# Separation of $PbWO_4$ and BGO signals into Čerenkov and scintillation components

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on behalf of the DREAM collaboration

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# Outline

- The Dual REAdout Method for hadronic calorimeters
- Extension to homogeneous detectors
- Test beam (summer 2007) setup
- Results on $PbWO_4$ crystal
- Results on BGO crystal
- Instrumental effects: light attenuation and reflections
- Light velocity in the crystal
- Conclusions

# The DREAM project for hadronic calorimetry

- Hadronic calorimeters performances limited by different response to electromagnetic ($\pi^0 \rightarrow \gamma\gamma$) and hadronic components

- Fraction of electromagnetic component ($f_{em}$) has large fluctuations:

→ non Gaussian, non-linear hadronic response function
hadronic resolution deviates from $E^{-1/2}$ scaling

Dual REAdout Module:
since $e^{+-}$ in em component are relativistic down to 1 MeV while most of the hadronic particles in non-em component are non relativistic:

→ measure $f_{em}$ event-by-event by measuring separately Čerenkov and scintillation light.

→ DREAM calorimeter: sampling calorimeter with different active materials. Resolution=64%/√E+0.6%. (photoelectron yield = 8 pe/GeV)

# Dual Readout for homogenous detectors

- Any scintillator crystal with large n should produce Č light
- No sampling fluctuations
- Separate Č from scintillation light exploiting differences:

| | Čerenkov | scintillation |
|---|---|---|
| time | prompt | decay |
| direction | cone | isotropic |
| spectrum | $1/\lambda^2$ | band |
| polarization | yes | no |

# Experimental Setup

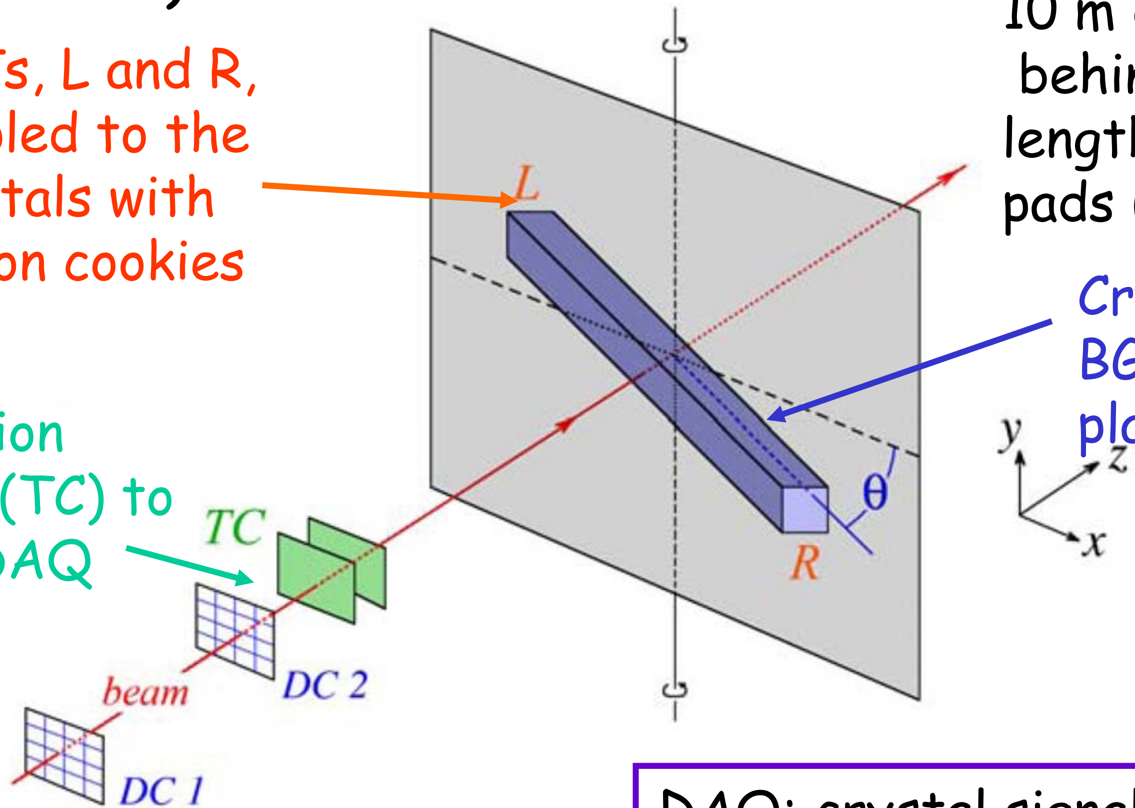
- 50 GeV $e^-$ and 200 GeV $\pi^+$ from H4 SPS beam line @CERN (summer 2007)

PMTs, L and R, coupled to the crystals with silicon cookies

10 m downstream, behind 20 interaction lengths, scintillation pads (muon counters)

Crystal ($PbWO_4$ or BGO) on a rotating platform

Scintillation counters (TC) to Trigger DAQ




Drift chambers (DC1,DC2) to track the beam particles, used to remove particles that missed the crystal

DAQ: crystal signals acquired with charge integrators and digital oscilloscope 5Gsample/s@ analog BW 2.5 GHz. 2ns, 0.8ns, 0.4ns sampling

# $PbWO_4$ and BGO crystals

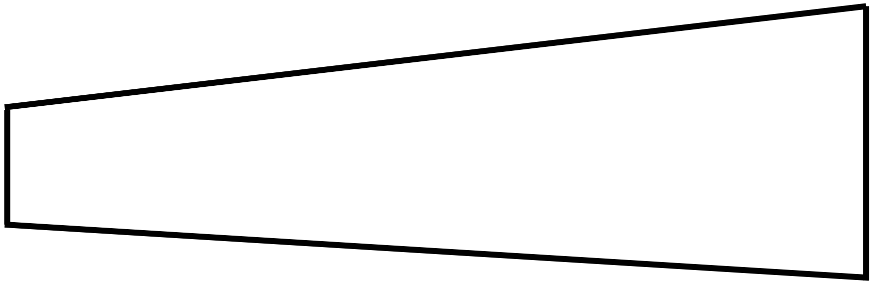
$PbWO_4$crystal: n=2.20 ρ=8.28 gr/cm$^3$, decay time=10ns, Peak λ=440nm. Rel(NaI) yield=0.3%

cross section: 2.2x2.2cm$^2$ (2.5$X_0$)

length: 18cm

BGO crystal: n=2.15 ρ=7.13 gr/cm$^3$, decay time=300 ns, Peak λ=480nm. Rel(NaI) yield=20%

cross section: 2.4x2.4cm$^2$ (2.2$X_0$)



cross section: 3.2x3.2cm$^2$ (2.9$X_0$)

length: 24cm

BGO crystal sides equipped with optical filters. For most measurement, UV filter on large side, Yellow filter on small side

# $PbWO_4$

# Čerenkov component in the $PbWO_4$ signals

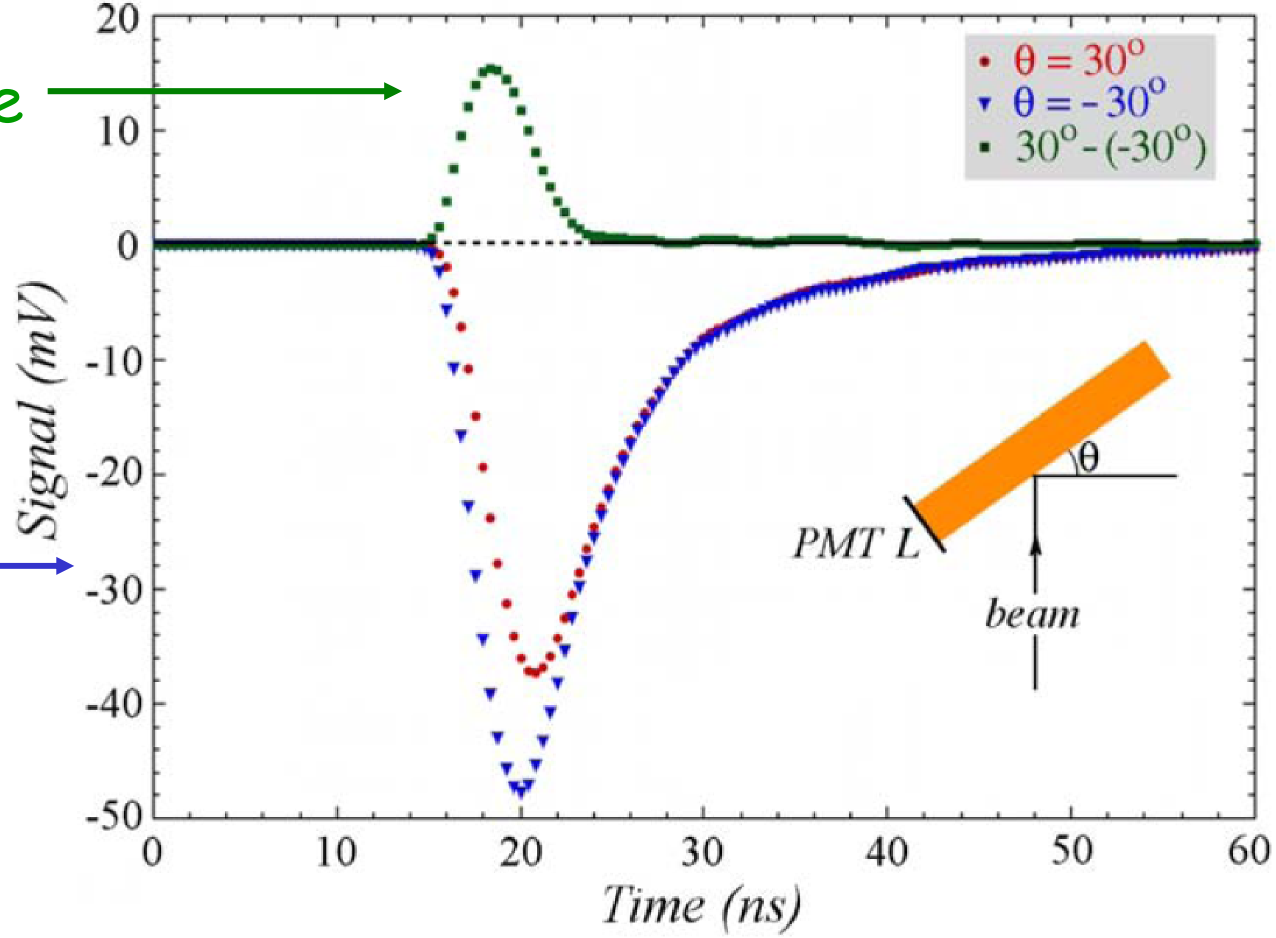
- 50 GeV electrons, average time structure

$\theta_{Čerenkov}$ = 63° => maximum acceptance for Č light is θ=-27° for PMTL and θ=27° for PMTR

(inverted) response function to Č component

Č angle: steeper leading edge, larger amplitude

similar trailing edge

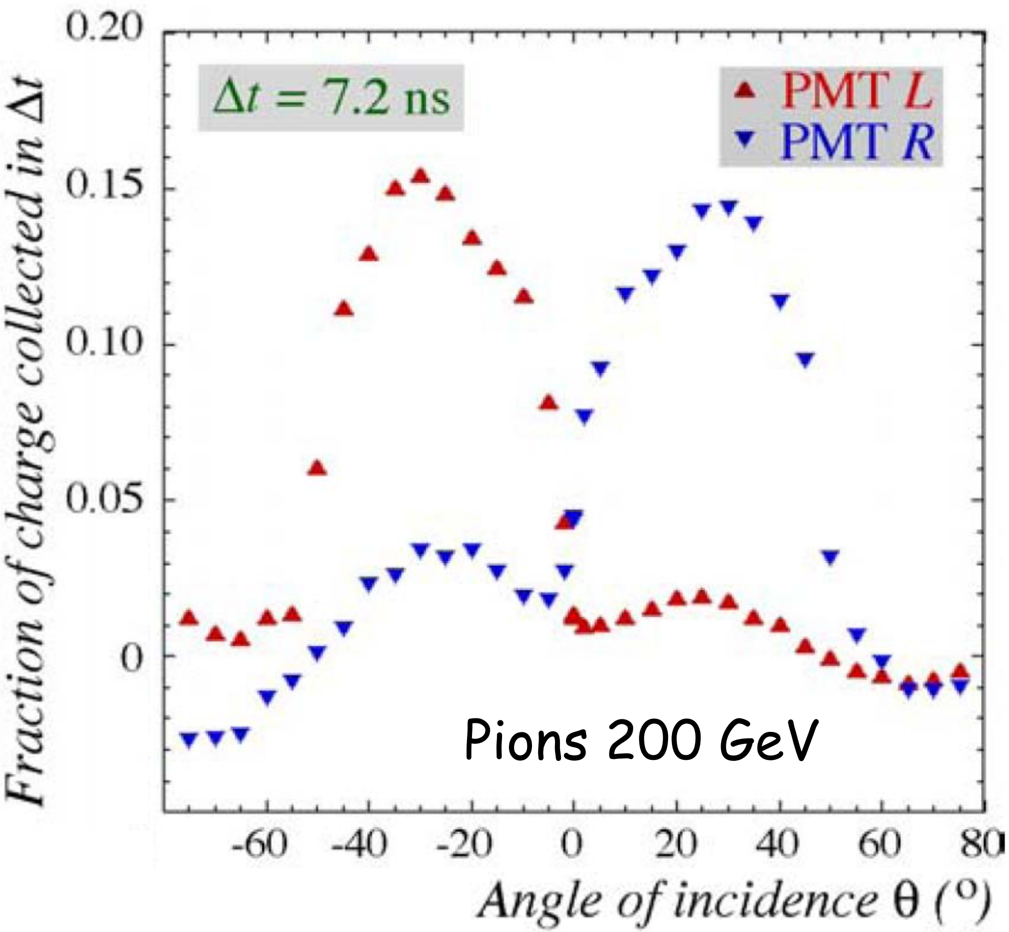


# Event-by-event measurement of the Čerenkov fraction

Several ways to use time structure of the signal to measure relative Č contribution e.g. fraction f(Δt) of the total charge collected in a given time window from the start of the pulse

- Peak at Č angle
(θ=-27° for PMTL and θ=27° for PMTR)

- Smaller peak at Anti-Č angle (reflection)

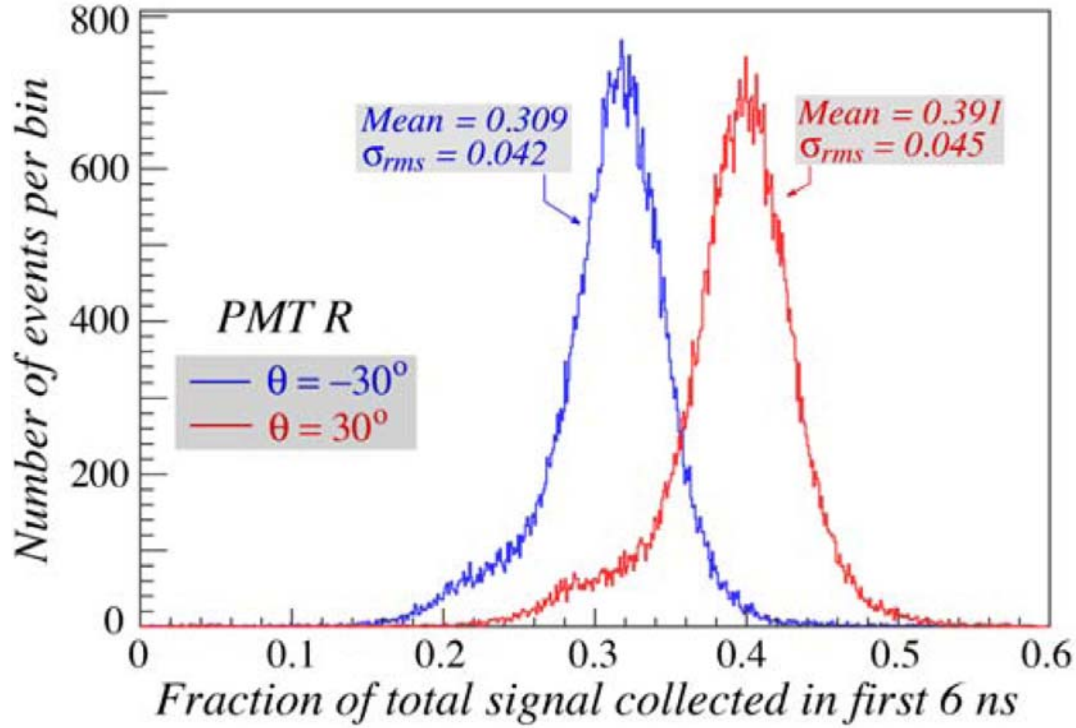


# Event-by-event measurement of the Čerenkov fraction: separation power and precision

Reference signal: consists almost exclusively of scintillation light => signal at anti-Č angle

PMTR 50 GeV electrons, $\Delta t$=6ns, 1 GeV deposit reference signal: anti-Čangle = -30°

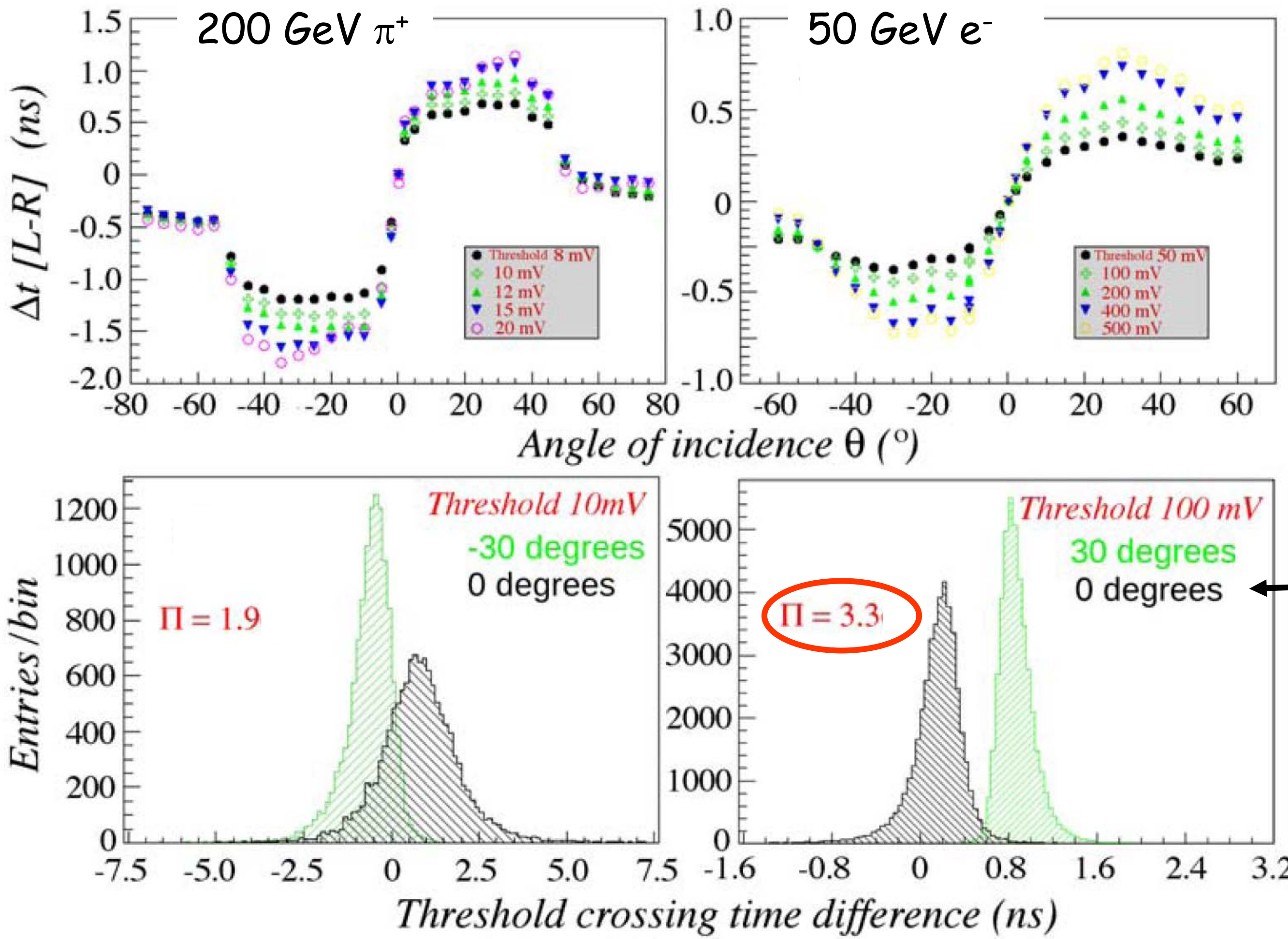
Čerenkov signal: Č angle =30°




Separation power = $\Pi$ = $(\mu_{ref}-\mu_{Č})/\sigma$ = 1.9, 8% precision for individual events

# Event-by-event measurement of the Čerenkov fraction (II)

- Method 2: use time structure of the signal + angular information: time difference between the moment at which the signal from the two PMTs crossed a given threshold: $\Delta t(L-R)$

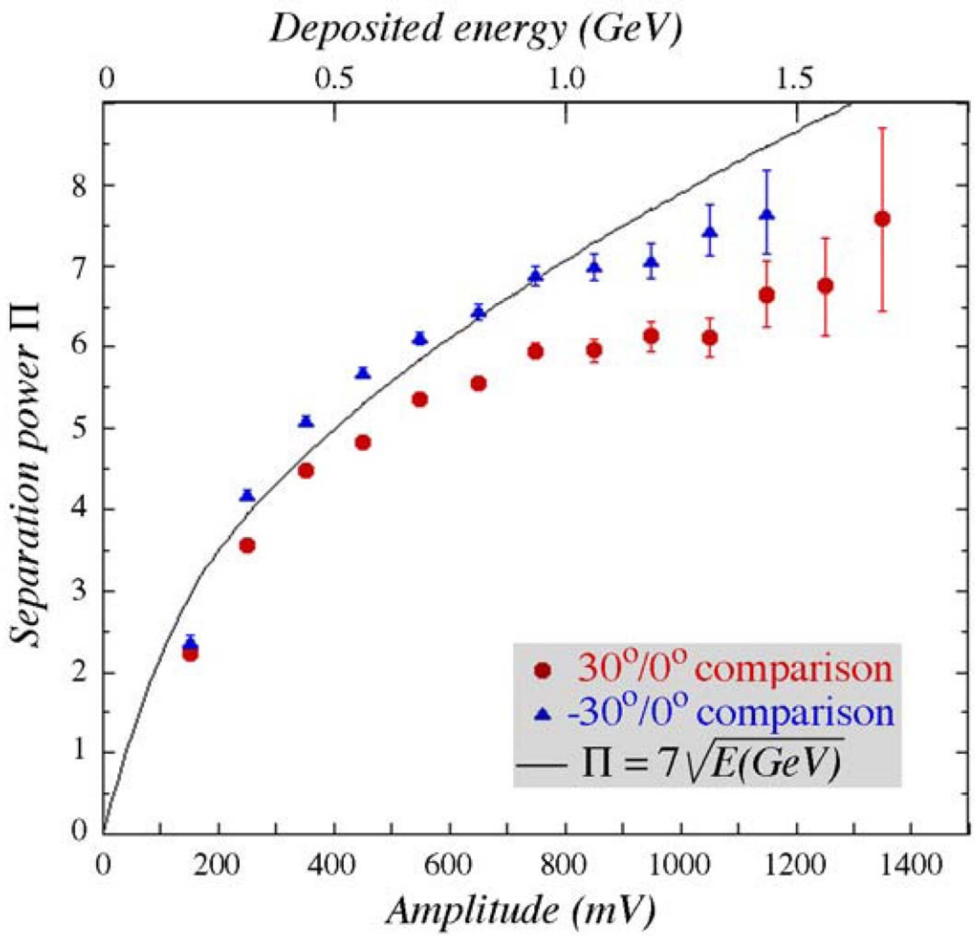



Reference signal

More info:
more discriminating power.

# Čerenkov photoelectron yield

Separation power obtained with the Δt(L-R) method as a function of the energy deposited in the crystal for 50 GeV $e^-$

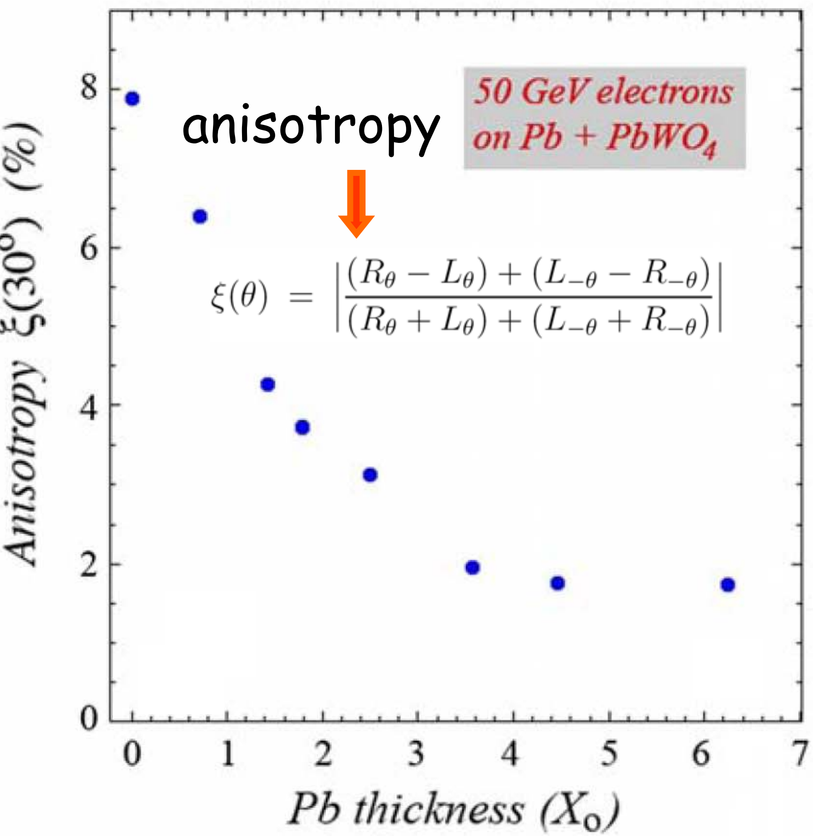


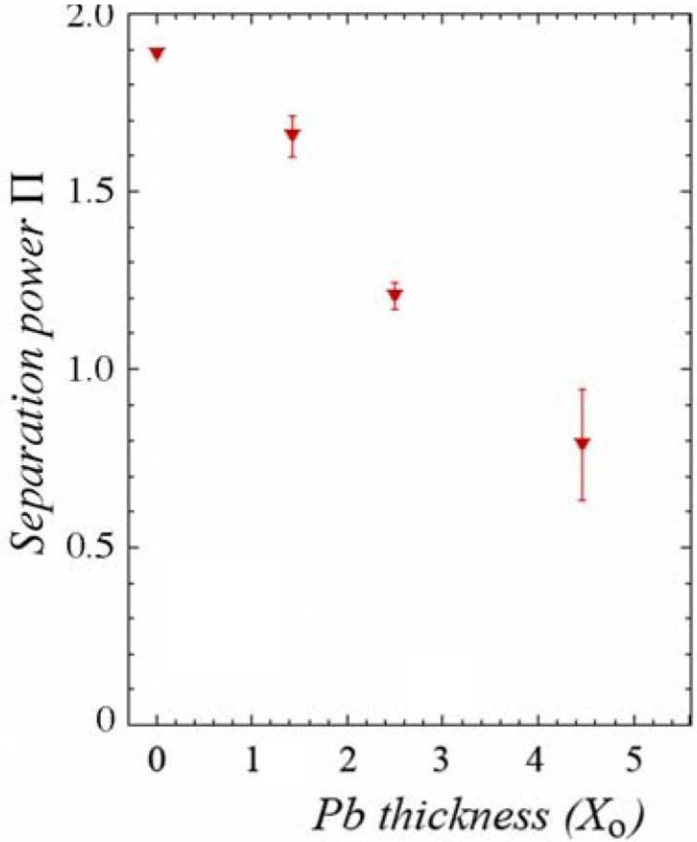

Solid curve:expected scaling if only photoelectron statistics contributed

from the solid curve => ~50 photoelectron per GeV .

# Čerenkov signal from developing showers

- Various thickness of Pb placed upstream of the crystal
- As the shower develops, the Č light is emitted more isotropically
- The shower cannot be anymore represented as a collection of mips going in the same direction



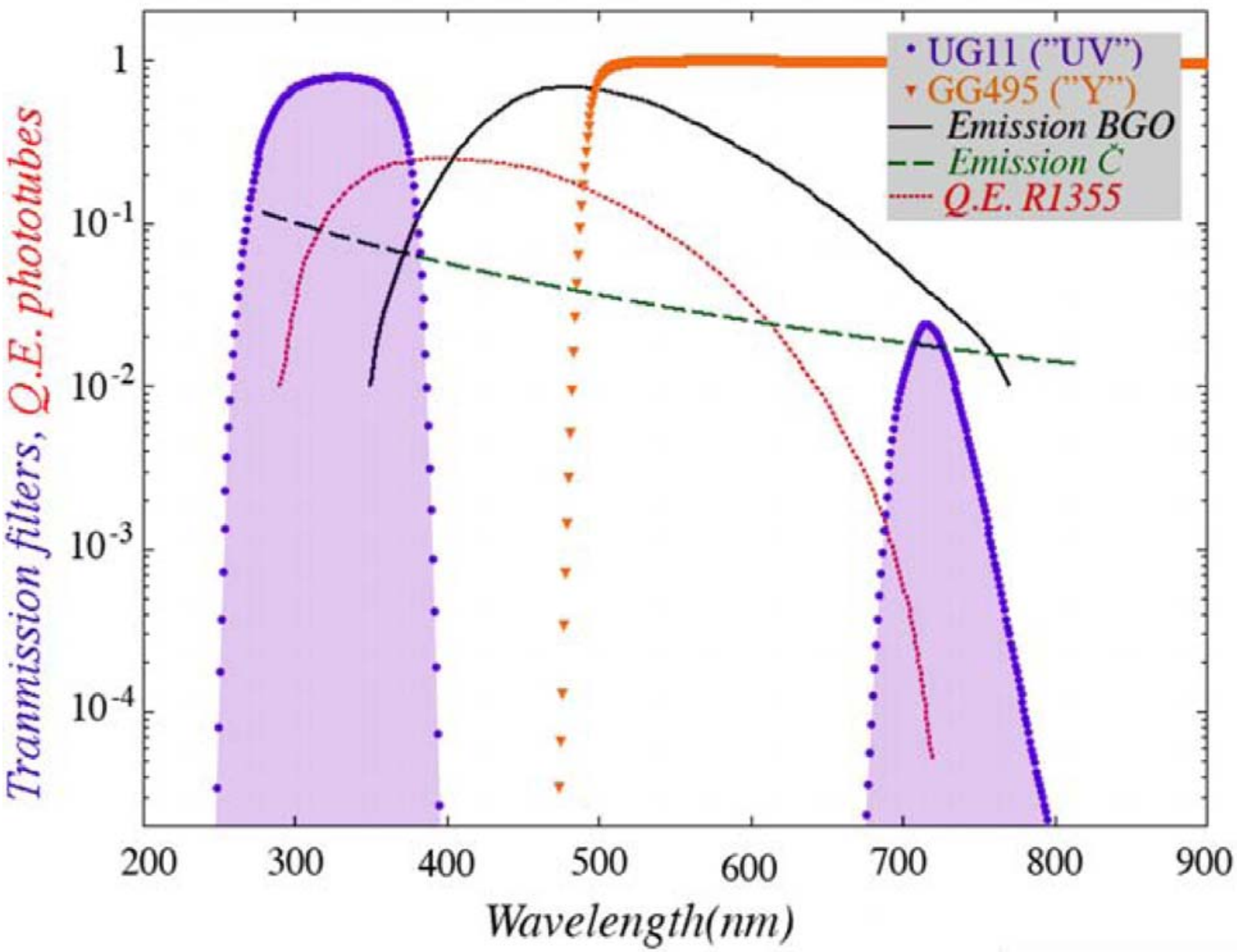




separation power computed using: f(Δt), Δt=6ns

# BGO

# UV and Y filters

Enanchment of Čerenkov component using spectral difference between Čerenkov and scintillation light => use Y and UV filters



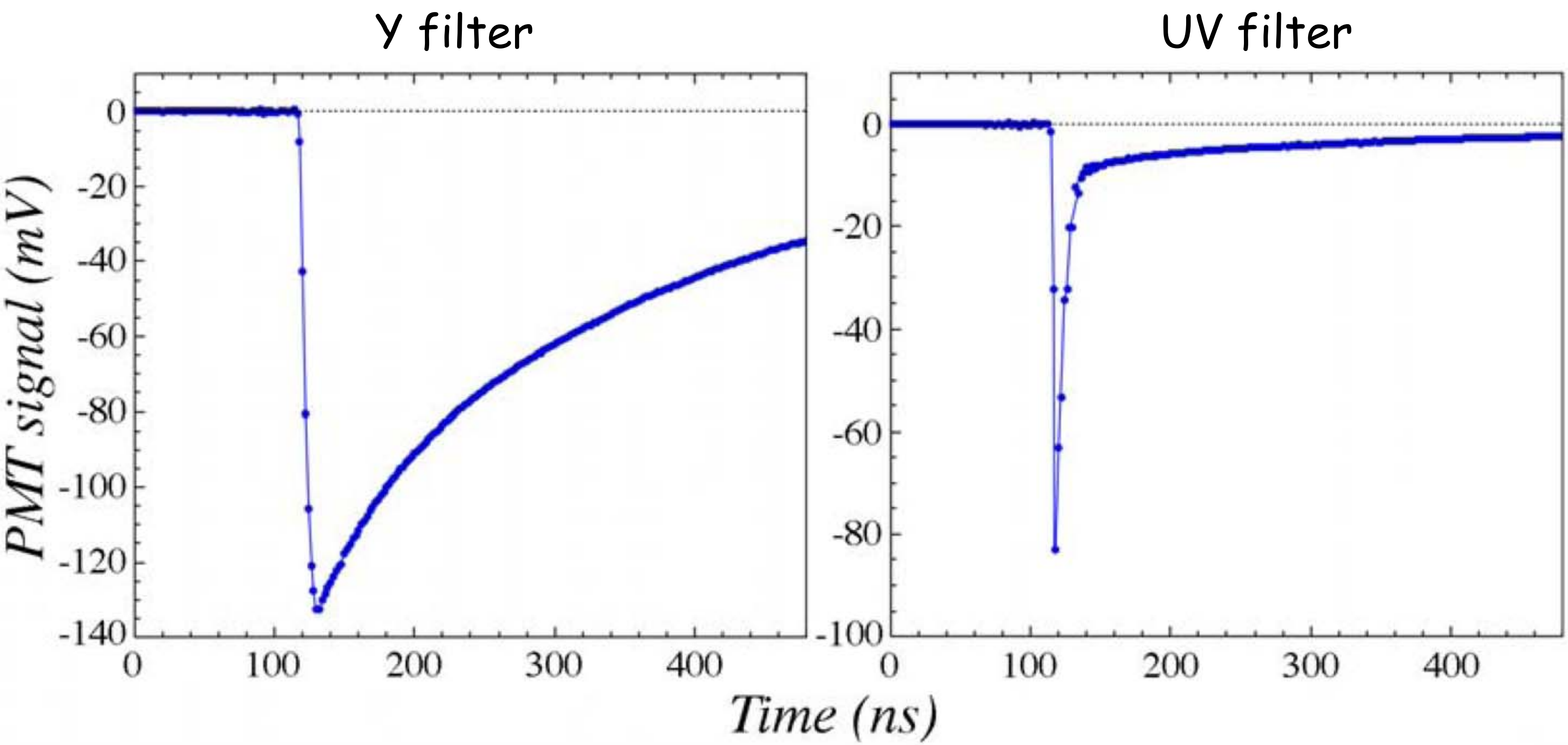

Y filter: highly transparent for BGO scintillation light (centered at 480 nm)

UV filter: highly transparent for Č light in the range 320-400 ns.
Less than 0.1% of the scintillation light penetrates this filter

# Time structure of UV and Y signals

Even though the Č light is a small fraction of the light produced, the UV signal is mostly Č light.

Average time structure for 50 GeV electrons



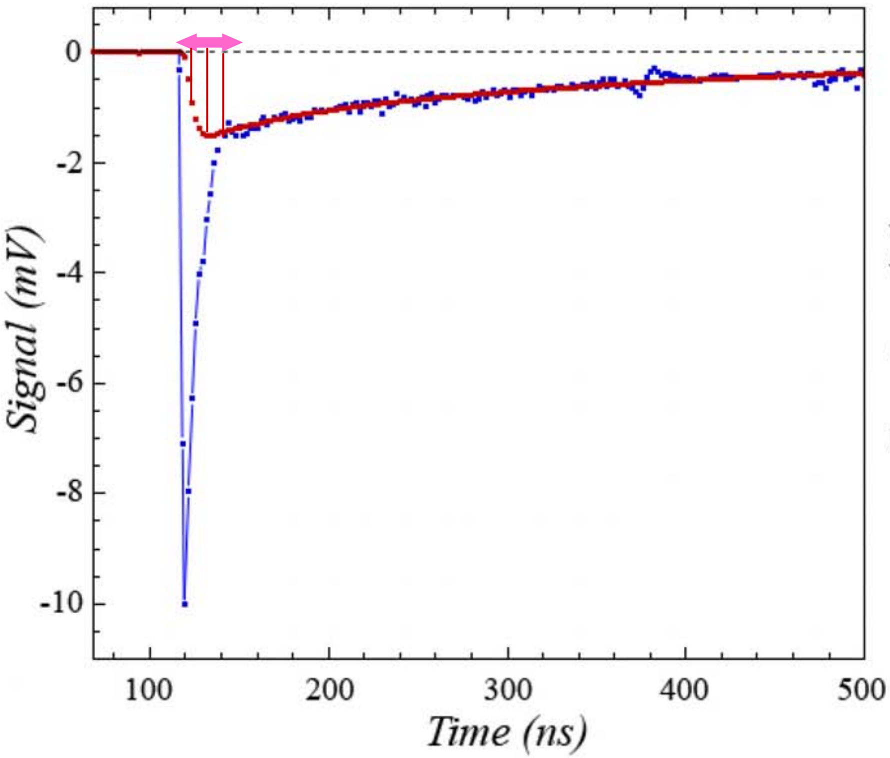
# Scintillation contamination in the UV signal

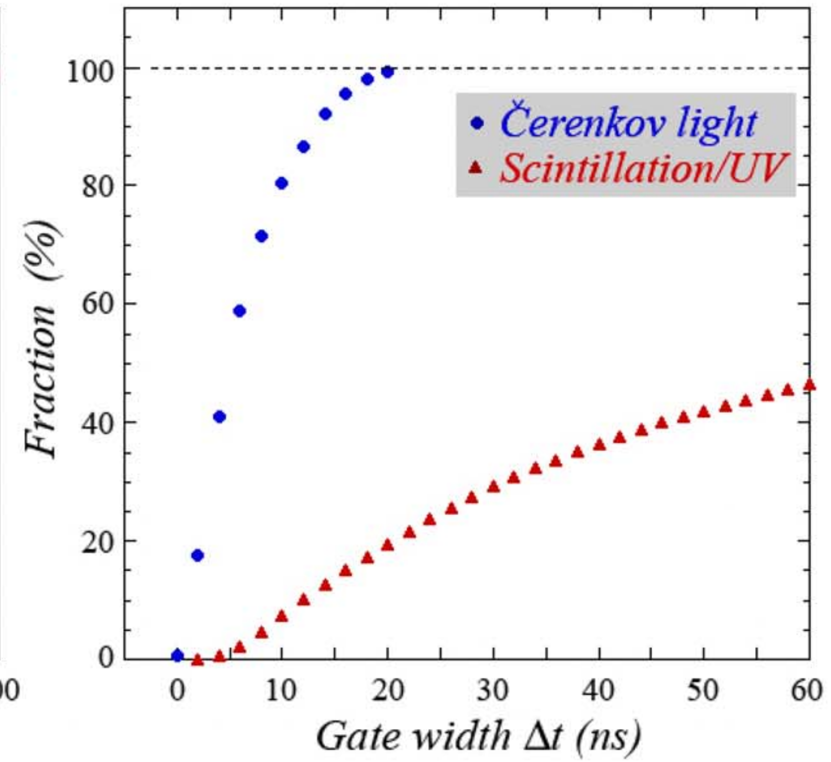
Average time structure for
200 GeV $\pi^+(\theta=0)$, UV side
The shape of scintillation component is taken from Y side and normalized to the tail of the UV side

Average fraction of total UV signal and average fraction of Č signal in a gate $\Delta t$ from the start of the pulse

Example: for $\Delta t$=20 ns the contamination of scintillation is 20%

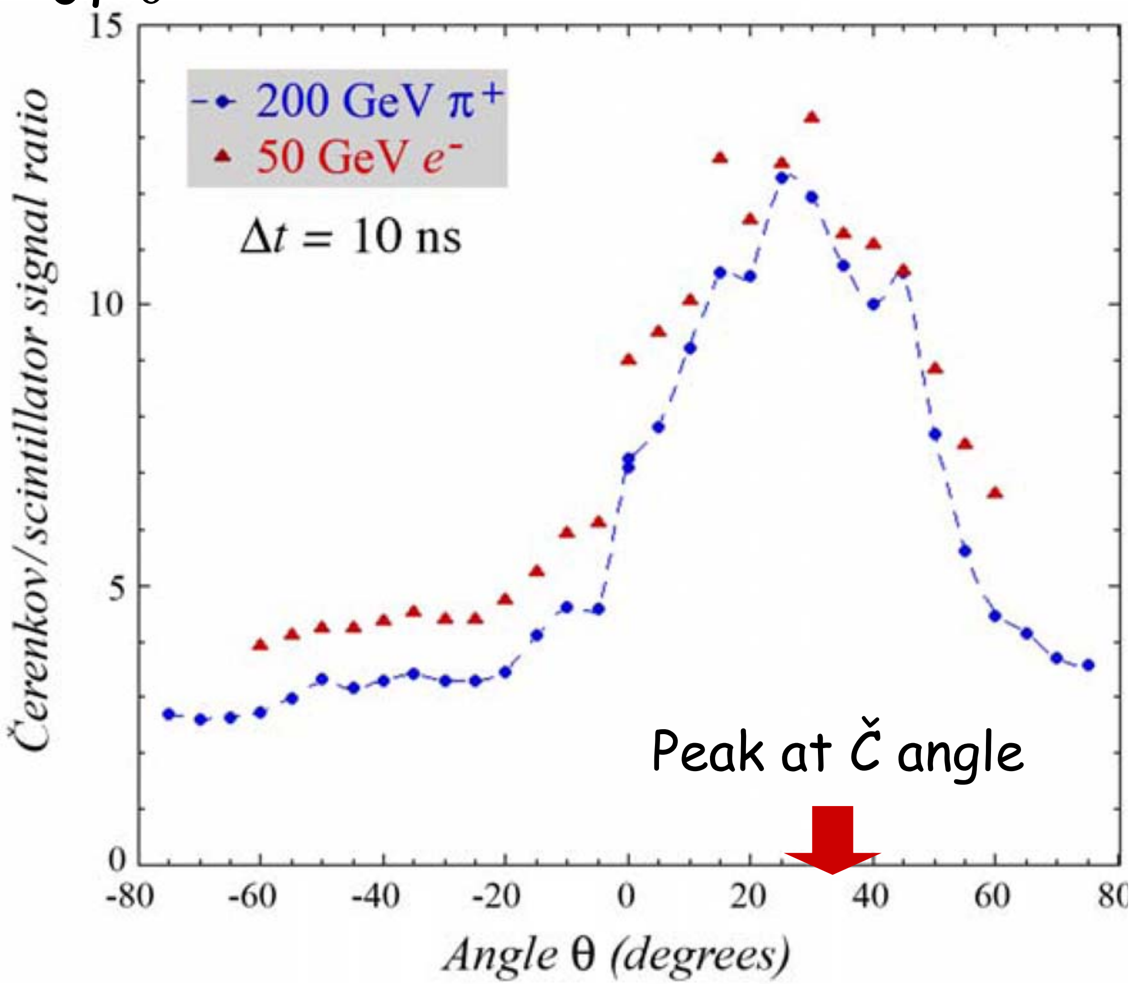
Gate $\Delta t$



# Angular Scan

Average Č/S ratio in the UV signal integrated in a time window Δt =10ns after the start of the pulse as a function of θ

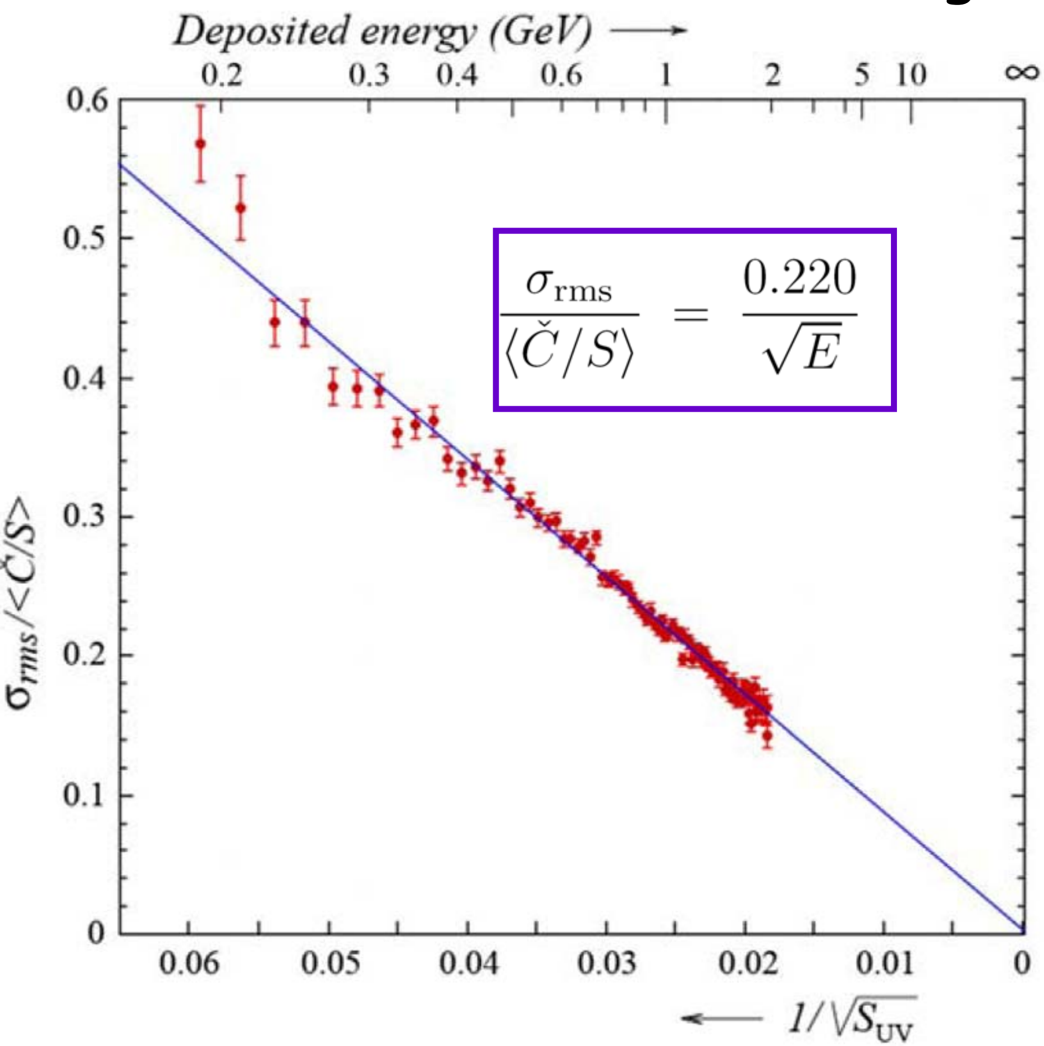



Fine-structure around Č angle probably related to light collection mechanism

Electrons larger than pions:
shower direction spread?

# Čerenkov light yield from 50 GeV electrons

Relative width of the Č/S event by event distribution at θ=30° as a function of the total UV signal, fitted to a straight line:




total number of scintillation photoelectrons

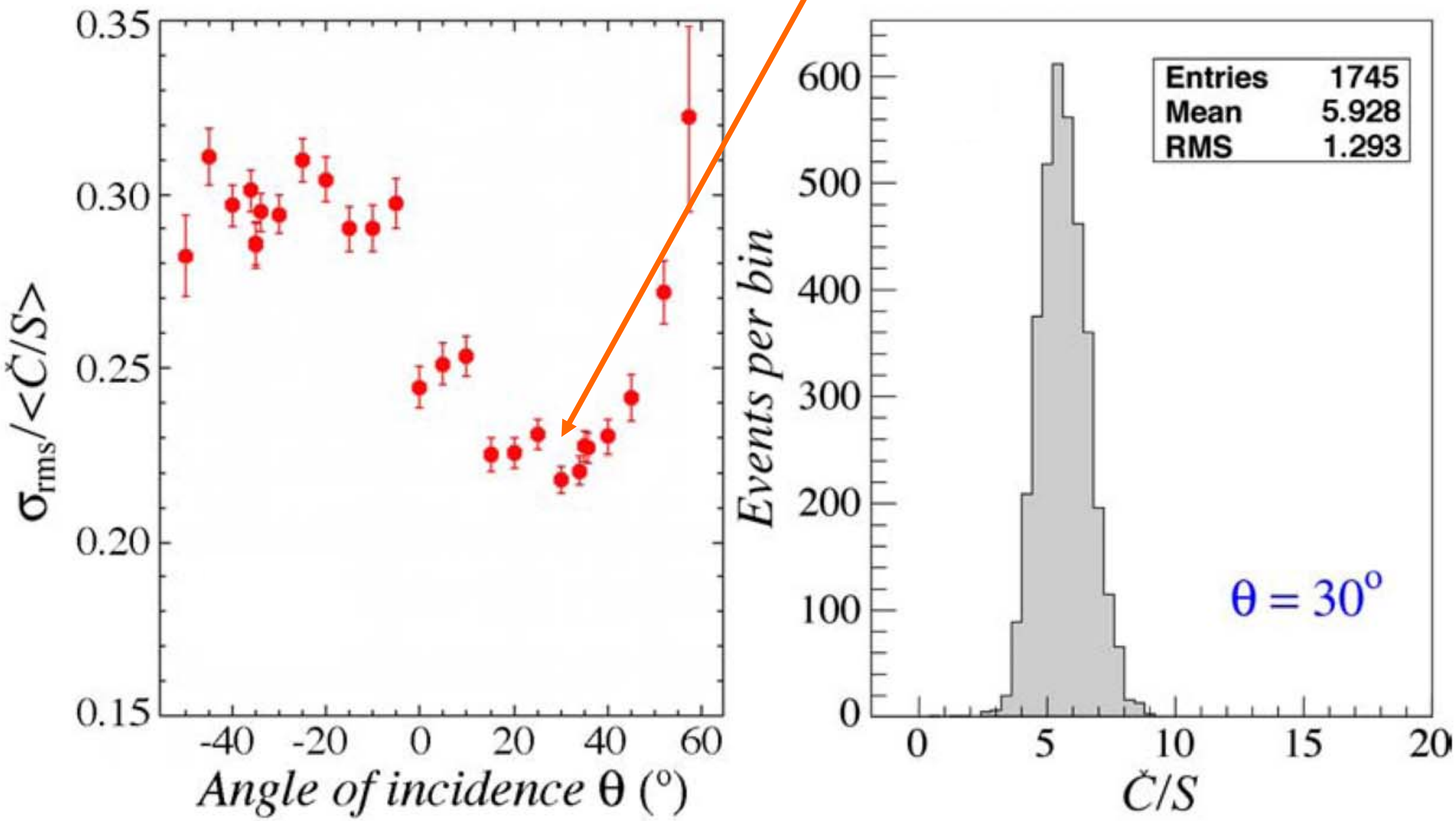
$$\frac{1}{\gamma_S} + \frac{1}{0.44\gamma_S} = (0.220)^2$$

Č photoelectrons (from the average time spectrum)

number of Č photoelectrons ~30 pe/GeV

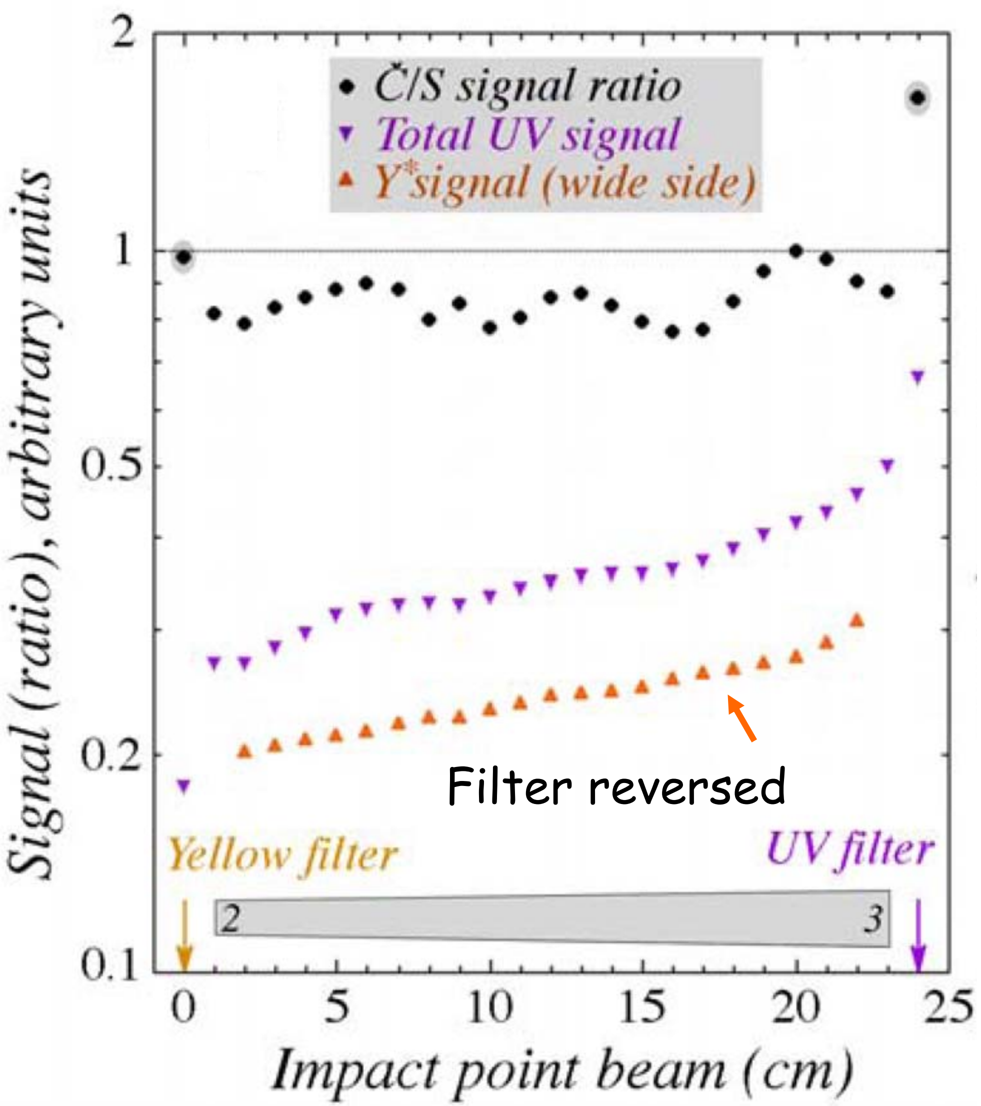
# The precision on Č/S measurement (50 GeV e⁻)

Relative width of the Č/S event-by-event distribution vs θ, for events with 1GeV deposit : ~22% precision at θ=30°



# Light attenuation

Horizontal scan of the crystal, 50 GeV electrons at $\theta=0$



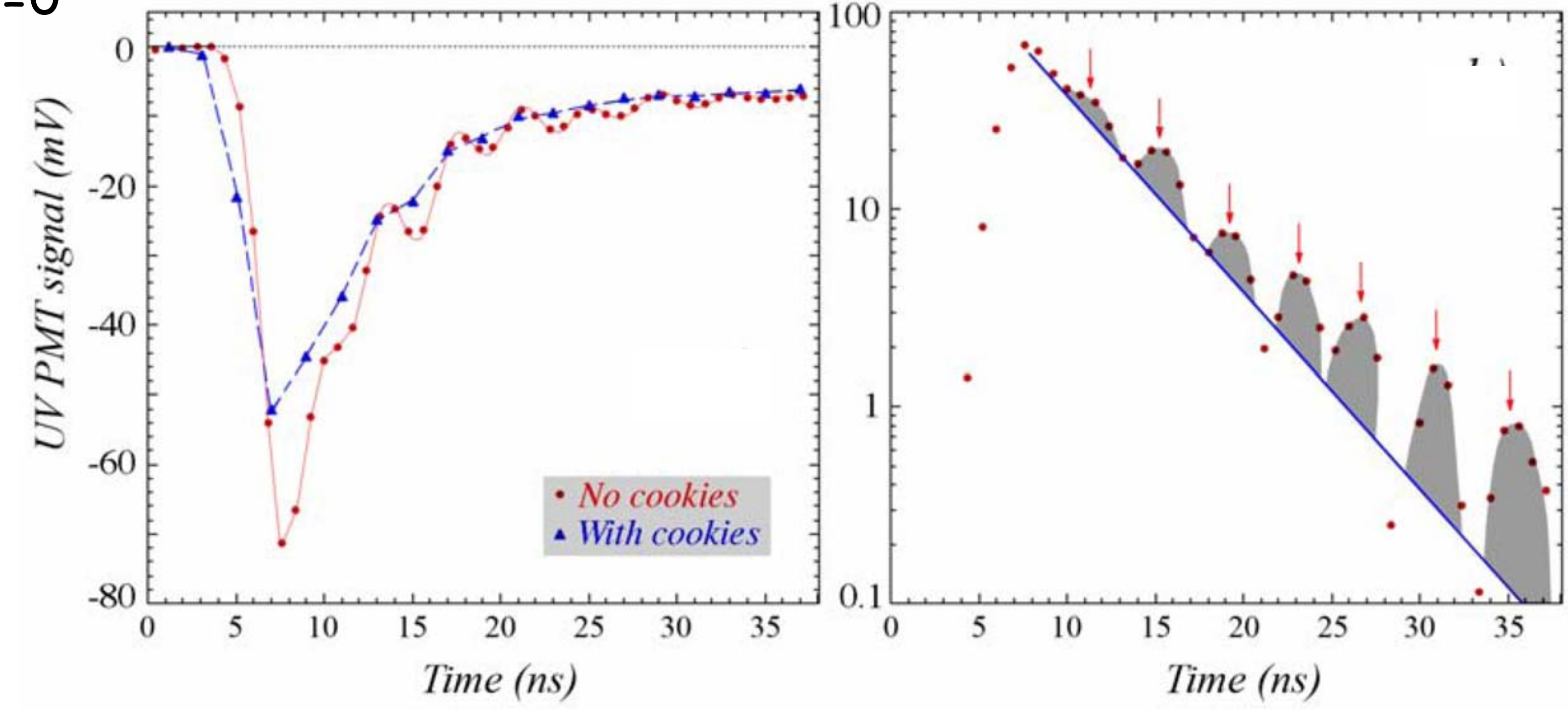

Most of the increase of the UV signal is geometrical, Č/S is ~constant, with oscillations superimposed (can be explained with the fact that the PMT surface covers ~65% of UV side)

# Reflections

(Fresnel) reflection coefficient of 4% (13% without cookies)

Comparison cookies-no cookies, UV signal, 50 GeV electrons at θ=0

inverted Č signal

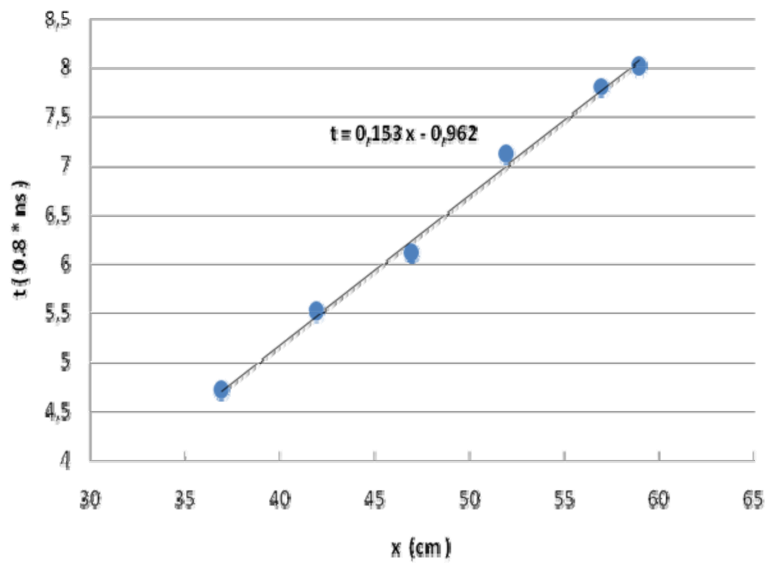



Peaks separated by 4ns, light travels twice the crystal length corrected for the angle of propagation => 55.8cm=4*30/2.15

From envelope of curve: attenuation length ~80 cm)

# Velocity of light in the BGO crystal

From the difference between the time of the first peake with respect to scope trigger as a function of the position of the impact point of the beam




$$\frac{dx}{dt} = 8{,}17\ cm/ns$$

Need correction for the the true longer light path in the crystal due to reflection:

$$v = \frac{ds}{dt} = 13{,}34\ cm/ns$$

The expected value is: $v = \frac{c}{n} = 13{,}95\ cm/ns$

# Conclusions

- PbWO4 and BGO produce a significant amount of Č light in addition to scintillation light
- Different methods to extract Č information have been investigated
- The BGO seems more favorable because the spectra of the two components are very different and allow to have signals of equal strength with the help of optical filters. Moreover the scintillation decay time is 300 ns, so Č signal can be separated easily from time structure
- In BGO a resolution of 20-30% on Ĉ/S for 1 GeV energy deposit has been obtained
- Both crystals produce at least 30 photoelectron per GeV which is a significant improvement with respect to DREAM fiber calorimeter (8 pe per GeV)

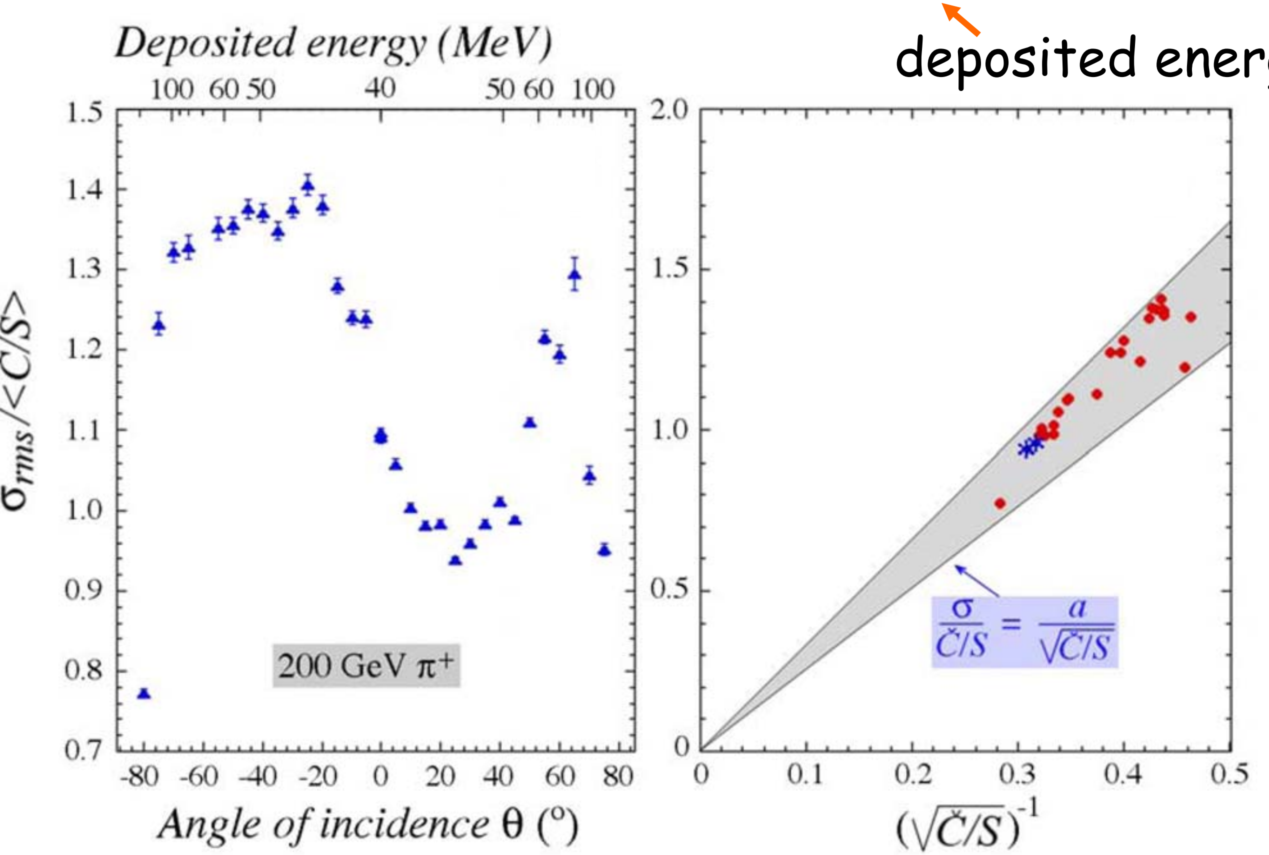
# Ĉerenkov light yield from 100 GeV $\pi^+$

relative width of the Ĉ/S distribution: if photoelectron statistics were the only contribution it would scale like:

$$\frac{\sigma}{C/S} = \frac{a}{\sqrt{C/S}} \qquad a = \sqrt{\frac{0.041 S^*}{\cos\theta}}$$

S*=number of scintillation photoelectrons per GeV

deposited energy




from a coefficient: lower limit on number of Ĉ photoelectrons = 28 pe/GeV

20 ns integration window