Philosophy and Feasibility of Dual Readout Calorimetry

The main simple idea is to measure a hadronic shower twice - as if two different calorimeters make an image of the same shower.

The first realization of this was the Dual Readout Module (DREAM) embedded with *scintillating fibers* and *clear fibers* (for *Cerenkov* light production) described by Wigmans, 7^{th} Calorimetry Conf., Tucson, 1997.

Scintillation light, **S**: all charged particles, mostly $\pi^{\pm}$, some slow p

Cerenkov light, **C**: charged particles above $\beta>1/n$, mostly $e^{\pm}$ from $\pi^0 \to \gamma\gamma$

The main goal was to improve hadronic calorimetry without the constraint that the sensitive-medium-to-absorber ratio be compensating, $e/h=1$.

A few "applications"

1. DREAM-1 (Scintillation+Cerenkov, exact separation of light in separate fibers)
2. DREAM-2 (Scintillation+Cerenkov light mixed into the same fibers)
3. DREAM-3, $PbWO_4$ (Scintillation+Cerenkov in one crystal: 4th concept, CMS-2)
4. TeV γ-ray astroparticle physics (Cerenkov+N_2 fluorescence)
5. Muon identification (4th)

(There must be a half-dozen more …)

This dual measurement doesn't have to be just with light …

- Dense spatial clusters: weight "EM" clusters
  □□ [Abramowicz, et al., NIM 180 (1981) 429]
- "two samplers": nice early discussion of possibilities
  [Paul Mockett, Calorimeter Review, SLAC Report 267, 1983]
- *dE/dx* & Cerenkov: in L-Argon calorimeter
  [Winn and Worstell, IEEE NS-36 (1989) 334]
- Radial Scintillation & Cerenkov profiles
  [DREAM "profile" paper, NIM A548 (2005) 336]

Mockett 1983 SLAC *Summer Institute*

- "A technique is needed that is sensitive to the relative fraction of electromagnetic energy and hadronic energy deposited by the shower. This could be done hypothetically if the energy were sampled by two media: one which was sensitive to the beta equals one electrons and another which was sensitive to both the electrons and other charged particles. For example one sampler could be lucite which is sensitive only to the fast particles, while the other sampler could be scintillator. Then the fraction of pizeros produced could be determined from the relative pulse heights of the two samplers. Another technique might be to utilize the slow scintillation pulse and the fast Cerenkov pulse in total absorbing materials such as scintillating glass or Barium fluoride. By appropriate gating for wave form sampling …"

This dual measurement doesn't have to be just with separate fibers, or "samplers"

. . .

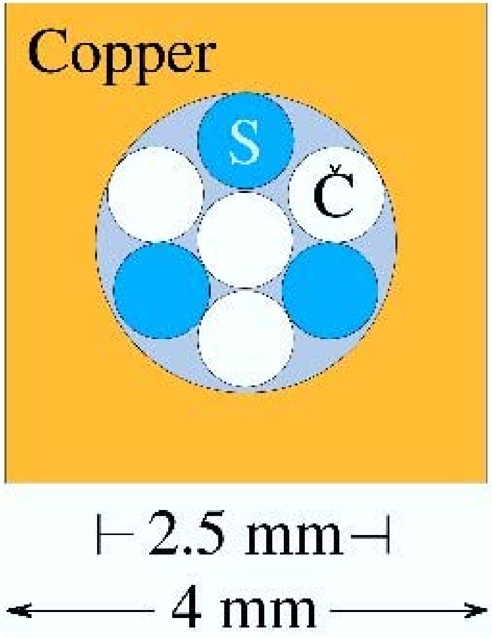
- Mixed light in one set of fibers (DREAM-2)
- Mixed light in a single crystal (4th, CMS-2, DREAM-3)
- Mixed light in the atmosphere (TeV astrophysics)
- Mixed light in noble liquids …

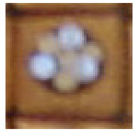
But, you must separate the light …

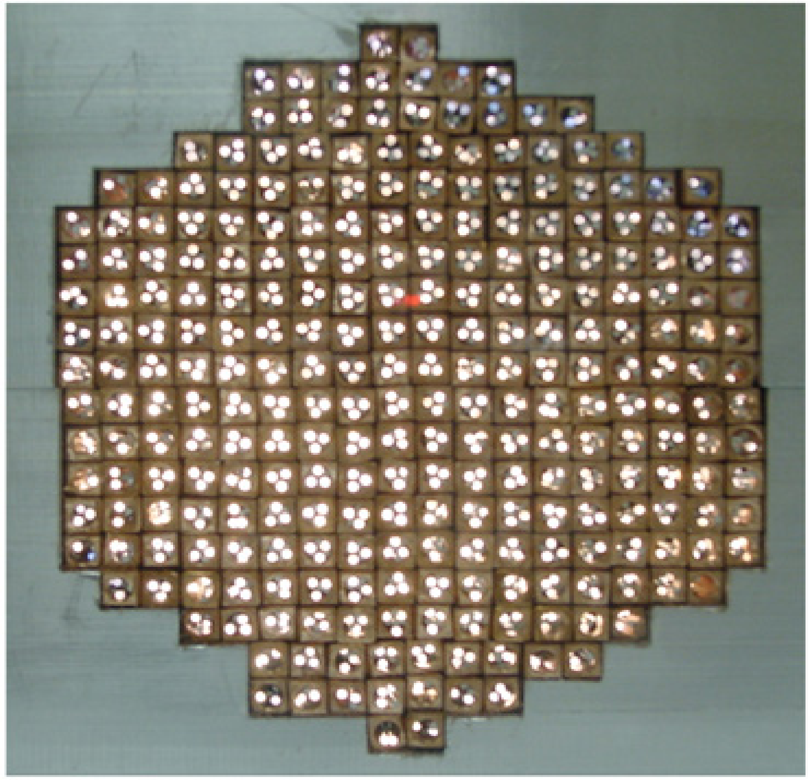
	Cerenkov	*Scintillation*
• Physically, *e.g.*, separate fibers	clear fiber	fiber with fluor
• By direction:	$\theta_{Cerenkov} \sim 45^0$	isotropic
• By wavelength:	$d\lambda/\lambda^2 \sim$ blue, UV	green, *etc.*
• By time:	$\tau \sim 0$	$\tau \sim$ many ns
• By polarization	few % (avg)	□ none

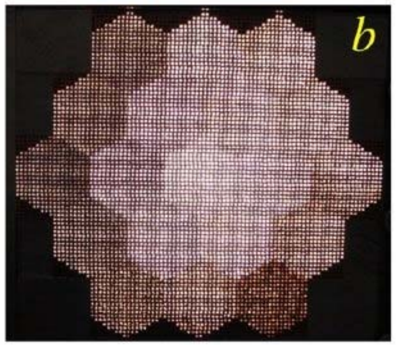
Physical separation

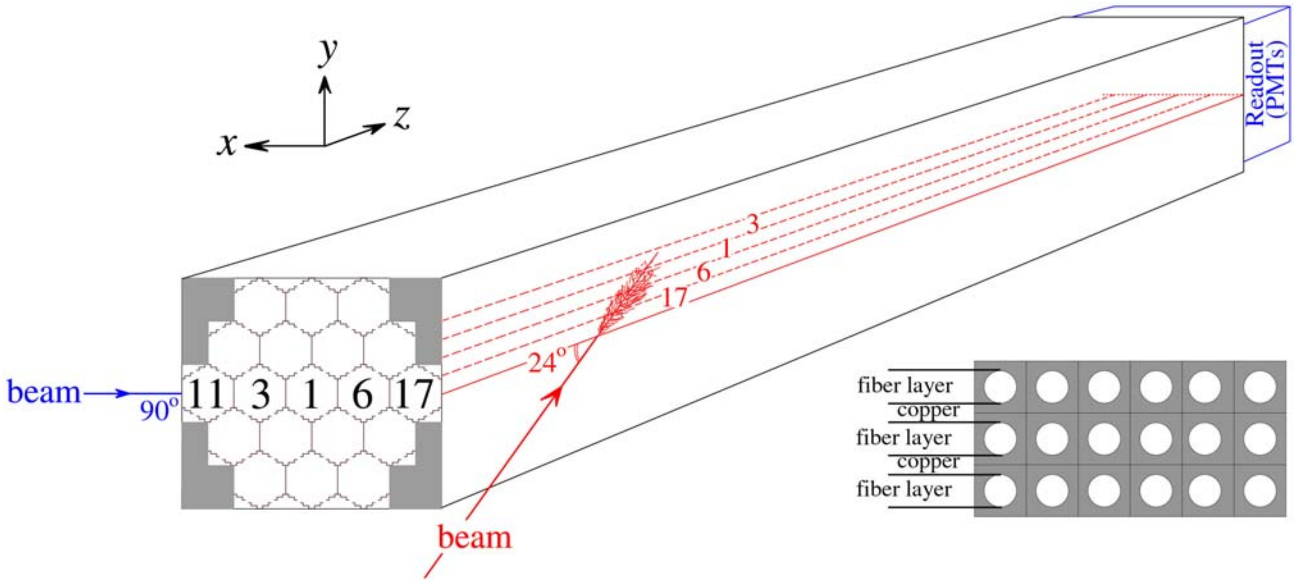
DREAM



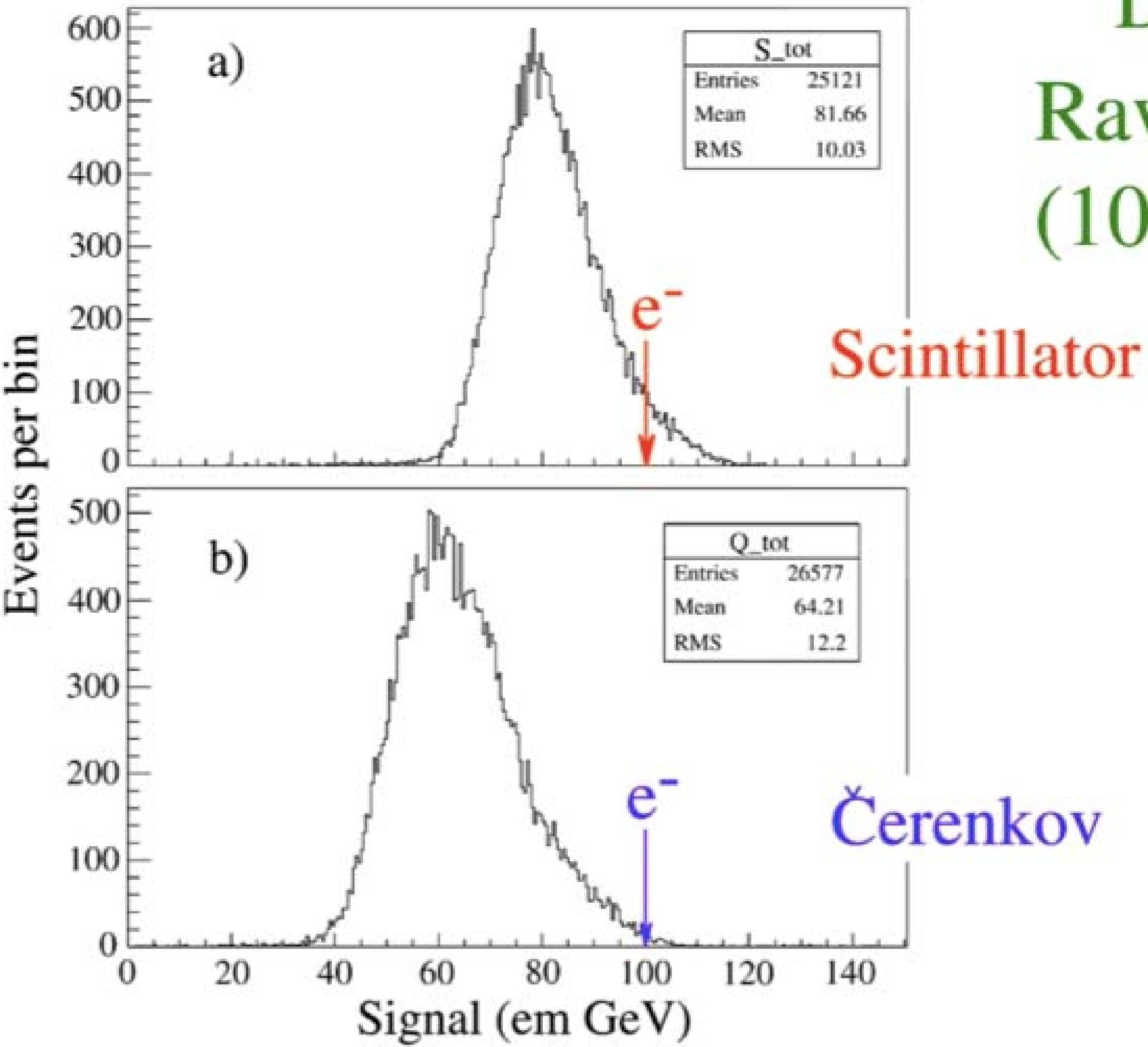




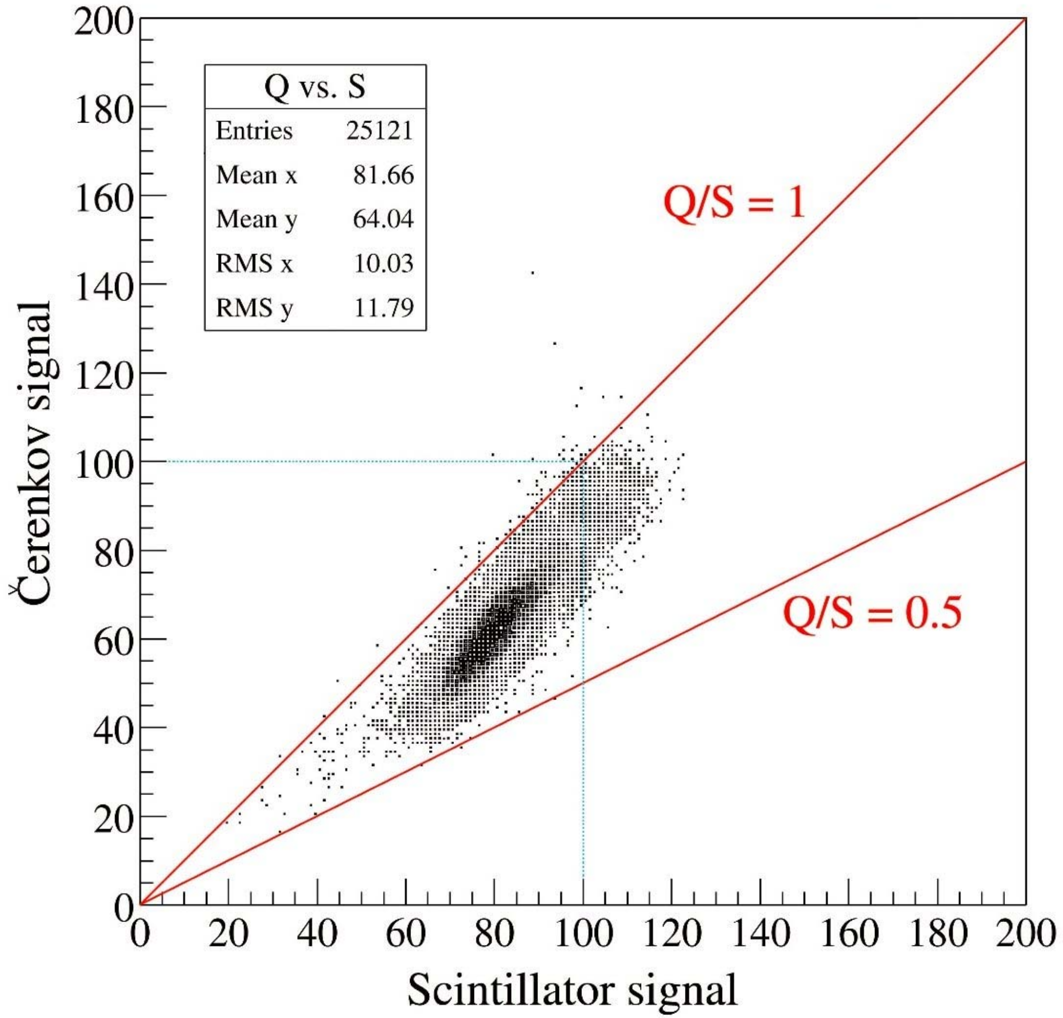




DREAM
Raw signals
(100 GeV π^-)



DREAM: Cerenkov *vs.* scintillation signal 100 GeV π^-



Raw data for 100 GeV π^- Cerenkov *vs* Scintillation signals, scale defined by response to 40 GeV e^-.

EM fraction fluctuations are obvious

Cerenkov signal is well correlated with EM fraction

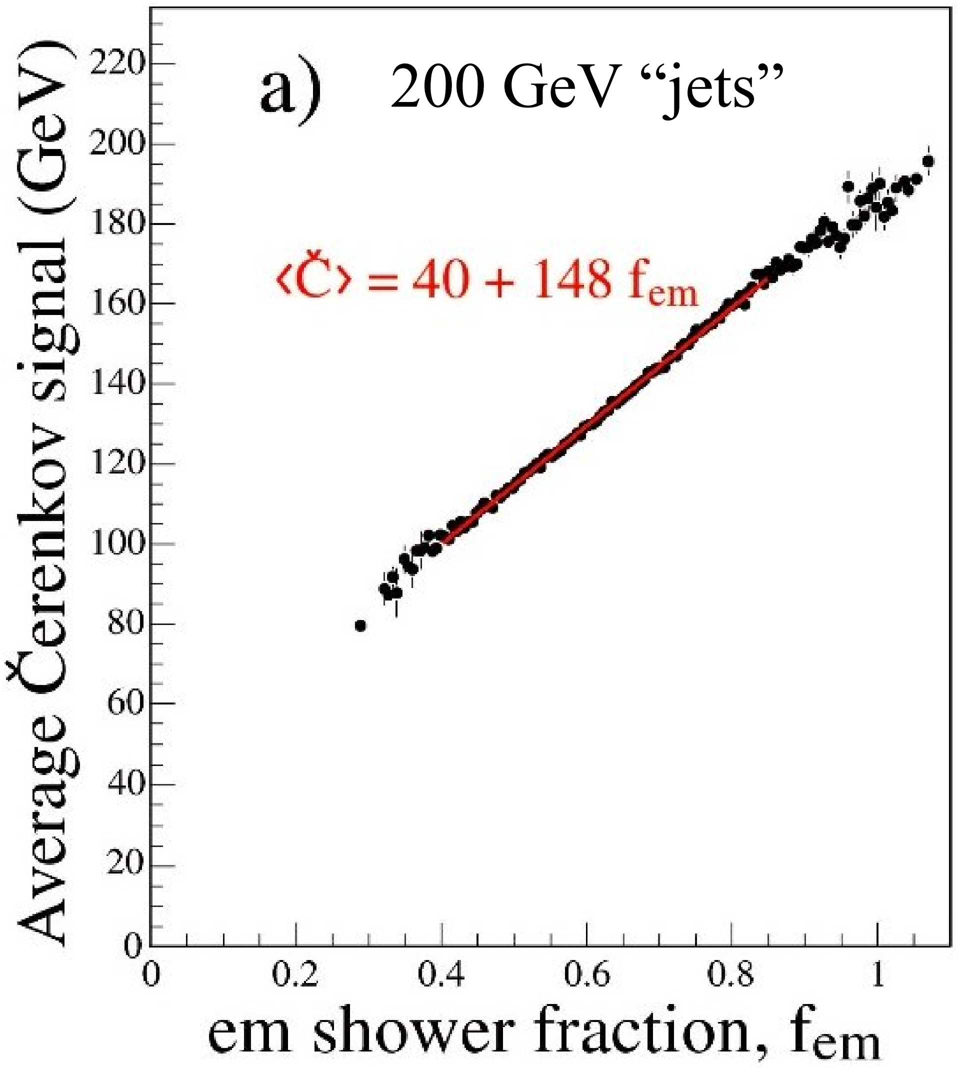
$(e/h)_S = \eta_S \approx 1.4$

$(e/h)_C = \eta_C \approx 5.0$

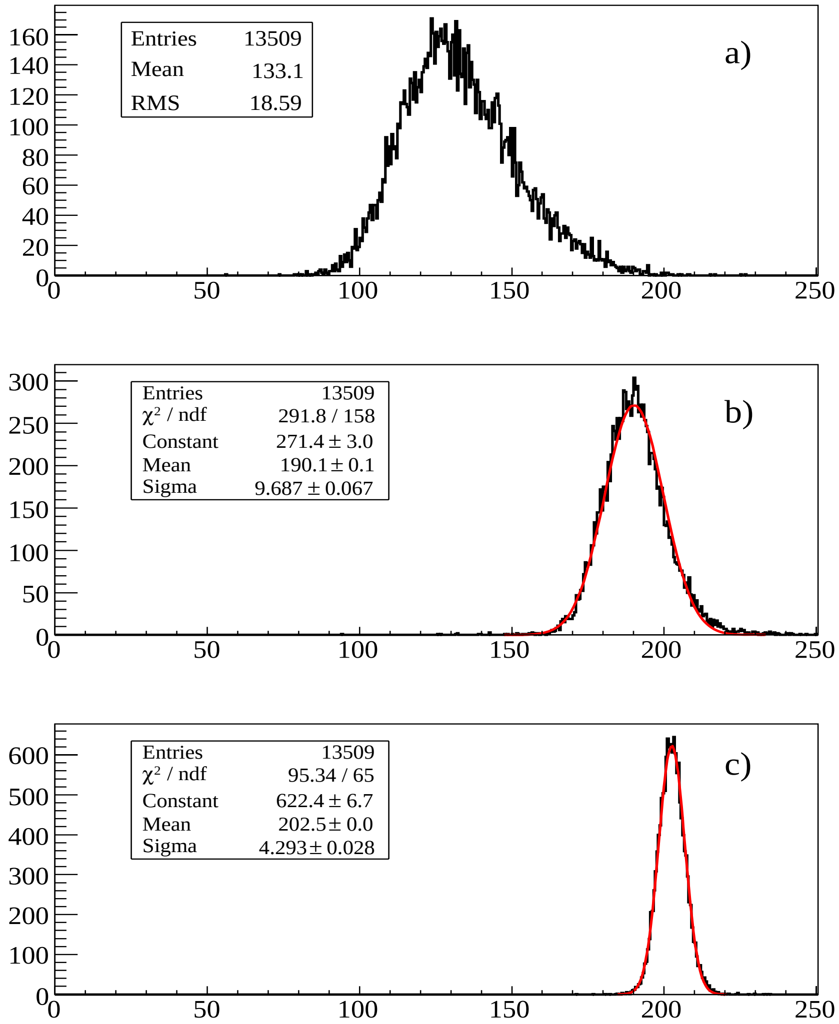
$C = [f_{EM} + (1\text{-}f_{EM})/\eta_C]\ E$

$S = [f_{EM} + (1\text{-}f_{EM})/\eta_S]\ E$

$C/E = 1/\eta_C + f_{EM}(1\text{-}1/\eta_C)$



DREAM data 200 GeV π: Energy response



Scintillating fibers

Scint + Cerenkov

$f_{EM} \propto (C/E_{shower} - 1/\eta_C)$

(4% leakage fluctuations)

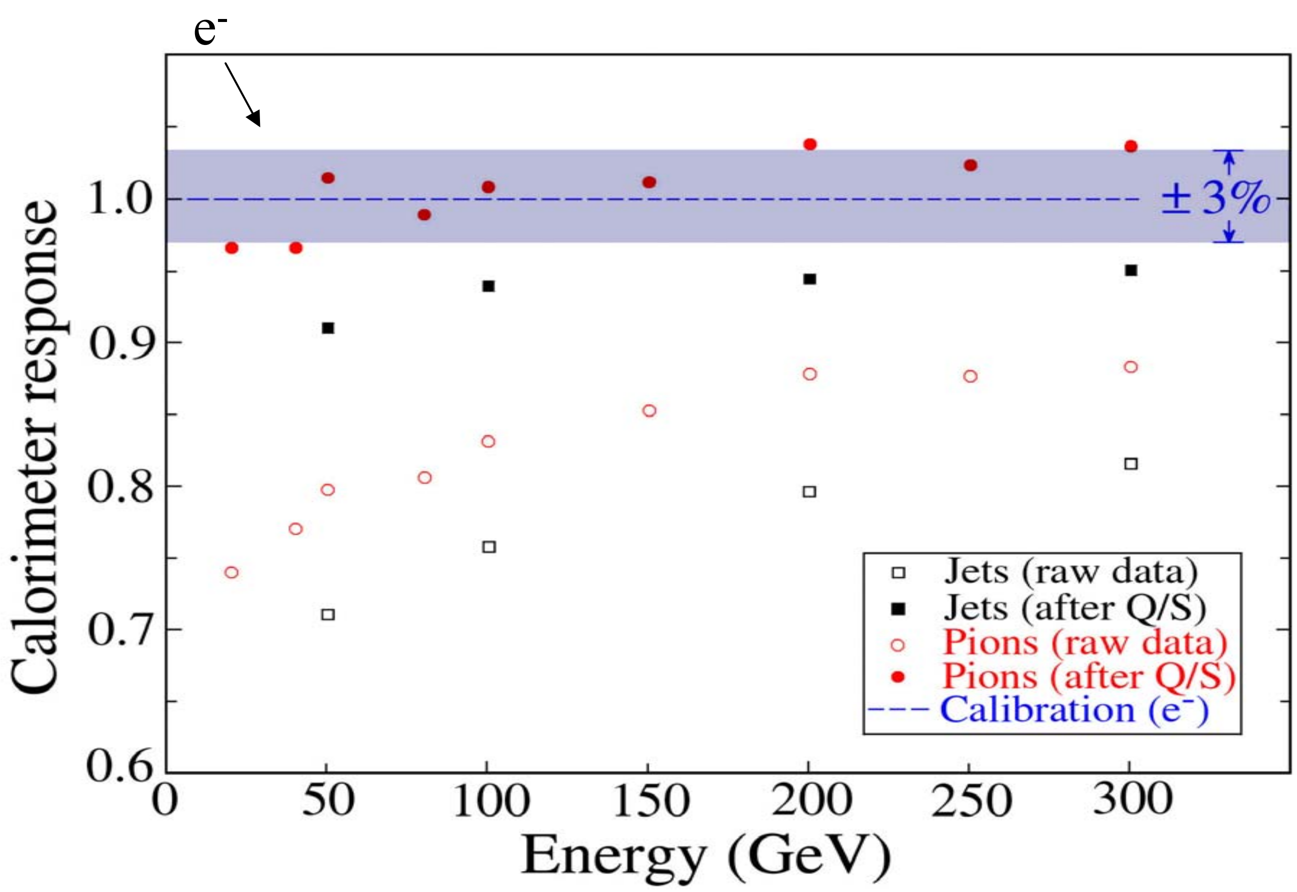
Scint + Cerenkov

$f_{EM} \propto (C/E_{beam} - 1/\eta_C)$

(suppresses leakage)

Data NIM A537 (2005) 537.

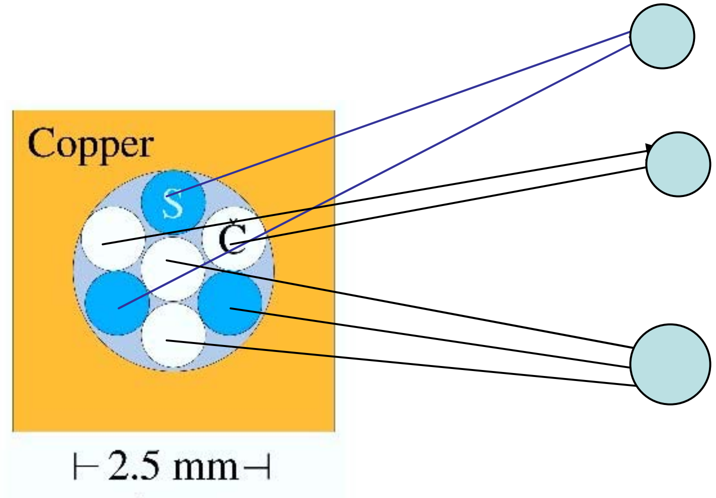
More important than good Gaussian response: DREAM module calibrated with 40 GeV e^- into the centers of each tower responds linearly to π^- and "jets" from 20 to 300 GeV.



Hadronic linearity may be the most important achievement of dual-readout calorimetry, so far.

Data NIM A537 (2005) 537.

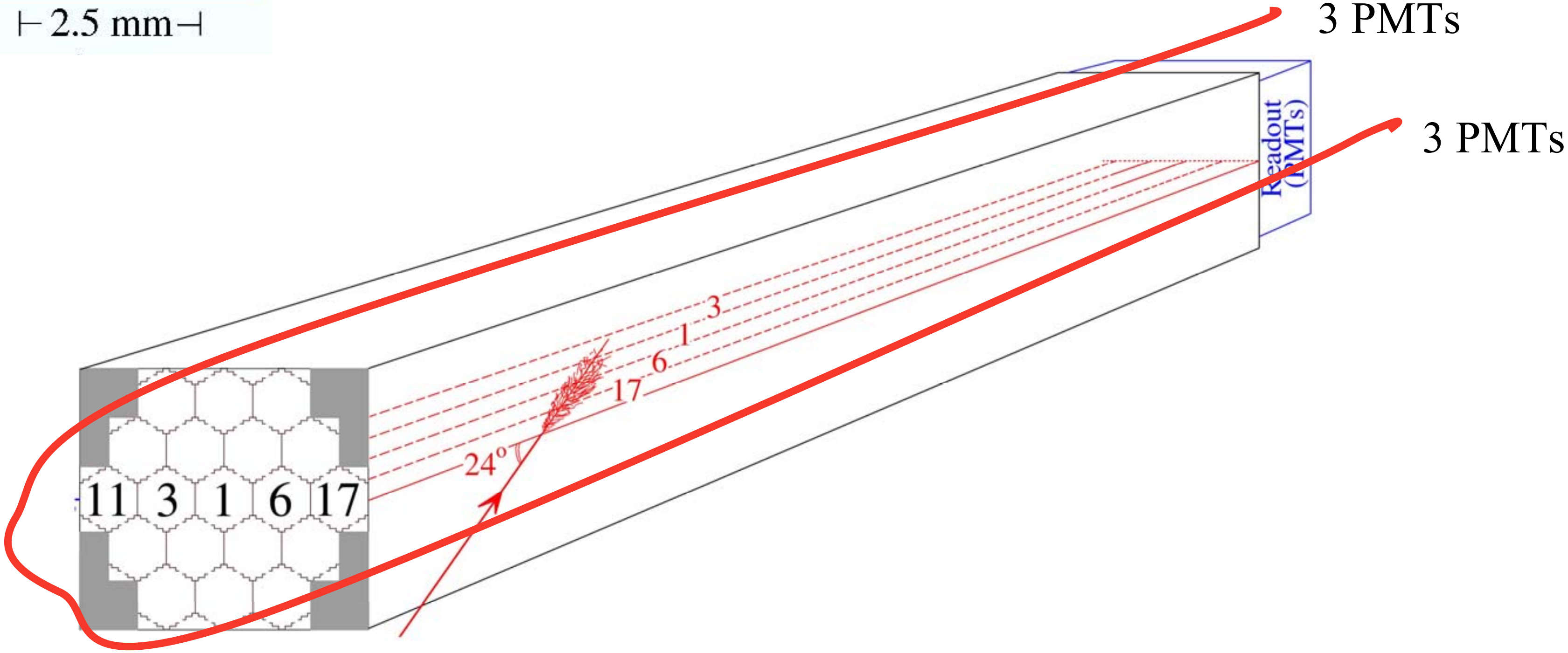
Deliberately mixing the light



S+S = pure scintillation

C+C = pure Cerenkov

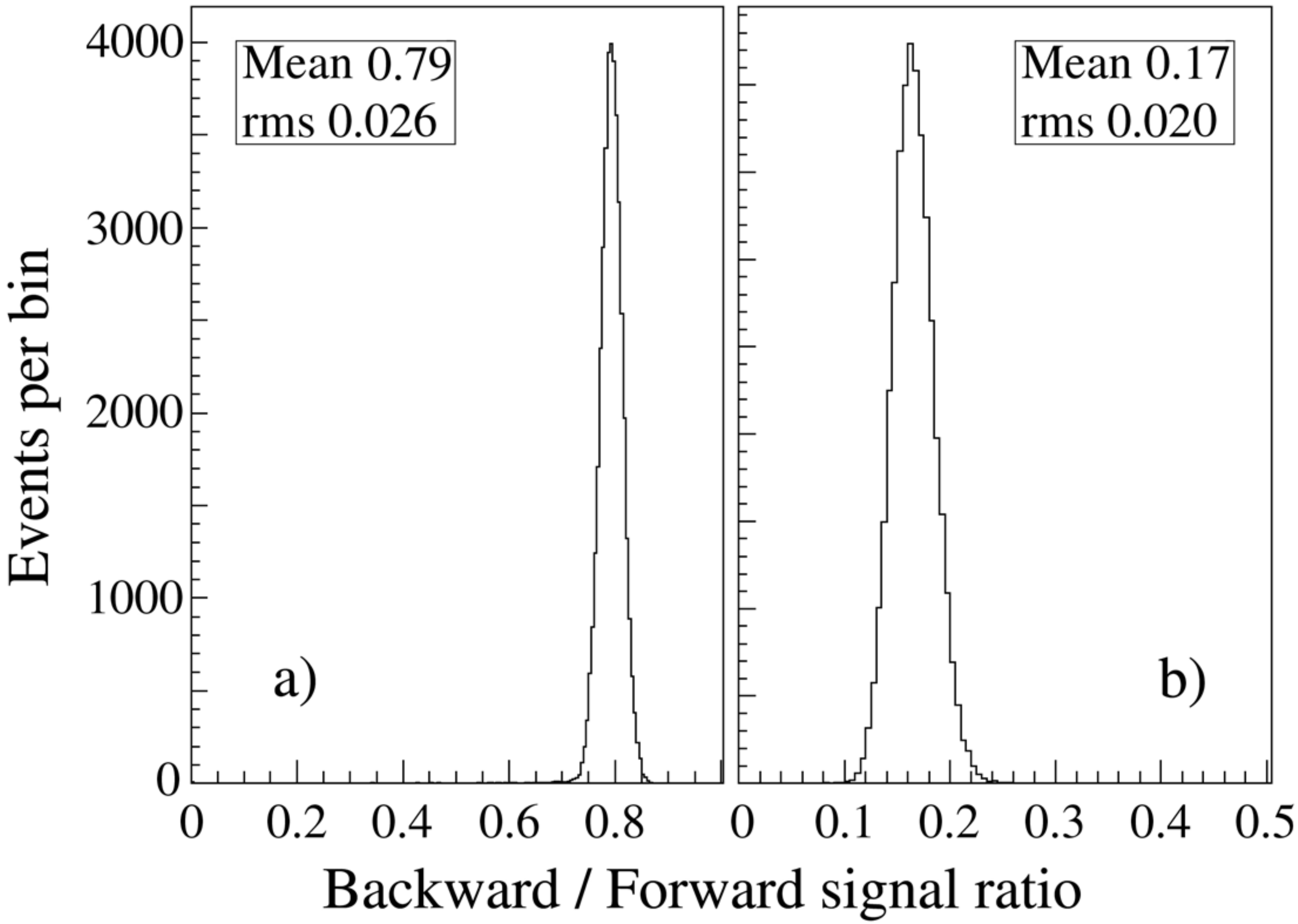
S+C+C = mixed light



Separation by direction: mixed light

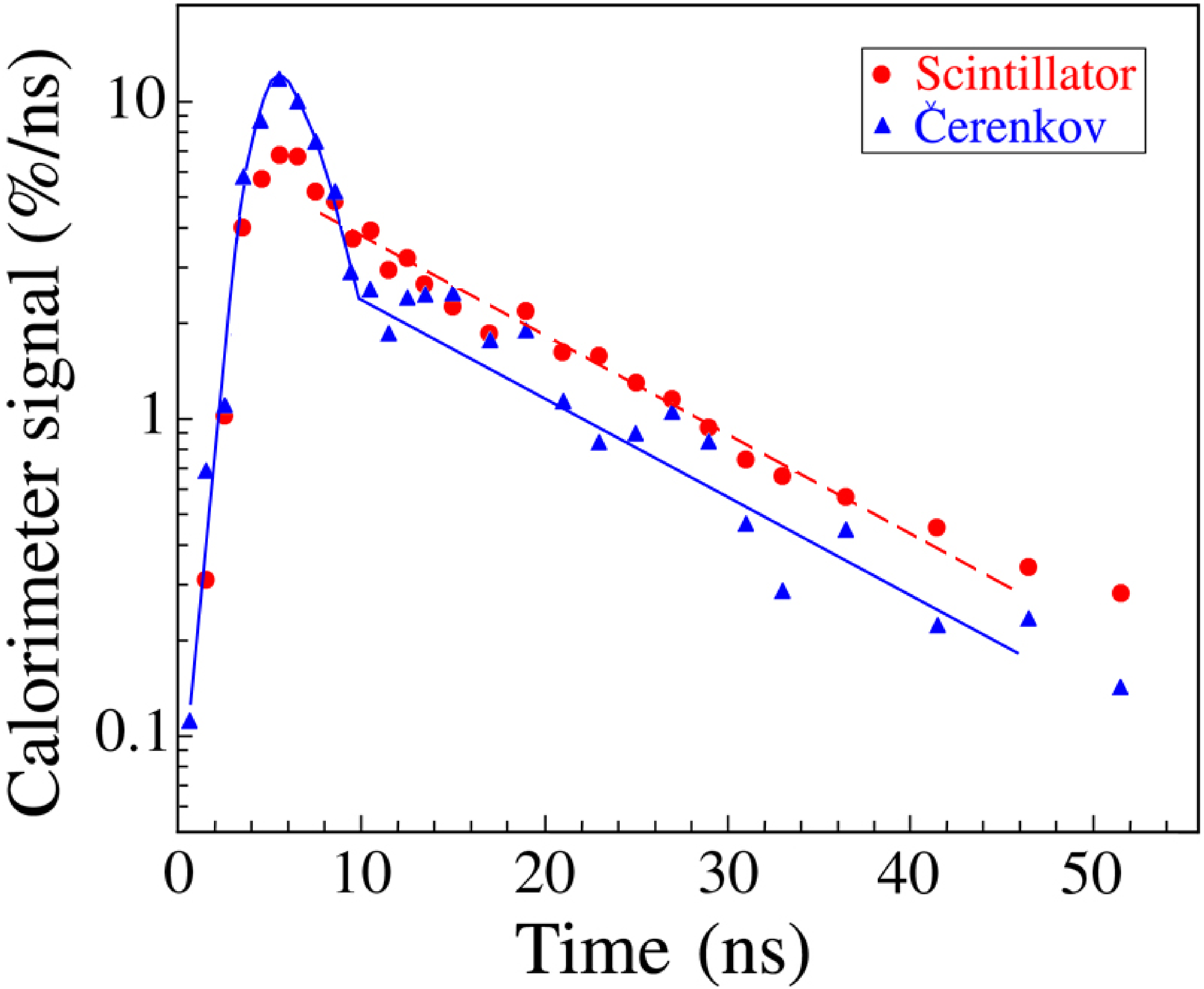
DREAM-2 test,

scintillation and
Cerenkov light
deliberately
mixed in same
fibers



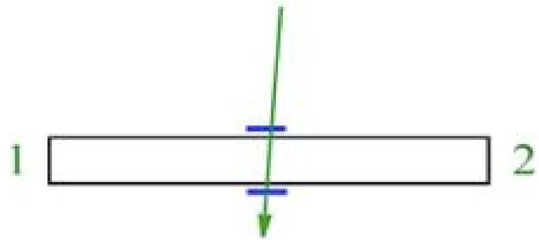
Time separation: DREAM-2 module, mixed light in fibers

Most of the light is inside 10-15 ns. A deliberate design would improve this separation. These signals were digitized at the ends of long cables.



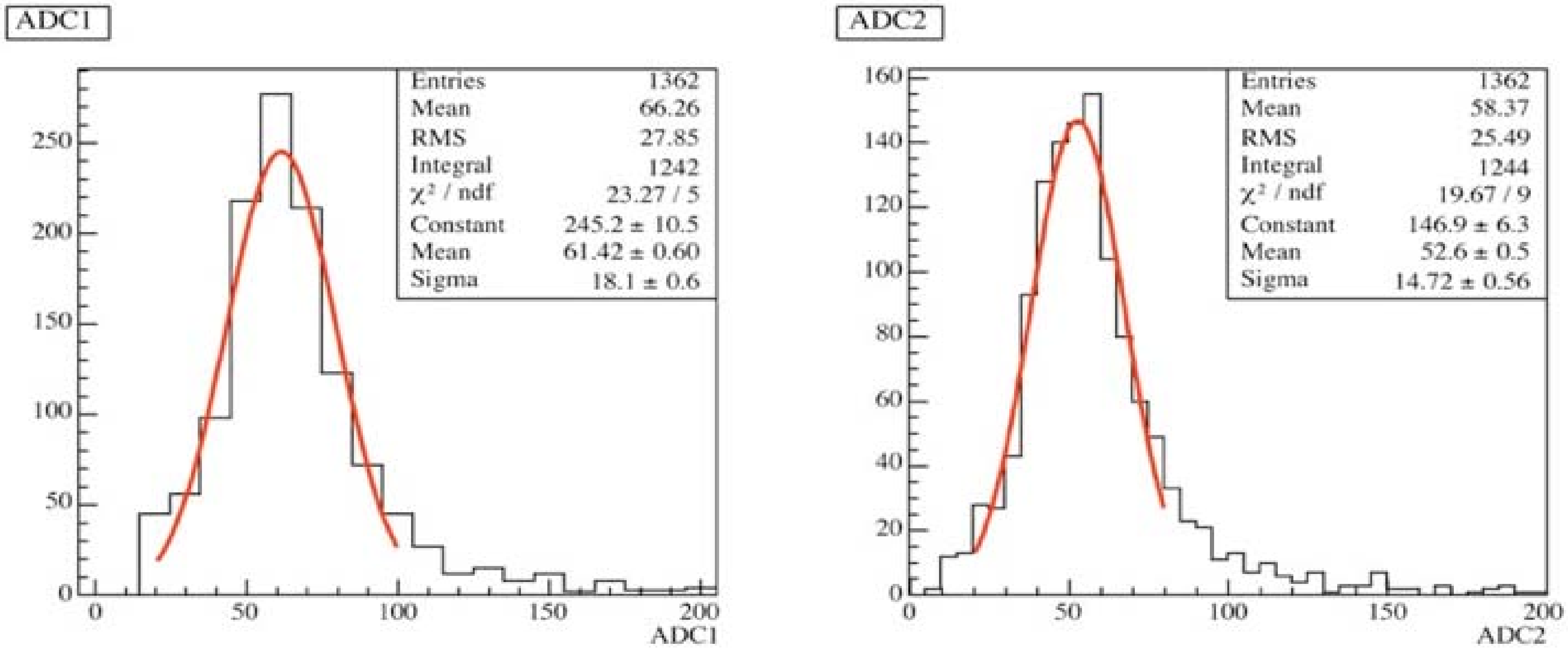
Light mixed in a single macroscopic medium

Signal distributions $PbWO_4$ crystal (cosmics)

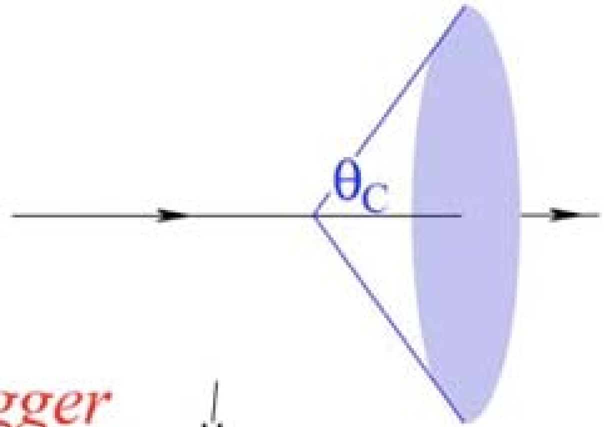


Average energy deposit (mip):

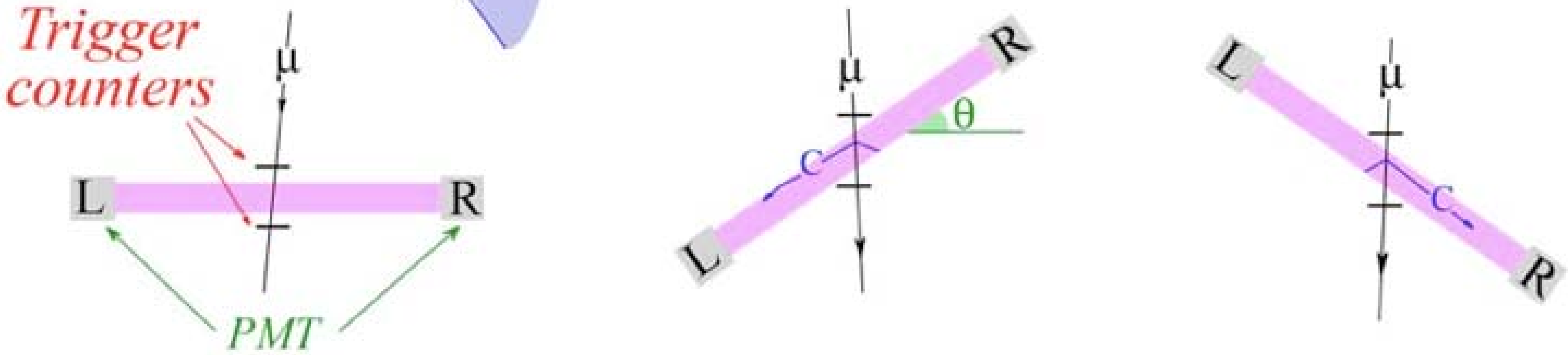
9.4 MeV/cm ⟶ 23.5 MeV



Identifying Čerenkov component on the basis of its directionality



$n = 2.2$, $\arccos \theta_C = 1/n \rightarrow \theta_C = 63^o$



Calibration:
L = R

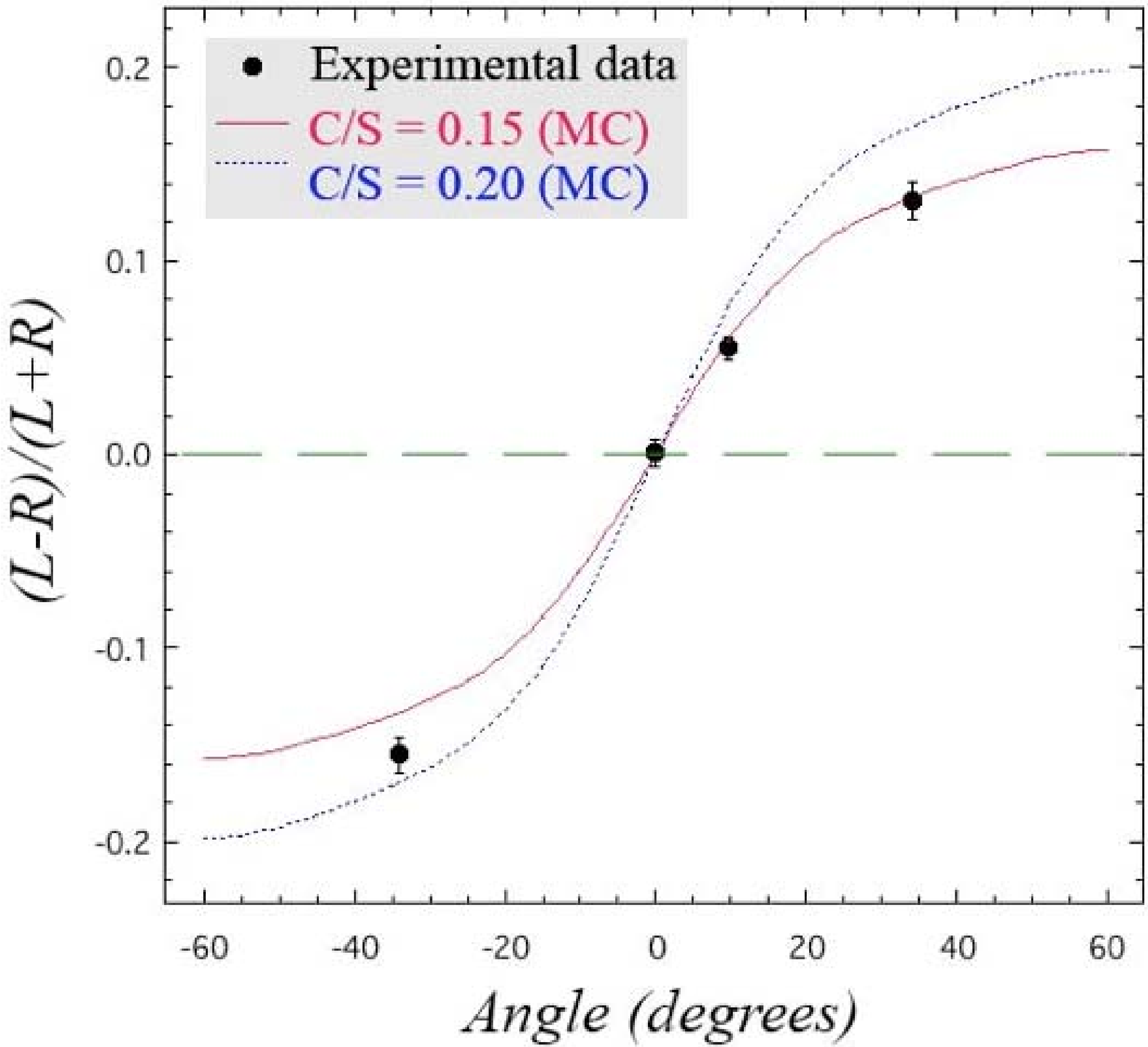
L > R

L < R

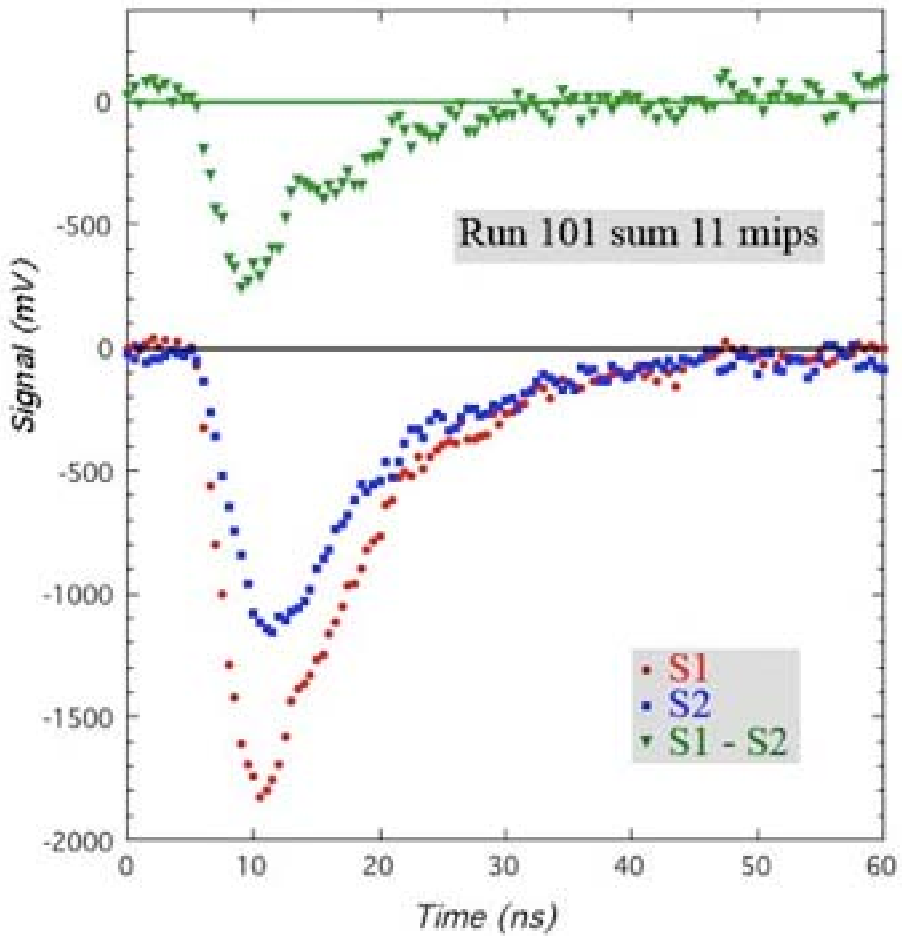
→ *Measure* $\frac{L - R}{L + R}$ *as a function of* θ

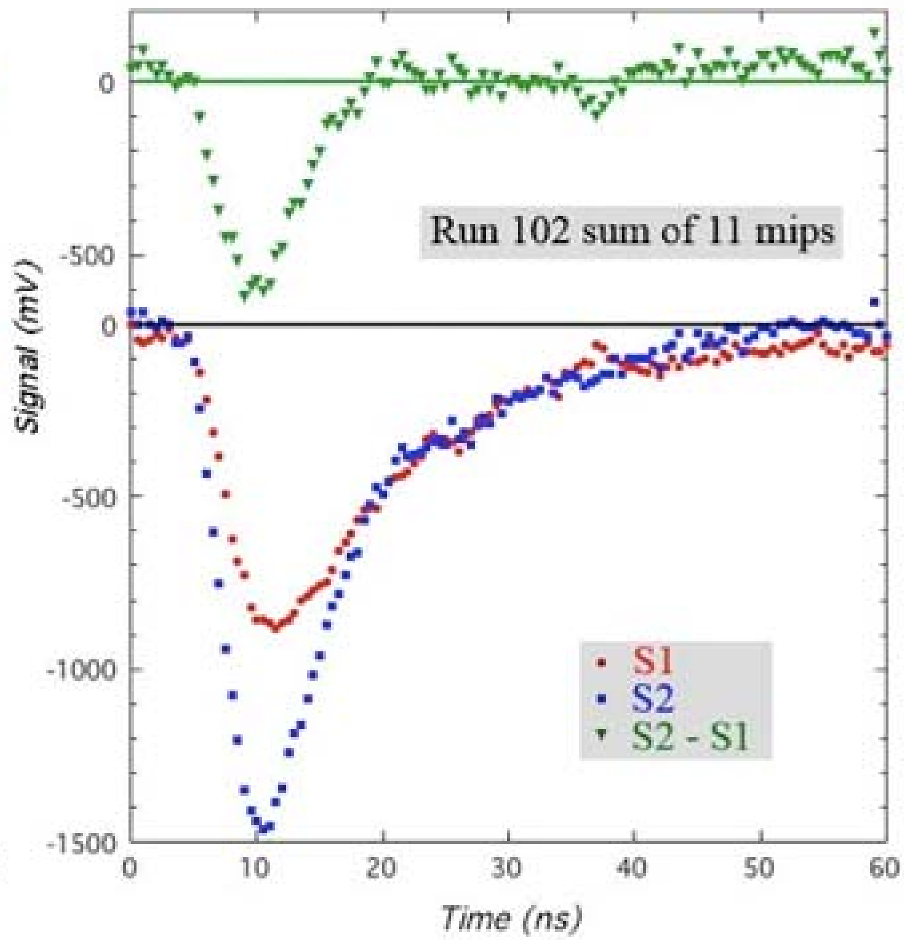
R. Wigmans Elba '06

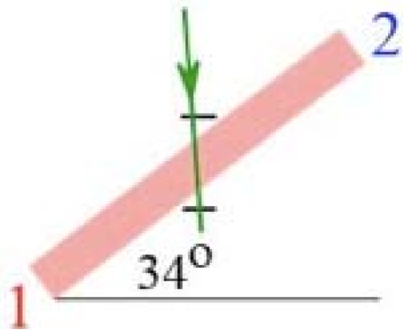
Experimental results, light directionality in $PbWO_4$



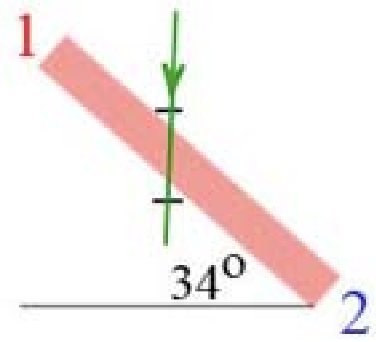
Time structure of cosmic ray events in $PbWO_4$ (ΔE = 25 MeV)



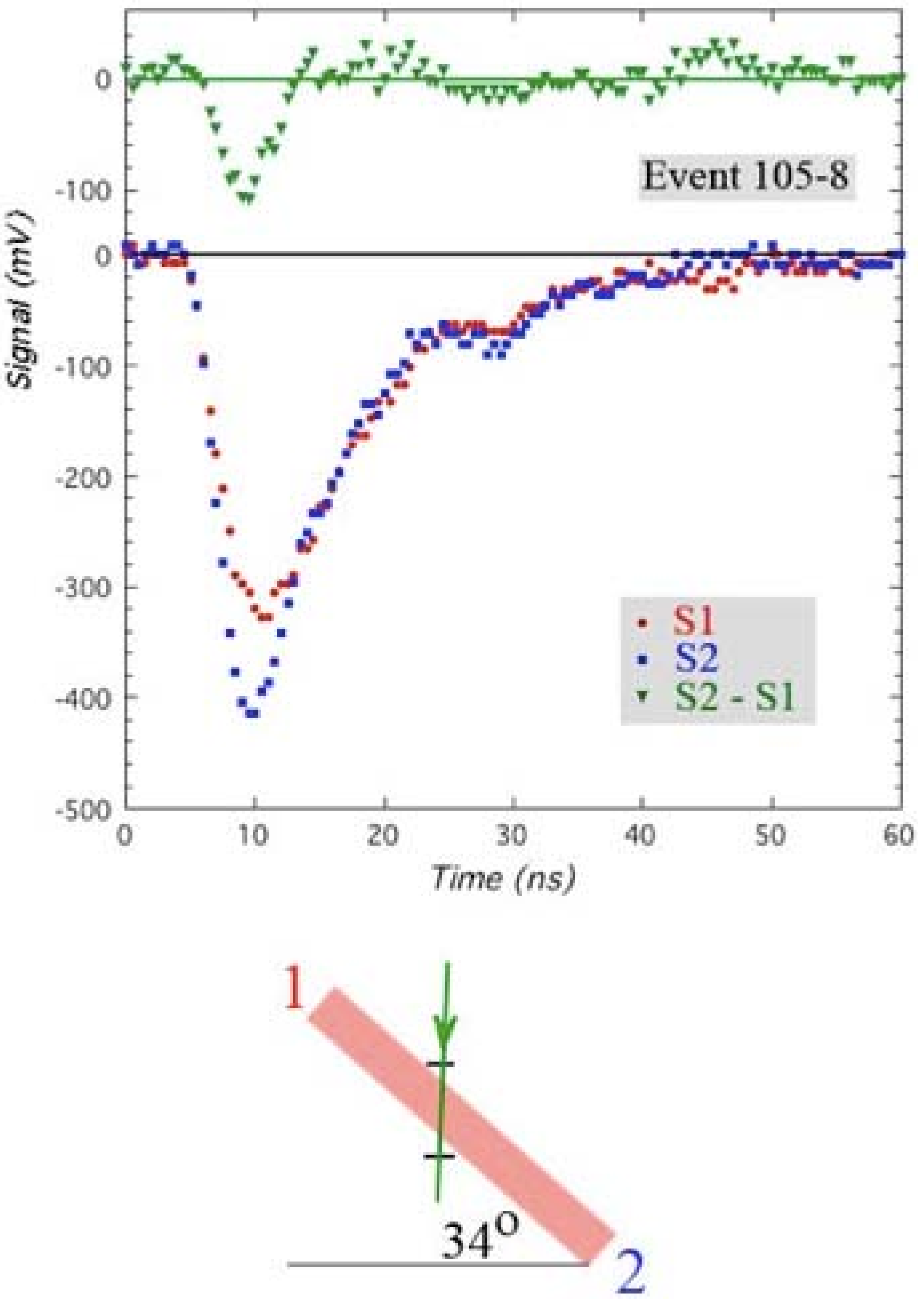


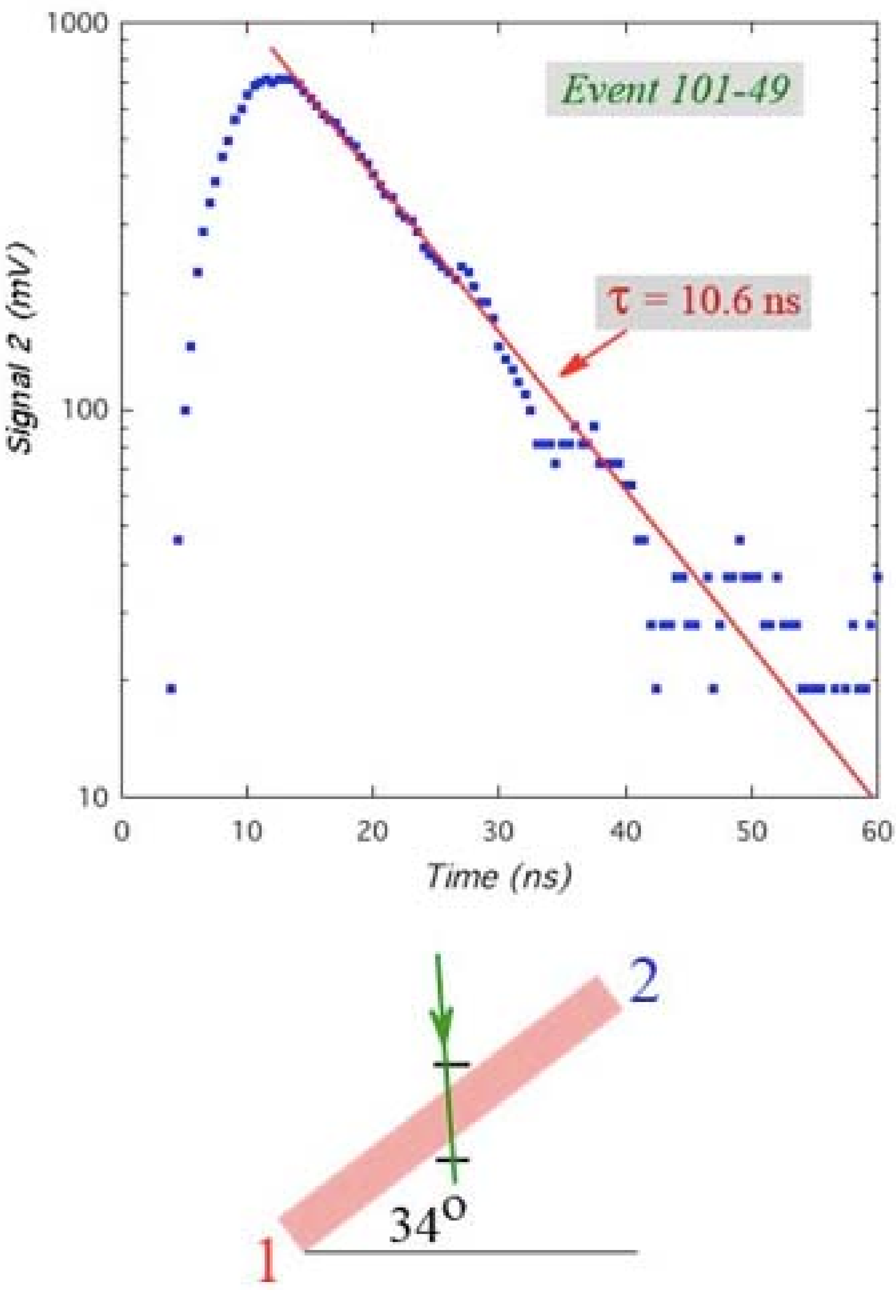


Slope *dL/dt*
measures C/S



Time structure of cosmic ray events in $PbWO_4$ (Landau tail)

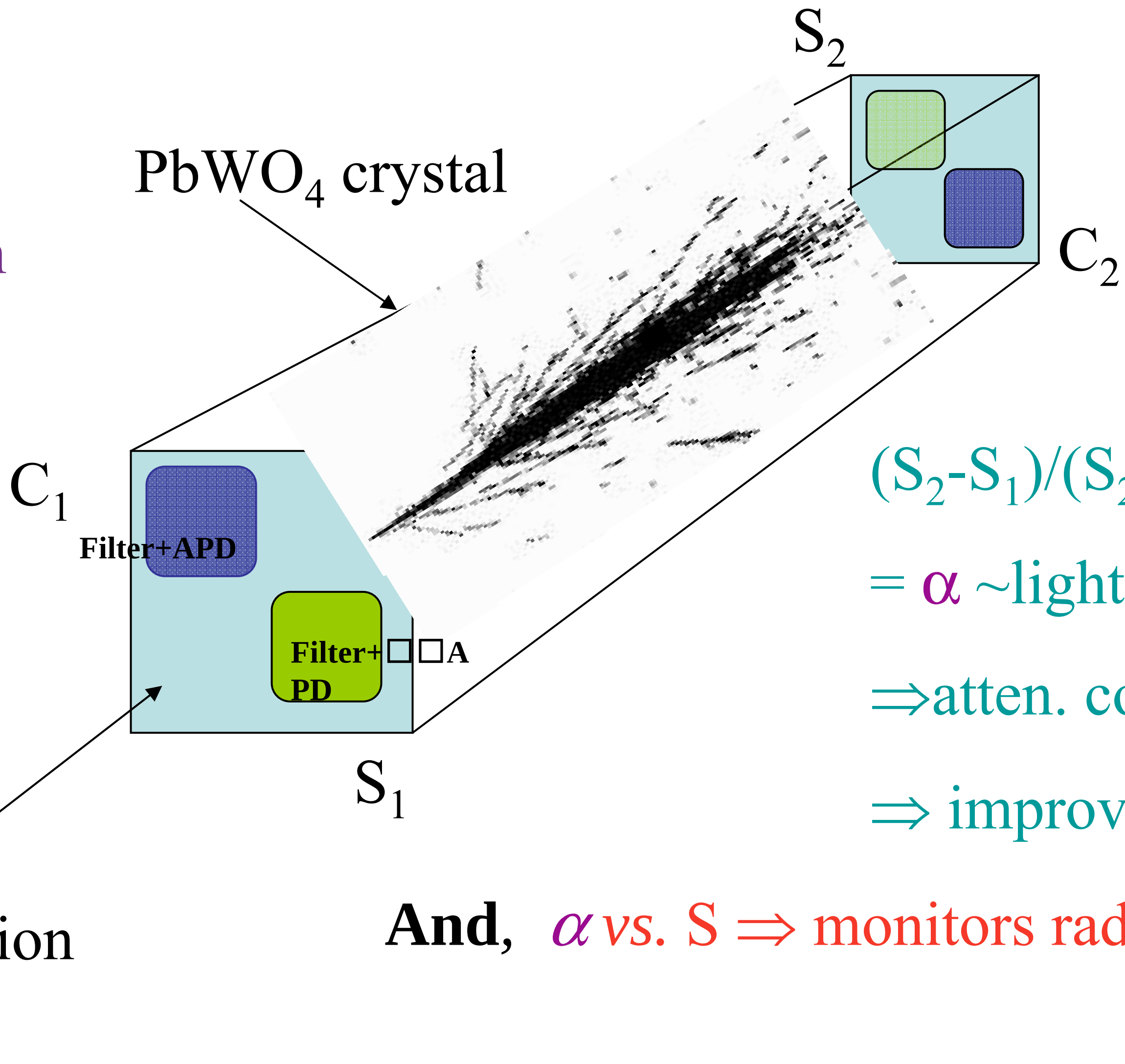




“Lamborghini” model crystal *(CMS-2 ?)*

C_2-C_1 ~ Cerenkov

$(S_1+S_2)/2$ ~ Scintillation



$(S_2-S_1)/(S_2+S_1)$

$= \alpha$ ~light depth

$\Rightarrow$atten. correction

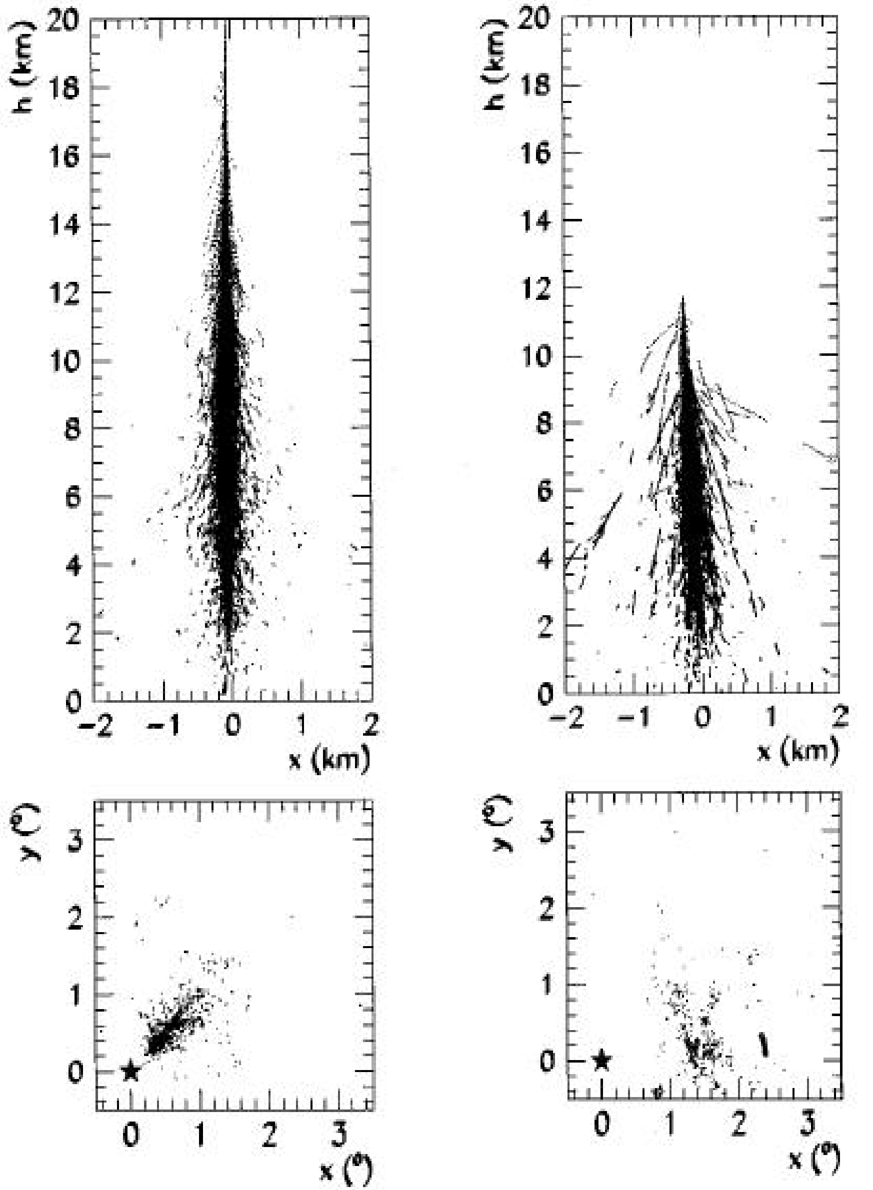
$\Rightarrow$ improve σ_E/E

And, α *vs.* S $\Rightarrow$ monitors rad damage

TeV particle astrophysics: separate γ from proton, He, and more … *problem at the Greisen (GZK) limit ?*

- Index of air $n = 1 + .00029\rho_{NTP}$
- Cerenkov $\beta_{th} = 1/n$

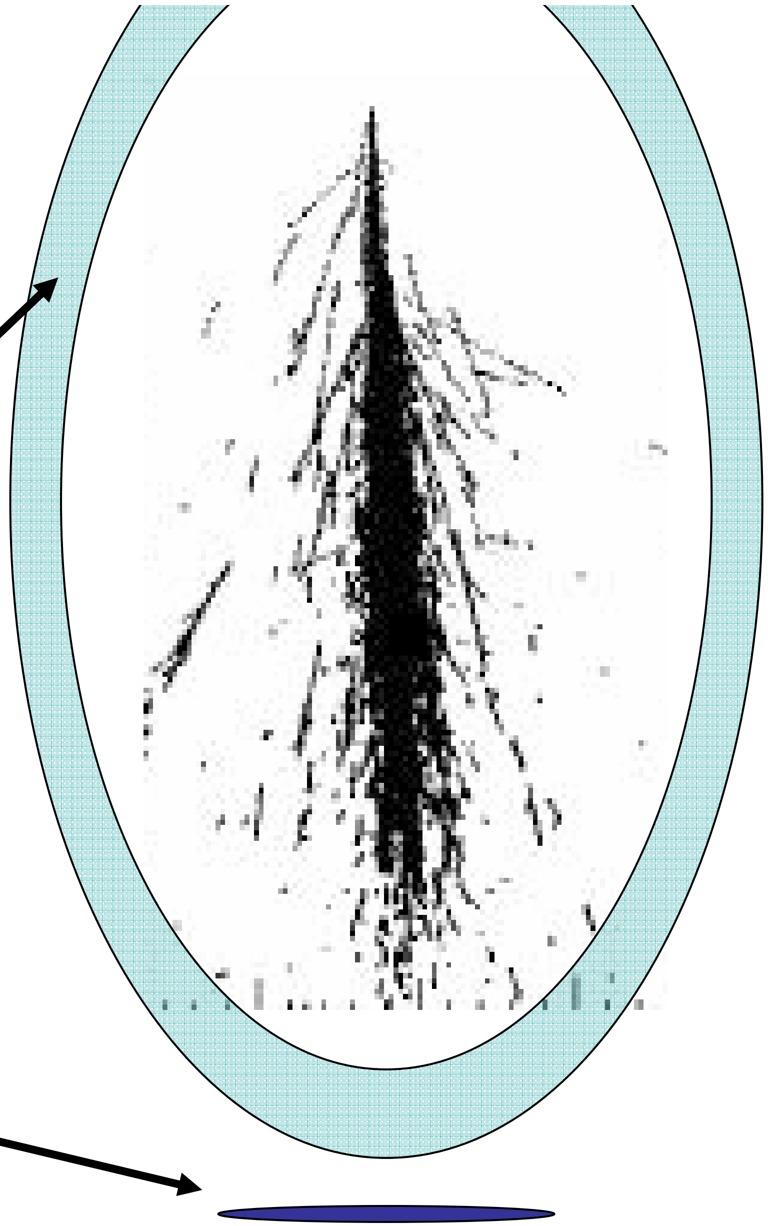
N_2 line emissions 300-400 nm and with lifetimes of several ns



γ-ray

proton

Hadronic showers in the atmosphere: separate by time and wavelength



Scintillation light for N_2 fluorescence
… (green and slow)

Pancake of Cerenkov light (~1m thick)
… (blue and fast)

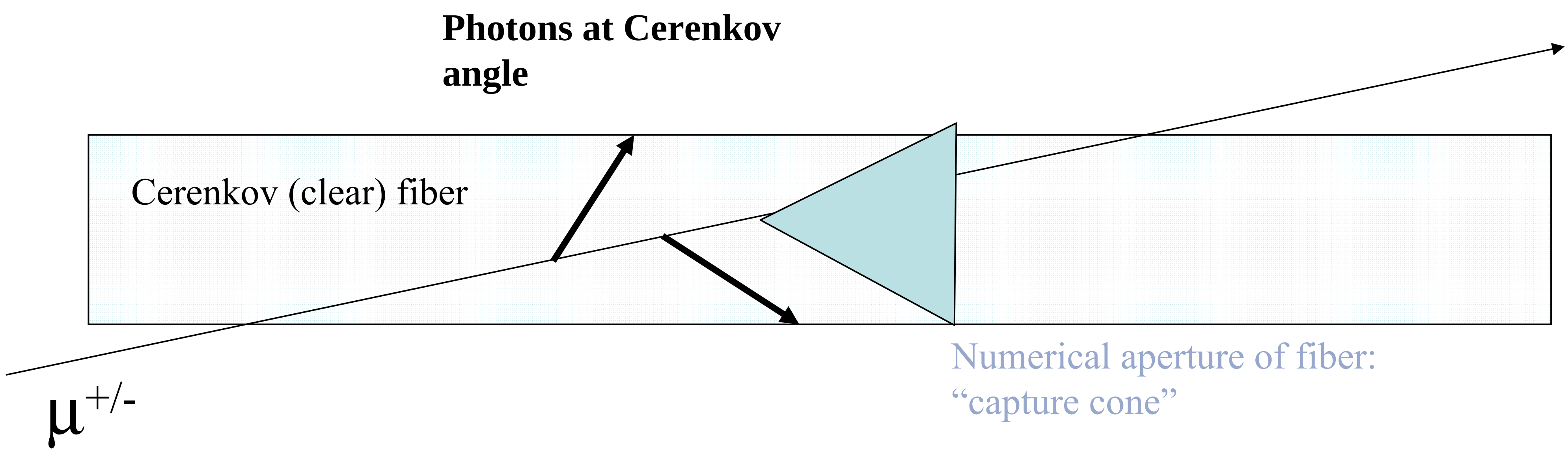
Fluxes and energy thresholds

- N_2 fluorescent yield: 0.02 *pe*/GeV
- Use Cerenkov trigger to open N_2 fluorescent gate for only 10-20 ns, so background is negligible
- This trigger Lowers energy threshold from 10^{18} eV down to 10^{16} eV, or lower
- Larger light gathering area … down to 10^{15} eV?

Goals would be to (1) discriminate γ-rays from protons and (2) make better hadronic energy measurements

Muon dual-readout identification

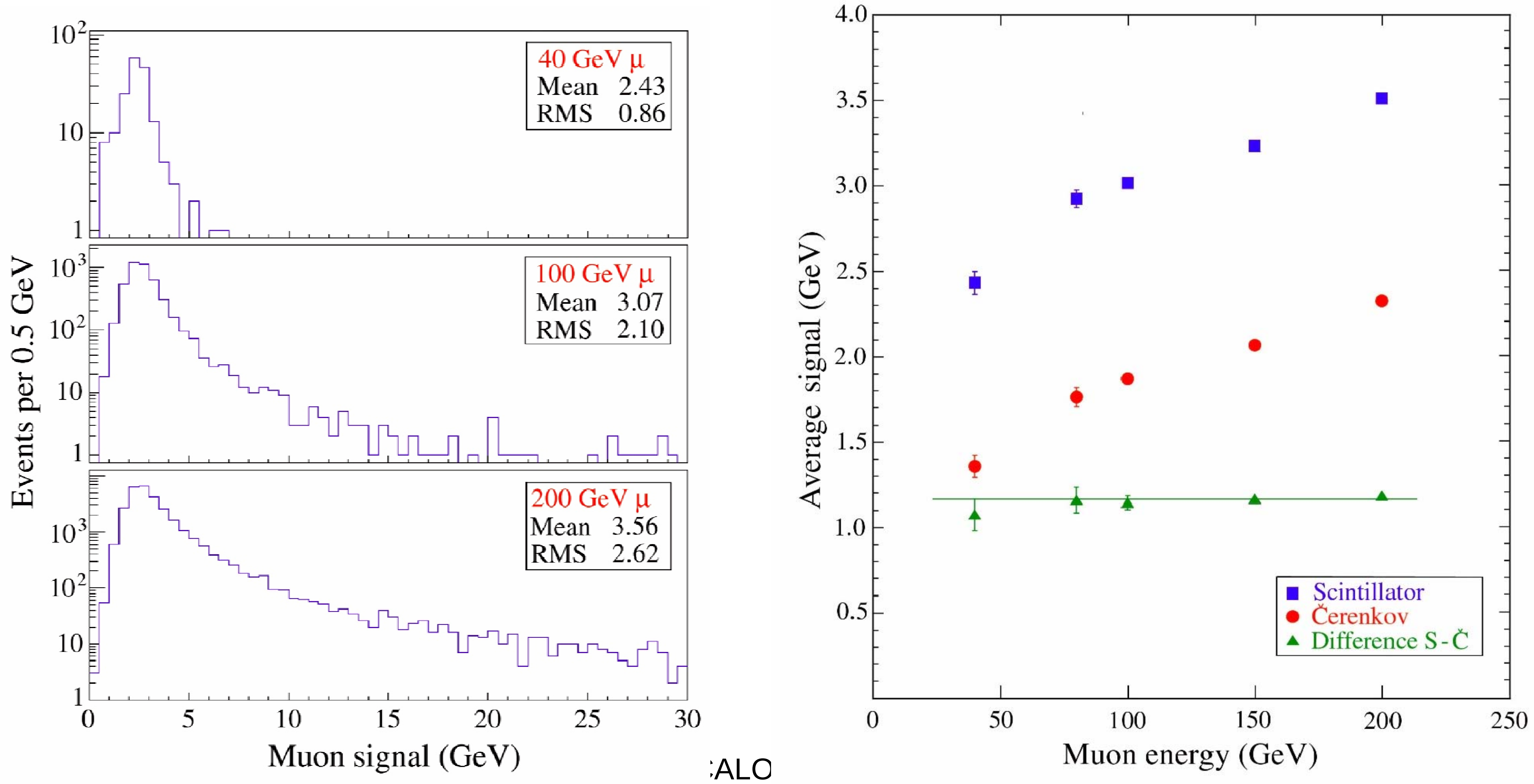
The Cerenkov signal from an aligned, non-radiating muon is zero



All of the Cerenkov light of an approximately aligned muon falls outside of the numerical aperture of the fiber.

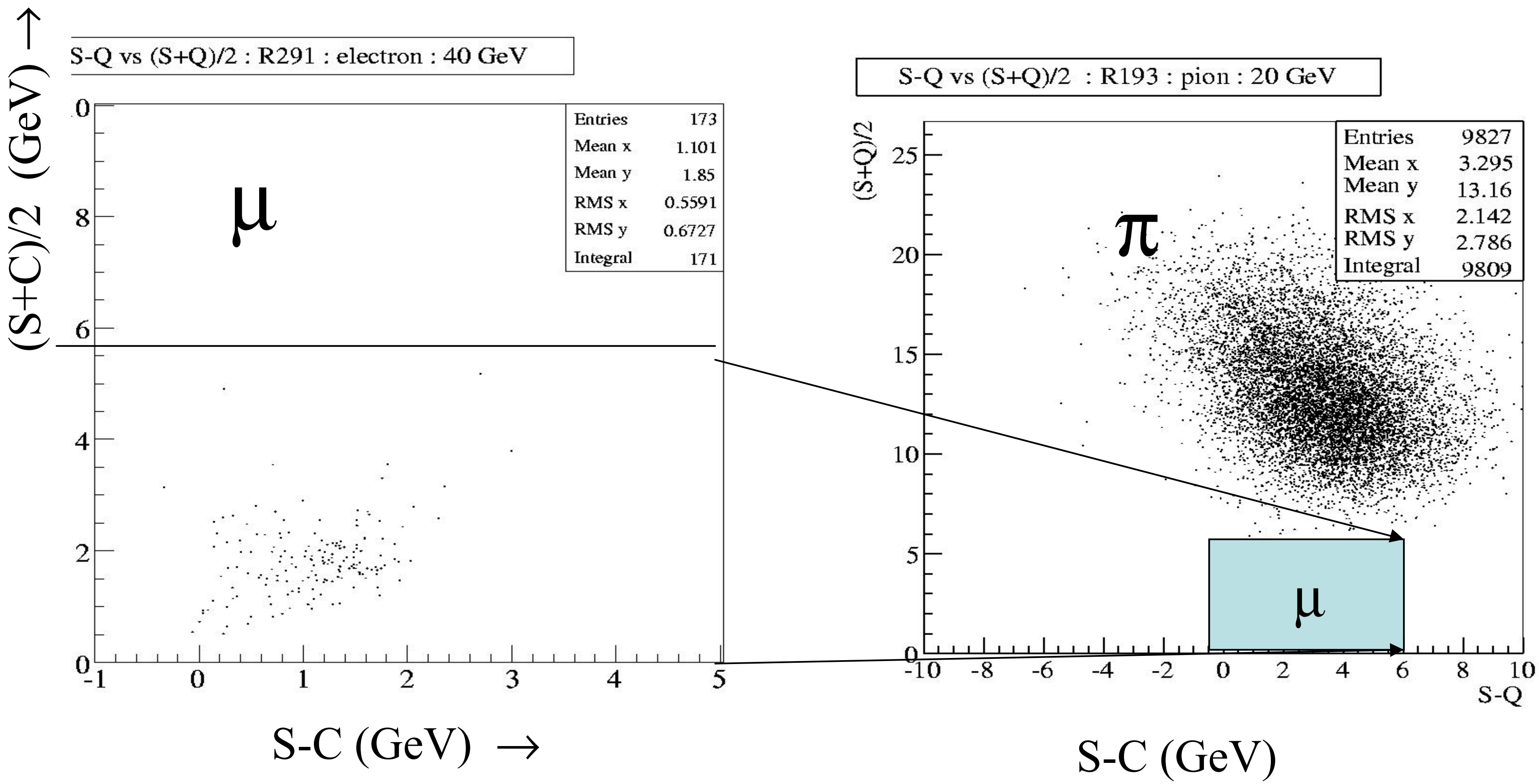
Therefore, for a single μ

* *dE/dx* energy loss yields S=*dE/dx* and C=0
* Radiative energy loss inside calorimeter volume yields: S ~ C

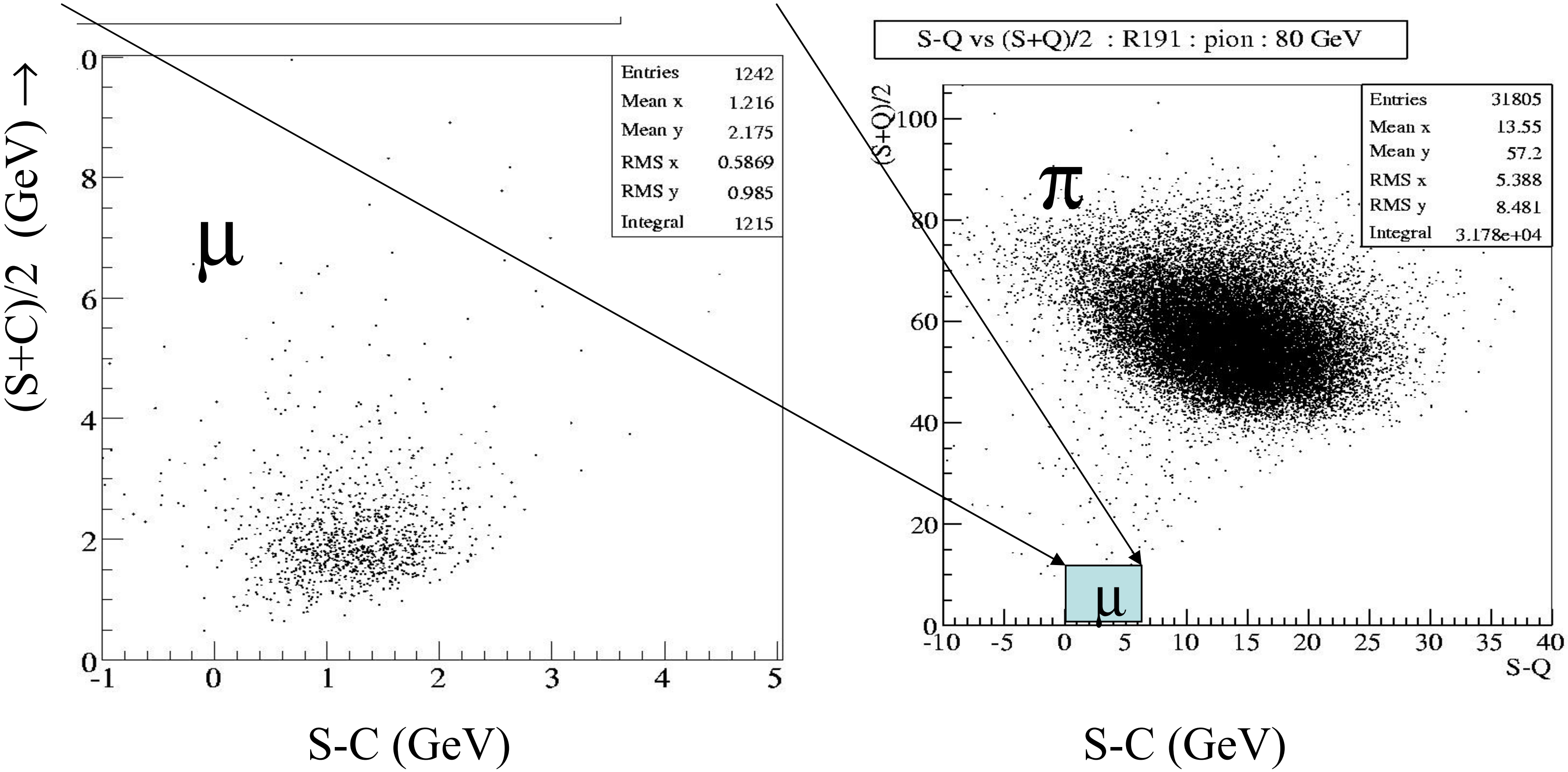


:ALO

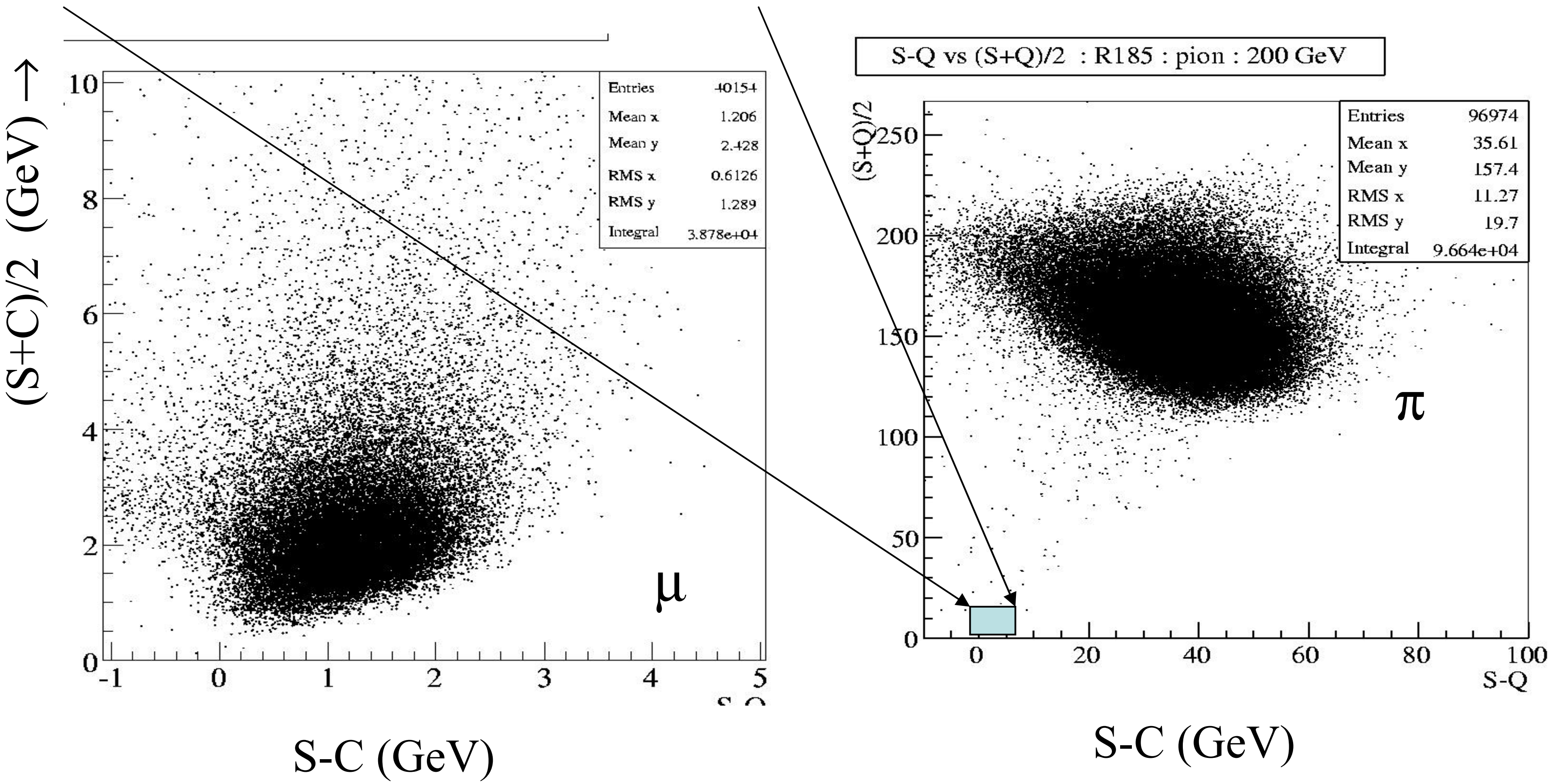
Muons (40 GeV) & Pions (20 GeV)



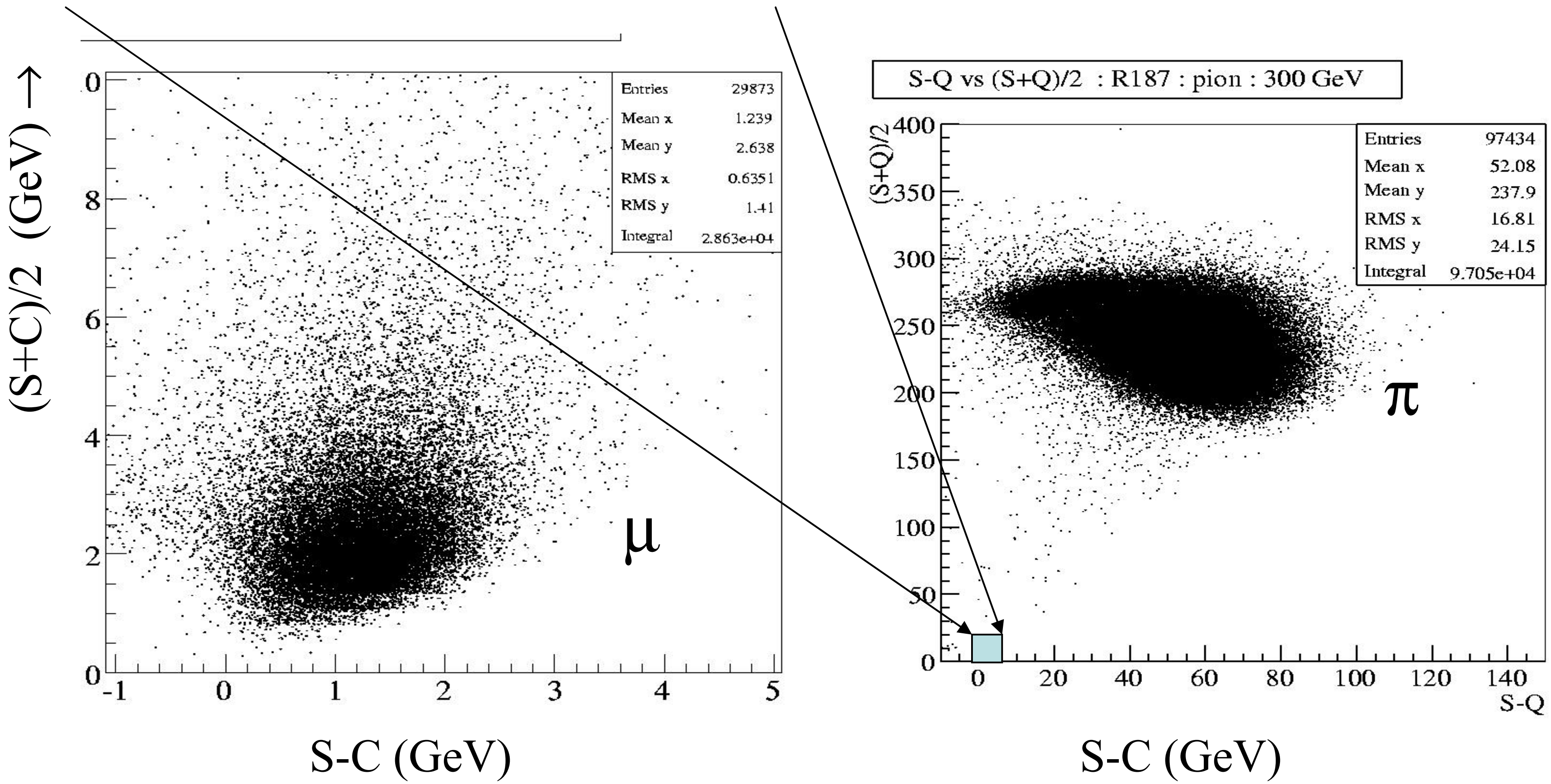
Muons and Pions (80 GeV)



Muons and Pions (200 GeV)



Muons and Pions (300 GeV)



Summary …

- In a fiber-calorimeter realization, dual readout is easy … “first shot”
- Likely to be “easy” in an “EM calorimeter” crystal
- Not restricted to *n=2 (“dual”)*: why not *n=3 “triple”* readout of scintillation, Cerenkov and neutron signals in hadronic showers.
- Not restricted to calorimeters: any measured quantity whose summed parts fluctuate benefits by those parts being separately measured.
- It is a time to be clever … there are likely another half dozen ideas not yet conceived.