Scintillating Glasses for Total Absorption Dual Readout Calorimetry

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Outline

- **Introduction**
- **Test with cosmics**
- **Tests with particle beams**
- **Conclusions and future work**

Materials suitable for the application of Total Absorption Hadron Calorimetry (TAHCAL) have been reviewed in the preceding talk by Ren-Yuan Zhu (this conf.) : the required characteristics are generally those of heavy scintillating crystals. Scintillating glasses would be a cheaper alternative but heavy glasses with the required characteristics are yet to be developed.

A lighter scintillating glass [2] which appears to have the required properties (except for λ_{int}) is presently available at FNAL as a legacy of E705

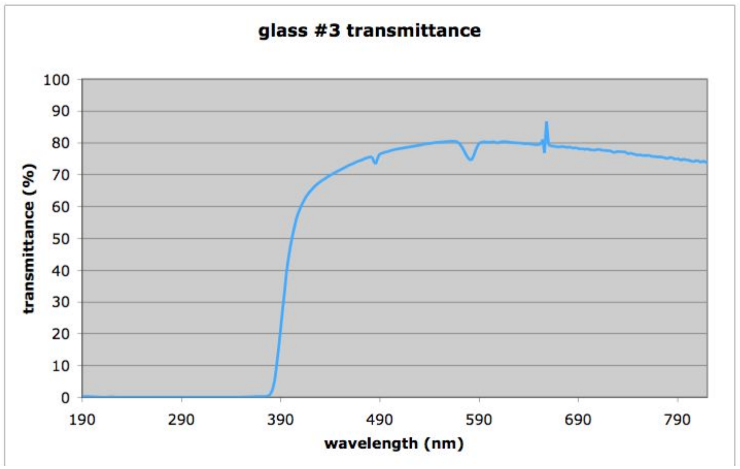
Although the glass is too light for implementation of TAHCAL in compact collider detectors it can be used to investigate problems related to light collection and separation of the C and S signals in homogenous calorimeters.

SCG1-C glass

- By Ohara Optical Glass, Inc. (1)
- Density is 3.36 g/cm^3 (3)
- Radiation length is 4.26 cm (3)
- Interaction length is 44.5 cm (for pions with 30-200 GeV energy) (3)
- Reminder for the simulation: for protons λ is shorter than for pions
- Refraction index: n=1.61 (4)
- Cherenkov emission angle θ_c=51.6°
- Scintillation decay time: 70 ns (2)
- Cherenkov to scintillation signal: C/S=40/60 (2)

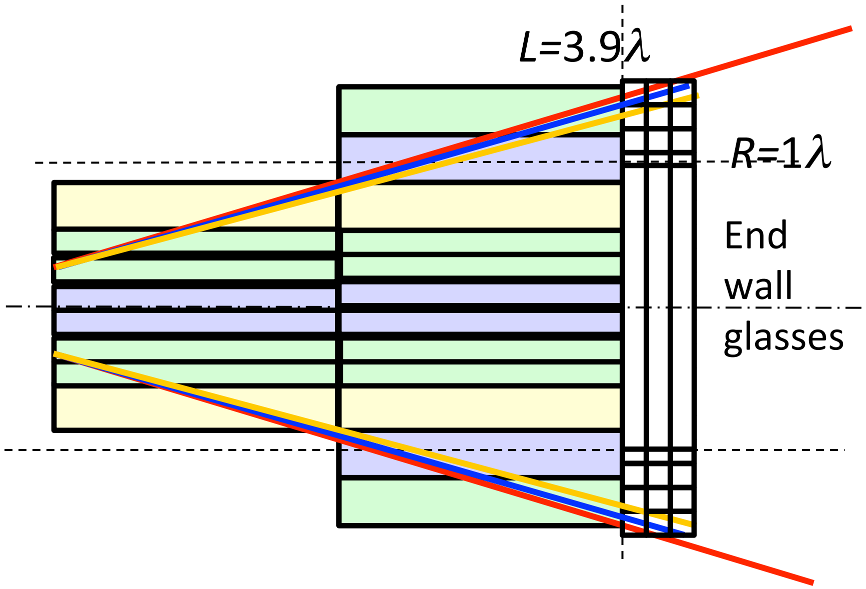
salt	Percent (by weight) (1)
BaO	43.4%
SiO_2 (α-quartz)	42.5%
Li_2O	4.0%
MgO	3.3%
K_2O	3.3%
Al_2O_3	2.0%
Ce_2O_3	1.5%

7.5x7.5x89 cm^3 and 15x15x89 cm^3

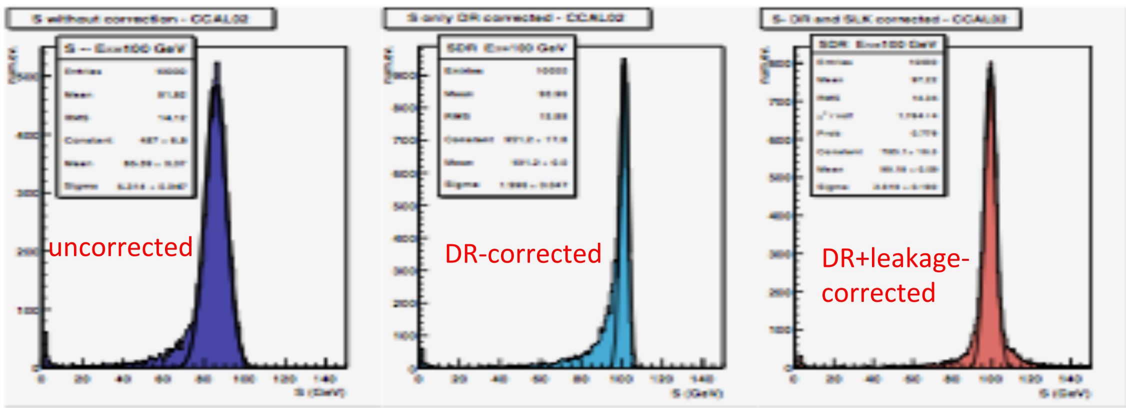


Assuming the glass characteristics reveal themselves suitable , one might use the available glass to configure a module for a proof of principle test of TAHCAL.

The figure illustrates a configuration of available glass expected to limit leakage to ~5%.

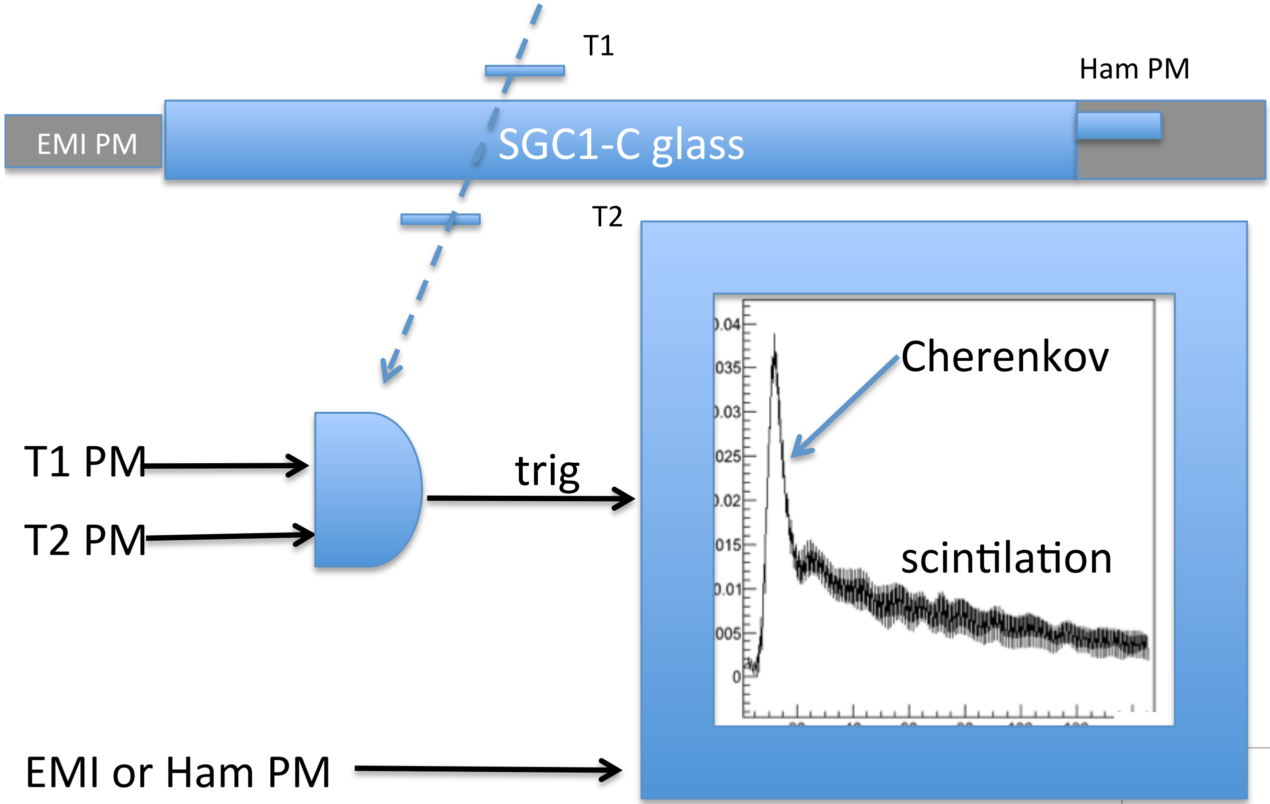


Segmentation also allows for efficient correction of leakage fluctuations [1] as illustrated by simulations of a highly segmented crystal TAHCAL.



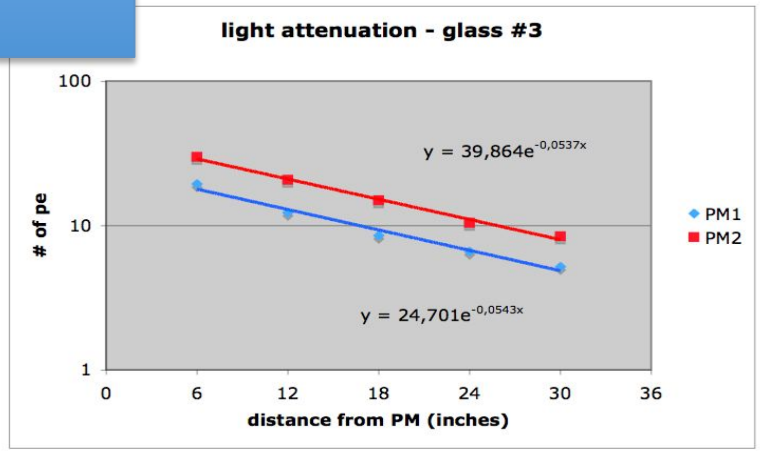
Tests with cosmics

Preliminary tests were performed ad FNAL using cosmics.



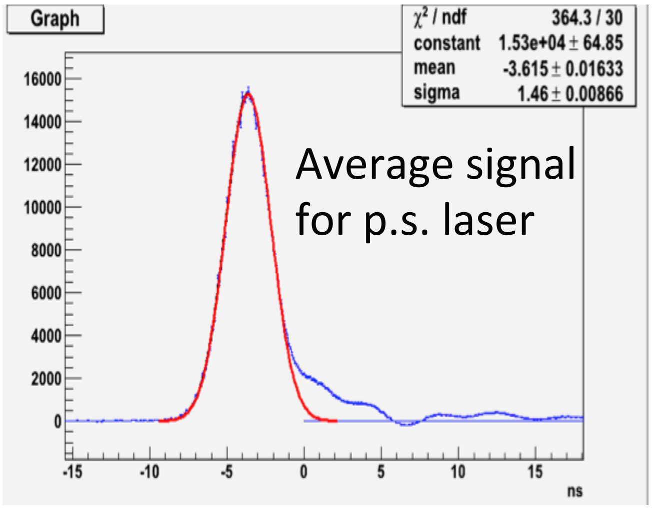
The averages of events selected by a simple cosmic trigger show clear evidence of Cherenkov and scintllation signal components of the PM outputs Evaluation of their respective contributions is clearly possible.

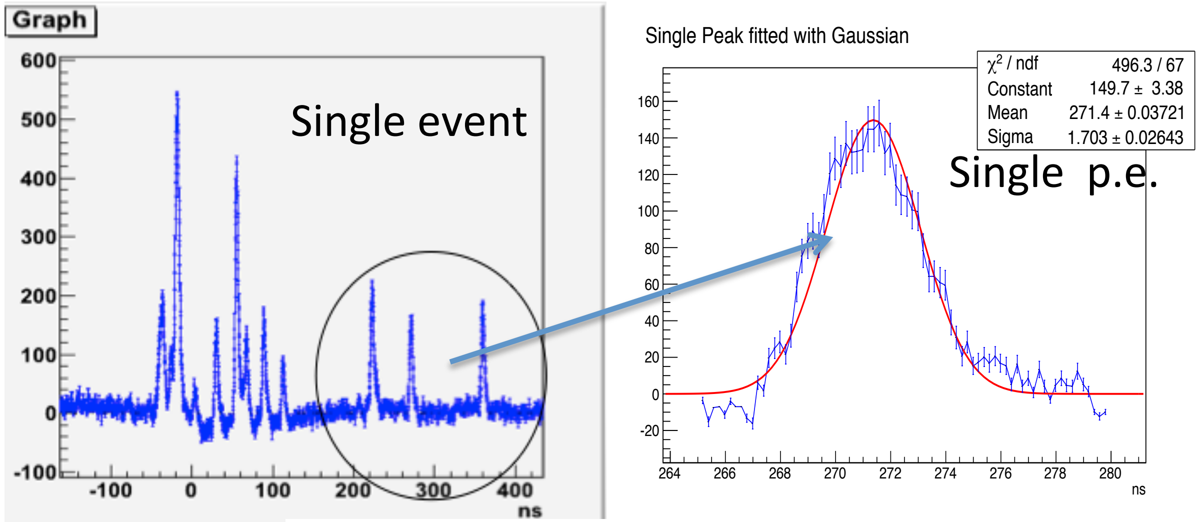
The absolute yield (p.e./mip)
Was measured independently



Line shapes due to the PM and DAQ electronics were measured using a p.s. infrared laser,

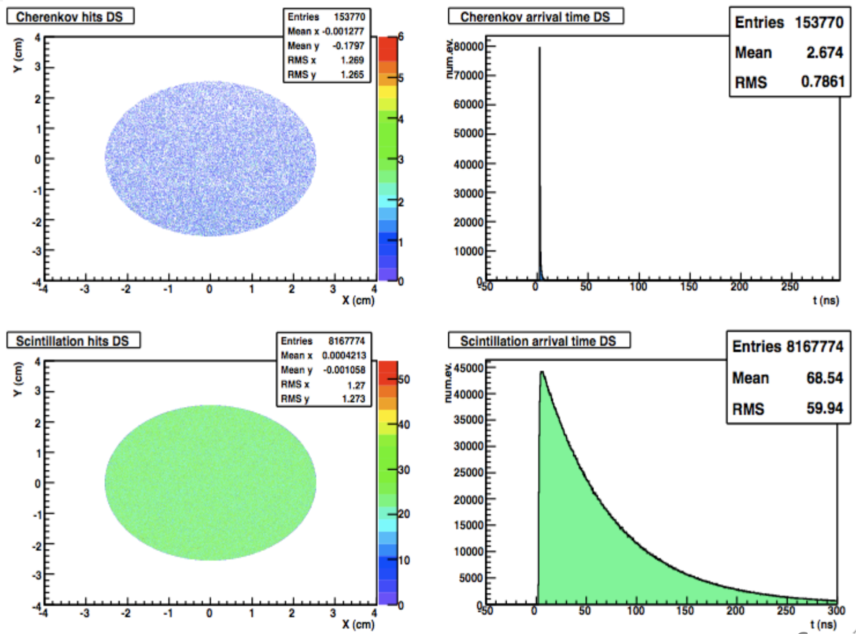
and, because individual events generate between ~ 10 and ~20 p.e., they can also be measured by analyzing individual events

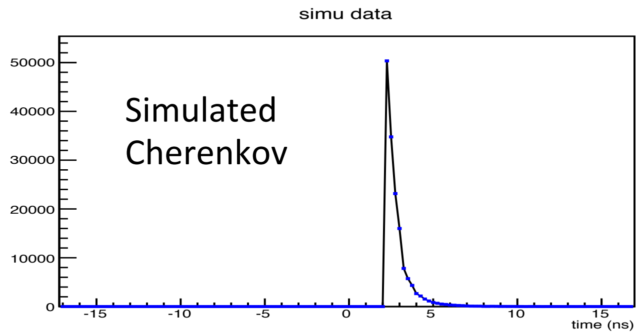


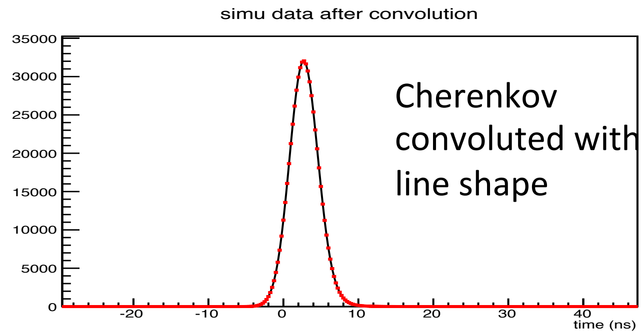


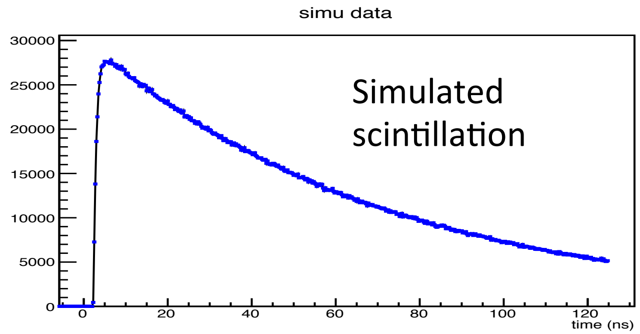
Althought it is slightly asymmetric, a gaussian approximation to the line shape, with $\sigma = 1.8$ ns was used for this analysis

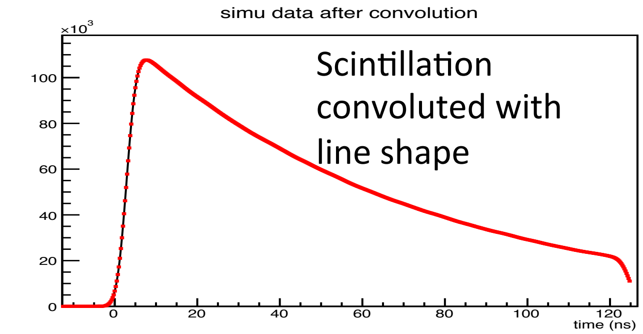
The GEANT 4 simulation package developed by Hans Wenzel (this conf.) was used to simulate the distribution of photons on the PM photocathodes



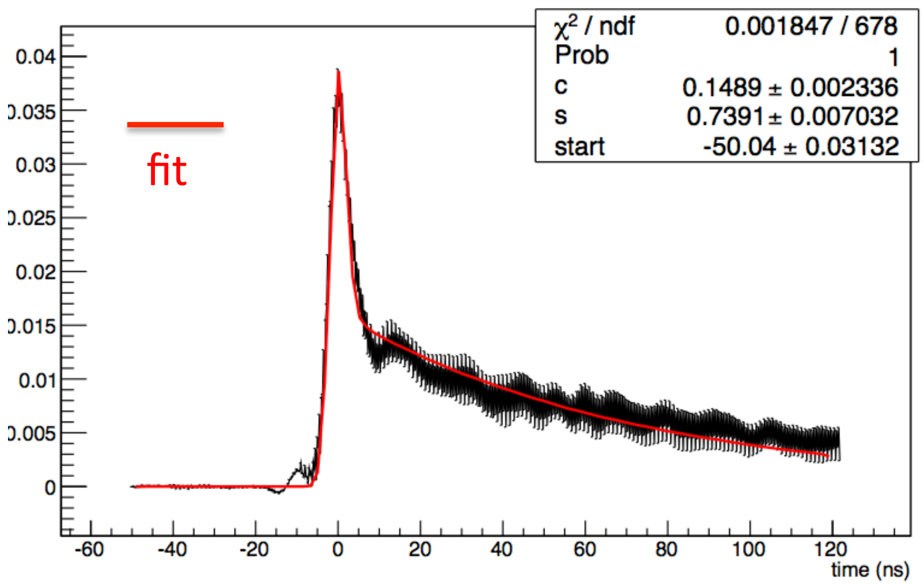






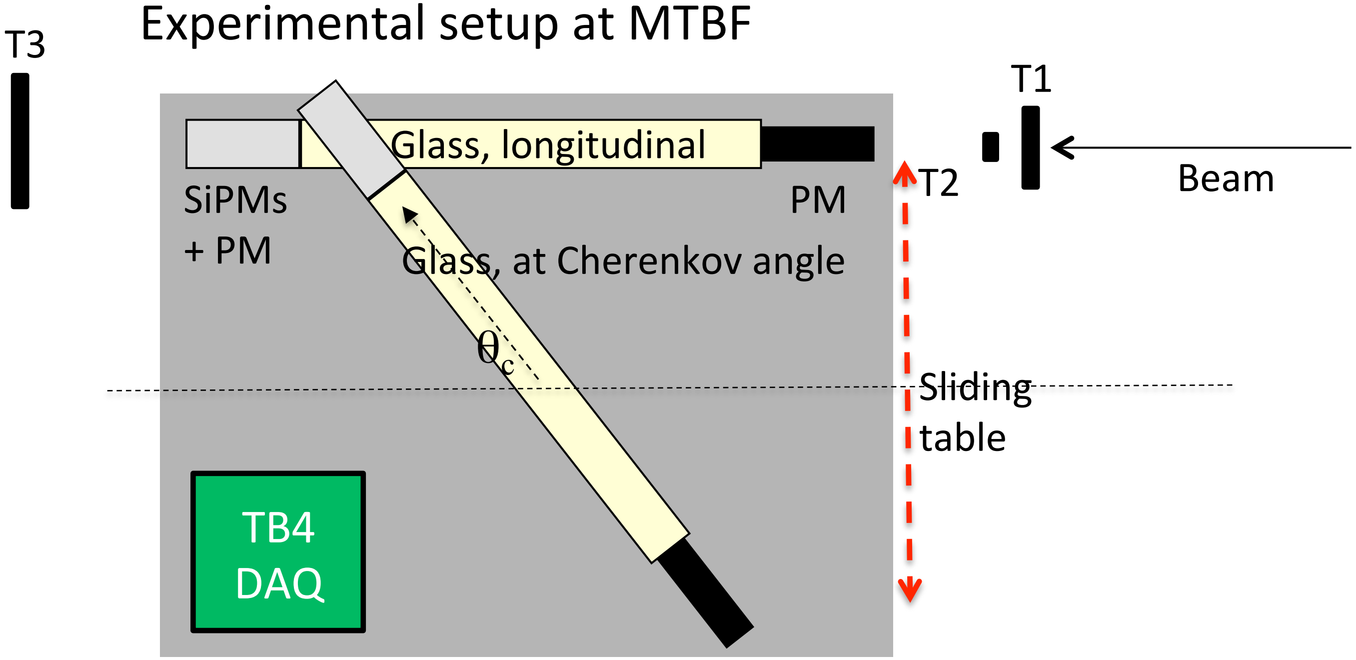


The time distributions of the simulated signals were convoluted with the measured line shapes and fitted to the data to obtain the ratio (C/S). Given the number of Cherenkov photons generated by the simulation, the fit was also used to calculate the number N_S of photons/MeV generated by the scintillating glass (~600 photons/MeV   as opposed to 8500 for BGO crystals)

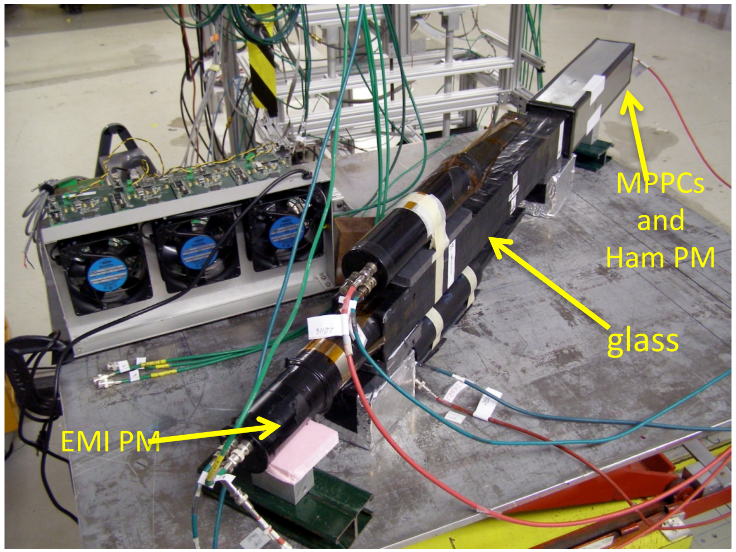


Tests using particle beams

Experimental setup at MTBF



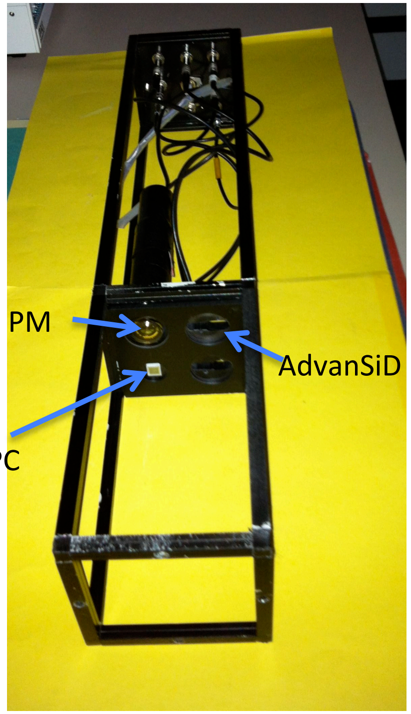
Particle beams from the Fermilab Meson Test Beam Facility (MTBF) were used to test the response of these glasses to hadrons and to investigate readout with silicon-based photodetectors : because of their much smaller sensitive areas, cosmic rates in these detectors were much too small to be useful. The experimental setup at MTBF is illustrated.



The photo detector assembly

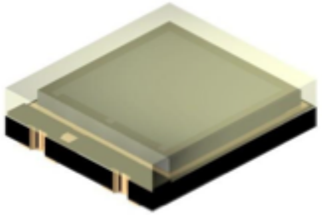
Several alternative silicon – based photodetectors, together with a Ham PMT were accomodated in the assembly illustrated below. The characteristics of two comparable ones by AdvanSid and Hamamatsu are shown below.

Frame for mounting SiPMs and Ham PM on end of SCG1-C glasses



ASD-SiPM3S-P

3x3 (4x4) mm^2 , 50 μm microcells



Parameter	ASD-SiPM3S-P Family (3×3 mm^2 active area SiPM in plastic package)			Unit
	ASD-SIPM3S-P-25	ASD-SIPM3S-P-50	ASD-SIPM3S-P-69	
Effective Active Area	3×3			mm^2
Cell Size	25×25	50×50	69×69	μm^2
Cells number	14400	3600	1936	-
Spectral response range	350 to 900			nm
Peak sensitivity wavelength	480			nm
Photon Detection Efficiency (2)	9.5	22	26	%
Breakdown voltage	35±7 (3)			V
Work voltage range	BV(1)+2 to BV+7			V
Dark count (4)	$1.15\cdot10^7 \div 2\cdot10^7$	$3\cdot10^7 \div 4.5\cdot10^7$	$3.5\cdot10^7 \div 5.5\cdot10^7$	Cps
Gain(5)	$1\cdot10^6$	$2.5\cdot10^6$	$4.8\cdot10^6$	-
Breakdown Voltage temperature sensitivity	76			mV/°C

Hamamatsu

2 x 2 array

3x3 mm^2 , 25-50 μm microcells

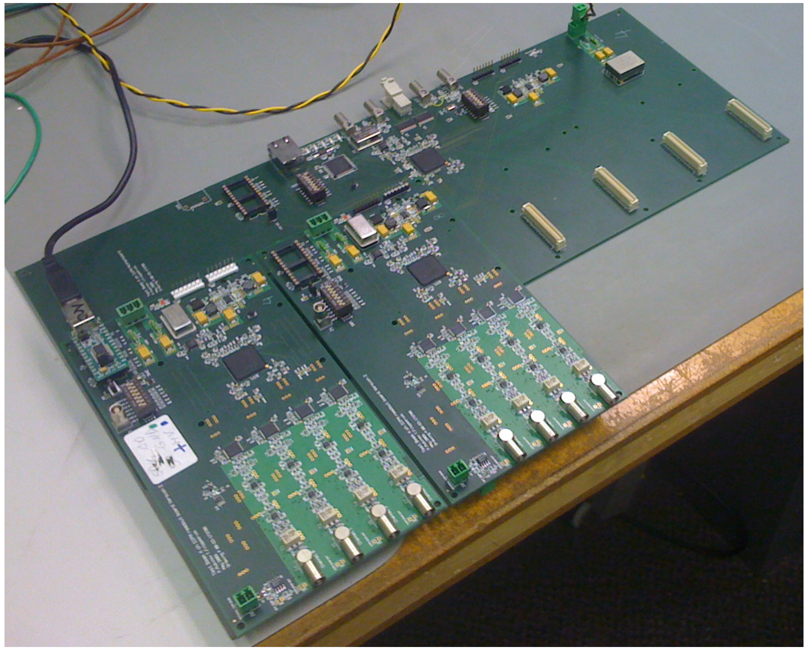
Parameter	S10985 series		
	-025C	-050C	-100C
Number of channels	4 (2 × 2)		
Effective active area/channel	3 × 3		
Number of pixels/channel	14400	3600	900
Pixel size	25 × 25	50 × 50	100 × 100
Fill factor *1	30.8	61.5	78.5
Spectral response range	320 to 900		
Peak sensitivity wavelength	440		
Operating voltage range	70 ± 10 *2		
Dark count/channel *3	4000	6000	8000
Dark count Max. /channel*3	8000	10000	12000
Terminal capacitance/channel	320		
Temperature coefficient of reverse voltage	56		
Gain	2.75×10^5	7.5×10^5	2.4×10^6

DAQ electronics

Two alternative DAQ systems were available:

a system (TB4) developed in – house at FNAL

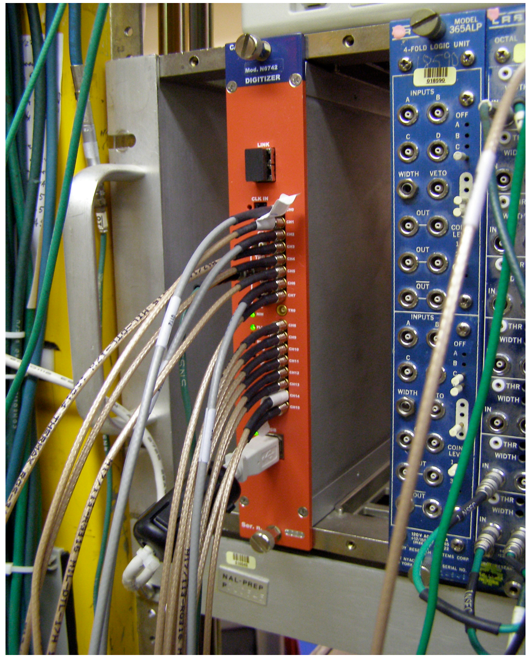
Was used with both PMs and Si-based photodetectors



- On-board bias – shares signal connection
- 50 ohm input, ~ x 100 amplification
- ~100 MHz bandwidth, noise ~ 30μV RMS
- 12 bit ADC →large dynamic range, 212 MSps, <4k samples/ch, 4,7 ns/ch
- Bipolar : pedestal is around half scale (8100)
- Set up over USB, read out over 100 Mbit/s ethernet

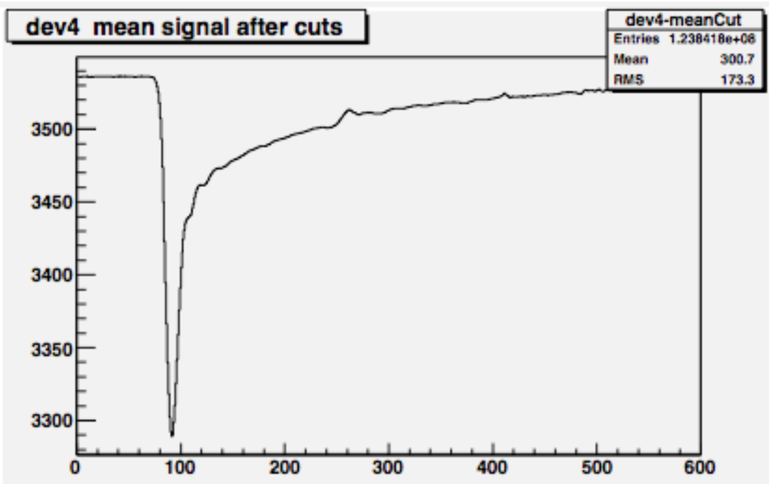
CAEN 2.5 GHz digitizer

Was used only for PM DAQ*

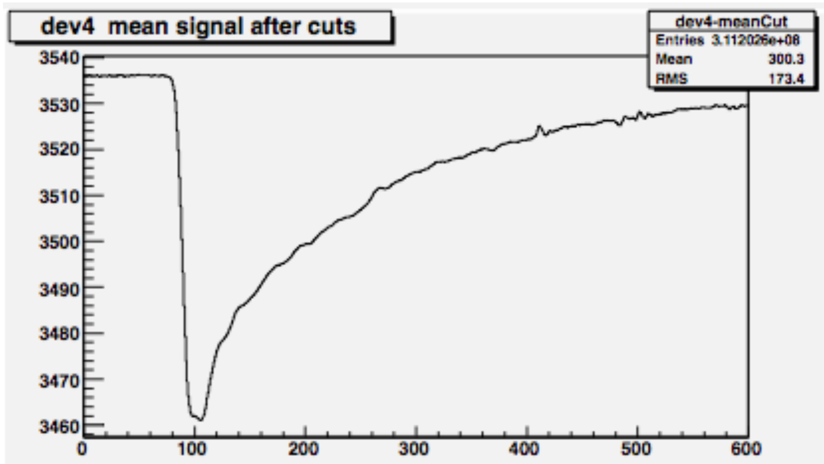


- CAEN N6742 16 + 1 ch 12 bit digitizer
- Based on DRS4 chip : switched capacitor ADC
- Up to 5GS/S
- Bandwidth < 500 MHz
- Nim - compatible

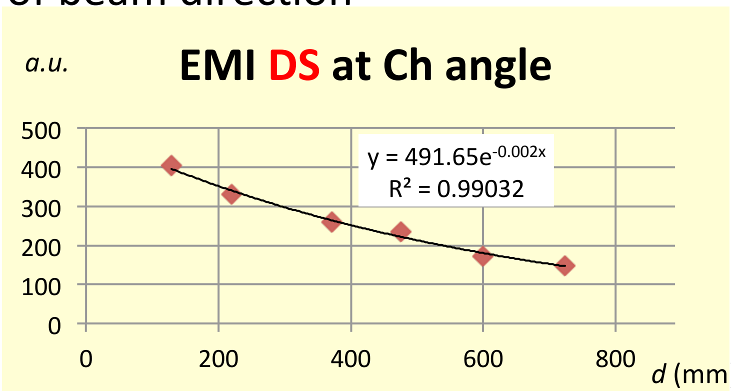
With the glass at the Cerenkov angle θ_c relative to the beam direction, the responses of all detectors were first measured for different points of incidence of the 120 Gev/c beam. The glass was then rotated by 180 degrees and the process repeated. Mean signals from the EMI PM (after correction for multiple hits *) before and after glass rotation (i.e., with EMI downstream and upstream of beam impact point) are shown below.

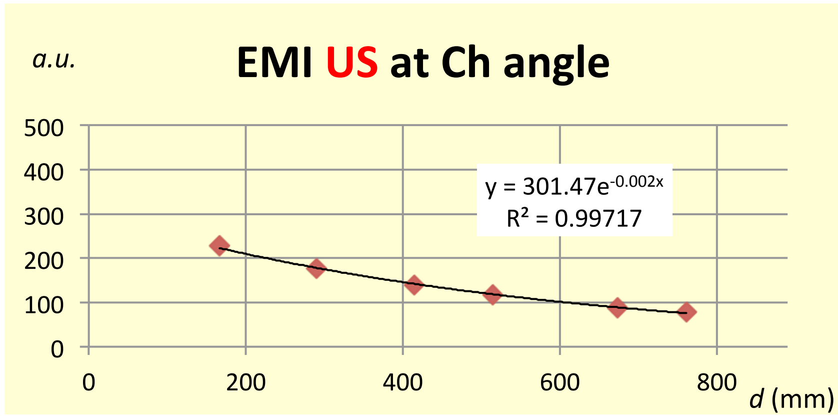


Mean signal with PM “downstream” (DS) of beam direction



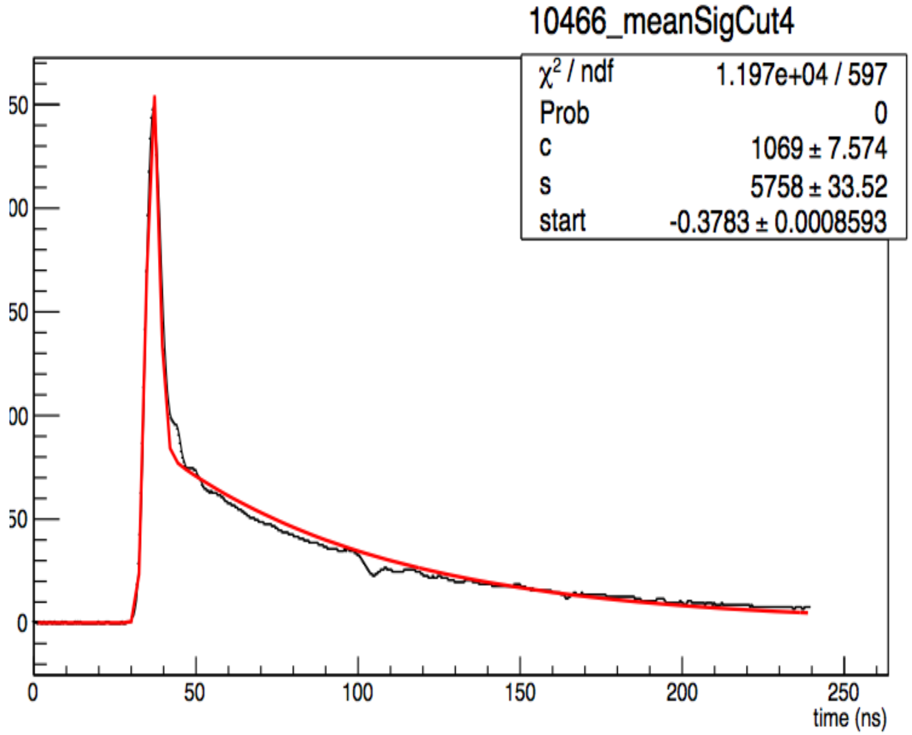
Mean signal with PM “upstream” (US) of beam direction

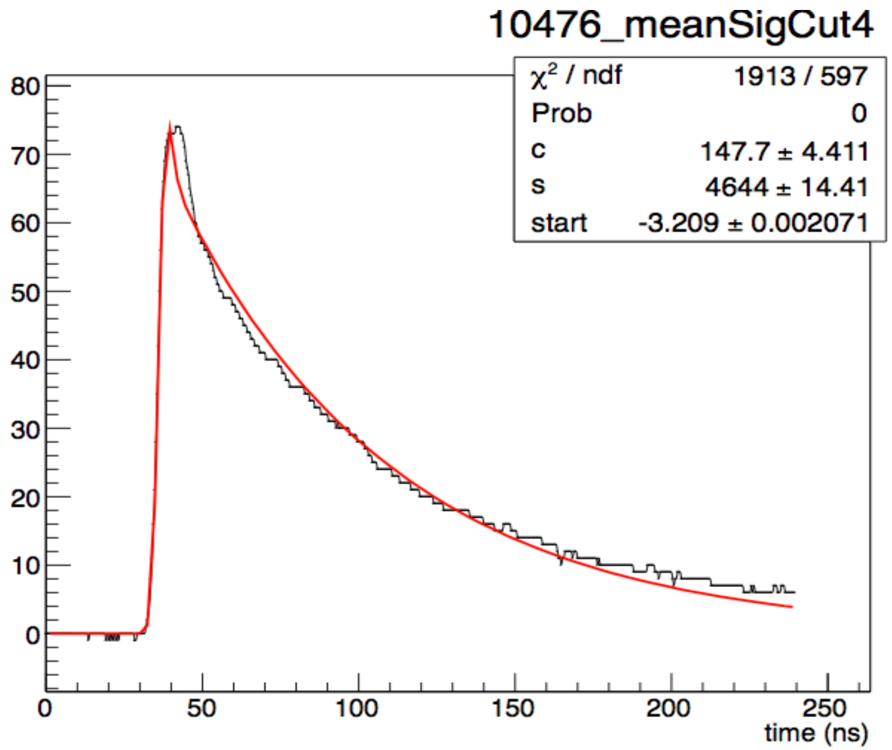




Attenuations for both orientations of the glass w.r.t. the beam

Simulations were performed for each beam position and they were used to extract the ratio (C/S) of Cherenkov/Scintillation components in all cases, as illustrated below .



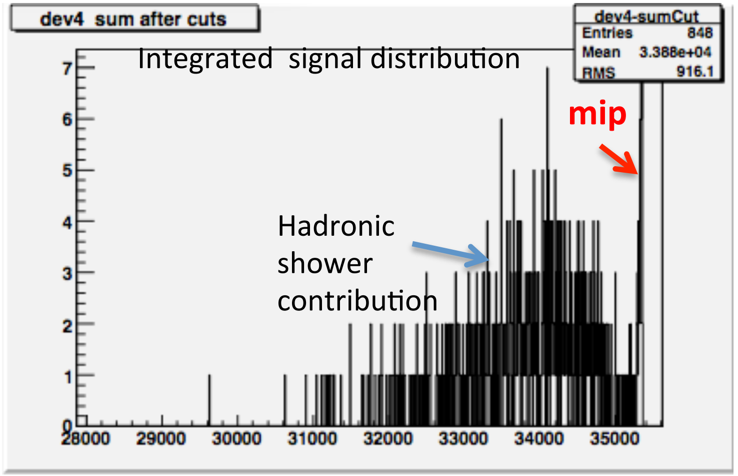


Although the simulations still need perfecting, it is clear that, despite a 20% contribution to the signal from hadronic showers (when the glass is oriented at the Cherenkov angle w.r.t. the beam), one will be able to separate the Cherenkov (C) and scintillation (S) signals reliably on the basis of their different time dependence.

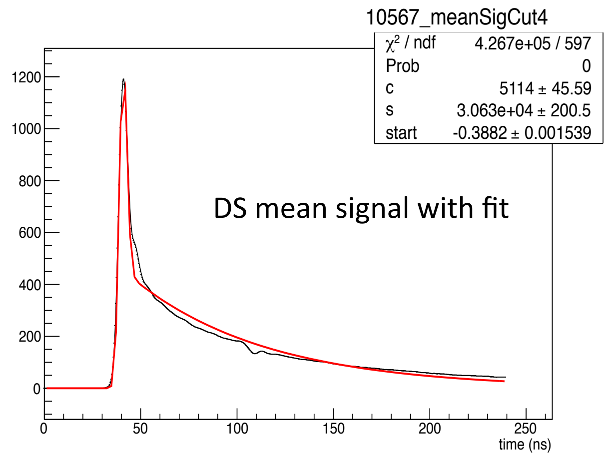
Scintillator light output is much smaller (~7%) than that of BGO , which facilitates the separation of C and S components while remaining sufficient for good energy resolution.

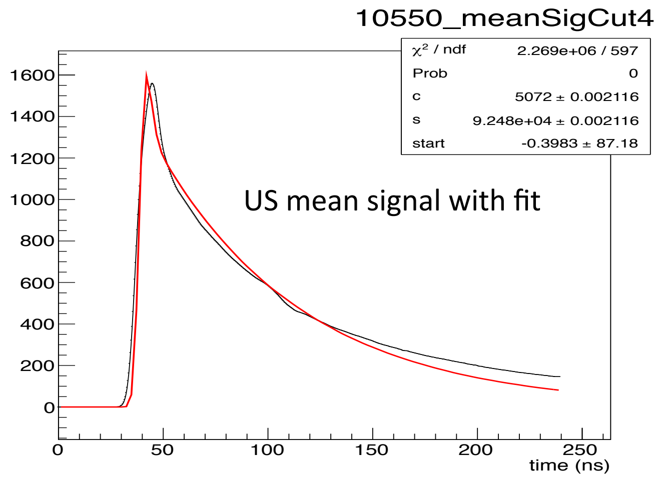
With the glass oriented in the beam direction , i.e. "longitudinally" (L), the showering probability increases to ~ 92.7% and, although much of the shower energy escapes the glass, the residual still dominates as shown by the distribution of signal integrals from the EMI PM

The distribution of signal integrals for the EMI PM, located Downstream (DS) of the beam direction after single hit selection. Statistics are limited because of the large multiple hit component due to beam structure

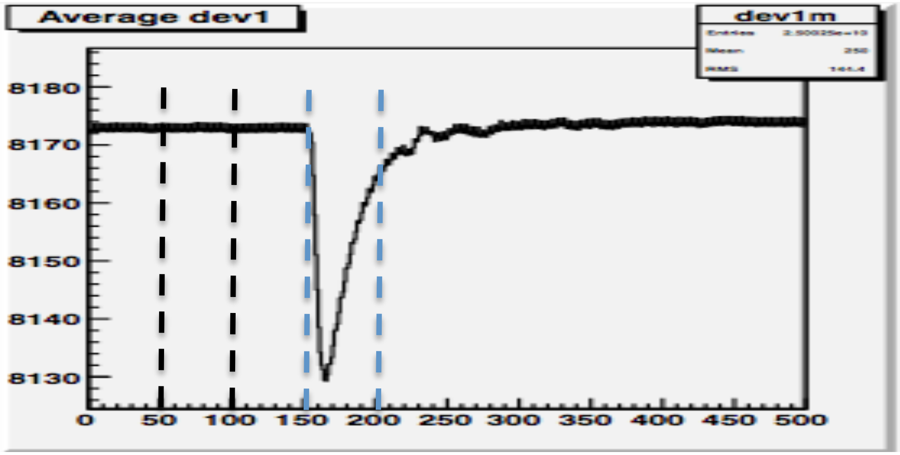


Average signals together with fits (in red) obtained using the simulated C and S contributions are shown below. It is evident that a time-based analysis allows for determination of the C/S ratio even in the presence of a large hadronic shower contribution to the total energy deposited.





The signals from the silicon – based photodetectors show similar characteristics as shown below. However, the bandwidth (<100 MHz) and sampling rate (212 MS/sec) of theTB4 DAQ used to acquire this data were not sufficient for the time-based analysis used with the PM signals to extract C/S. There is no reason to expect it will not be possible using the same DAQ as for PMs*.



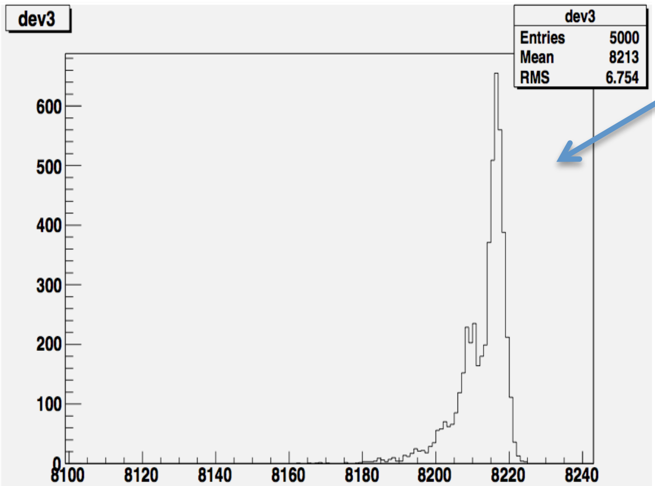
Mean signal from one of the four (50 x 50 μm^2) components of a 2 x 2 MPPC array located "downstream" of the beam direction .
Note that it corresponds to little more (~ 25 % shower probability at Cherenkov angle) than the energy deposited by a mip .

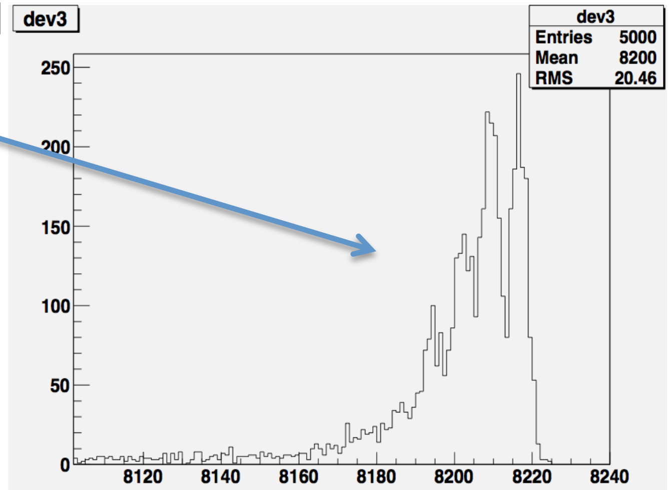
Analysis of the MPPC data must account for thermal noise ("dark count") as illustrated below

Baseline integrated between channels 50 and 100

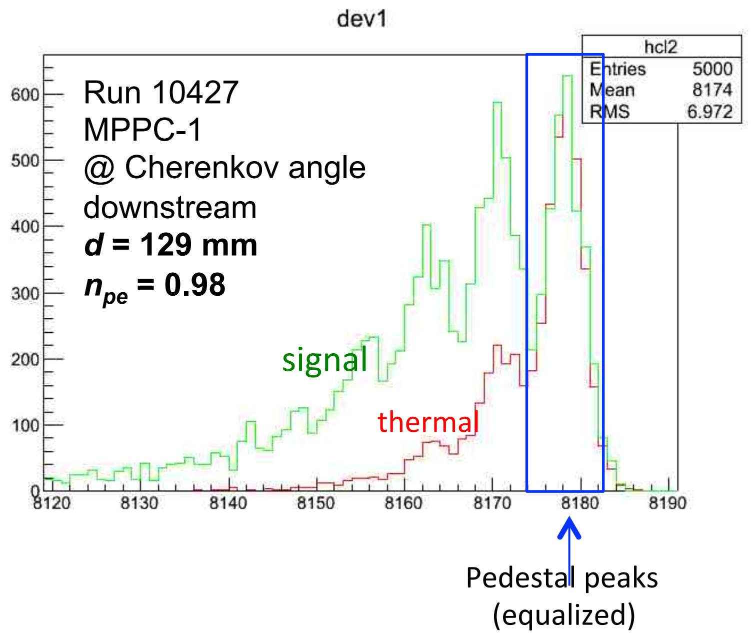
The background must be subtracted from the signal

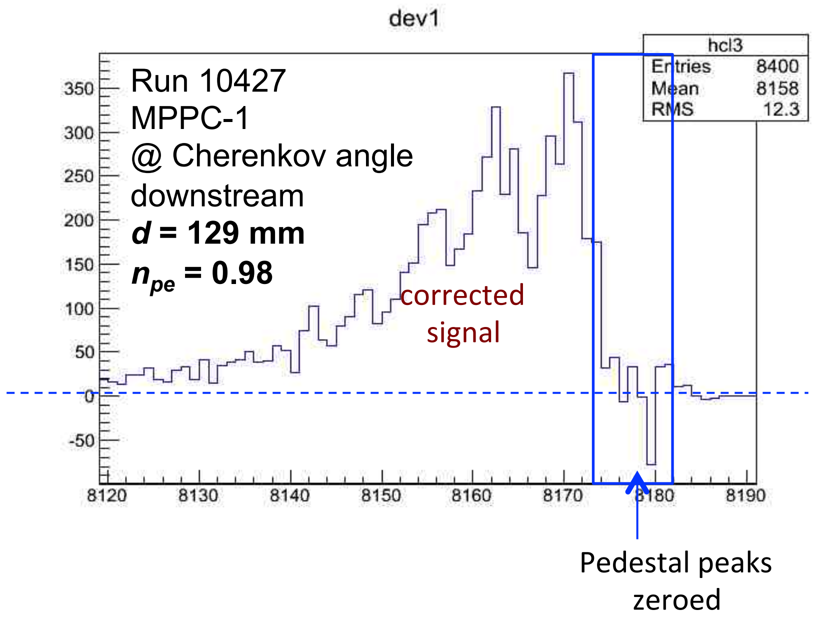
Signal integrated between channels 150 and 200

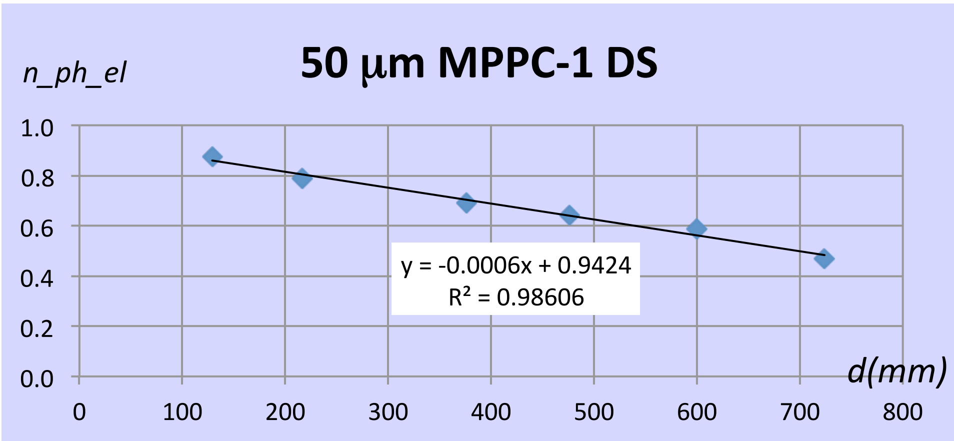




Correction for background is done by assuming Poisson statistics and subtracting the backgound integral , renormalized to equalize the pedestal peaks *





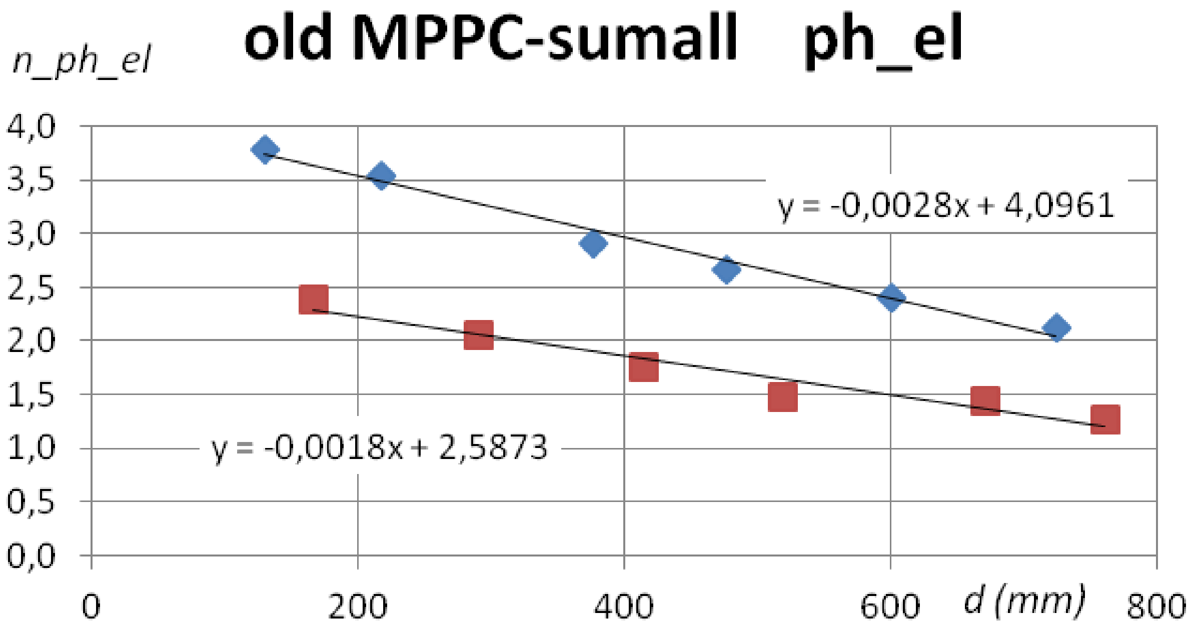


An example of measured signal attenuation (in # of p.e. s) as a function of distance *d* of incident protons from the MPPC.

By comparing the signals from upstream and downstream detectors, the Cherenkov contribution is evaluated at ~ 30%.

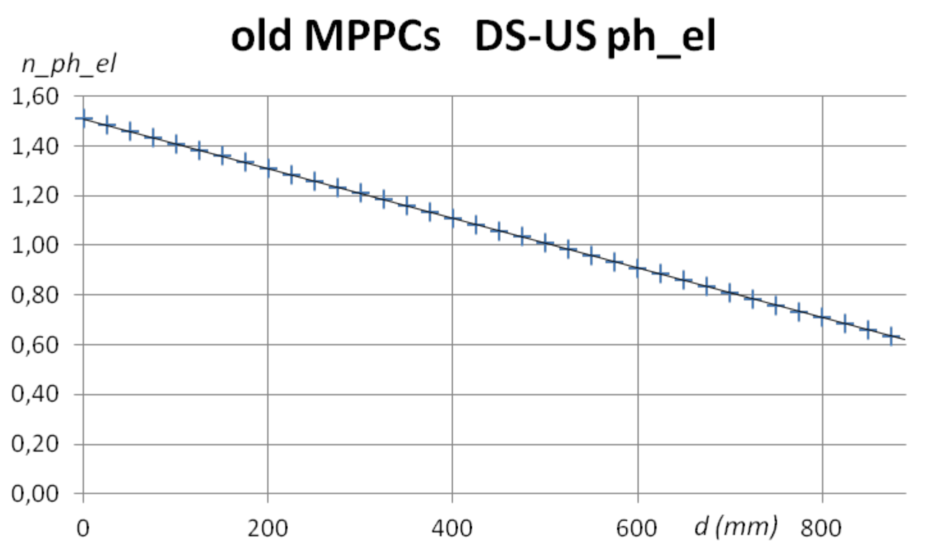
Ph_electrons produced by protons at θ_c

- As expected we have more photons DS than US, due to the directionality of the Cherenkov radiation
- Since we have small numbers, we sum the contribution of the four MPPCs, as if we had a single MPPC four times larger

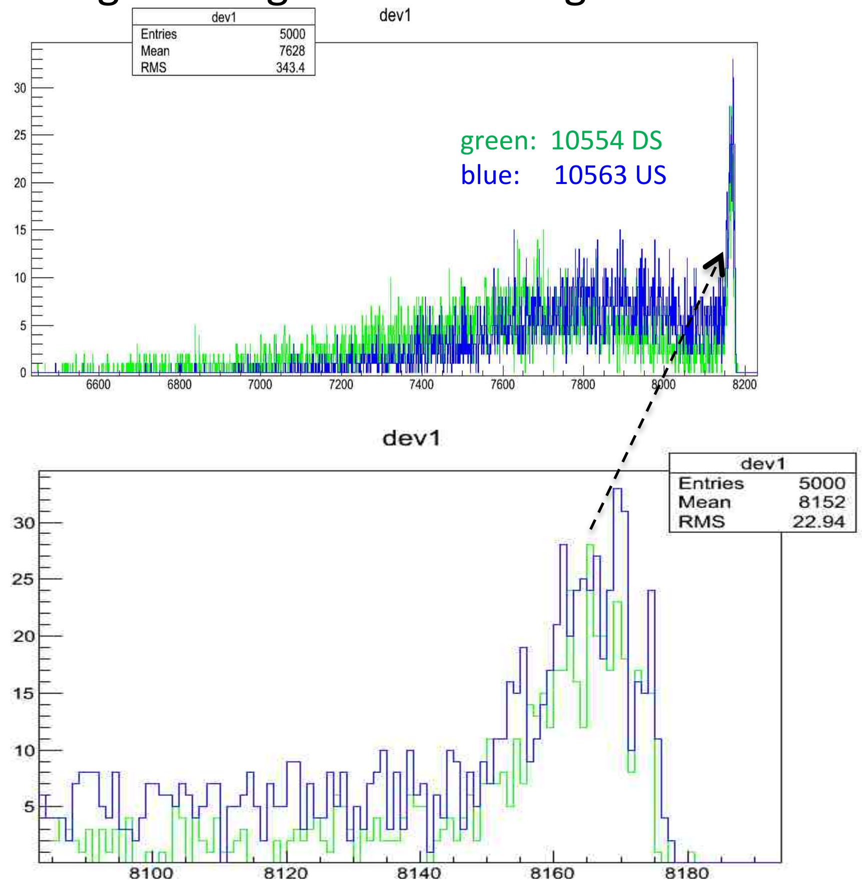


Estimate of Cherenkov ph_electrons

- We have computed the difference of the photo-electrons in the DS and US case, using the linear interpolations
- This gives an indication of the number of photo-electrons due to Cherenkov radiation
- NOTE: This number is in fact underestimated, because Cherenkov photons are present also in the US case



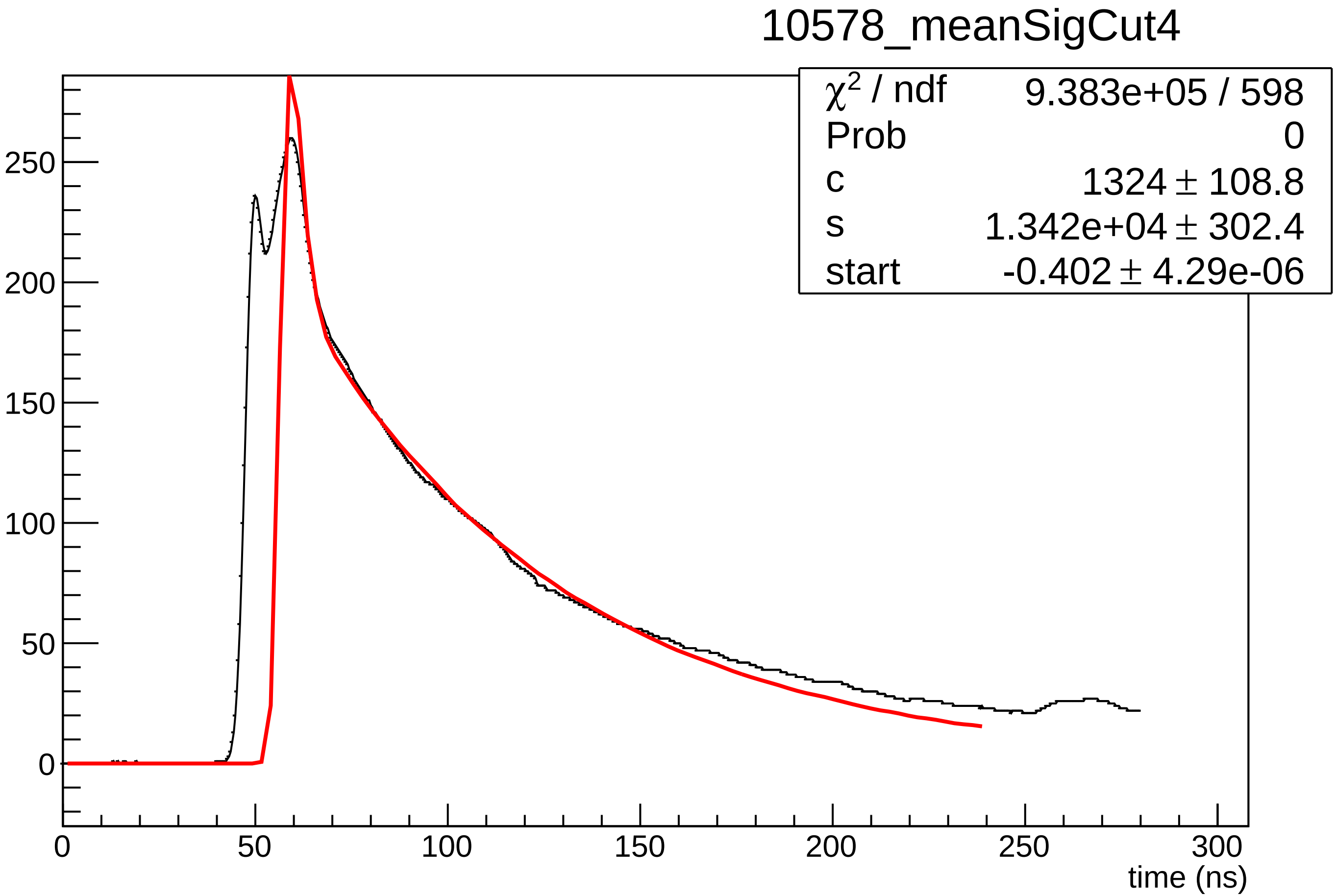
With the glass oriented in the beam direction , i.e. “longitudinally” (L), the showering probability increases to ~ 93% and, although much of the shower energy escapes the glass, the residual still dominates as shown by the distributions of signal integrals from a single MPPC pad.



The green and blue distributions correspond, respectively, to “Downstream” (DS) and “Upstream” (US) positions of the MPPC’s.

A blow-up of the mip peak displays distinct photoelectron peaks, as expected, and is amenable to the same analysis for thermal background correction . This analysis yields 2.3 and 2.0 p.e. for the DS and US orientations, respectively.

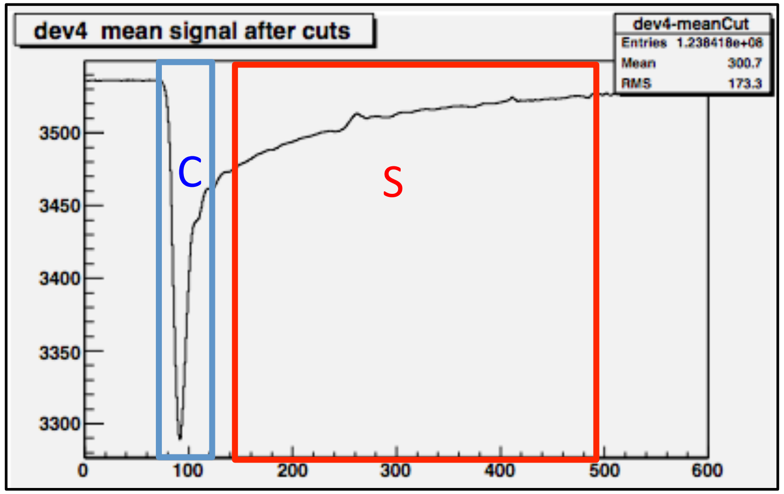
Data was also taken with 32 GeV muons for the longitudinal glass orientation*. The number of p.e./mip is slightly smaller (~ 1.8 p.e./mip).


10578_meanSigCut4
χ² / ndf 9.383e+05 / 598
Prob 0
c 1324 ± 108.8
s 1.342e+04 ± 302.4
start -0.402 ± 4.29e-06
0
50
100
150
200
250
0
50
100
150
200
250
300
time (ns)

Conclusions

1) From a preliminary analysis of data taken with cosmics and particle beams , it appears that the timing characteristics, the C/S ratio (~ 10 – 30%) and the light output (~ 7 % BGO) of SCG1-C glass are appropriate for Dual readout Total Absorption Calorimetry.

2) The sampling rate of 2.5 GHz used to digitize the PM signals is more than adequate for a time – based off – line separation of C and S components, even when the hadronic shower predominates. Given the circumstances, simple cuts on the signal time distribution would seem sufficient for an on-line DR analysis.



3) A 2 x 2 array of 3 x 3 mm^2 silicon, faced up against the glass surface, collects enough light to measure the energy deposition of single mips (for energy calibration) and, with sufficient bandwidth and sampling rate, one will be able to perform the same time – based analysis as for PMs to detemine C/S*.

4) When the thermal noise (dark count) is sufficiently low (below ~ 1 MHz as was the case for the MPPCs), one is able to separate single photoelectrons at the mip level so that the device is auto-calibrating (in photoelectrons). This is an important property for monitoring stability and saturation.

Conclusions ctd.

5) Analysis of data taken with other conditions and SiPMs is still in progress but it already appears clear that, though they are not heavy enough for use in a compact collider calorimeter, glasses with the SCG1-C characteristics may be used for a test of the principle of Total Absorption Dual Readout Hadron calorimetry, assuming leakage corrections can be reduced to a tolerable level [1] . It also appears that ~ 1 cm^2 of silicon – based photodetector, faced up against the glass, collects enough light and that it may be substituted for conventional PMs .

Bibliography

[1] A Driutti et al , CALOR 2010, published in: J. Phys.: Conf. Ser. 293 012034, 2011

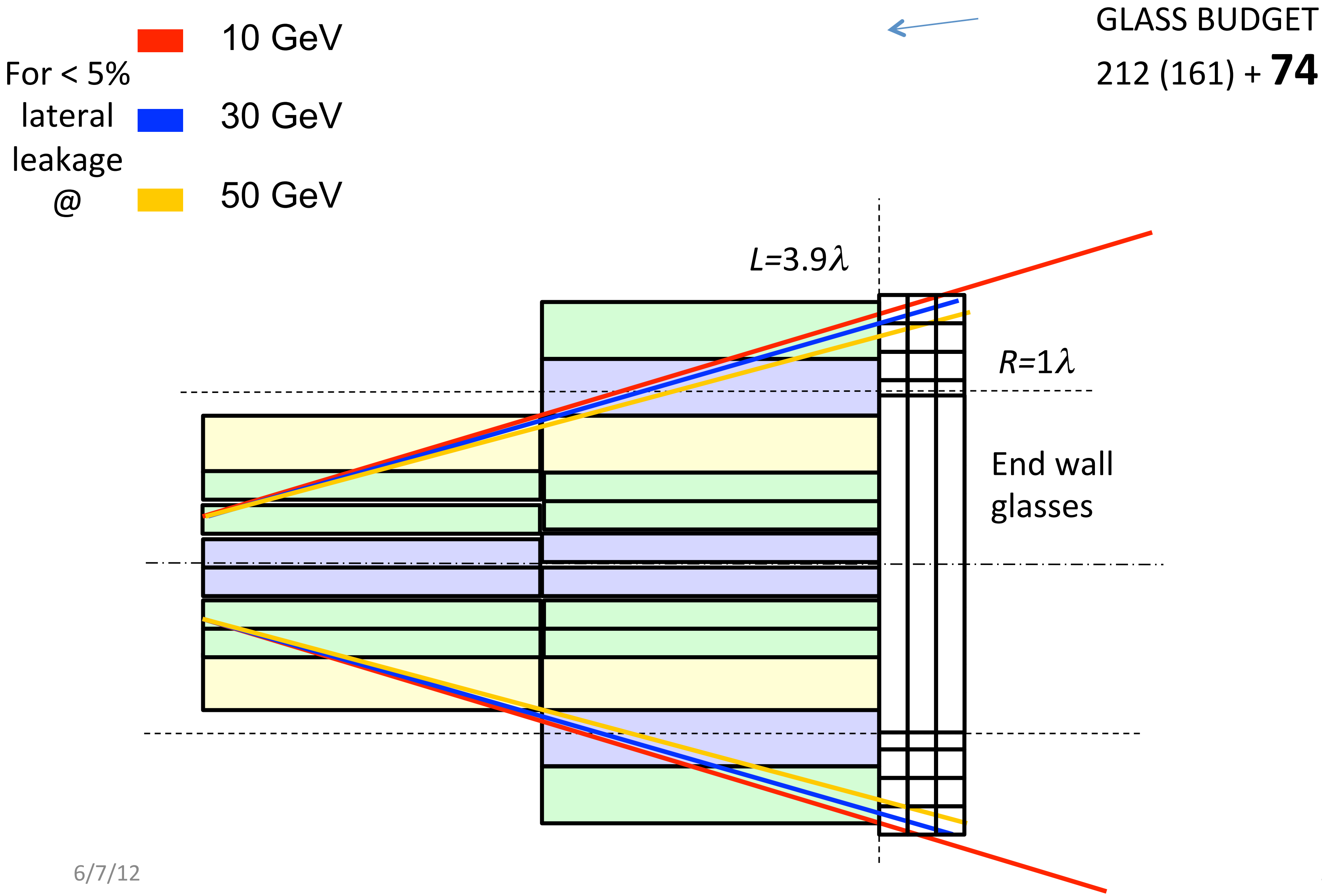
[2] 1) B. Cox, et al., IEEE Transactions on Nuclear Science, Vol. NS-30, No 1, 1983

2) G.E. Theodosiou, et al., IEEE Transactions on Nuclear Science, Vol. NS-31, No 1, 1984

3) L. Antoniazzi, et al., The Experiment 705 Electromagnetic Shower Calorimeter, FERMILAB-Pub-93/001 E705, 1993

Backup

A configuration of available SGC1-C glasses for a TAHCAL calorimeter module with < 10% leakge



Computation of the photo-electrons

- The electrons detected by the MPPC are due
  - in part to 'external' photons produced by the beam particles, in number n_ϕ, probability function Φ and mean value M
  - in part to 'internal' thermal electrons, n_θ, probability function Θ and mean value m
- Let's suppose the contributions are independent and of Poissonian character
- In total we have n electrons with probability function D

Computation of the photo-electrons

- The total probability function *D* is

$$D(n) = \sum_{k=0}^{n} \Phi(k)\Theta(n-k) = \sum_{k=0}^{n} \left(e^{-M} \frac{M^k}{k!} \right) \left(e^{-m} \frac{m^{n-k}}{(n-k)!} \right) =$$

$$= e^{-(M+m)} \frac{1}{n!} \sum_{k=0}^{n} \frac{n!}{k!(n-k)!} M^k m^{n-k} = e^{-(M+m)} \frac{(M+m)^n}{n!}$$

- namely Poissonian at its turn with mean value *M+m*
- For a set of $\mathscr{N}$ events where both contributions are present, the number of events with a total of *n* electrons is

$$N_{tot}(n) = \mathscr{N} D(n)$$

Computation of the photo-electrons

- In the absence of beam only the thermal contribution in present and for a set of $\mathscr{N}$ events, the number of events with a total of *n* thermal electrons is $$N_\theta(n) = \mathscr{N}\Theta(n)$$
- Let's define the ratio

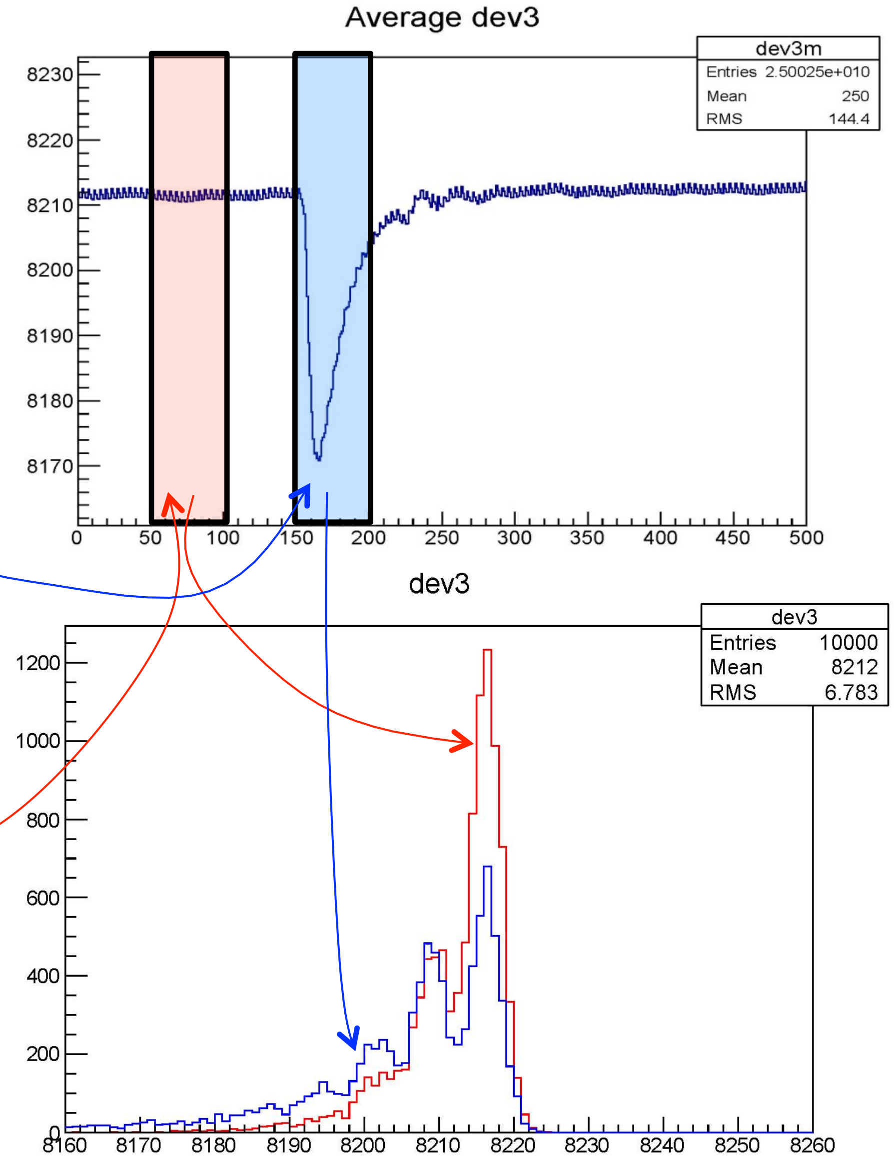
$$R(n) = \frac{N_{tot}(n)}{N_\theta(n)} = \frac{D(n)}{\Theta(n)} = e^{-M}\left(\frac{M+m}{m}\right)^n$$

- For *n=0* (pedestal peak) we can determine the mean number of photo-electrons

$$M = -\log R(0) = \log \frac{N_\theta(0)}{N_{tot}(0)}$$

Computation of the photo-electrons

- An easy way to determine *M* is by a linear combination (with a real parameter α) of the histogram of events in a time interval within the beam spill (giving the function $N_{tot}(n)$) and of the histogram of events in a time interval outside the beam spill (giving $N_{\theta}(n)$)



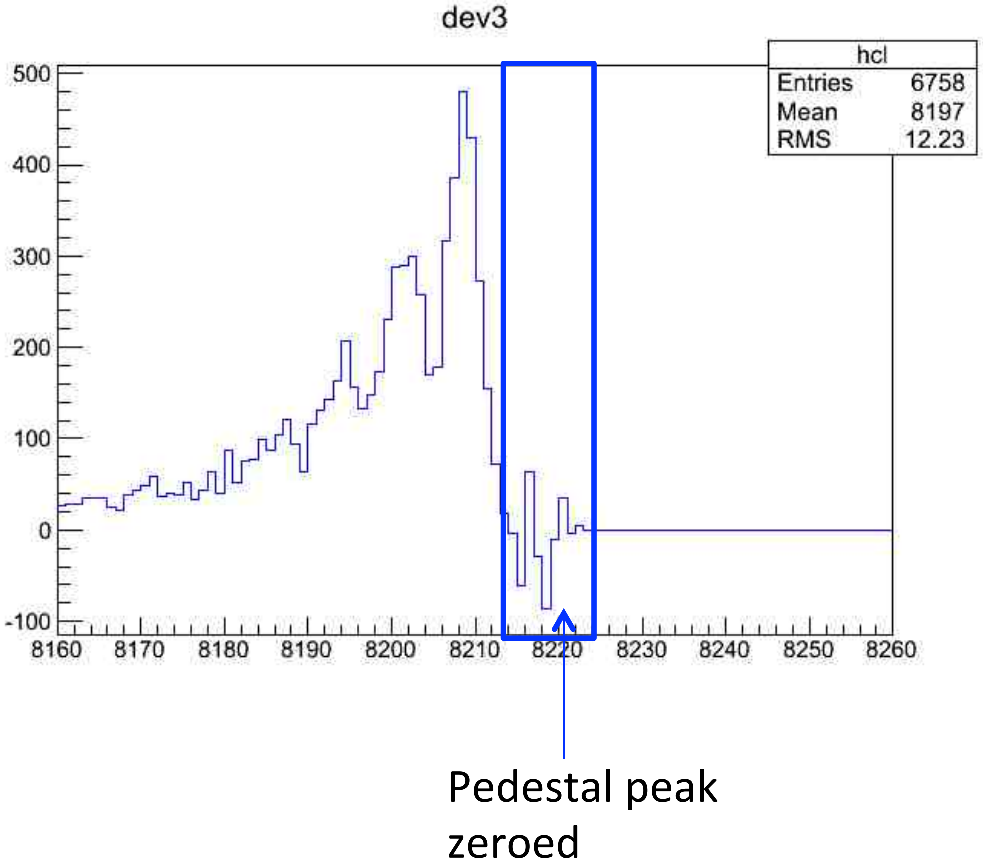
Computation of the photo-electrons

- By trial and error, we find the value of α which zeroes the pedestal peaks

$$\alpha N_{tot}(0) - N_{\theta}(0) = 0$$

- Whence it follows

$$M = \log \frac{N_{\theta}(0)}{N_{tot}(0)} = \log \alpha$$



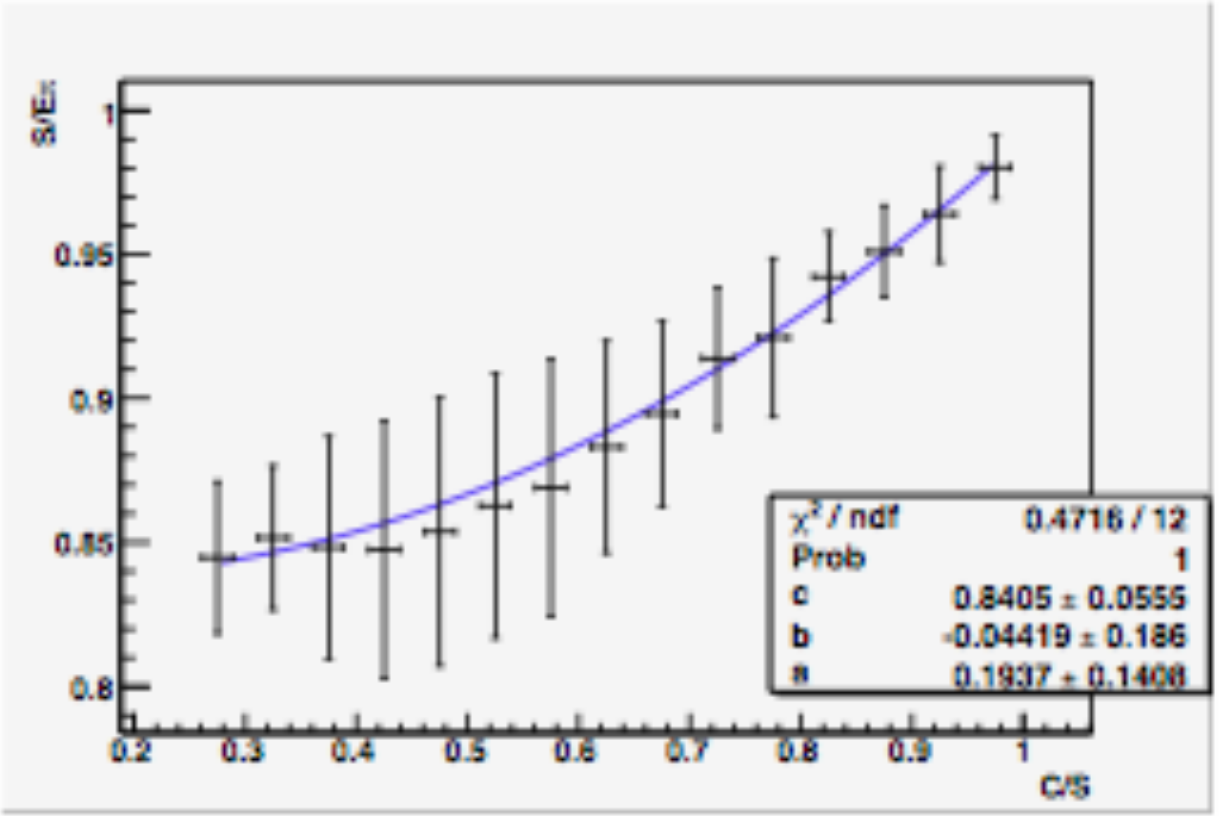


Figure 3.9: Example of the correlation of S/E as a function of C/S where leakage is excluded.

Polynomial Correction Functions: E=S/Pn