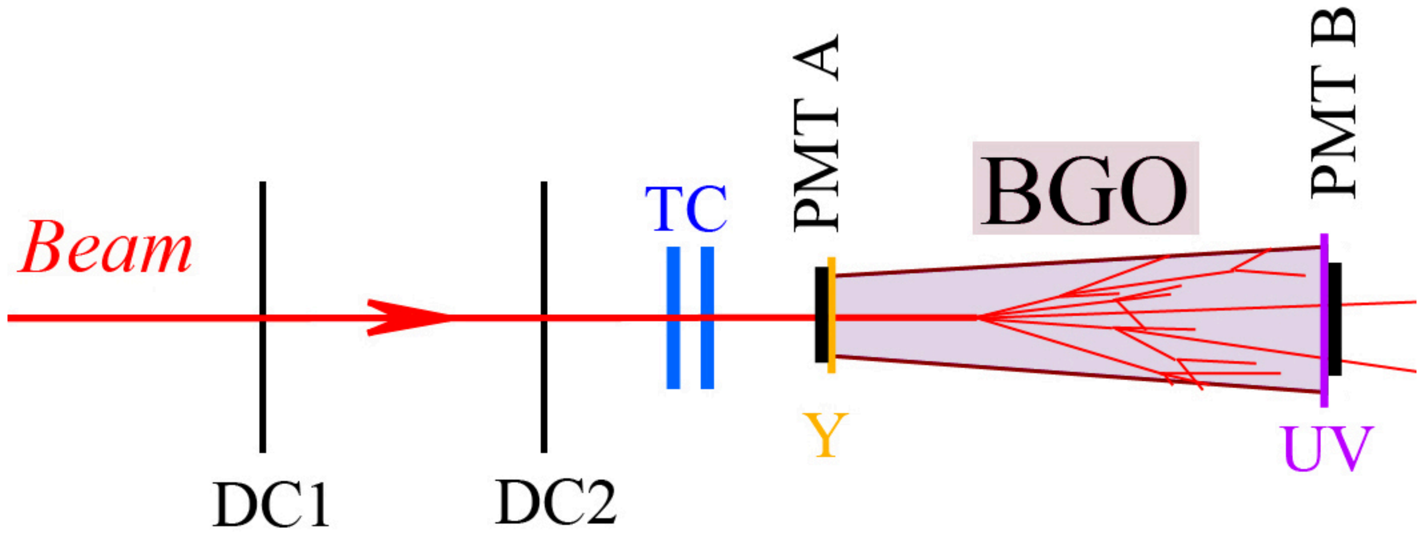
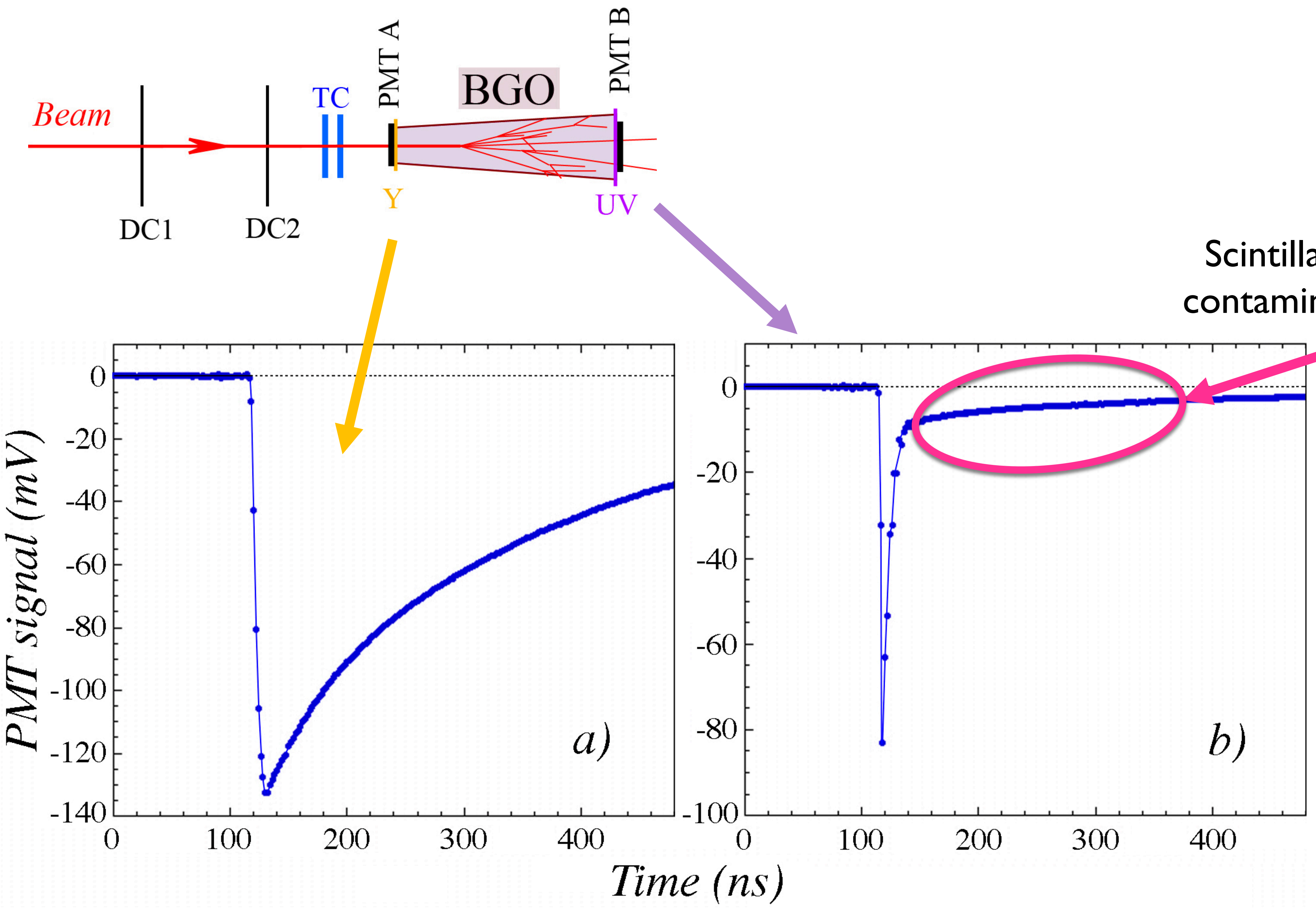


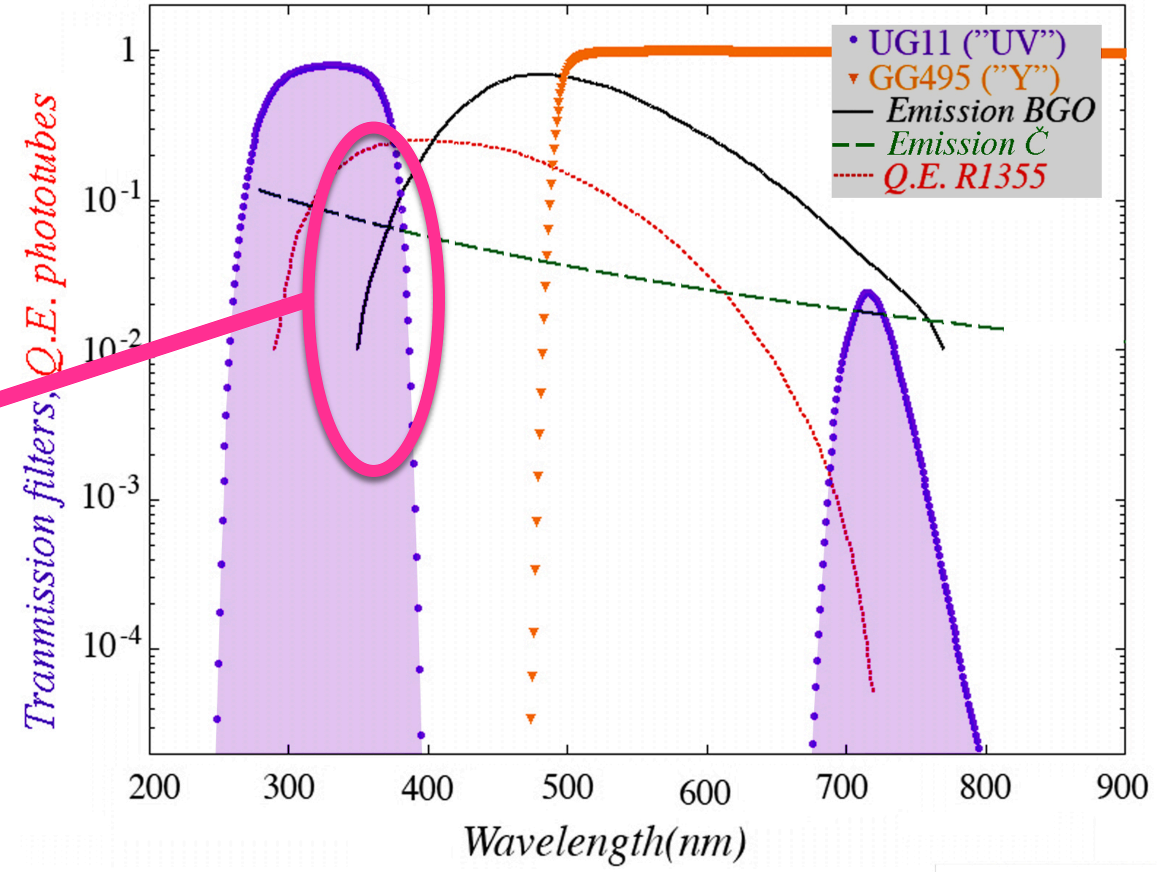


Use optical filters to separate lights

C to S separation: optical spectra



Scintillation contamination



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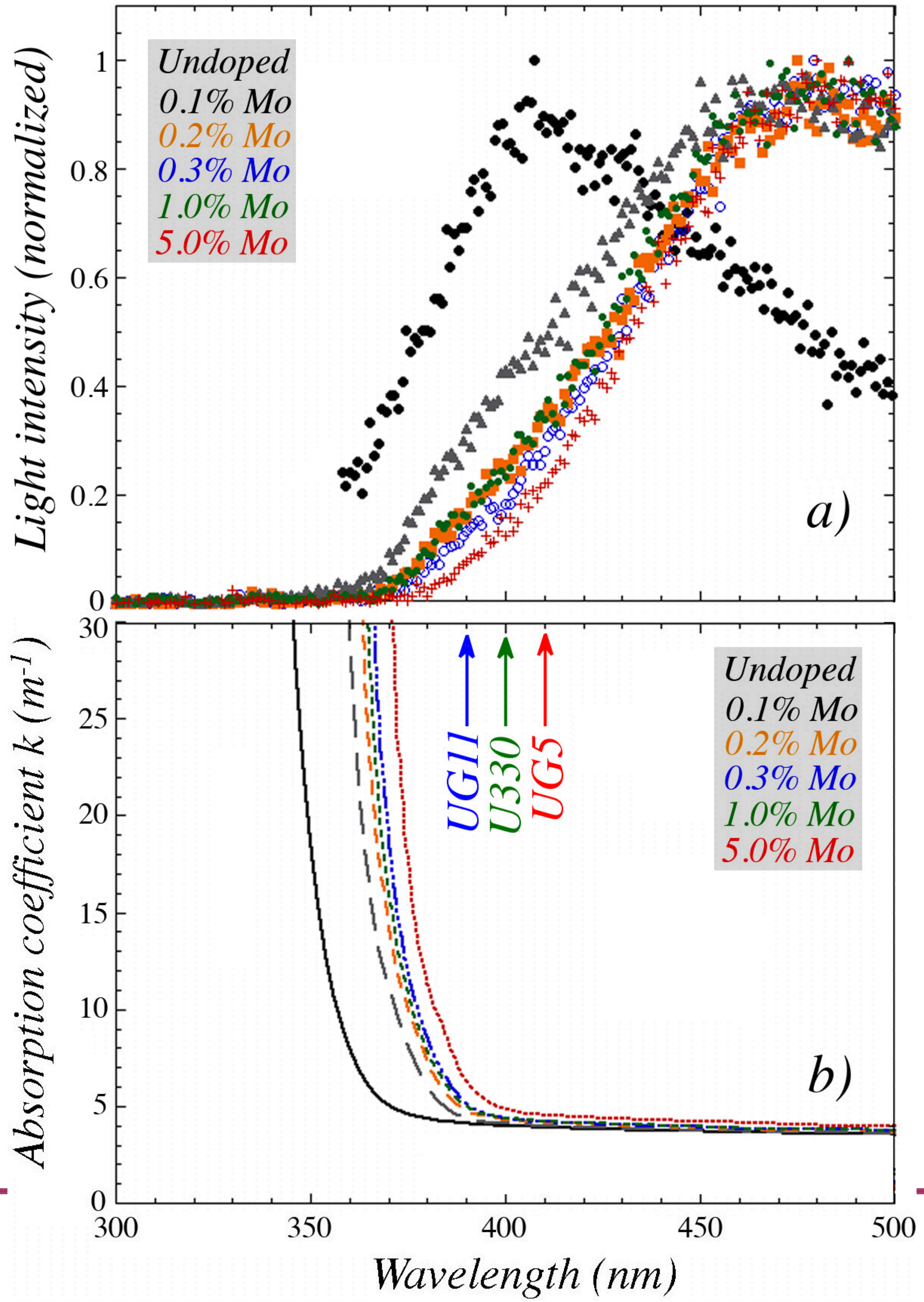
C to S separation: optical spectra



$PbWO_4$

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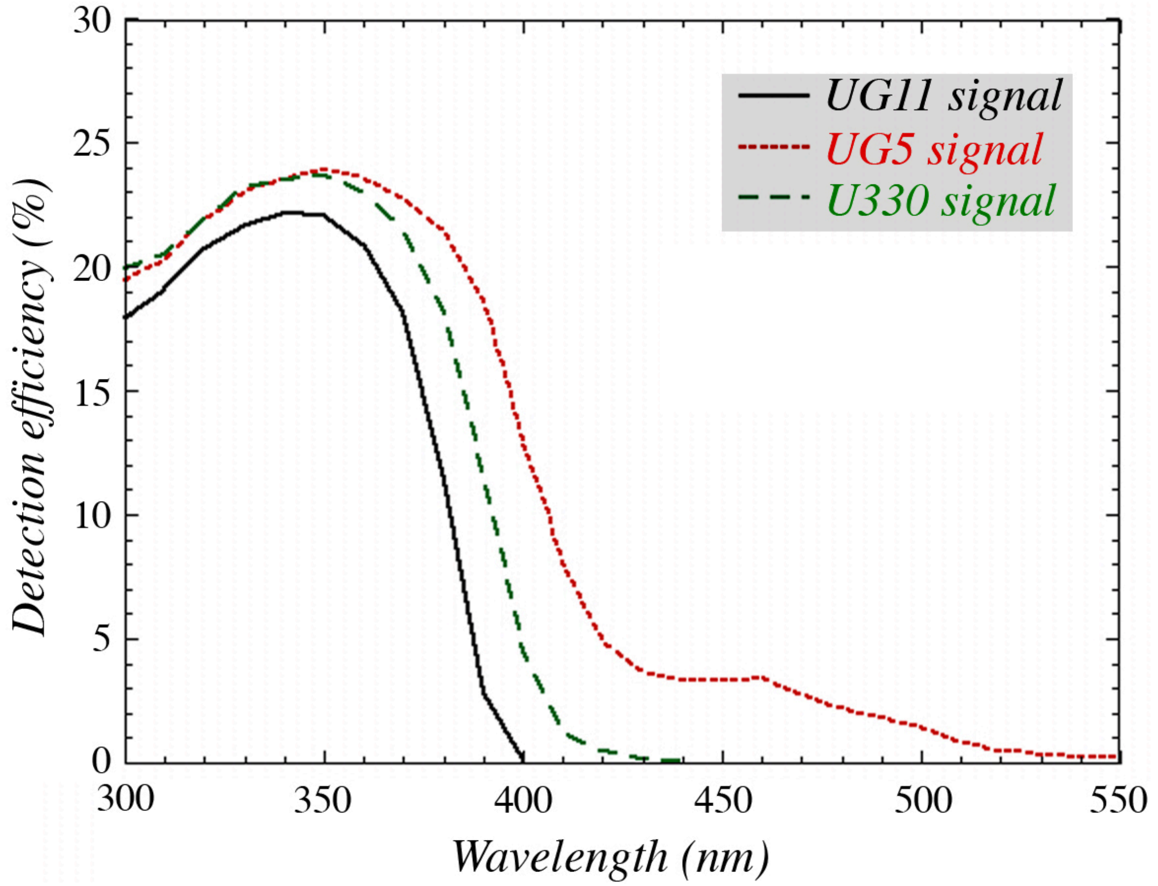
C and S (peak 420nm) are competitive in the same spectral region

Doping with Molybdenum impurities allows to shift the scintillation peak to higher wavelenght → possible to use filters

Mo impurities substitute W ions in the matrix and forms MoO4 complex, which acts as a wavelength shifter

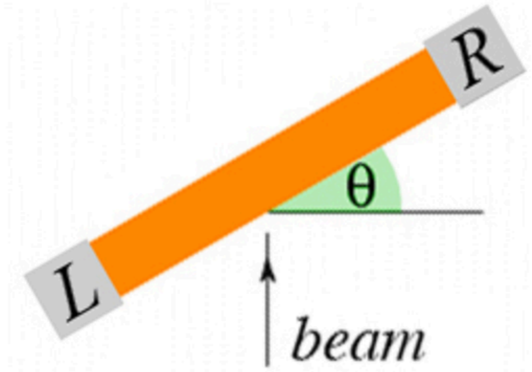


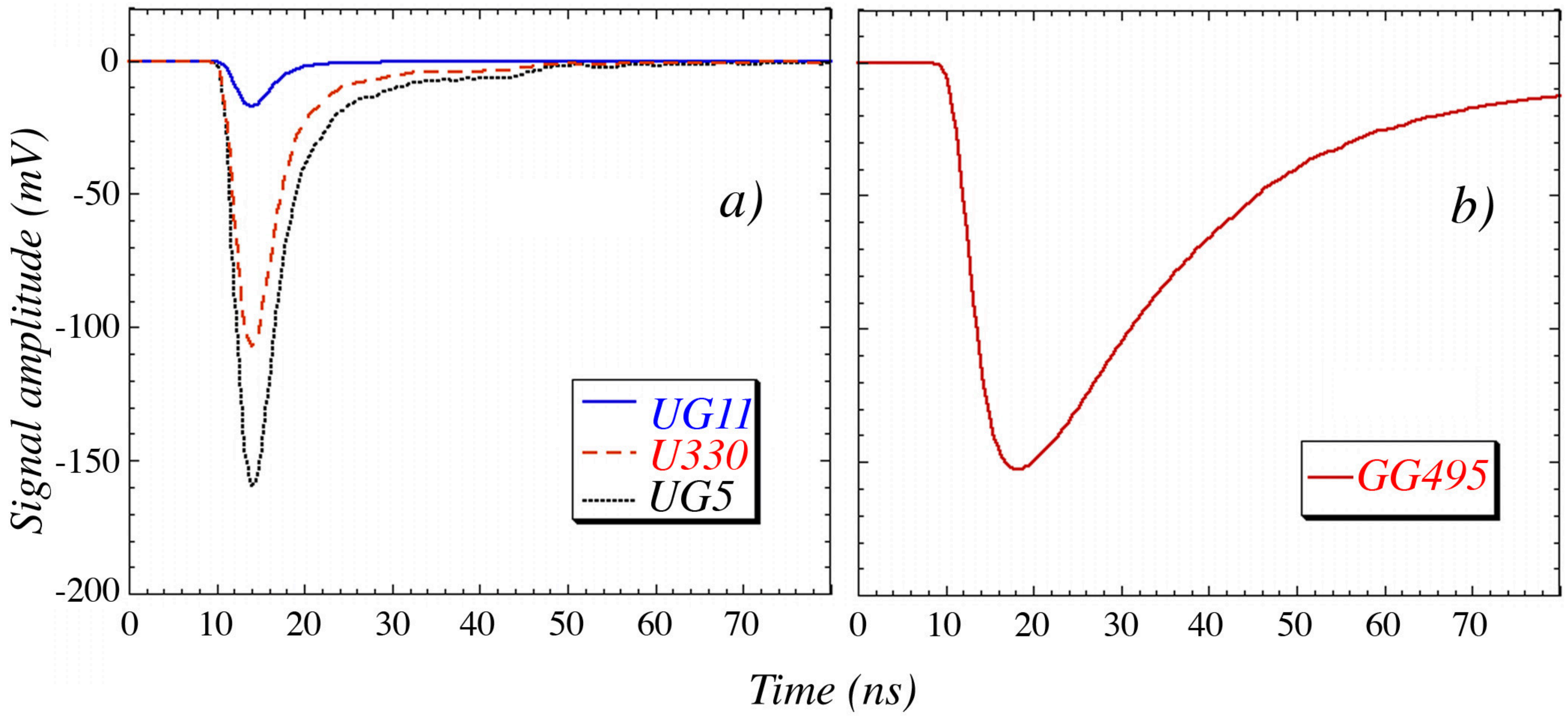
C to S separation: optical spectra

$PbWO_4$

S-side: yellow filter (GG495)

C-side: UV-filter





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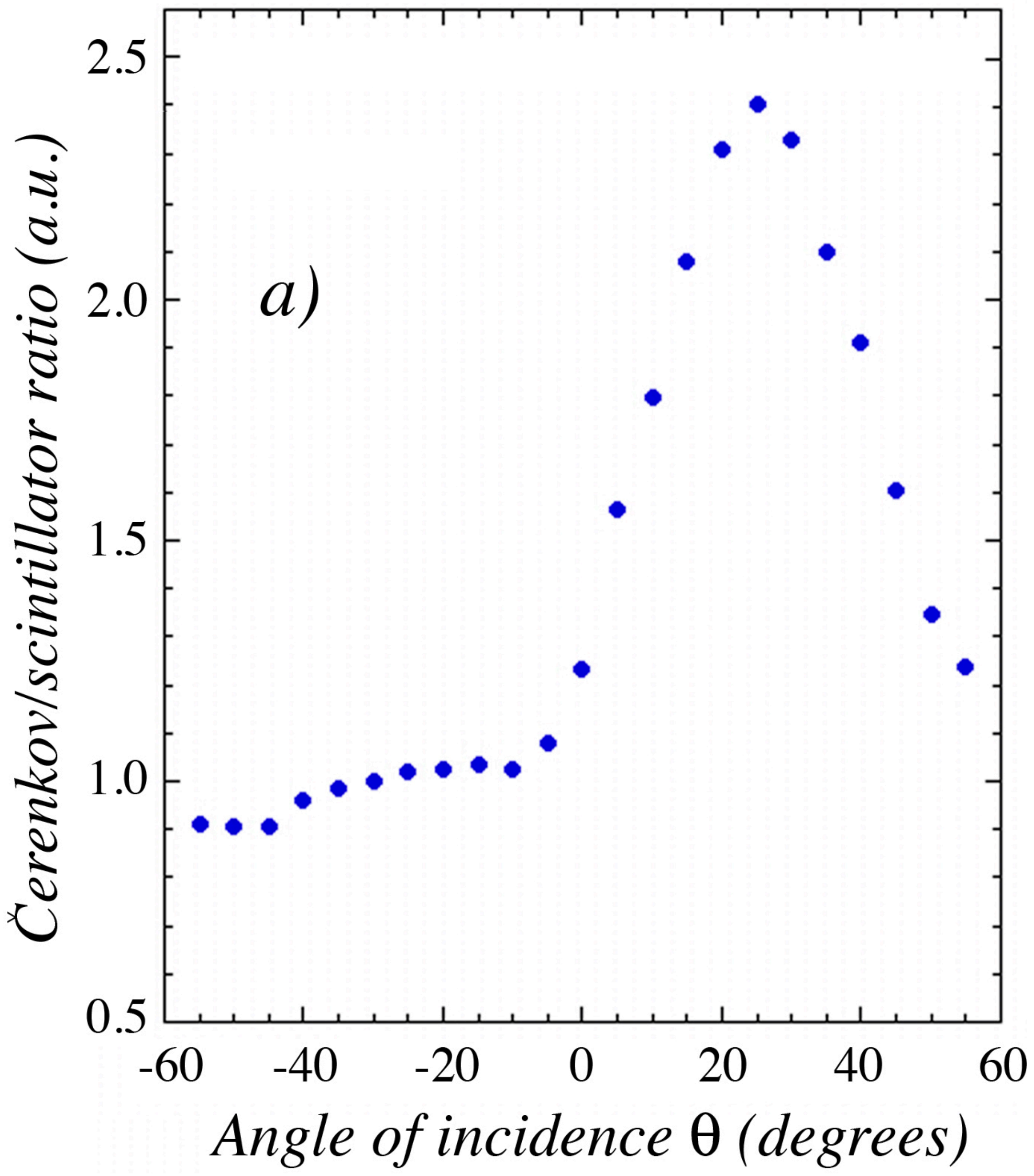
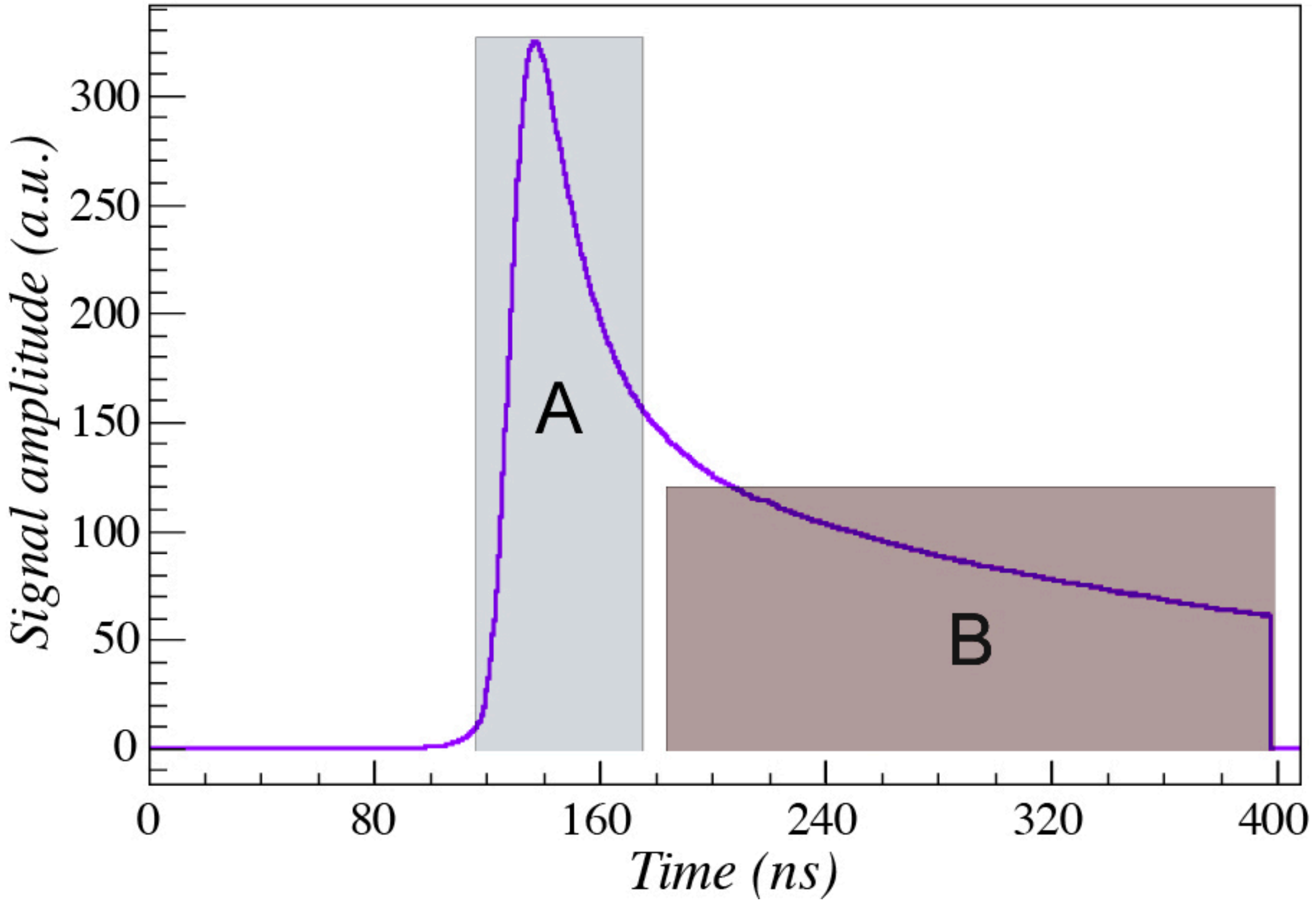


C to S separation: time structure

Properties	Čerenkov	Scintillation
Time structure	Instantaneous, short signal duration	Light emission is characterized by one (or several) time constant(s). Long tails are not unusual (slow component)



PMT signal (inverted) containing both Cherenkov and scintillation.

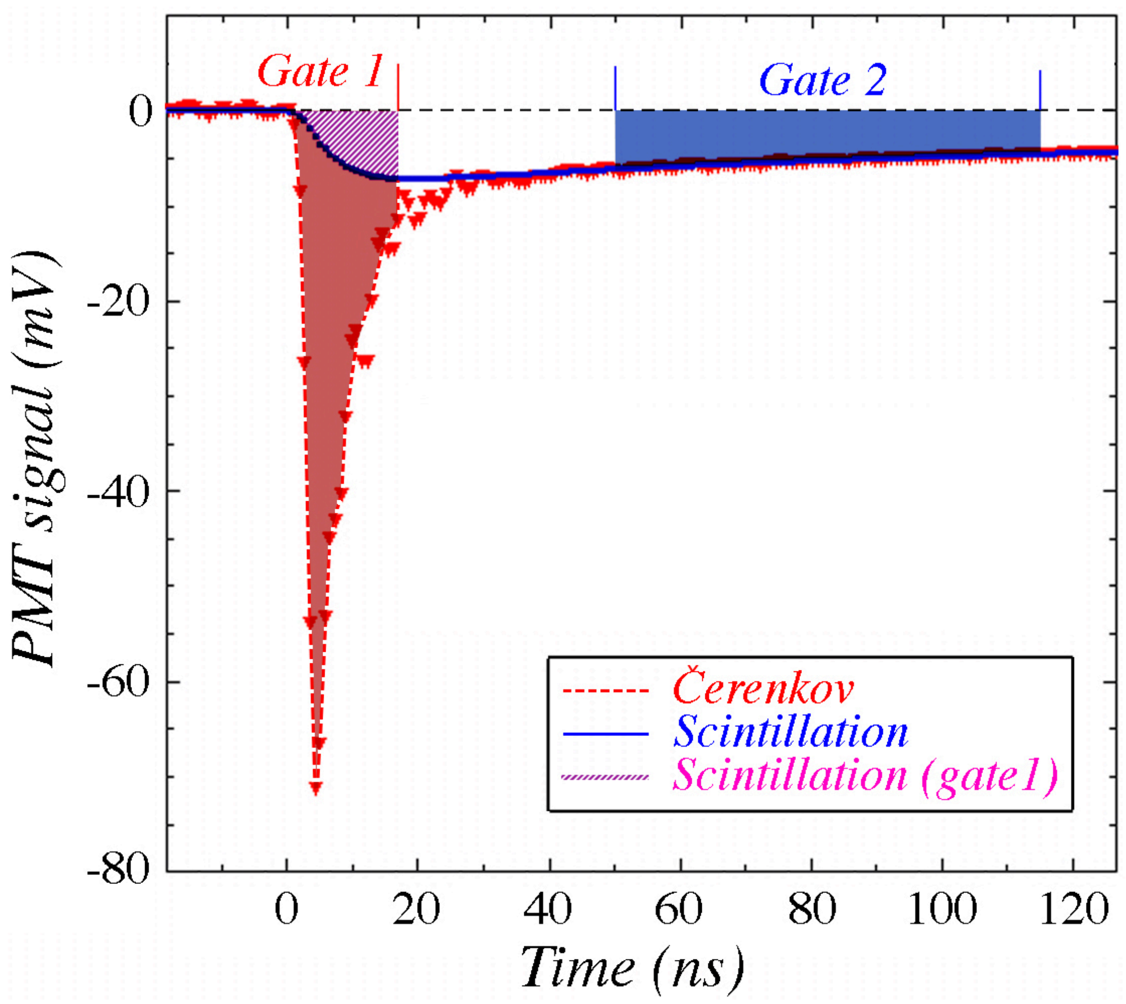
- From pure scintillation channel determine S content
- Integration over to gates gives

$$S = (1 + f_S) * Q_B$$

$$C = Q_A - f_S * Q_B$$

C to S separation: time structure

BGO: different time structures of C and S components manifest themself in the (optically) filtered signal from PMT



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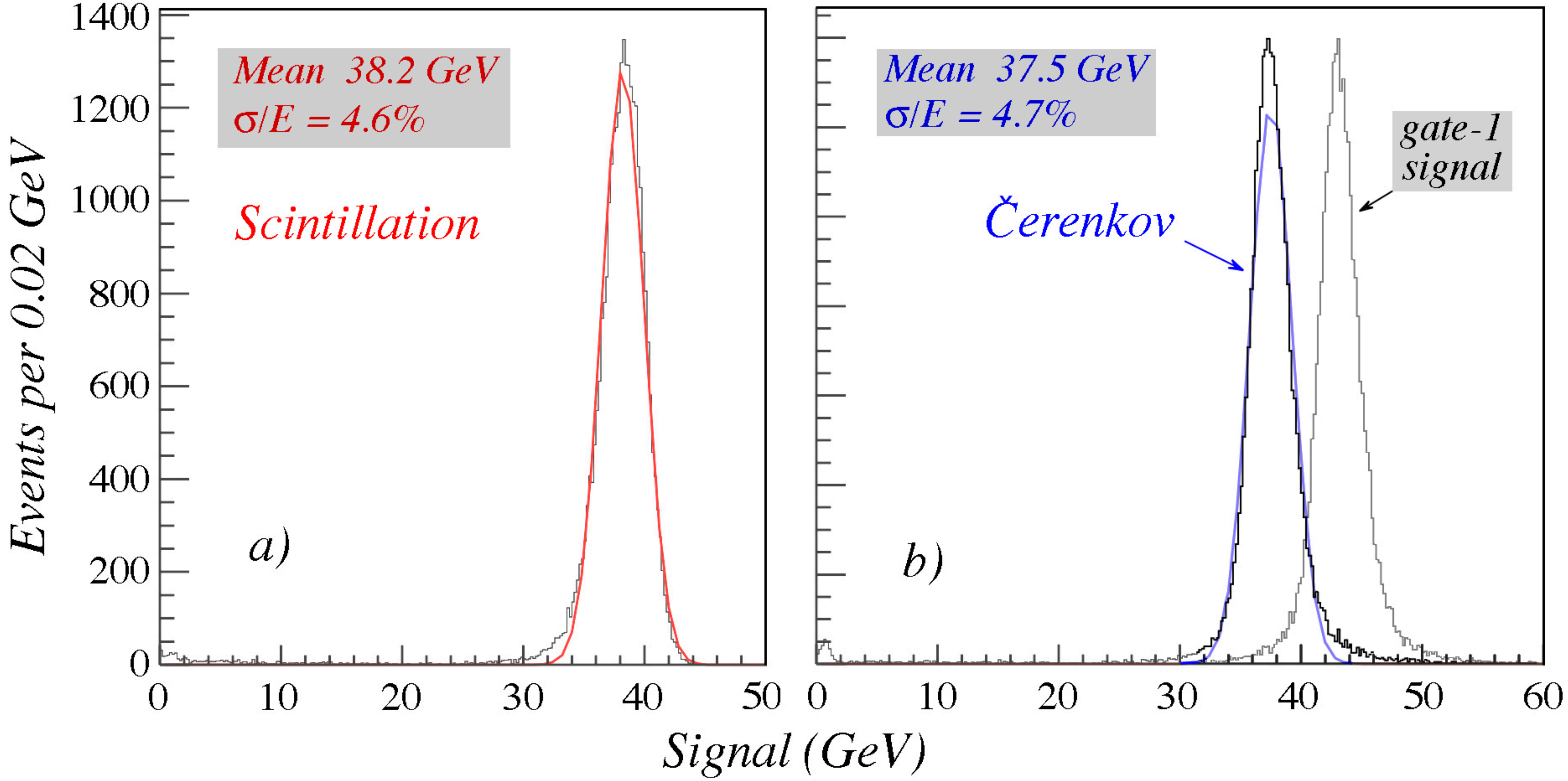


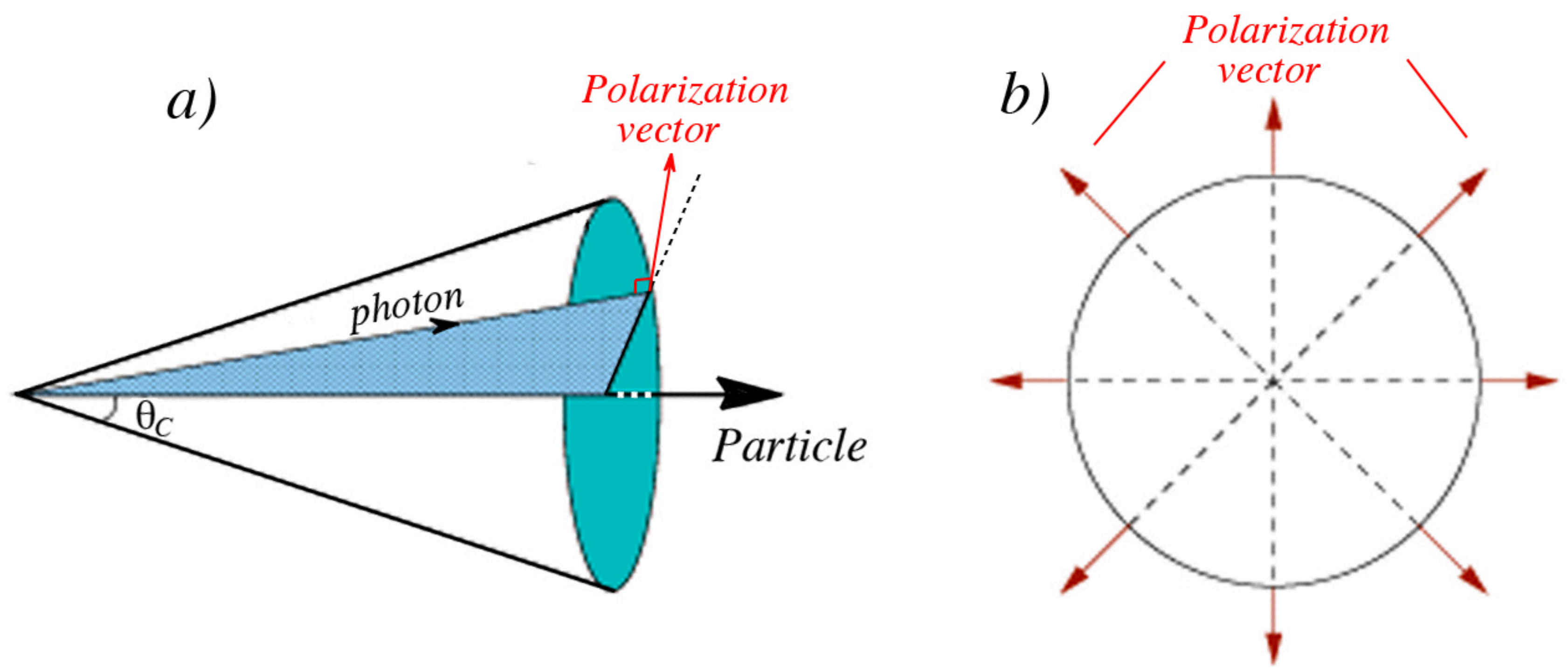
50 GeV e^- (not fully contained in the crystal)

C to S separation: polarization

Properties	Čerenkov	Scintillation
Polarization	polarized	not polarized

Polarization vector is perpendicular to the arc segment of the emission cone

C polarized horizontally



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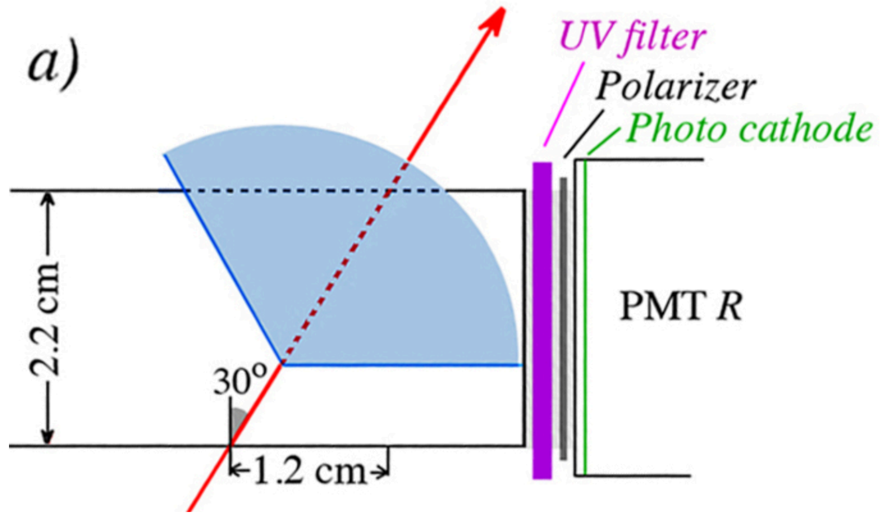
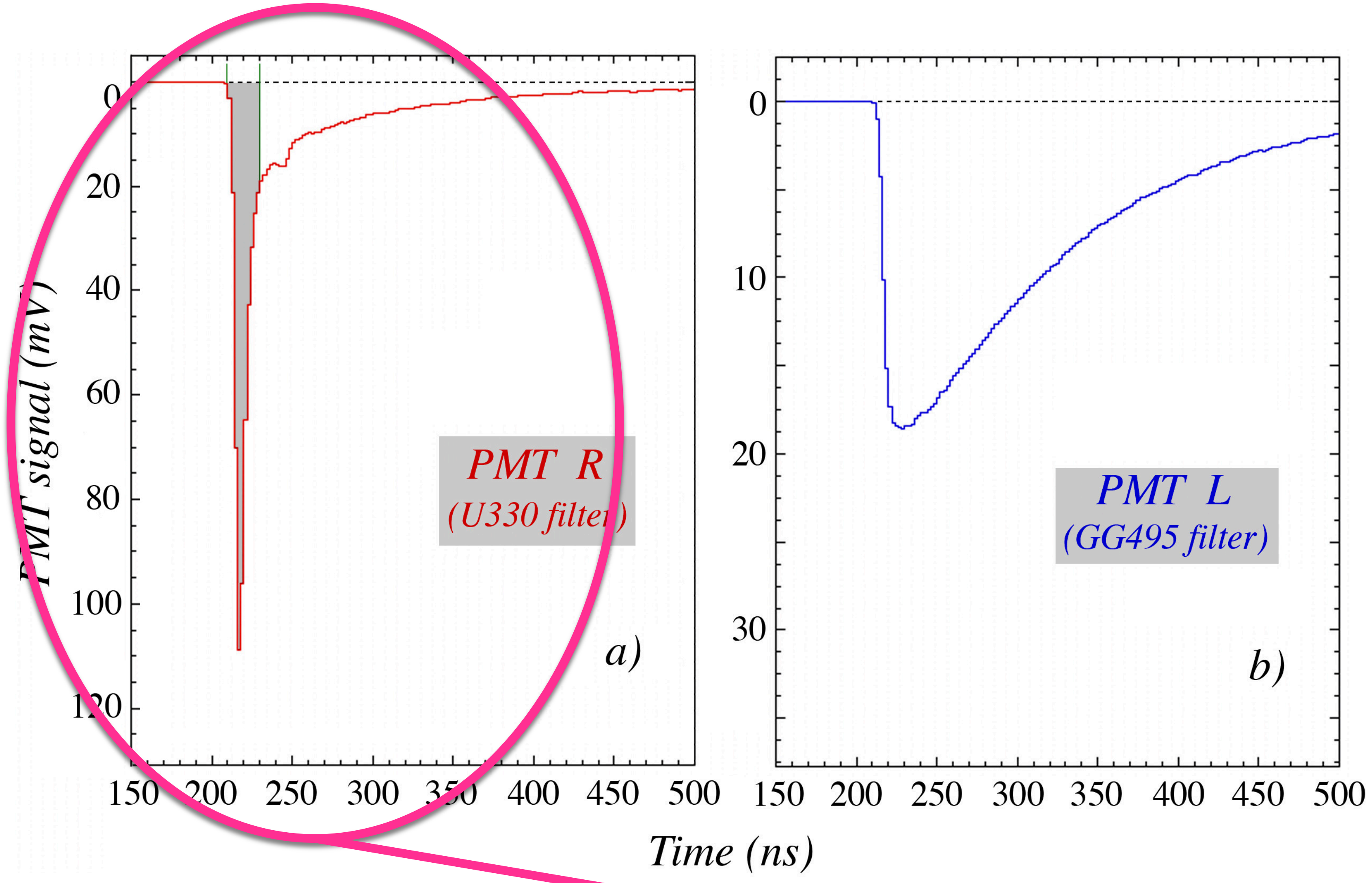


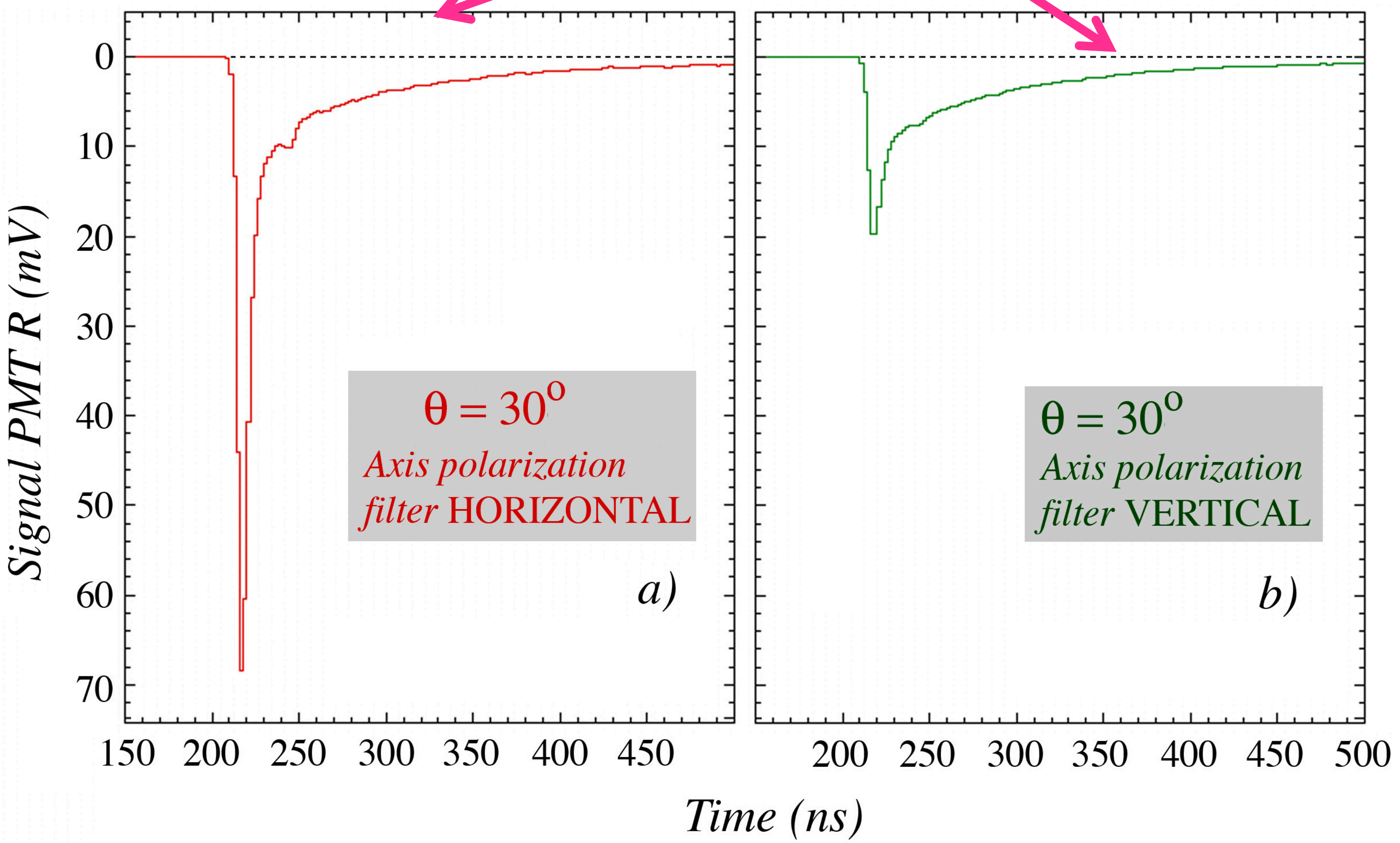
C to S separation: polarization

BSO: spectral separation with filters, similar to BGO



Scintillation component not affected by polarizer

Adding polarizer



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Cherenkov to scintillation separation

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Optical spectra	$\frac{dN_C}{d\lambda} = \frac{k}{\lambda^2}$	Strongly dependent on the crystal type, usually concentrated in a (narrow) wavelength range
Polarization	polarized	not polarized

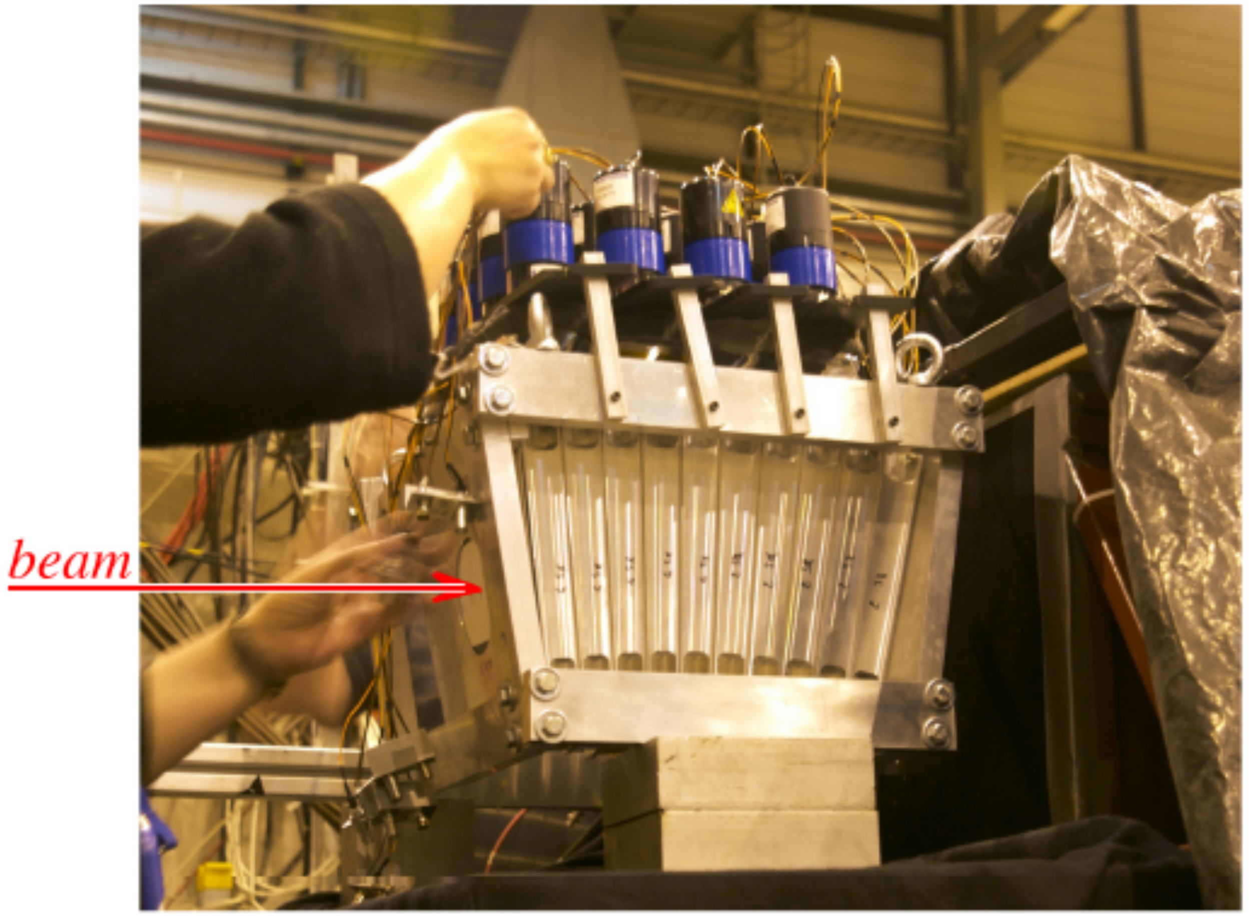
Combination of these two techniques were applied to crystal matrix readout together with DREAM fiber calorimeter

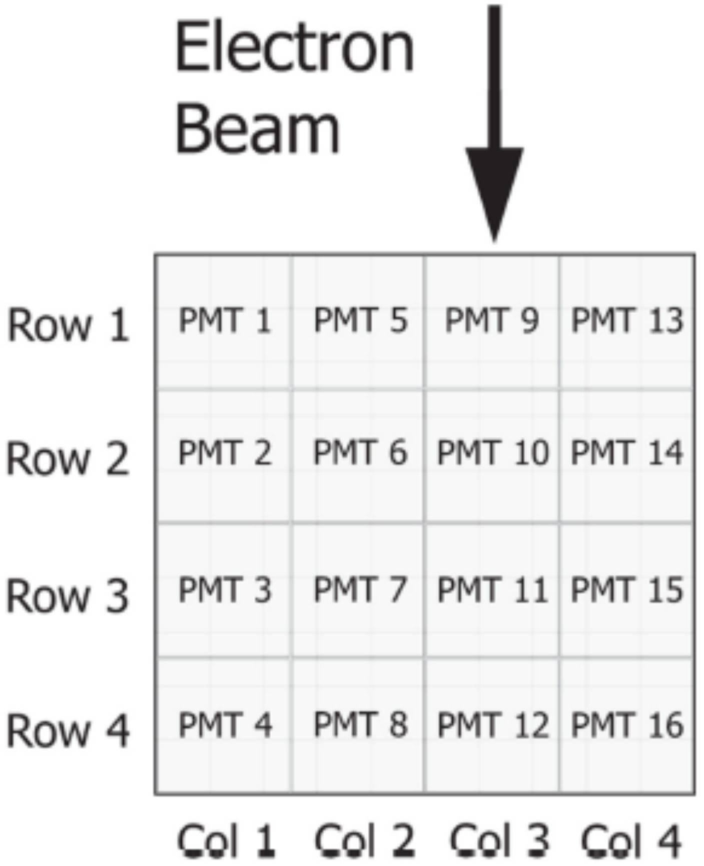
BGO ECAL

- ✦100 BGO crystals from a projective tower of the L3 experiment

- ✦Dimensions:
  - ✦ 24 cm long and tapered
  - ✦ end faces: 2.4 x 2.4 cm^2, 3.2 x 3.2 cm^2
  - ✦ effective thickness: 2.8 cm = 25 X_0

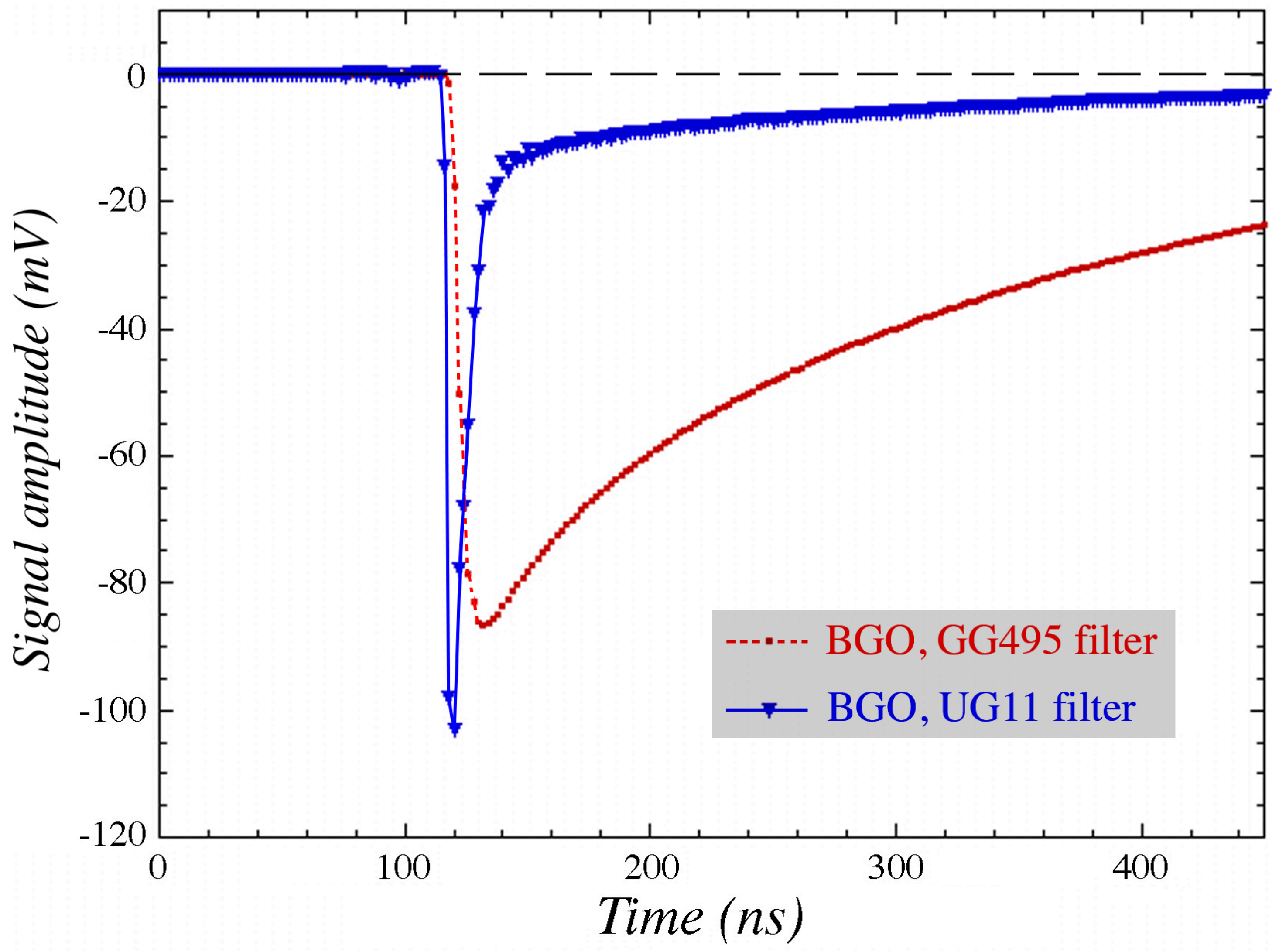
- ✦ 16 PMTs Hamamatsu R1355
  - ✦ Each PMT collected light produced by a cluster of at least 9 adjacent crystals

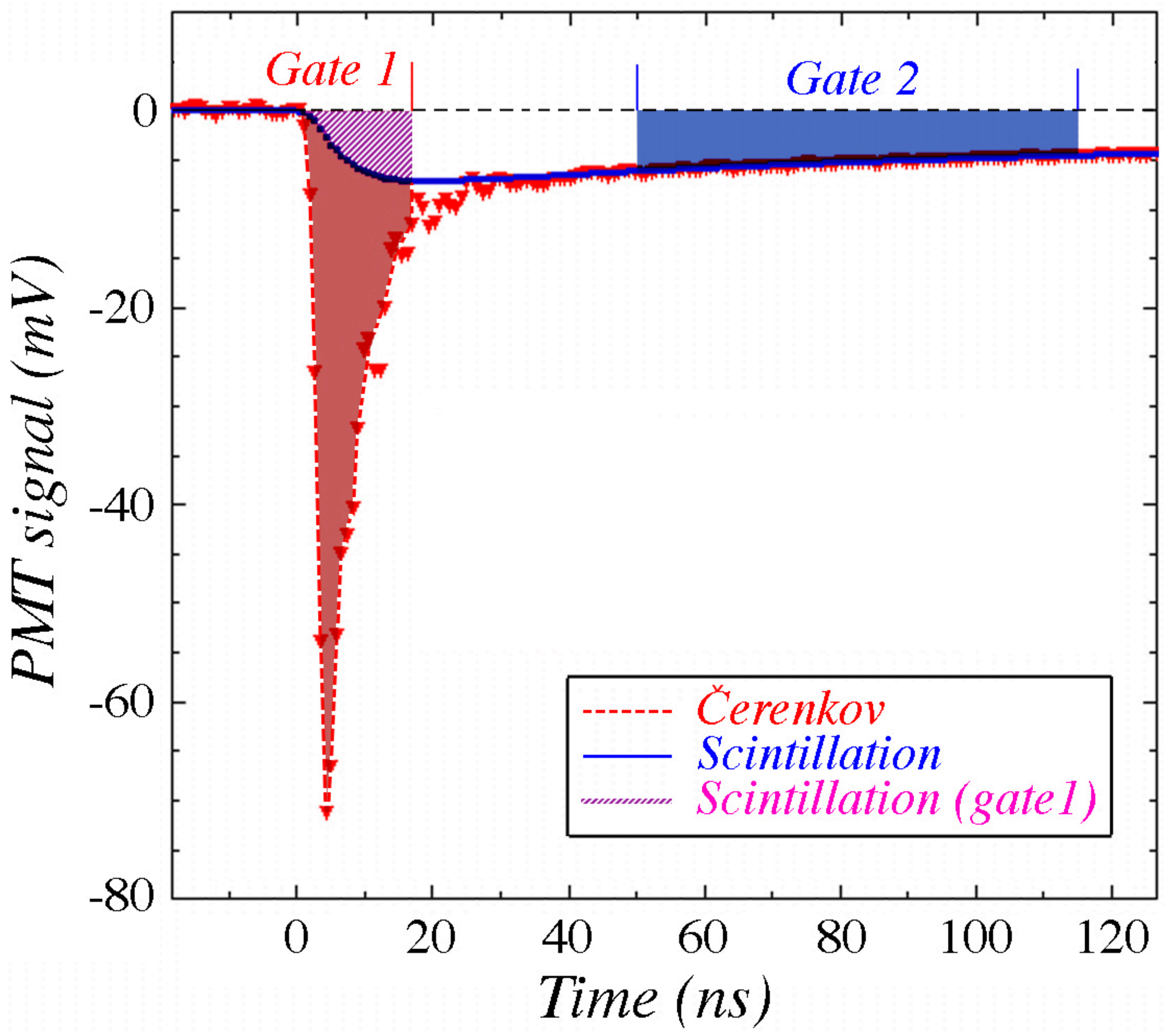




	Col 1	Col 2	Col 3	Col 4
Row 1	PMT 1	PMT 5	PMT 9	PMT 13
Row 2	PMT 2	PMT 6	PMT 10	PMT 14
Row 3	PMT 3	PMT 7	PMT 11	PMT 15
Row 4	PMT 4	PMT 8	PMT 12	PMT 16

BGO C and S signal extraction

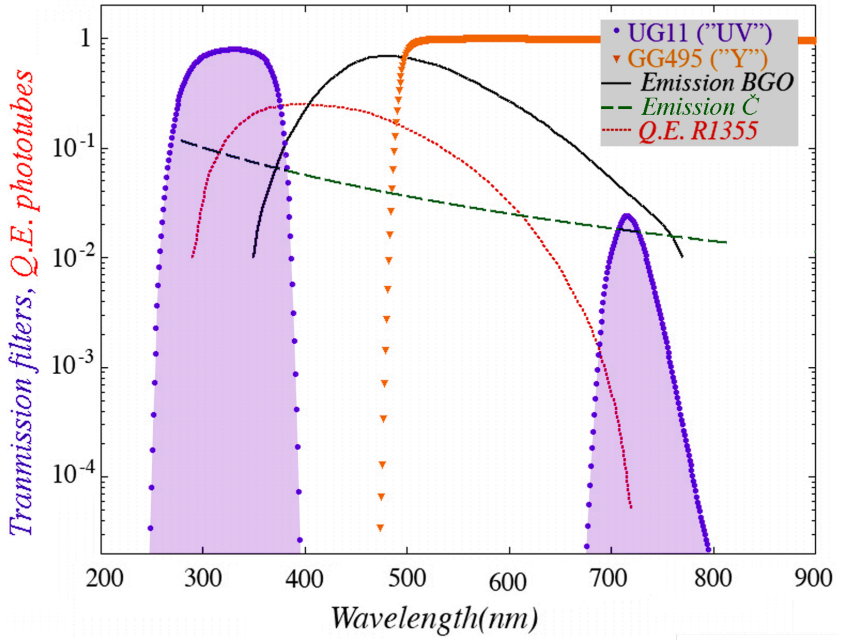




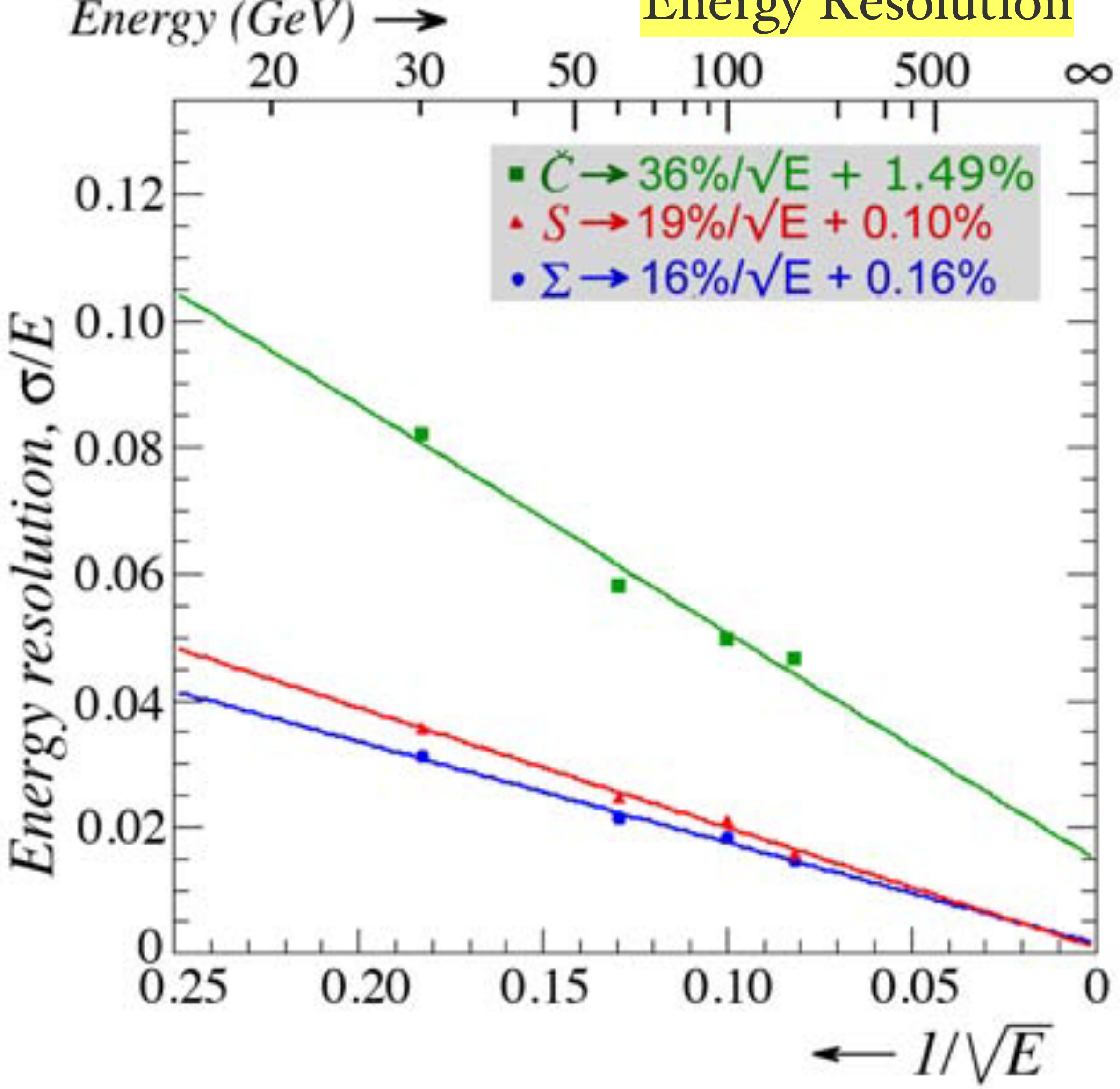
BGO matrix results: EM performance

Results:

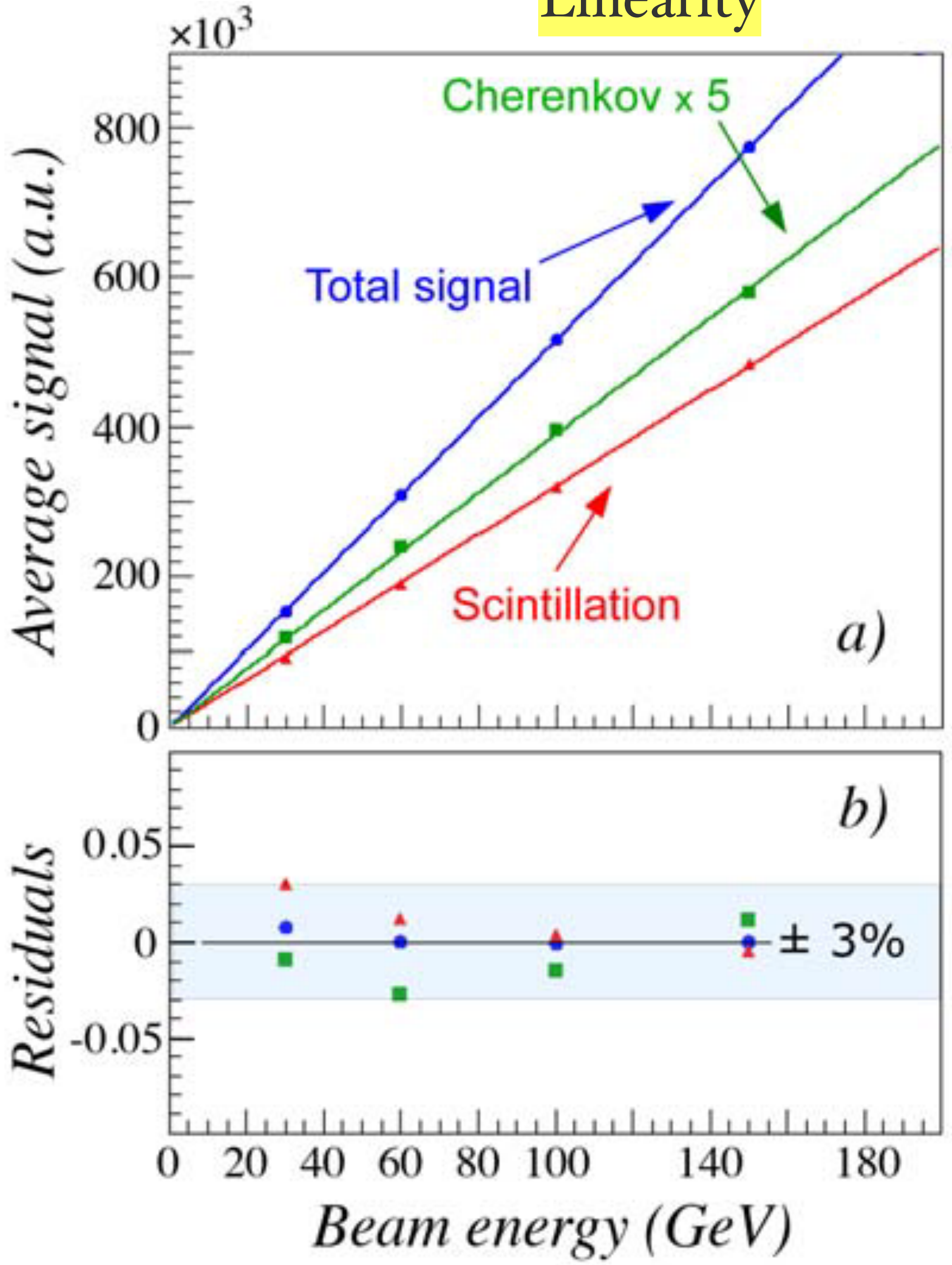
- Čerenkov energy resolution shows a constant term of about 1.5%
- good linearity (within ± 3%)
- Čerenkov light yield about 6 p.e./GeV



Energy Resolution



Linearity



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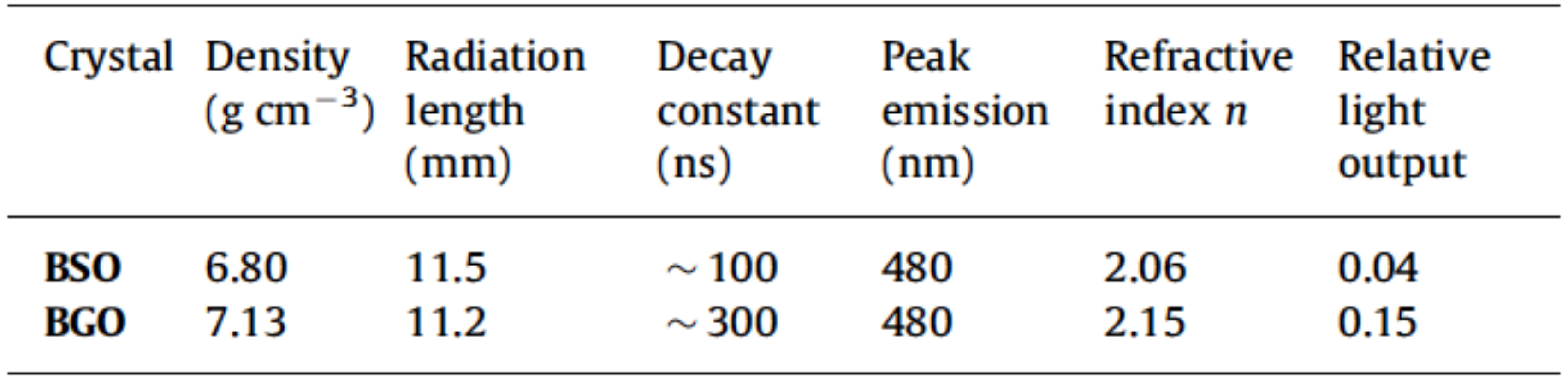
BGO vs BSO: single crystals

Comparison of BGO and BSO in terms of properties for use for dual readout calorimetry

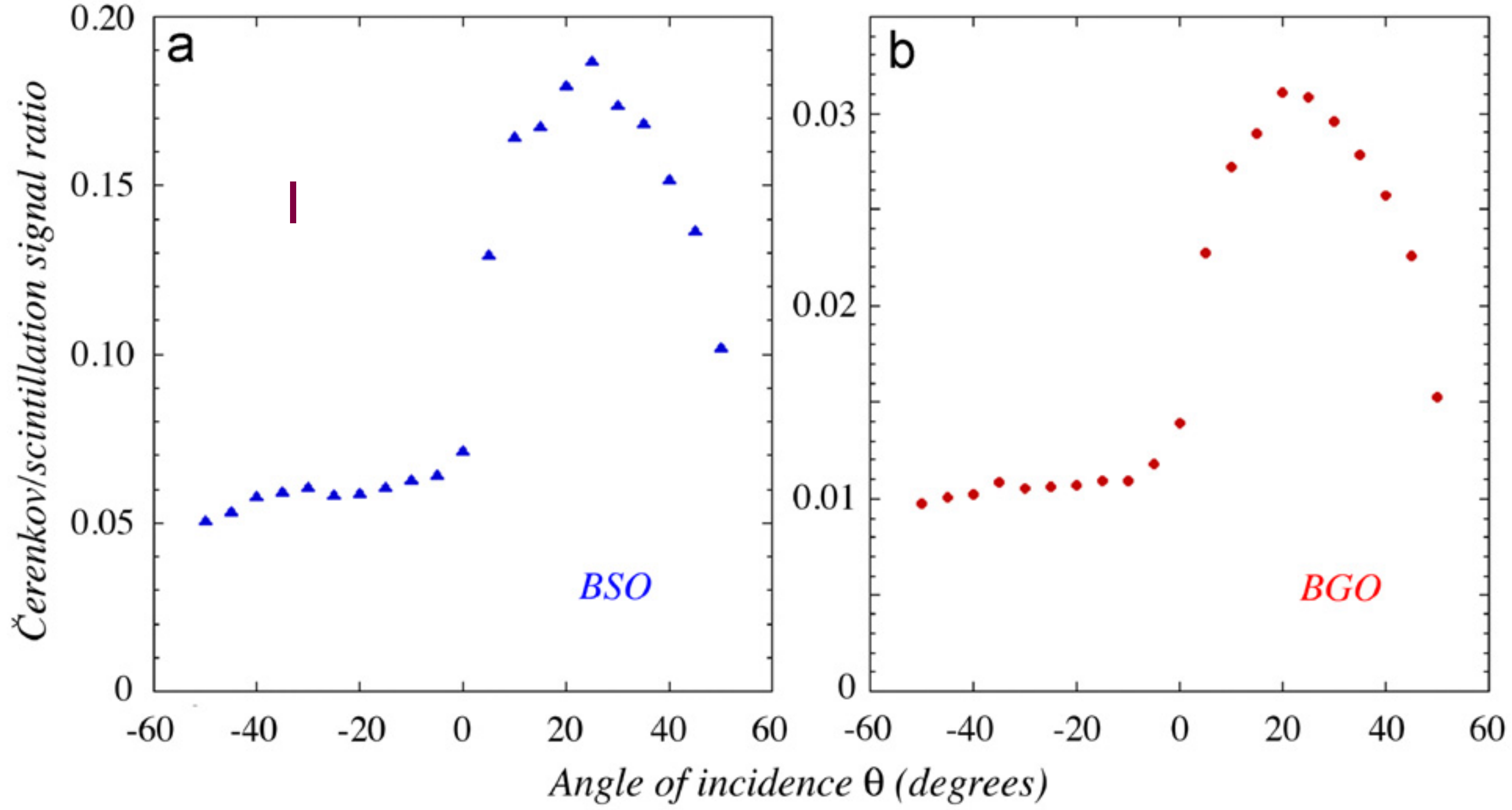
- ✦ single crystal test (18 cm long, 2.2 x 2.2 cm^2 in x-sect)
- ✦ pion beam 180 GeV

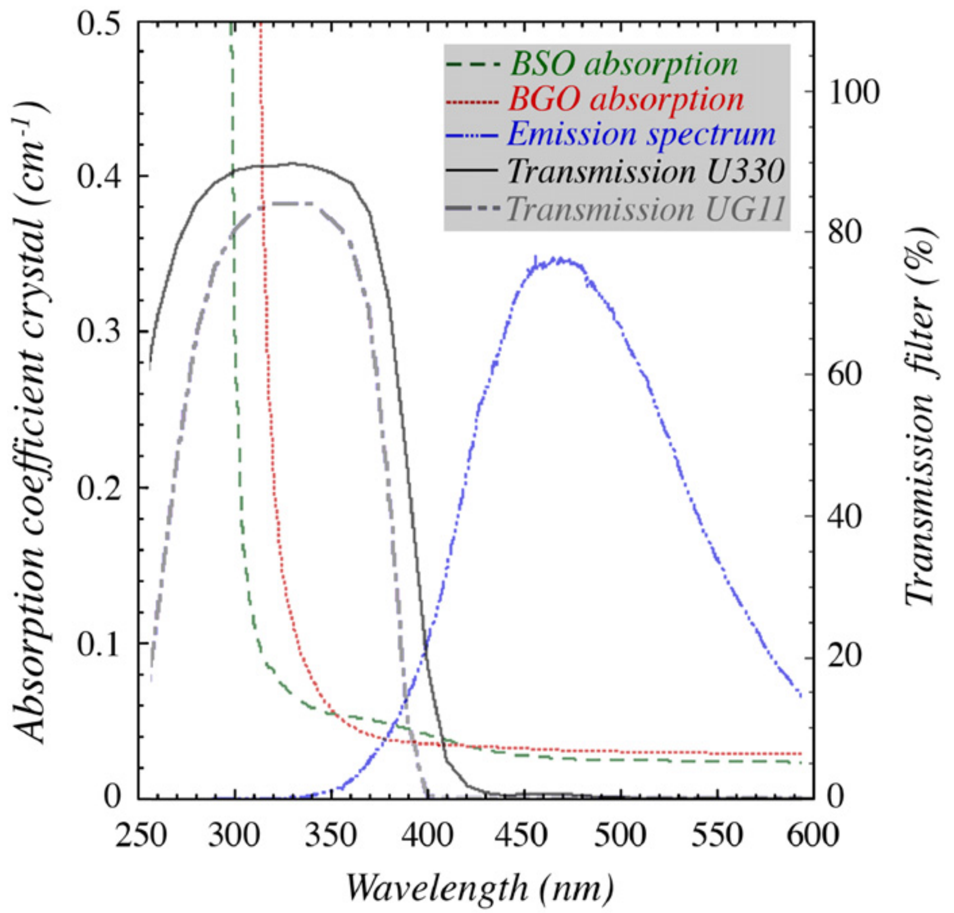


Crystal	Density (g cm^{-3})	Radiation length (mm)	Decay constant (ns)	Peak emission (nm)	Refractive index n	Relative light output
BSO	6.80	11.5	~ 100	480	2.06	0.04
BGO	7.13	11.2	~ 300	480	2.15	0.15

Results:

1.purity of the Č signal obtained with filters: separation power better by a factor of 6

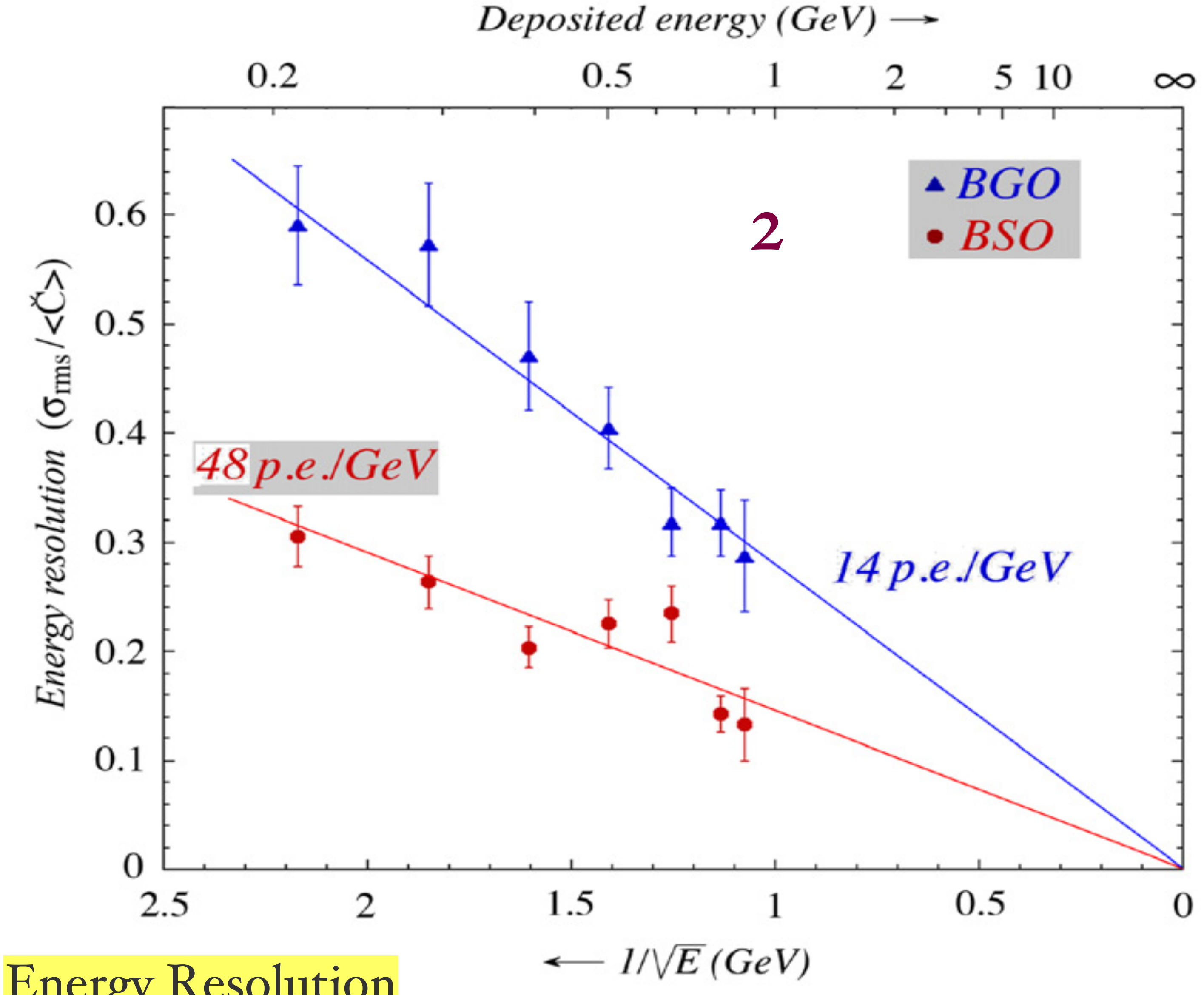




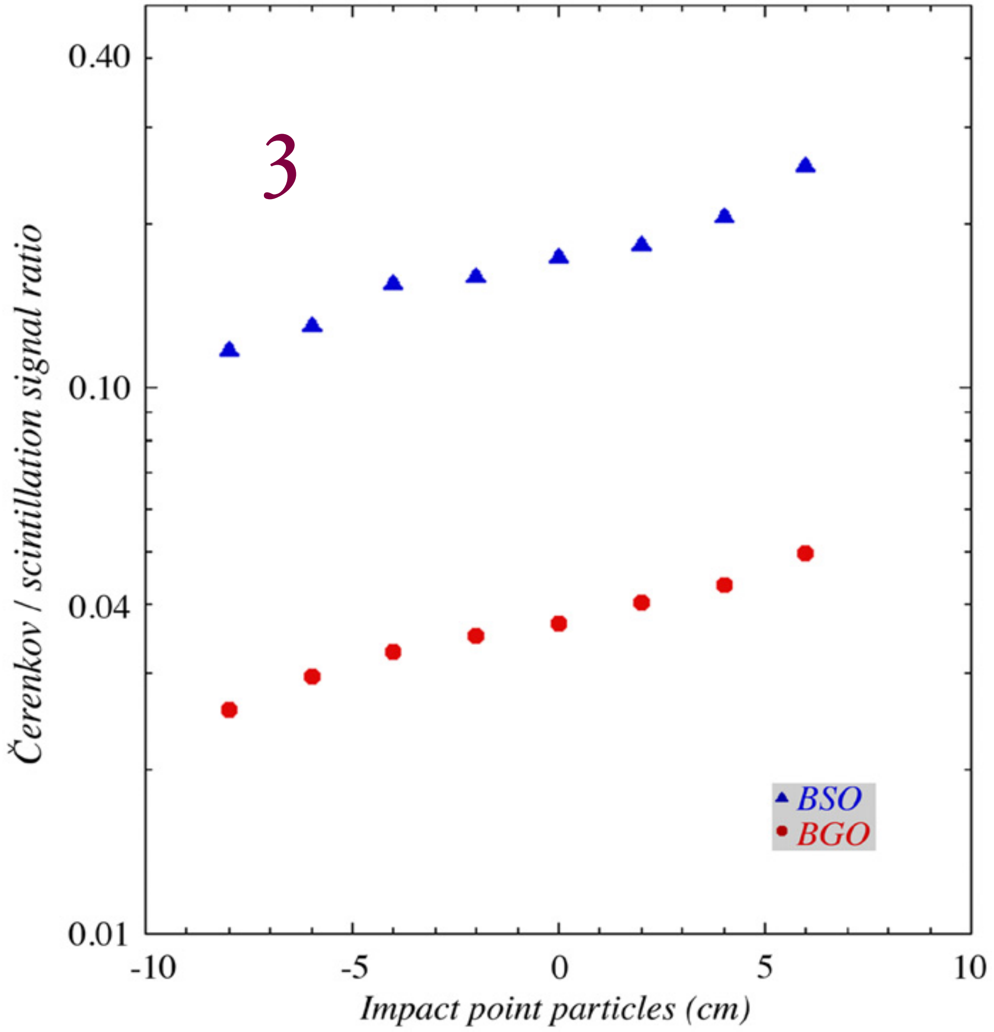
BGO vs BSO: single crystals

Results:

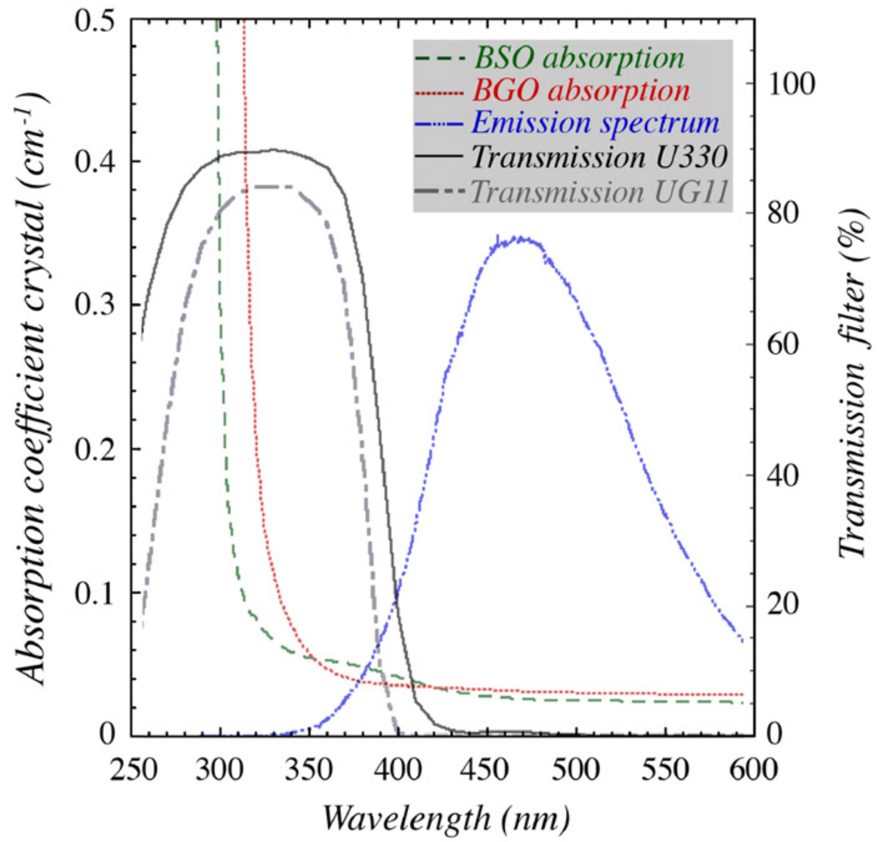
2. Č light yield: p.e. detected per unit deposited energy 2-3 times larger in BSO
3. light attenuation length for Č light: mostly the same in both crystals



Energy Resolution



Response Uniformity



BSO is promising as crystal for dual readout
No further test performed afterwards

Dual-readout hybrid calorimeter

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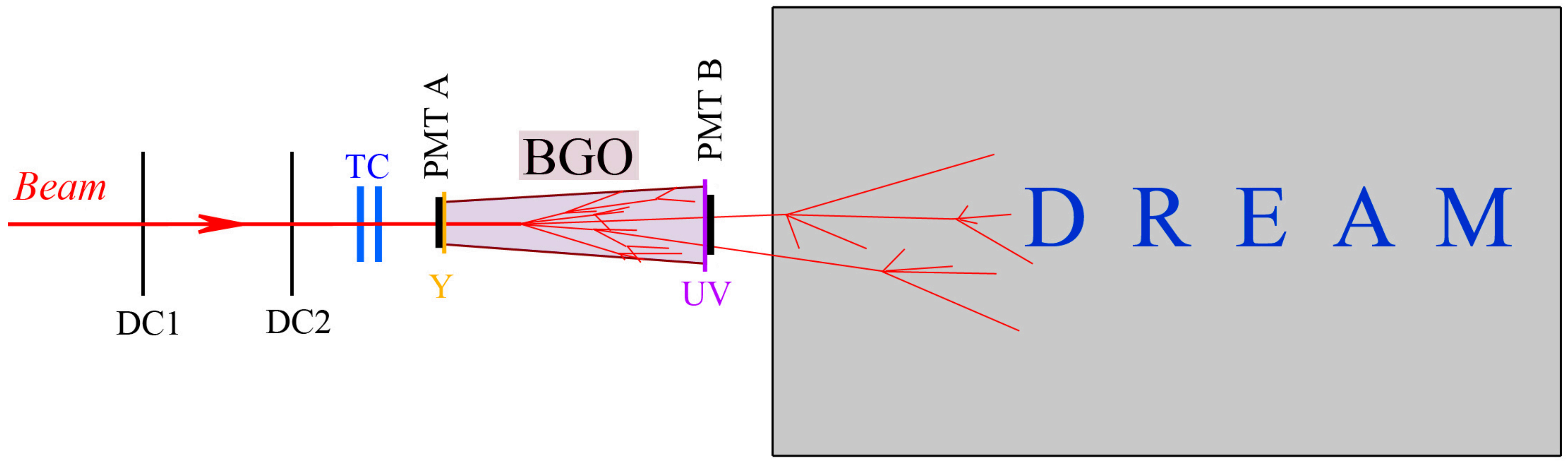
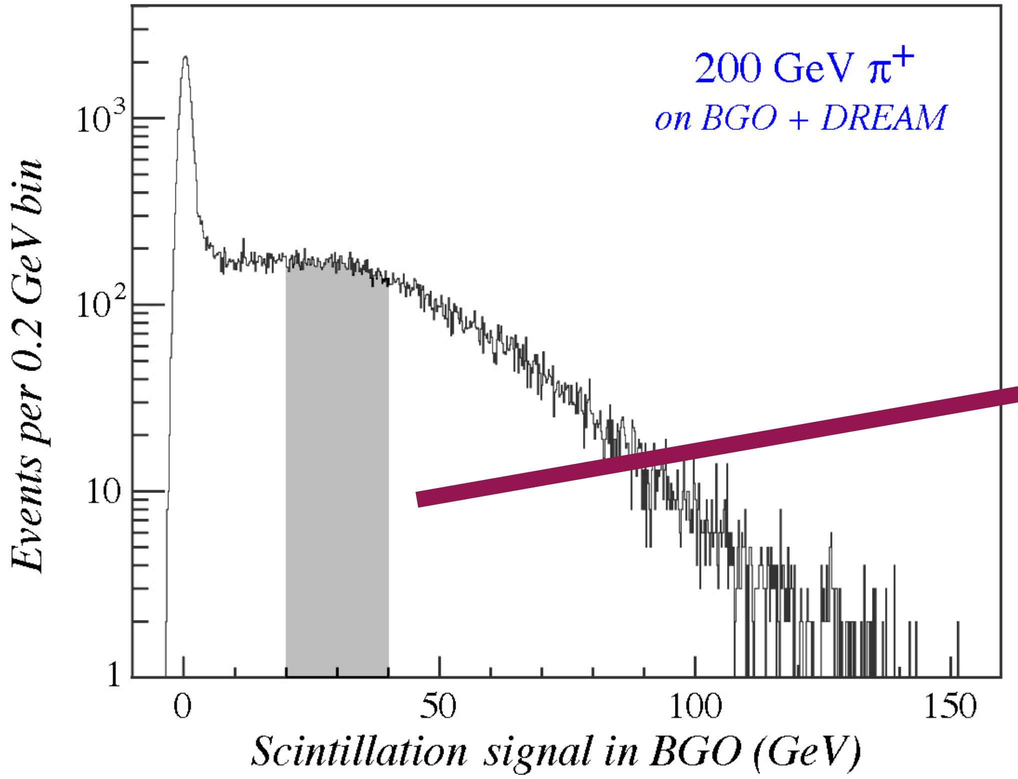
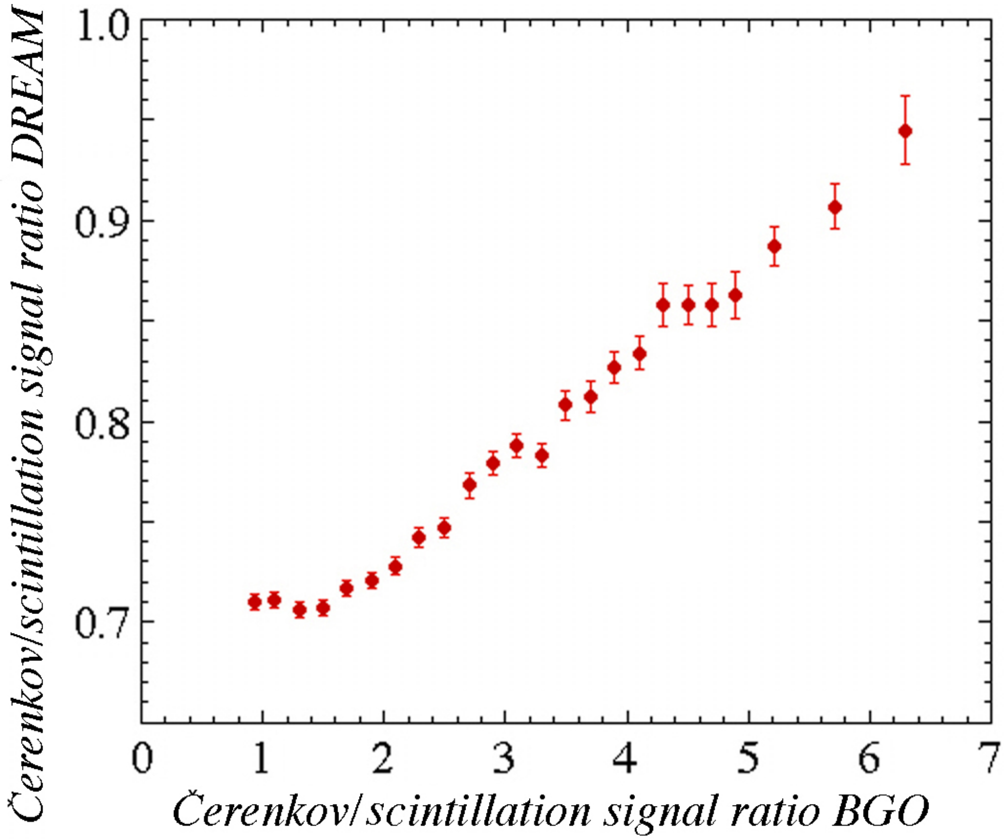




Pions depositing energy in the xtals
Mainly energetic **π0** produced in early stage of the shower



Dual-readout hybrid calorimeter

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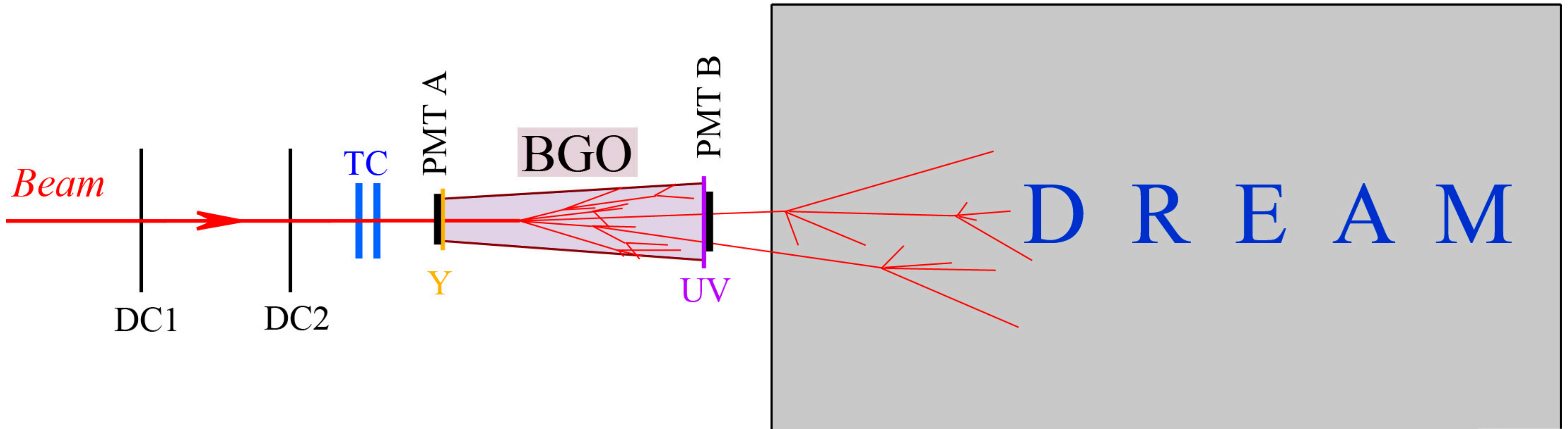

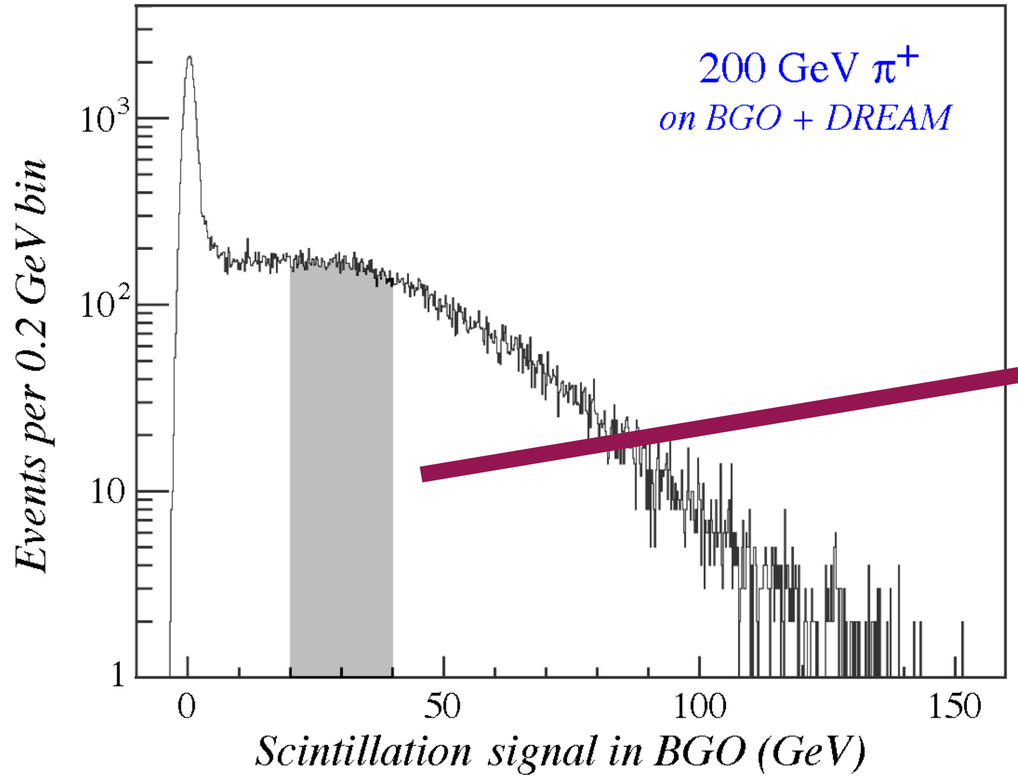

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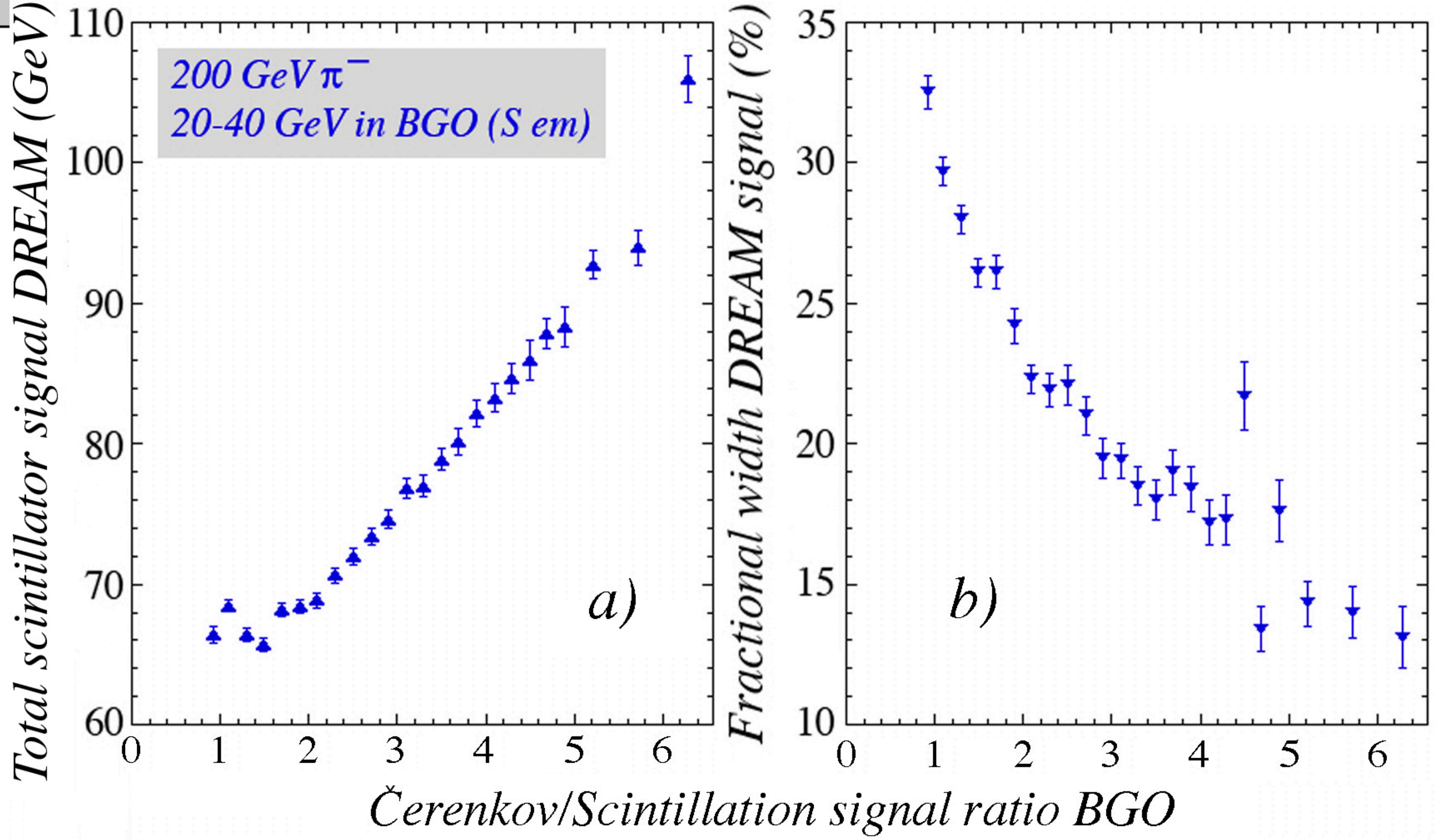
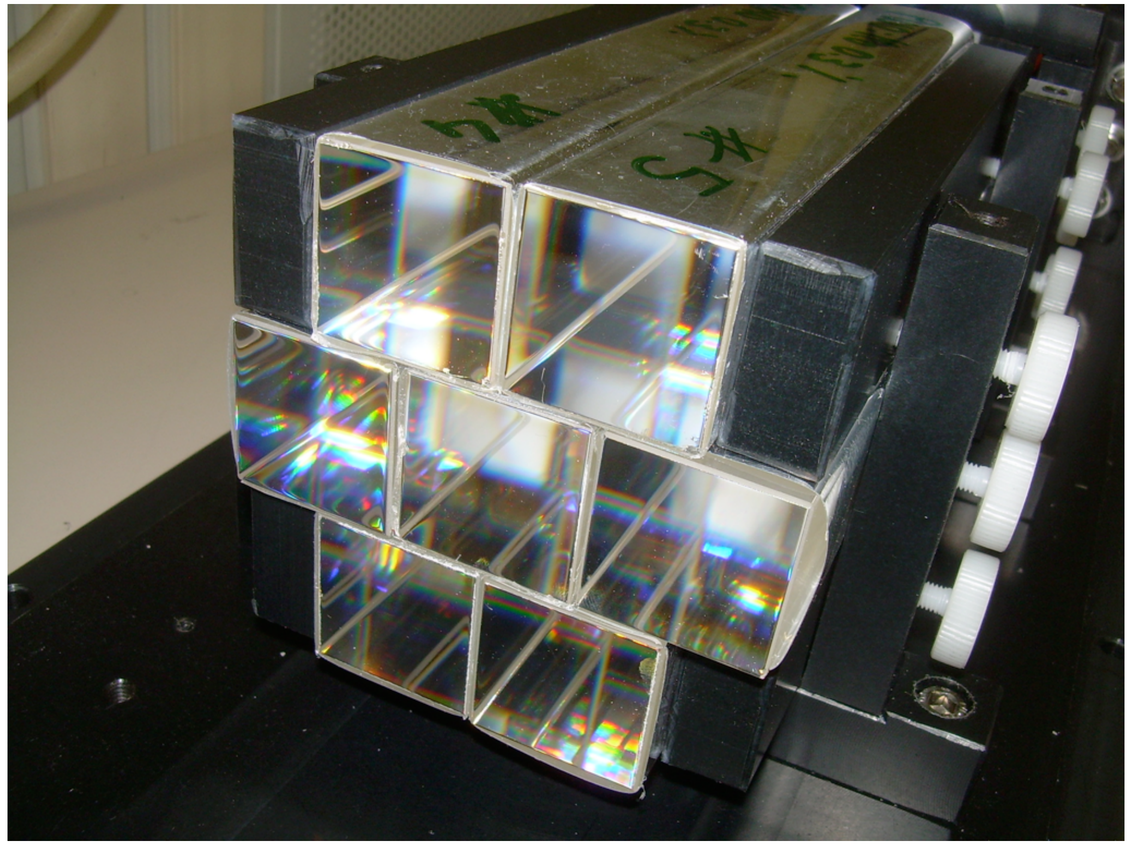


Mo:$PbWO_4$ measurements

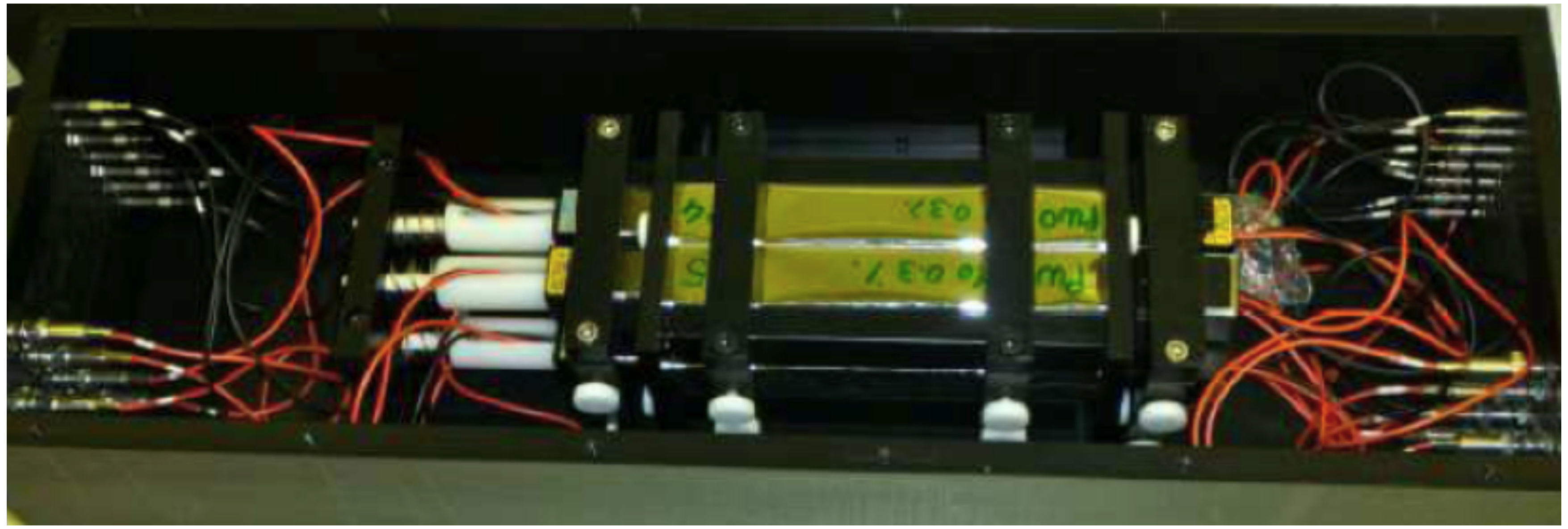
- 7 custom made(*) PbW04 crystals doped with 0.3% Mo

- Dimensions:
  - $3\times3\times20\ cm^3$
  - 25 X_0 1.36ρ_M

- 2 PMTs for each crystal (14 in total)
  - Hamamatsu 8900 and 8900 (SBA)



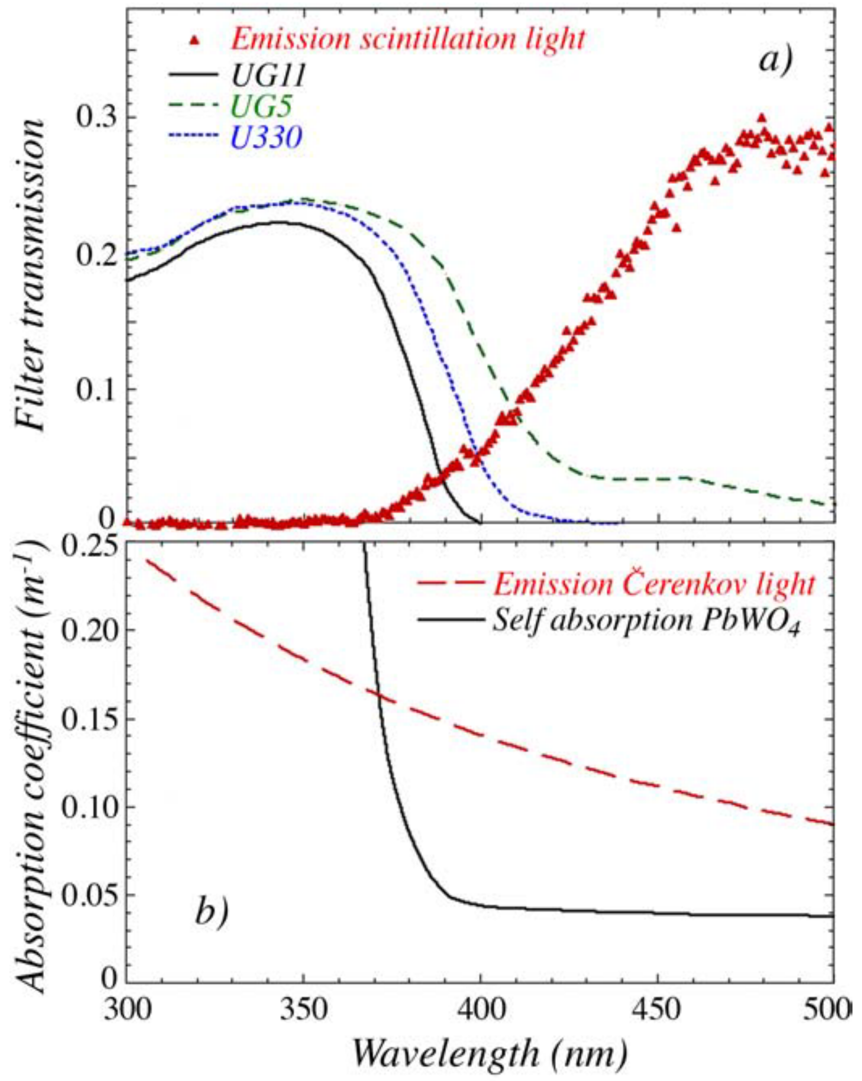
Different filter combinations were used during the $PbWO_4$ matrix test, each optimizing one aspect of the readout

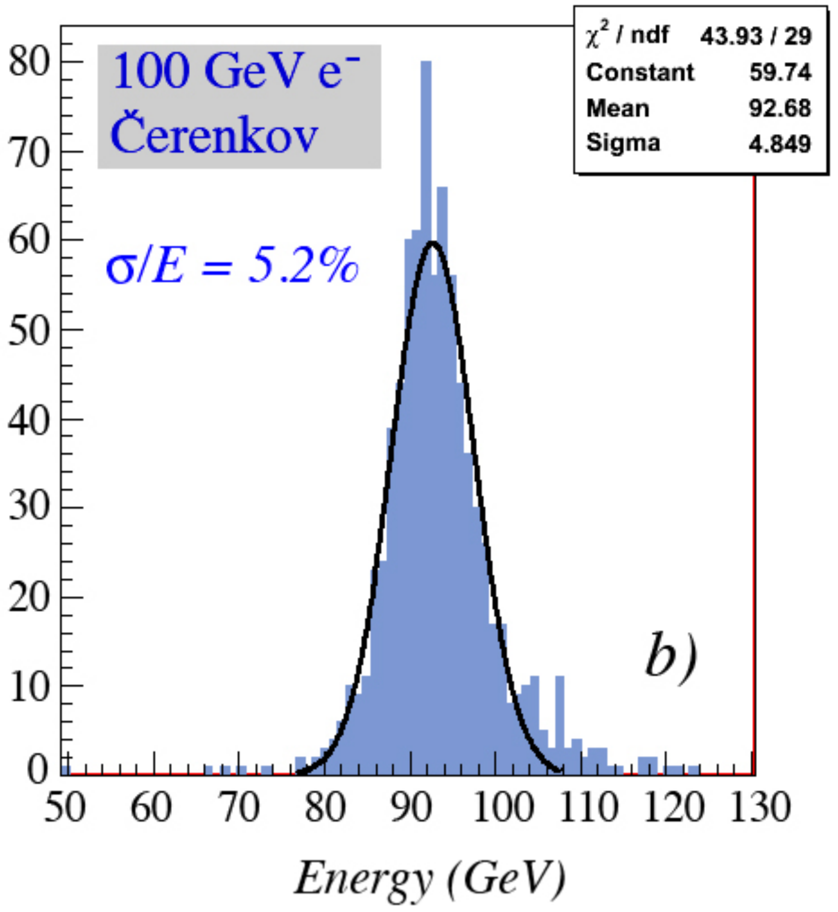


M0:PbWO$_4$ results: Cerenkov

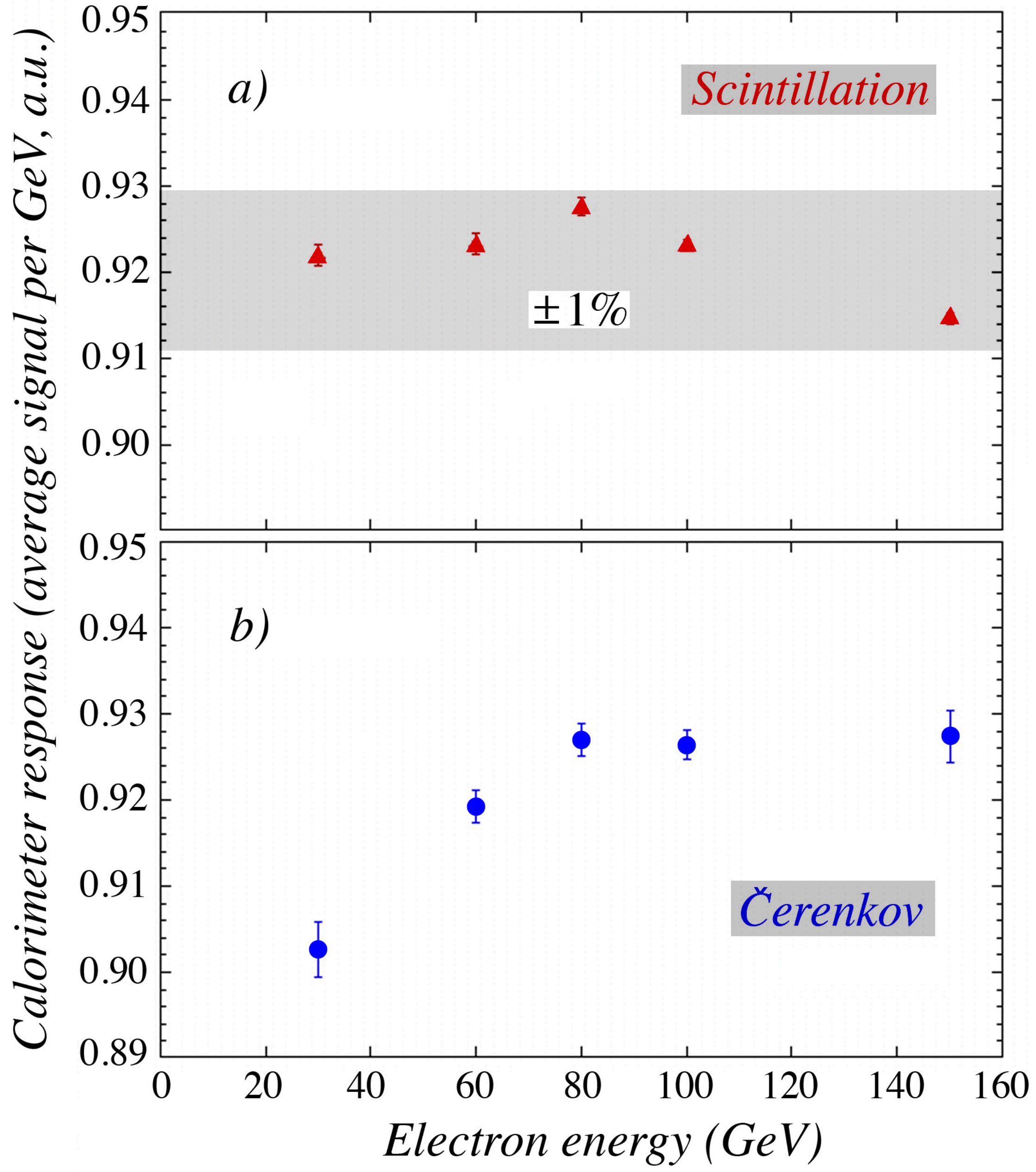
Upstream GG495 (yellow), downstream U330:

- good for S: measured resolution: ~ 1% for 100 GeV electrons
- poor for Č due to self absorption. Strong non linearity





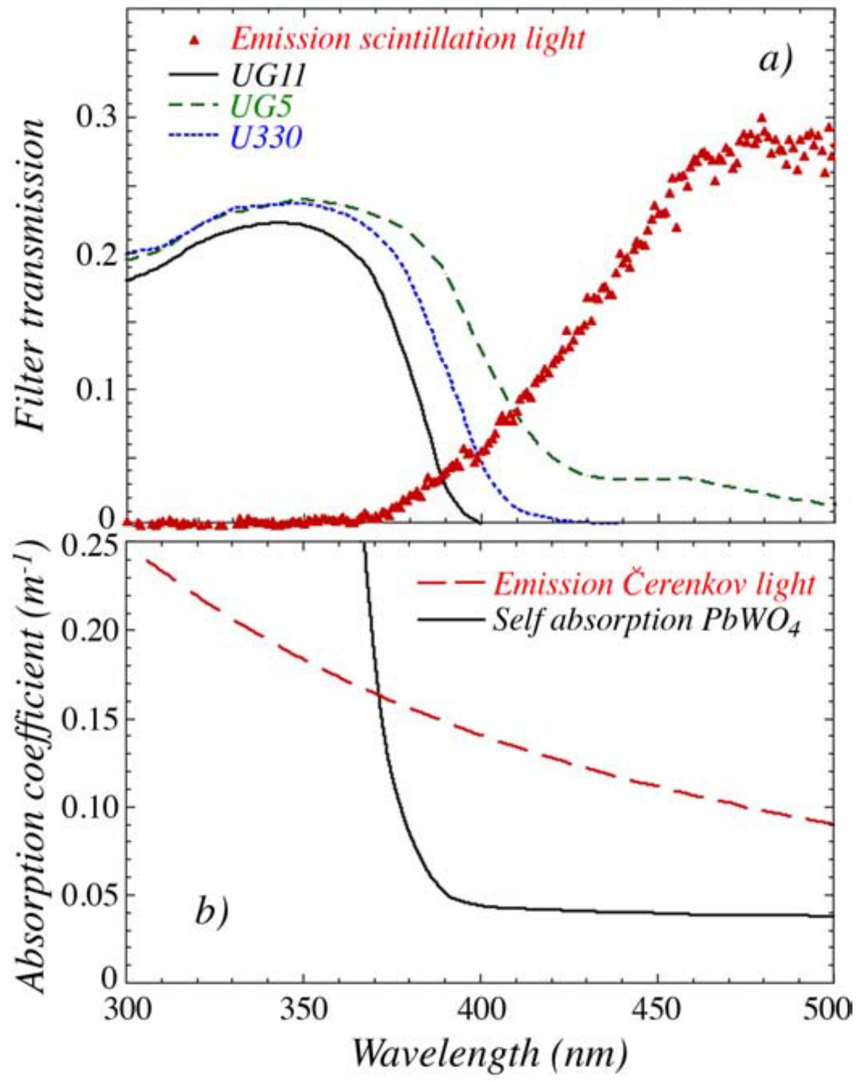
Linearity

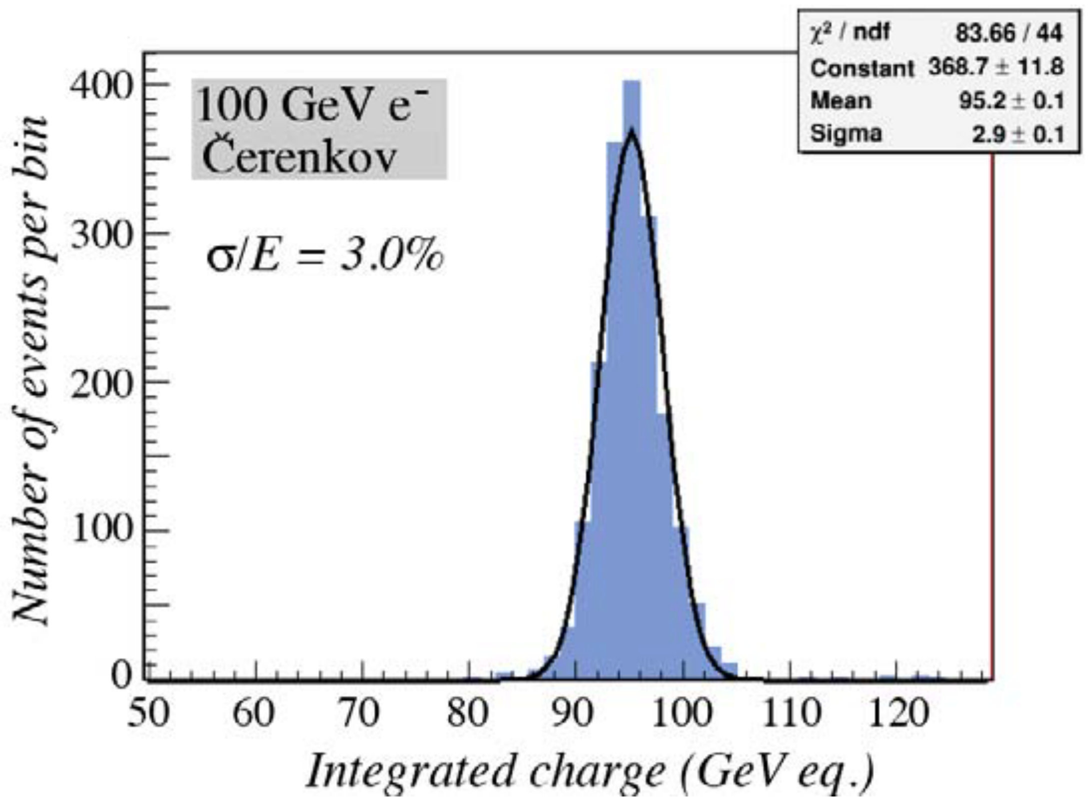


M0:PbWO$_4$ results: Cerenkov

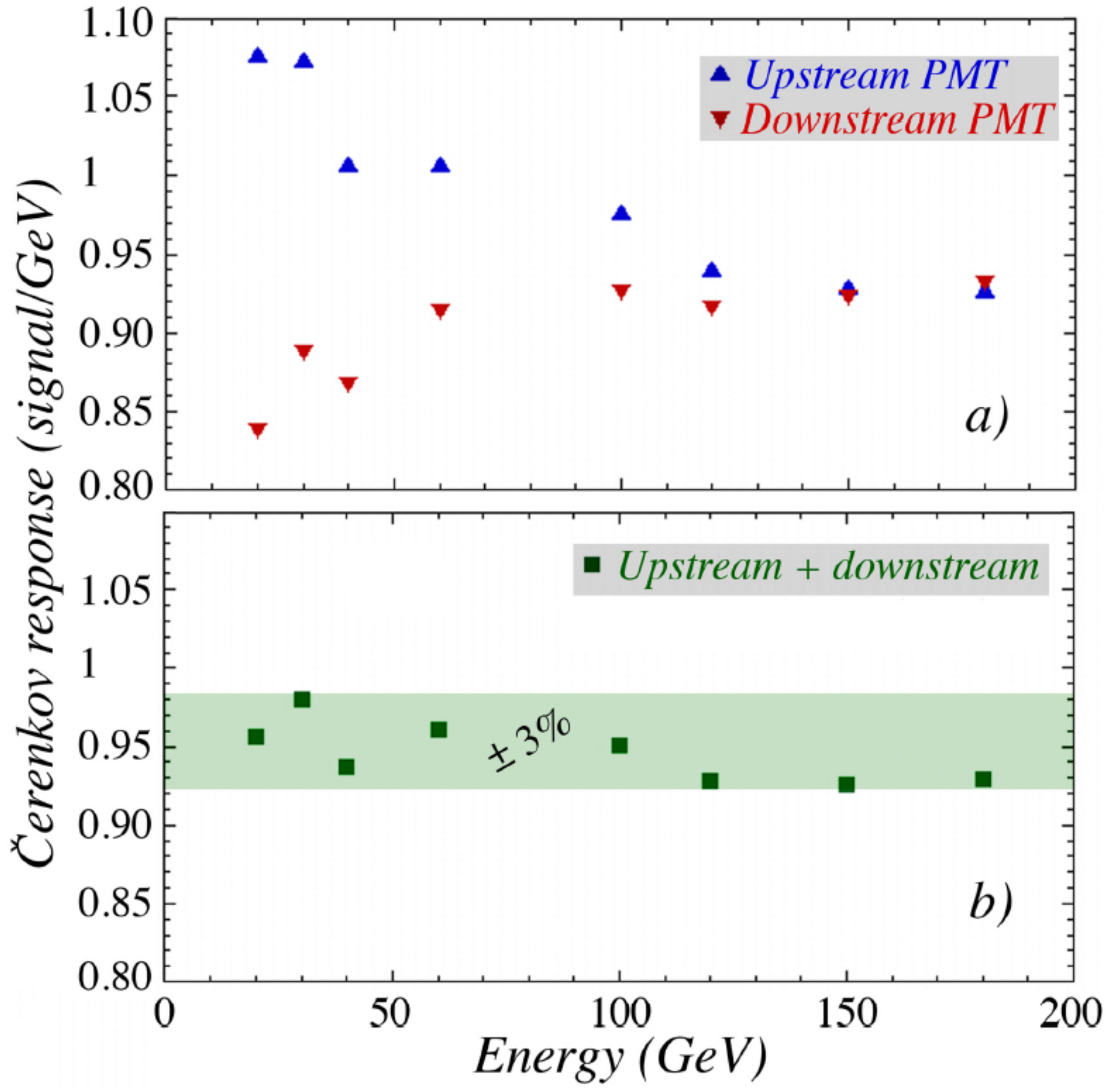
U330 both sides

- good for Č (sum of two sides)
- almost no S signal





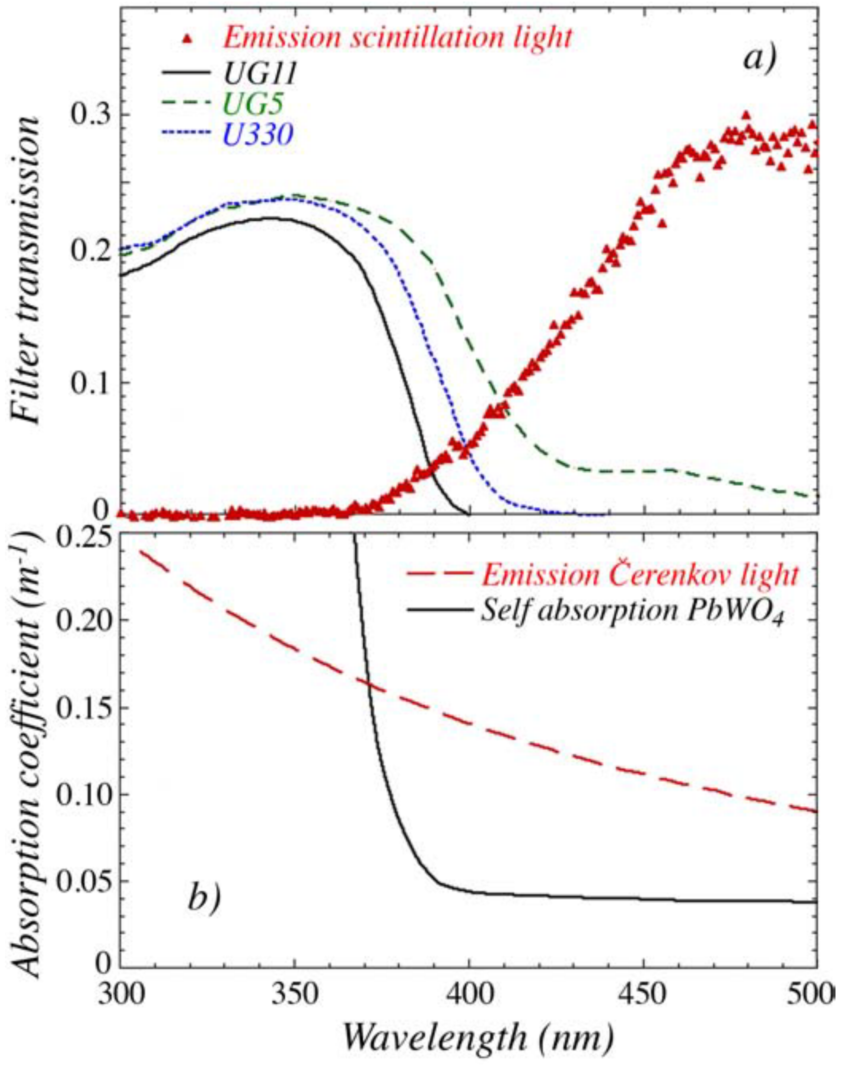
Linearity

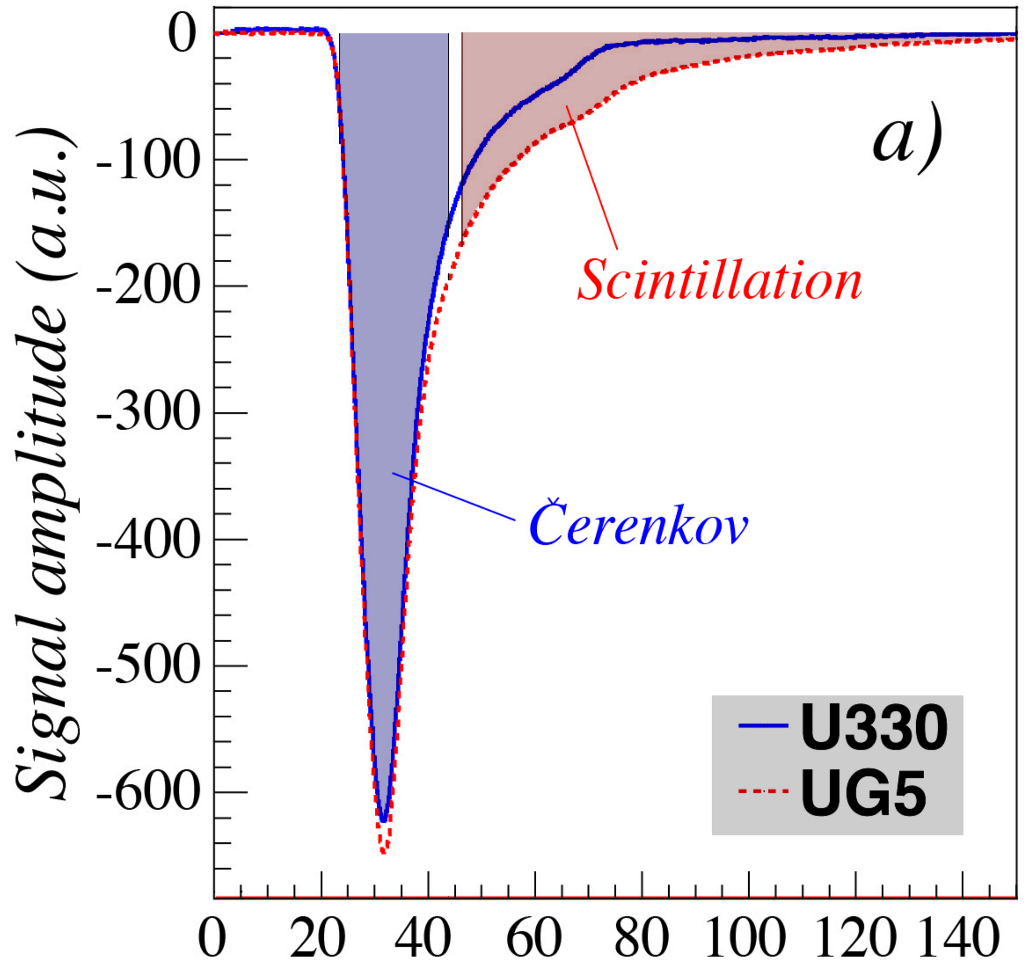


M0:PbWO$_4$ results: Cerenkov

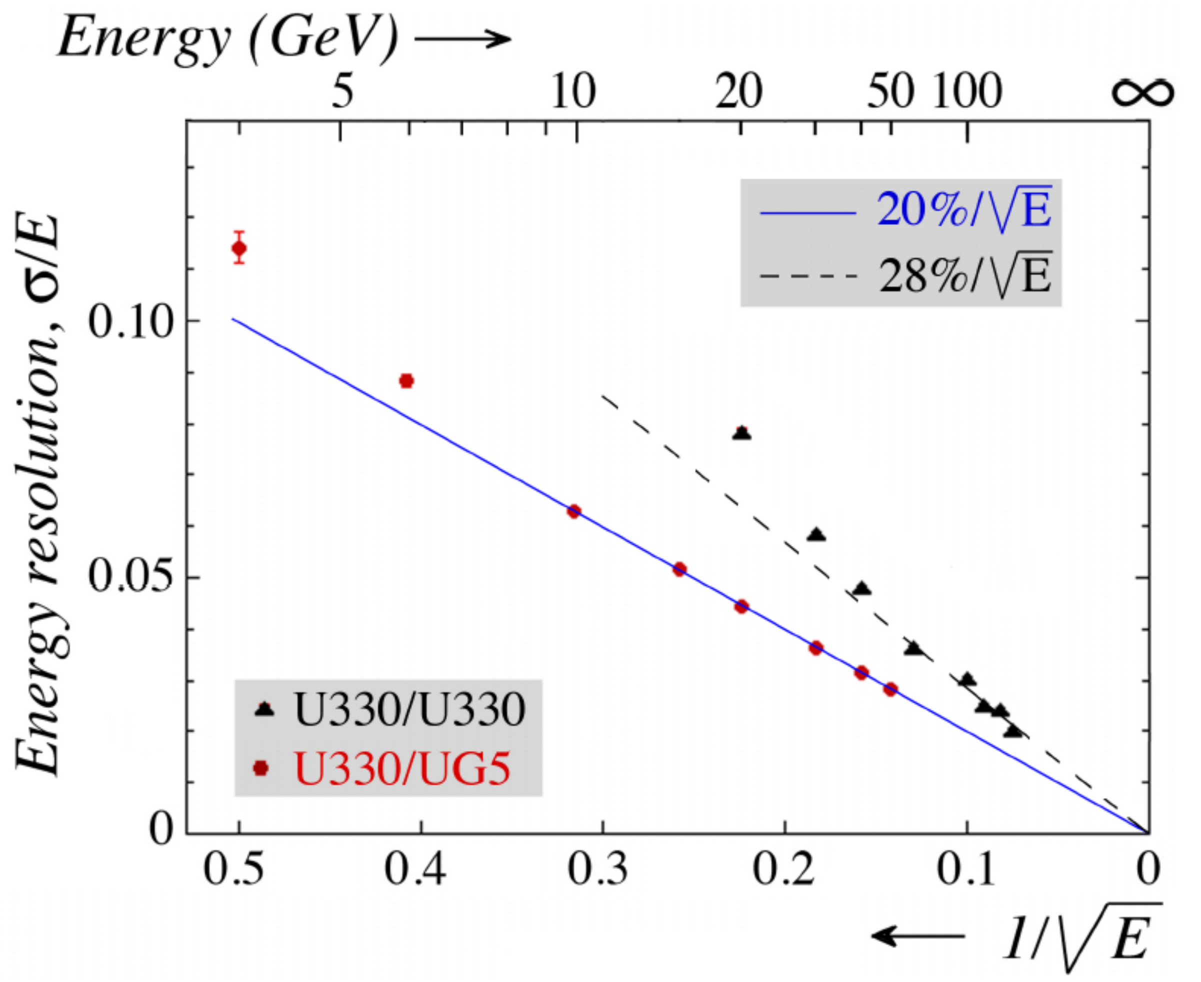
Upstream UG5 (blue), downstream U330

- good for Č: sum of two sides, reduction of effects of self absorption. Linearity at 3%
- poor for S: S extracted from the tail of the time structure, hence few photoelectrons.





Energy Resolution



Conclusion from testing DR crystals

Consideration before testing

ADVANTAGES:	**FORESEEN DISADVANTAGES:**
• No sampling fluctuations • simpler calibration	• No sensitivity to neutrons • high cost • rad hardness

Additional outcomes from performed tests:

To separate the C and S component, crystals have to be *readout in non conventional way*
→ results not good as the ones obtained by standard EM calorimetry

Extraction of pure C and S signals implies
- *To sacrifice a large fraction of available C photons* (optical filters)
- *C photons are attenuated by crystal UV self absorption*

Conclusions and Outlook

- DREAM/RD52 collaboration didn't proceed in the DR crystals calo studies due to new results obtained with an optimized layout with DR fiber calorimeter (13%/sqrt(E) with a costant term smaller than 1%.)
- A proof of principle that DR xtal ECAL combined with DR fiber HCAL can hold both good EM and HAD resolutions was made
- Advancements/improvements in RO techniques could overcome limitation on DR crystals found (~ 10 y ago)