Measurement of the neutron fraction event-by-event in DREAM

We have measured the neutron fraction event-by-event in beam test data taken at CERN by the DREAM collaboration. I will review these measurements in the context of the importance of neutrons to future high-precision calorimetry, and I will bring together the data from SPACAL, the GLD compensating calorimeter, and DREAM to estimate the impact neutron fraction measurements will make on hadronic energy resolution and hadronic particle identification in dual-readout calorimeters.

John Hauptman
CALOR 10, Beijing, China
10-14 May 2010

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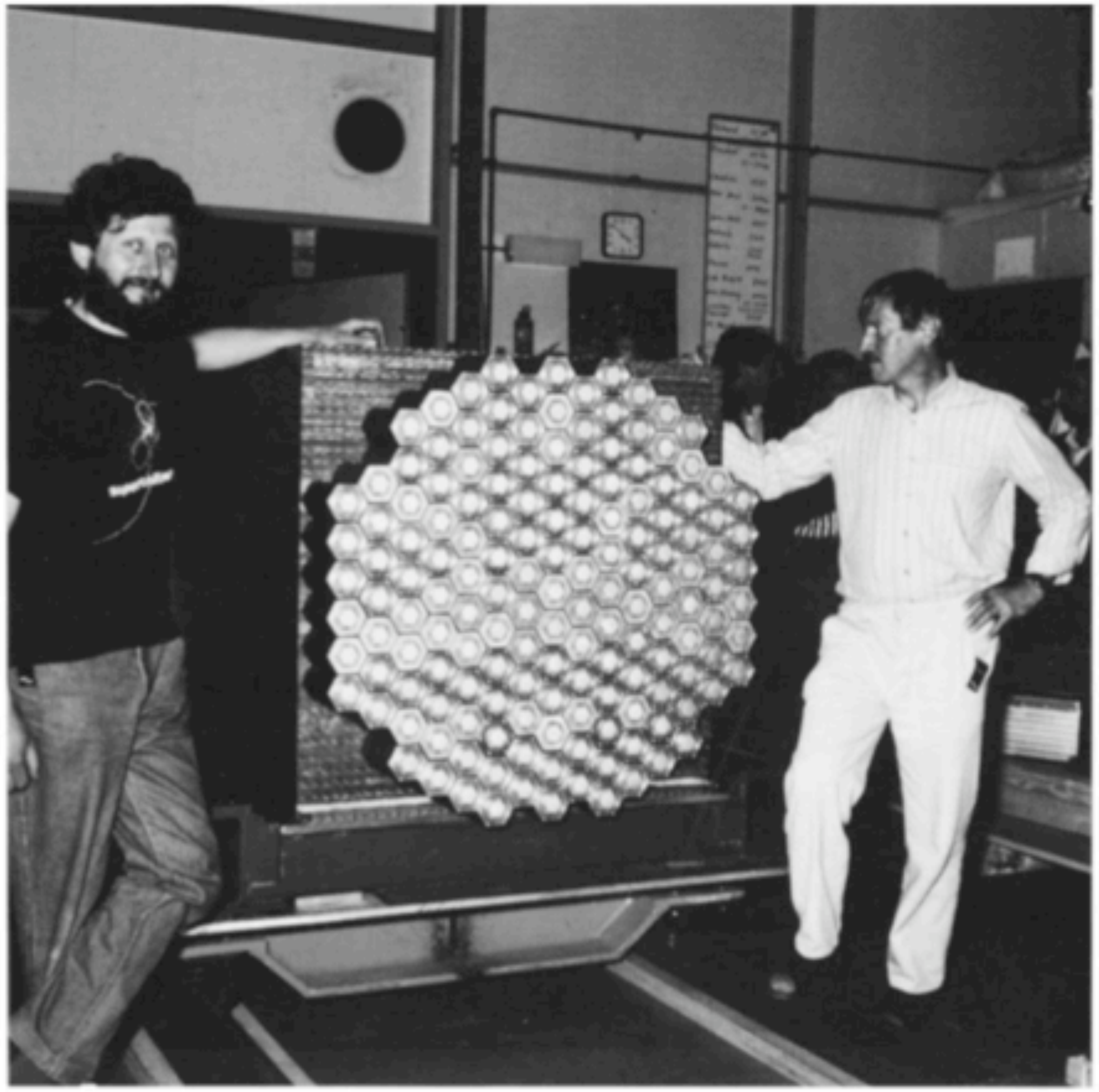


FIG. 1. SPACAL detector built at CERN as a research and development project for detectors at a multi-TeV proton–proton collider. This calorimeter consists of scintillating plastic fibers embedded in a lead matrix at a volume ratio 4:1, needed for compensation. In total 176,855 fibers, bunched together in 155 hexagonal towers, were used to build this 13-ton, 9.5 nuclear interaction lengths deep detector. Each tower is read out by one photomultiplier. The fibers are running longitudinally, that is in the direction of the incoming particles.

SPACAL: (1991)

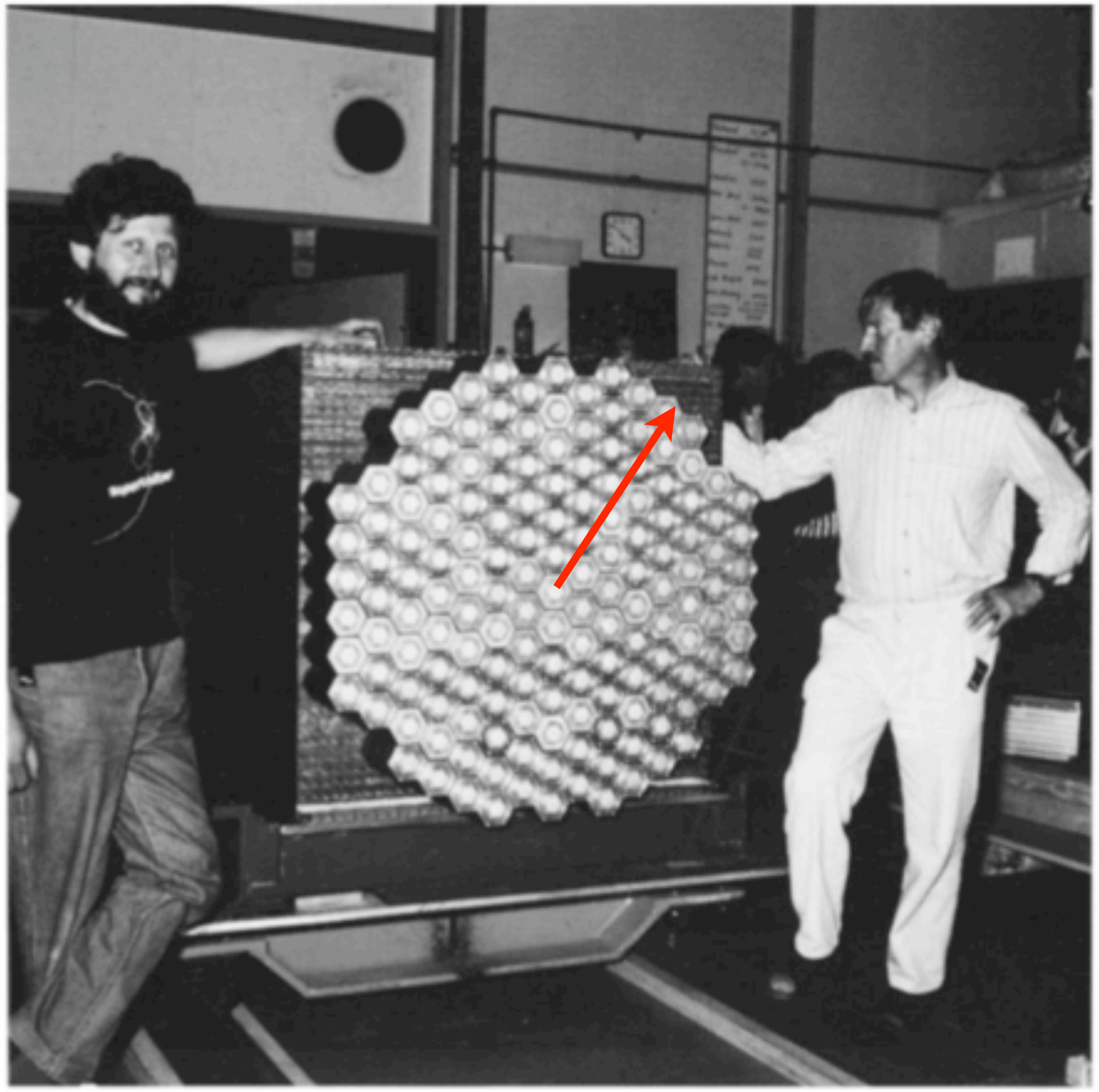
π break up nuclei, lose BE/nucleon

n liberated from nuclei are slow and fill a large volume

Pb:scint in 4:1 ratio is about right for $np \rightarrow np$ scatters to make *hadron* and *electron* response equal

compensation: $e/h=1$

Huge fluctuations between $\pi^0 \rightarrow \gamma\gamma$ and π^+/π^- no longer matter.



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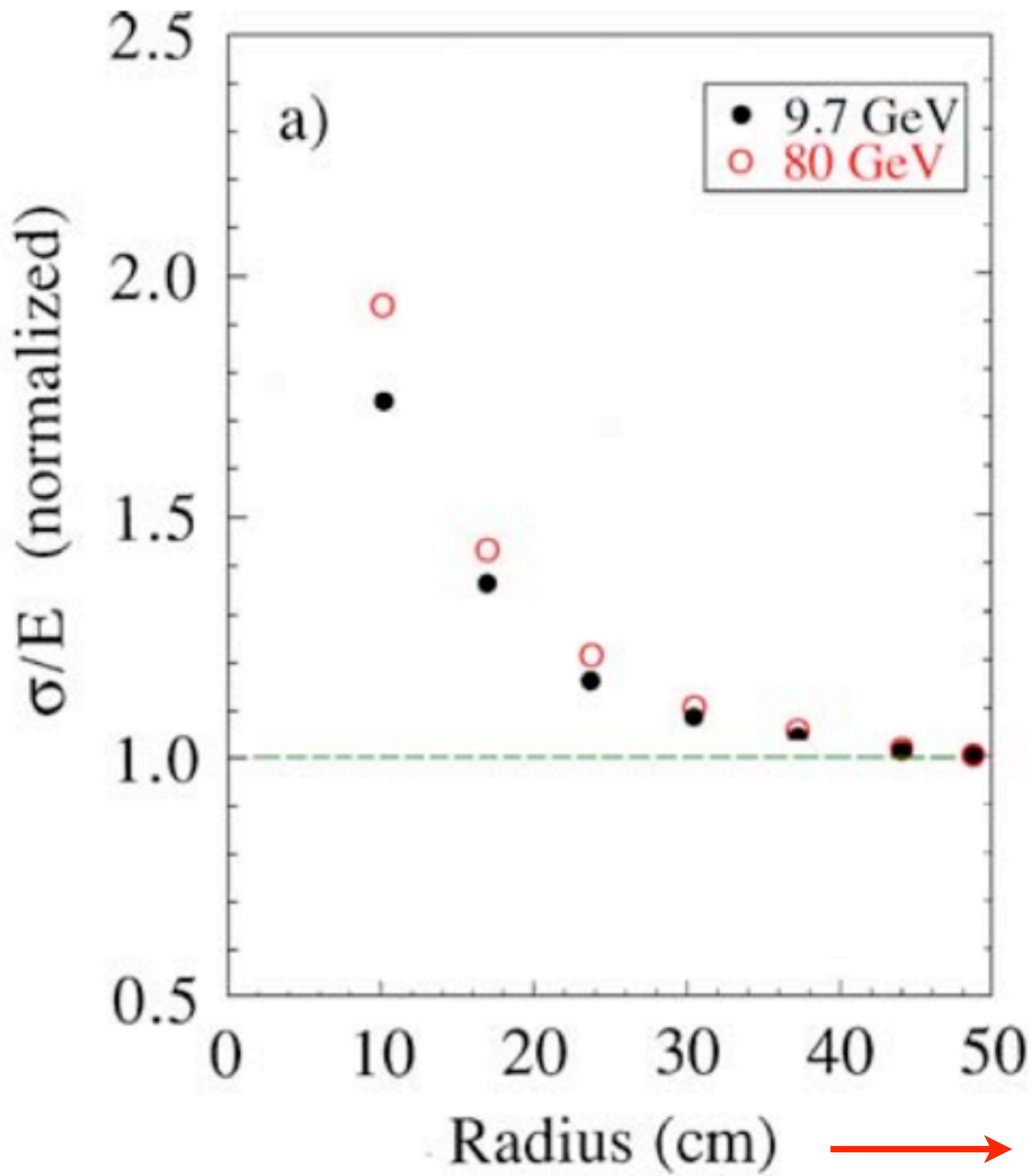
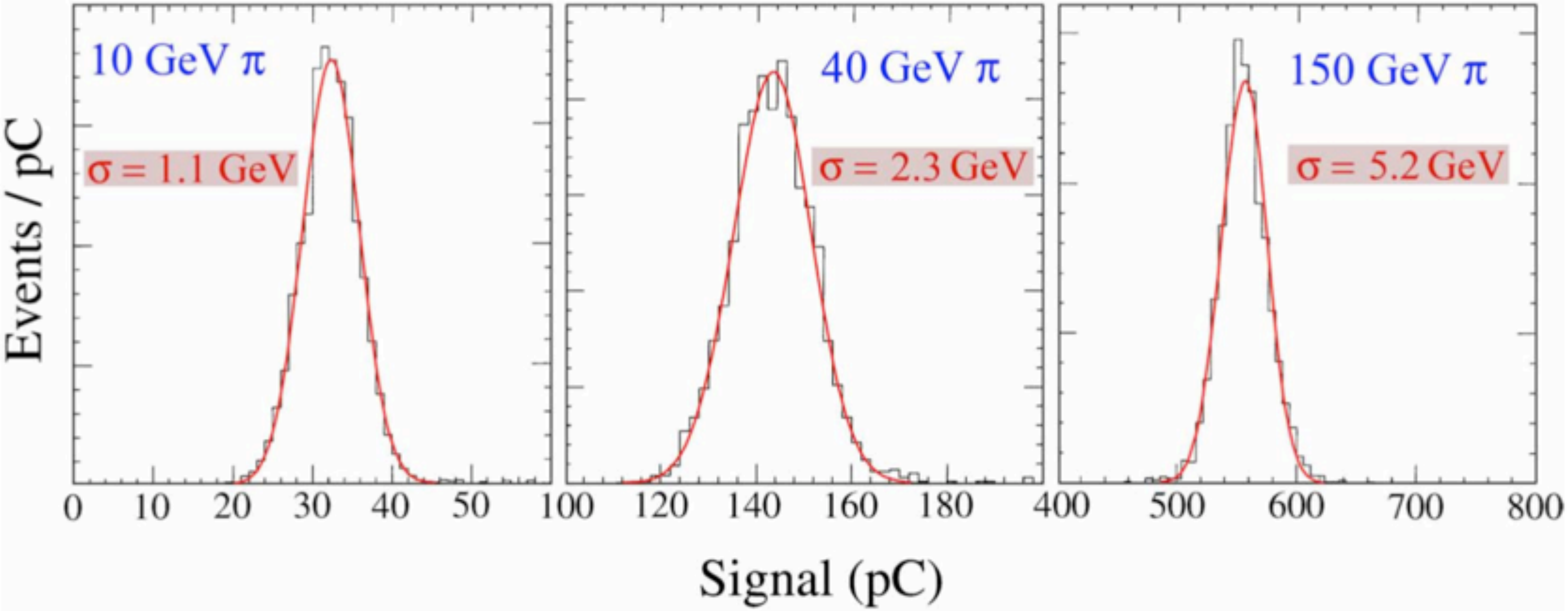




from: NIM A308 (1991) 481

SPACAL

Best resolution *ever* achieved
(this was a long time ago)

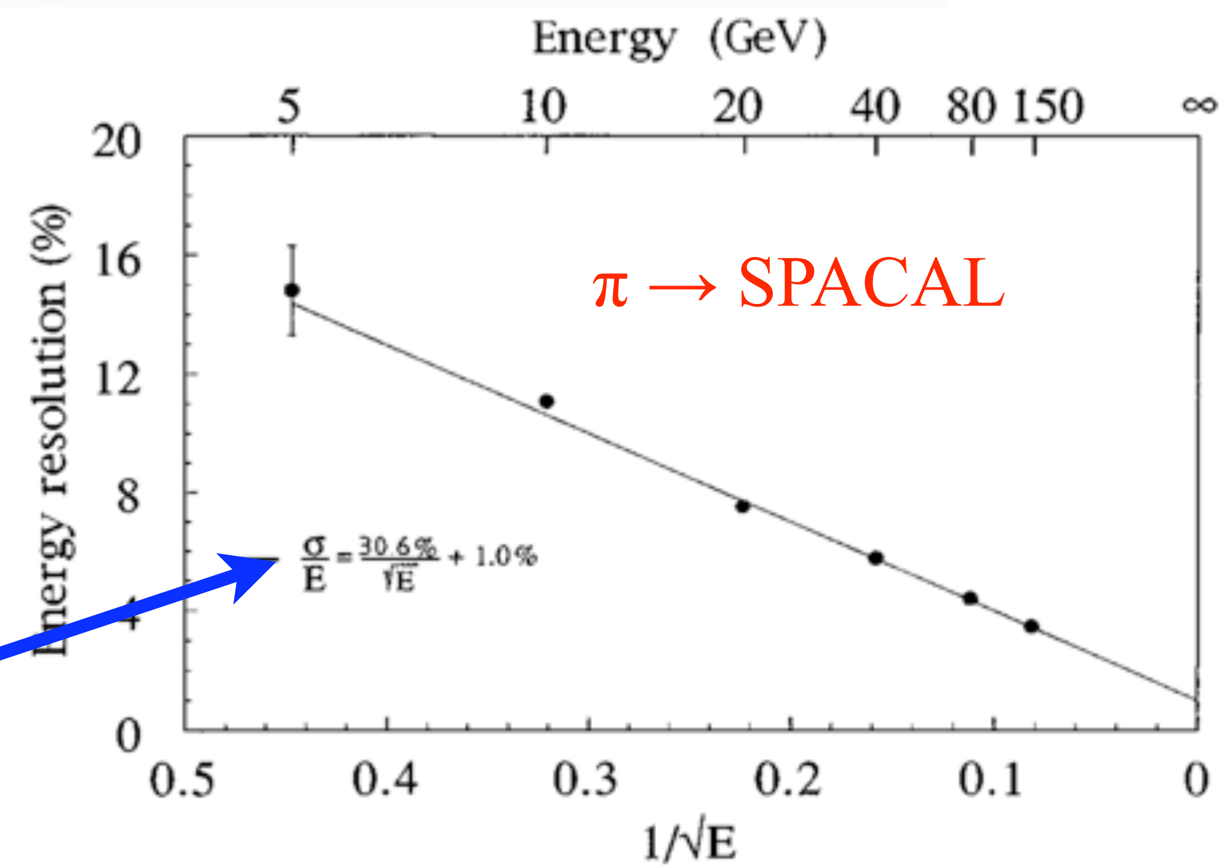
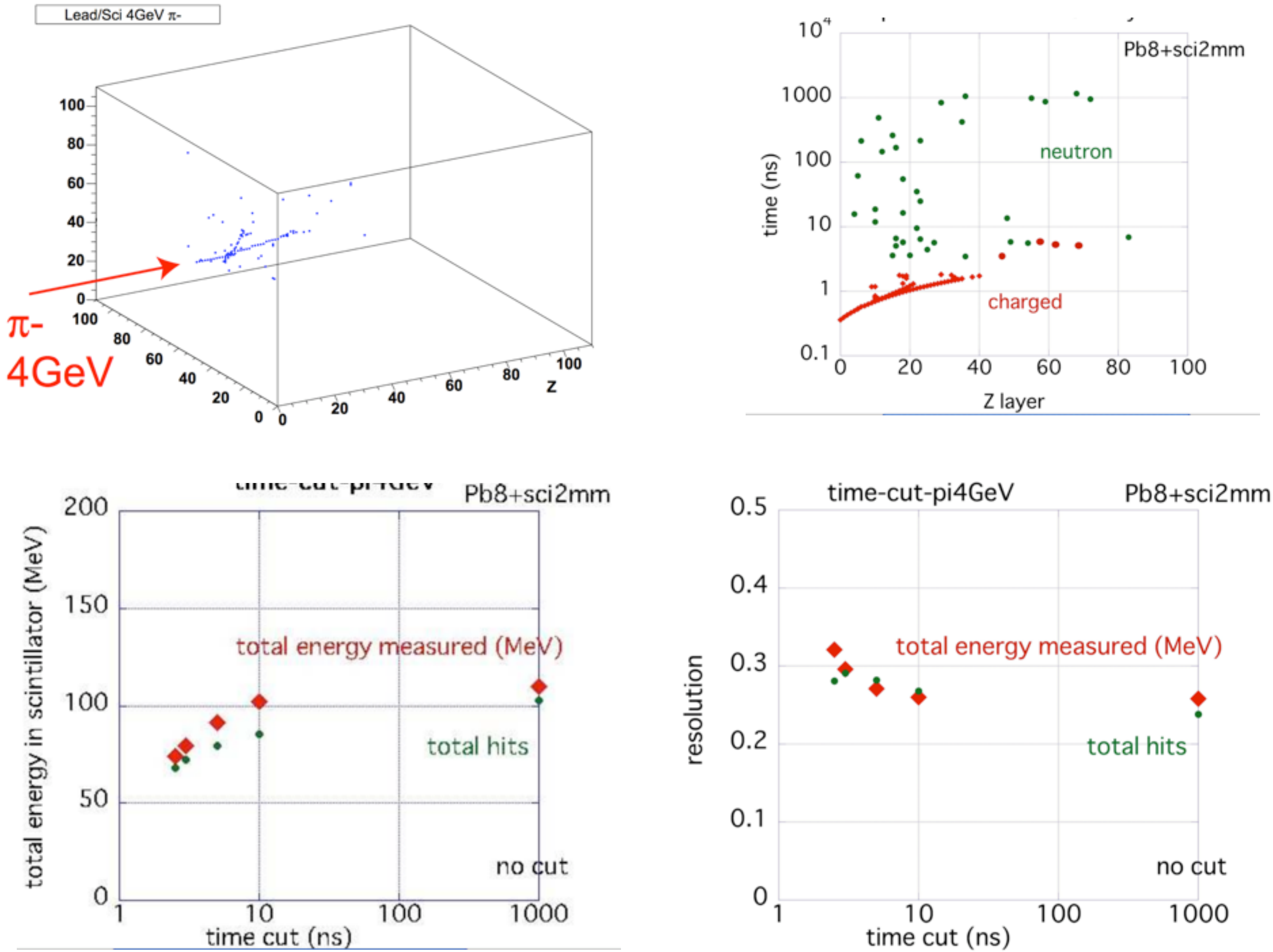
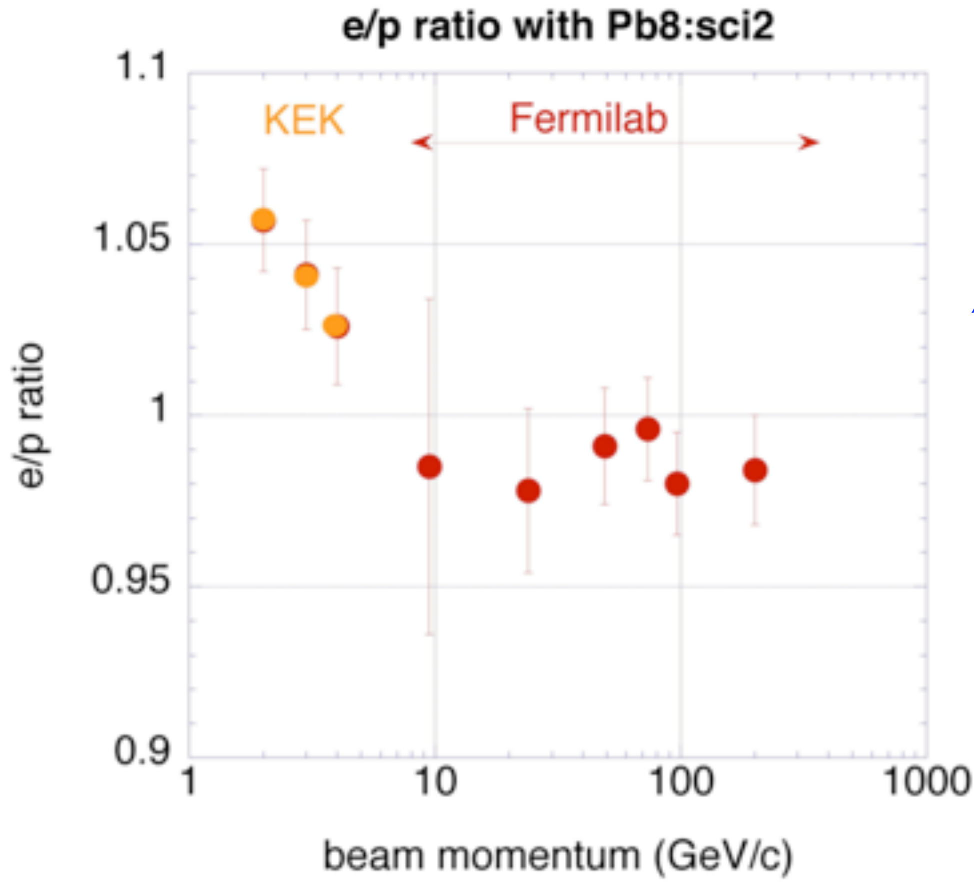


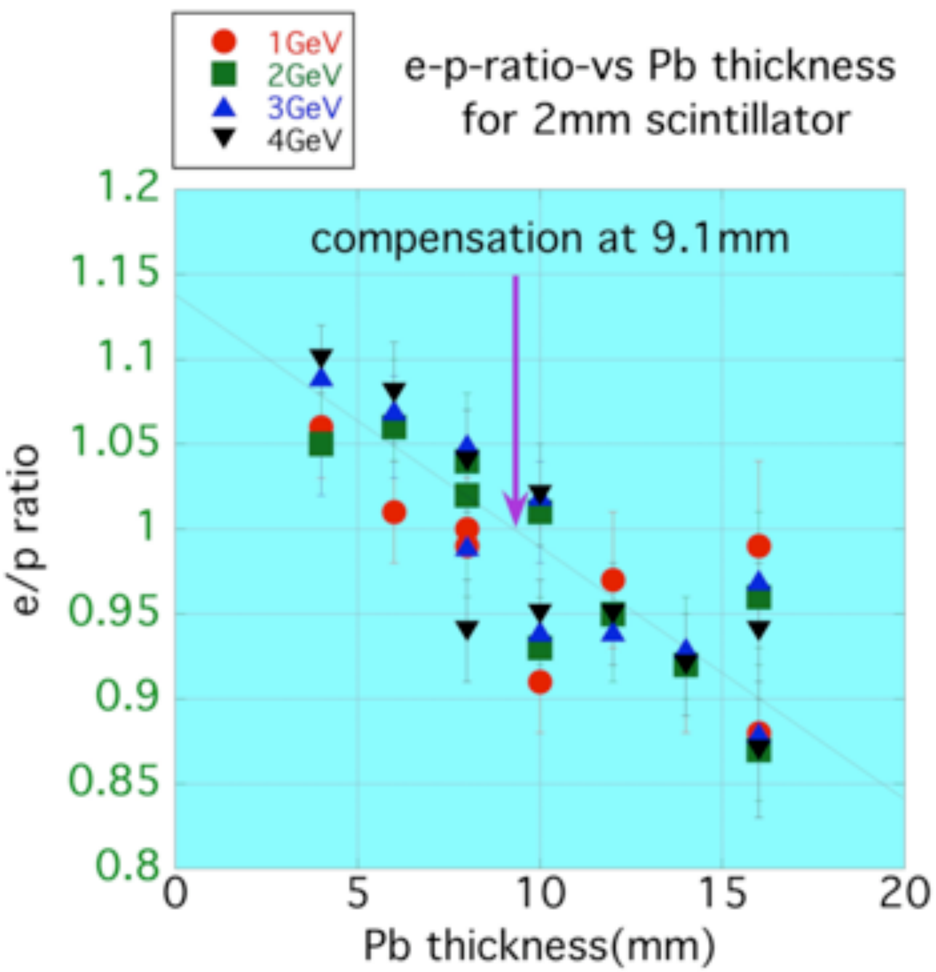
FIG. 10. Hadronic energy resolution as a function of energy, for the compensating SPACAL lead/plastic-scintillator calorimeter (Ref. 16).

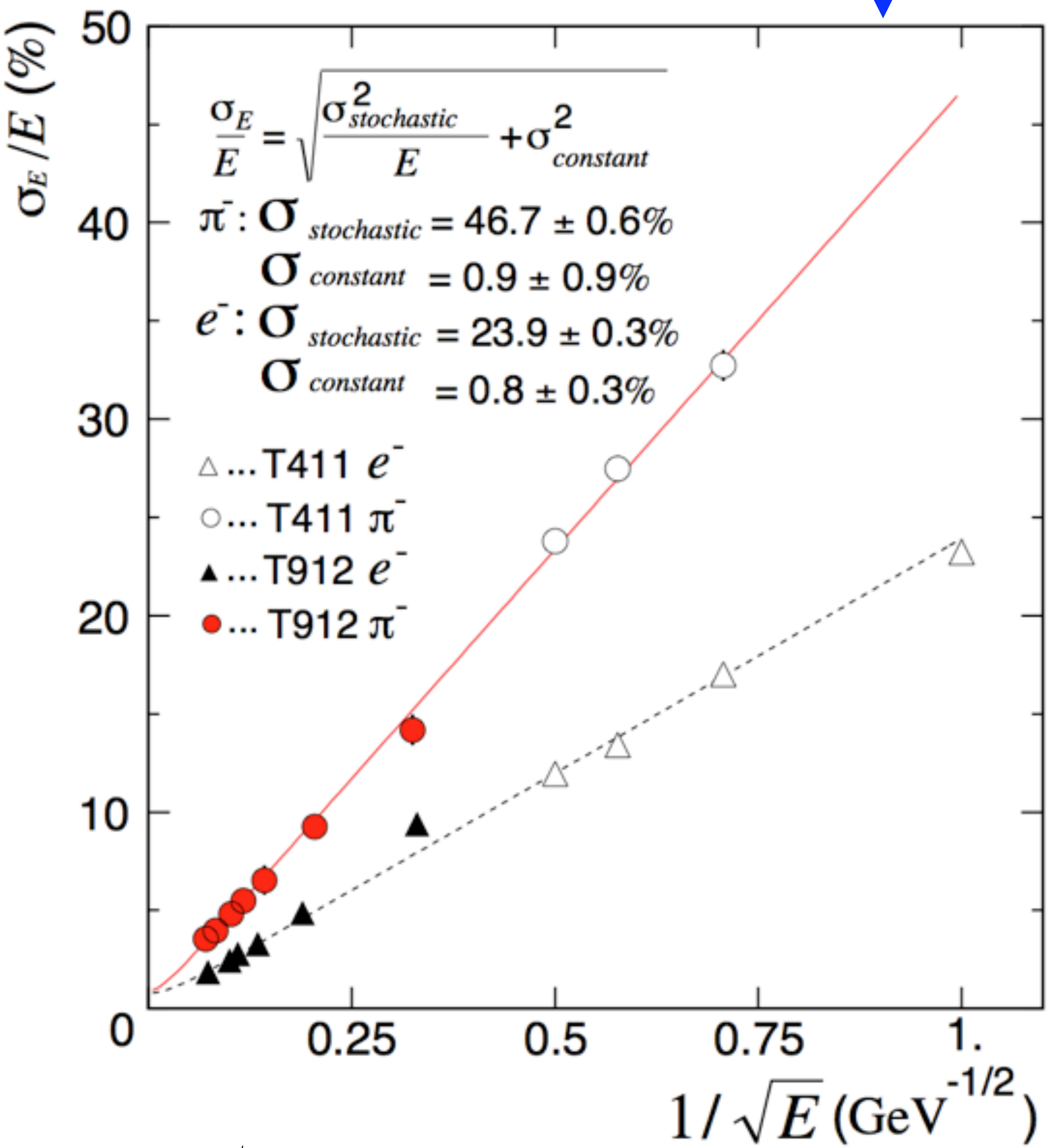
More recently, the GLD concept detector:



Tuning *e/h* results







(GLD~√2 SPACAL)

Compensation (*via np→np*)

Advantages

• same energy scale for electrons, hadrons, jets, muons
• excellent hadronic energy resolution
• Gaussian response function
• linearity in hadronic energy
• understood: no mysteries left

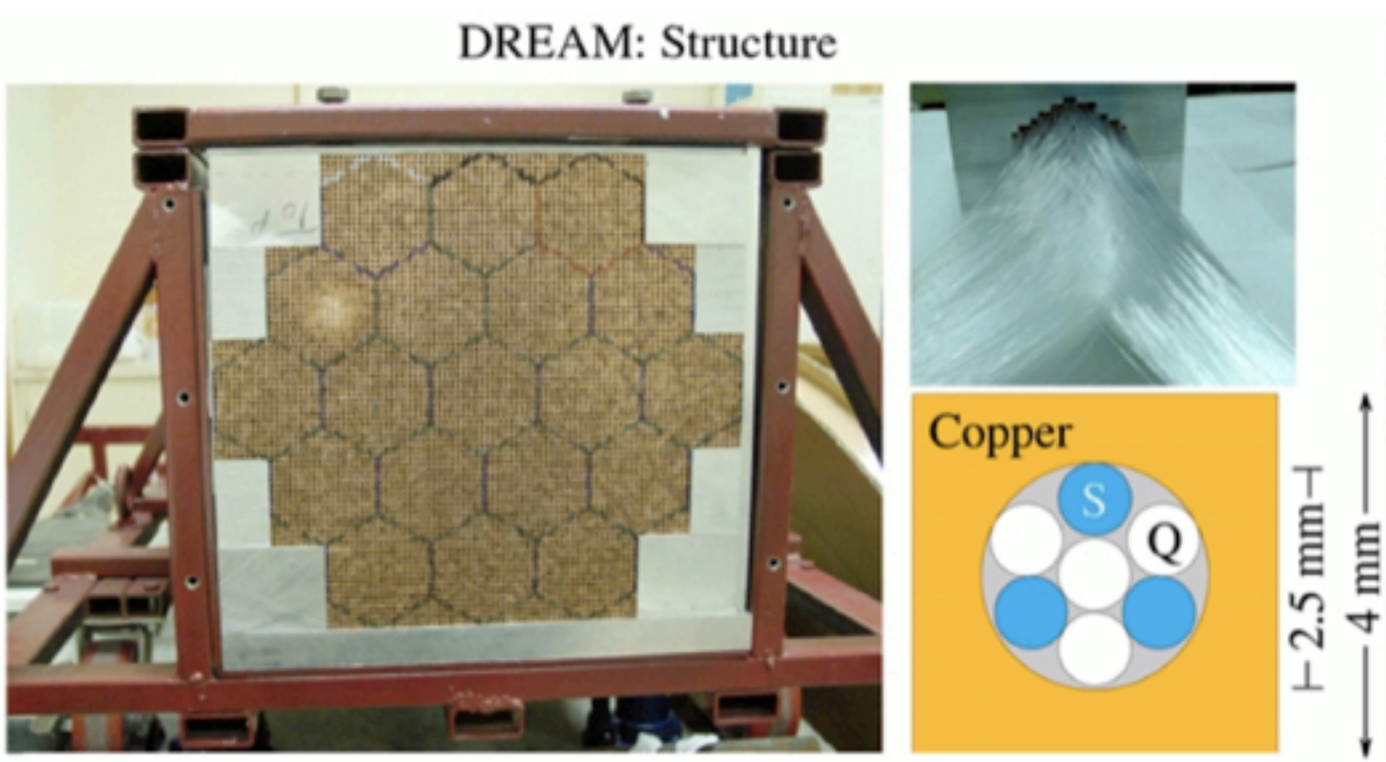
Disadvantages

• fixed sampling fraction (Pb:scint=4:1)
• small sampling fraction (2.4%) limits EM resolution

Dual-readout allows "dynamic compensation"

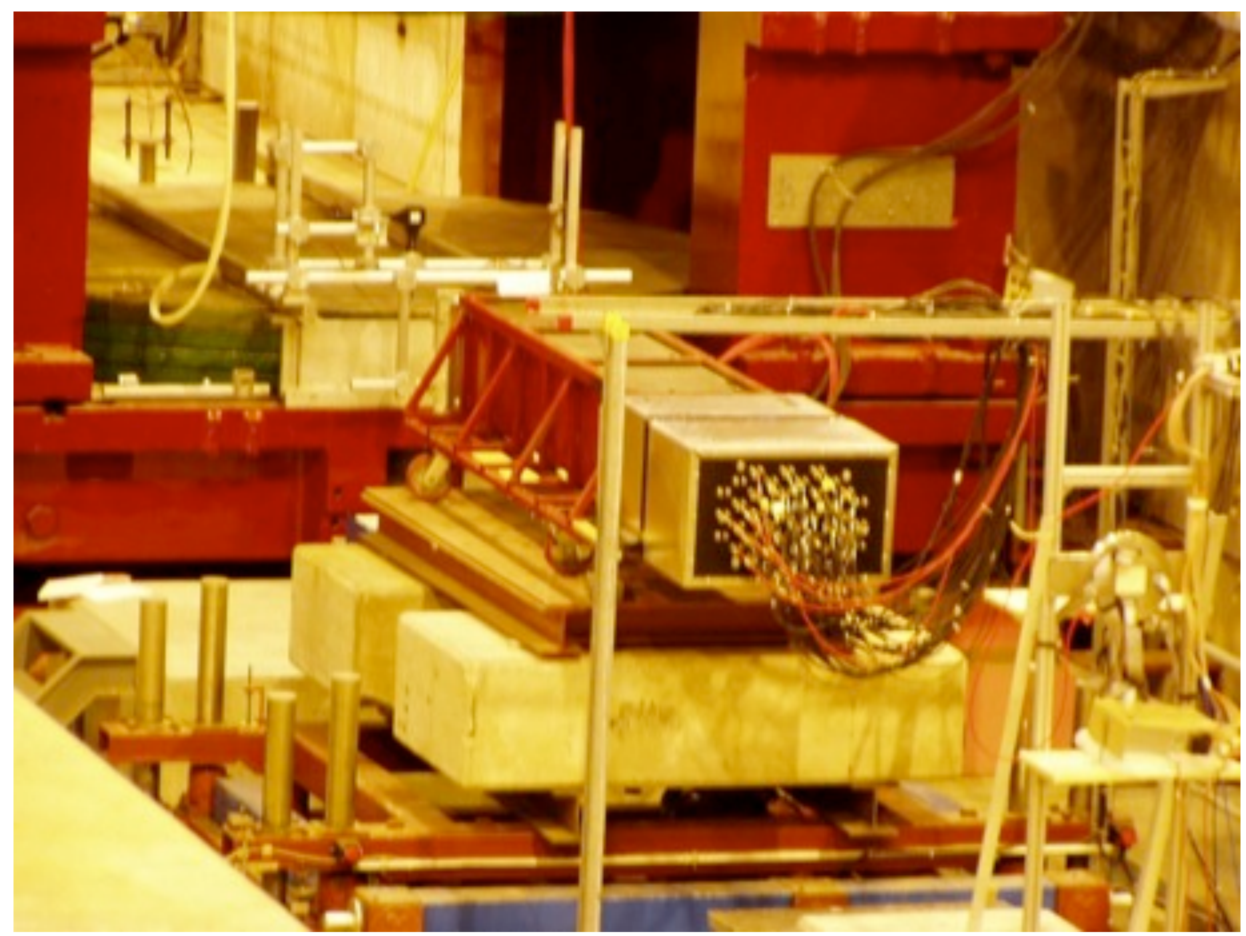
• any sampling fraction, any absorber, almost any geometry
• retain all the advantages of compensation

DREAM: Dual-REAdout Module

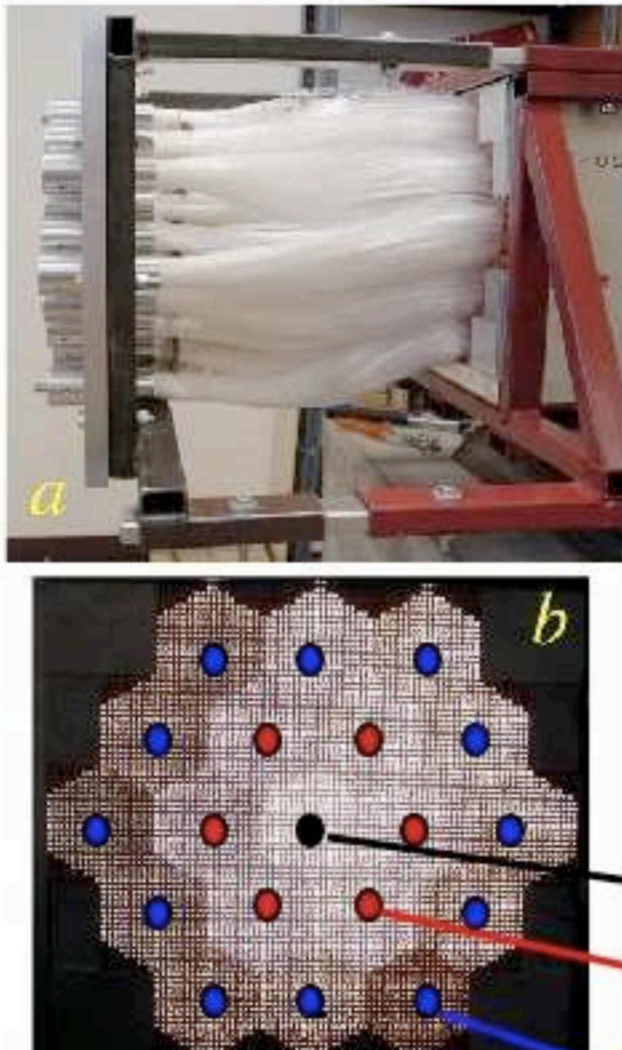


test the principle with a simple module

- *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



Reconfigure DREAM module



DAQ was 1 GHz 4-chan
digital storage scope

transfer to counting house in
fast air-core cables

Scintillating fibers

"Fast 1" S central

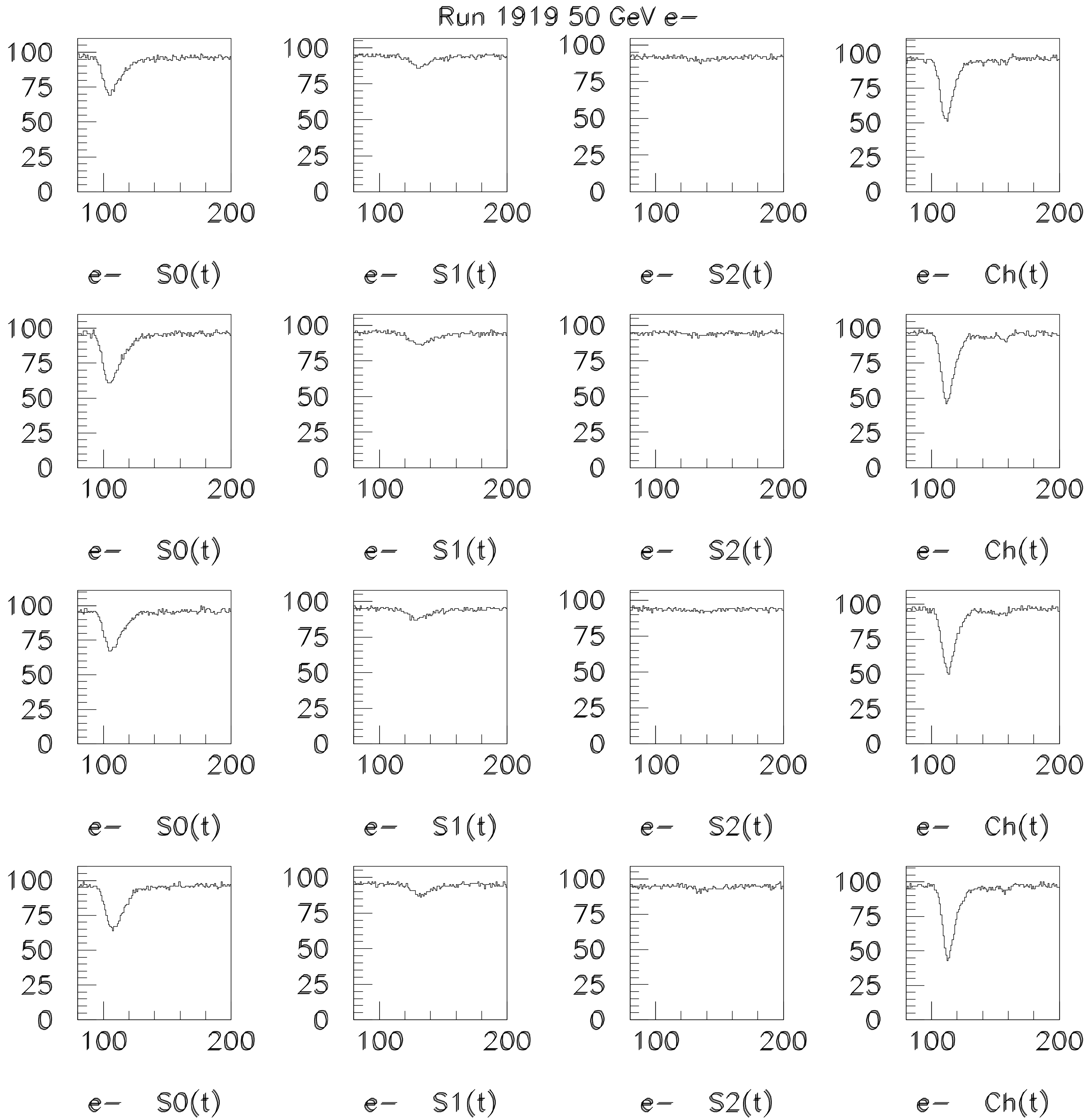
"Fast 2" S inner ring

"Fast 3" S outer ring

Cerenkov fibers

1● + 6● + 9● → "Fast 4" Cerenk sum

S central S inner S outer Cer sum



50 GeV e^- scope traces

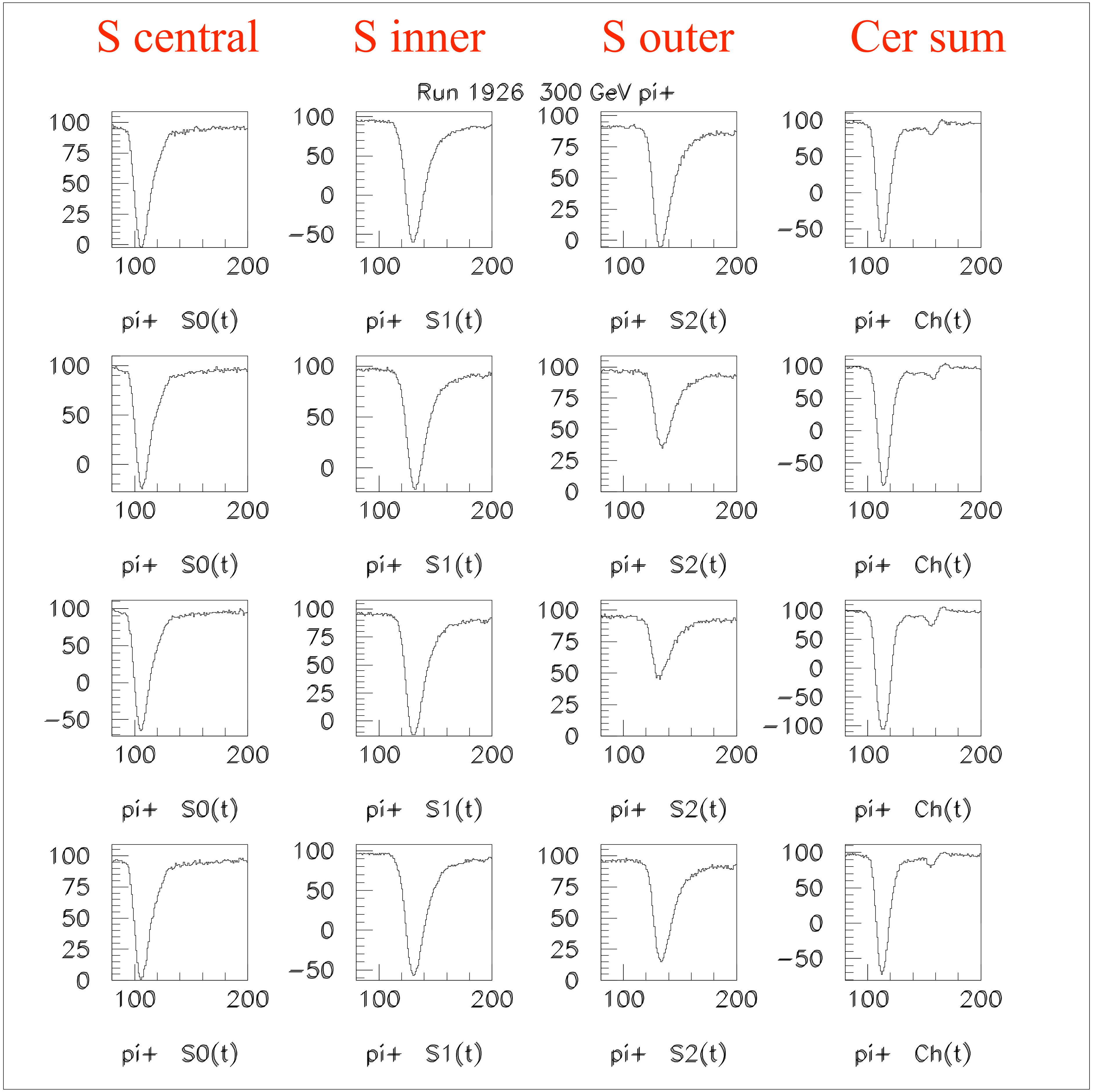
event #1

event #2

event #3

event #4

(clearly electrons)



300 GeV π^- scope traces

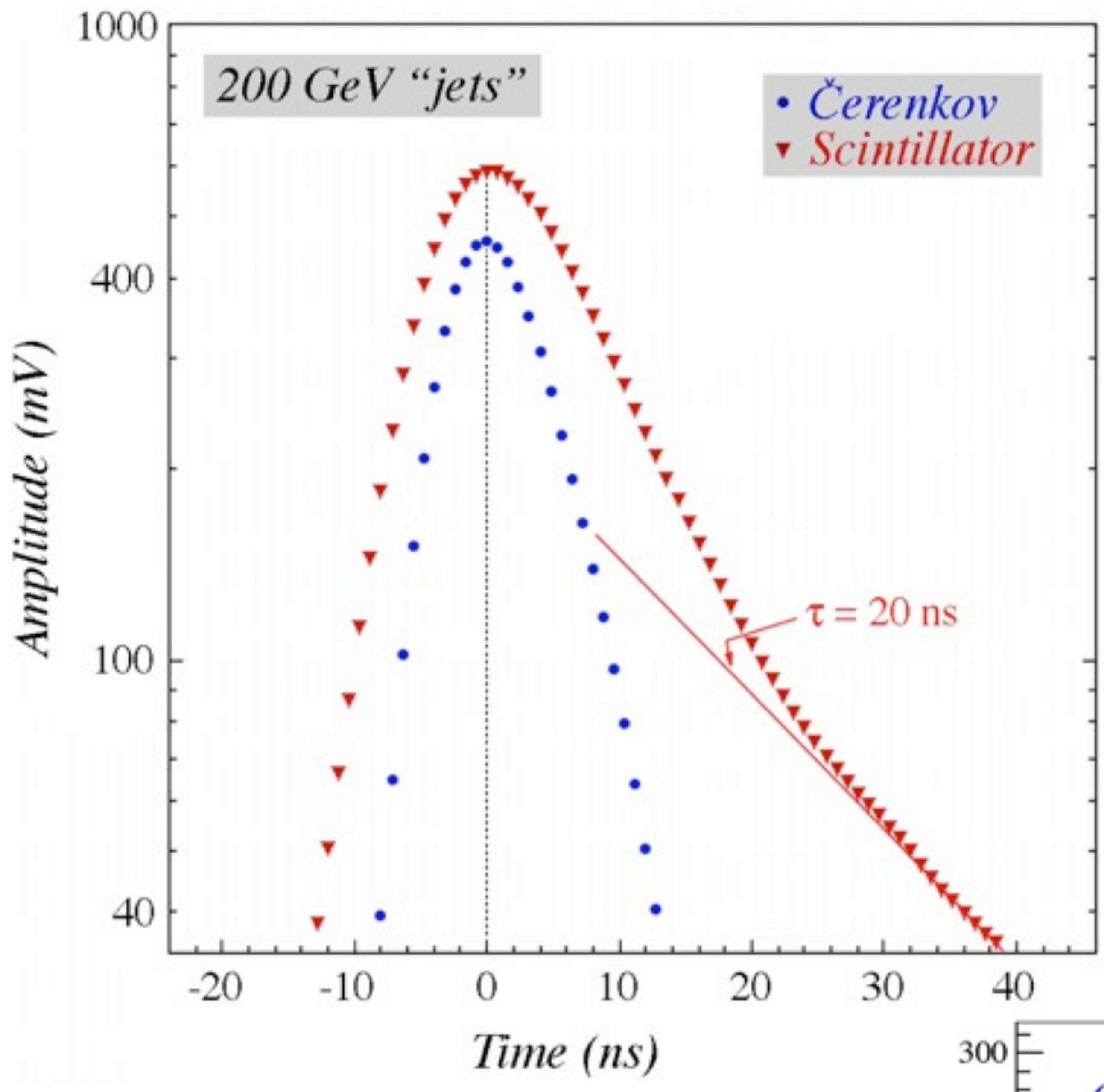
event #1

event #2

event #3

event #4

(clearly pions)

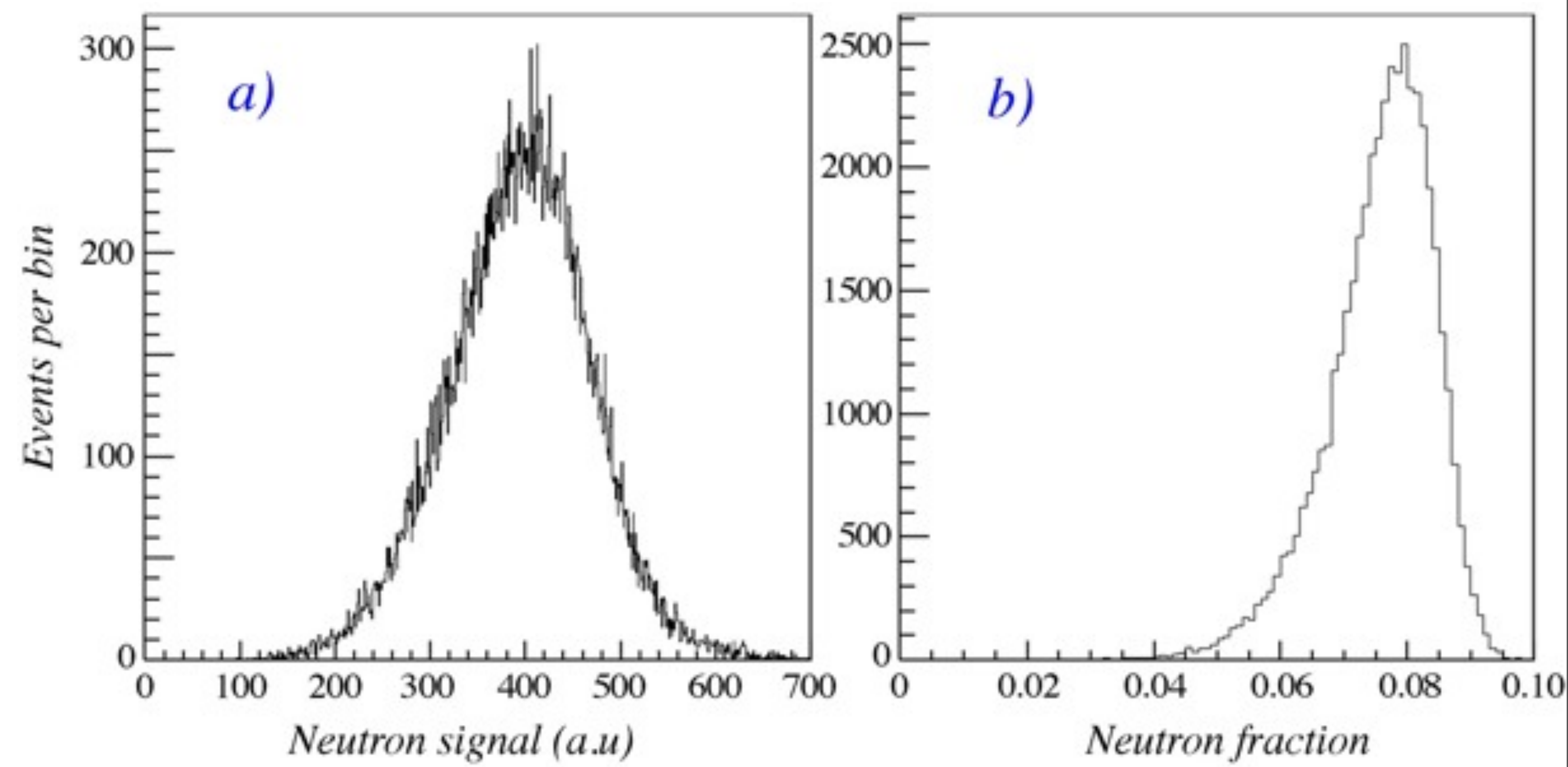


Scintillating fibers see late neutrons by *np→np*

S_n is integral of Scint pulse over 20-40 ns

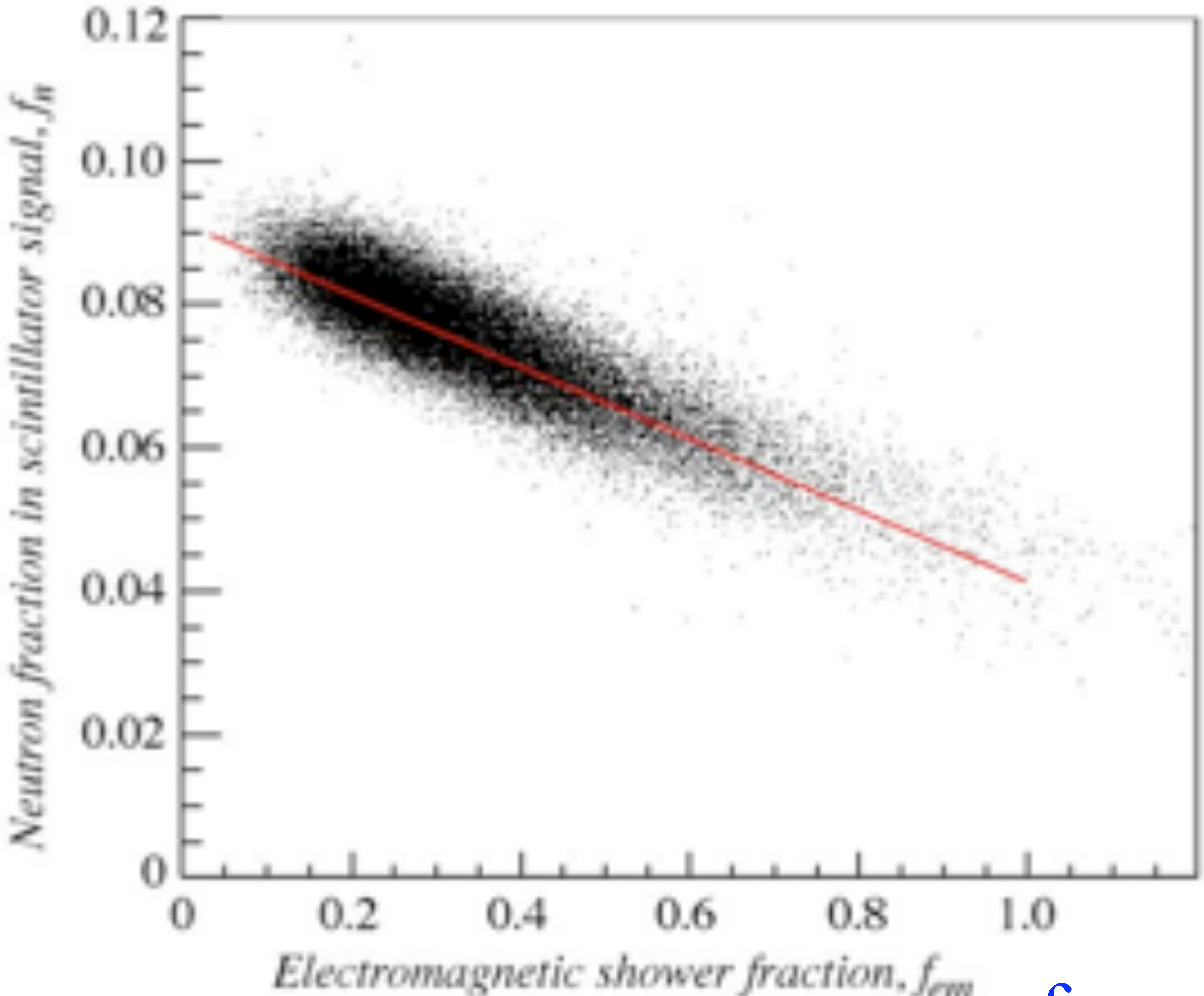
$f_n = S_n / S_{tot}$

Cerenkov fibers do not see neutrons



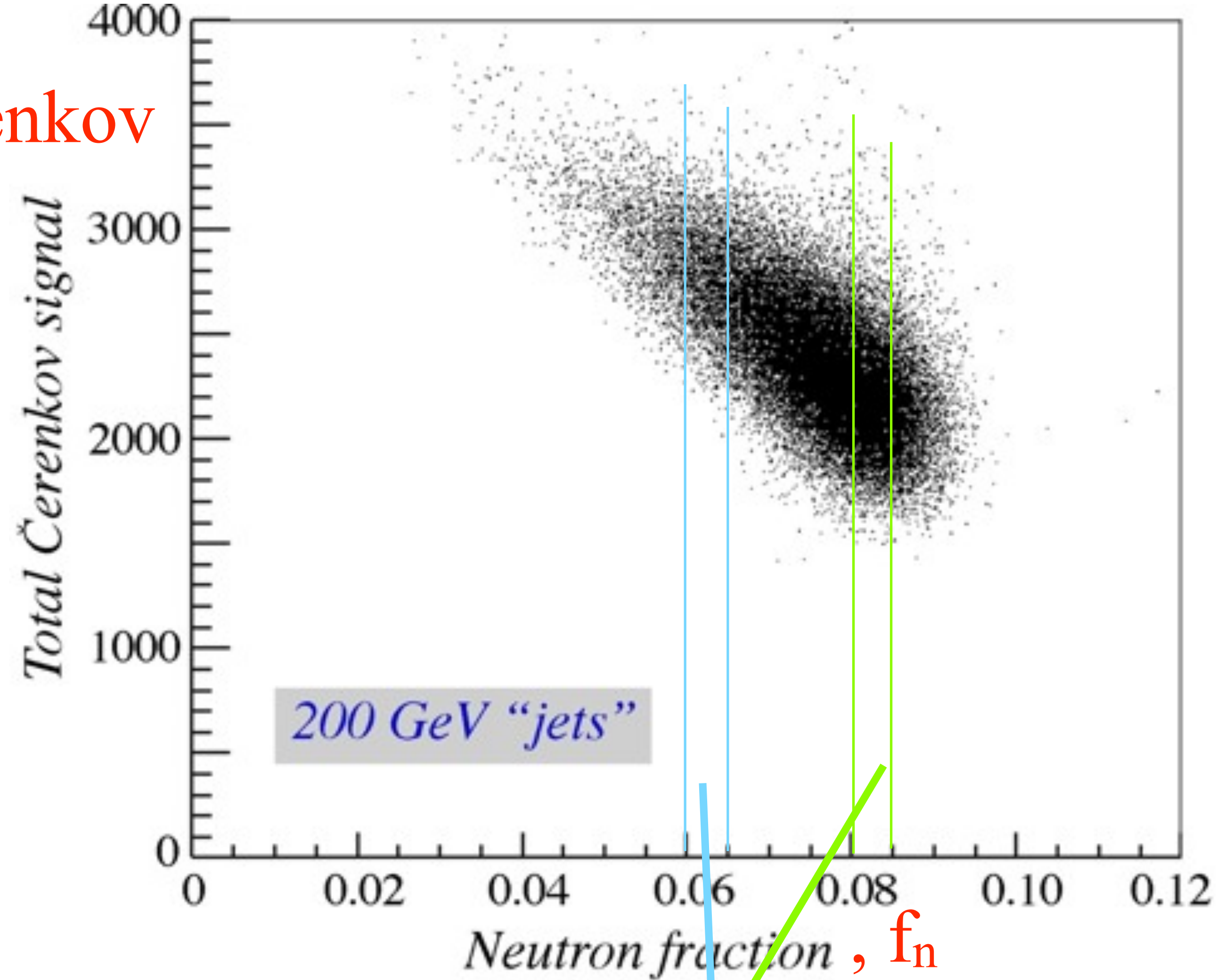
Is it physical? Yes, anti-correlated with f_{EM}.

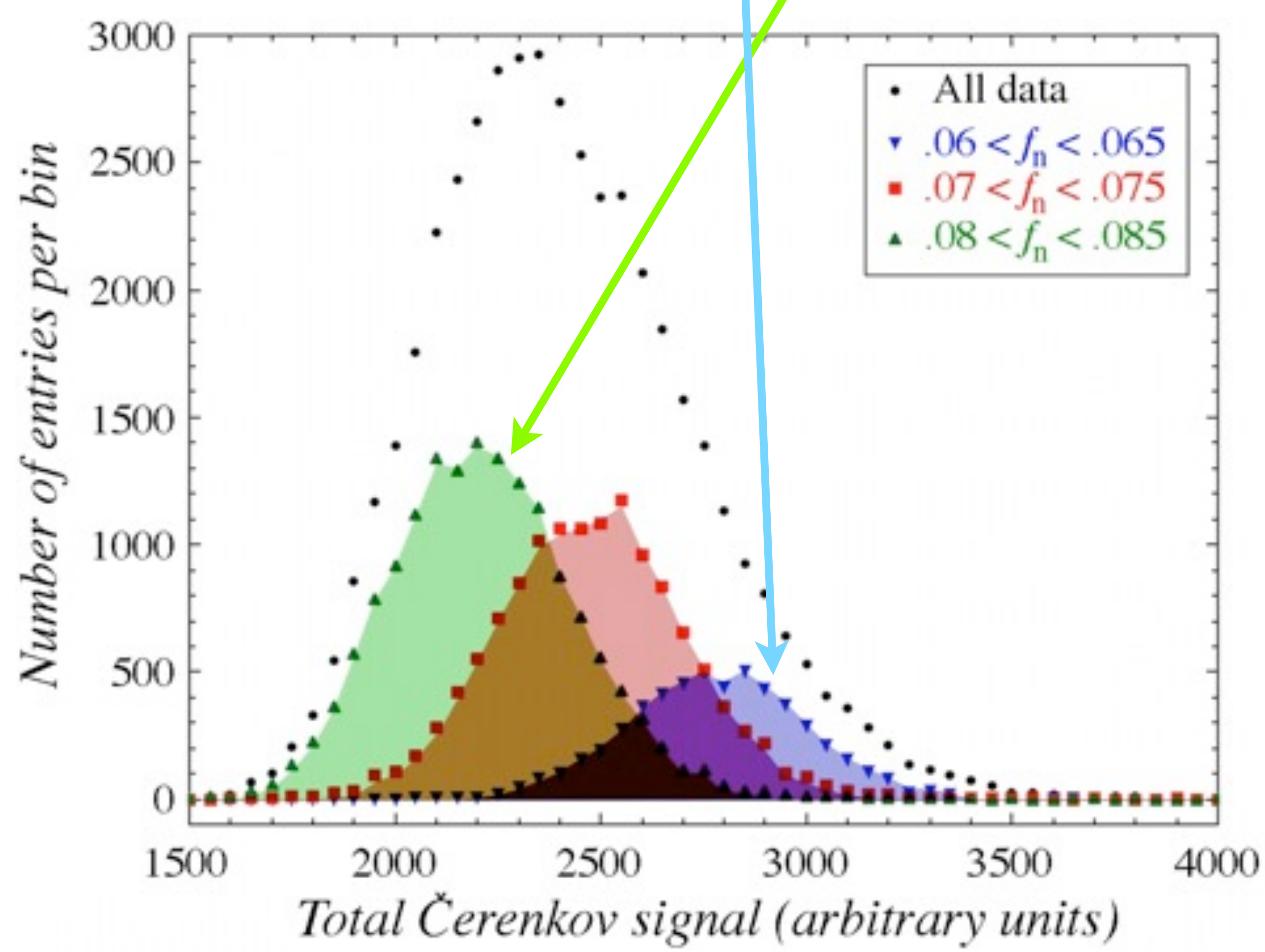
$\uparrow$ f_n



f_{EM} $\rightarrow$

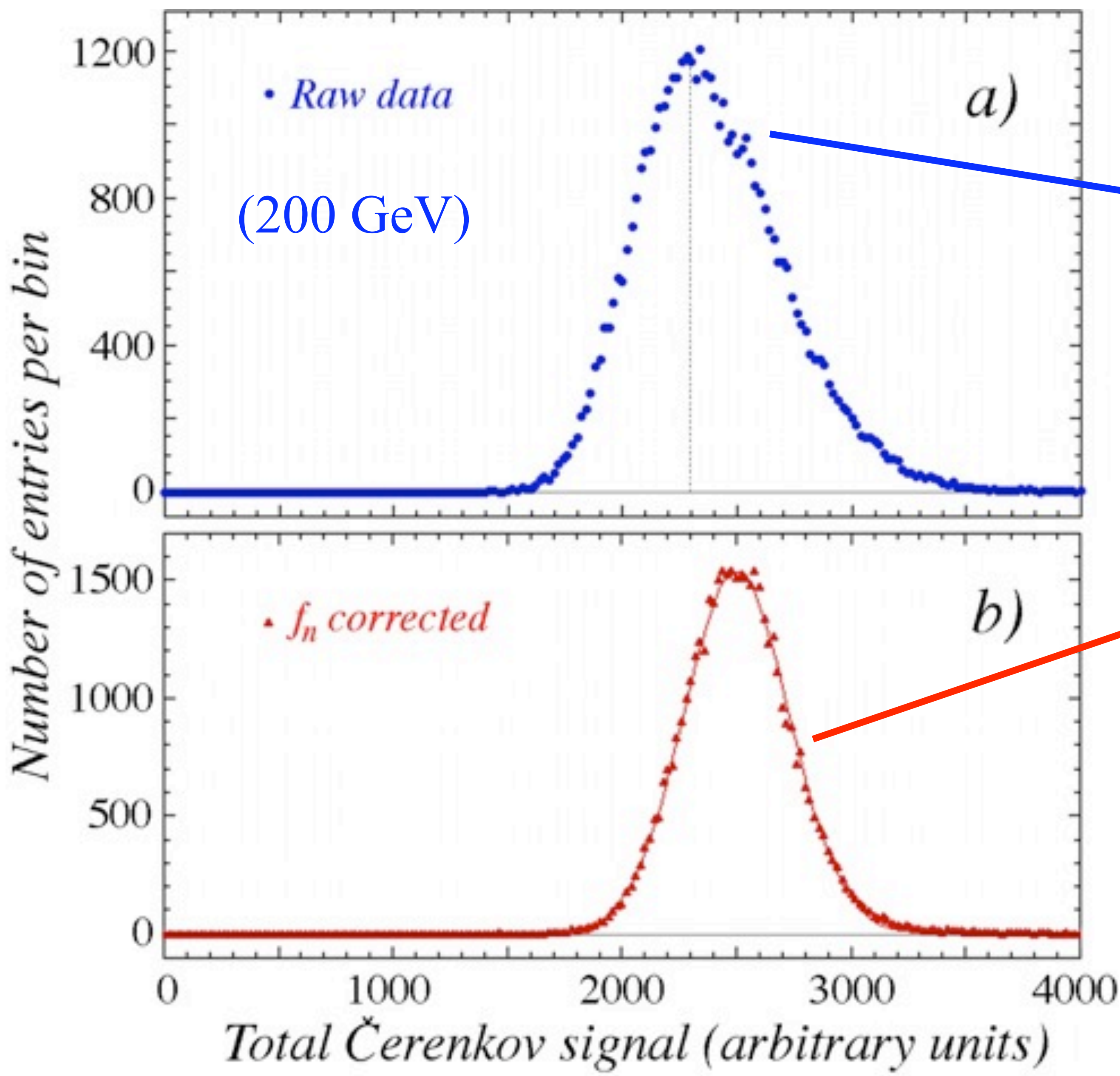
fluctuations in shower development between $\pi^0 \rightarrow \gamma\gamma$ and π^+/π^-

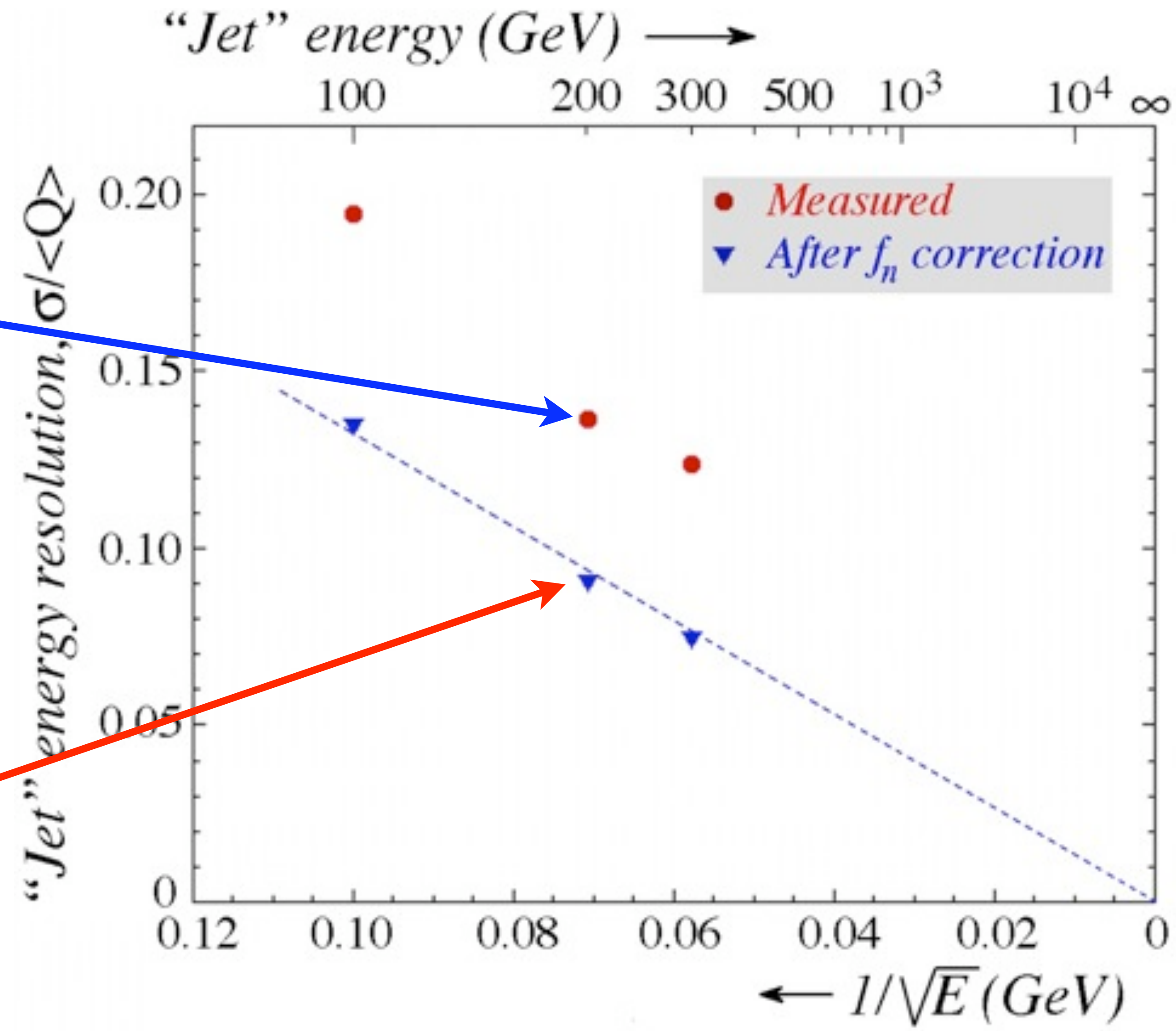




Broad, asymmetric Cerenkov response is a sum of narrow Gaussians

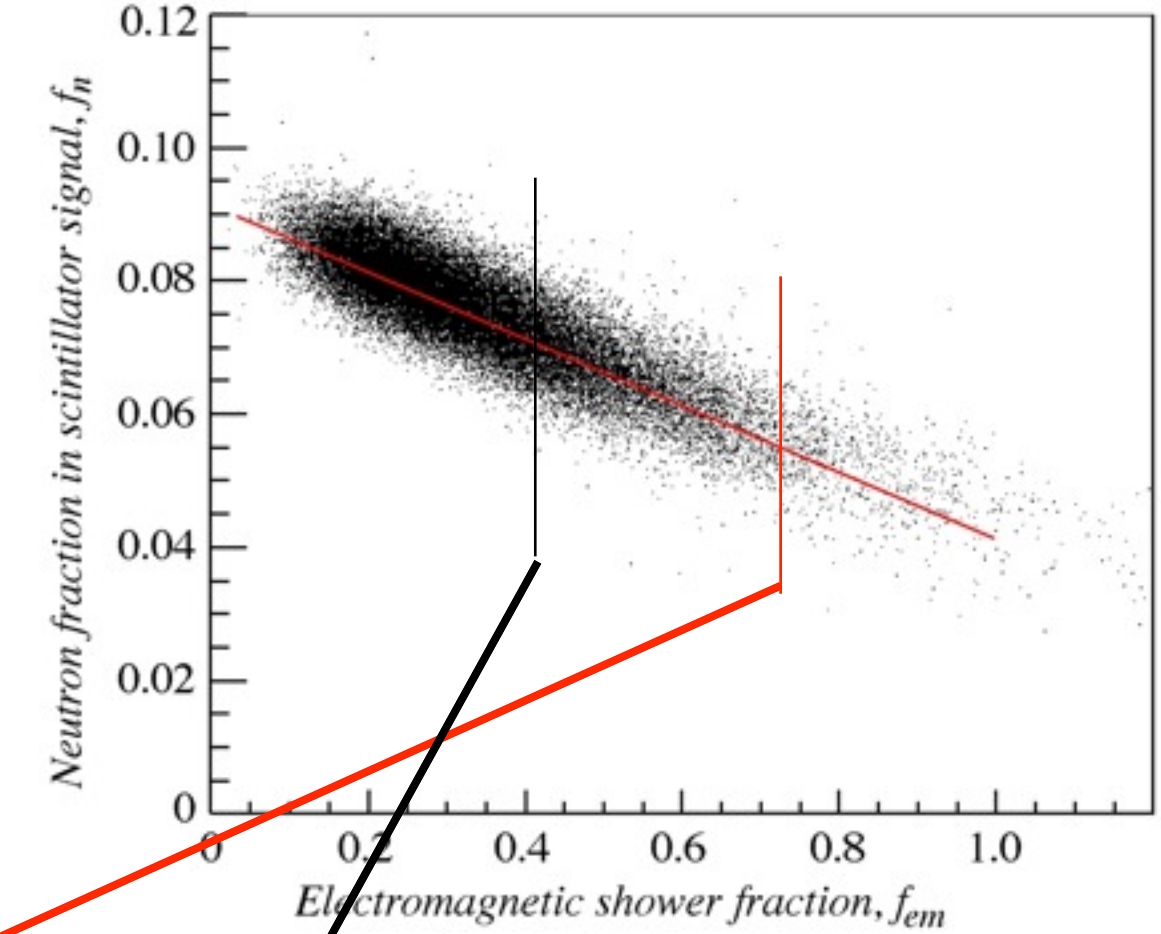
Linearly shift each Cerenkov distribution to $f_n \sim 0.07$ (arbitrary, middle value)

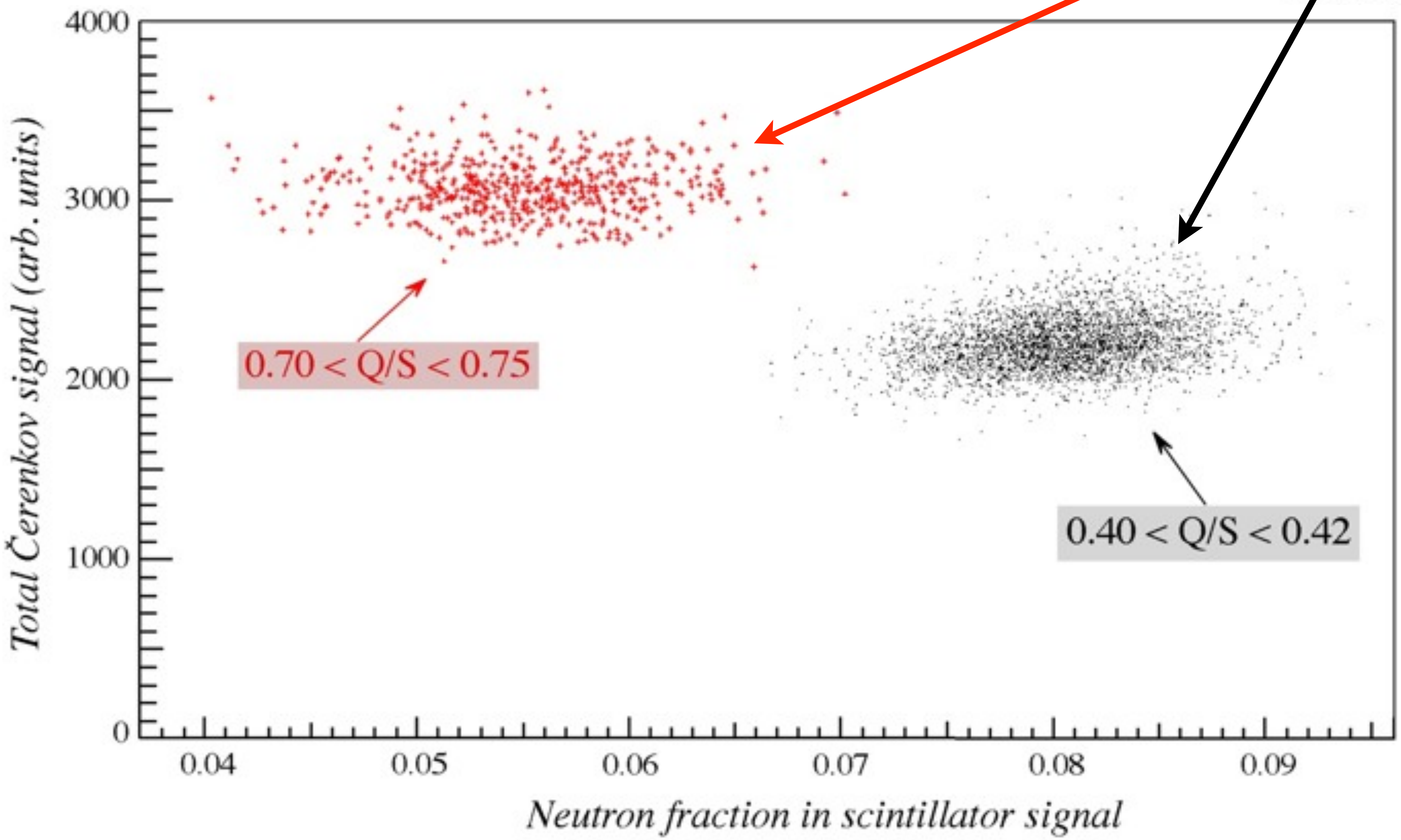




f_n-corrected resolution improves, improves with energy, and leaves no evidence of a constant term ... *the importance of neutrons*

For fixed f_{EM}, the neutron fraction varies by ~15% or more; *these are the binding energy loss fluctuations on top of the EM fraction fluctuations.*



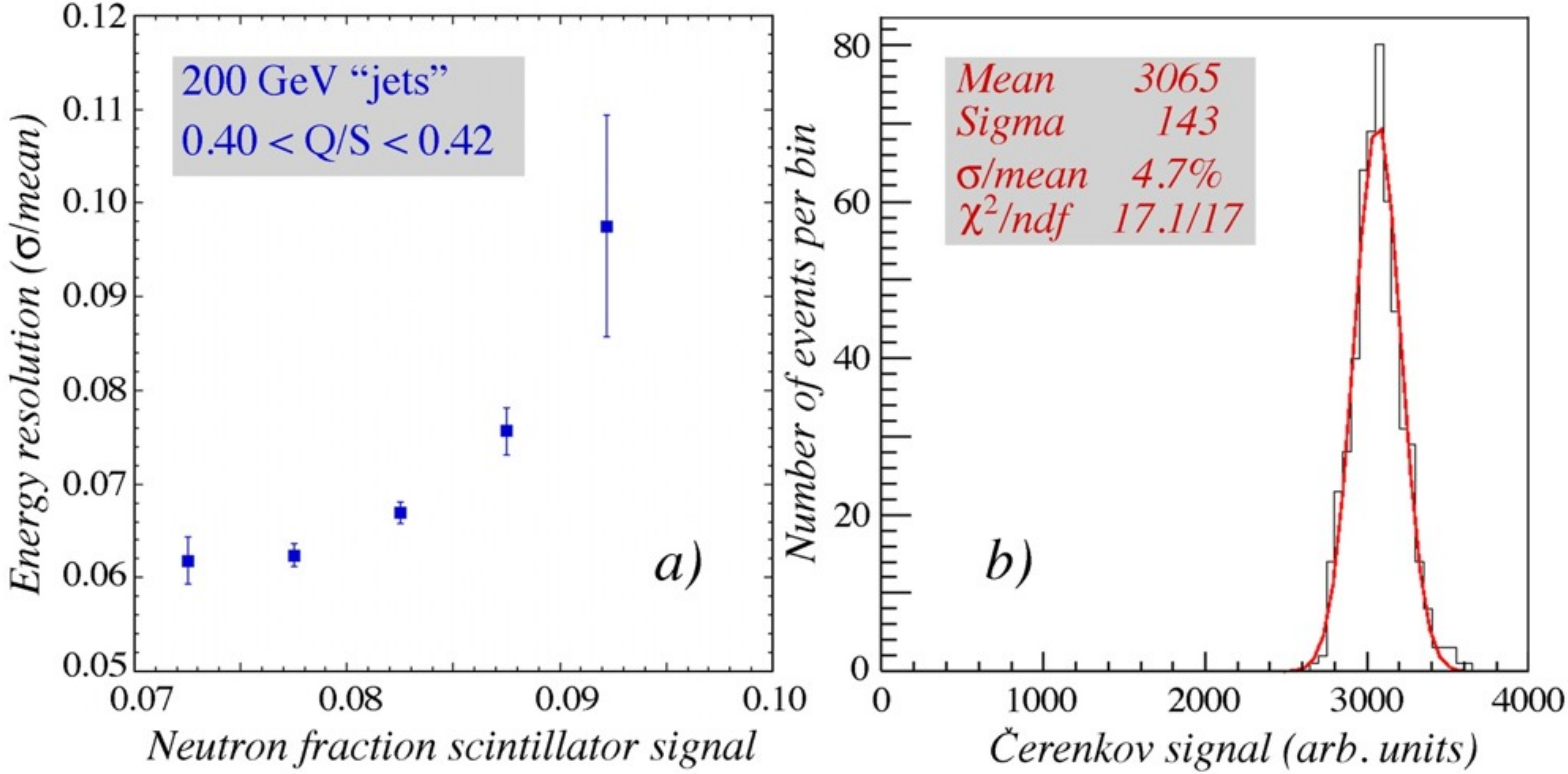


ZEUS(H) *vs* D0(LAr)

For fixed f_{EM}, the resolution in the Cerenkov signal worsens as the neutron fraction grows larger, and its fluctuations grow larger.

For f_{EM}~0.55 and f_n slices

$0.045<f_n<0.065$, $\sigma/mean$~4.7%
$0.050<f_n<0.055$, $\sigma/mean$~4.4%

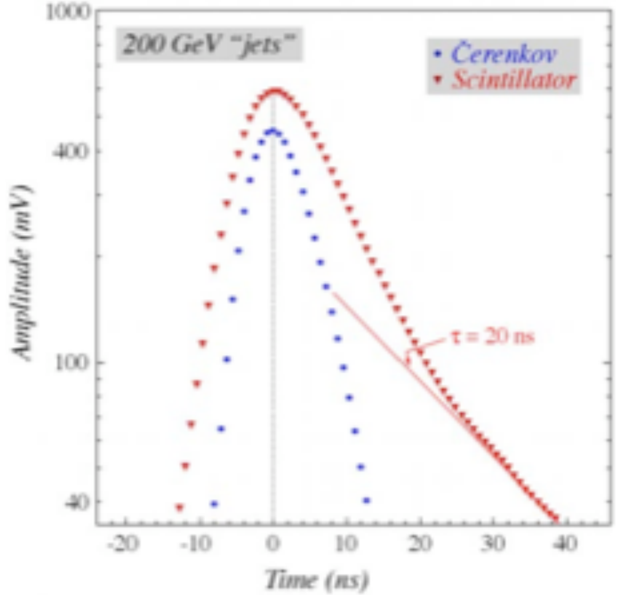


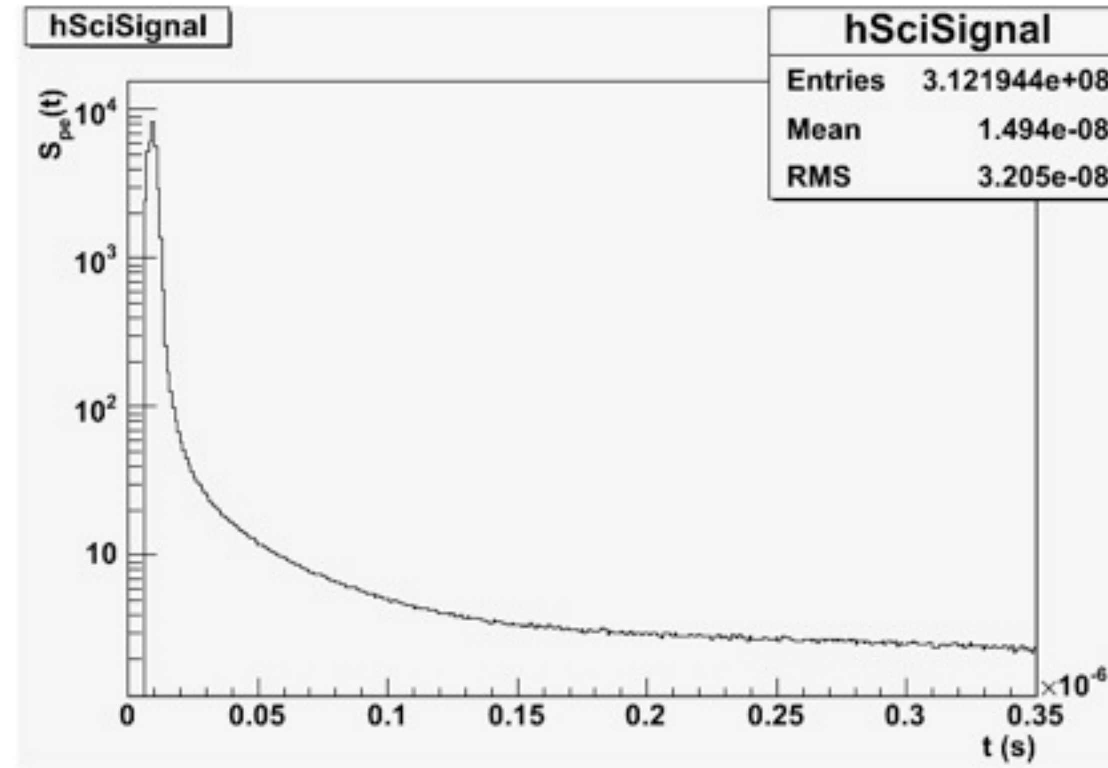
We are pushing the limits of DREAM: leakage fluctuations are ~4%.

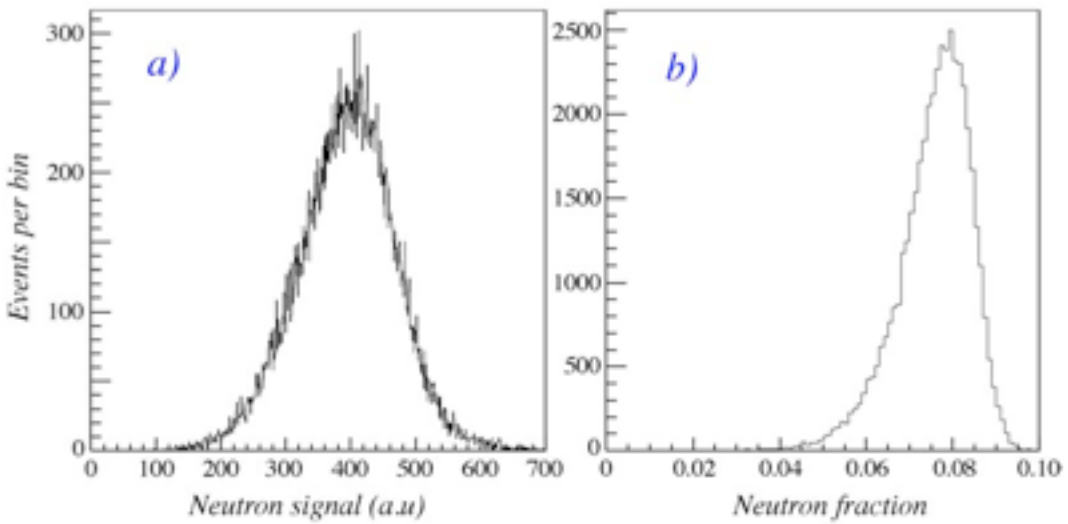
Summary and plans for neutrons in DREAM

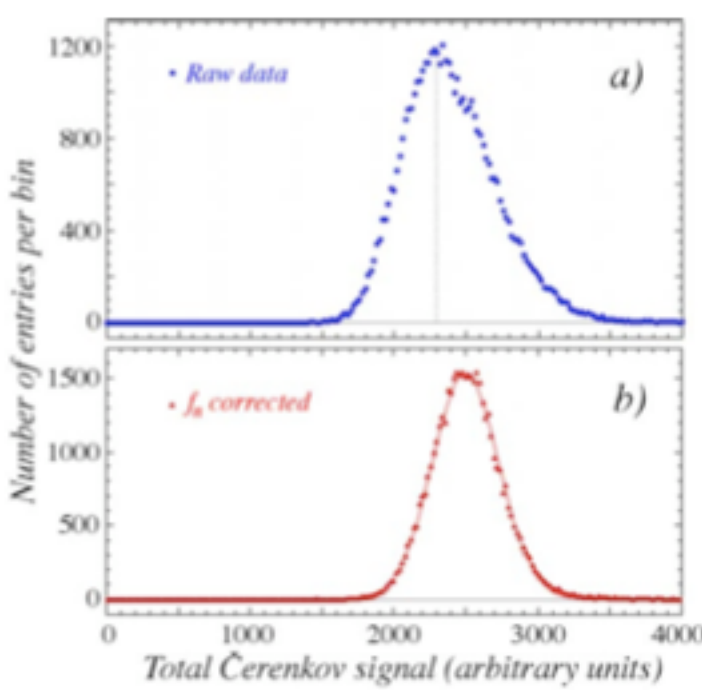
- Larger DREAM module - keep leakage below 1%
- Time-readout of all channels (DRS4)
- temporal and spatial image of hadronic shower development
- Search ultimate limits on hadronic energy resolution:
  $\sim 13\%/\sqrt{E}$ (Pb) $\sim 15\%/\sqrt{E}$ (Cu) $\sim 20\%/\sqrt{E}$ (U)
  fundamentally limited by the correlation of neutron kinetic energies with binding energy losses.

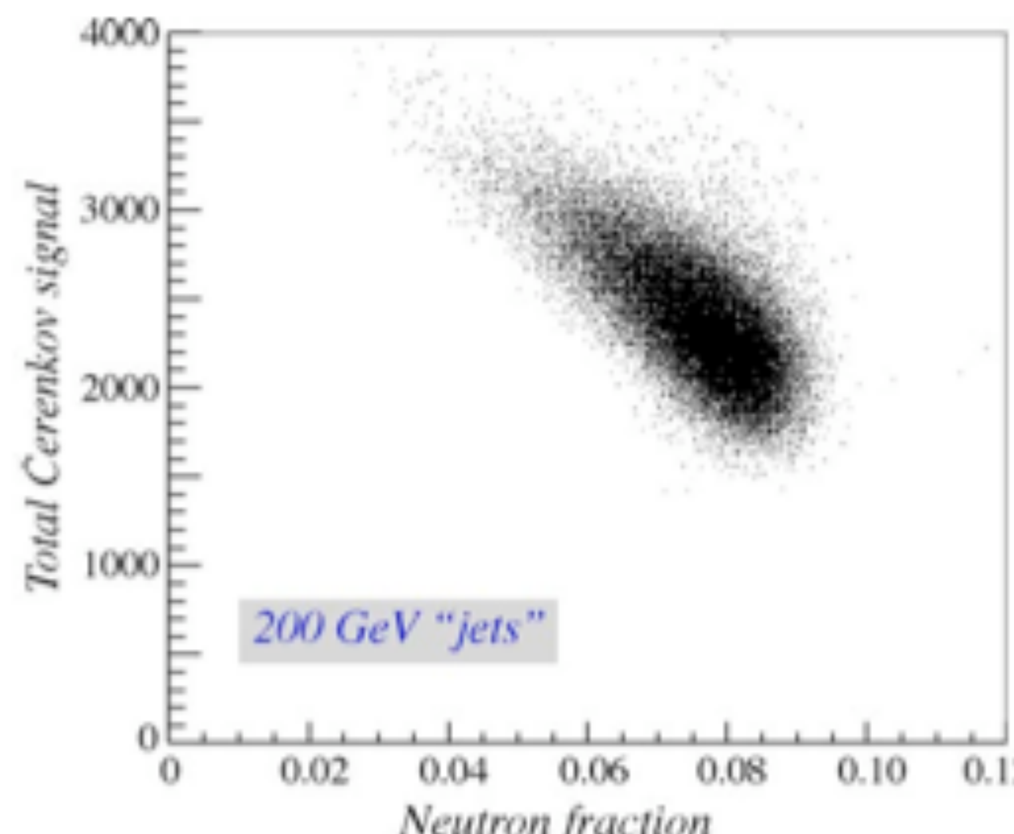
SPARE PLOTS


200 GeV "jets"
Čerenkov
Scintillator
τ = 20 ns
Amplitude (mV)
Time (ns)

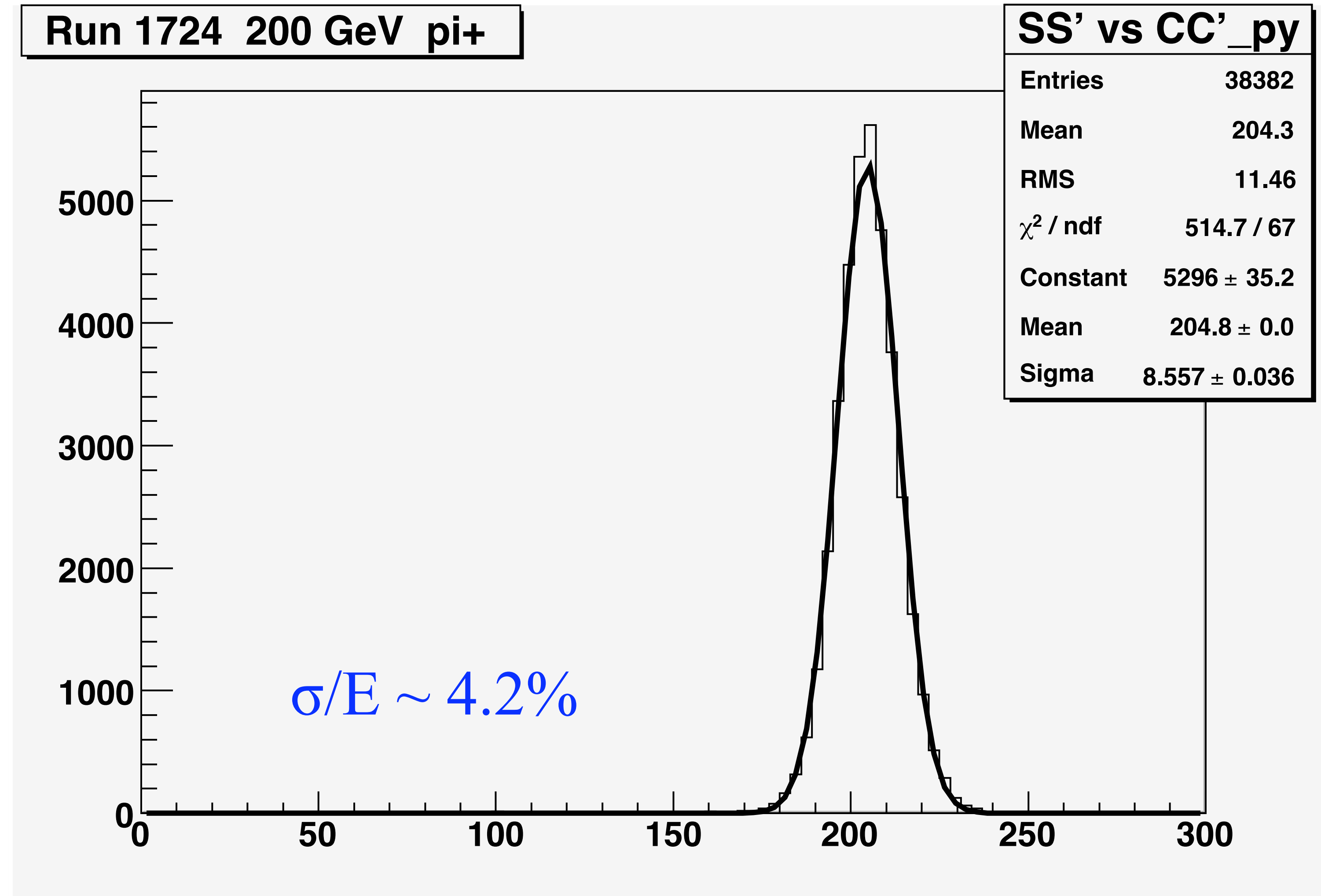

hSciSignal
hSciSignal
Entries 3.121944e+08
Mean 1.494e-08
RMS 3.205e-08
$S_{pe}(t)$
$\times 10^{-6}$
t (s)


a)
b)
Events per bin
Neutron signal (a.u)
Neutron fraction

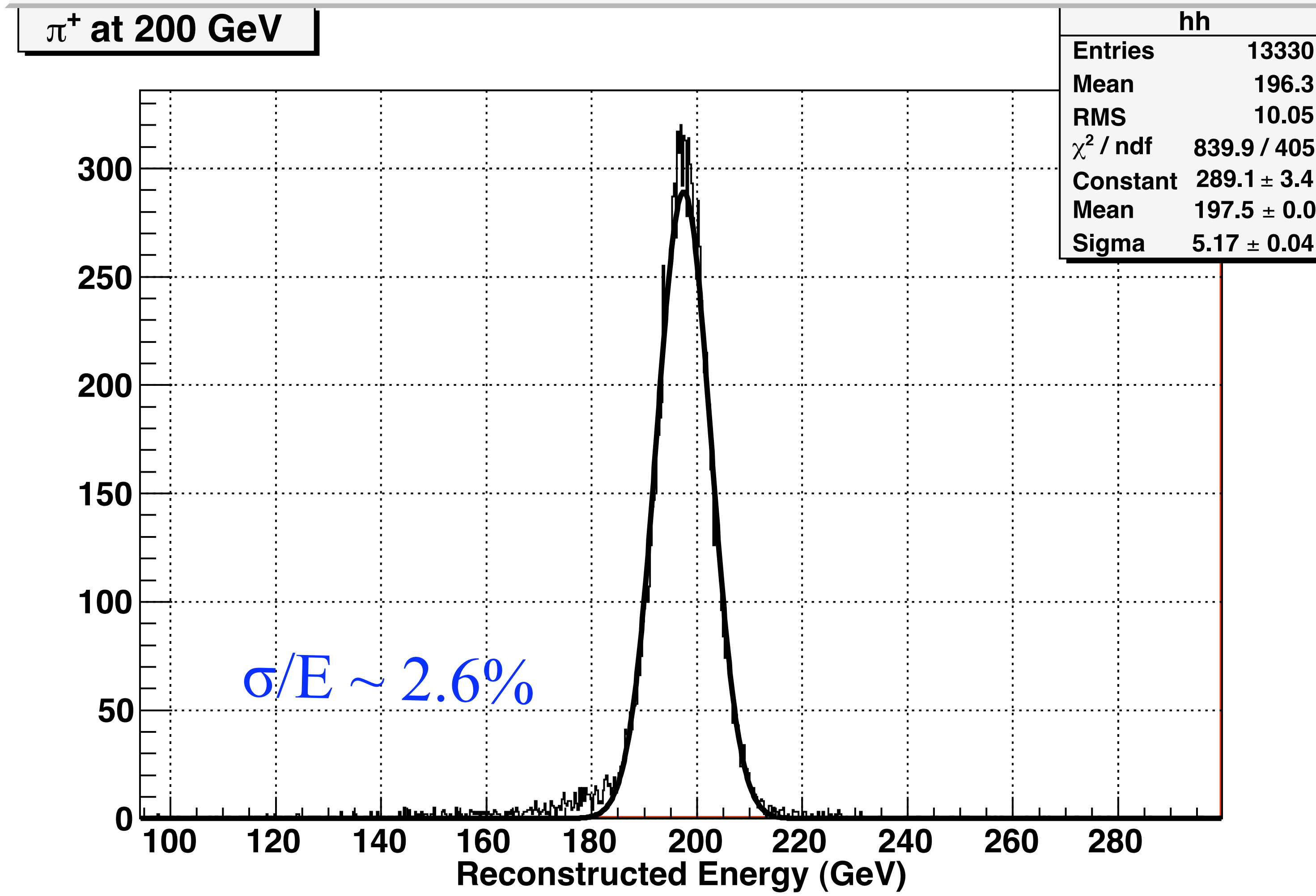

Raw data
a)
f_n corrected
b)
Number of entries per bin
Total Čerenkov signal (arbitrary units)


Total Čerenkov signal
Neutron fraction
200 GeV "jets"

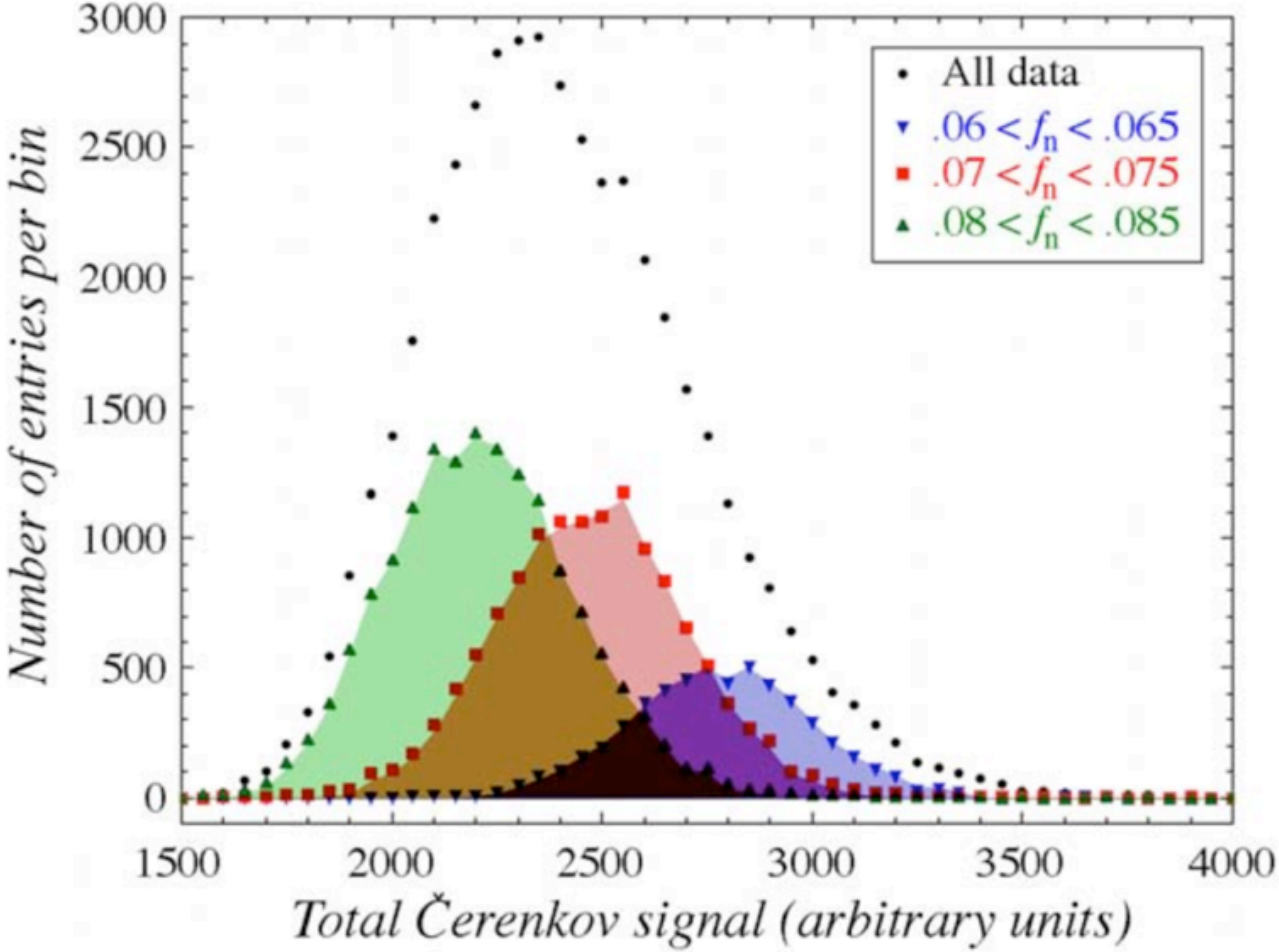
DREAM data
π^+ 200 GeV



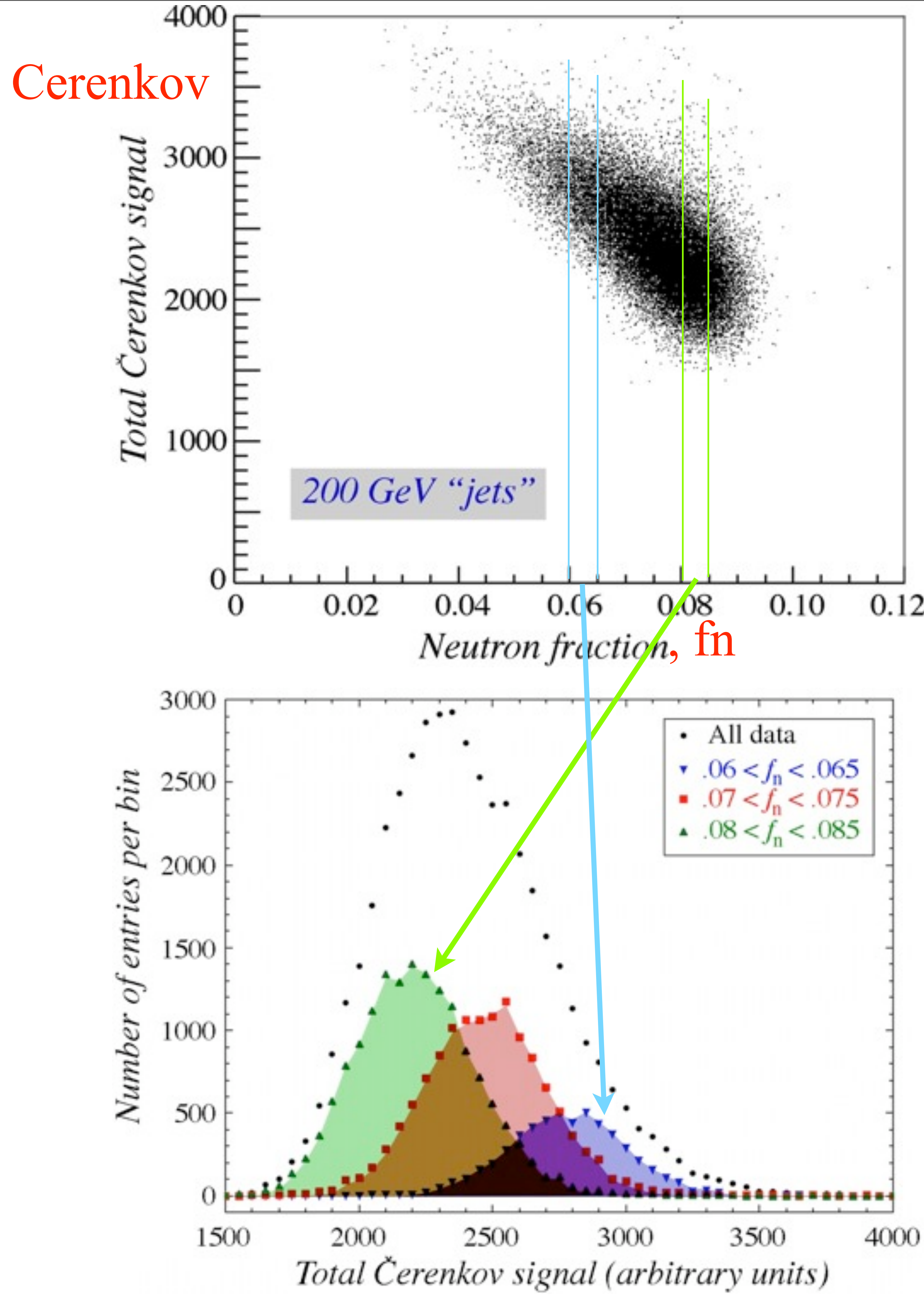
Fluka simulation
π^+ 200 GeV
(4π detector)



Broad, asymmetric Cerenkov response is a sum of narrow Gaussians

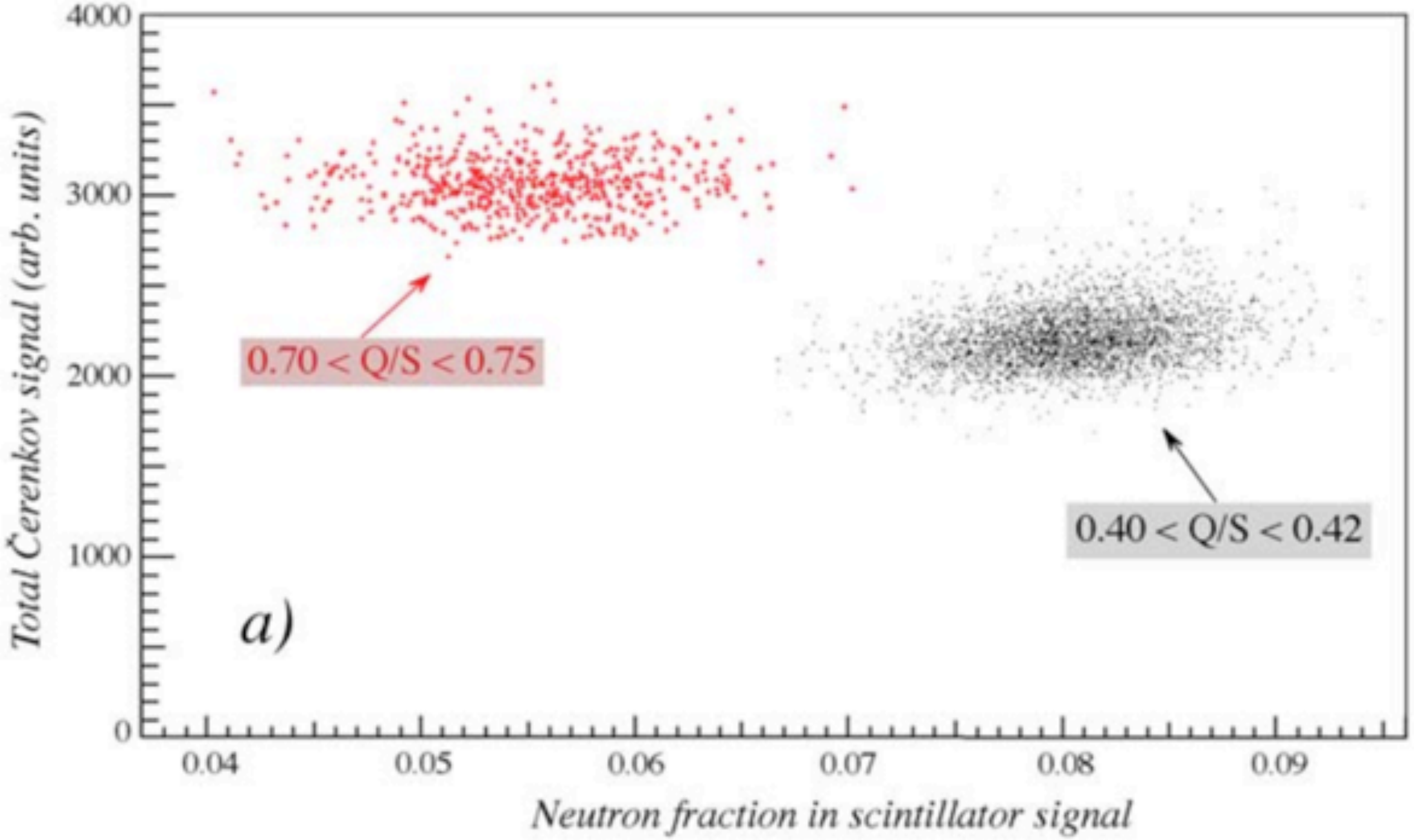


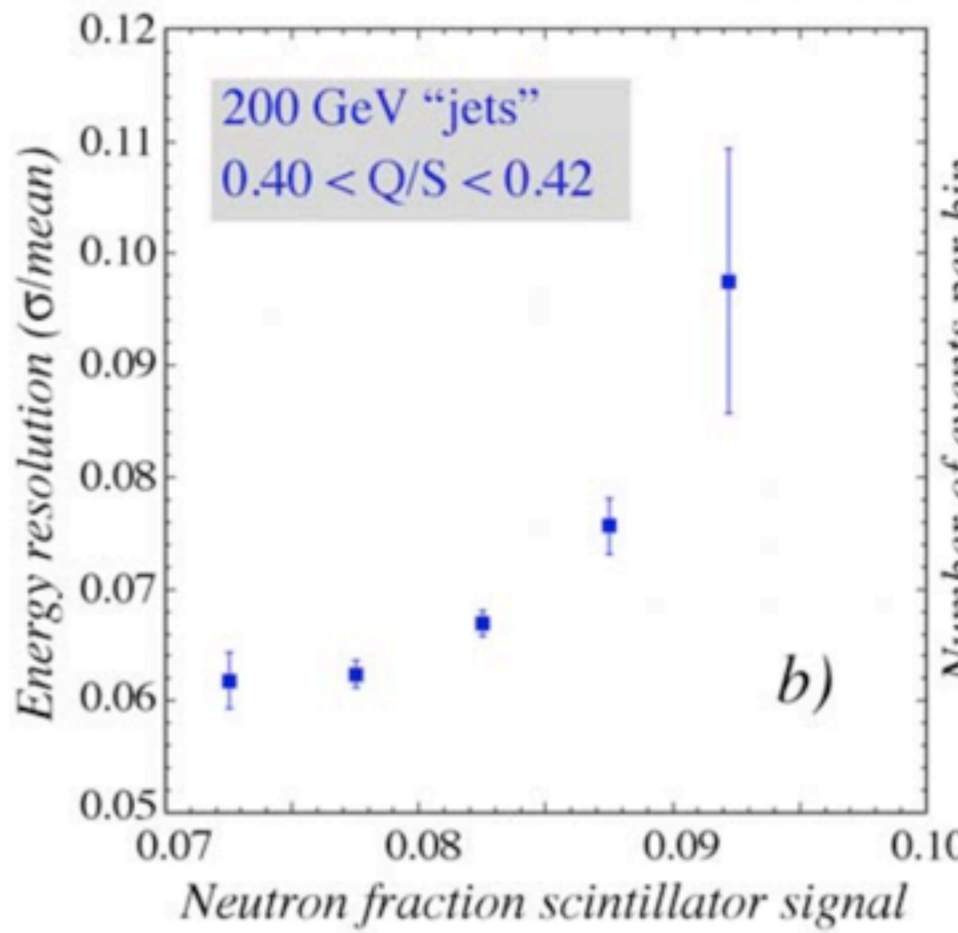
The neutron fraction is anti-correlated with the Cerenkov signal - as expected

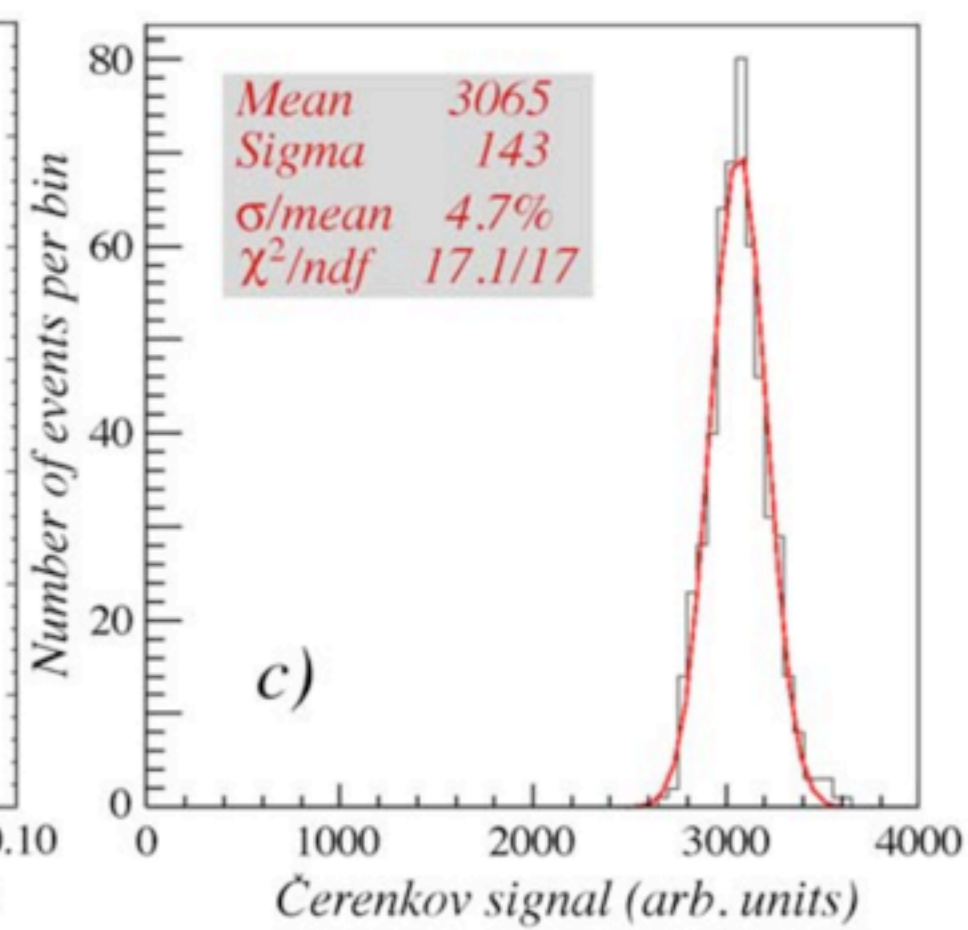


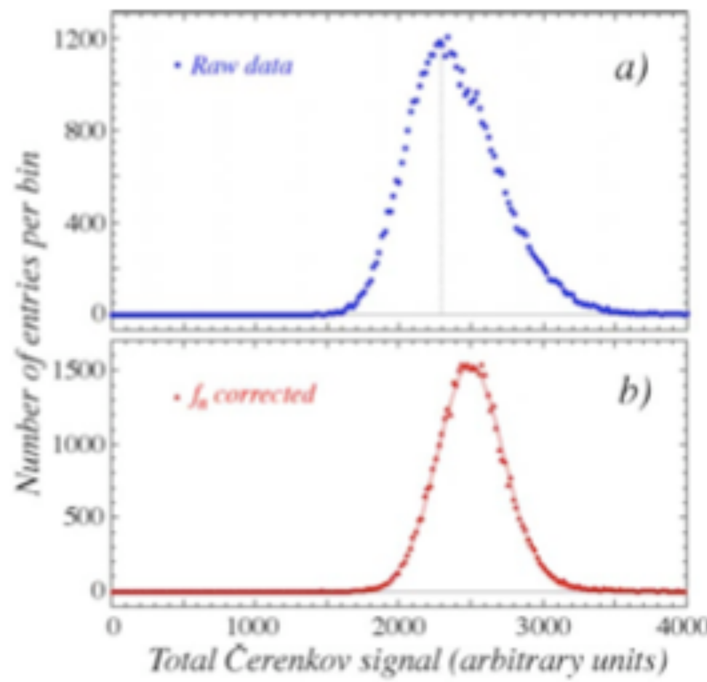
More interestingly, the total Cerenkov distribution can be decomposed into its constituent parts as a function of fn.

This is the analog to the same plot decomposed into fEM parts.

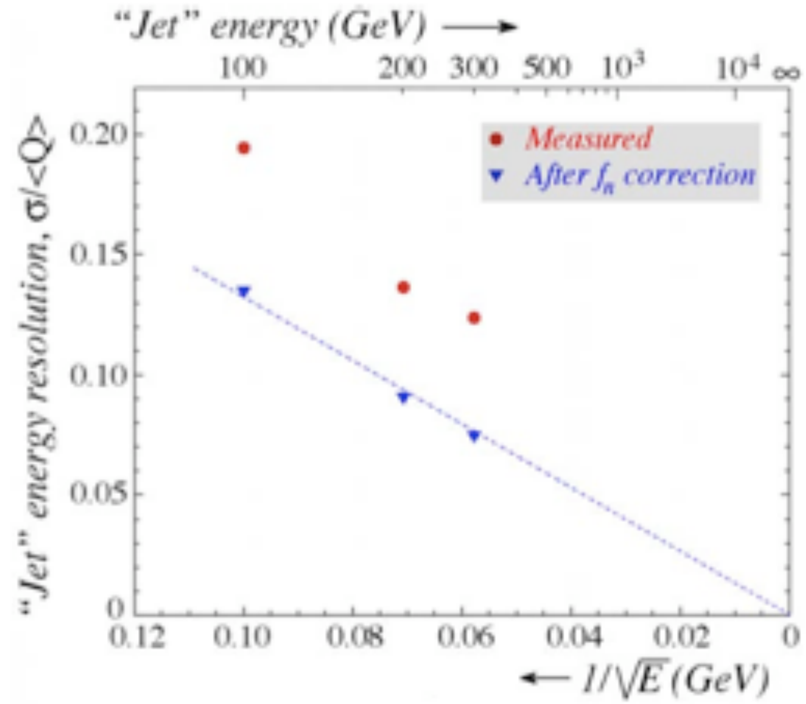

Total Čerenkov signal (arb. units)
0.70 < Q/S < 0.75
0.40 < Q/S < 0.42
a)
Neutron fraction in scintillator signal


200 GeV "jets"
0.40 < Q/S < 0.42
Energy resolution (σ/mean)
b)
Neutron fraction scintillator signal

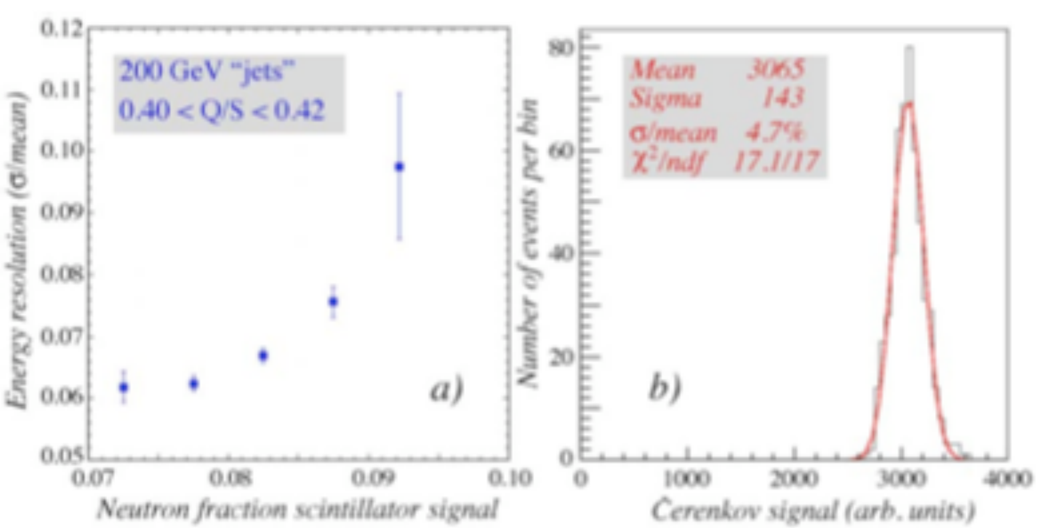

Mean 3065
Sigma 143
σ/mean 4.7%
χ2/ndf 17.1/17
Number of events per bin
c)
Čerenkov signal (arb. units)



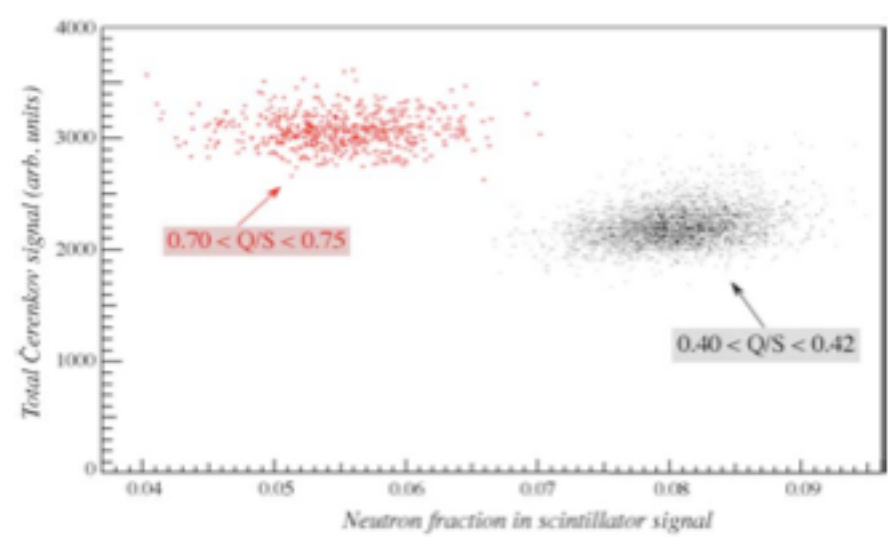
Raw data
a)
f_n corrected
b)
Number of entries per bin
Total Čerenkov signal (arbitrary units)



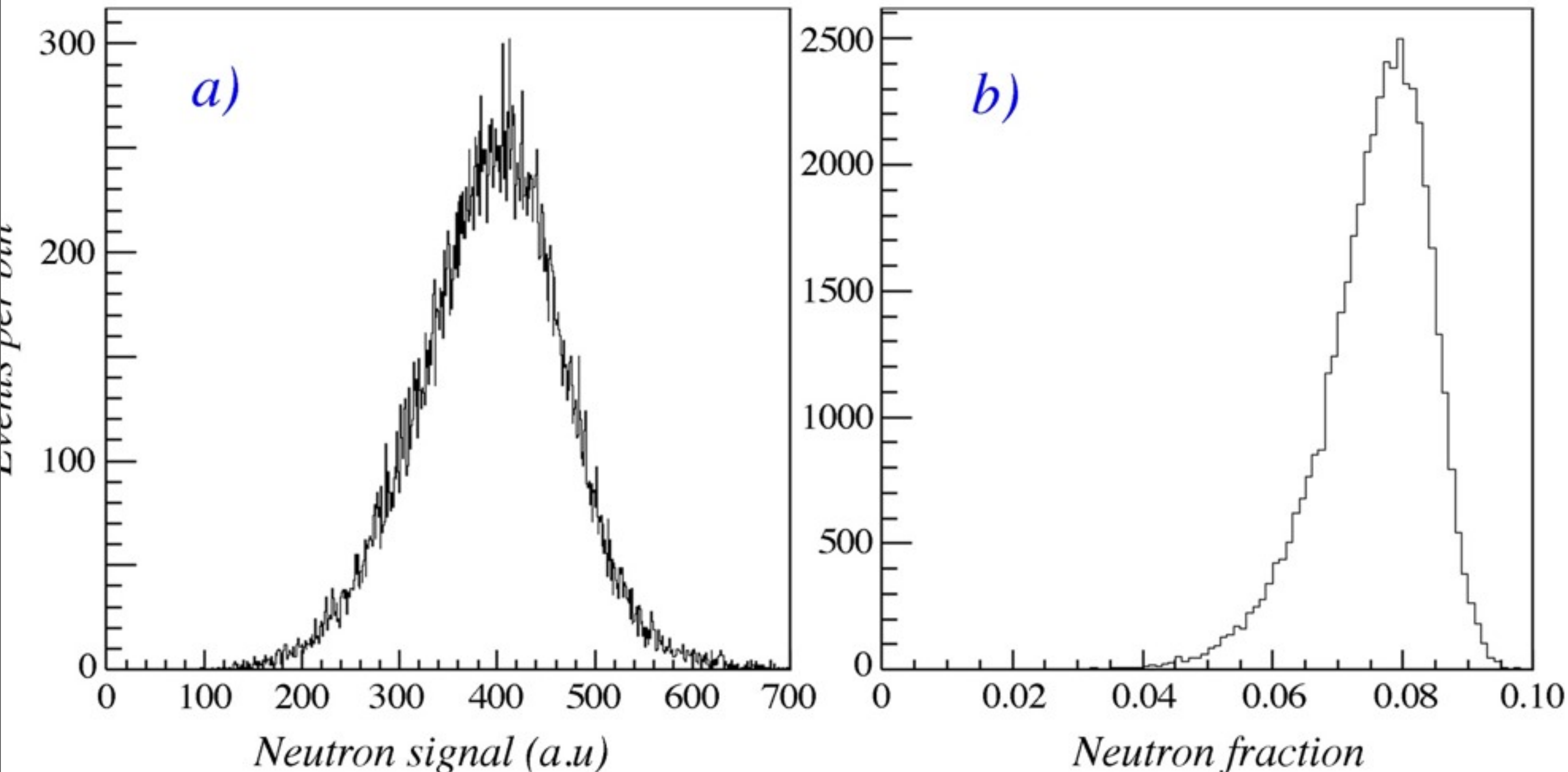
"Jet" energy (GeV)
100
200
300
500
10^3
10^4
∞
Measured
After f_n correction
"Jet" energy resolution, σ/<Q>
$1/\sqrt{E}$ (GeV)



200 GeV "jets"
0.40 < Q/S < 0.42
Energy resolution (σ/mean)
Neutron fraction scintillator signal
a)
Mean 3065
Sigma 143
σ/mean 4.7%
χ^2/ndf 17.1/17
Number of events per bin
Čerenkov signal (arb. units)
b)



0.70 < Q/S < 0.75
0.40 < Q/S < 0.42
Total Čerenkov signal (arb. units)
Neutron fraction in scintillator signal



fn = En (EM energy units) / 200 GeV

Resolution (rms width of response) and constant term are both improved