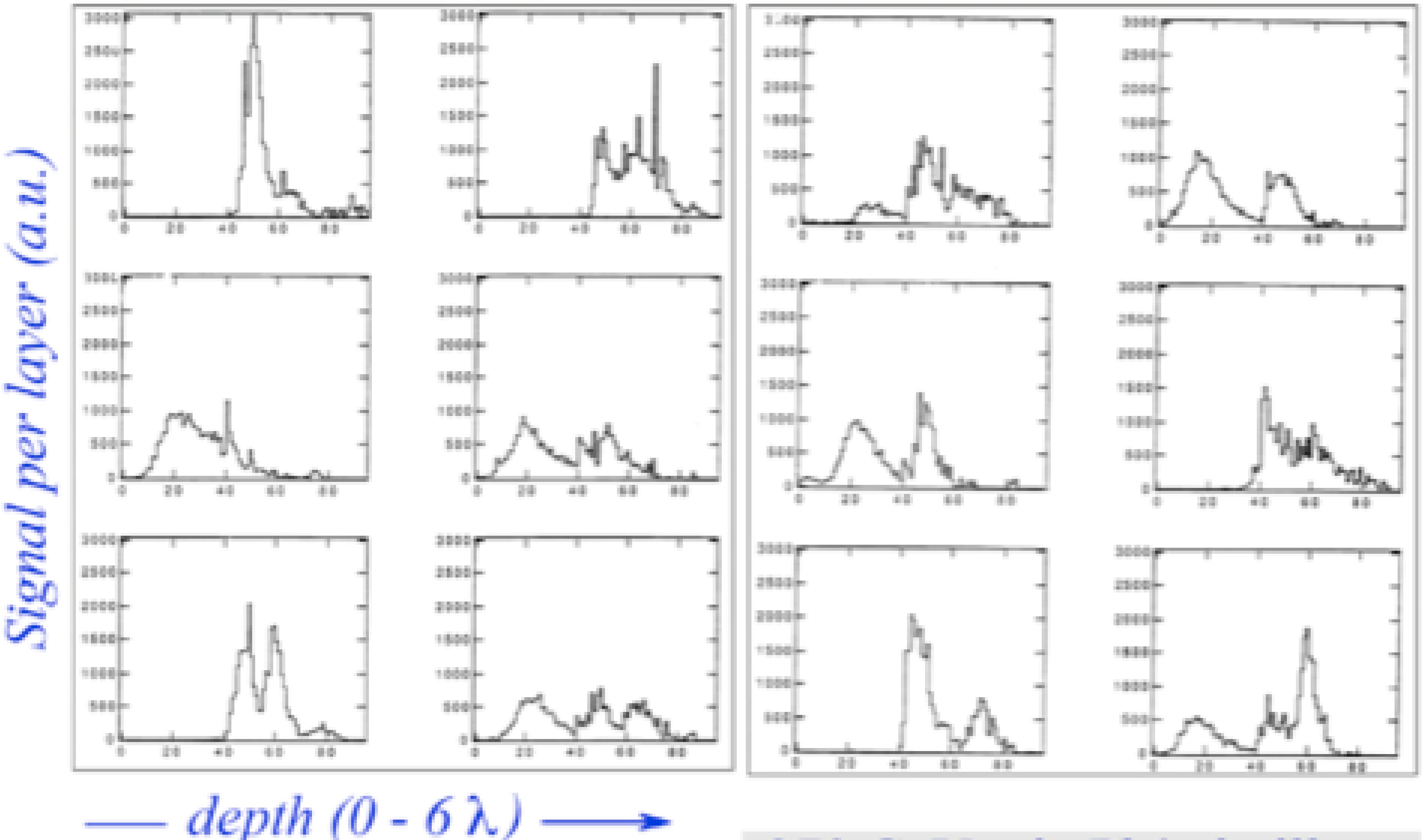
“Hadronic calorimetry: as easy as 1, 2, 3, ... readouts”

John Hauptman, Fermilab, ALCPG, May 10, 2007



270 GeV π in Pb/scintillator
(hanging-file experiment)

Thanks to R. Wigmans for this, and many other plots

Triple-readout optical fiber calorimeter:

"LESSON 6: To improve energy resolution, measure every fluctuation event-by-event"

- Spatial fluctuations are huge, λ_{Int}, with local high density EM deposits.

→ fine spatial sampling with scintillation fibers every 2-3 mm.

- EM fraction fluctuations are huge, 10% - 90%, of total shower energy.

→ measure EM content with Cerenkov fibers, Eth ~ 0.25 MeV, mostly electrons from $\pi^0 \rightarrow \gamma\gamma$

- Binding energy (BE) loss fluctuations from nuclear breakup

→ measure MeV neutron content of showers

Average values for one particle species or another are of no consequence - only fluctuations from the average are important.

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 …"

Thanks to Erik Ramberg for this reference.

Platitudes

All calorimeters to date, whether sampling or continuous, measure energy by summing the physical signal left by charged particles in the calorimeter volume. For electromagnetically interacting particles (EM), only two processes are involved, bremsstrahlung and pair production, multiplying the number of shower particles by two each radiation length. This is very simple. Almost all EM calorimeters work well, even when badly designed.

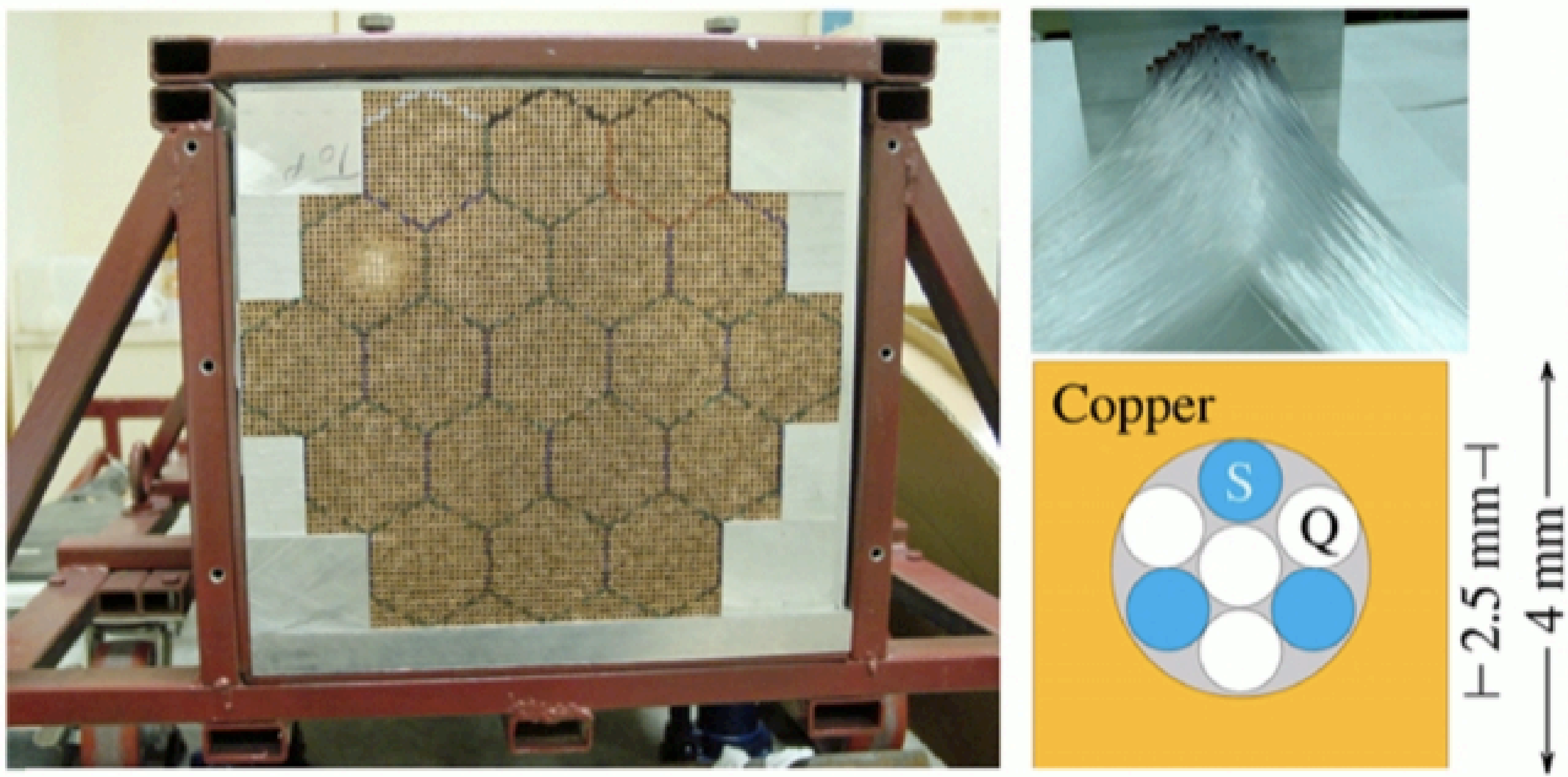
Hadronically interacting particles have many processes available. It suffices to consider two: charged and neutral pion production and decay, and nuclear break-up. The (large) fluctuations in these processes limit the energy resolution of calorimeters. Even well-designed and well-intentioned hadronic calorimeters turn out to be disappointments.

At the outset, I urge anyone thinking about building a calorimeter to read Richard Wigmans papers, talks [Snowmass (2005), SLAC (2005), Fermilab (HSS06)], and even his very good book [Oxford Press].

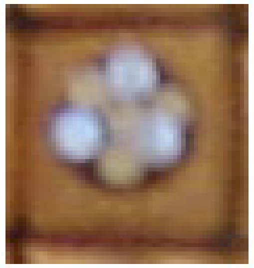
DREAM: Dual REAdout Module

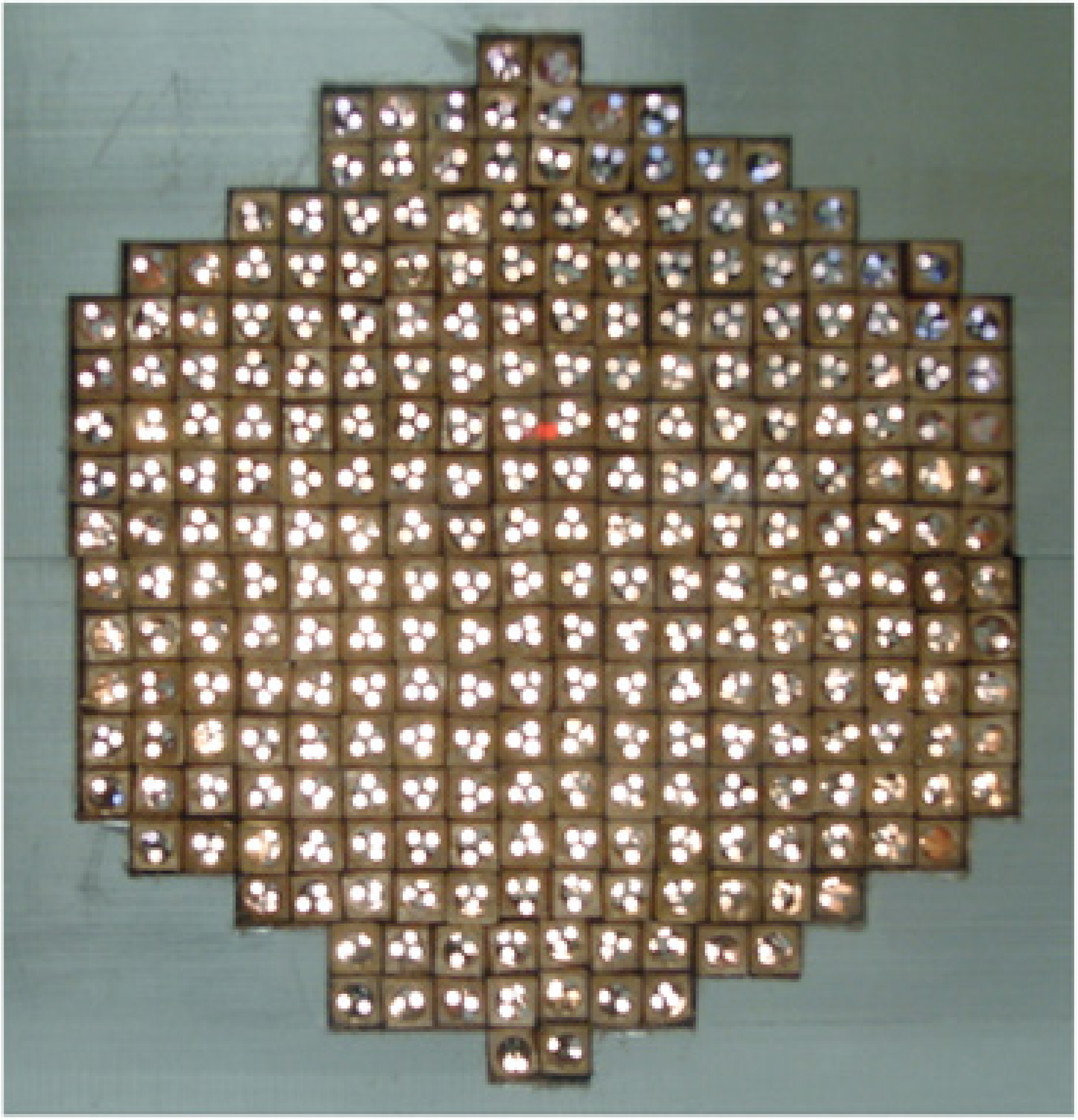
Fill the absorber with two kinds optical fibers, Cerenkov (clear) and scintillating fibers. Both “calorimeters” see the same particles. Generated lights in each fiber are exactly separated.

DREAM: Structure

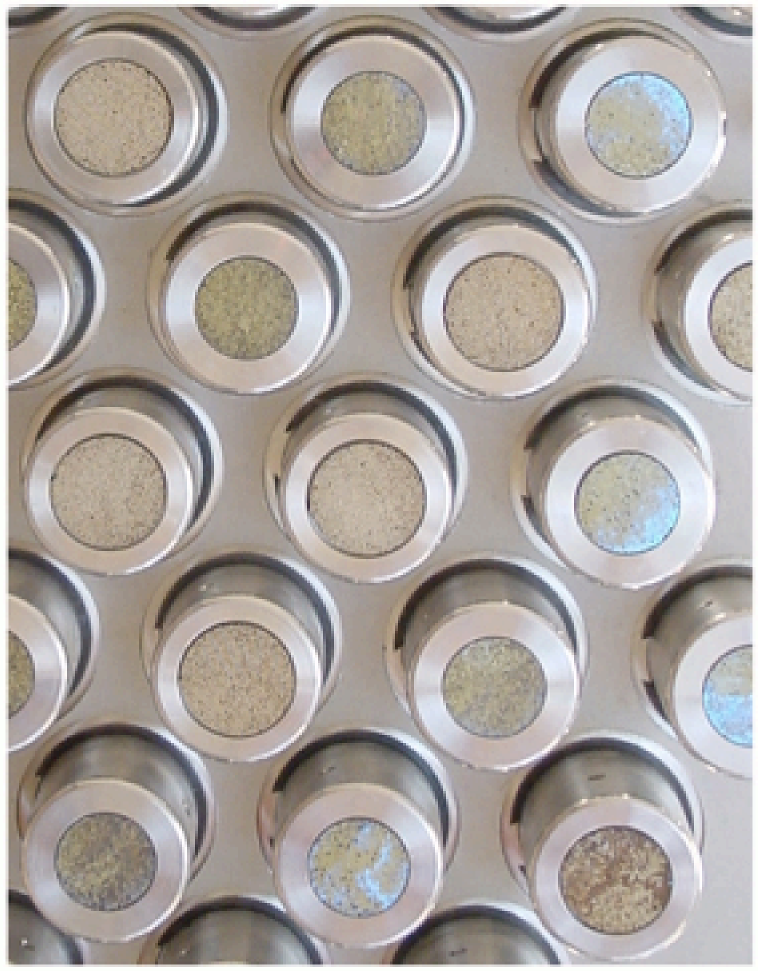


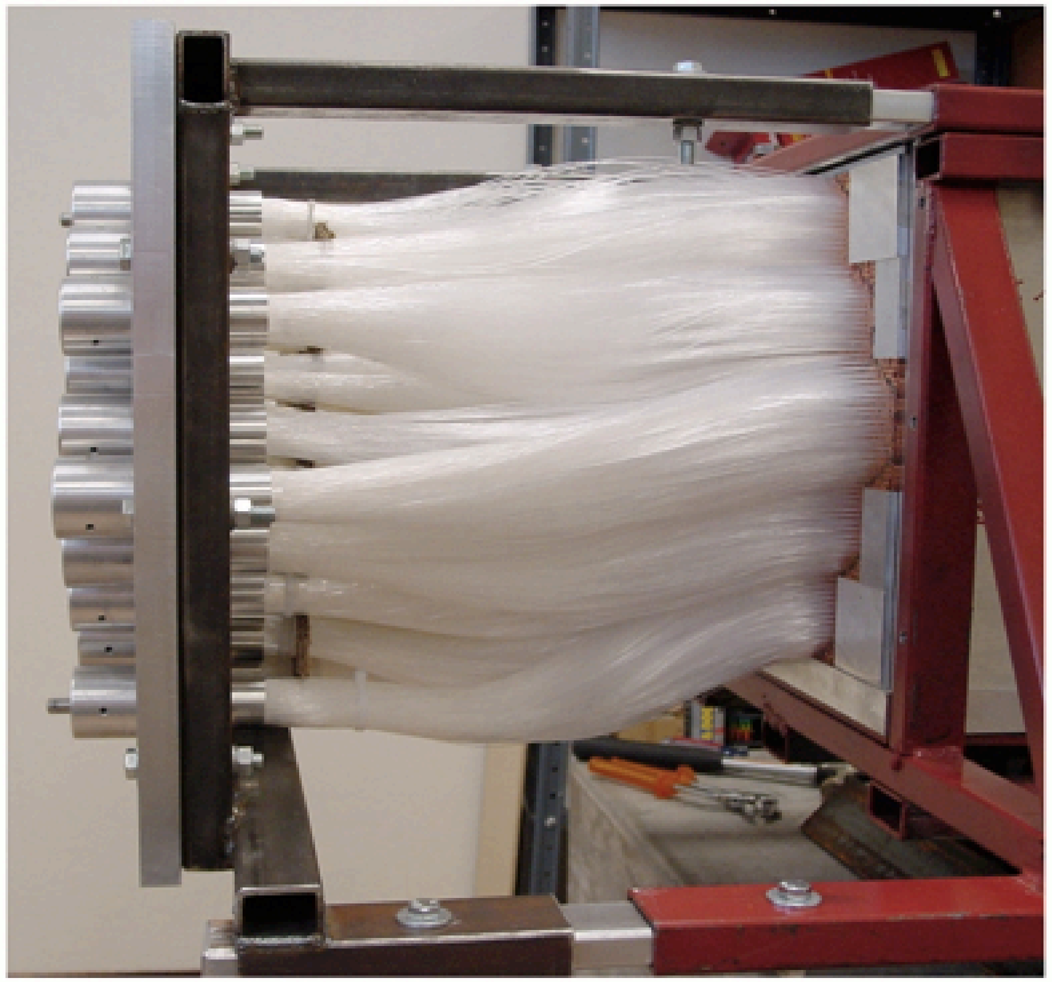
- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 $\lambda_{\rm int}$)
  - Effective radius 16.2 cm (0.81 $\lambda_{\rm int}$, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

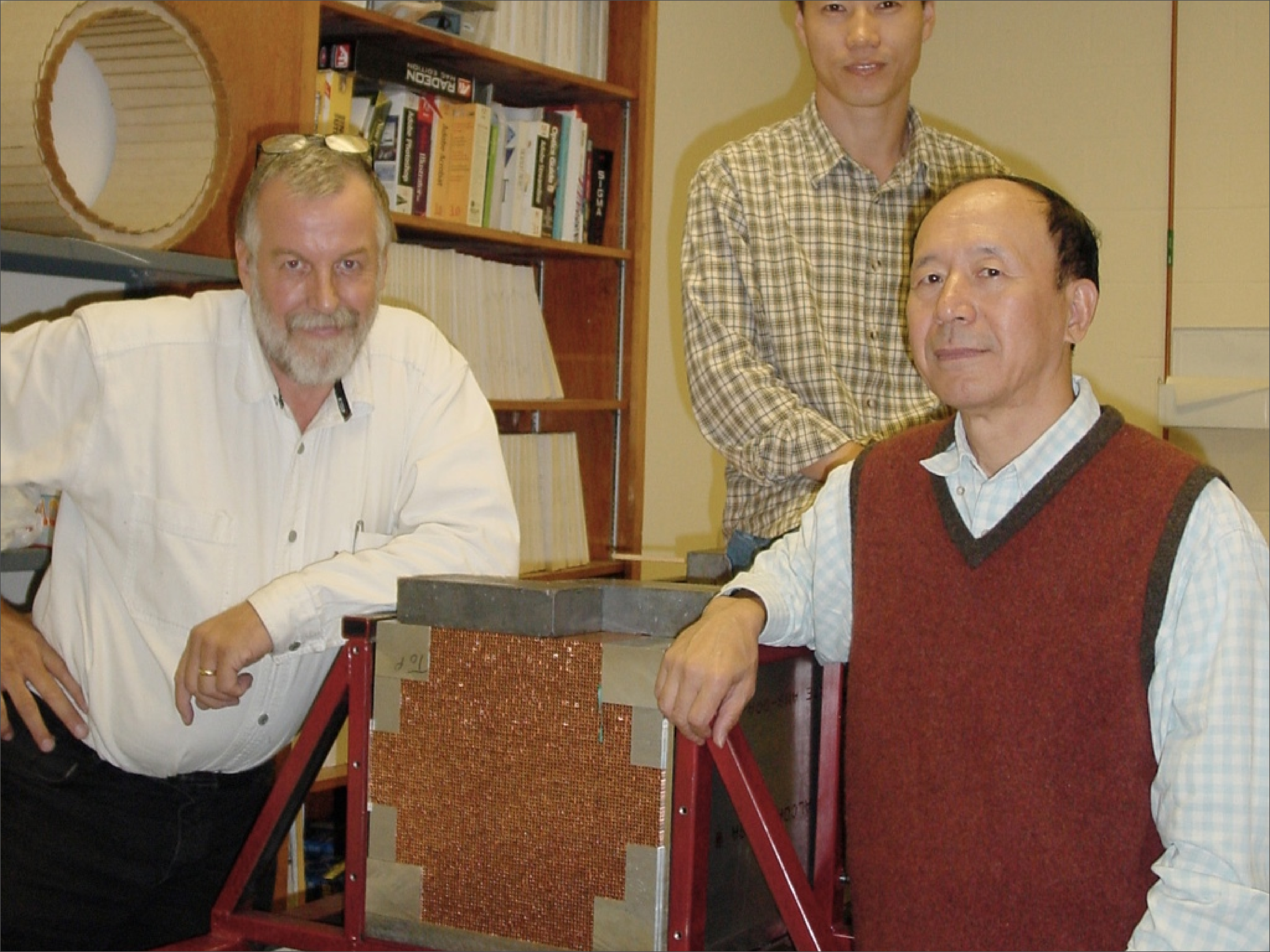


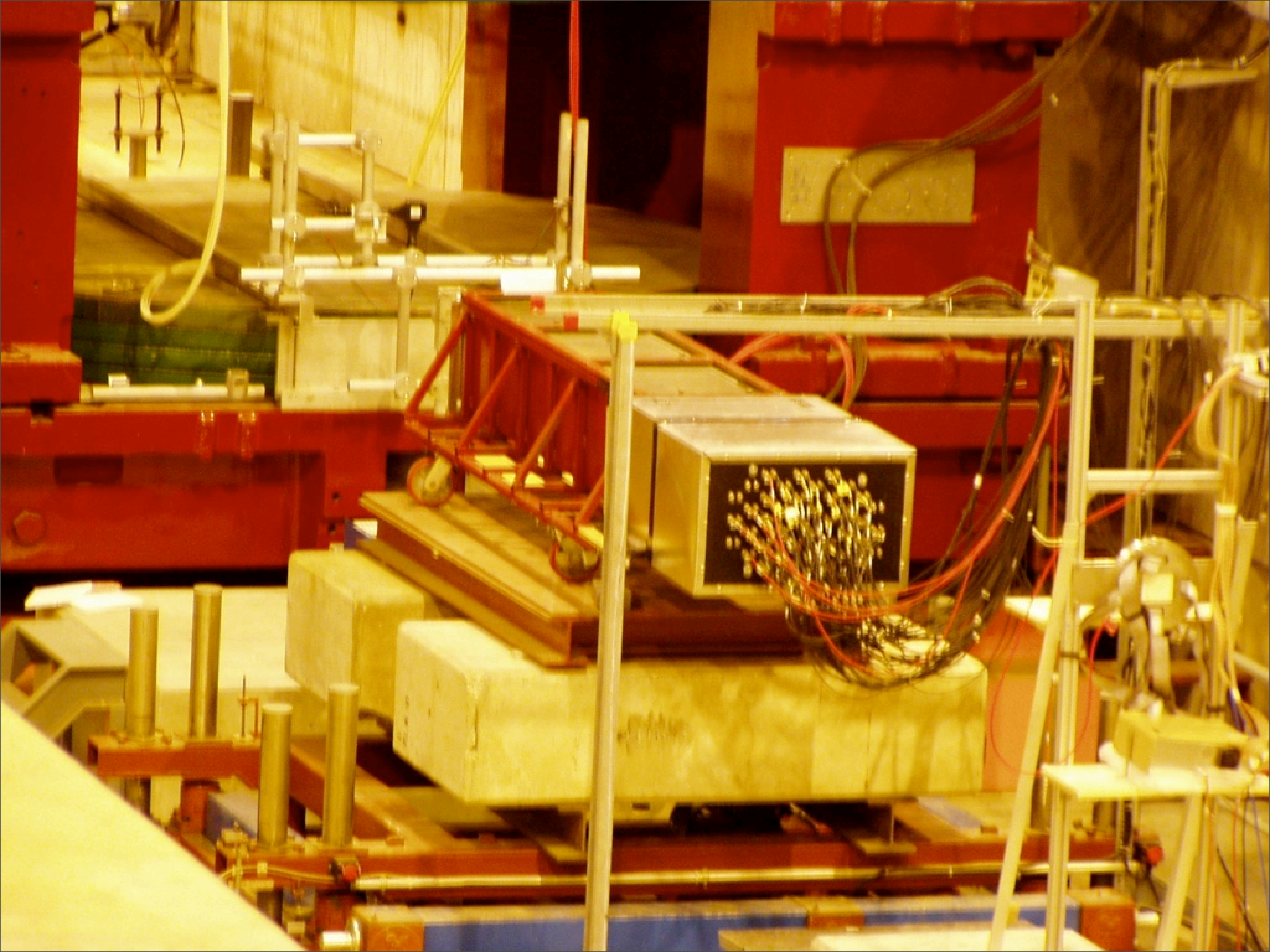


DREAM readout





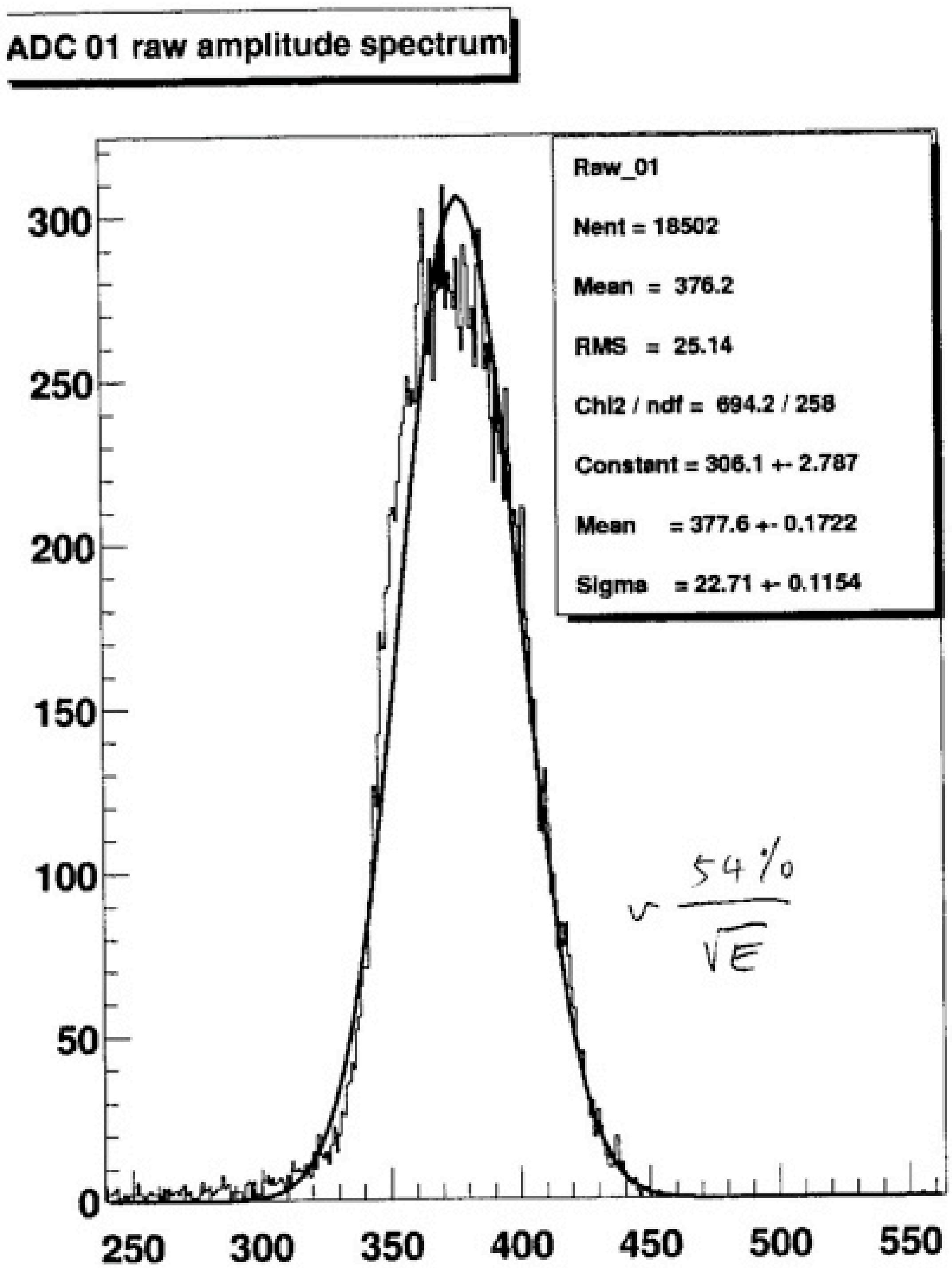

RADEON
SIGMA

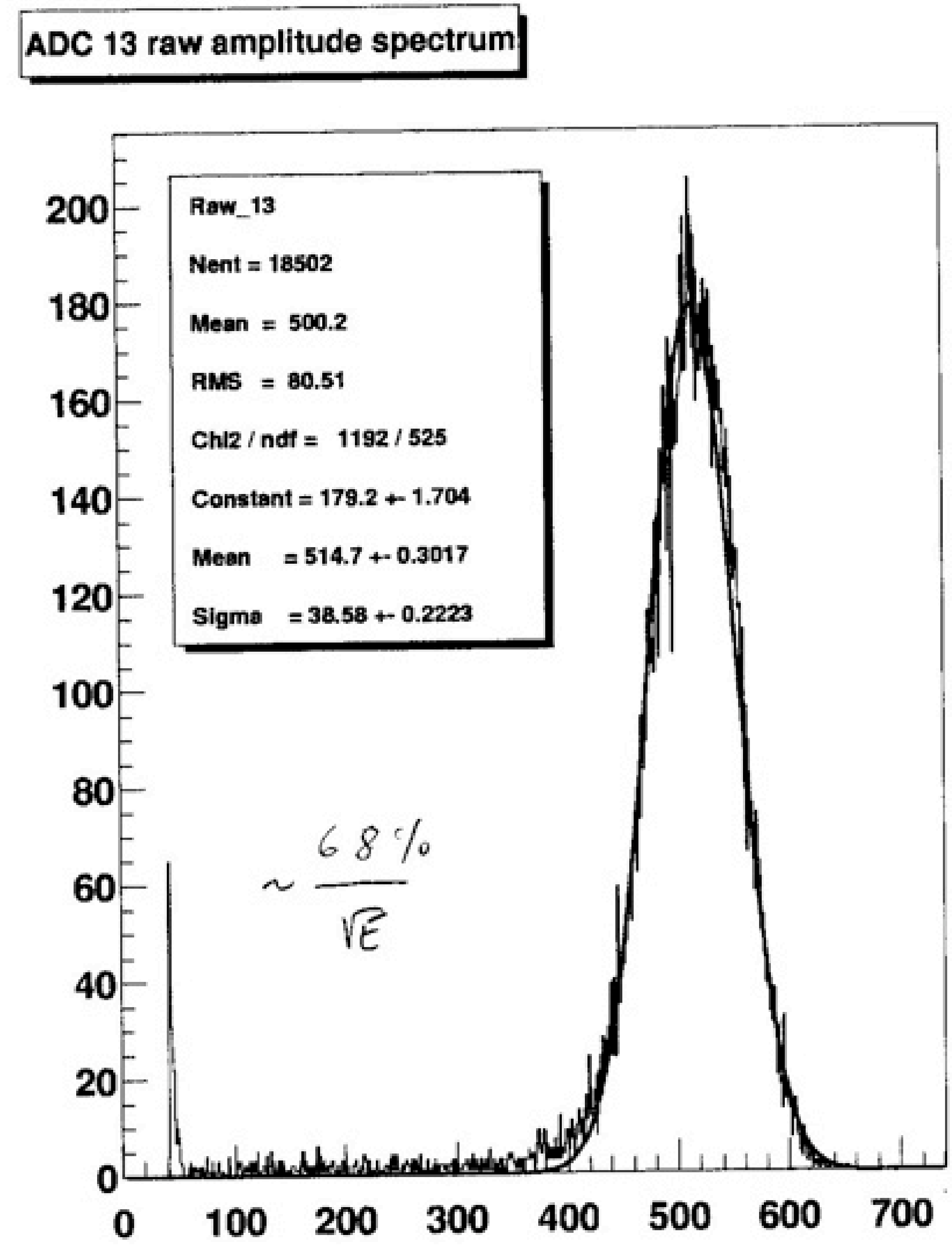



110 CERN SL 19-06-03 22:14:32
SPS-Protons updated: 19-06-03 22:10:17
CYCLE Type 950: 400 Gev/c SCTS:
Flat top: 4800 ms length:
RATE*E11: MTG Cycle:
269 CPS RAMP 207.5
SSE
to beam dump:
Targ p/pE11 Mul %Sym Expmt Singles Spill
T1 22.6 13 a 86 Alice 0.0E+00
LHCb
T2 36.5 1 a 90 CMS 0.0E+00
DREAM 4.5E+01
T4 8 a 91 NA48
T6 9 a 88 NA58
T10 NA48
Comments 19-06-03 22:15h :
North to repair a
intervention will
about 1 hour.
be off during the intervention
EA:Phone : 77500 + Natel 160137

FIRST SHOT!

SCINTILLATOR   80 GeV e⁻ (?)   QUARTZ

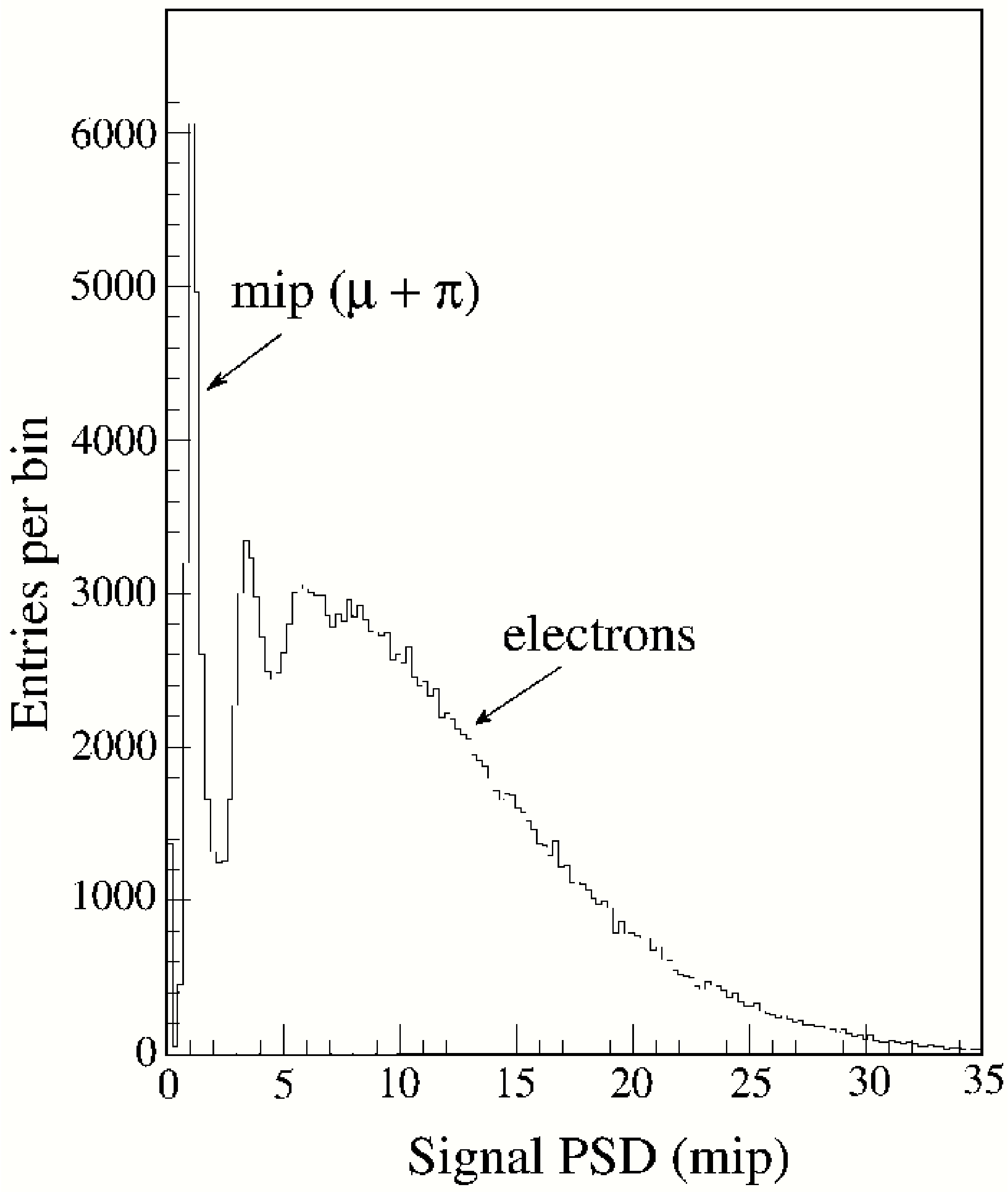




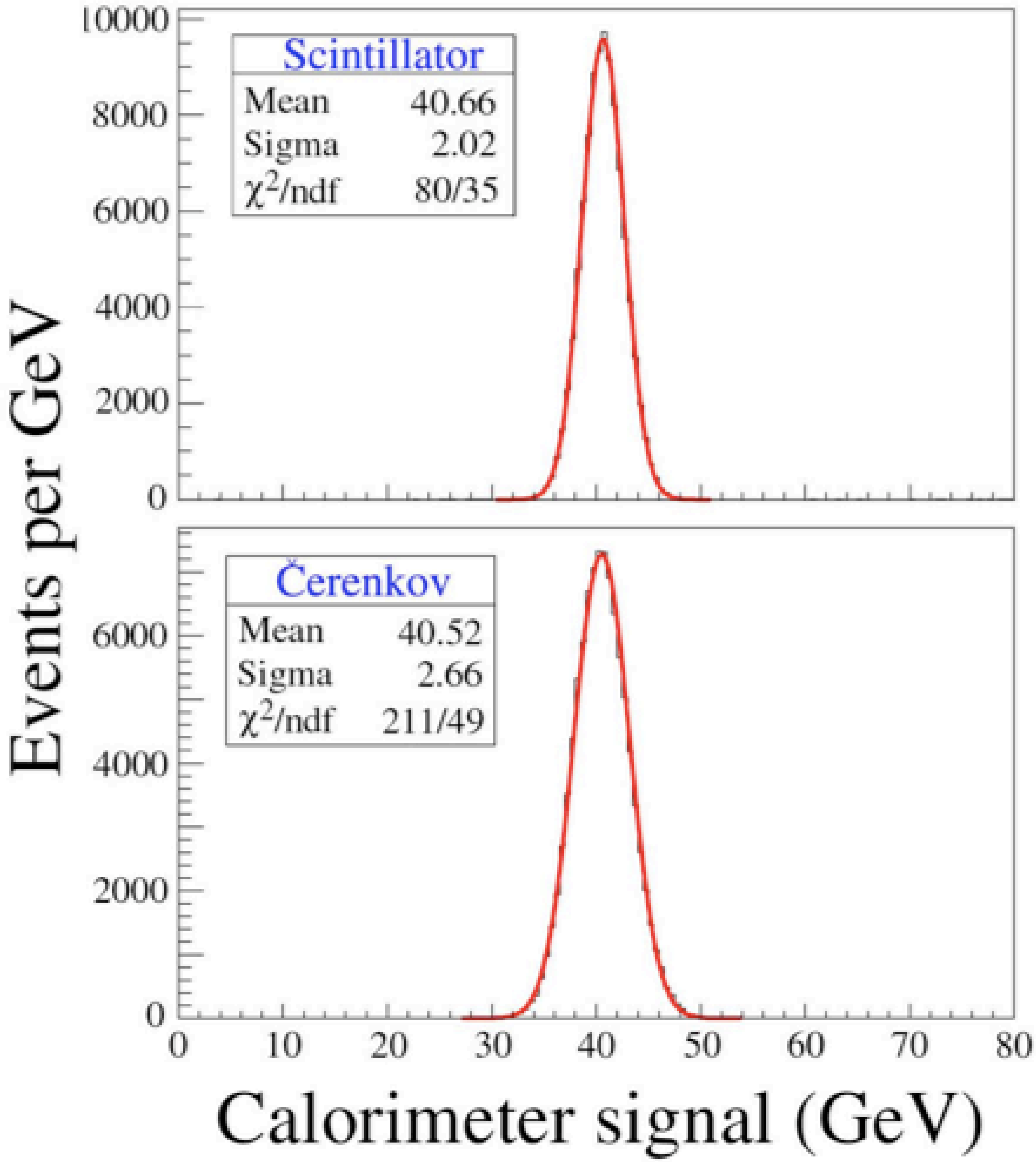
Simple, robust, Korean housewives, "inert", stable, you can even drop it.

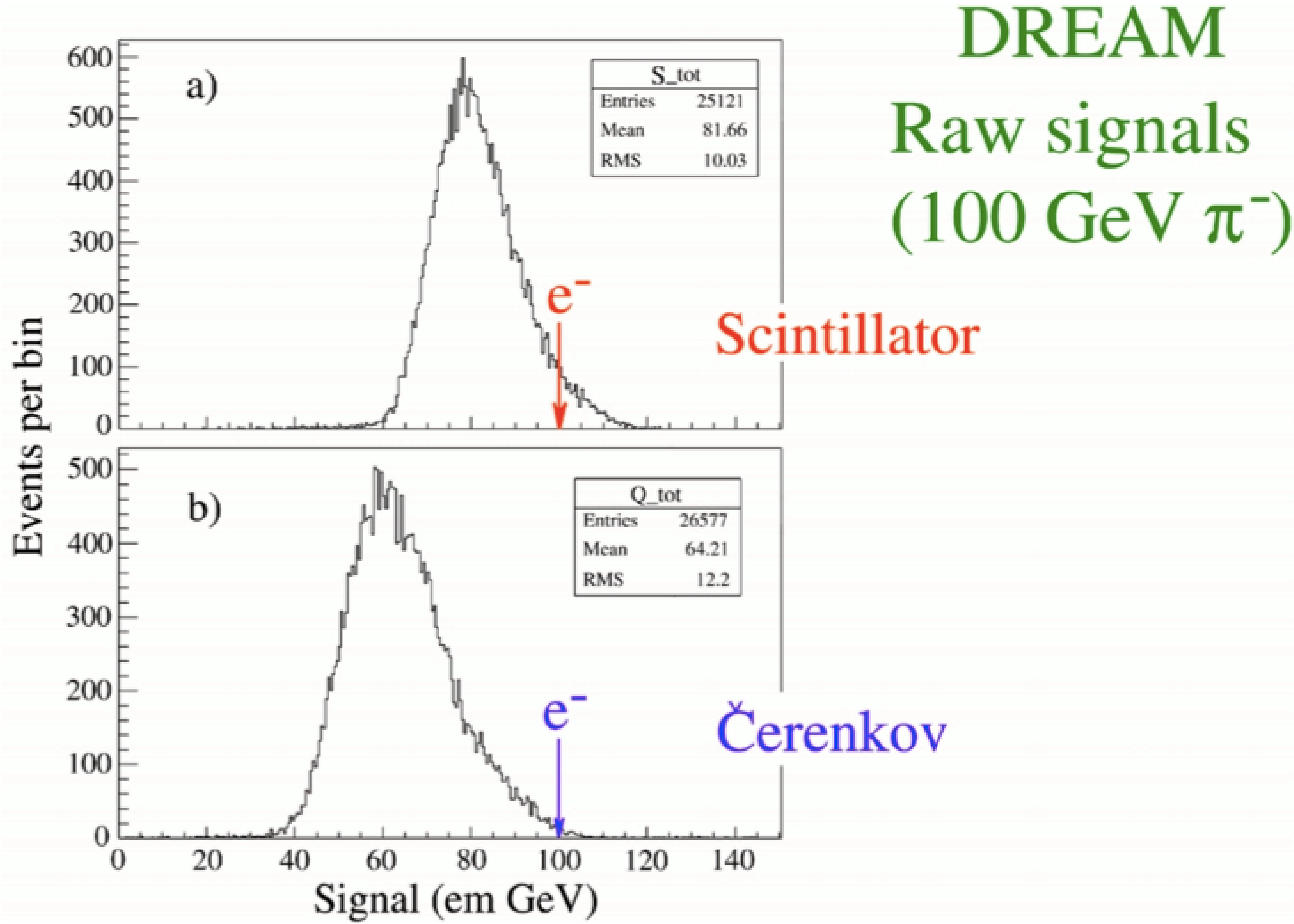
H4 beam

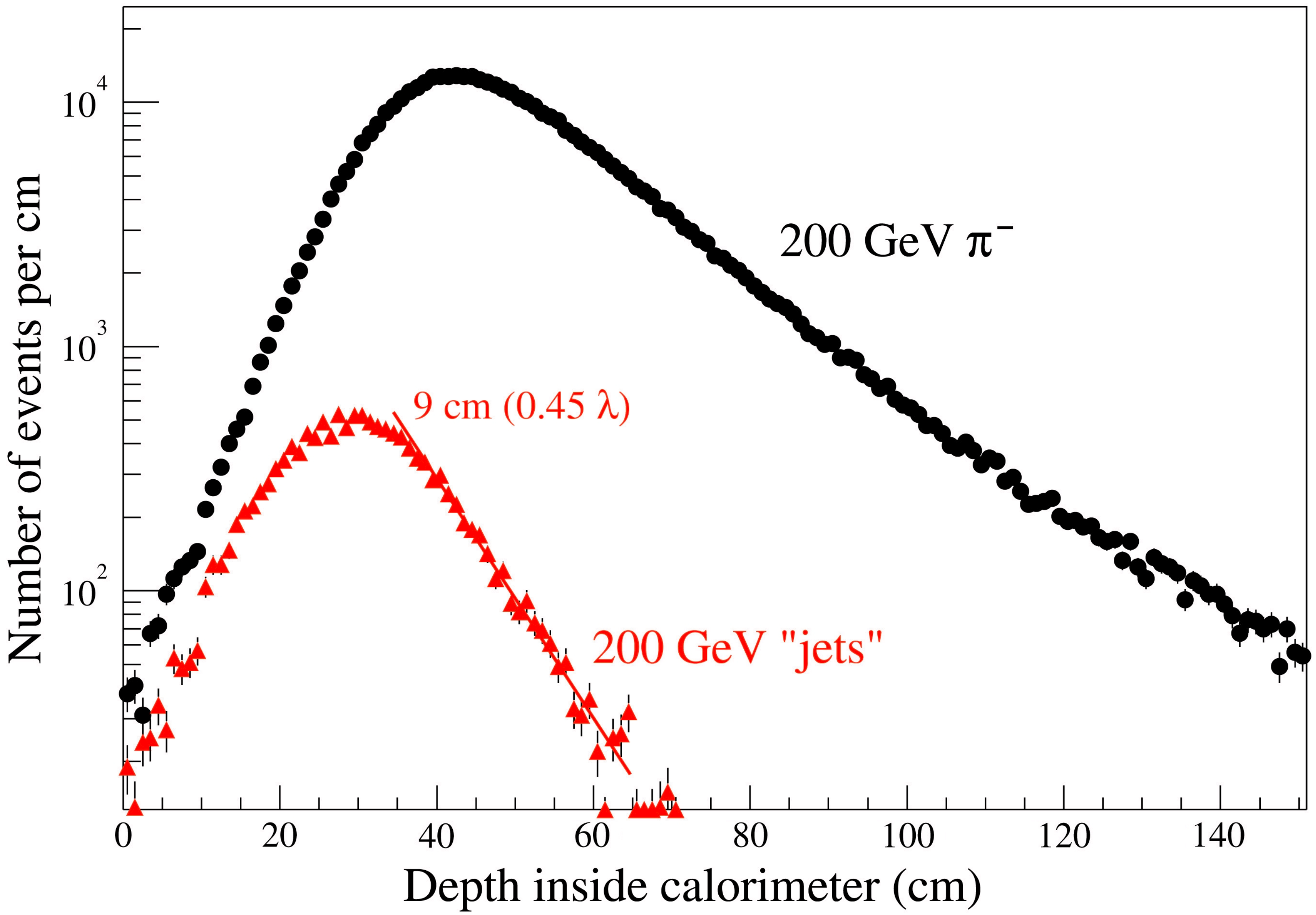
- TC: Trigger Counters
- HOD: fiber xy hodoscope
- PSD: pre-shower detector, 5mm Pb + scintillator
- ITC: Interaction Trigger Counter, 10cm lucite + scintillator
- MU: Muon tagger, scintillator



Calibration with 40 GeV electrons (tilt 2^o)




DREAM
Raw signals
(100 GeV π⁻)
a)
S_tot
Entries 25121
Mean 81.66
RMS 10.03
e⁻
Scintillator
b)
Q_tot
Entries 26577
Mean 64.21
RMS 12.2
e⁻
Čerenkov
Events per bin
Signal (em GeV)
0
20
40
60
80
100
120
140
100
200
300
400
500
600



5.0 Int. Len. 7.5 Int. Len.

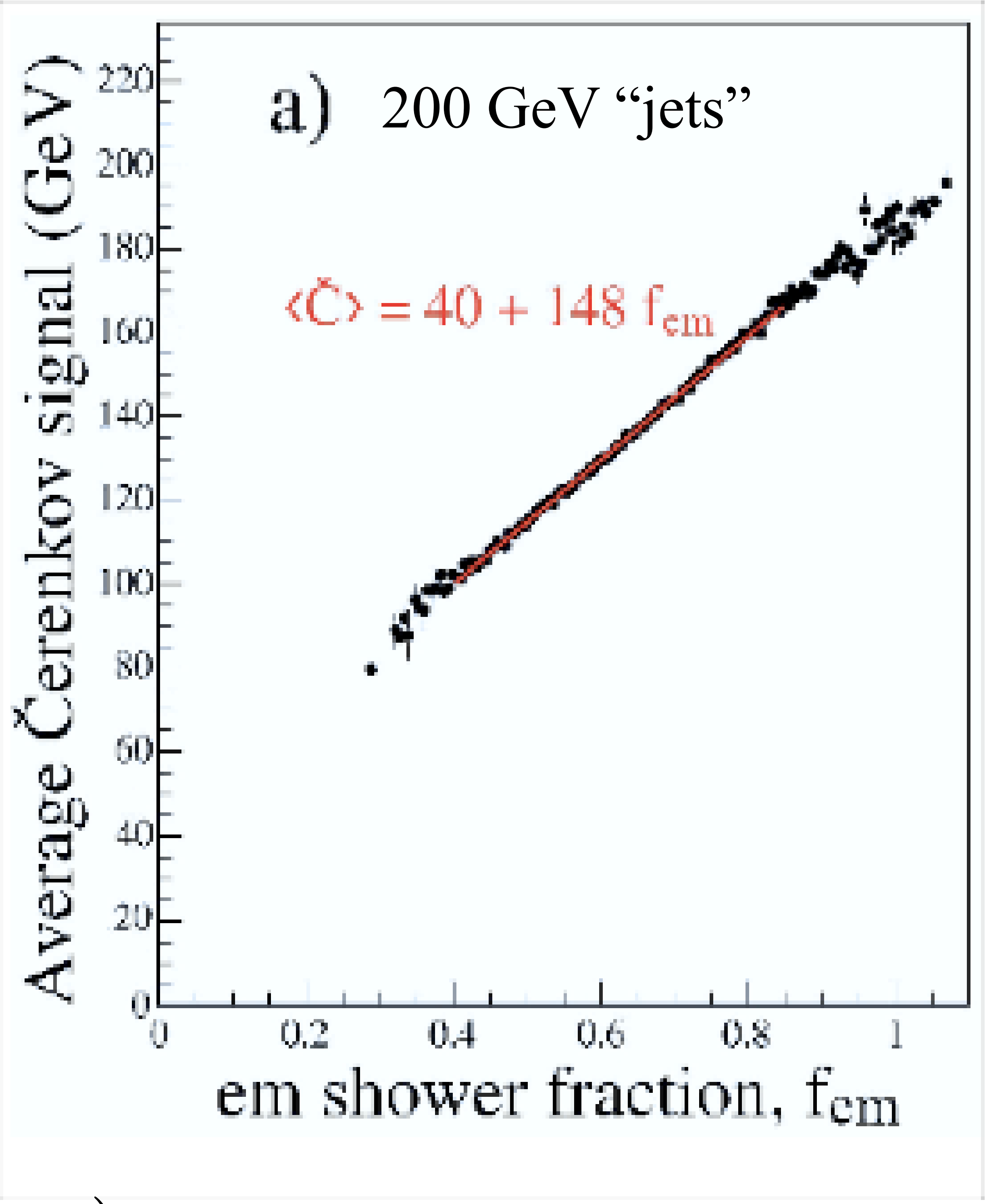
EM fraction in hadronic showers ...

... nicely and linearly correlated with the Cerenkov signal. The simplest possible description of the calorimeter "response" to hadronic energy, E, is ...

$$(e/h)_C = \eta_C \approx 5$$
$$(e/h)_S = \eta_S \approx 1.4$$

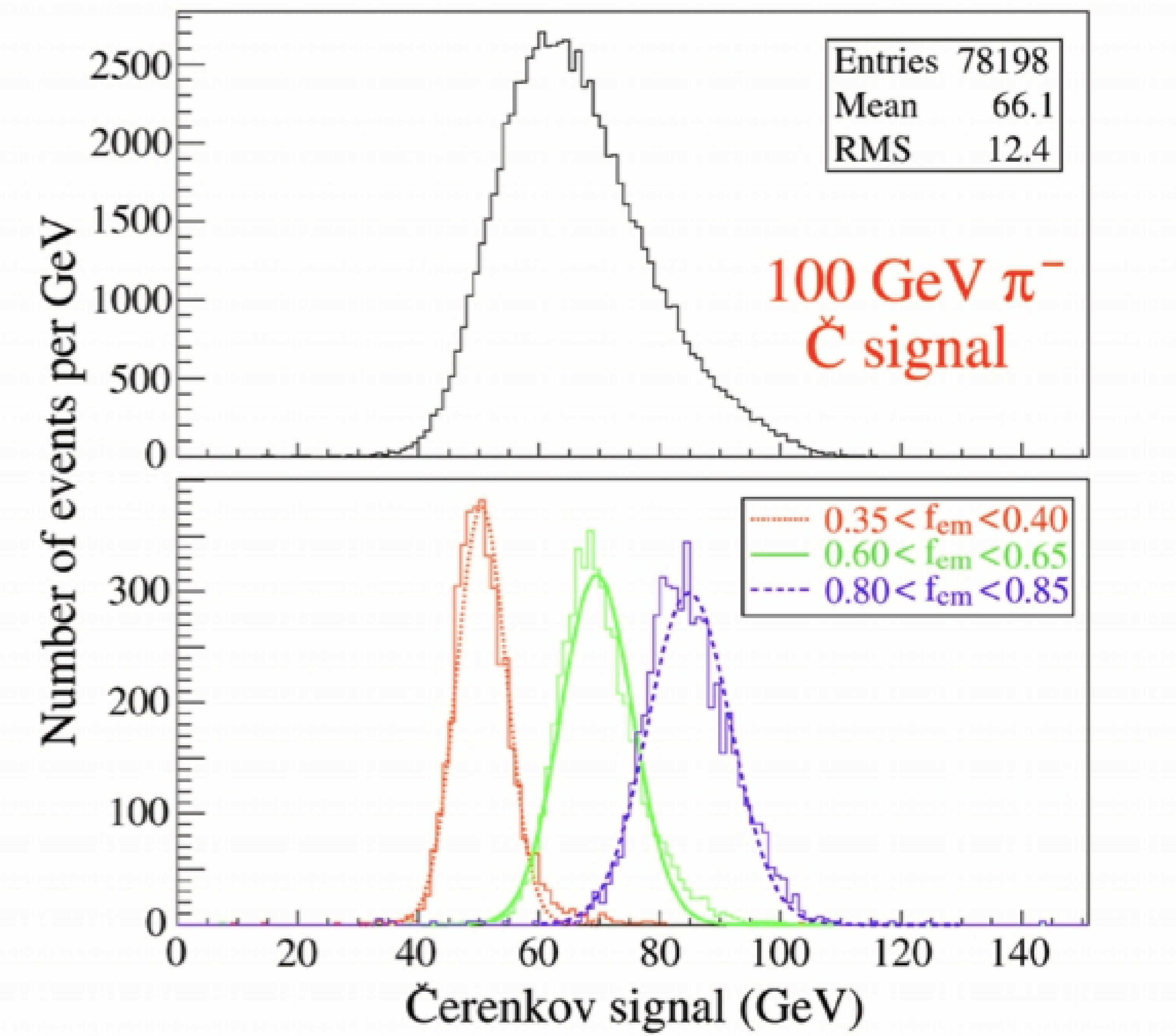
$$C = [f_{em} + (1 - f_{em})/\eta_C]E$$
$$S = [f_{em} + (1 - f_{em})/\eta_S]E$$

$$\rightarrow C/E = 1/\eta_C + f_{em}(1 - 1/\eta_C)$$



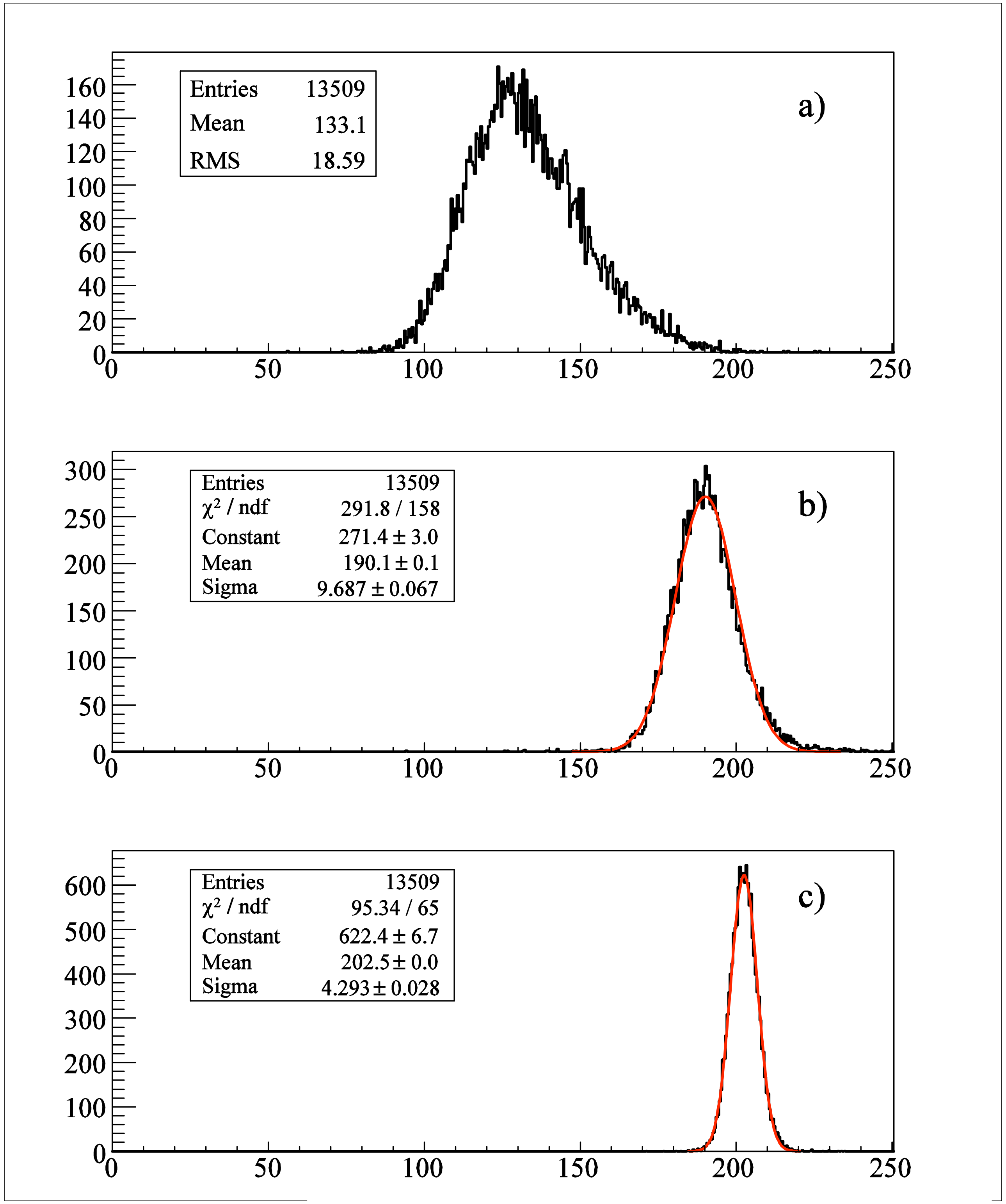
Data NIM A537 (2005) 537.

DREAM: Effect of event selection based on f_{em}



“Everything in calorimetry is obvious once you understand it.” - R. Wigmans

DREAM data 200 GeV π^-: Energy response



Scintillating fibers

Scint + Cerenkov

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

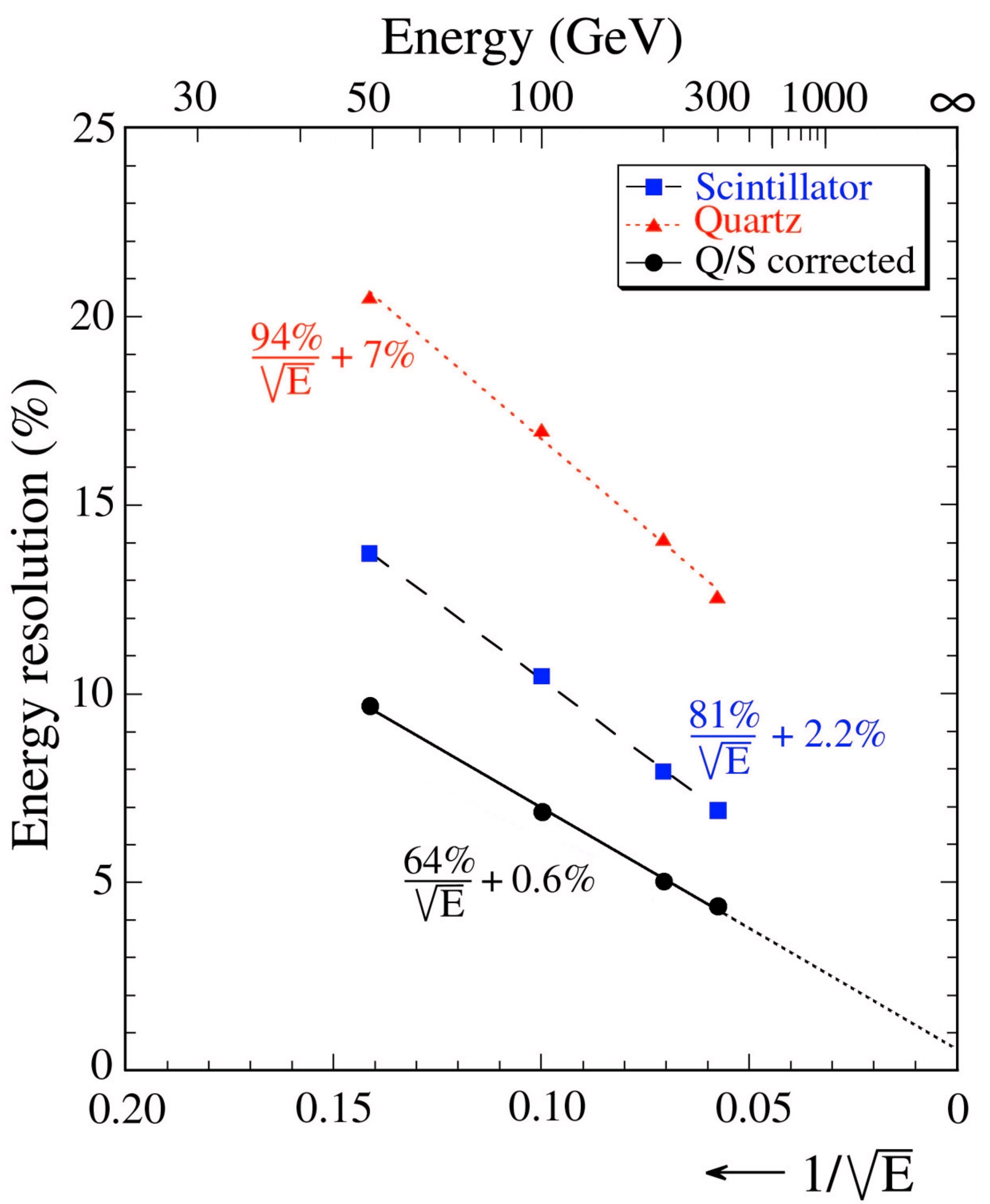
(4% leakage fluctuations)

Scint + Cerenkov

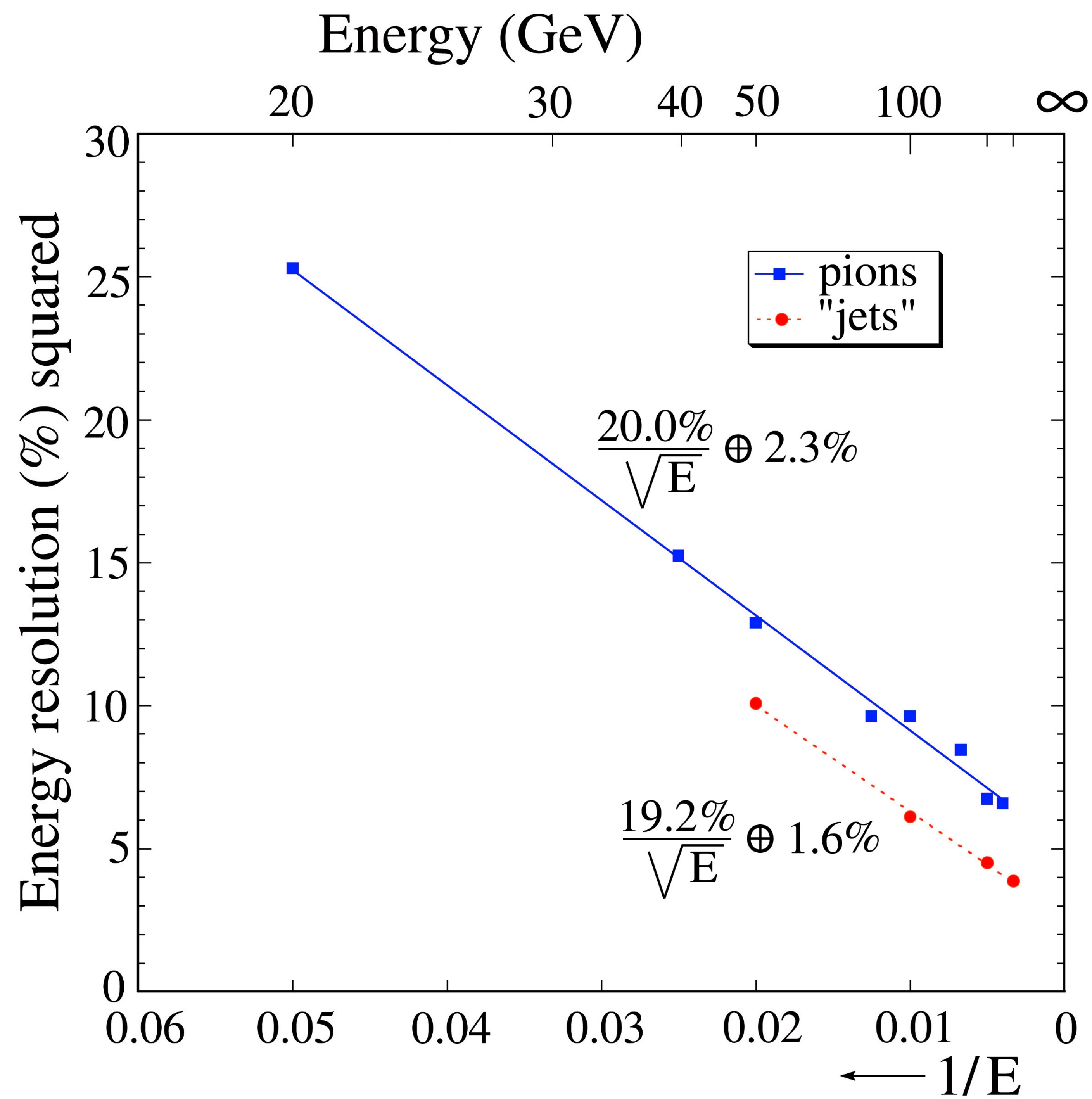
$f_{EM} \propto (C/E_{beam} - 1/\eta_C)$

(suppresses leakage)

Data NIM A537 (2005) 537.



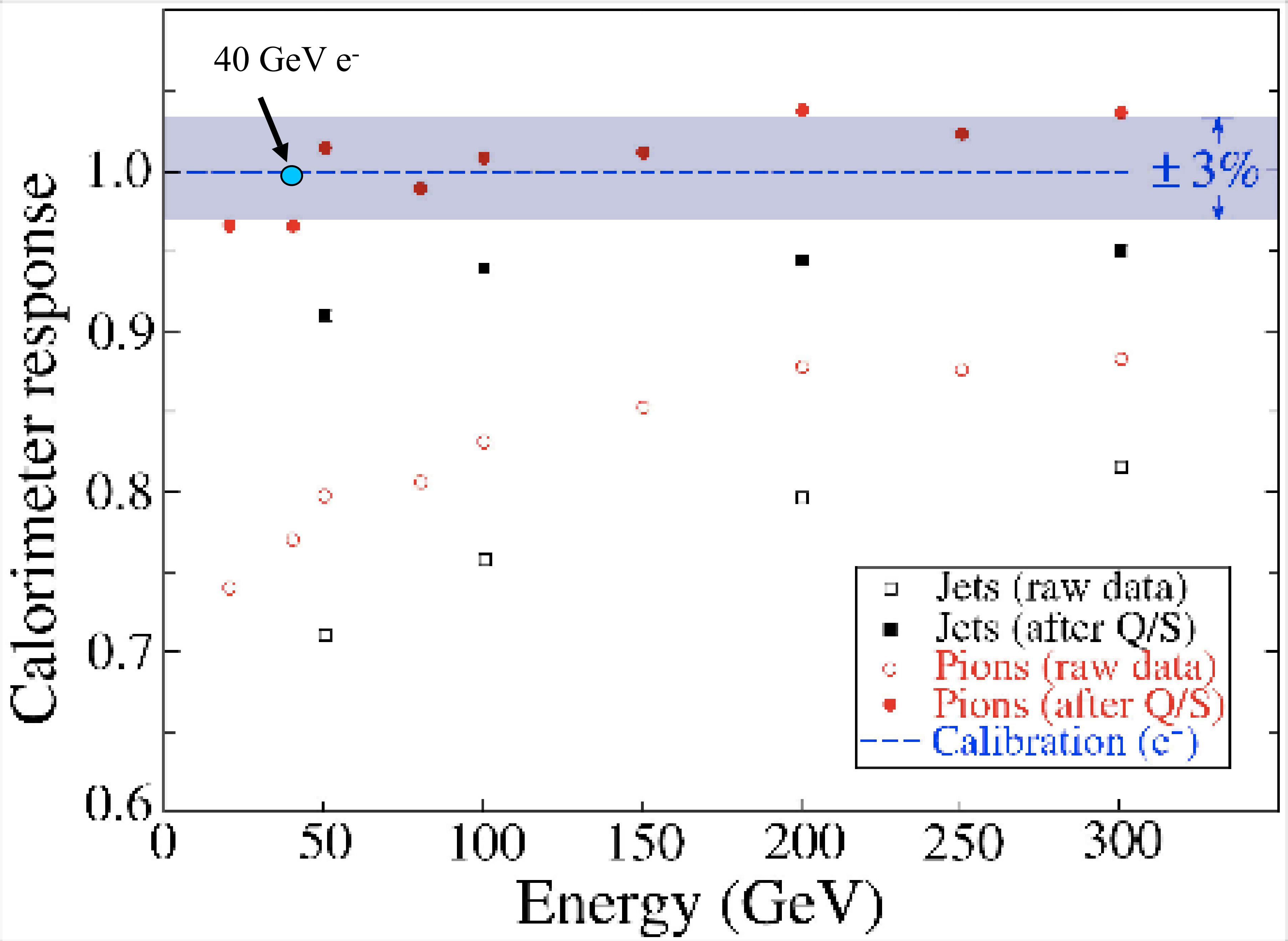
Energy (GeV)
30
50
100
300
1000
∞
Energy resolution (%)
Scintillator
Quartz
Q/S corrected
94%/√E + 7%
81%/√E + 2.2%
64%/√E + 0.6%
0.20
0.15
0.10
0.05
0
← 1/√E

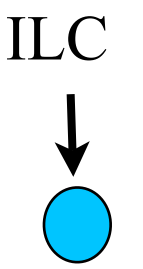


Energy (GeV)
20
30
40
50
100
∞
Energy resolution (%) squared
pions
"jets"
20.0%/√E ⊕ 2.3%
19.2%/√E ⊕ 1.6%
0.06
0.05
0.04
0.03
0.02
0.01
0
← 1/E

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.



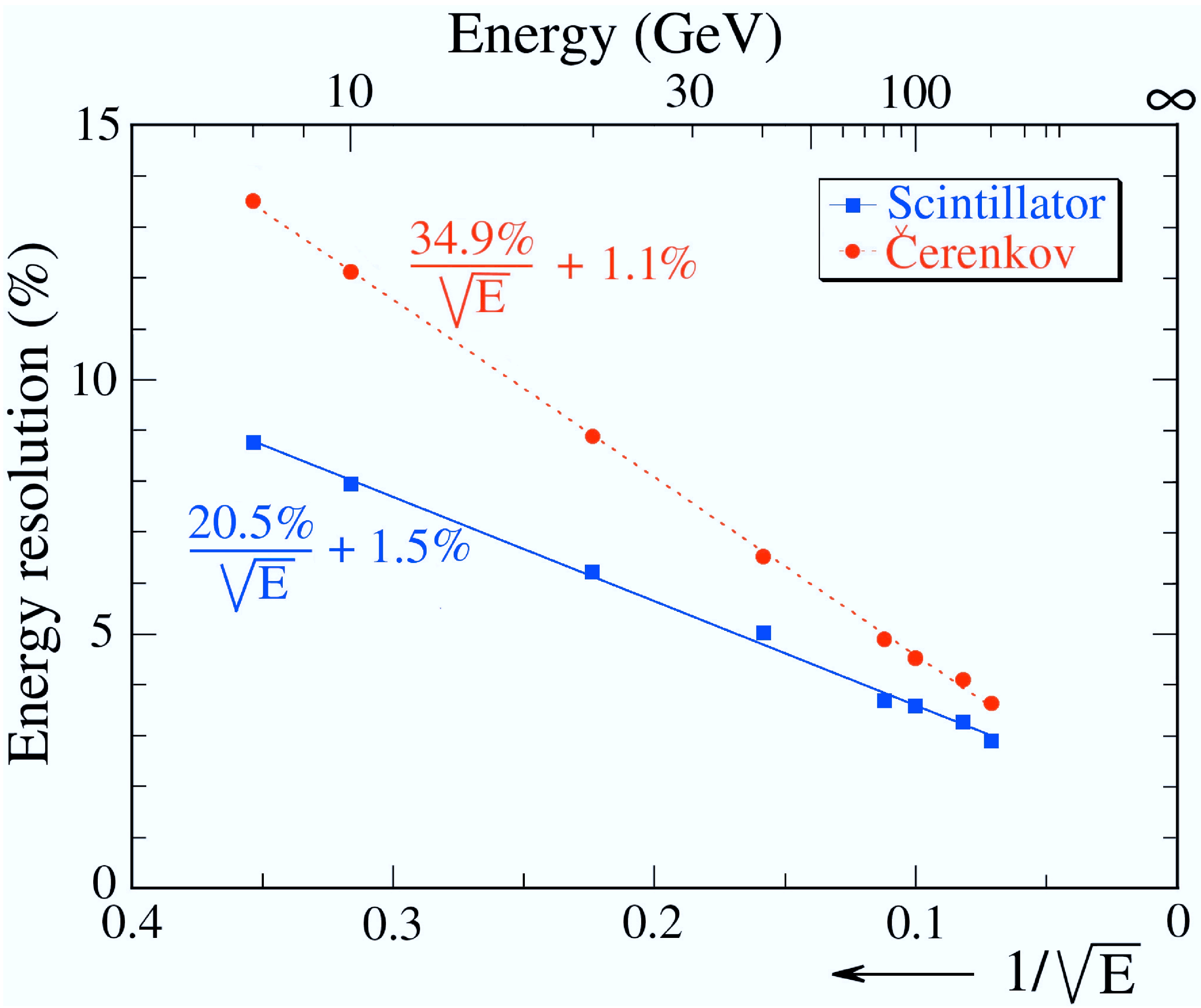


Hadronic linearity may be the most important achievement of dual-readout calorimetry.

ILC

Data NIM A537 (2005) 537.

DREAM was a proof-of-principle module, never intended to be the "best" at anything; for example, EM resolution.



- Electron energy resolution independently in Cerenkov and Scintillator fibers:
- Cerenkov limited by photoelectron statistics: ~8pe/GeV gives resolution of 35%/√E
- Limits EM fraction resolution
- Limits hadronic resolution

$$C/S = \frac{f_{em} + (1 - f_{em})/\eta_C}{f_{em} + (1 - f_{em})/\eta_S}$$

Here is all that we know and think we understand about the stochastic and the constant terms in the energy resolution of the DREAM dual readout calorimeter, including guesses about its extensions to triple readout. These are all derived from the beam test data of the DREAM module and described in the DREAM papers (1-3). We write the overall resolution as $\sigma_E/E = a/\sqrt{E} \oplus b$.

Calorimeter	a(%)	b(%)
Sampling Čerenkov fibers only	94	7
Sampling Scintillation fibers only	81	2.2
"Q/S" method: use only Čerenkov and Scintillation	64	0.6
↓ Subtract out leakage fluctuations (4%)		
↓ Subtract out Čerenkov *pe* fluctuations ($35\%/\sqrt{E}$)		
FLUKA simulations (all energy)	30-34	–
↑ Add in "jet reco" fluctuations (2-3% ?)		
↑ Add in E_{shower} fluctuations ($30\%/\sqrt{E}$?)		
$f_{EM} \sim$ (C/Ebeam - $1/\eta_C$)	19.2	1.6
Ultimate hadronic energy resolution; based on a first principles calculation in *Calorimetry*, R. Wigmans	14.5	-

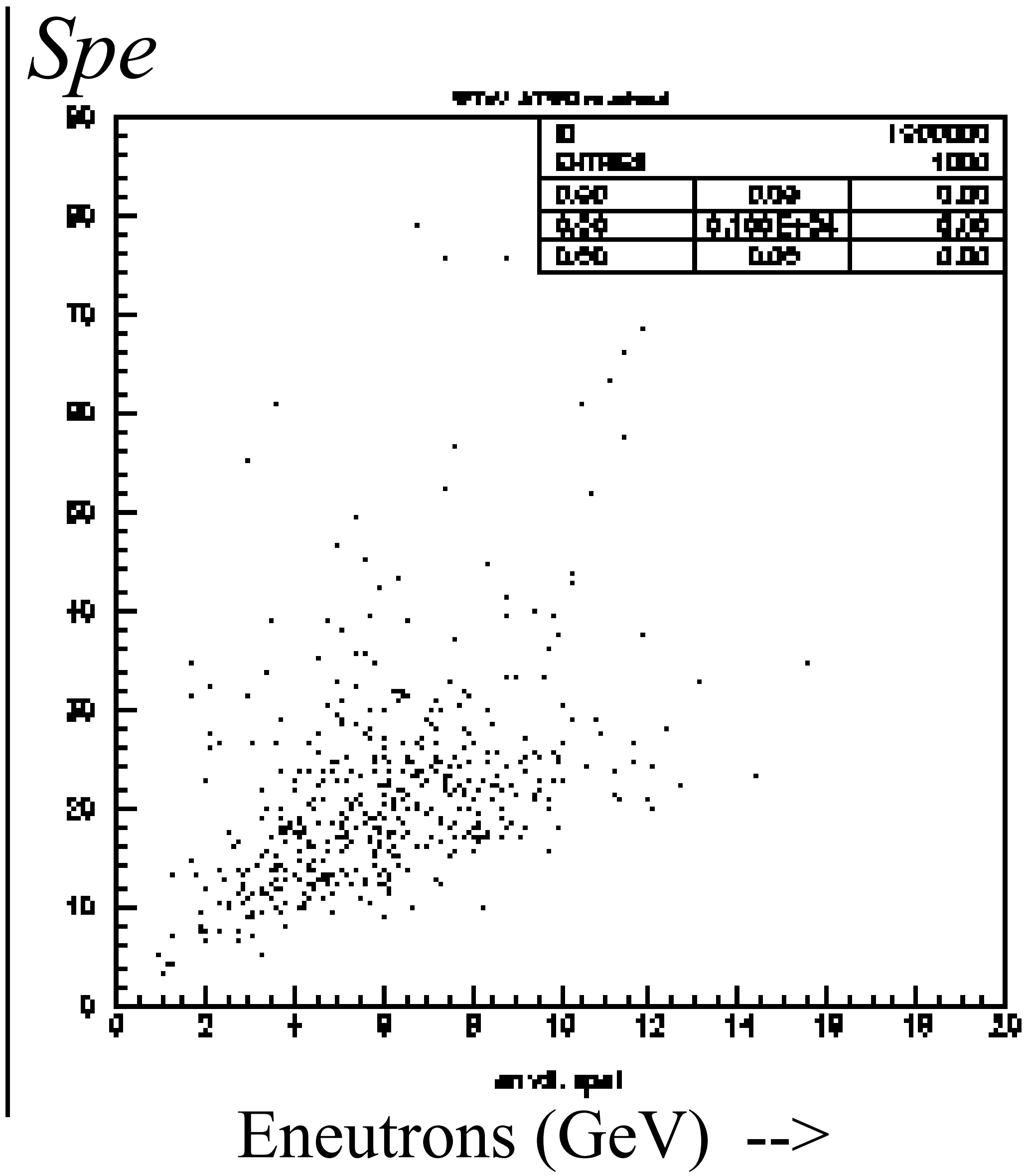
Number 3. Binding energy (BE) loss fluctuations.

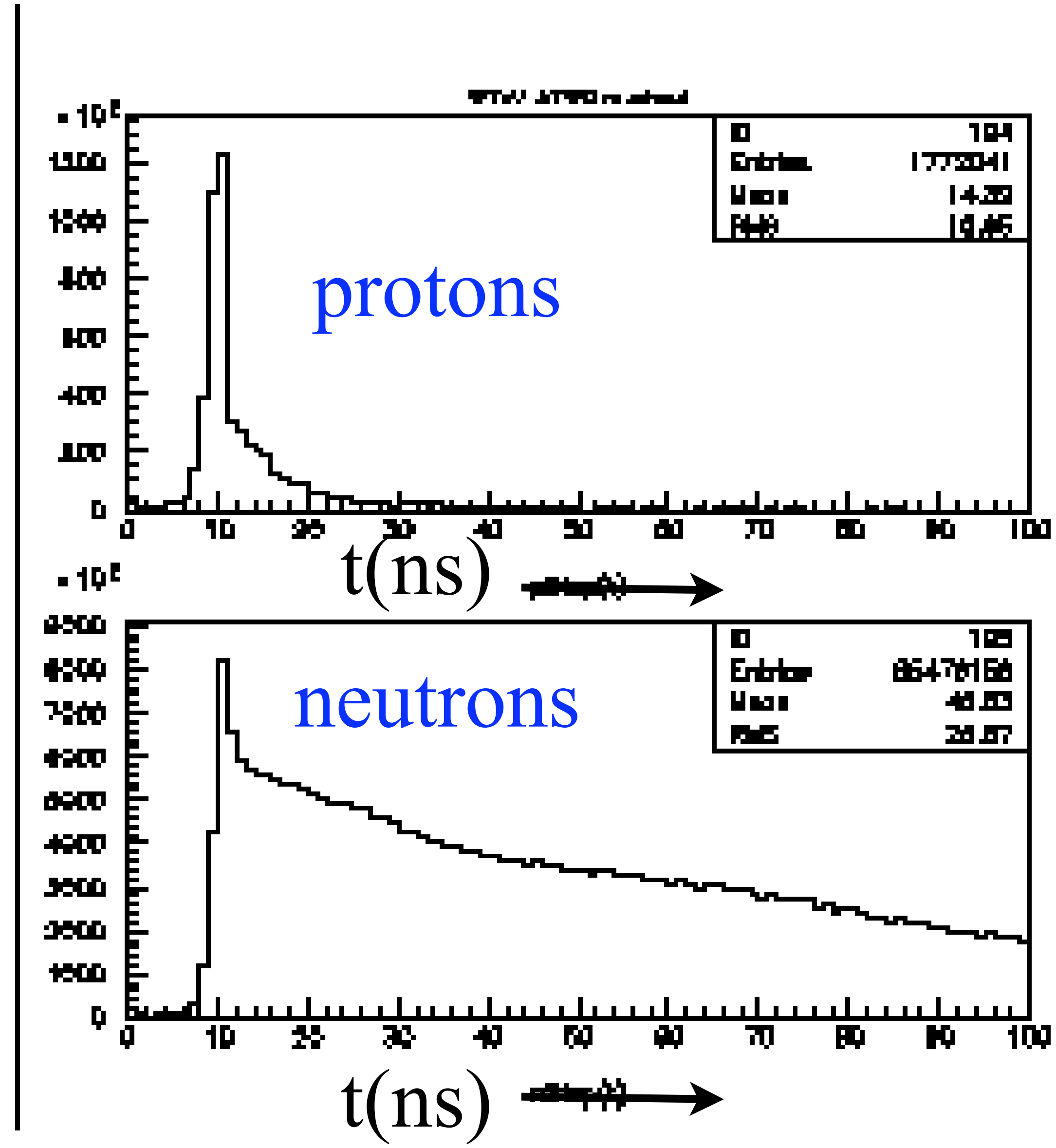
The mean energy lost is about 20% of the hadronic energy in a shower, and is proportional to the number of energetic hadrons in the shower. Fluctuations about this mean degrade the energy resolution. This binding energy is correlated with the evaporation neutrons (~20 neutrons per GeV of shower energy) that are liberated in nuclear break-up.

Strategy:

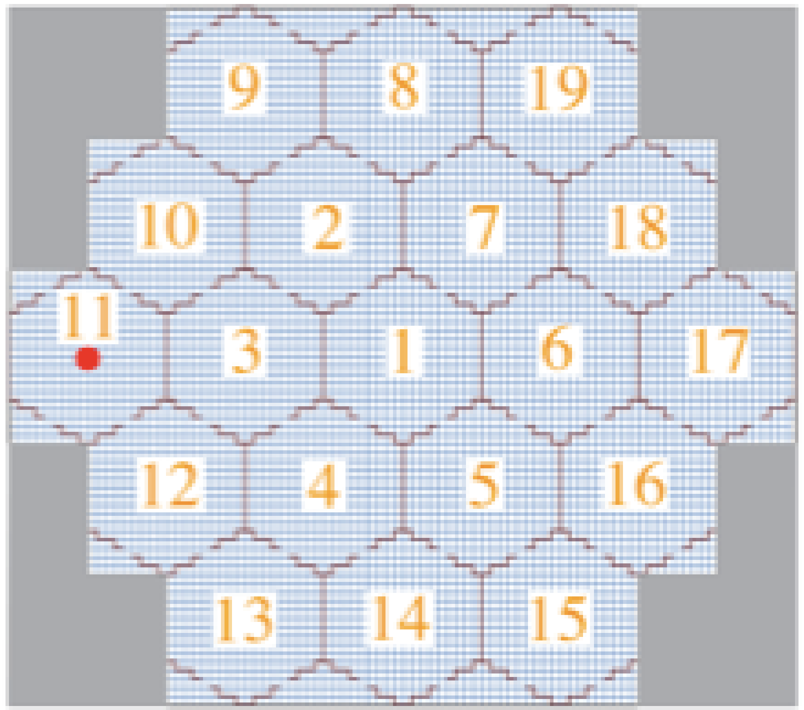
1. Calculate (see next page, also Brau and Gabriel for Uranium)
2. Measure neutrons in DREAM module (done, more to come)
3. Think (pp. 256-265 of Wigmans book)
4. Choose scintillating fiber wisely: small Birks constant, relative H volume compared to Cerenkov fibers, luminosity, attenuation, ...)
5. Simulate with FLUKA: we need some kind of “system” simulations, even if it is flawed
6. Test in beam, first electrons in small scalable module, then pions in a 3x3 module set-up.

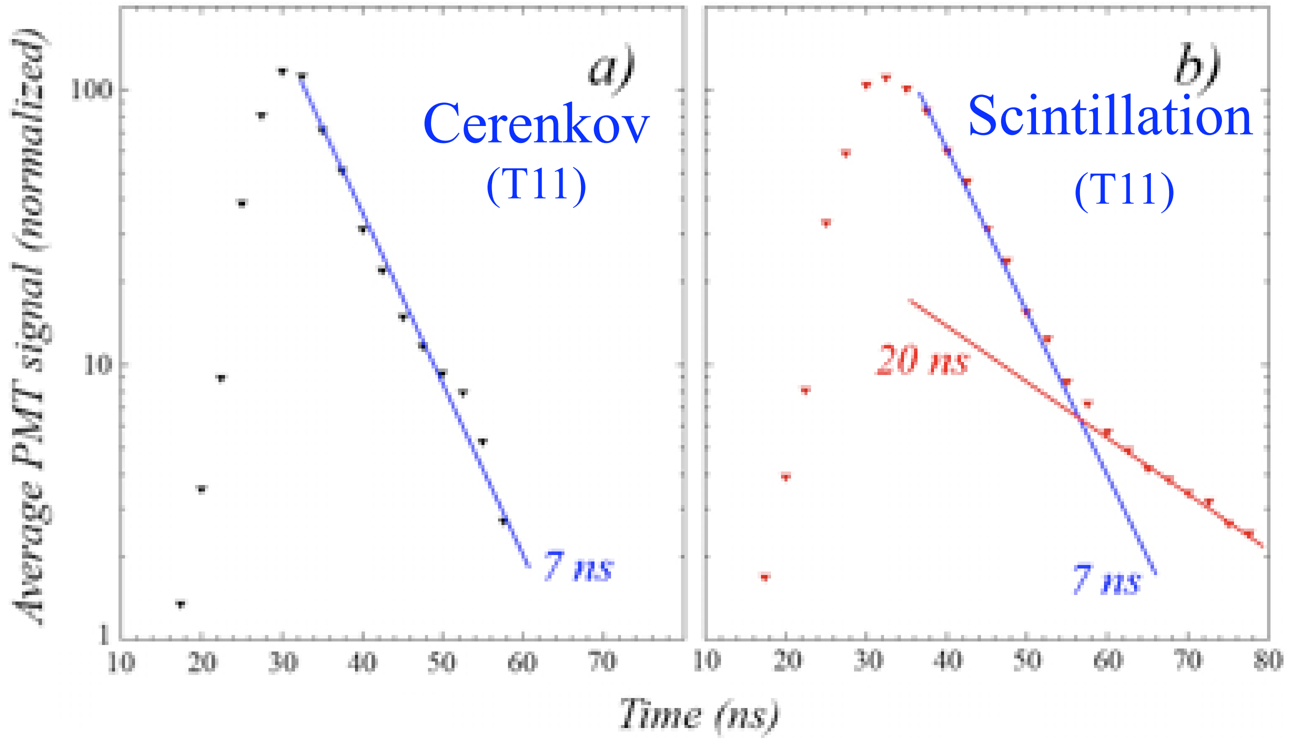
Neutrons by time-history: 100 GeV pions (G3)



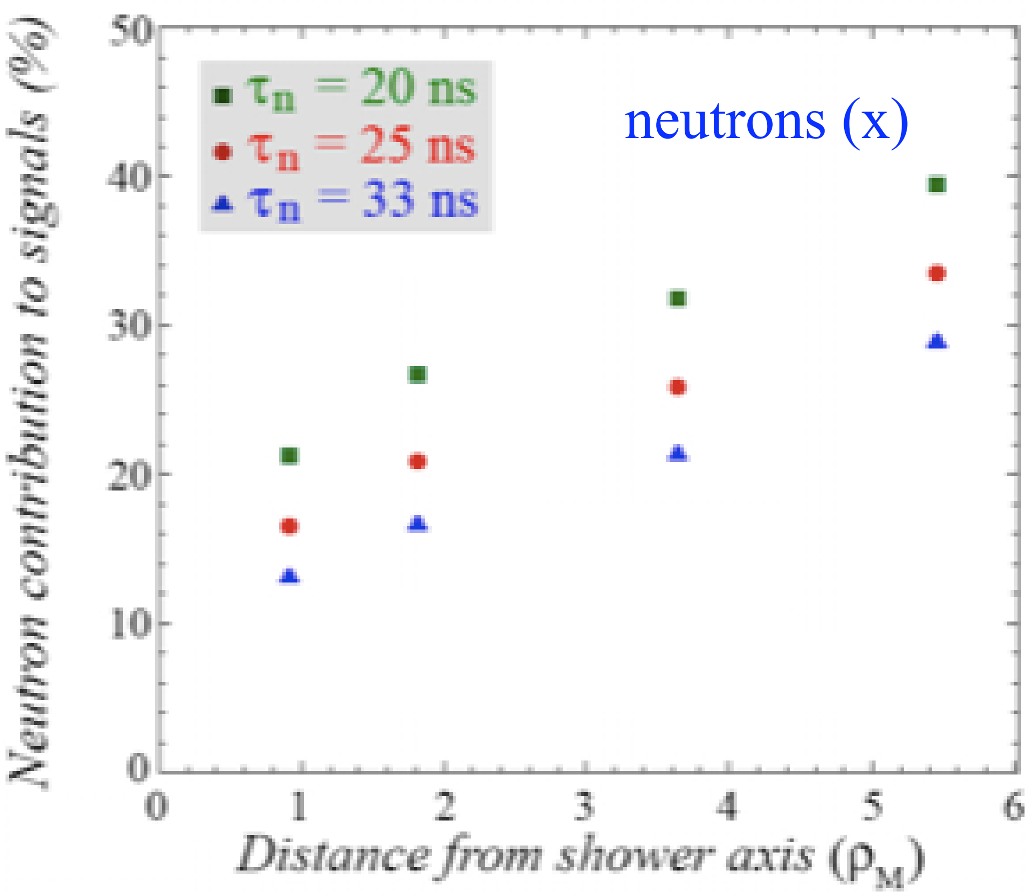


Neutrons measured in the DREAM module, Nov-Dec 2006





Send pion beam into center of channel 11, clock out scintillator/PMT signals in channels 3, 1, 6 and 17.



This completes the 1, 2, 3.

Ingredients for a new "scalable" dual-readout fiber module:

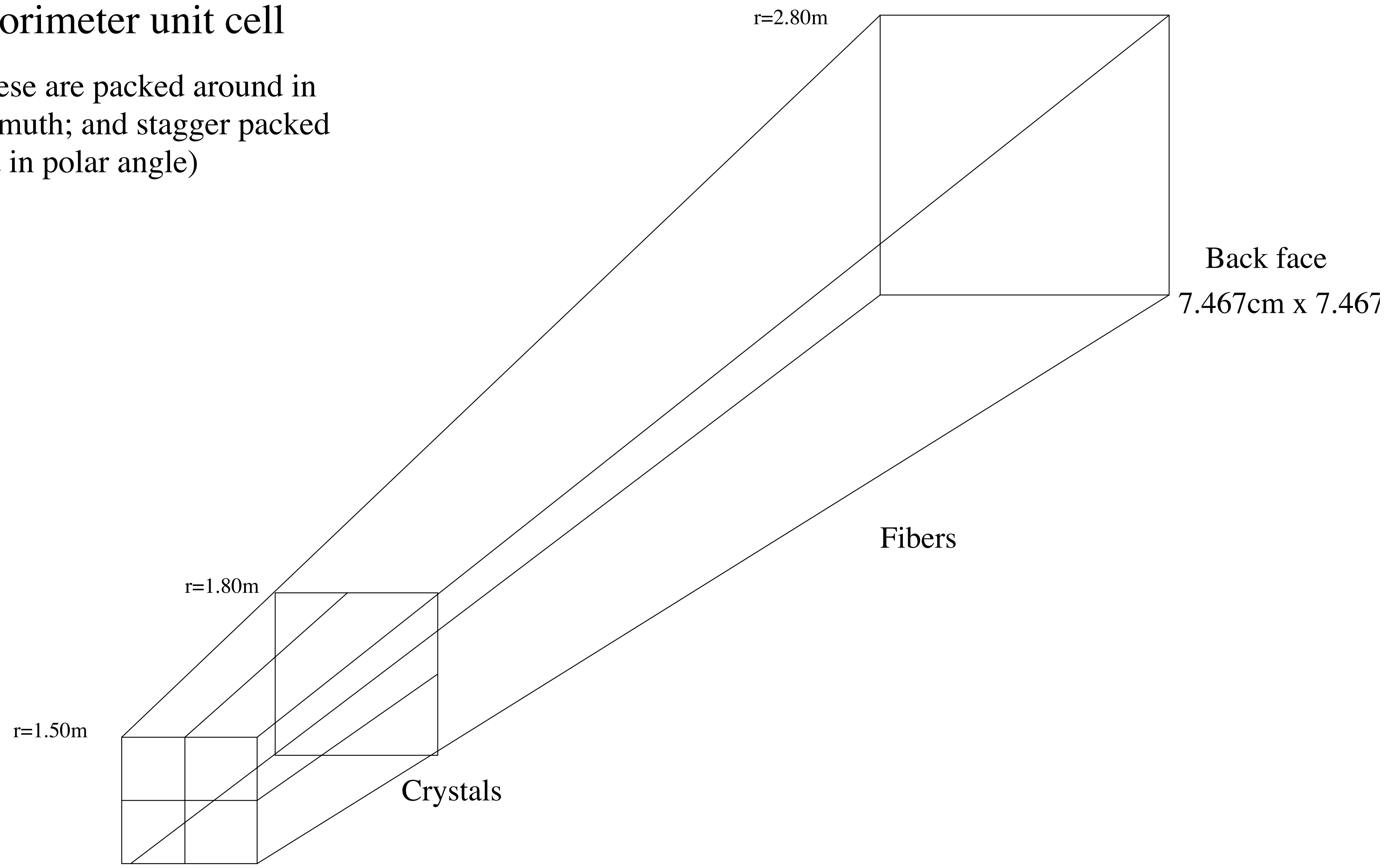
1. Cerenkov (clear) fibers, double clad, square, NA ~ 0.7 and with a larger fiber volume to increase photoelectron yield to 100 pe/GeV.
2. Scintillating fibers, double clad, square, NA ~ 0.7, more strongly filtered to increase attenuation length to above 5m.
3. Fiber geometry that is easier for a truncated pyramid module, and scalable for negligible inter-module dead volume. A dual-readout calorimeter like DREAM has all its readout at the rear, not the sides, and therefore has the possibility to be perfectly hermetic.
4. Photo-converter for B = 3.5 T. The usual suspects: SiPM, HPD, special B-resistant PMTs, microchannel plate PMs.
5. Readout both scintillation and Cerenkov fibers in 2-5ns buckets to measure neutrons and to monitor the volume for EM activity.

This is the next step for 4th.

4th Concept calorimeter configuration

Calorimeter unit cell

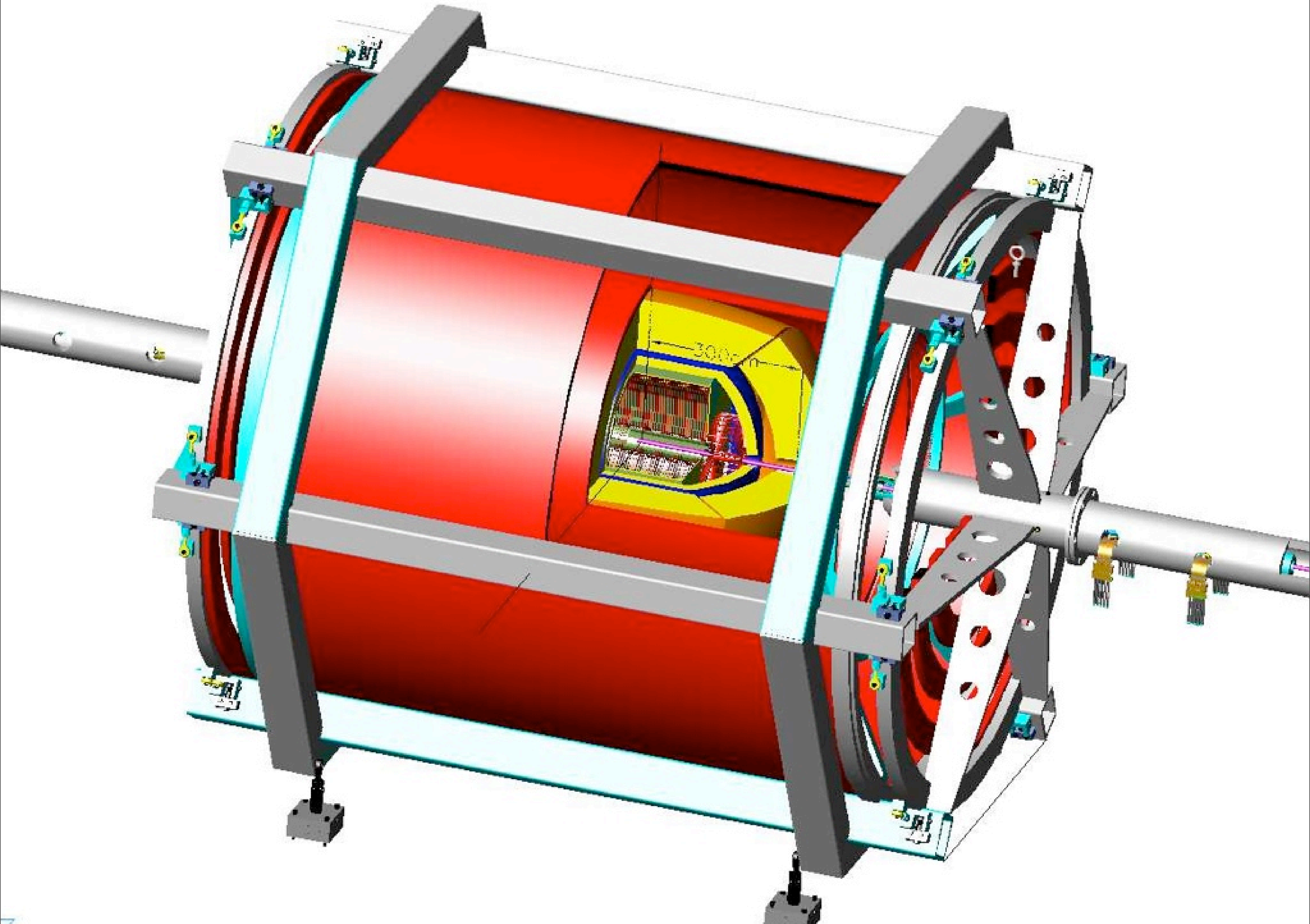
(these are packed around in azimuth; and stagger packed out in polar angle)



Front face is 4cm x 4cm

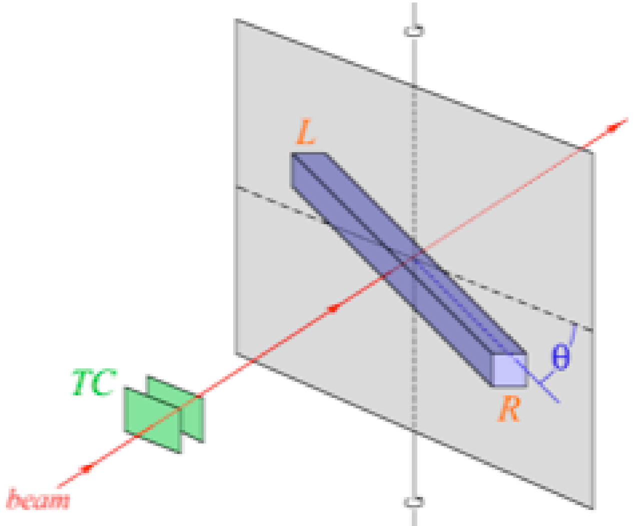
Crystals are 2cm x 2cm x 30cm

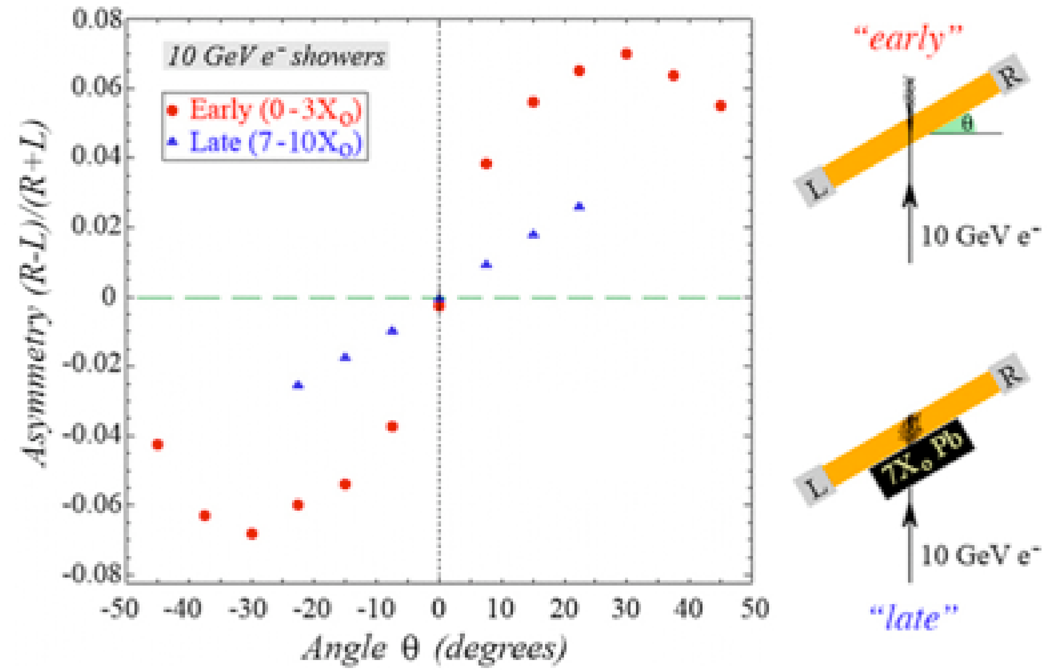
A “scalable” module; excellent electron & photon measurement; excellent hadron measurement.



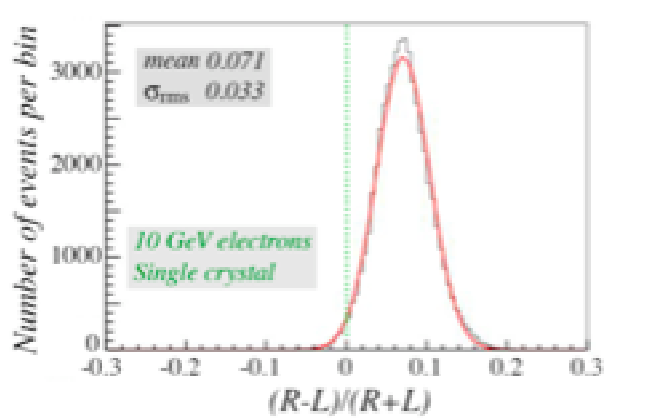
Dual readout of a single $PbWO_4$ crystal

(CERN test beam, Nov-Dec 2006)

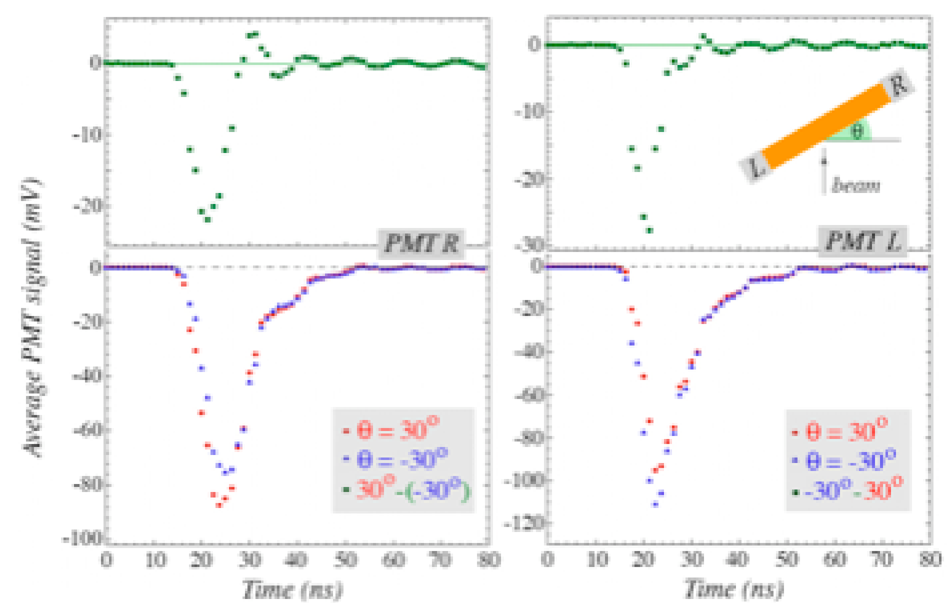




Event-by-event measurement of asymmetry

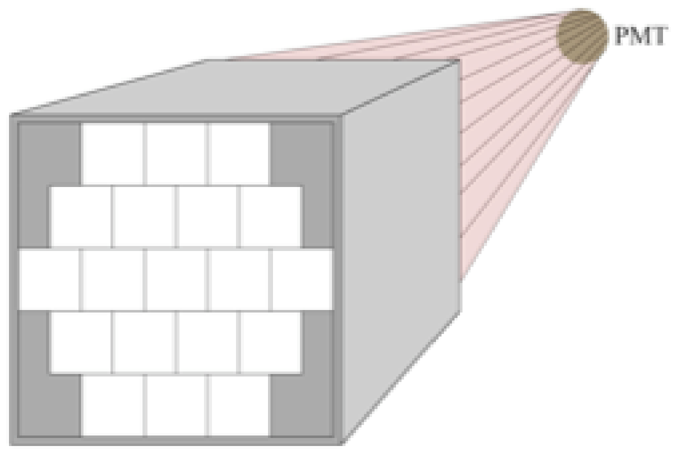


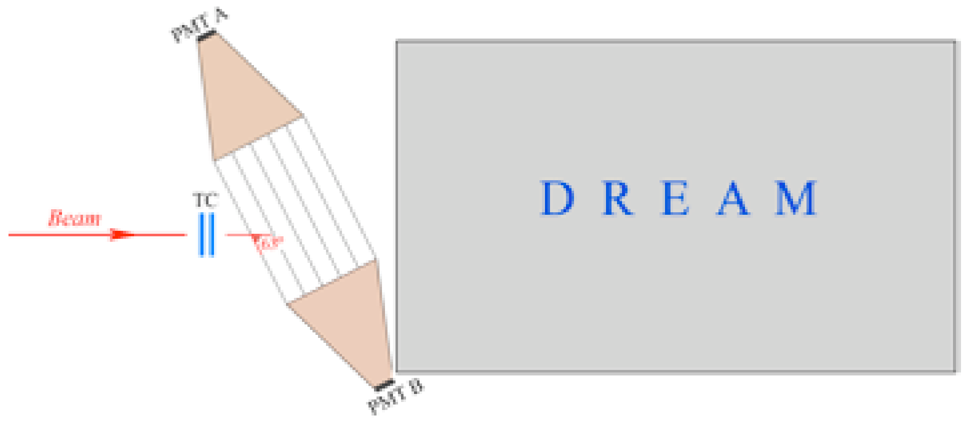
If $\frac{R-L}{R+L} = 0.08 \longrightarrow$ R contains $14.8 \pm 6.1\%$ Č

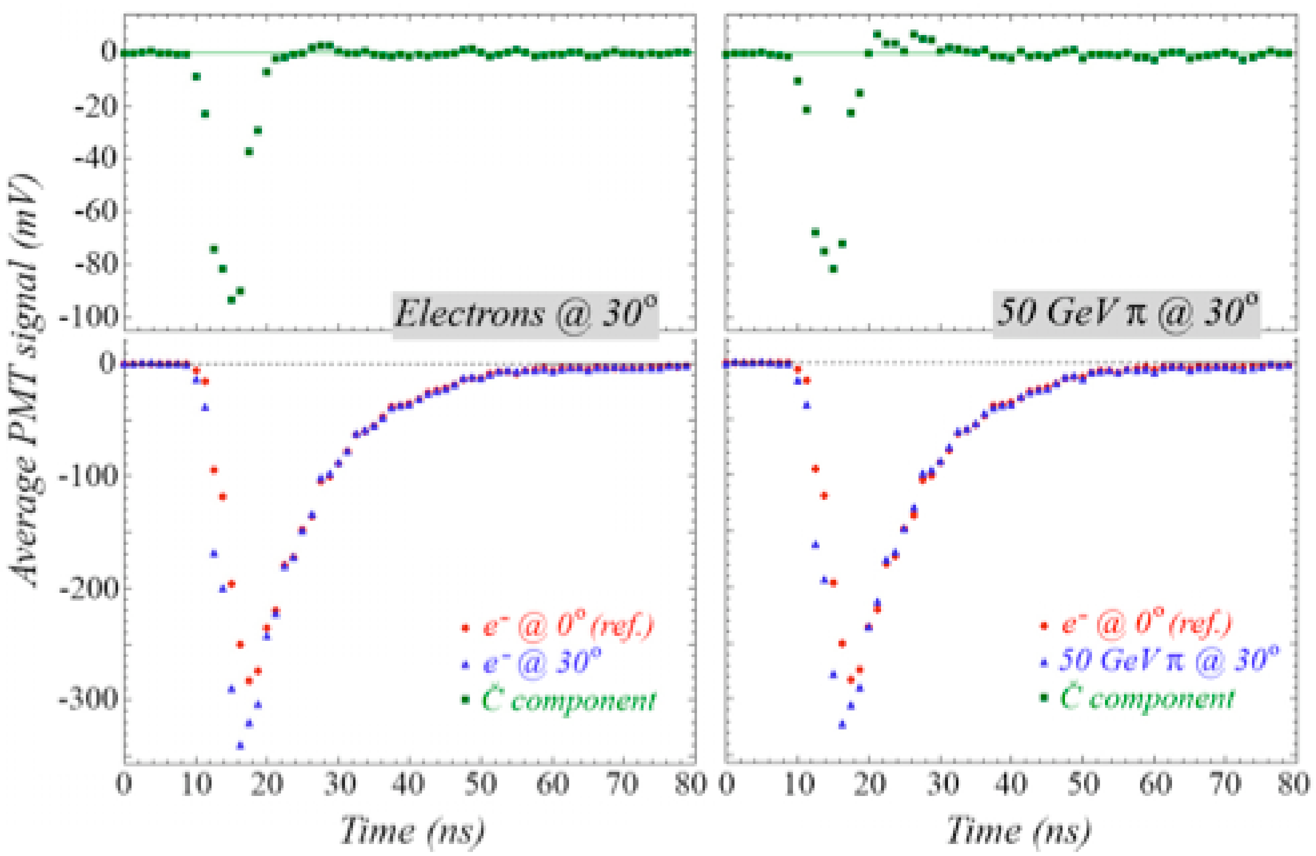


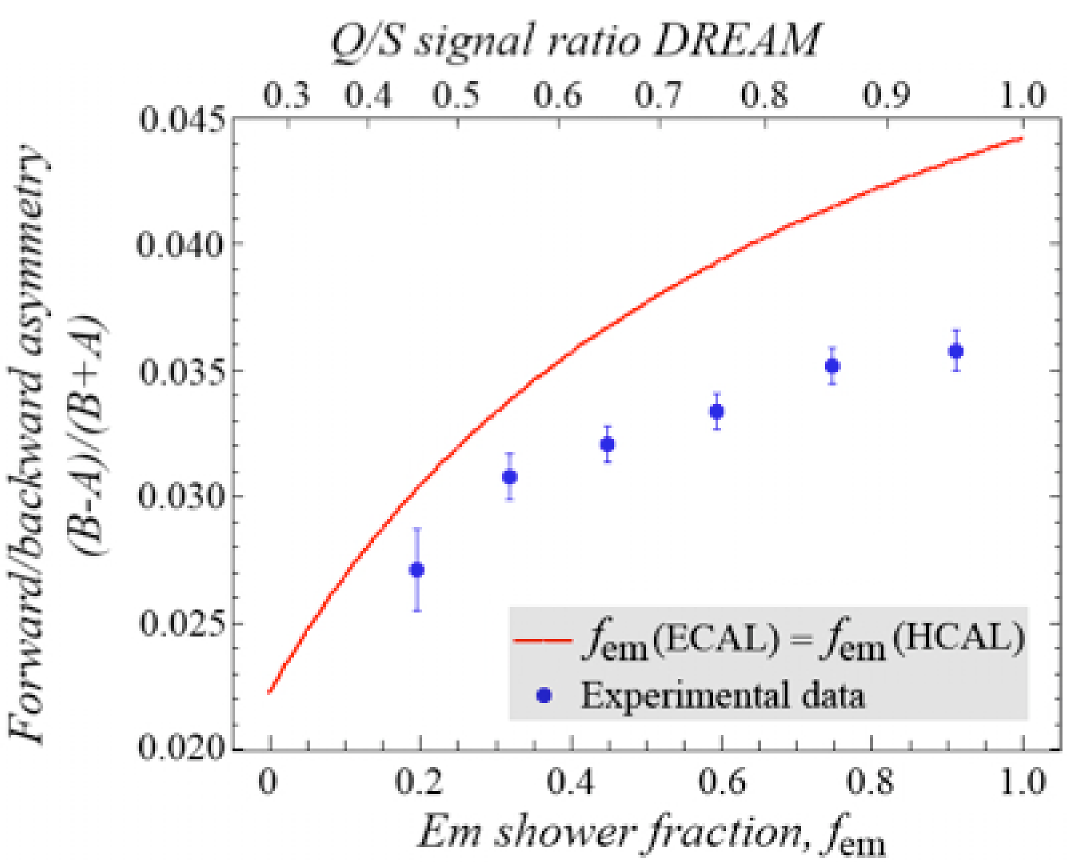
Dual readout of an array of 19 PbWO4 crystals

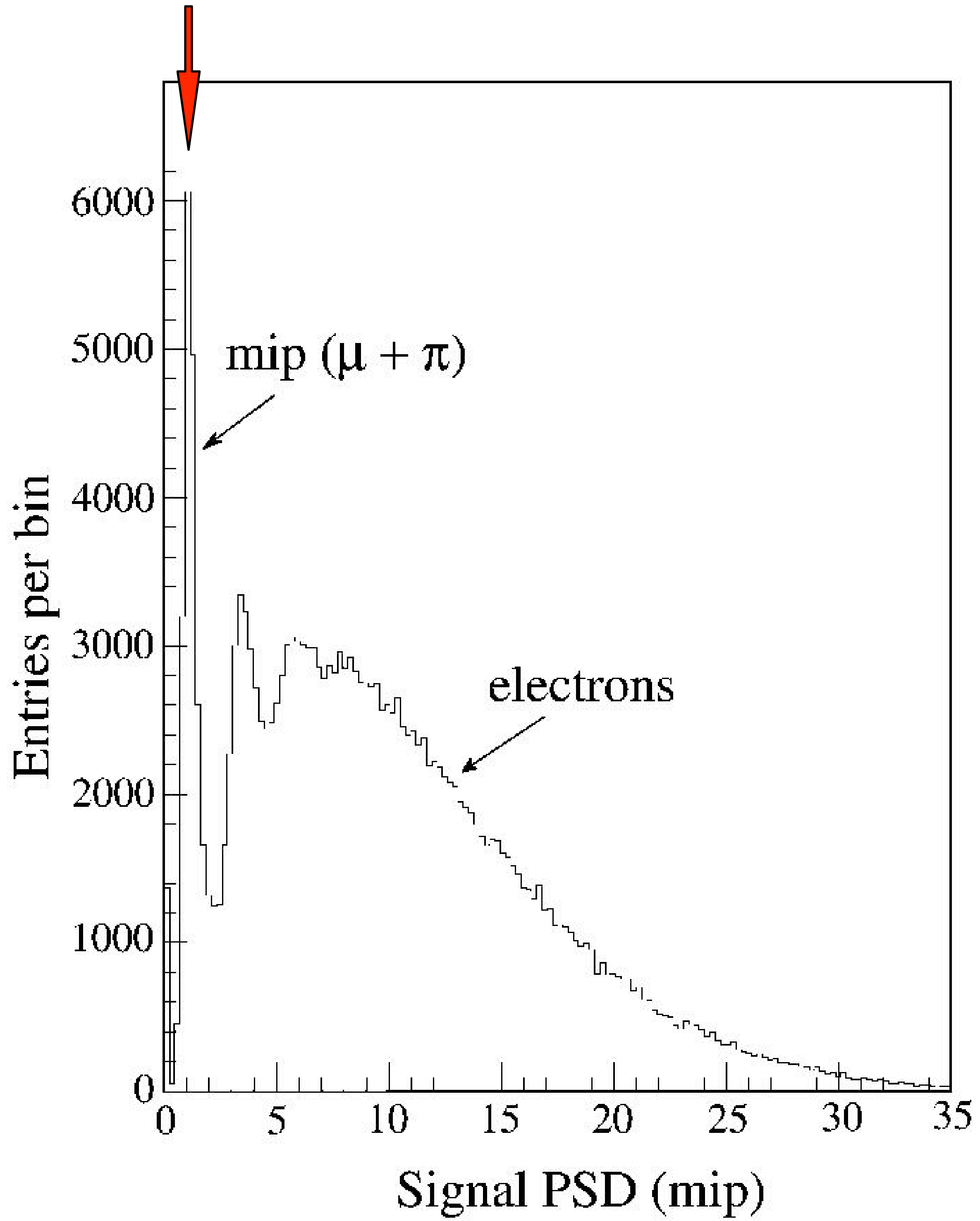
(CERN test beam, Nov-Dec 2006)

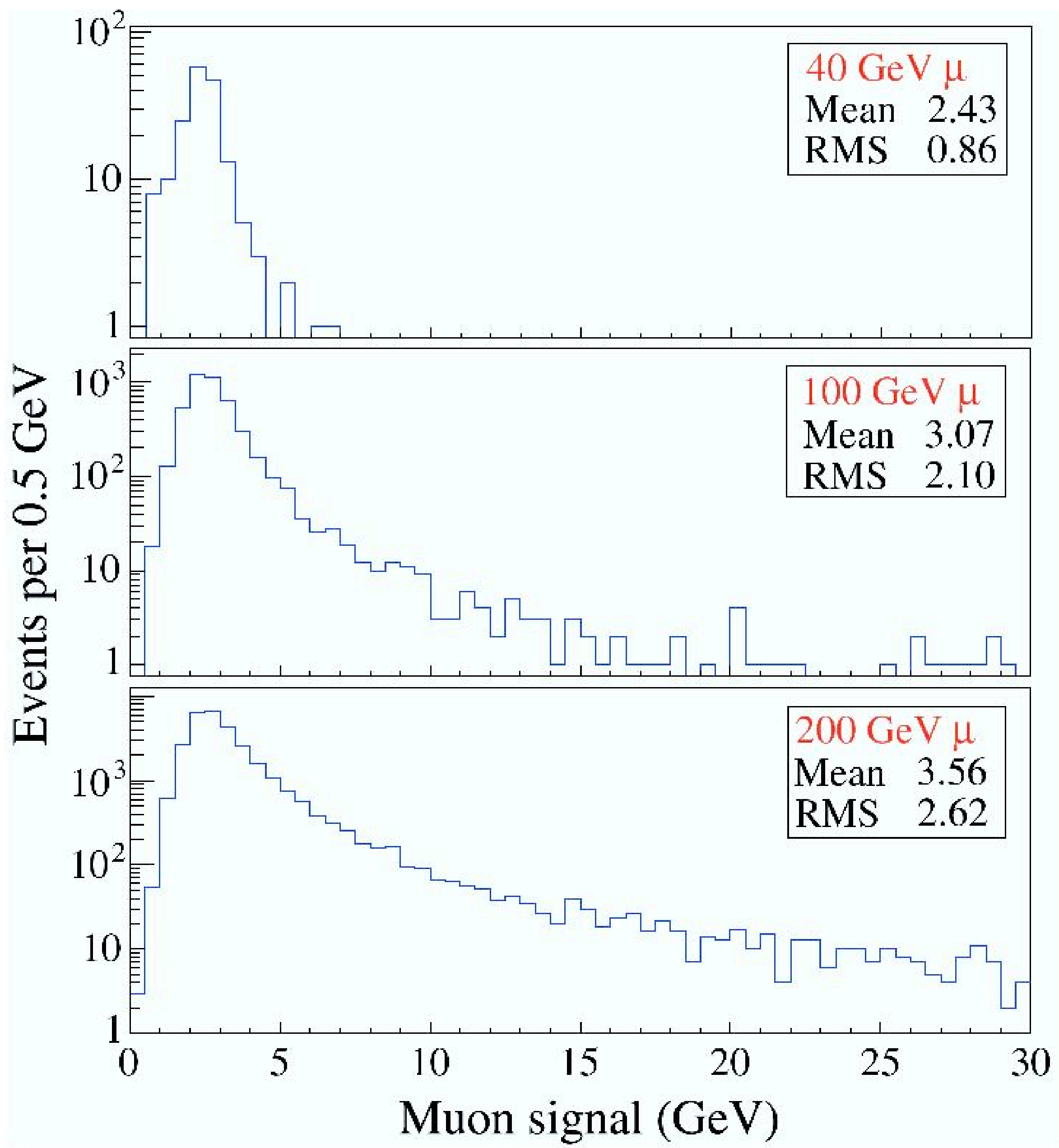






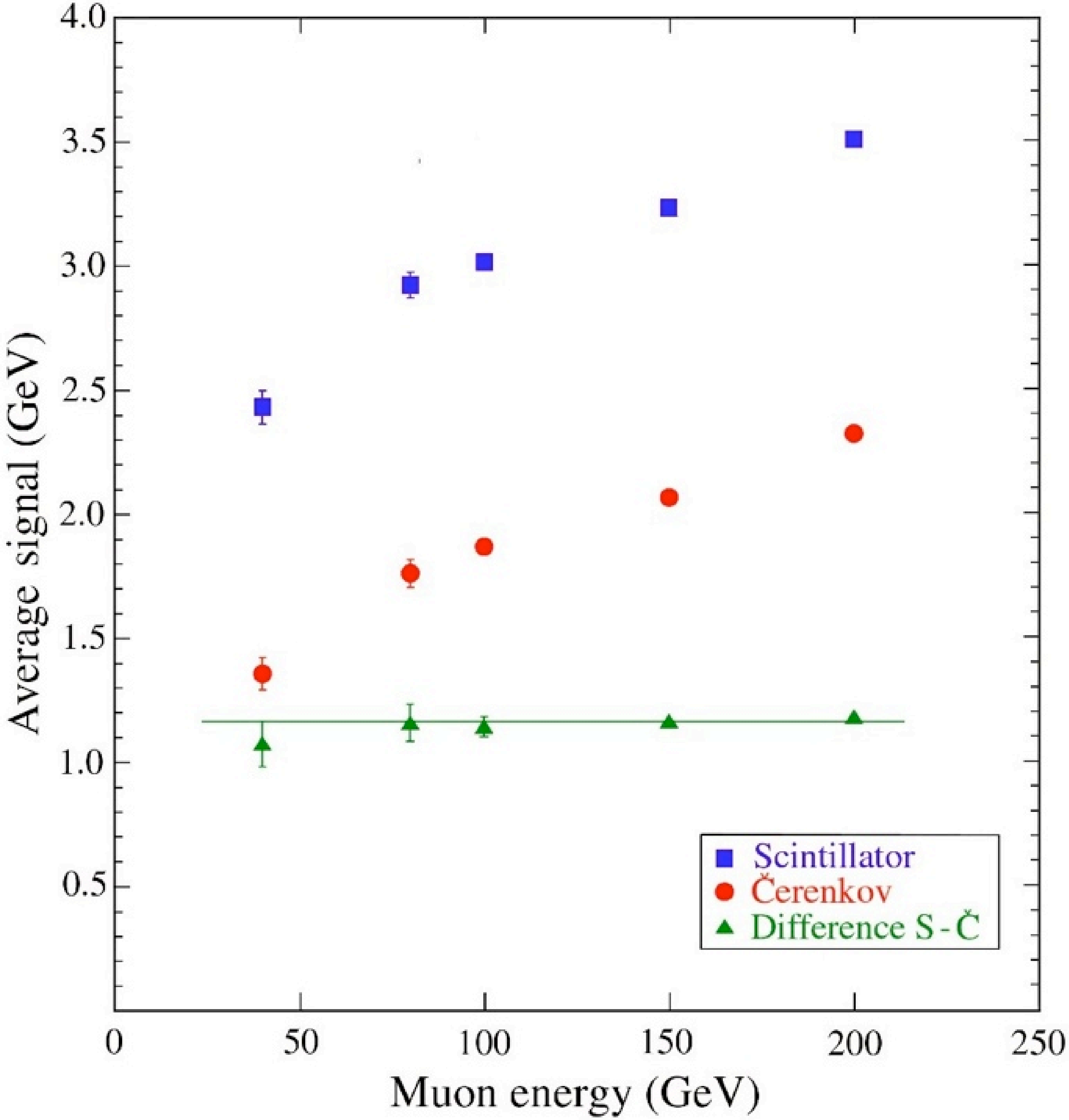






NIM A533 (2004) 305-321.

First measurement of separate ionization and radiation of muons in a medium

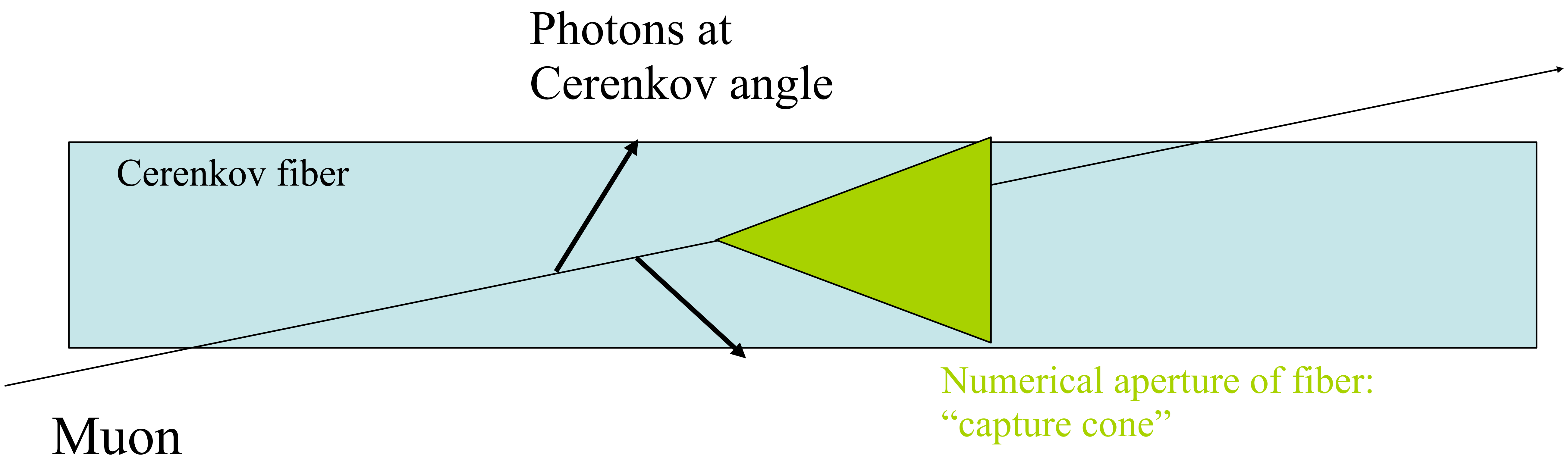


S = dE/dx + radiation

C = radiation

S-C = $dE/dx \sim 1$ GeV

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

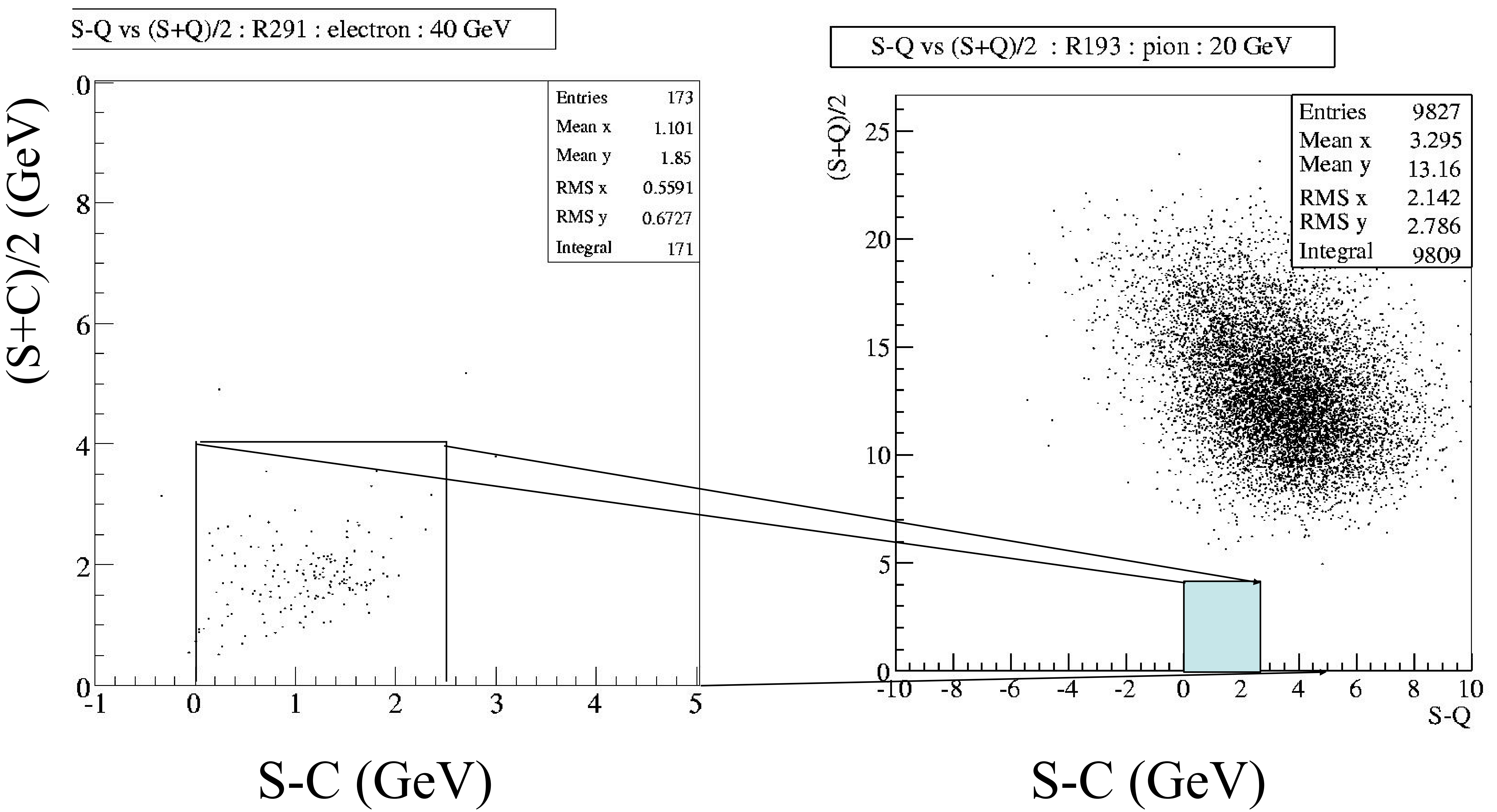


All of the Cerenkov light of an approximately aligned muon falls outside of the numerical aperture of the fiber.

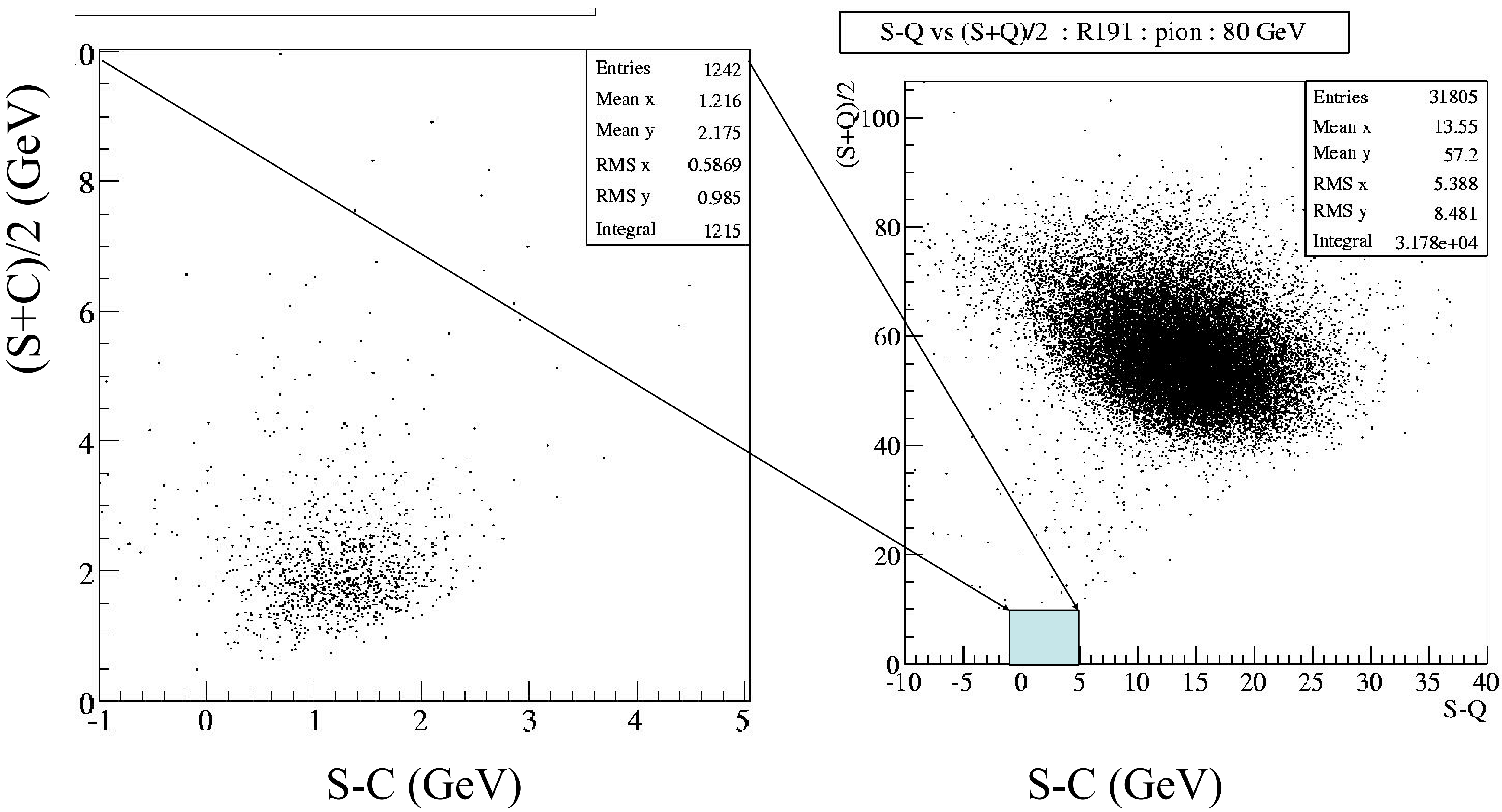
$C \sim 0$ $S \sim dE/dx$

Use it for muon identification

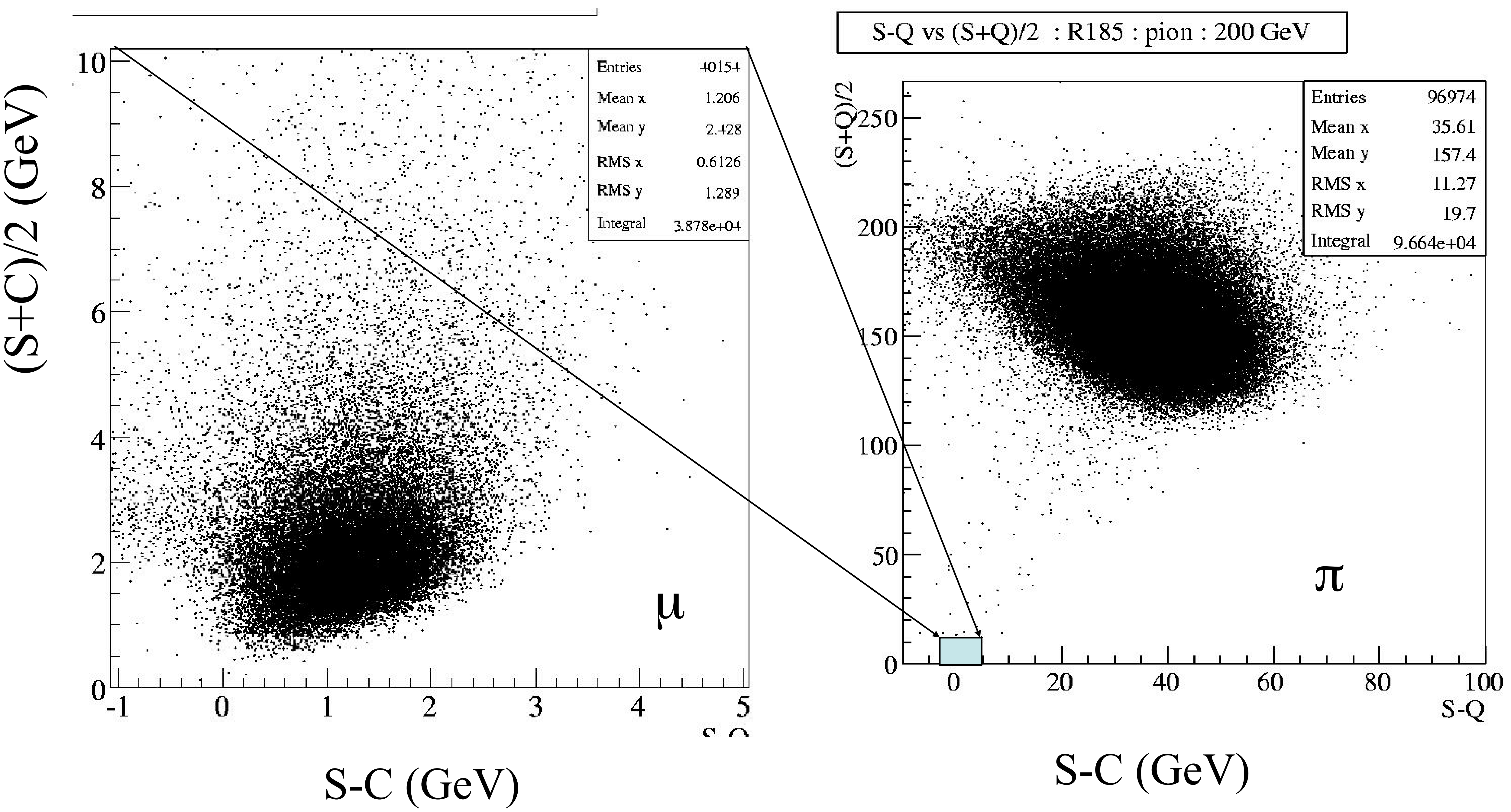
Muons (40 GeV) & Pions (20 GeV)



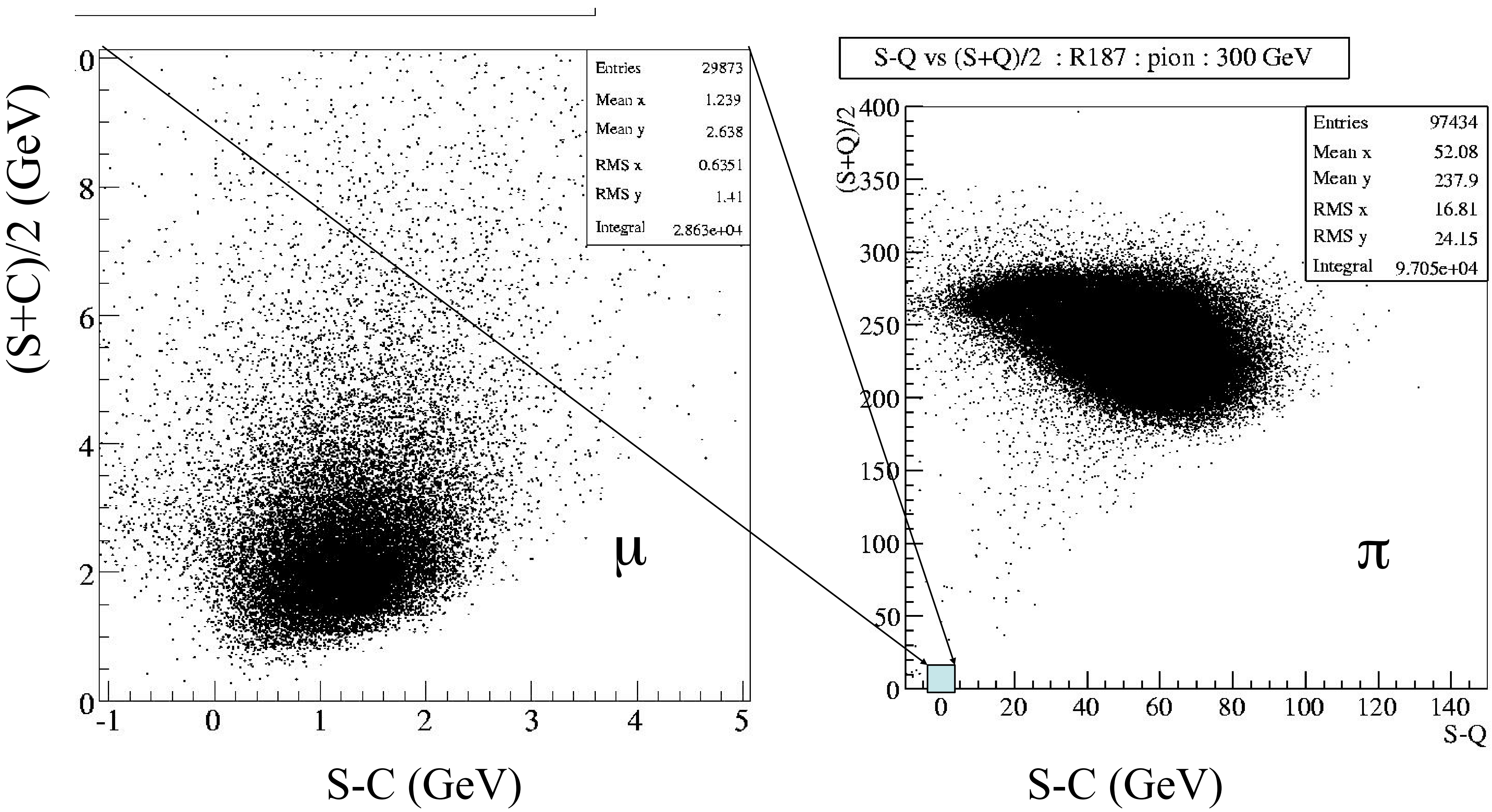
Muons and Pions (80 GeV)



Muons and Pions (200 GeV)



Muons and Pions (300 GeV)



Some objections to dual-readout fiber calorimeters:

a. particles can "channel" down a fiber: No, not likely, and in a B=3.5T field, it will never be a problem. The crystals in front convert all photons.

b. only one depth section? Yes, absolutely. Hadronic depth development fluctuations are best summed over, not measured. ("Depth segmentation is asking for trouble"-Wigmans). Dual readout provides at least three physical measurements per shower that discriminate between jets, photons, electrons, single hadrons, and muons.

c. can't measure $\tau^{\pm} \to \rho^{\pm}\nu \to \pi^{\pm}\pi^{0}\nu \to \pi^{\pm}\gamma\gamma\nu$? I think we can ["Can the decay $\tau^{\pm} \to \rho^{\pm}\nu$ be measured directly?", J. Hauptman, SLC-37, Aug. 25, 1981.] with the 2cm x 2cm dual readout crystals in front.

d. can't measure some odd object not from the origin: I am not sure, but the crystal and fiber channels are small, so we can do some "tracking".

e. you're too small a group: no problem so far, but many are interested.

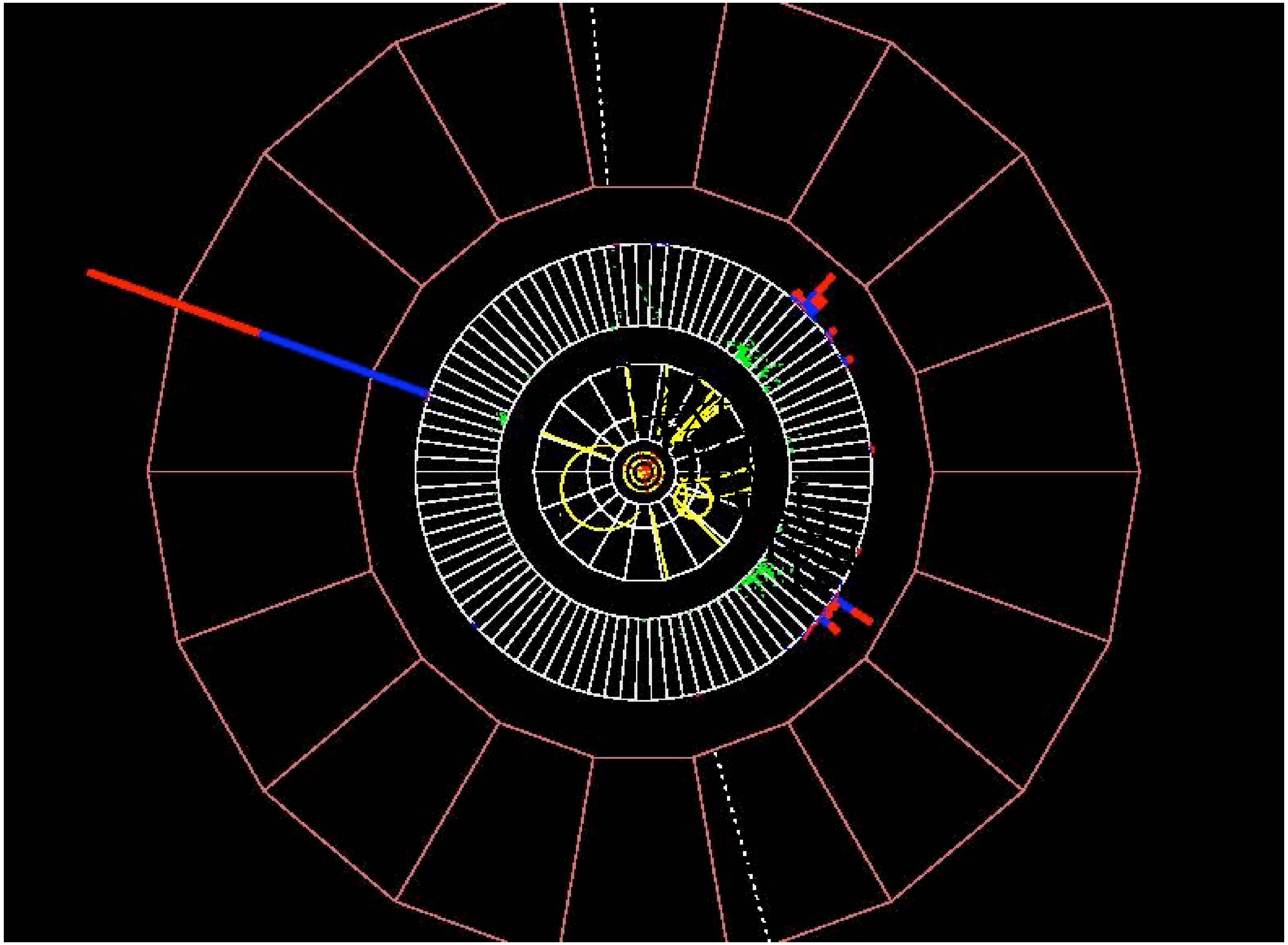
f. FE electronics, DAQ: all at back of modules, PM, FADC.

g. mechanical support: we have an engineering model to support the wedges like a Roman arch.

h. EMI, flyers, beam losses: complicated, but we have 10 int. lengths and time history of Cerenkov fiber volume.

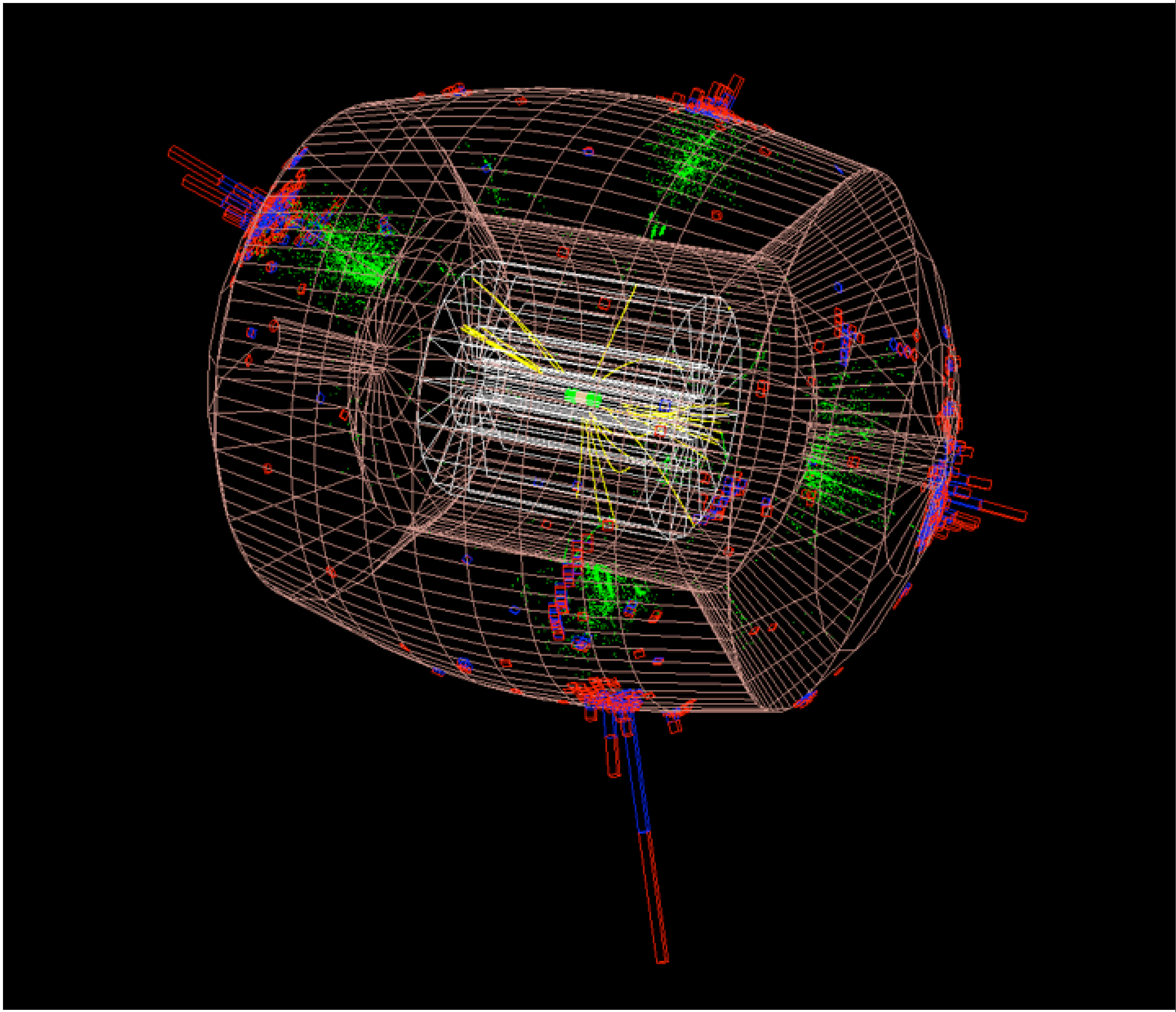
ILCroot software developed by the Lecce group, Corrado Gatto

$$e^+e^- \rightarrow H^0 Z^0 \rightarrow W^+W^-\mu^+\mu^- \rightarrow jj \;\; e^-\nu \;\; \mu^+\mu^-$$

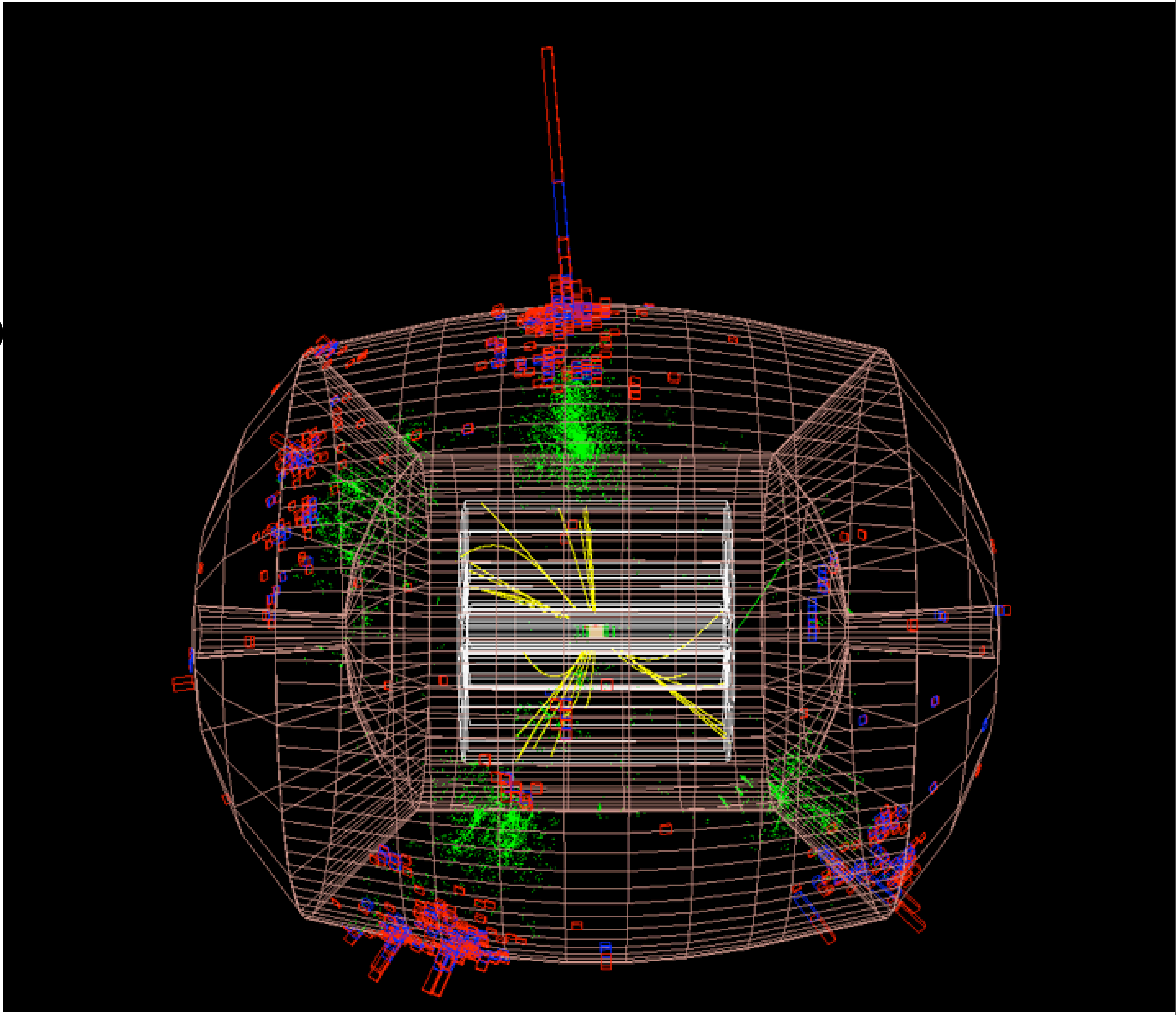


Illustrates all the detectors of 4th Concept … particle ID "obvious"

e^+e^-
$\rightarrow H^0 Z^0$
$\rightarrow b\bar{b}q\bar{q}$



e^+e^-
$\to H^0 Z^0$
$\to b\bar{b}q\bar{q}$



Multiple readout calorimetry and its advantages:

1. Good control of fluctuations in widely and multiply fluctuating hadronic showers;
2. Very rich area for new and clever ideas;
3. Very interesting particle identification strengths (not just for muons). [channel width, S-C width (ch-ch & shower), fem, fn]
4. We hope our thinking is clear enough for a good shot at the design of a scalable module;
5. Simulations, other than FLUKA in ILCsim, not much of a help as far as precision design calculations are concerned;
6. "Ultimate" energy resolution near 15%/√E. We will be quite happy with 20-25%/√E; and,
7. As always, collaborators and observers/visitors welcome.