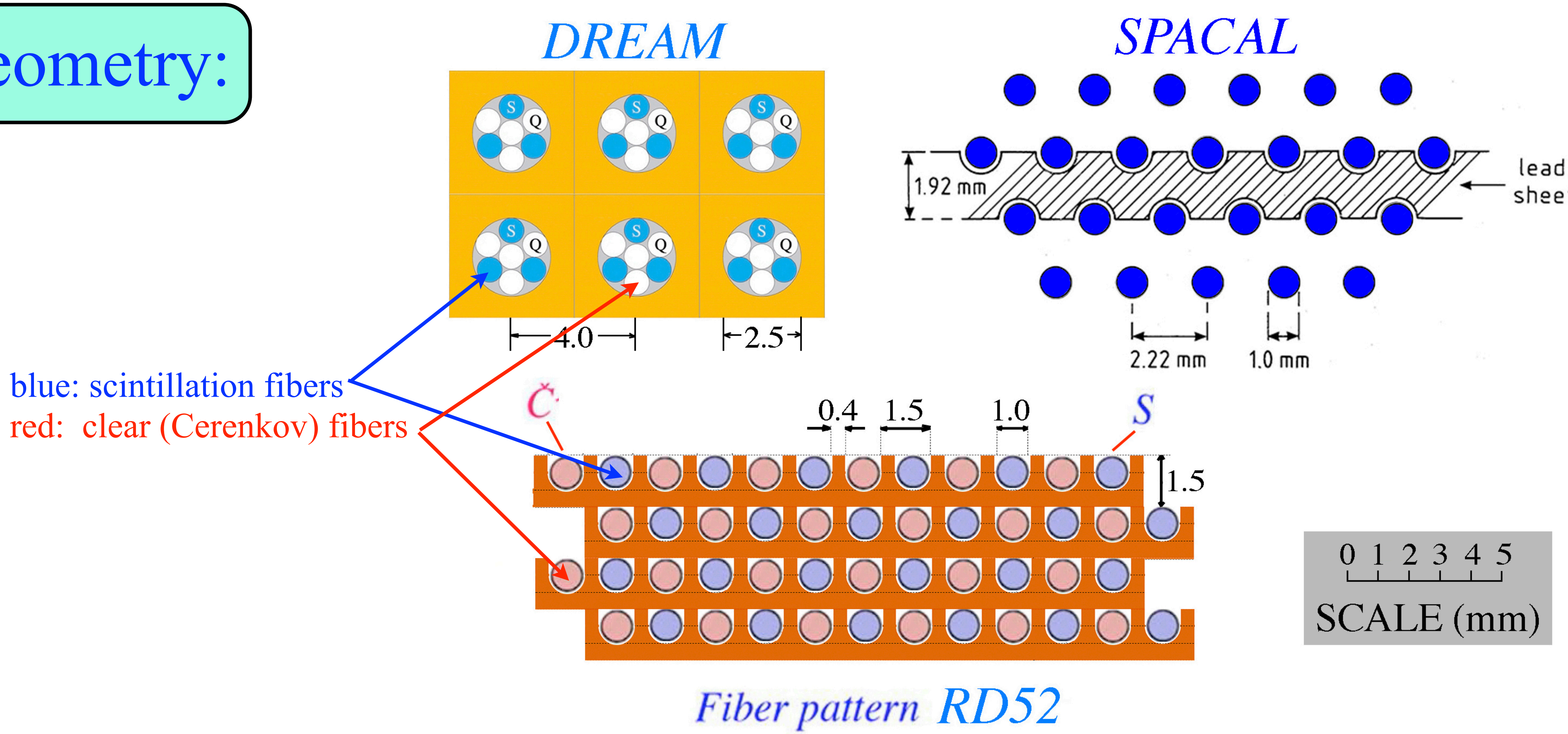
Dual-readout calorimetry: recent results and plans

John Hauptman, Iowa State University
on behalf of the RD52 collaboration:
Texas Tech University, INFN and Universita Pavia, INFN and Universita Pisa, INFN Cagliari, INFN Roma,
INFN Cosenza, INFN Lecce, CERN, Tufts University, Iowa State University, and LIP Lisbon

- the DREAM collaboration is now CERN Project RD52.
- we plan to build and test 4-5 tons of copper-absorber and lead-absorber hadronic calorimeters, which we call SuperDREAM.
- the scientific goal is to understand the fundamental limitations to hadronic calorimeter performance in all respects: energy resolution, linearity, response function, and ease of experimental calibration.
- we anticipate achieving absolute 1% energy resolution at high energy.
- we expect that this calorimeter will be Gaussian, linear in energy, and trivially calibrated like our current smaller modules.
- we have made detailed data-MC comparisons with GEANT4.

Geometry:



- *Every one of these fiber geometries works quite well*

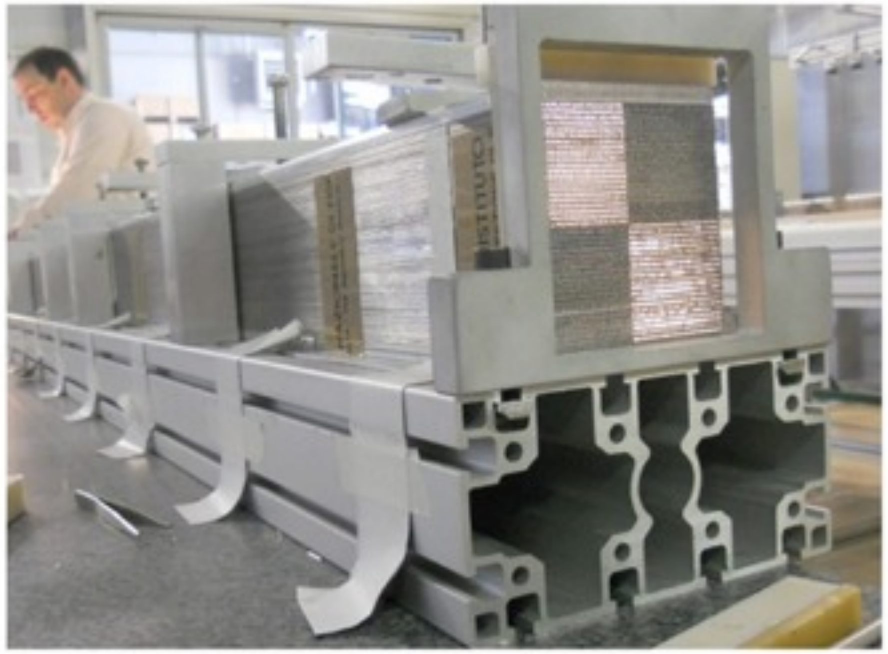
  (results published as DREAM, SPACAL, and RD52, respectively)

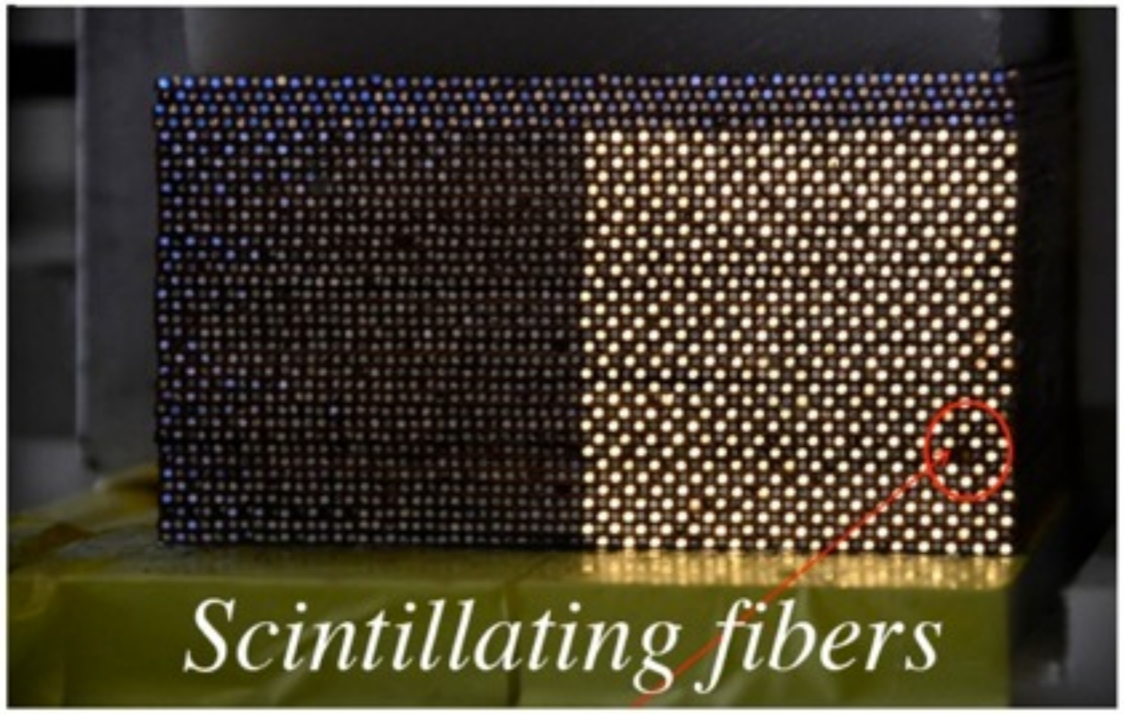
- *Spatially fine and uniform sampling: essential for a good calorimeter*

  (we understand easily the differences between the performances of these geometries)

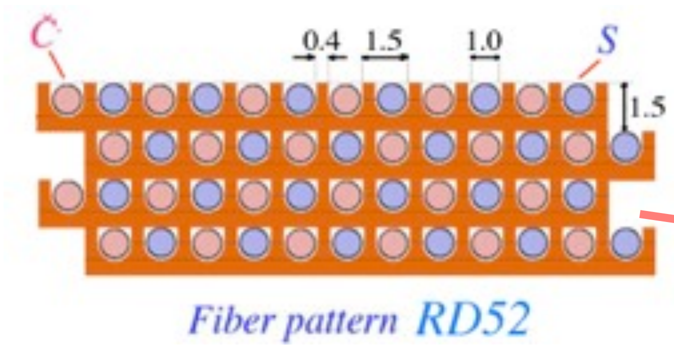
Geometry:

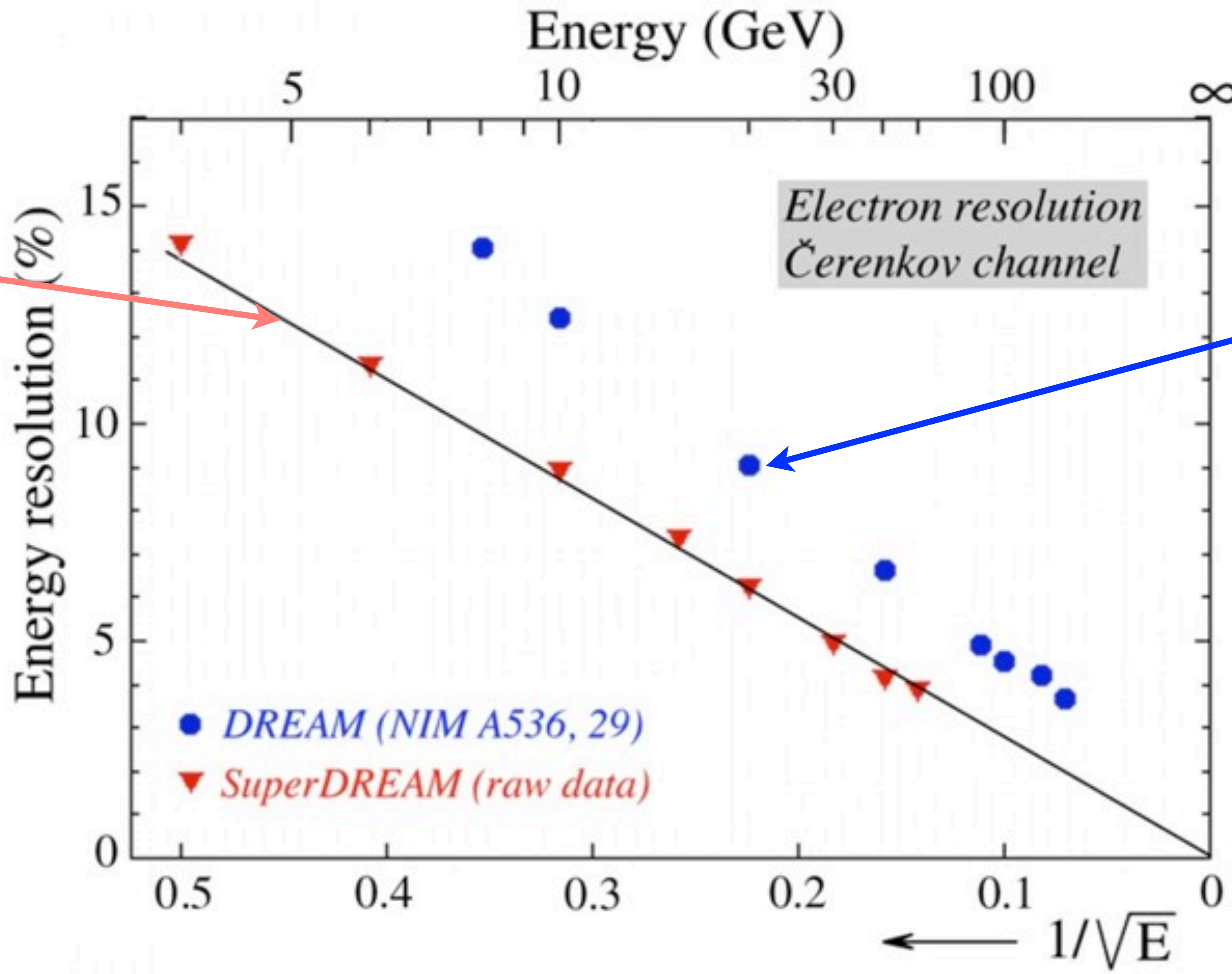
Copper module, Pisa: 10cm x 10cm x 10λ_{int}

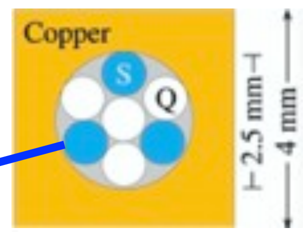




Geometry: RD52 improvement over DREAM

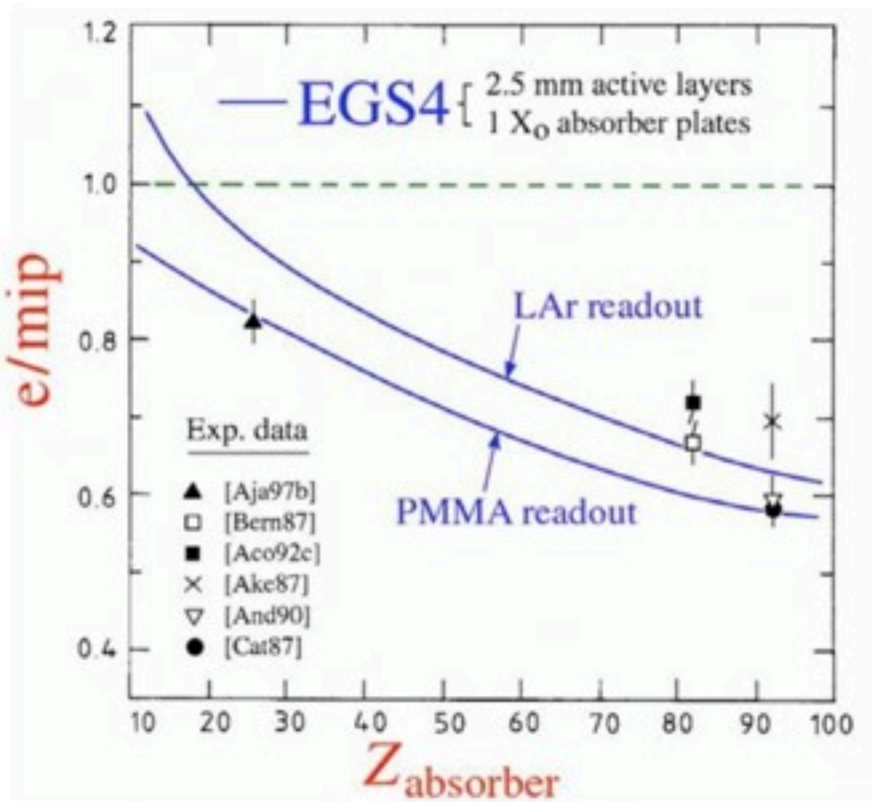


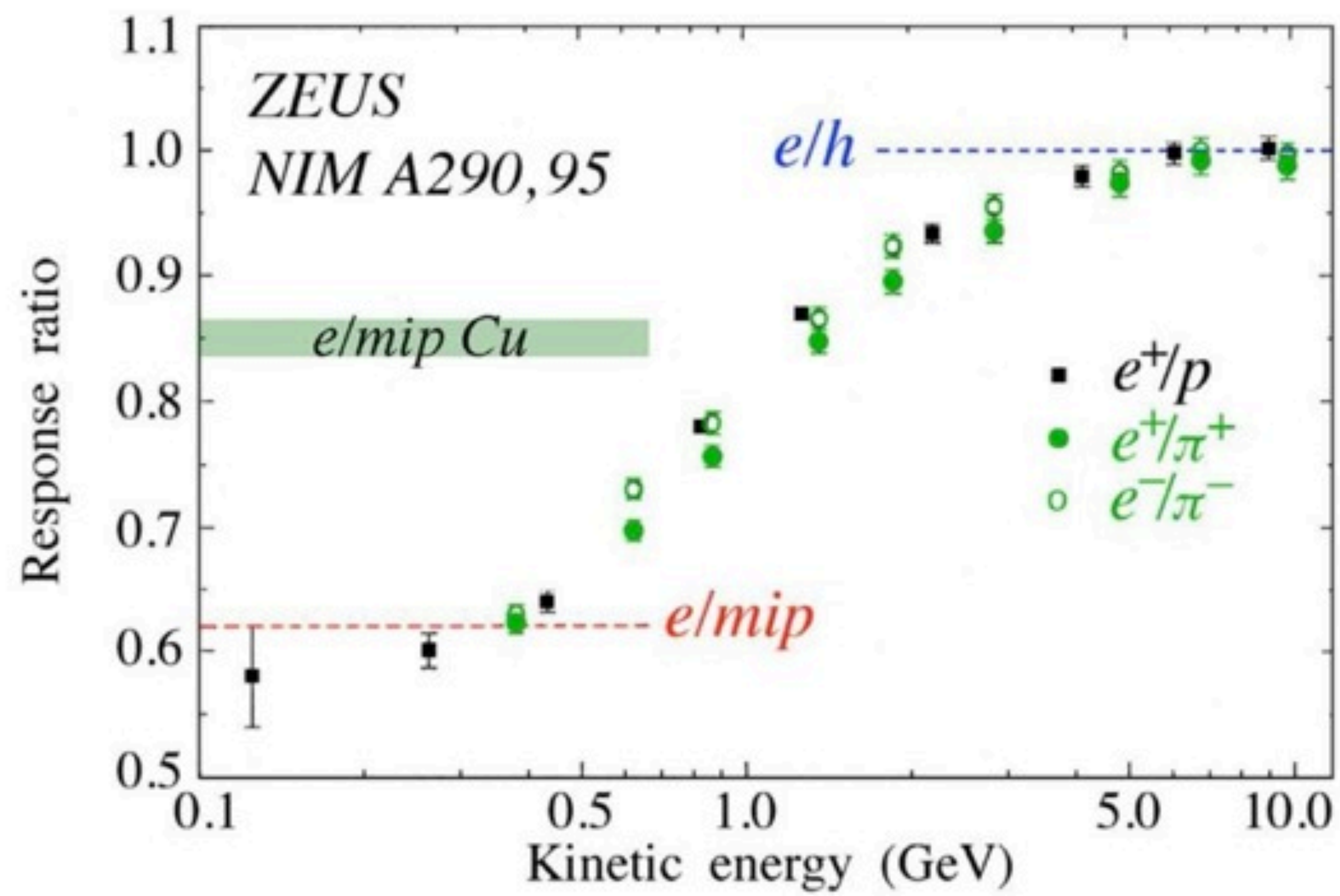




Perfect energy scaling and no constant term.

Absorber: why Cu is better than Fe, Pb, W, or U for a hadronic calorimeter





Signal non-linearities at low energy (< 5 GeV)
due to non-showering hadrons
Many jet fragments fall in this category

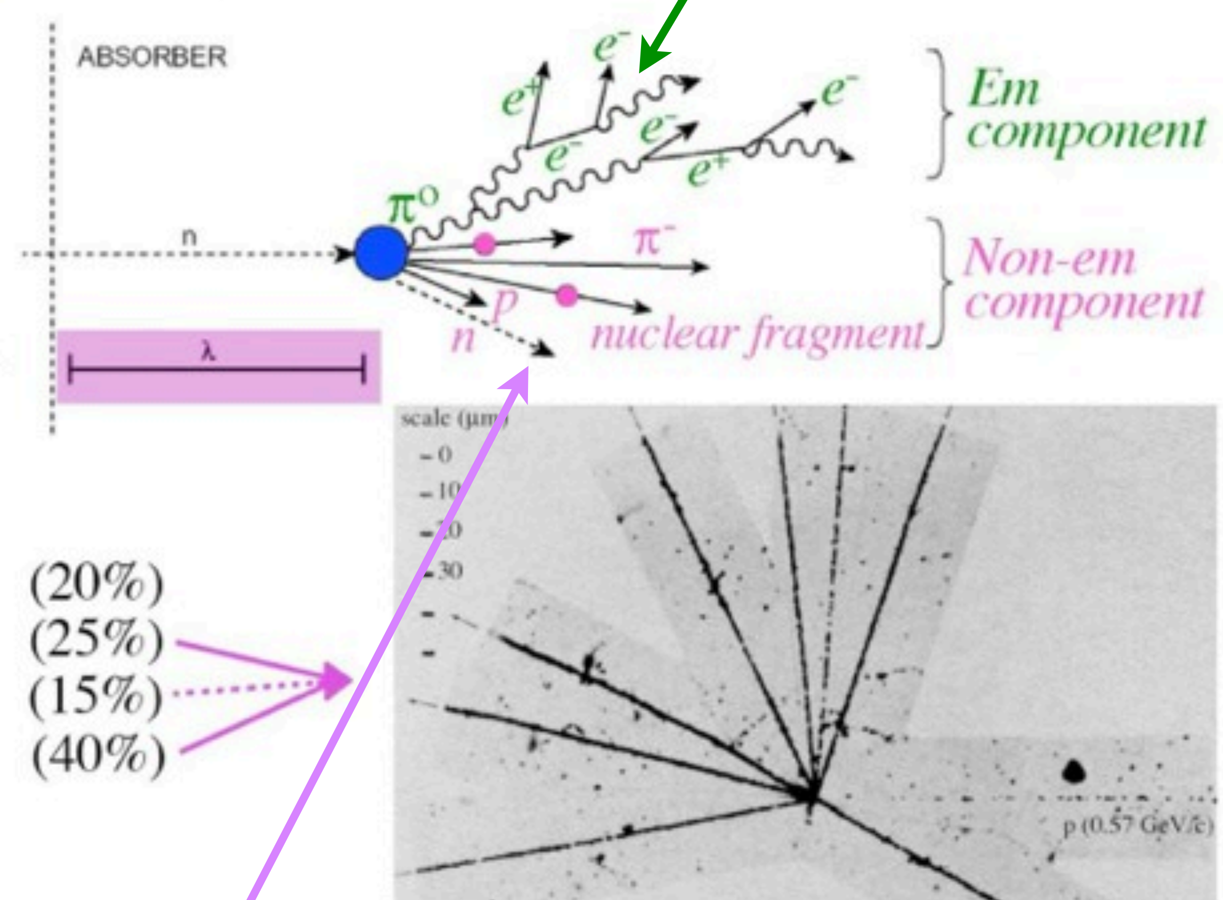
Two Fiber types: "dual"

Cerenkov fibers: relativistic e^+/e^- generate light in C-fibers, independently measures EM component

(Mitsubishi)

Large stochastic fluctuations between these event-to-event

- **Electromagnetic component**
  - electrons, photons
  - neutral pions → 2 γ
- **Hadronic (non-em) component**
  - charged hadrons π±,K± (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft γ's (15%)
  - break-up of nuclei ("invisible") (40%)

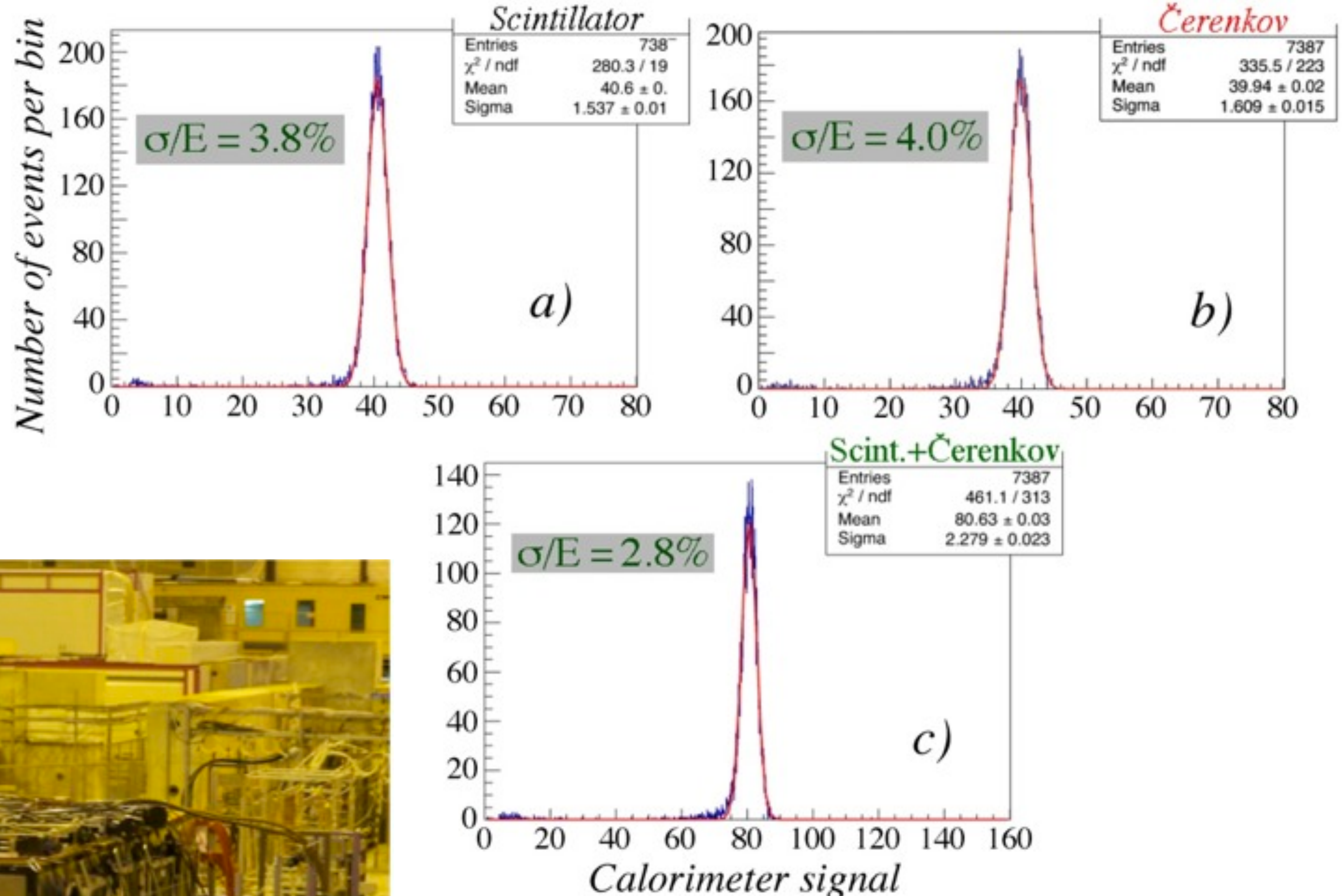


Scintillating fibers: all charged particles, *p, π, K, e, nuclear fragments, α, p from np→np, etc.*

(Kuraray)

EM fraction: $f_{EM} \sim C / S$

Calibration:

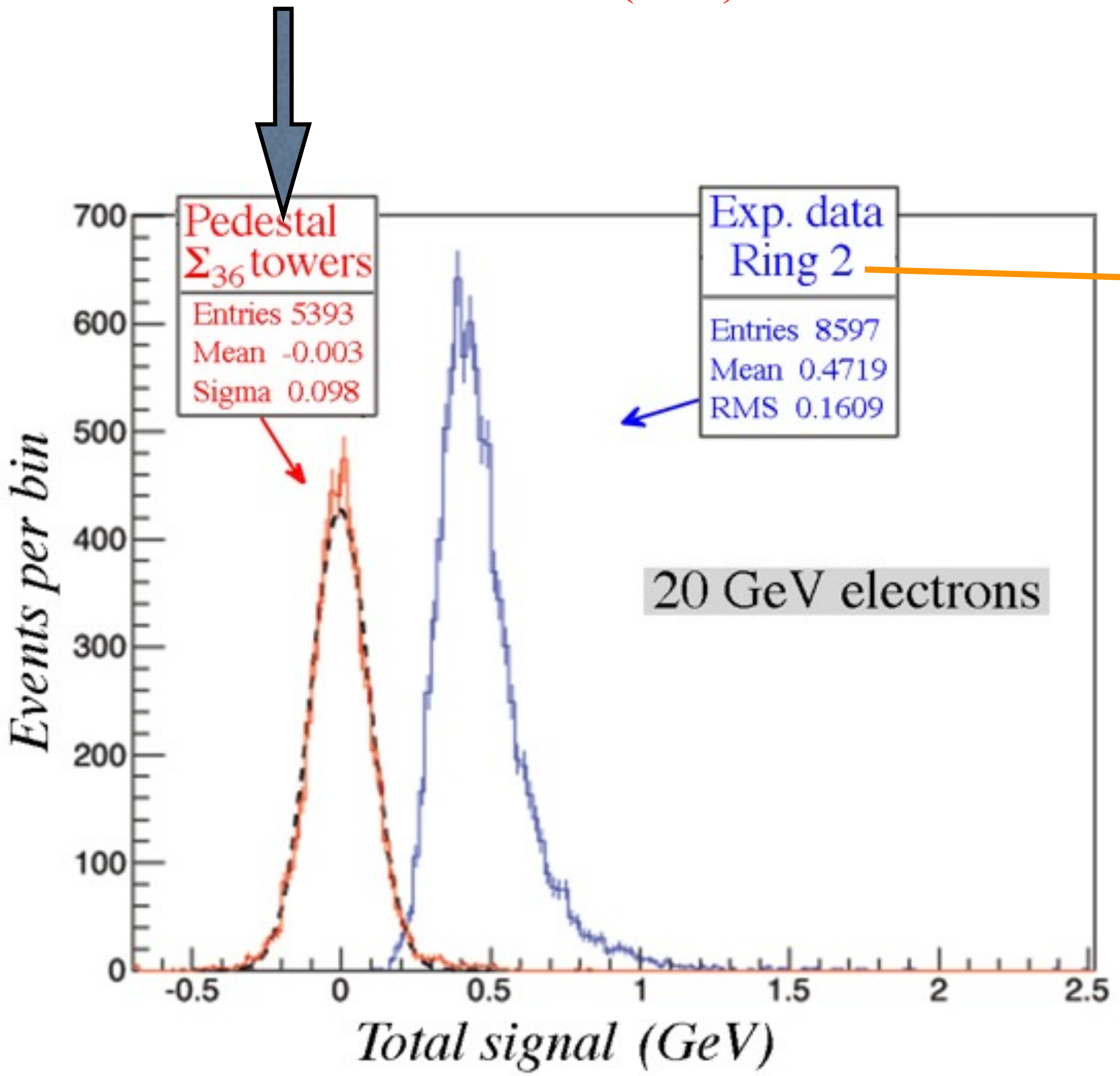


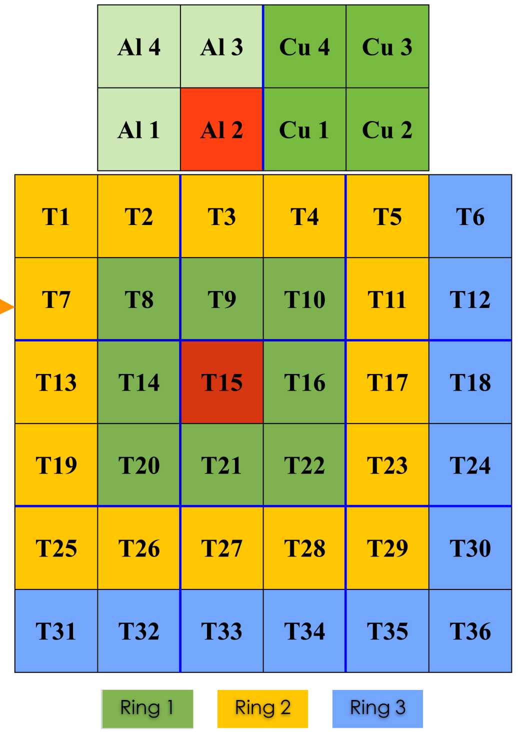
Direct and simple:

- electron beam at any energy
- record GeV/ADC each channel

Electronic Noise: getting ready for hadronic testing (late 2014)

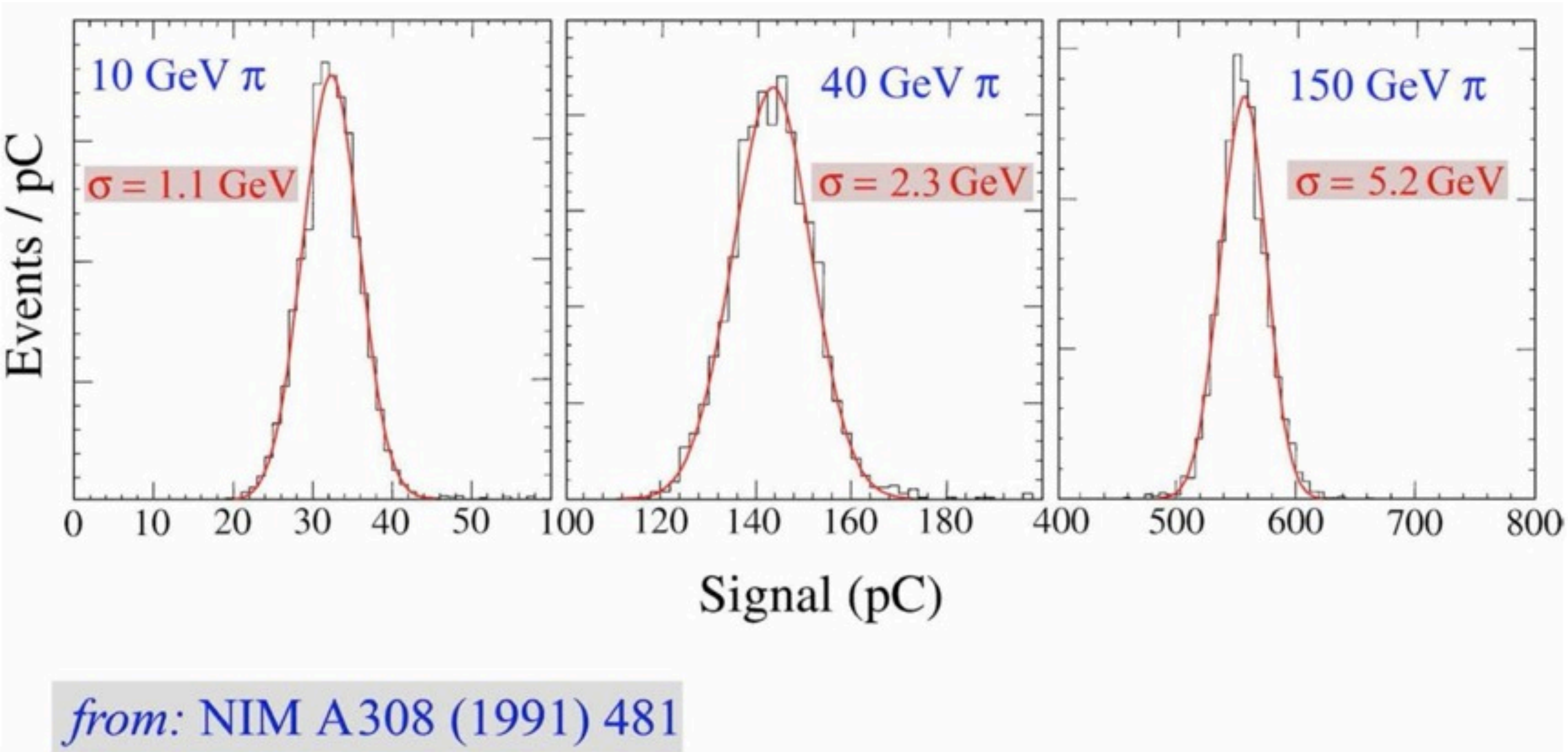
rms noise less than 100 MeV
summed over 36 modules (1.2t)



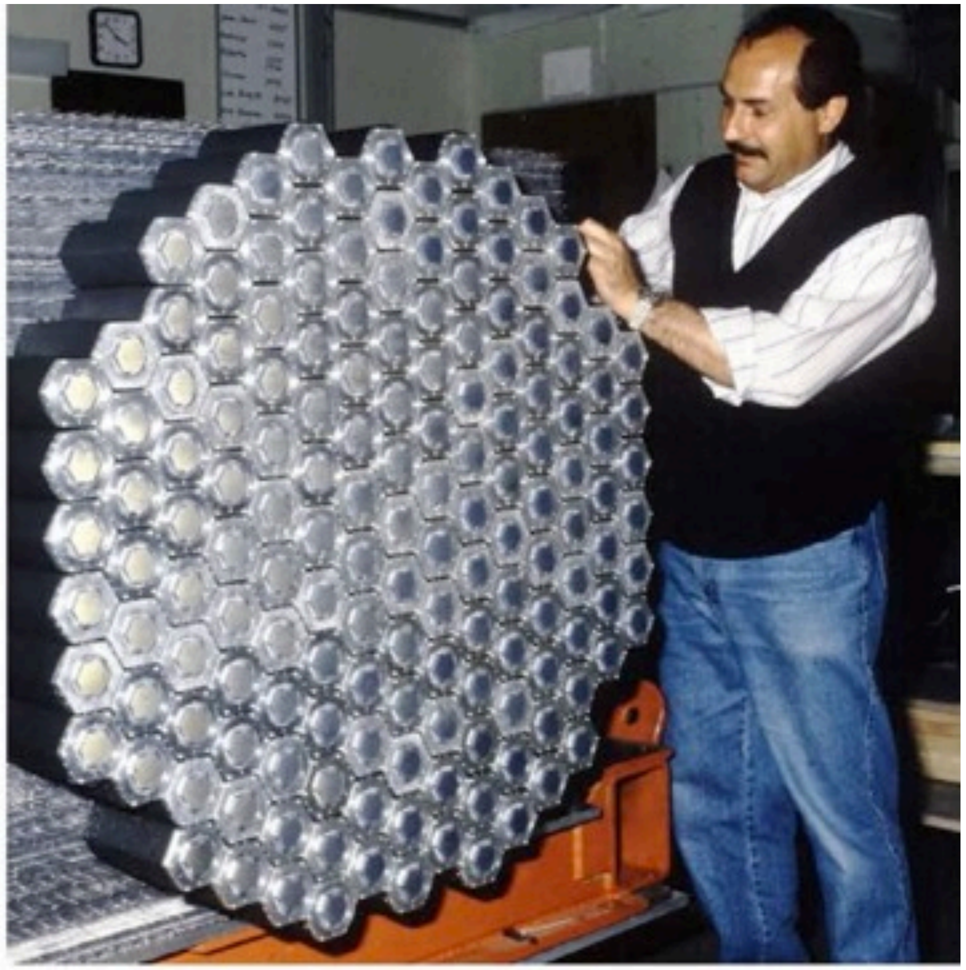


World Record (1991): $\sigma/E = 31\% \oplus 1\%$

SPACAL test module: scintillating fibers
20 tons Pb
100's ns integration time
Gaussian response
linear in hadronic energy



SPACAL 1989



SPACAL: first compensating (*e/h = 1*) calorimeter

RD52 goal: lower mass (use copper), higher precision (dual-readout)

Dual-Readout: the simplest possible formulation

average EM response is "*e*"
average hadron response is "*h*"   Ratio is called: $\eta = h/e$

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

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

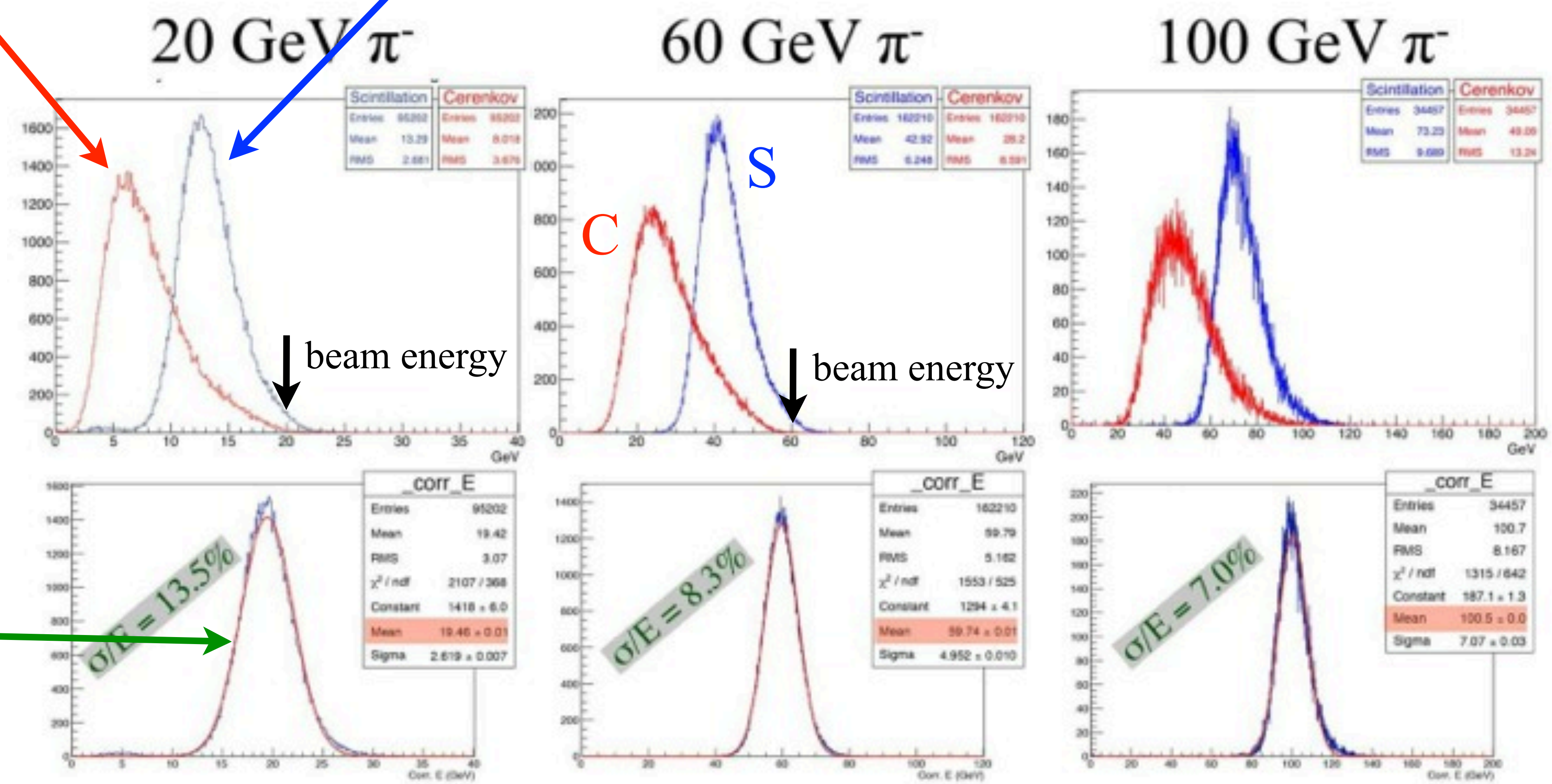
Event-to-event, E and f_{EM} are unknown. Measure S and C, solve for E:

$$E = \frac{S - \chi C}{1 - \chi} \quad \text{with} \quad \chi = \frac{1 - \eta_S}{1 - \eta_C}$$

Look at data: 20, 60, and 100 GeV π^- in H6 beam at CERN.

Dual-Readout:

C (Cerenkov) and S (scintillator) response functions



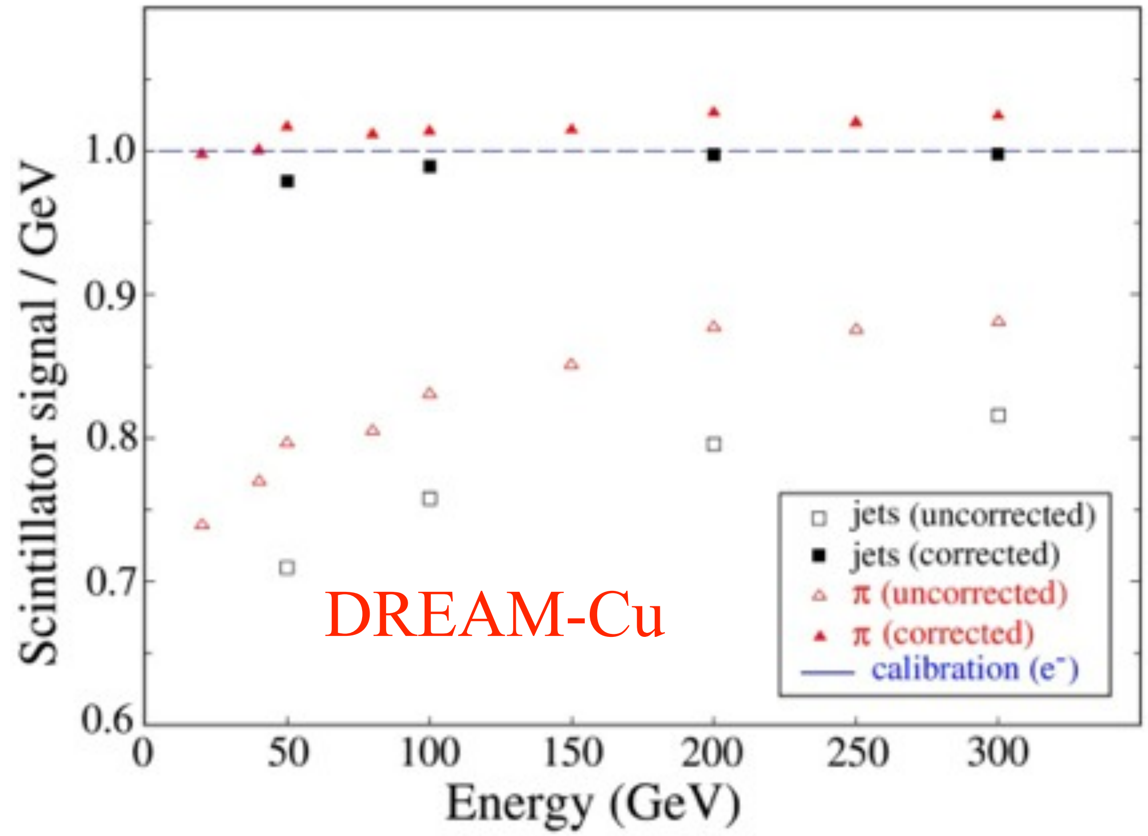
Dual-readout response functions

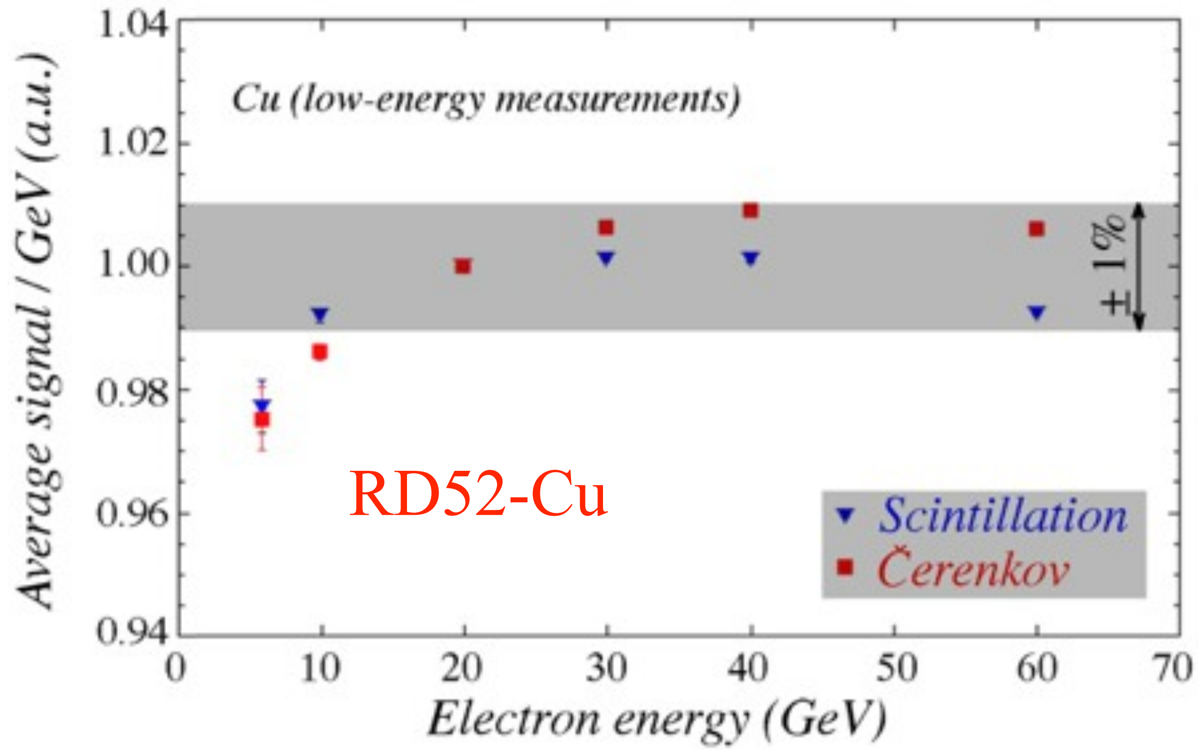
The "hat-trick"

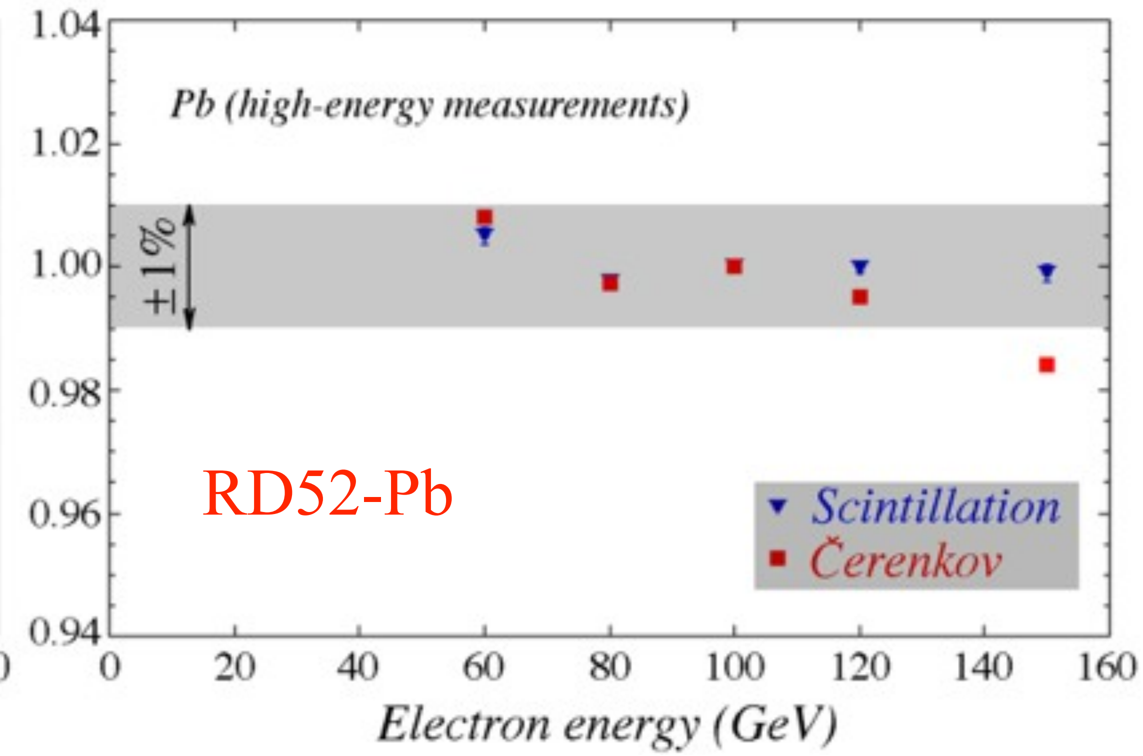
- Gaussian response
- correct hadronic shower energy (electron calib at *one* energy)
- linear in energy "

Linearity:

Absolute calorimeter linearity is essential
at a new collider to study new phenomena

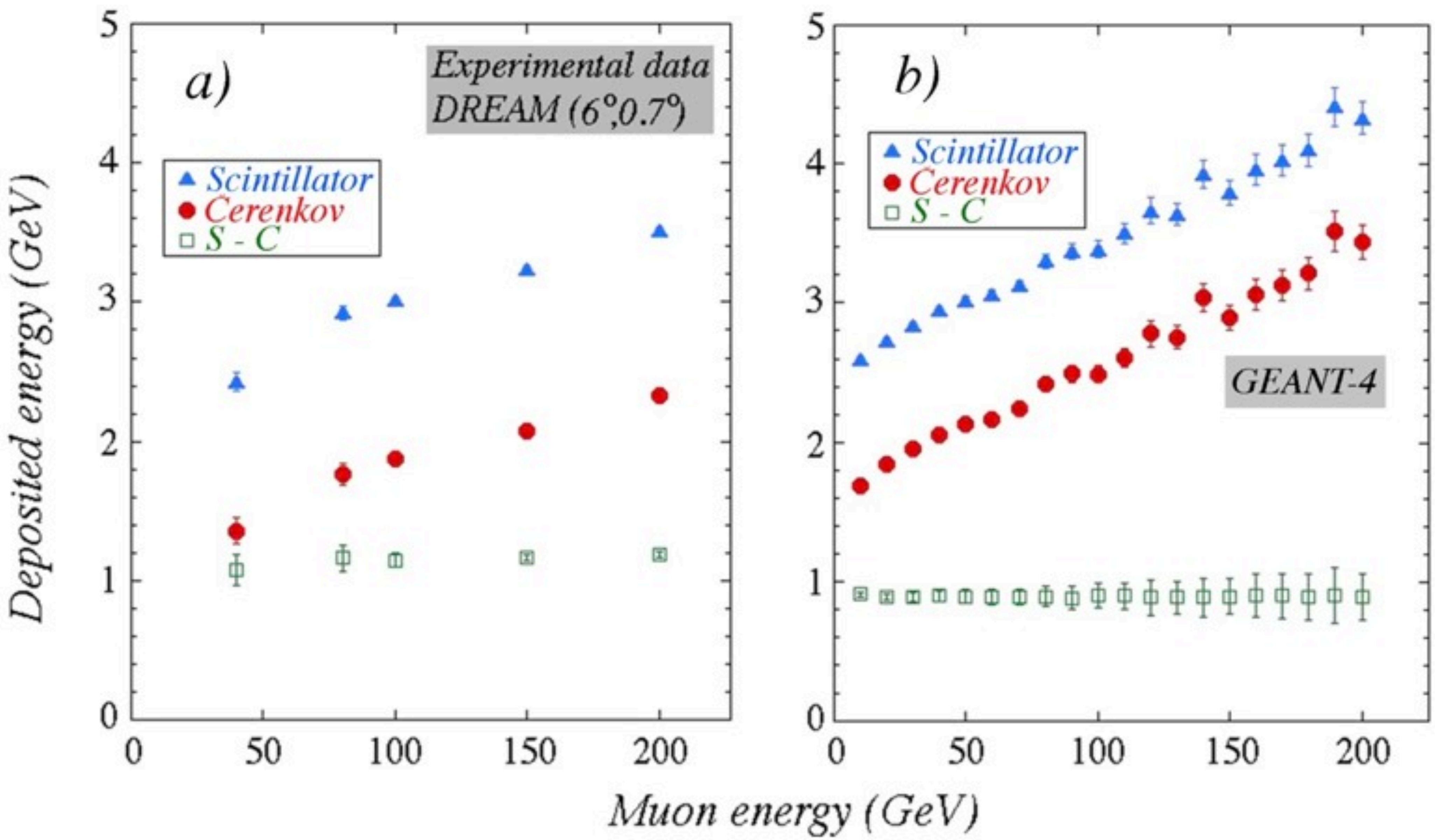






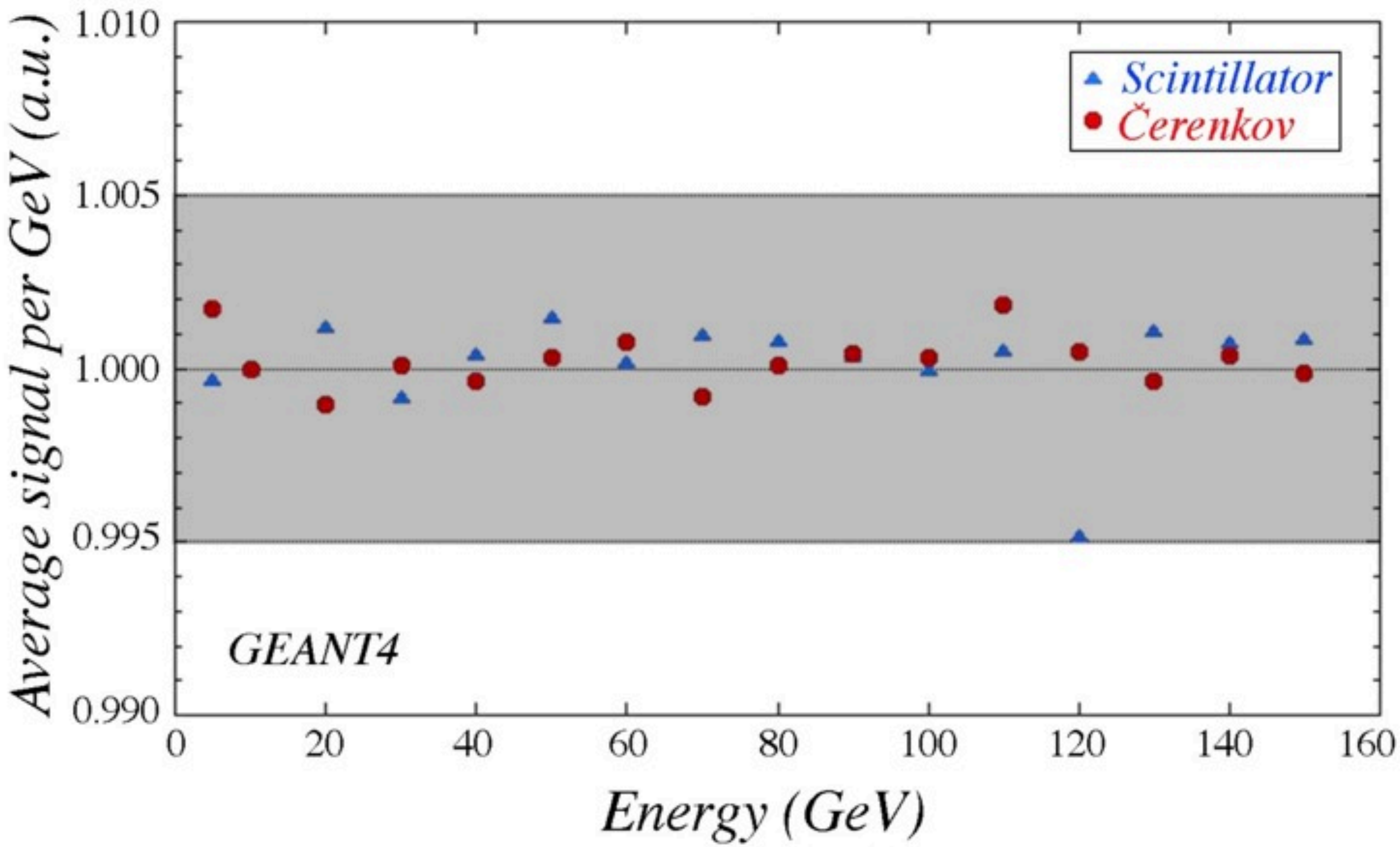
GEANT4 simulation:

Muons look similar enough.



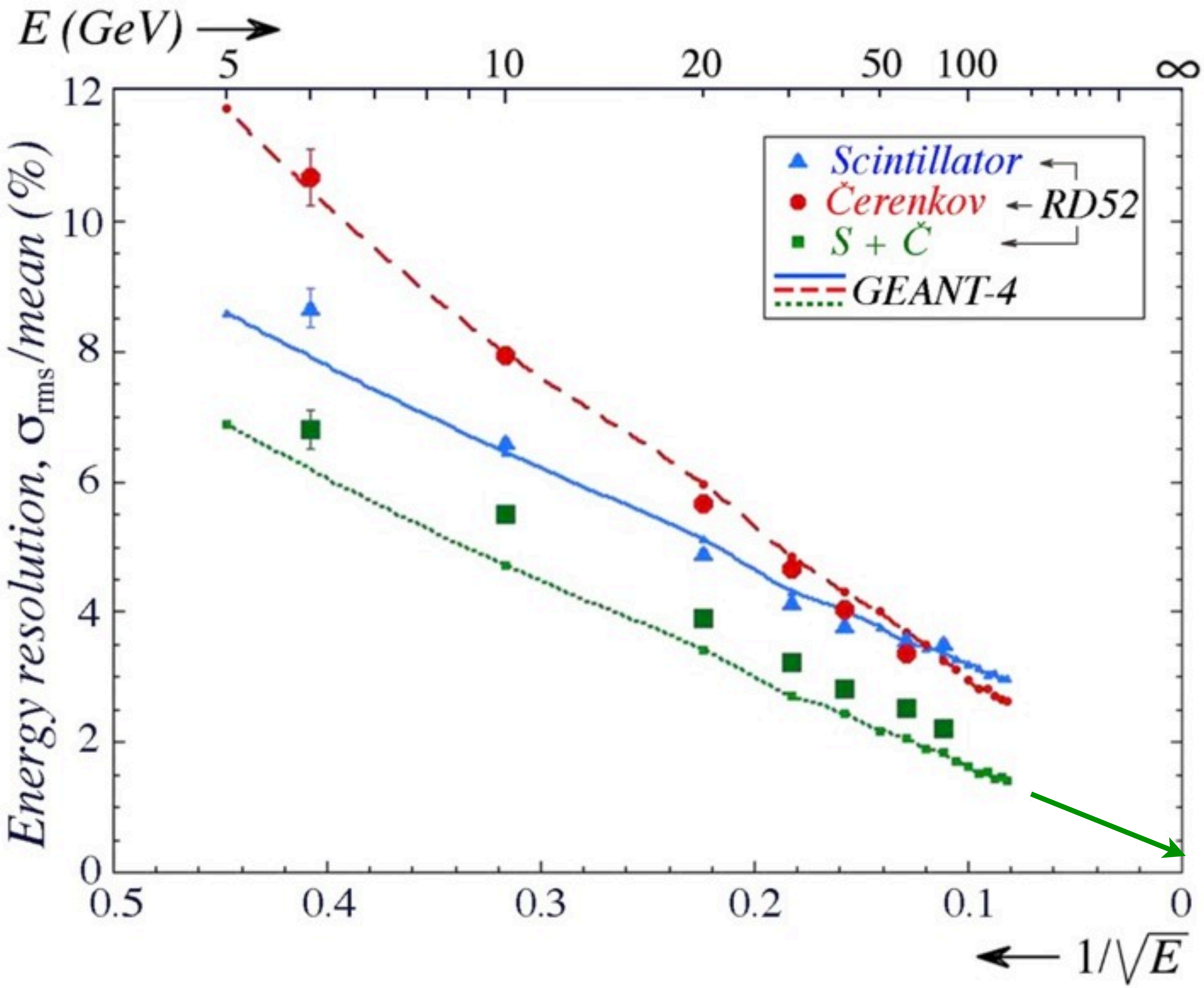
GEANT4 simulation:

Linearity is better in simulation
(not a surprise)



GEANT4 simulation:

EM energy resolution looks similar



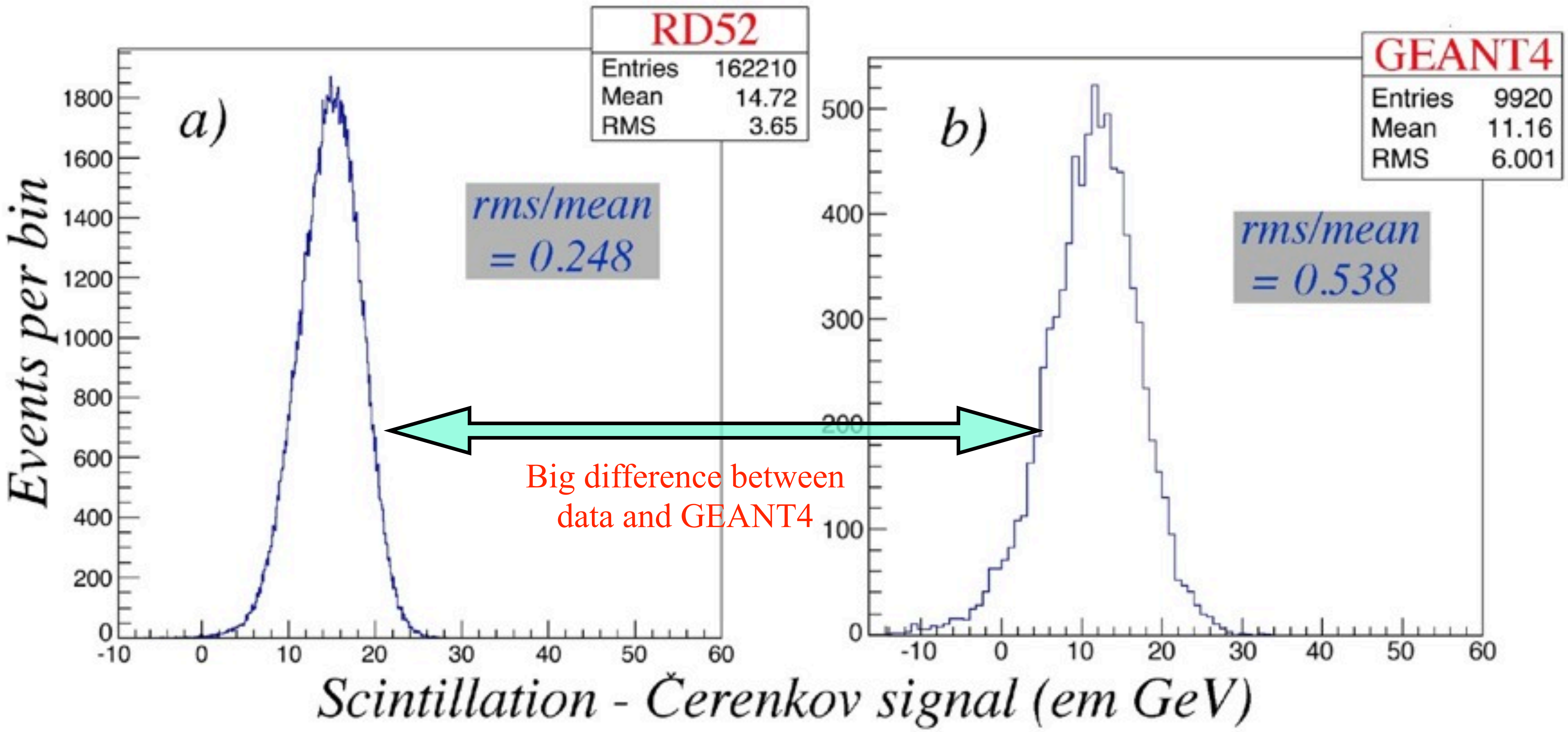
constant term extrapolates to 0.25%

GEANT4 simulation:

Hadrons are another story:

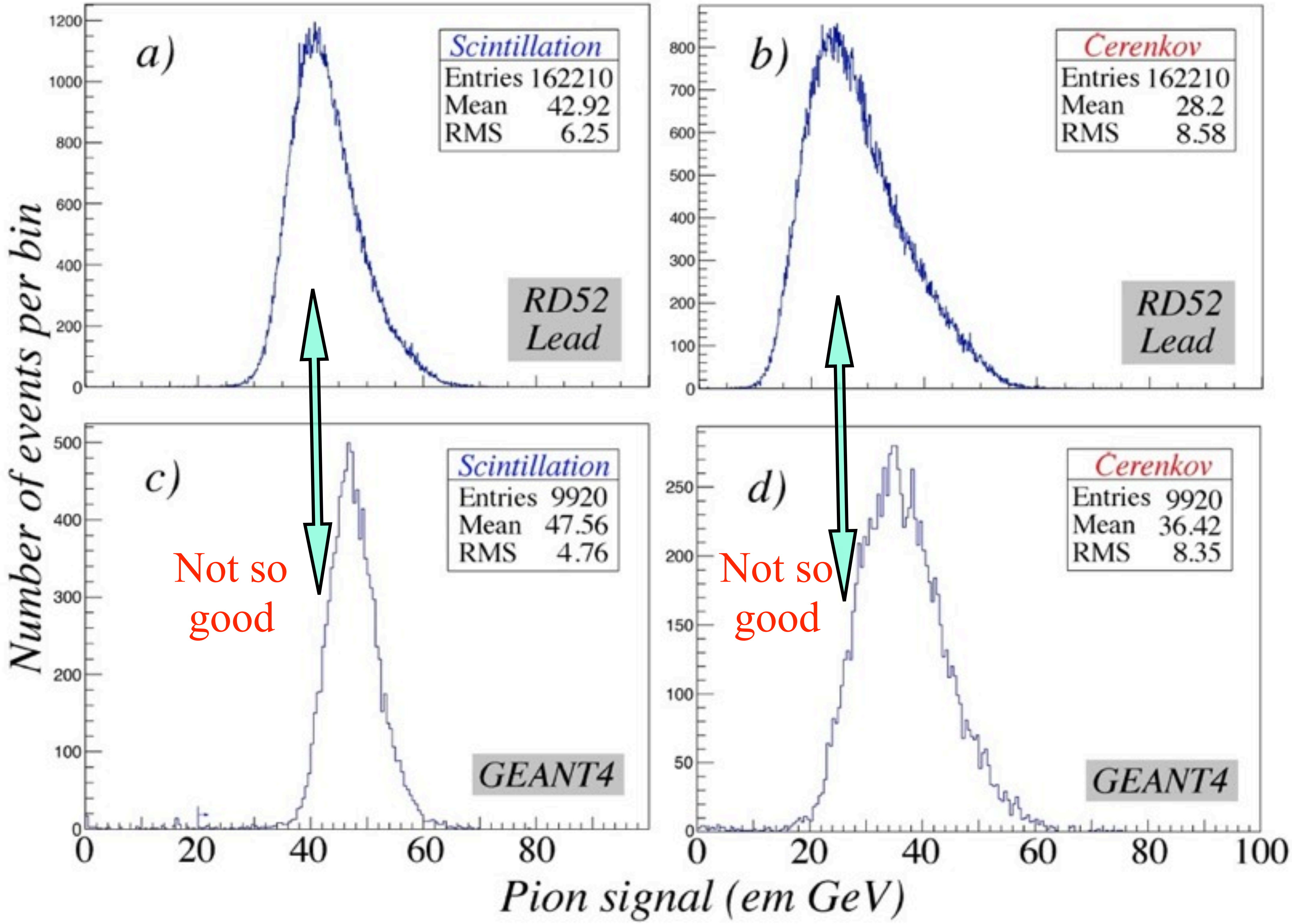
$C \sim e^+ e^-$ only
$S \sim e^+ e^-$ + all non-EM stuff

➡ *(S-C) ~ non-EM*



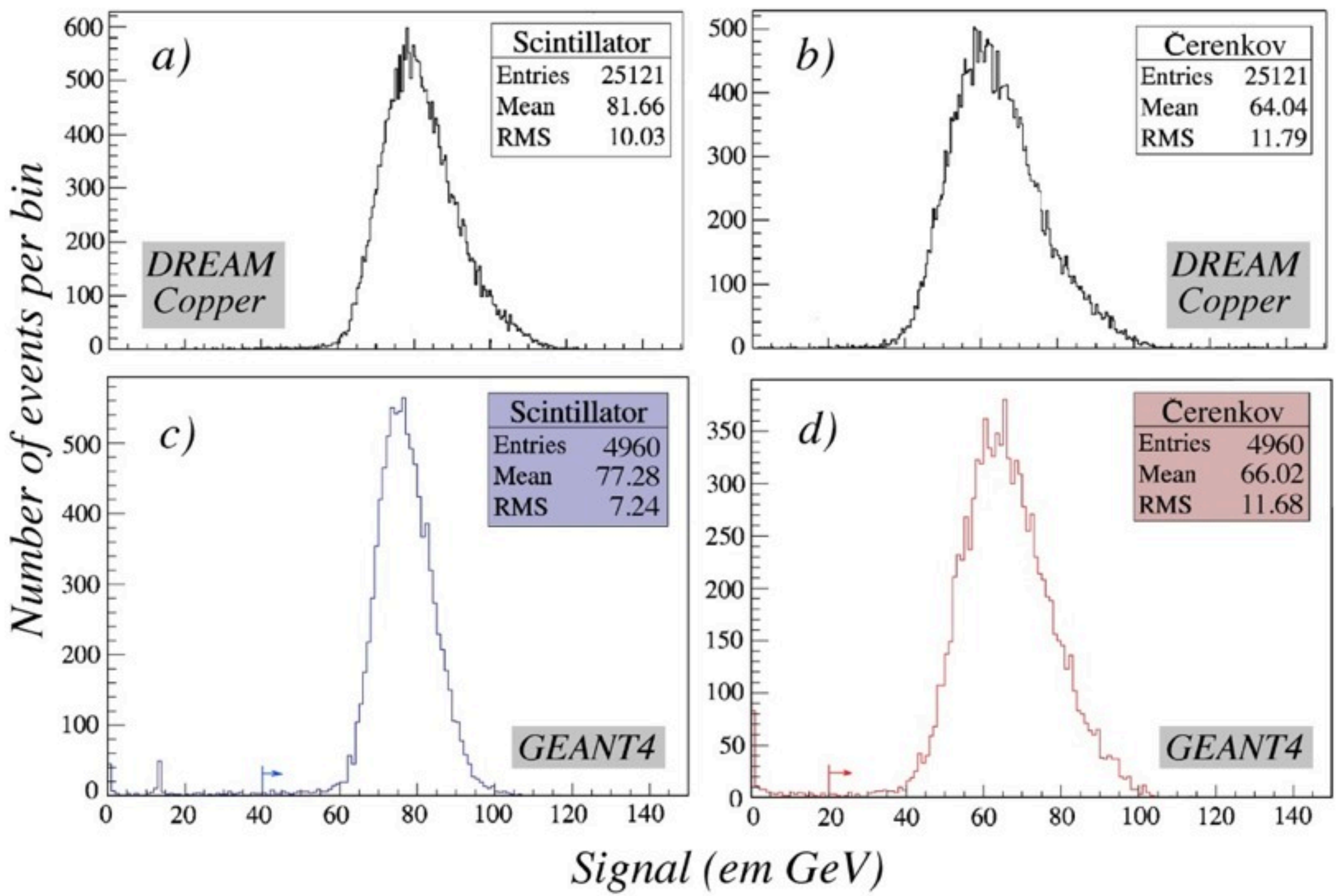
GEANT4 simulation:

π^- beam: RD52-GEANT4 comparison in S & C for the Pb modules



GEANT4 simulation:

π^- beam: Cu not much better than Pb modules



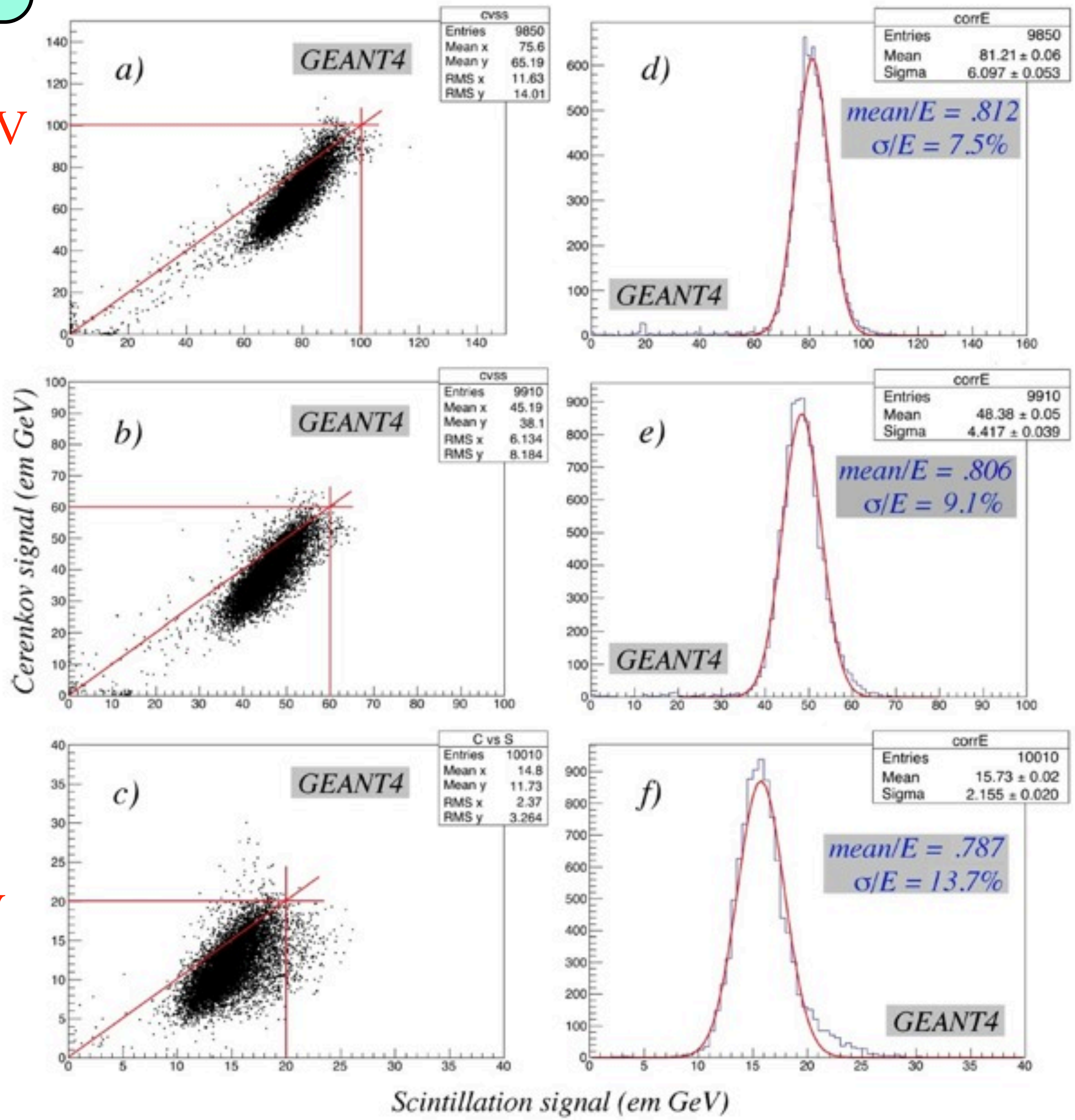
GEANT4 simulation:

π^- beam at 20 GeV

60 GeV

100 GeV

Classic dual-readout *fails* with GEANT4 pions



Particle Identification:

A dual-readout calorimeter is rich in particle ID measurements:

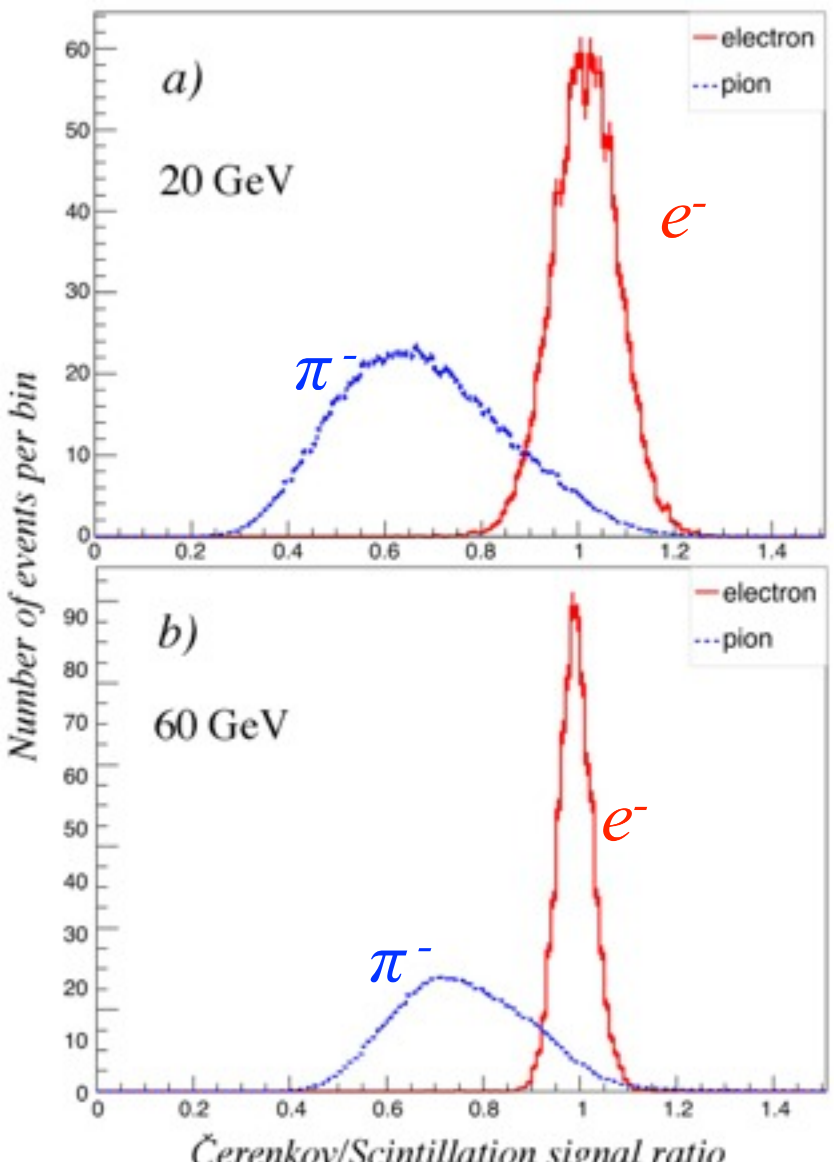
e, π, γ, p, μ, W, Z (by jet-jet invariant mass)

See 4th Letter of Intent:
www.4thconcept.org/4LoI.pdf

Illustrate with three *independent* measurements: time, space, and EM/Had (C/S)

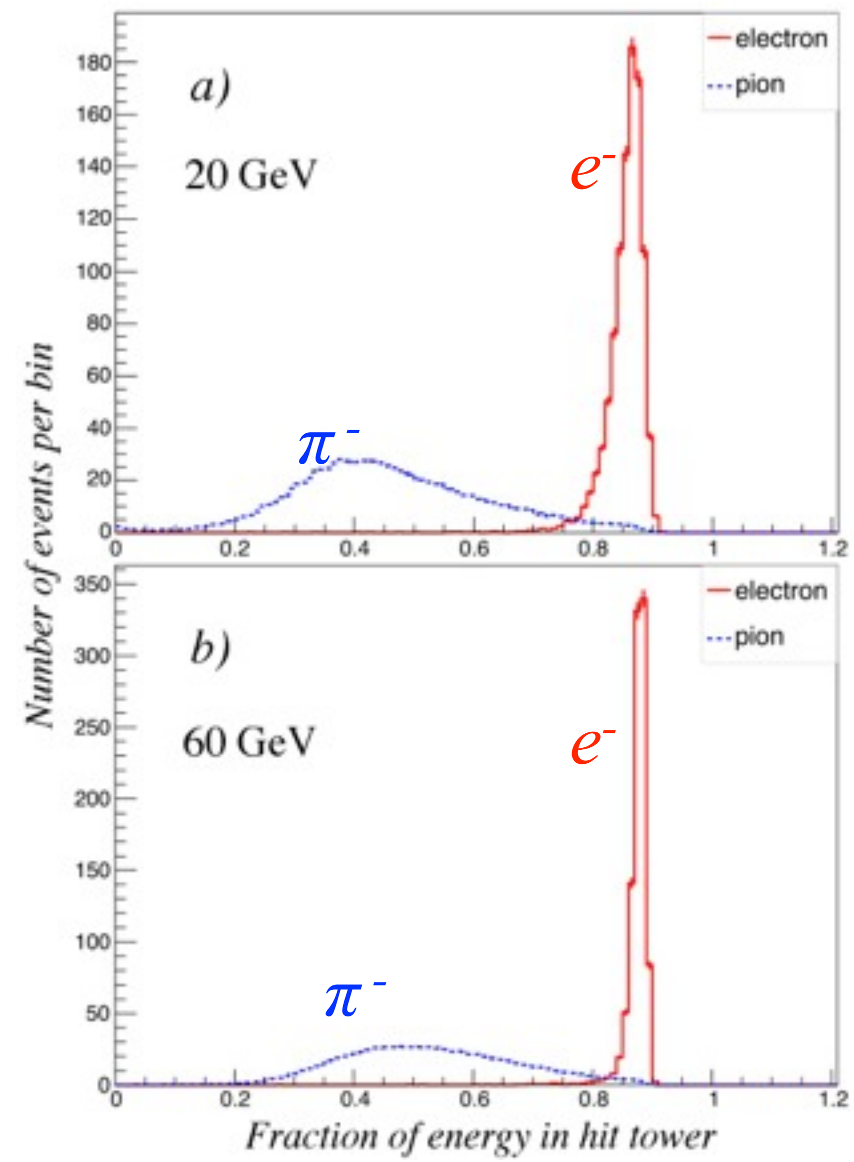
Particle Identification:

EM-Hadron structure



C/S →

Spatial structure



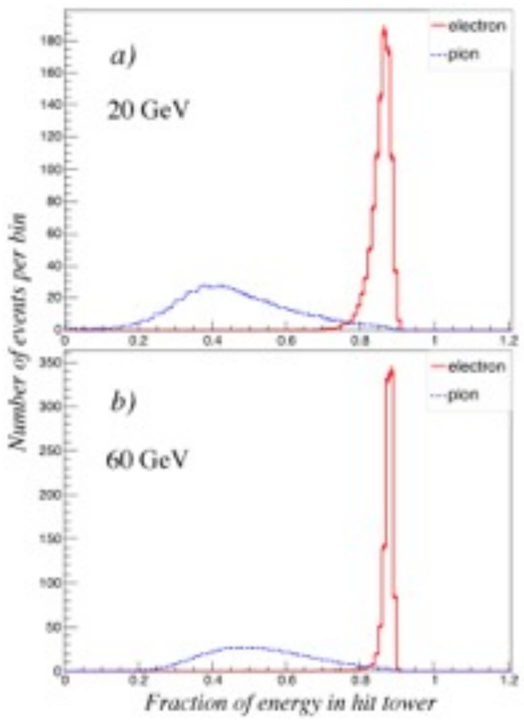
f_{center} →

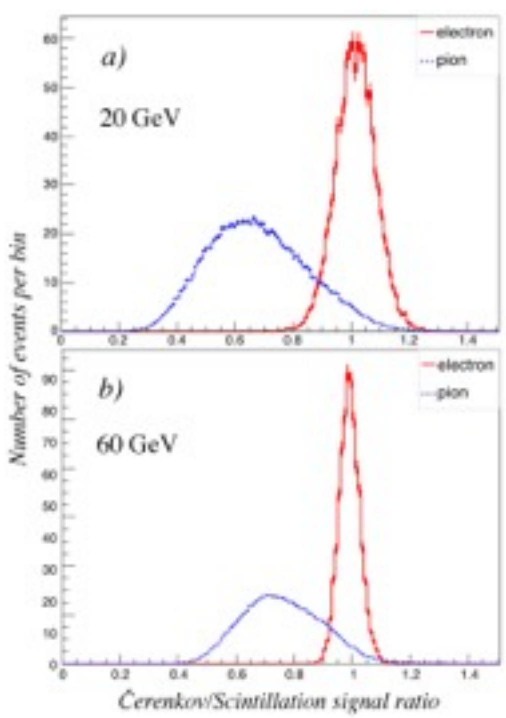
Particle Identification:

From recent paper:
NIM A735 (2014) 120.

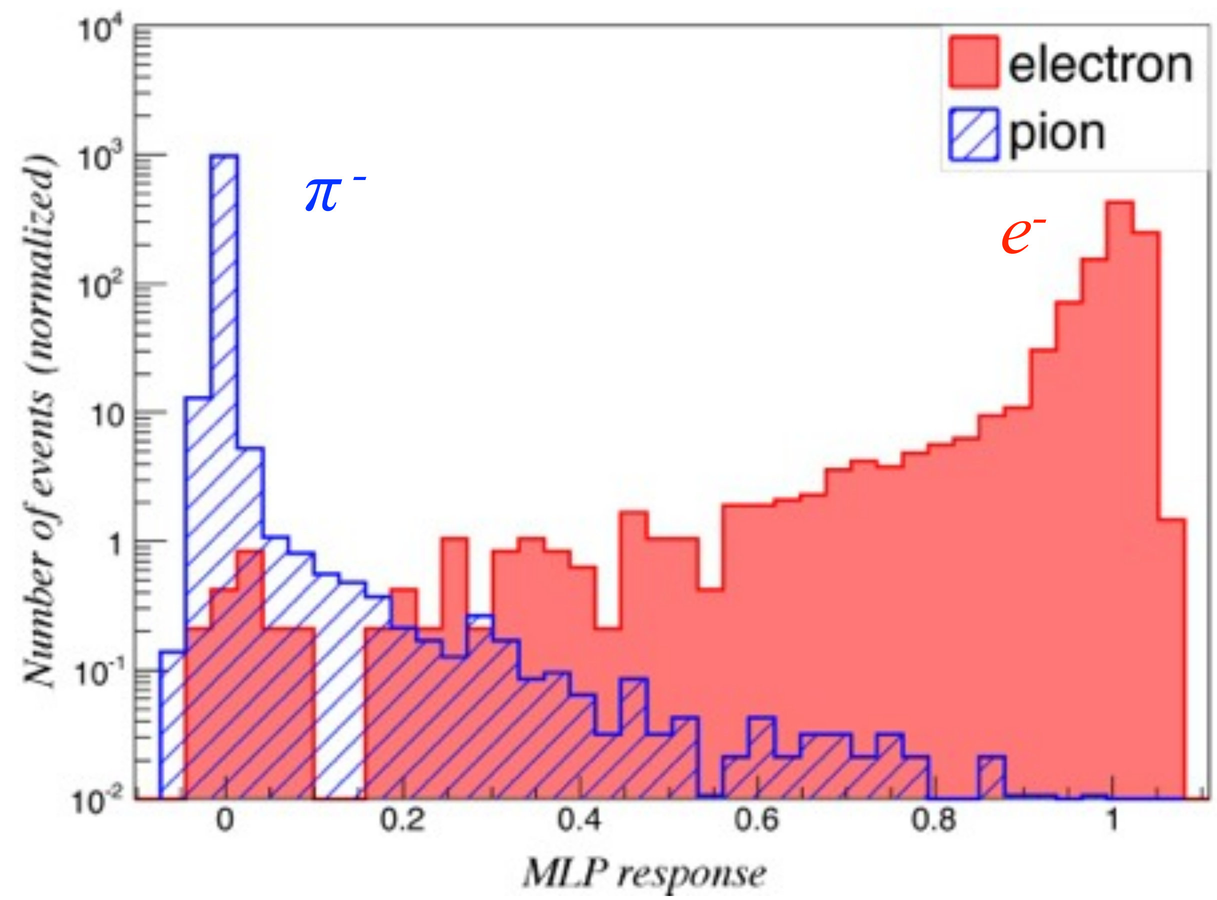
99.8% efficiency for e^-
0.2% acceptance for π^-

500-to-1



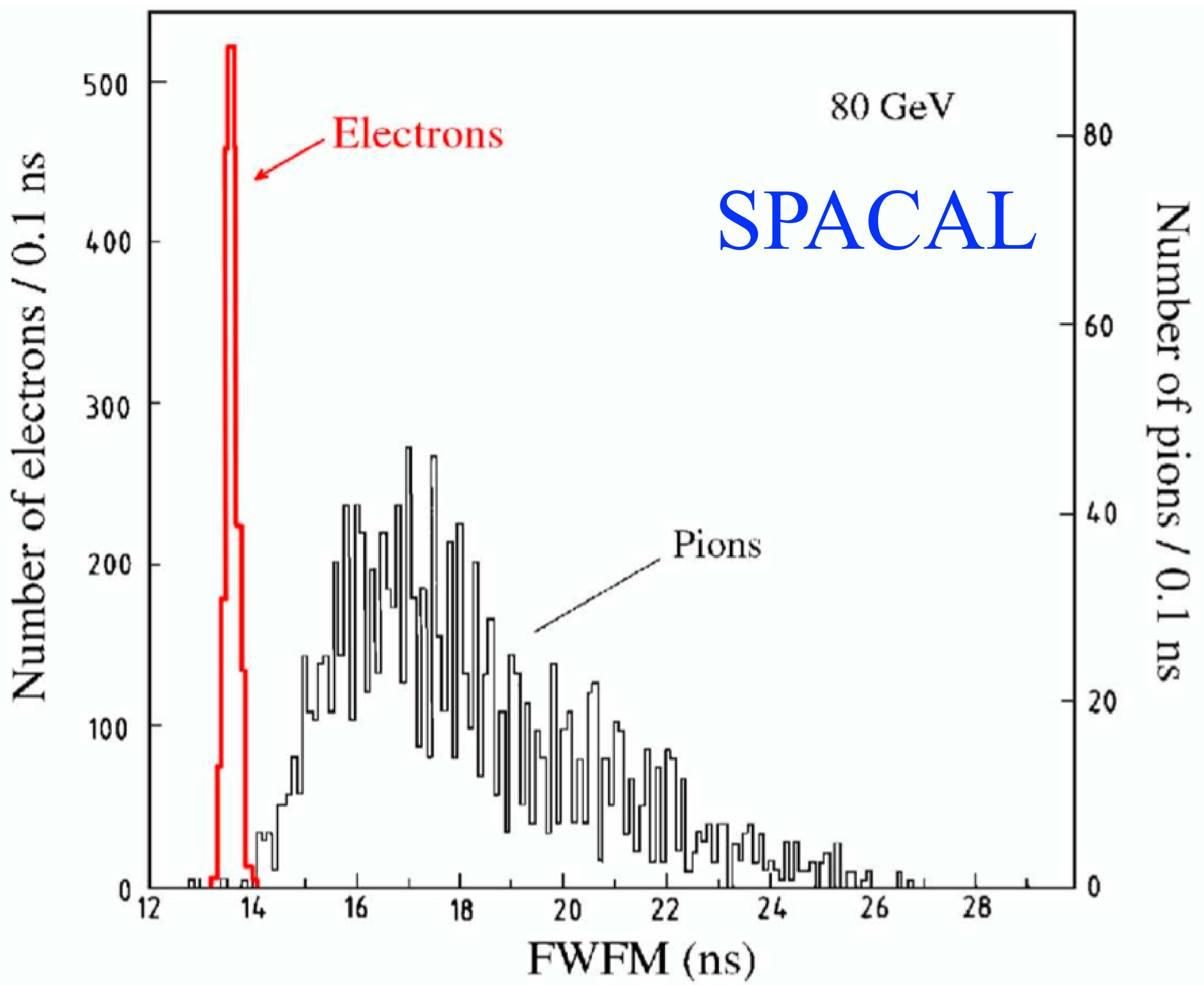


Spatial
+
EM/Had



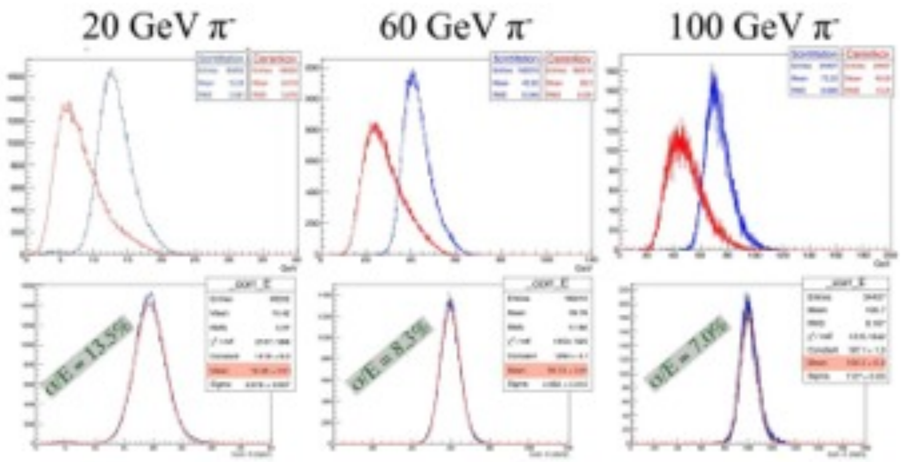
Particle Identification:

Time structure

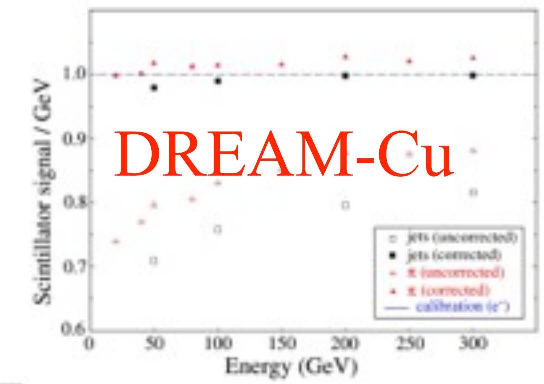


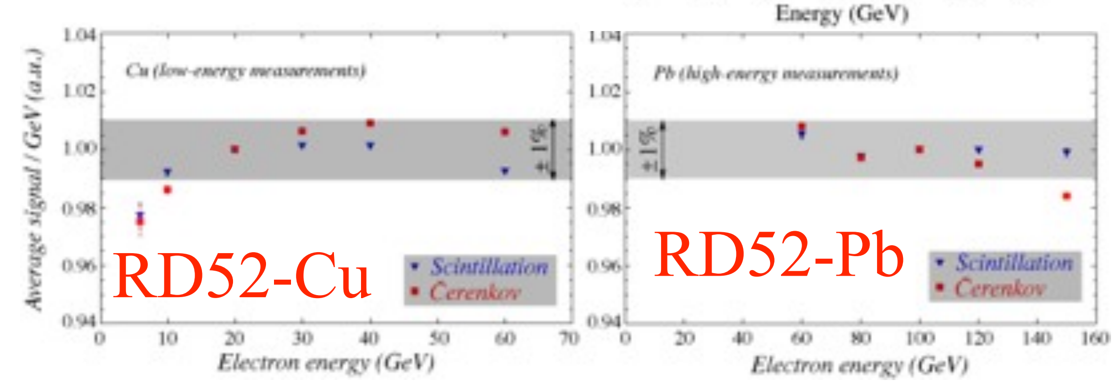
100-to-1

Hadronic resolution:



Already Gaussian
and linear





What about
energy resolution?

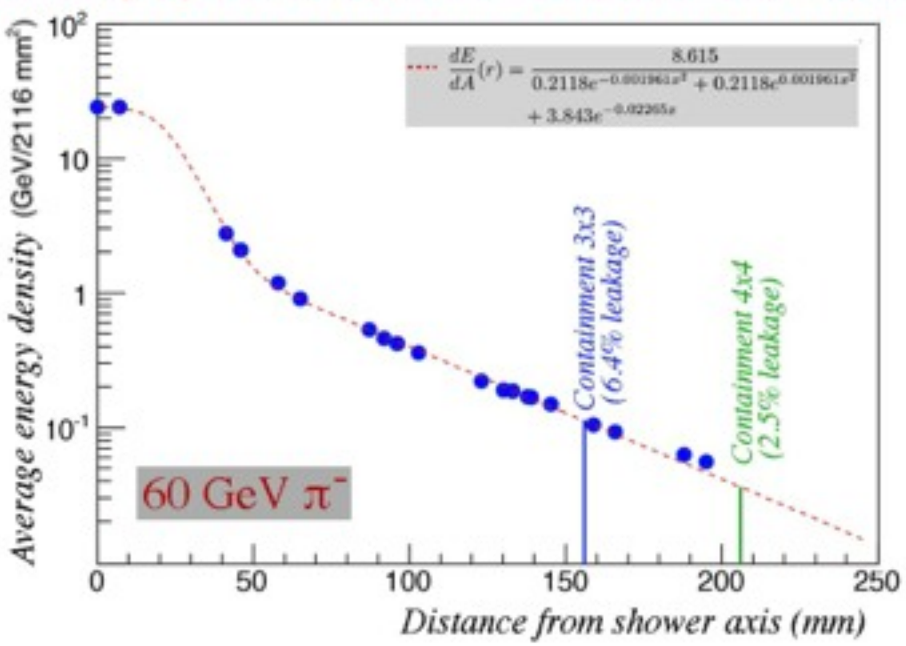
(we are not there yet)

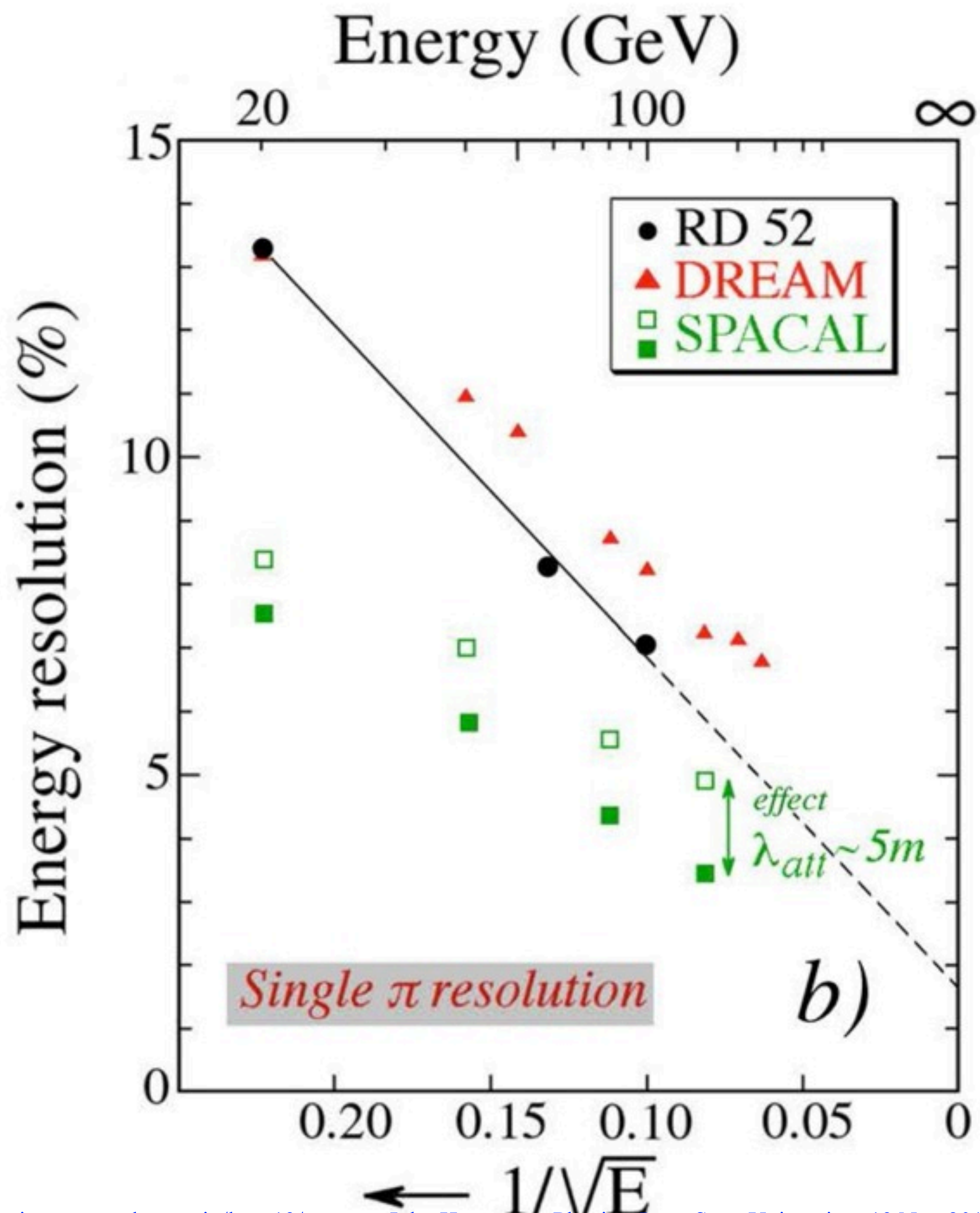
Hadronic resolution:

Limited by
- lateral leakage in 1.3ton RD52 module
- no attenuation correction for RD52 data
- in principle must be better than SPACAL.

Estimate $\sigma/E \sim 25\text{-}28\% / \sqrt{E}$

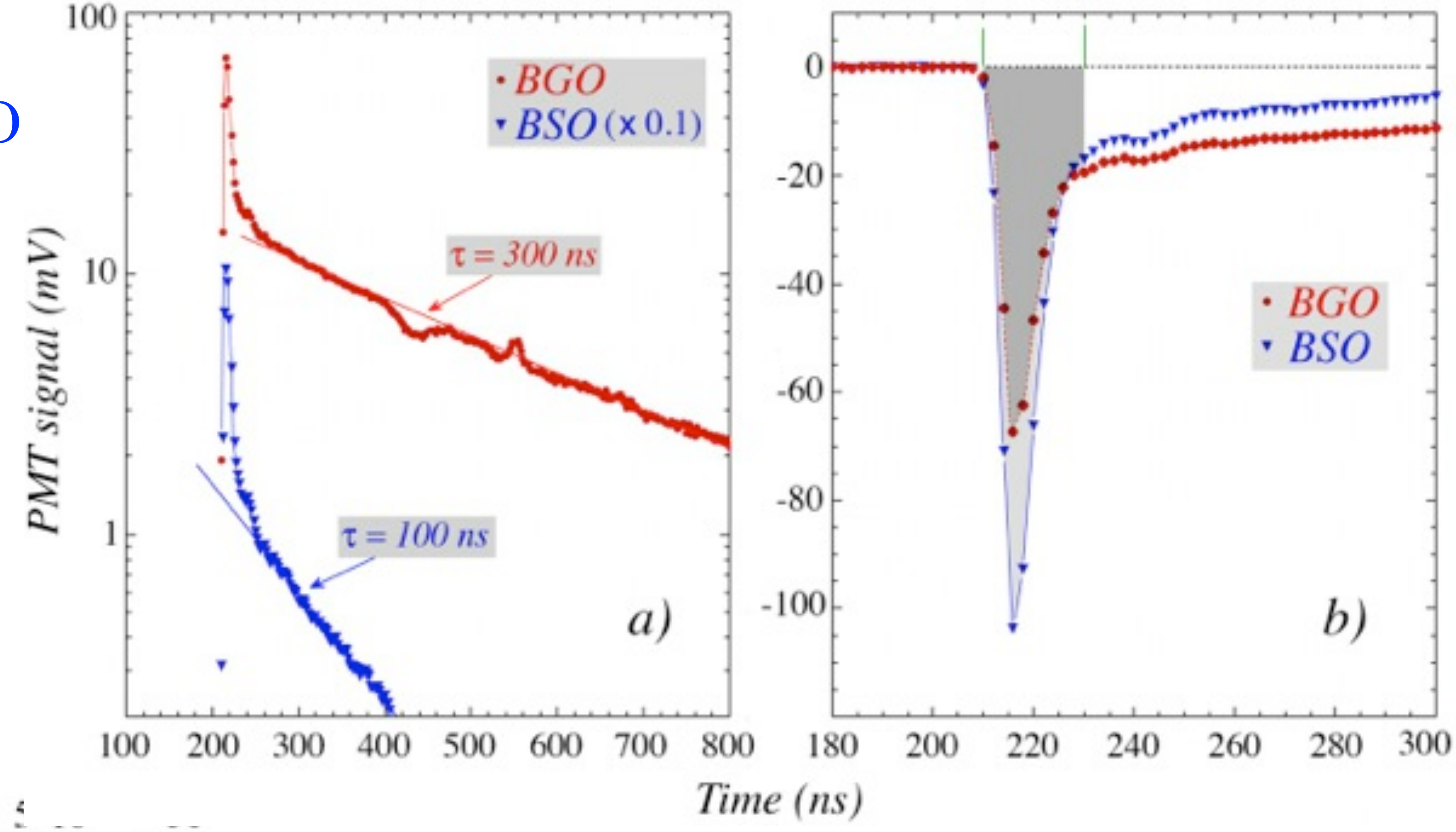
Radial profile and hadronic shower containment



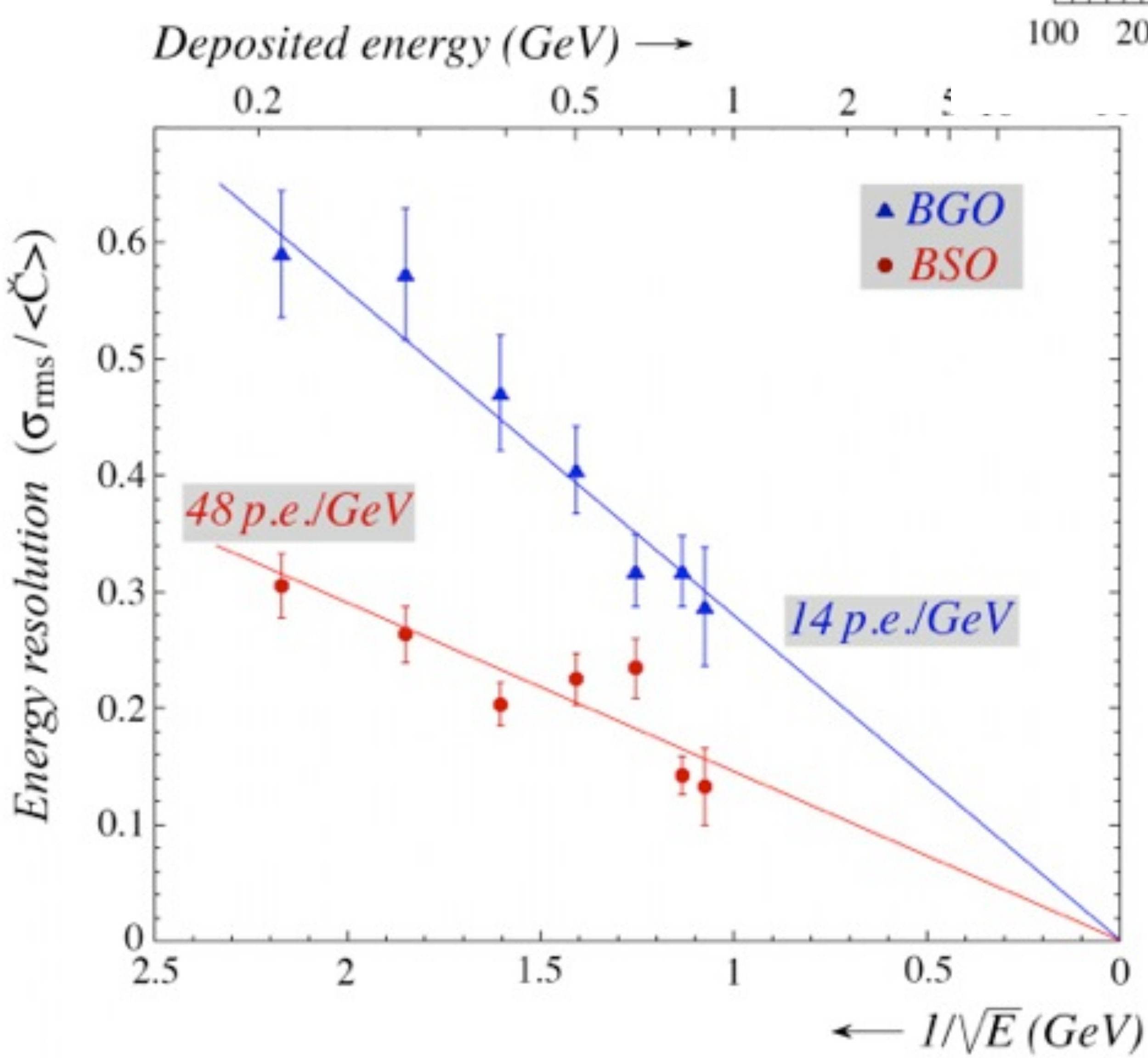


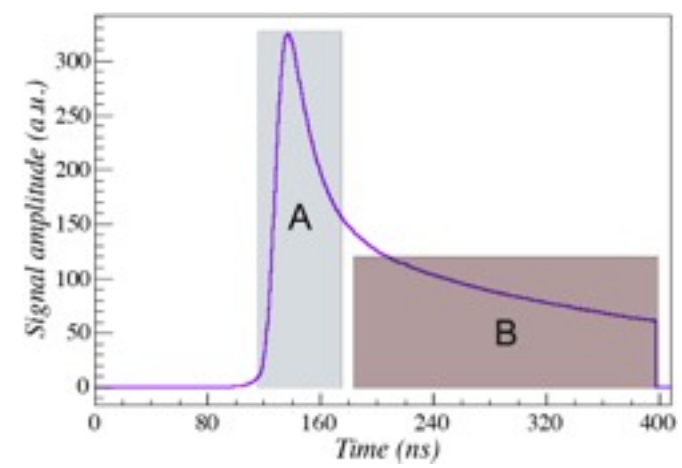
Crystals:

BSO vs. BGO



BSO compliments of
Dr. Hajime Shimizu

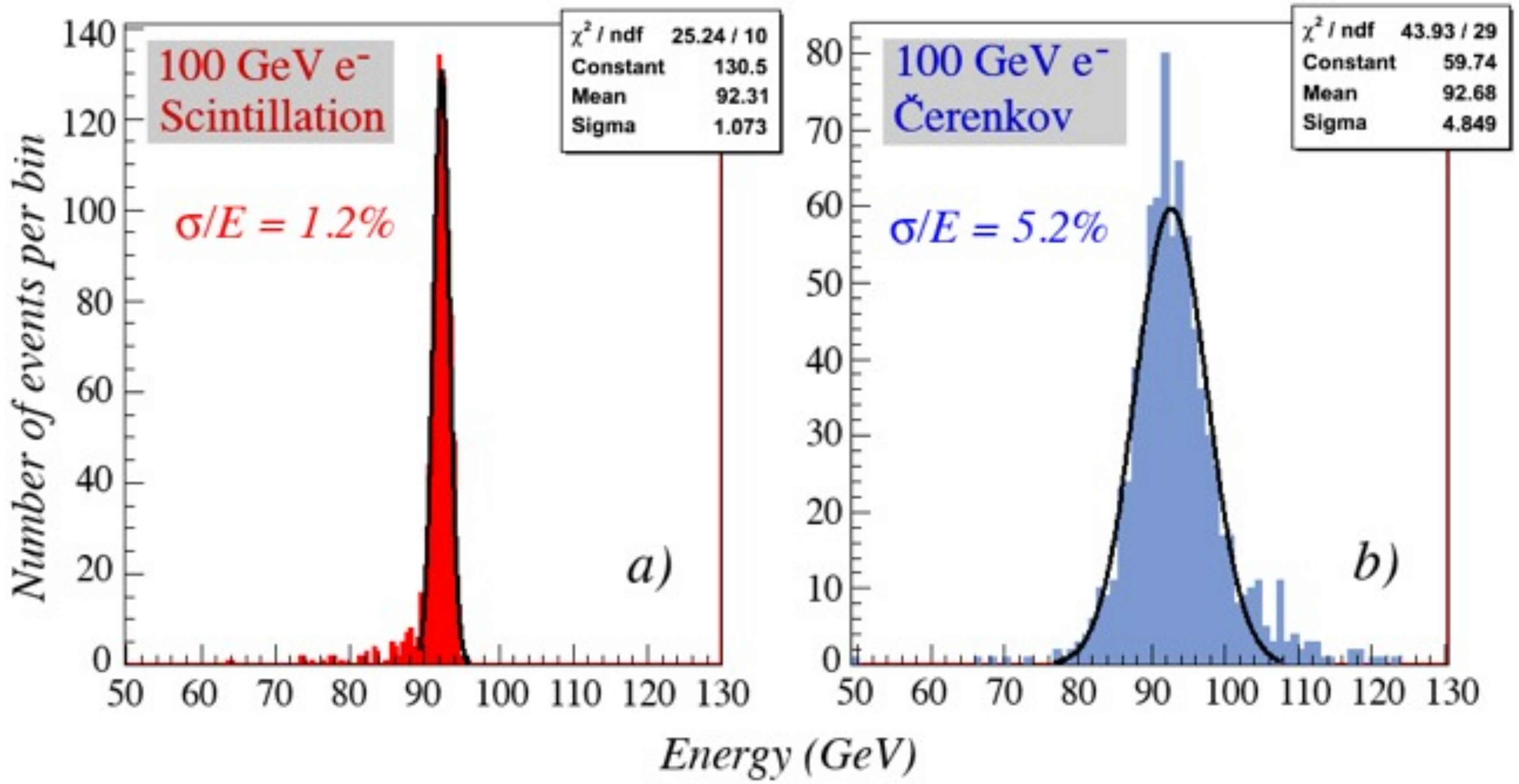


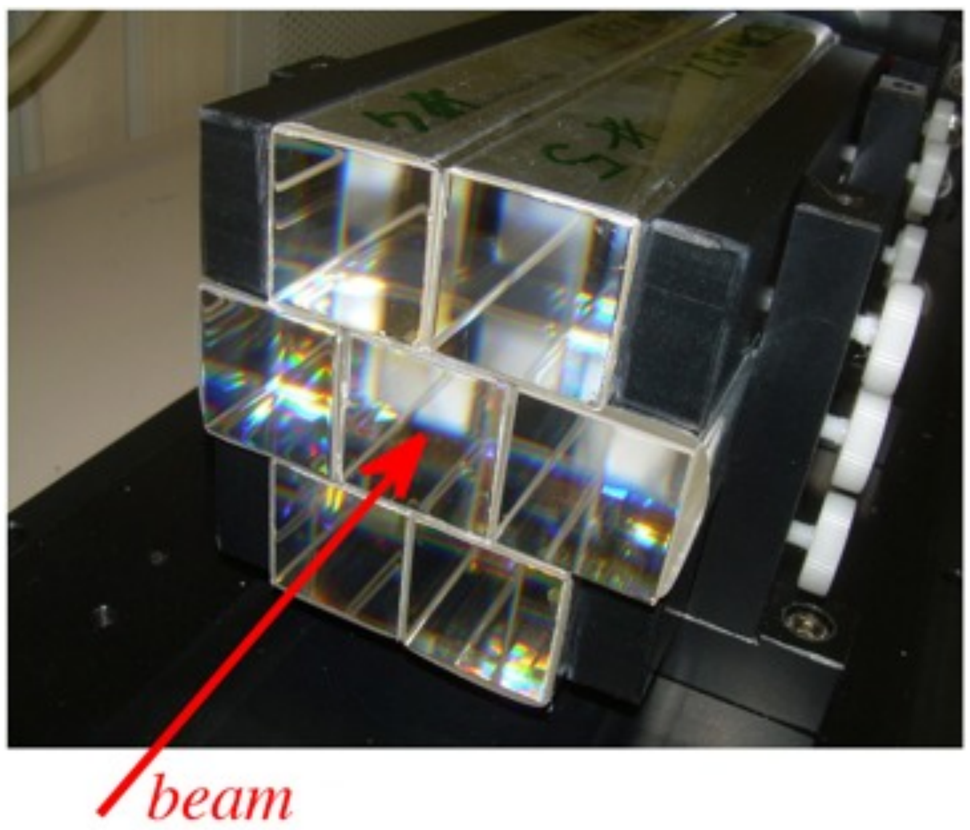


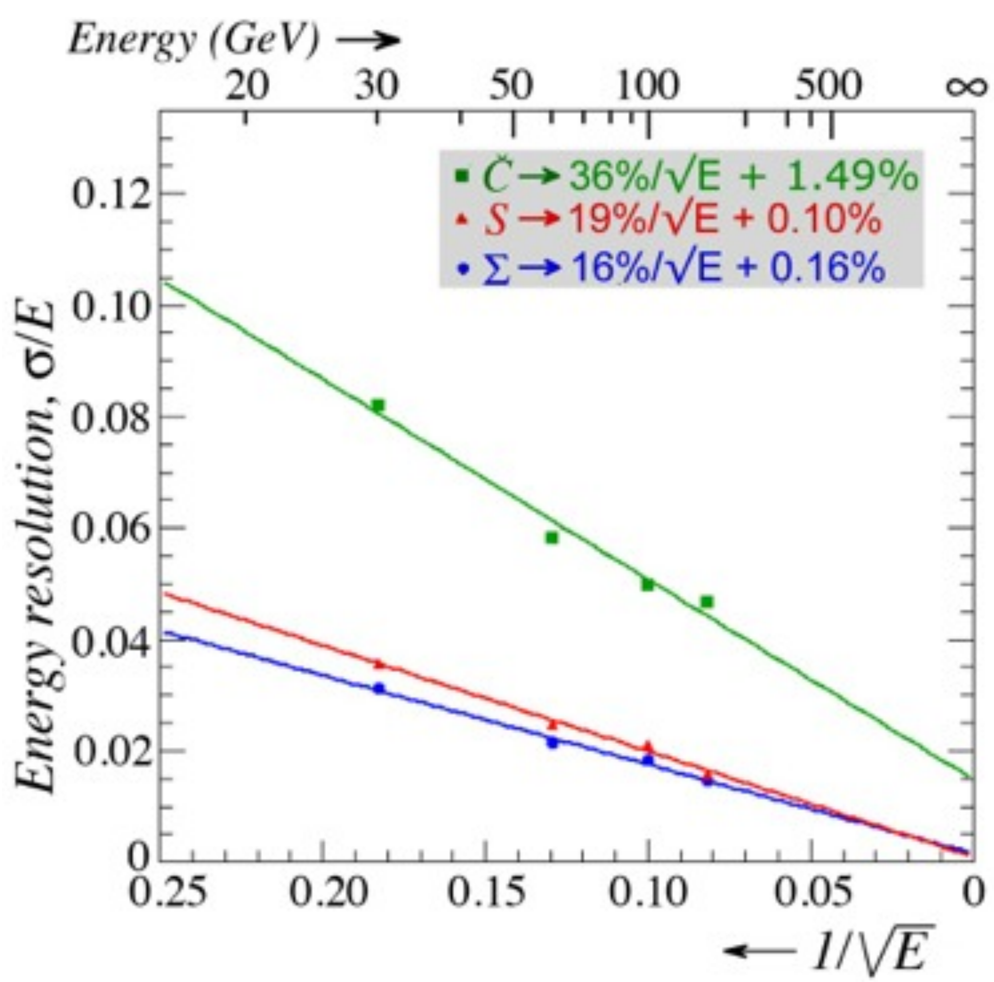
We conclude that BSO is far superior to BGO for dual-readout purposes

Crystals:

PWO







No constant term

Future Plans:

- Complete 5-6 tons of Pb and Cu modules: *reduce mean leakage to 1%*

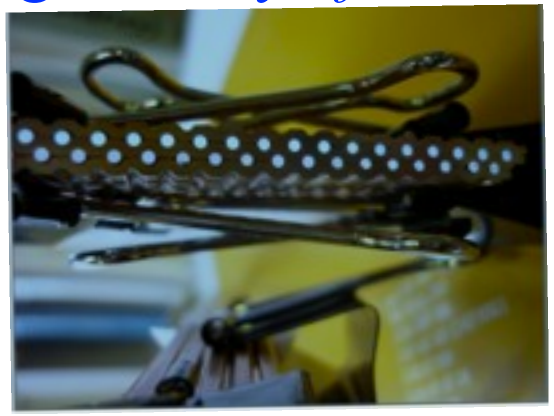
  → *test hadronic performance*

- Test as "Pb calorimeter" and as "Cu calorimeter": *measure (Z,A) dependence*

  → *test theoretical limit to hadronic energy resolution ~ 15% / √E*

- Construct a test "W-Cu calorimeter" of RD52 geometry: *for colliders?*
  - worse EM resolution
  - worse hadronic resolution
  - *but* at twice the density a tungsten dual-readout calorimeter is big cost savings in SCoil and muon system

    → *depth vs. σ/E*



- Build and test a "projective wedge" design: *4π collider geometry*

  → *essential for a collider detector (several plans)*

- See **http://highenergy.phys.ttu.edu/dream/** for proposals, progress reports, NIM papers, and talks … more than you find in this talk.

Thank you for your attention.