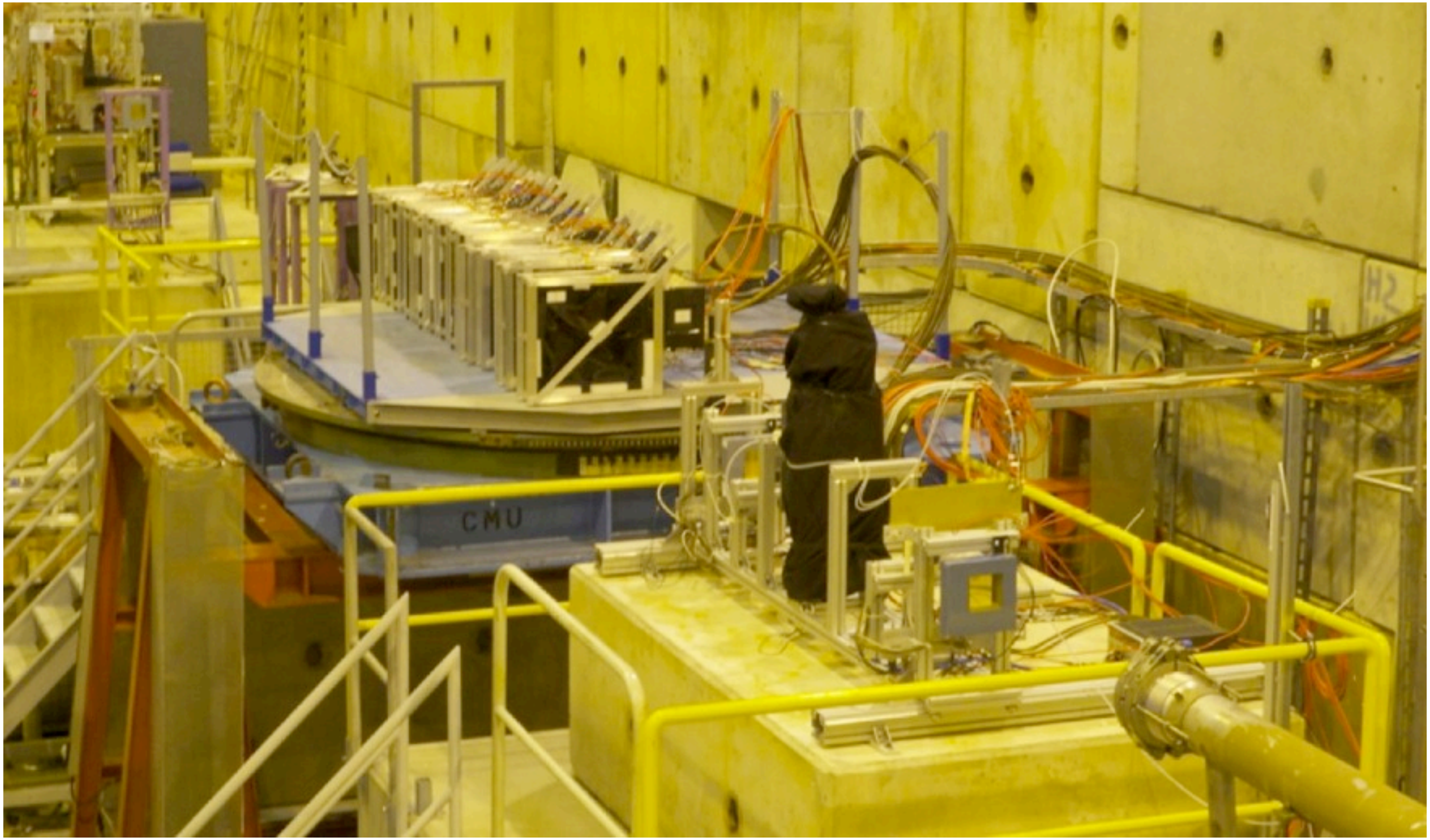
Recent Developments in Dual-readout Calorimetry

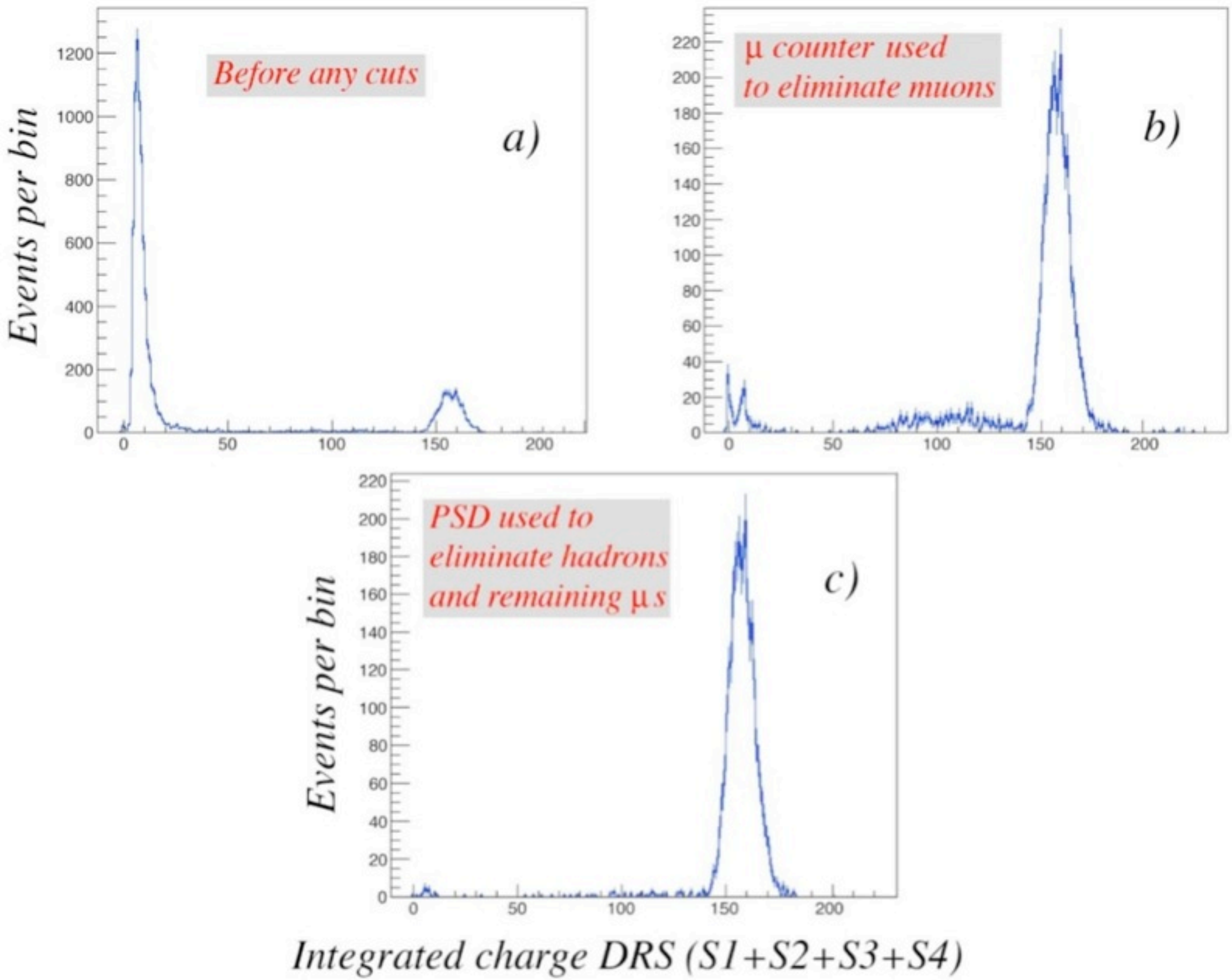
- new crystal measurements
  (essentially completes our work with crystals)
- polarization measurements
  (for fun, and maybe physics)
- energy resolution in small Pb modules, Cu *vs.* Pb
  (checking each step)
- the efficacy of measuring the escaping neutrons from hadronic showers
  (a beam module is finite-sized, all hadronic calorimeters leak neutrons)
- we are moving towards a 6-tonne module with small leakage
  (shower leakage effects, Cerenkov light yield, sampling fluctuations)
- W-based hadronic modules with twice the density of our Pb and Cu modules
  (potentially *huge* consequences for collider detectors)

John Hauptman, for the DREAM collaboration (RD52, CERN)
KILC, Daegu, 23-26 April 2012

Beam infrastructure: H8 CERN



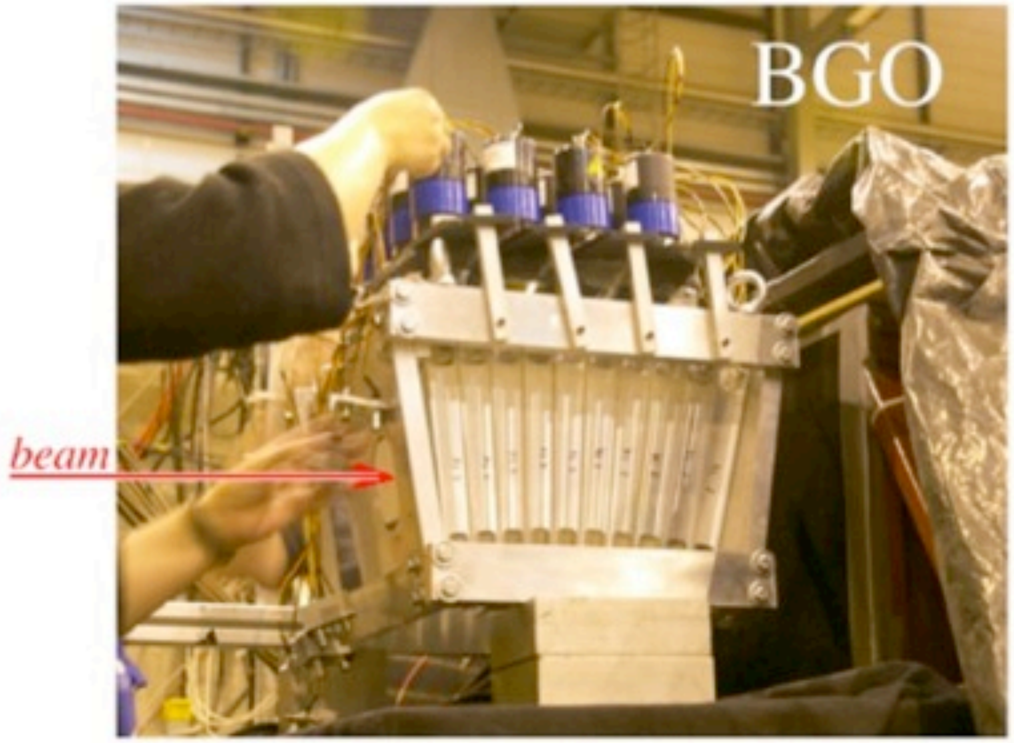
First, get a good beam: 160 GeV electrons

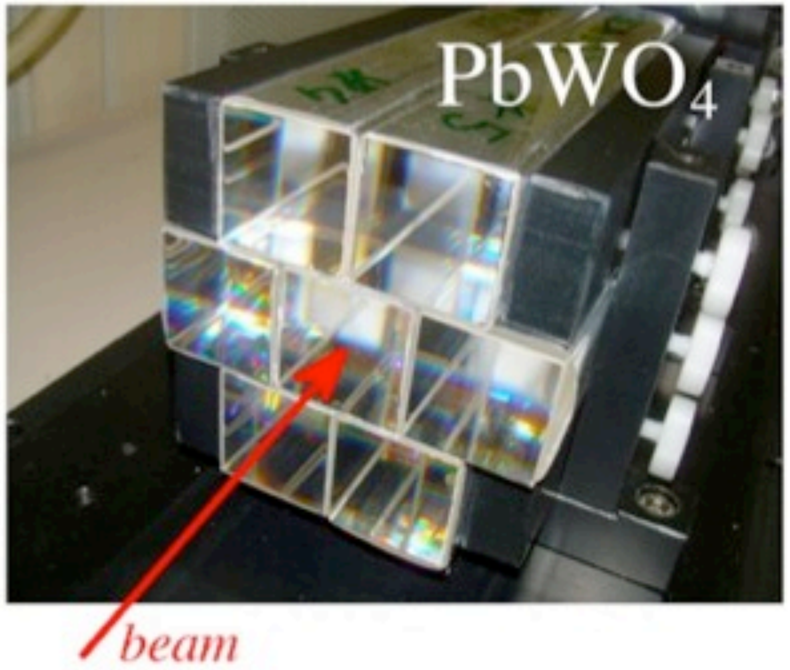


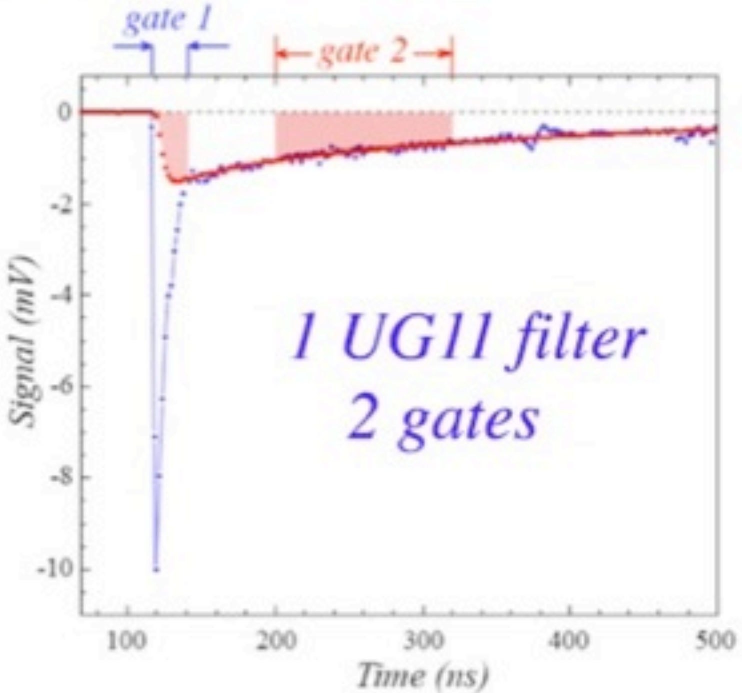
Crystal measurements

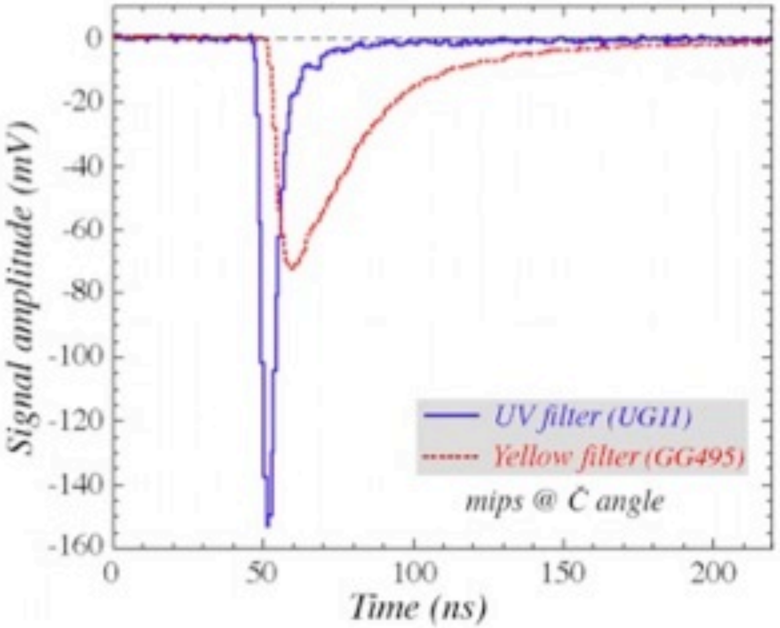
Tests of Dual-Readout crystal matrices with electron beams

Selection of Čerenkov, Scintillation signals



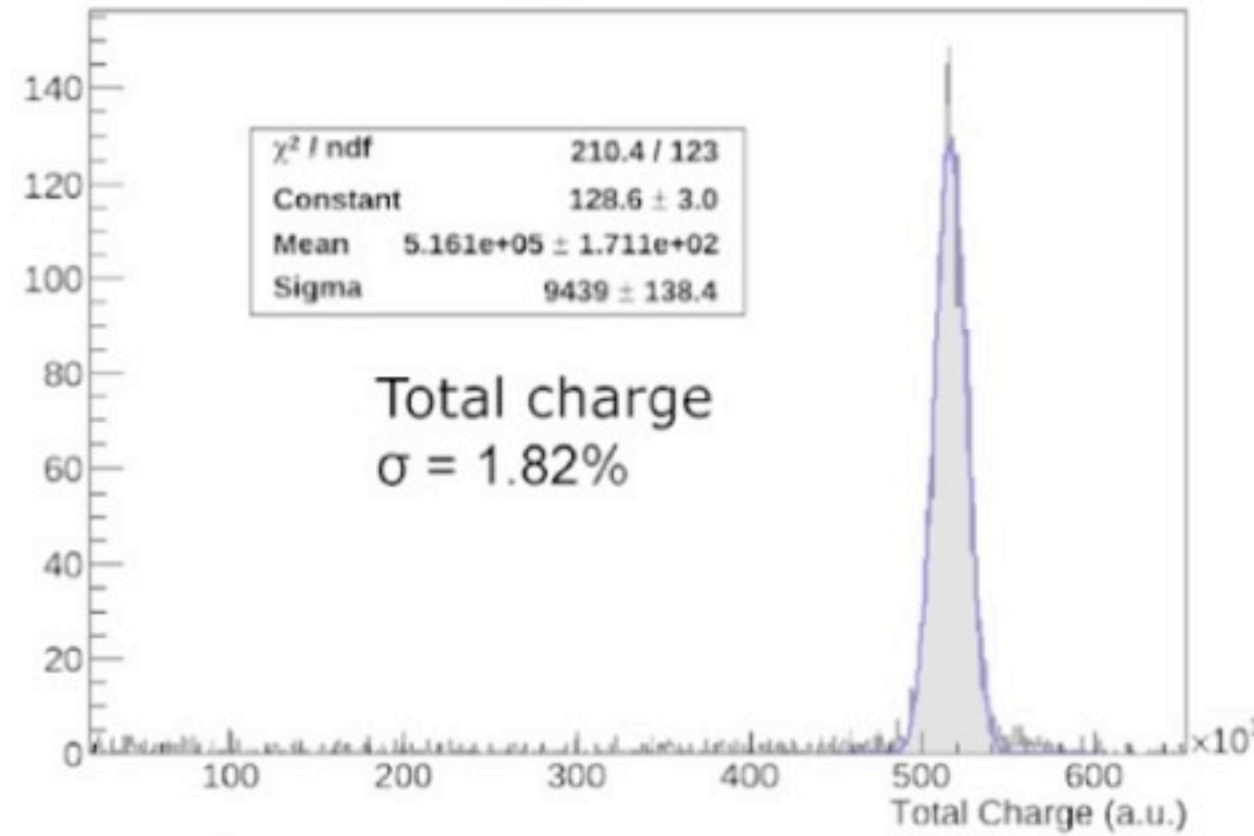


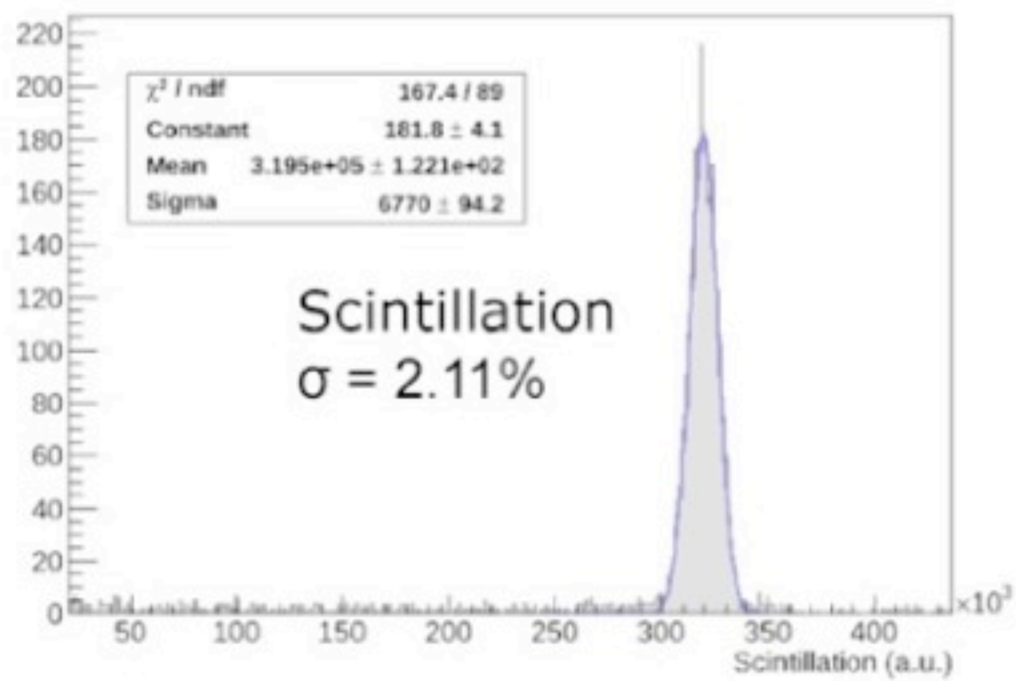


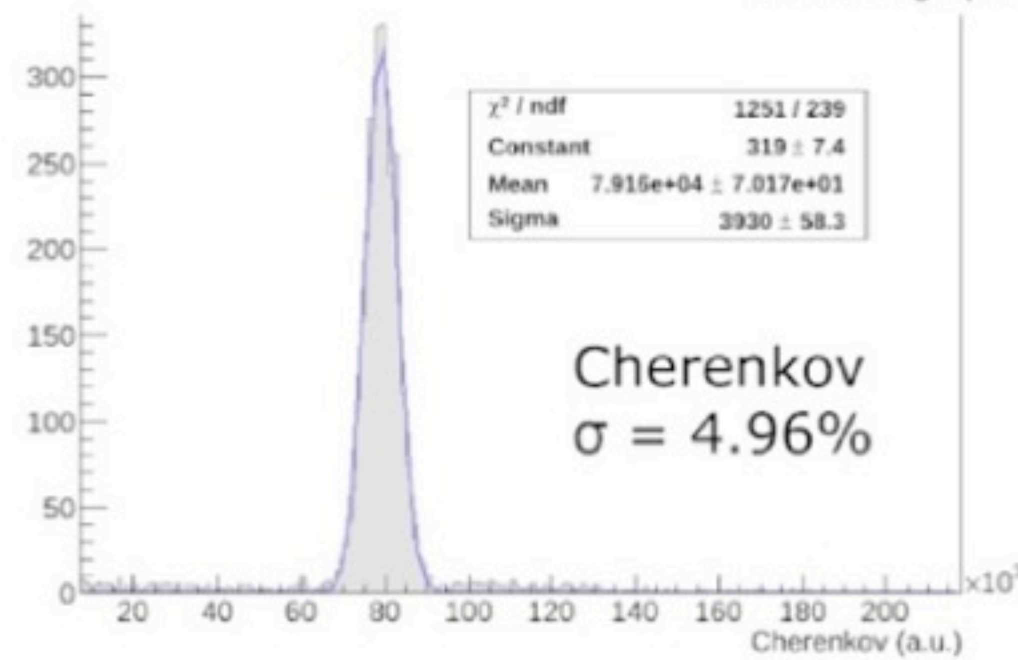


Dual-Readout BGO calorimeter: Resolution for 100 GeV electrons

Signals decomposed into Scintillating and Čerenkov components on the basis of their time structure

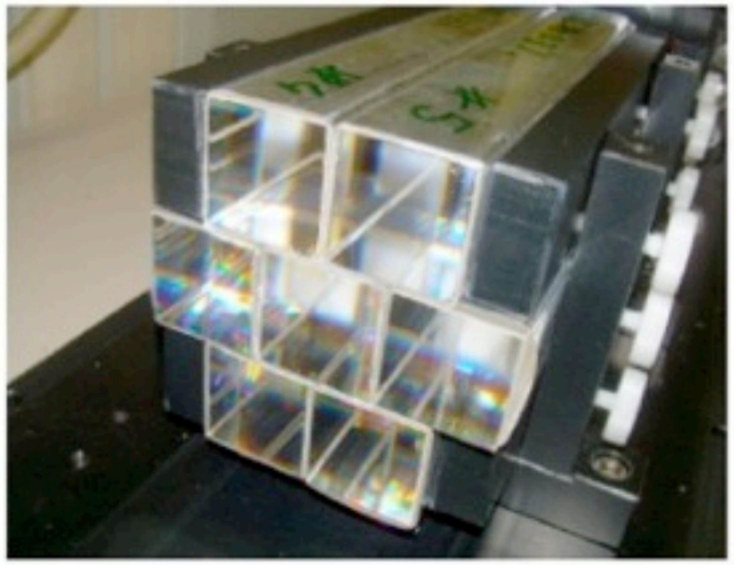




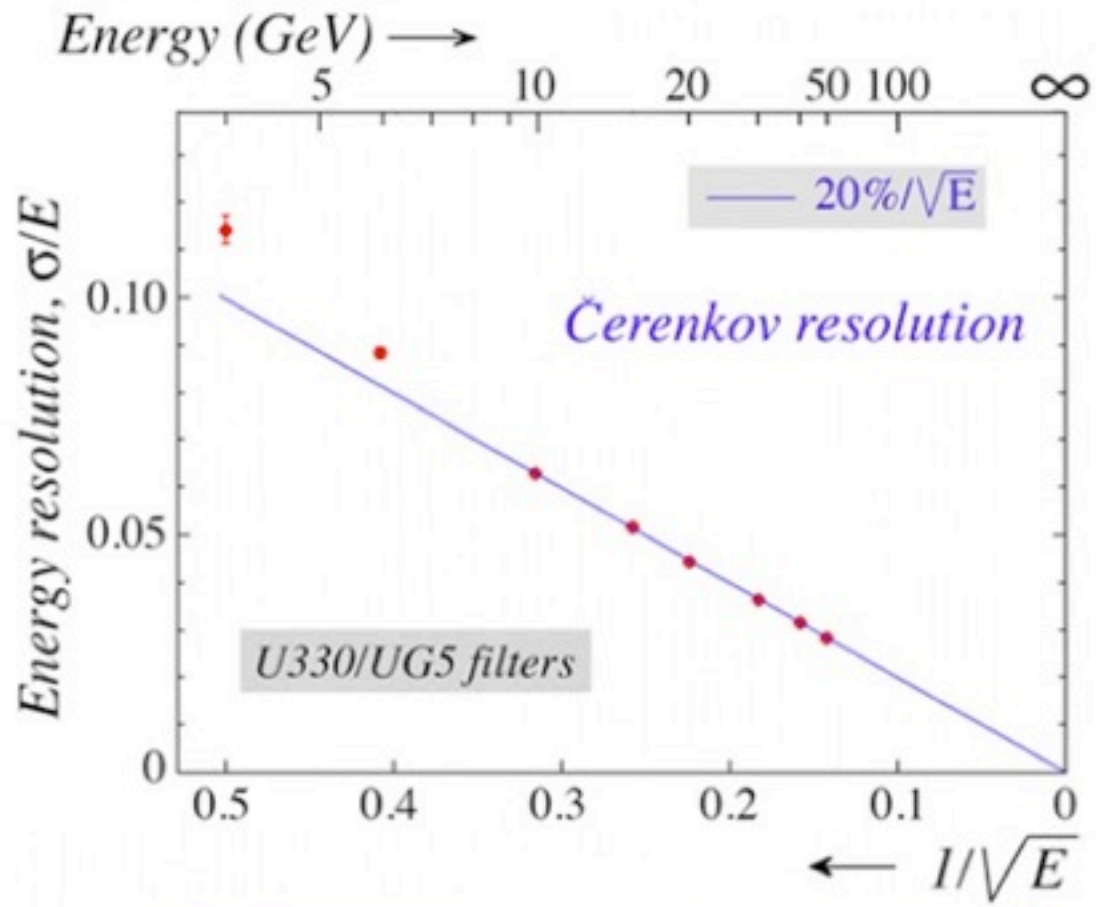


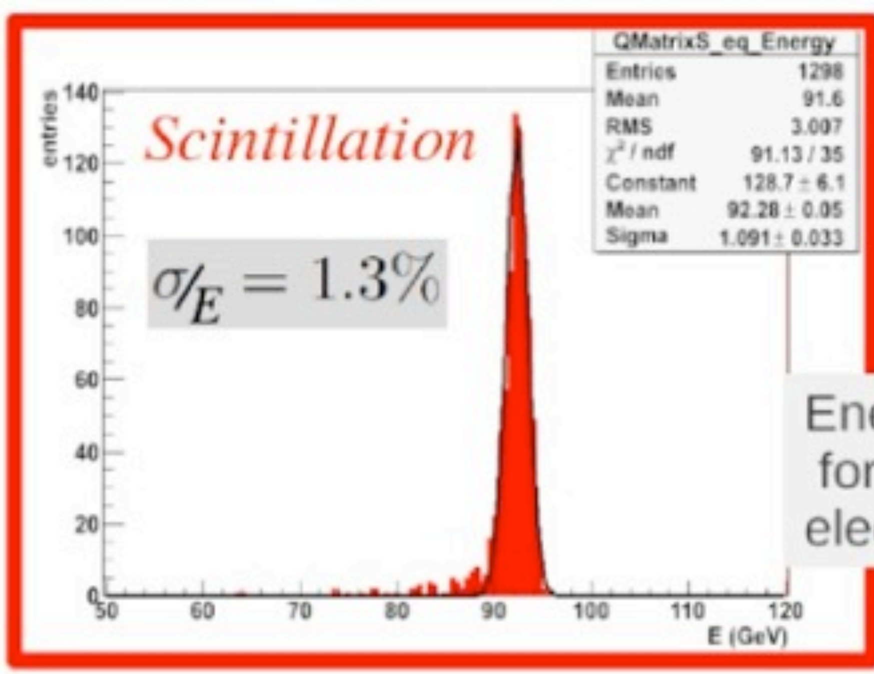
D. Pinci, IEEE, Valencia 2011

Dual-readout crystal calorimetry
S/C signal separation with filters

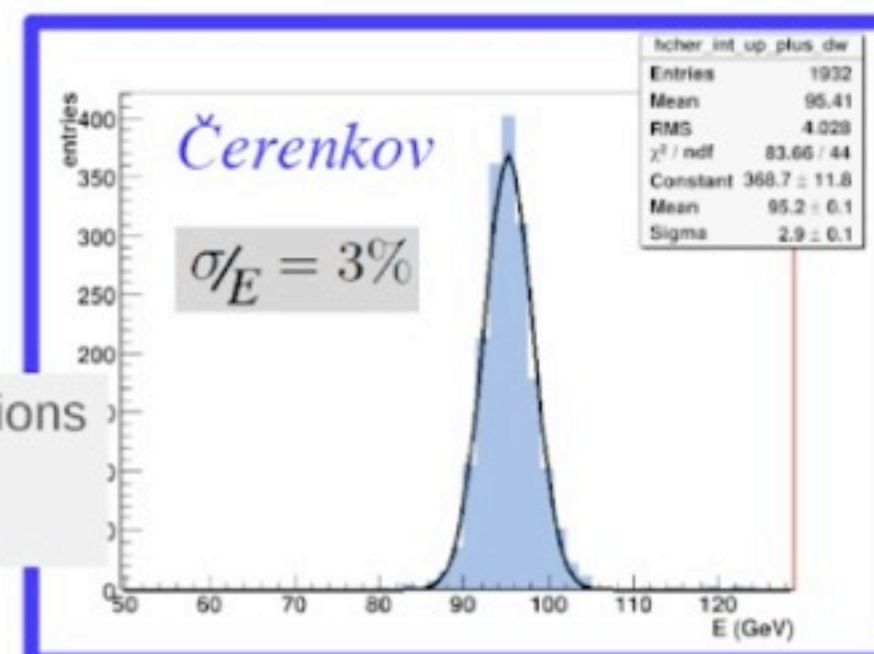


Mo-doped $PbWO_4$ crystal matrix
7 crystals, 3 x 3 x 20 cm^3



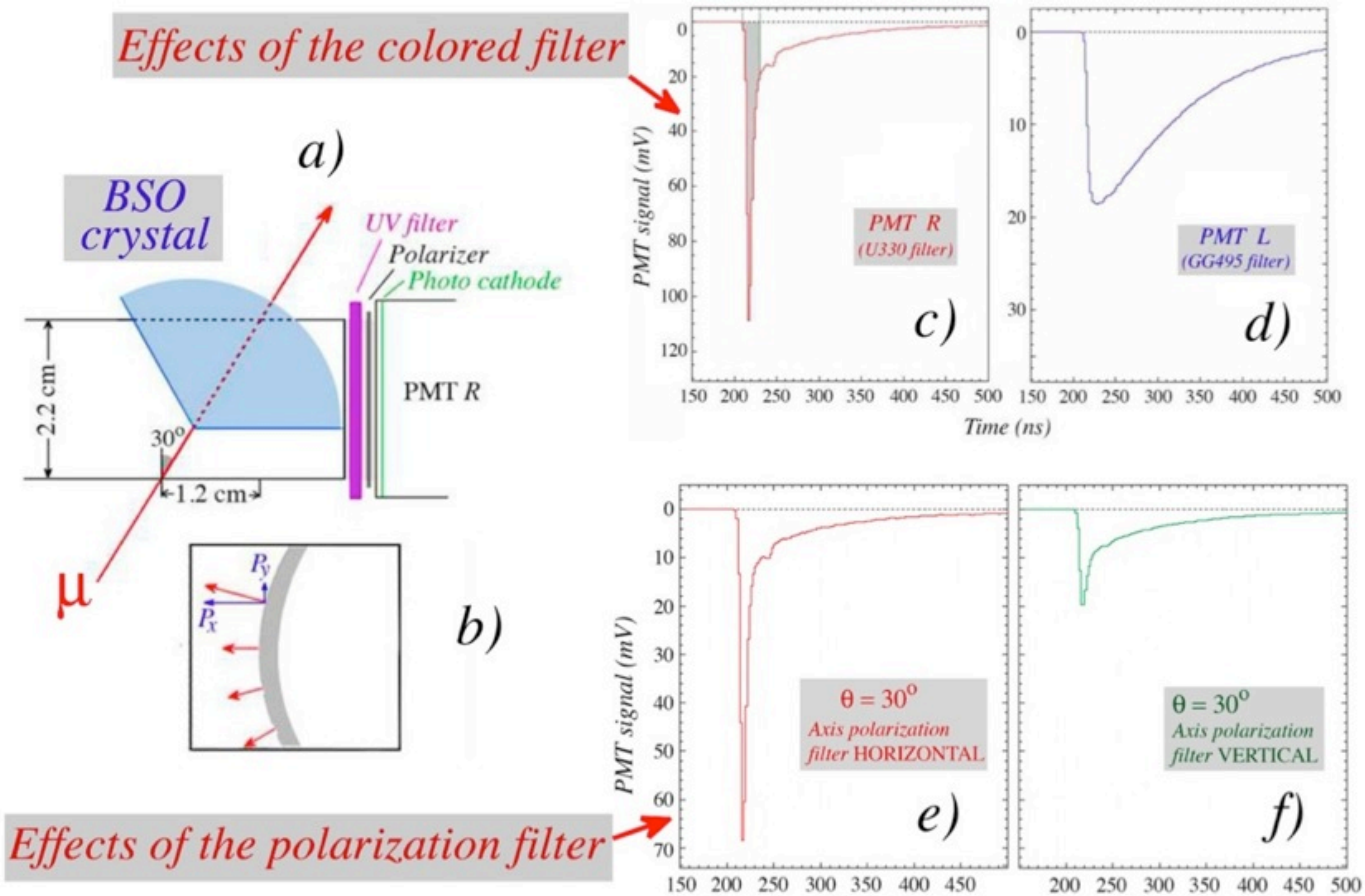


Energy distributions for 100 GeV electron beam



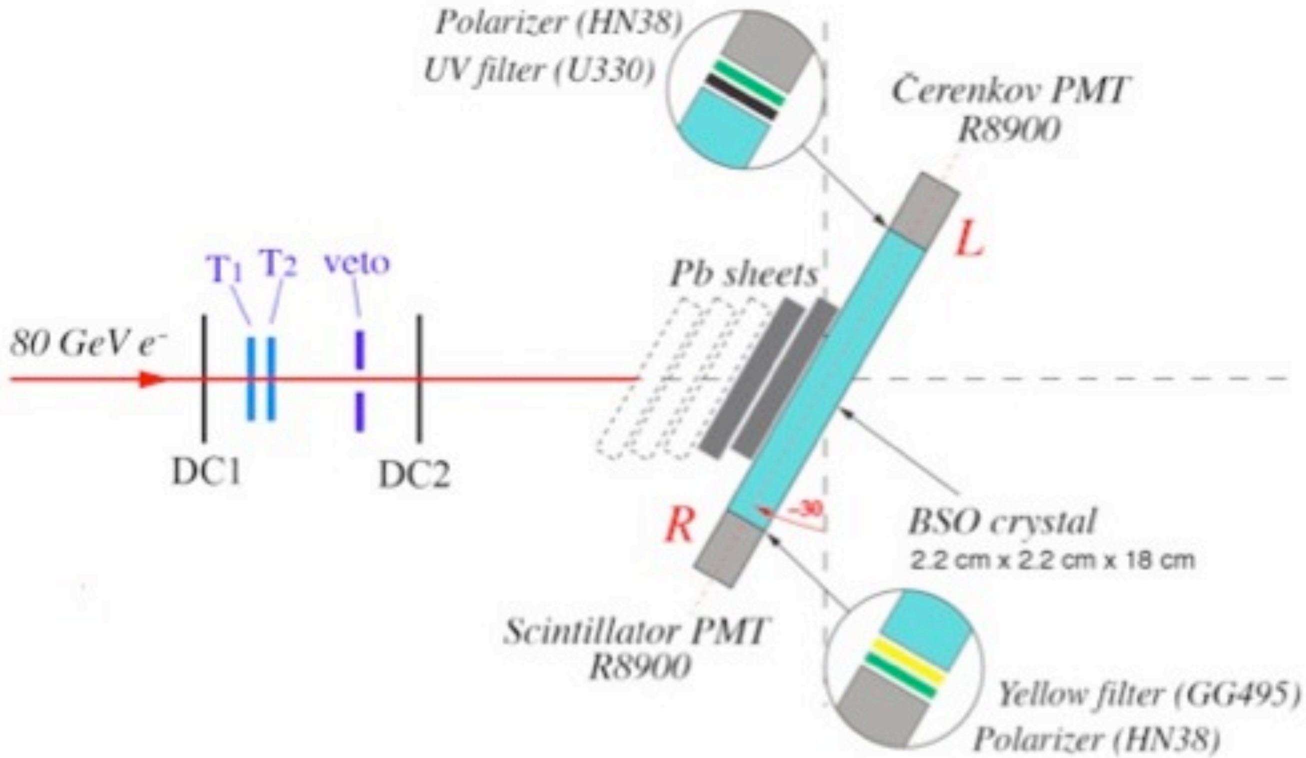
S. Franchino, IEEE, Valencia 2011

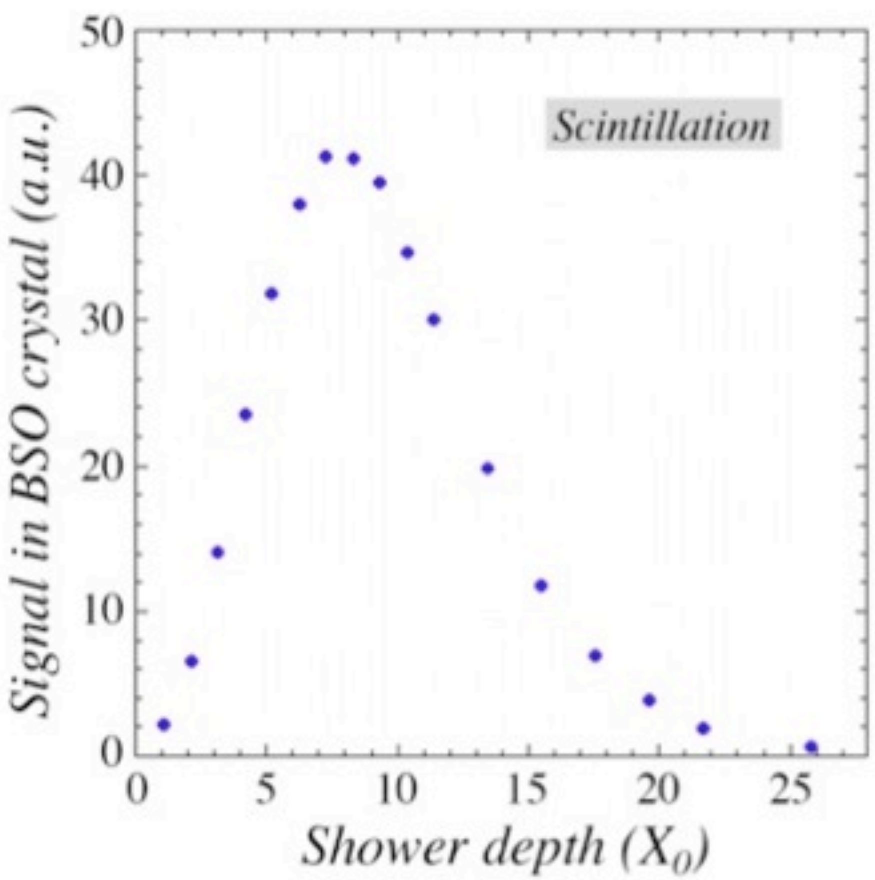
Polarization measurements

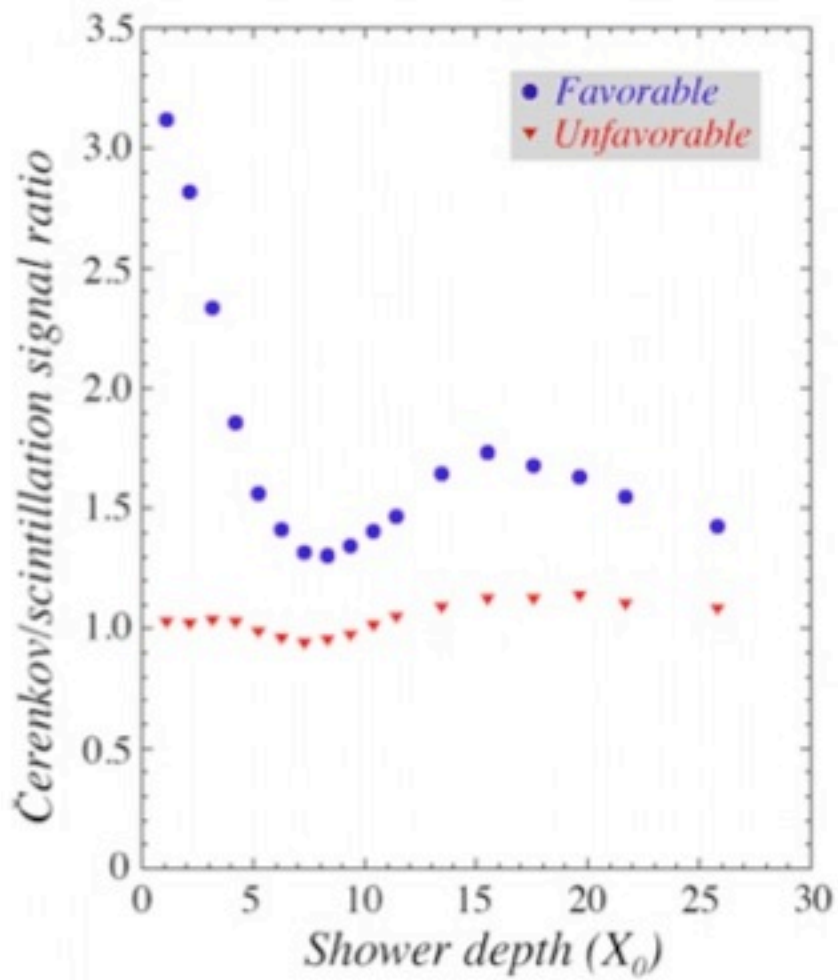


from: NIM A638 (2011) 47

Polarization measurements



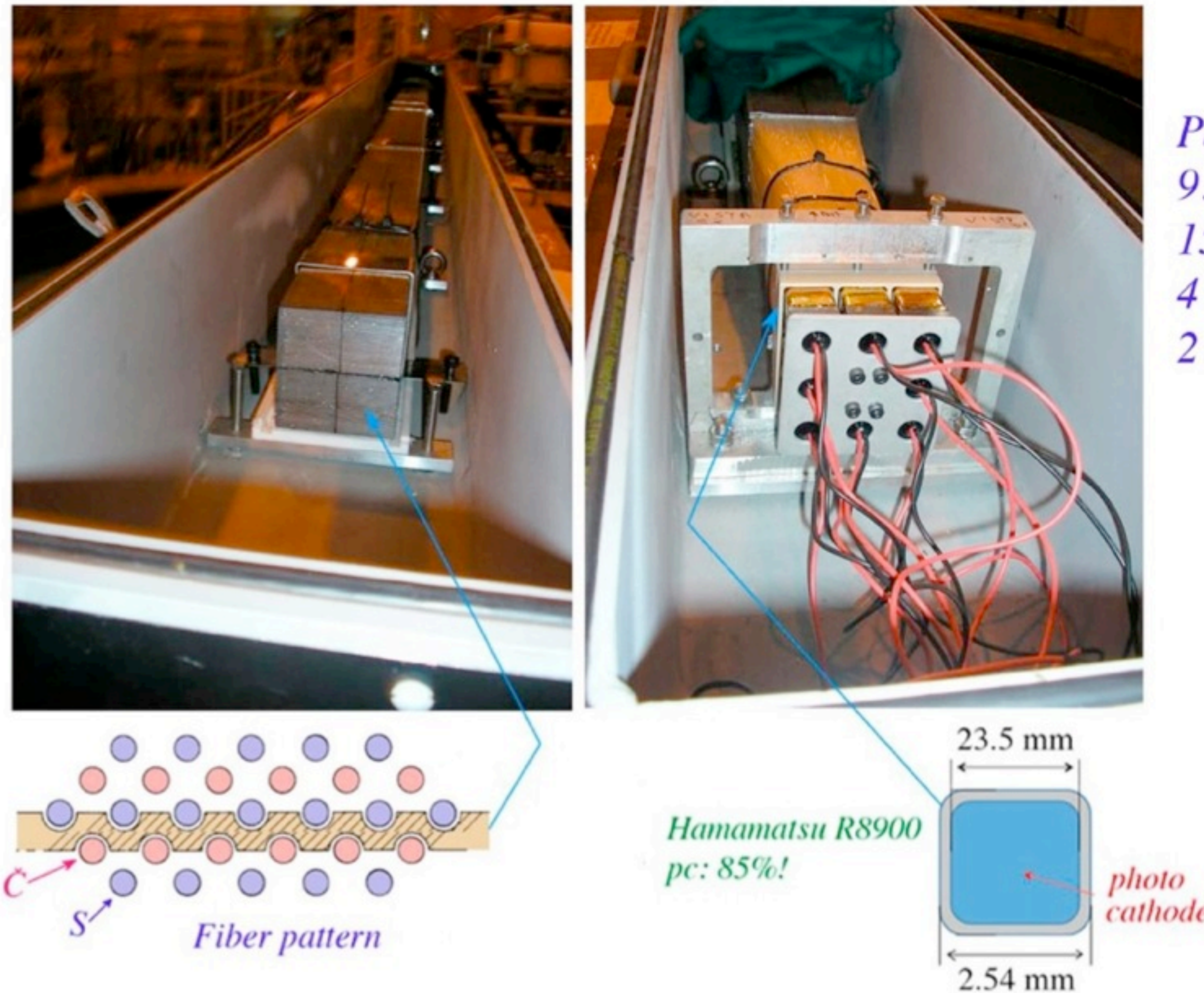




Polarized Cerenkov signal is prompt and sees the first ~5 Xo of the shower

SuperDREAM modules

The first SuperDREAM module tested at CERN

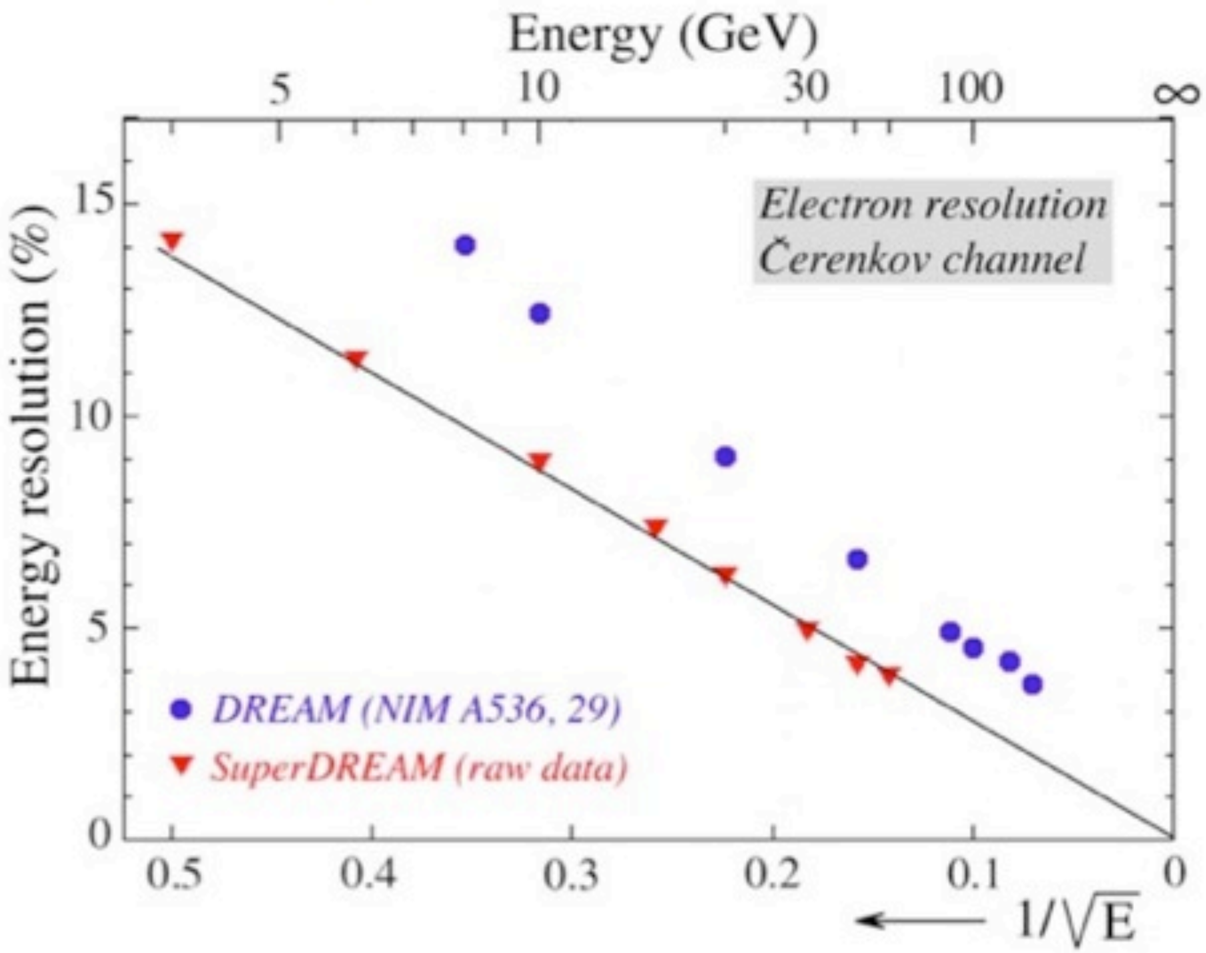


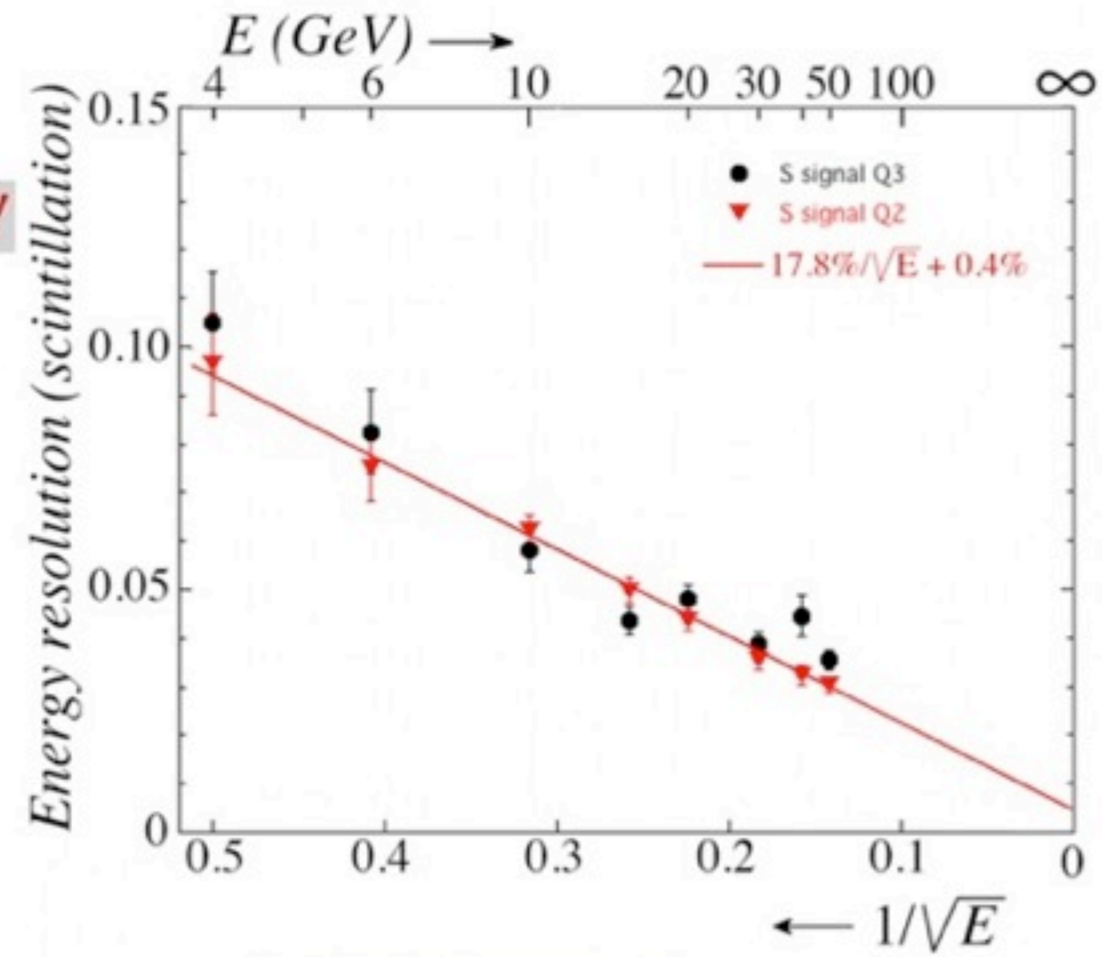
Pb absorber
9.3 x 9.3 x 250 cm
150 kg
4 towers, 8 PMTs
2 x 2048 fibers

Electromagnetic energy resolution in one (Pb) SuperDREAM module

Čerenkov signals
(beam hits in 4-corner region)

RESOLUTION MUCH BETTER THAN IN DREAM!





Scintillation signals
(beam centered on two different quadrants)
Small deviation from $1/\sqrt{E}$ scaling

Further improvements:
- *Combine different modules → better containment for beam in tower centers*
- *Alumizing upstream end of (C) fibers → more light*
- *Light mixers → eliminate position dependence of response*
- *Reduce noise contribution of readout electronics*

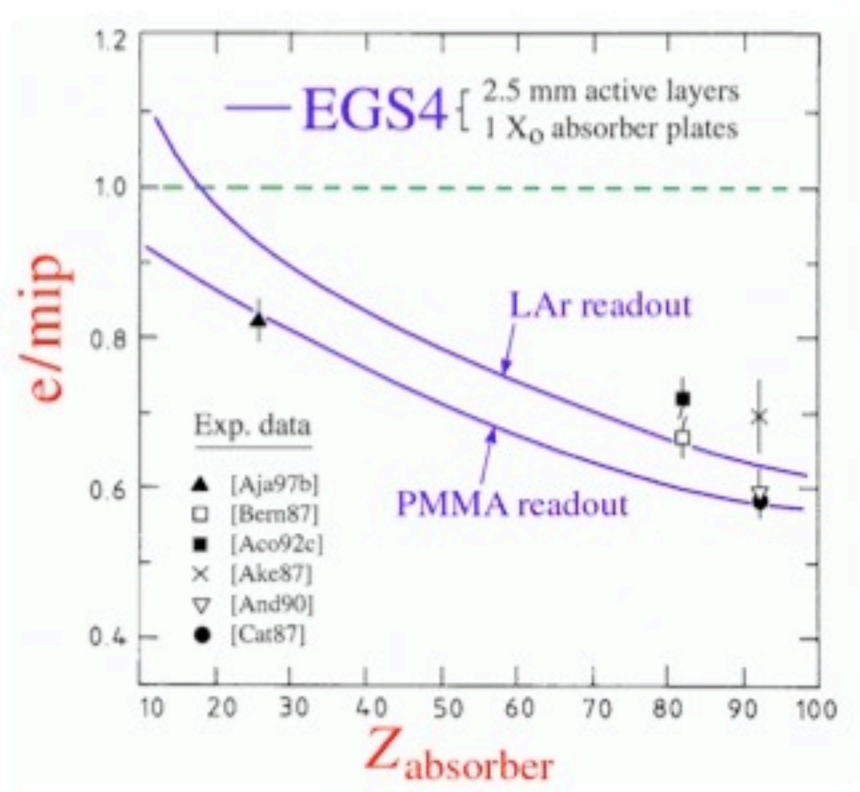
Expect $10\%/\sqrt{E}$ by combining signals from two types of fibers

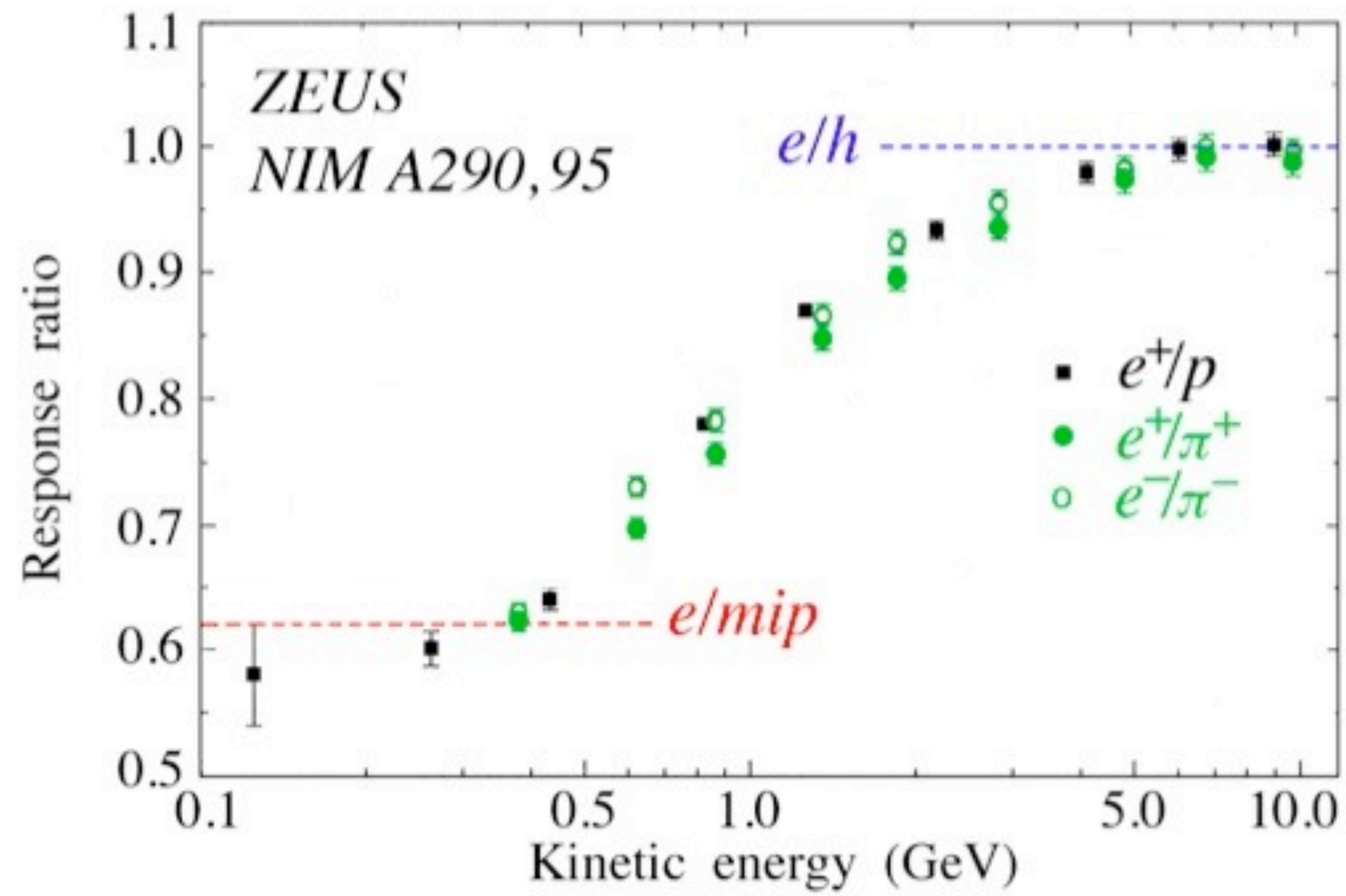
Absorber choice: Cu vs Pb

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

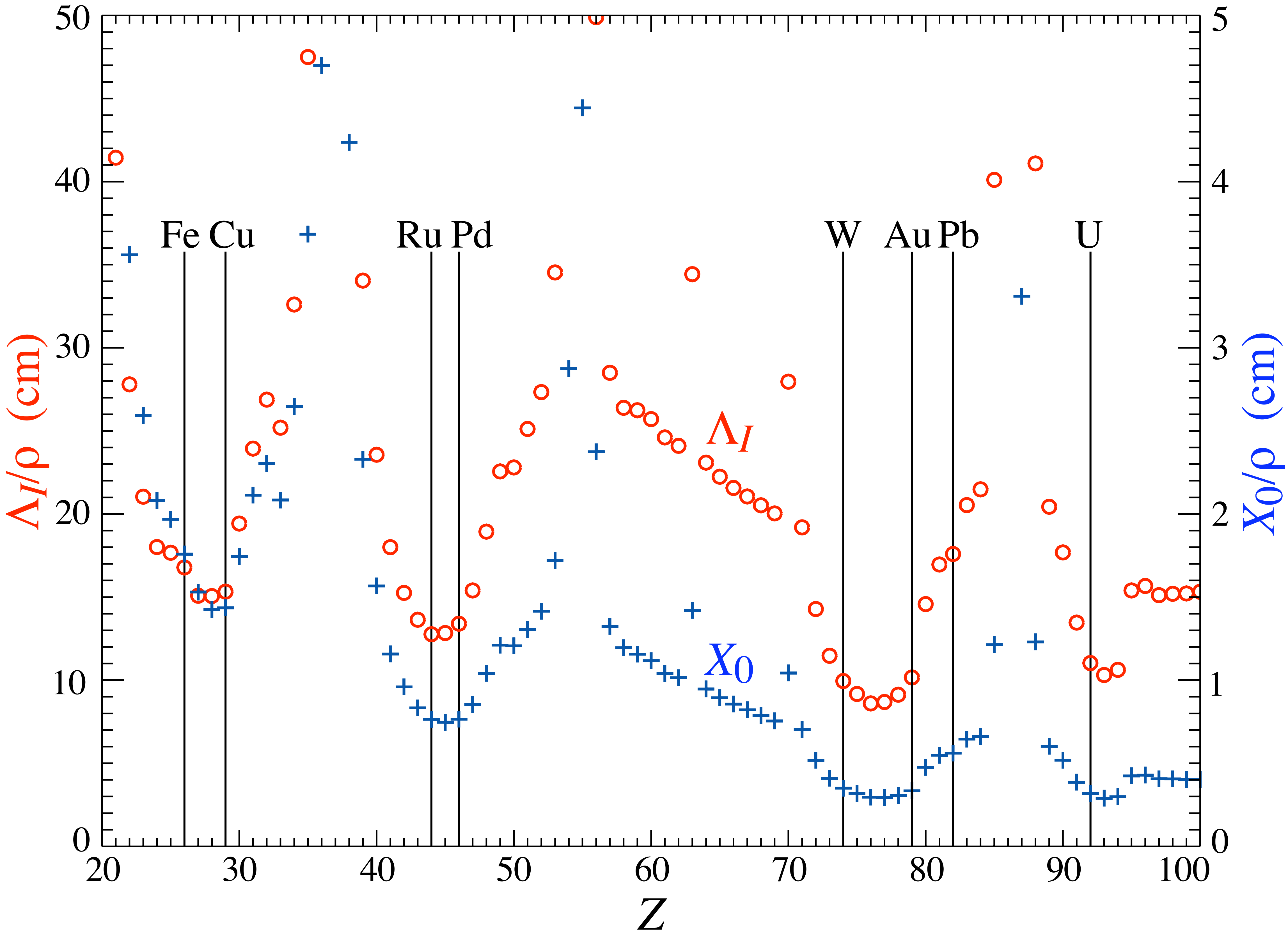
- *e/mip ⟶ Čerenkov light yield Cu/Pb ~ 1.4*
  (Showers inefficiently sampled in calorimeters with high-Z absorber)

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

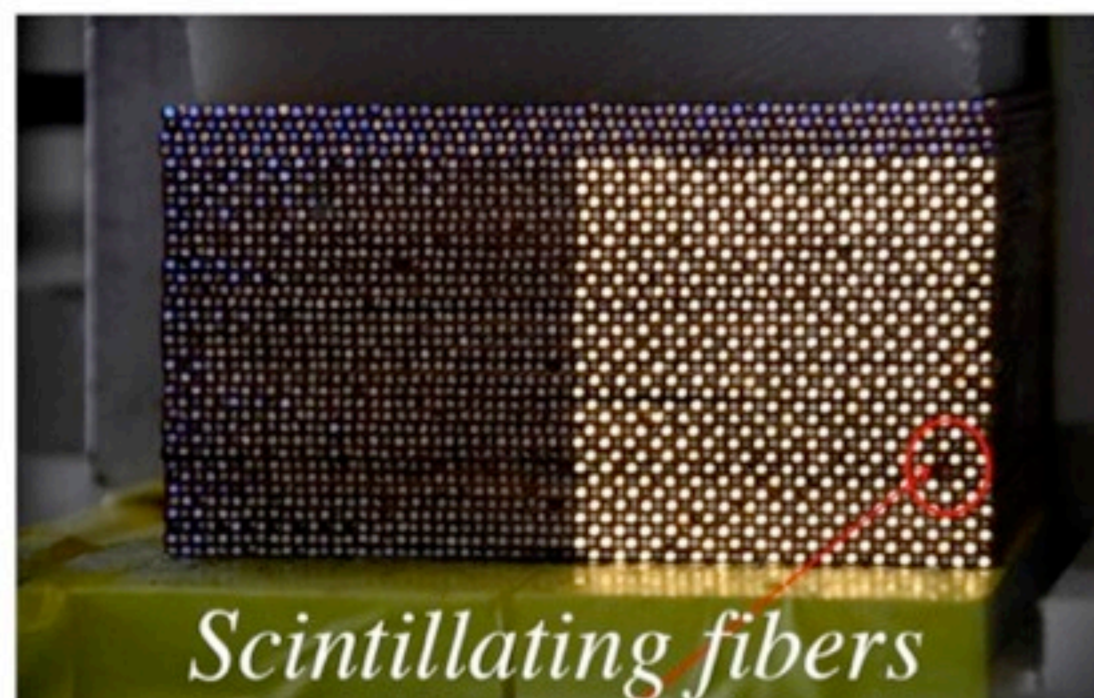




Don Groom, PDG plot: W>U>Cu (for hadronic) and U>W>Pb>Cu (for electromagnetic)



The first copper module



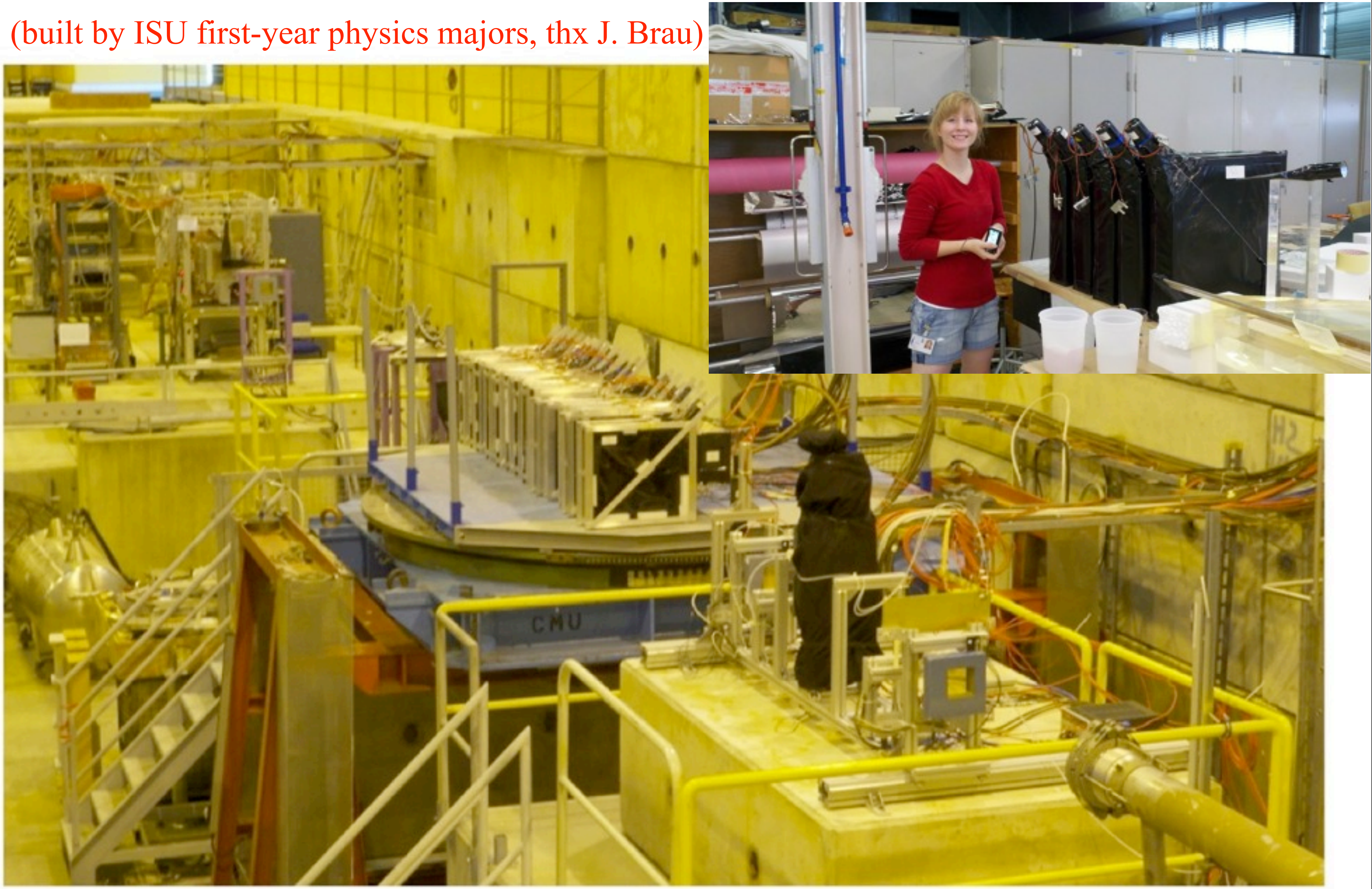
neutron counters

First hadrons in SuperDREAM (1 Pb module + n-shield)

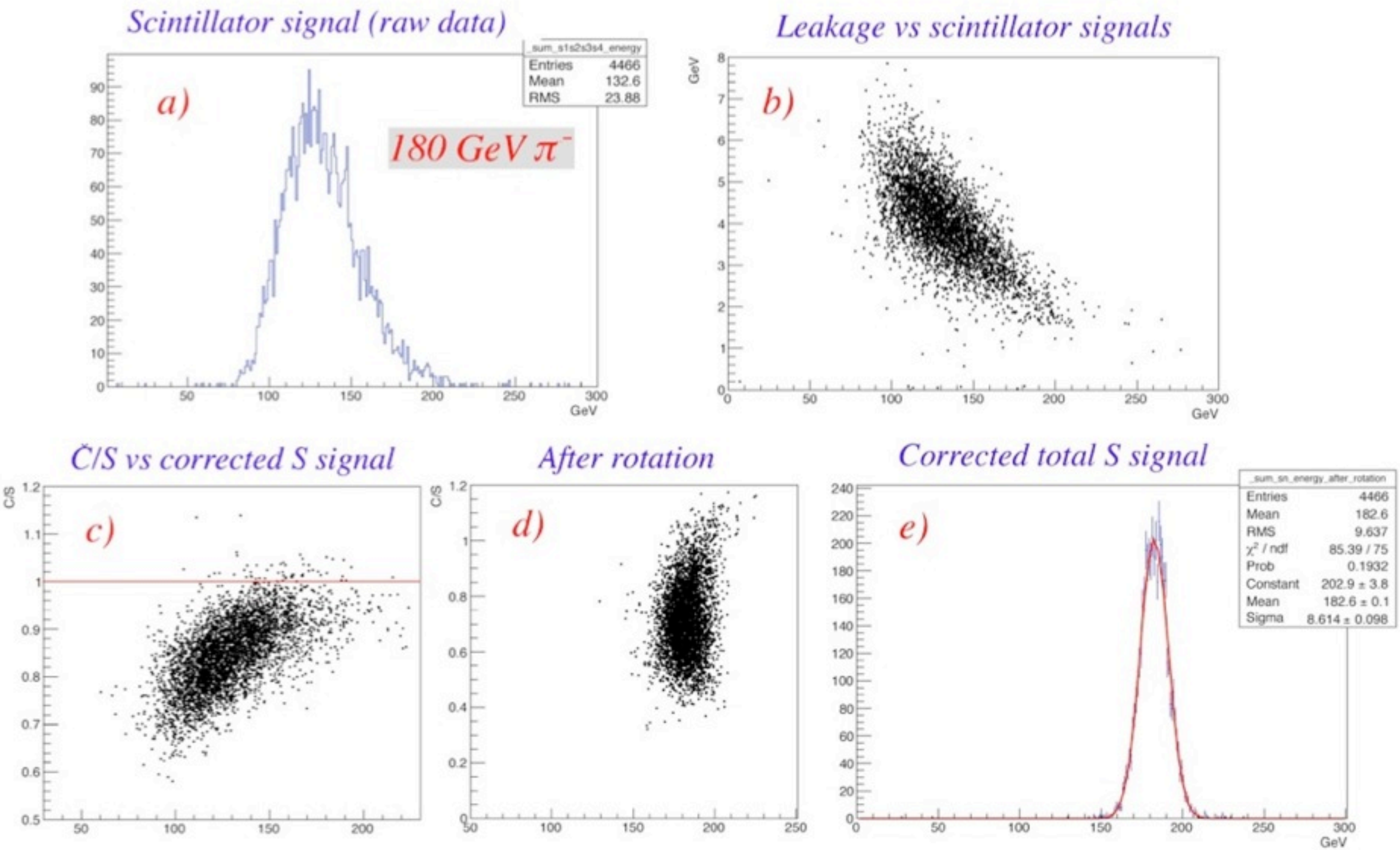
Severe test of neutron leakage counters

Calibration of neutron shield (muon beam)

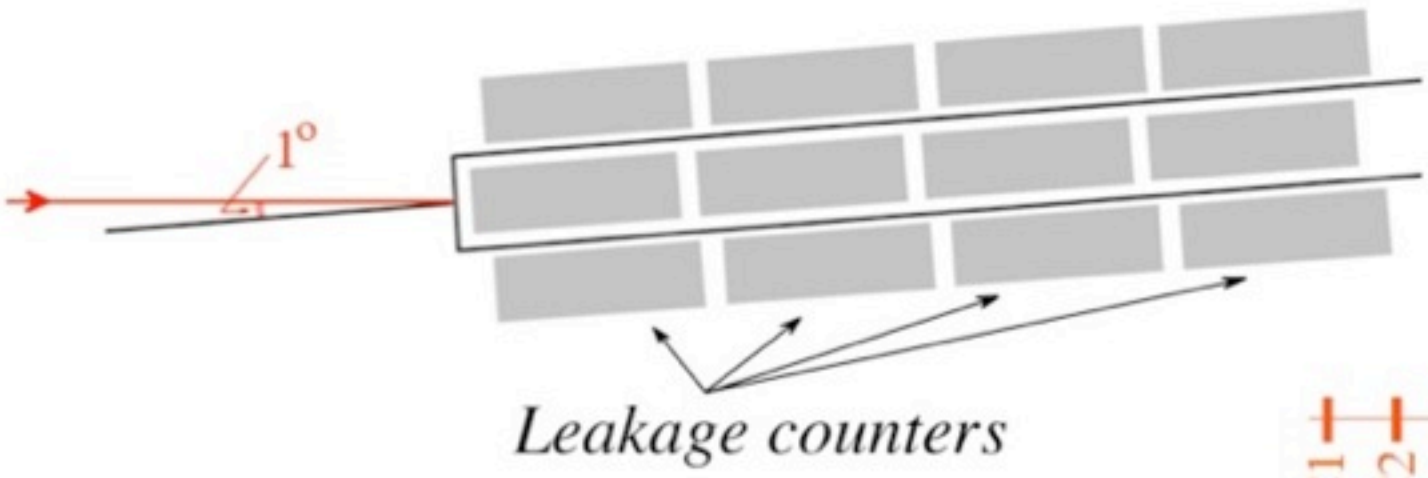
(built by ISU first-year physics majors, thx J. Brau)

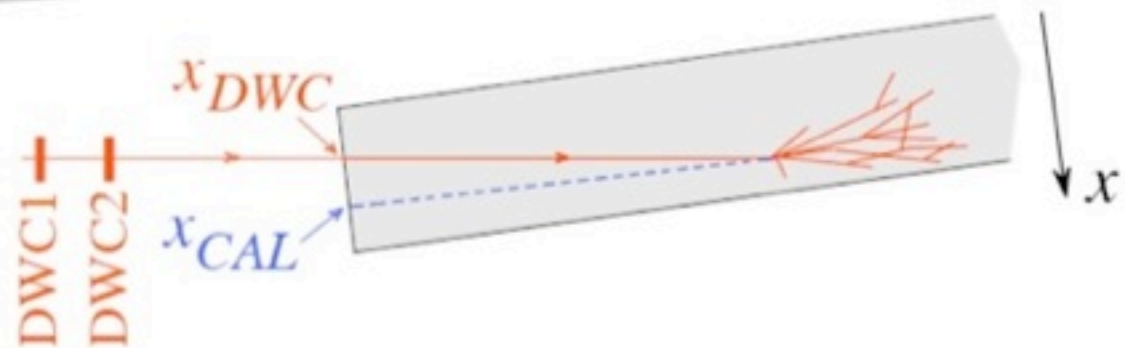


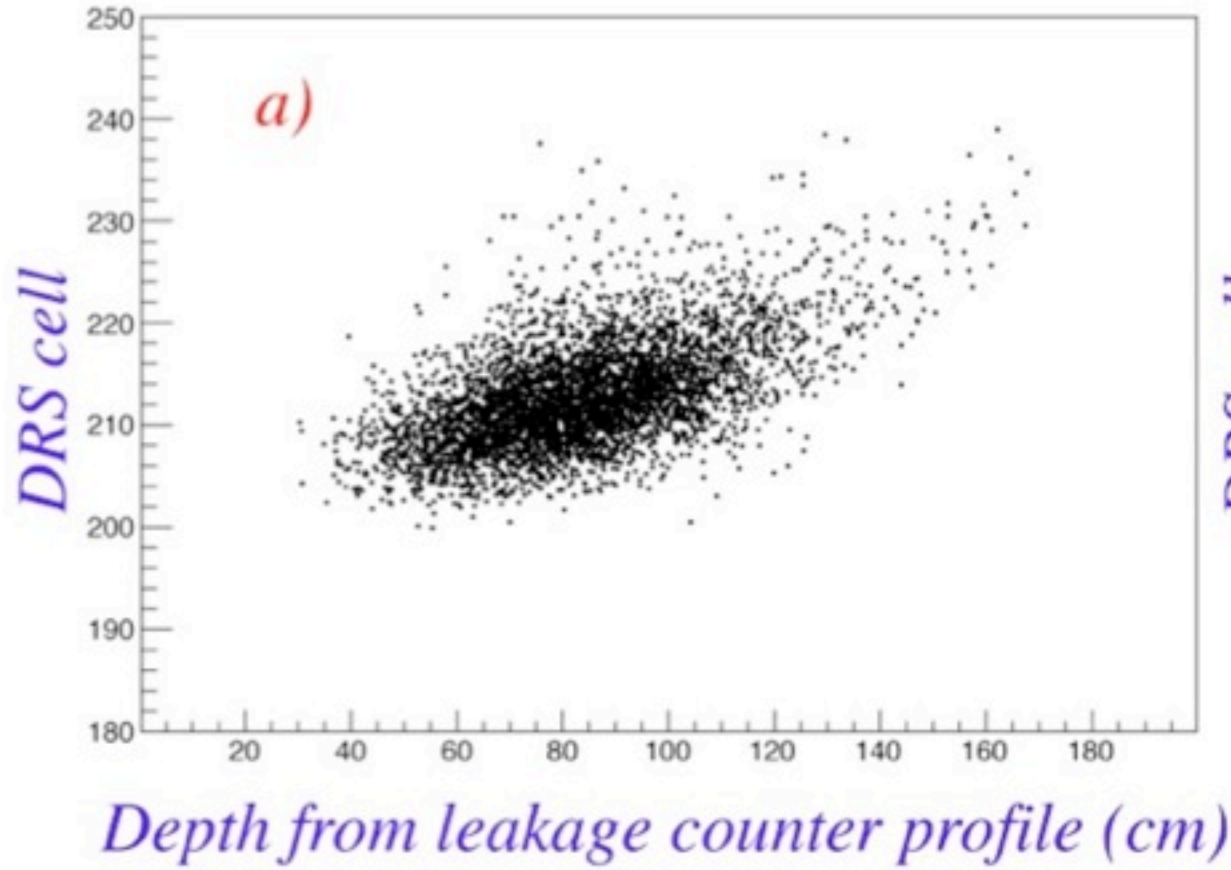
First results on pion detection in the new fiber calorimeter

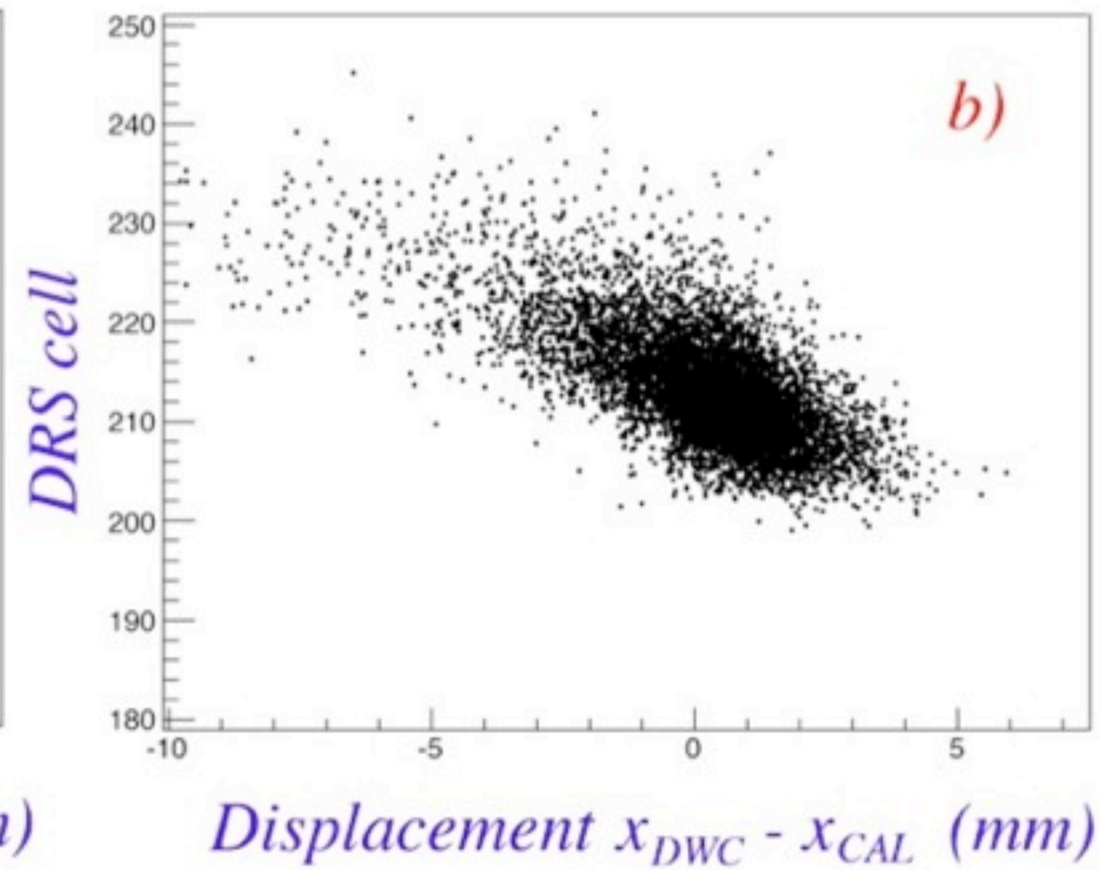


Check that DRS time measures shower depth







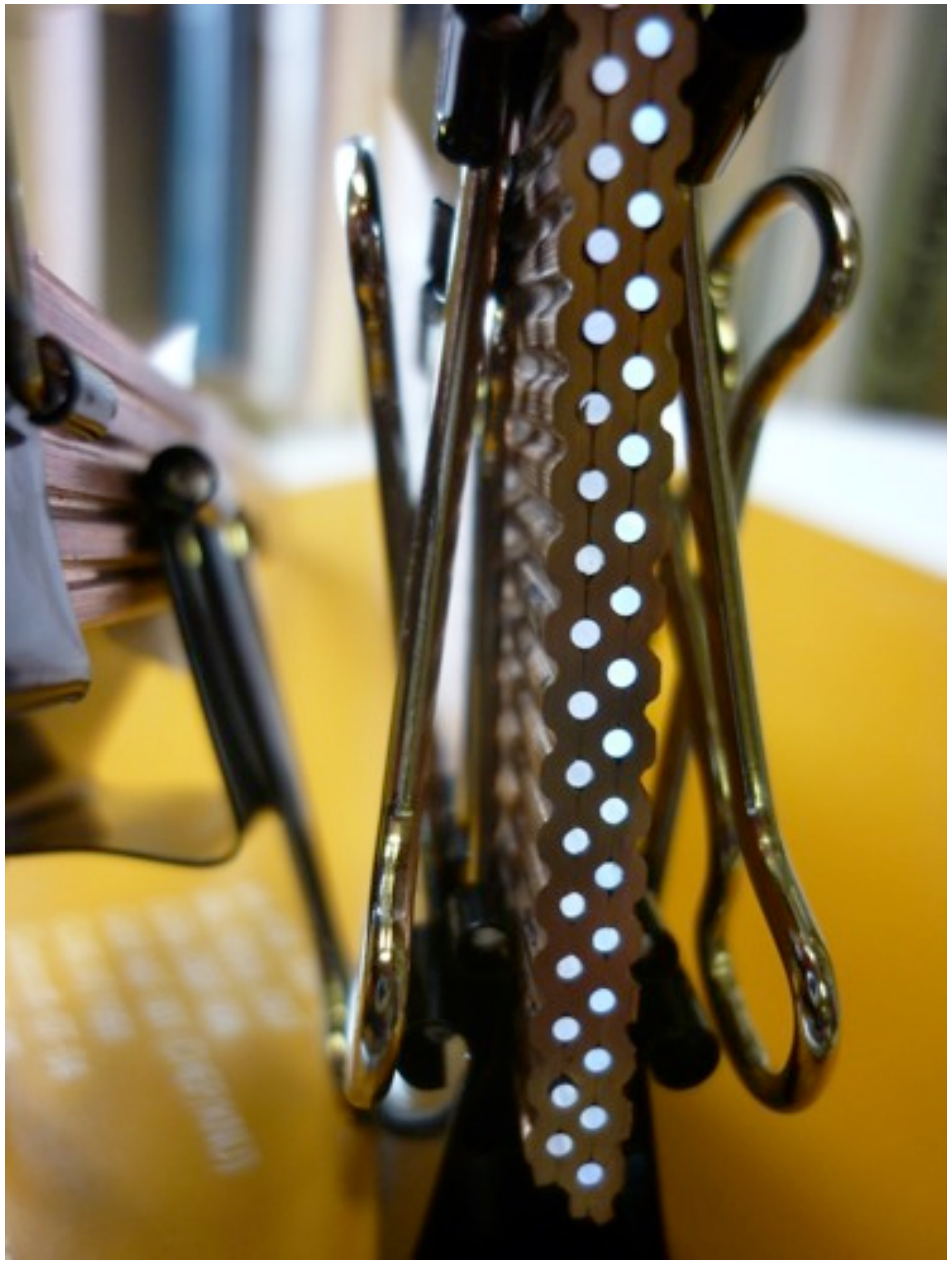


Preparing for 6-tonne superDREAM module

- Improve Cerenkov *pe* yield
  - 8 *pe*/GeV in the quartz fibers of DREAM
  - 18 *pe*/GeV in the plastic fibers of DREAM
  - 32 *pe*/GeV measured in PMMA fibers of Pb superDREAM module
  - ~50 *pe*/GeV expected with higher QE PMTs (~x1.5)
  - ~70 *pe*/GeV expected for *e/mip* in Cu (~x1.4)
  - ~105 *pe*/GeV expected for aluminized mirror on C fibers (~x1.5)
  - >150 *pe*/GeV with light-mixer (~x1.5)
  - measuring depth-of-light in C-fibers corrects attenuation in S-fibers (reduce constant term)
- Reduce leakage
  - 1-tonne to 6-tonnes
  - neutron shield
- Spatial sampling fraction inprovement
  - individual fibers on 2-mm centers
- Direct comparison of Pb-calorimeter and Cu-calorimeter
  - build individual Pb and Cu modules: stack in various configurations
- Test all calorimeters with & without crystal EM arrays in front
  - we have done this before with the small DREAM module
- Instrument one module with SiPM readout
  - a natural evolution for these fine-grained optical calorimeters

Tungsten-based dual-readout calorimeters

Tungsten metallurgy is not simple, but the Ames Laboratory (US DoE) is very skilled. We expect to be able to replace our rolled Cu with rolled W (e.g., W-80% Cu-20%), and optimize sampling fractions, spatial pitch, etc. If we succeed, this will have *huge* consequences for big detectors.



Summary of dual-readout

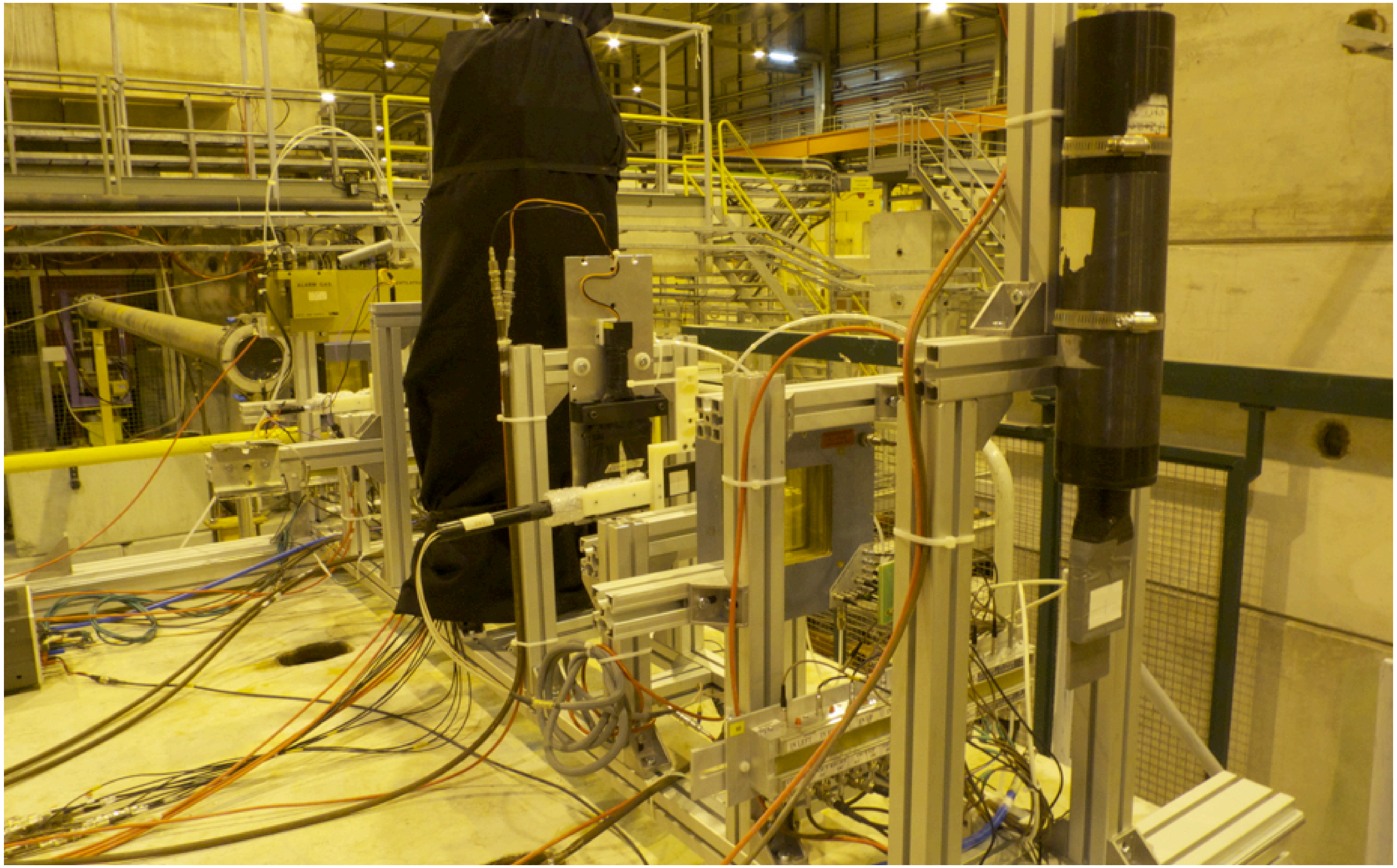
- The DREAM collaboration is now an official CERN project RD52
  (it is a purely instrumental investigation without regard to any experiment)

- We continue to improve dual-readout calorimetry with new ideas and new methods
  (Cerenkov *pe* yield, neutrons, fibers, SiPMs, tungsten)

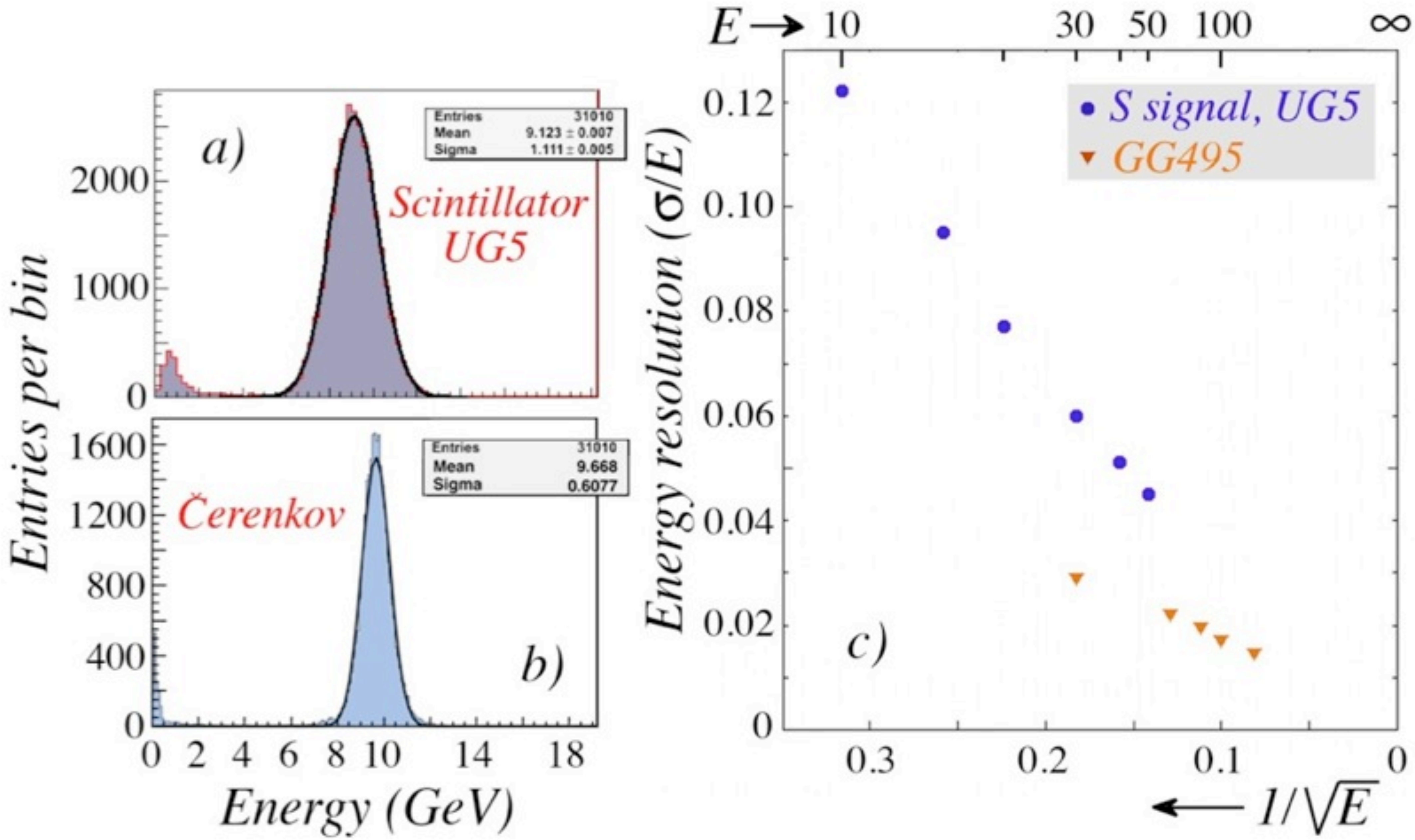
- We now believe that $20\%/\sqrt{E}$ for hadrons and jets is reachable, that is, ~1% hadronic energy resolution at high energies
  (theoretical limit is around $15\%/\sqrt{E}$)

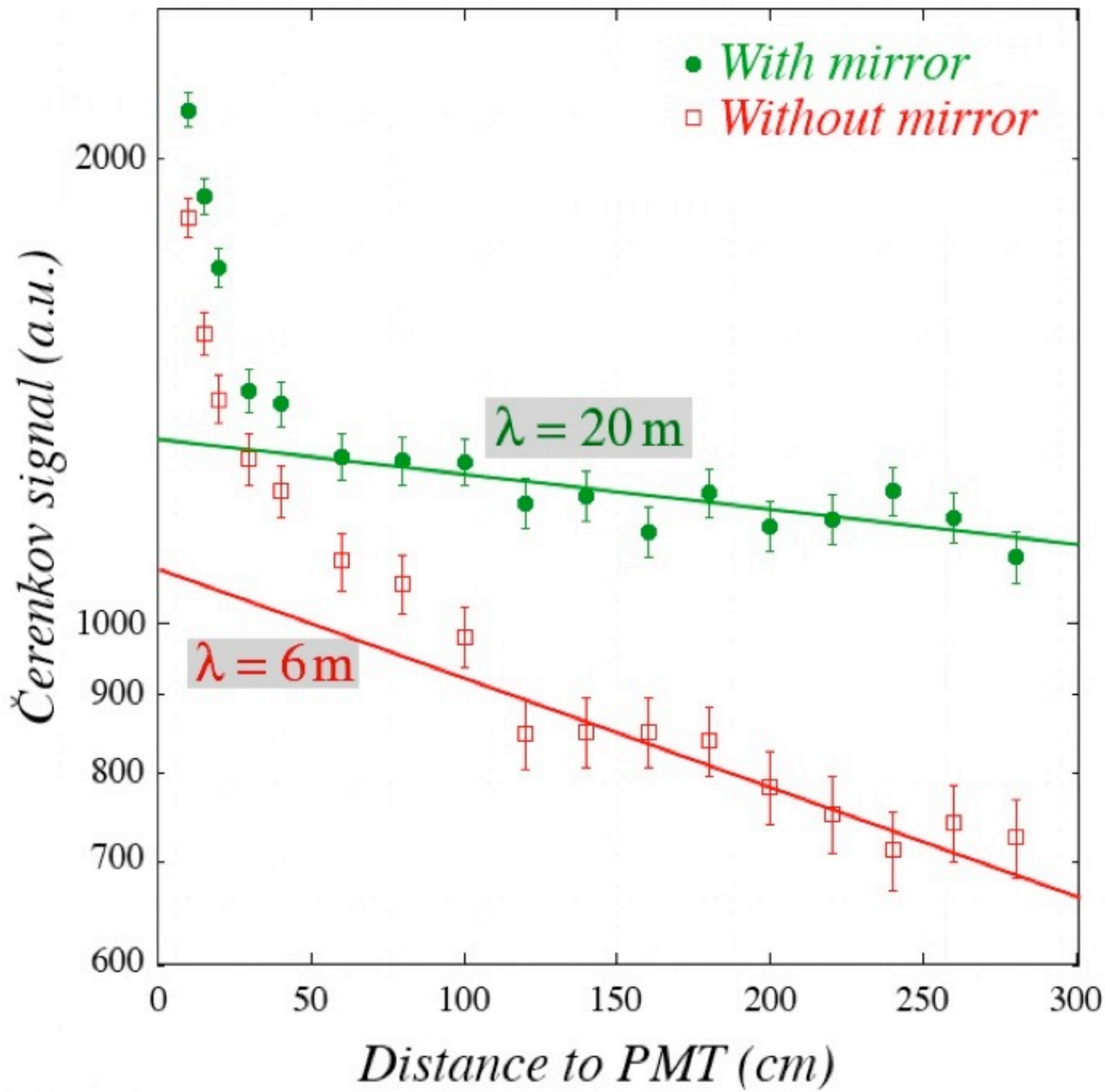
- We pay very close attention to all potential constant terms
  (this is non-trivial)

Moveable beam definition/trigger system for RD52

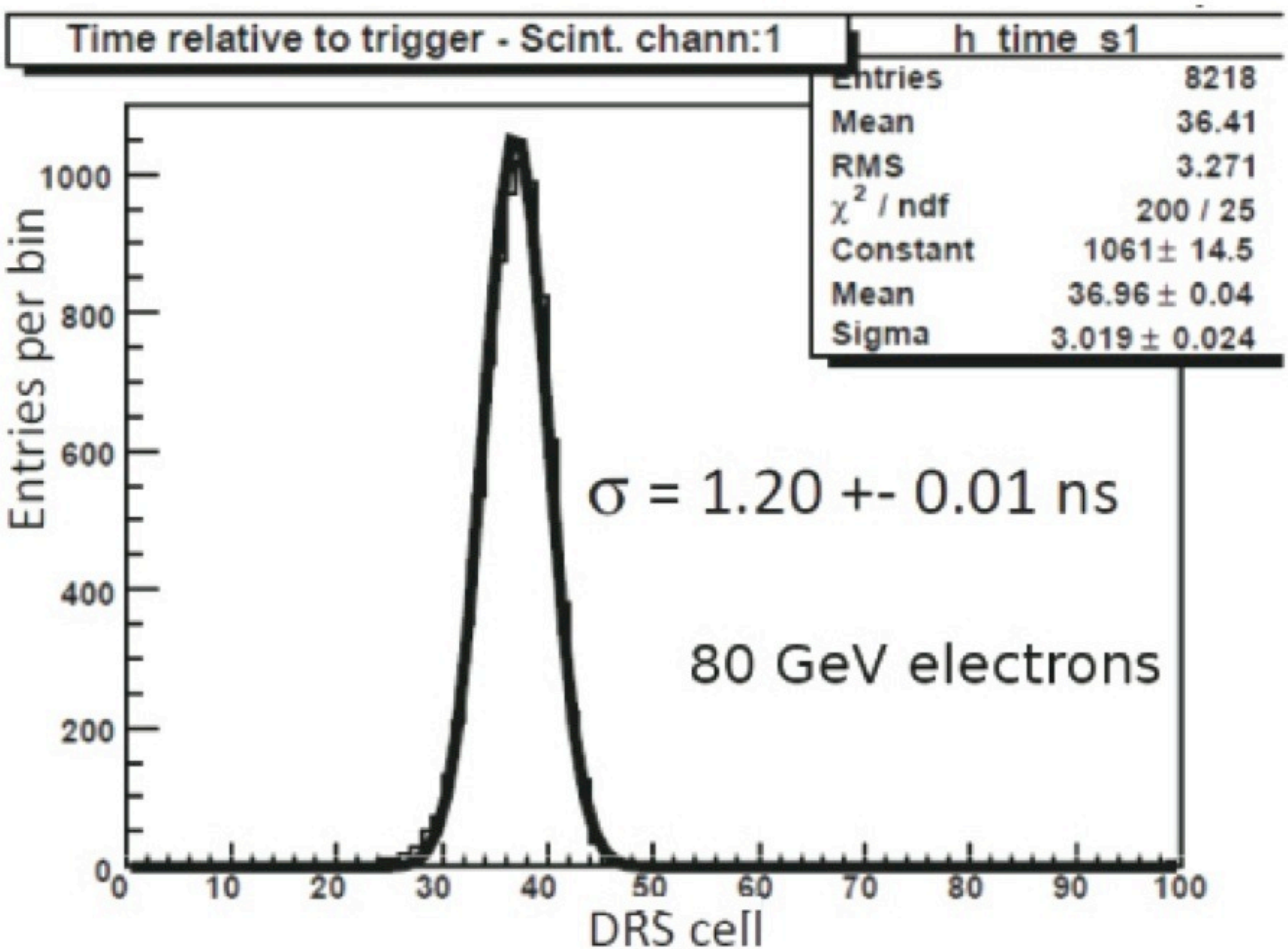


Scintillation signals in $PbWO_4$ matrix optimized for detection of Čerenkov light





With mirror
Without mirror
λ = 20 m
λ = 6 m
Čerenkov signal (a.u.)
2000
1000
900
800
700
600
0
50
100
150
200
250
300
Distance to PMT (cm)


Time relative to trigger - Scint. chann:1
h_time_s1
Entries 8218
Mean 36.41
RMS 3.271
χ² / ndf 200 / 25
Constant 1061 ± 14.5
Mean 36.96 ± 0.04
Sigma 3.019 ± 0.024
σ = 1.20 +- 0.01 ns
80 GeV electrons
Entries per bin
DRS cell
0
200
400
600
800
1000
10
20
30
40
50
60
70
80
90
100

From:

NIM A604 (2009) 512