Dual-readout Calorimetry

Primarily work of the DREAM collaboration,
led by Richard Wigmans, Nural Akchurin,
and including INFN groups from Pavia (Livan, Ferrari),
Rome I, Pisa (Franco Bedeschi), Cagliari, and Cosenza

Also, work in all-crystal dual-readout by Adam Para,
Hans Wenzel at Fermilab

John Hauptman
Muon Collider Workshop, Fermilab
10-12 November 2009

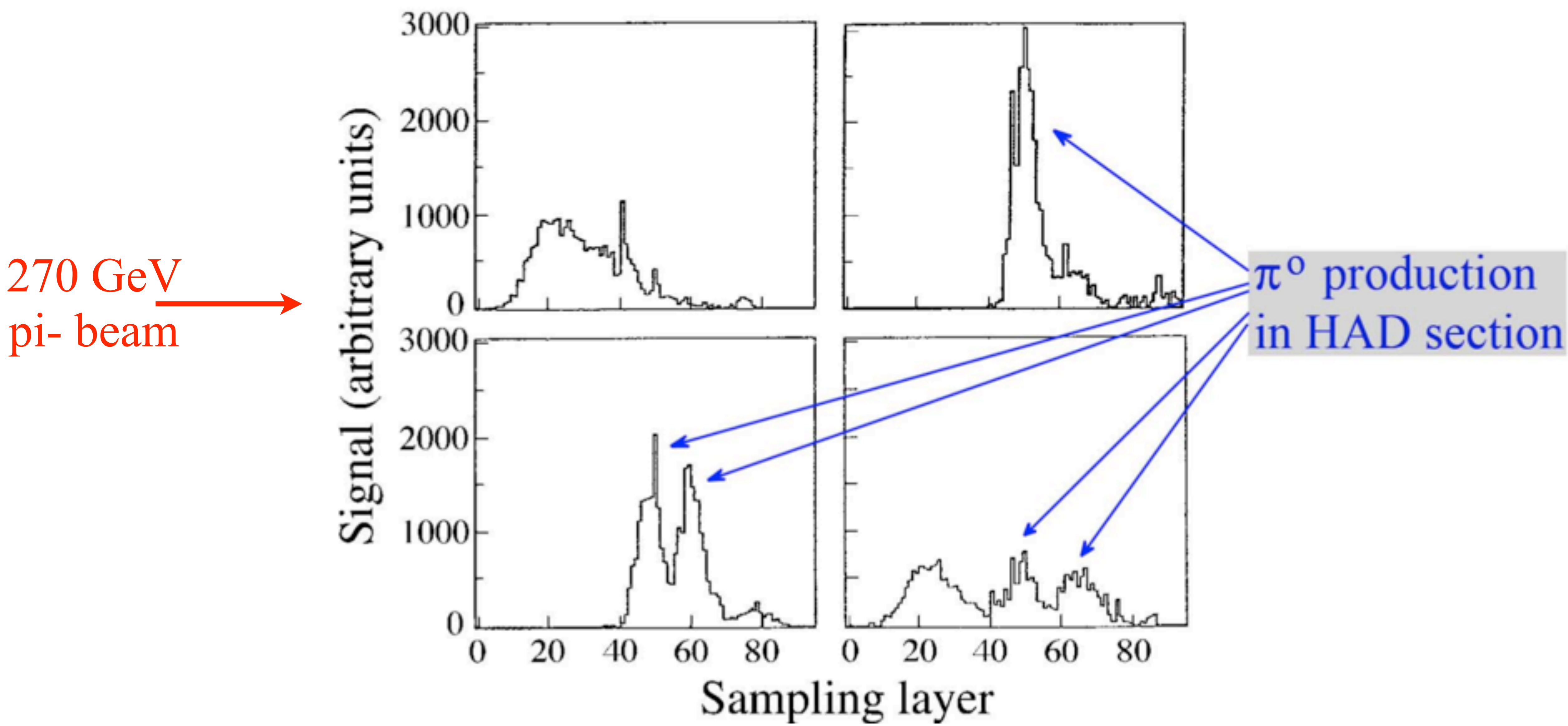
I believe that dual-readout calorimetry, or something akin to it, will be the calorimeter choice in all future big detectors.

Dual-readout calorimetry: (measure EM fraction every event)

Hadronic showers consist of two very different components:

1. an EM part (*"e"*) from pi-zero and eta decays to photons,
2. a non-EM part (*"h"*) consisting of everything else,

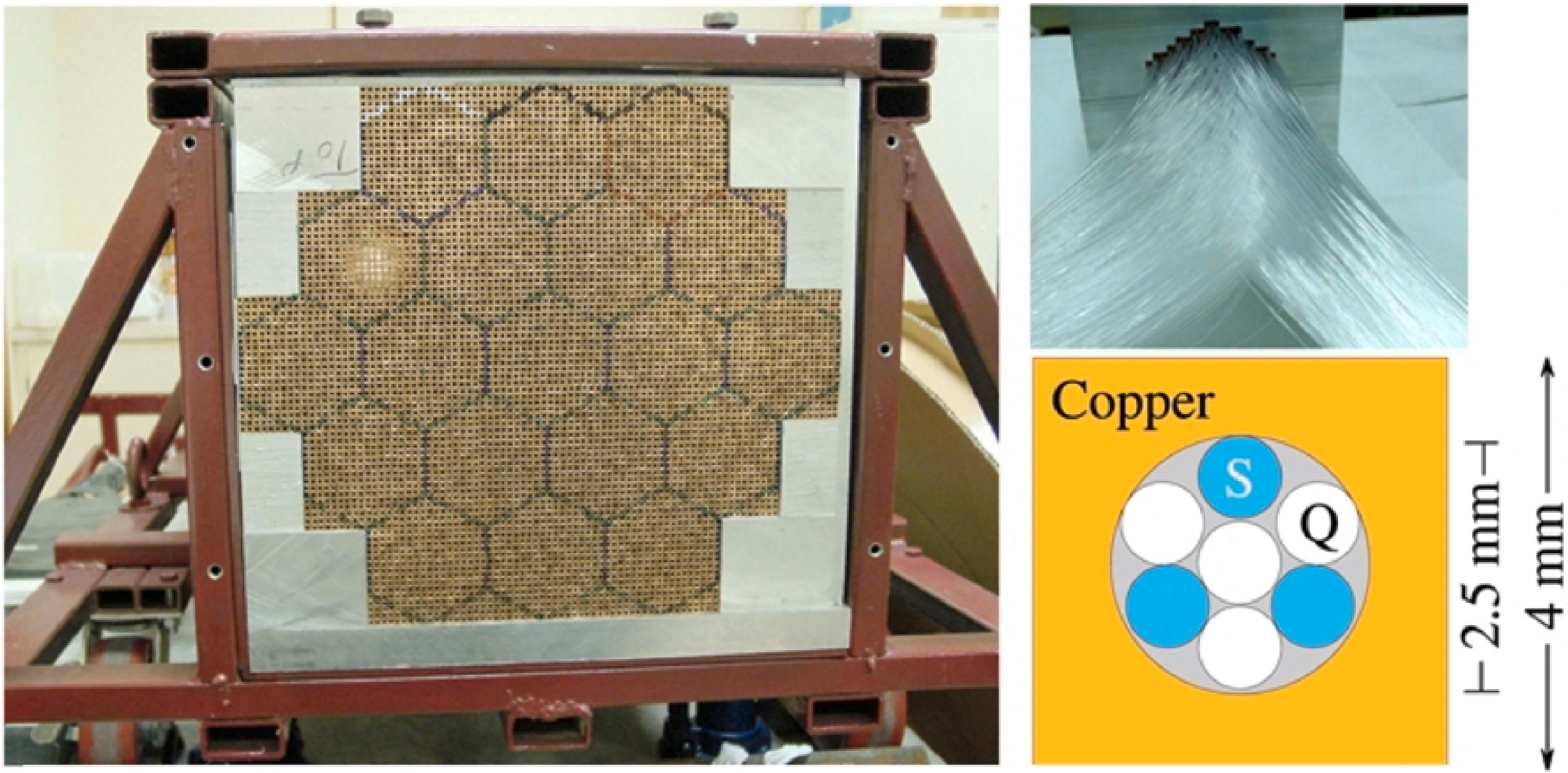
and this non-EM part contributes less to the calorimeter signal than the EM part, (e/h) > 1, called "non-compensating". Fluctuations in the EM fraction of hadronic showers leads to all the problems of hadronic calorimetry: poor energy resolution, non-linear response with energy, and non-Gaussian line shape.



The "proof-of-principle" DREAM module

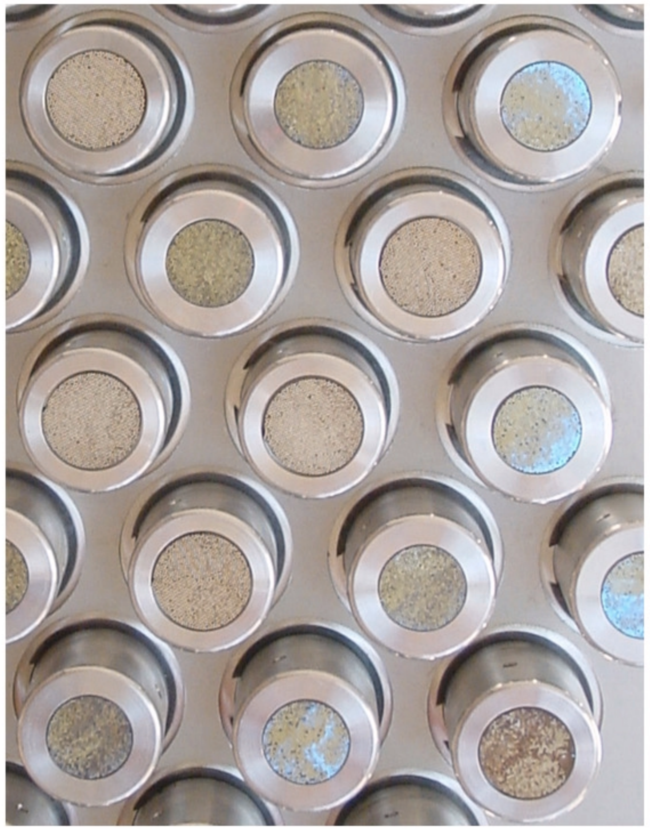
S = scintillating fibers
Q = quartz (clear) fibers

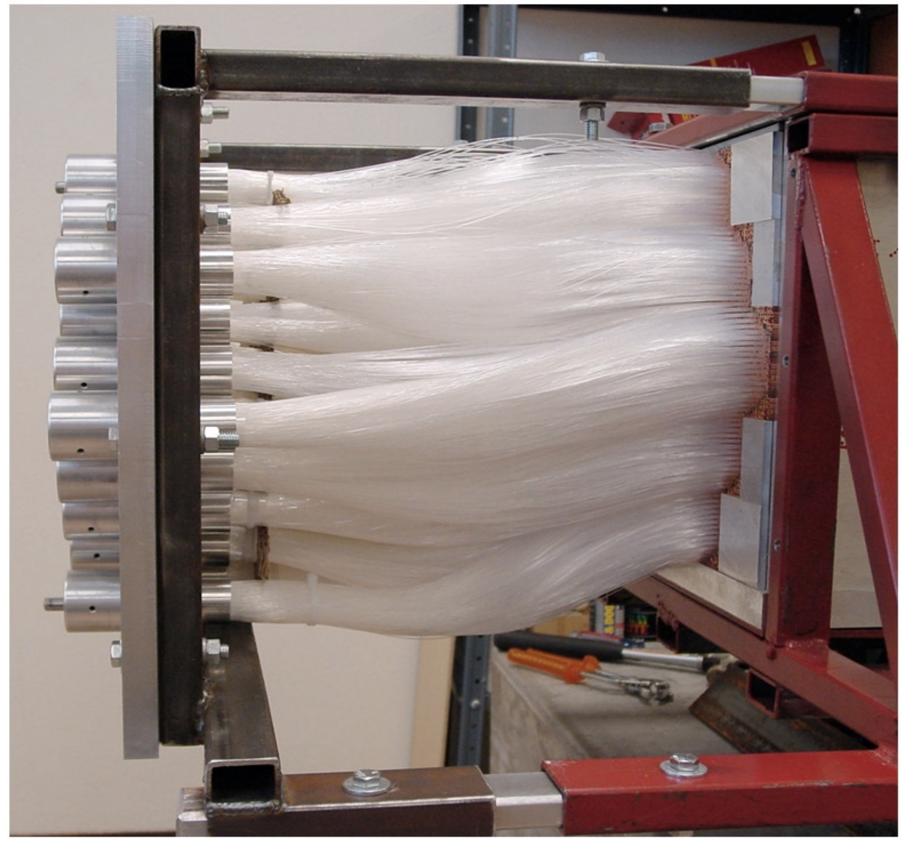
DREAM: Structure



- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{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

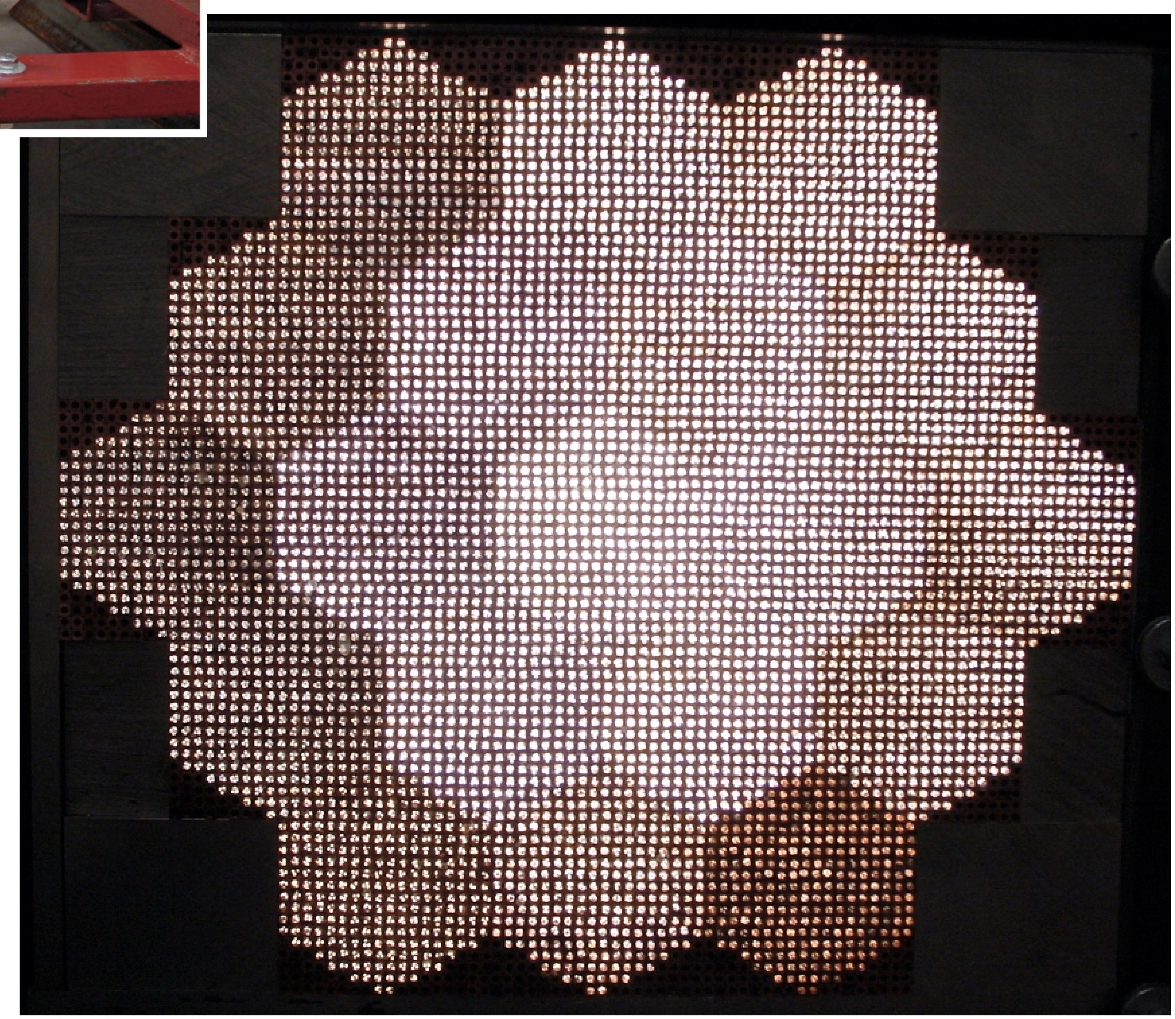
DREAM readout





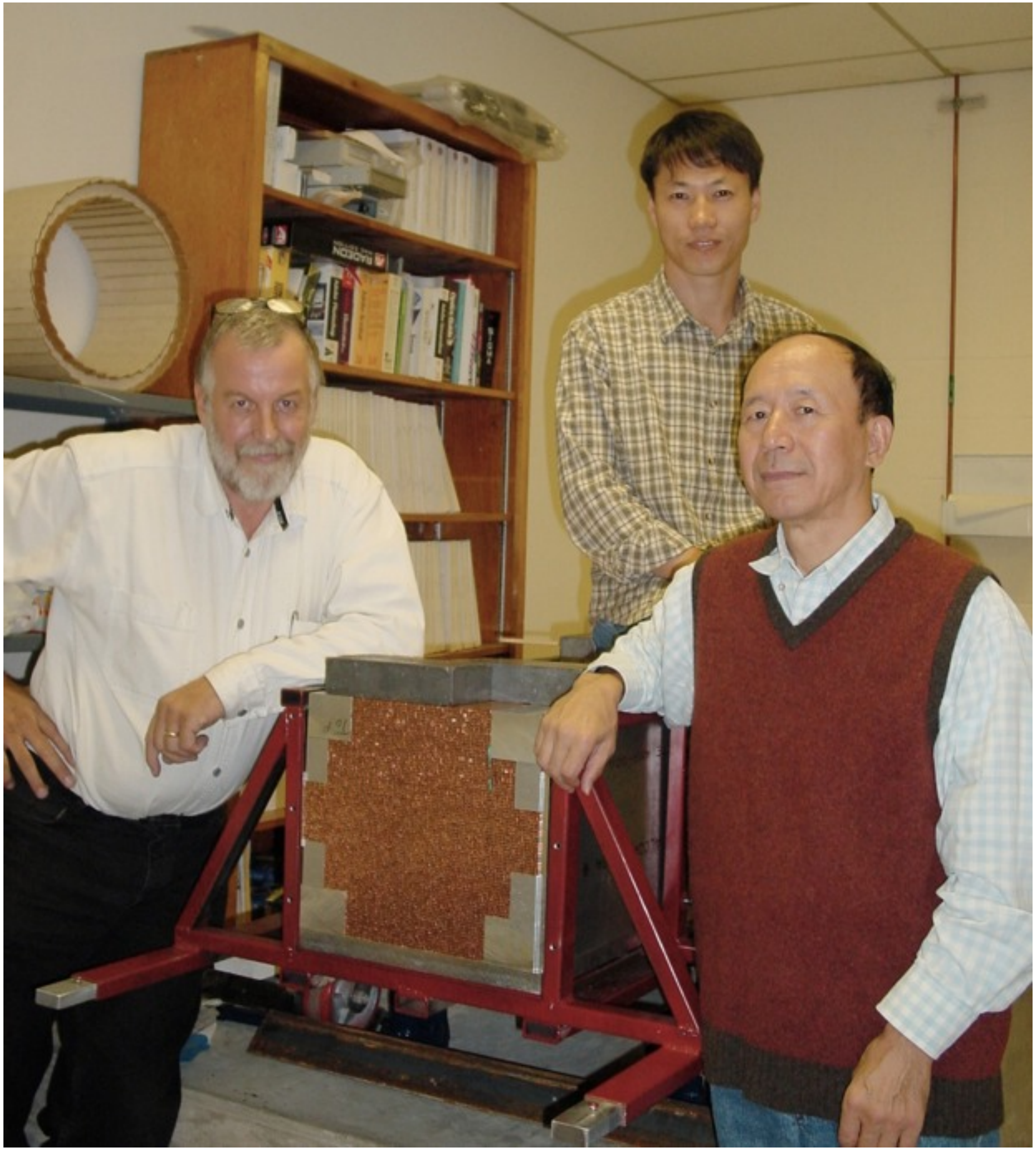
Channel structure defined by bundled scintillation and Cerenkov fibers

Shine light through module

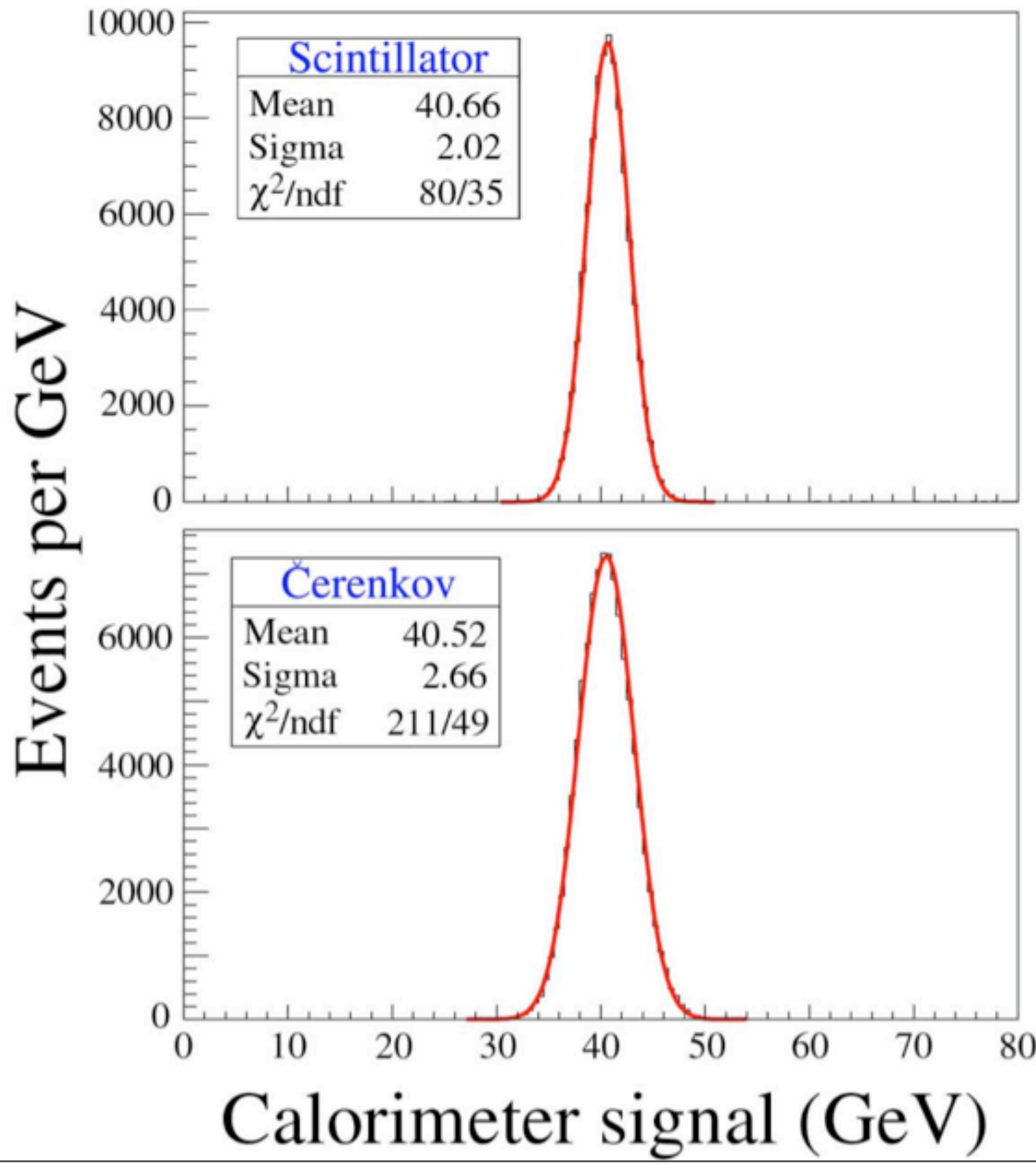


Simply built, inexpensive, proof-of-principle DREAM module

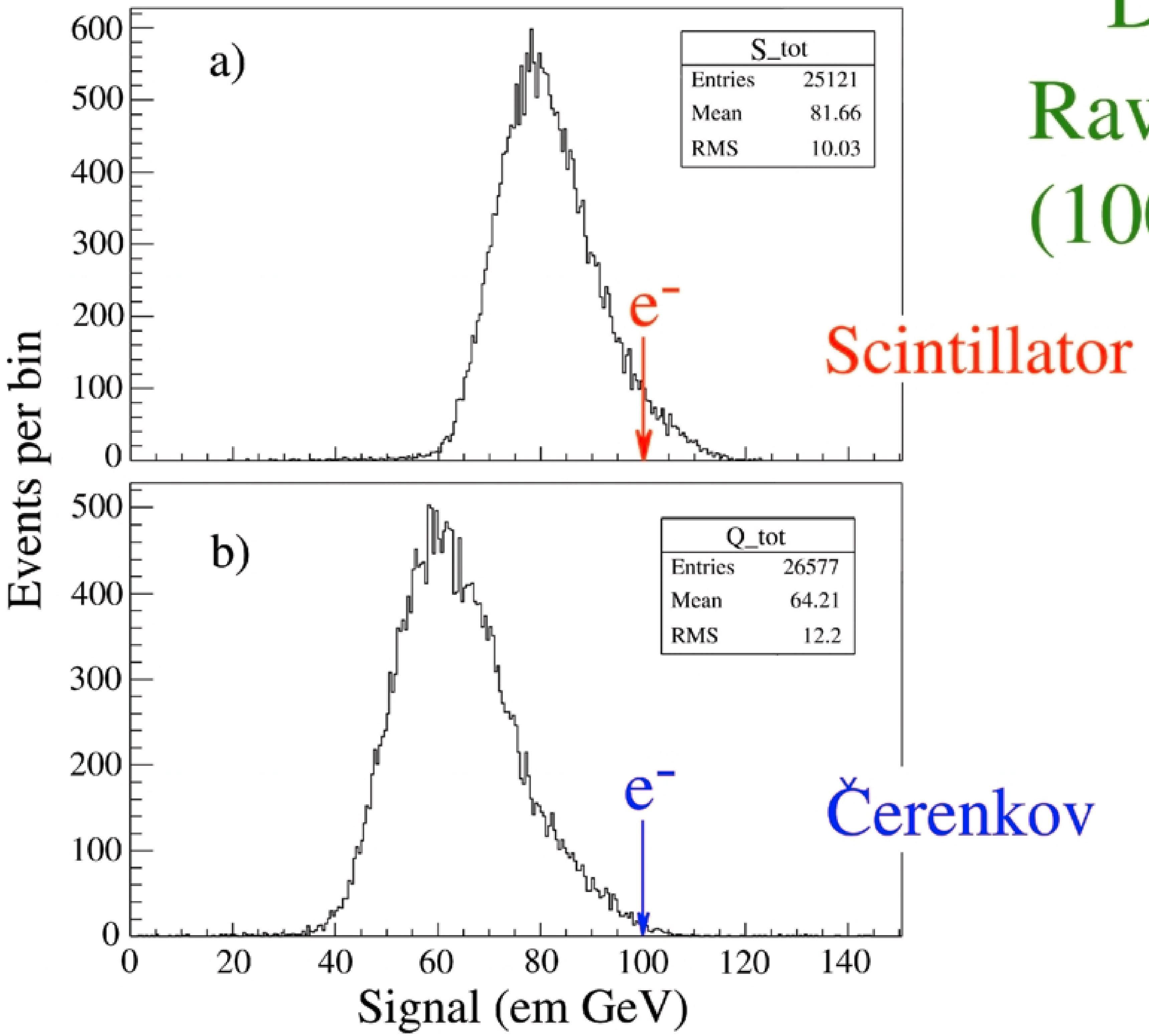
(~4% leakage fluctuations for hadronic showers in this small module)



Calibrate with 40 GeV electrons: set GeV/ADC for both scintillation and Cerenkov to get <data> = 40 GeV



Response to 100 GeV negative pions: asymmetric, non-Gaussian, and wrong energy

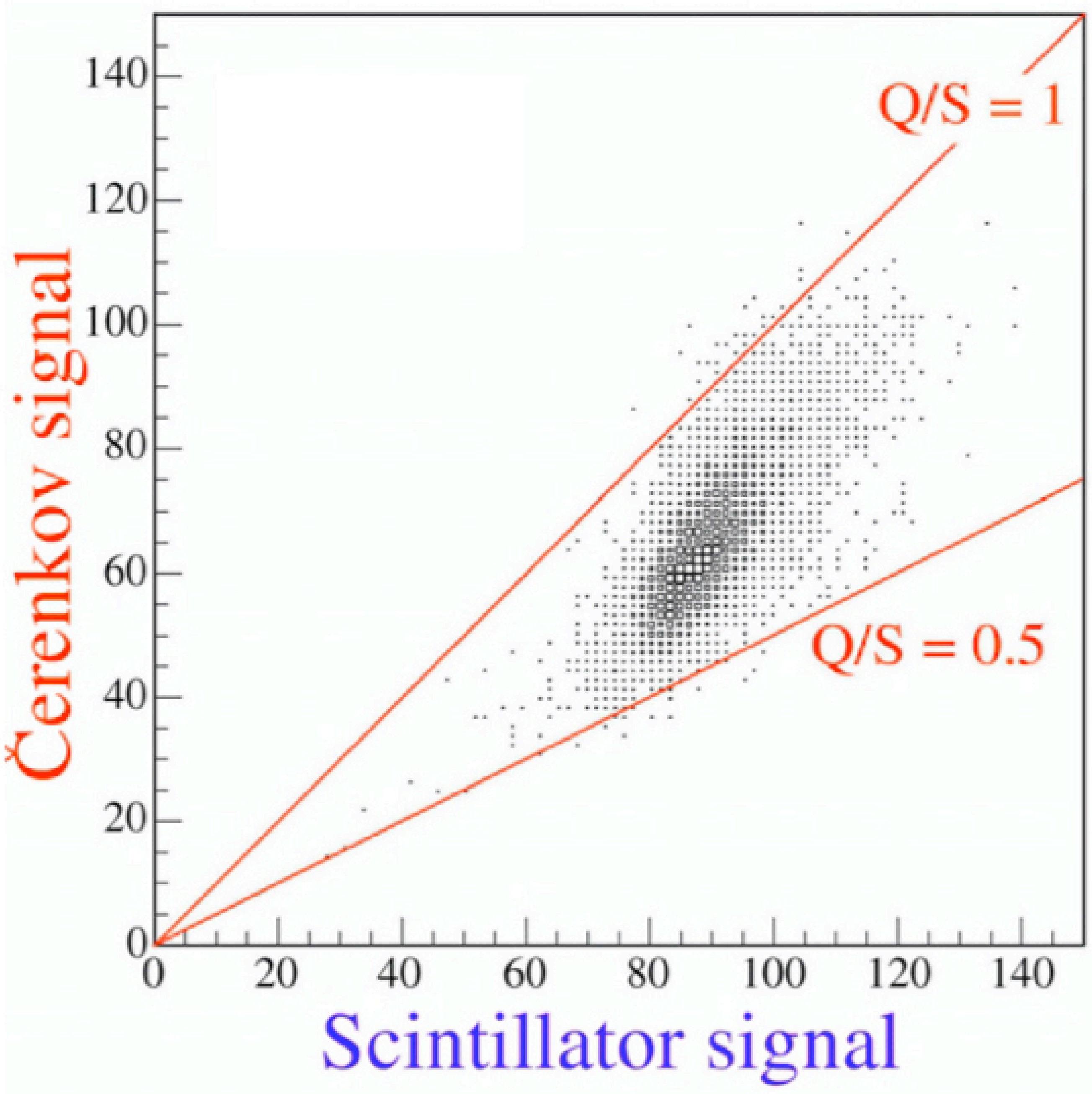


DREAM

Raw signals

(100 GeV π^-)

Basic dual-readout: "Hadron and Jet Detection with a Dual-Readout Calorimeter" NIM A537 (2005) 537-561.



$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right] \qquad (1)$$

$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right] \qquad (2)$$

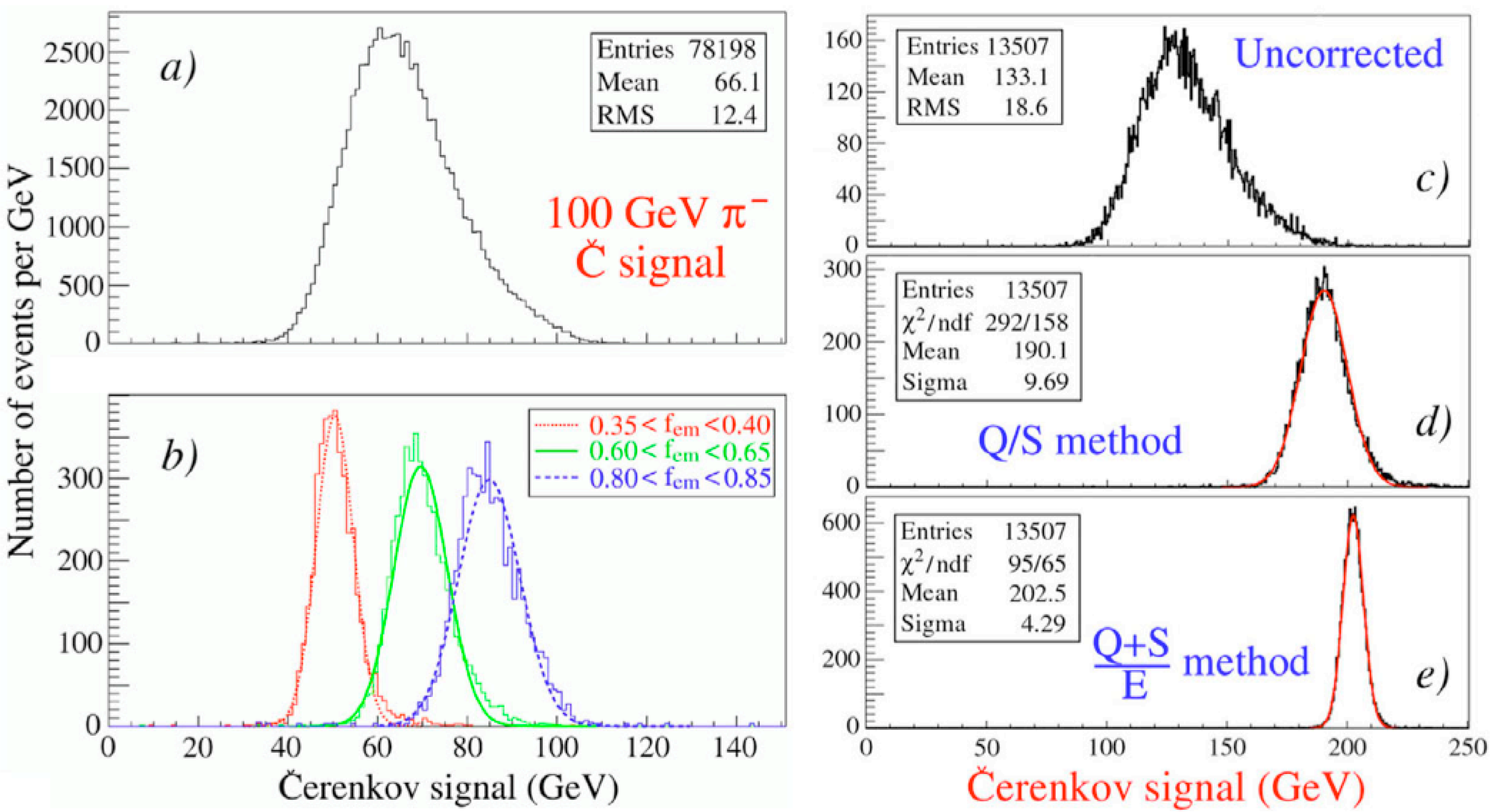
e.g. If $e/h = 1.3\ (S),\ 4.7\ (Q)$

$$\frac{Q}{S} = \frac{f_{em} + 0.21\,(1 - f_{em})}{f_{em} + 0.77\,(1 - f_{em})} \qquad (3)$$

$$E = \frac{S - \chi Q}{1 - \chi} \qquad (4)$$

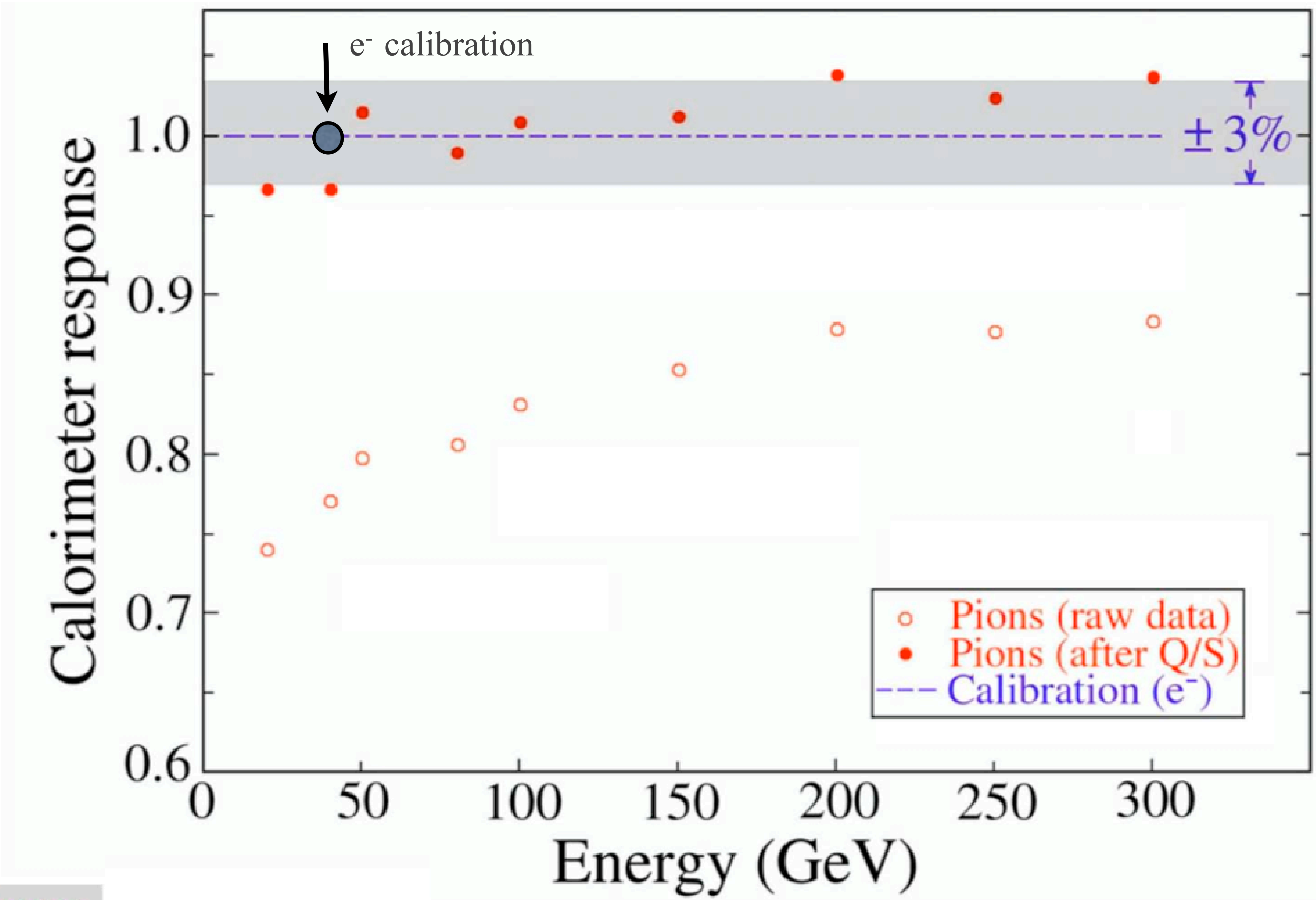
with $\chi = \dfrac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

The asymmetric, non-Gaussian, broad, off-energy response function is the sum of narrow Gaussians !



Hadronic response linearity

1/2 μ beam energy



From:
NIM A537 (2005) 537

After the easy success with the DREAM module, we immediately began to think of improvements

- Cerenkov photo-electron statistics (~8pe/GeV) limited the EM resolution and f_{EM} measurement, and therefore the hadronic energy resolution ... try crystals for dual-readout.

- next largest fluctuation is the binding energy loss fluctuations in nuclear break-up, proportional to the MeV neutrons liberated in the shower ... measure late $S_{pe}(t)$.

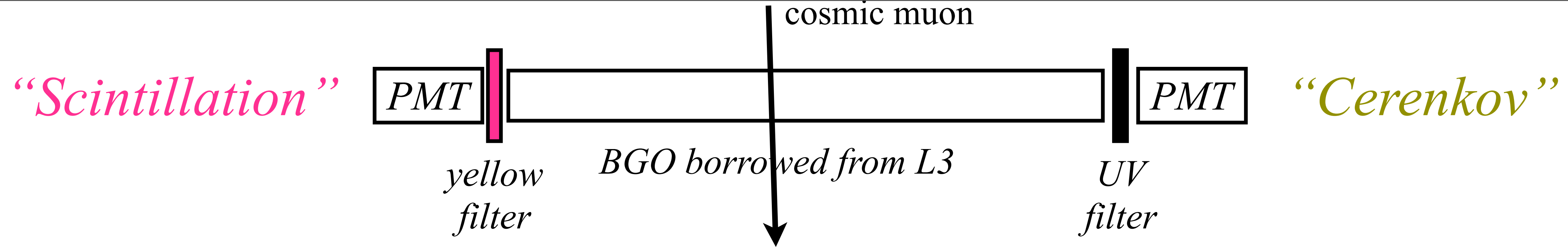
- leakage only suppressed by more mass (and $), so make crude measurement of leakage (mostly neutrons).

Crystals as dual-readout media

The DREAM collaboration has tested several crystals as dual-readout media, and all can be made to work (good reference: Silvia Franchino talk at TIPP09):

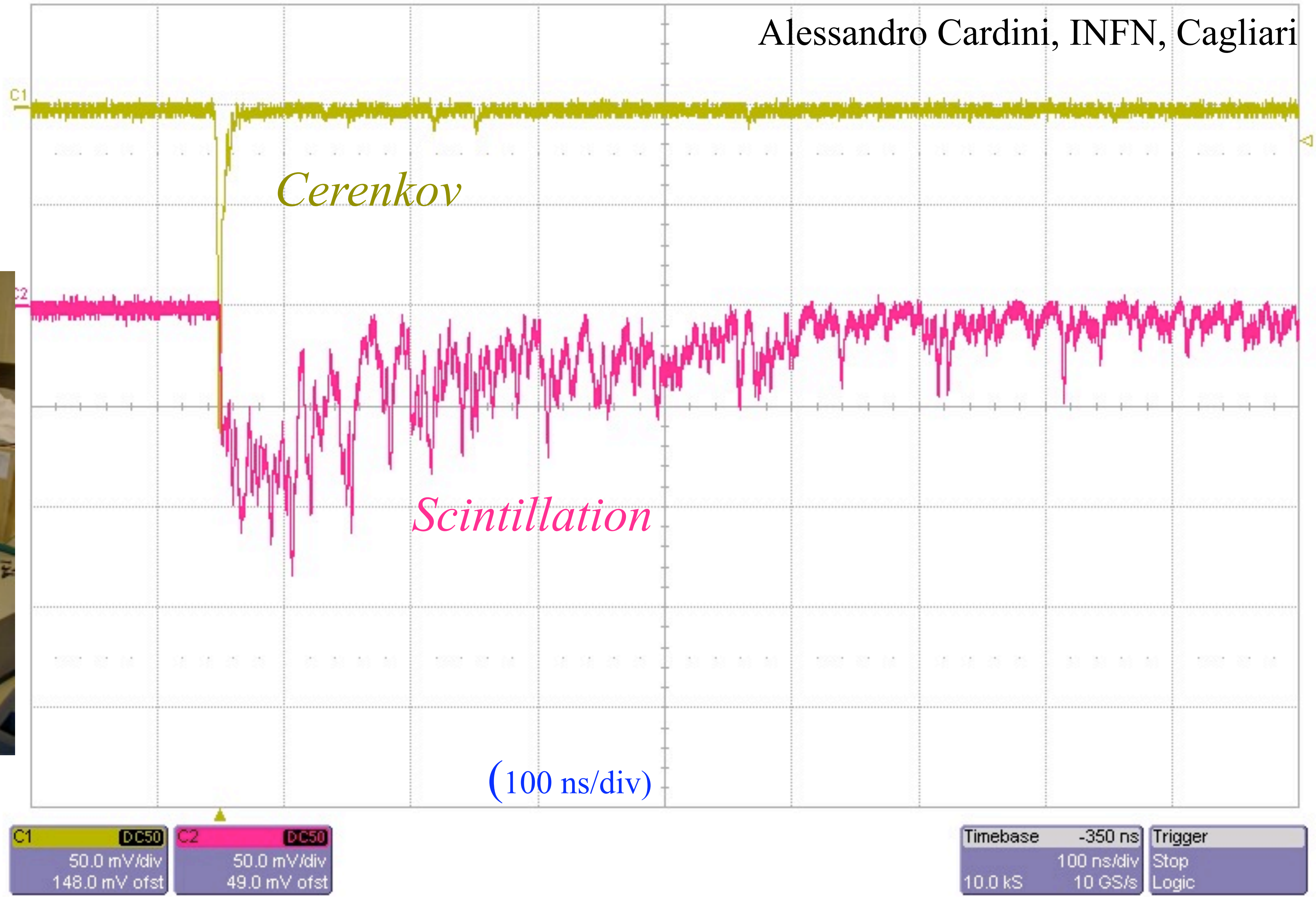
- $PbWO_4$ is hard ("too fast, too blue, and too luminous")
- $PbWO_4$:Pr is OK, but too slow
- $PbWO_4$:Mo is OK, but too much attenuation
- BGO is easy, and it is in 4th design (although we want a less expensive replacement, e.g., BSO)

- We are thinking of many more crystals (better doped $PbWO_4$, doped PbF_2, etc.)



BGO ...

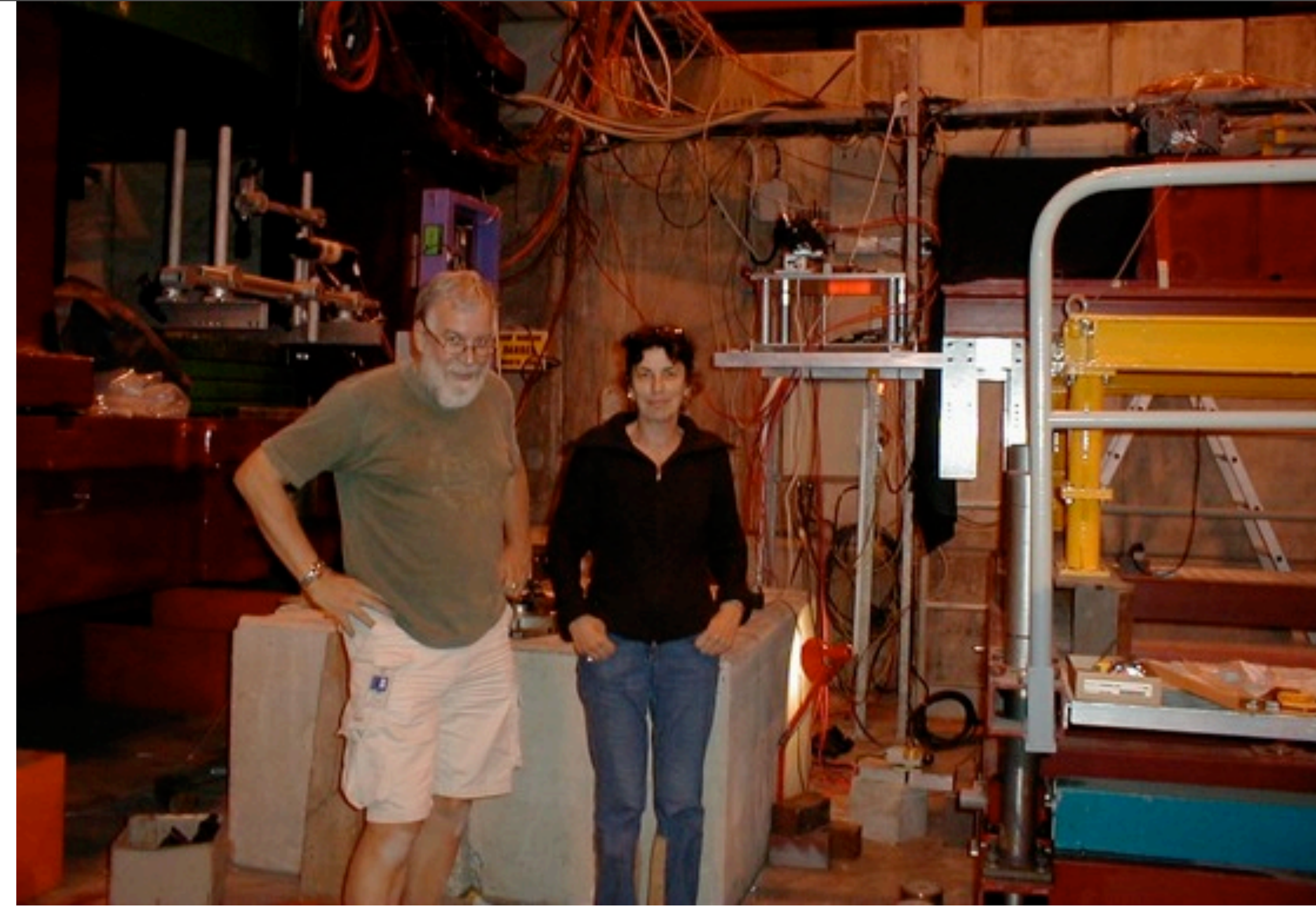
by time and wavelength

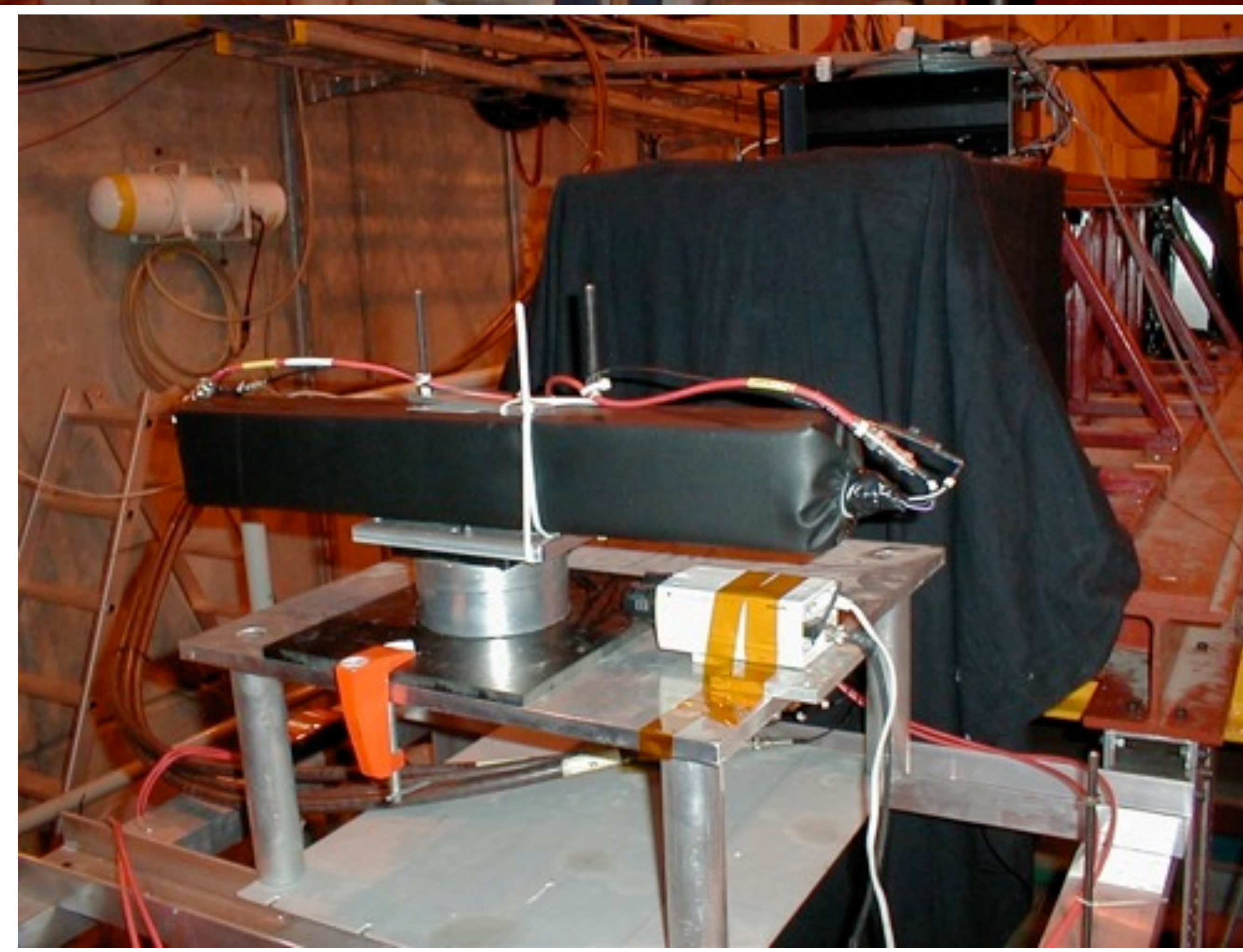


We can now do dual-readout in a single crystal ==> EM precision

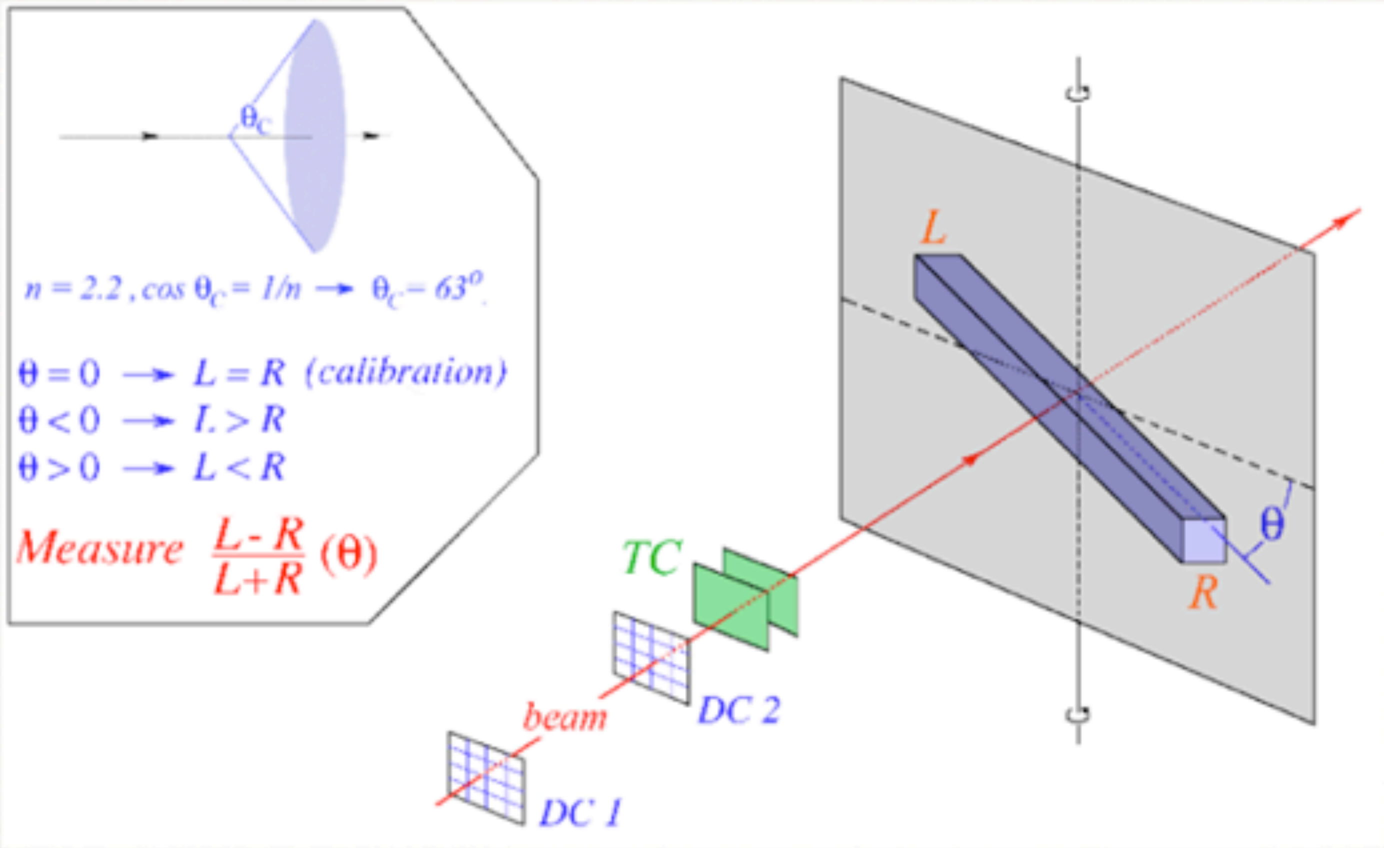
Dual-readout of BGO crystals

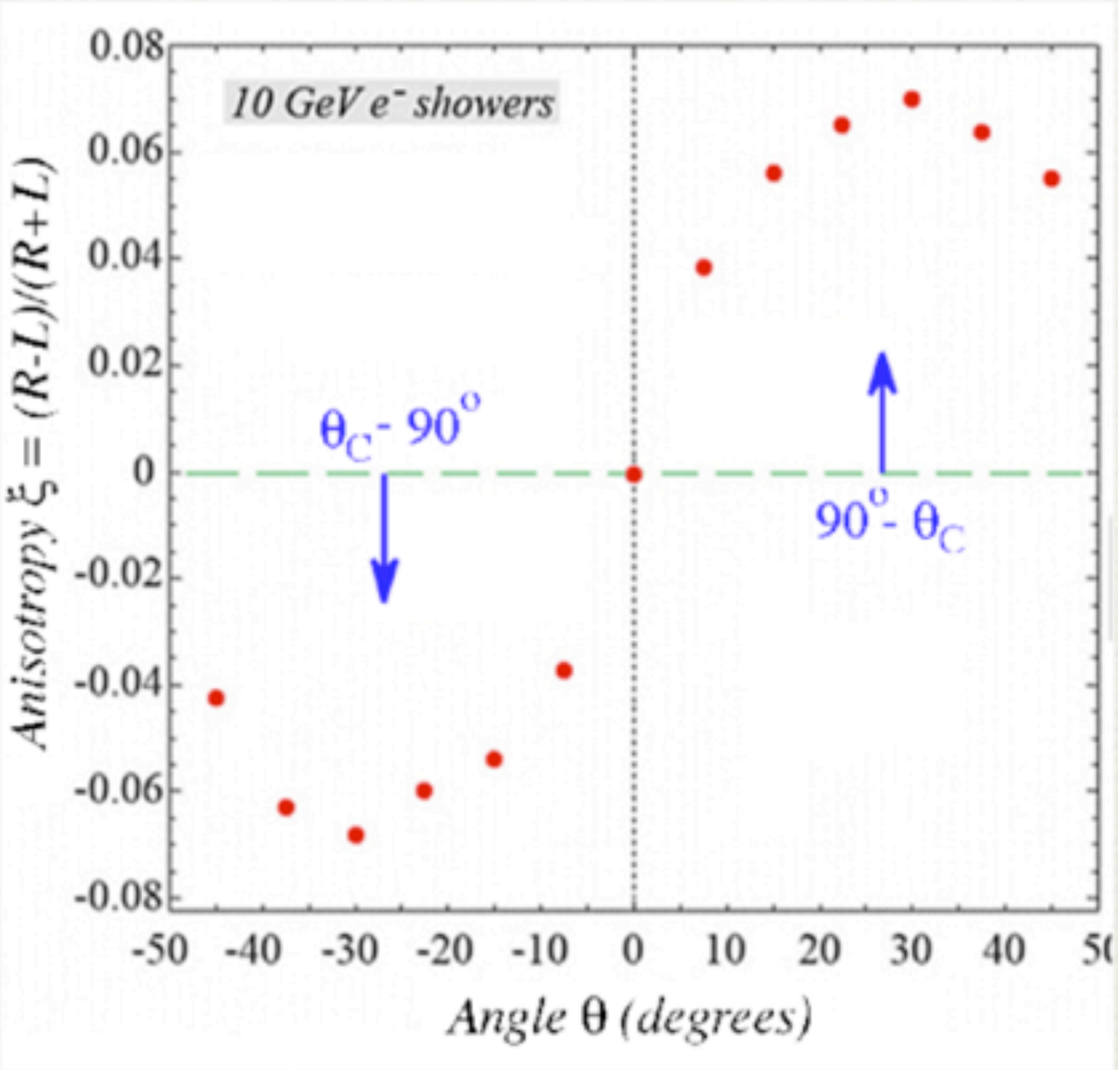
BGO crystal, its housing, and in the beam in front of DREAM module





Lead Tungstate ($PbWO_4$) - I





- Take advantage of directionality of Cherenkov light to observe asymmetry as a function of angle of incidence between Left and Right

Lead Tungstate ($PbWO_4$) - II

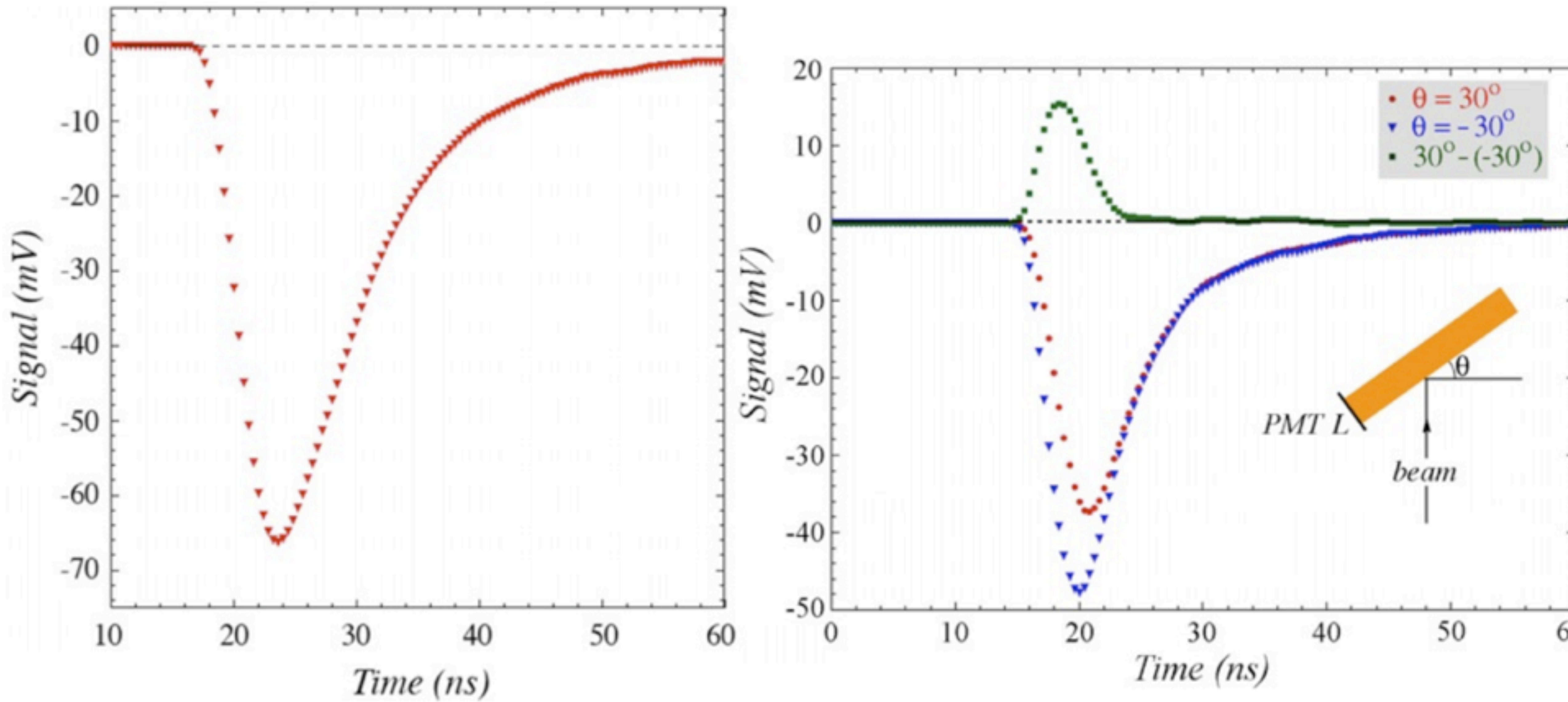
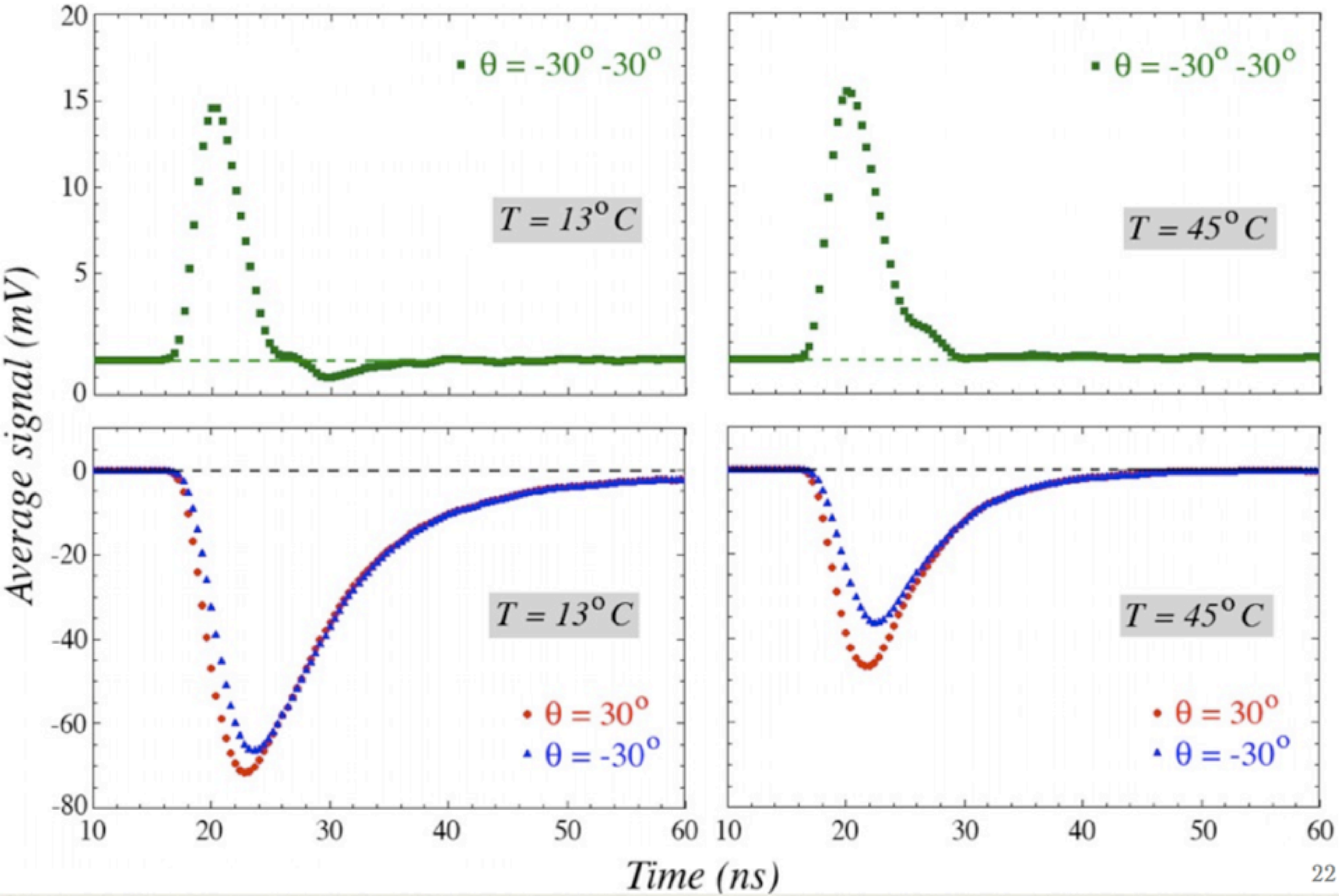


Figure 12: Average time structure of the signals measured with the PMT reading out one end (L) of a $PbWO_4$ crystal traversed by 10 GeV electrons, for two different orientations of the crystal, and the difference between these two time distributions. At $\theta = -30°$, Čerenkov light contributes to the signals, at $\theta = 30°$, it does not [14, 15]. When the crystal was read out from the other side, the prompt excess signal was detected for $\theta = 30°$, and was absent for $\theta = -30°$ [15].

Lead Tungstate ($PbWO_4$) - III



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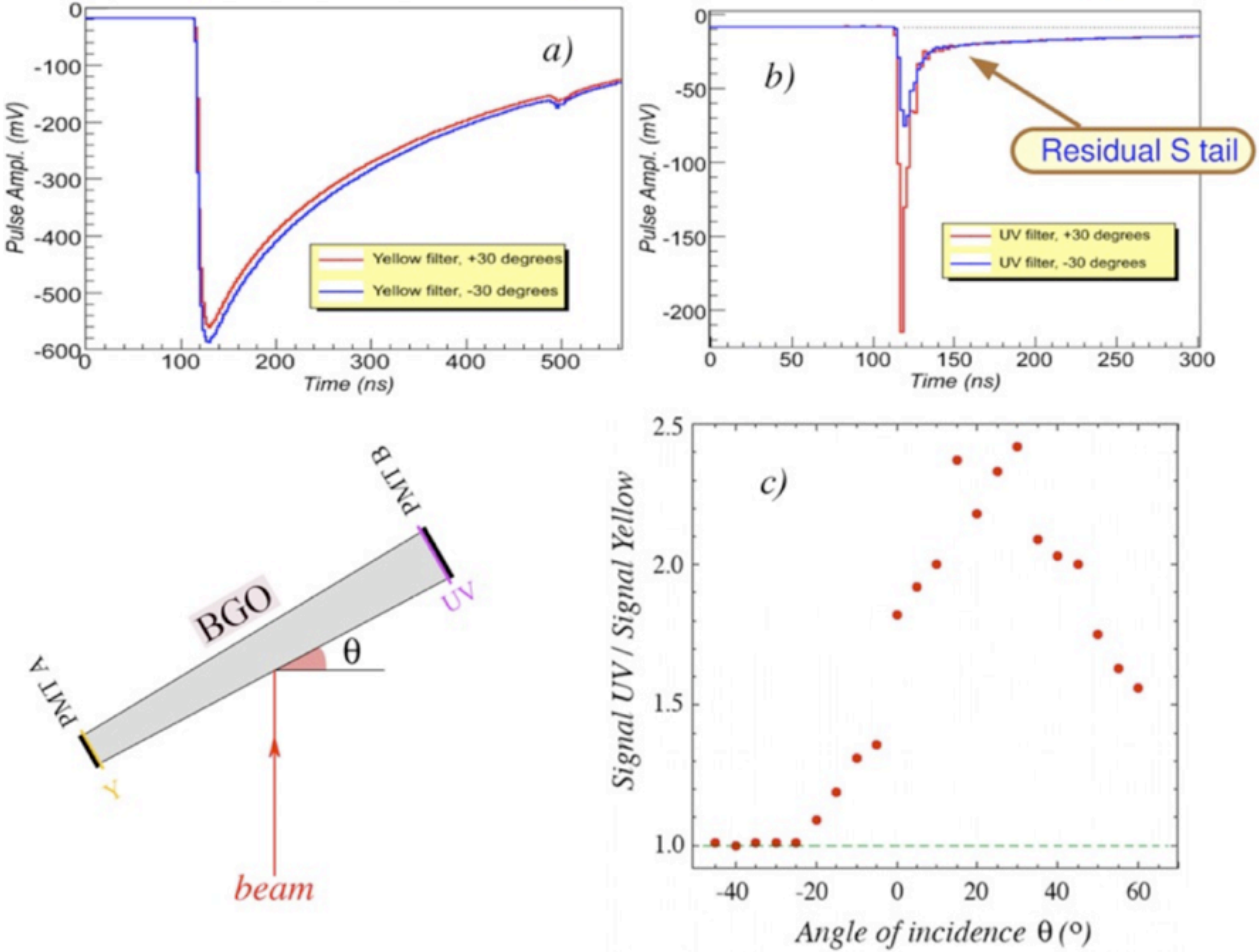
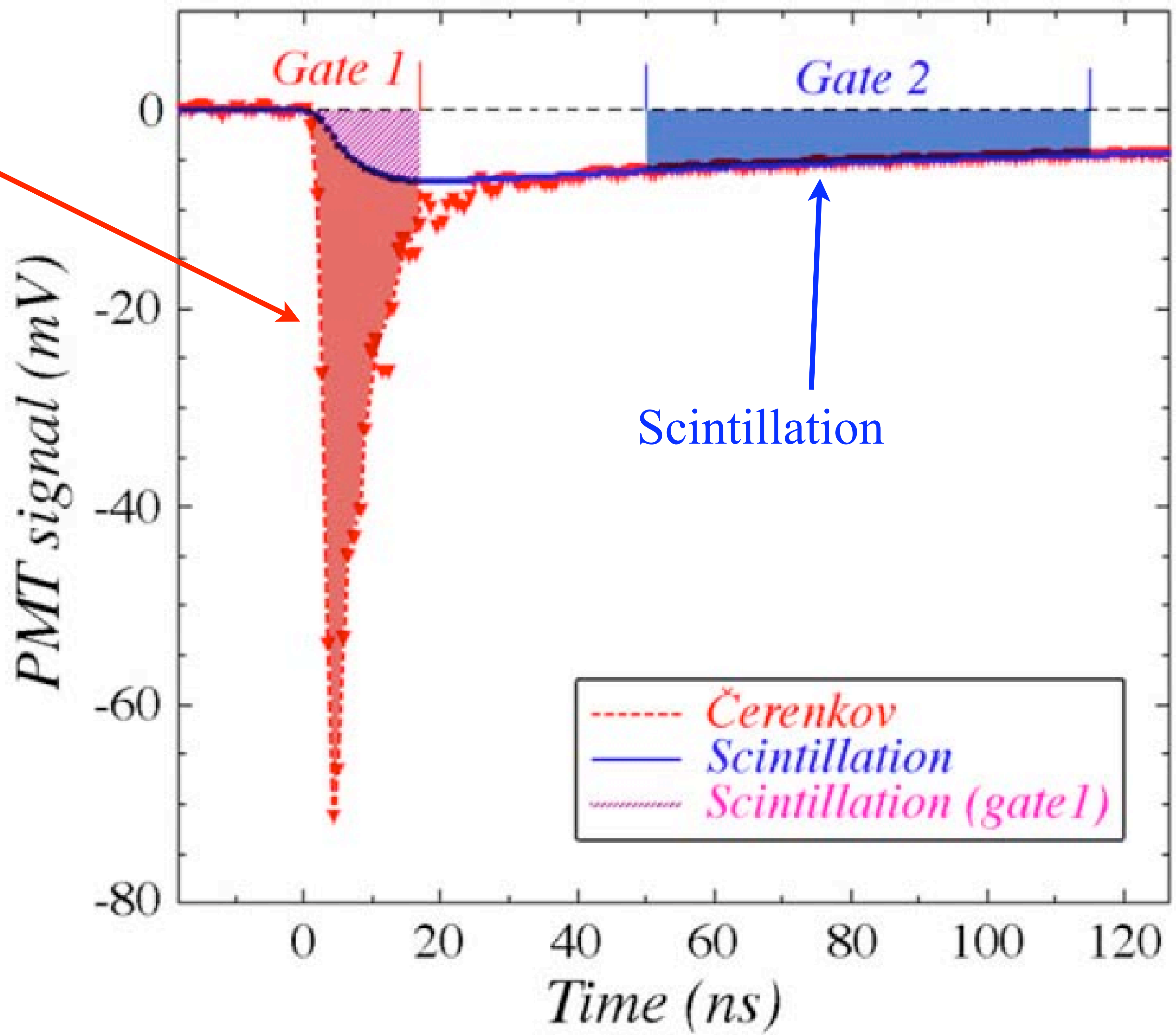
BGO - II


a)
Pulse Ampl. (mV)
Time (ns)
Yellow filter, +30 degrees
Yellow filter, -30 degrees
b)
Residual S tail
UV filter, +30 degrees
UV filter, -30 degrees
PMT B
PMT A
BGO
UV
Y
θ
beam
c)
Signal UV / Signal Yellow
Angle of incidence θ (°)

BGO crystals are easy by two different techniques:

BGO crystal + 1 PMT
+ 2 timing gates

Cerenkov



Scintillation

All-crystal hadronic dual-readout calorimeter:

(Adam Para and Hans Wenzel, et al.)

Good: lots of light, can make small volumes read by SiPMs, and bridge to PFA ideas. Can make almost any shape of crystal (or glass). These alone justify the work.

Not-so-good: our experience with crystals is not completely positive. For a 1% calorimeter, the light yield must be controlled to 1%, therefore every bounce counts: every refraction, every reflection, every transfer of light from one medium into the next. Nothing fundamental, just requires careful "optical engineering" (and maybe money).

“4th geometry” CERN beam test of BGO array with DREAM module behind, plus neutron leakage counters.

e, μ, π

20-300 GeV

Dual-Readout Calorimetry with a Full-Size BGO Electromagnetic Section

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Published to *Nucl. Instrs. Meths.*

17th DREAM paper

Abstract

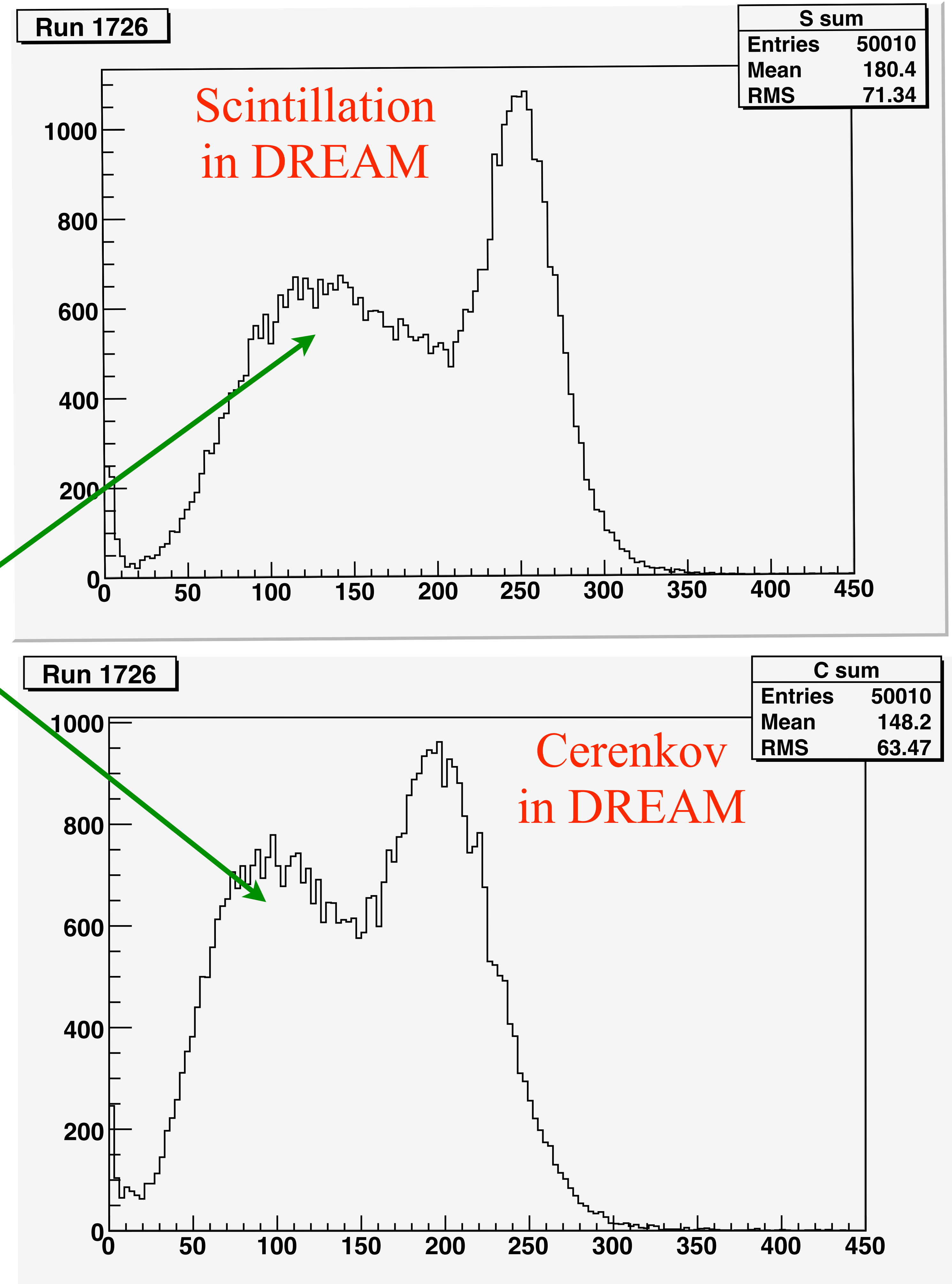
Beam tests of a hybrid dual-readout calorimeter are described. The electromagnetic section of this instrument consists of 100 BGO crystals and the hadronic section is made of copper in which two types of optical fibers are embedded. The electromagnetic fraction of hadronic showers developing in this calorimeter system is determined event by event from the relative amounts of Čerenkov light and scintillation light produced in the shower development. The benefits and limitations of this detector system for the detection of showers induced by single hadrons and by multiparticle jets are investigated. Effects of side leakage on the detector performance are also studied.

PACS: 29.40.Ka, 29.40.Mc, 29.40.Vj

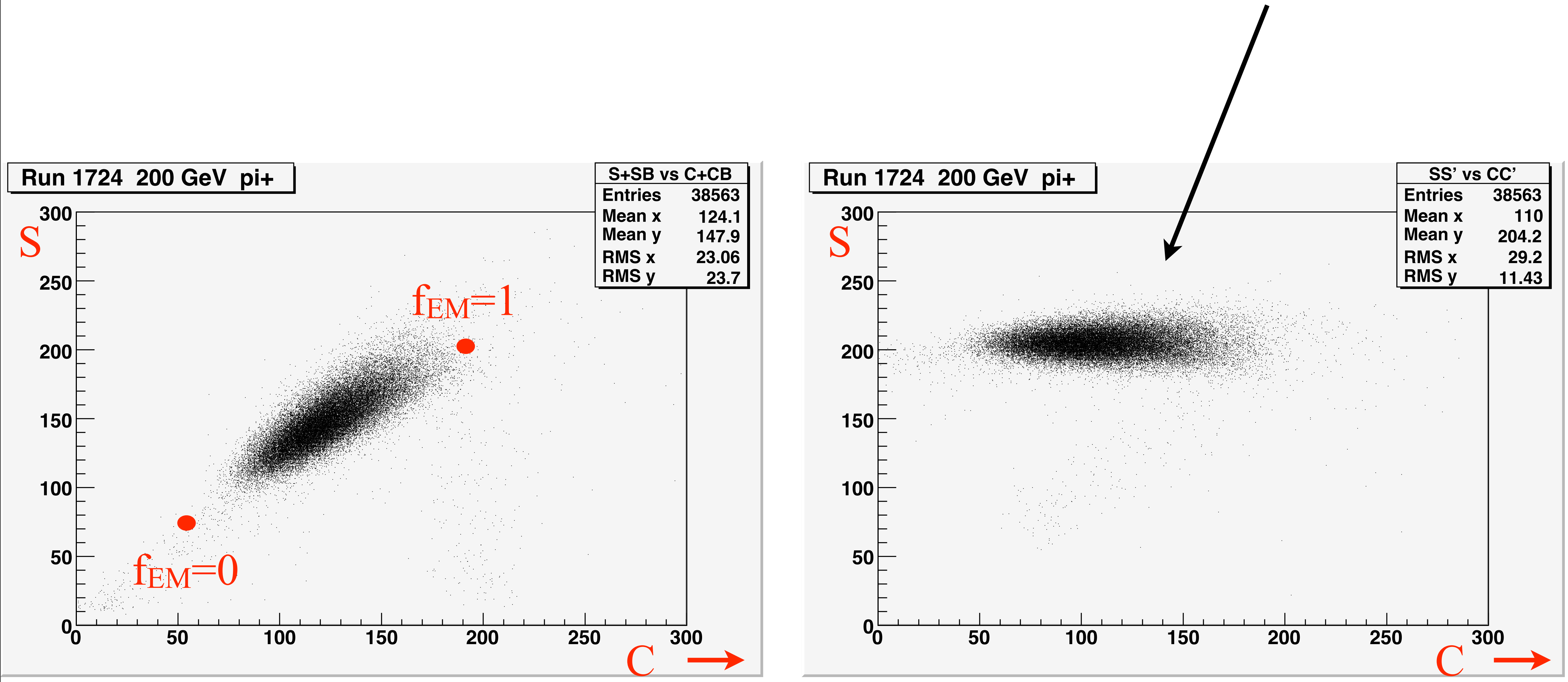
Key words: Calorimetry, Čerenkov light, crystals, optical fibers

The BGO+DREAM calorimeter is a complicated beast. In my opinion, we can still do better with the analysis.

Pion interacted in BGO



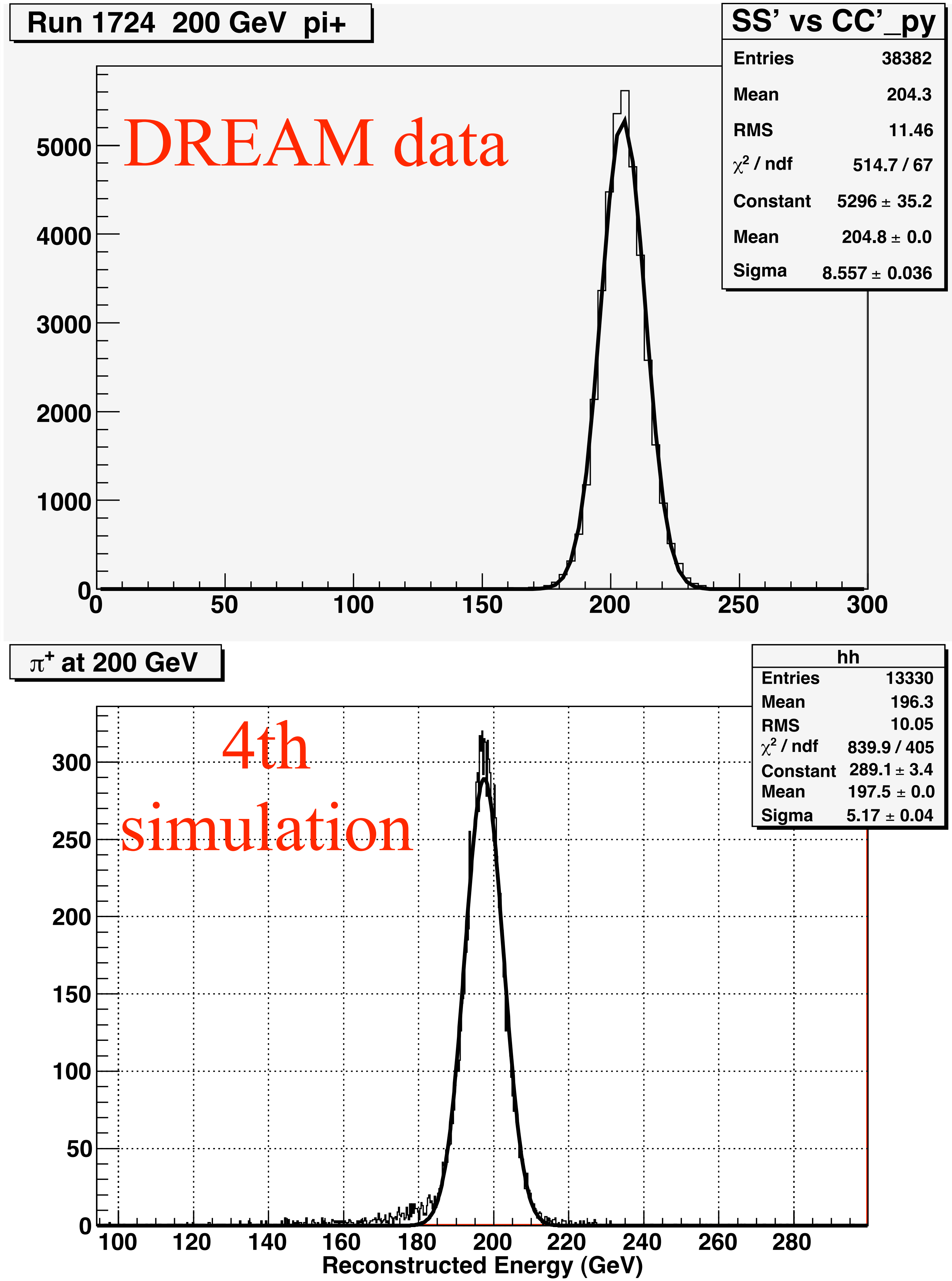
Dual-readout in the BGO+DREAM configuration for 200 GeV pi+. Measuring C allows a simple rotation of this figure, which achieves "compensation".



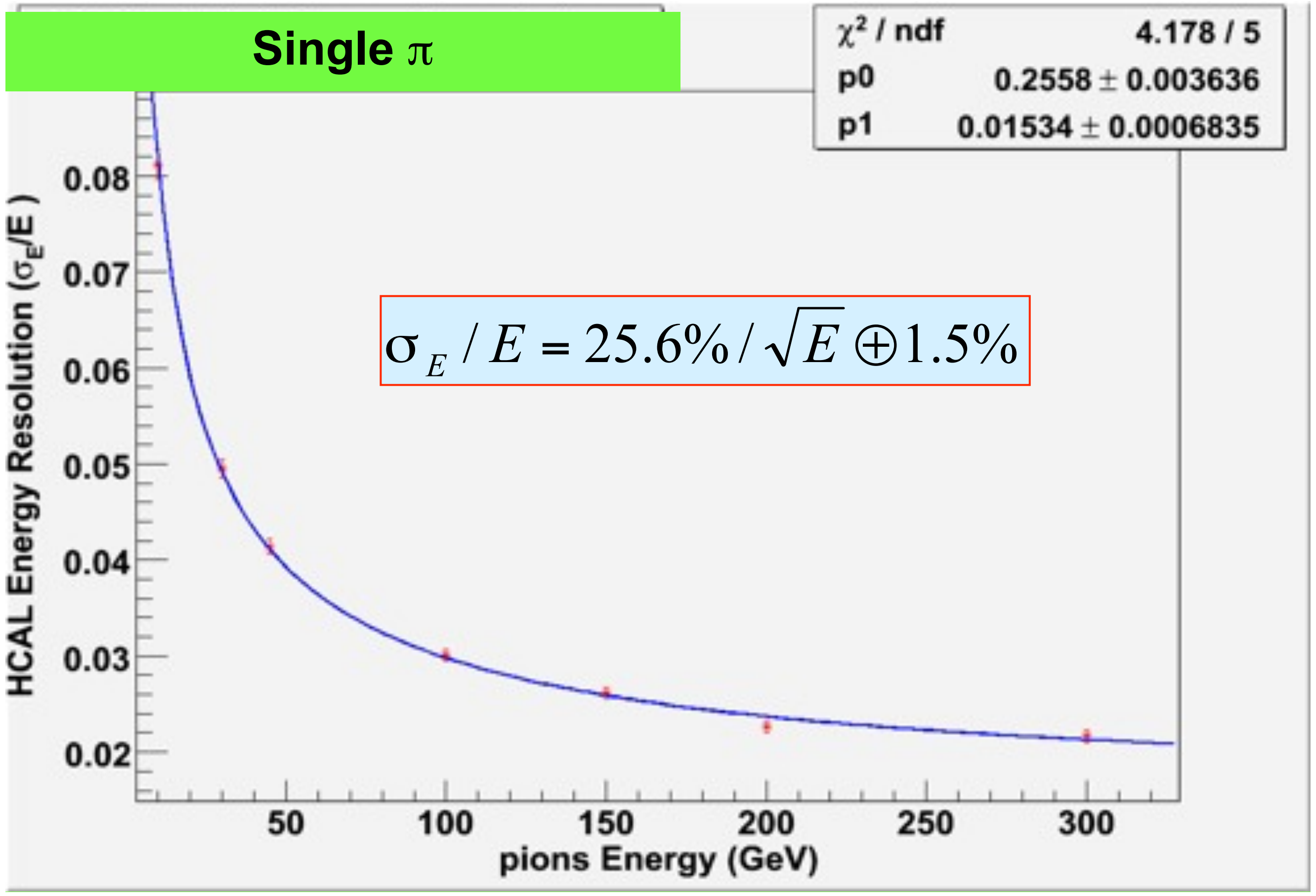
This BGO+DREAM configuration caused us months of grief: to be frank, I do not understand why it works so well when we use ($S+S_{bgo}$) and ($C+C_{bgo}$). I suspect we have more to learn (and more to gain).

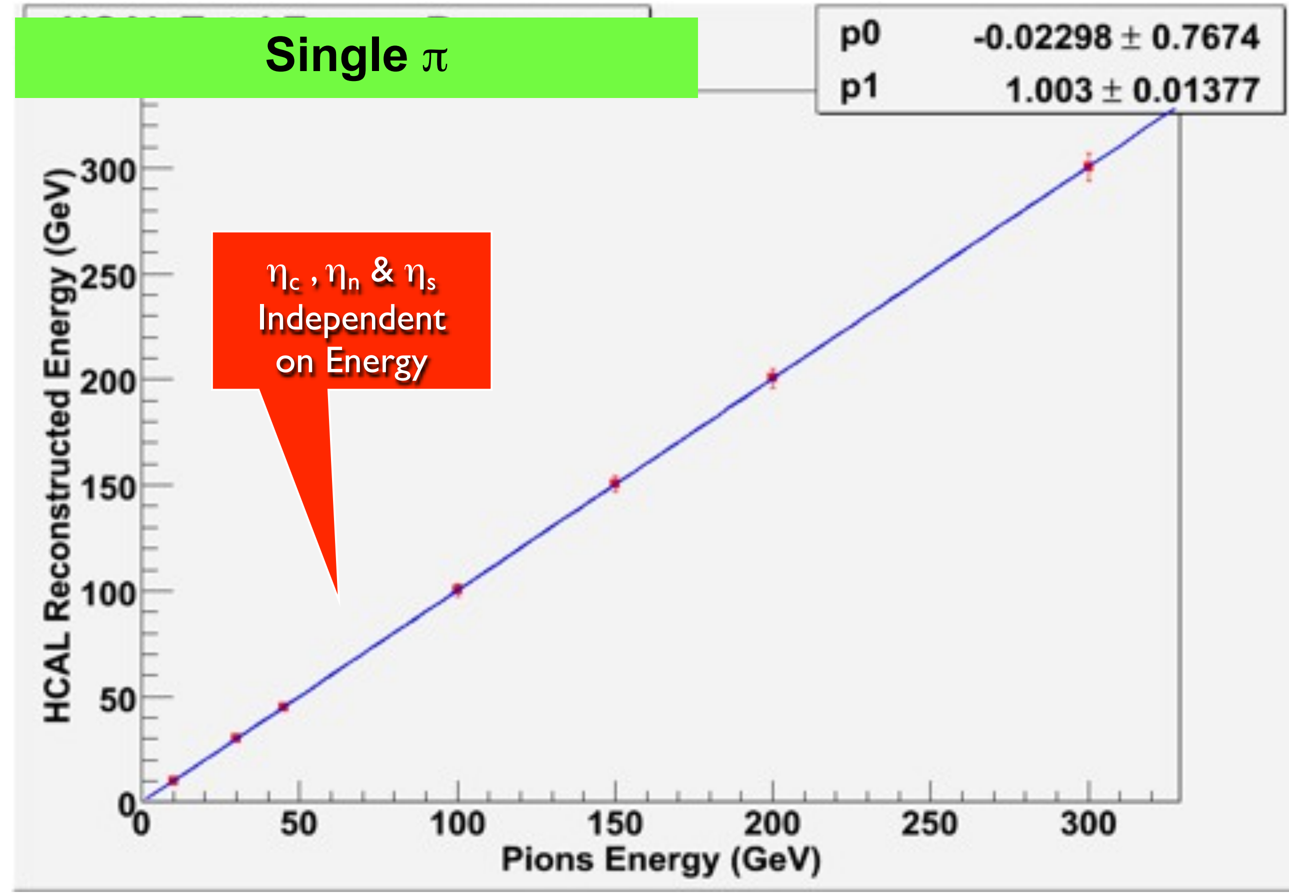
BGO+fiber calorimeter:
DREAM data and 4th simulation

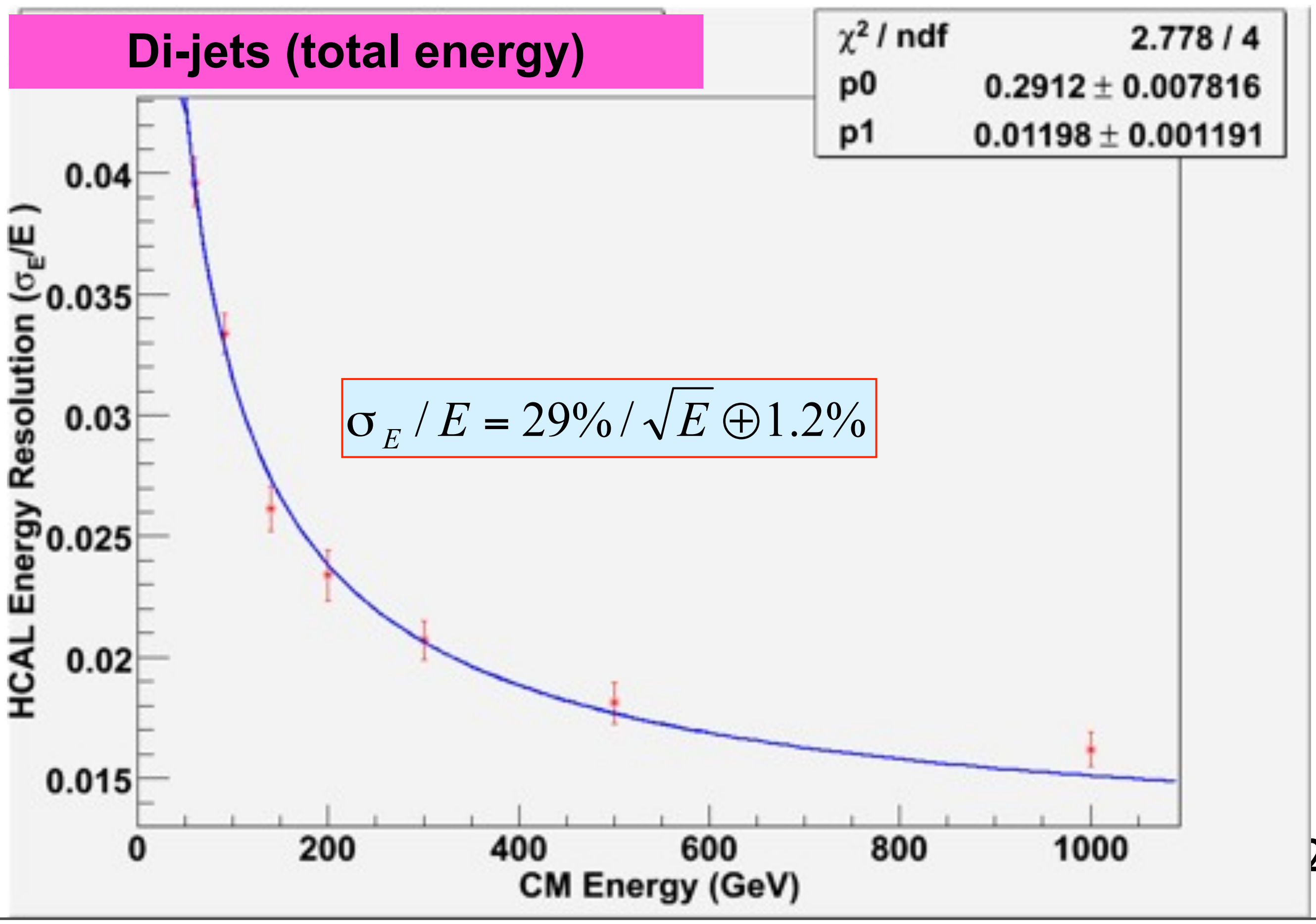
Note the rare occurrence here of the data being “cleaner” than the simulation: no tails, no background. This is because the DREAM module is simple (e.g., uniform fiber density) and we had good control of the beam quality, whereas the simulation is fiber-for-fiber exact with slight non-uniform fiber densities at the boundaries of the modules.

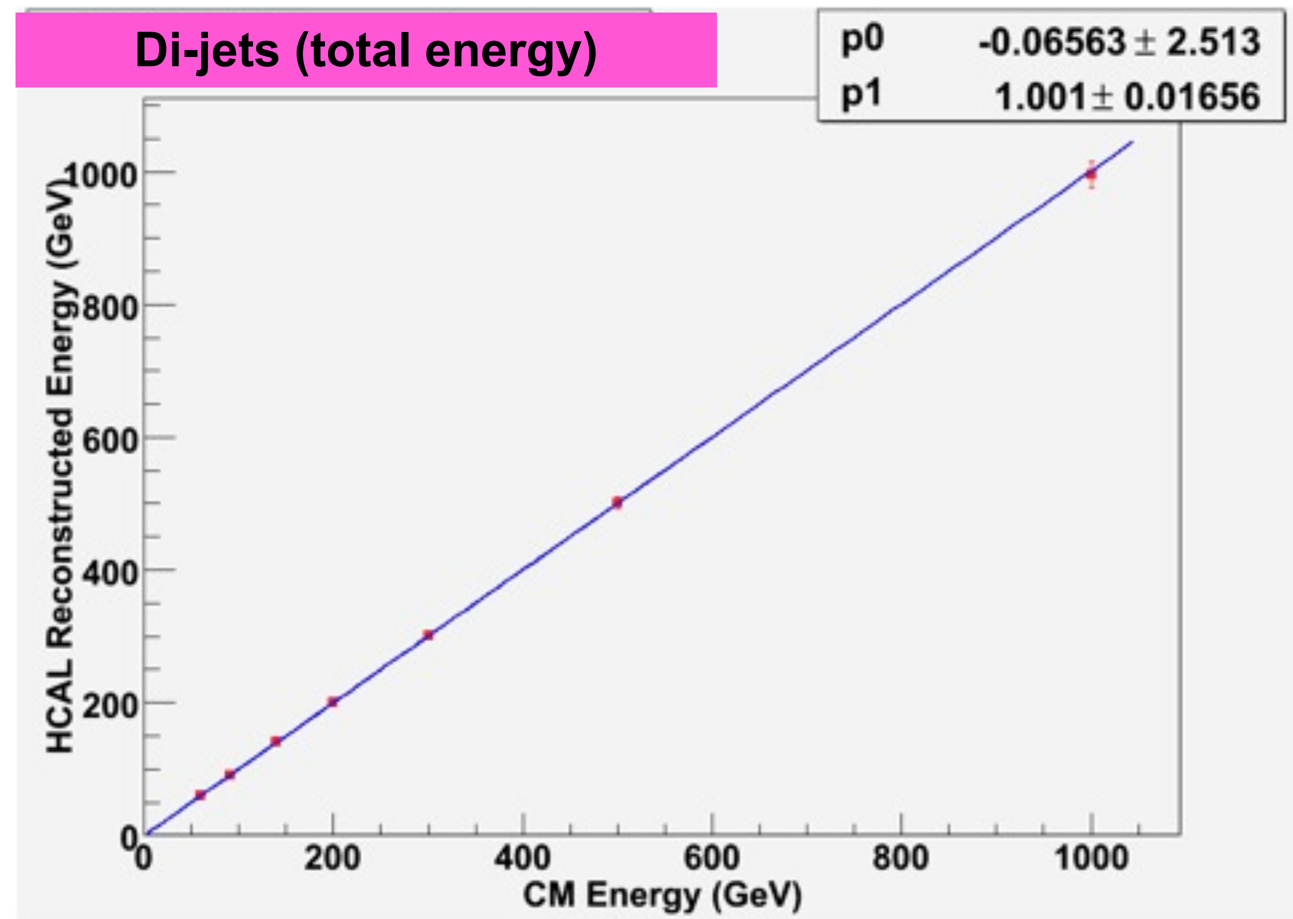


4th dual-readout simulation performance up to 1 TeV









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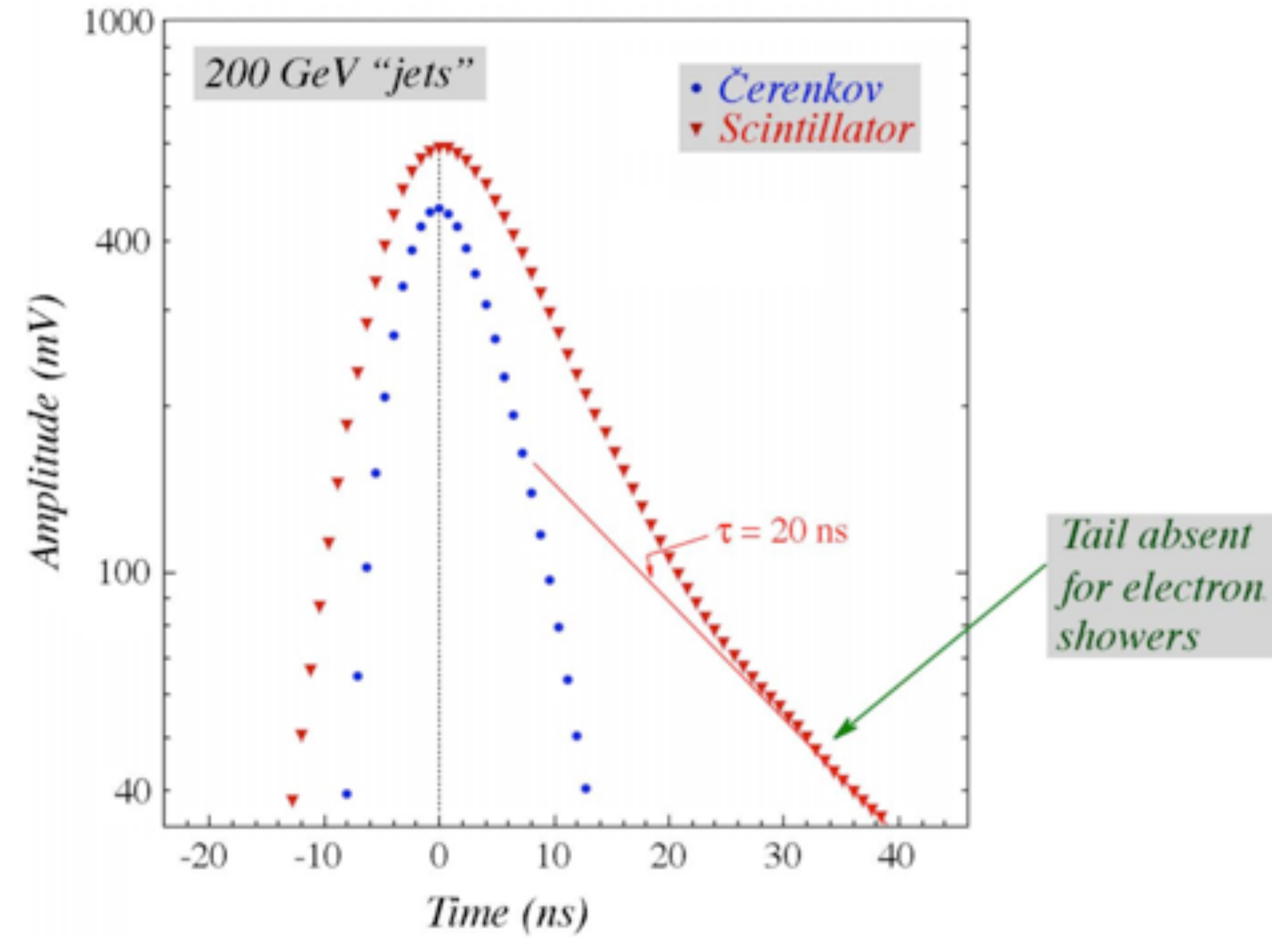
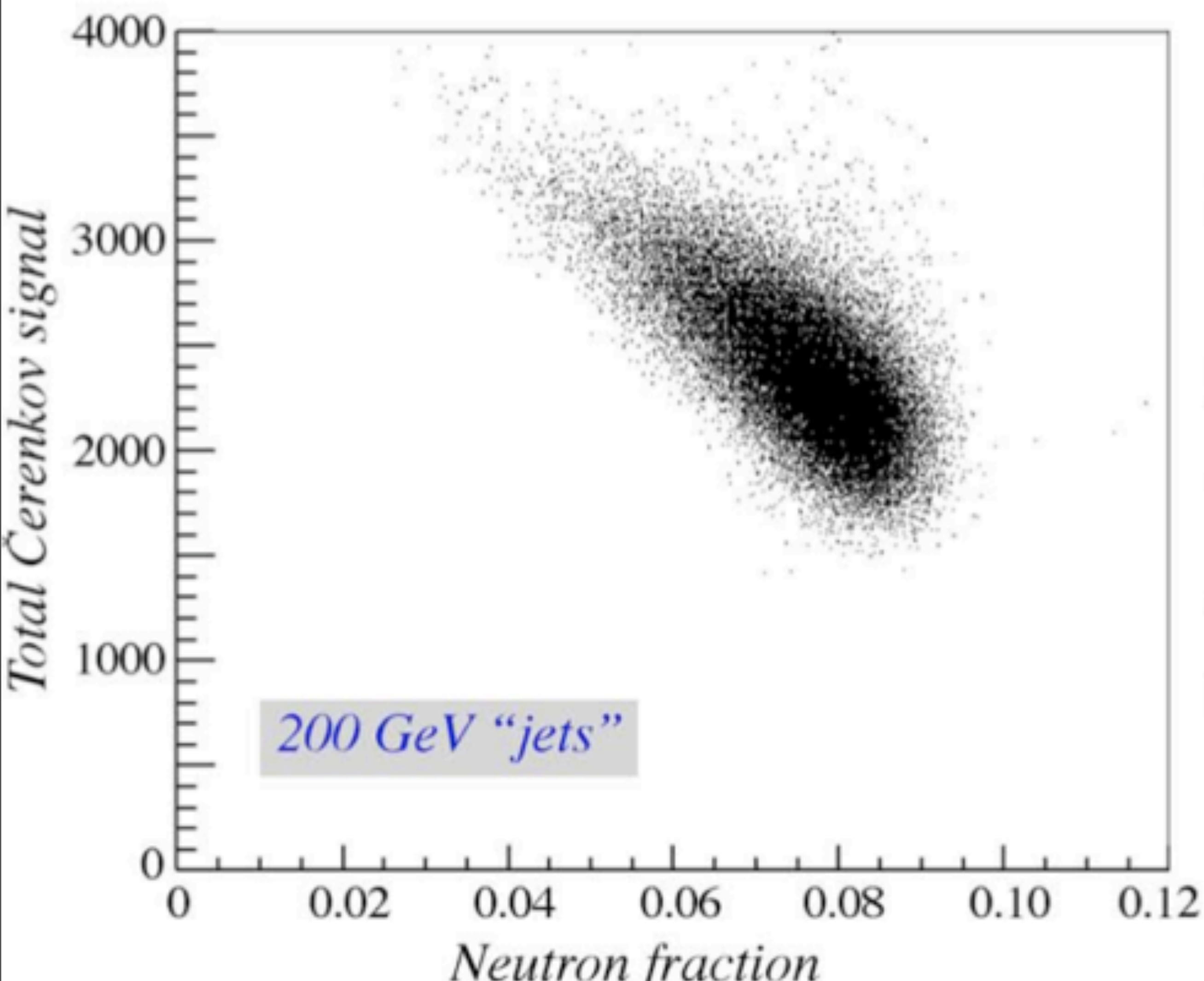
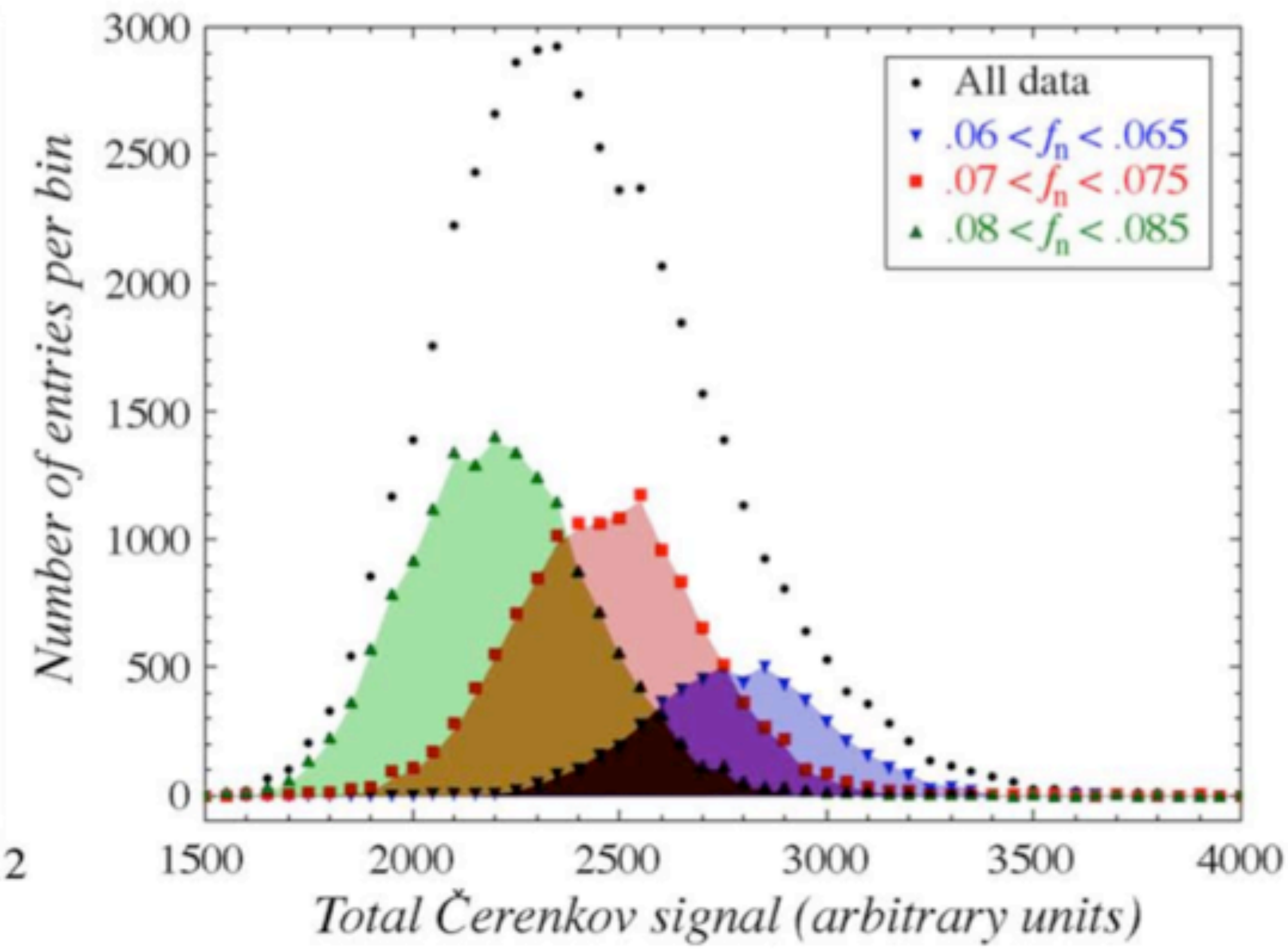
MeV neutrons

Neutron fraction, f_n, measured in scintillating fibers event-by-event:

(1) improve energy resolution
(2) tag "hadronic" showers.

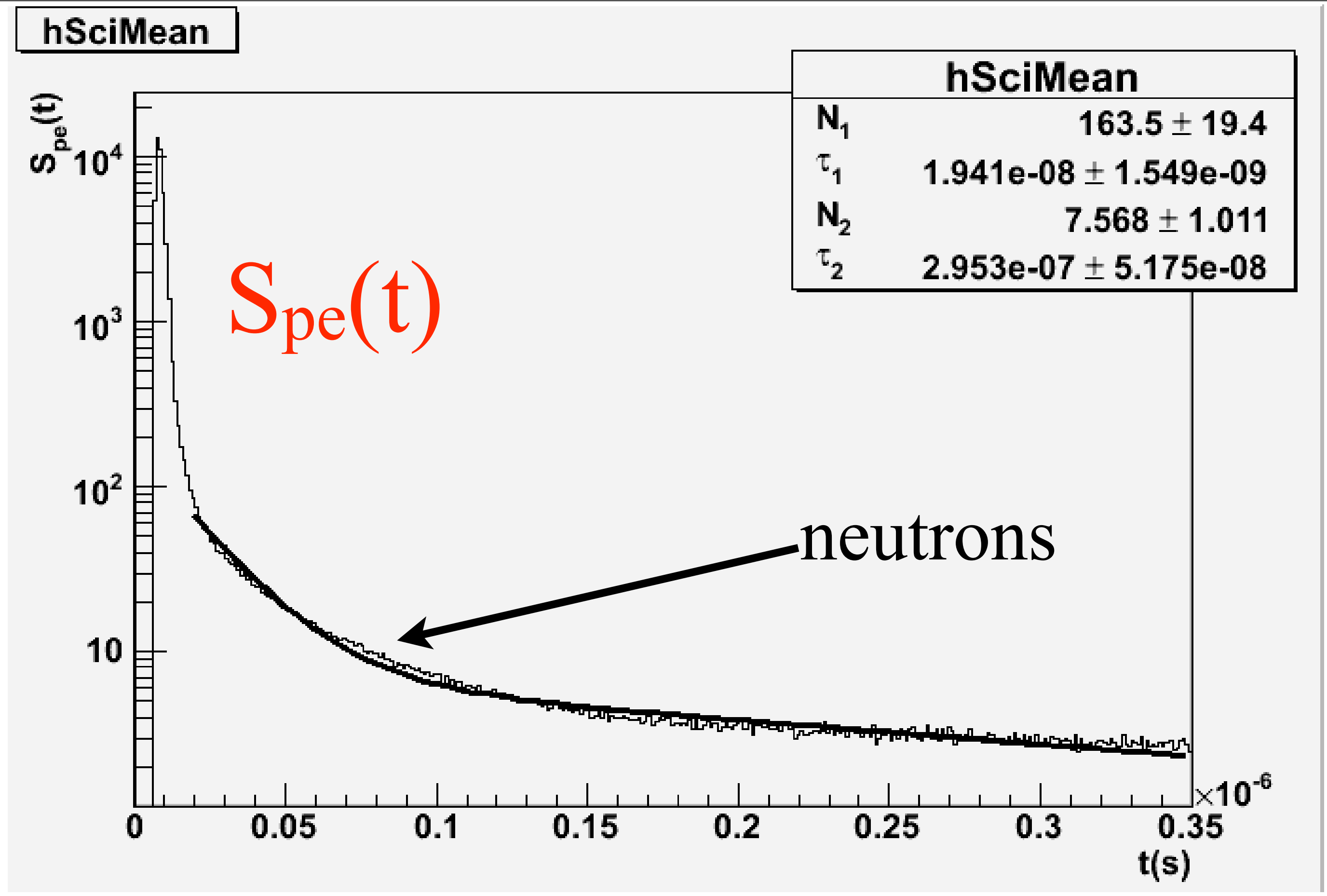


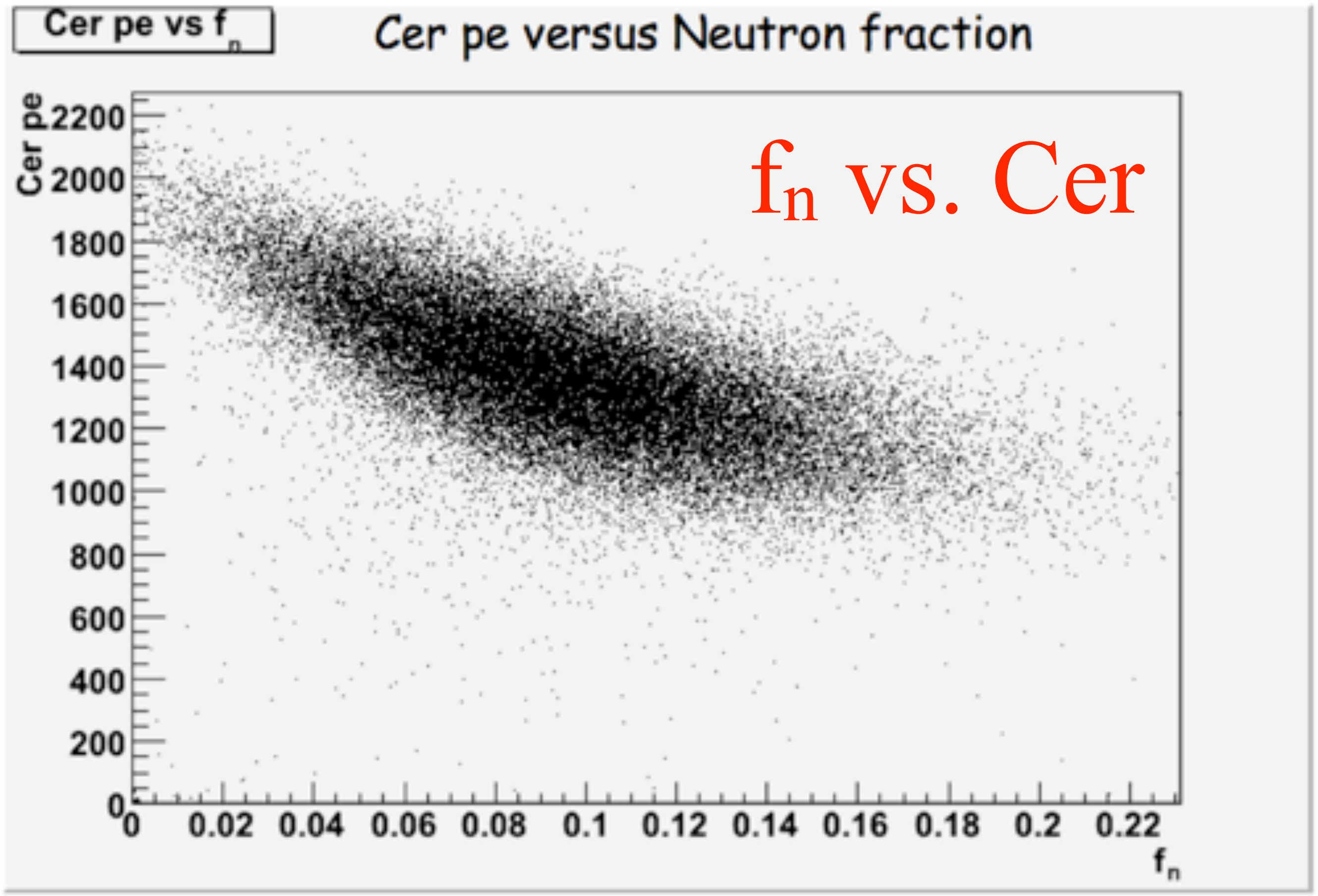




In the 4th simulation, we do the same things:

I find good agreement, considering wide differences between 4th and the small DREAM module





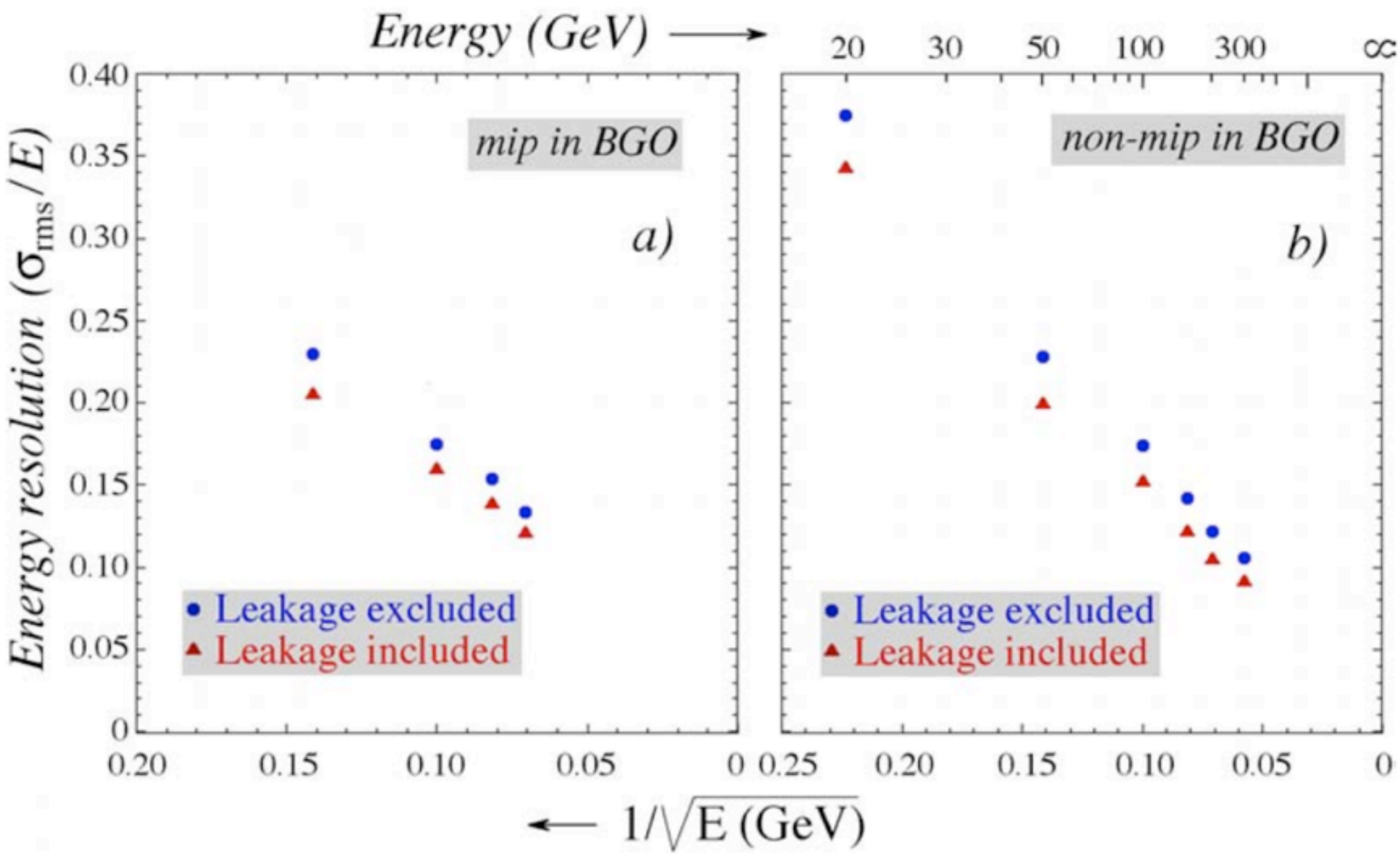
November 18th, 2008

LCWS08 V. Di Benedetto

Leakage from DREAM

Energy resolution of DREAM module improved by 10-15% when leakage counters are included.

(these counters were very crude; try to do better next test)



Particle Identification:

must be a priority for any new detector at a precision collider

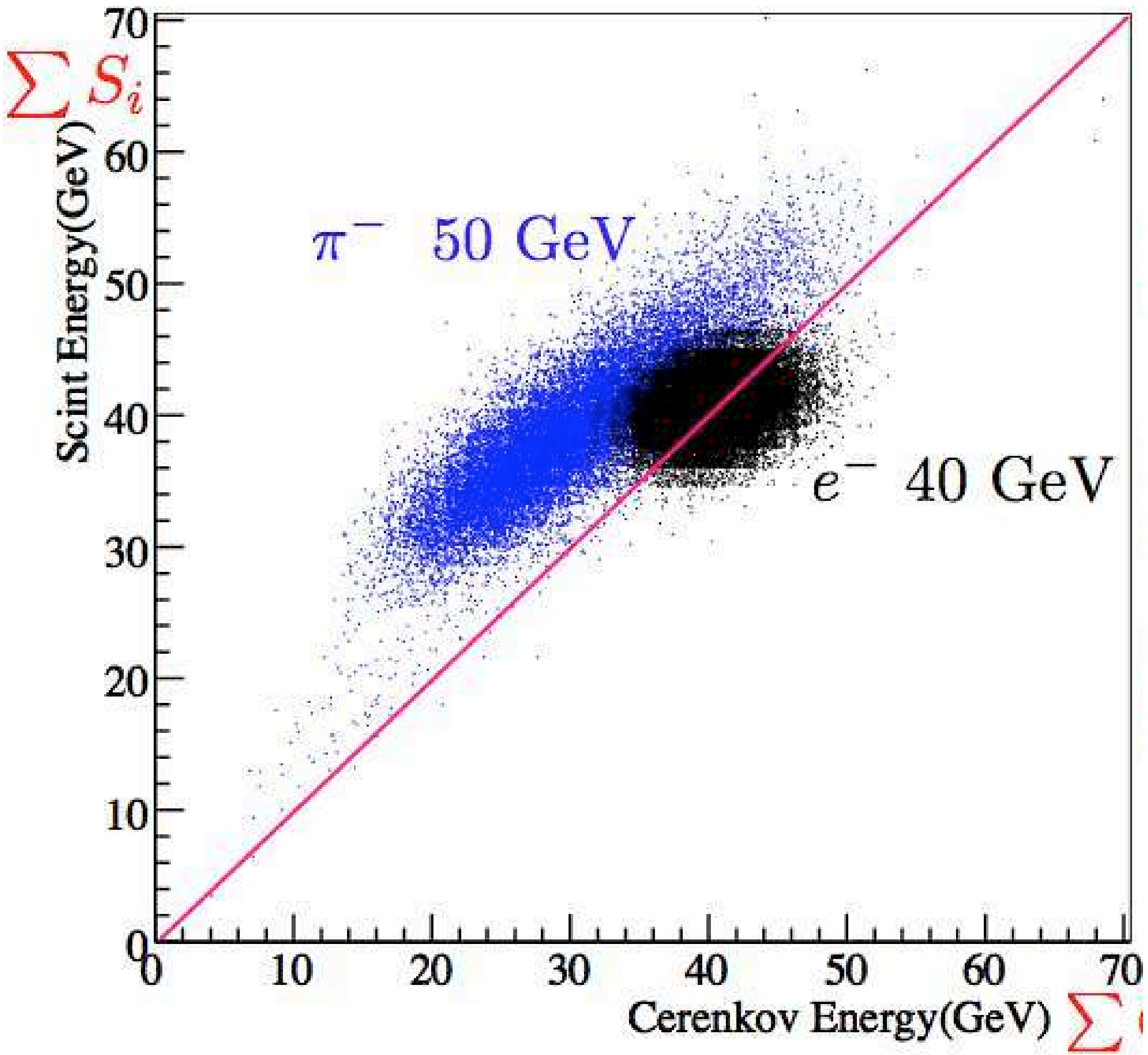
- *uds* quarks (jet energy resolution)
- *c,b* quarks (vertex tagging)
- *t* quark (reconstruction)

- *electron* (dual-readout)
- *muon* (dual-readout and iron-free field)
- *tau* (reconstruction)
- *neutrino* (by subtraction; resolution)

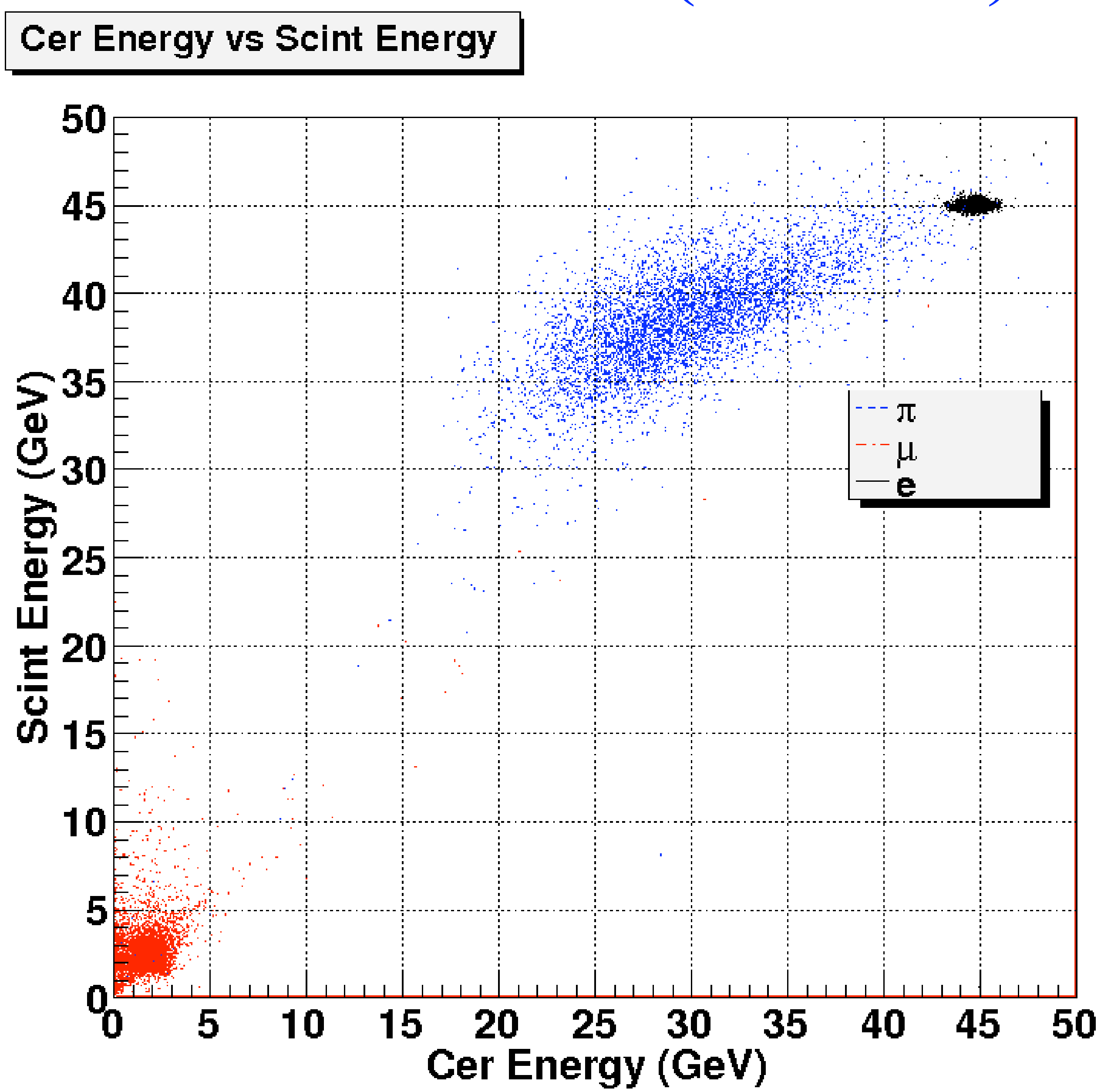
- *W,Z* (hadronic jet reconstruction)
- *photon* (BGO dual readout)

Immediate particle ID from the S vs. C plot

DREAM data

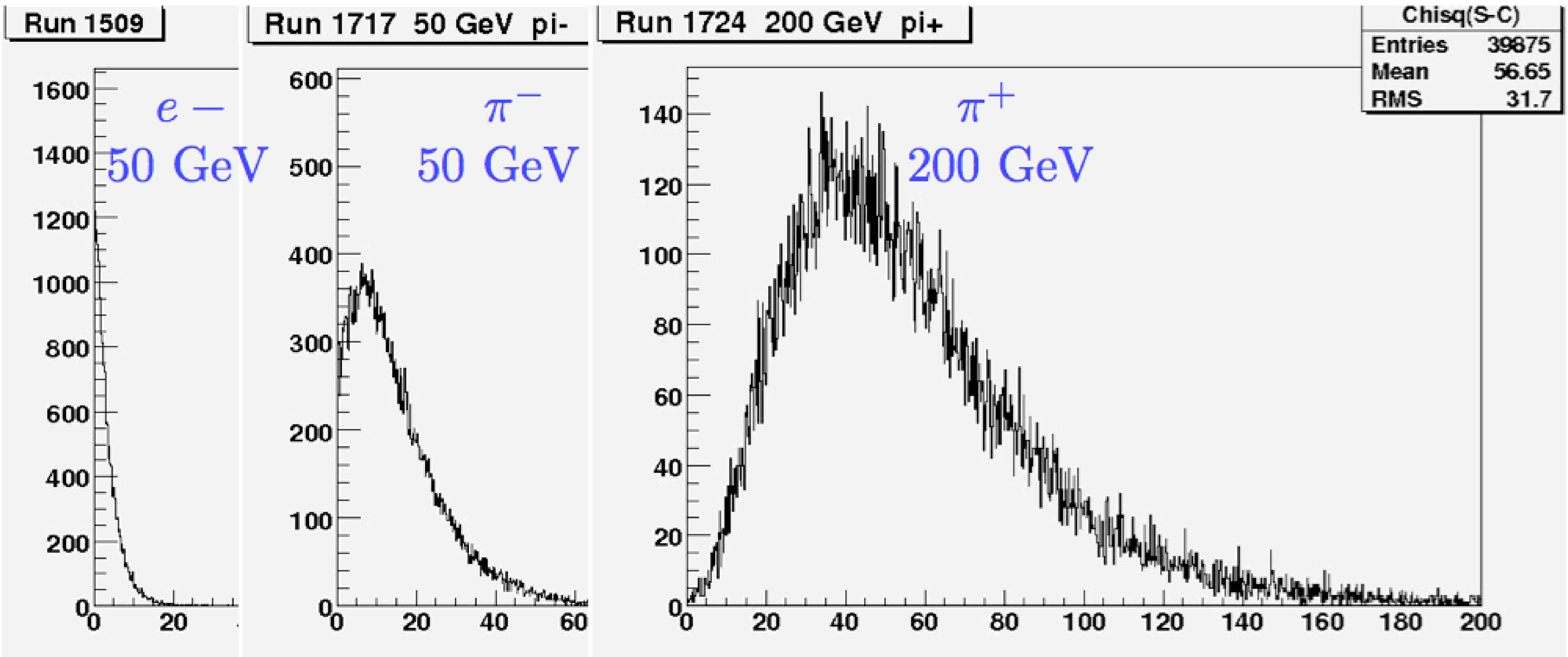


4th simulation (45 GeV)

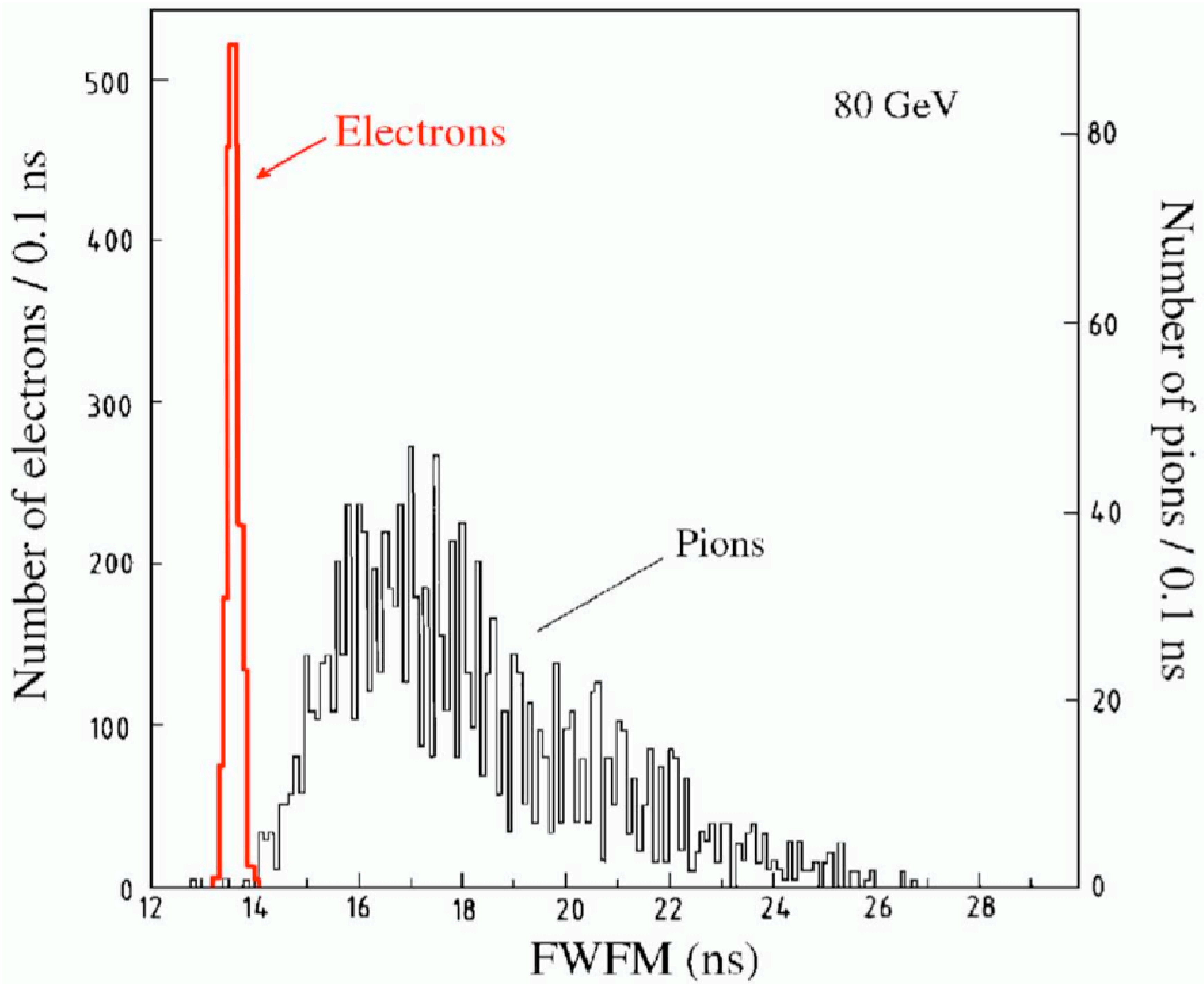


e-π from the fluctuations in S-C among the channels of a shower

$$\chi^2 = \sum_k^N \left[\frac{(S_k - C_k)}{\sigma_k}\right]^2 \quad \sim 0 \text{ for } e^\pm, \text{ large for } \pi^\pm$$

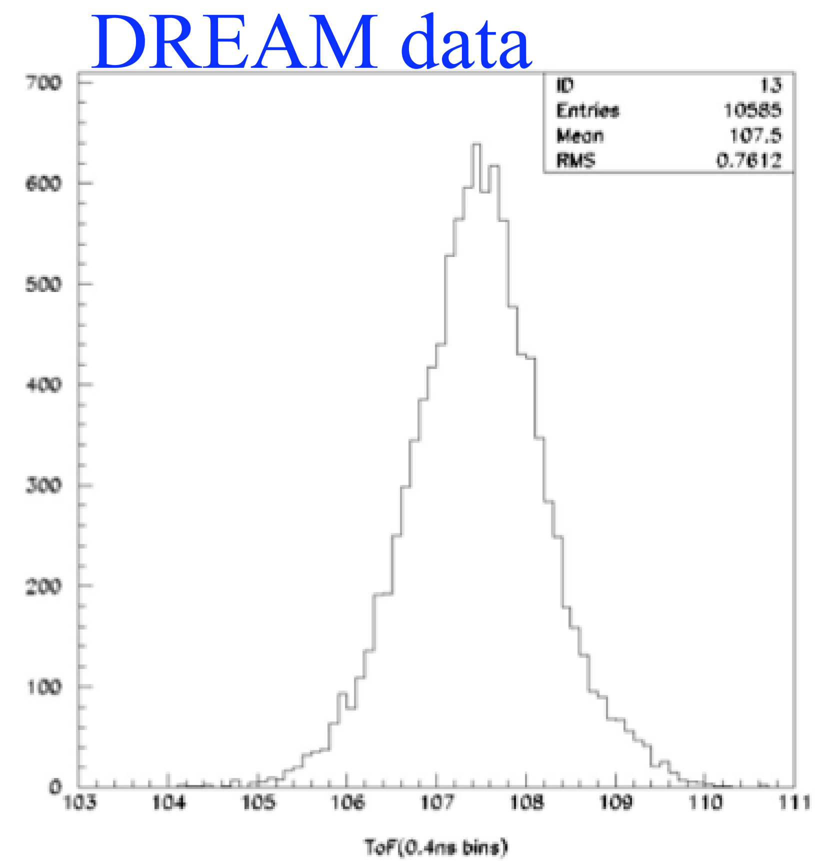


Time-history of scintillating fibers: duration of pulse at 1/5-maximum (SPACAL data)



Time-of-flight in Cerenkov fibers of DREAM

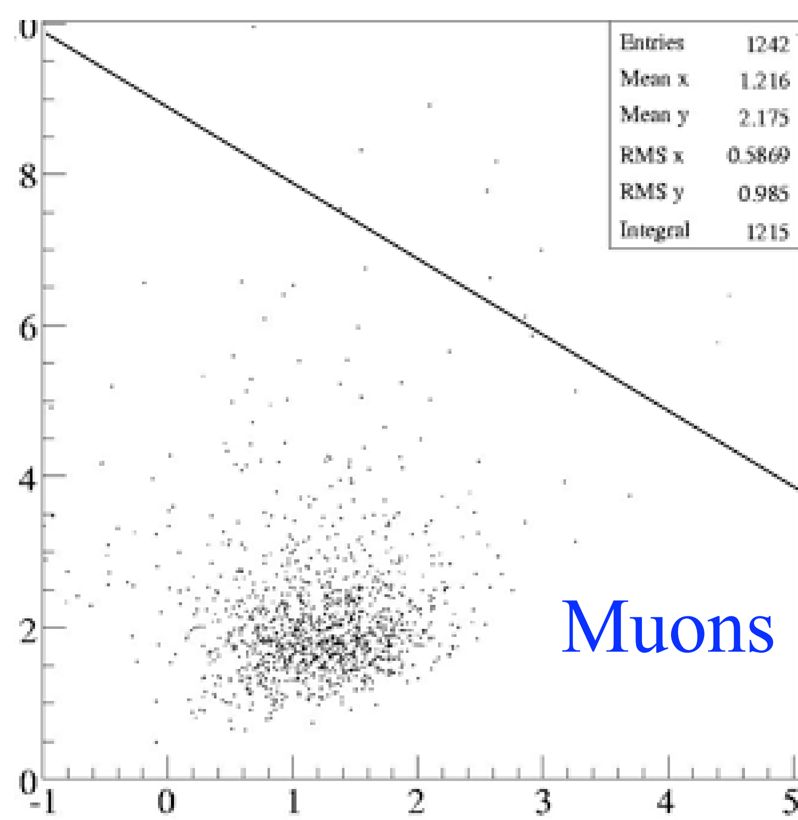
sigma ~ 0.3 ns

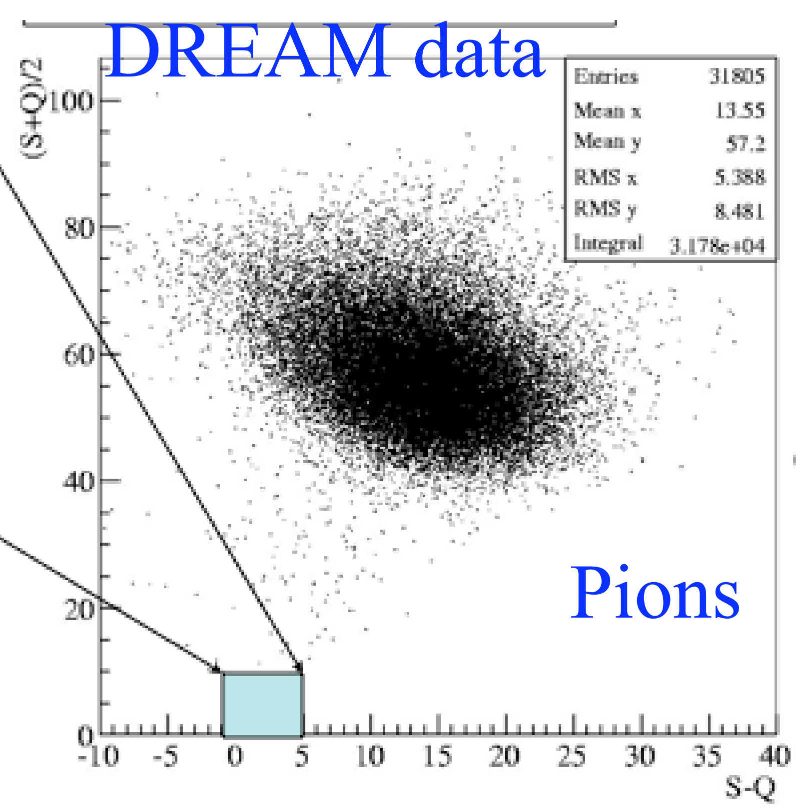


Muon tagging in DREAM:

S-C ~ *dE/dx* (muons)

(S+C)/2 ~ Ebrems



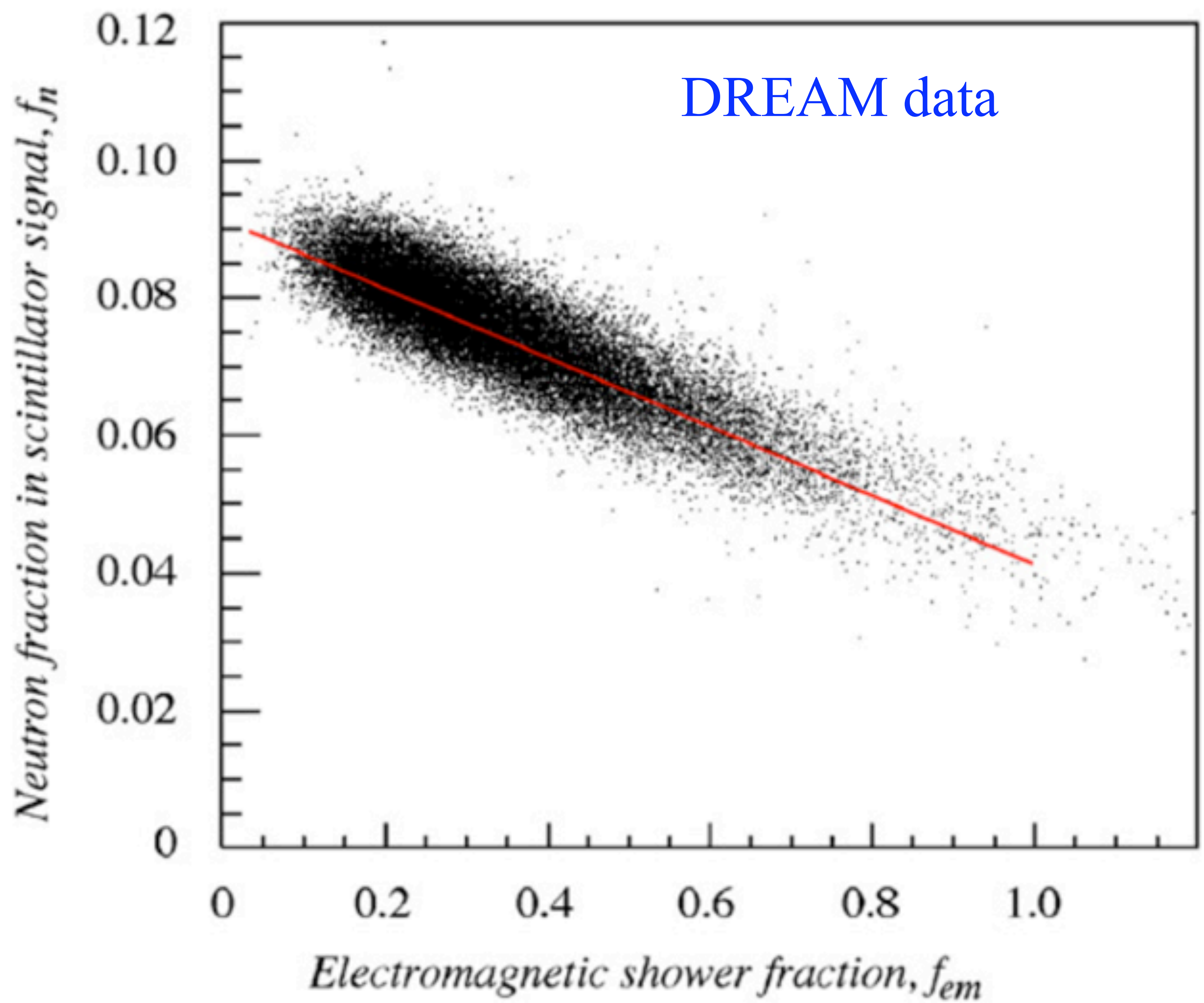


Neutron fraction *vs.* electromagnetic fraction: "hadronic" ID tag

Expected anti-correlation of

f_n (hadronic content) and

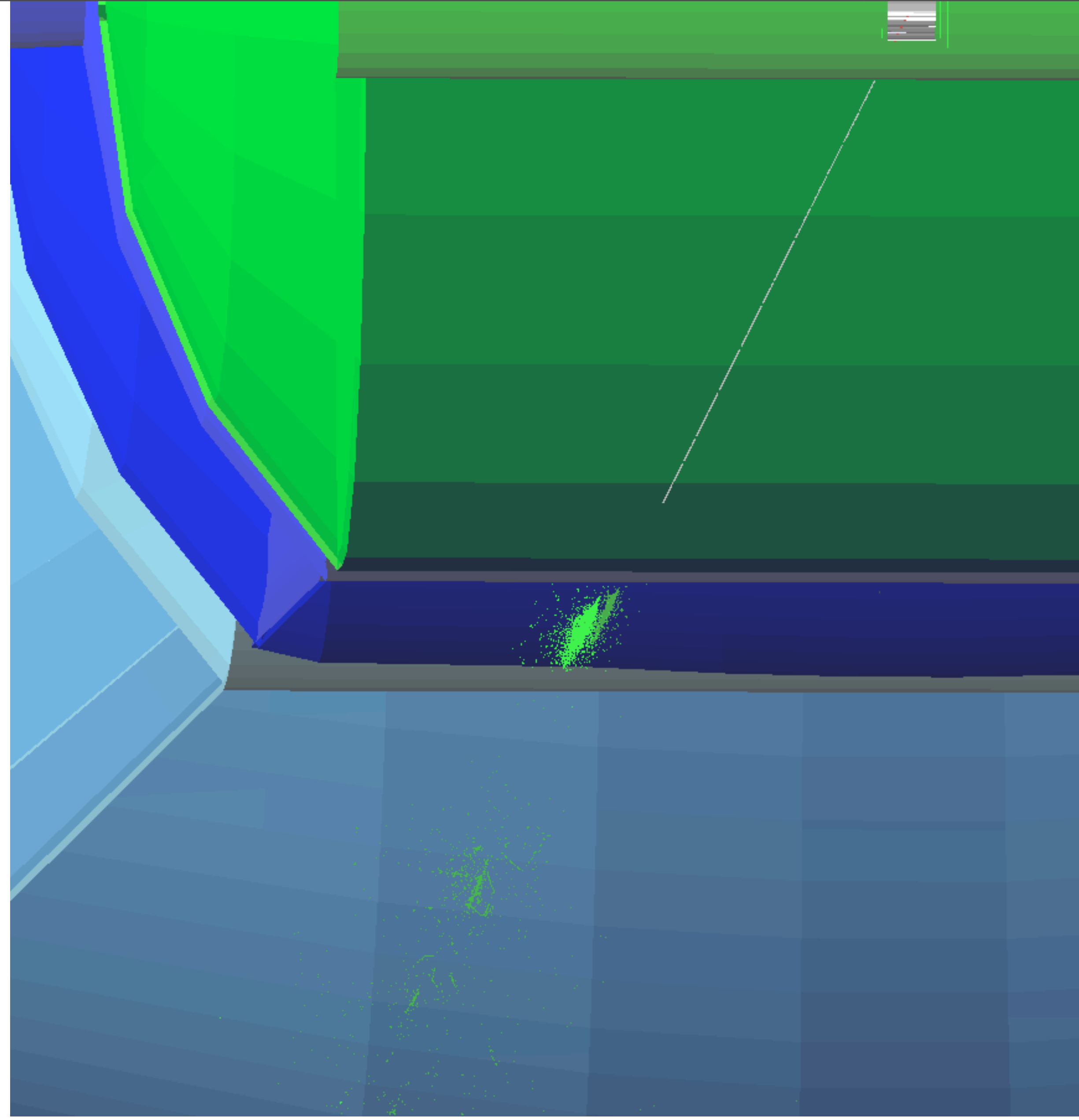
f_{EM} (electromagnetic content)

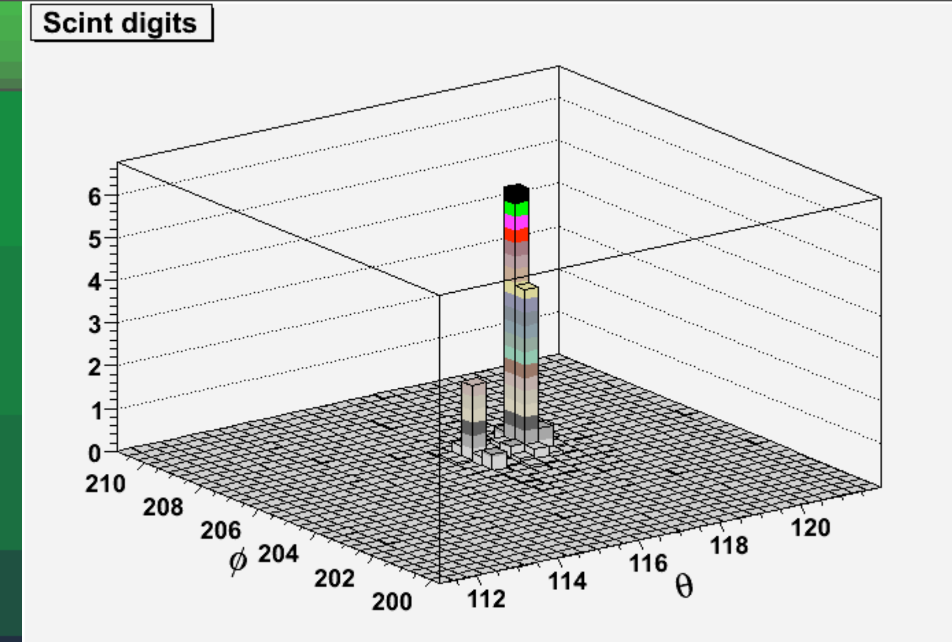


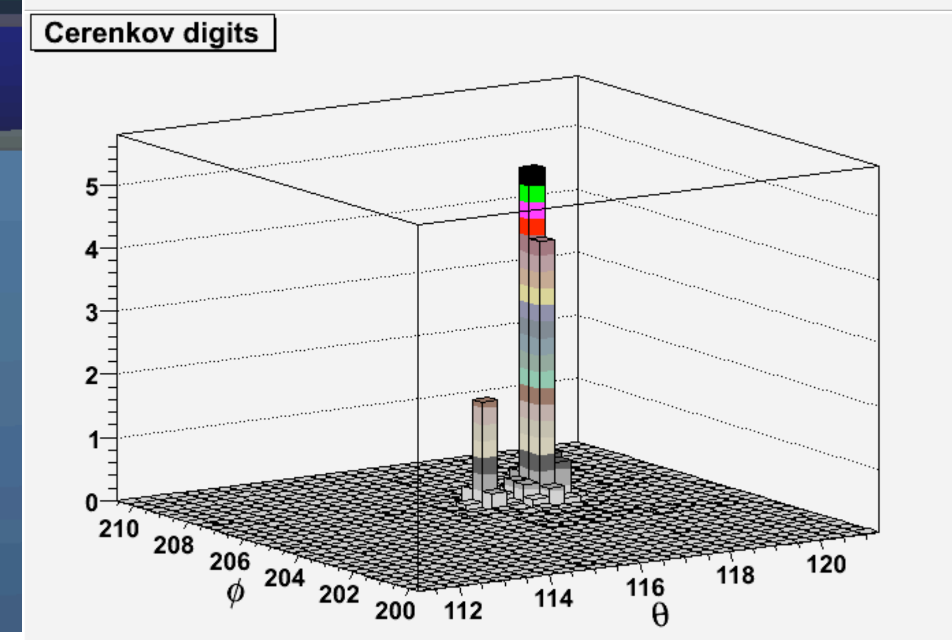
$\tau^{\pm}$ ID

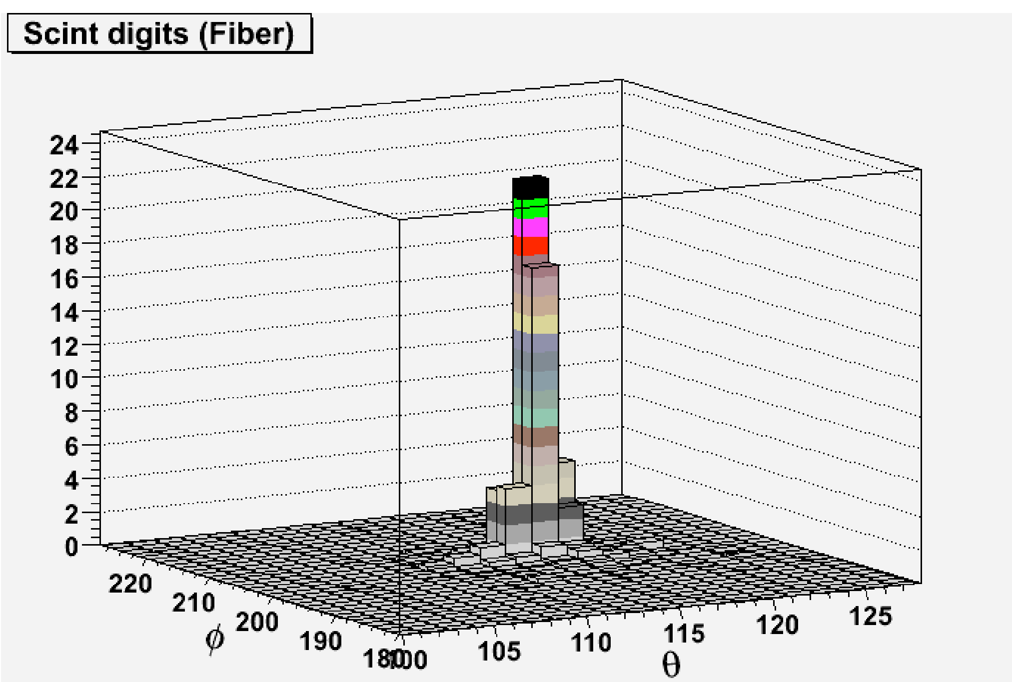
(for polarization)

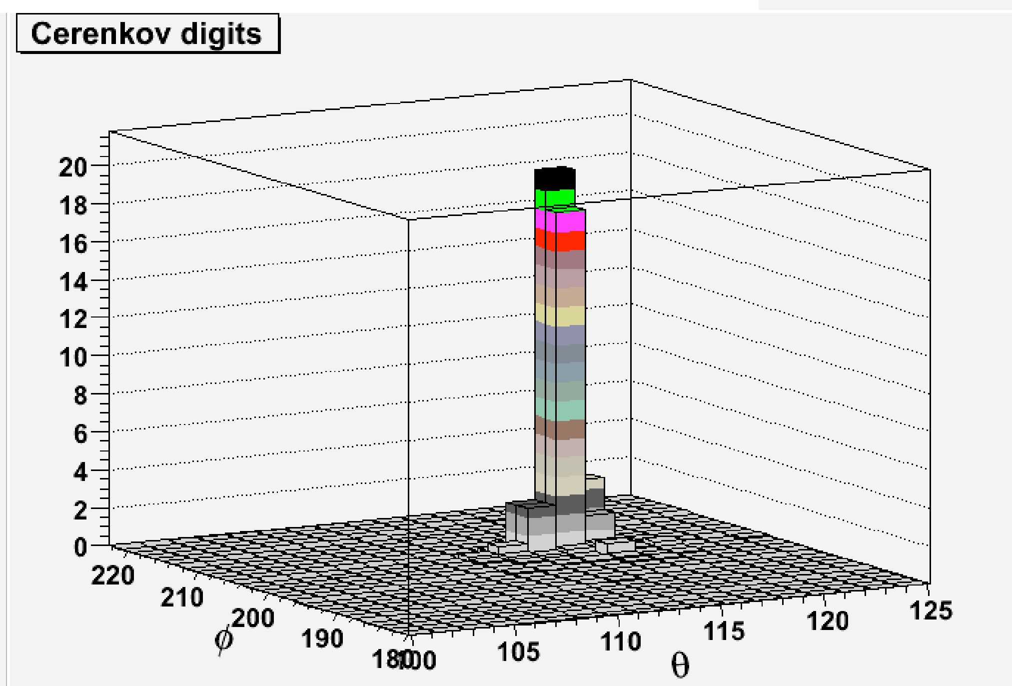
$$\tau^- \to \rho^- \nu$$
$$\to \pi^- \pi^0$$
$$\to \pi^- \gamma\gamma$$



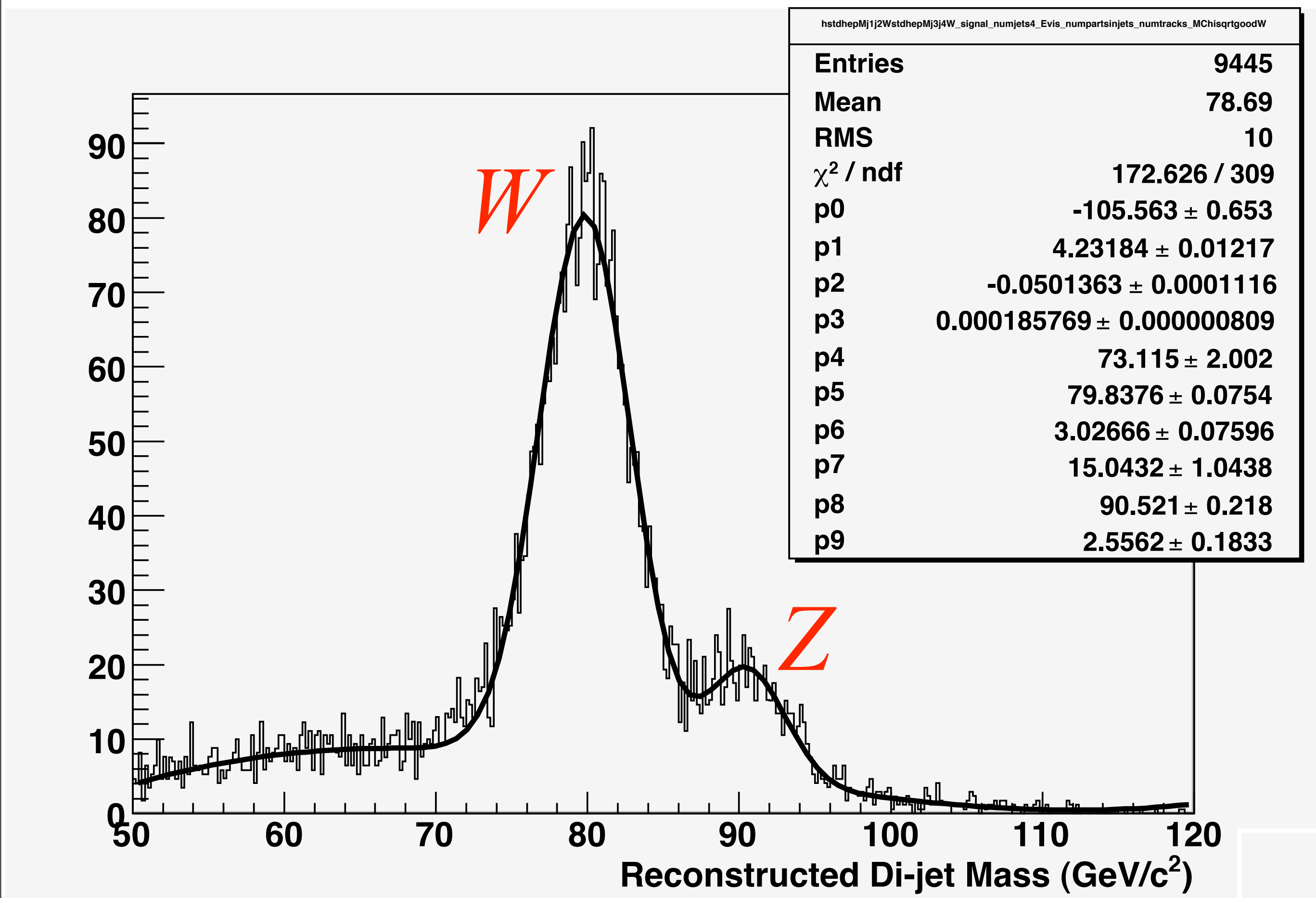


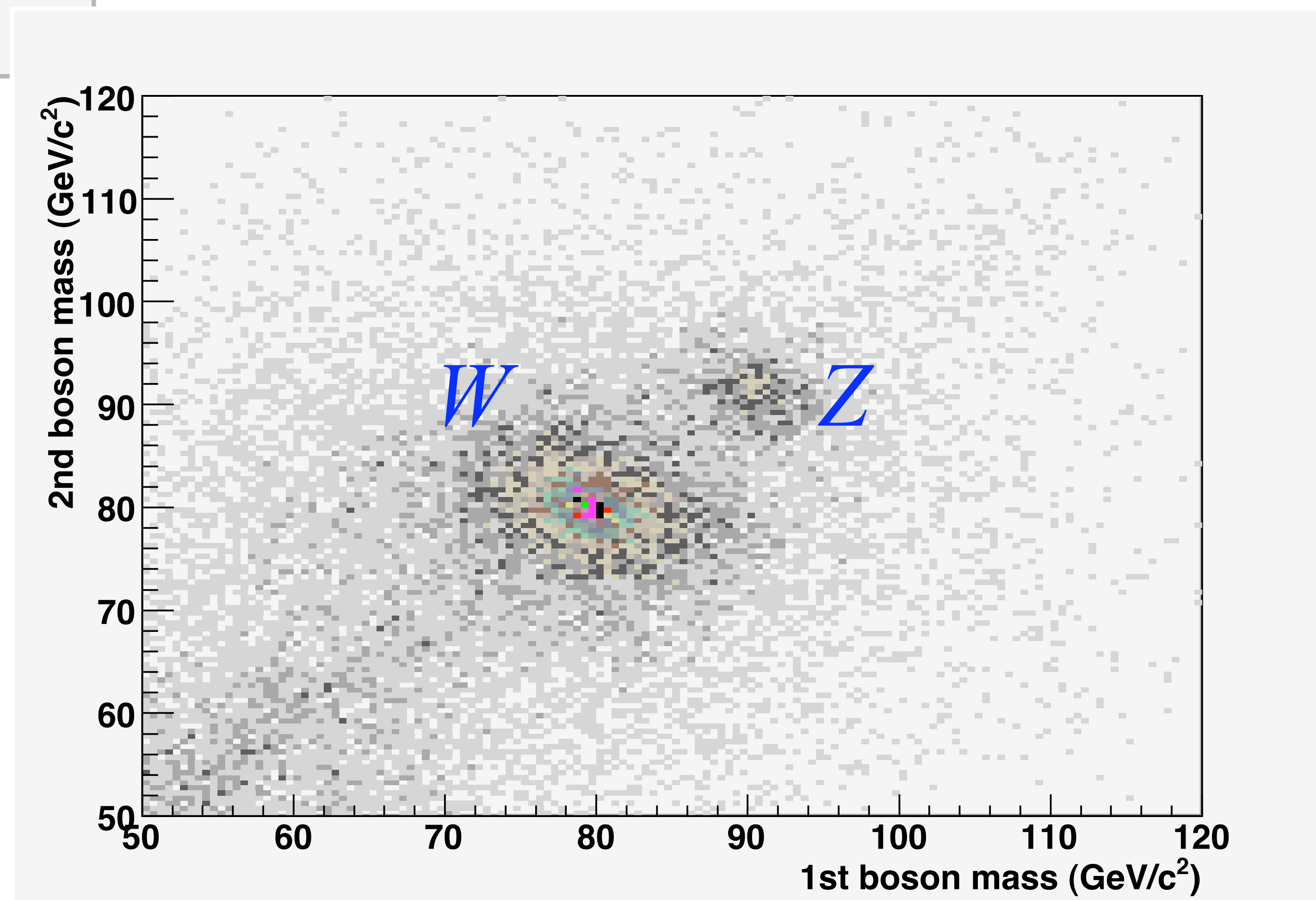






W and Z mass measurement and discrimination



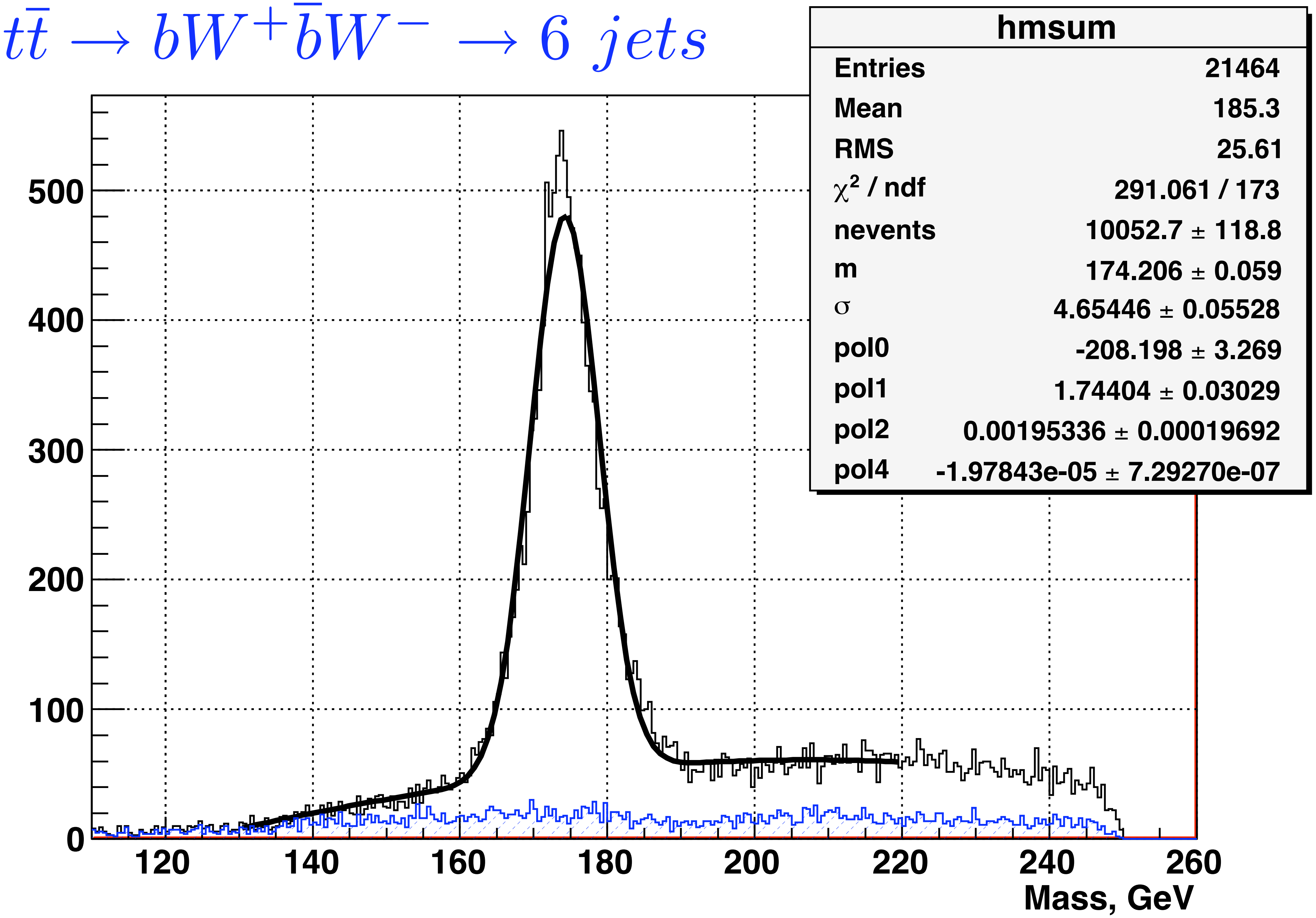


From the SUSY pt. 5 analysis
by Anna Mazzacane

top → 6-jet final state

Fedor Ignatov (Budker)

$$e^+e^- \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow 6\ jets$$

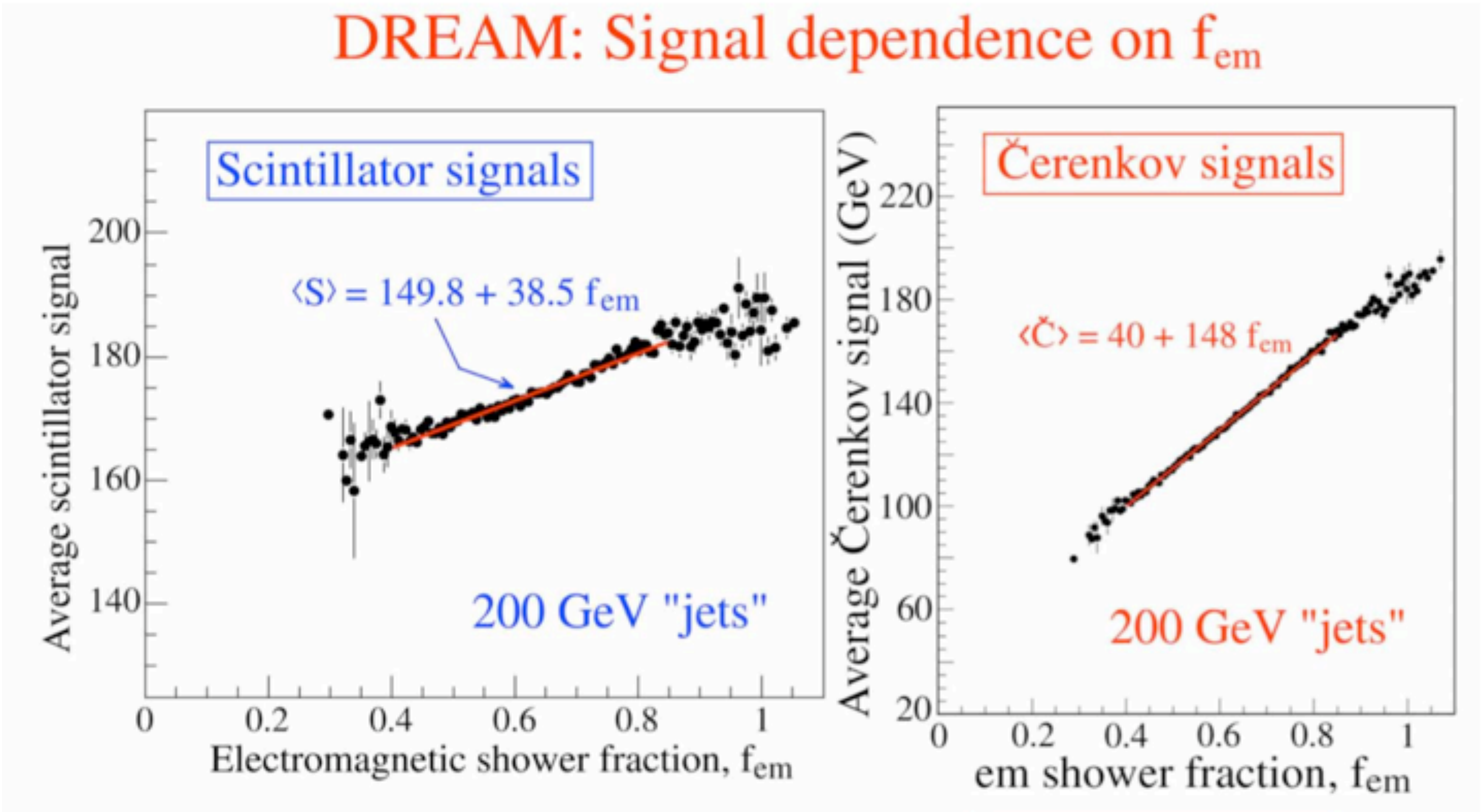


Summary

The DREAM group has published 17 papers on many aspects of dual-readout calorimetry, and will continue with the building of a large module over the next two years, and interested in pure calorimeter R&D.

The DREAM module (now 6 years old) was only a proof-of-principle module and never intended to be a real calorimeter. There are a dozen improvements we can make for a new module [NA, mirrored ends, fiber size, geometry, photo-converters, digitizers (DRSn), smart readout, etc.]

Spares



DREAM: Signal dependence on f_{em}
Scintillator signals
⟨S⟩ = 149.8 + 38.5 f_{em}
200 GeV "jets"
Average scintillator signal
Electromagnetic shower fraction, f_{em}
Čerenkov signals
⟨Č⟩ = 40 + 148 f_{em}
200 GeV "jets"
Average Čerenkov signal (GeV)
em shower fraction, f_{em}