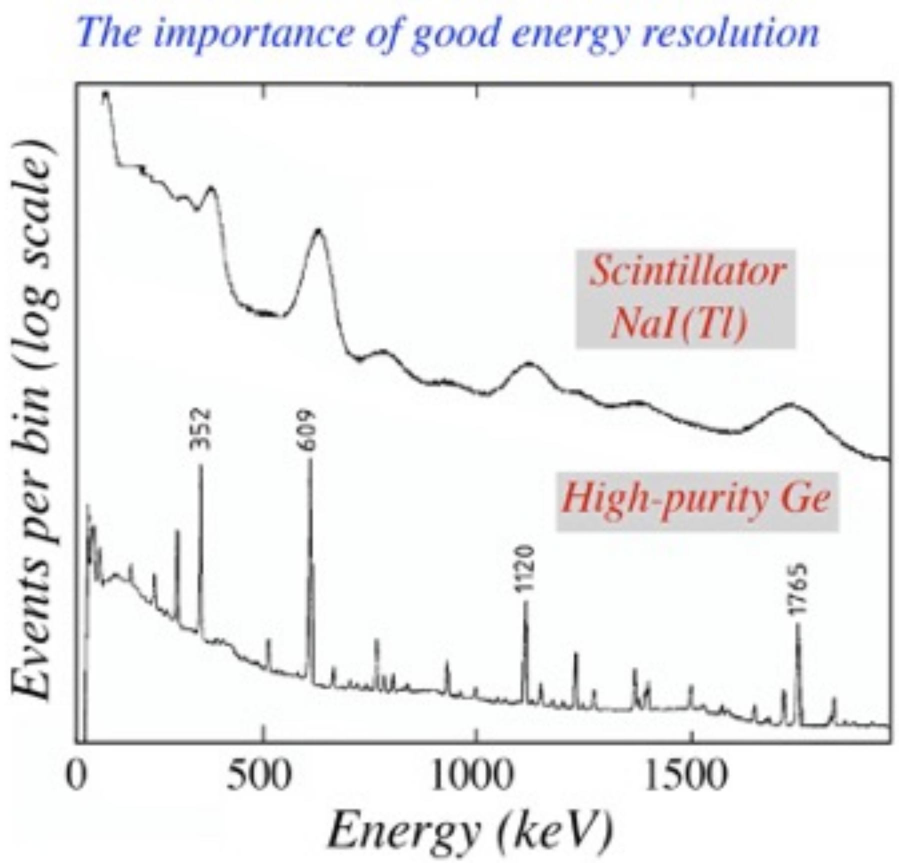
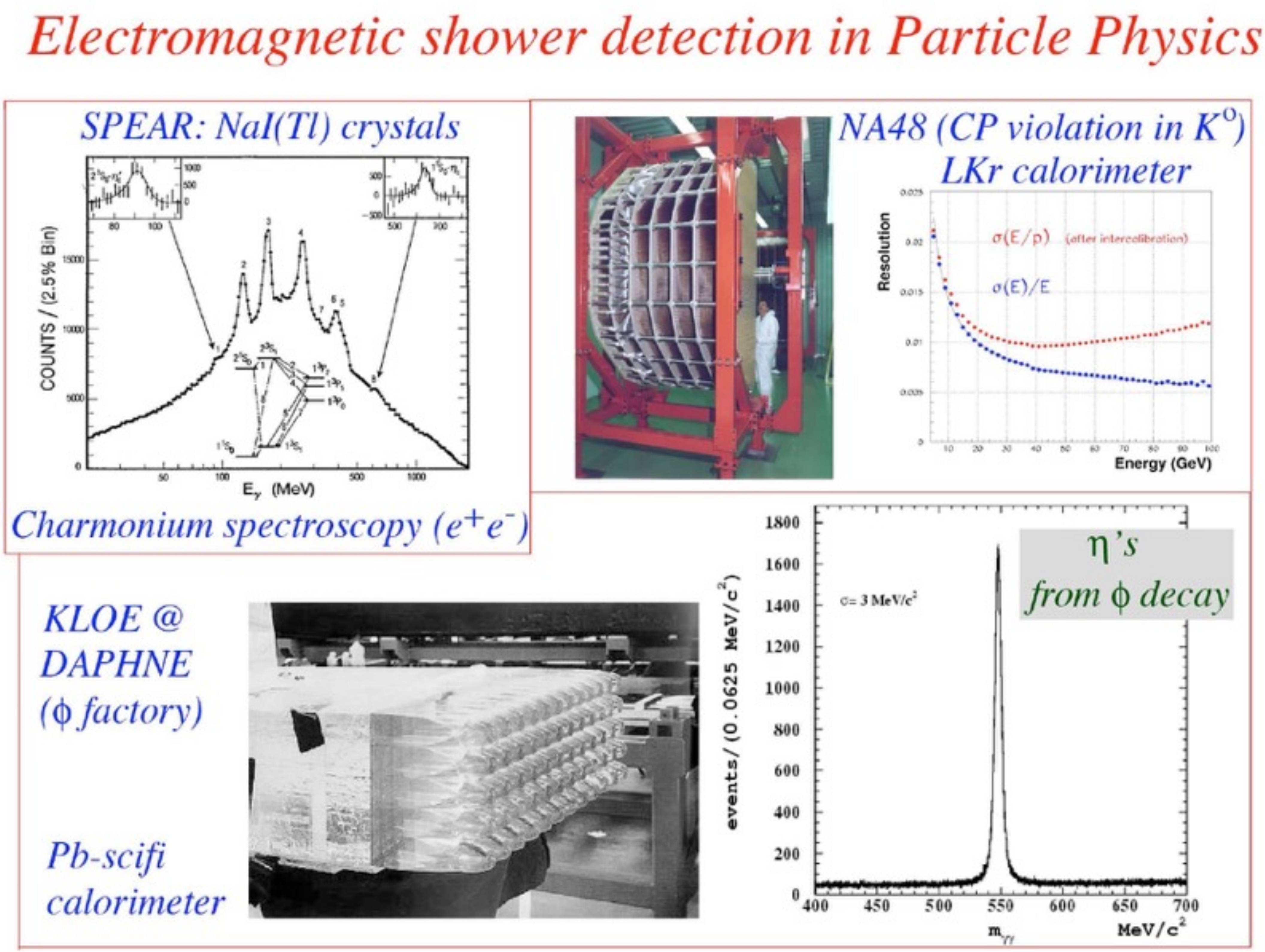
High-precision and high-quality hadronic calorimetry for the next collider

The problem of direct four-vector reconstruction of hadronic W and Z decays, along with many other physics measurements, is not yet solved. I will discuss the history, the difficulties, and the prospects for energy measurements, and the problems in designing a calorimeter for a large detector.

John Hauptman
IHEP, Beijing, 23 May 2016



History (but don't forget the mistakes, e.g., Magnetic Detector EM shower counter)

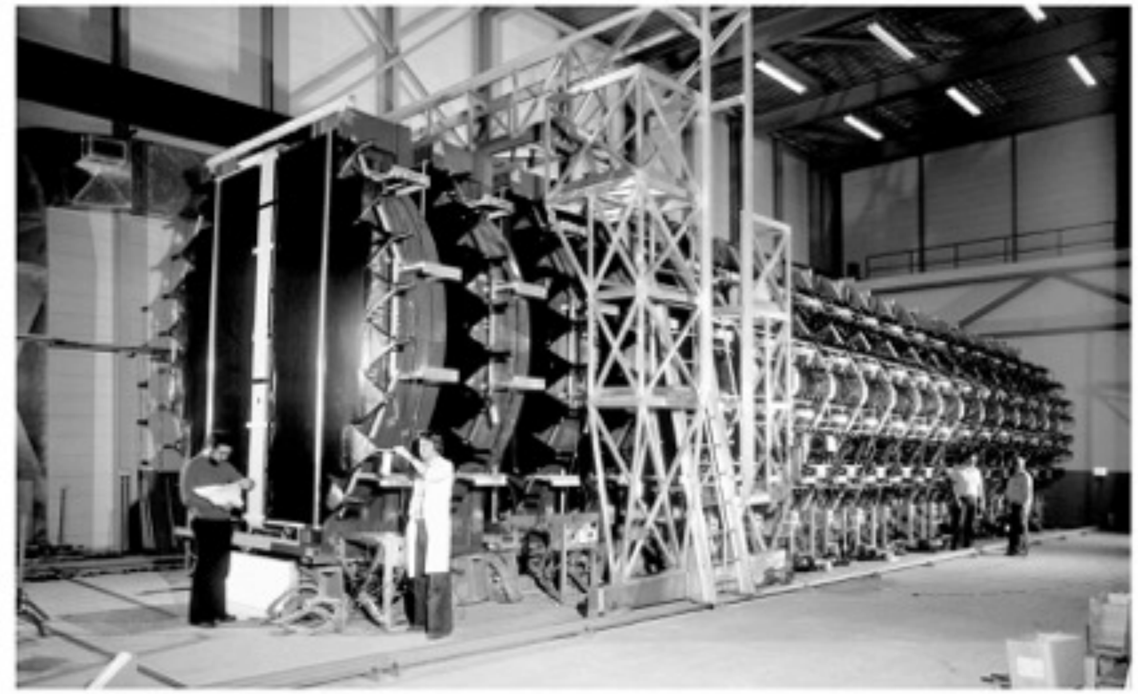


History

* target, detector & tracker
* sophisticated
* powerful particle ID

The WA1 neutrino experiment (1976)

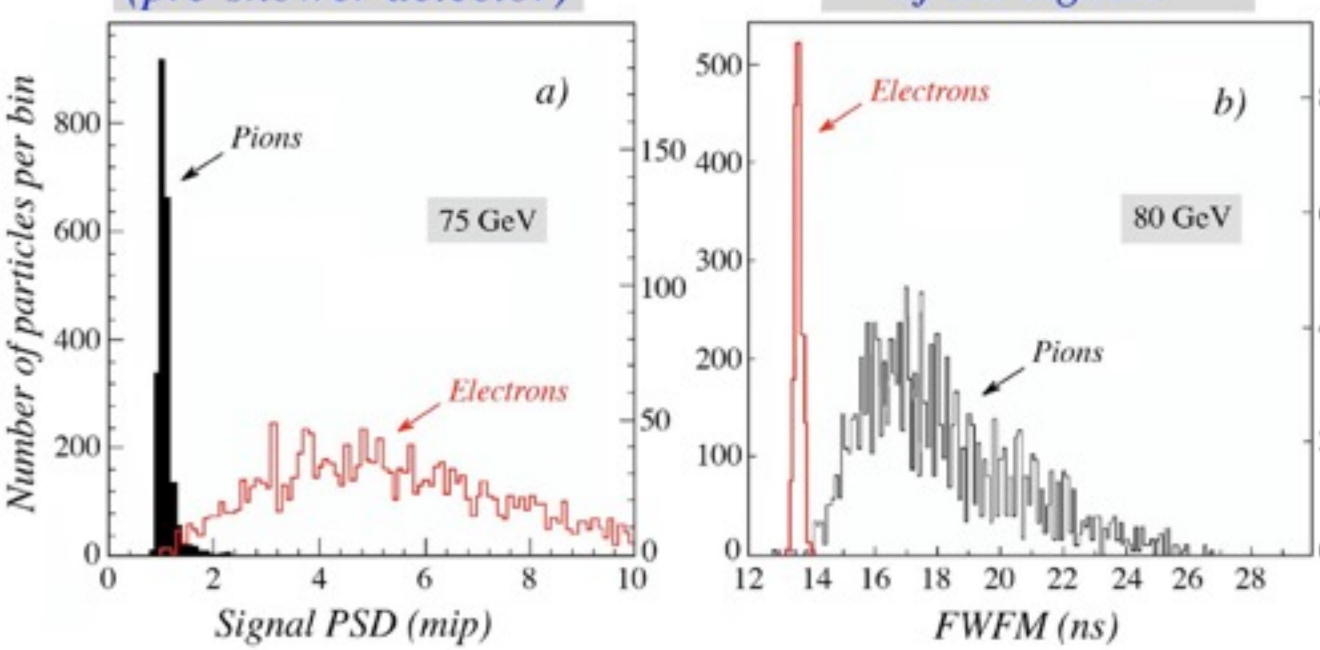
(integrated target, calorimeter, tracker)



Particle identification with calorimeters

Using shower profile (pre-shower detector)

Using time structure of the signals

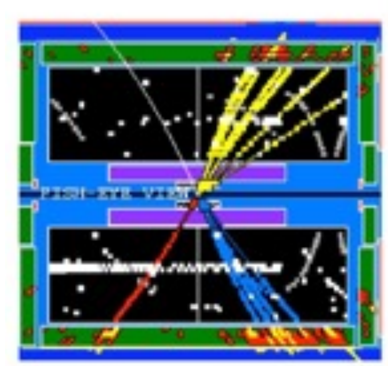


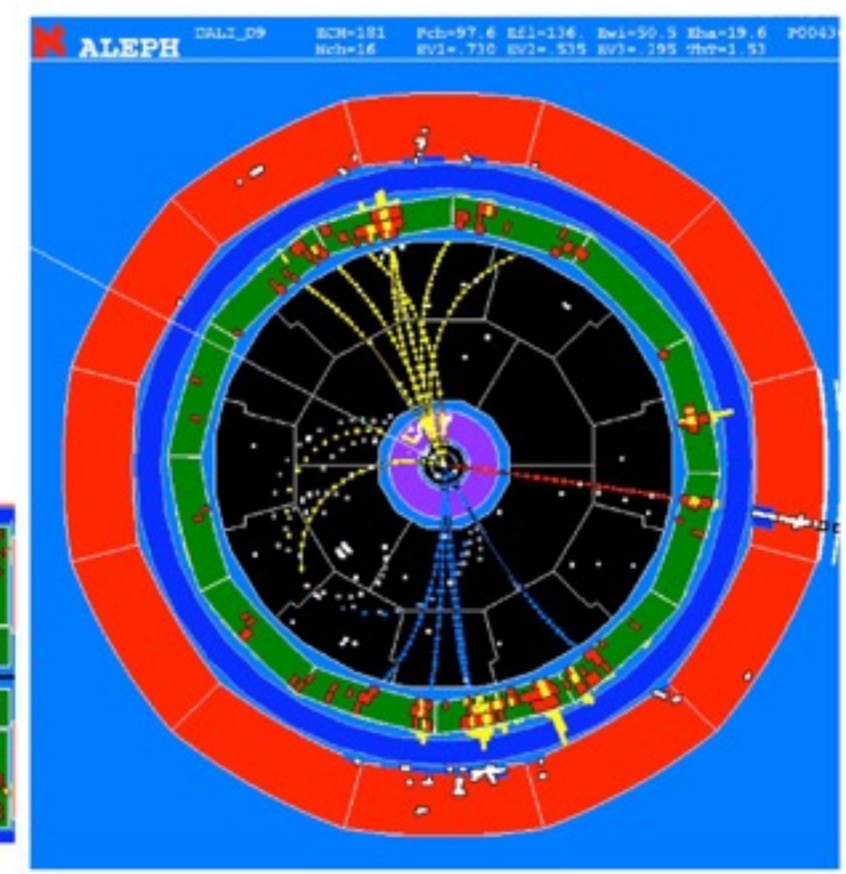
Example of energy flow information

$e^+e^- \rightarrow W^+W^-$
$(\sqrt{s} = 181$ GeV$)$

$WW \rightarrow qq\mu\nu_\mu$

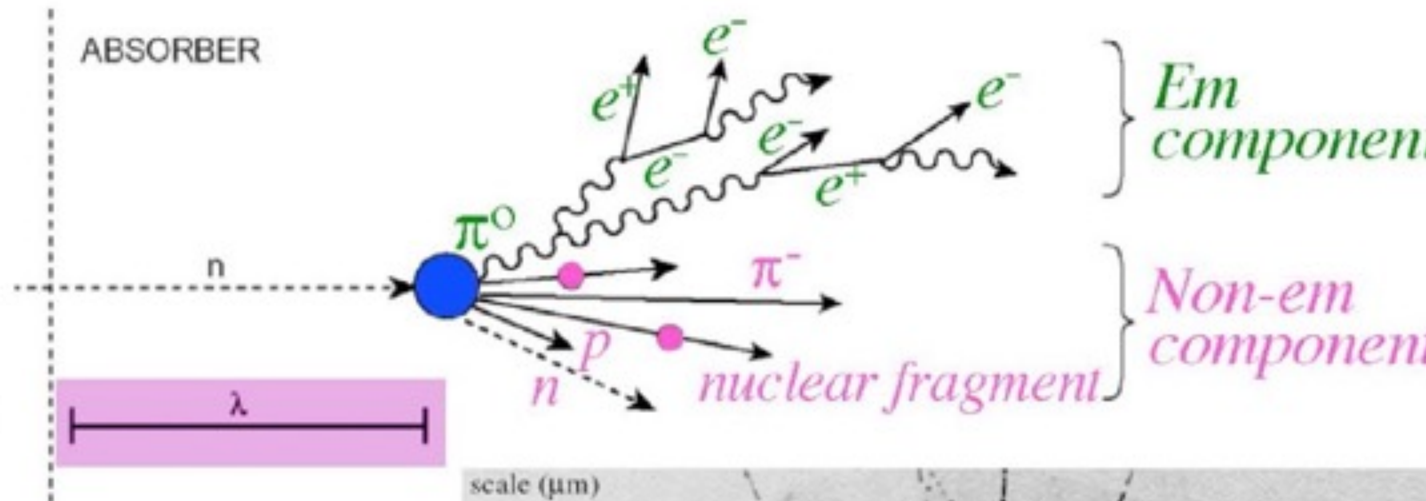
In final state:
2 hadronic jets
1 energetic muon
missing E_T (ν_μ)



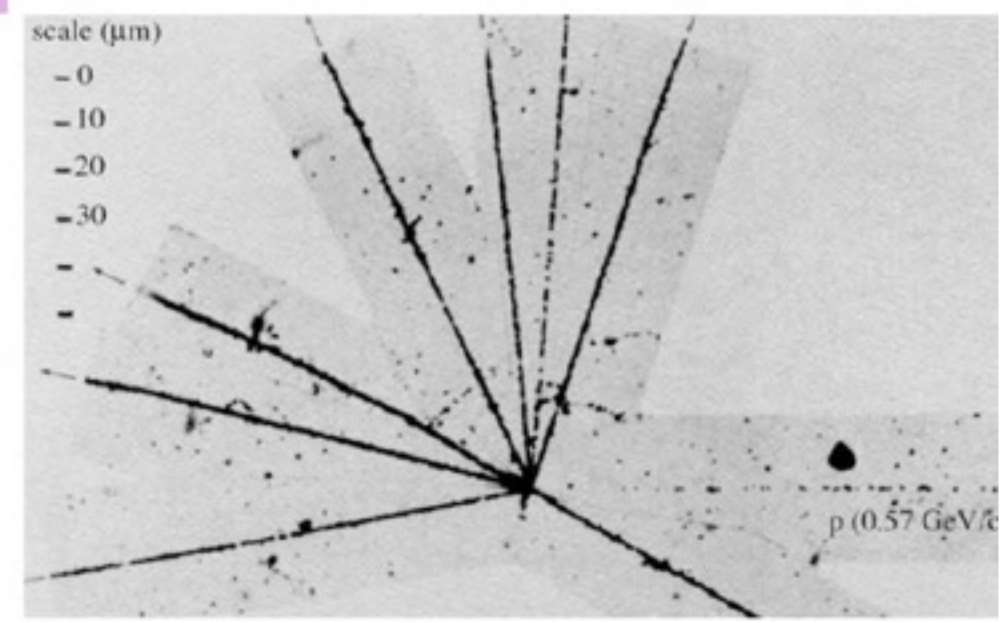


The physics of hadronic shower development

- *A hadronic shower consists of two components*



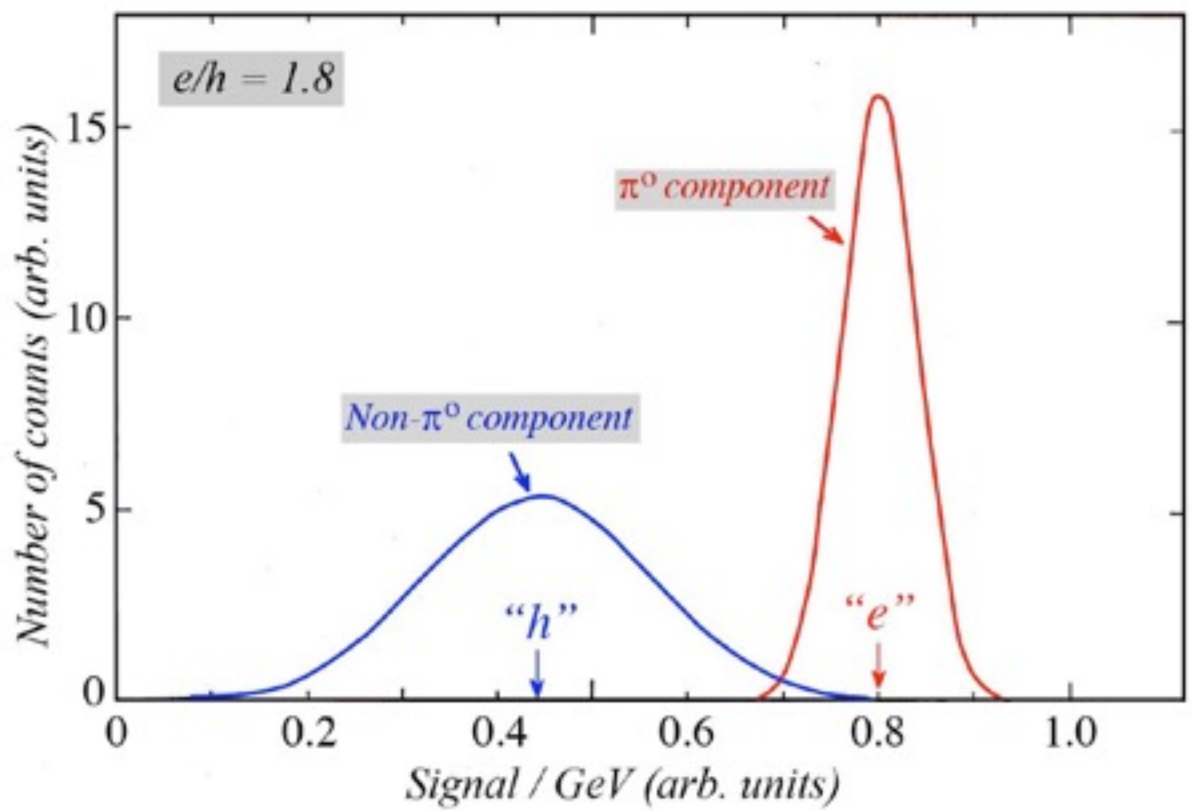
- *Electromagnetic component*
  - electrons, photons
  - neutral pions → 2 γ
- *Hadronic (non-em) component*
  - charged hadrons $\pi^\pm$,$K^\pm$ (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft γ's (15%)
  - break-up of nuclei *("invisible")* (40%)



- *Important characteristics for hadron calorimetry:*
  - *Large, non-Gaussian fluctuations in energy sharing em/non-em*
  - *Large, non-Gaussian fluctuations in "invisible" energy losses*

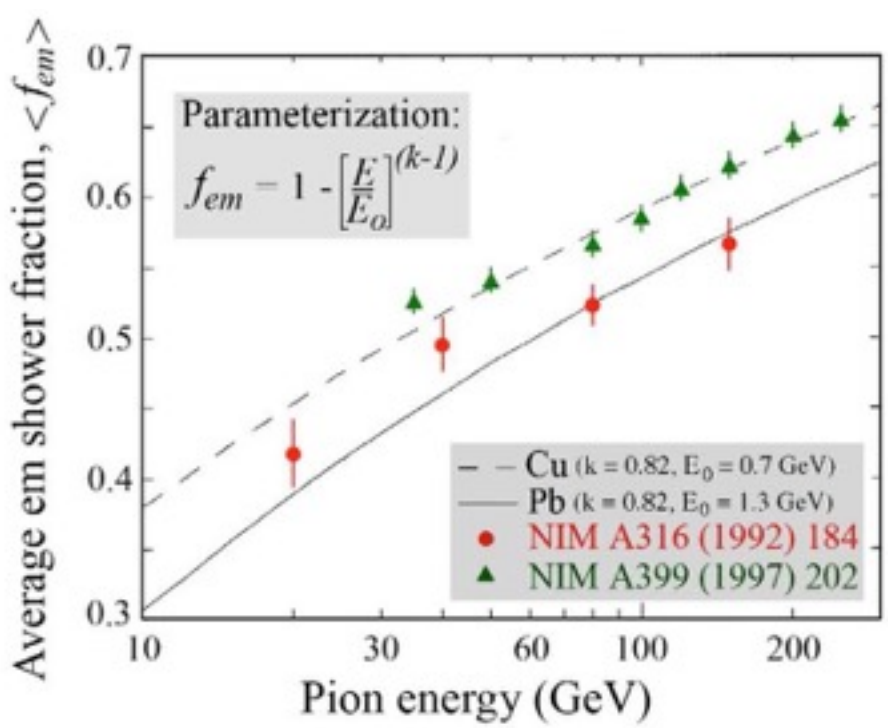
The calorimeter response to the two shower components is NOT the same

(mainly because of nuclear breakup energy losses in non-π^o component)

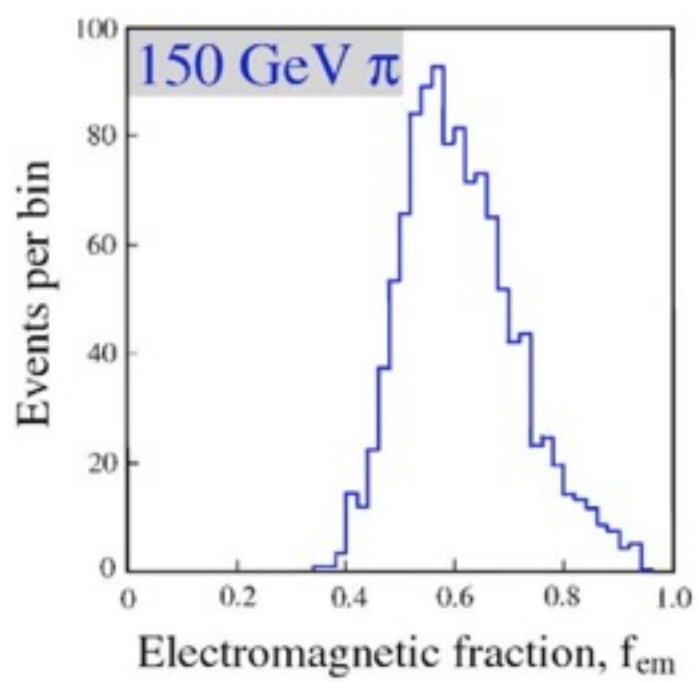


In addition to shower "aging", these three effects are the main reasons for all problems in hadronic energy measurement:

* Poor energy resolution
* Non-Gaussian response
* Non-linear energy scale
* Different for *e* and *h*
* Calibration problems in depth



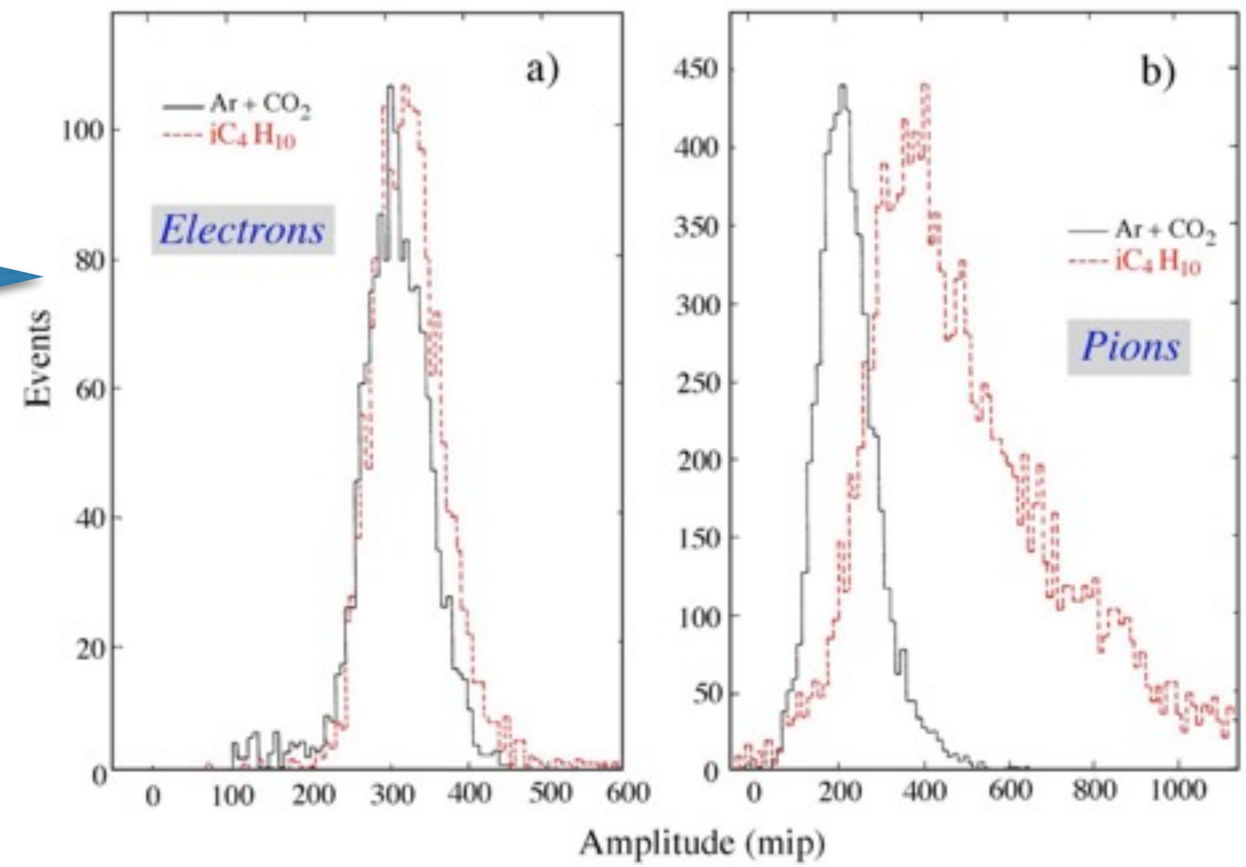
The em fraction is, on average, *large and energy dependent*



Fluctuations in f_{em} are *large and non-Poissonian*

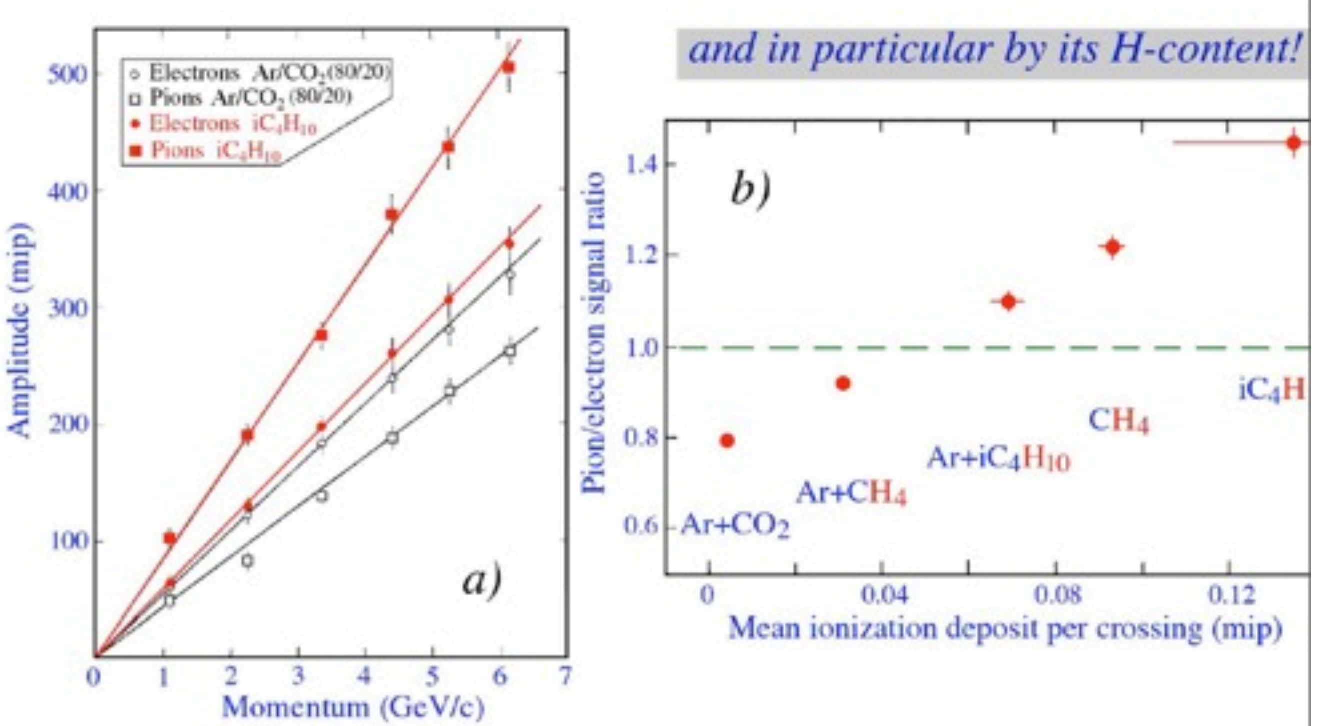
The L3 response to pions depends on the gas! Not the absorber U, Pb, Fe, …

Compensation and energy resolution in L3 hadron calorimeter



The compensation puzzle solved!

The e/h value is not determined by the absorber, but by active mediu

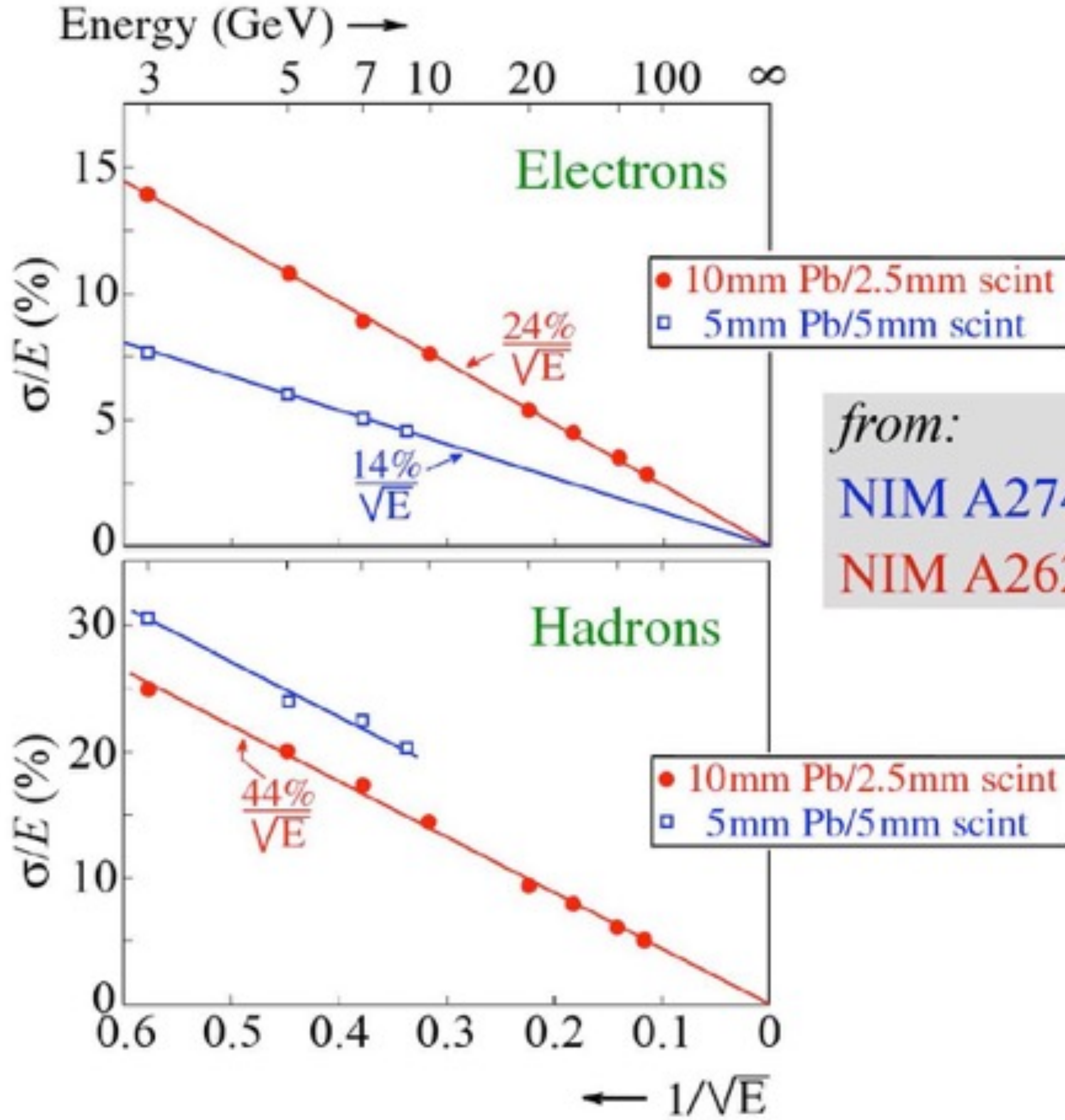


… and it scales with H content. This is the clue to "compensation." The neutrons liberated (energy cost is 8 MeV/neutron) from broken-up nuclei scatter elastically from the protons in the gas.

For Pb-scintillator calorimeter, the compensating ratio is 4-to-1 Pb-to-scintillator: $e/h = 1$

Proof is the ZEUS hadron calorimeter testing.

Calorimetric effects of efficient neutron sampling



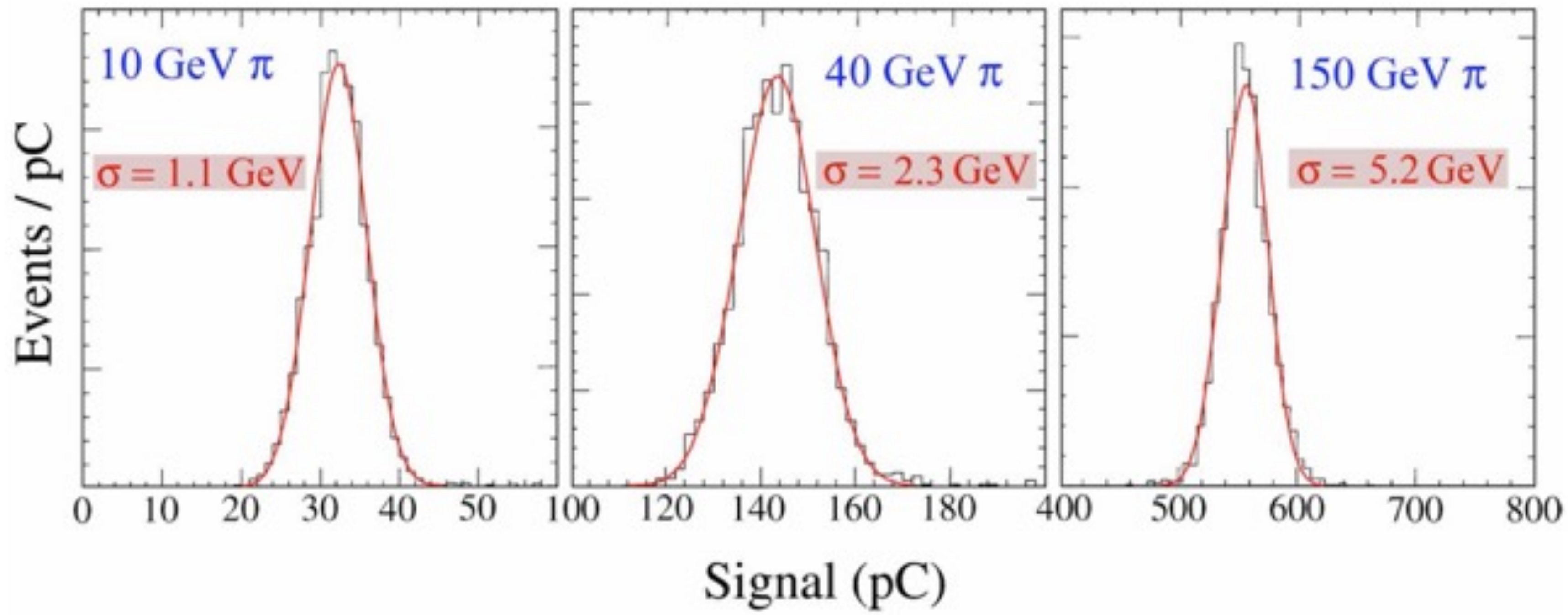
from:
NIM A274 (1989) 134 $e/h \sim 1.5$
NIM A262 (1987) 229 $e/h = 1.05$

The response to neutrons is increased (relative to the other shower particles) by a factor of 4 in the more crudely sampling calorimeter

Neutrons are special: they efficiently increase the hadronic response through np elastic scattering, and their kinetic energy is strongly correlated with the lost nuclear binding energy.

World's second compensating calorimeter: SPACAL, CERN (nearly 30 years ago)

Hadronic signal distributions in a compensating calorimeter



from: NIM A308 (1991) 481

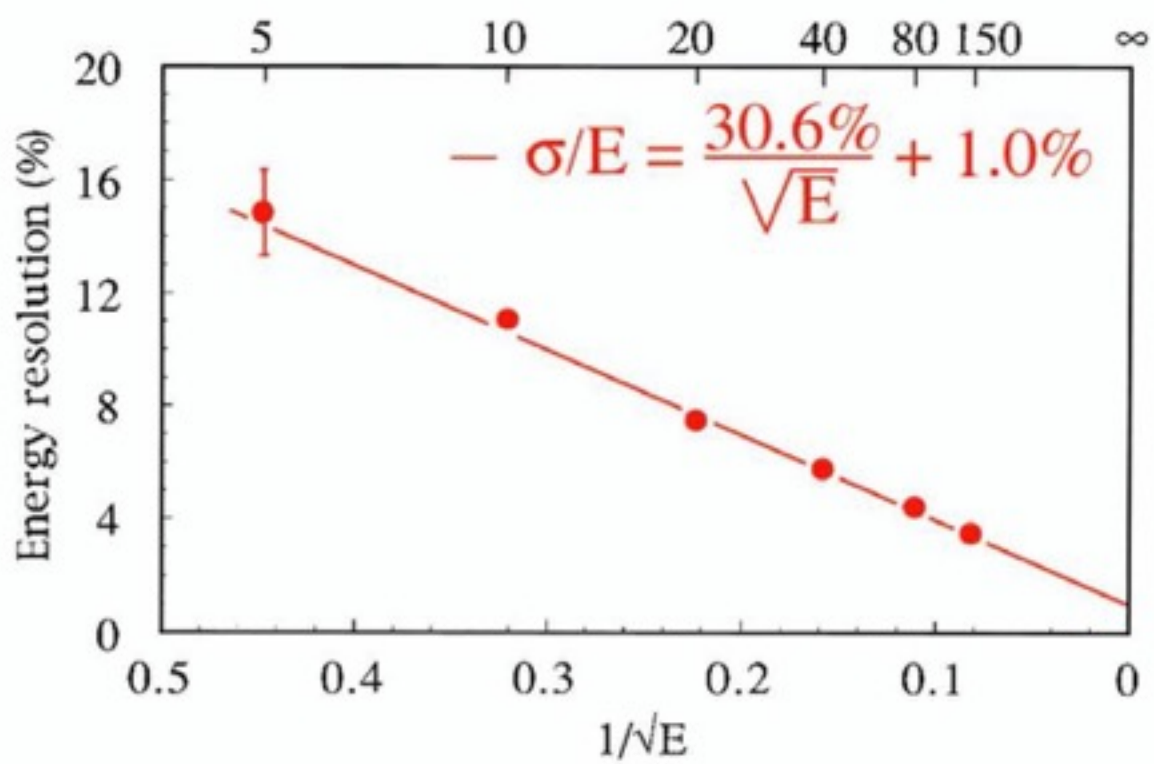
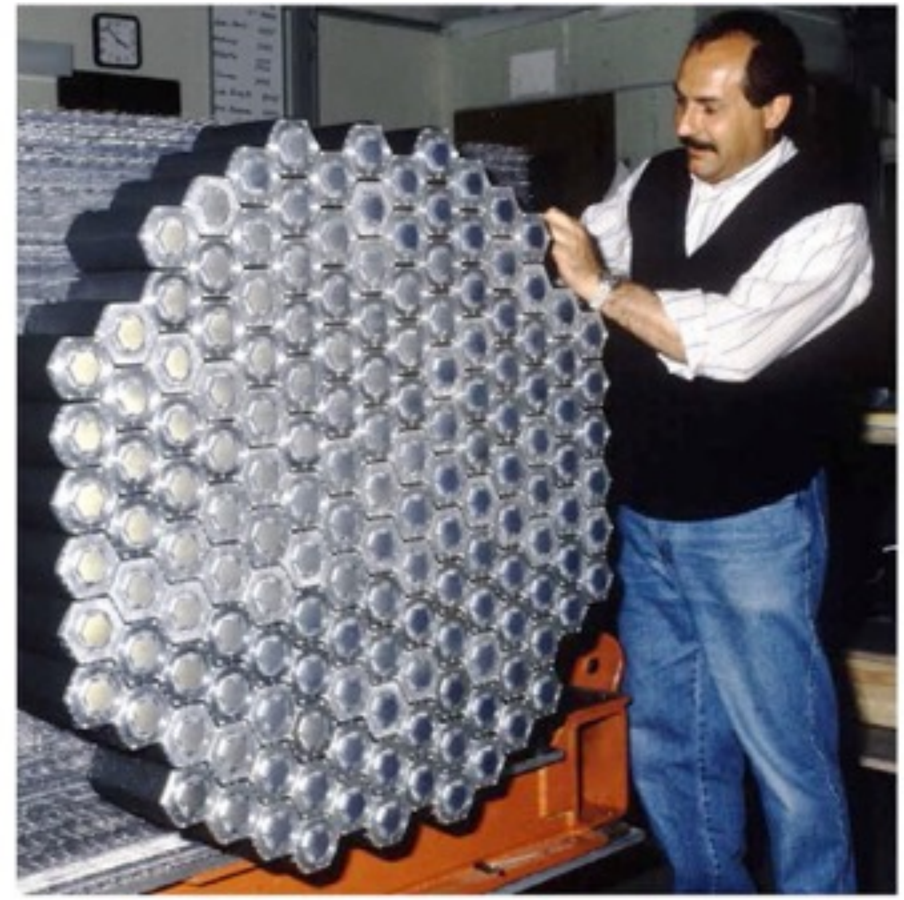


Figure 10: The hadronic energy resolution as a function of energy, for the compensating SPACAL *lead/plastic-scintillator calorimeter (sampling fraction 2%)*

NIM A308 (1991) 481

SPACAL 1989



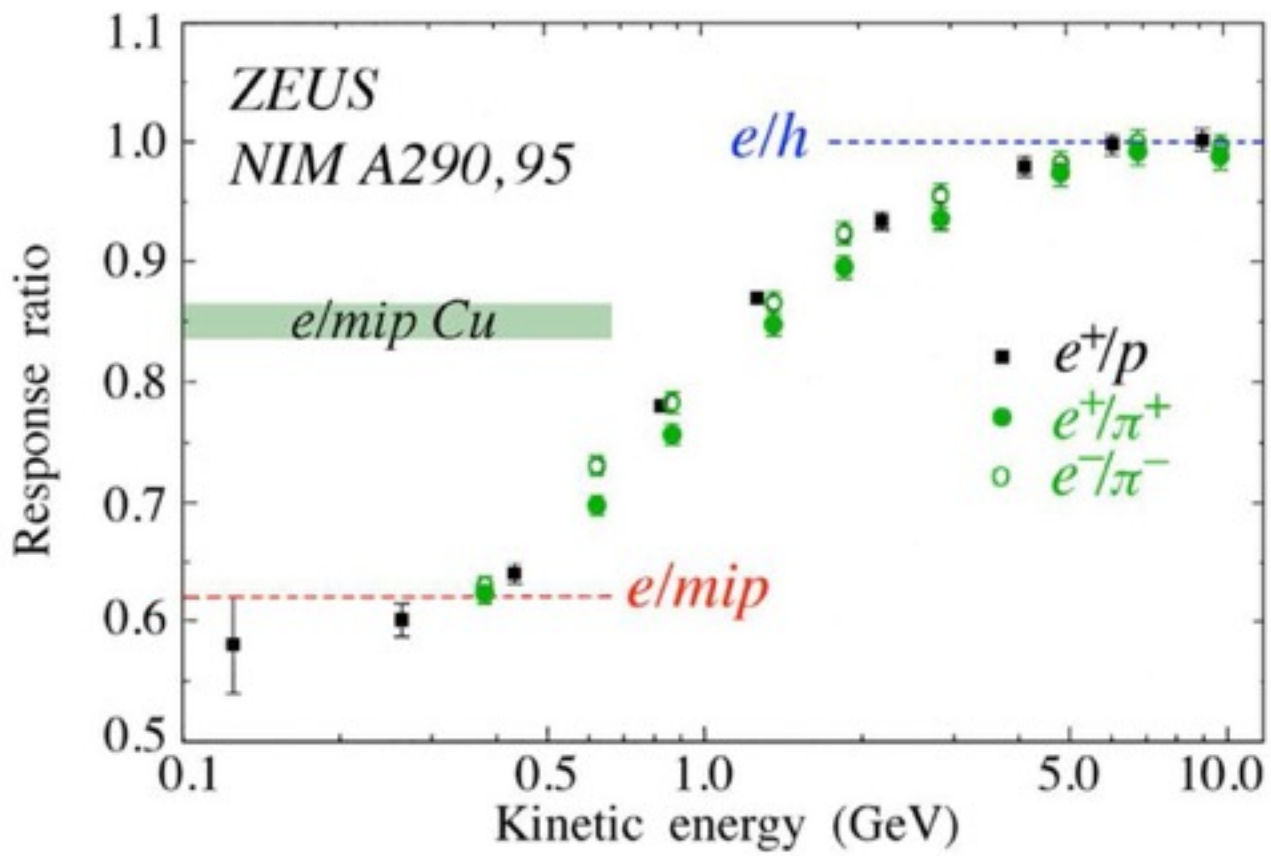
* 20 tons of Pb and scintillating fiber
* needs long integration time to collect neutrons
* Pb:scintillator requirement of 4:1 forces small sampling fraction ~ 2%
* used in H1 at HERA, but not in any future collider experiment
* simple construction: gather fibers onto PMTs

How do you improve on SPACAL?

1. improve sampling fluctuations which limit the EM energy resolution:

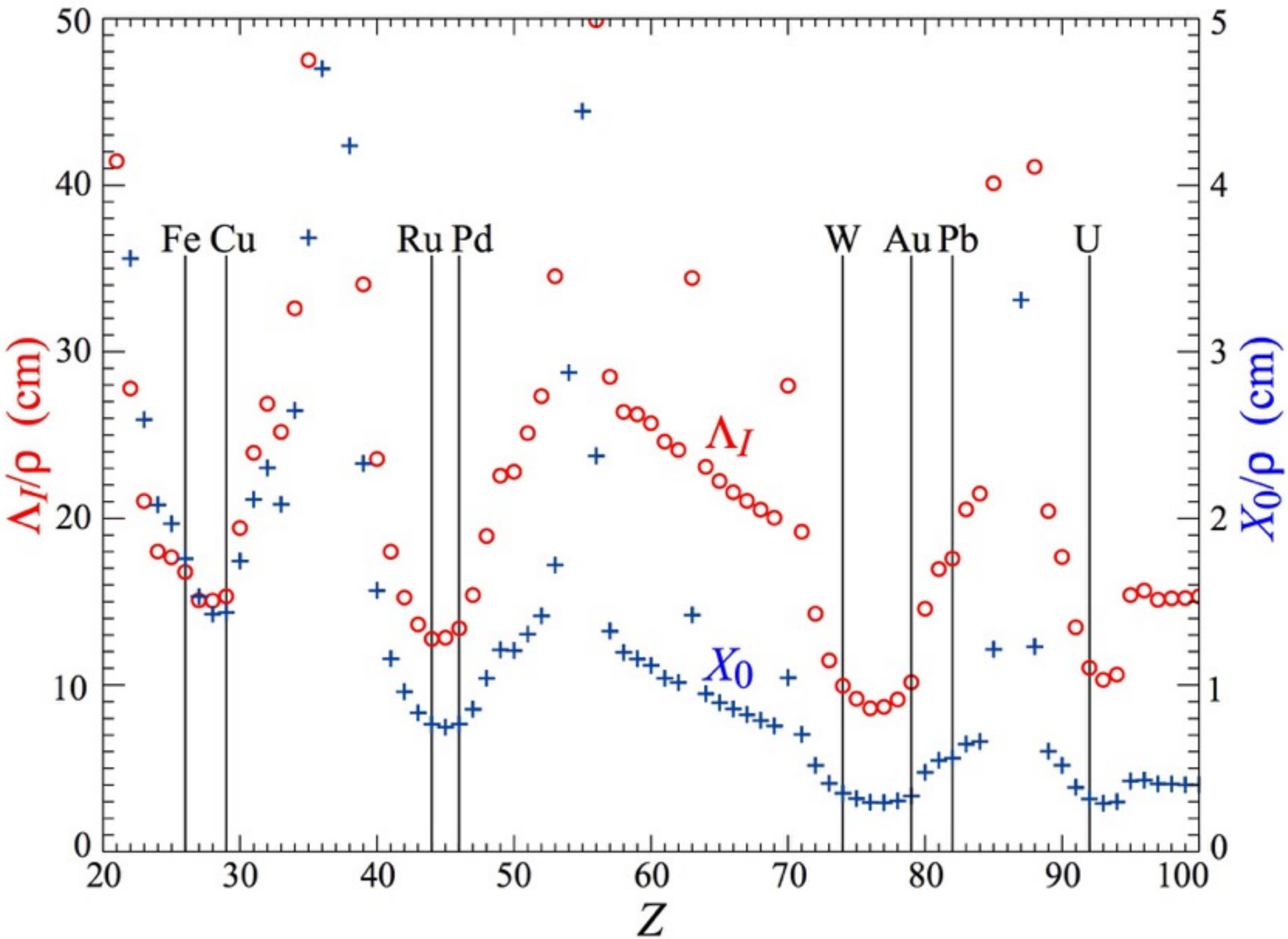
   ZEUS $\sigma/E \approx 18\%/\sqrt{E}$
   SPACAL $\sigma/E \approx 13\%/\sqrt{E}$

2. use a lower-Z absorber to reduce response non-linearity in 1-5 GeV region



3. maintain advantages of compensation: reduce effects of EM fraction fluctuations and binding energy loss fluctuations.

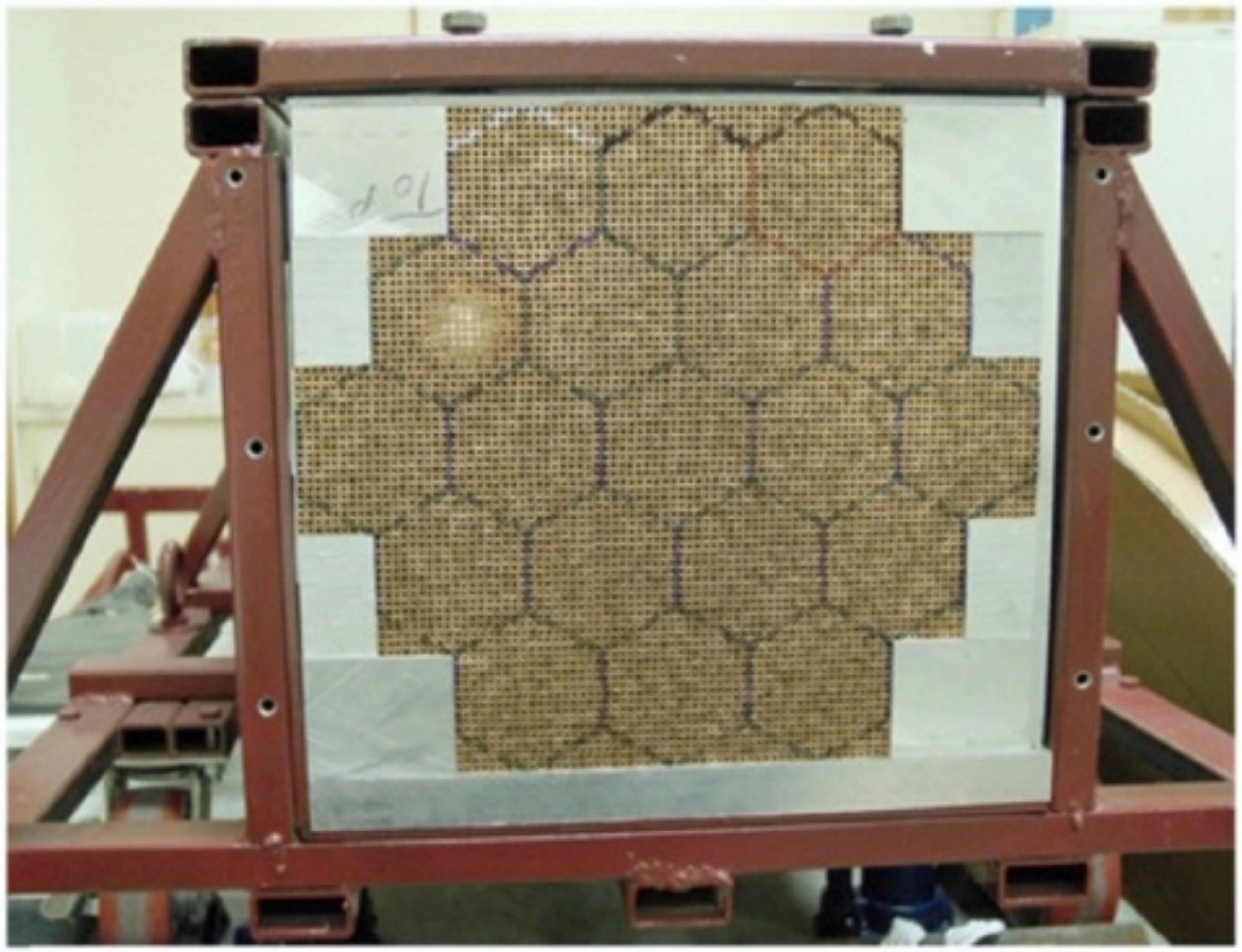
Cu is better than Pb for hadrons: per cubic interaction length, the mass is ~1/2

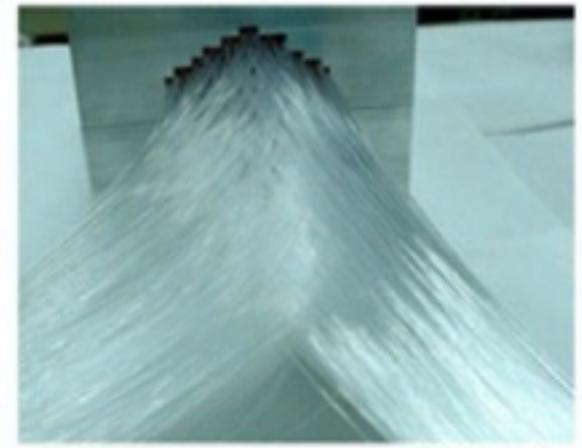


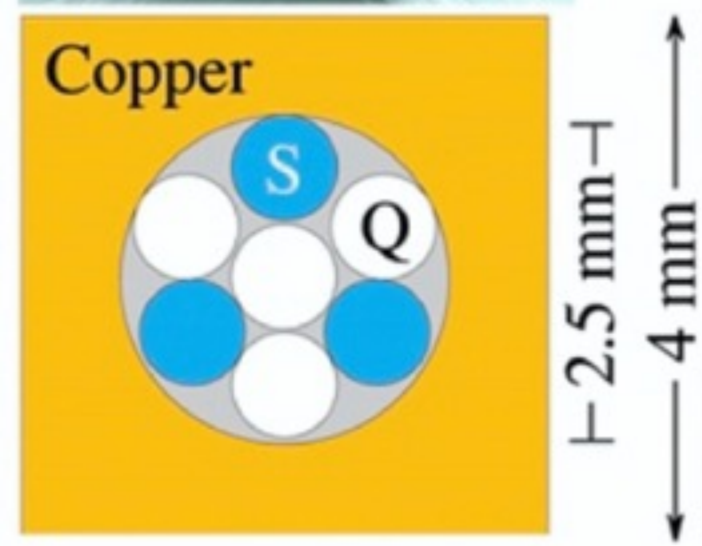
Particle Data Group, Don Groom

Dual Readout ——> DREAM module built, tested, published (2005)

DREAM: Structure

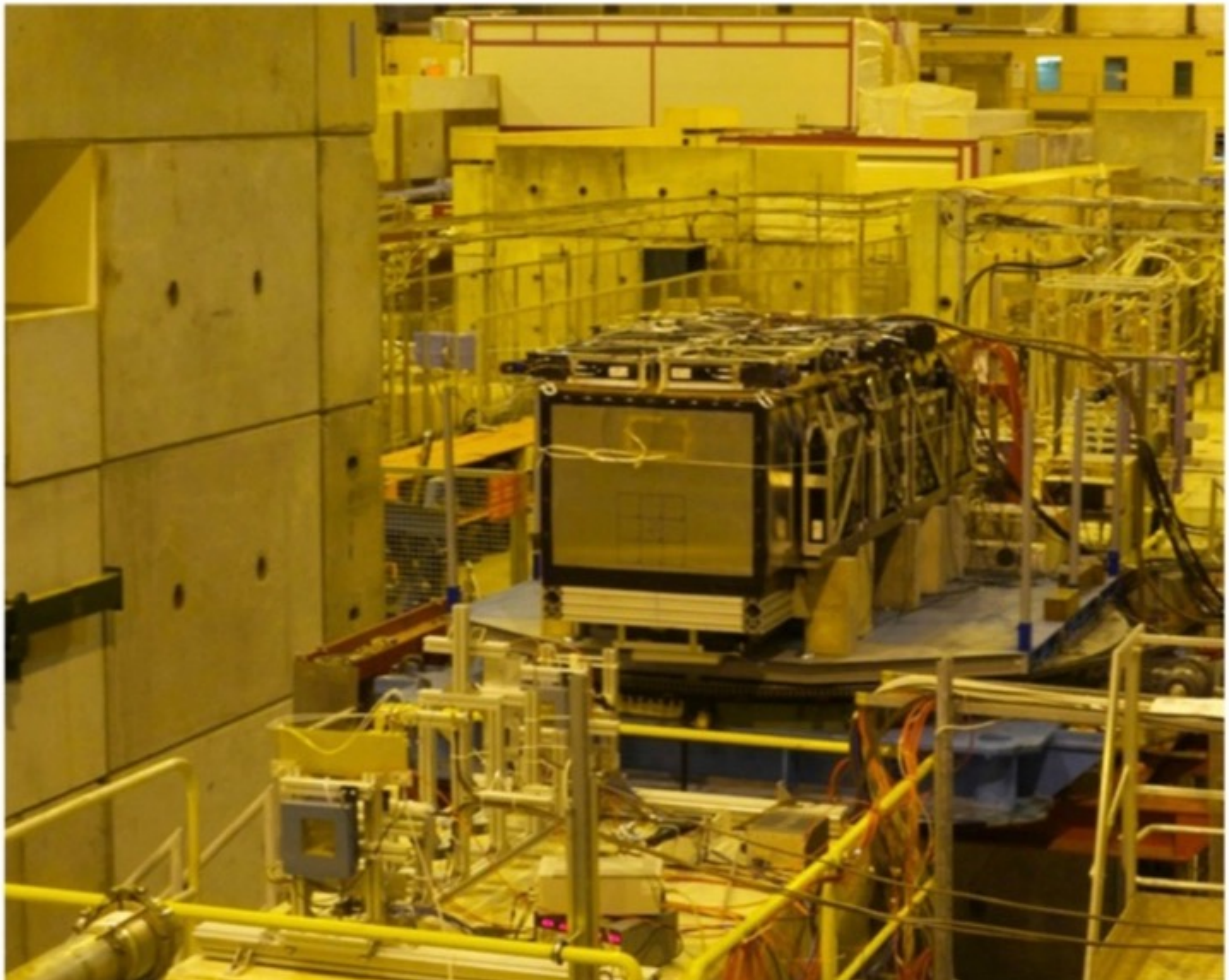






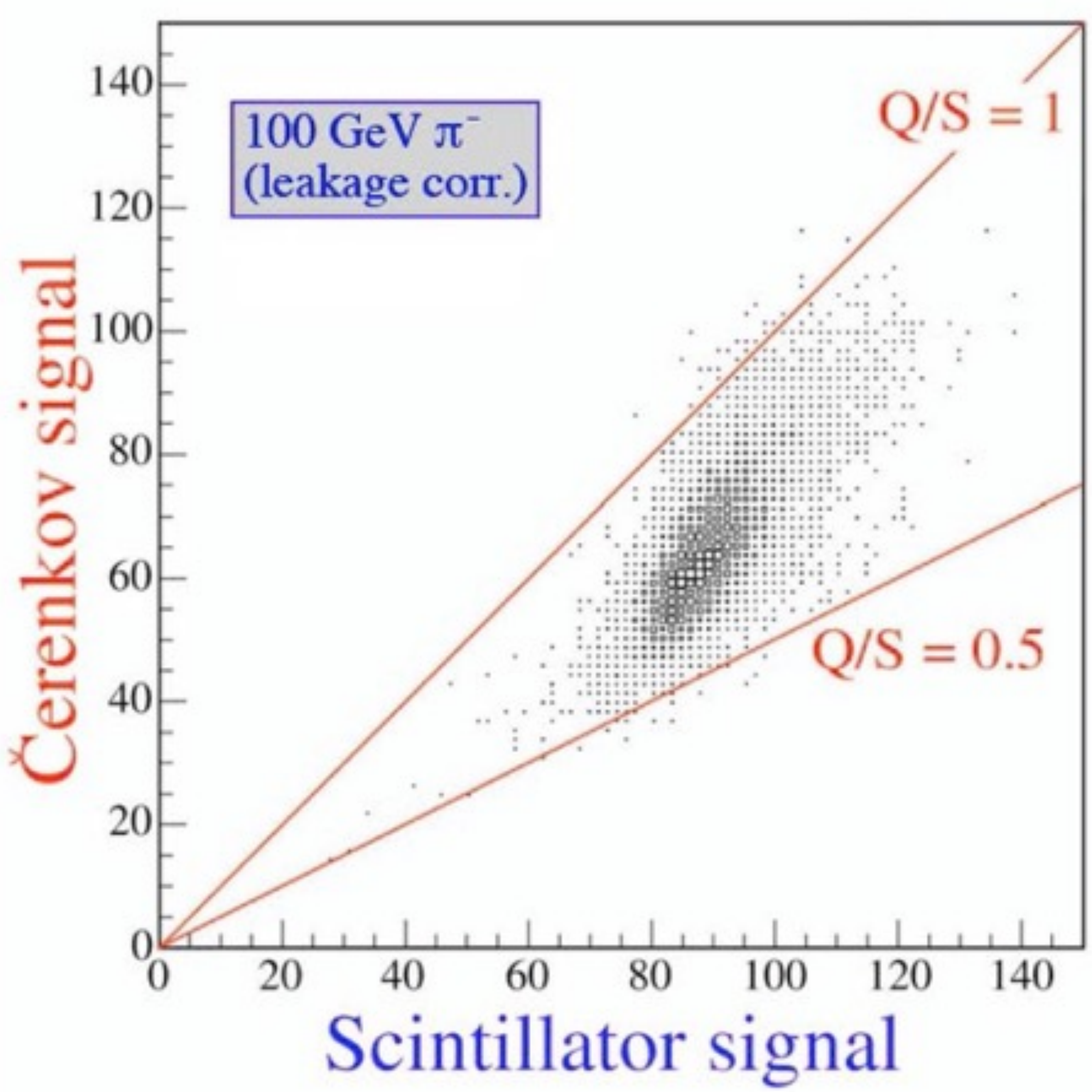
- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

CERN North Area H8 beam. Our own beam area and counting room, which we only share with AMS. One of the benefits of being a CERN Project



Calorimeters go inside the aluminum box; neutron counters surround the box.

Read out both S and C PMTs, digitize and plot



Mean response constants:

$$\eta_S = h/e \sim 0.72 \qquad \text{(S-fibers)}$$

$$\eta_C = h/e \sim 0.22 \qquad \text{(C-fibers)}$$

Expected S and C response:

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

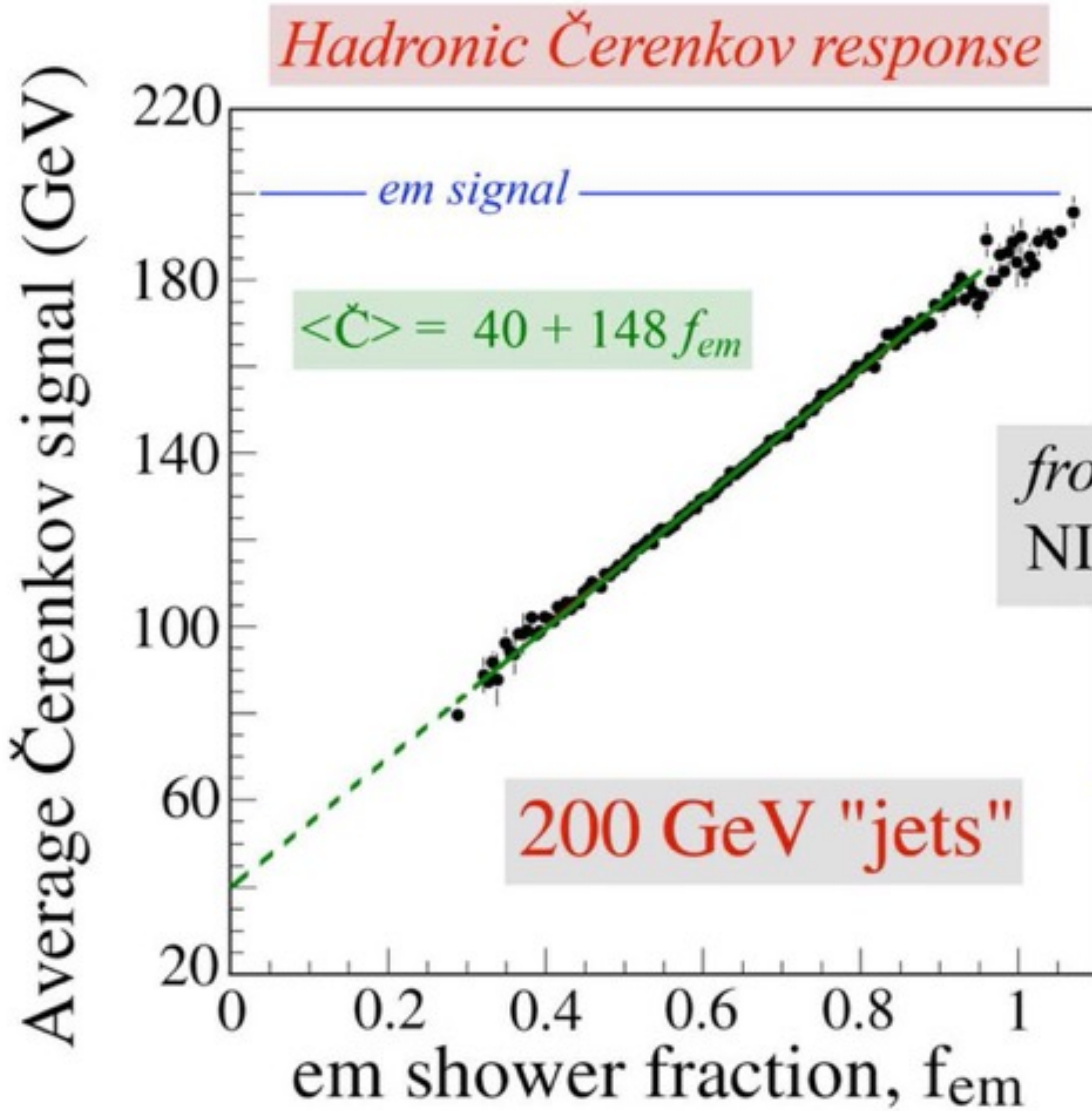
$$C = E[f_{\text{EM}} + \eta_C(1 - f_{\text{EM}})]$$

$S/C \to f_{\text{EM}}$. Define $\xi = \frac{1-\eta_S}{1-\eta_C}$.

Dual-readout energy:

$$E = \frac{S-\xi C}{1-\xi}$$

The dual-readout method



$R = f_{em} \cdot e + (1 - f_{em}) \cdot h$
$\quad = p_0 + p_1 f_{em}$

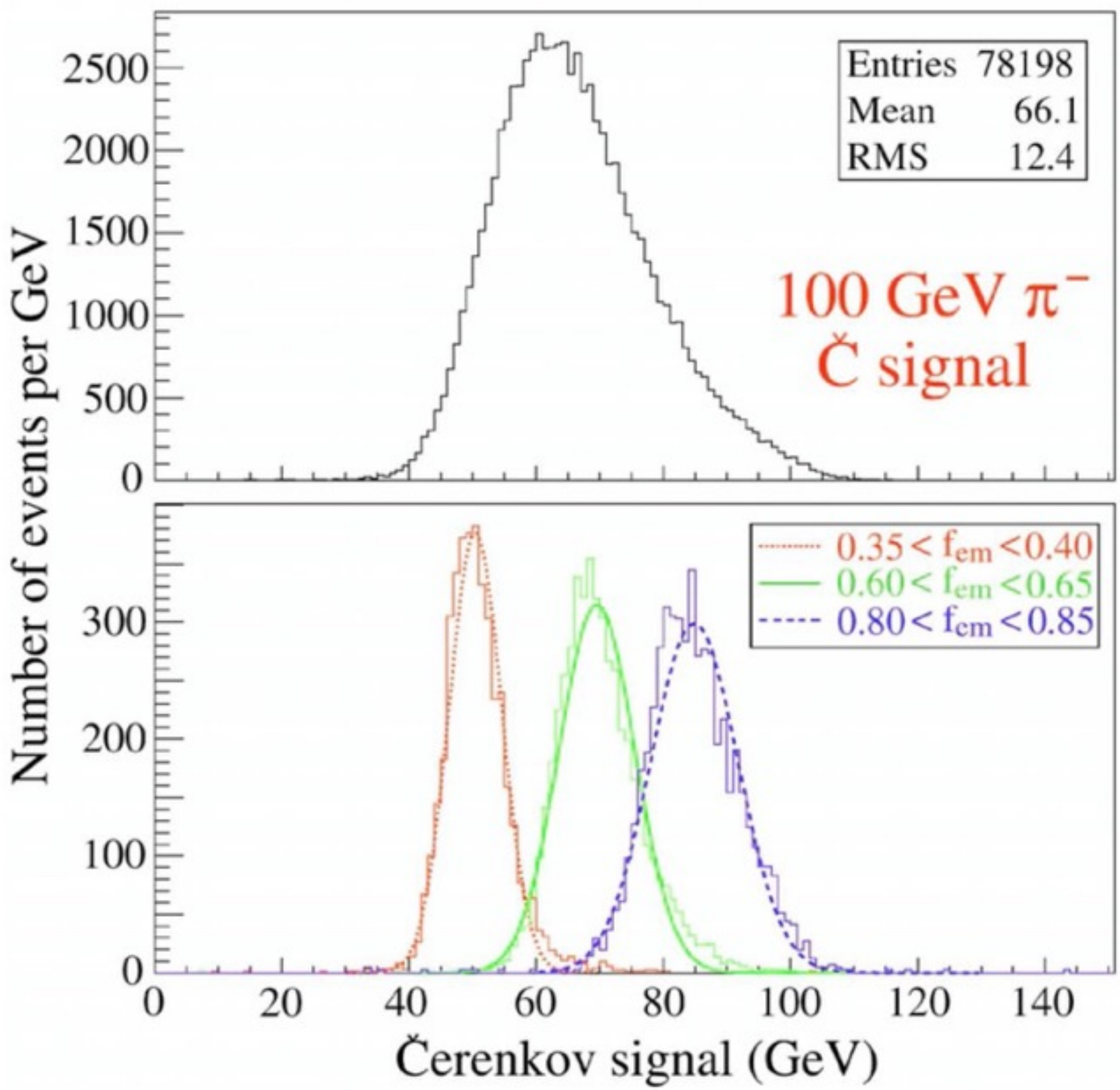
$e/h = \frac{p_1}{p_0} - 1 = 4.7$

from:
NIM A537 (2005) 537

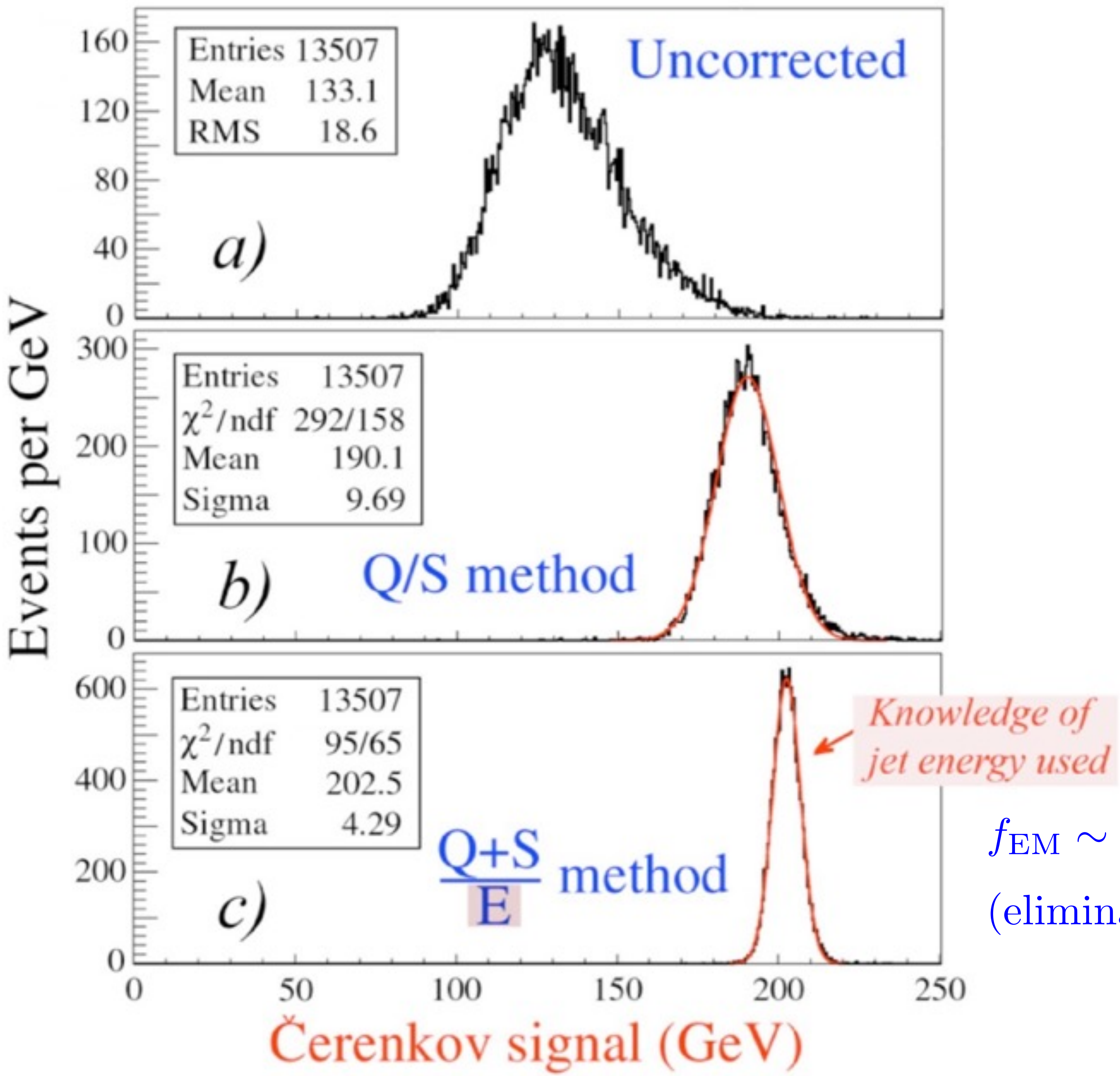
$f_{em} = 0 \longrightarrow R_h = 0.2\ R_{em}$
$\quad < 0.2\ R_{mip}$

Experimentally, one measures f_{em} event by event
Scale signal up to $f_{em} = 1$, i.e. the em scale

The broad non-Gaussian response is just a *sum of narrow Gaussians*



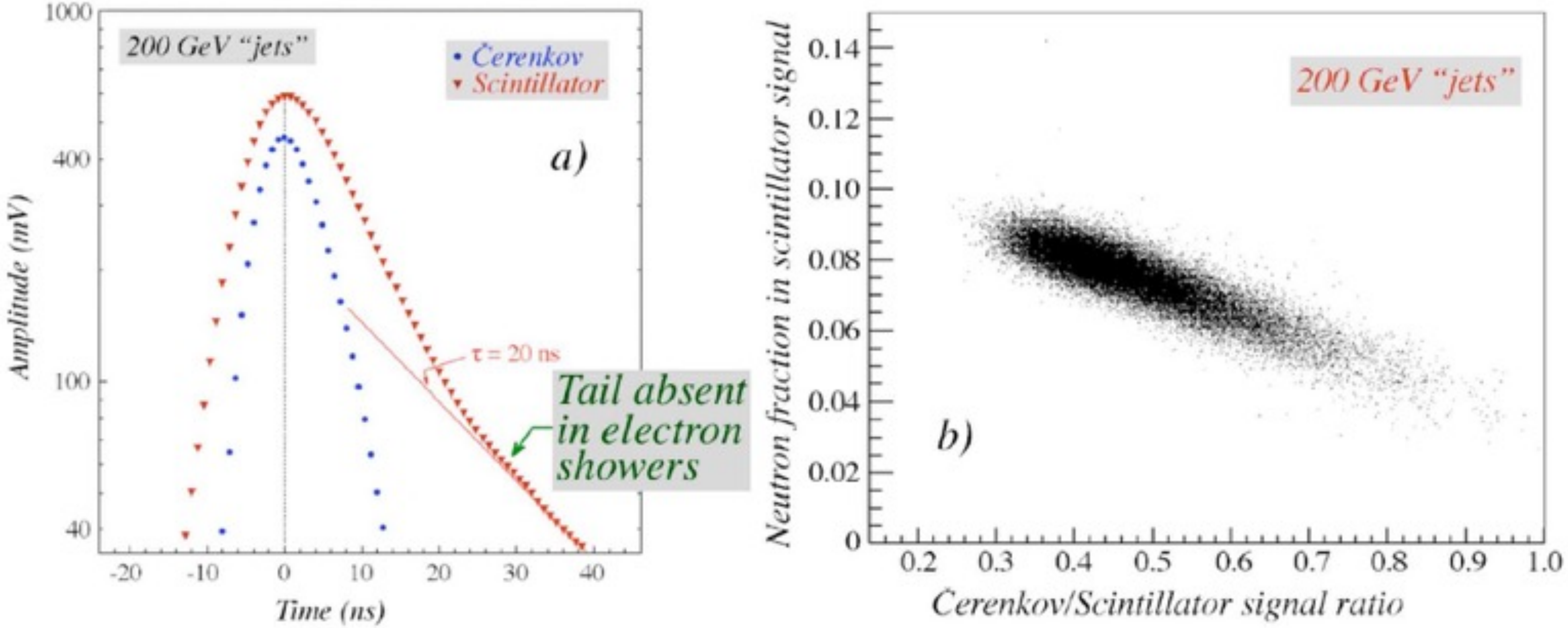
From:
NIM A537 (2005) 537

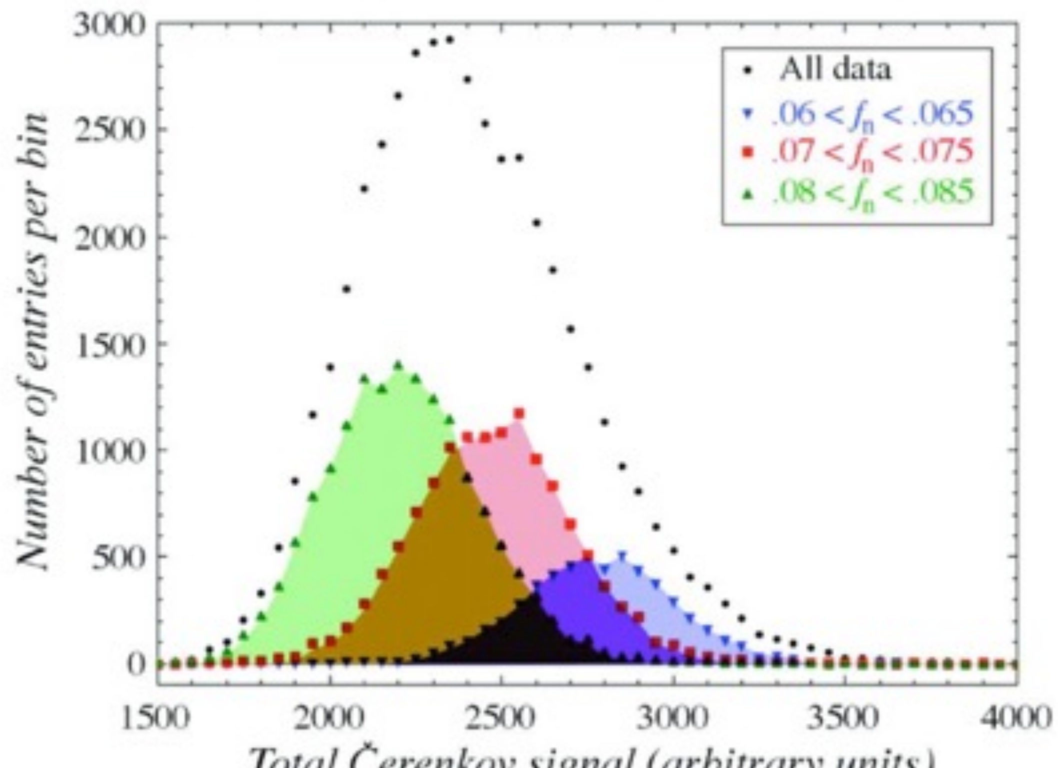


$f_{\mathrm{EM}} \sim C/E \rightarrow C/E_{\mathrm{beam}}$

(eliminates leakage fluctuations)

Time structure of the DREAM signals: the neutron tail (anti-correlated with f_{em})



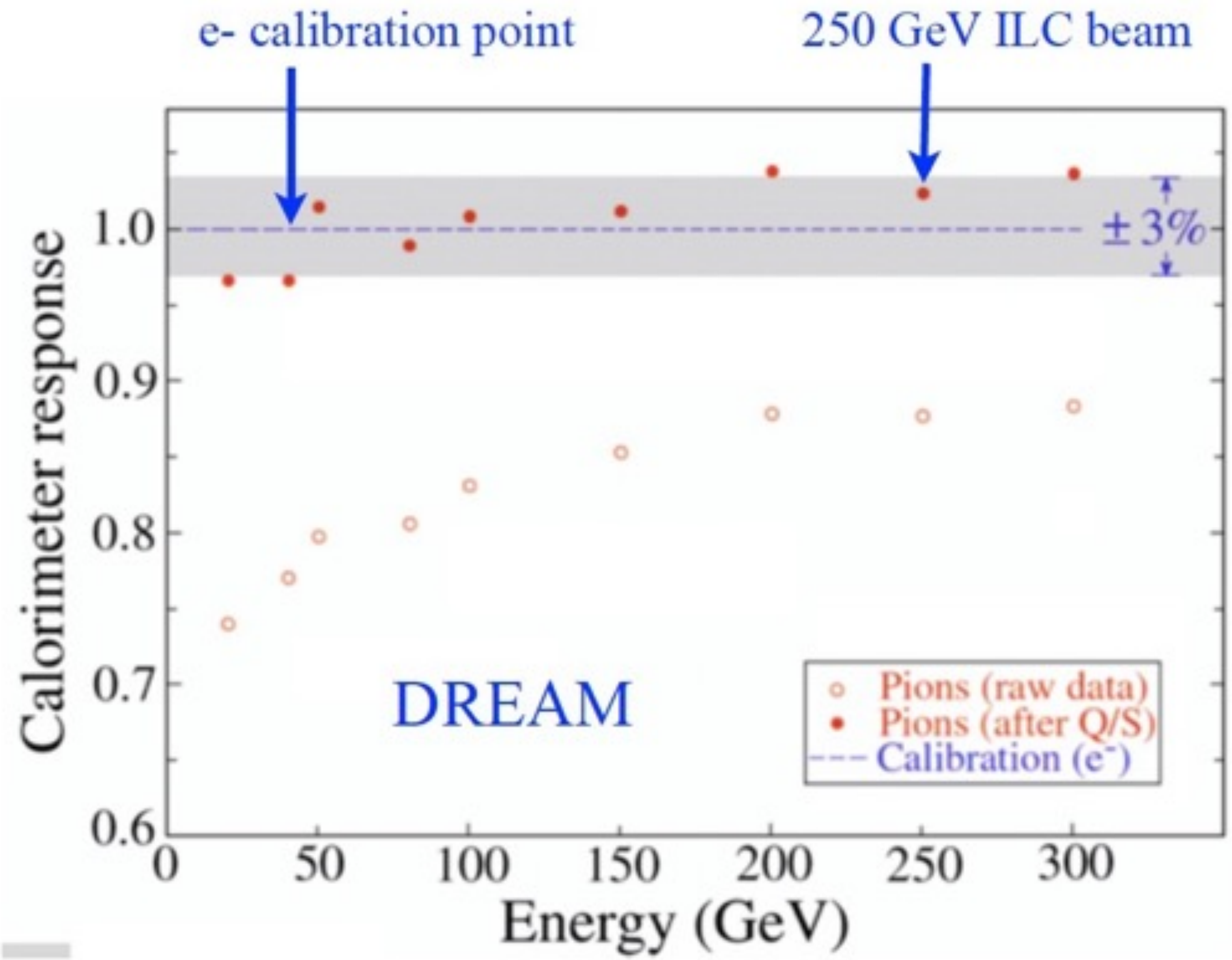


neutron measurements within DREAM module

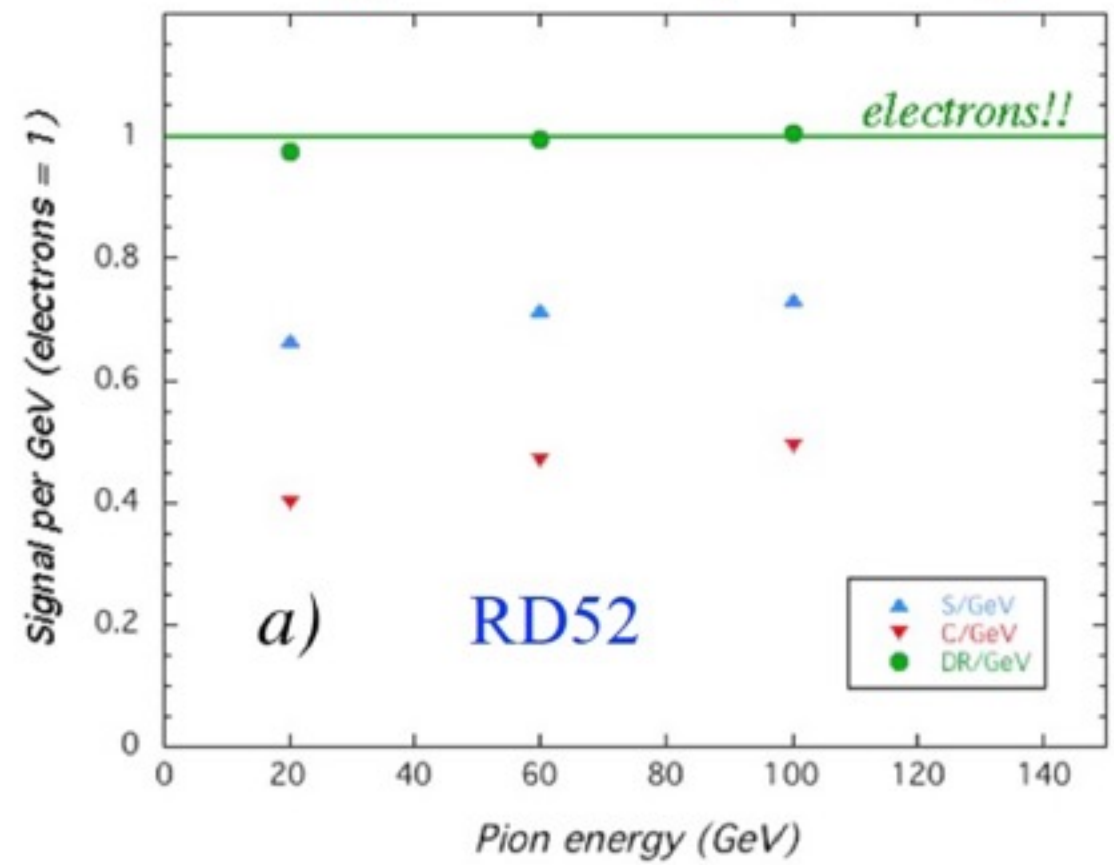
From:

NIM A598 (2009) 422

Hadronic energy linearity over the whole SPS range, 20-300 GeV



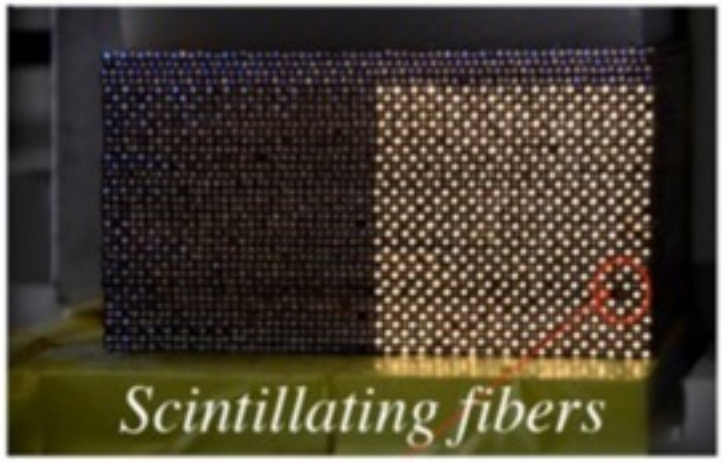
Electron energy scale well reproduced by DR!!



Data NIM A537 (2005) 537.

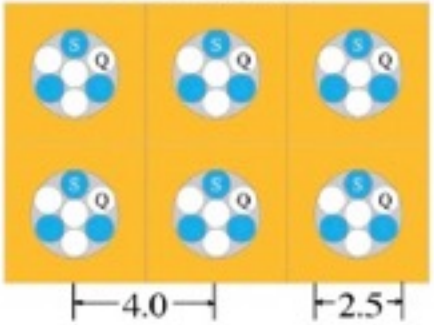
Nov-Dec CERN test 2012

Fiber-impregnated absorber volumes

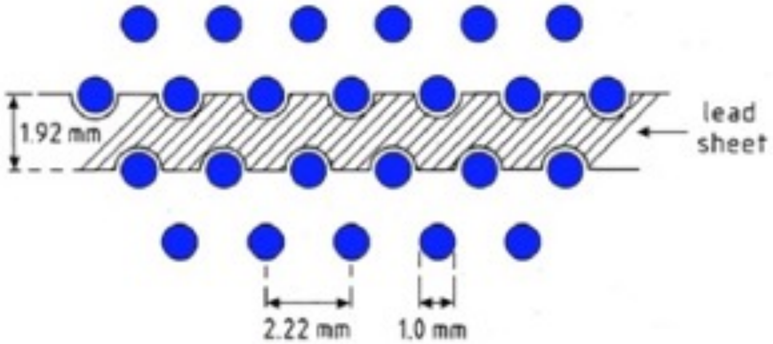


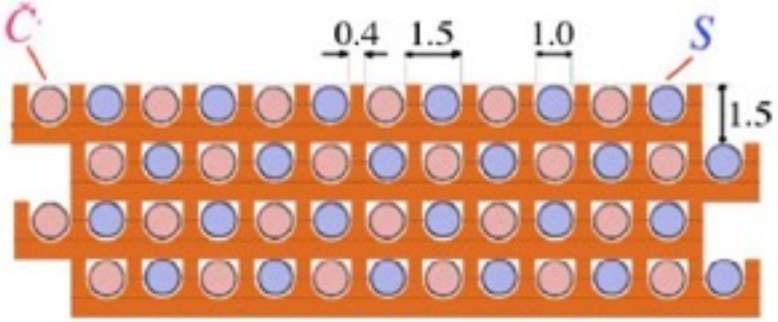
Sampling fraction & frequency

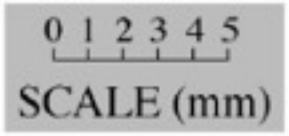
DREAM



SPACAL





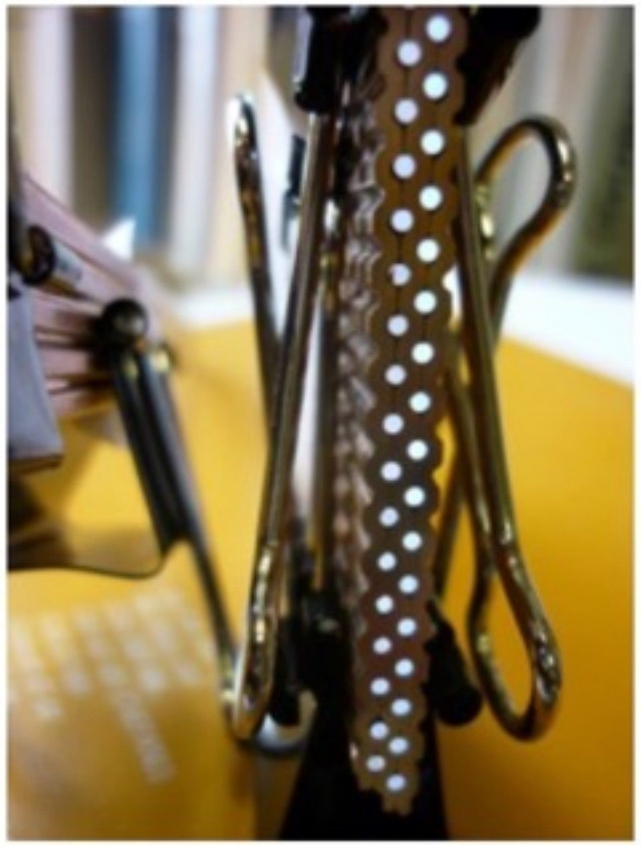


Fiber pattern *RD52*

Absorber thickness between sampling layers (Moliere radii):

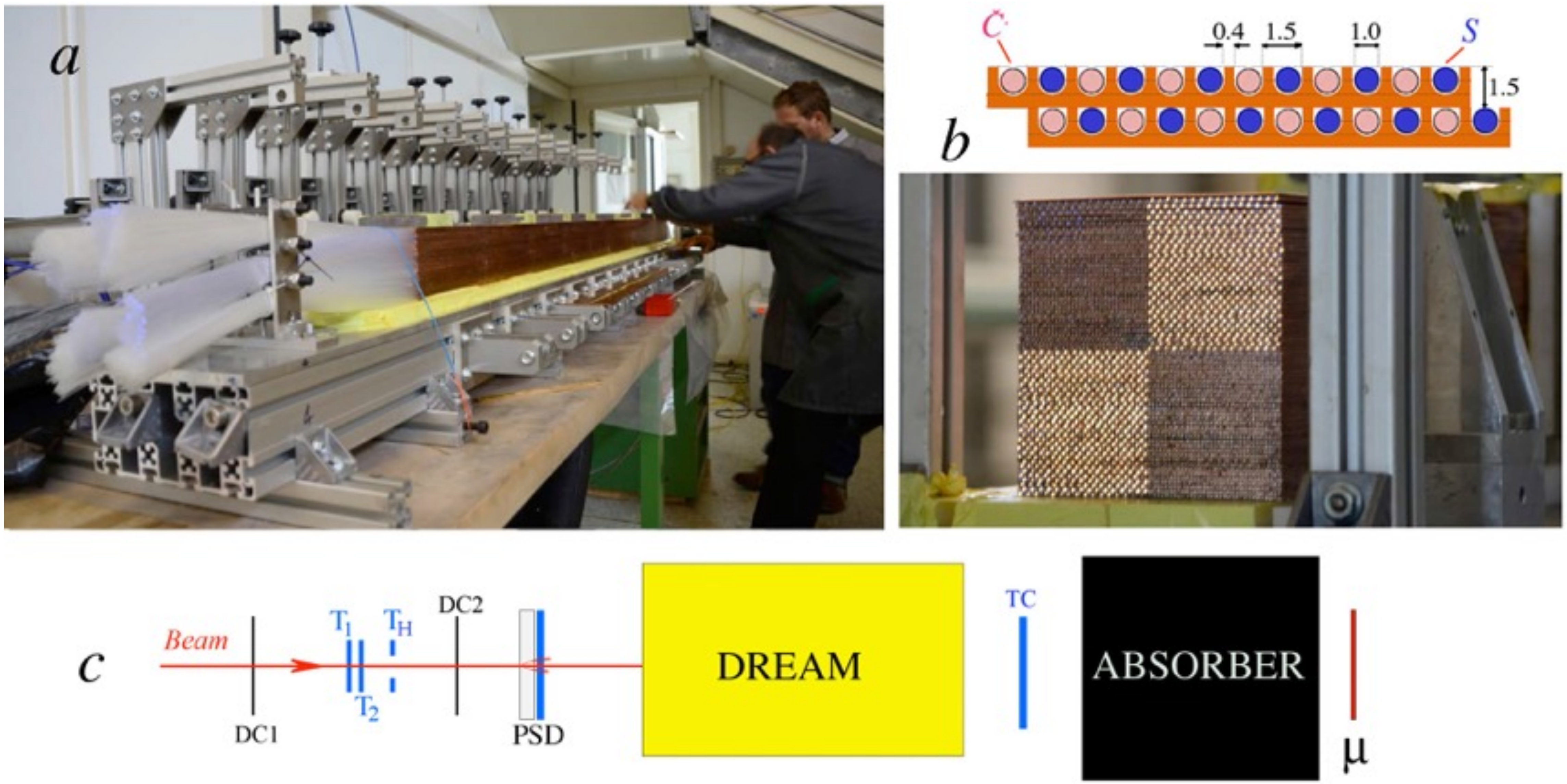
SPACAL 0.071 *DREAM 0.099* *RD52 0.027*

Pure Cu

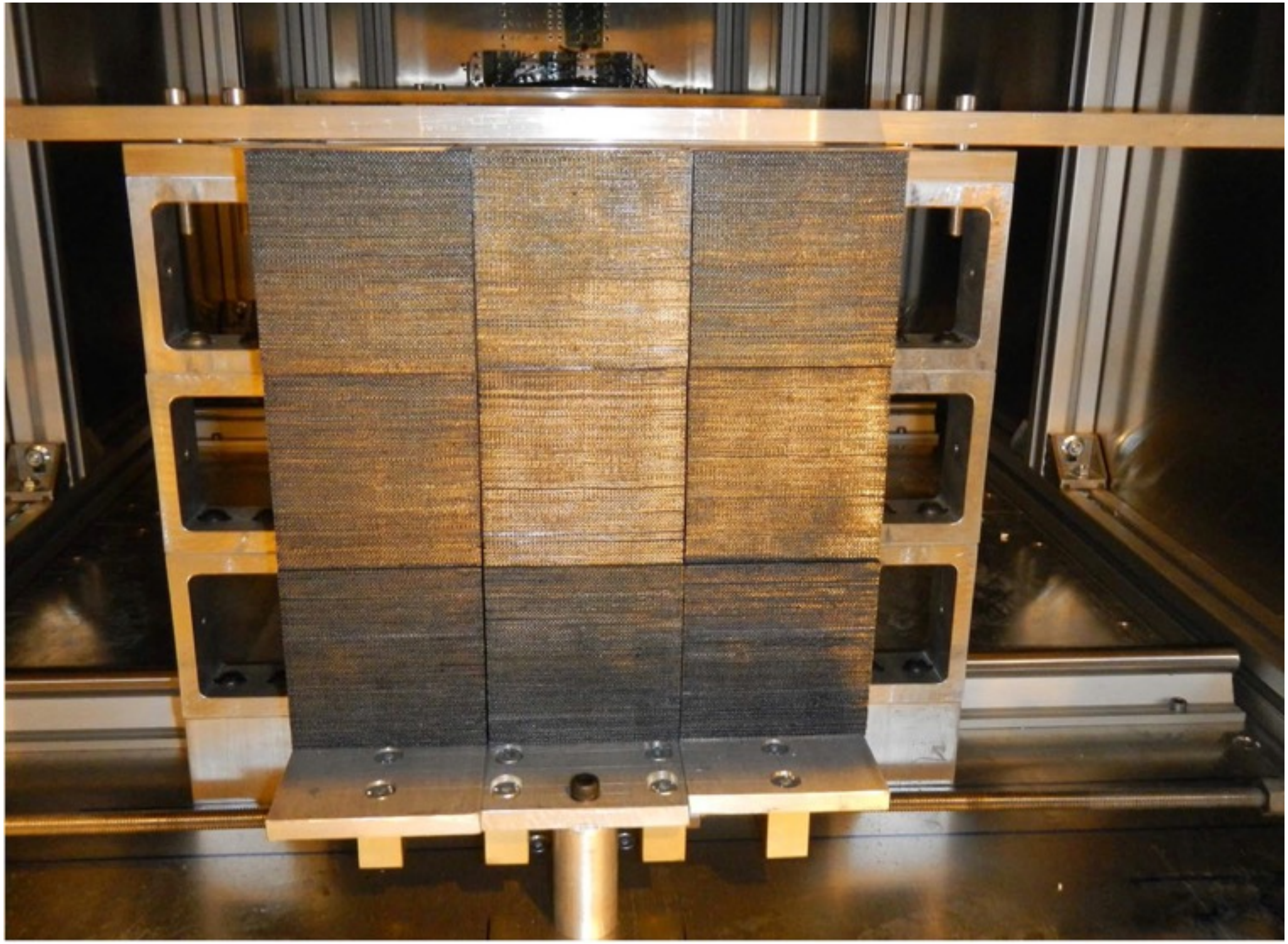


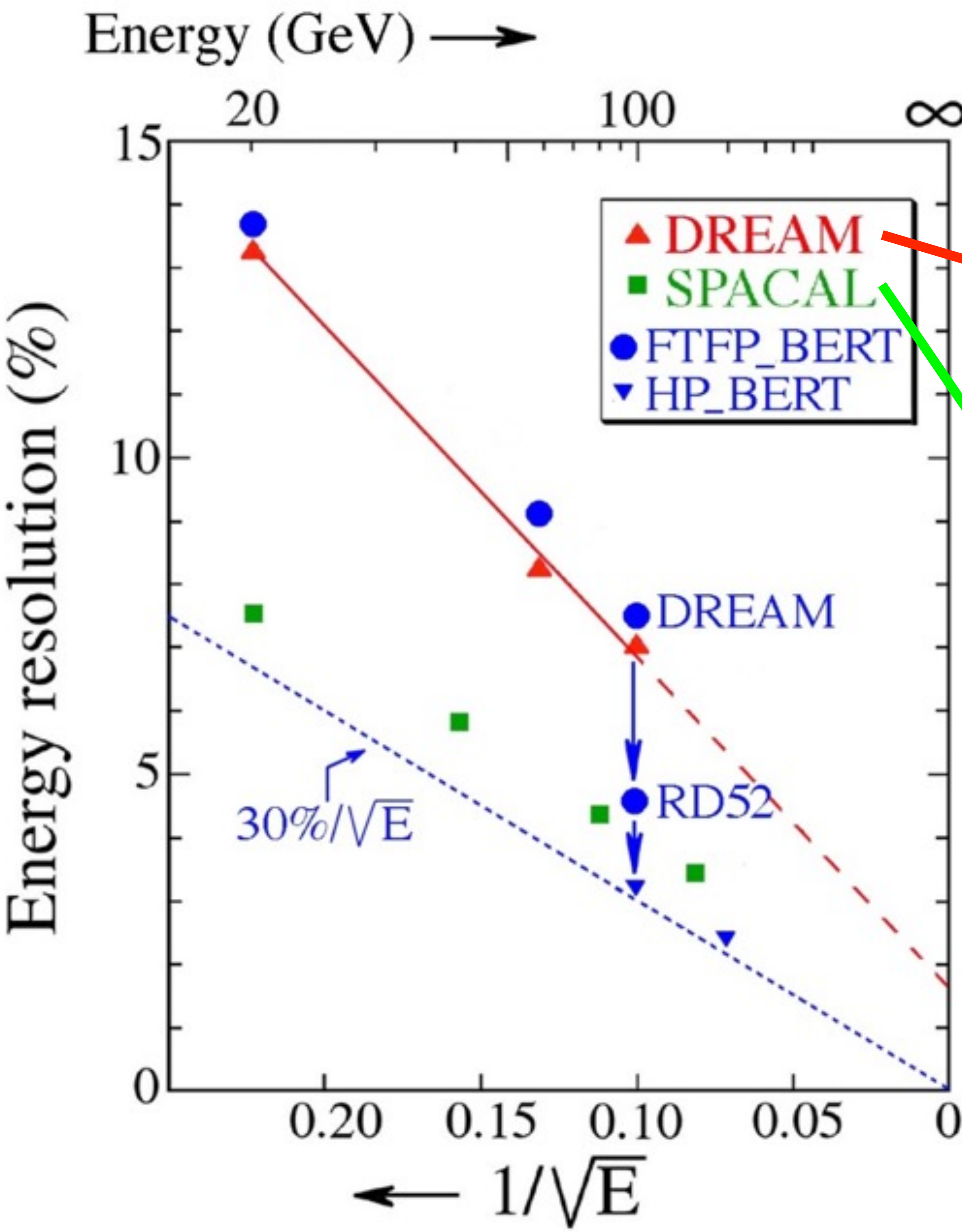
Cu + Zn(10%)

One (of two) Cu RD52 modules, INFN Pisa



Nine Pb RD52 modules, INFN Pavia





Yunyong Wang, Beijing U.

One ton of copper

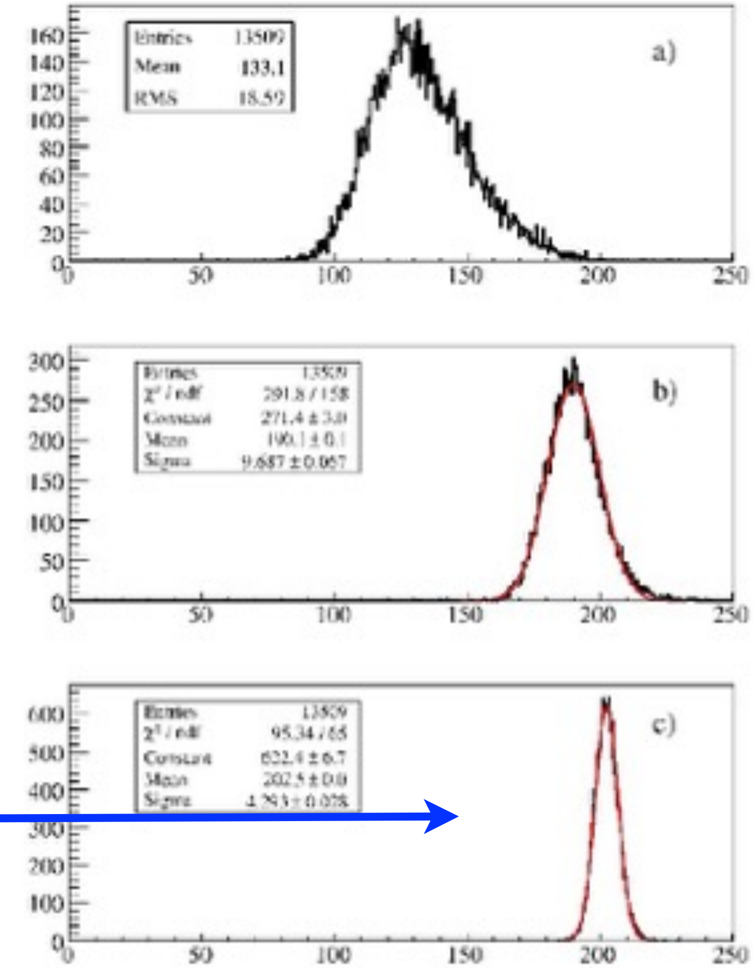
SPACAL 1989

Twenty tons of lead

Do we think this is possible?

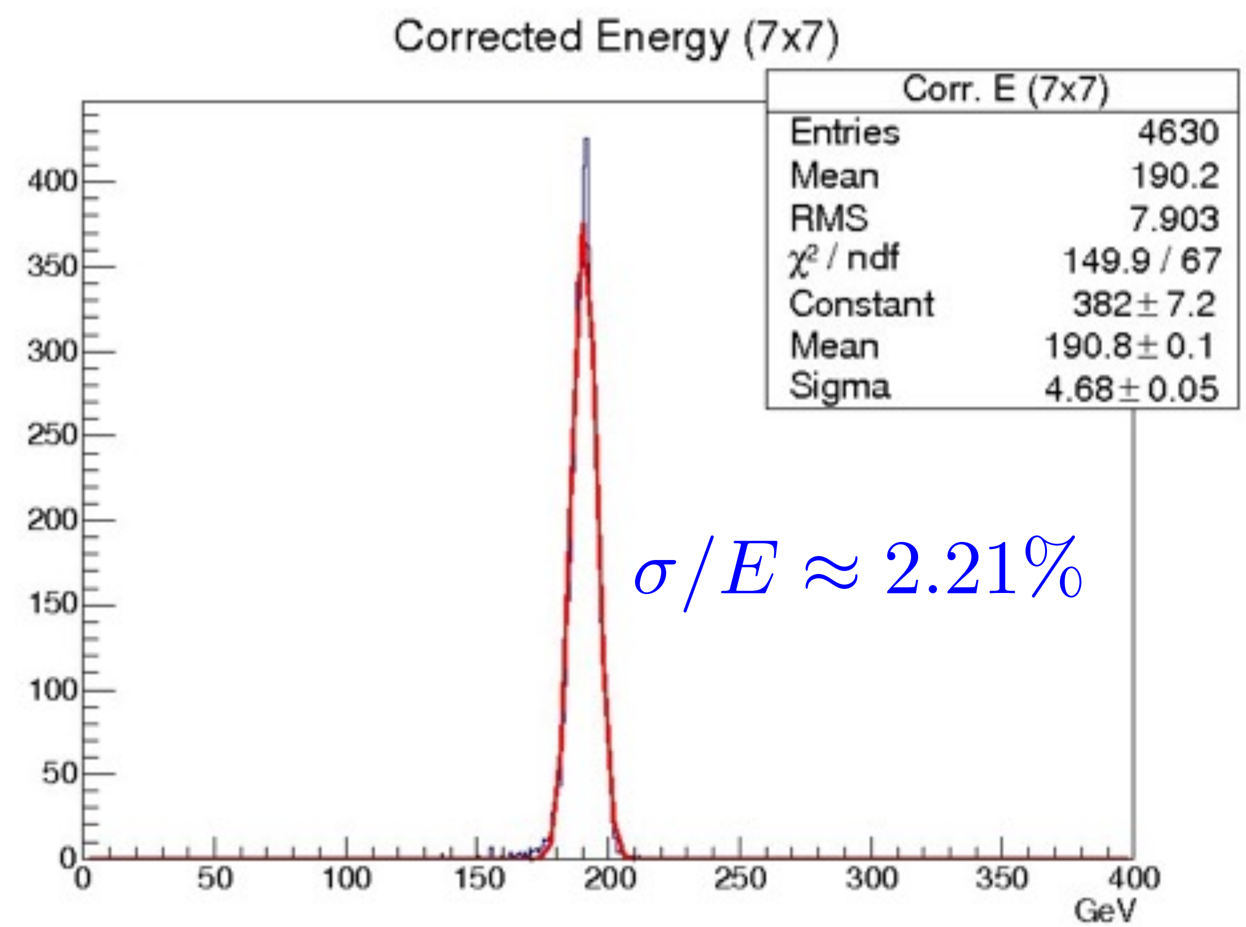
DREAM data

(leakage suppress using beam energy)



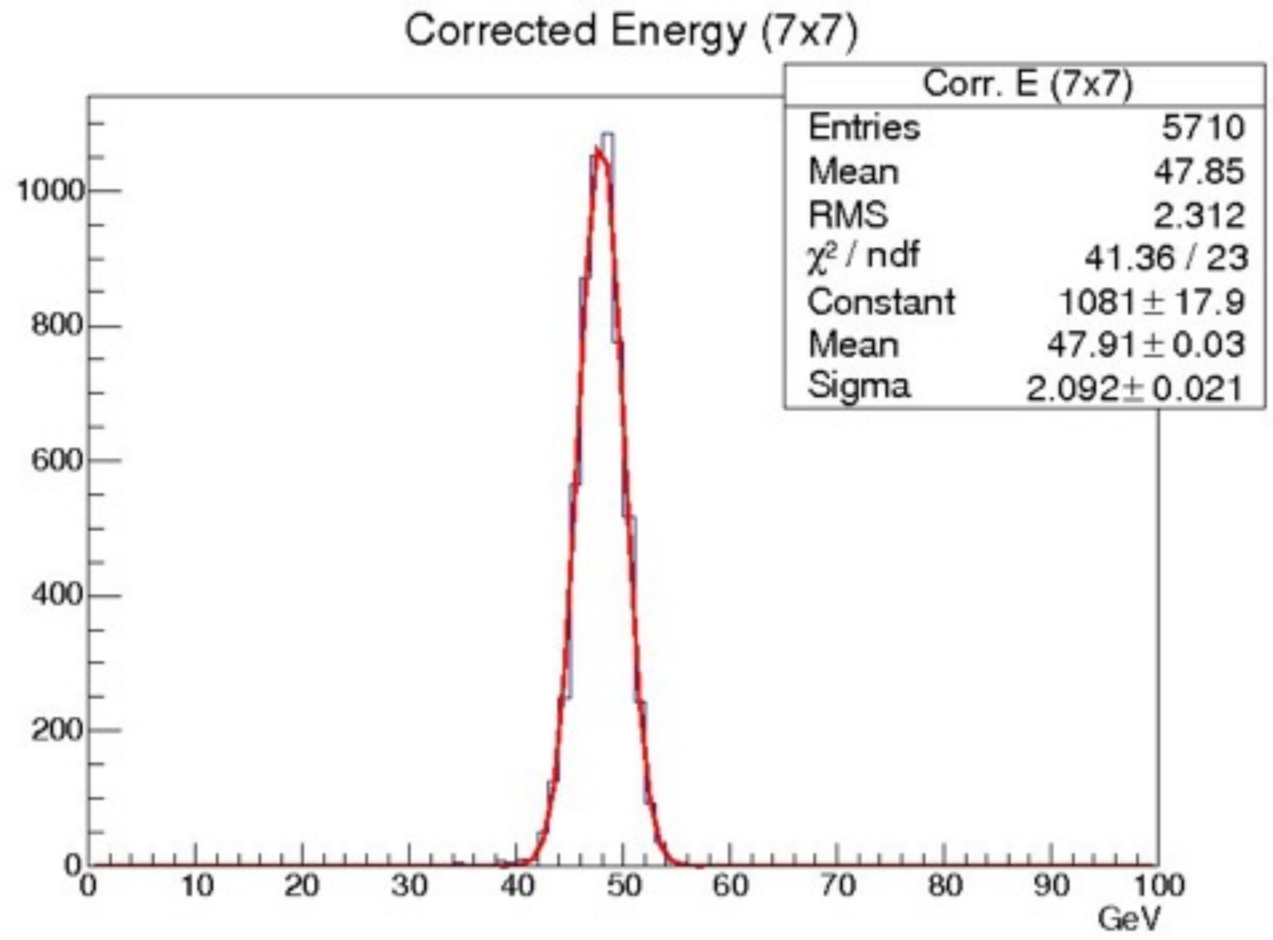
$\sigma/E \approx 30\%/\sqrt{E}$

GEANT simulation, HP means "high precision" which means the neutrons were treated more properly



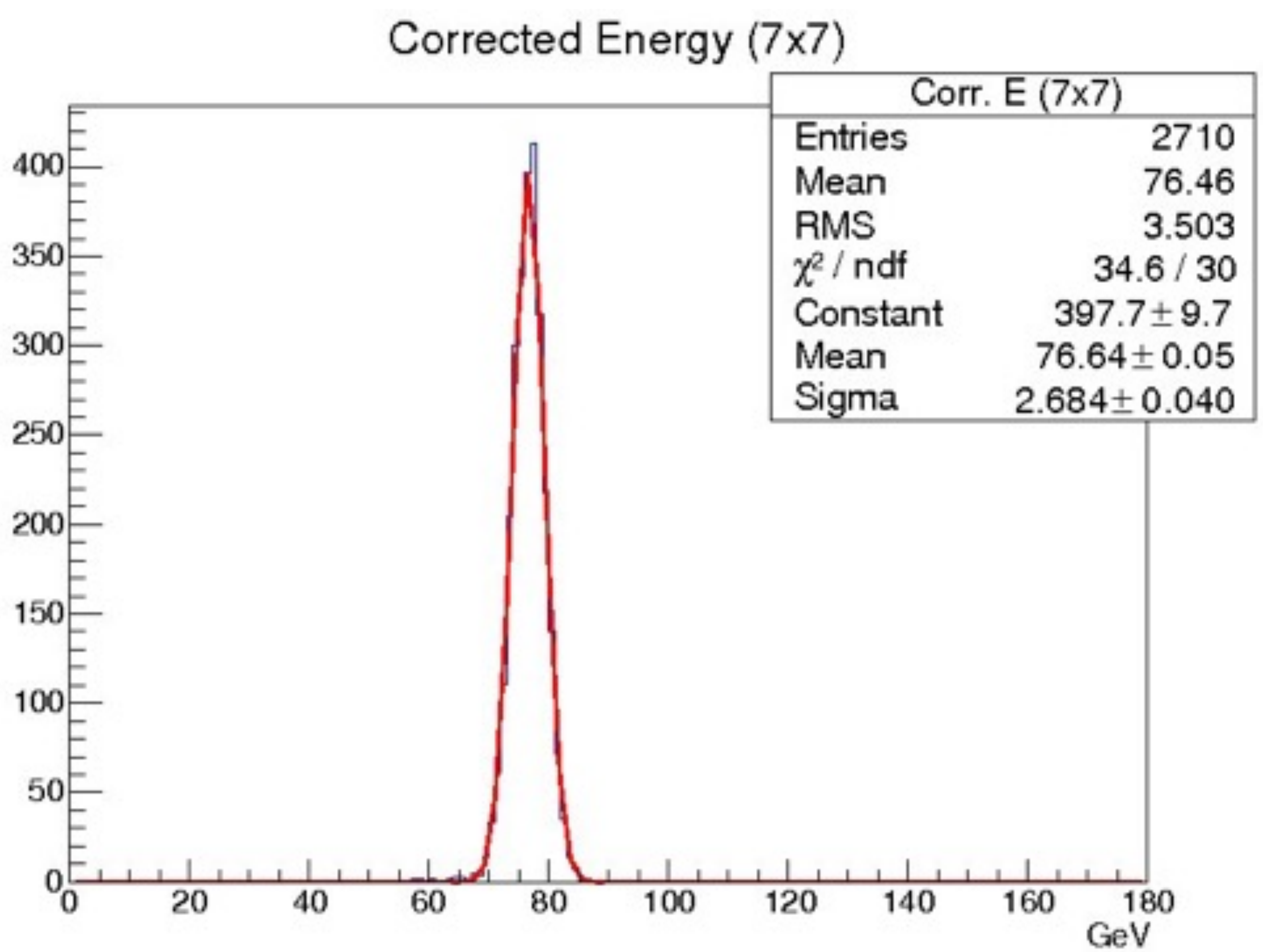
$\sigma/E \approx 2.21\%$

Figure 9: RD52 energy resolution.



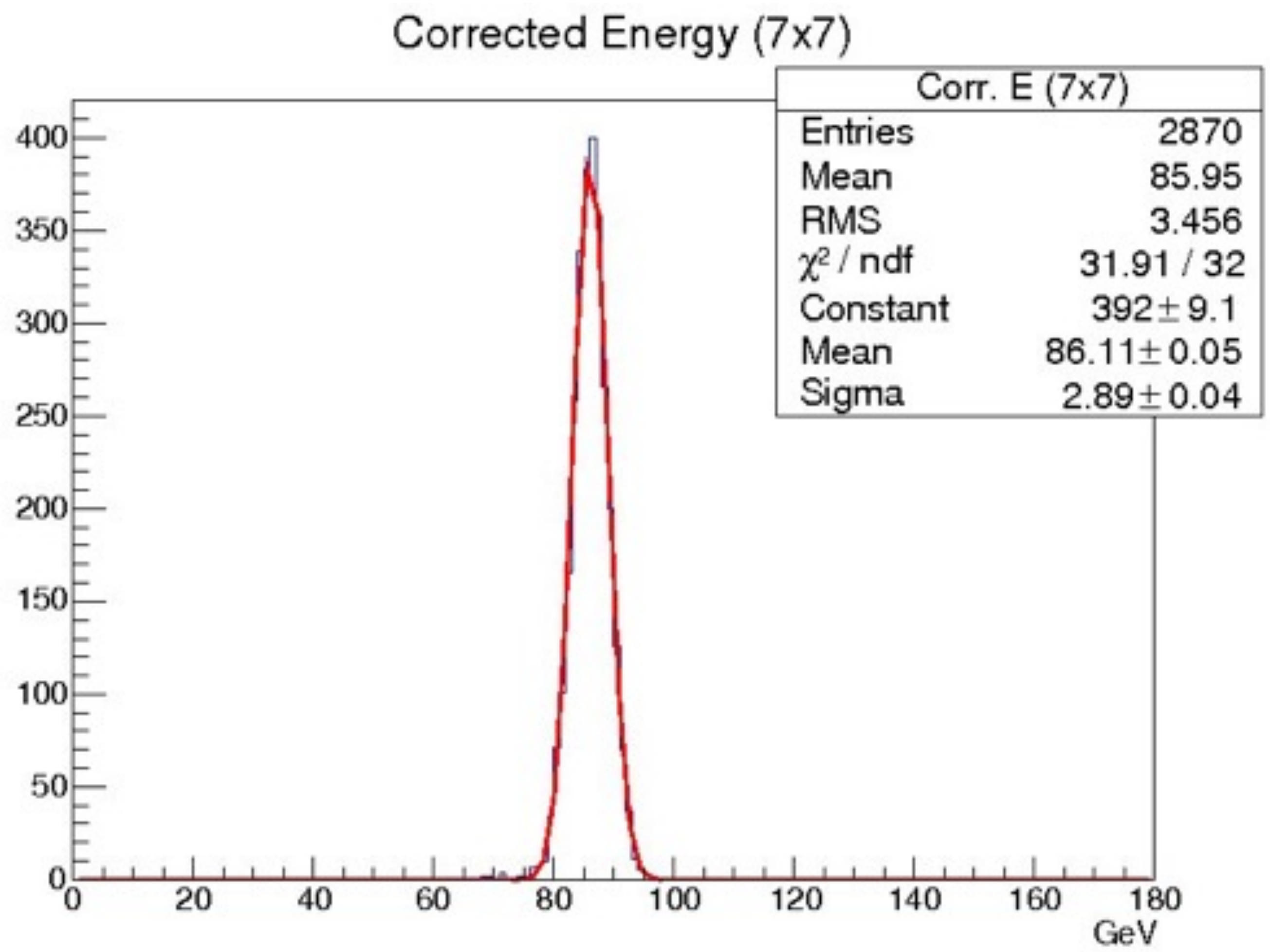
π^- 50 GeV

$\sigma/E \approx 4.36\%$



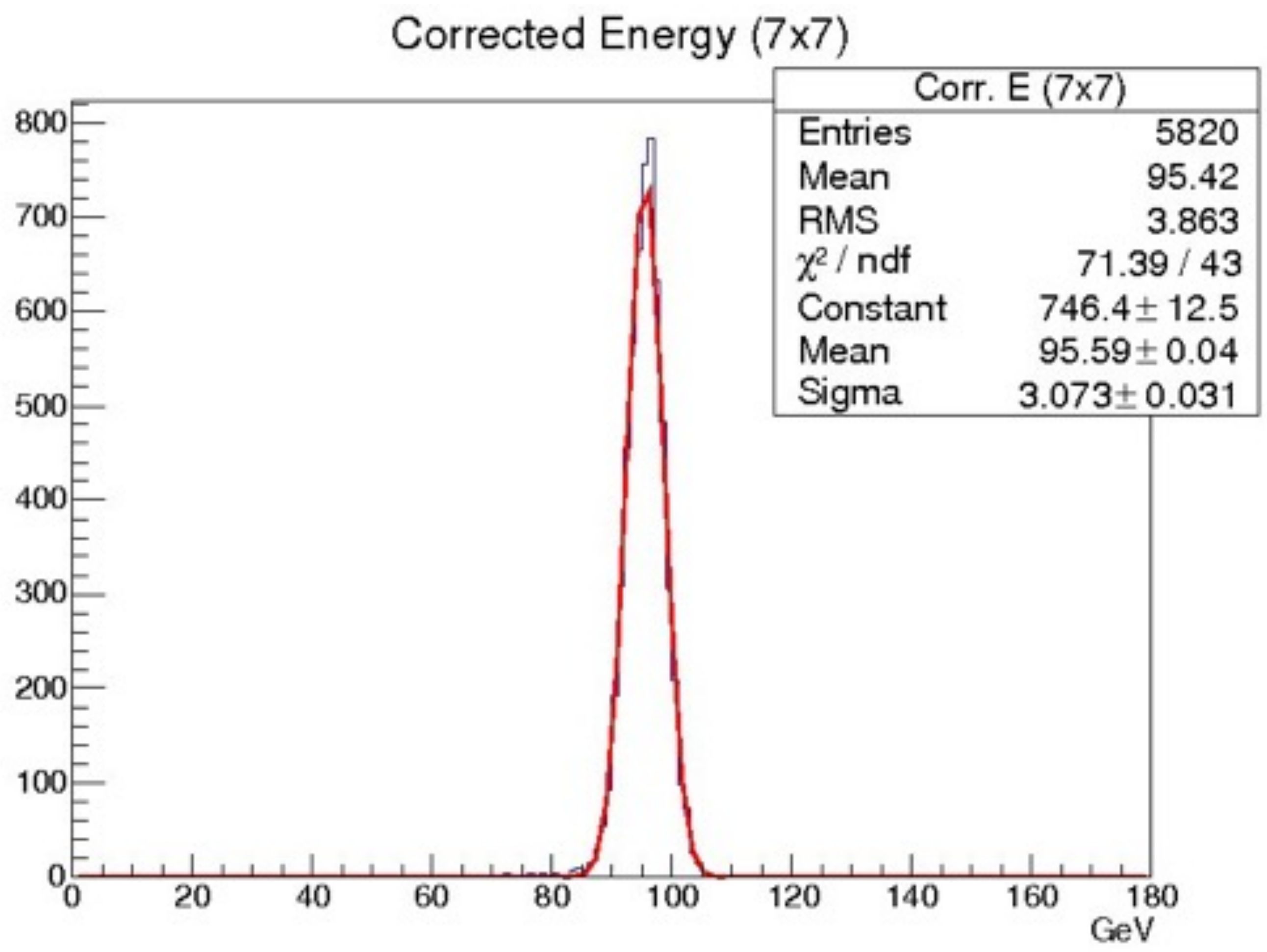
π^- 80 GeV

$\sigma/E \approx 3.50\%$



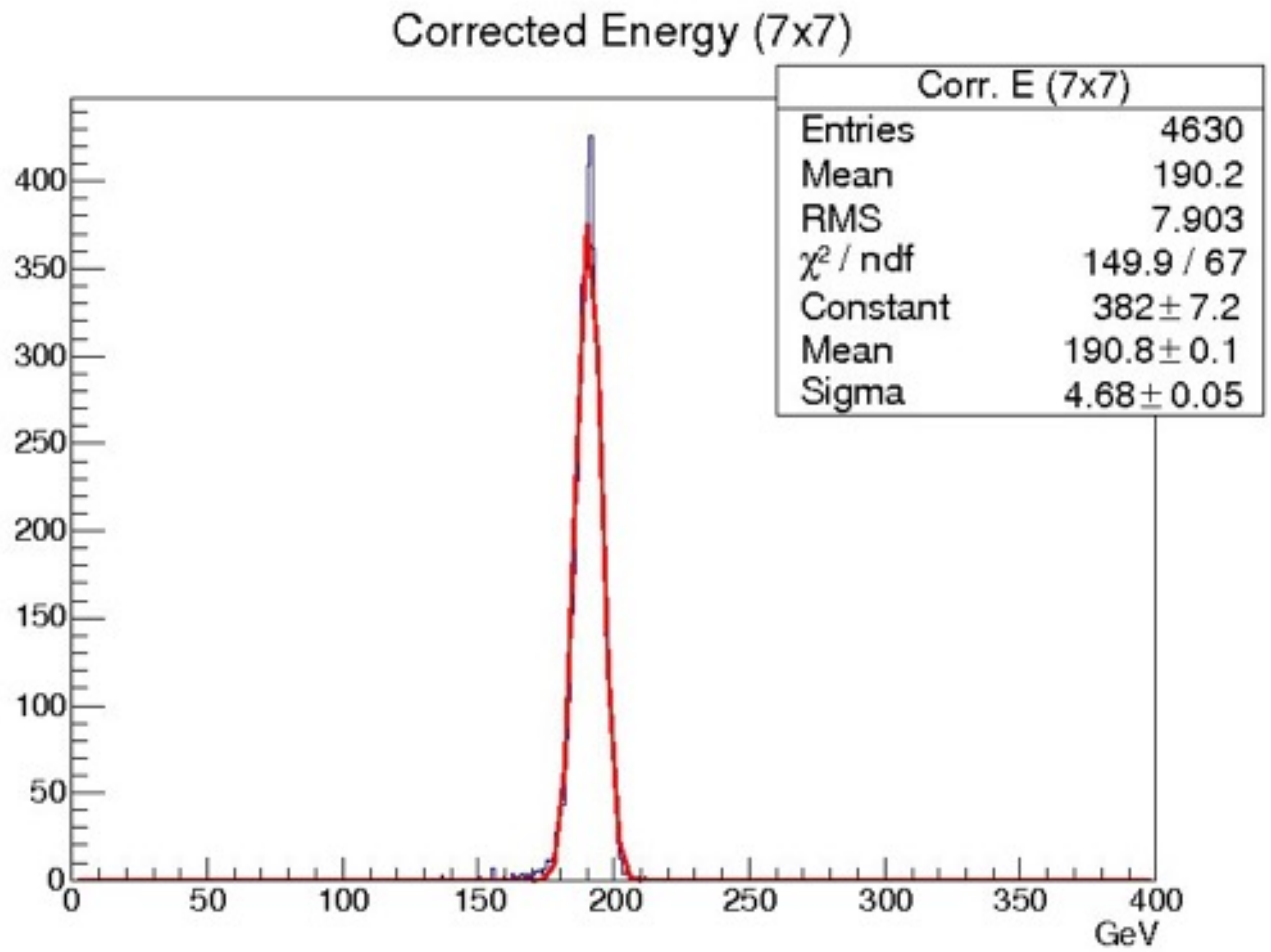
π^- 90 GeV

$\sigma/E \approx 3.36\%$



π^- 100 GeV

$\sigma/E \approx 3.21\%$



π^- 200 GeV

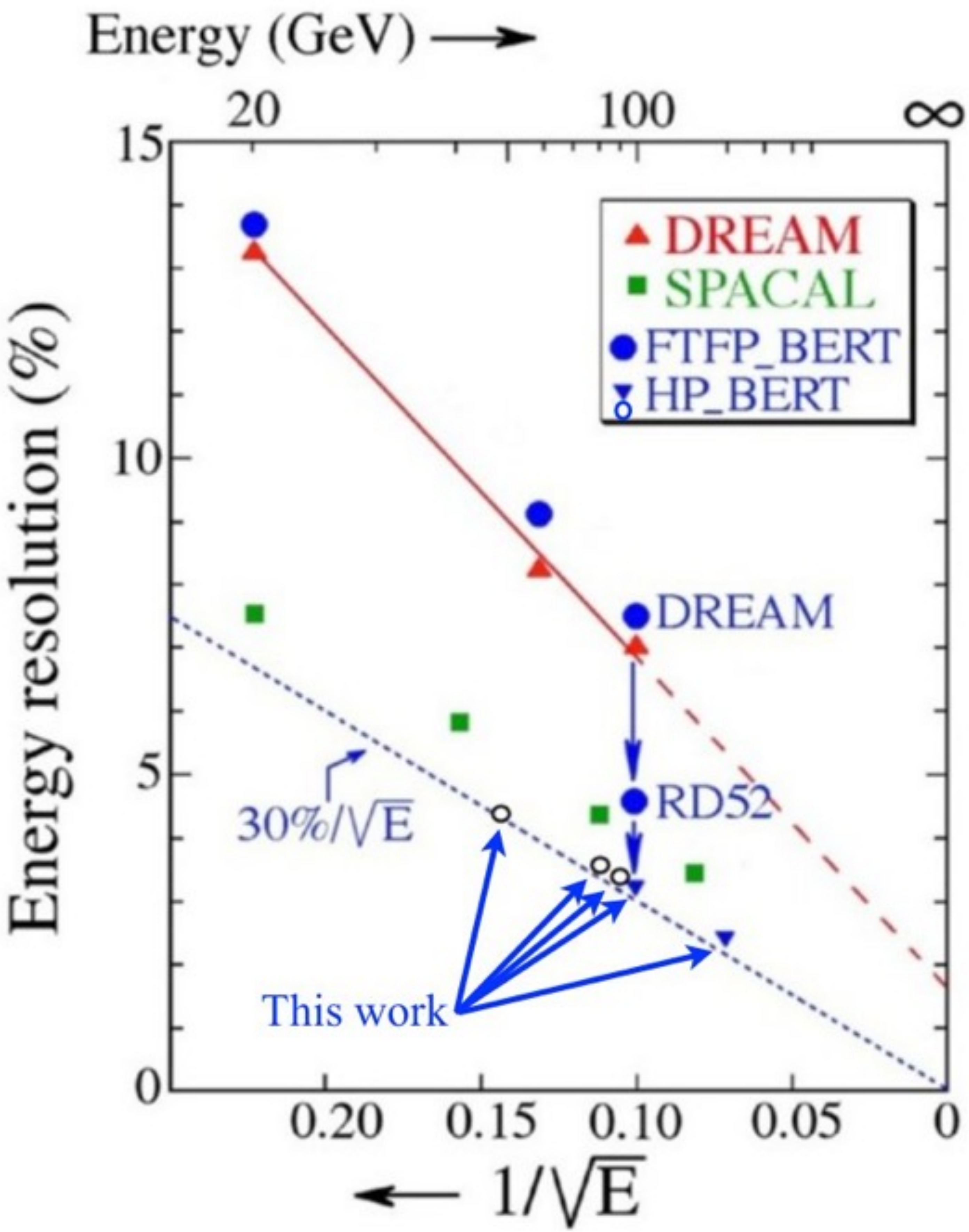
$\sigma/E \approx 2.45\%$ $(\rightarrow 2.21\%)$

Note well:

(1) all of these response functions are Gaussian

(2) no correction for leaked neutrons, etc.

(3) simple direct dual-readout

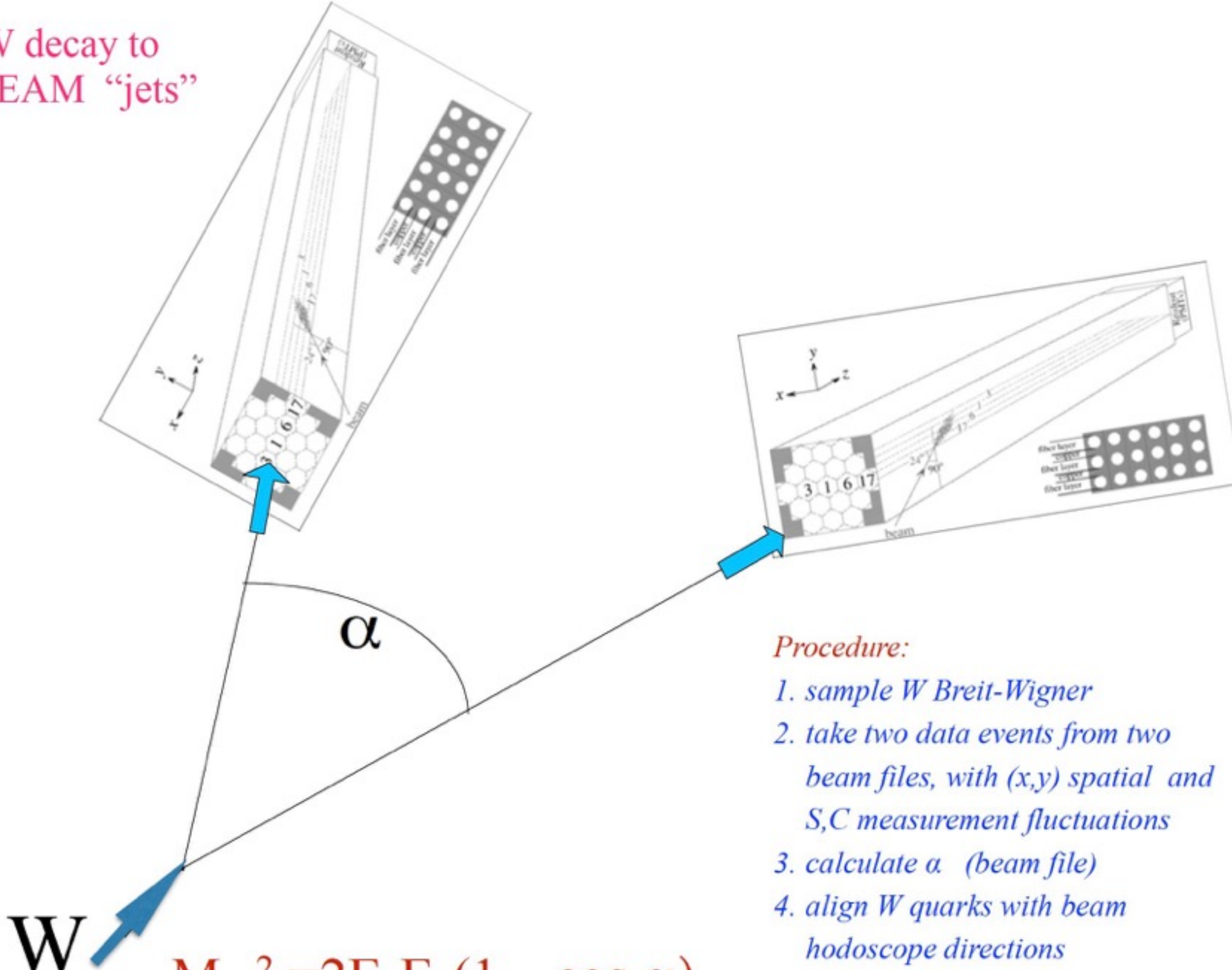


Dual-readout is close to achieving
(in GEANT high-precision simulation)

$$\sigma/E \approx 30\%/\sqrt{E}$$

Next step for us: built and test
a large (4t) copper module to test this.

W decay to DREAM “jets”



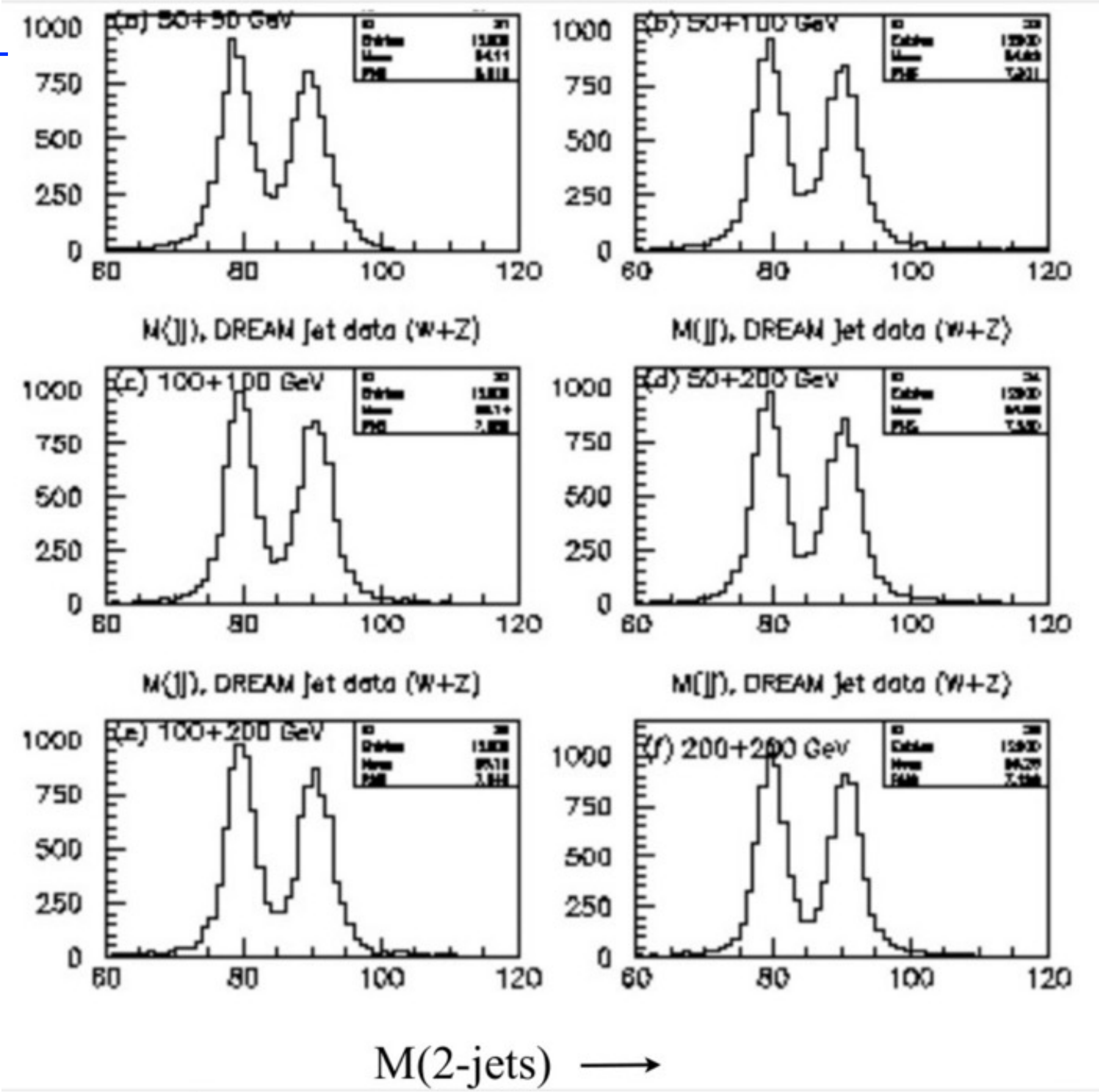
$$M_W^2 = 2E_1E_2(1 - \cos\alpha)$$

Procedure:

1. *sample W Breit-Wigner*
2. *take two data events from two beam files, with (x,y) spatial and S,C measurement fluctuations*
3. *calculate α (beam file)*
4. *align W quarks with beam hodoscope directions*
5. *calculate and plot di-”jet” mass*

This is the W and Z di-jet mass distribution you get from leakage-suppressed DREAM events:

$$\frac{\sigma_E}{E} \approx \frac{30\%}{\sqrt{E}}$$



This is really important, and we want to demonstrate this experimentally: *built a multi-ton module*

Do we think this is possible?

DREAM data

(leakage suppress using beam energy)

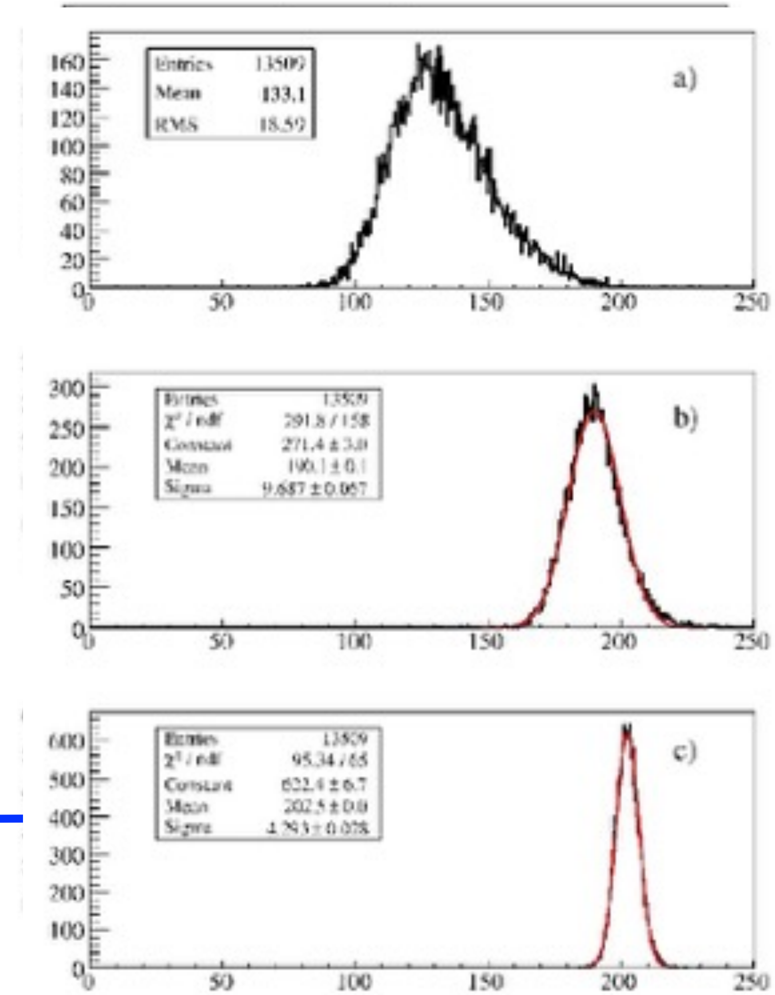


Figure 8: DREAM energy resolutions.

$E \approx 30\%/\sqrt{E}$

GEANT simulation, HP means "high precision" which means the neutrons were treated more properly

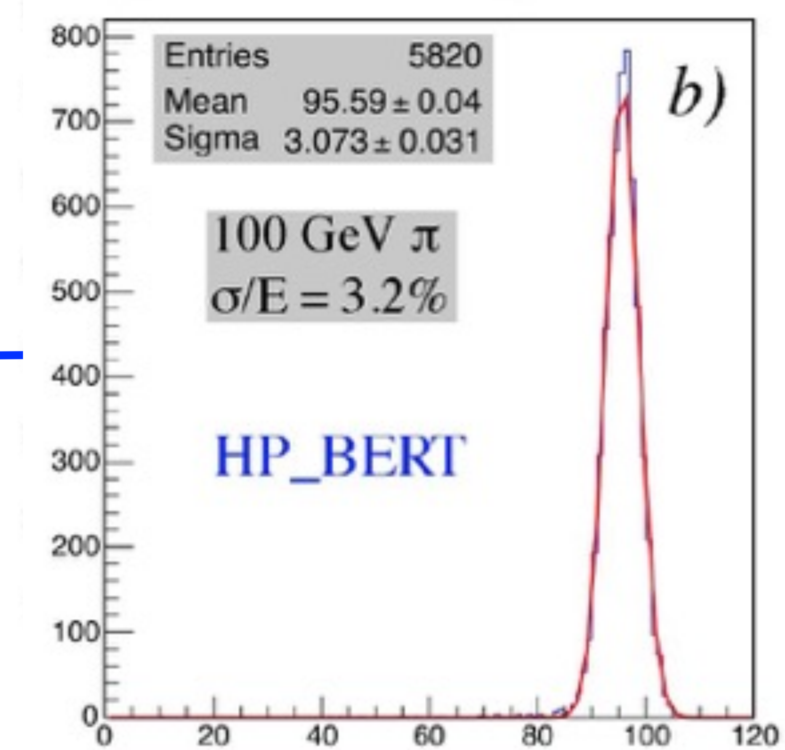
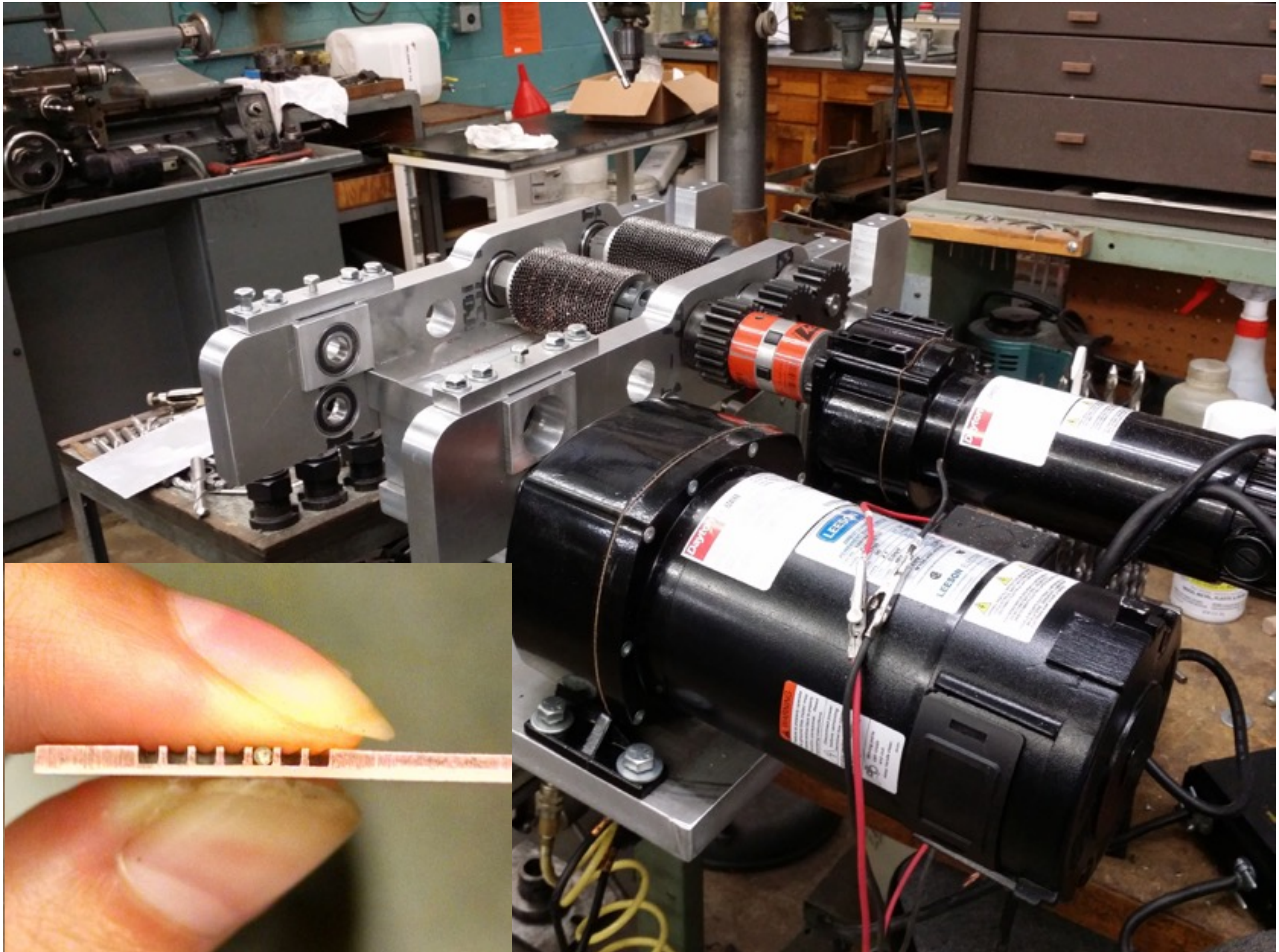


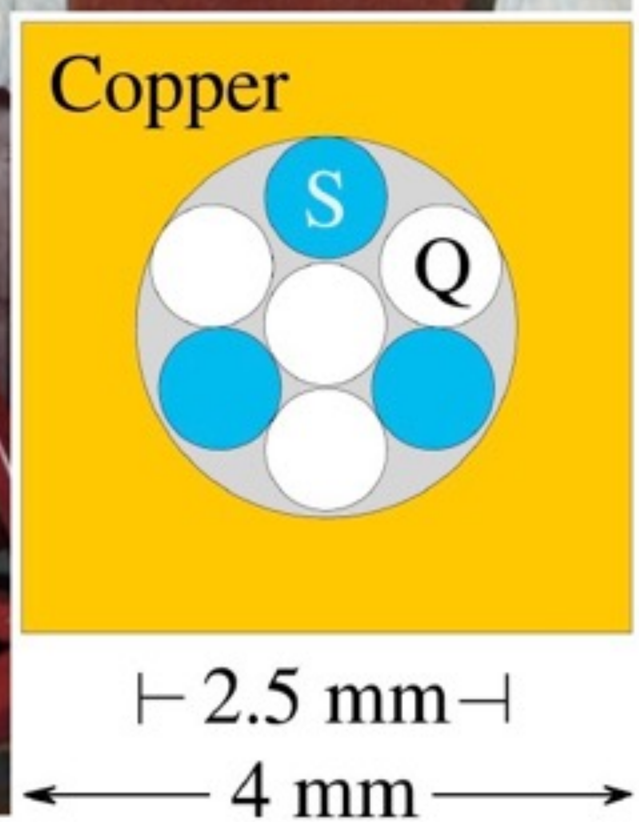
Figure 9: RD52 energy resolution.

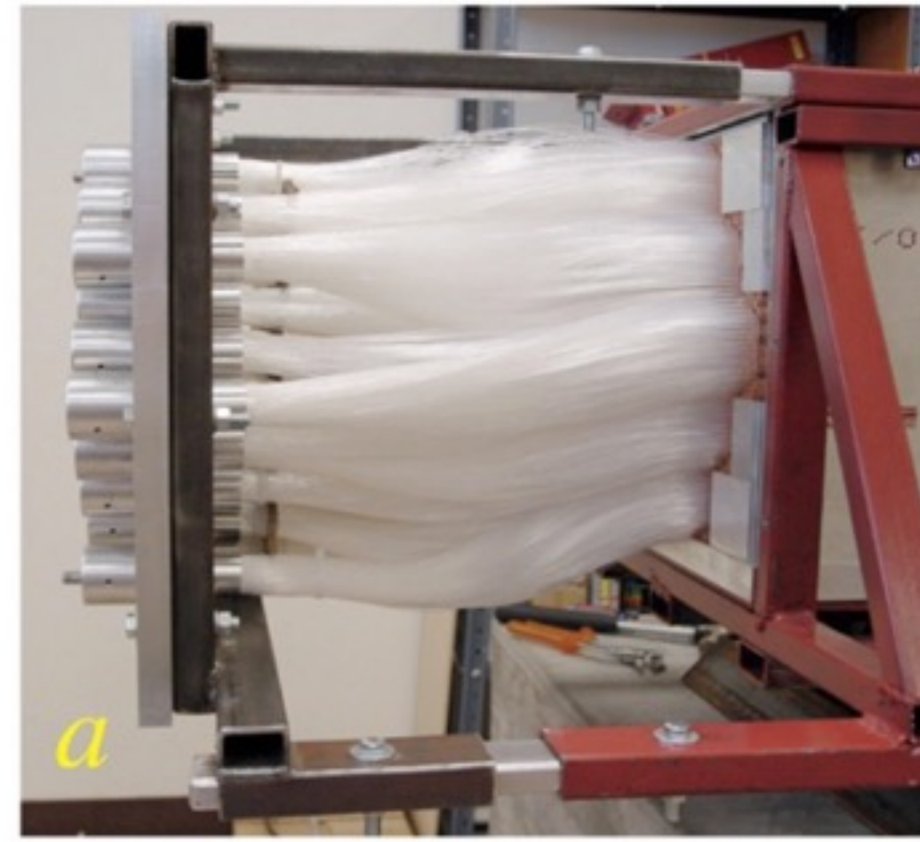
$/E \approx 32\%/\sqrt{E}$

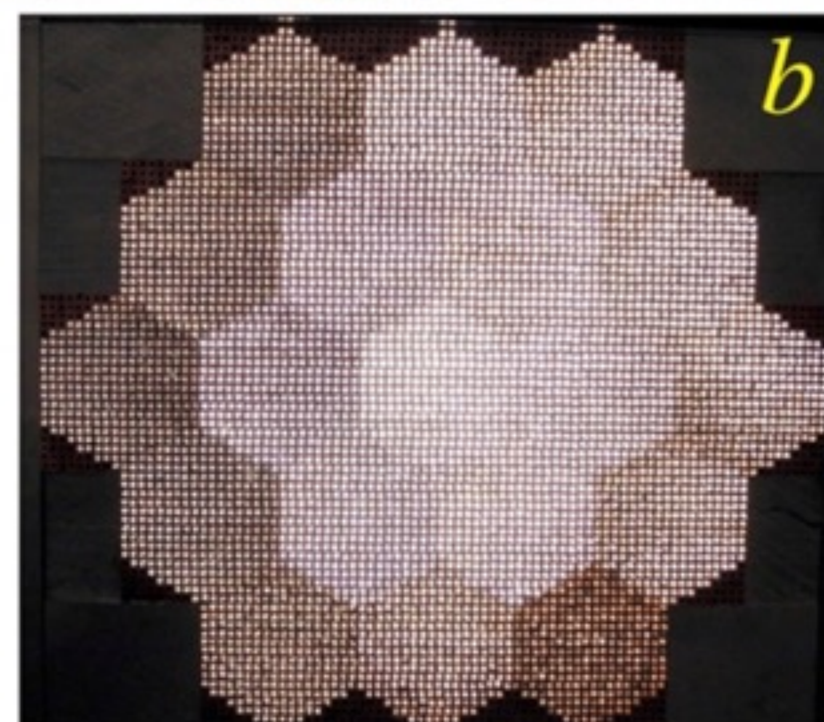
Produce our own copper absorber plates: load with fibers (try square fibers)



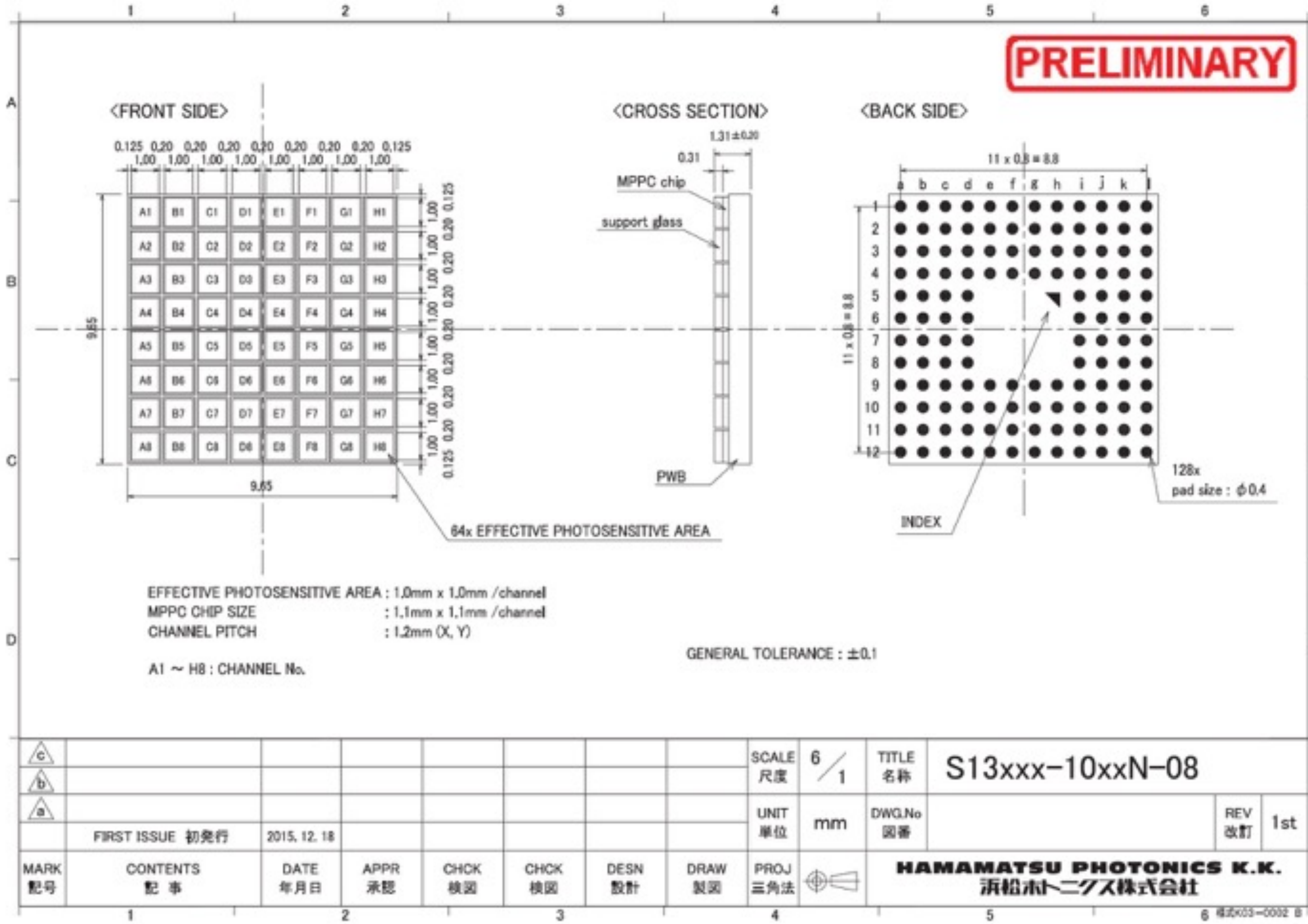
DREAM module,
“proof-of-principle”





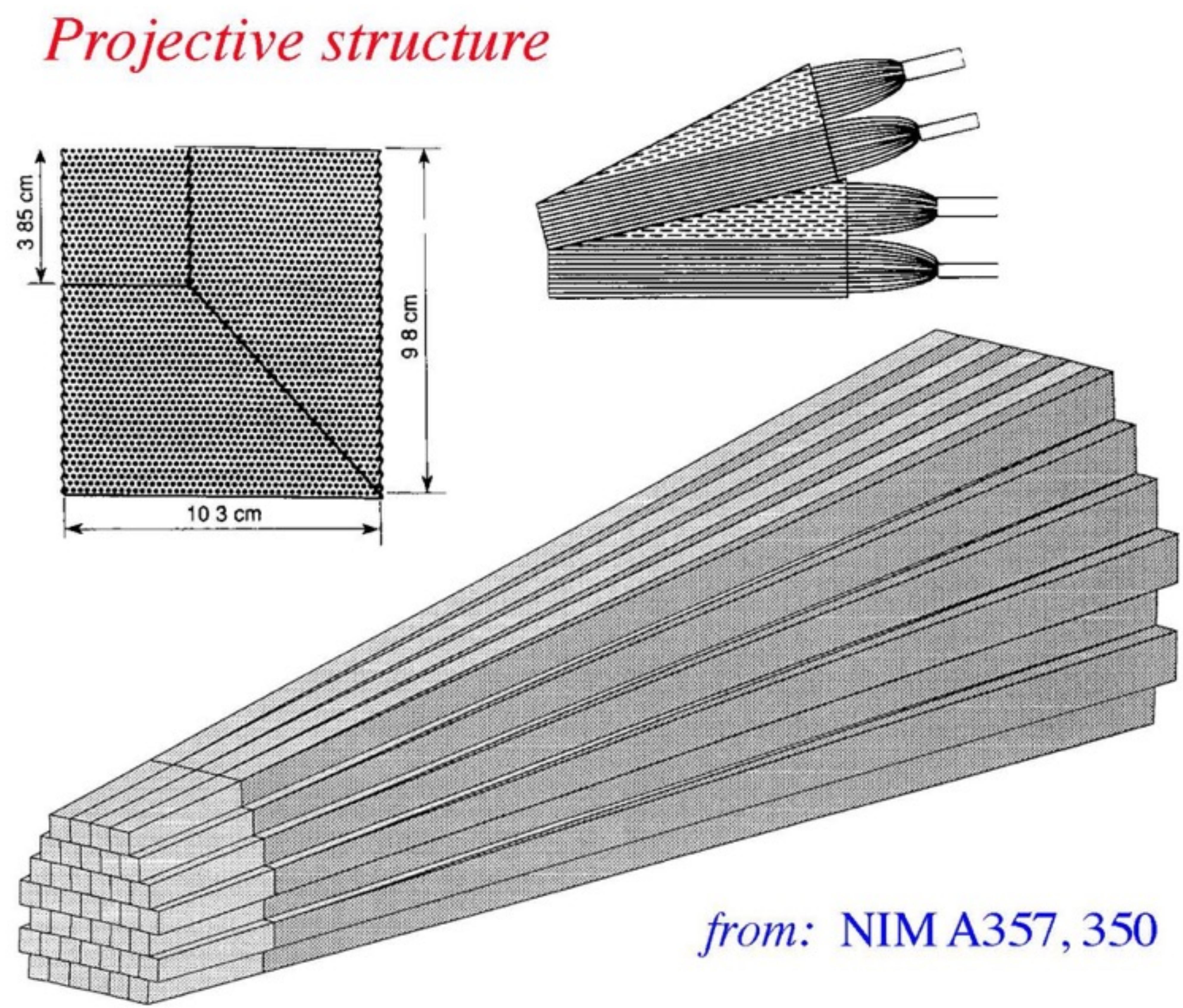


We will test one fiber per SiPM pixel: the ultimate in transverse granularity



The CAEN DRS4 at 5 GHz gives us 4 cm longitudinal segmentation: one physical channel!

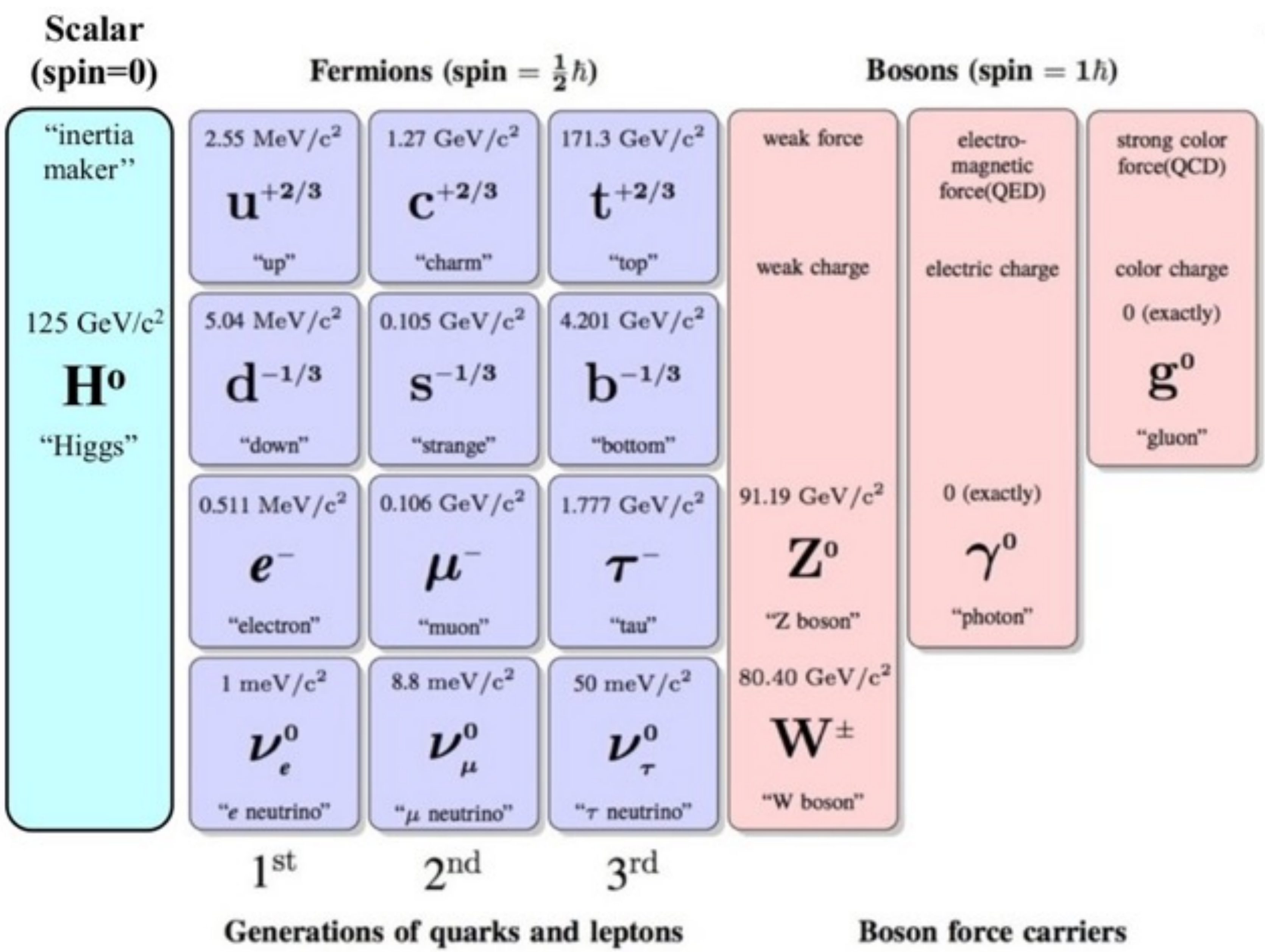
We did this in GEANT, now we just have to do it in copper.



from: NIM A357, 350

"Unification of experimental resolutions" near 2% for all the partons of the Standard Model

This is a scientific goal worthy of the next big collider



We would be most happy for you at IHEP and Tsinghua University to join RD52 as major participants in this interesting instrumentation program.

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or
hauptman@iastate.edu

IEEE

IEEE Nuclear and Plasma Sciences Society

takes pleasure in presenting the

2012 Radiation Instrumentation Outstanding Achievement Award

to

Richard Wigmans

For original and profound contributions to high energy physics calorimetry, in particular hadronic calorimetry, including compensating and dual-readout calorimeters, novel geometries, and the education of young colleagues.

Edward J. Lampo
Chairperson,
Radiation Instrumentation Steering Committee

Sara Pozzi
Chairperson,
NPSS Honors and Awards Committee

2012 IEEE RADIATION INSTRUMENTATION OUTSTANDING ACHIEVEMENT AWARD
October 30, 2012

Dear colleagues,

I would like to thank all of you who have sent me your congratulations with the IEEE Outstanding Achievement award I will receive at the NSS symposium two months from now. I know that some of you have actually been instrumental in achieving that the award committee came to this decision, and I would like to thank those colleagues in particular.

I have never been someone who is interested in pursuing personal glory for my work, but I must admit that it was a very nice surprise to discover that my colleagues appreciate it to such an extent that they put in the effort that led to this result.

I also want to say that, even though this is a personal award, I consider it very much a recognition for the work we have done together over the years on projects such as SPACAL and RD52. Without the work done by the very talented and committed collaborators I have had the pleasure working with over the years, this award would not be justified. So please consider this also first and foremost a sign of appreciation of the scientific community for the things we have accomplished TOGETHER.

I am looking forward to our continuing collaboration in the context of RD52.
Kind regards, and all the best

Richard

RD52 - CERN Project - http://highenergy.phys.ttu.edu/dream

"Dual-Readout Calorimetry for High Quality Energy Measurement"

Goal is a fundamental understanding of hadronic calorimetry and the achievement of 1-2% energy resolution at high energy.

1. Build 4-6 tons of Cu-fiber Pisa-like modules
   * reduce leakage fluctuations down to ~1%.
   * pay close attention to optics

2. Reduce fiber antenna by using SiMs directly onto fibers
   * reduces backgrounds
   * OK in magnetic field

3. Build and test "projective" fiber modules
   * buildable large detector

Thank you for your attention.