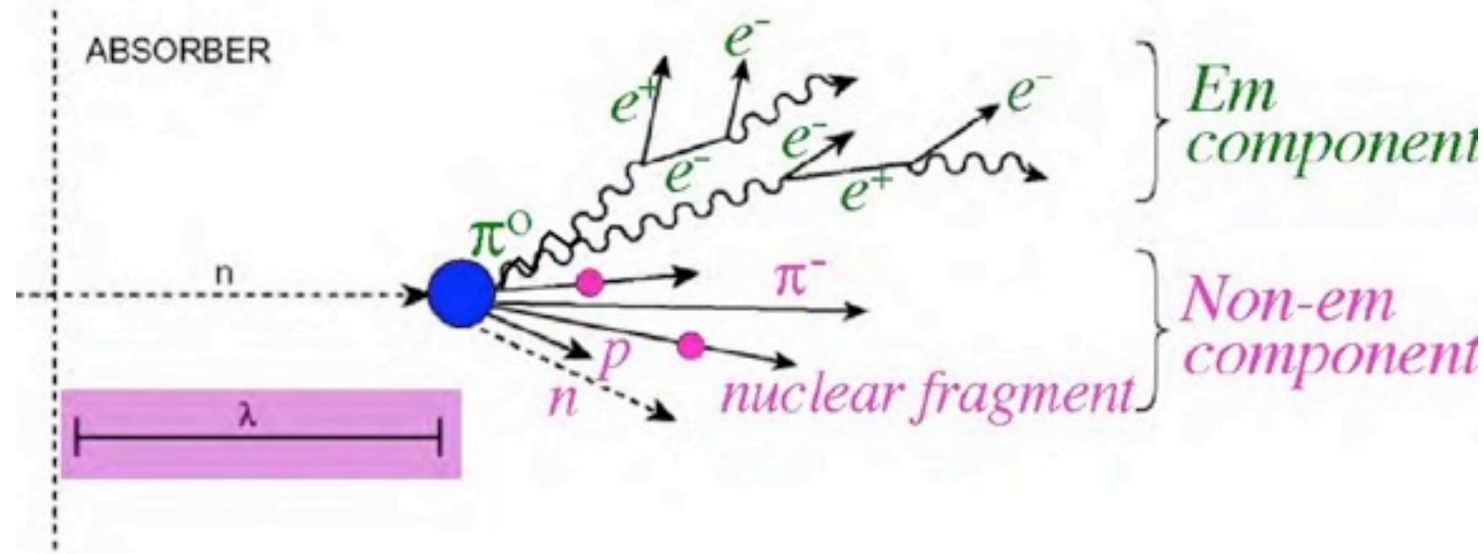
Hadronic Calorimetry - fsPHENIX meeting

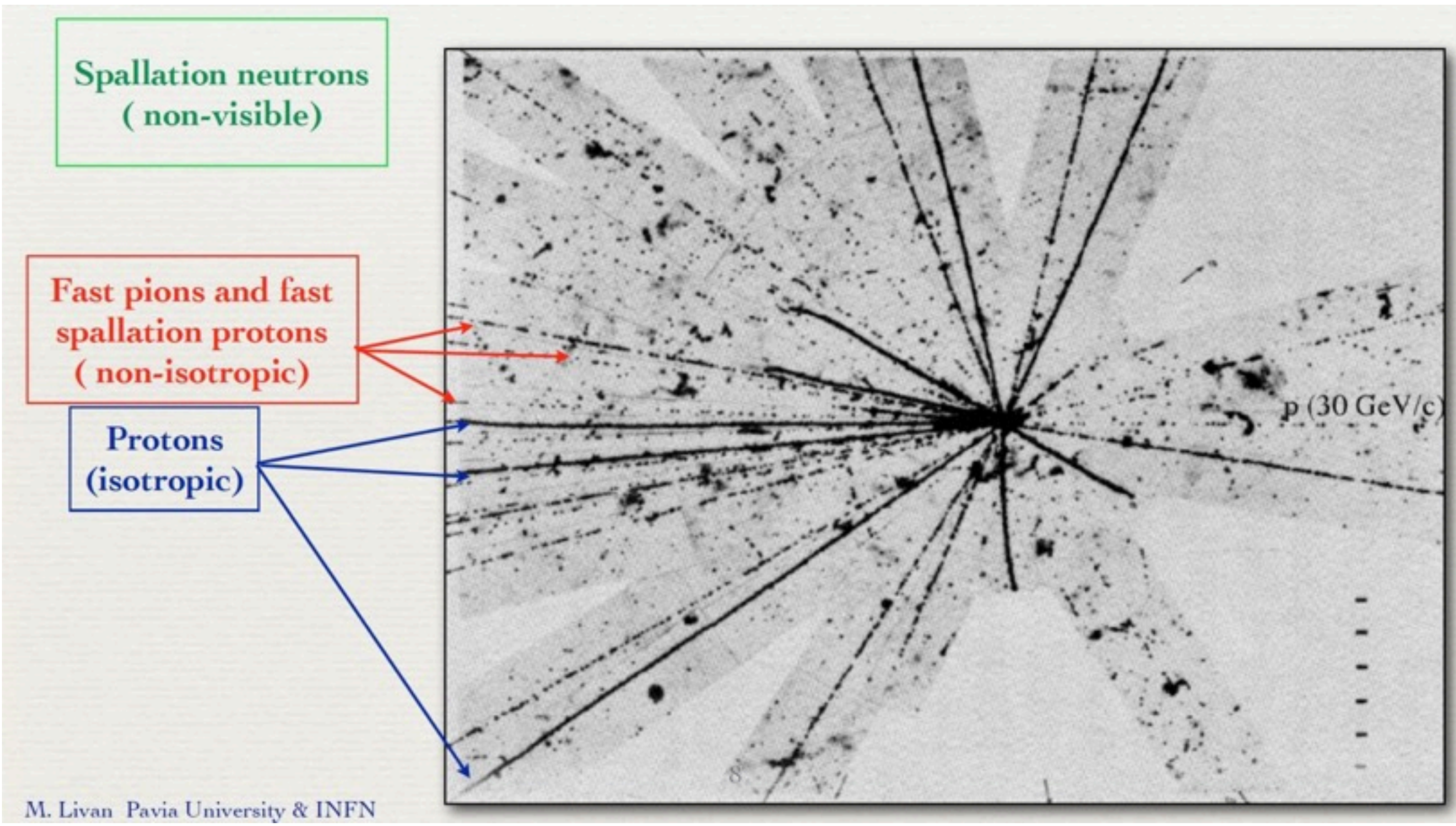
John Hauptman, ISU (DREAM, RD52), 12 March 2016

No need to lecture seasoned experts here.

- Why it's hard
- Dual-readout - DREAM
- What we've learned - RD52
- Where I think we will end up

Interactions of hadrons with nuclei have huge fluctuations in π^0 relative to π^+ and π^-, and huge fluctuations in binding energy losses from nuclear break-up.





Fluctuations in π^0 production,

especially in the first nuclear interaction, result in fluctuations in the "electromagnetic fraction," f_{EM}, and the mean f_{EM} grows with energy:

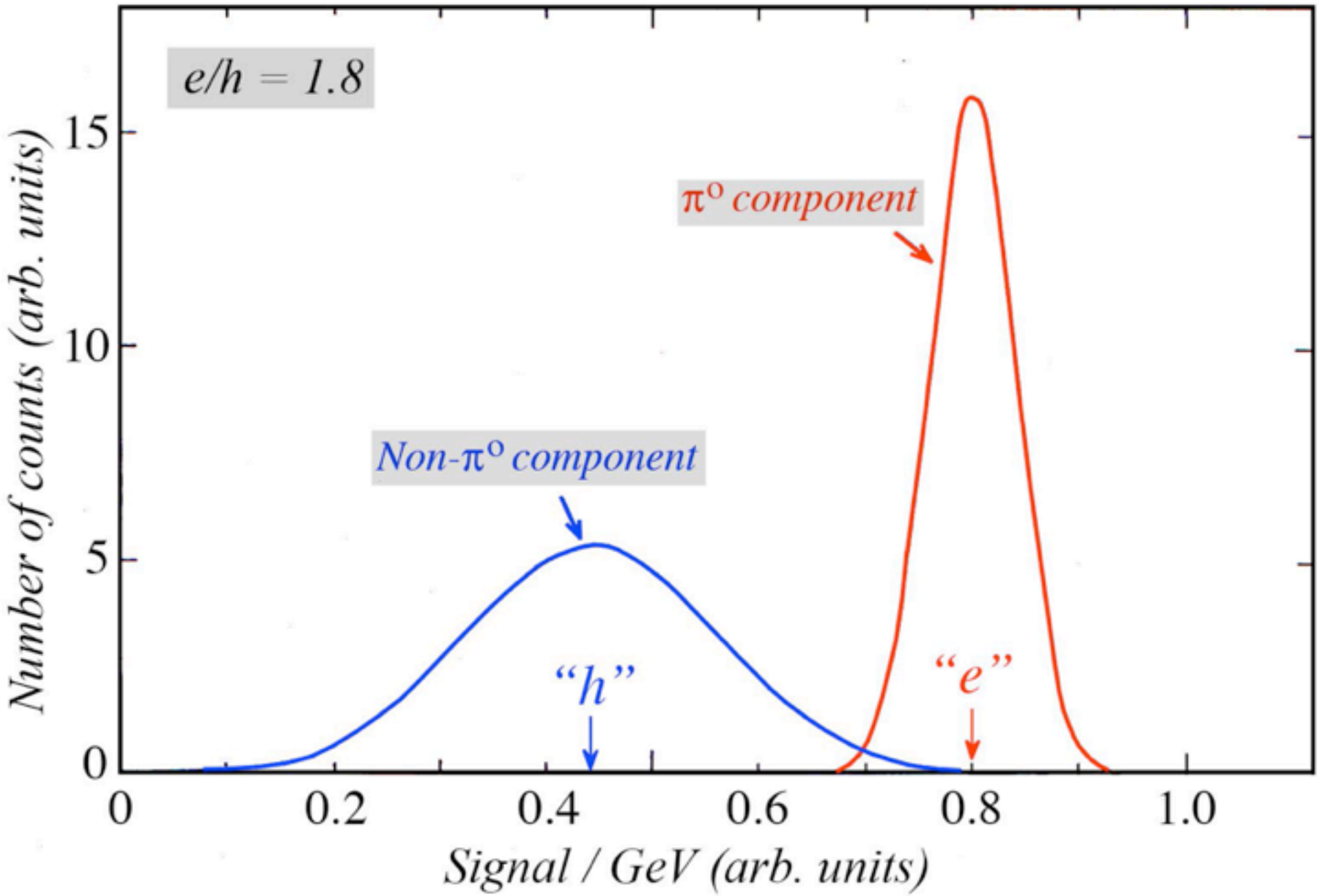
- energy resolution is poor
- mean response with energy is non-linear
- response function is non-Gaussian

Fluctuations in nuclear break-up

result in fluctuations in binding energy losses, liberated neutrons, the "neutron fraction," f_n.

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

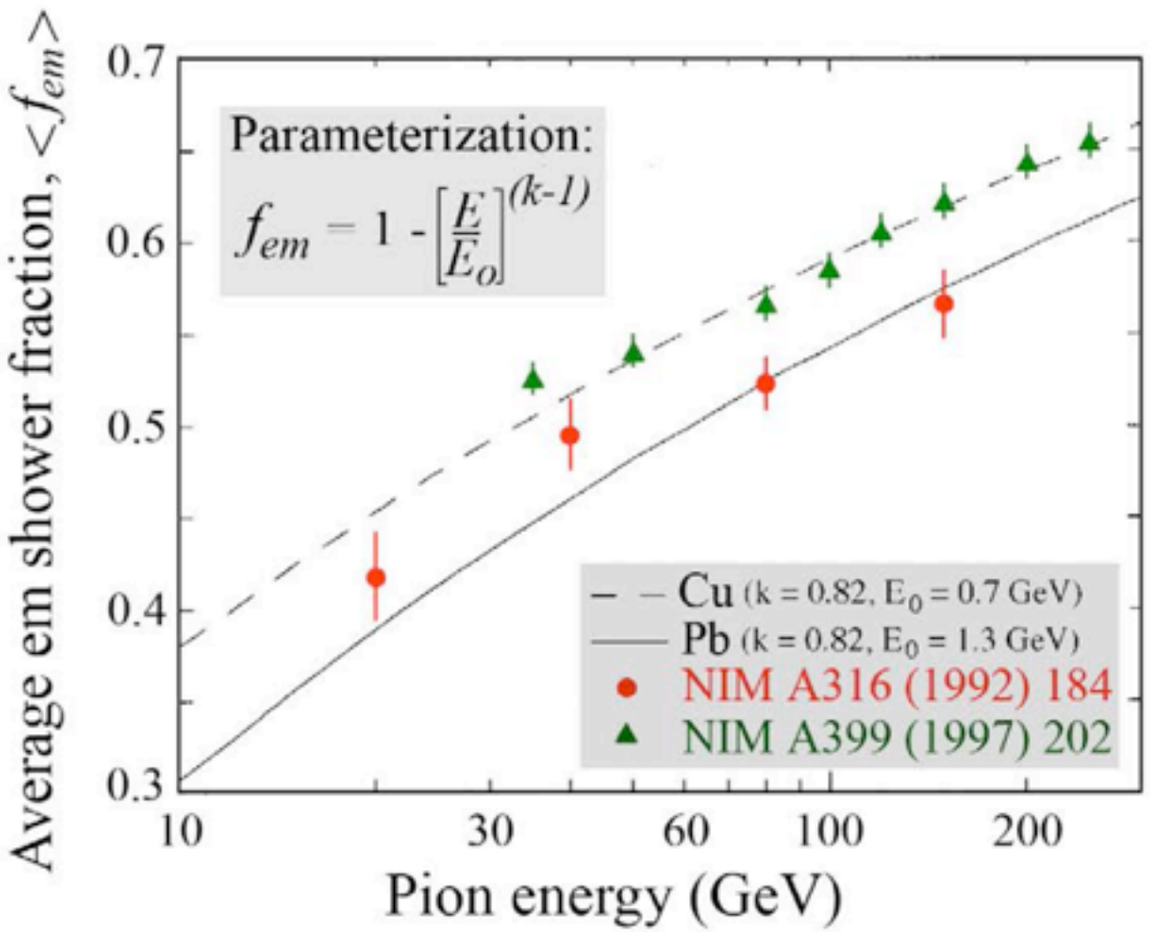
(mainly because of nuclear breakup energy losses in non-π^0 component)

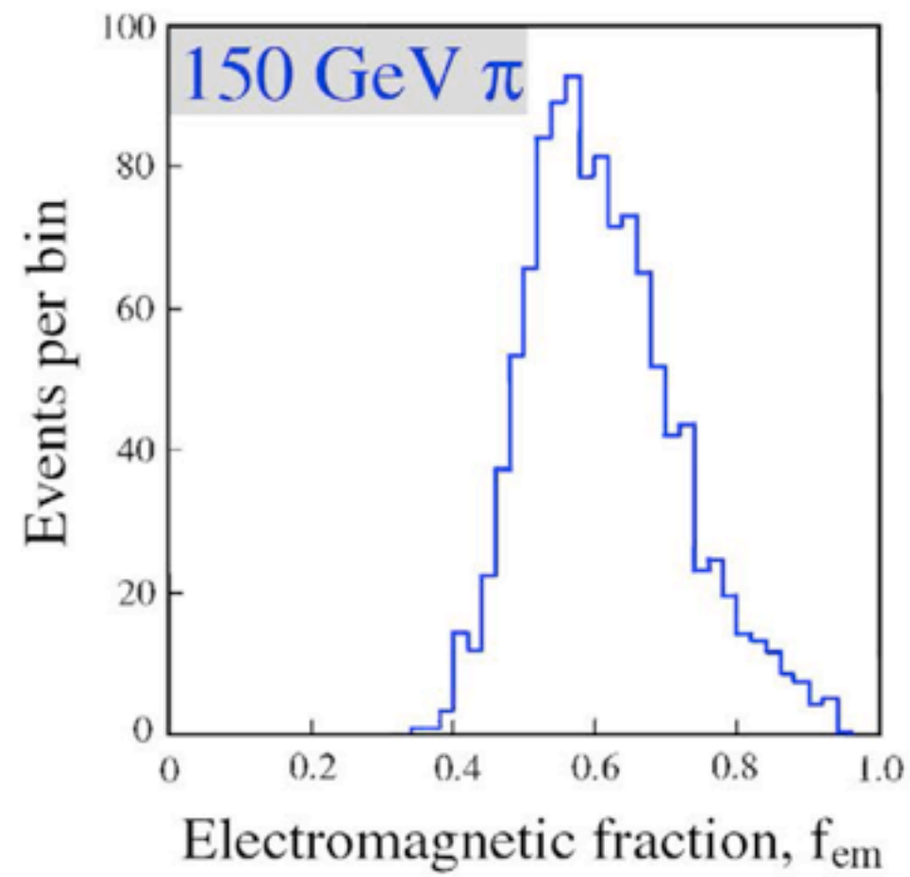


"e/h">1

(Fluctuations in) the electromagnetic shower fraction, f_{em}

i.e. the fraction of the shower energy deposited by π^os





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

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

Make $e=h$, $e/h=1$ (by design, "compensation")

(1) make e smaller
(saturation, suppress high density signals)

(2) make h larger
(detect neutrons through np-->np in hydrogenous medium, e.g. plastic scintillator)

The special role of neutrons in calorimetry

In calorimeters with hydrogenous active material, neutrons lose a major fraction of their kinetic energy through elastic *n-p* scattering in that material.

The recoil protons may contribute to the signals.

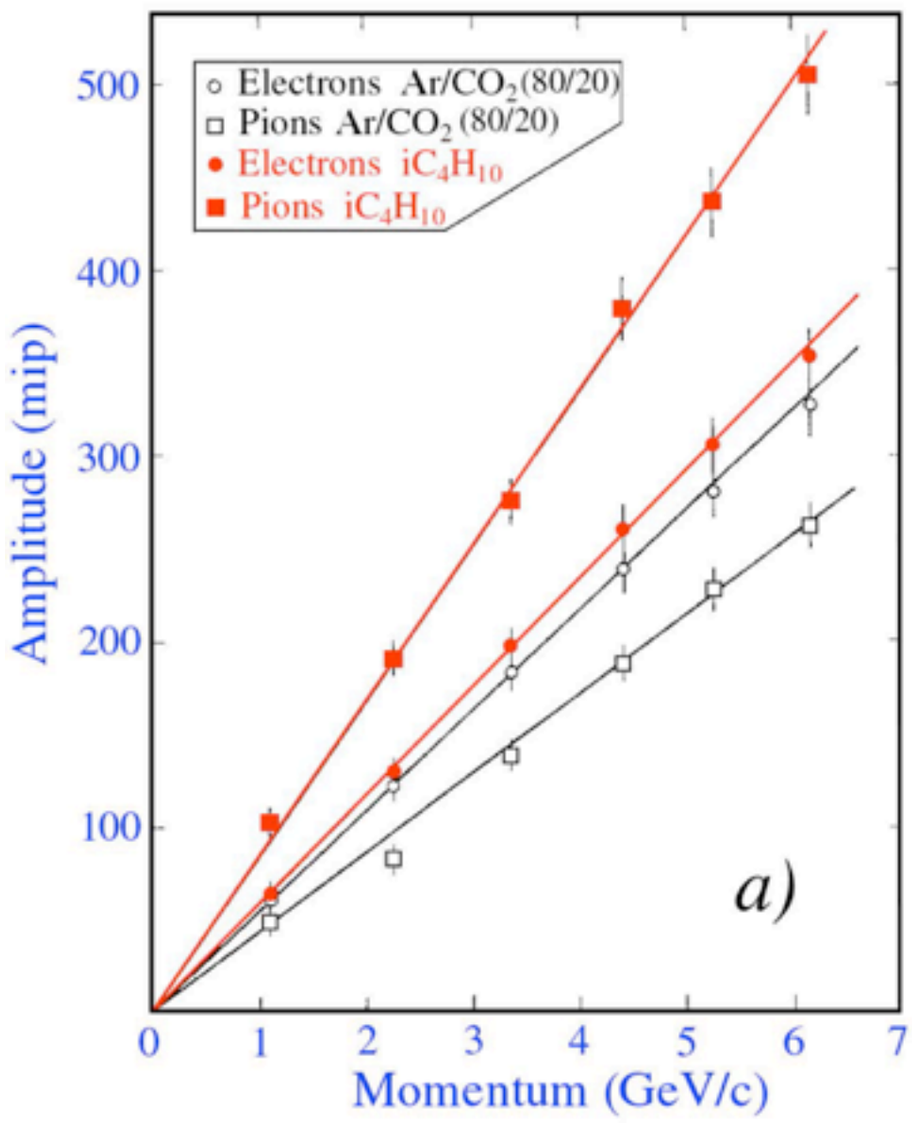
Therefore, the *neutron component may be very efficiently sampled* in such calorimeters. The sampling fraction may be much larger than for the other shower particles .
This is the key element of *compensation* ($e/h = 1$).

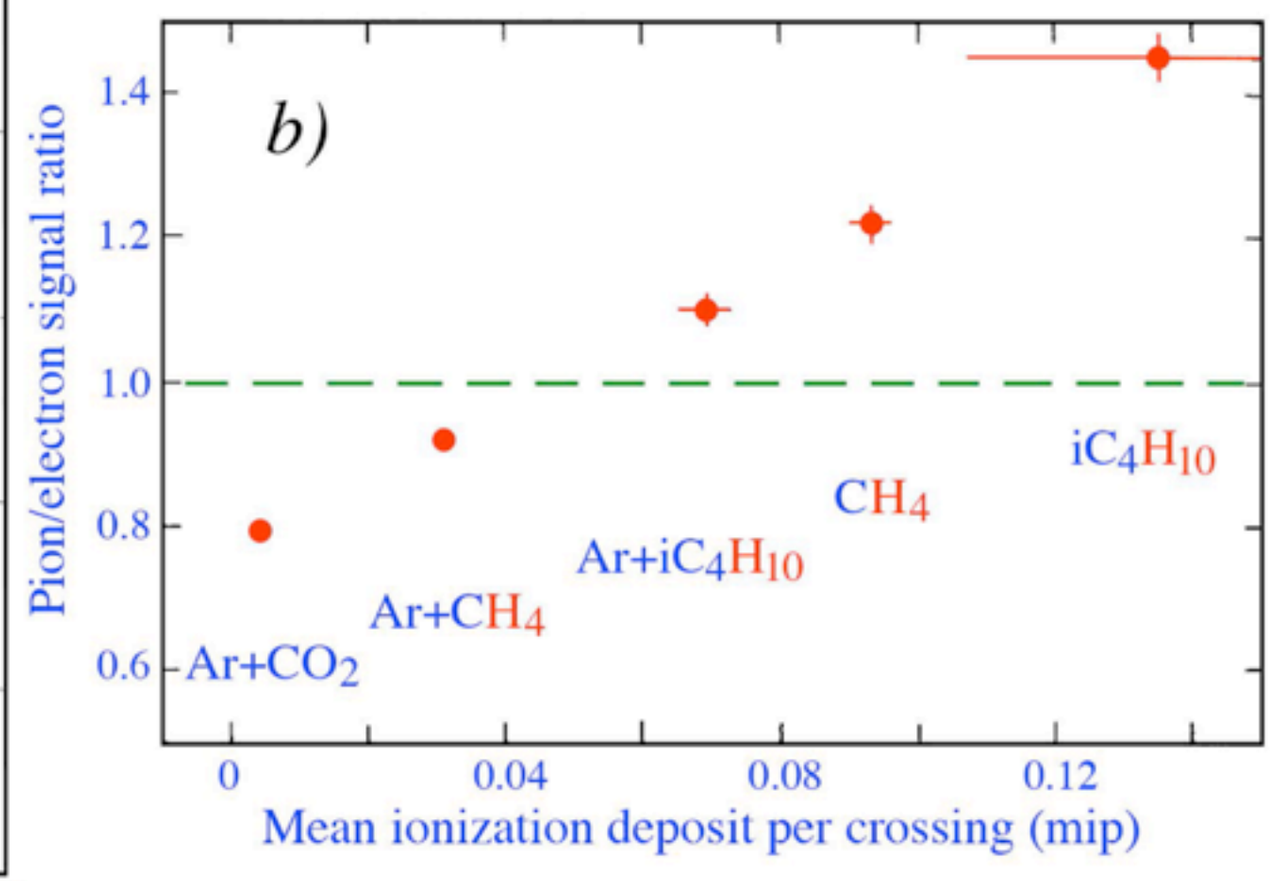
In addition, the total kinetic energy of the neutrons is strongly correlated with the lost nuclear binding energy.
Therefore, efficient neutron detection is crucial for reducing the contribution of fluctuations in "invisible energy" to the resolution.

The compensation puzzle solved!

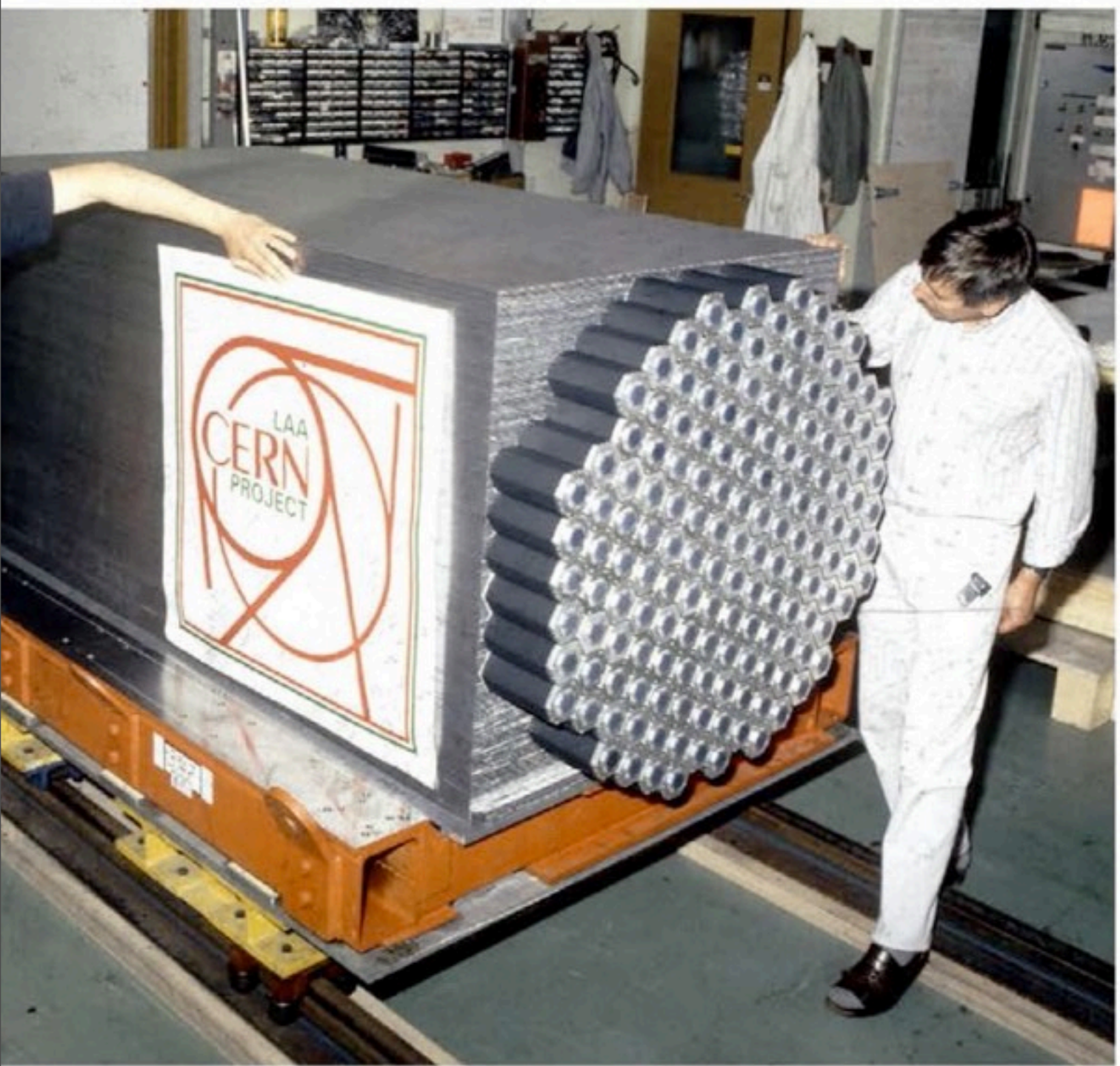
The e/h value is not determined by the absorber, but by active medium

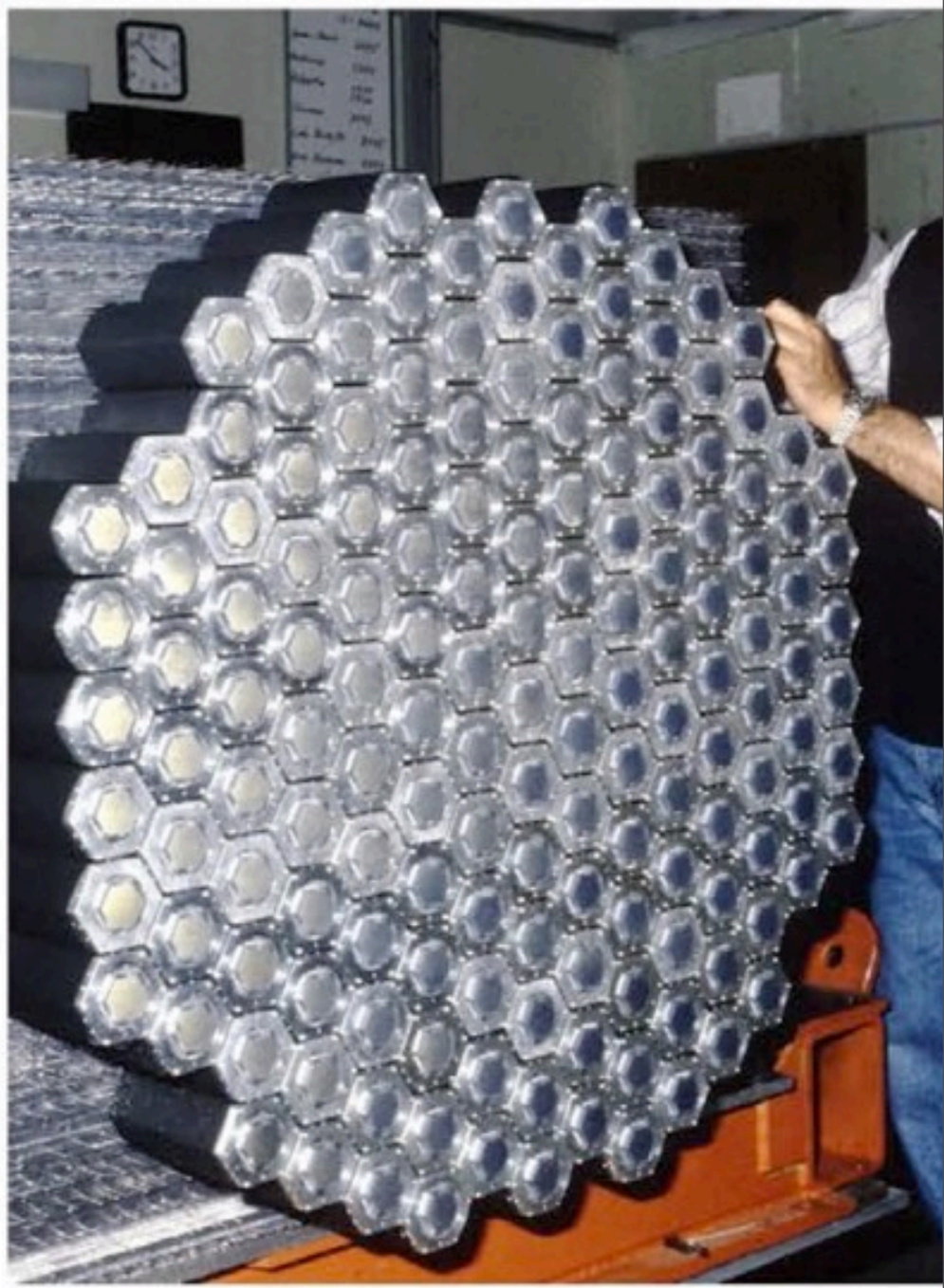
and in particular by its H-content!





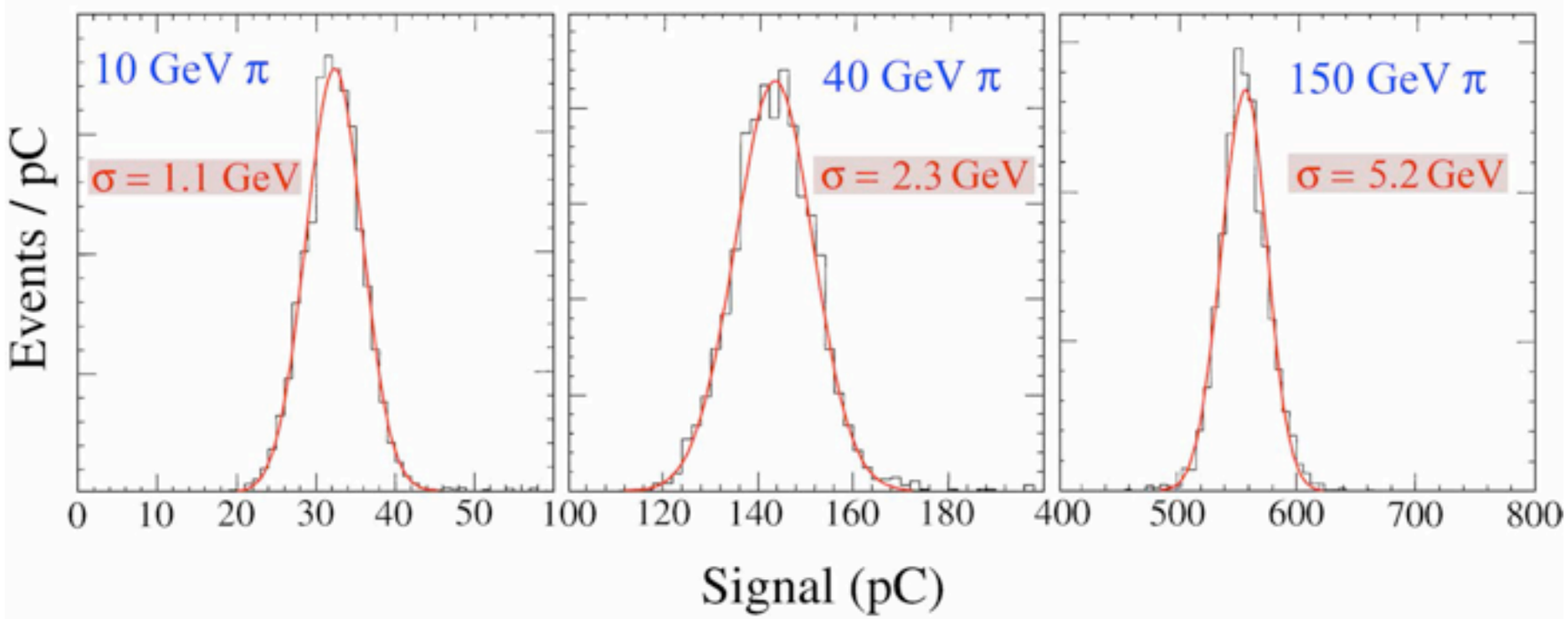
SPACAL 1989





Pb-scintillating fiber;
20 tons of Pb, long
integration time

Hadronic signal distributions in a compensating calorimeter



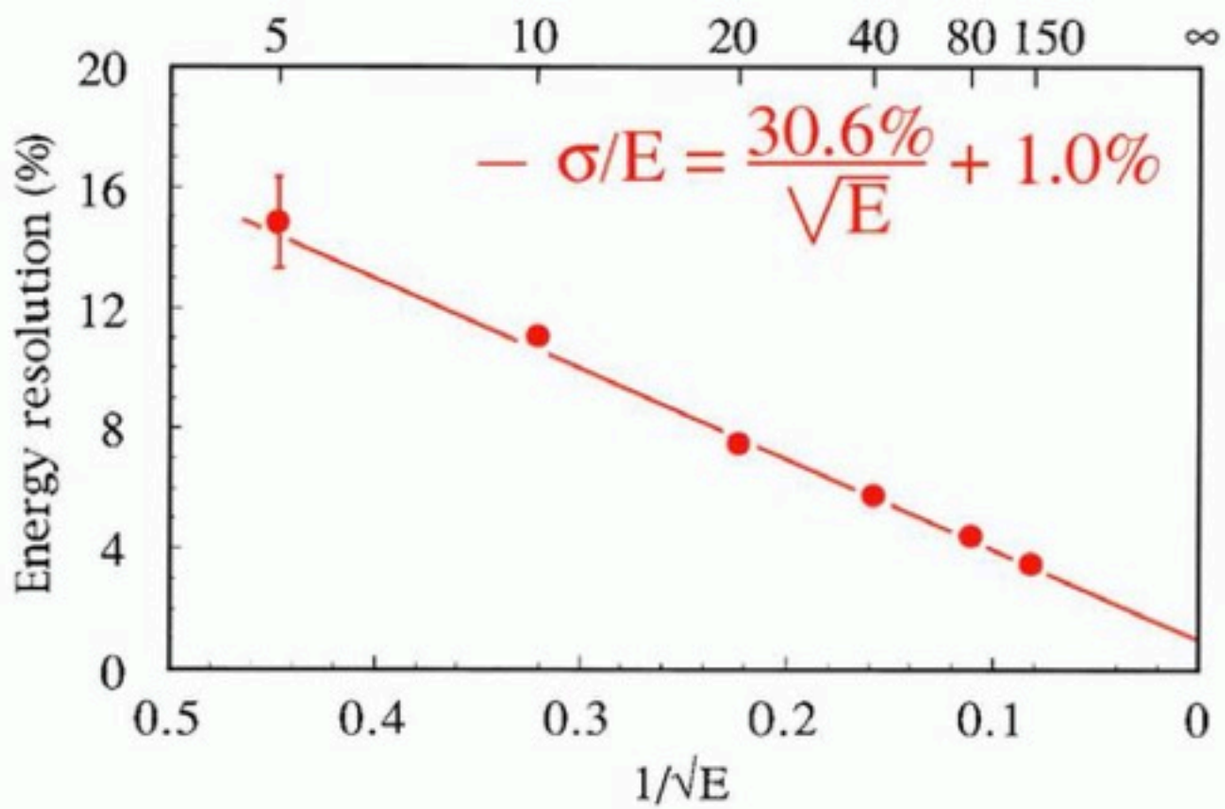


Figure 10: The hadronic energy resolution as a function of energy, for the compensating SPACAL *lead/plastic-scintillator calorimeter (sampling fraction 2%)*

NIM A308 (1991) 481

Still the world record after 25 years.

A compensating calorimeter is constrained by the absorber (high-Z like Pb) and the sensitive medium (hydrogenous) in a very specific ratio:

Pb : scintillator == 4 : 1

This is a rather small “sampling fraction” leading to a poor electromagnetic energy resolution, in addtion to the tonnage and the long integration time required to collect the MeV-energy neutrons.

Is it possible to measure “*e*” and the neutrons separately? Yes, now called “dual-readout”

Measure "electromagnetic" part,

by measuring π^os (mostly)

from their showering electrons and positrons,

which are relativistic and therefore

generate Cerenkov light in an optical medium,

e.g., clear fibers

Measure "hadronic" part,

by measuring scintillation light from π^+s,

π^-s, protons, e.g., in scintillating fibers

Measure neutrons,

by measuring late (10's of nanoseconds)

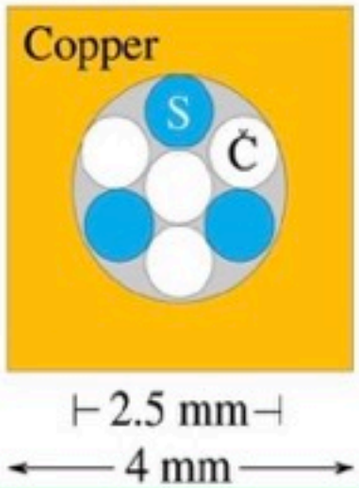
scintillation light in scintillating fibers

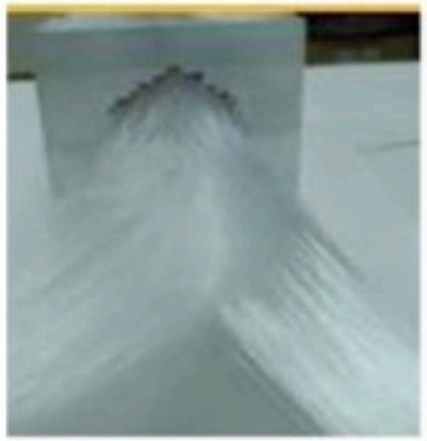
DRC fiber calorimeters

RD52 DREAM

2003 DREAM

Copper
2m long, 16.2 cm wide
19 towers, each 2 PMT
Sampling fraction: 2%

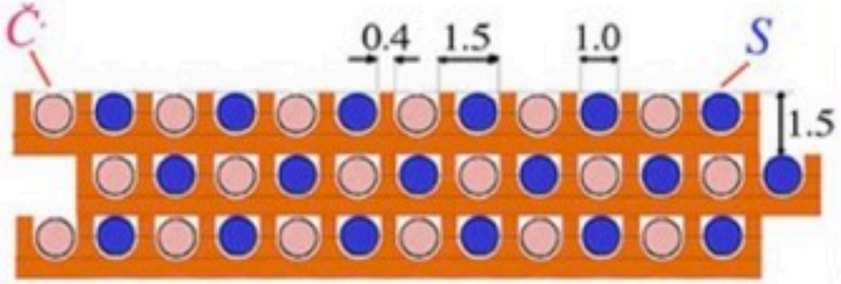




Texas Tech Uni

2012 RD52

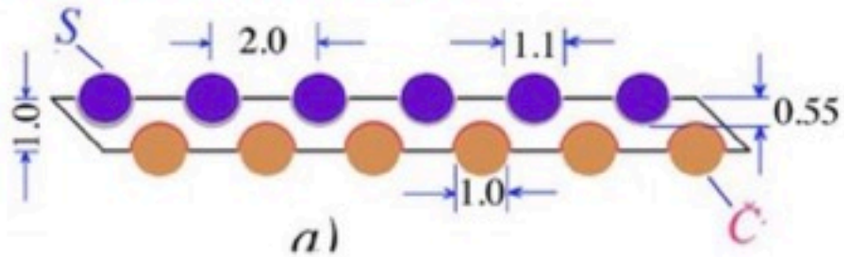
Copper,
2 modules



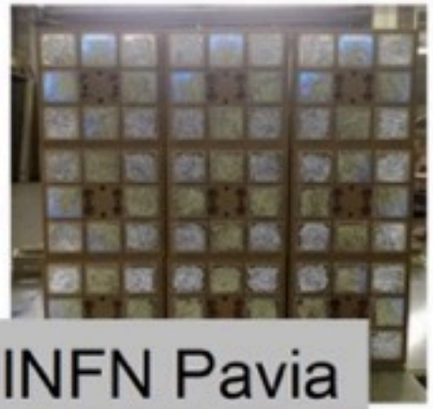
INFN Pisa

Each module: 9.3 * 9.3 * 250 cm3 (10 λint)
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 4.5, 5%

2012 RD52



Lead, 9 modules



INFN Pavia

Dual-readout: one page

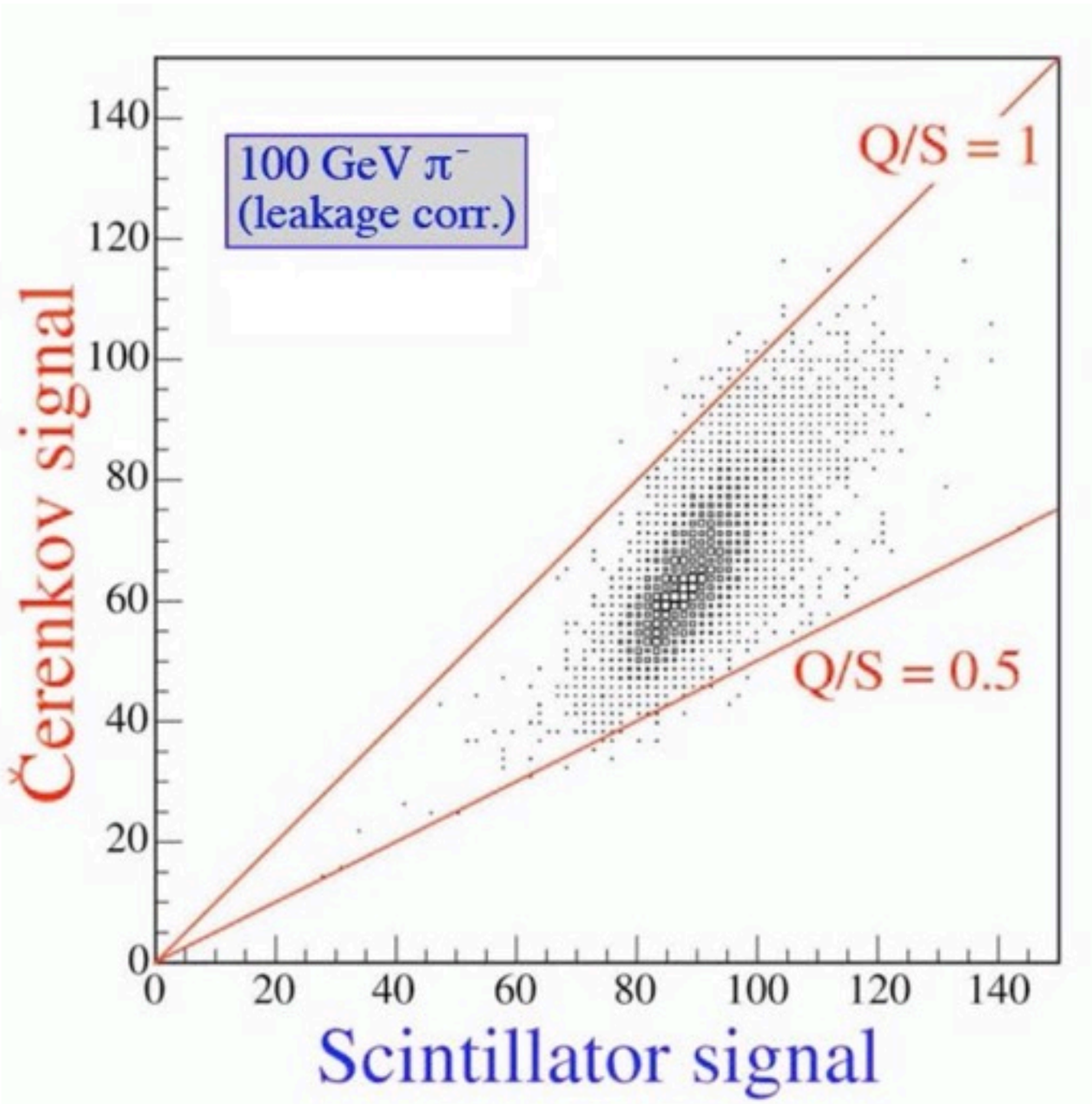
$$S = E\,[f_{EM} + (1 - f_{EM})\eta_S]$$
$$C = E\,[f_{EM} + (1 - f_{EM})\eta_C]$$

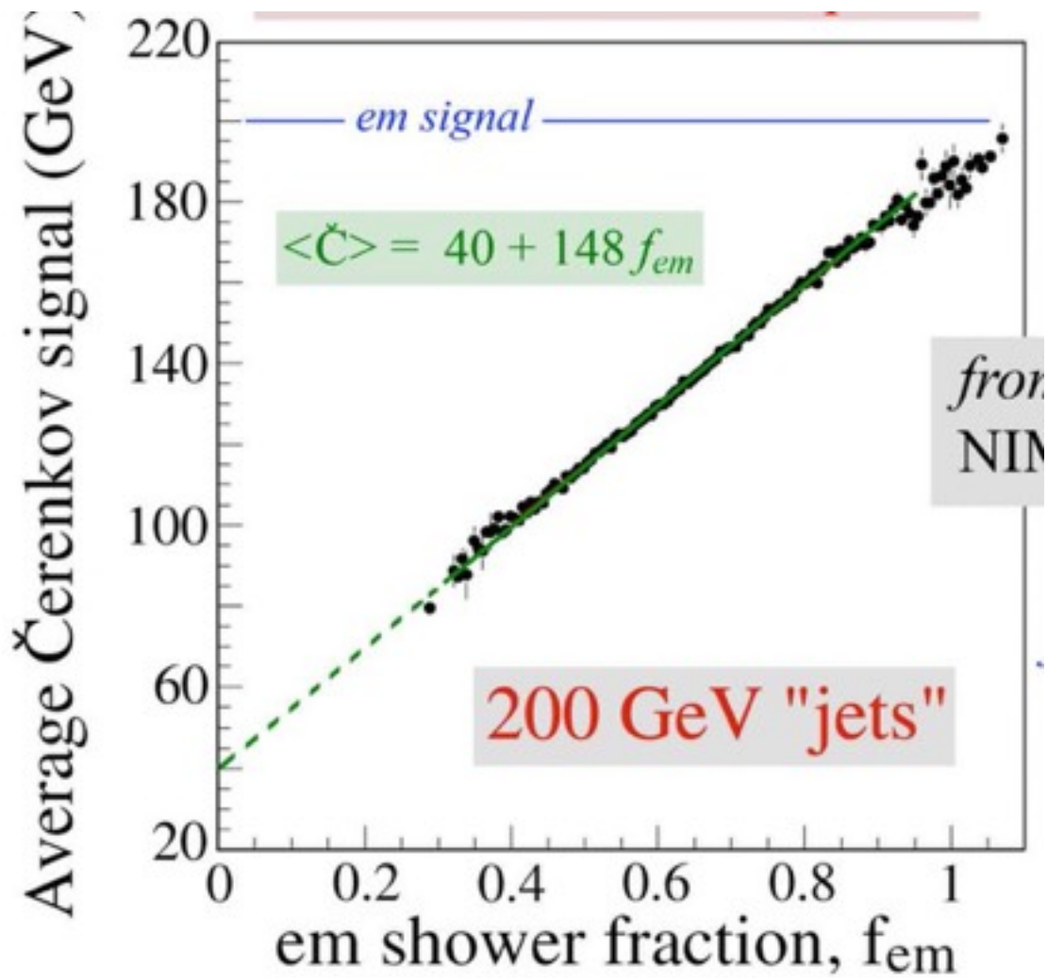
$$\eta_S = (h/e)_S \approx 0.7$$
$$\eta_C = (h/e)_C \approx 0.2$$

$$C/S \rightarrow f_{EM}$$

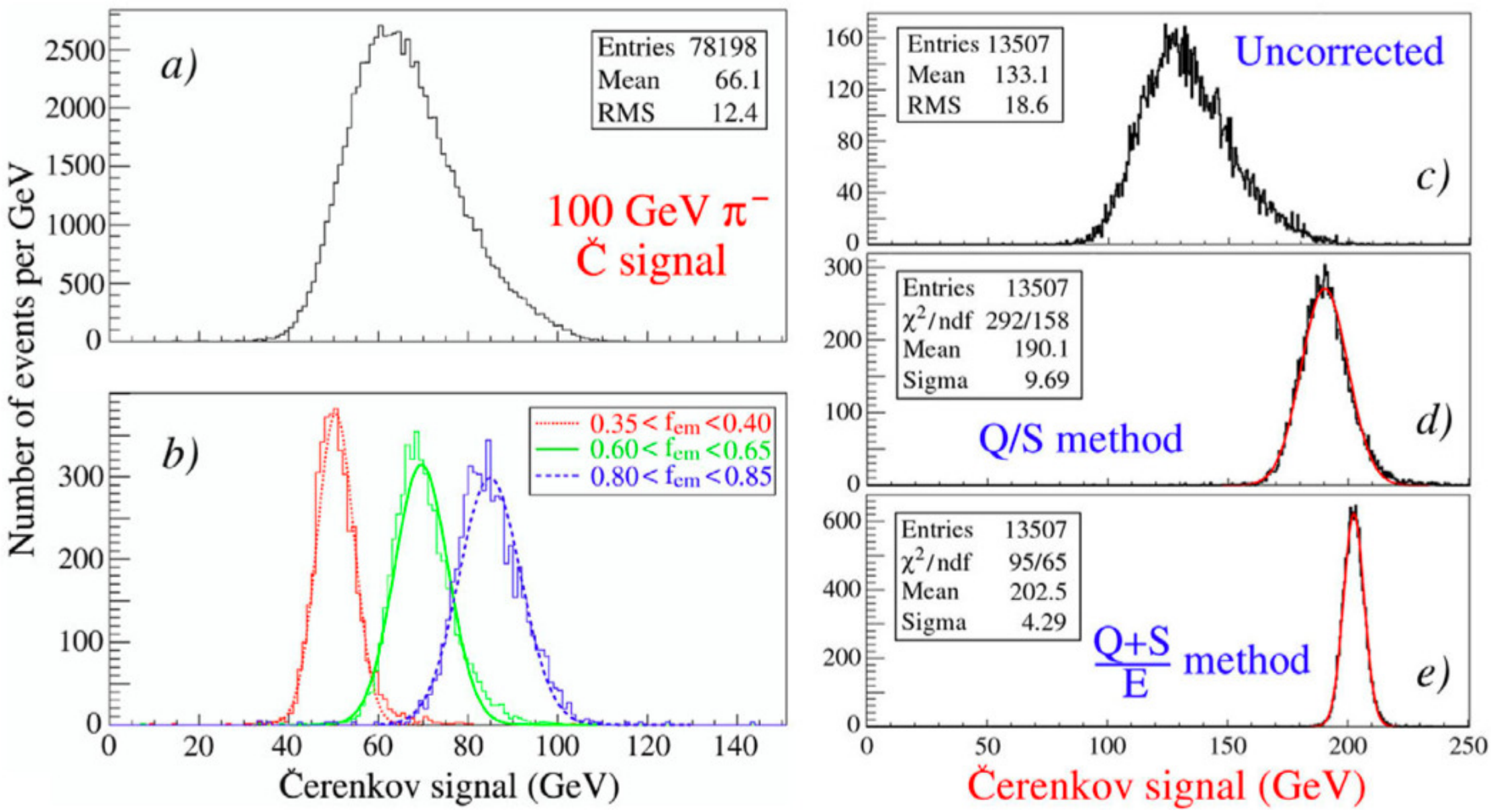
$$E = (S - \chi C)/(1 - \chi)$$

$$\chi = \frac{1-\eta_S}{1-\eta_C} \approx 0.3$$



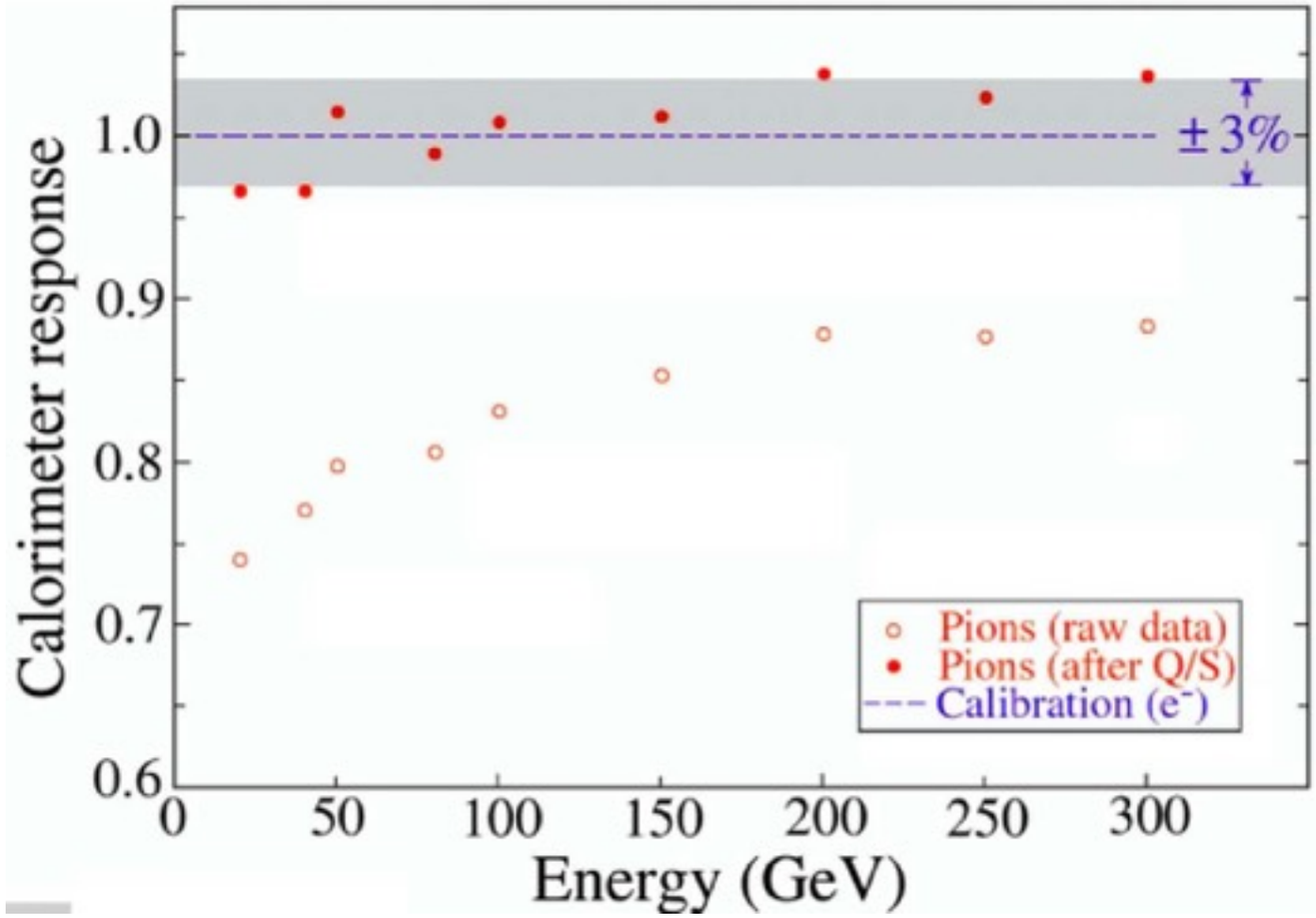


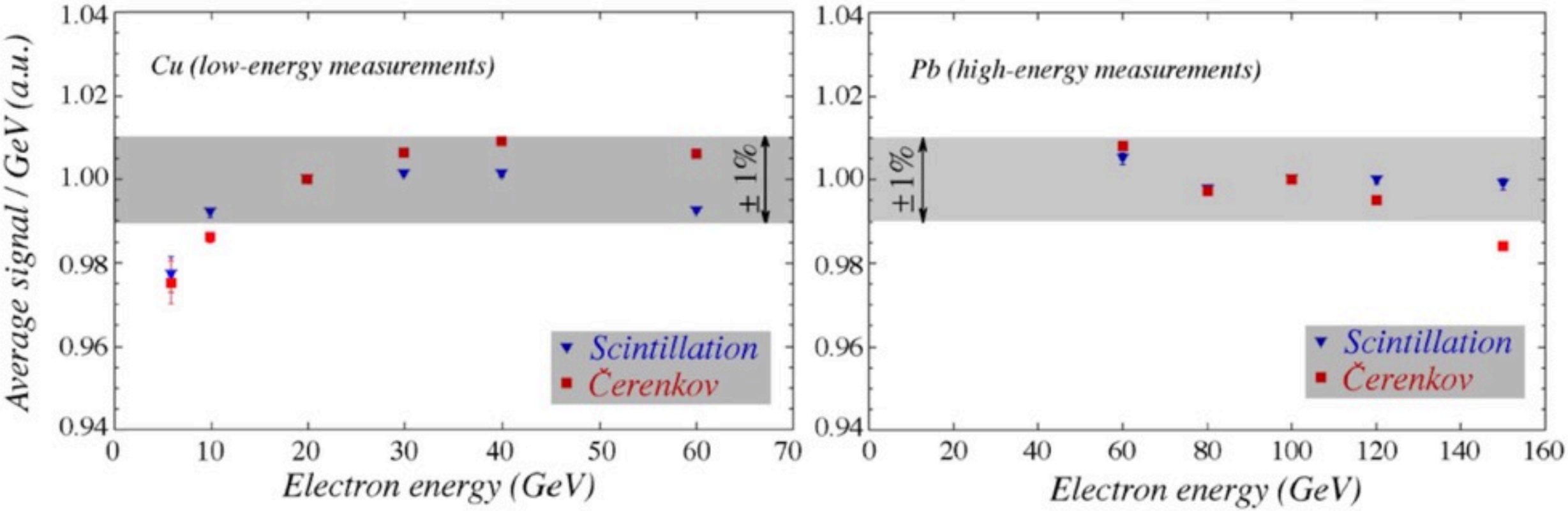
Test beam data: 100 and 200 GeV: *NIM* 537 (2005) 537.



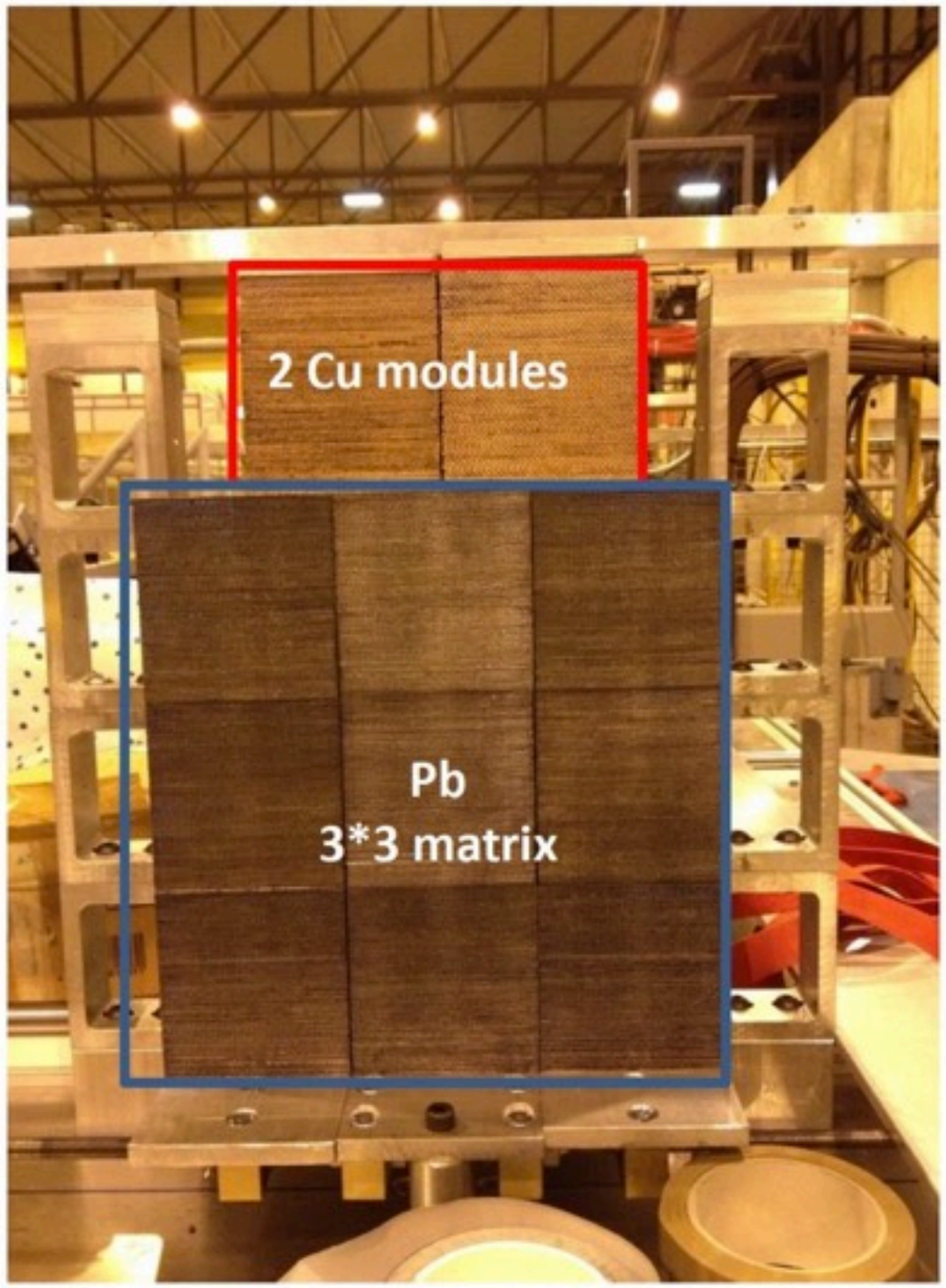
Frame (e) is consistent with 30%/ sqrt(E) and with the GEANT4 BERT_HP simulations

Absolute hadronic energy linearity (all RD52 and DREAM modules) in a device calibrated with electrons at one energy





We've built a variety of modules:



One Cu module equipped with reflecting Al on upstream Cerenkov fiber ends for attenuation correction in scintillating fibers.

Detailed results next week:
Sehwook Lee, Michele Cascella

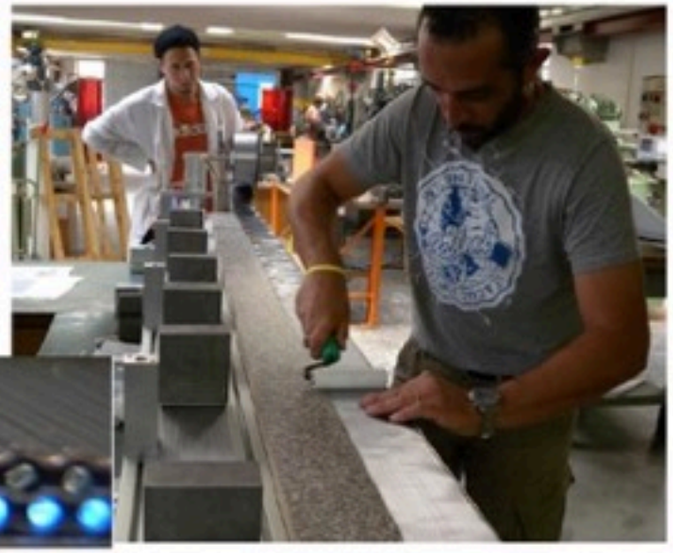
Pb – fiber construction (INFN Pavia)

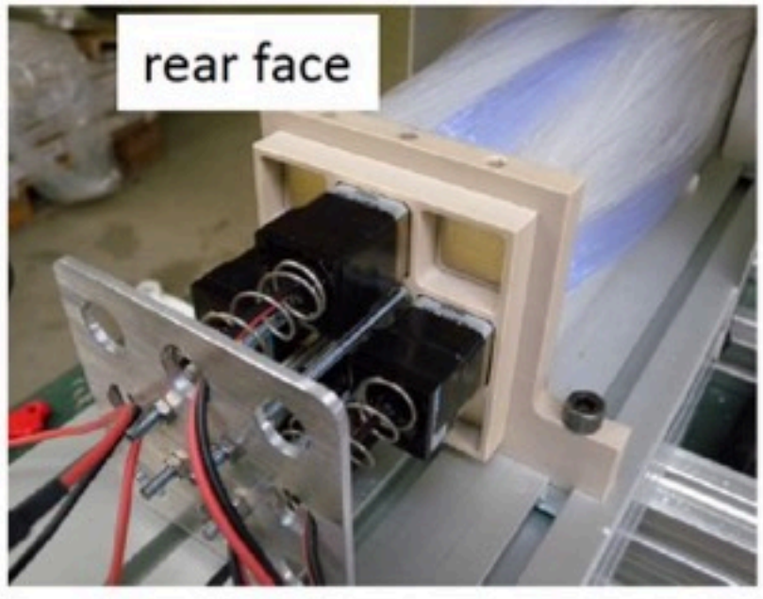
RD52 DREAM

Pb fabrication:

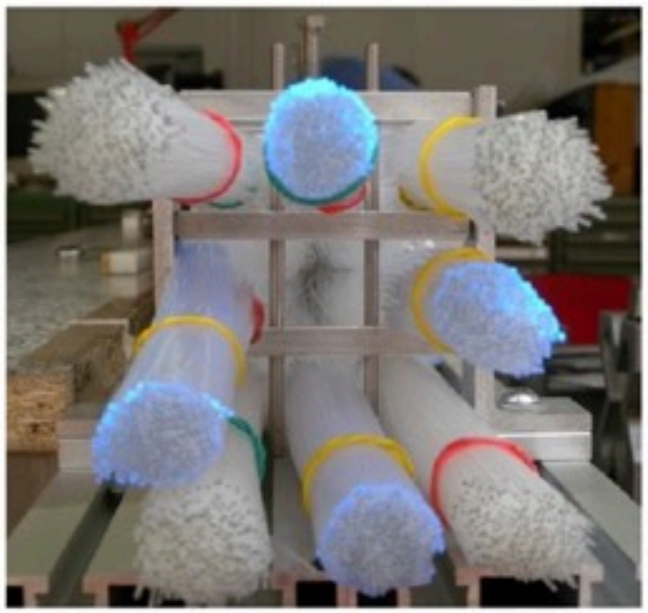
Cold extrusion (industry, Italy), both sides.

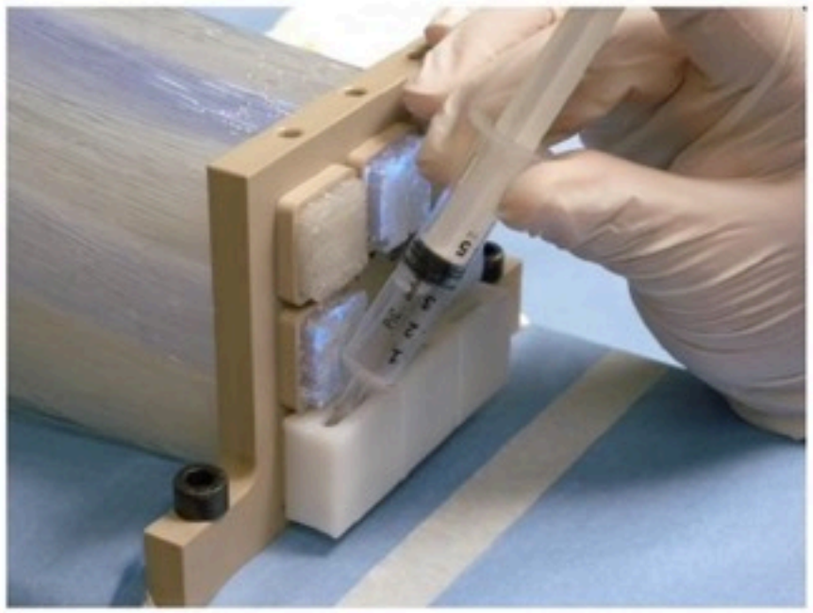
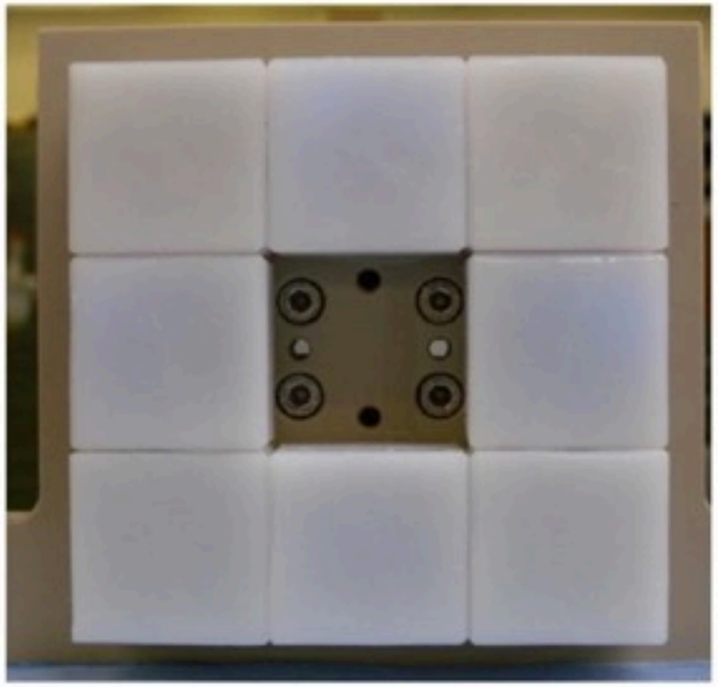
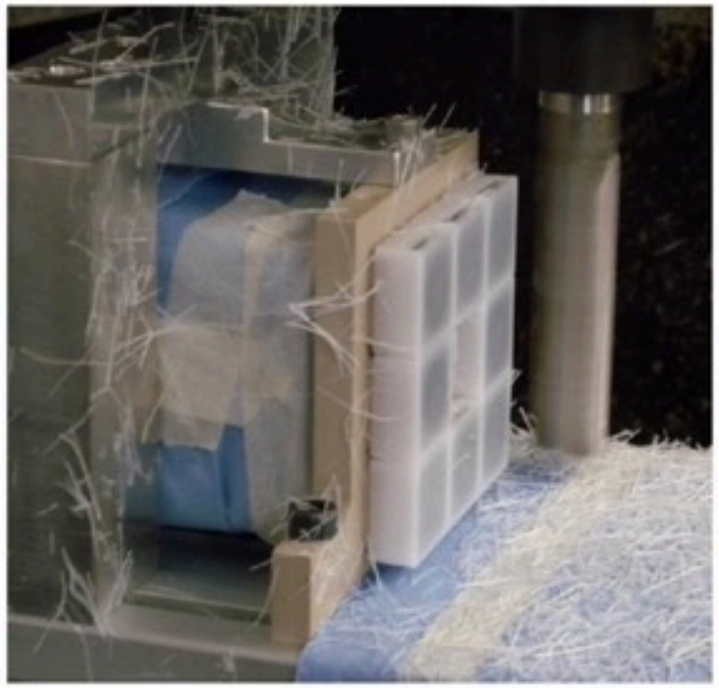
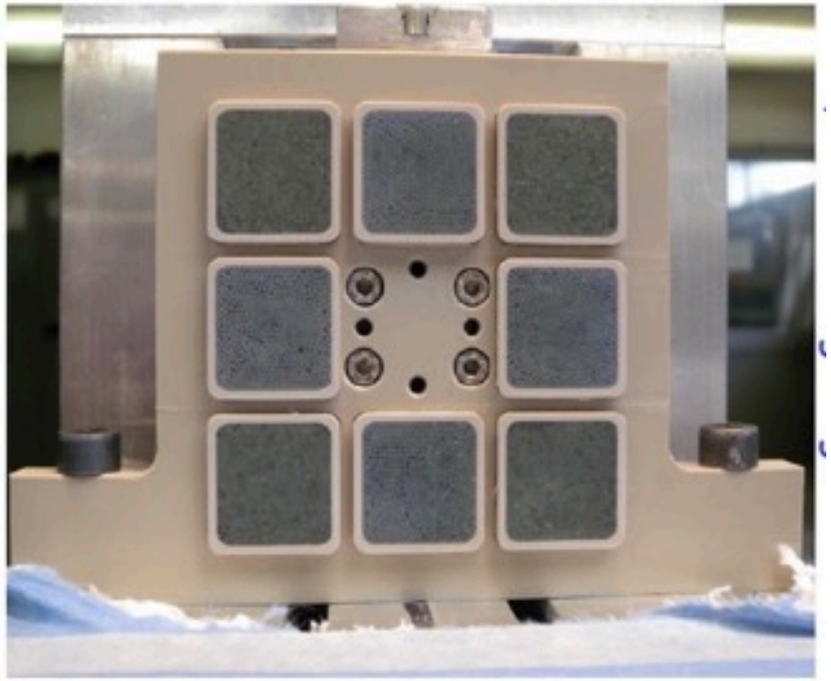
Assembling in INFN Pavia, no glue used



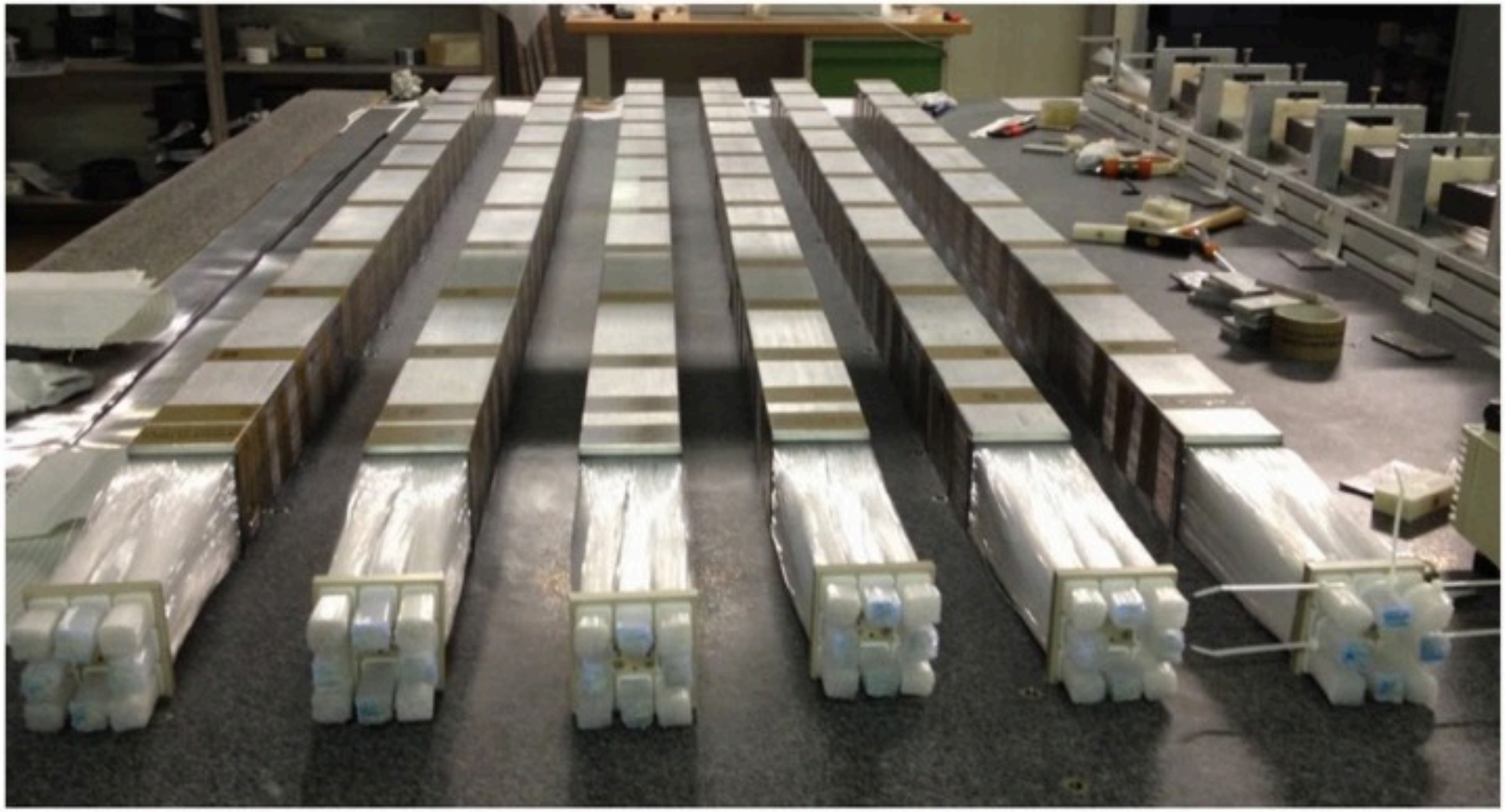


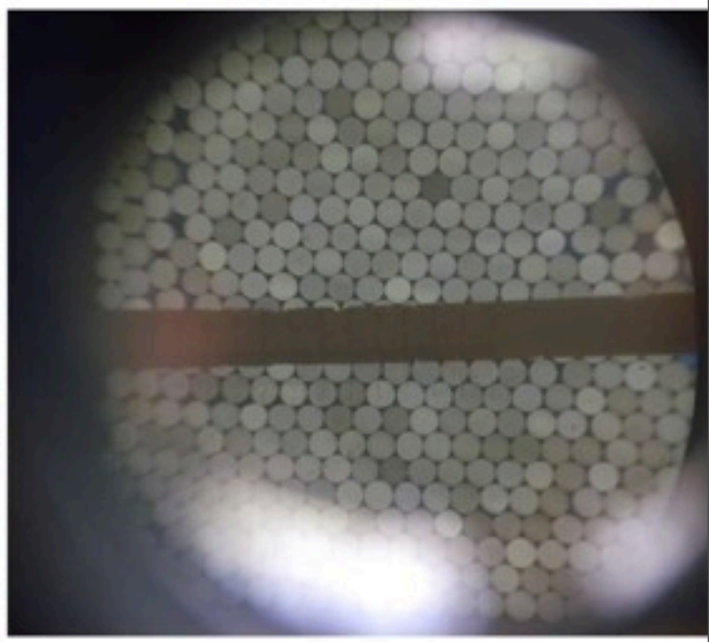
INFN, Pavia



INFN, Pavia



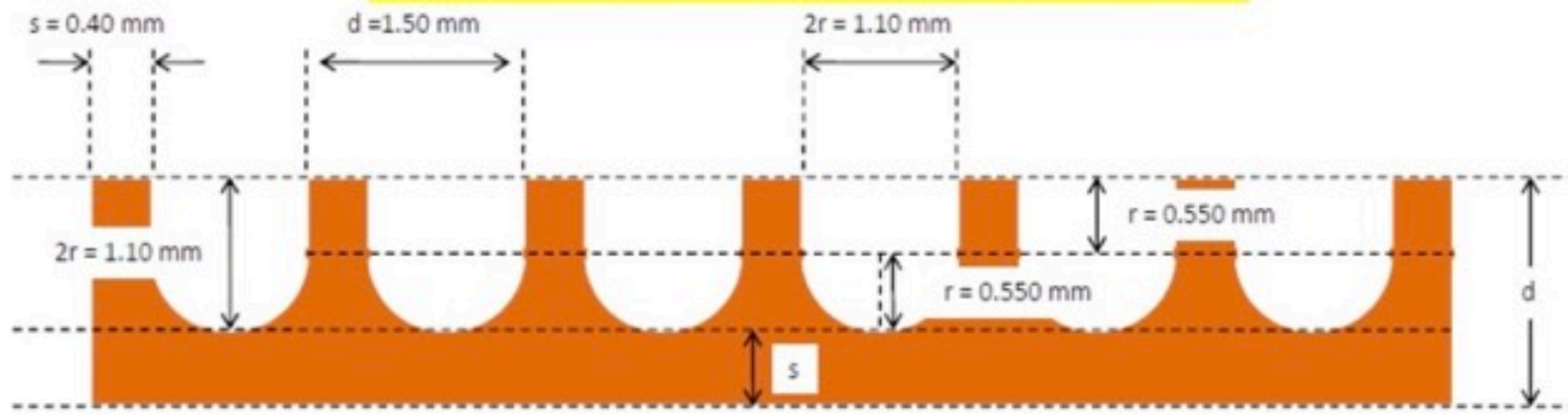


INFN, Pisa

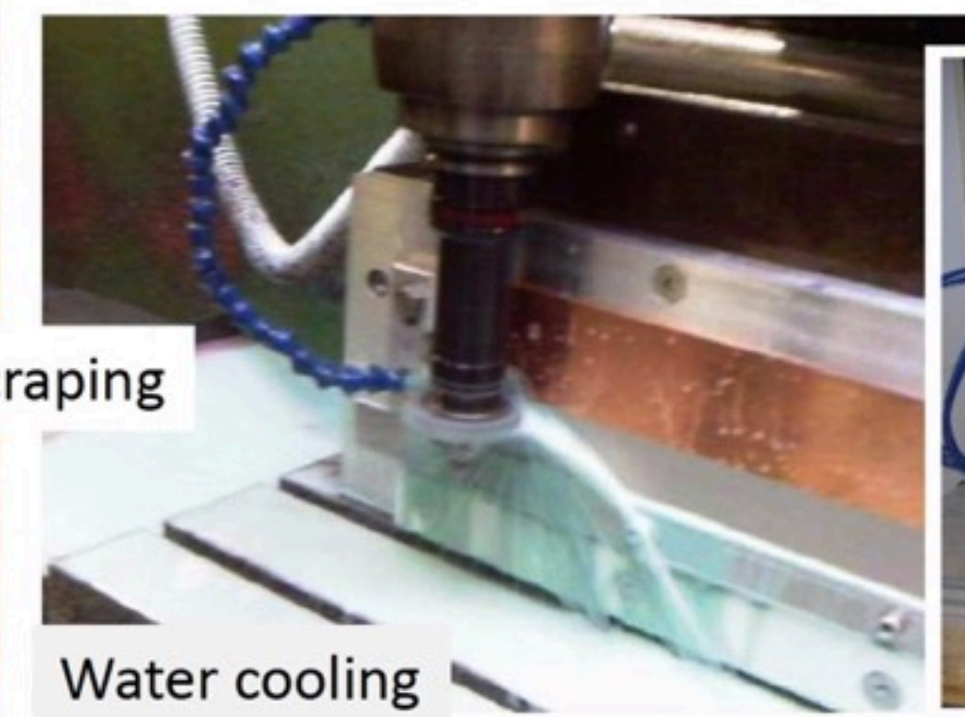
Cu fabrication:

Saw scraping (INFN Pisa) on one side

(tried both sides but more complicated alignment, stacking ...)



Saw scraping

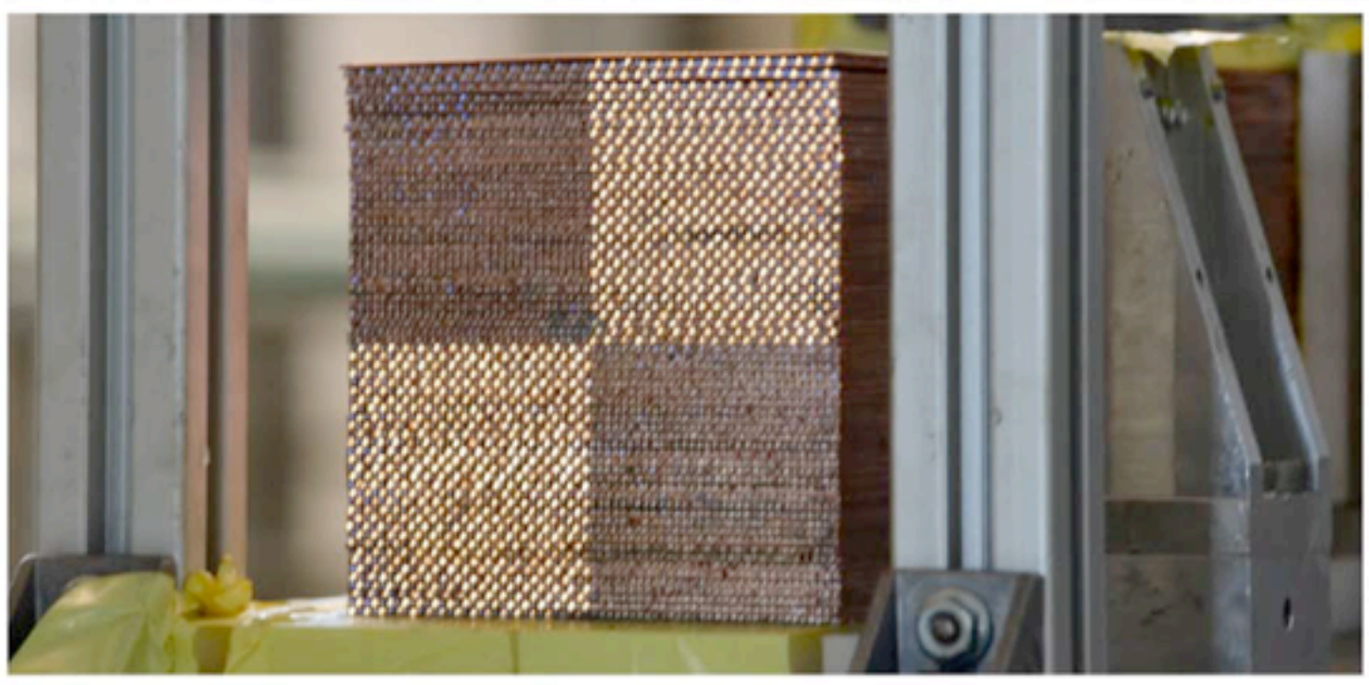


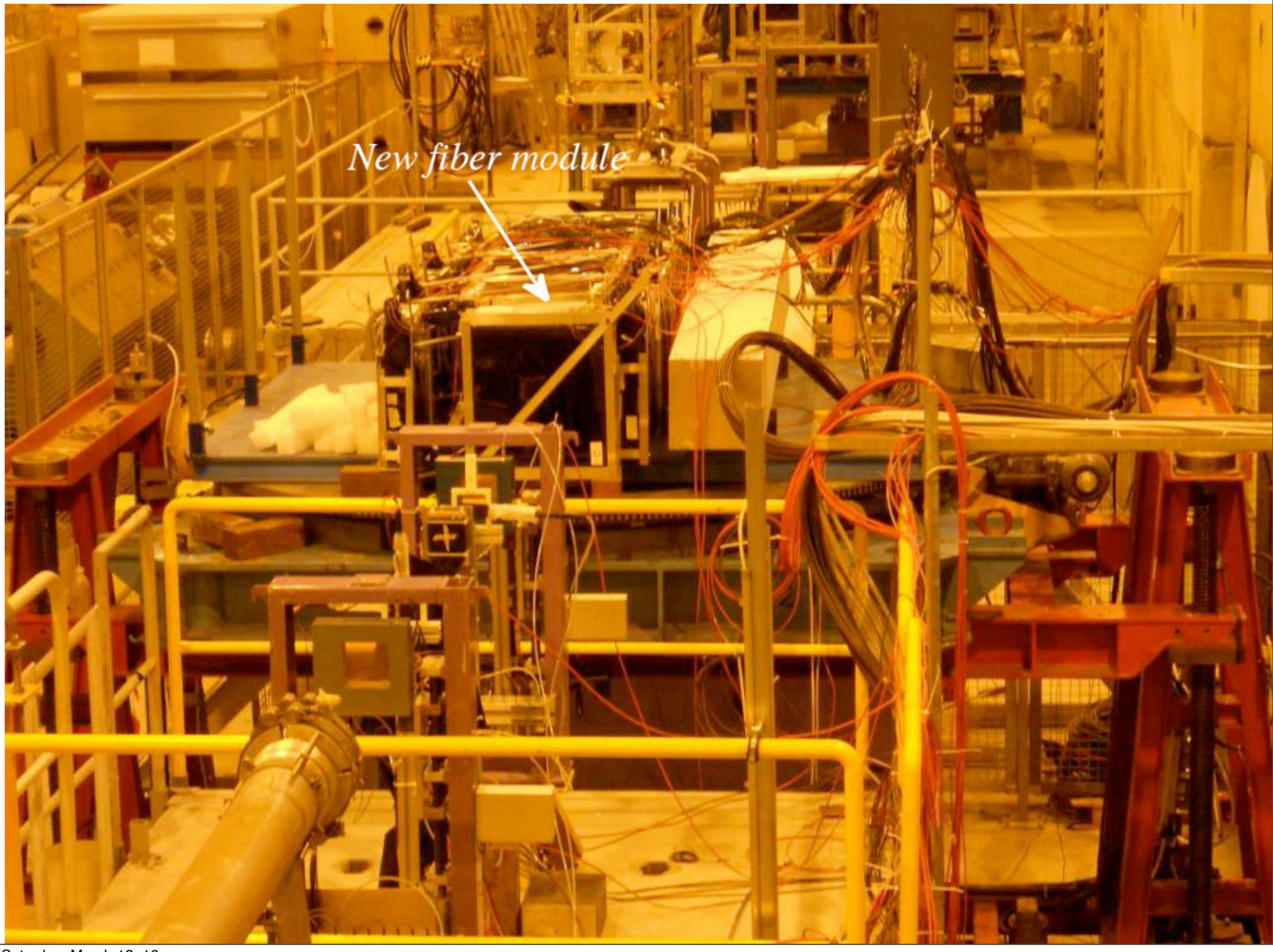
Water cooling

Assembling, pressure for gluing

~ same assembling technique as PAVIA but with glue

The first copper module




New fiber module

Why Copper rather than lead?

RD52 DREAM

1) Detector mass

2) Čerenkov light yield

3) Linearity, and thus resolution for jet detection

Detector mass

Hadronic shower development governed by nuclear interaction length, λ_{int}

Lead: λ_{int} = 170 mm, ρ = 11.3 g/cm^3

Copper: λ_{int} = 151 mm, ρ = 8.96 g/cm^3

What is the mass of a calorimeter of 10 x 3 x 3 λ_{int}^3 ?

Lead: 4996 kg
Copper: 2776 kg

Čerenkov light yield

Čerenkov light is almost exclusively produced by the em shower components in hadron absorption

Lead: e/mip = 0.6

Copper: e/mip = 0.9

For a structure with a given sampling fraction, we get 50% more Čerenkov photons per GeV deposited energy

This will directly affect the hadronic energy resolution, since Čerenkov light yield is a major limiting factor

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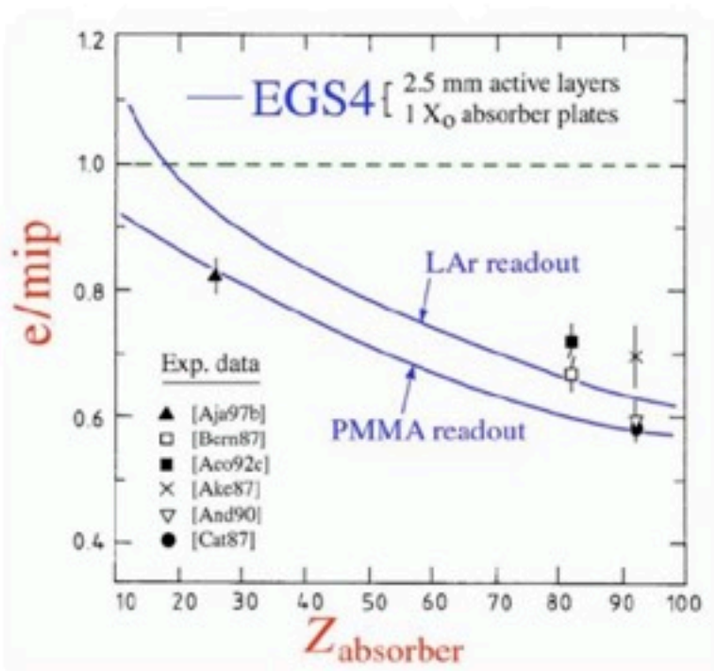
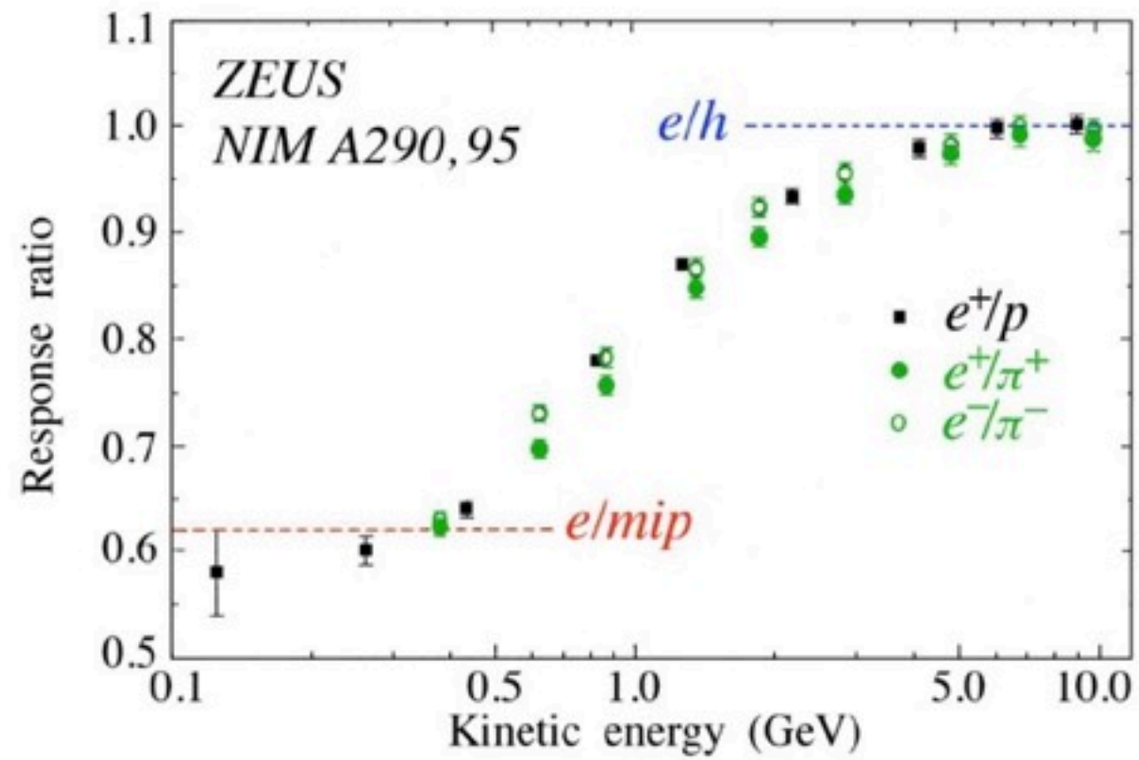
Absorber choice: Cu vs Pb

- *Detector mass:* λ_{Cu} *= 15.1 cm,* λ_{Pb} *= 17.0 cm*
  Mass $1\lambda^3$ *: Cu/Pb = 0.35*

- *e/mip* $\longrightarrow$ *Čerenkov light yield Cu/Pb ~ 1.4*
  (Showers inefficiently sampled in calorimeters with high-Z absorber)

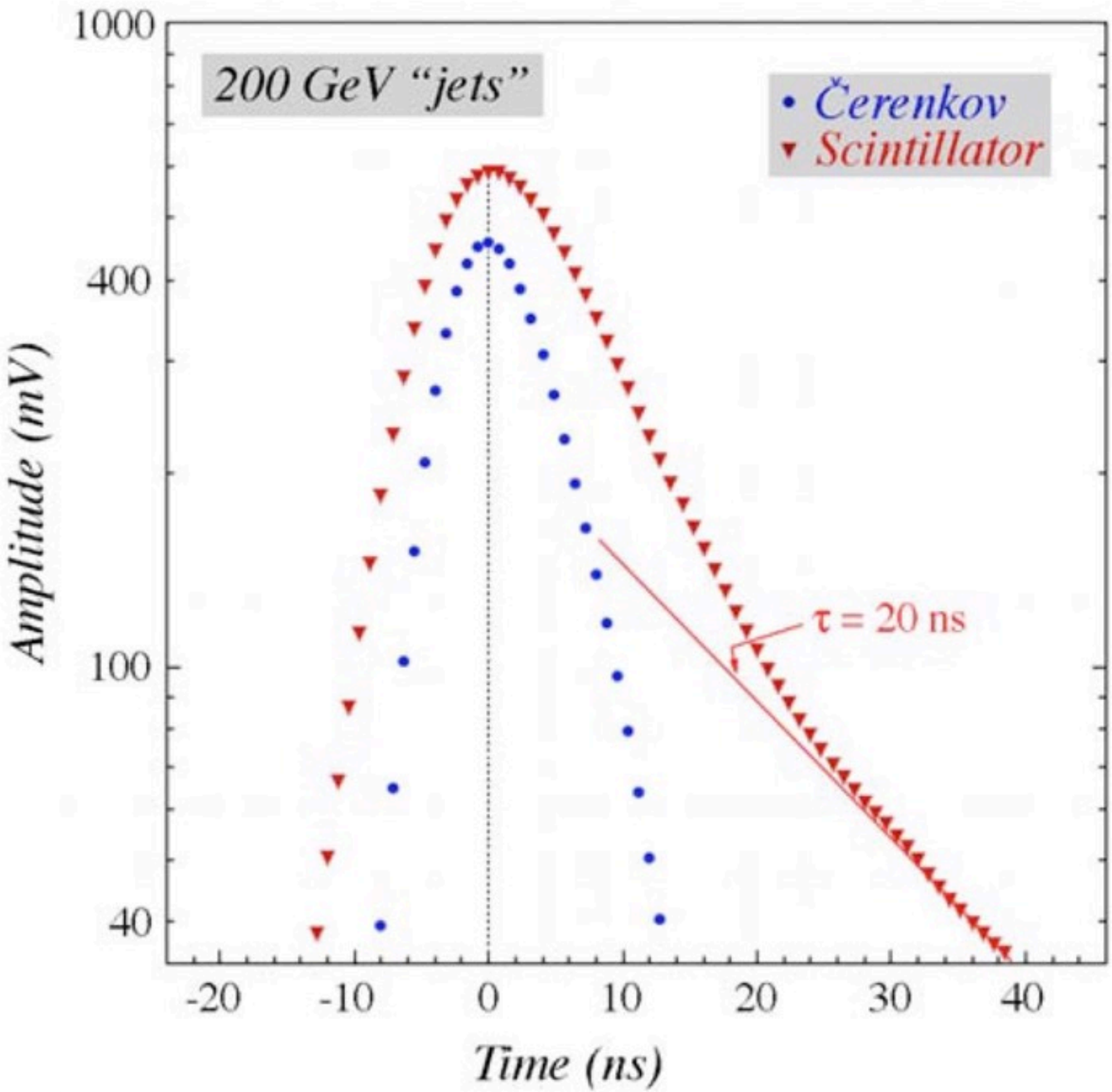
- *Non-linearity at low energy in calorimeters with high-Z absorber*
  Important for jet detection





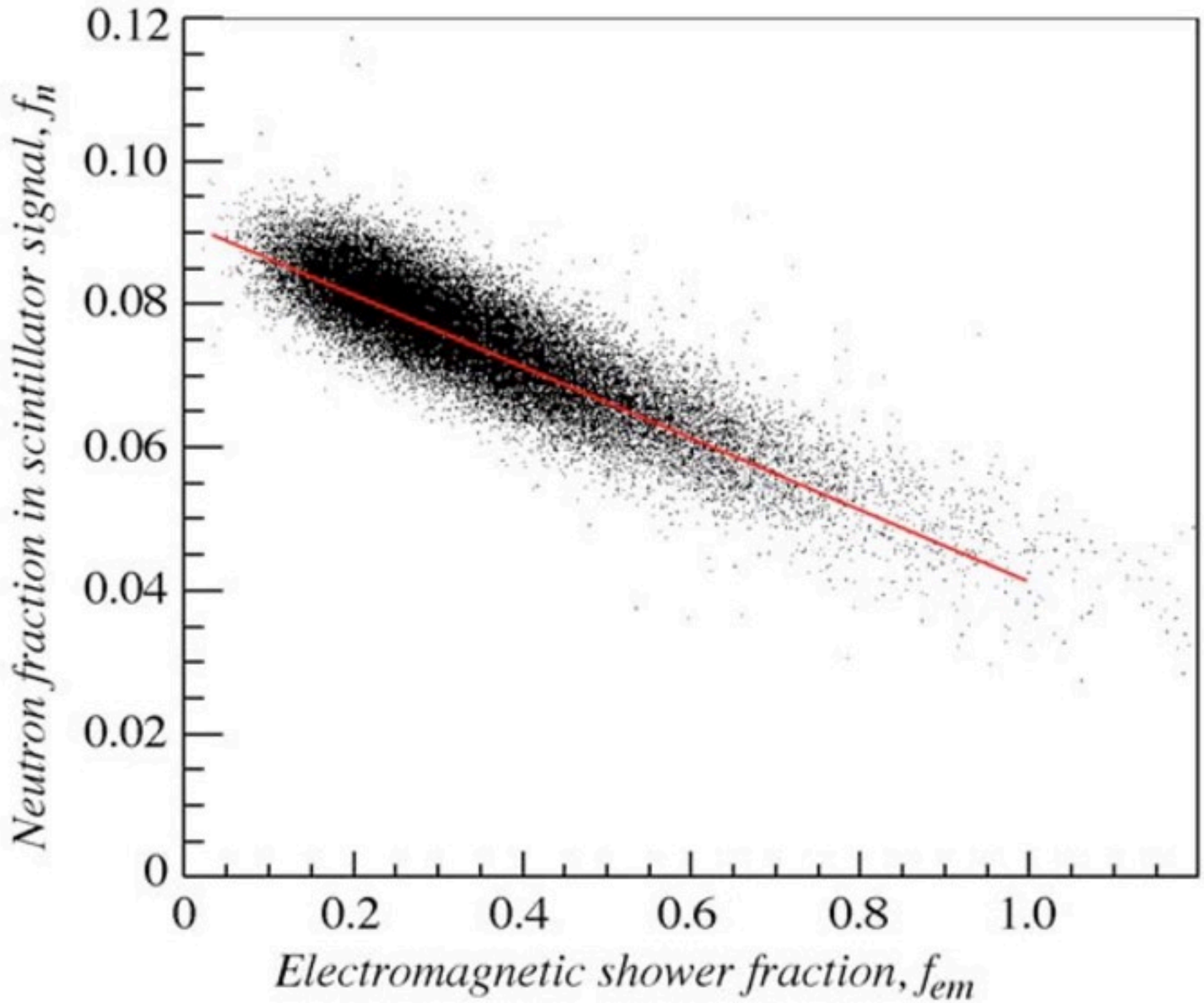
We hope to build a 4-ton copper module this year.

- reduce leakage fluctuations from 4% to less than 1%.
- readout with 2.5 GHz RDS5 module.
- mirror upstream Cerenkov fibers, measure depth of light, correct attenuation in S fibers.
- use neutron signals from S-fibers.
- use external neutron counters to estimate effect of non-infinite calorimeter volume.

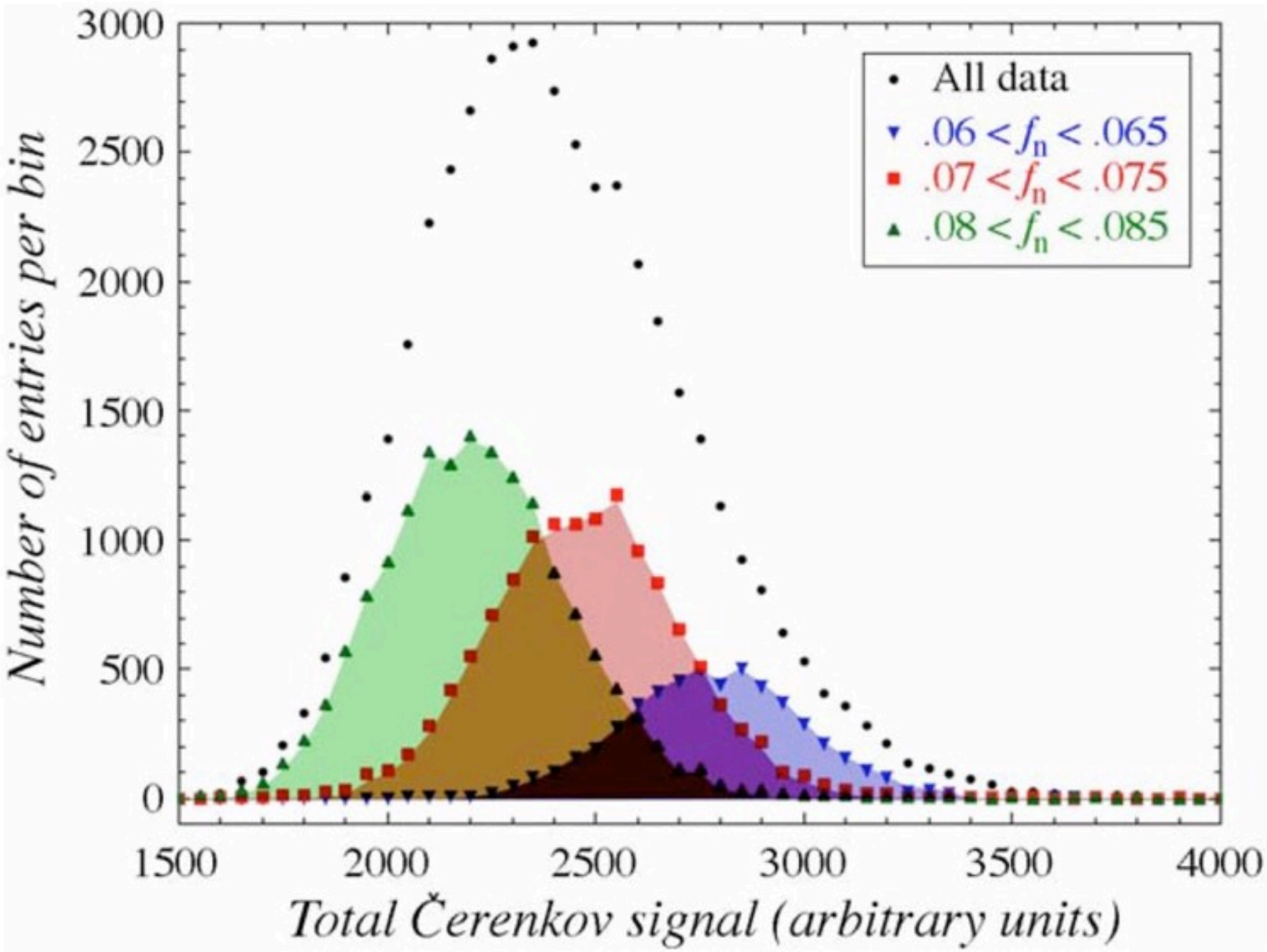


Neutrons seen through np elastic scatters in S-fibers

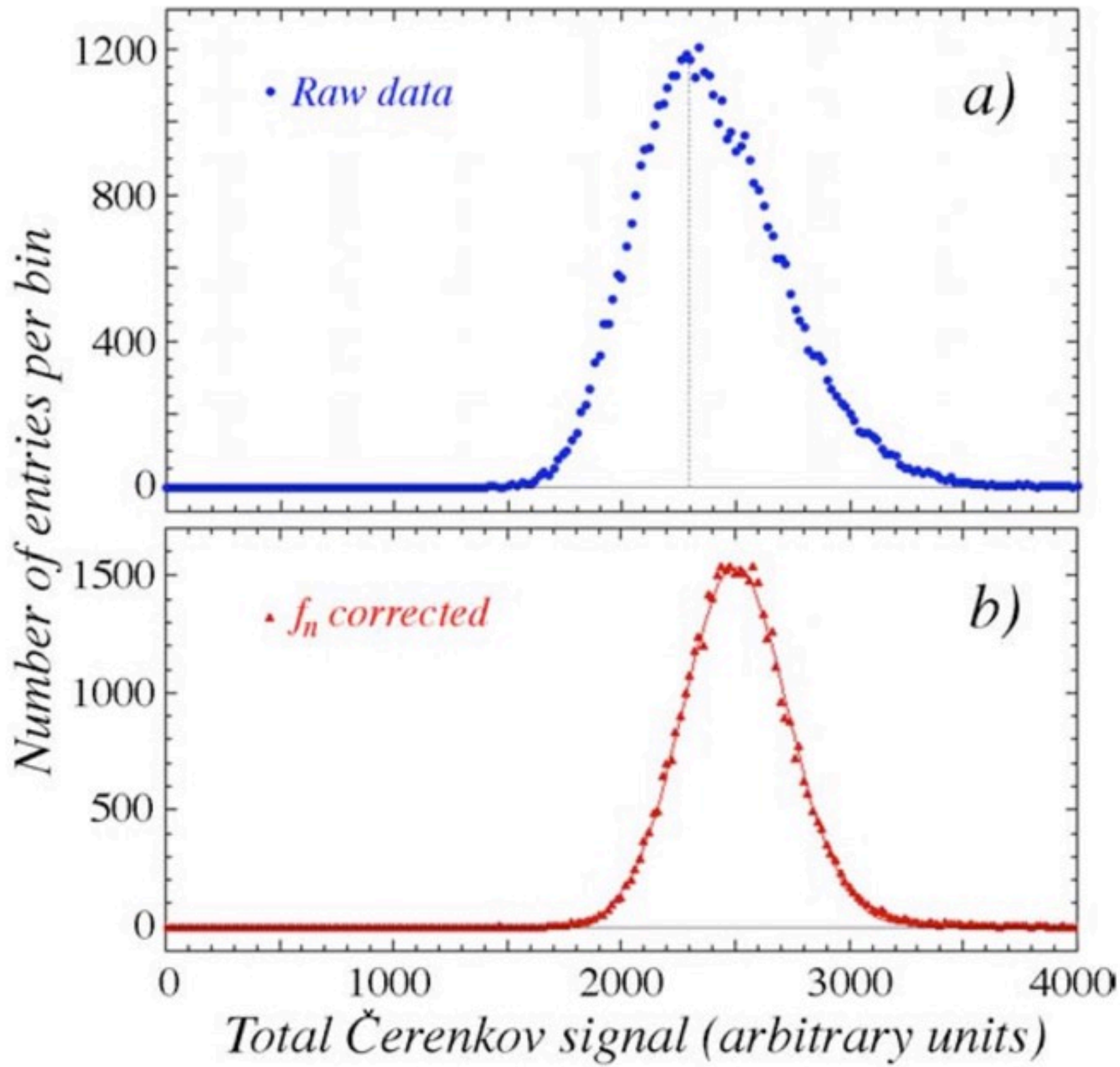
Plot “neutron fraction” vs. EM fraction, each event.



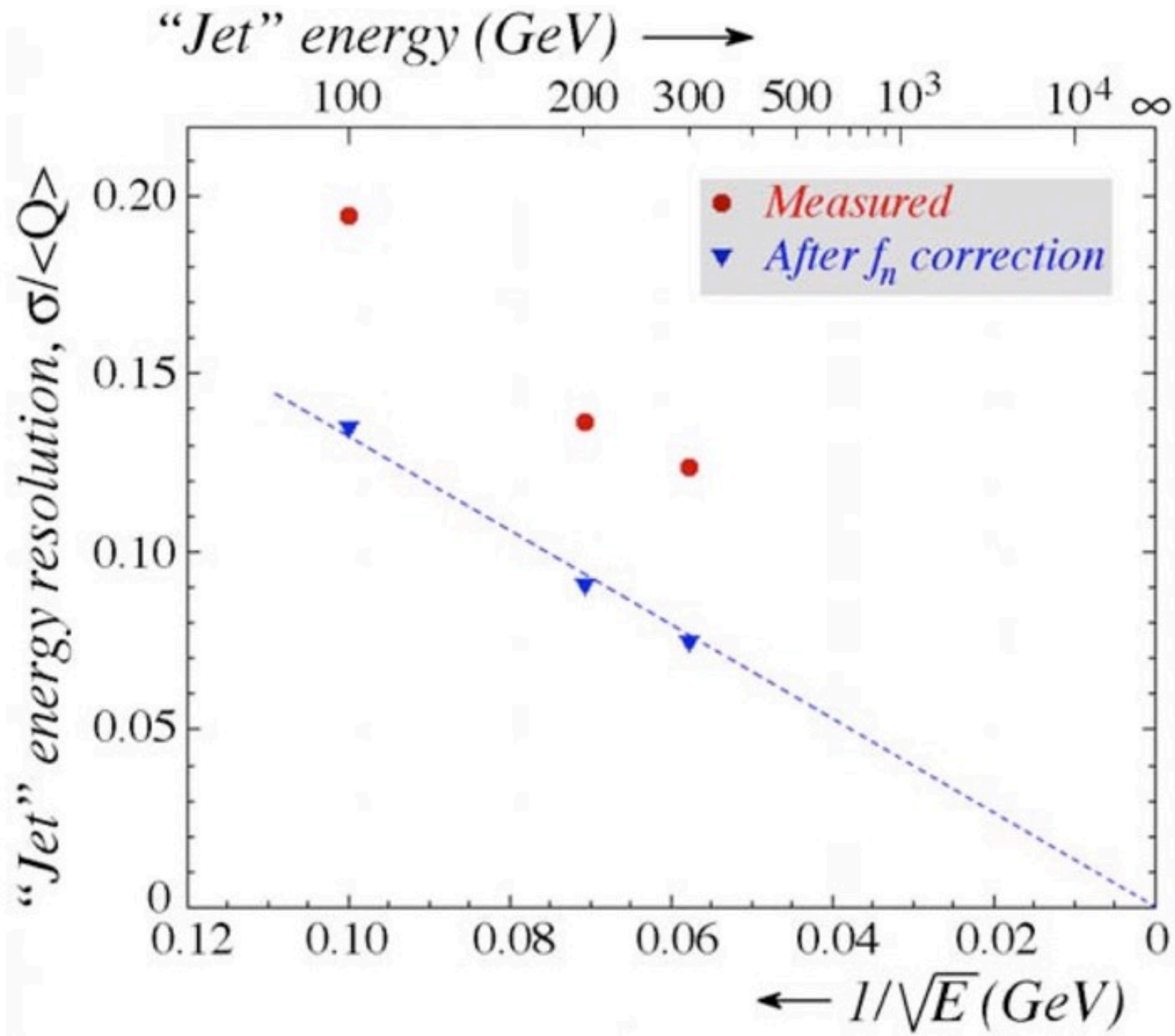
Slice Cerenkov signal by "neutron fraction" ----- just like the EM fraction, we find that narrower Gaussians make up the broad calorimeter signal



Resolution improves using "neutron fraction"

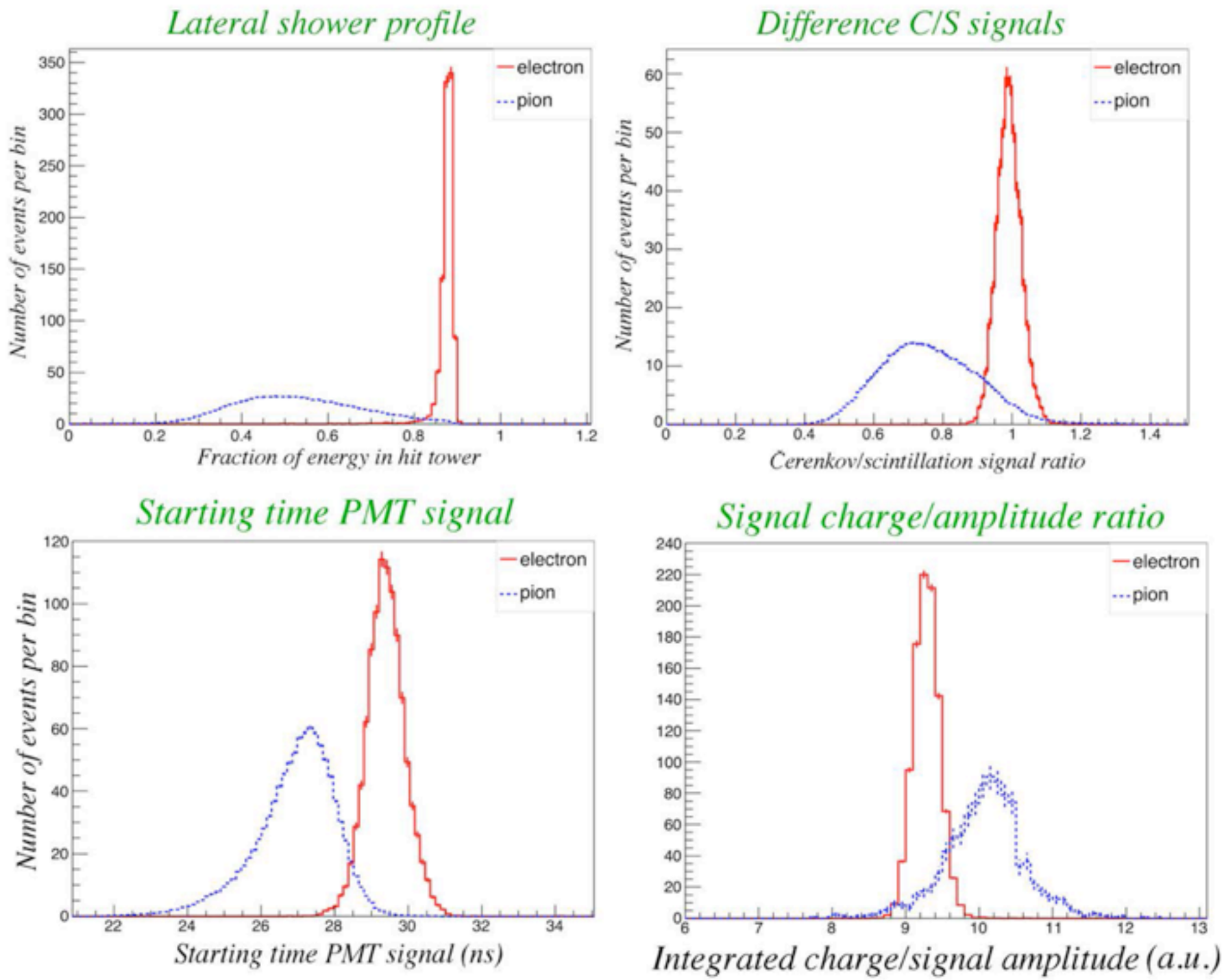


... and no constant term.



What we get: *e* ID

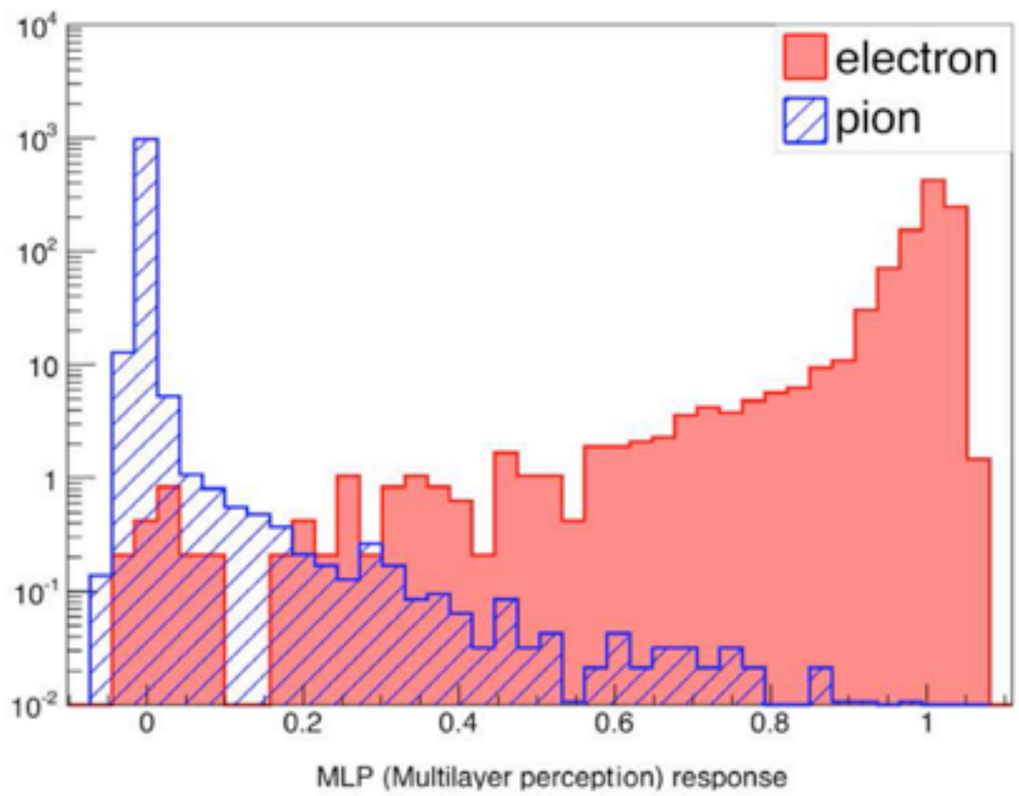
Methods to distinguish e/π in longitudinally unsegmented calorimeter

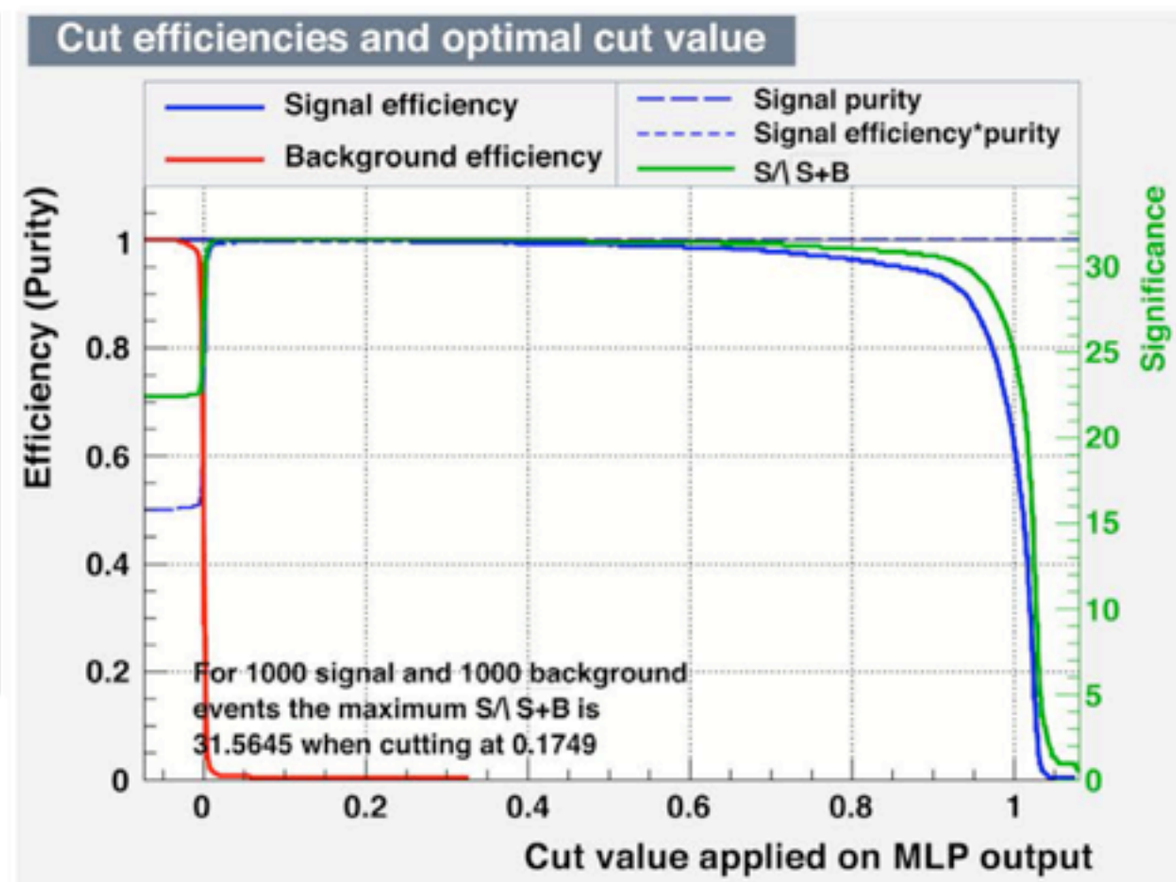


Combination of cuts: >99% electron efficiency, <0.2% pion mis-ID

What we get: e - π discrimination

Neural network analysis 60 GeV e/π separation

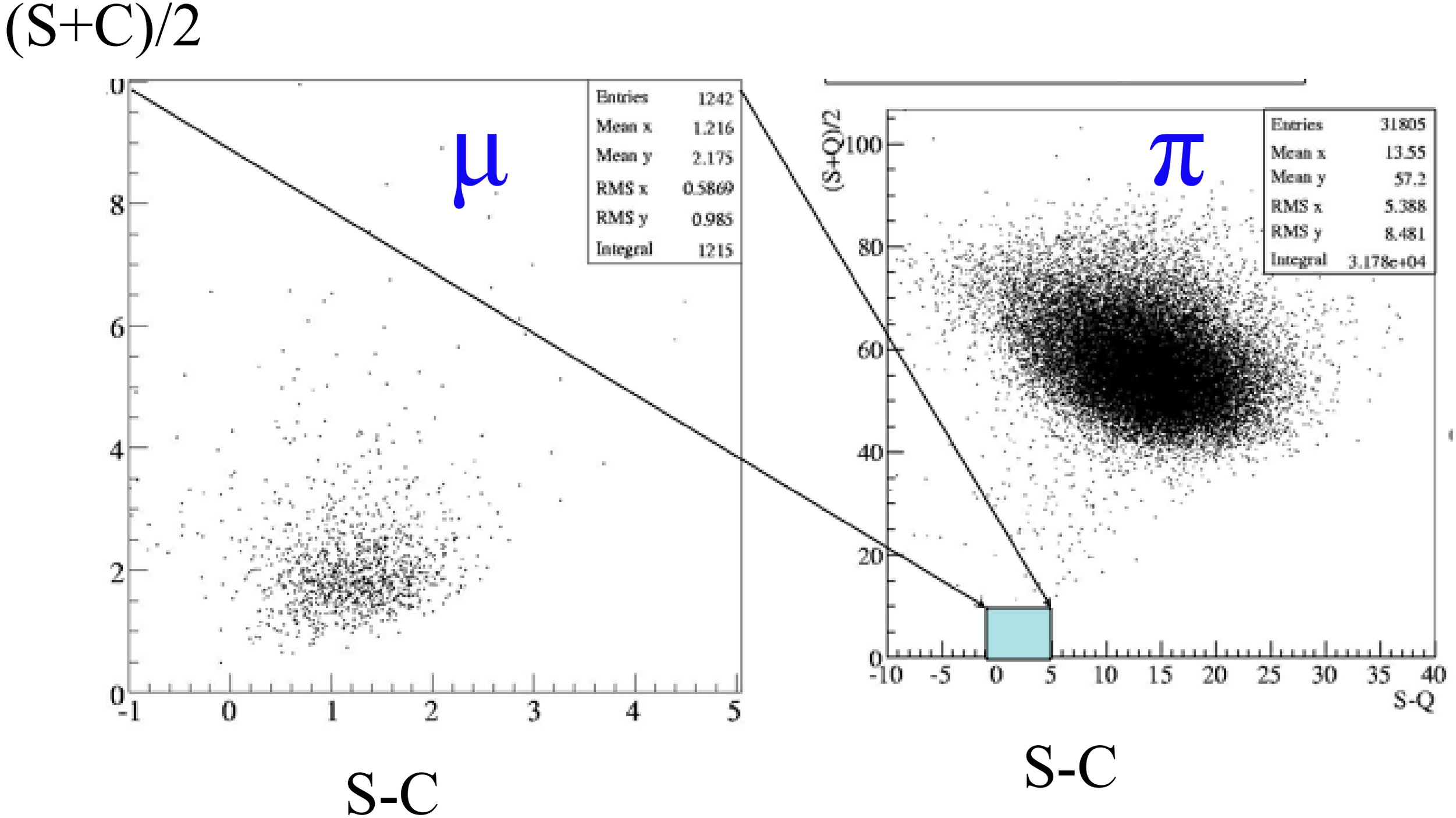




for MLP > 0.17 : *99.81% electron ID*
0.20% π mis-ID

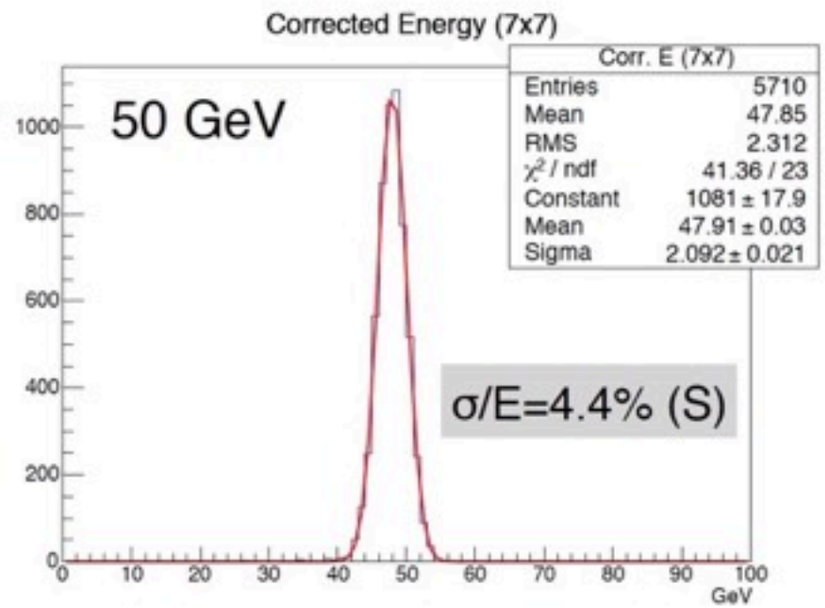
NIM A735 (2014) 120

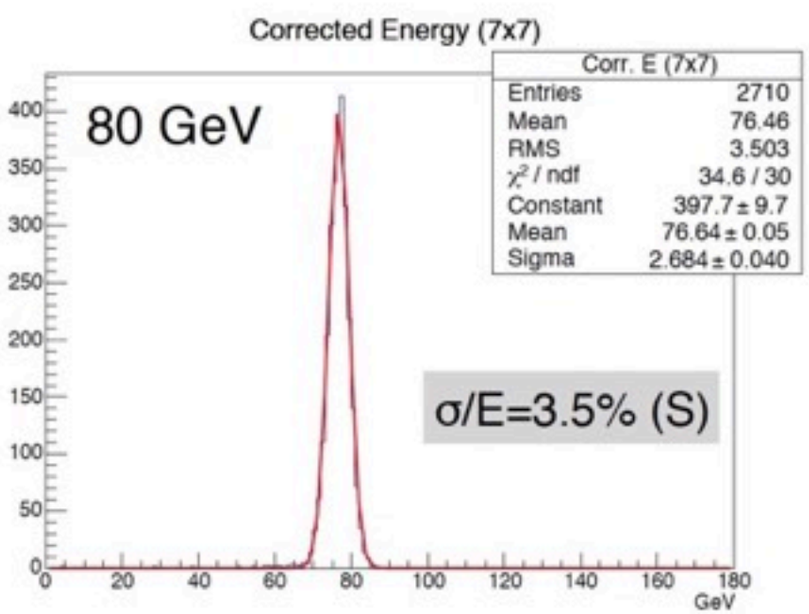
What we get: μ ID

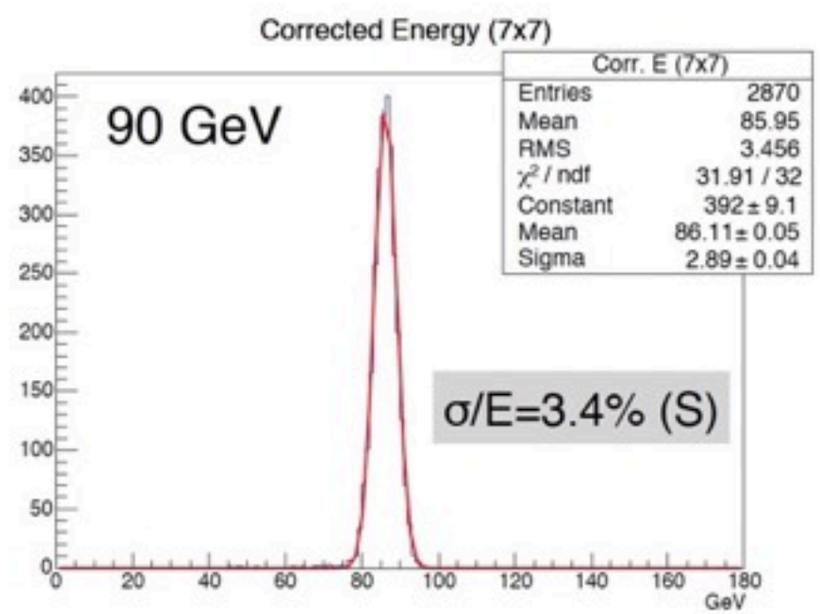


What we get: hadronic energy resolution (GEANT4 - BERT_HP code)

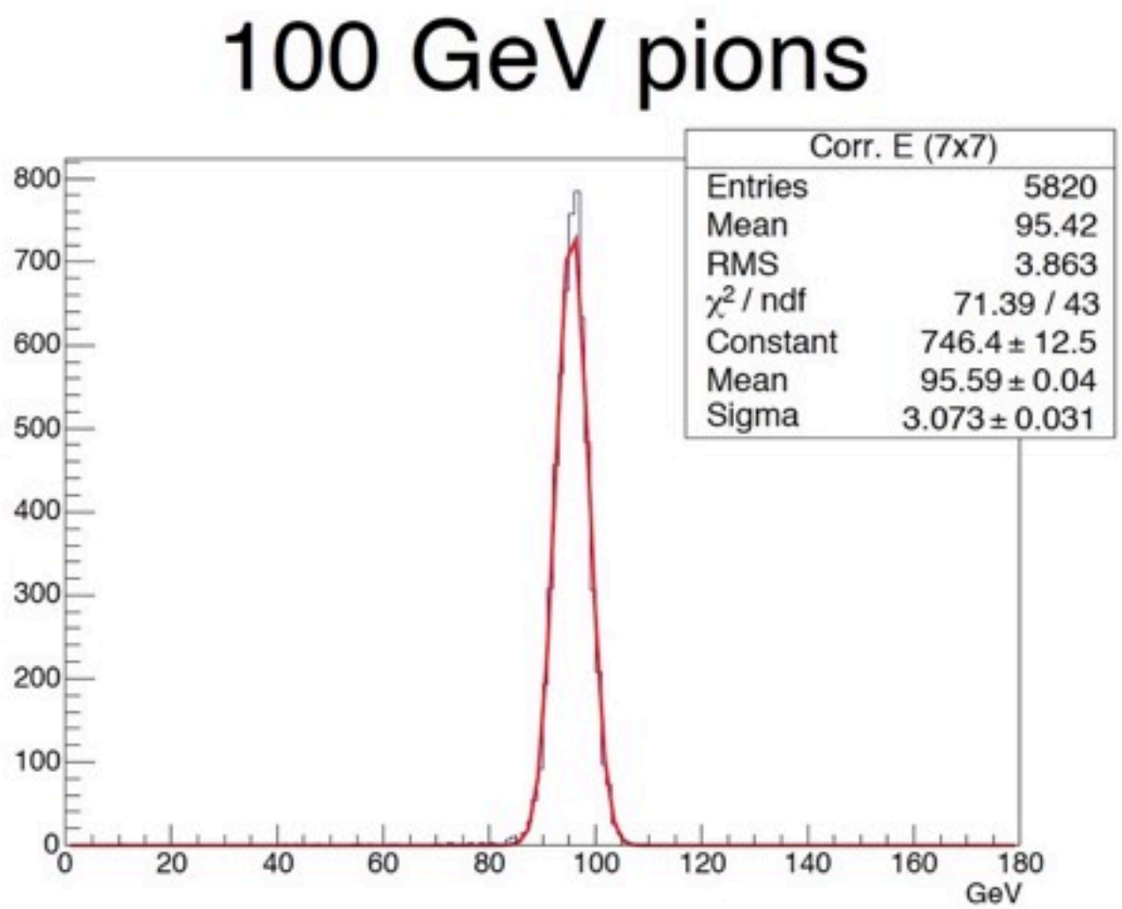
50 GeV, 80 GeV, and 90 GeV pions (GEANT 4 simulation)

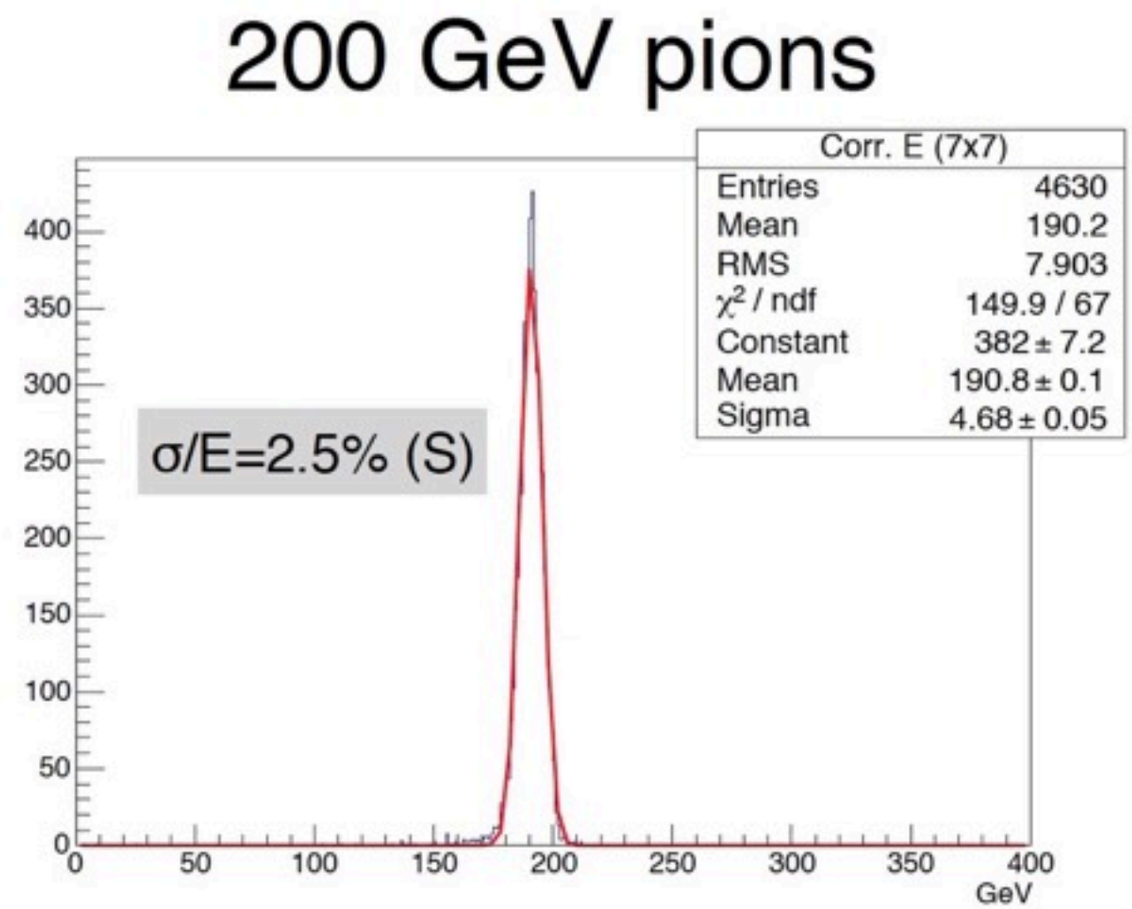




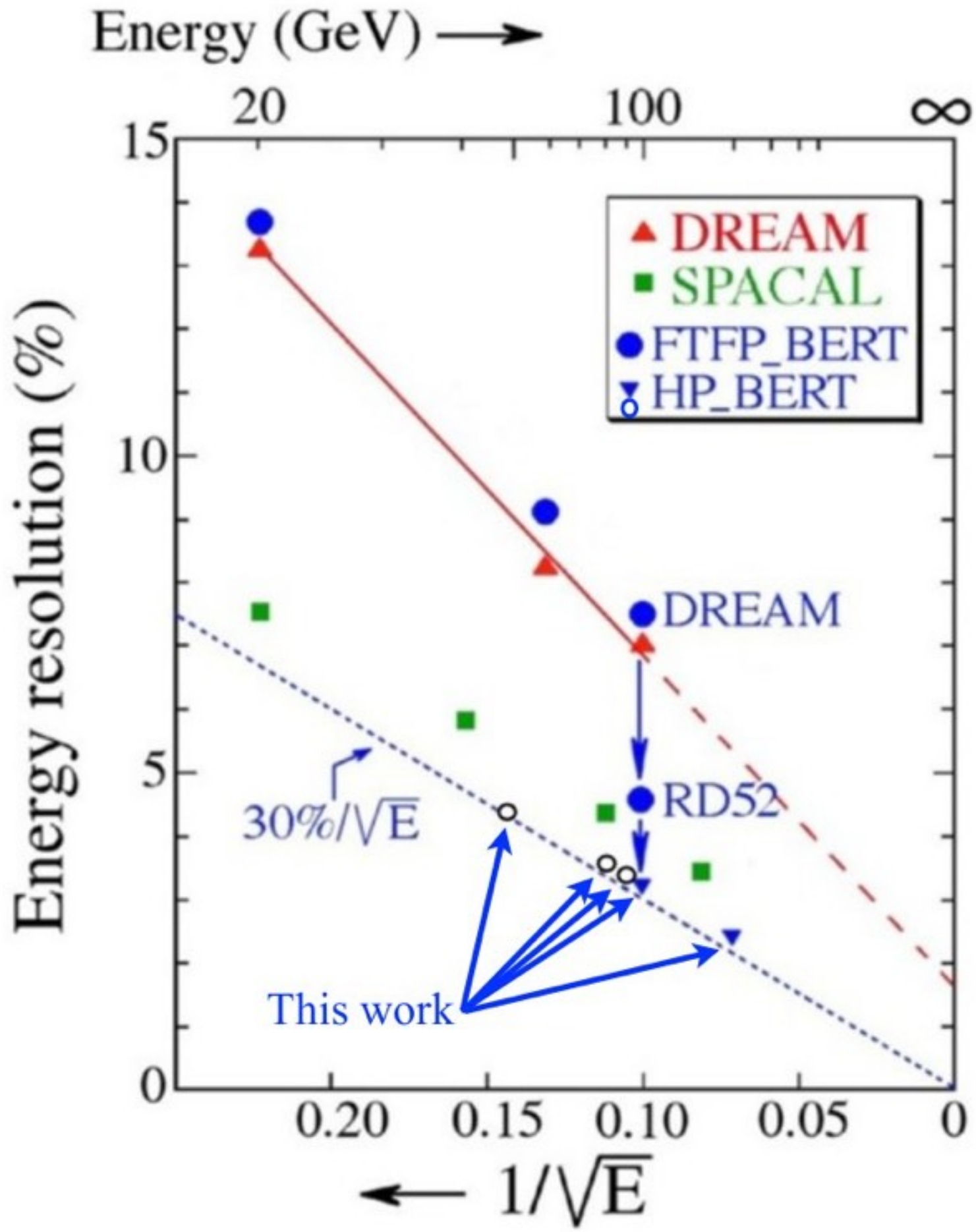


What we get: hadronic energy resolution (GEANT4 - BERT_HP code)

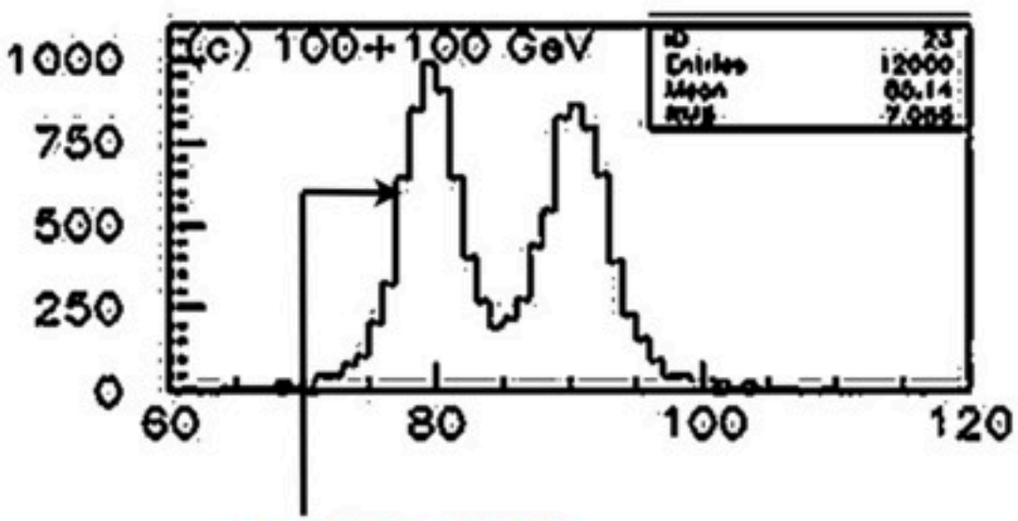




Hadronic energy resolution

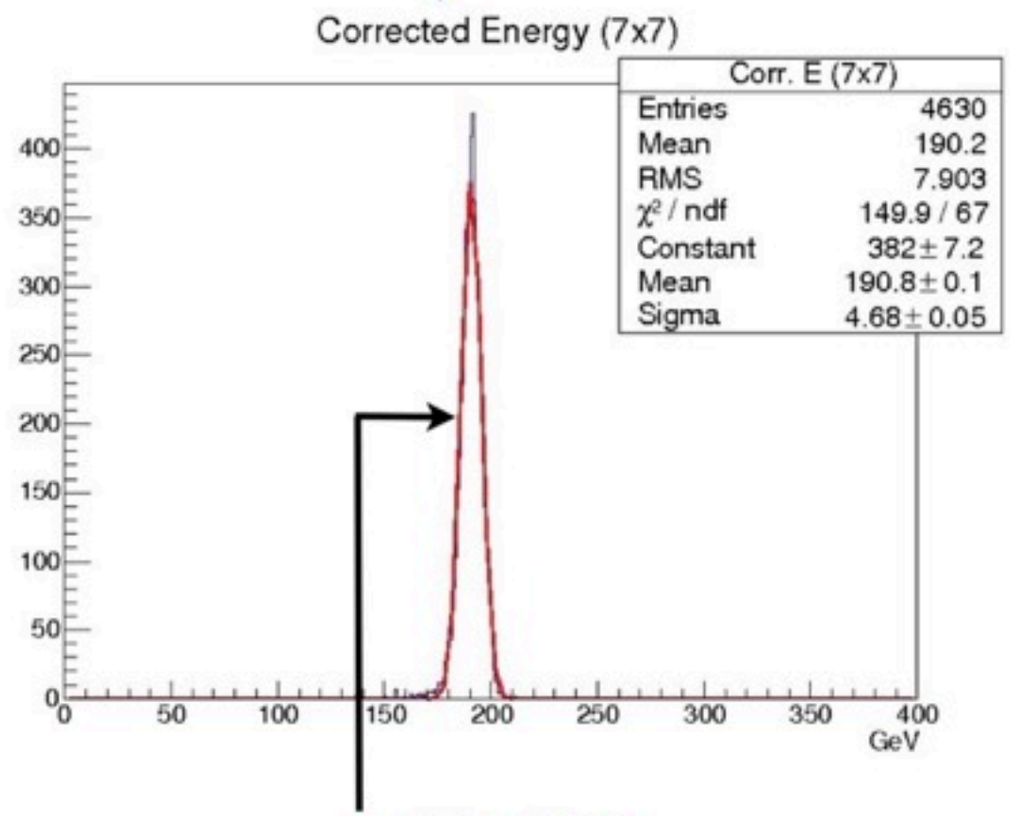


200 GeV
DREAM
W & Z



$\sigma_M/M \approx 2.5\%$

200 GeV
GEANT/DREAM
hadronic shower

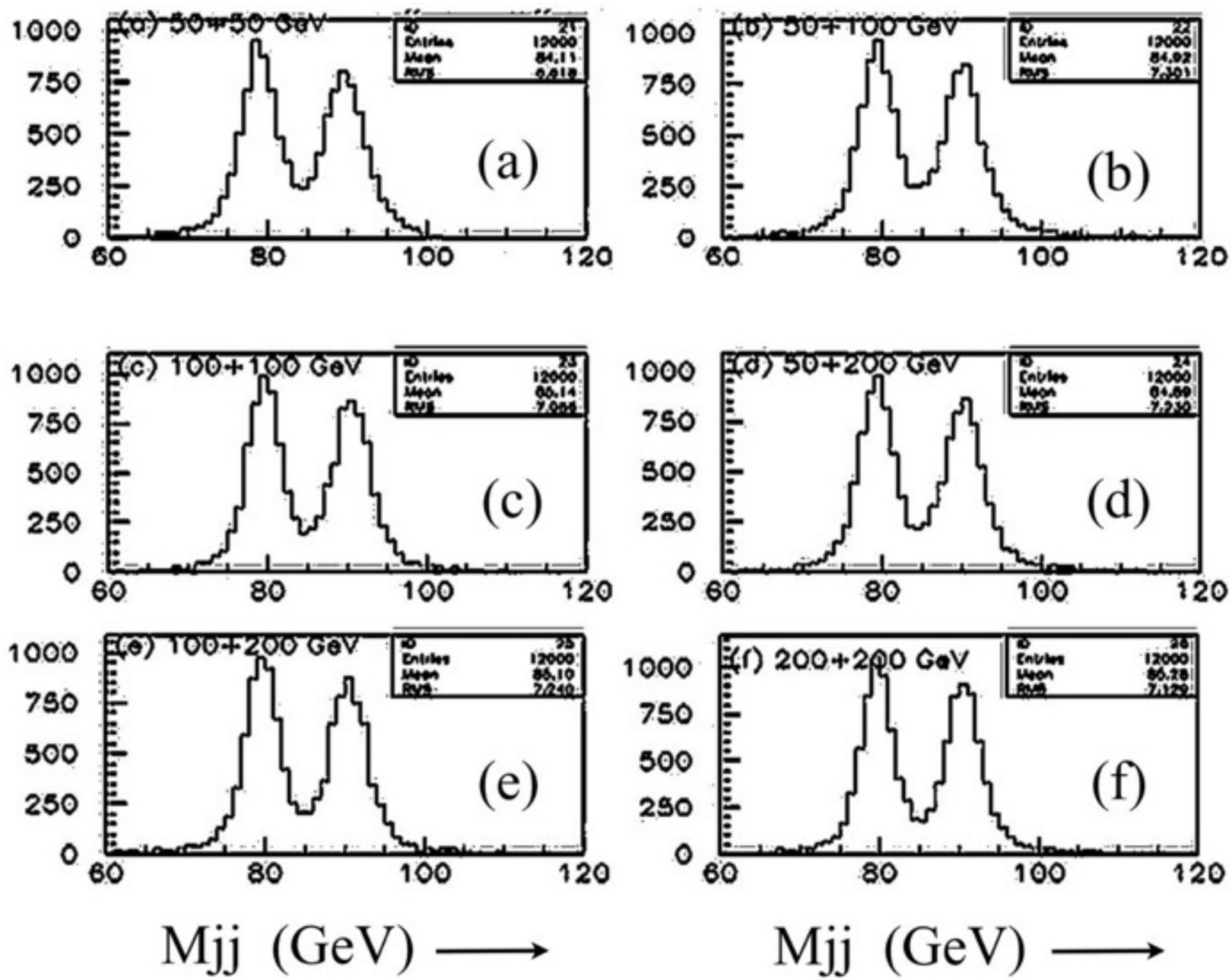


$\sigma_E/E \approx 2.3\%$

Leakage-suppressed
page 15, Fig. (e)

Making $W \to q\bar{q}$ and $Z \to q\bar{q}$ events from two DREAM module leakage-suppressed events

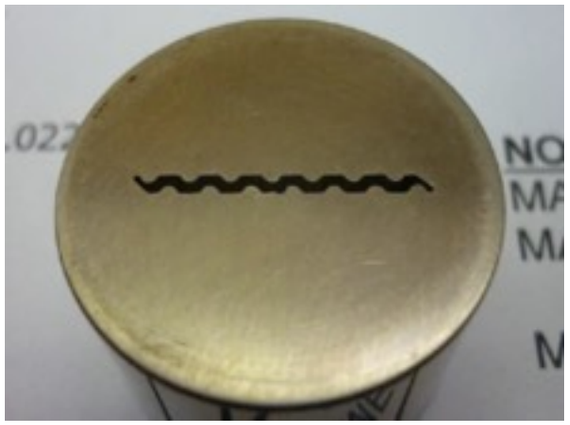
(a) 100 GeV
(b) 150 GeV
(c) 200 GeV
(d) 250 GeV
(e) 300 GeV
(f) 400 GeV



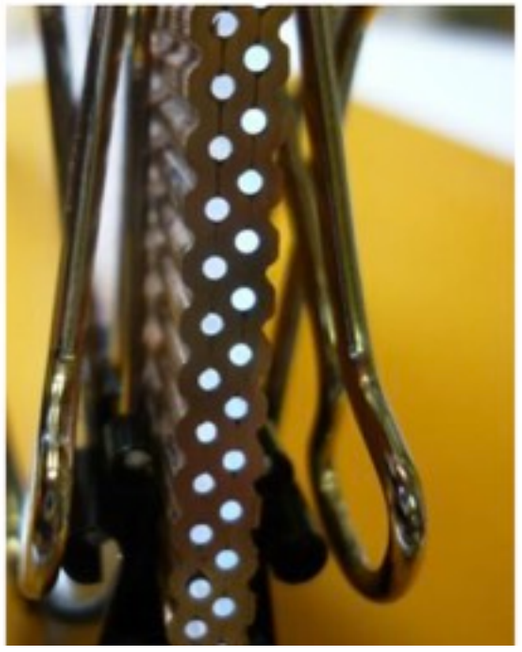
Next test beams:

- Use SiPMs instead of PMTs (Oct. 2016 CERN test)
- Build a large multi-ton copper module (final judgment on dual-readout depends on this)

Extrusion

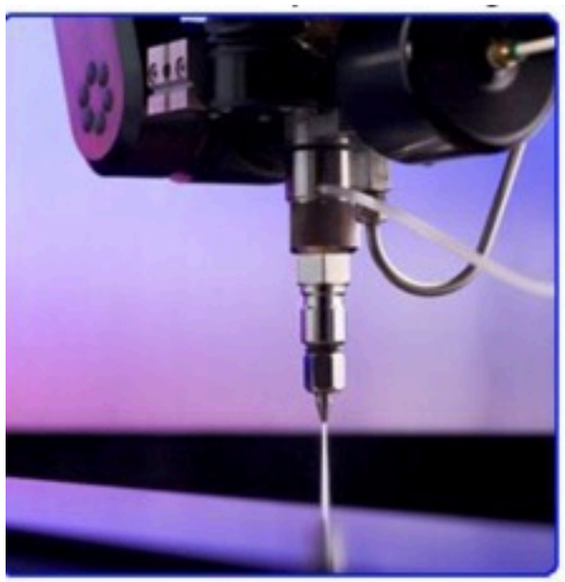


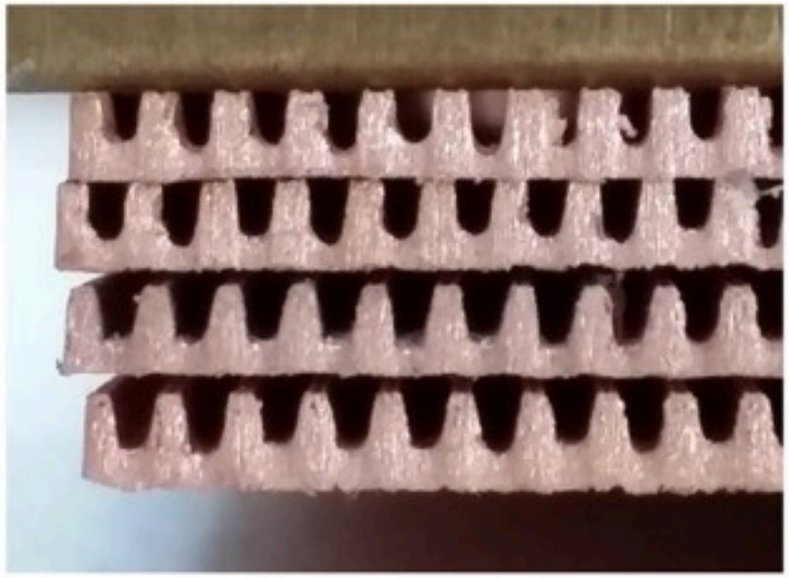
Rolling (2-sided)



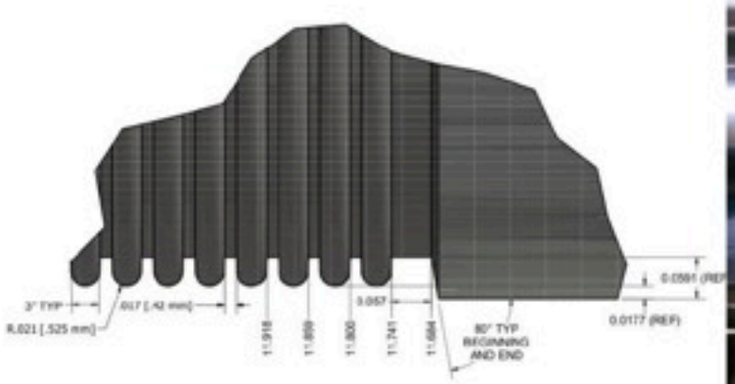
Sawing

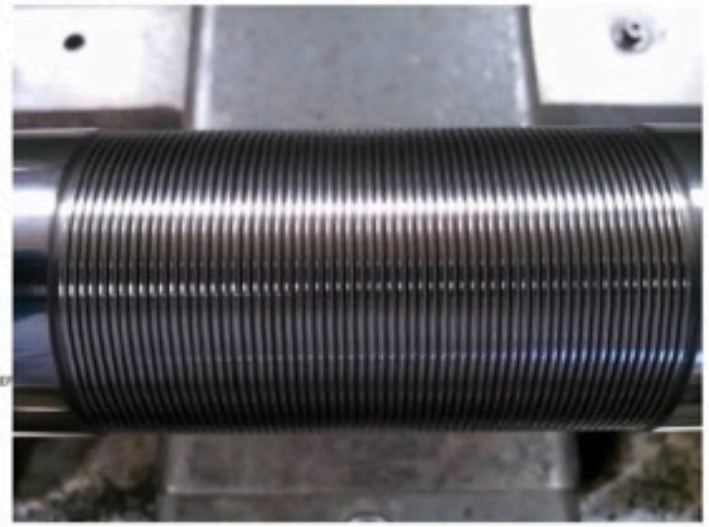
Water-jet & rolling (1-sided)



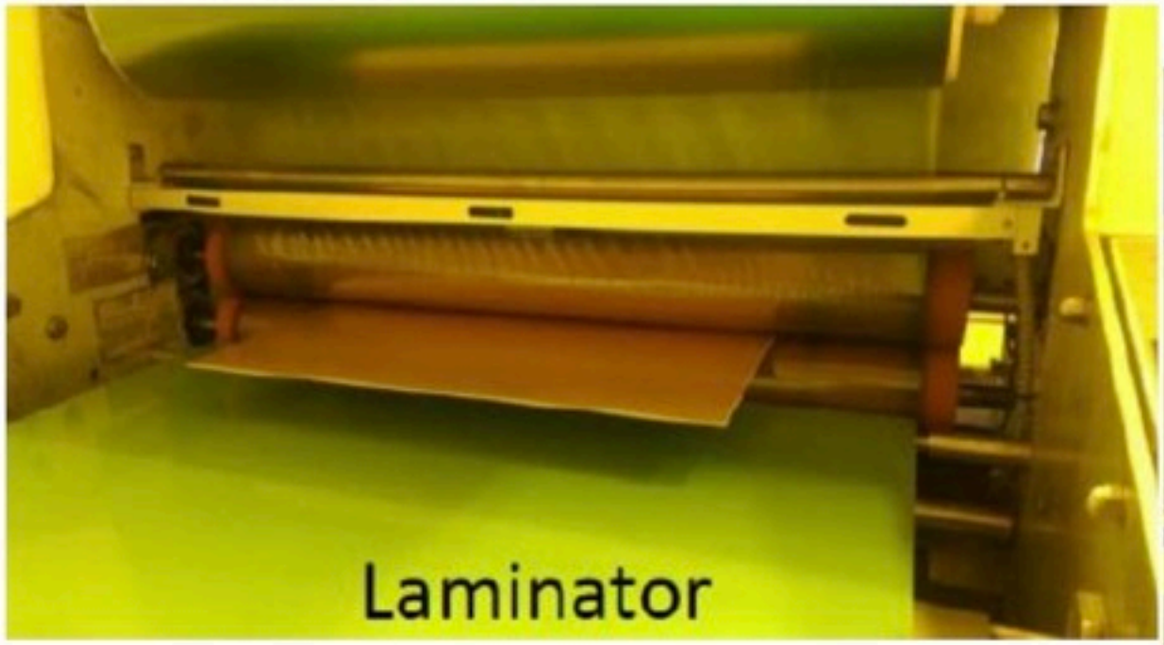


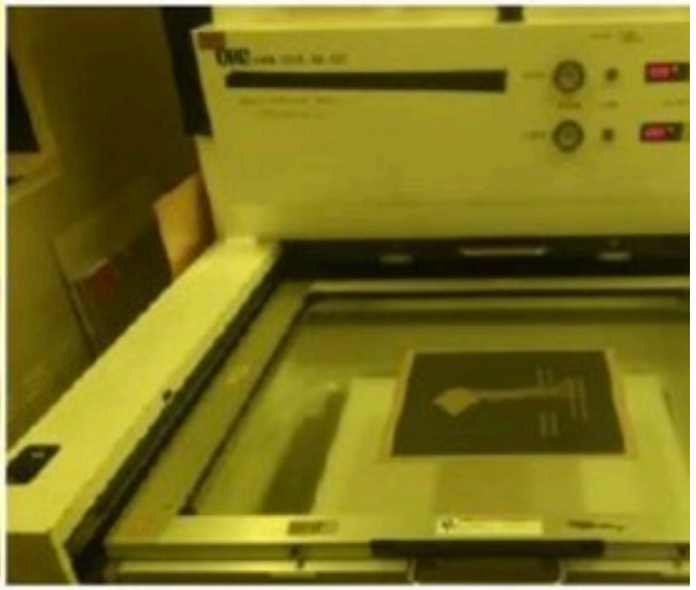
Additional rolling to smooth the surface and remove irregulari

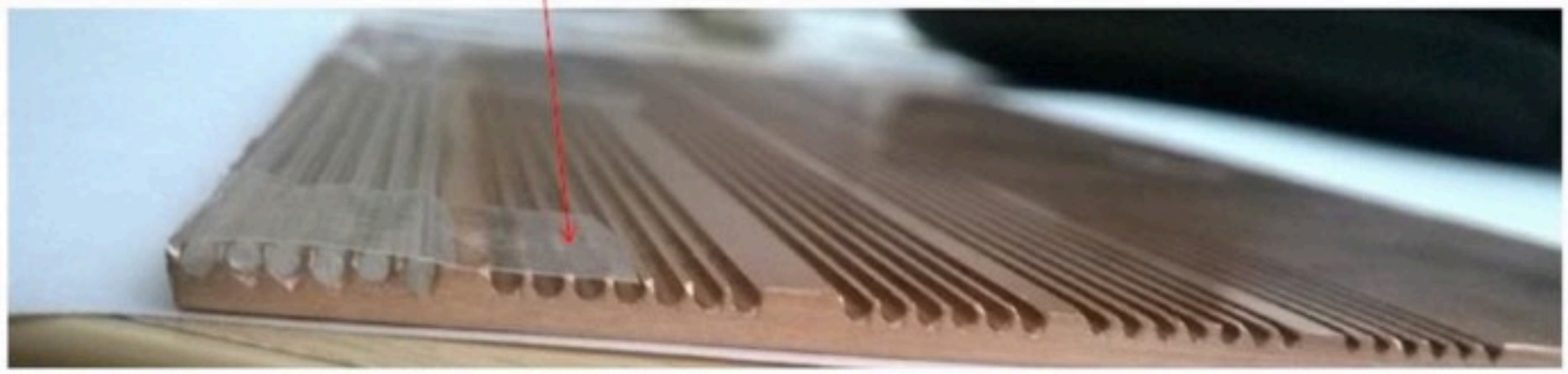




Chemical milling







ask slit width	300 µm	250 µm	200 µm	150 µm	100 µm
oove average depth (µm)	740	717	709	661	593

Fi
fir

When you have a lot of options, it means that none of them are any good. - Feynman

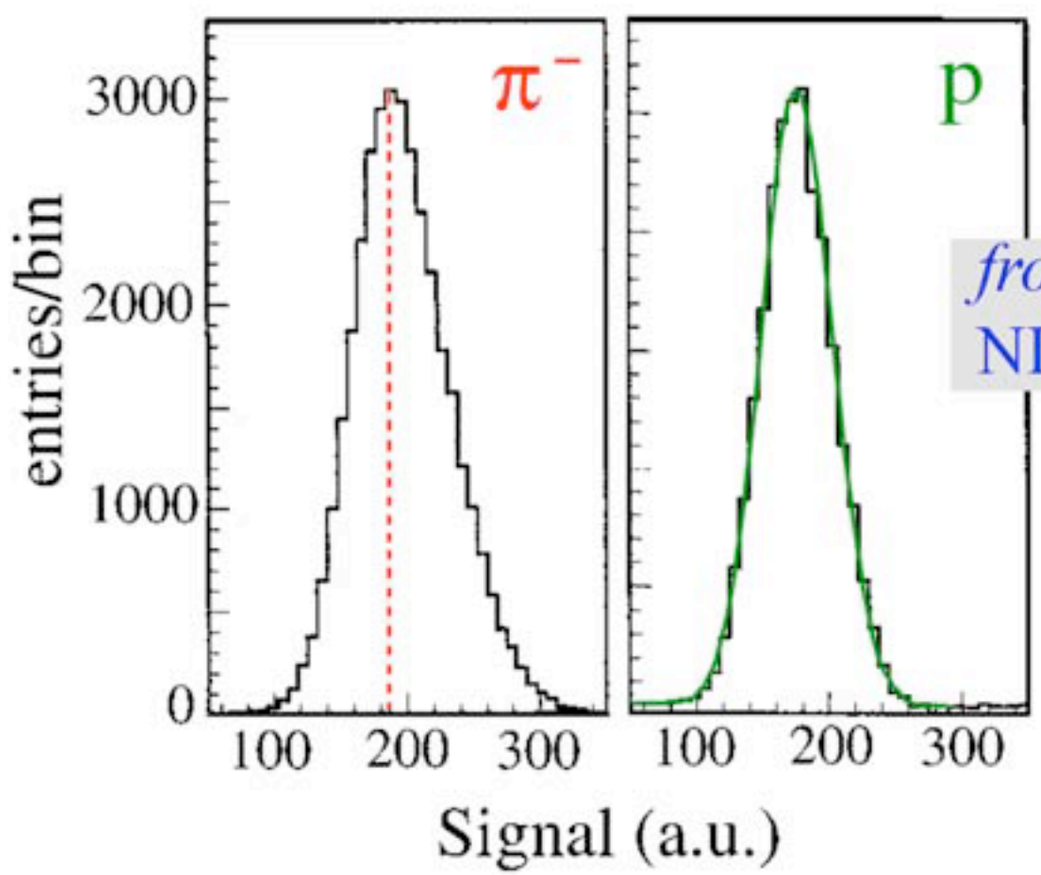
I think we will end up near

$$\sigma/E \approx 30\%/\sqrt{E} \oplus 0.5\%$$

and this will require careful uniformity control of the copper forming to 1%, reflectivity of the Cerenkov fibers and attenuation correction to 1%, neutron measurements, and leakage control to 1%.

Thank you.

The em shower fraction, f_{em} (4)

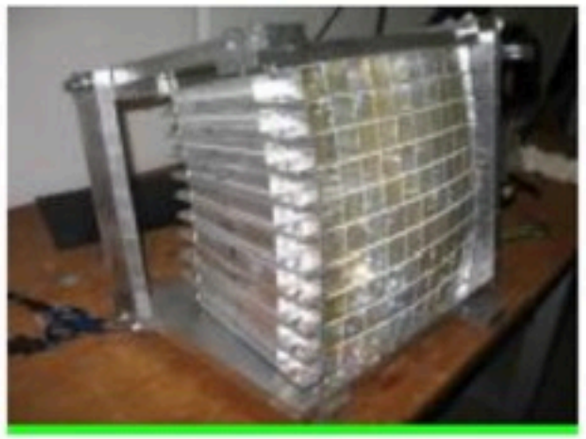


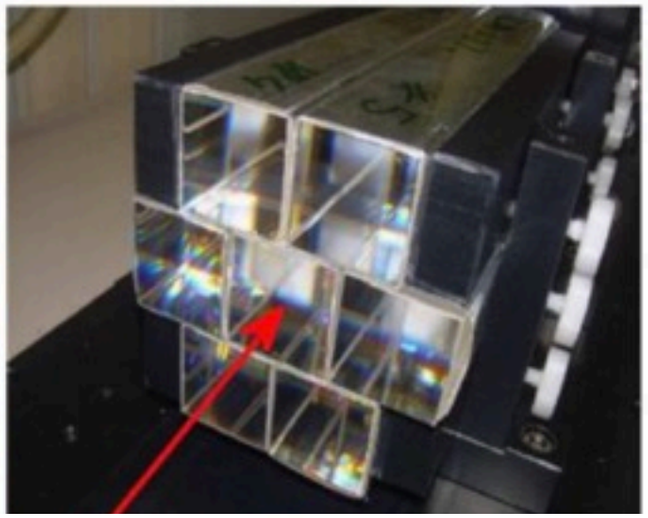
300 GeV showers in Cu

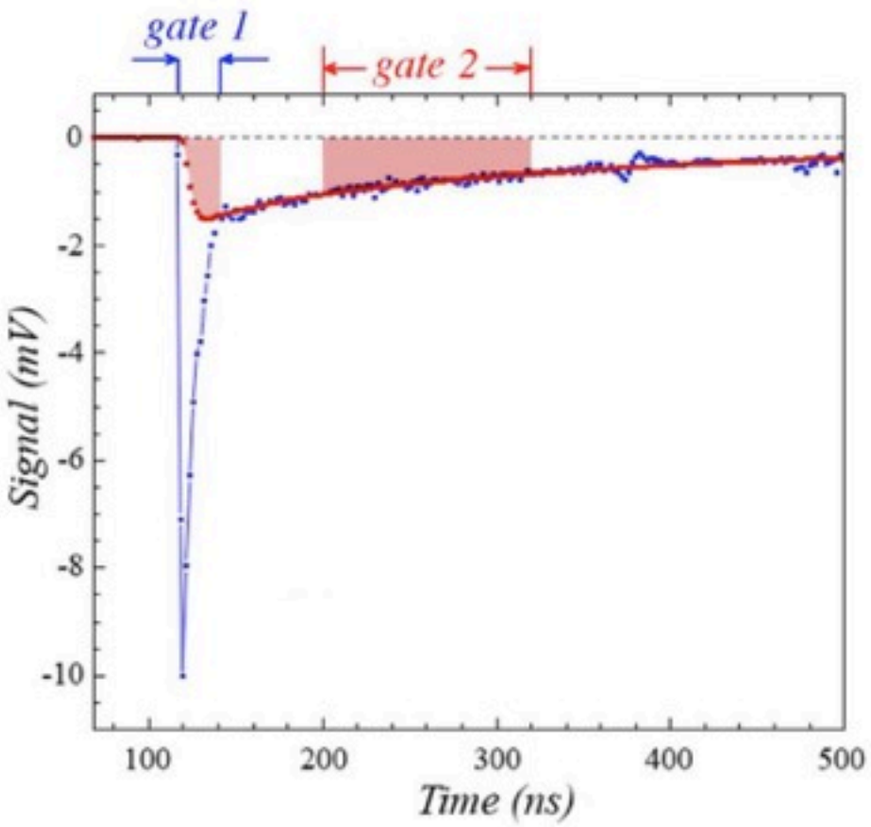
from:
NIM A408 (1998) 380

f_{em} fluctuations are different in π- and *p*-induced showers

Dual readout with homogeneous materials (Crystals)





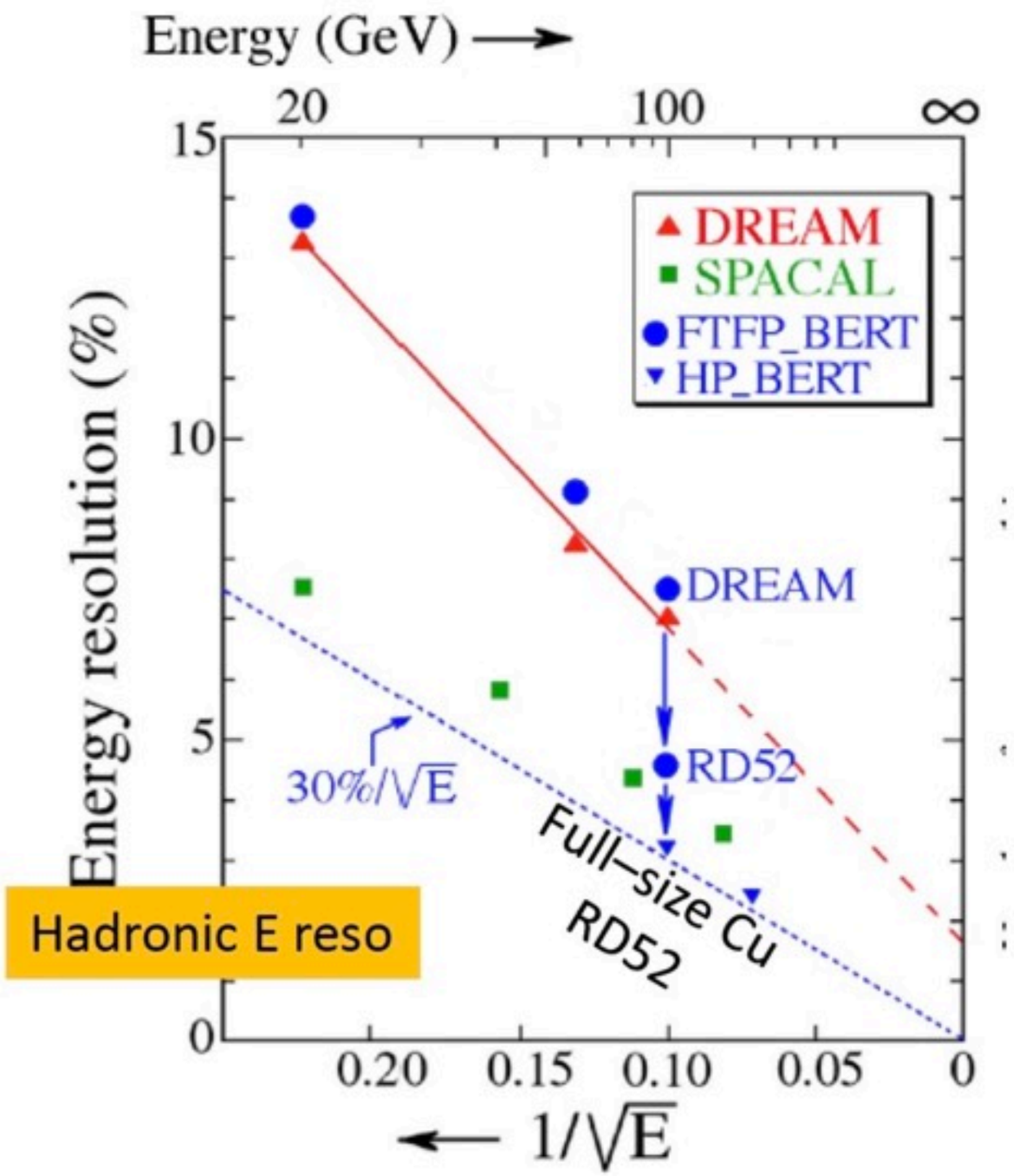


BGO crystal
UG 11 (UV) filter

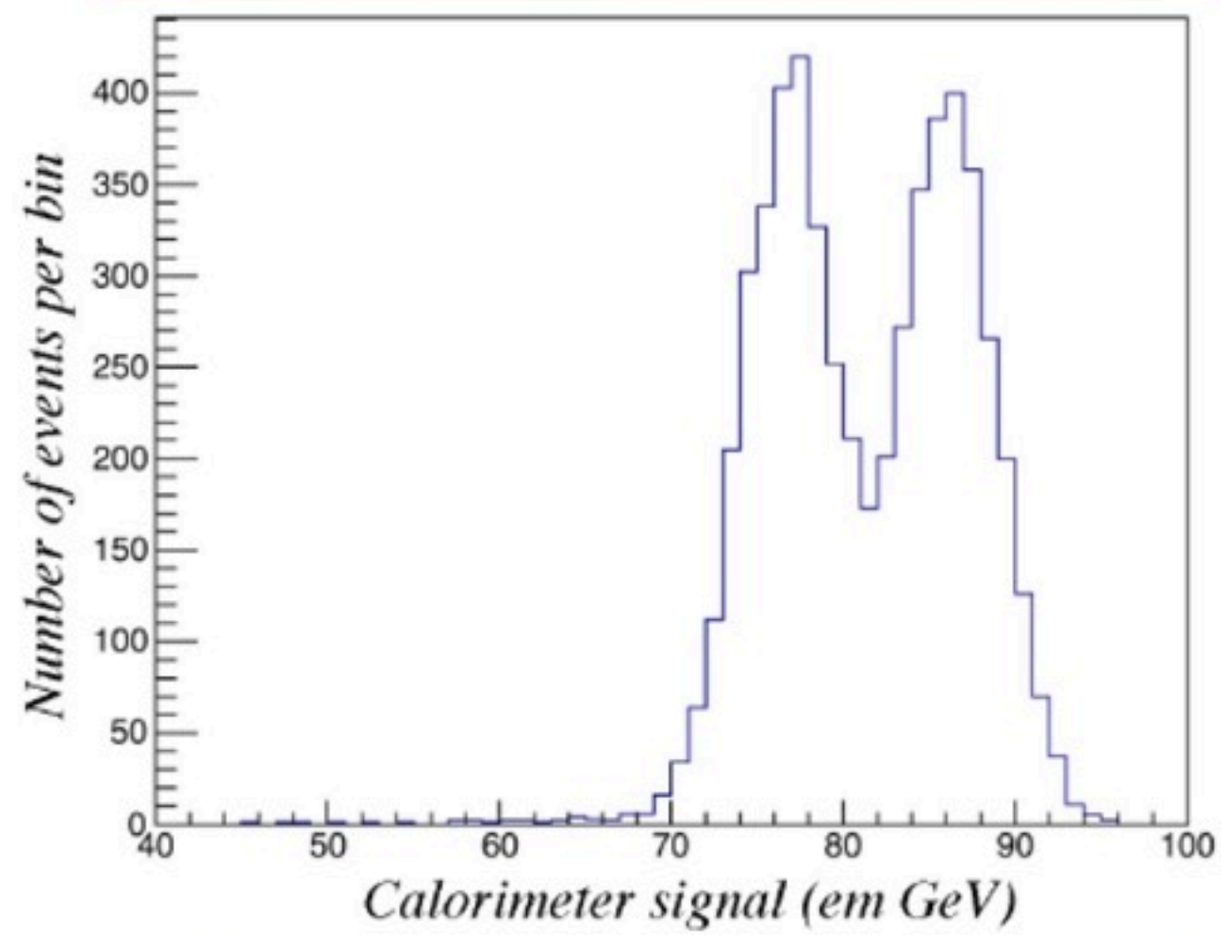
From:
NIM A595 (2008) 359

(BGO, BSO, PWO, PWO:Mo; comment)

What we get: hadronic energy resolution (GEANT4 - BERT_HP code)

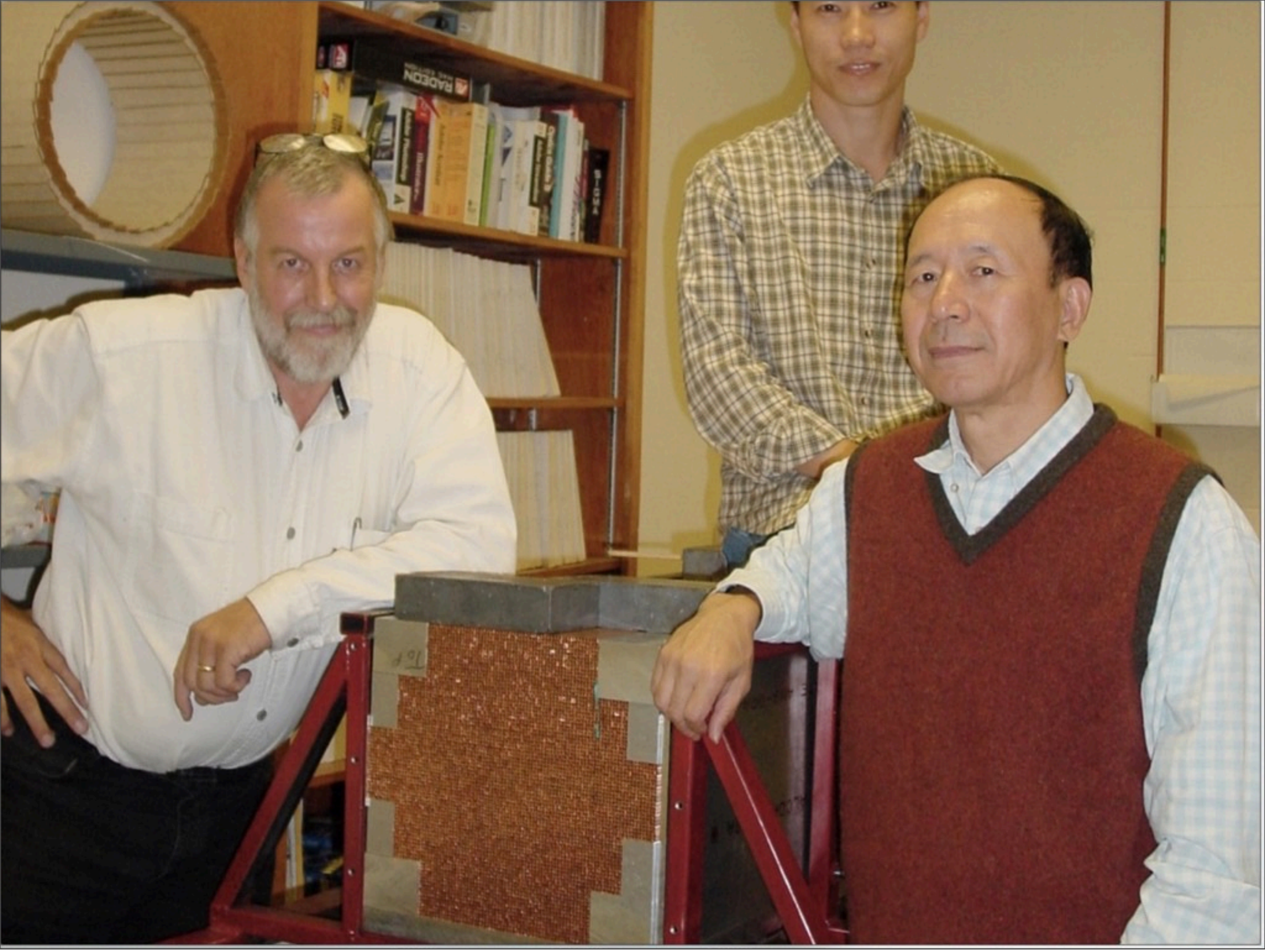
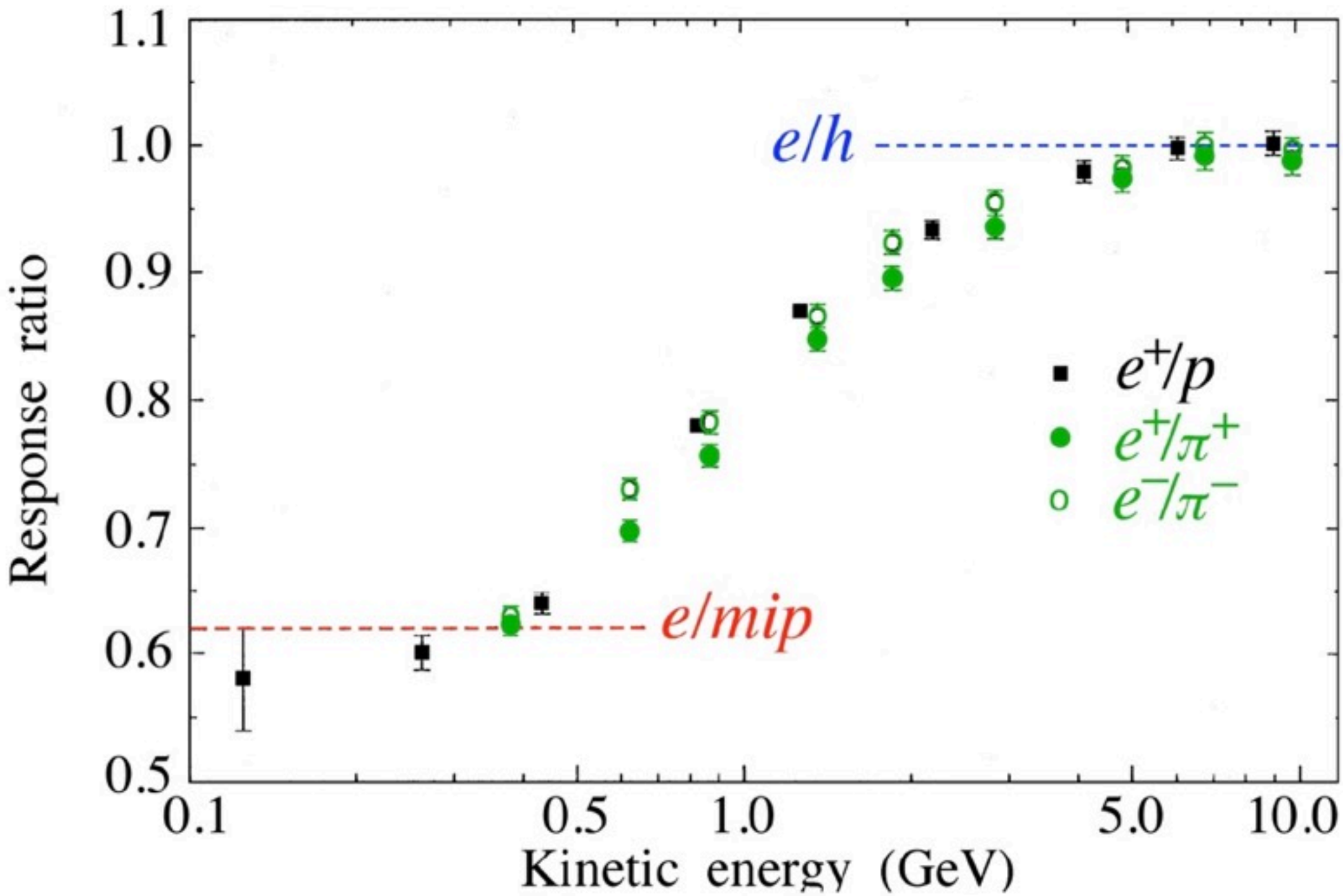


W/Z hadronic decay separation, high precision GEANT4 full-size Cu RD52



Goal for future e+e- accelerators

Scalar (spin=0)	Fermions (spin $= \frac{1}{2}\hbar$)			Bosons (spin $= 1\hbar$)		
"inertia maker"	2.55 MeV/c^2 $u^{+2/3}$ "up"	1.27 GeV/c^2 $c^{+2/3}$ "charm"	171.3 GeV/c^2 $t^{+2/3}$ "top"	weak force	electro-magnetic force(QED)	strong color force(QCD)
				weak charge	electric charge	color charge
125 GeV/c^2 H^0 "Higgs"	5.04 MeV/c^2 $d^{-1/3}$ "down"	0.105 GeV/c^2 $s^{-1/3}$ "strange"	4.201 GeV/c^2 $b^{-1/3}$ "bottom"			0 (exactly) g^0 "gluon"
	0.511 MeV/c^2 e^- "electron"	0.106 GeV/c^2 μ^- "muon"	1.777 GeV/c^2 τ^- "tau"	91.19 GeV/c^2 Z^0 "Z boson"	0 (exactly) γ^0 "photon"	
	1 meV/c^2 ν_e^0 "e neutrino"	8.8 meV/c^2 ν_μ^0 "μ neutrino"	50 meV/c^2 ν_τ^0 "τ neutrino"	80.40 GeV/c^2 $W^\pm$ "W boson"		
	1st	2nd	3rd			
	Generations of quarks and leptons			Boson force carriers		


RADEON

ZEUS results on low-energy hadronic nonlinearity