Dual readout calorimetry: how does it work and why does it matter

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IHEP

Summary

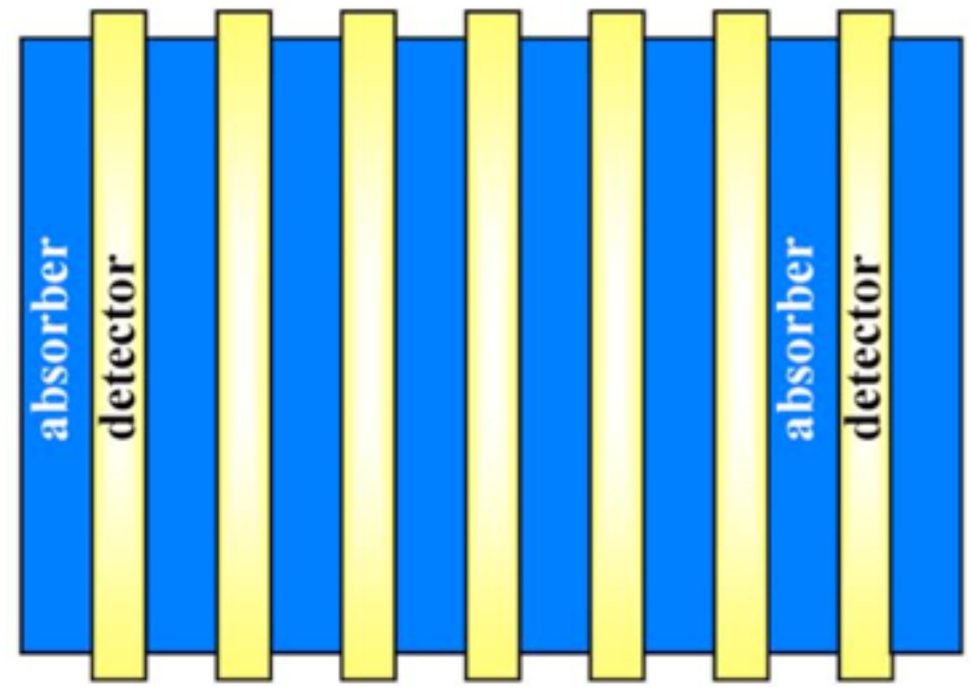
- Principles of calorimetry
  - em showers
  - had showers
  - compensation
- dual readout calorimetry
  - principles
  - results
- prospectives

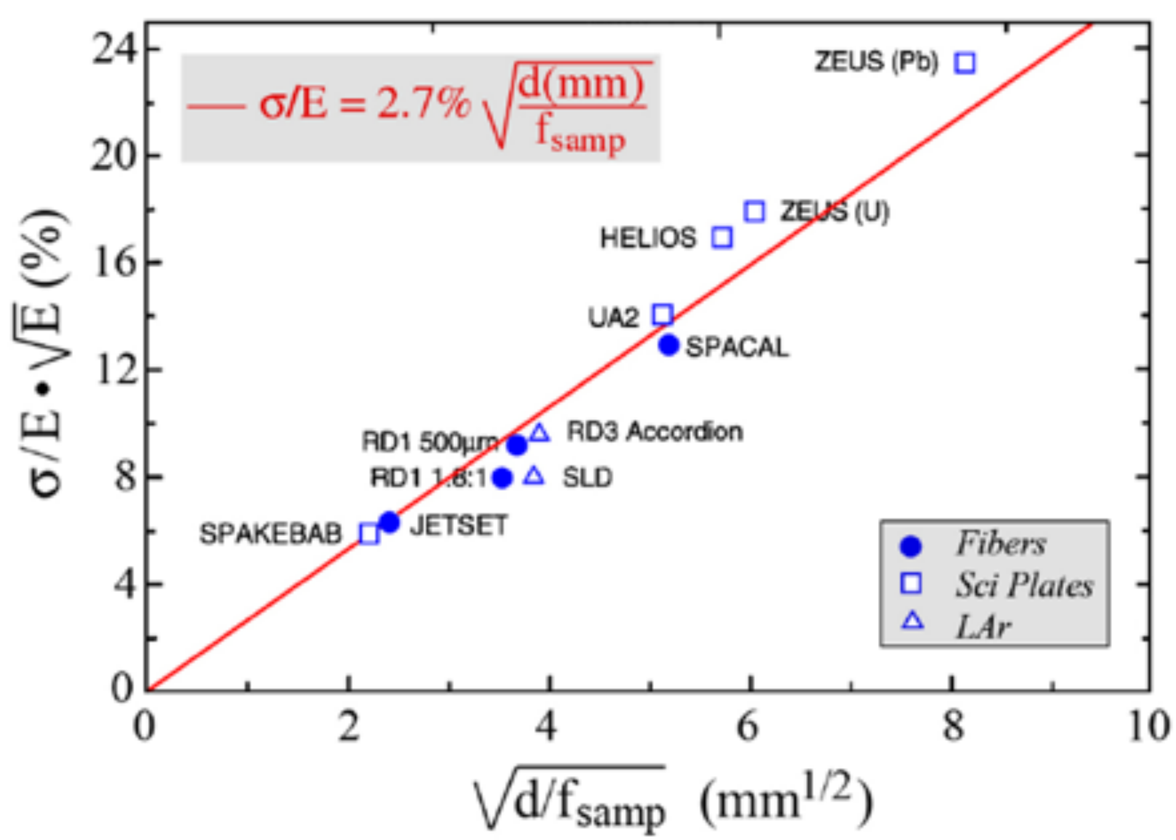
Why calorimeters?

- Calorimeter are the heart of modern collider detectors
  - Energy, flow and topology (jets, E_T^{miss})
  - Fast (trigger)
  - Resolution improves with energy
- They can also be a thorn in the side
  - Jet energy scale
  - Non linearity

Sampling vs homogeneous

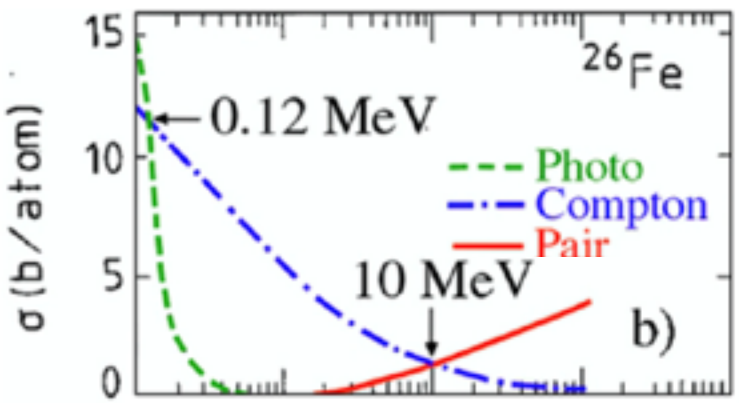
- Homogeneous calorimeters
  - great resolution
  - impractical for hadrons
- Sampling calorimeters
  - sampling fraction (f_{samp})
  - sampling frequency



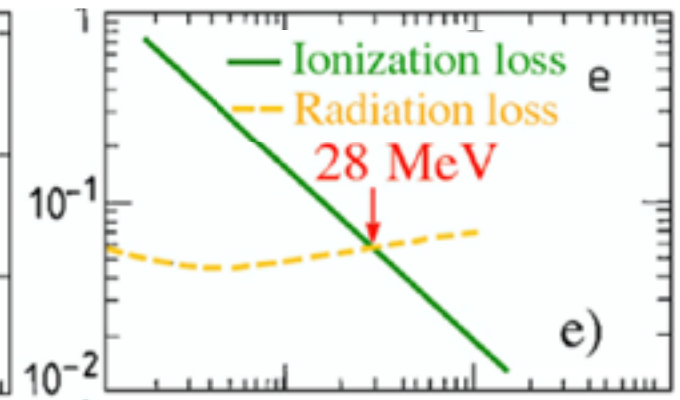


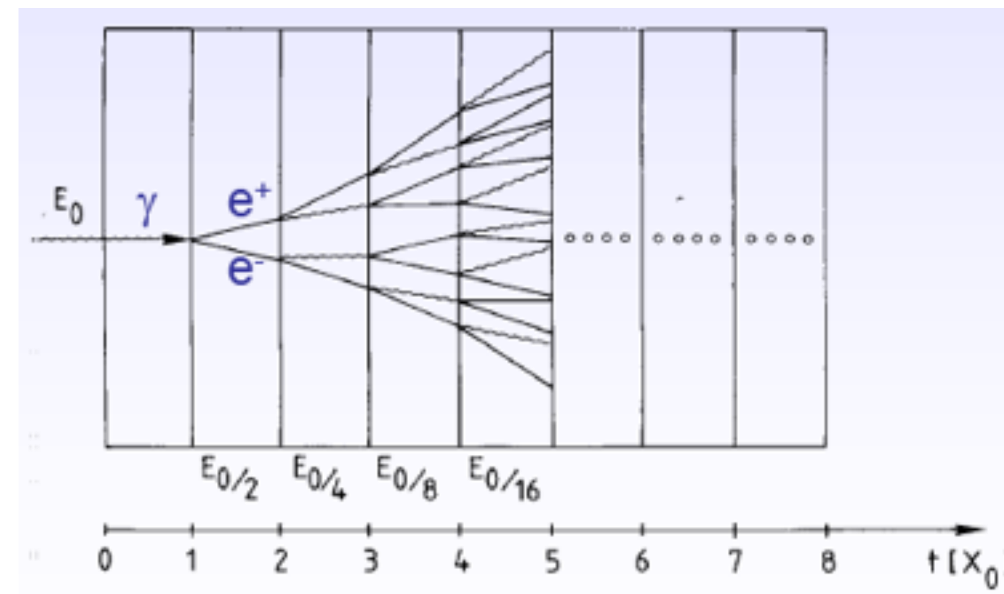
Electromagnetic showers

Photons

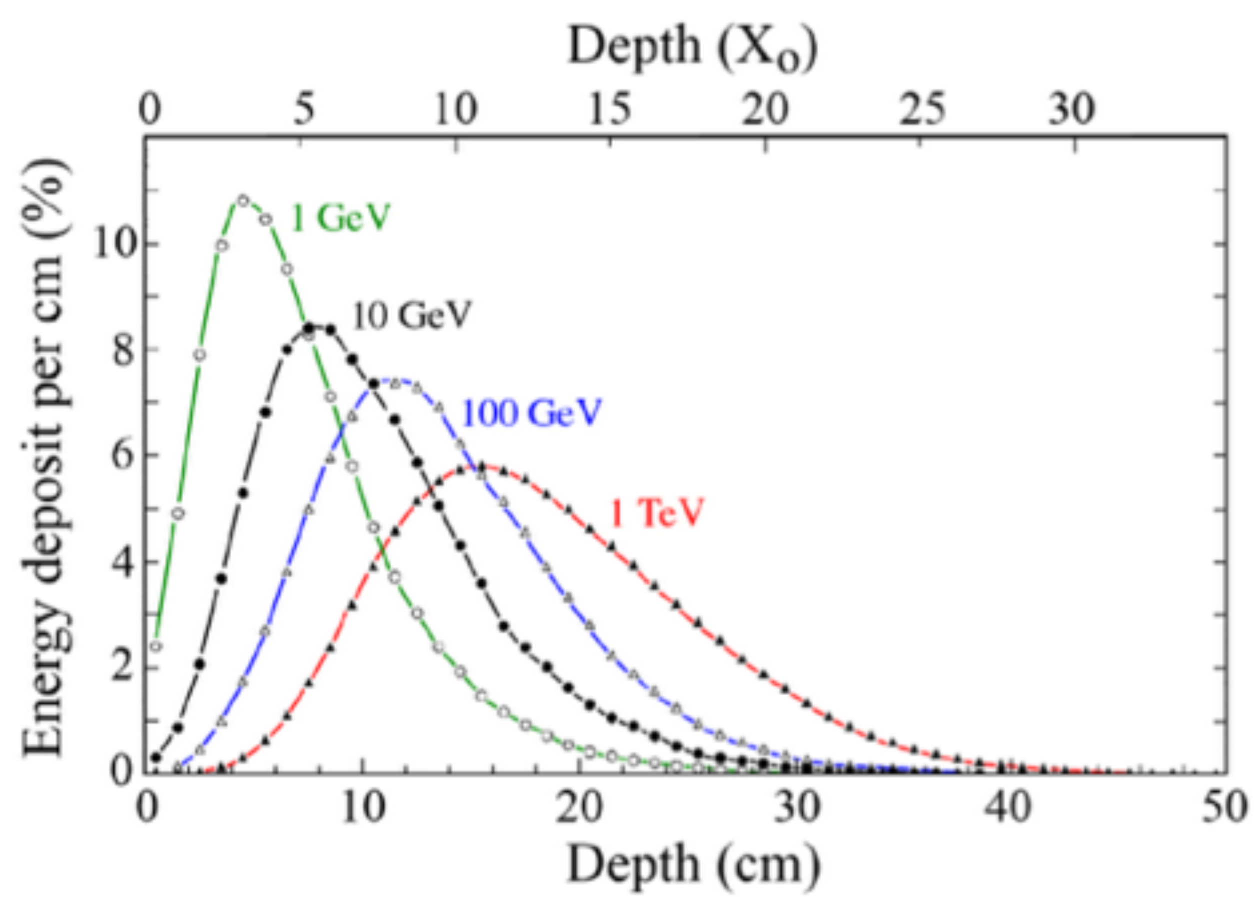


Electrons

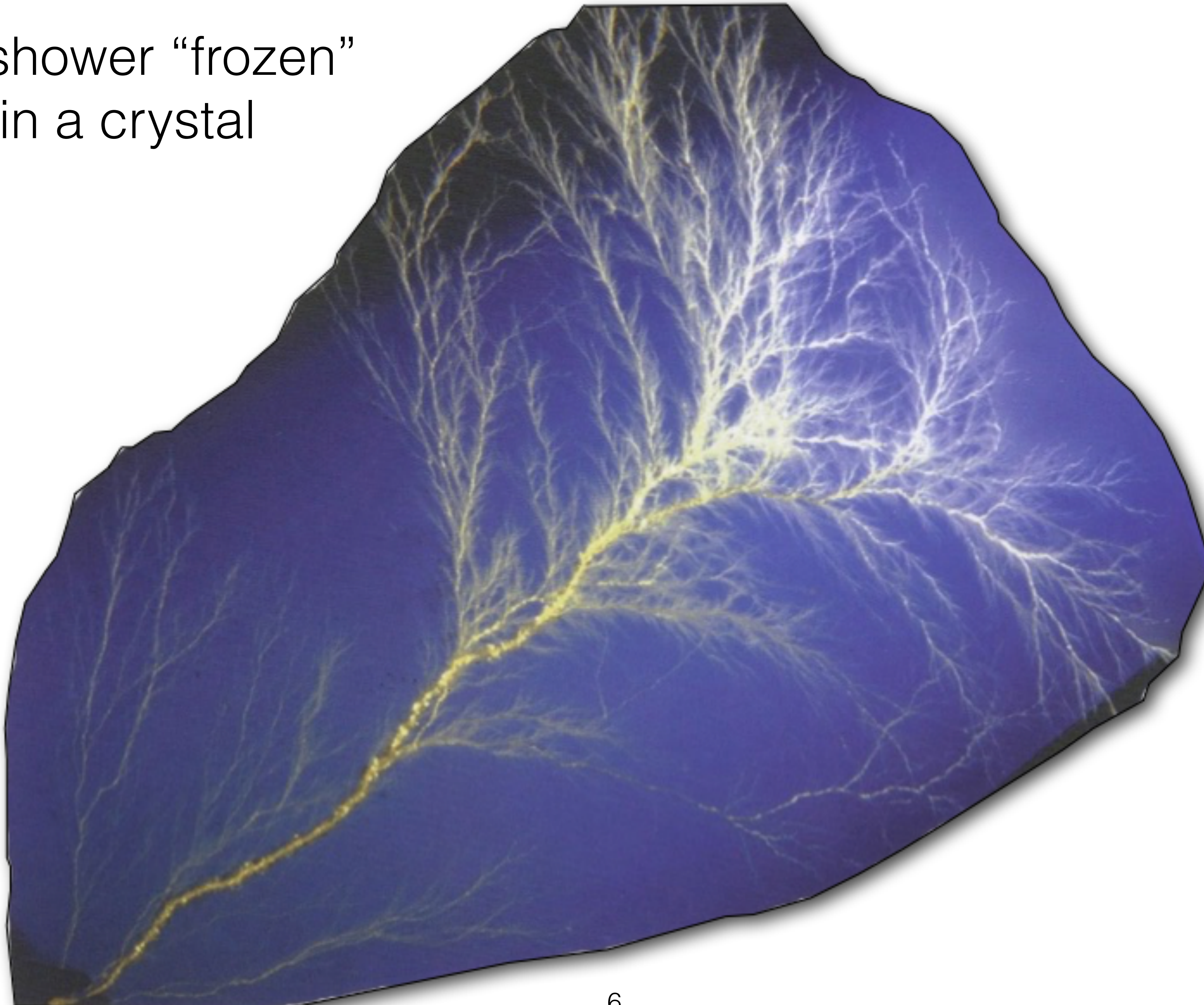




- E_0, $X_0 \sim \lambda_{pair}$
- $E_c = E(t_{max}) = E_0/2^{t_{max}}$
- $t_{max} \sim \ln(E_0)$
- $E \sim N$

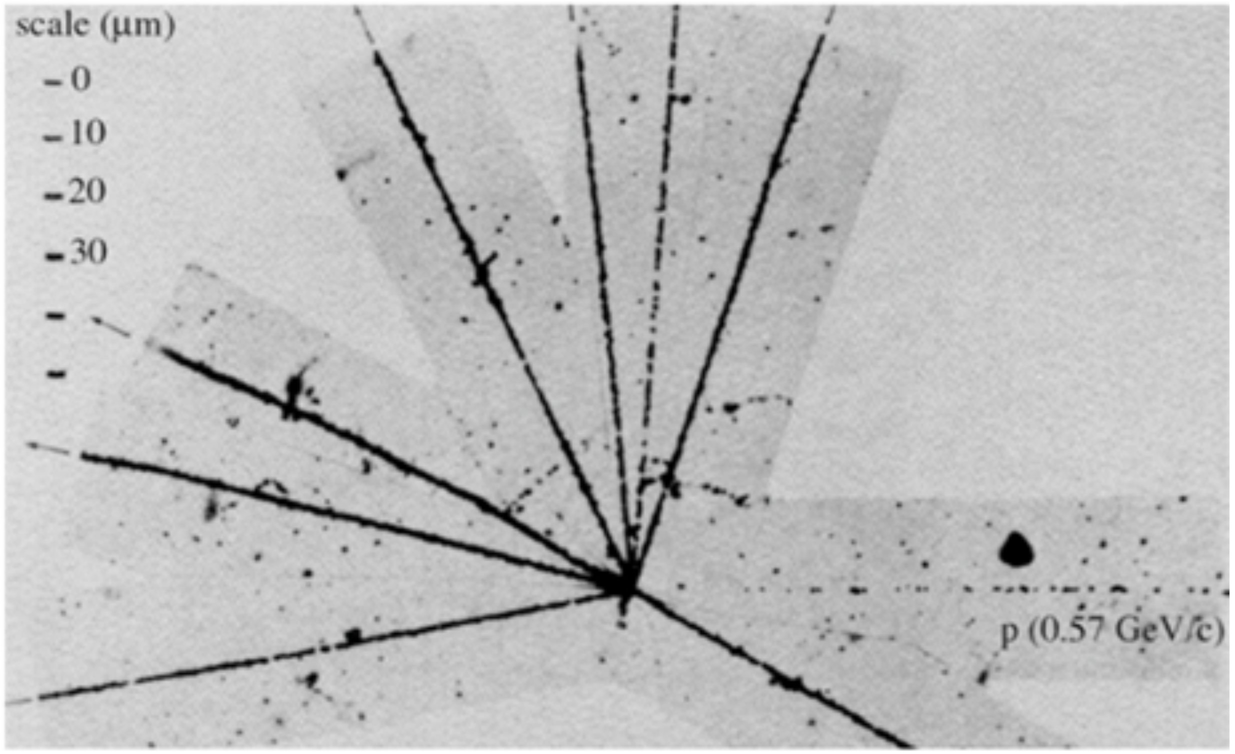


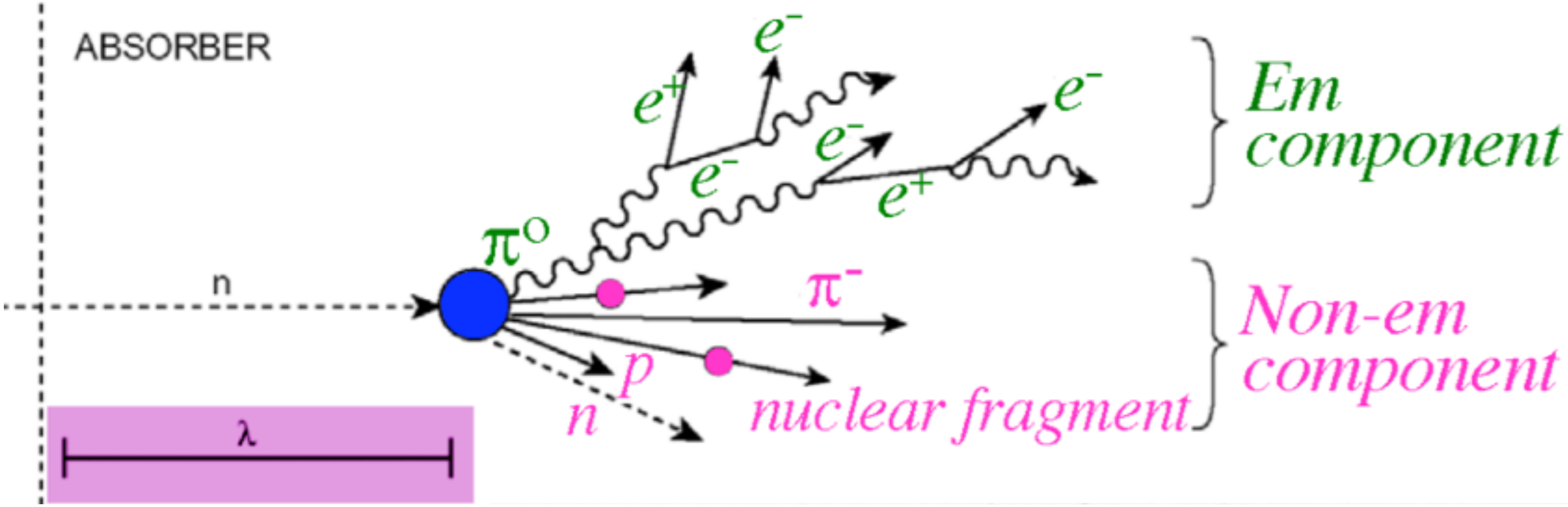
em shower “frozen”
in a crystal



Hadronic showers

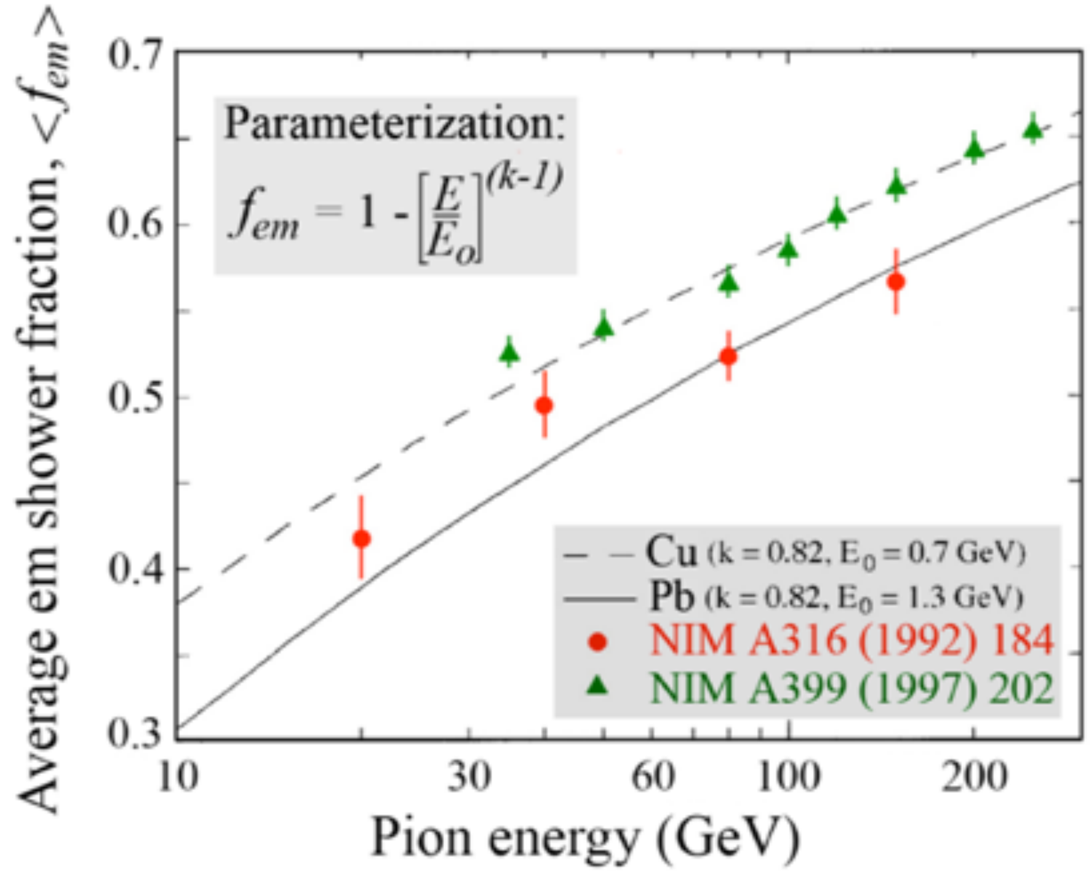
- mip + strong interaction
- η_0, π_0 → em showers
- neutrons
- invisible energy

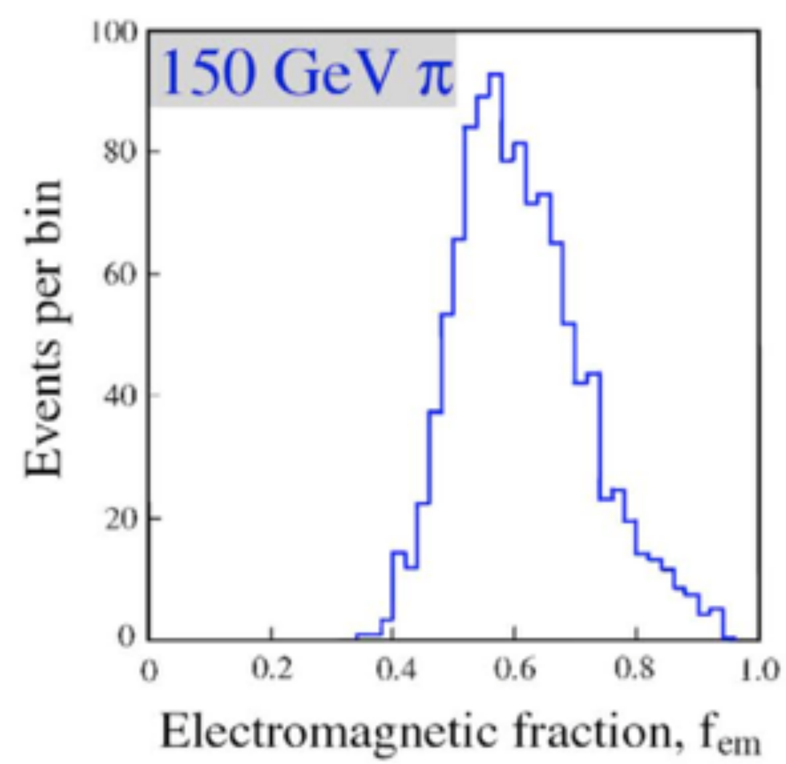




A simple model?

- $\eta^{\pm}, \eta^0, \pi^{\pm}, \pi^0$ P(em)=1/3
- f_{em}=1/3 + 2/3*1/3 + 5/9*1/3… = $1-(1-1/3)^n$
- Does not work
- f_{em} non poissonian
- π signal < e signal

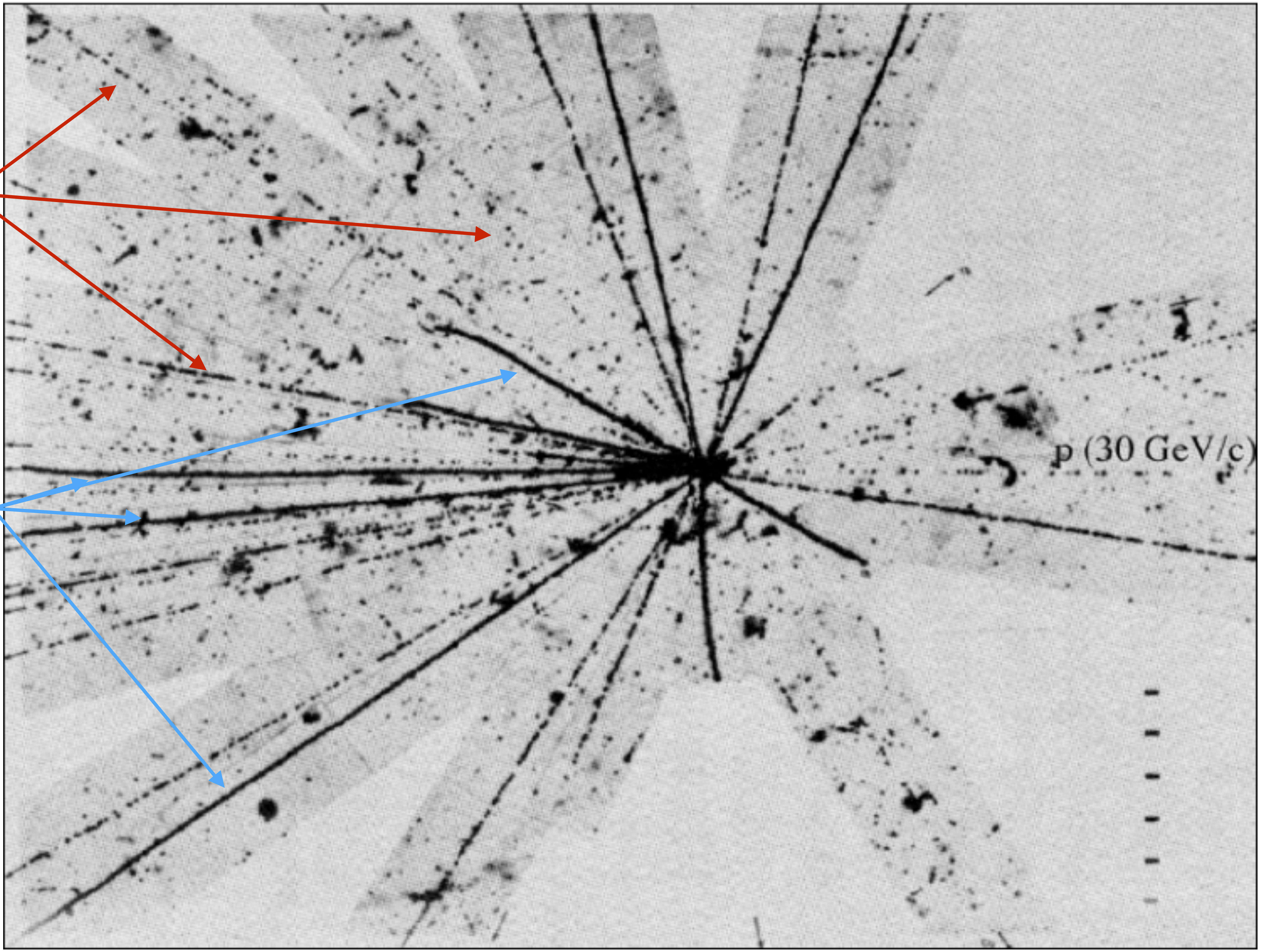




pions
(and fast p)
mips

protons
highly ionising

neutrons
(invisible)

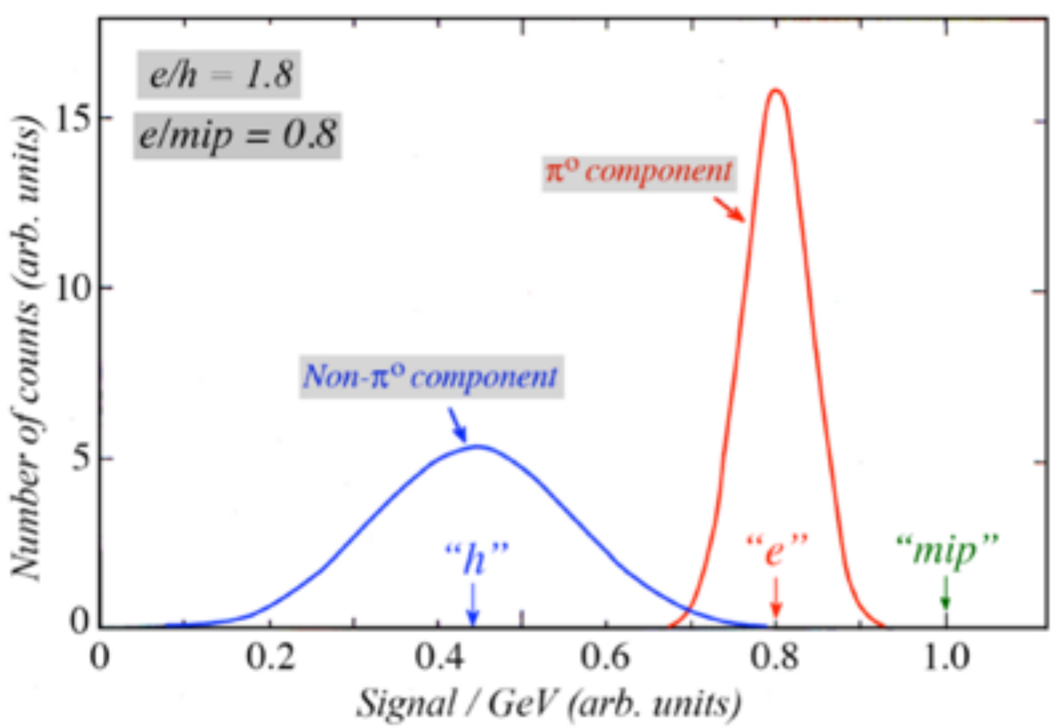


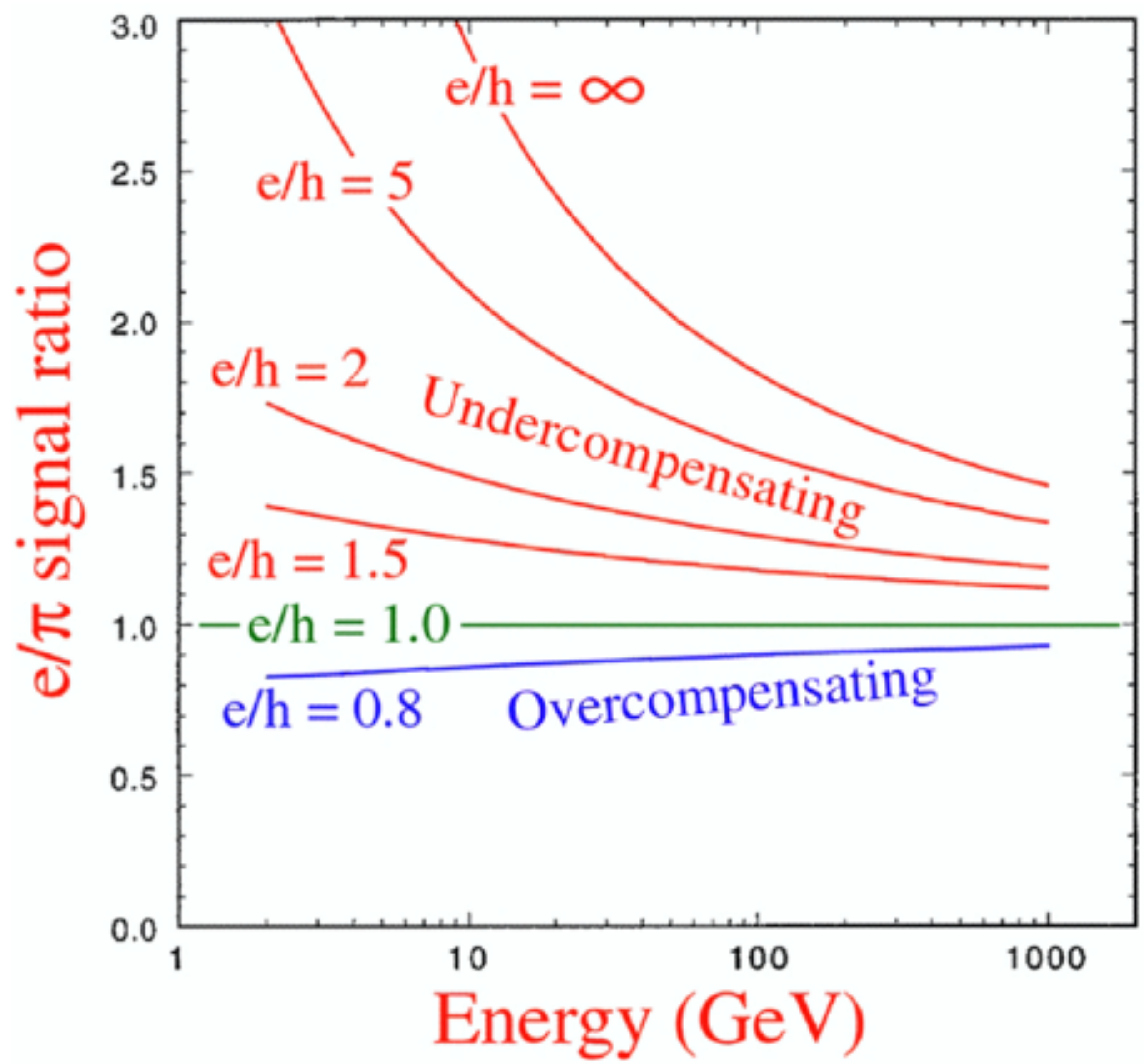
Hadronic shower composition

	Lead	*Iron*
Ionization by pions	19%	21%
Ionization by protons	37%	53%
Total ionization	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
Total invisible energy	34%	21%
Kinetic energy evaporation neutrons	10%	5%
per GeV of non-em energy		
Number of charged pions	0.77	1.4
Number of protons	3.5	8
Number of cascade neutrons	5.4	5
Number of evaporation neutrons	31.5	5
Total number of neutrons	36.9	10
Neutrons/protons	10.5/1	1.3/1

Compensation

- e = response to electronic component
- h = response to hadronic component
- e=h compensating calorimeter



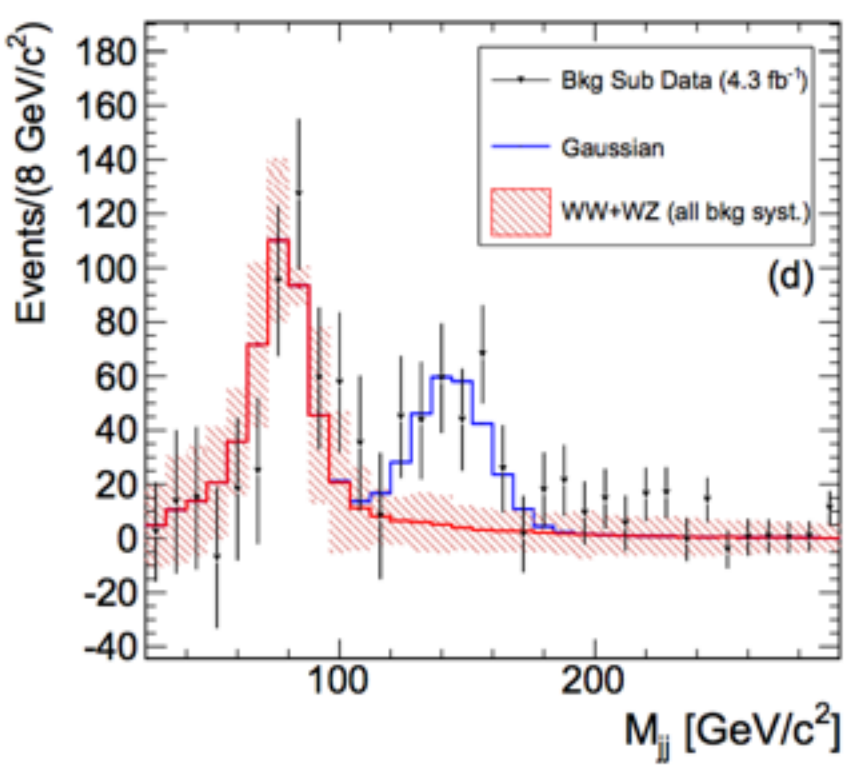


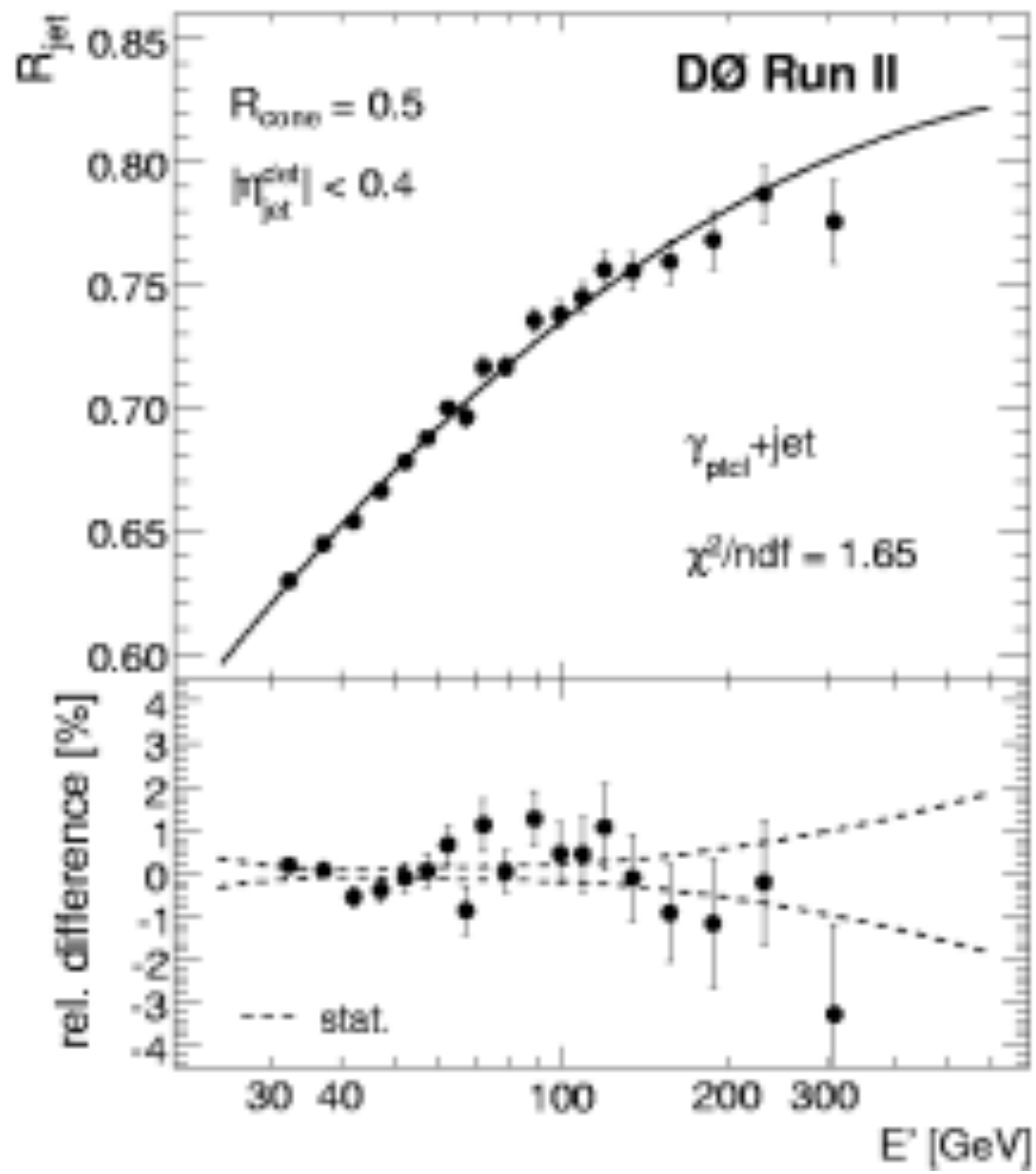
Resolution of hadronic calorimeters

- Same issues that affect em showers
- Invisible energy
- Non poissonian fluctuations in the em shower fraction, f_{em}
  - Dominating effect in most hadron calorimeters ($e/h \neq 1$)

Non linearity

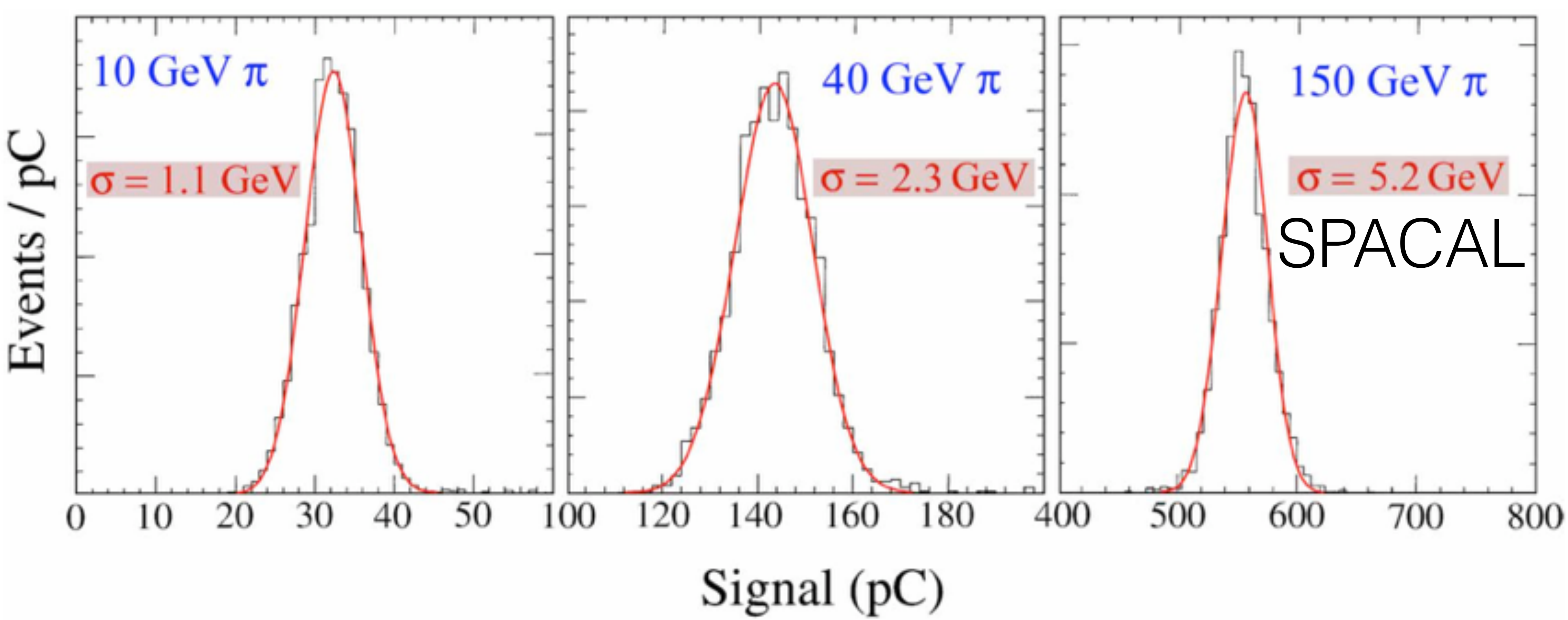
- Non compensation → non linearity
- Offline compensation can distort jet energy scale





Compensating calorimeters

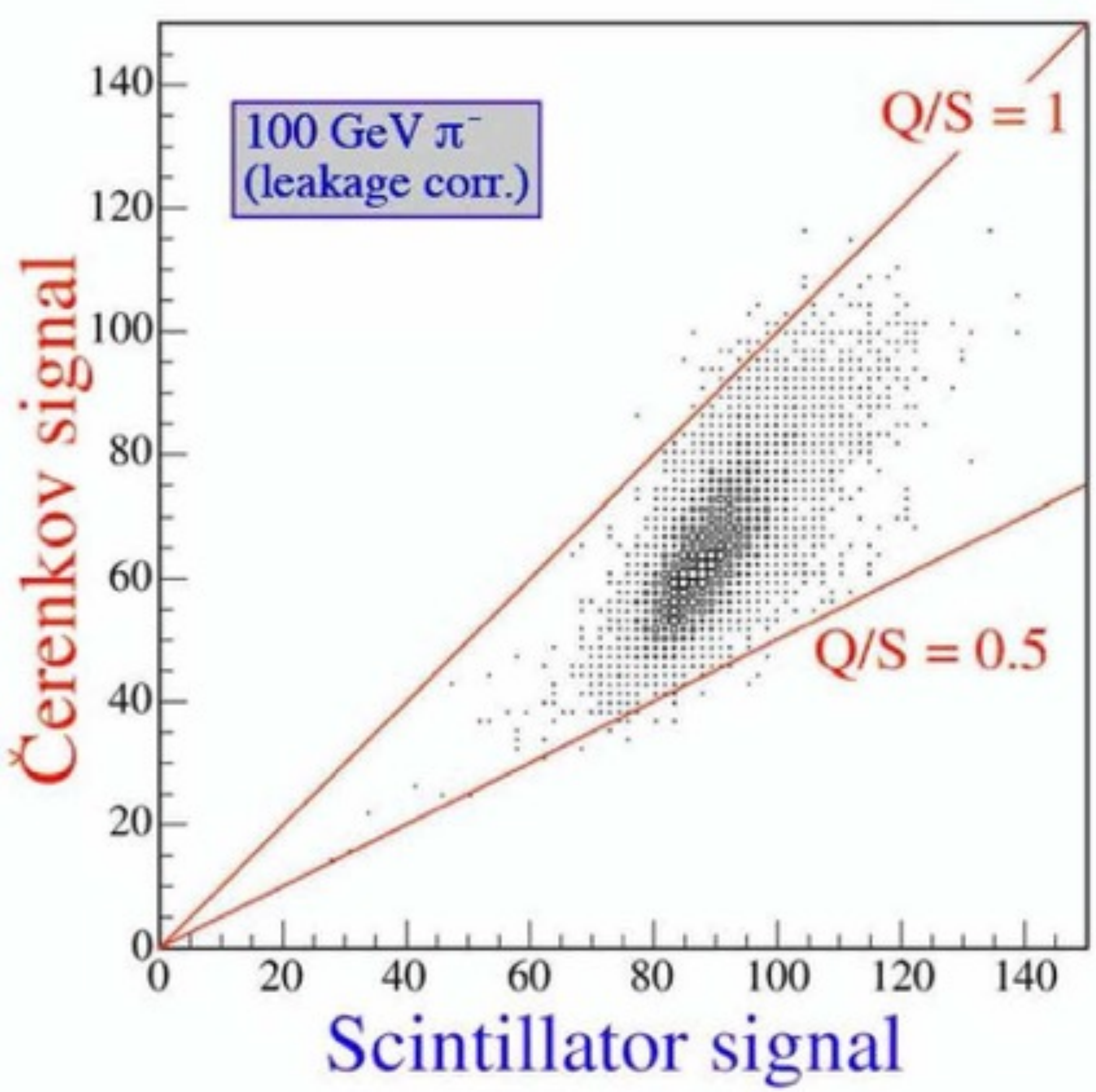
- You can tune e/h by
  - reducing the sampling fraction (e↓ but σ↑)
  - hydrogen in active material (h↑ but Texas towers)
- Only works for specific integration time



Dual Readout calorimetry

Compensation with dual readout

- Measure the same shower twice, with two different calorimeters



$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$

$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right]$$

$e.g.$ If $\quad e/h = 1.3\ (S),\ 4.7\ (Q)$

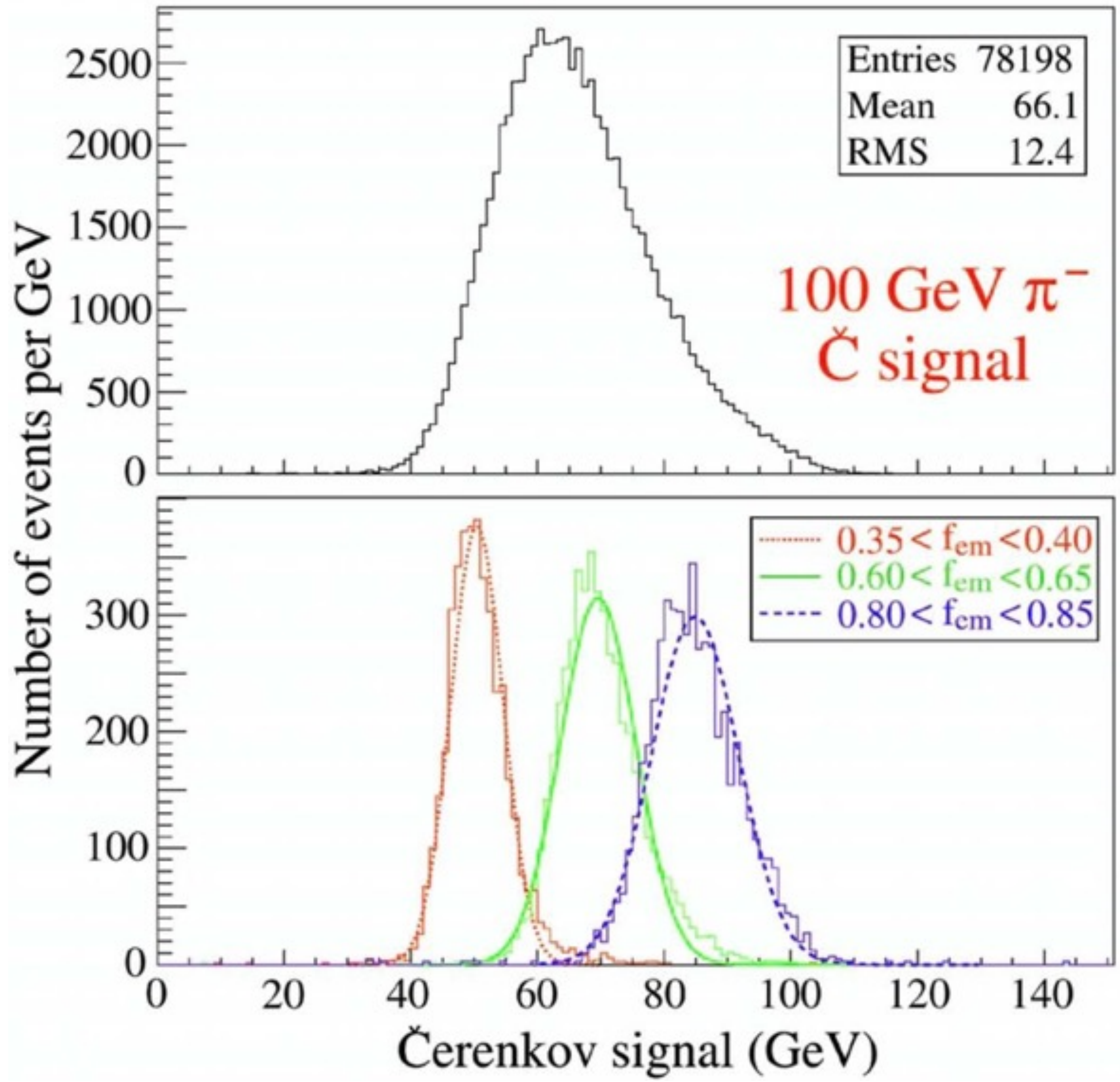
$$\boxed{\frac{Q}{S} = \frac{f_{em} + 0.21\,(1 - f_{em})}{f_{em} + 0.77\,(1 - f_{em})}}$$

$$\boxed{E = \frac{S - \chi Q}{1 - \chi}}$$

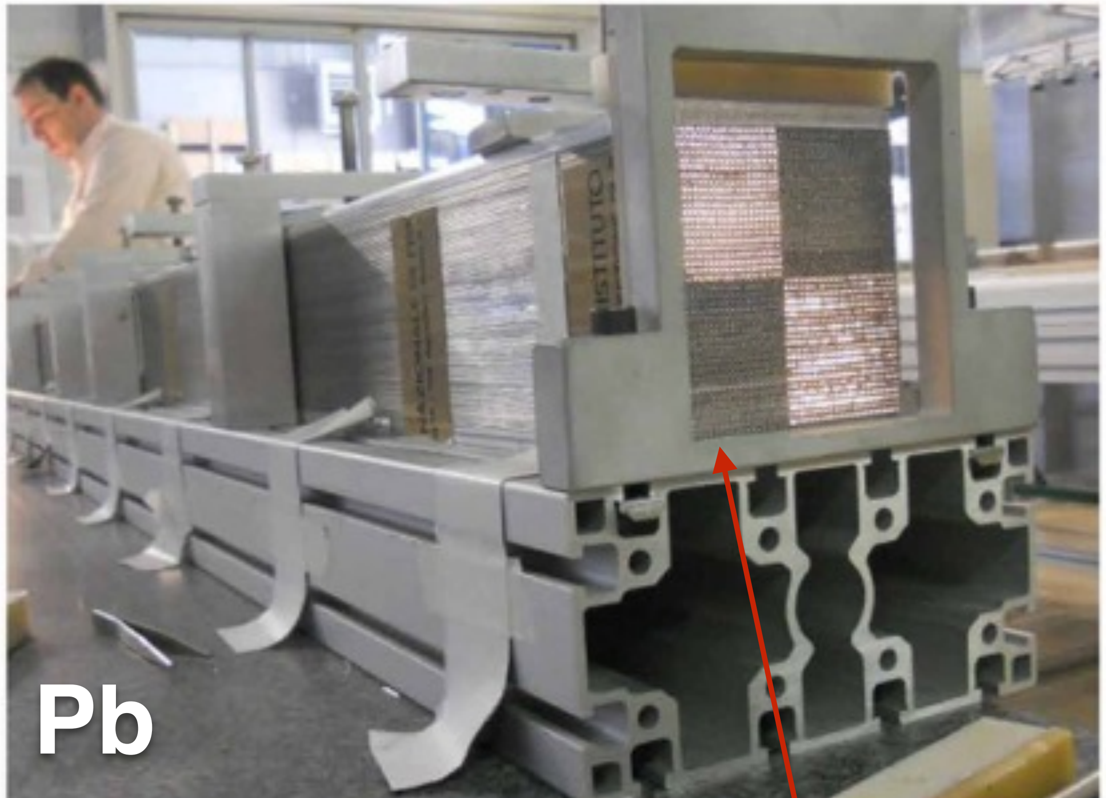
with $\quad \chi = \dfrac{1 - (h/e)_S}{1 - (h/e)_Q}$

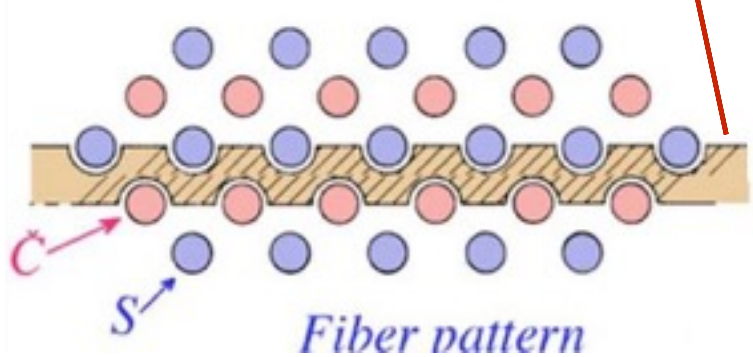
Selection by f_{em}

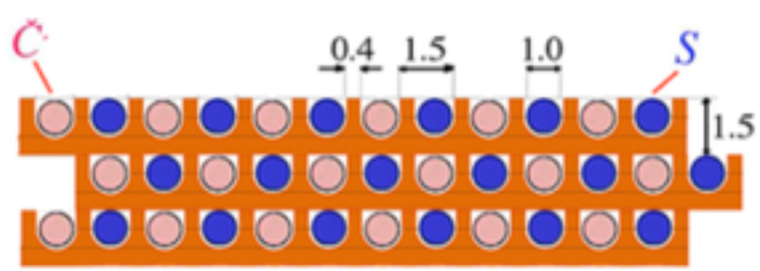
- Each "slice" of f_{em} has a better resolution
- knowledge of f_{em} enables event-by-event compensation



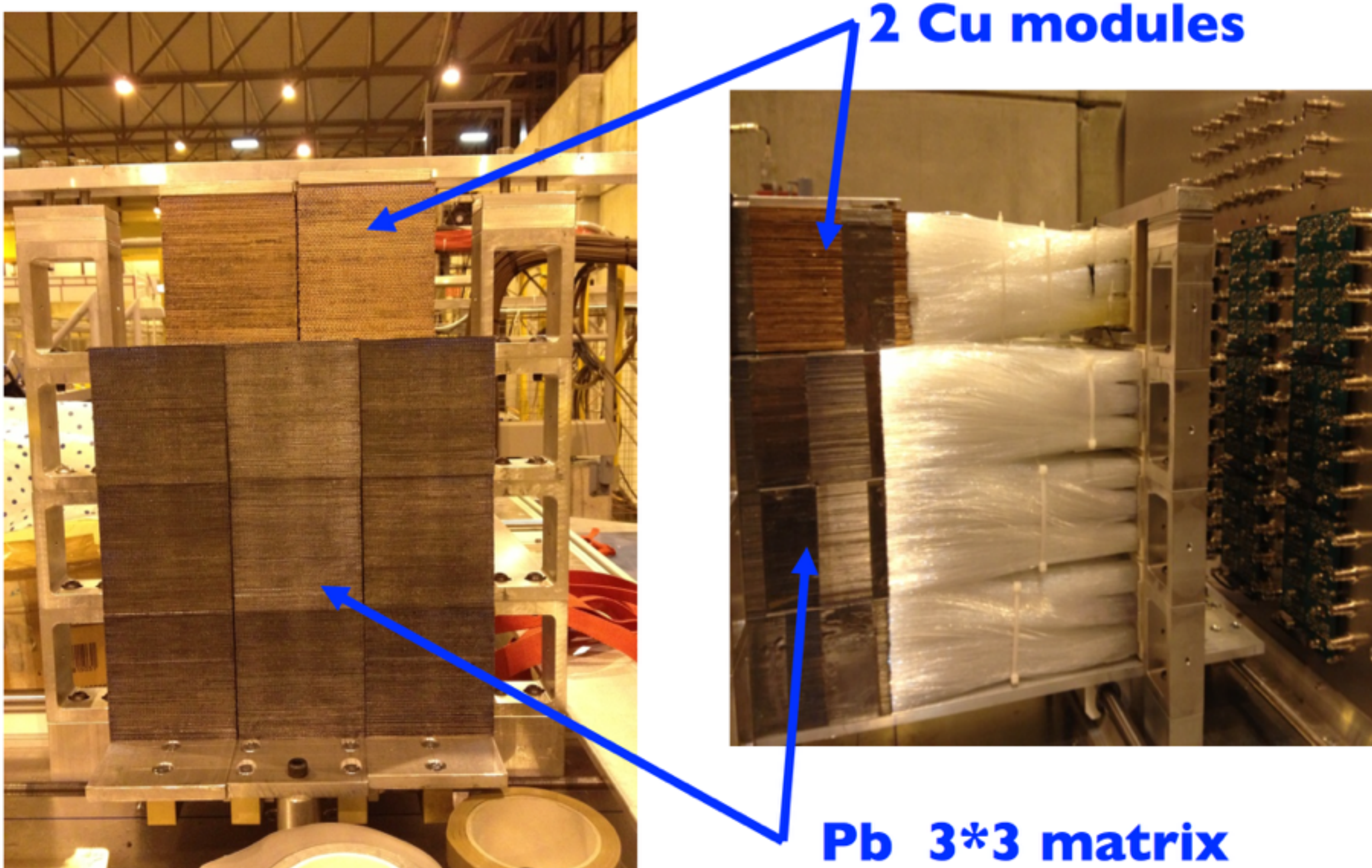
Construction



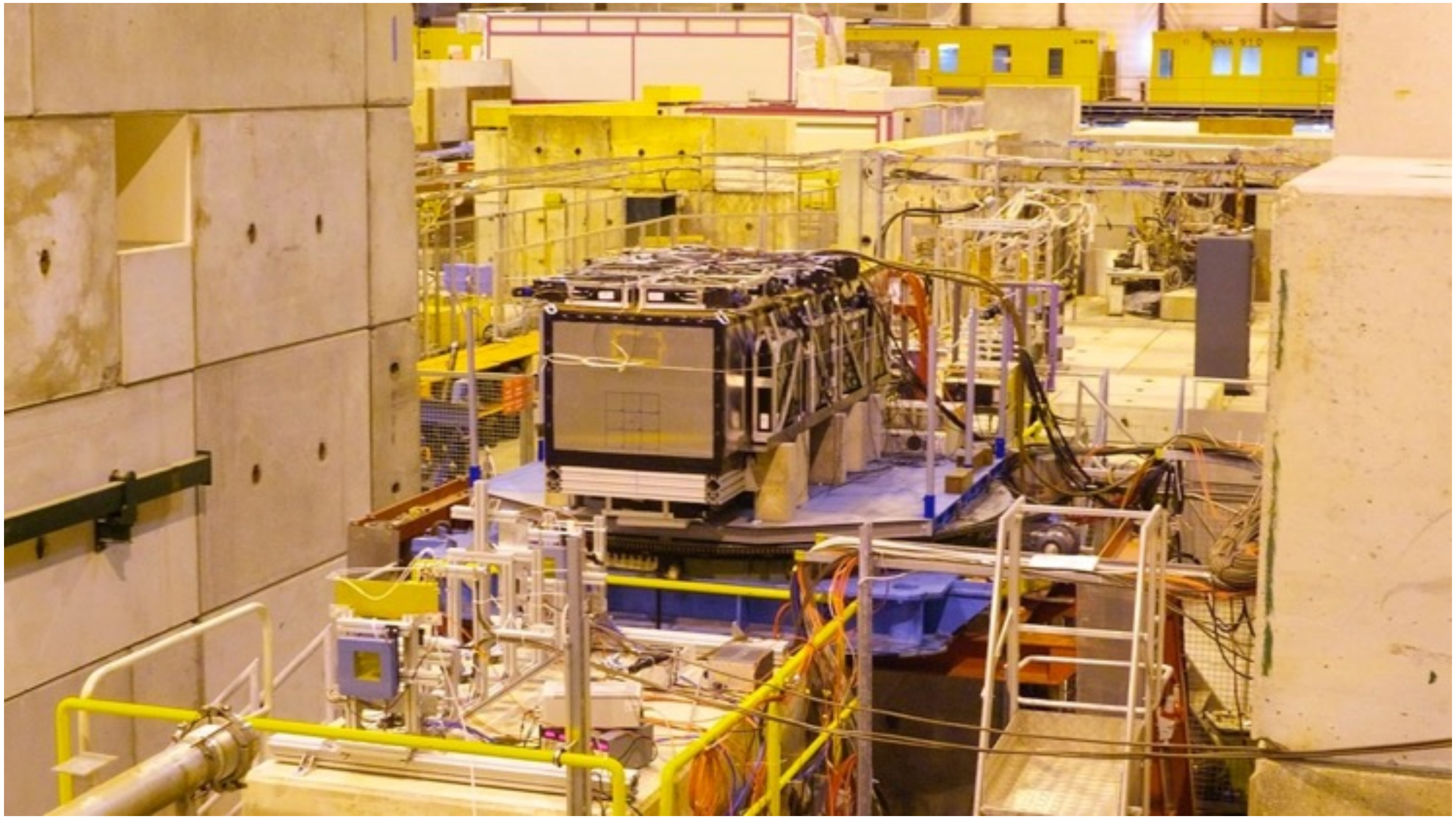


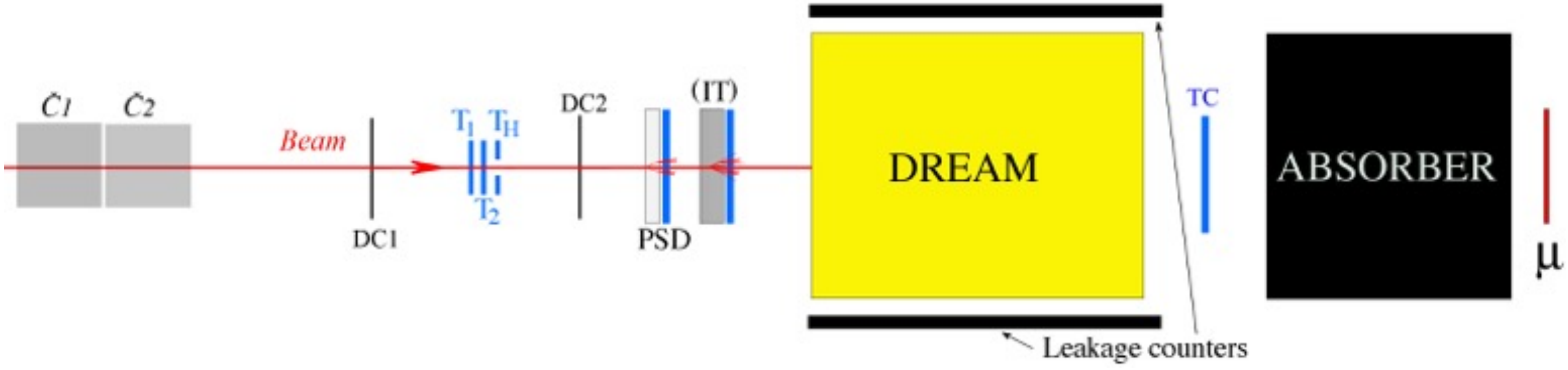


The detector

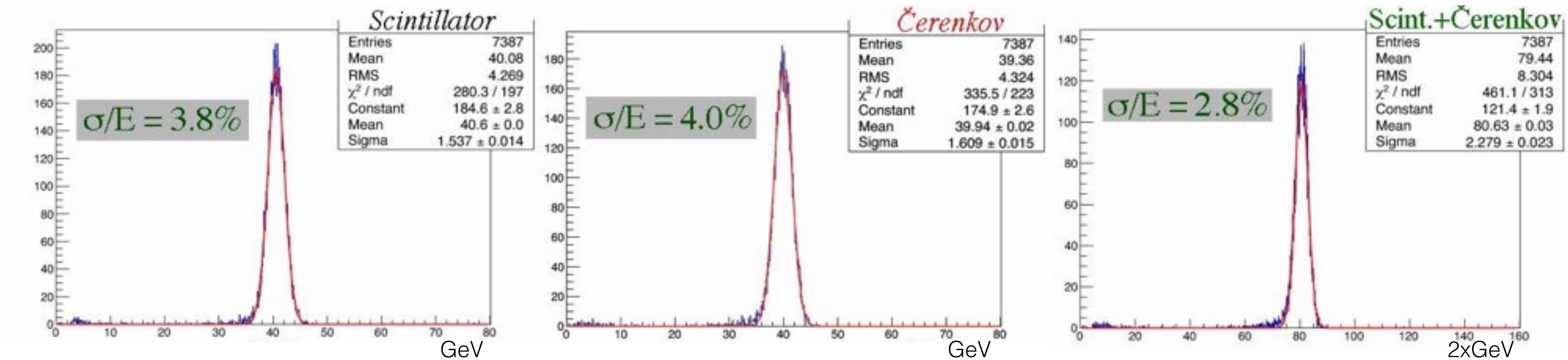


The test beam



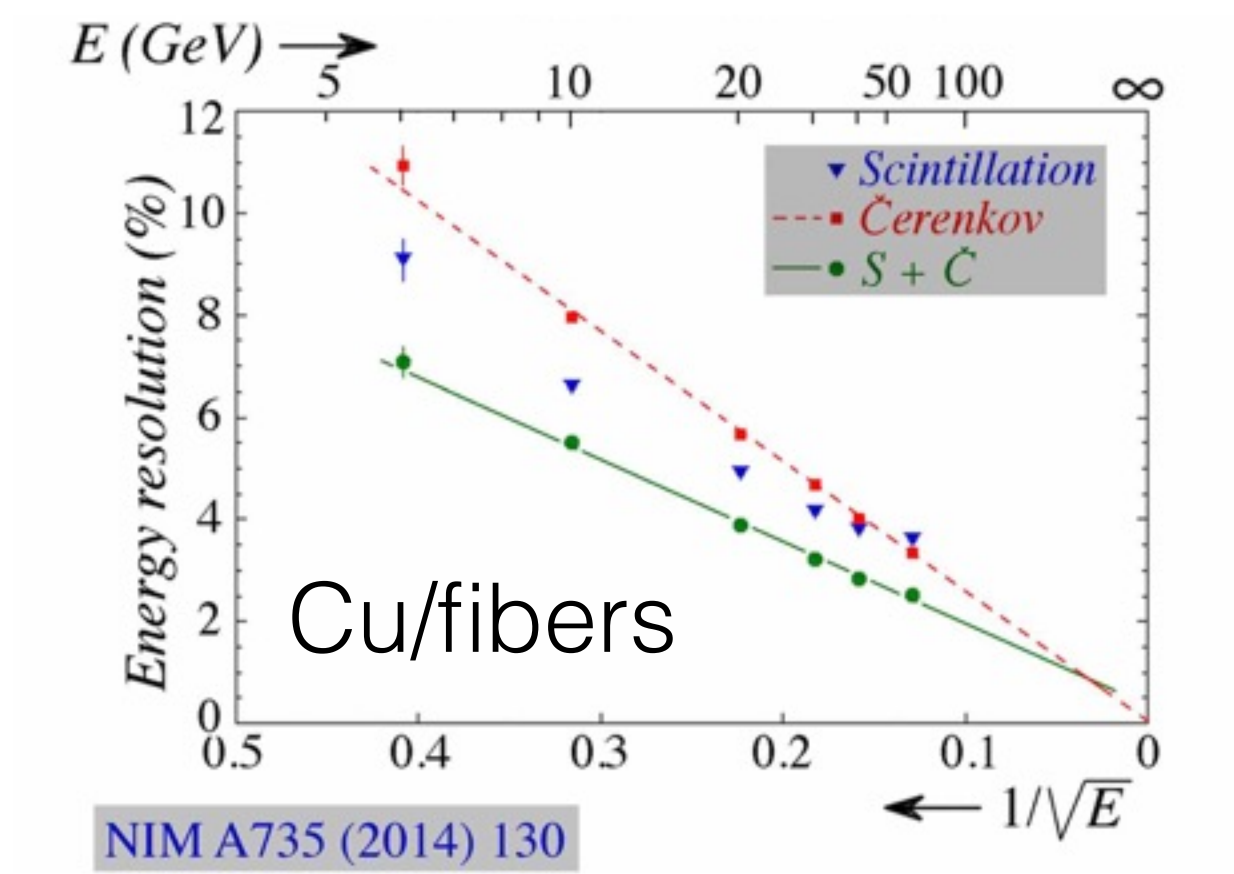


Electromagnetic performcance

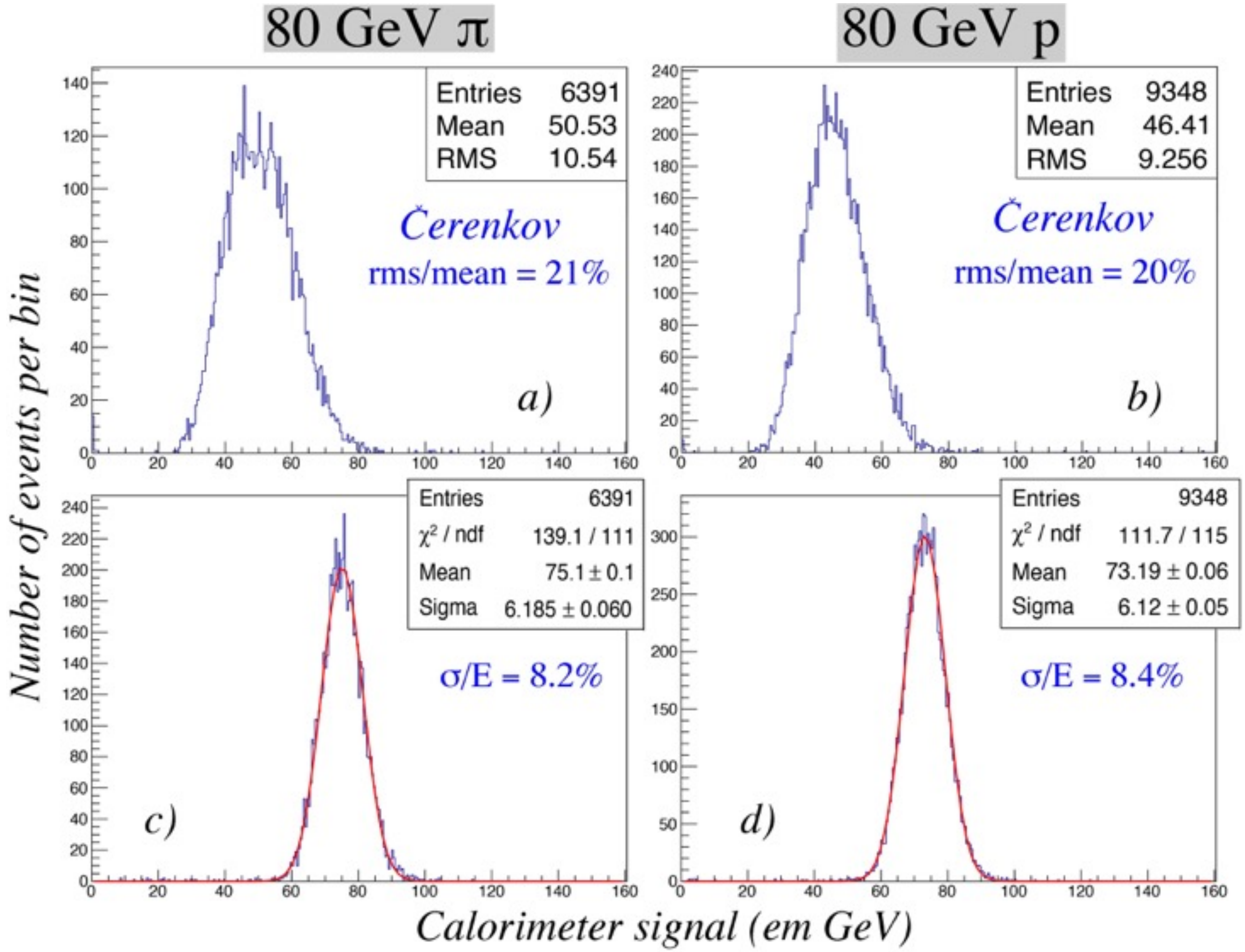


- Combination of S and C channel improves em resolution

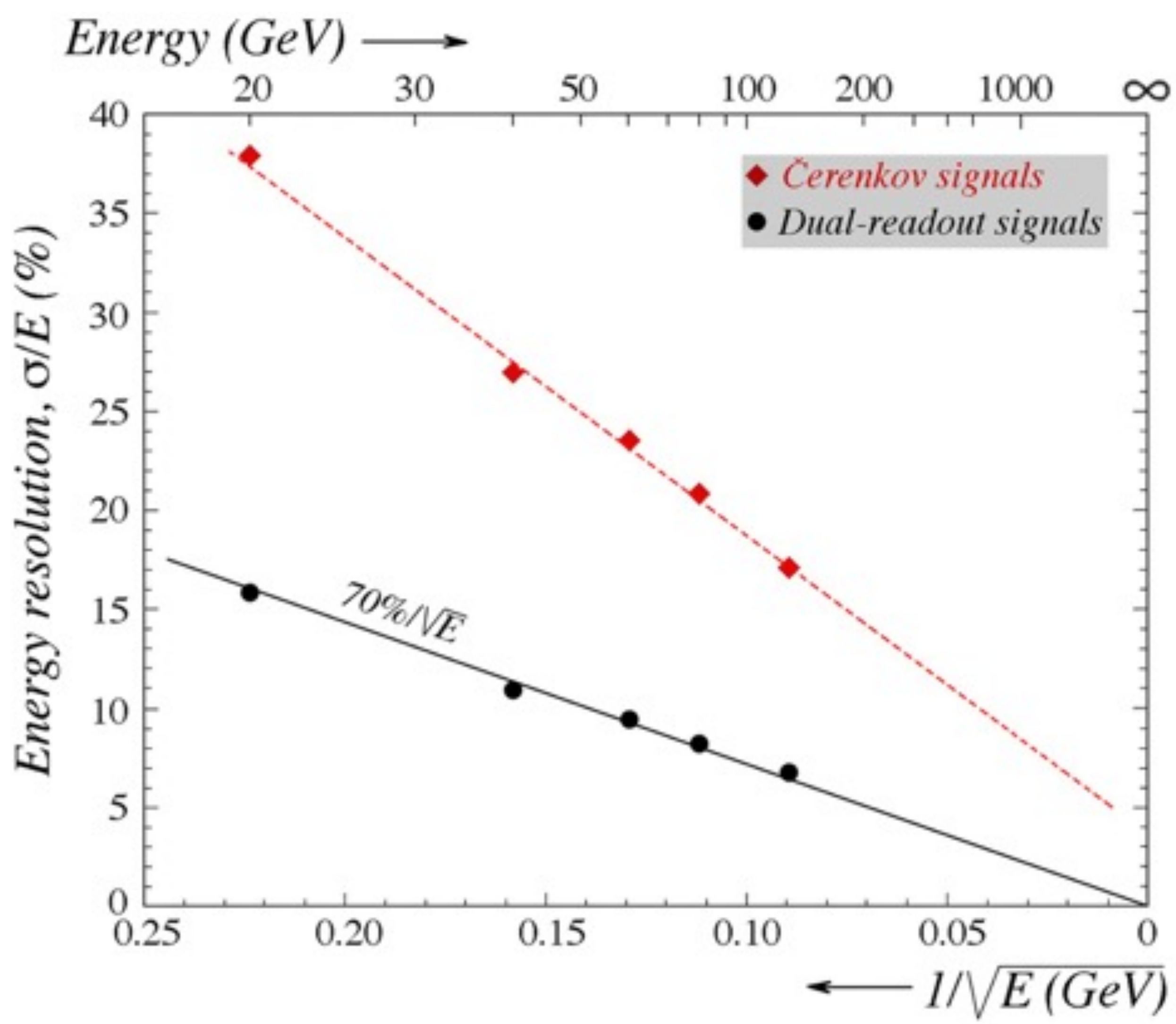
- Stochastic term dominates

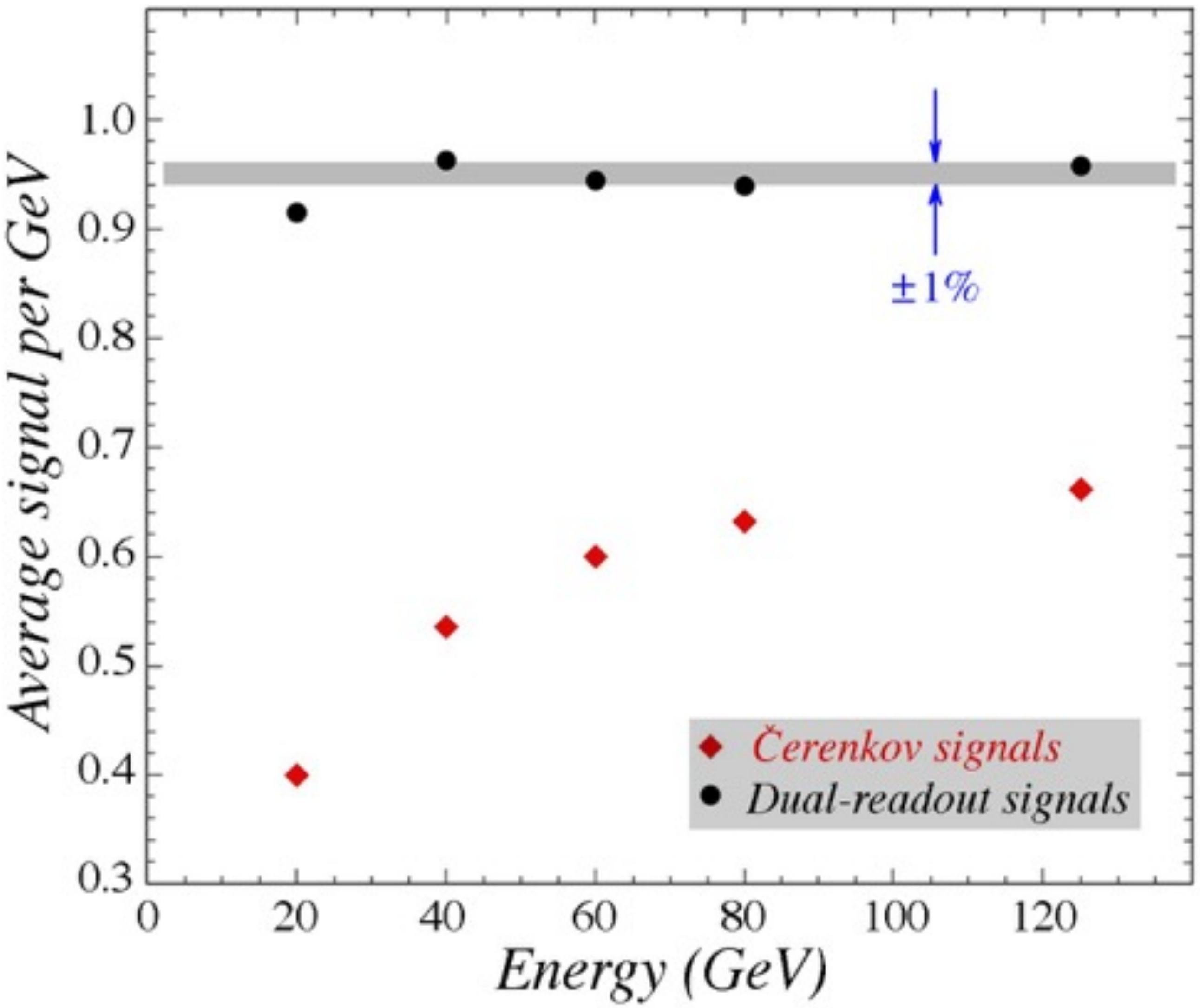


Hadronic performance



Hadronic resolution



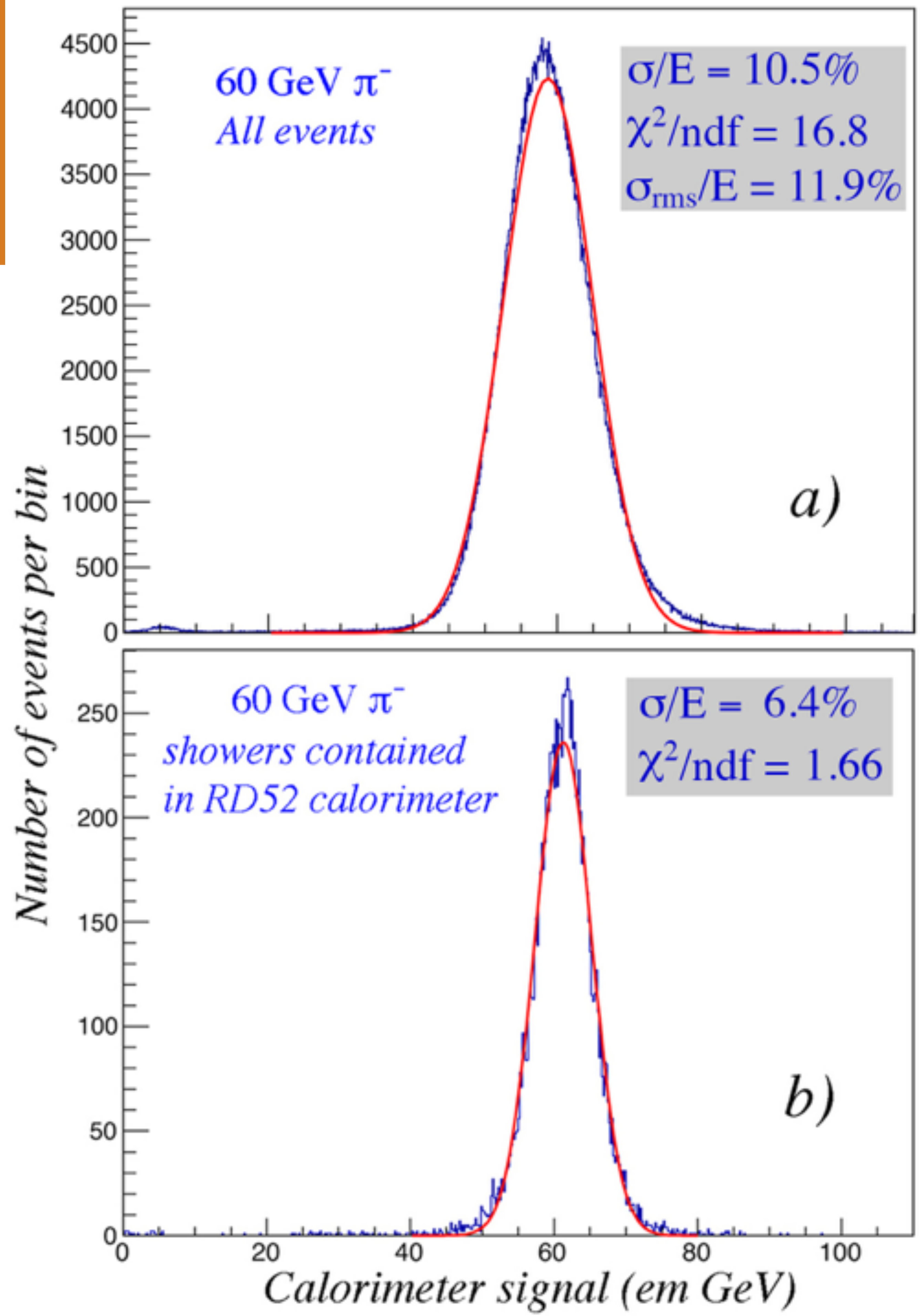


- Good linearity
- Resolution to be improved

Limits to resolution

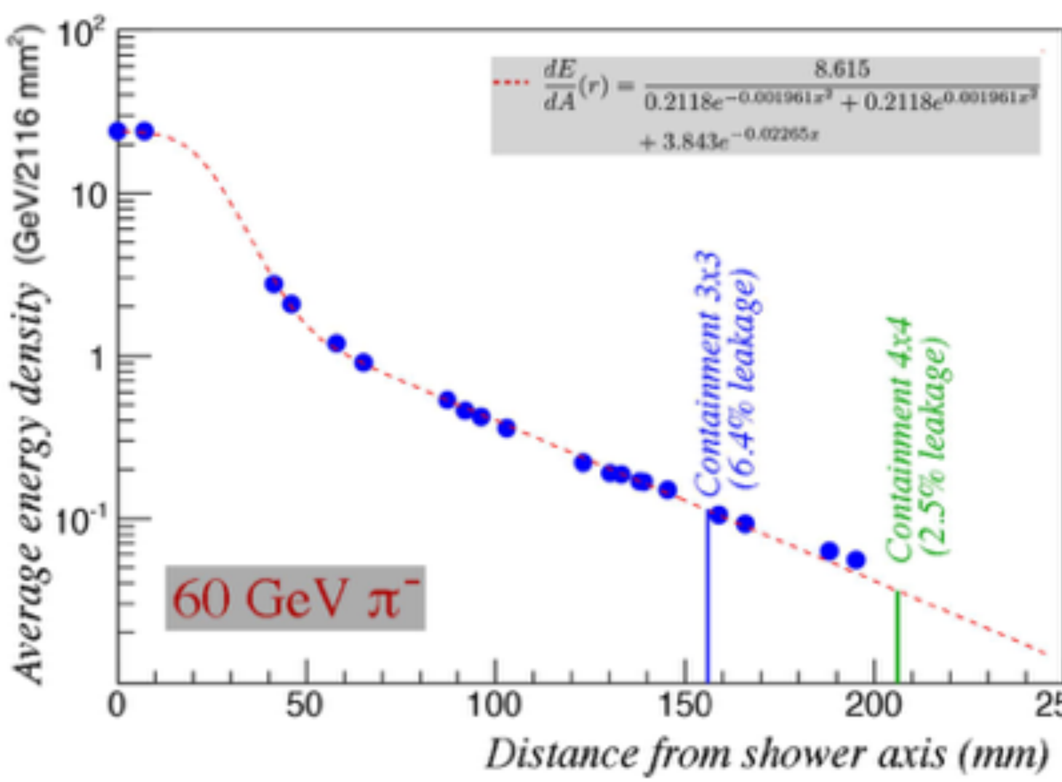
- The Pb matrix resolution is mainly limited by the lateral leakage

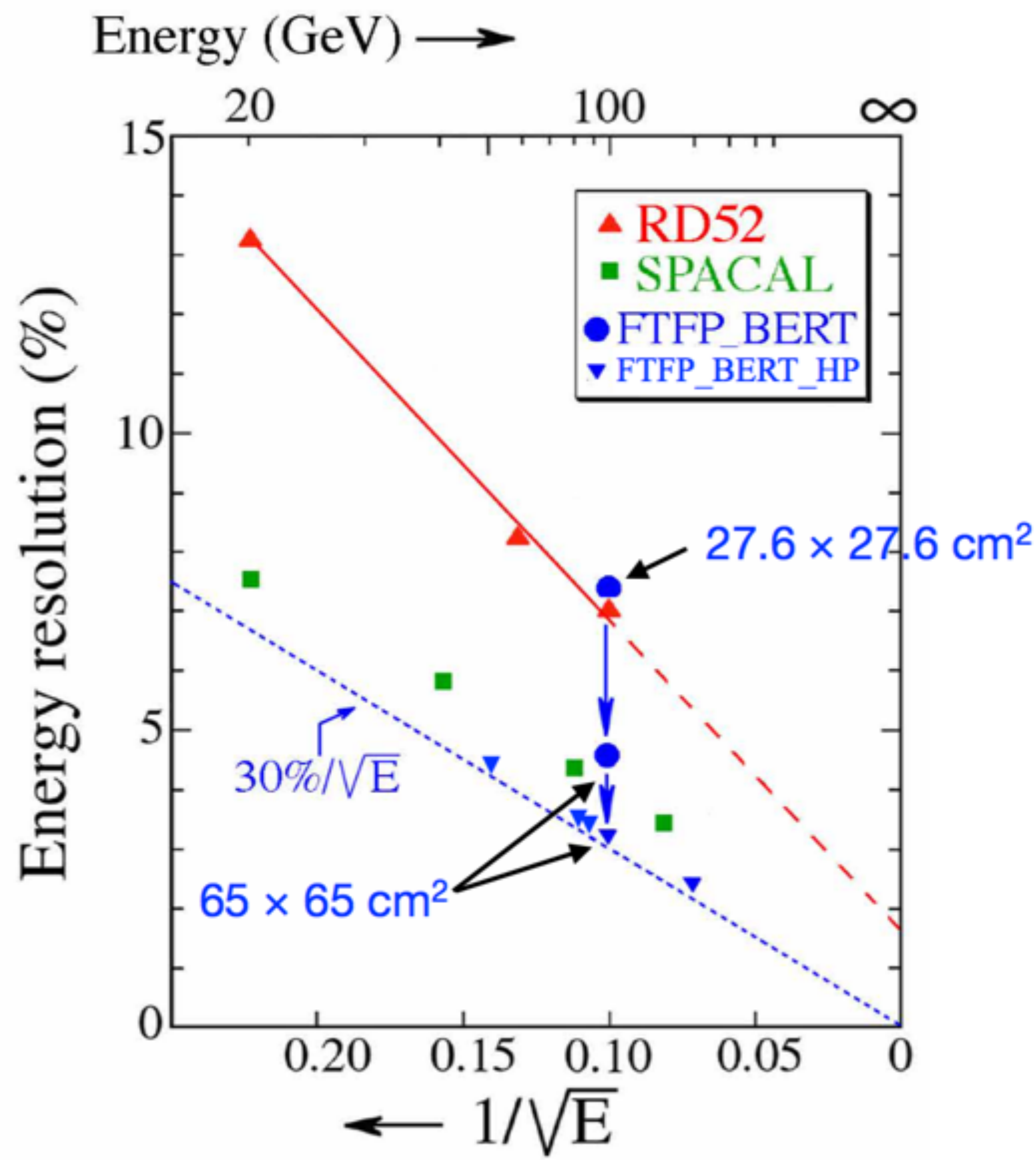
- Resolution almost doubles for well contained events



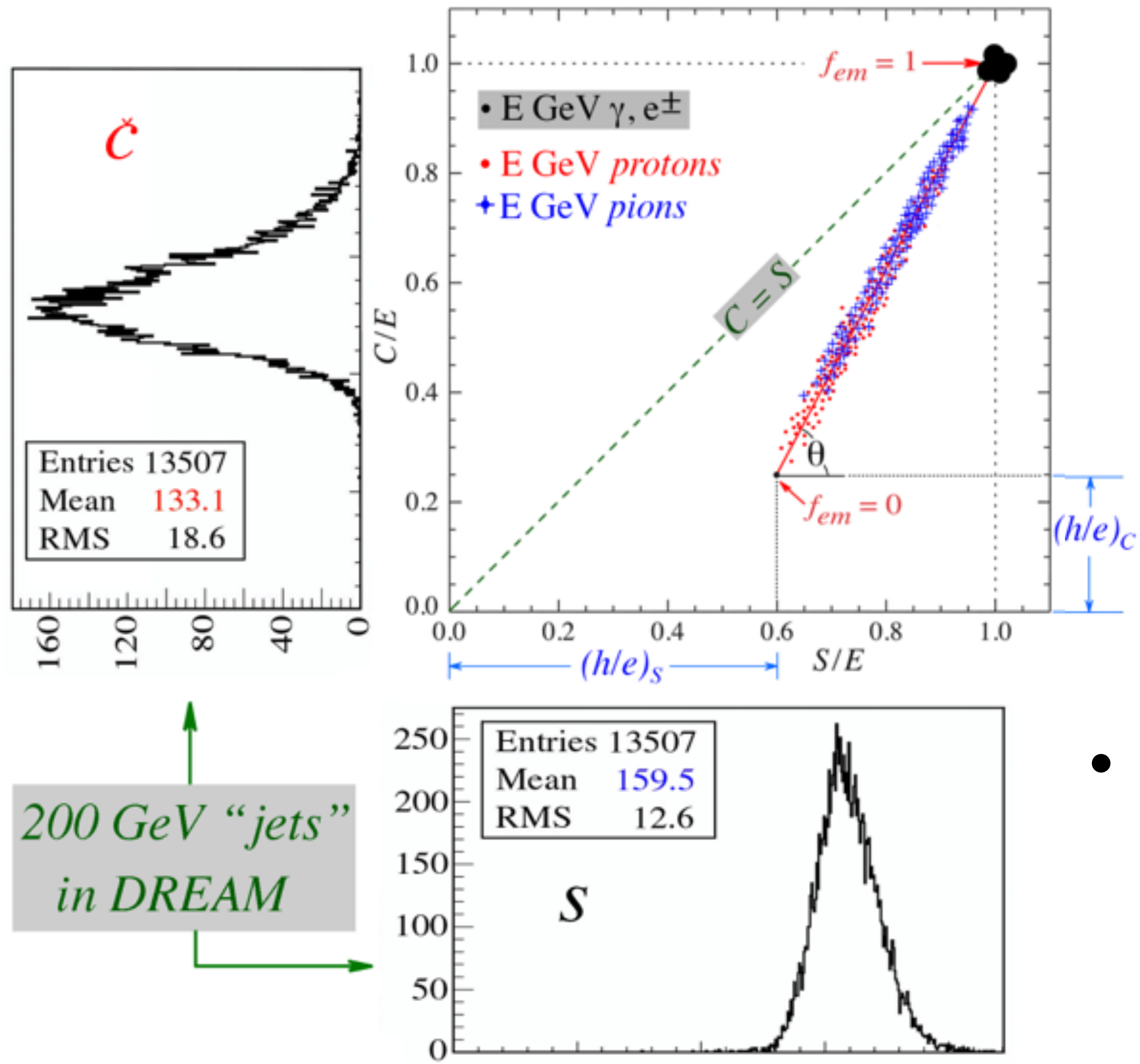
Final hadronic performance

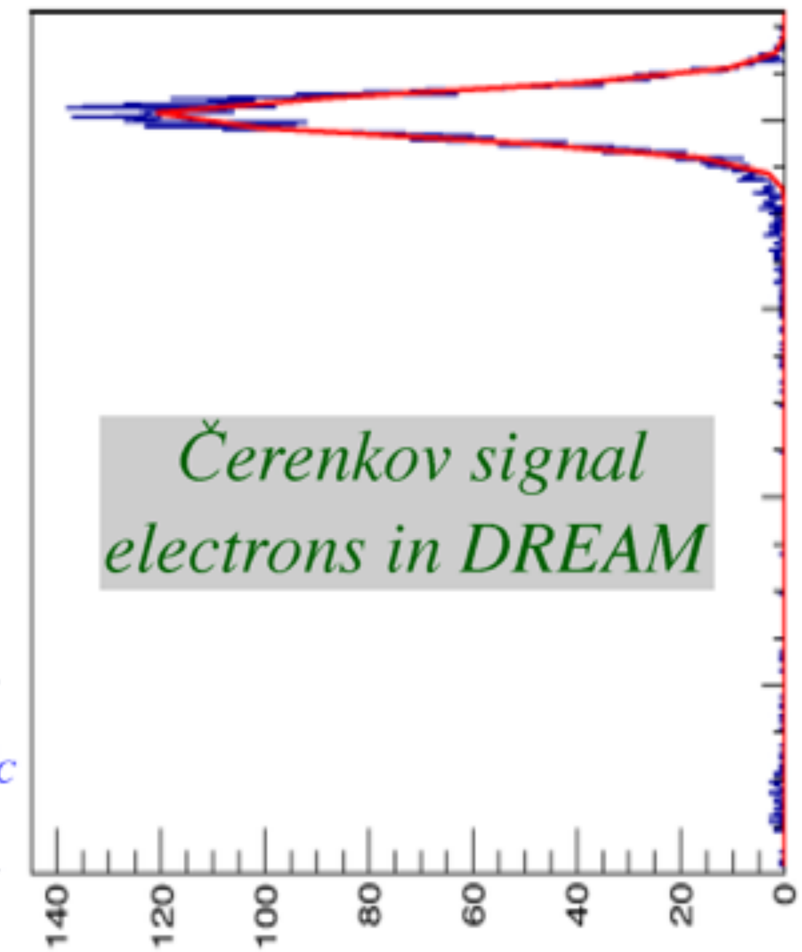
- Larger detector required for full containment
- Simulation suggest large improvement





Rotation method

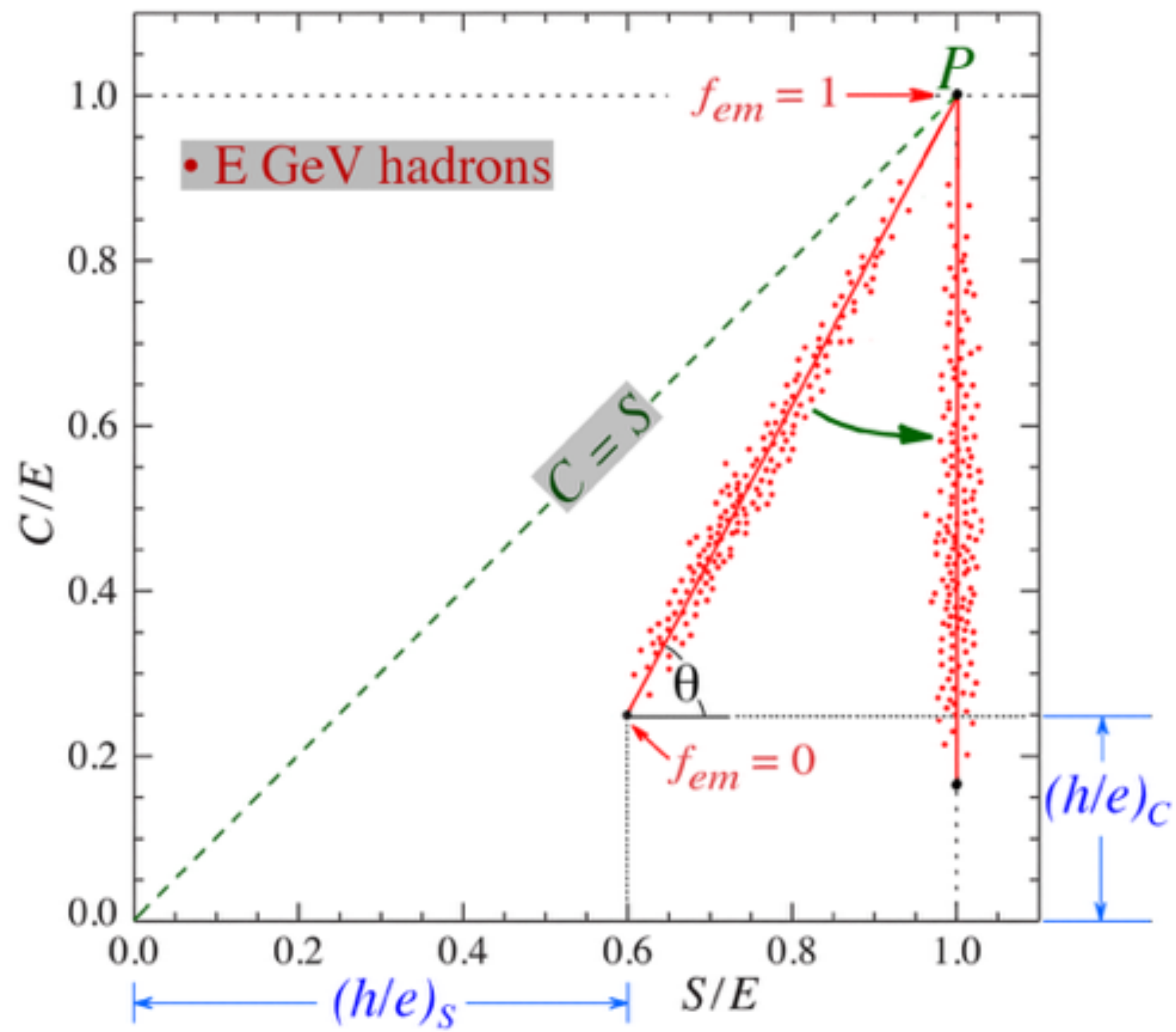


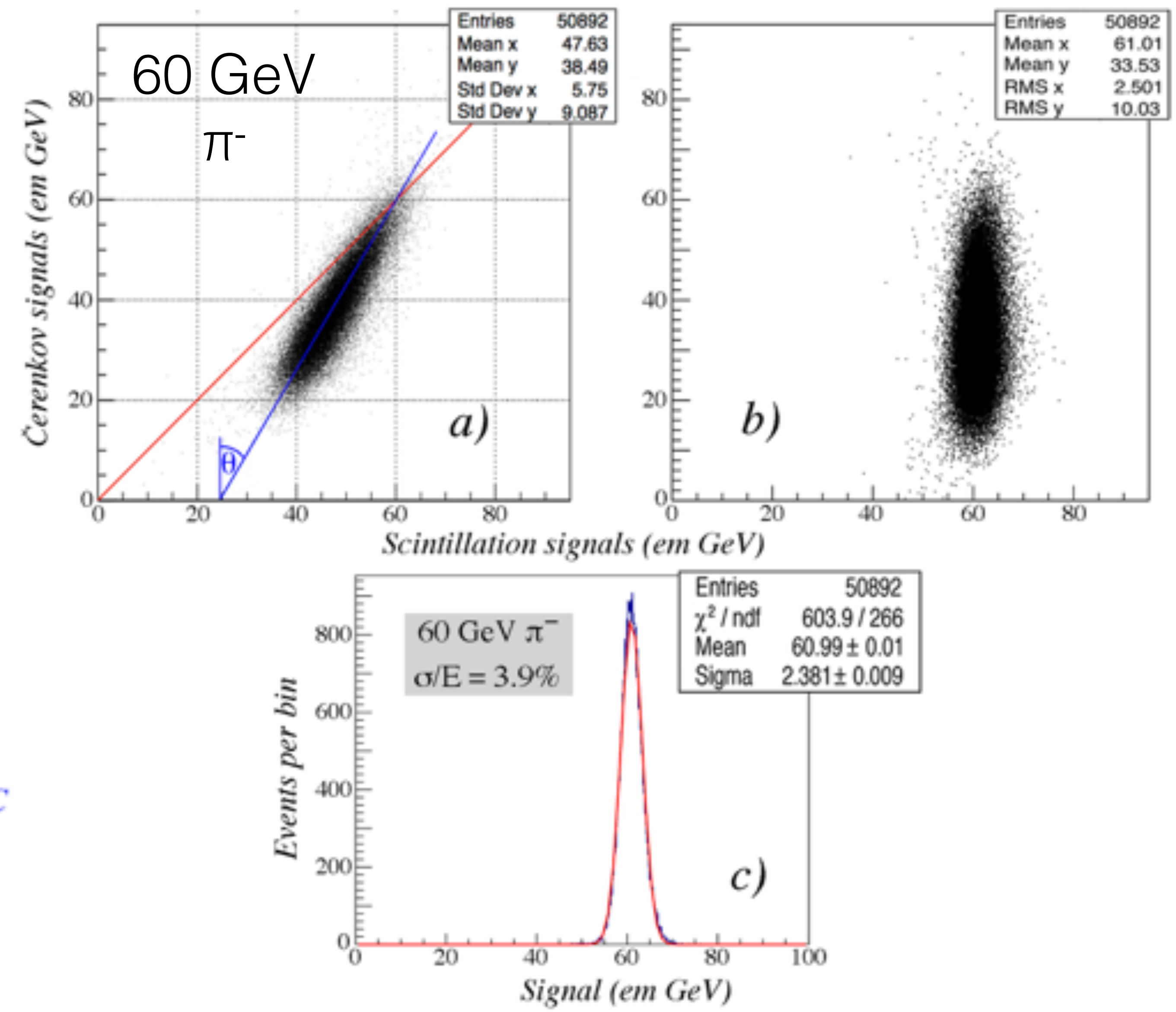


- θ in depend of energy, particle

$$cotg\,\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

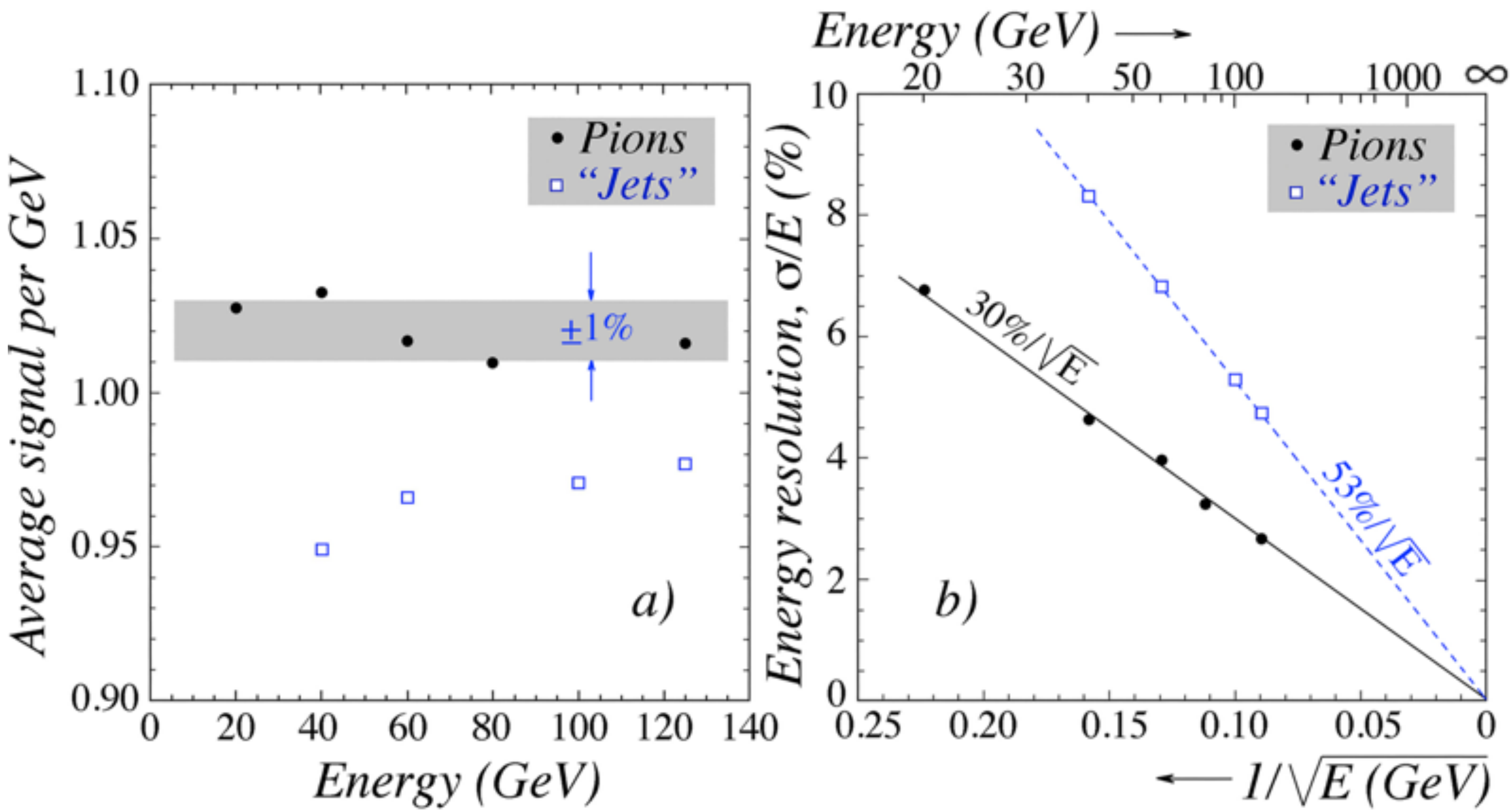
Rotation method





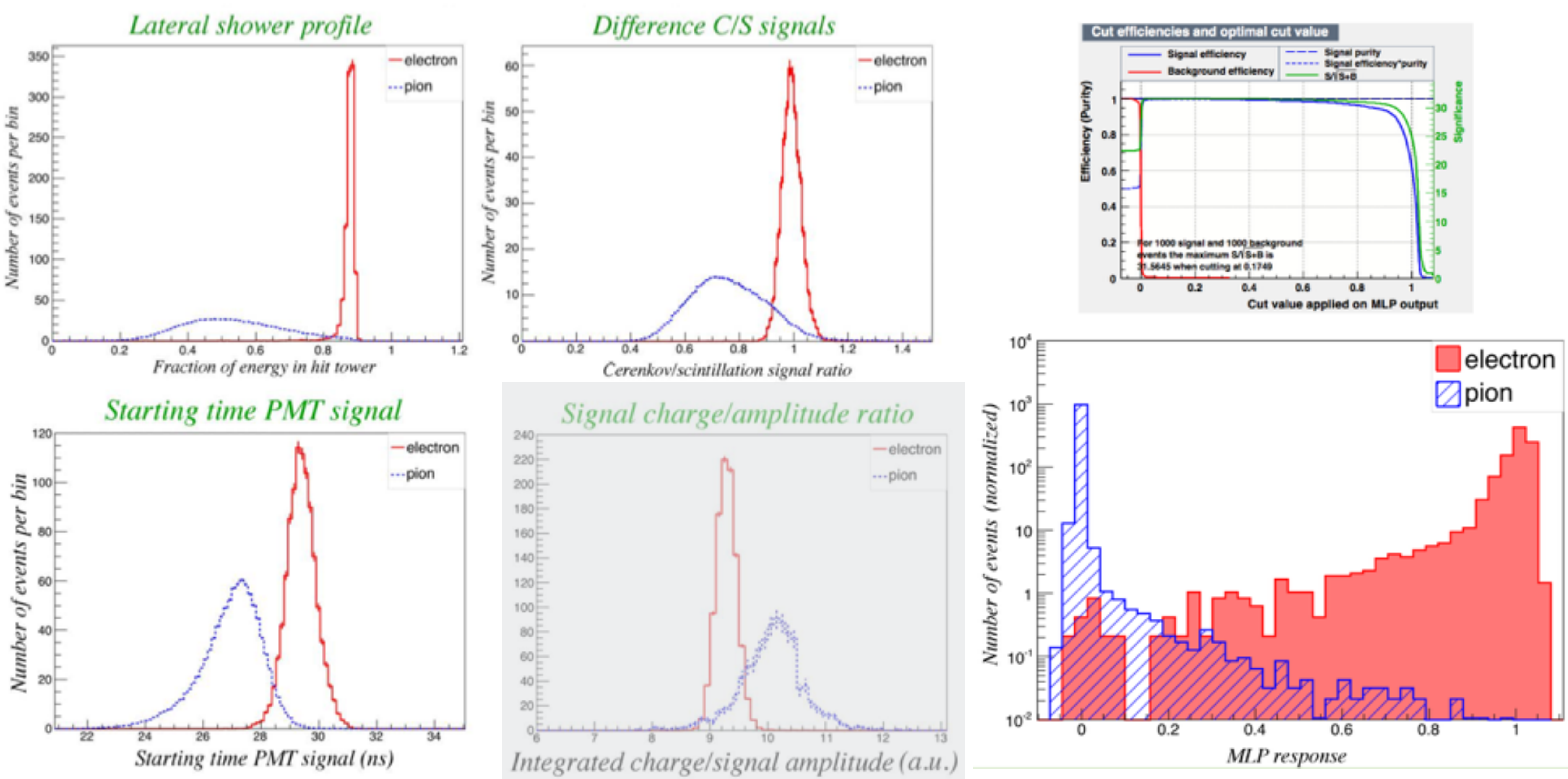
- P can be found by fitting the data with a straight line

Rotation results



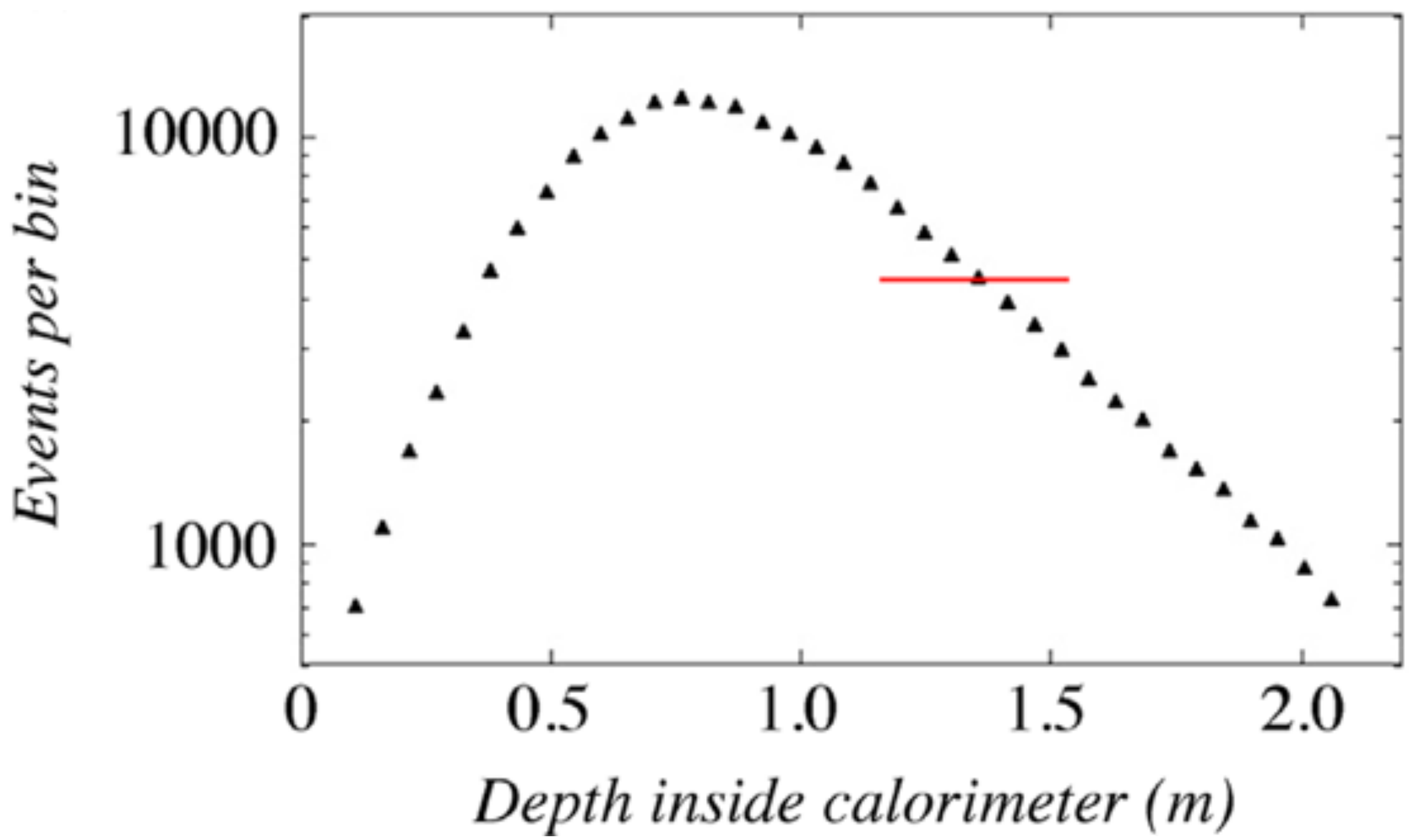
- Caveat, this only works for ensembles of particles
- "Jet" resolution still impacted by detector size

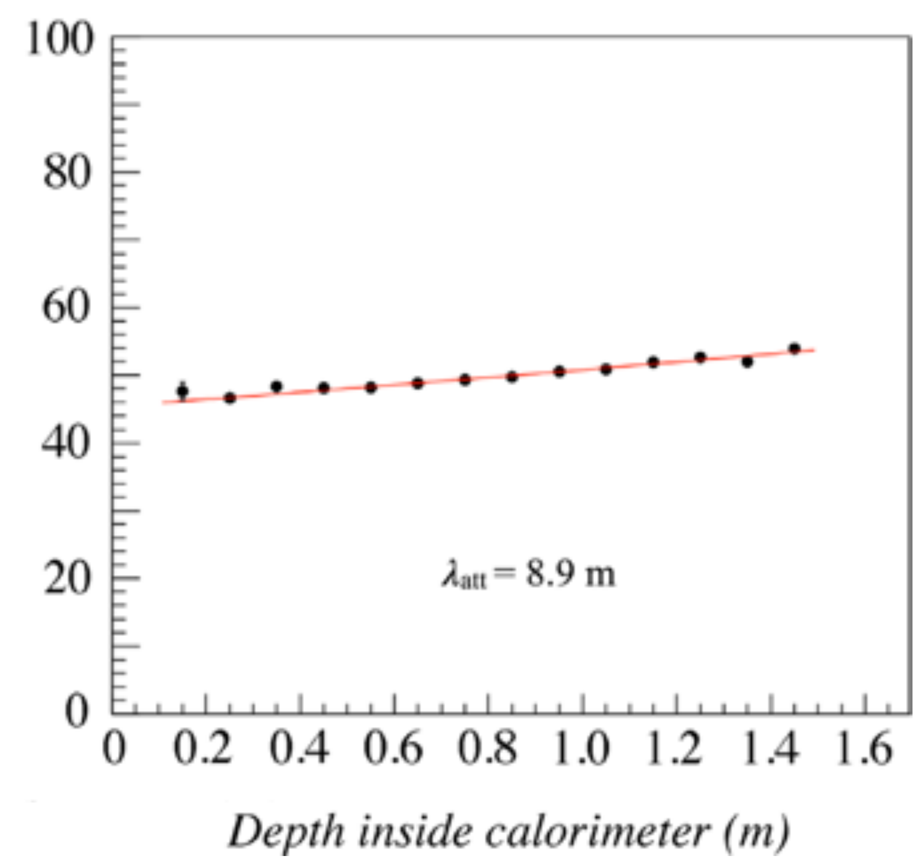
Particle identification



- 99.8 % electron ID, 0.2 % pion mis-ID

Time structure



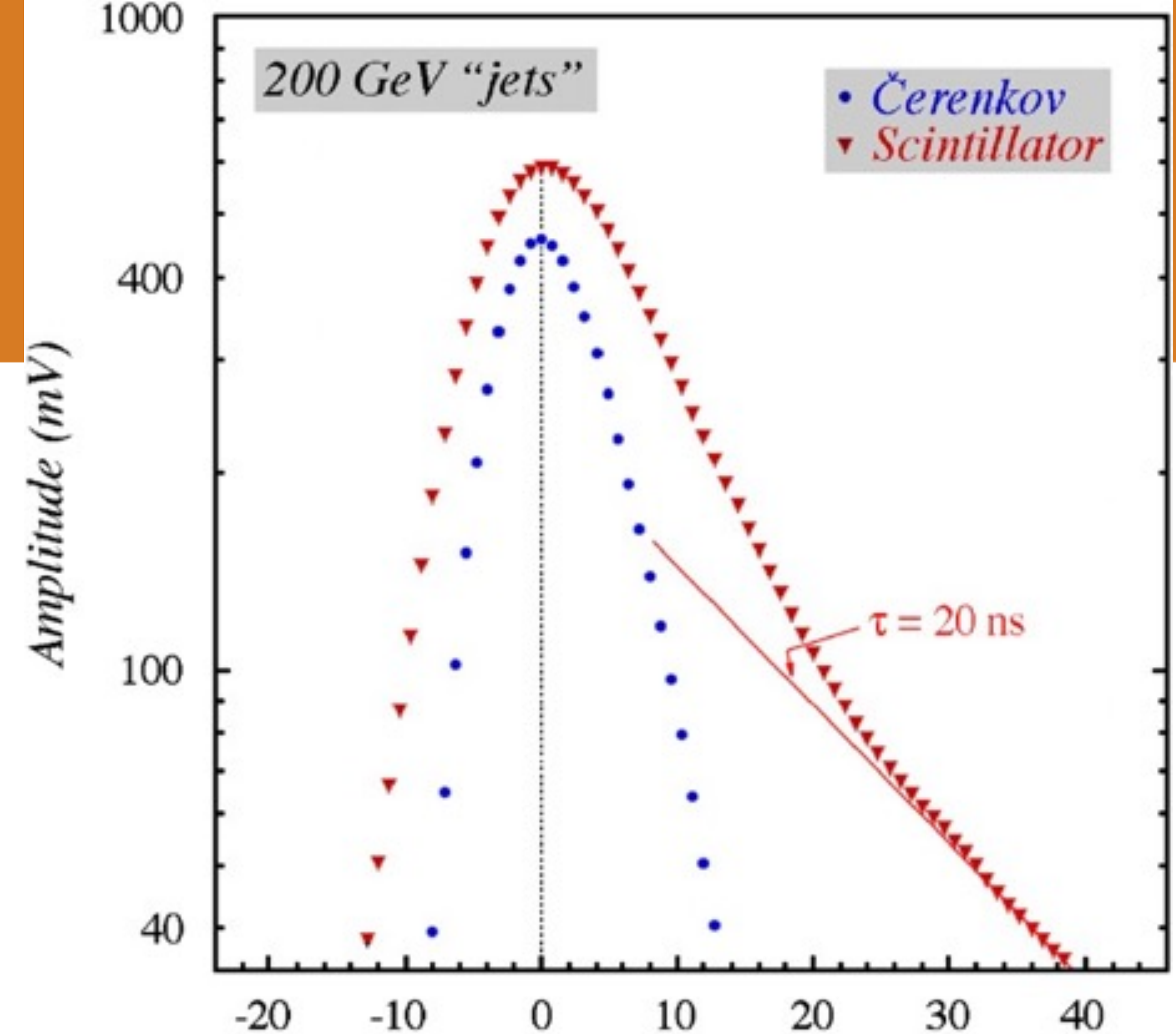


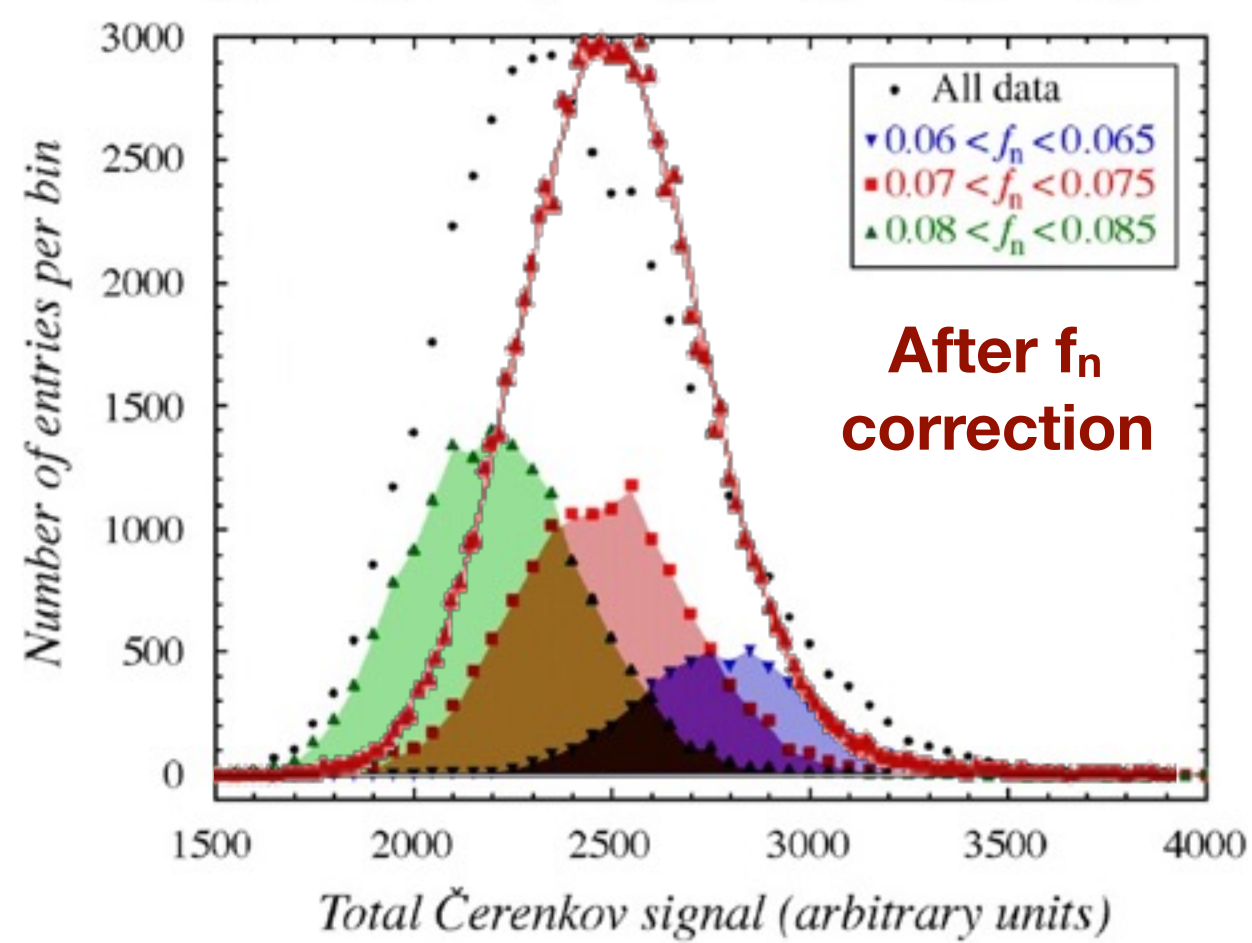
- Delay of the PMT signal correlated with shower starting position
- Correct for light attenuation in fibres.
- No longitudinal segmentation required (easier calibration)

Future perspectives

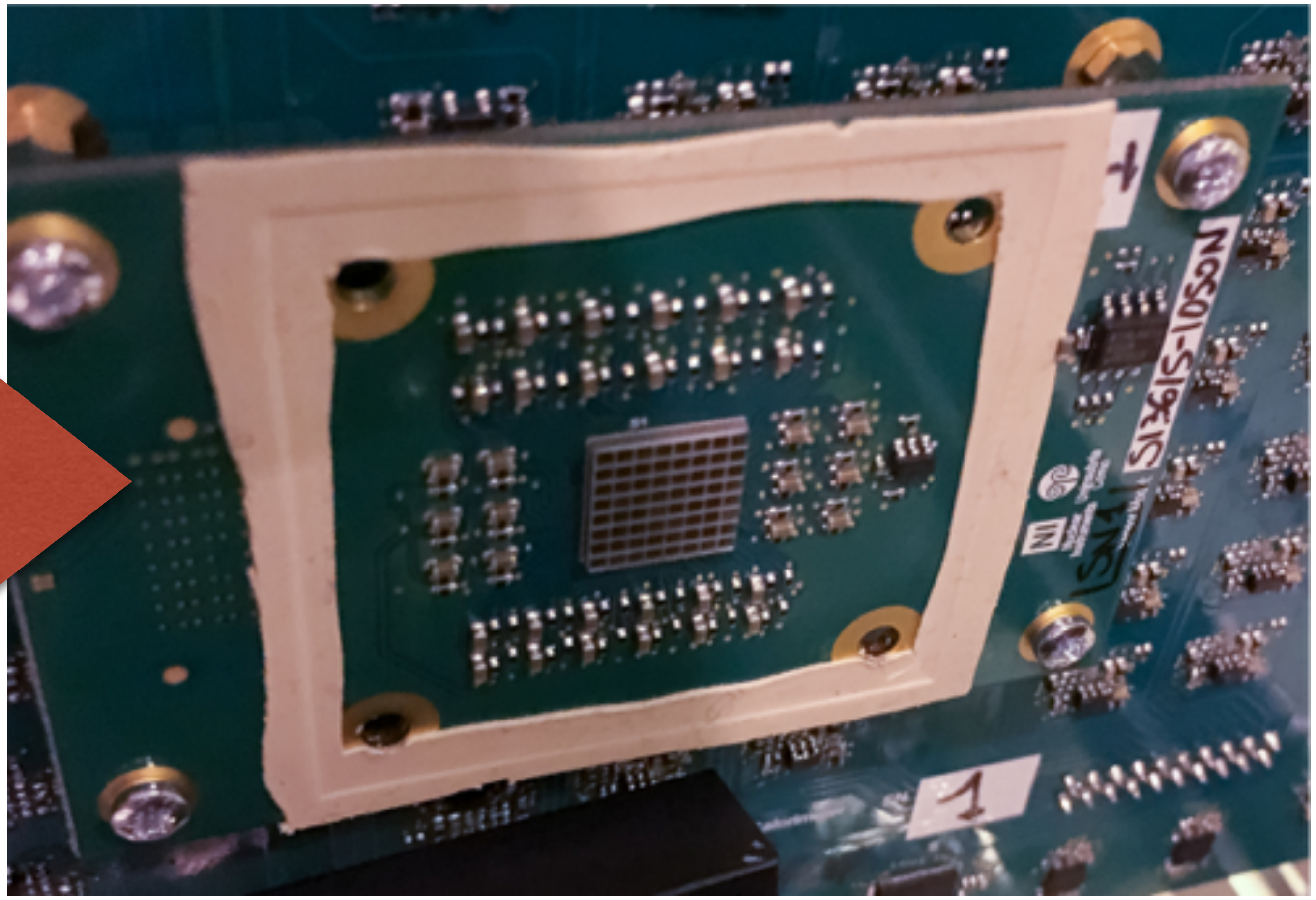
The neutron fraction

- Waiting for the neutron to be absorbed takes too long
- Elastic scattering of n on H in plastic fibres (exponential signal with τ~20ns)
- We cal the relative size of this tail f_n
- f_n is complementary to fem, could be used to further improve the had resolution



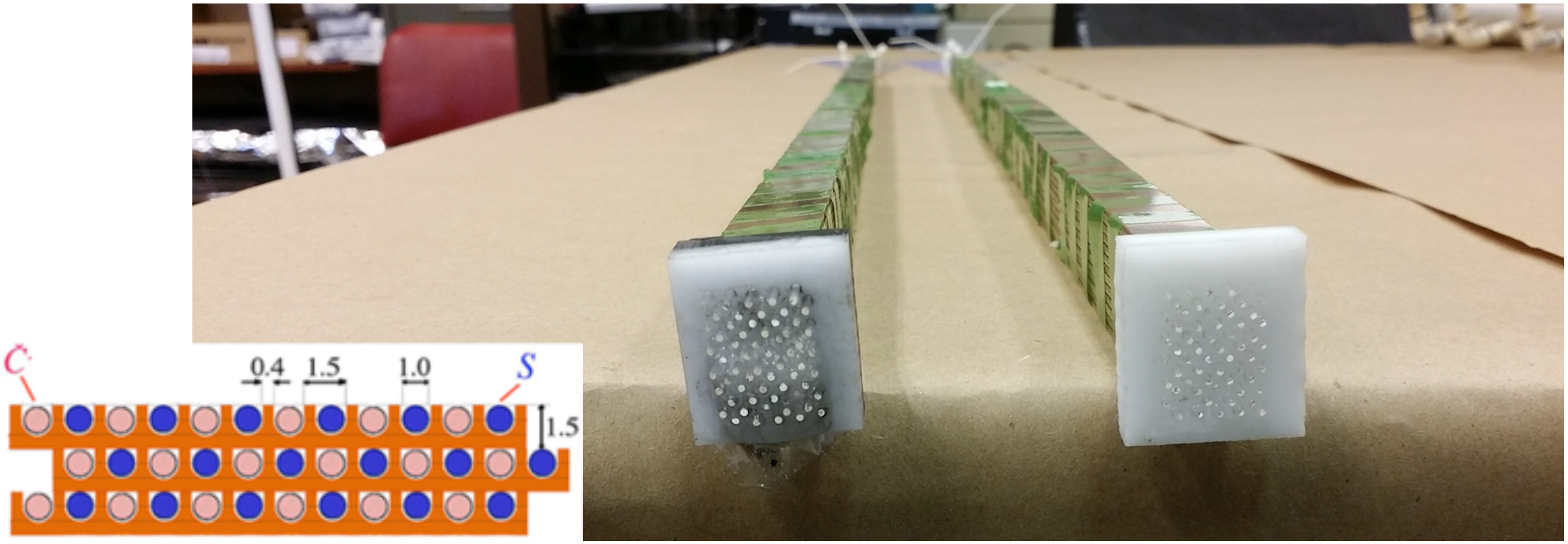


New readout



- The end of the fibre forest
- Longitudinal segmentation

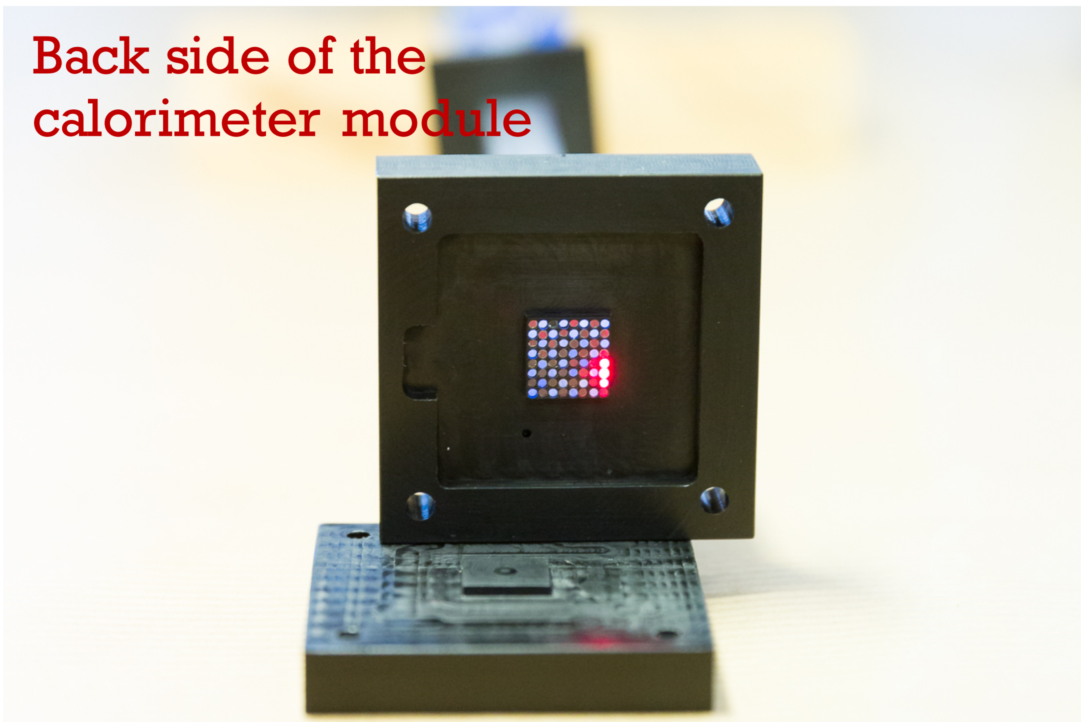
Test modules

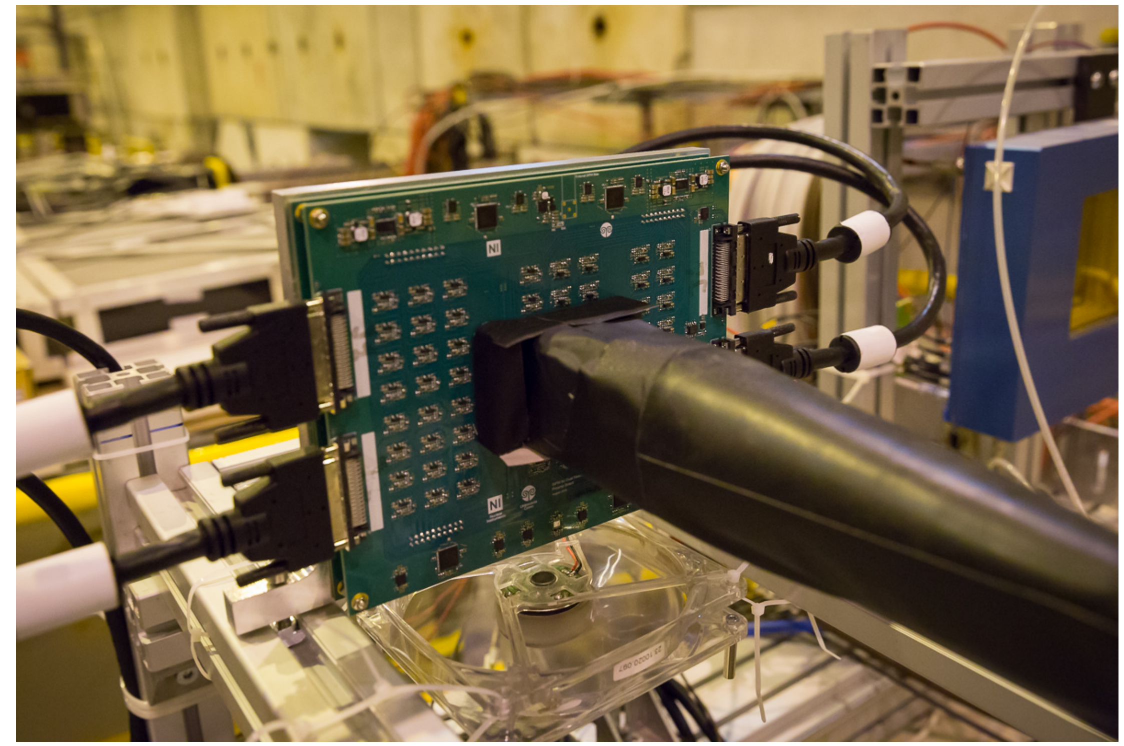


- 2 small copper modules (10x10 fibers) 1x1x100cm^3

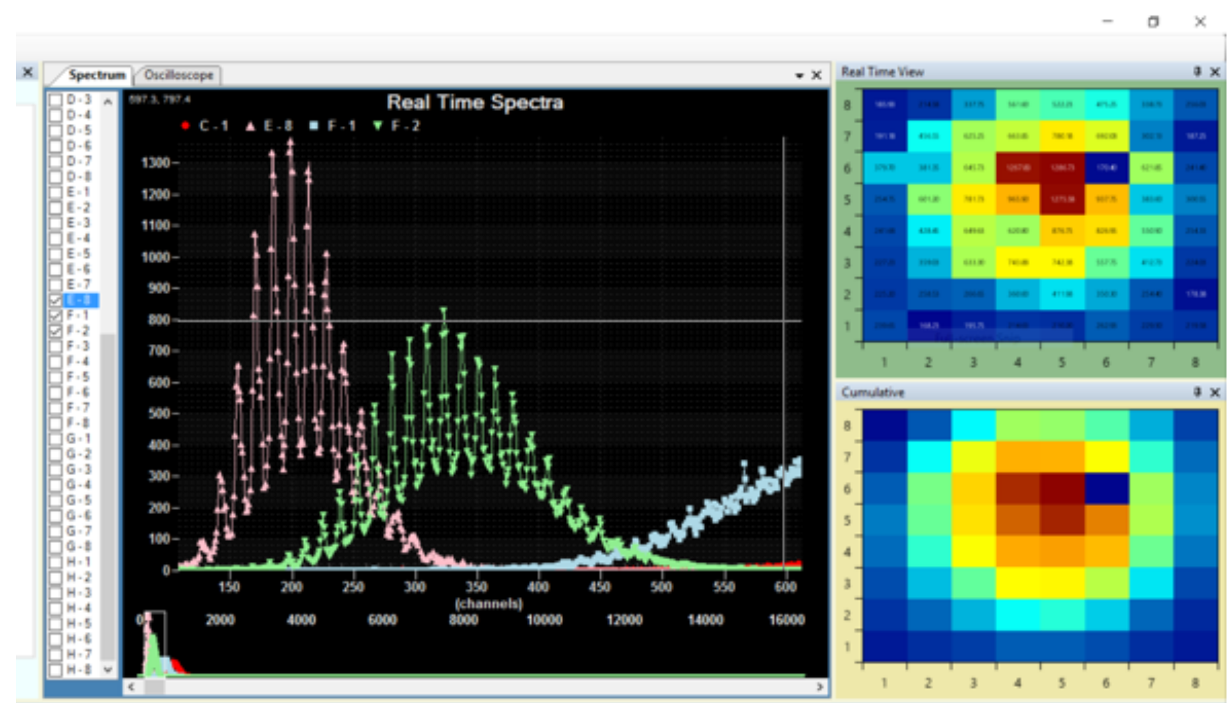
- Still large enough to reasonably contain an electromagnetic shower

SiPM readout



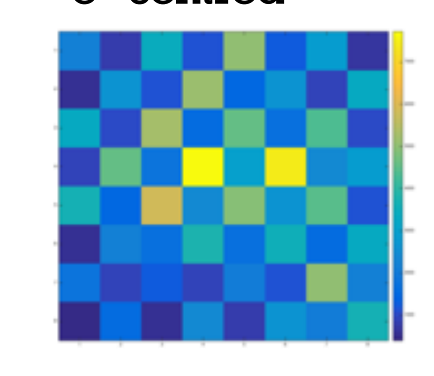


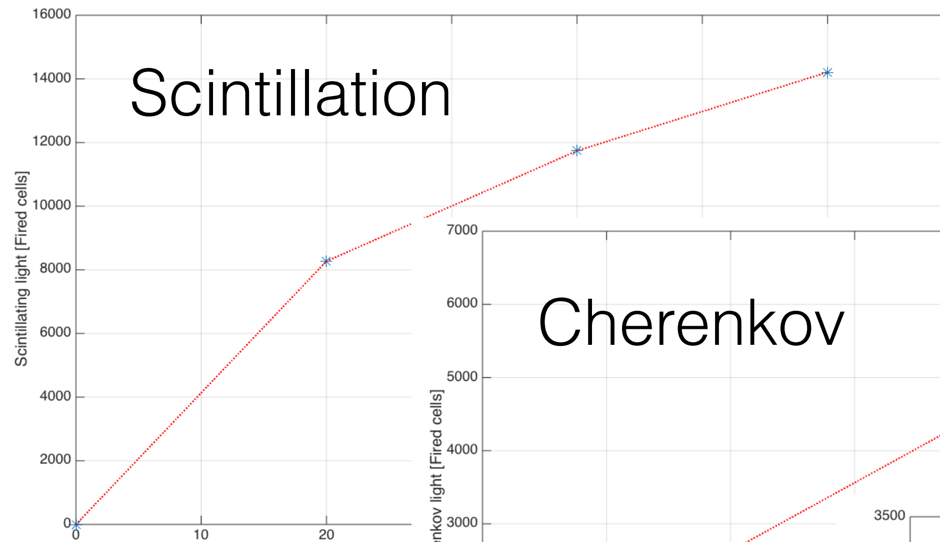
- Coupled to a 8x8 SiPM matrix (HAMAMATSU 25/50um)
- Characterisation



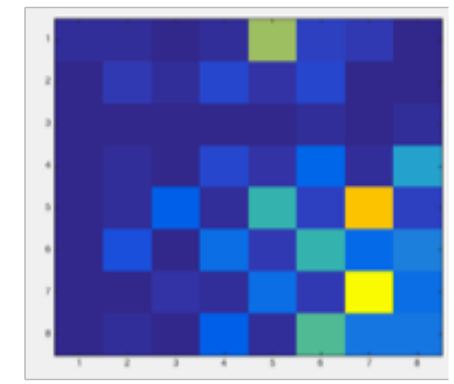
SiPM results

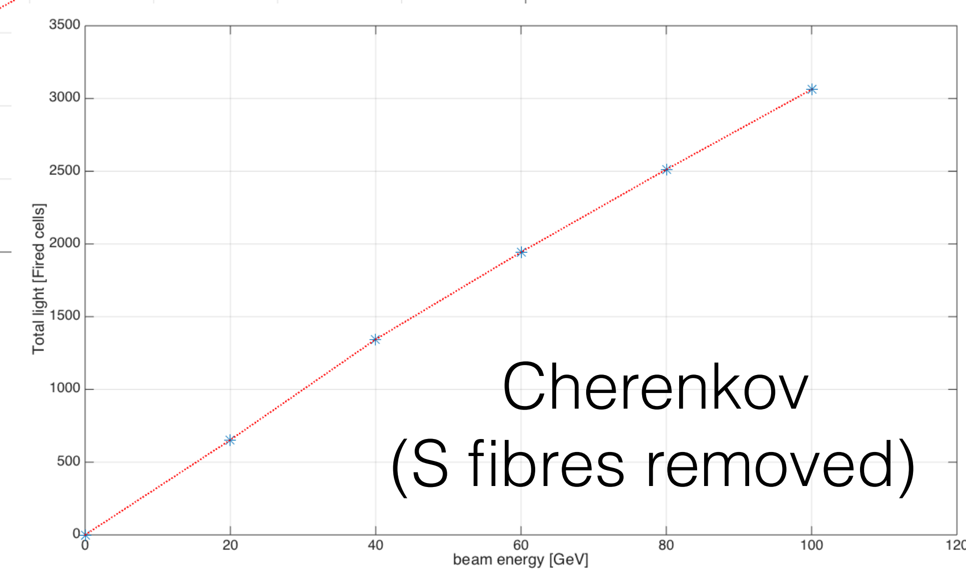
e$^+$ centred





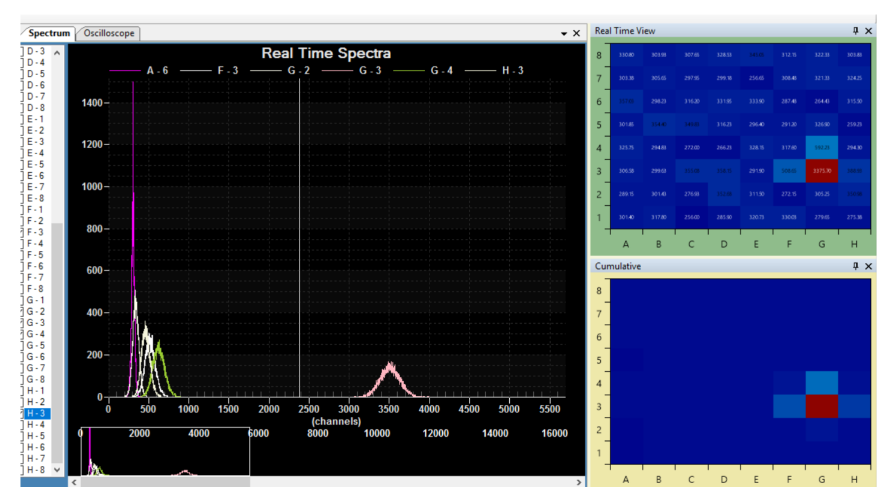
e$^+$ off centred



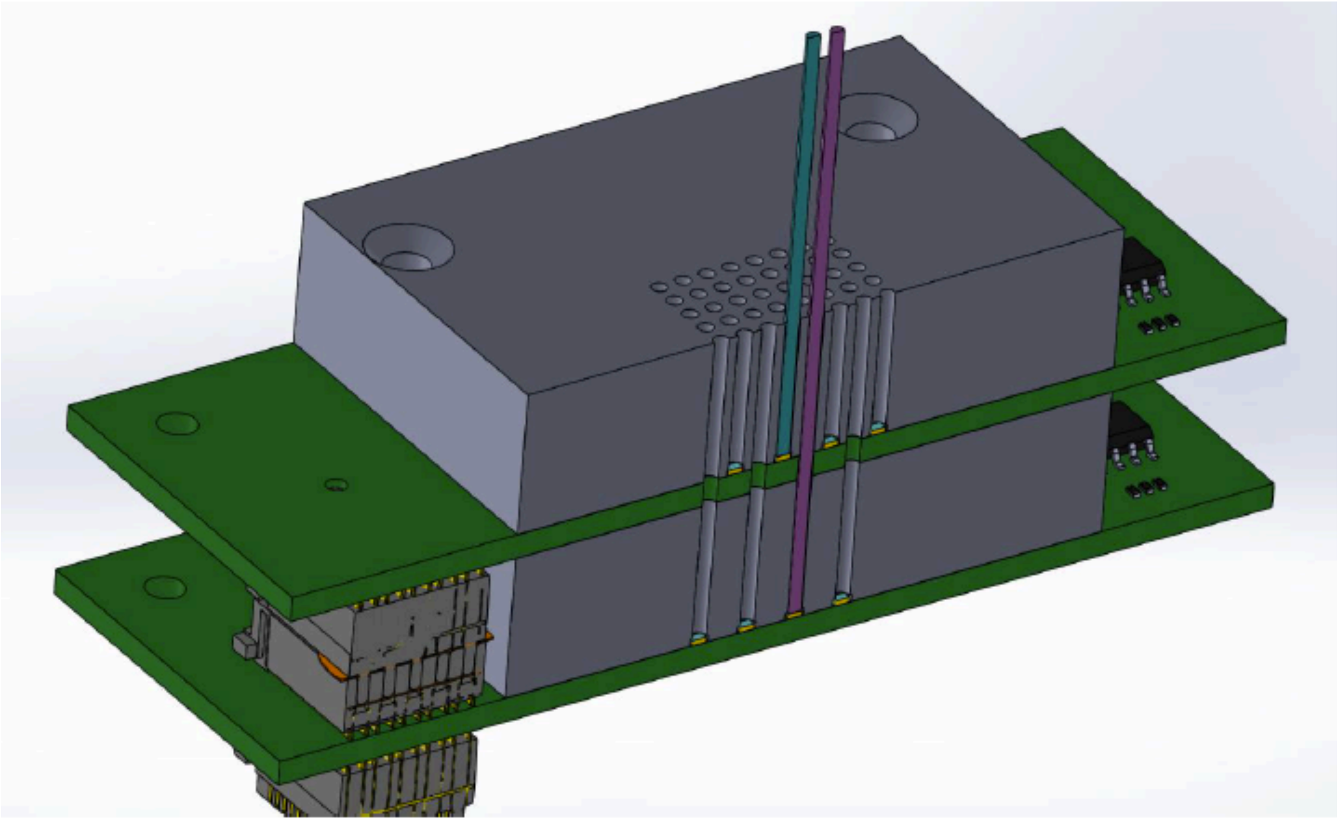


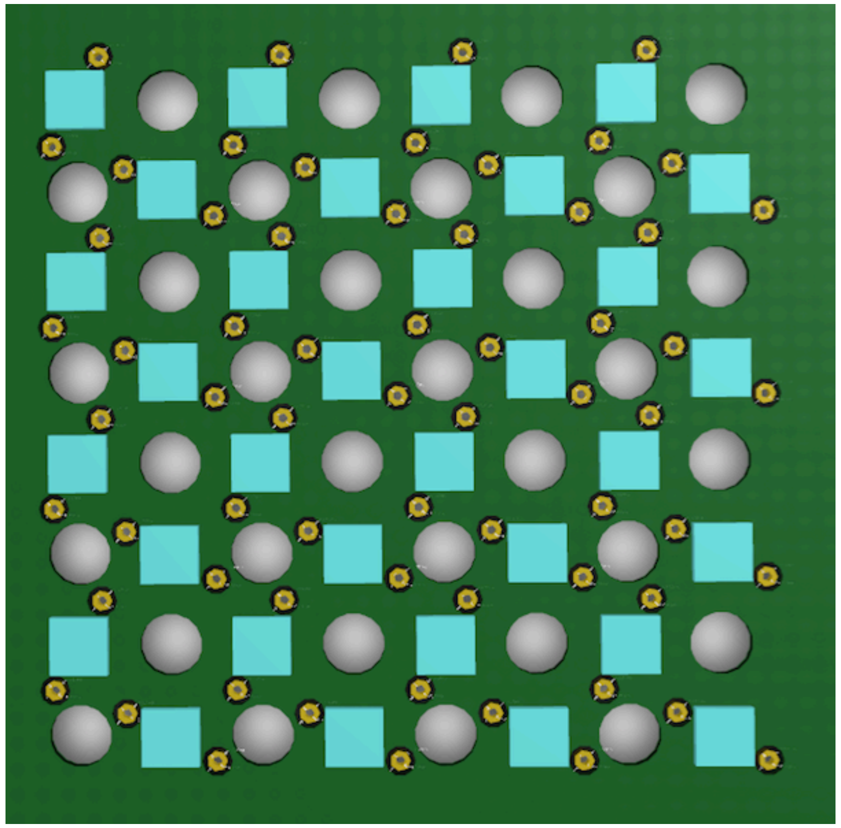
- Non linearity due to SiPM response saturation and cross talk

- Residual non linearity is possibly due to leakage



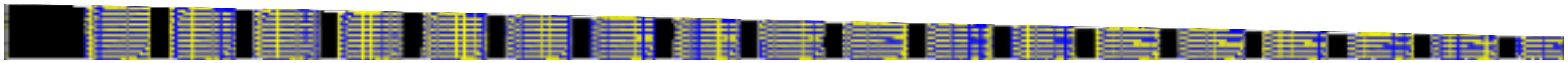
SiPM plans

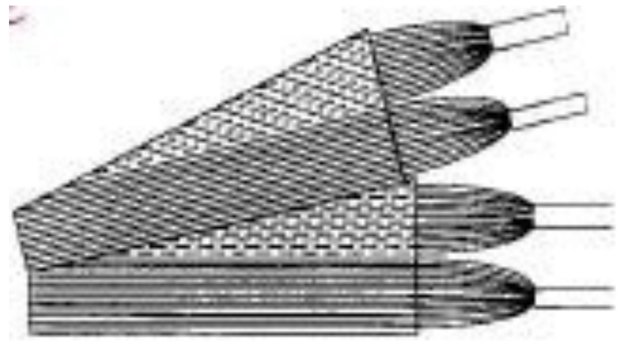


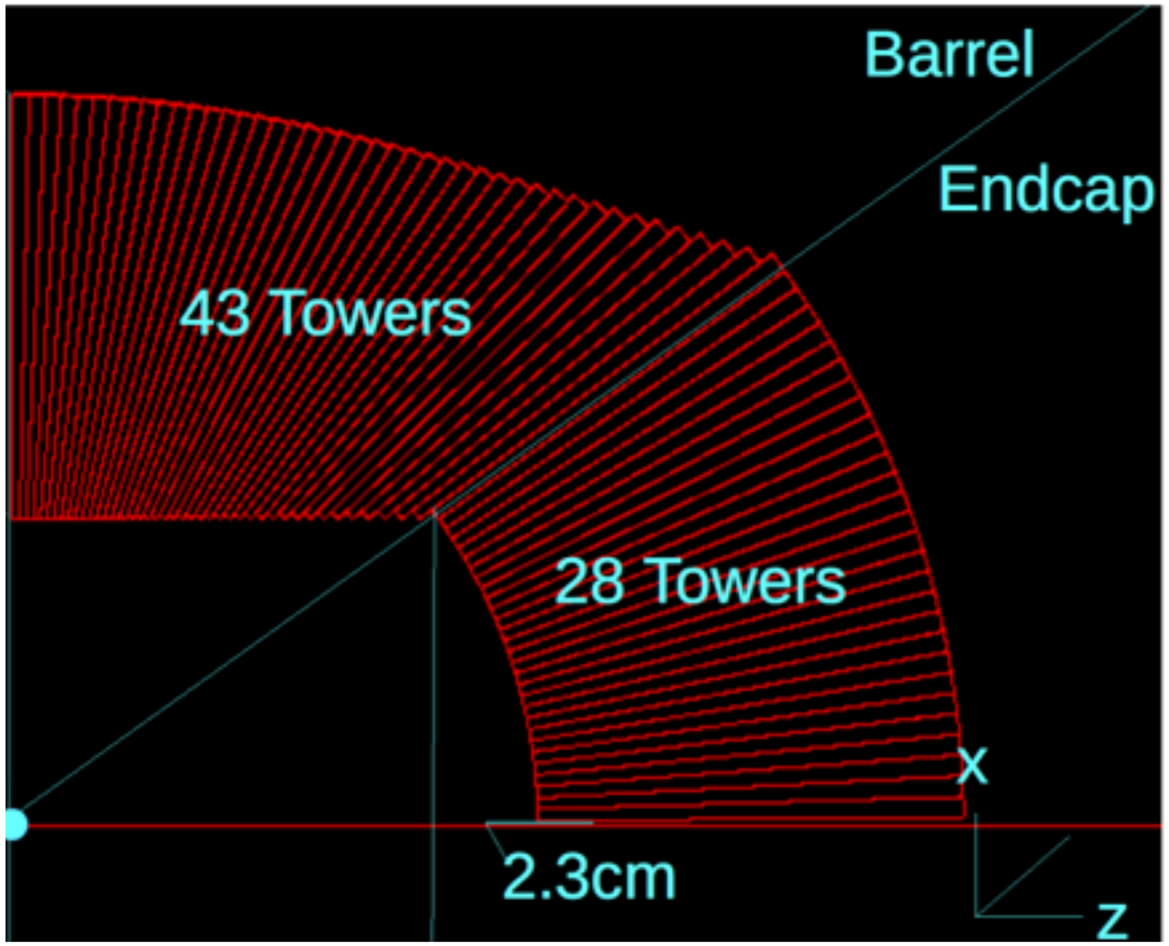


- Double readout board to physically separate S and C
- Improved readout electronics

4π detector





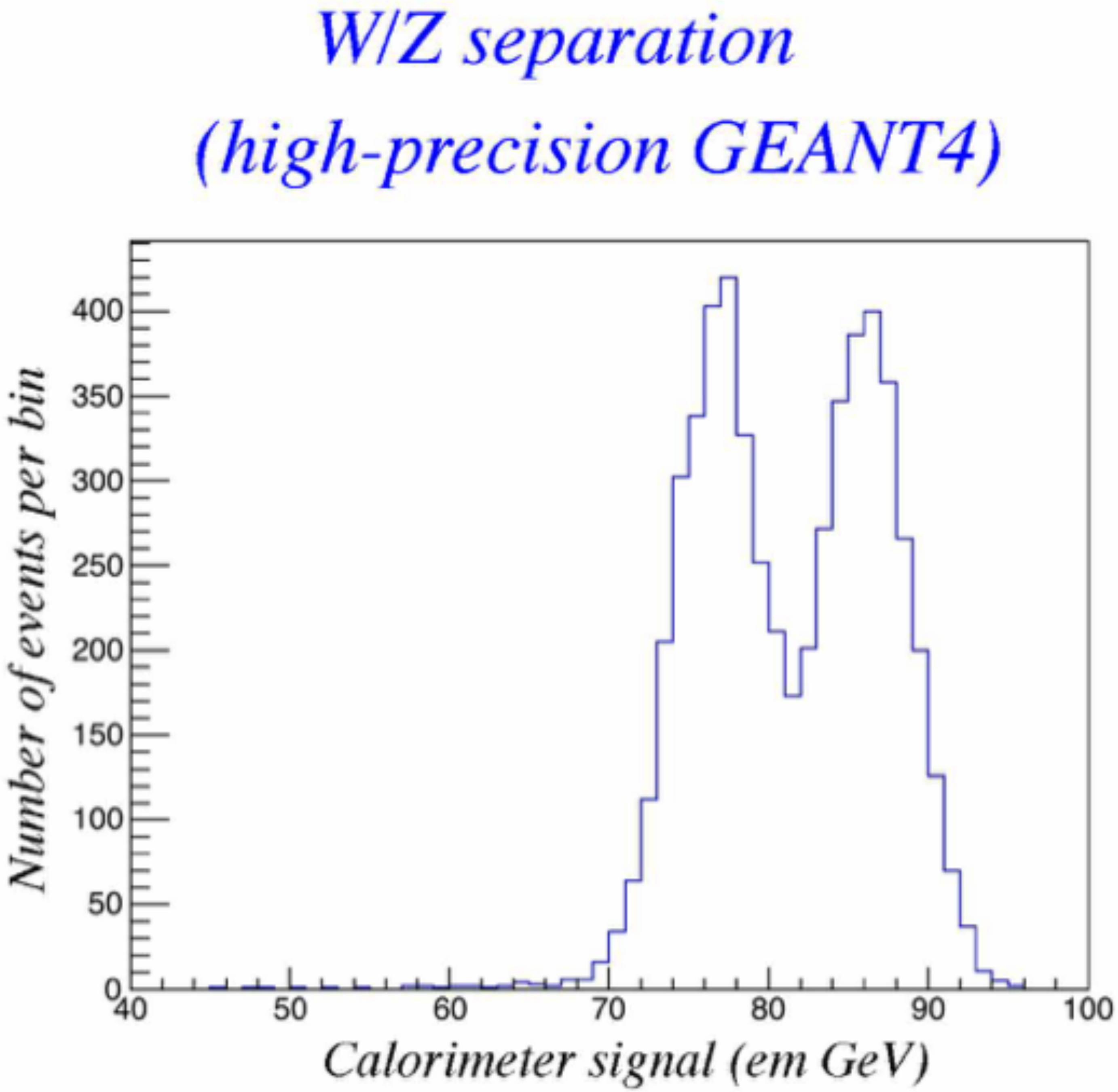


- DREAM born as a detector independent R&D

- Effort to simulate a 4π geometry undergoing

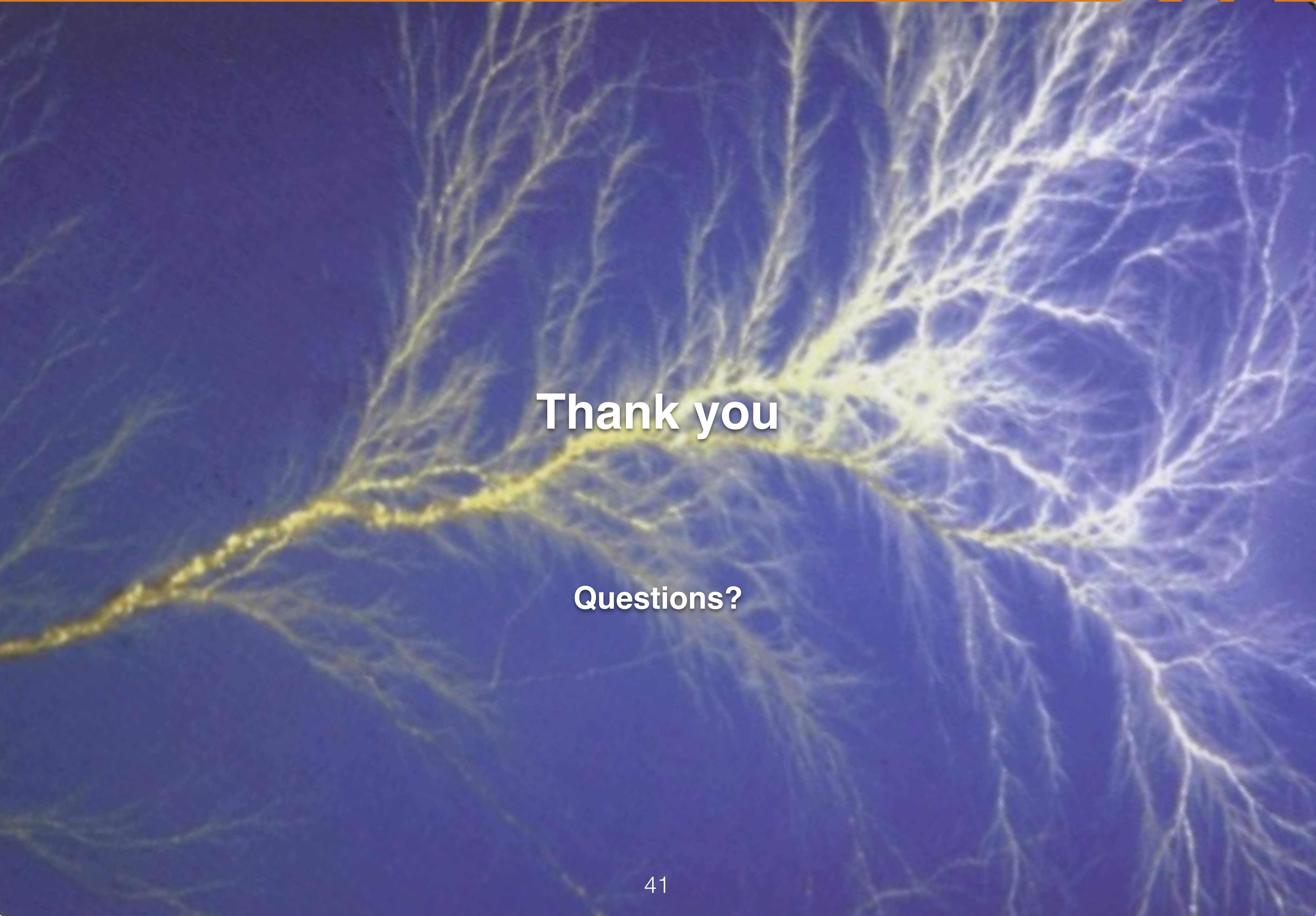
Hadronic W/Z separation

- Most common figure of merit for next collider calorimetry
- The first Geant4 simulations suggest it's possible



Conclusions

- A simple but powerful approach to hadronic calorimetry
- Experimental evidence and simulations prove an unparalleled hadronic resolution
- Ongoing activity to integrate in detector proposal



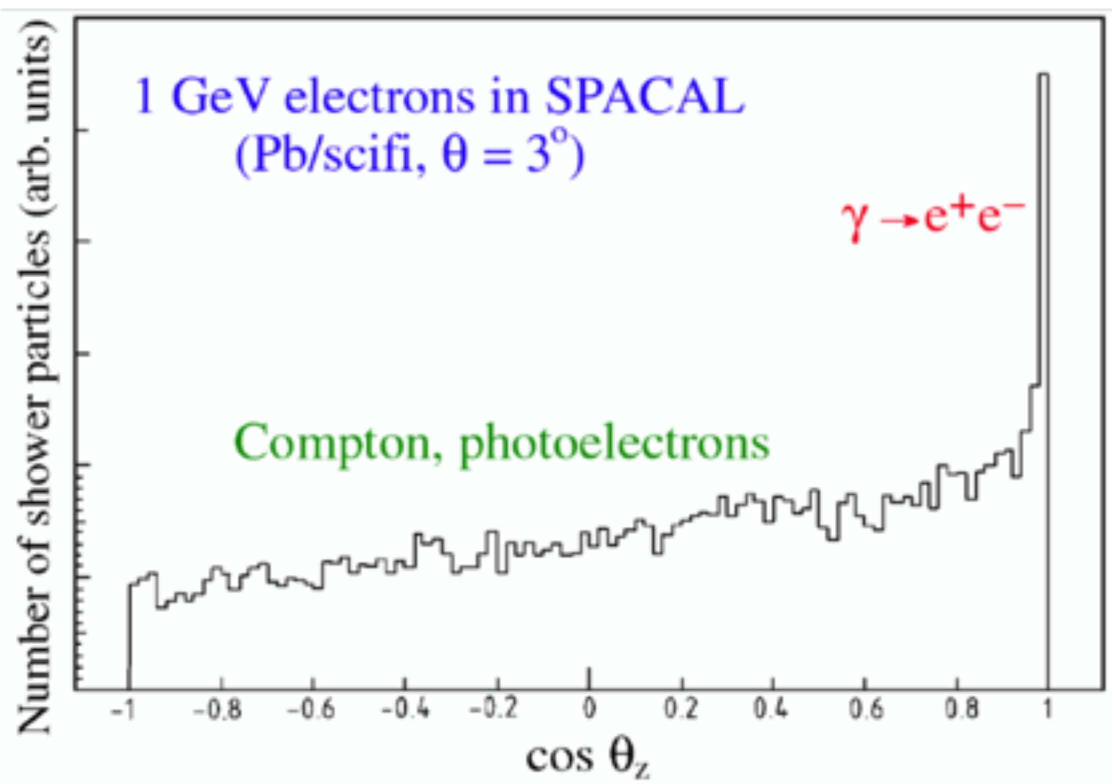
Thank you

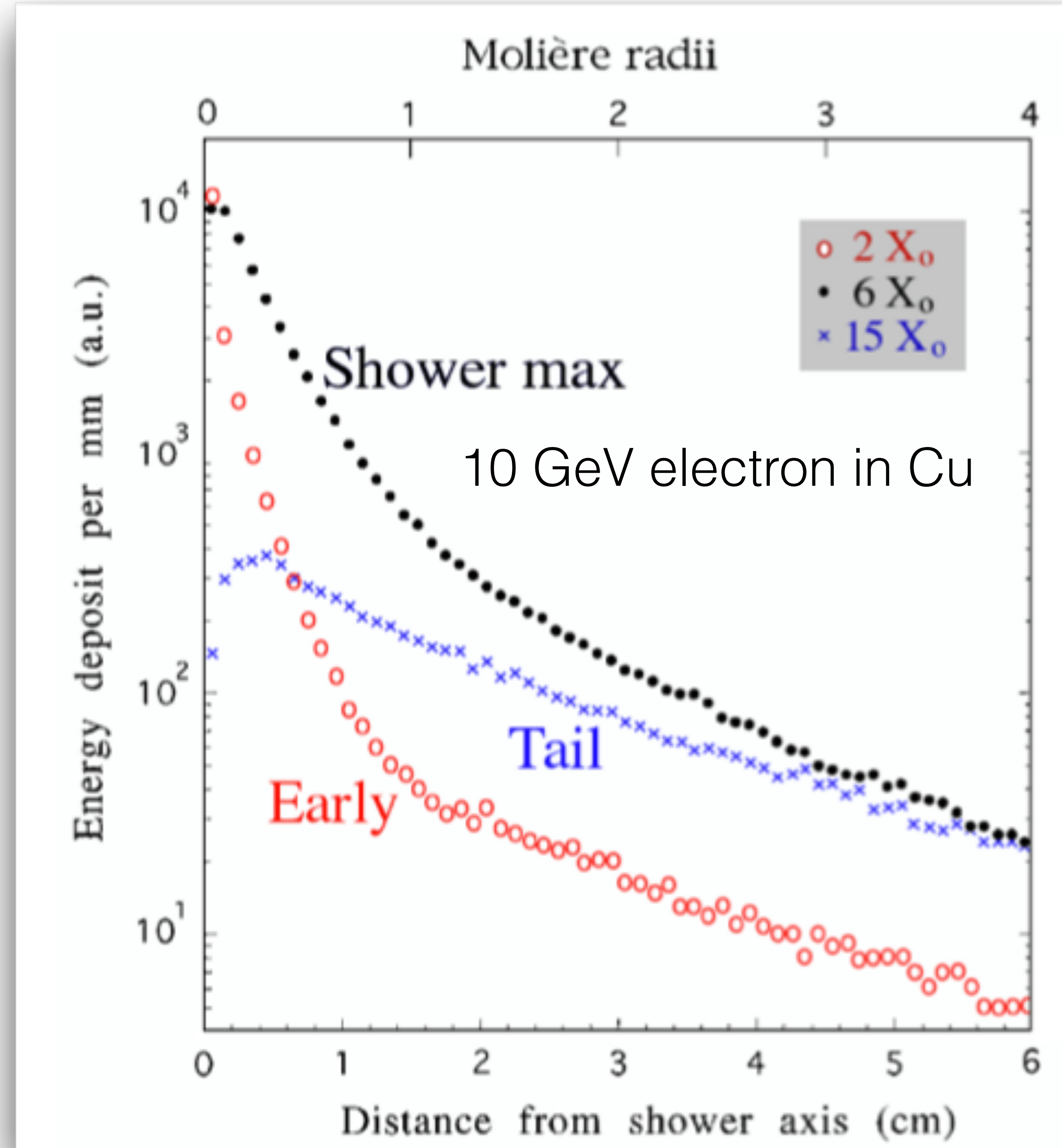
Questions?

Electromagnetic showers

- Molière radius
  $\rho_M \sim A/Z$

- 50% energy deposit
  isotropic



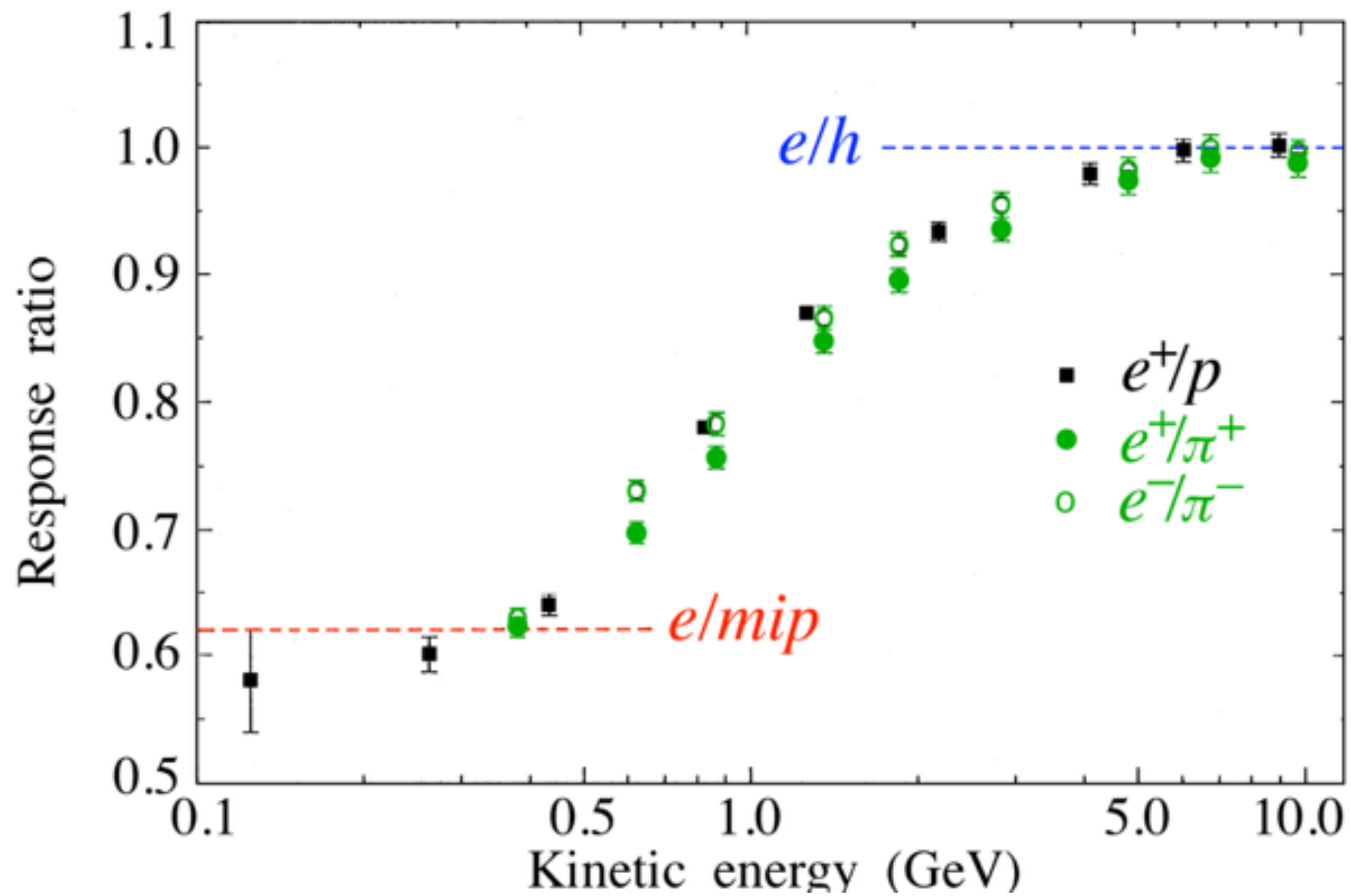


Response

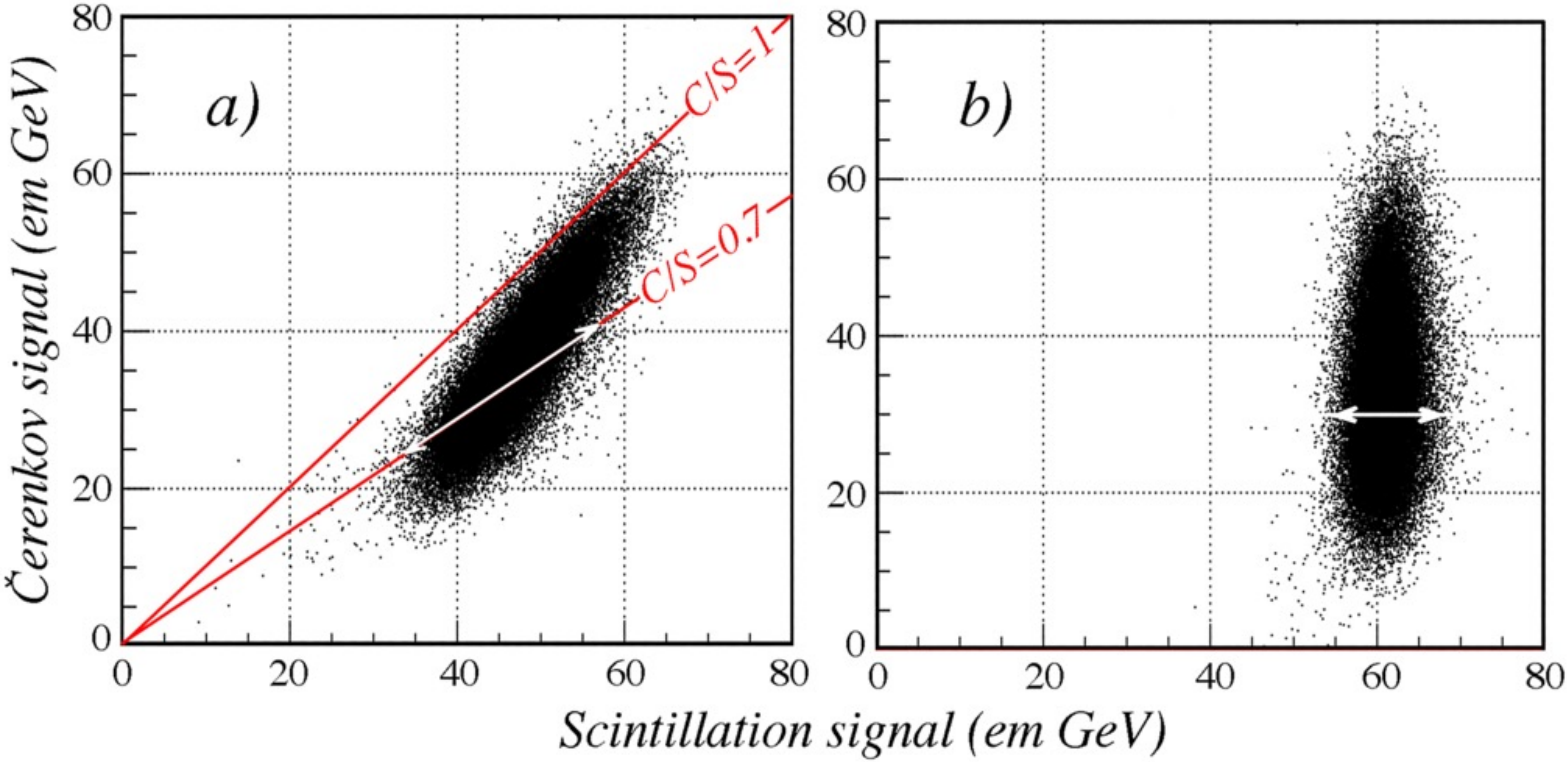
- e/π ≠ e/h ≠ 1

- e/π depends on energy

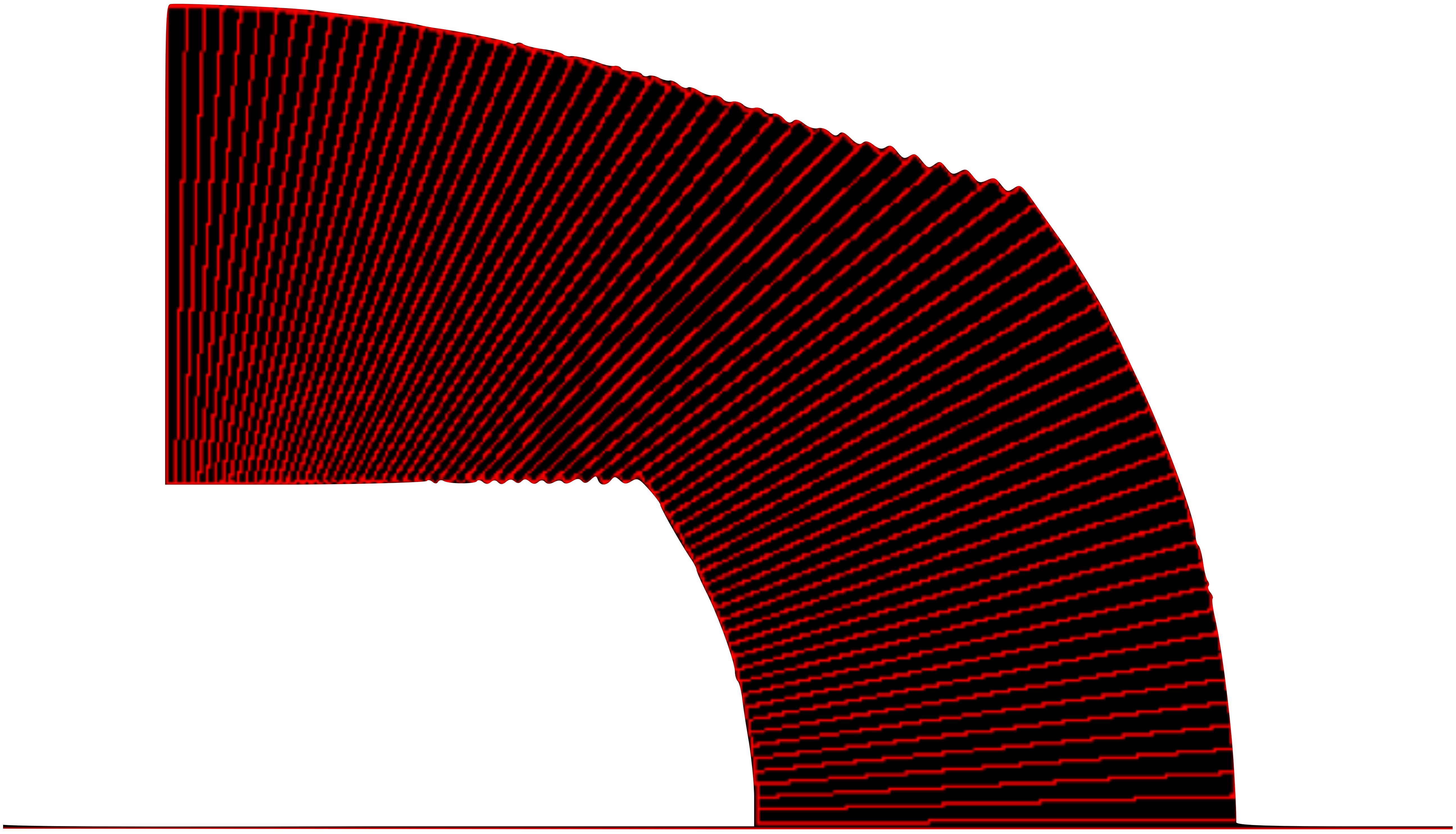
ZEUS results on low-energy hadronic nonlinearity



Rotation method interpretation



Calorimeter resolution



Length and width

- $t \sim \ln(E)$
- but leakage goes down with energy (f_{em} increases)