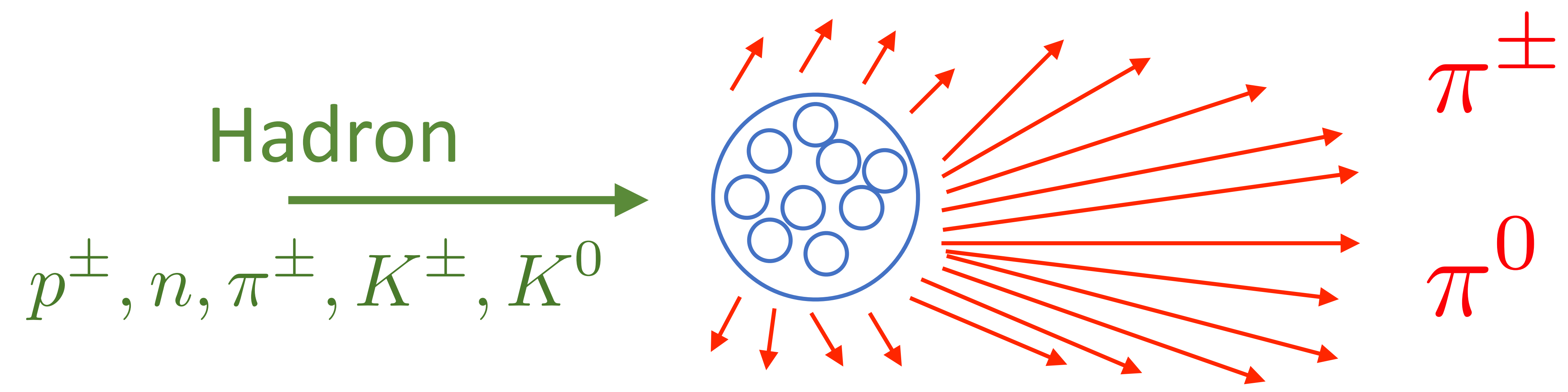
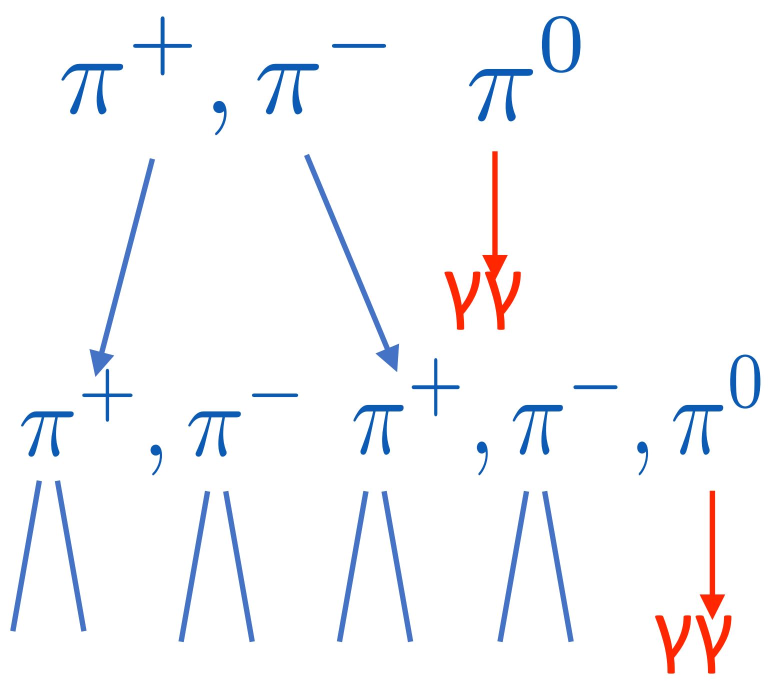
Hadronic Calorimetry



Strong Interaction

Approximate Energy Distribution

~50%



Hadron Cascade

~20%

Nuclear Excitation

5-30 MeV

p, n, γ

~30%

Slow Nucleons

π^0 → γγ → Electromagnetic Component

In Hadronic Cascades the longitudinal Shower is given by the Absorption Length λ_a

$$I \sim \exp^{-\frac{x}{\lambda_a}}$$

In typical Detector materials λ_a is much larger than X_0

$$\lambda \sim \frac{1}{9} \cdot 35 A^{\frac{1}{3}}$$

	ρ	X_0	λ
Fe	7,87	1.76cm	~17cm
Pb	11,35	0.56cm	~17cm

Energy Resolution:

- A large fraction of the Energy “disappears” into:
  - Binding Energy of the emitted Nucleons
  - π→μ+ν which are not absorbed
- π^0’s decaying into γγ start EM Cascade ($\tau \sim 10^{-16}$s)

Energy resolution is worse than for EM Calorimeters

Video of the lecturer

Hadron Calorimeters are Large because λ is large

Video of the lecturer

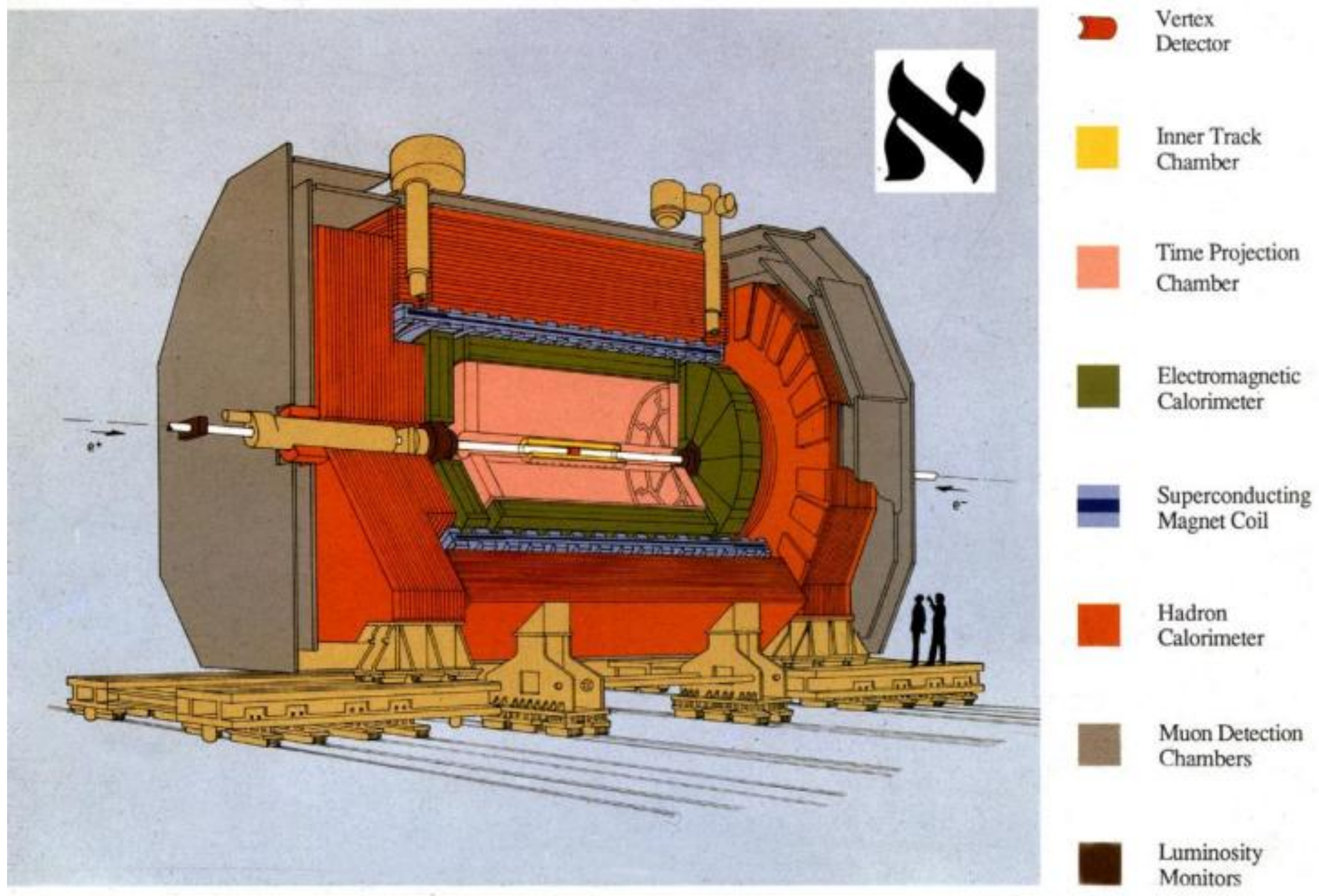
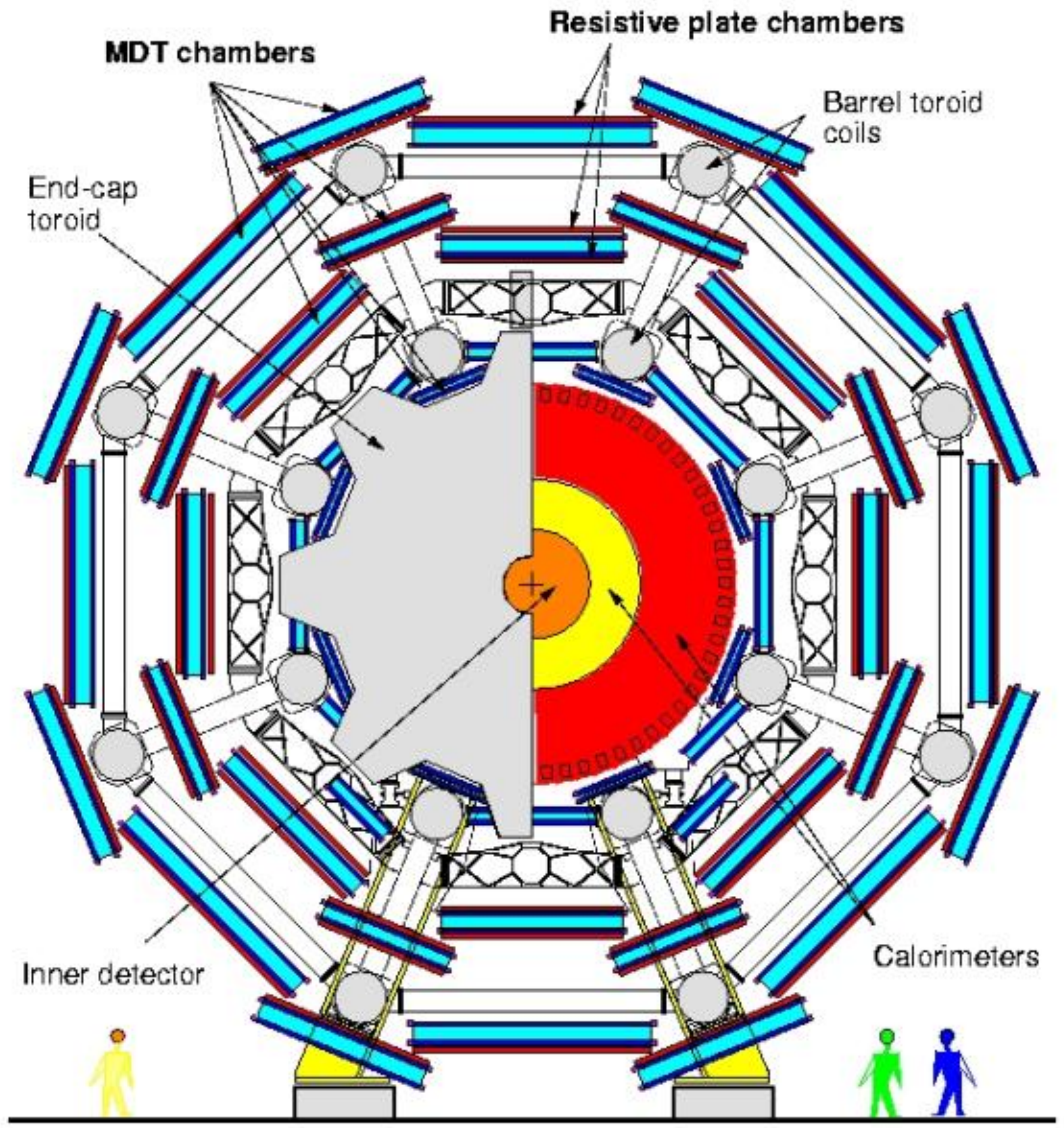


Fig. 1 - The ALEPH Detector

Hadron Calorimeters are large and heavy because the hadronic interaction length λ, the "strong interaction equivalent" to the EM radiation length X_0, is large (5-10 times larger than X_0)



Hadron Calorimeters

Video of the lecturer

By analogy with EM showers, the energy degradation of hadrons proceeds through an increasing number of (mostly) strong interactions with the calorimeter material.

However the complexity of the hadronic and nuclear processes produces a multitude of effects that determine the functioning and the performance of practical instruments, and make hadronic calorimeters more complicated instruments to optimize.

The hadronic interaction produces two classes of effects:

First, energetic secondary hadrons are produced. Their momenta are typically a sizable fraction of the primary hadron momentum i.e. at the GeV scale.

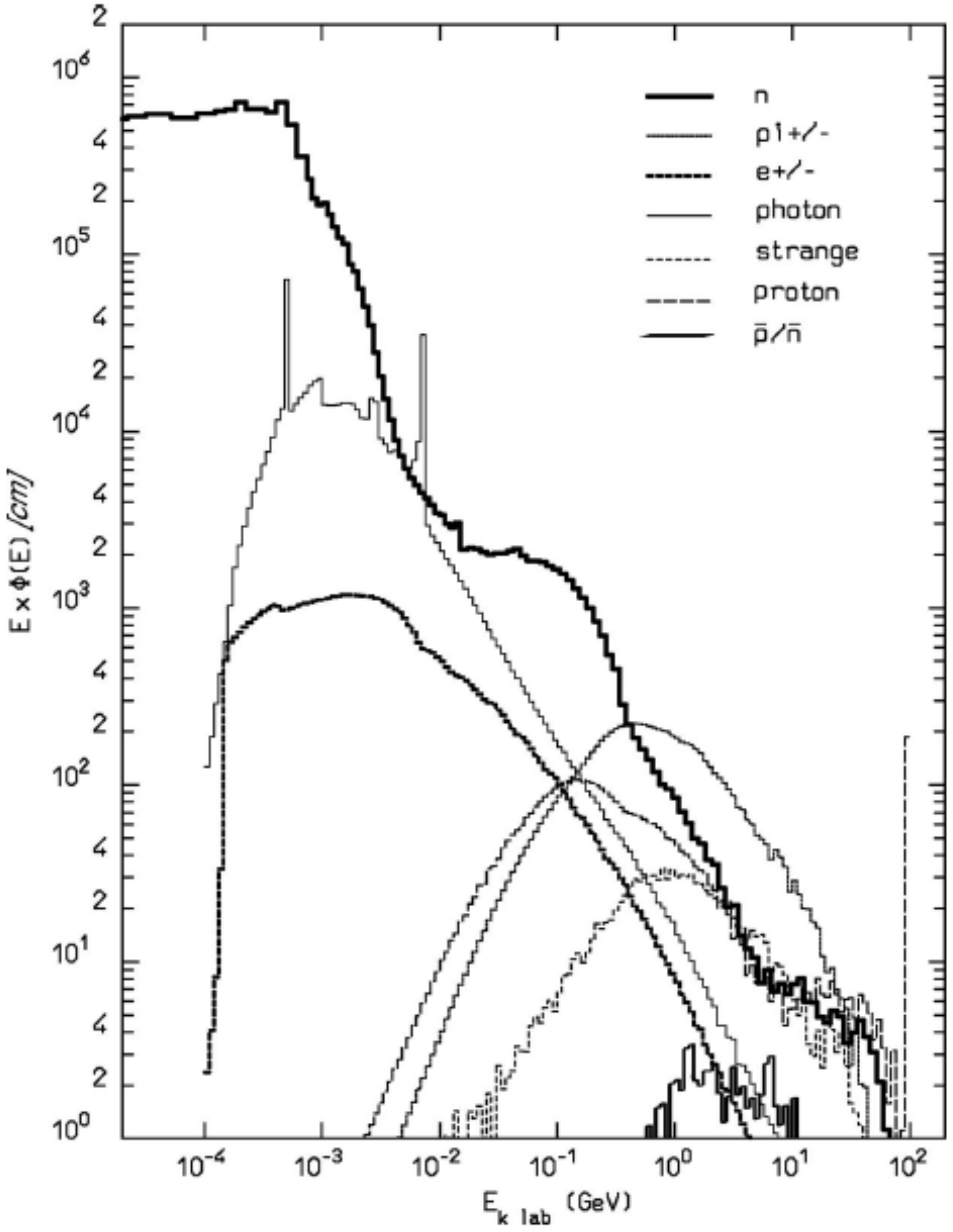
Second, in hadronic collisions with the material nuclei, a significant part of the primary energy is consumed in nuclear processes such as excitation, nucleon evaporation, spallation etc., resulting in particles with characteristic nuclear energies on the MeV scale.

Because part of the energy is therefore 'invisible', the resolution of hadron calorimeters is typically worse than in EM calorimeters 20-100%/Sqrt[E(GeV)] .

C.W. Fabjan and F. Gianotti, Rev. Mod. Phys., Vol. 75, N0. 4, October 2003

Hadron Calorimeters

Video of the lecturer



‘Deciphering this message becomes the story of hadronic calorimetry’

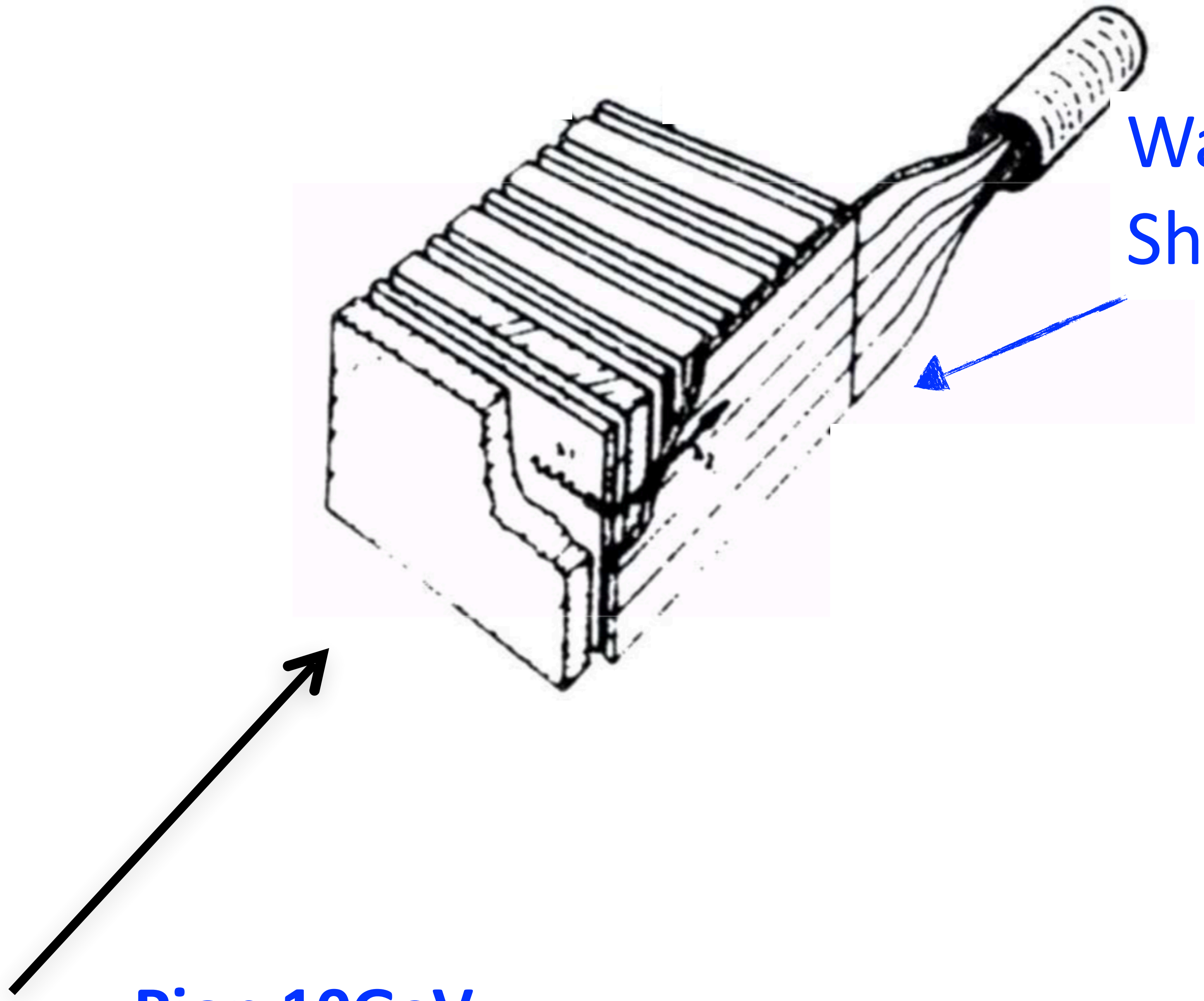
C.W. Fabjan and F. Gianotti, Rev. Mod. Phys., Vol. 75, N0. 4, October 2003

FIG. 19. Particle spectra produced in the hadronic cascade initiated by 100-GeV protons absorbed in lead. The energetic component is dominated by pions, whereas the soft spectrum is composed of photons and neutrons. The ordinate is in “lethargic” units and represents the particle track length, differential in log *E*. The integral of each curve gives the relative fluence of the particle. Fluka calculations (Ferrari, 2001).

Hadron Calorimeters

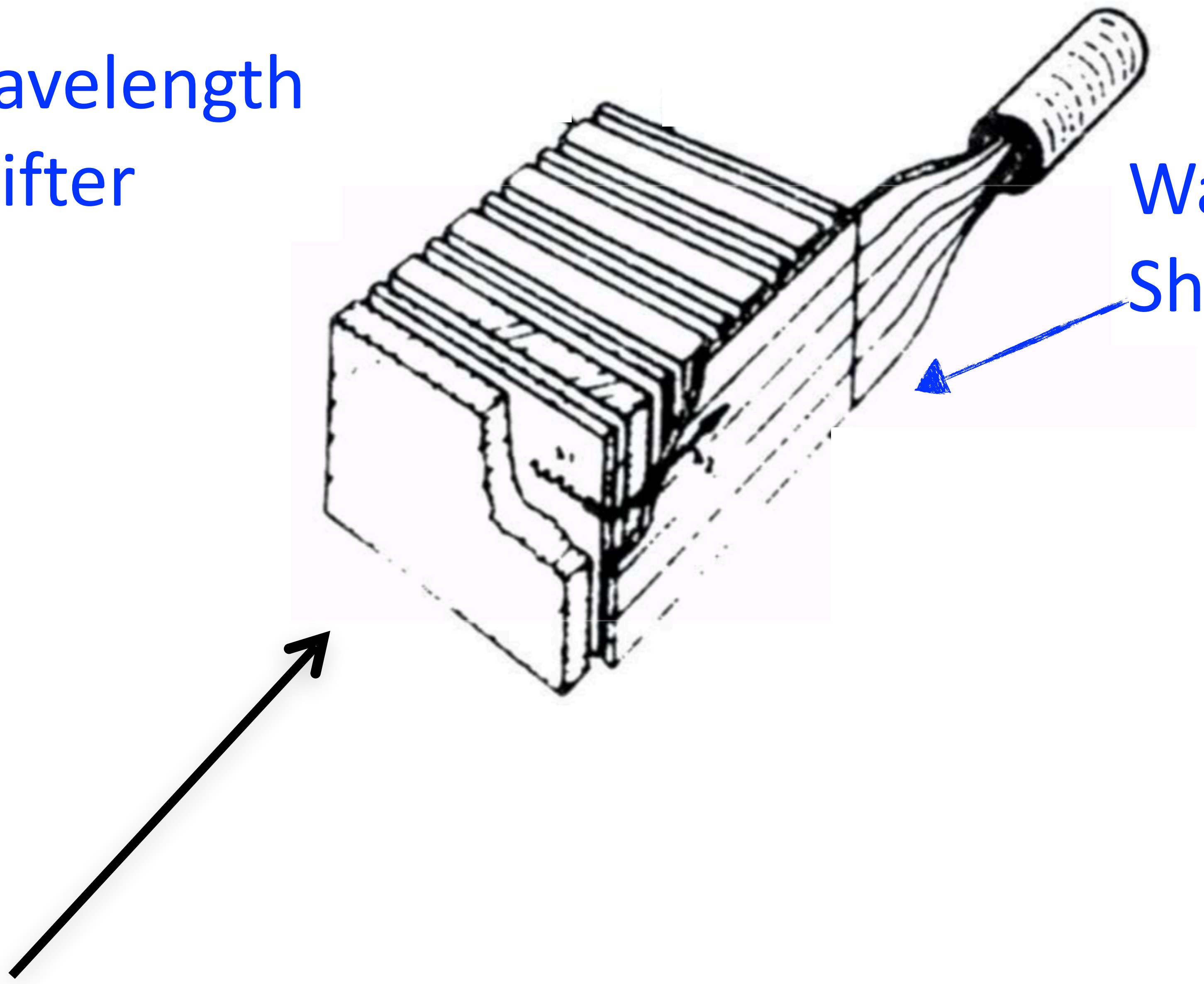
Video of the lecturer

The signals from an electron or photon entering a hadronic calorimeter is typically larger than the signal from a hadron cascade because the hadronic interactions produce a fair fraction of invisible effects (excitations, neutrons …)



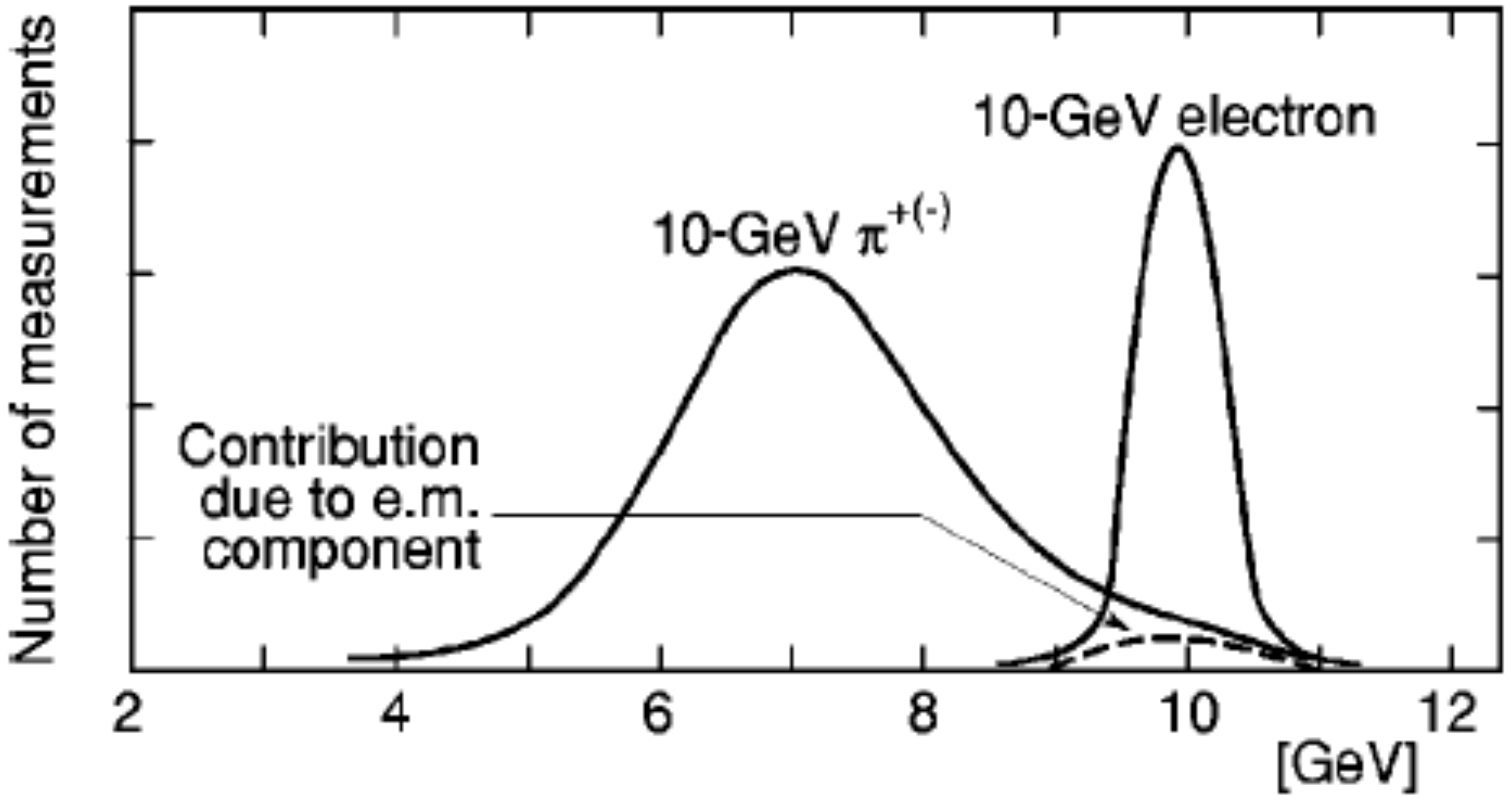
Wavelength Shifter

Pion 10GeV



Wavelength Shifter

Electron 10GeV



Signal (in energy units) obtained for a 10 GeV energy deposit

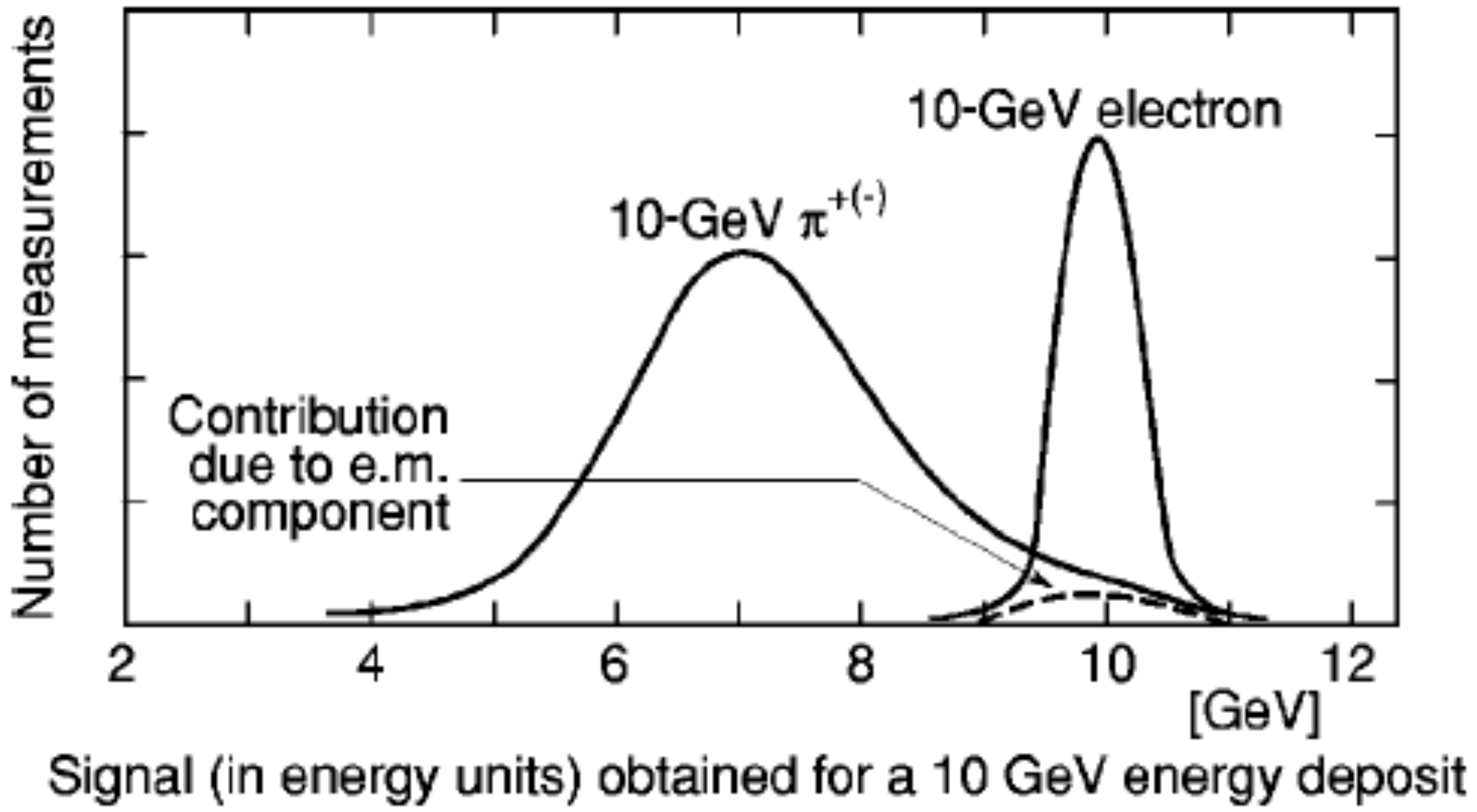
Hadron Calorimeters

Video of the lecturer

Because a fair fraction of shower particles consists of π^0 which instantly decay into two photons, part of the hadronic cascade becomes an EM cascade – 'and never comes back'.

Because the EM cascade had a larger response than the Hadron cascade, the event/event fluctuation of produced π^0 particles causes a strong degradation of the resolution.

Is it possible to build a calorimeter that has the same response (signal) for a 10GeV electron and 10GeV hadron? → compensating calorimeters.



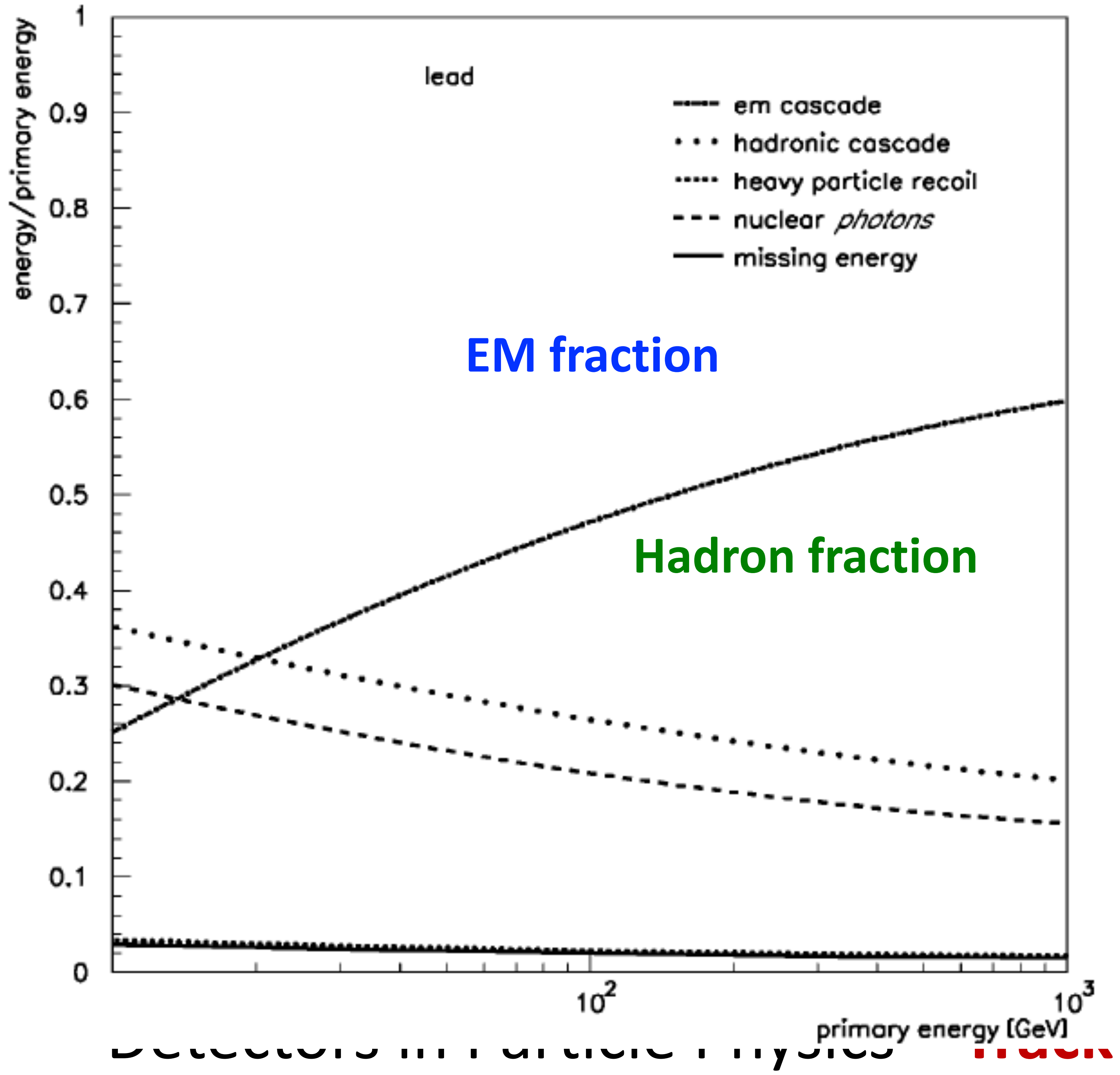


FIG. 21. Characteristic components of proton-initiated cascades in lead. With increasing primary energy the π^0 component increases (Ferrari, 2001).

Compensating Hadron Calorimeters

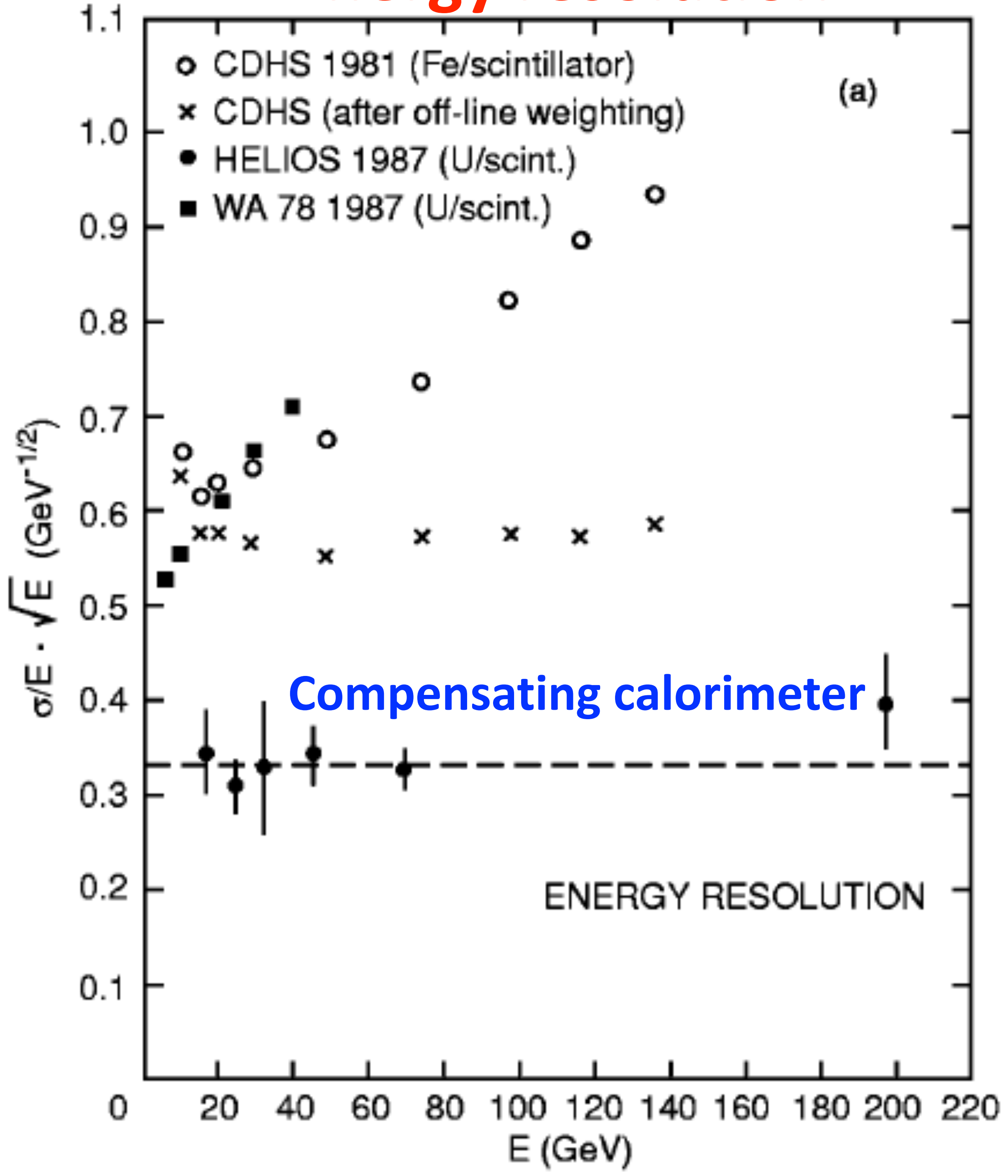
Video of the lecturer

In a homogeneous calorimeter it is clearly not possible to have the same response for electrons and hadrons.

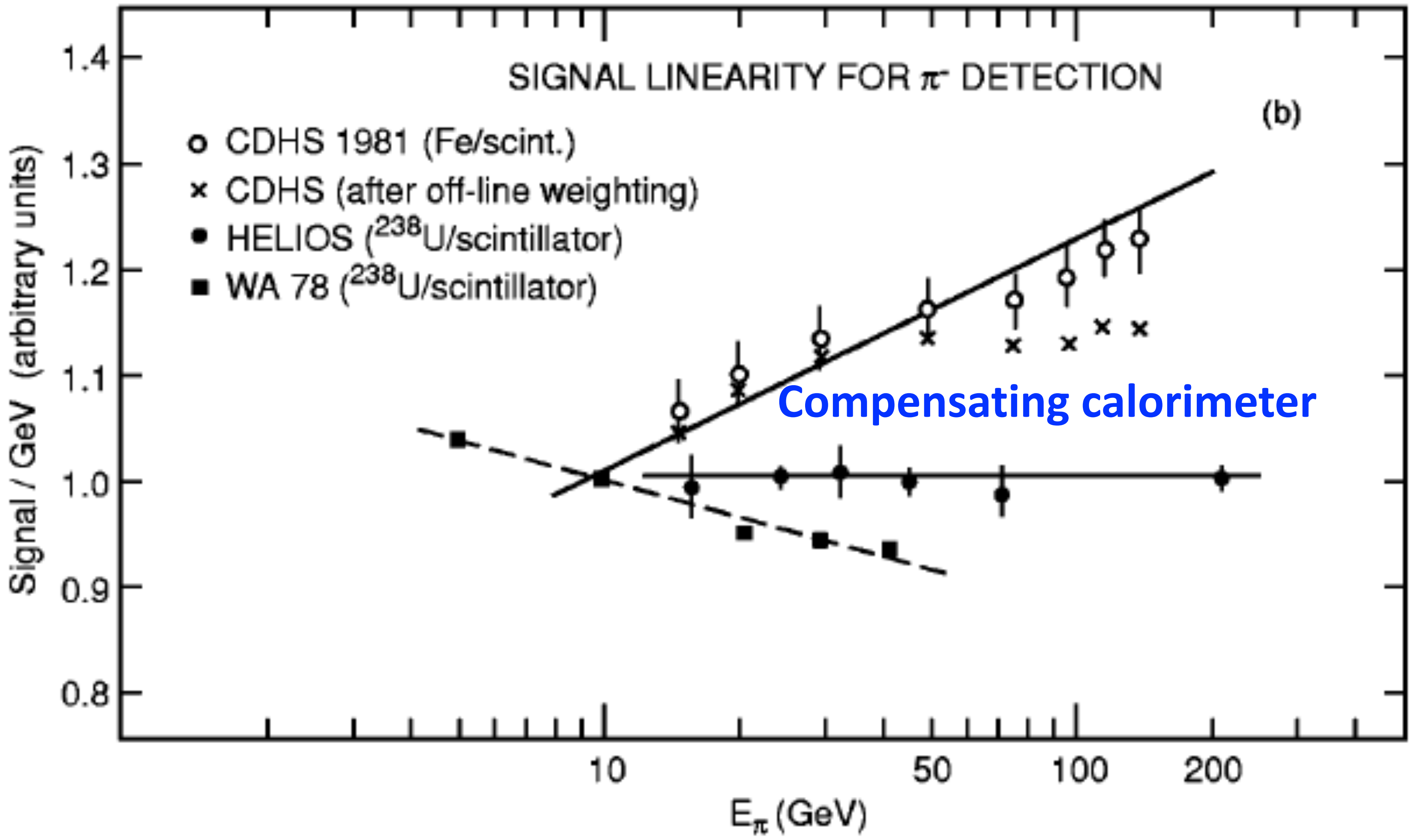
For sampling calorimeters the sampling frequency and thickness of active and passive layers can be tuned such that the signal for electrons and hadrons is indeed equal!

Using Uranium or Lead with scintillators, hadron calorimeters with excellent energy resolution and linearity have been built.

Energy resolution



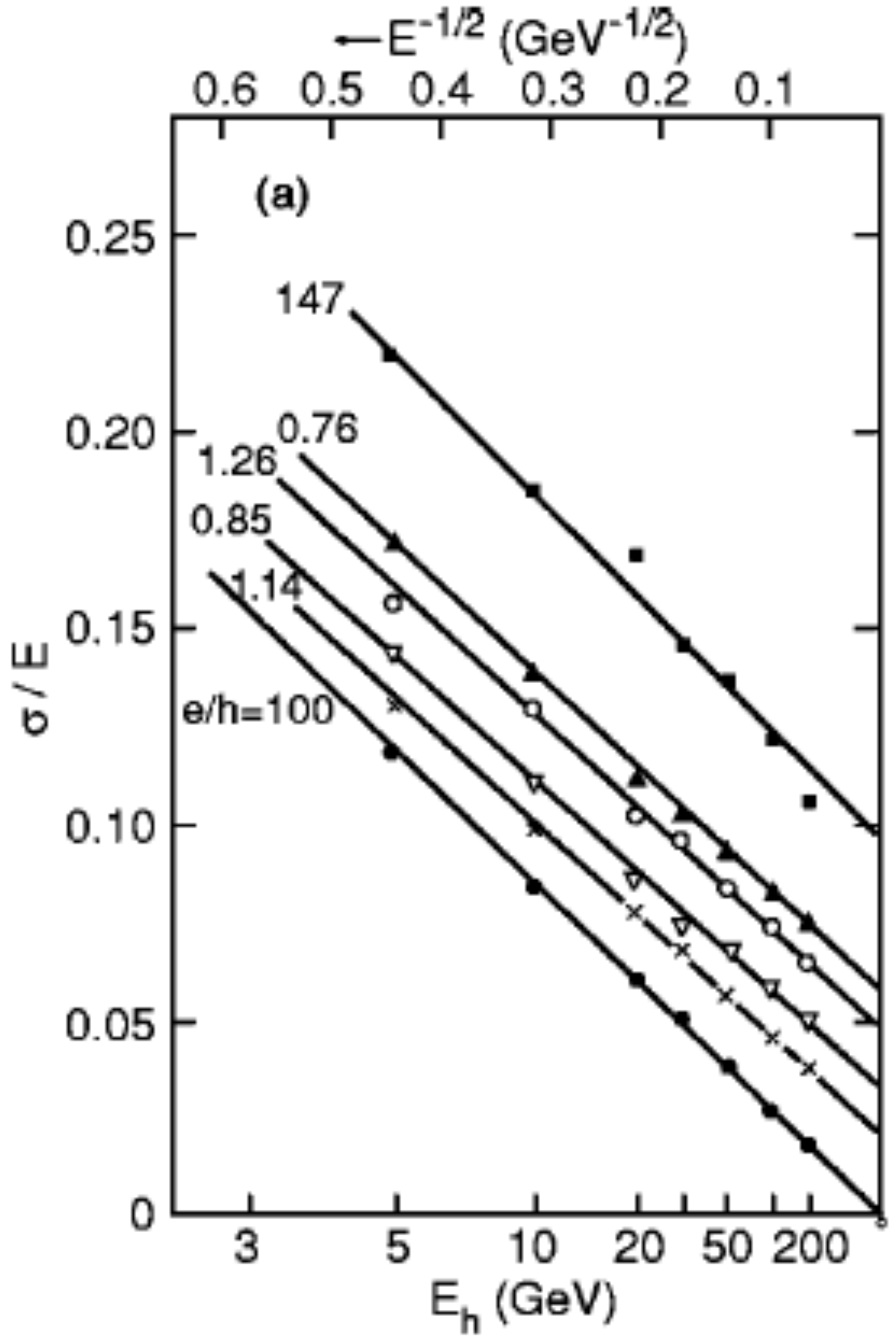
Linearity



Compensating Hadron Calorimeters

Video of the lecturer

Resolution and linearity of a hadron calorimeter is best if e/h=1. For all other values, the resolution in linearity is worse.



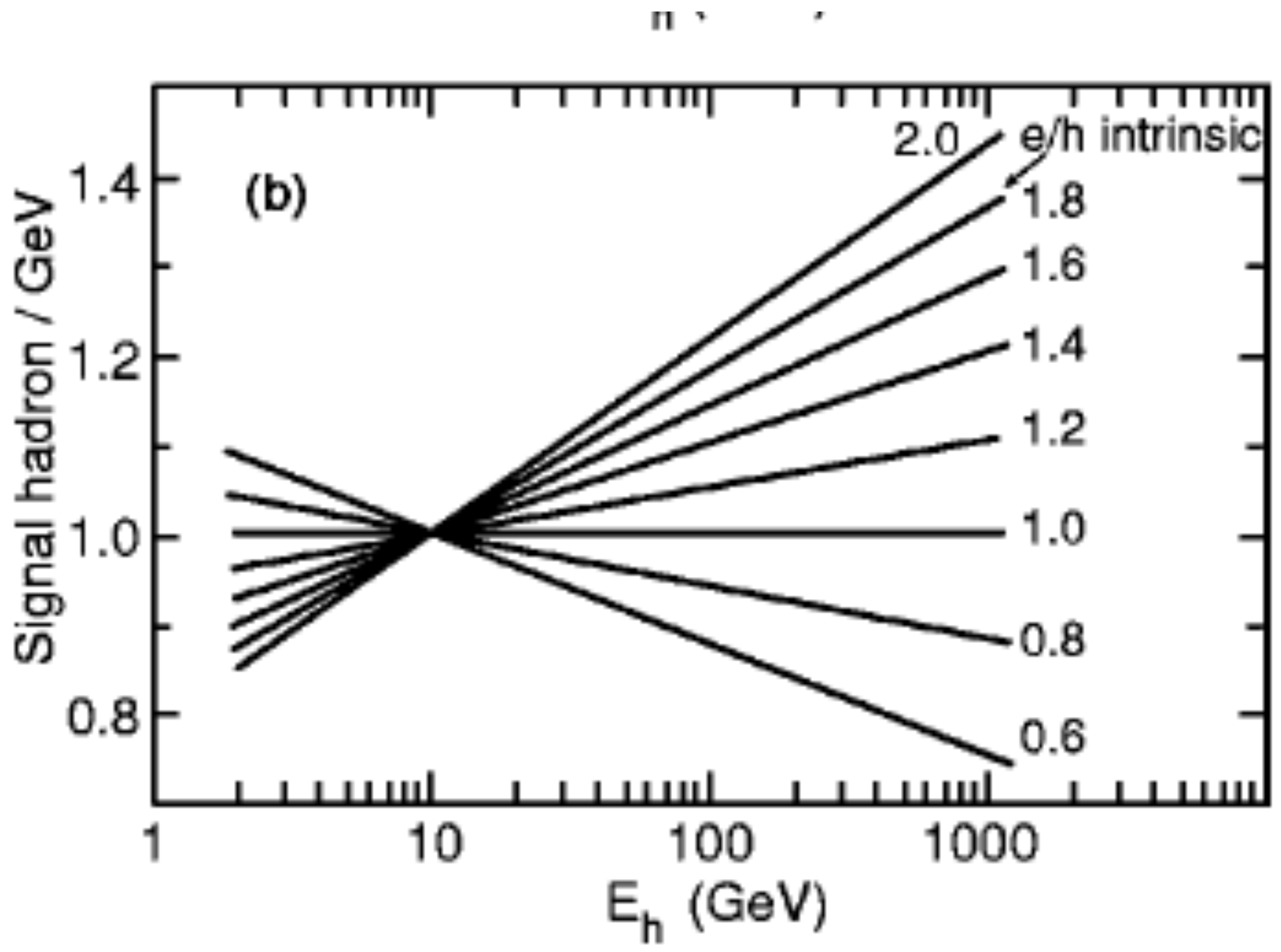
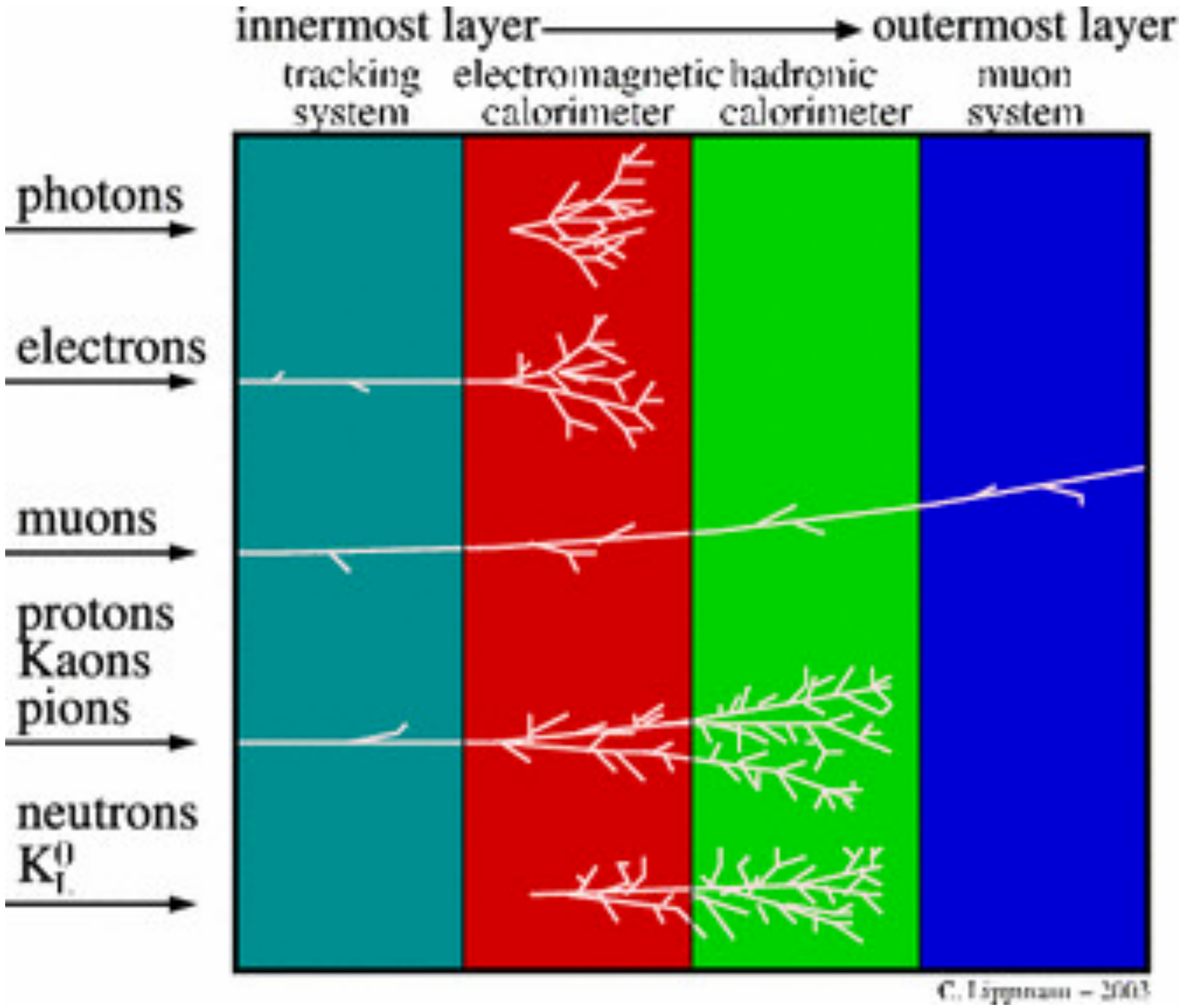


FIG. 24. Monte Carlo simulation of the effects of $e/\pi \neq 1$ on energy resolution (a) and response linearity (b) of hadron calorimeters with various values for e/h (intrinsic), where h (intrinsic) denotes the response to the purely hadronic component of the shower (Wigmans, 1988).

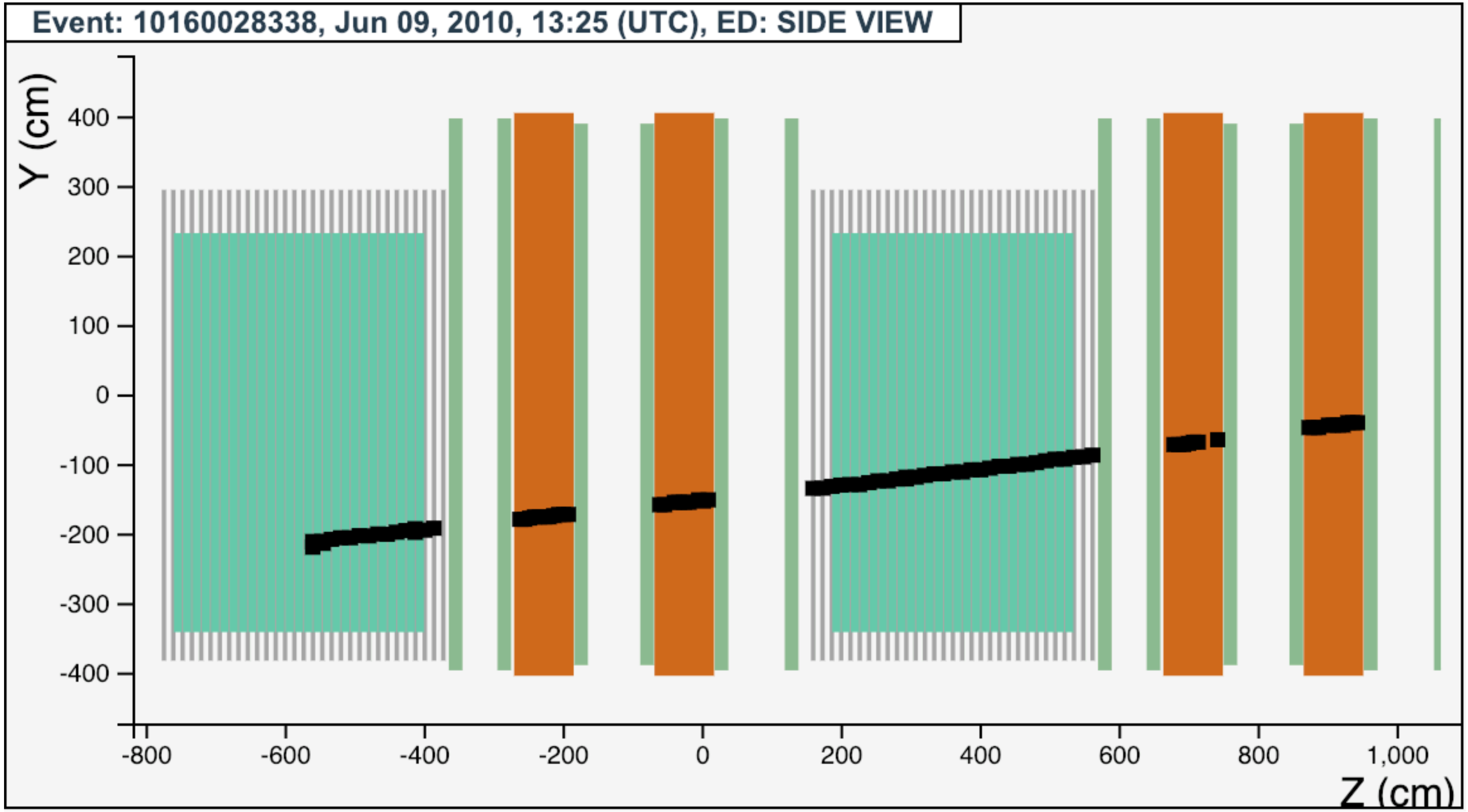
Particle ID



Video of the lecturer

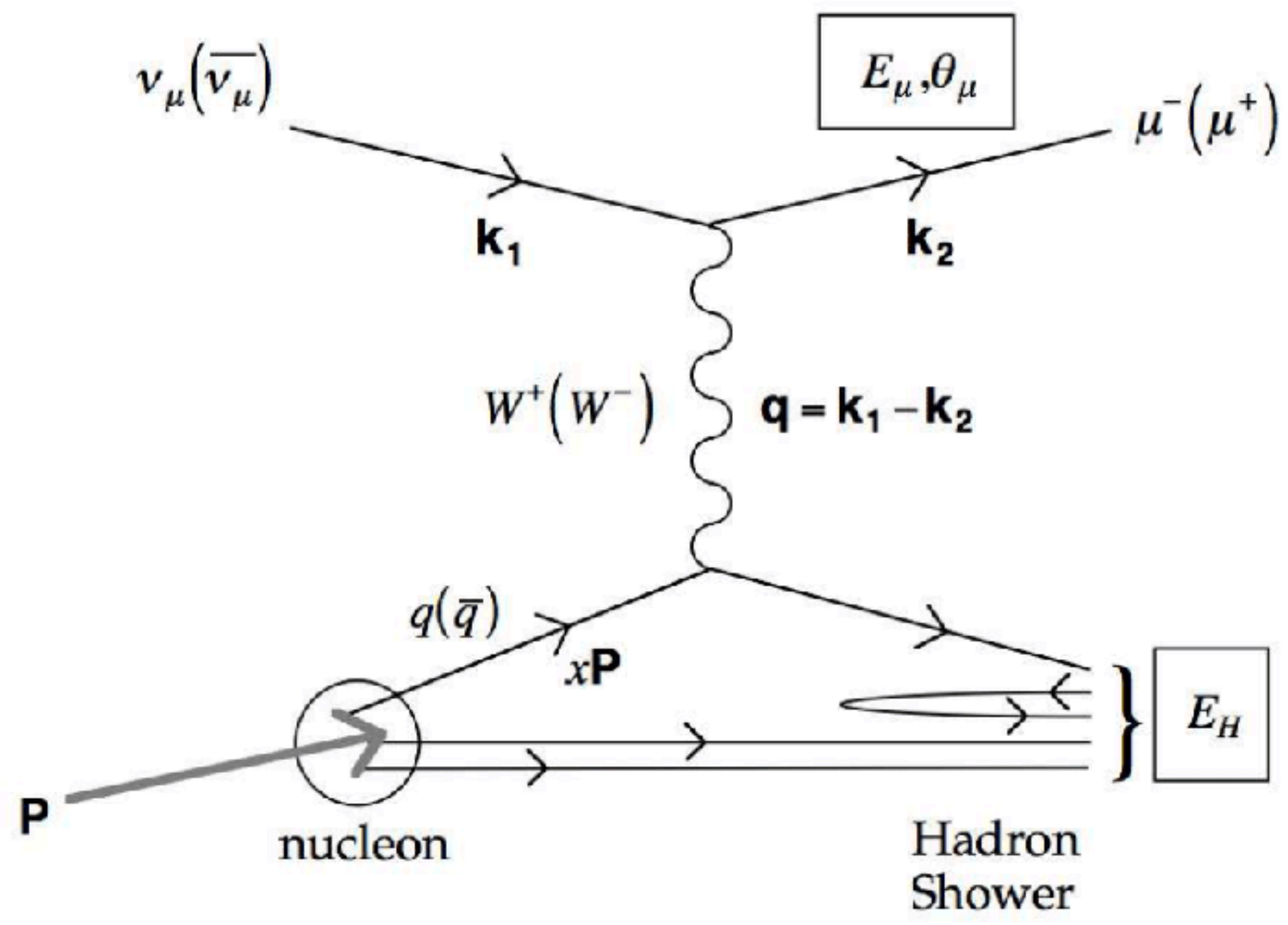
Measuring the neutrino energy: the OPERA experiment as an example

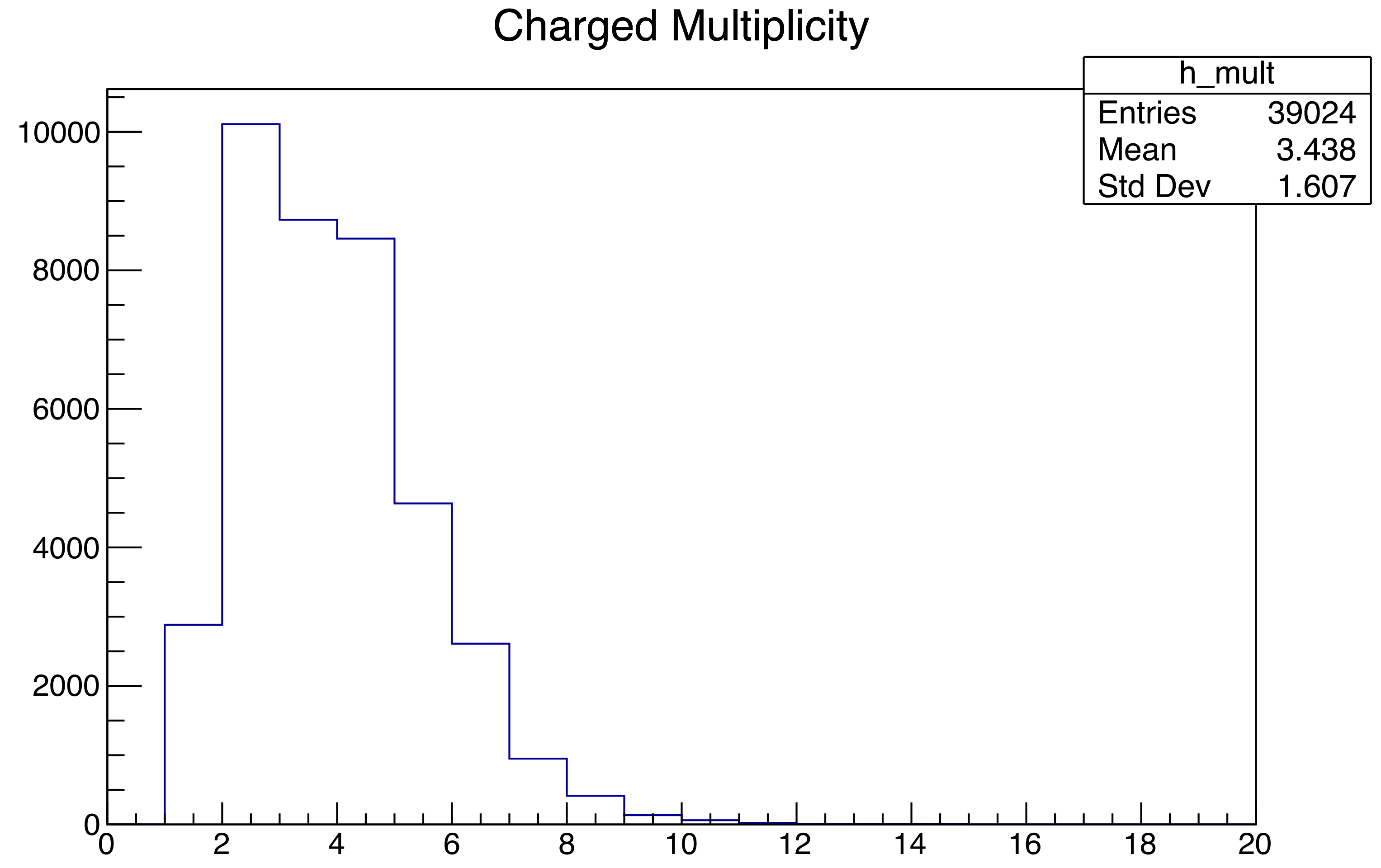
Video of the lecturer



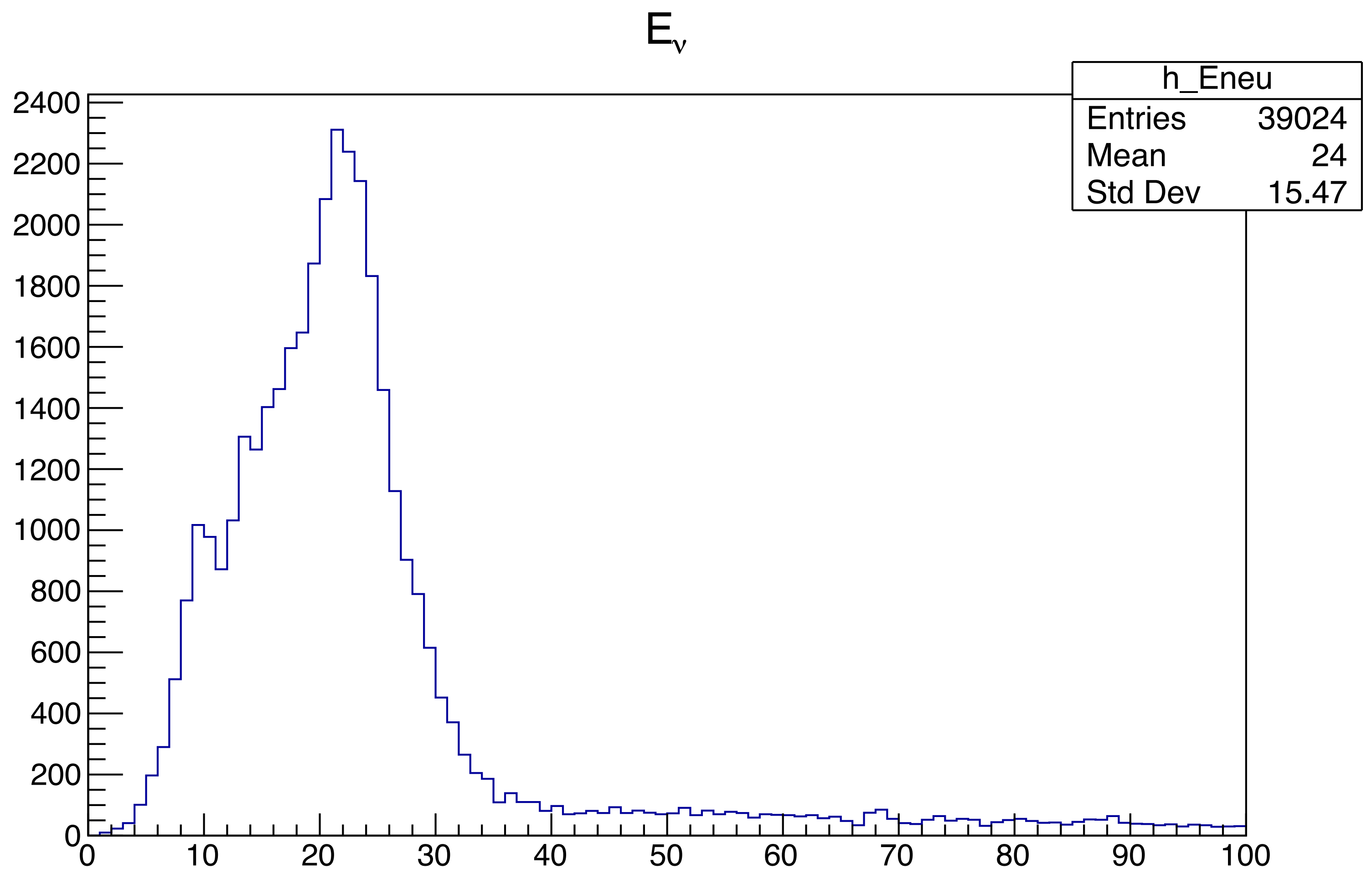
Measuring neutrino energy in OPERA

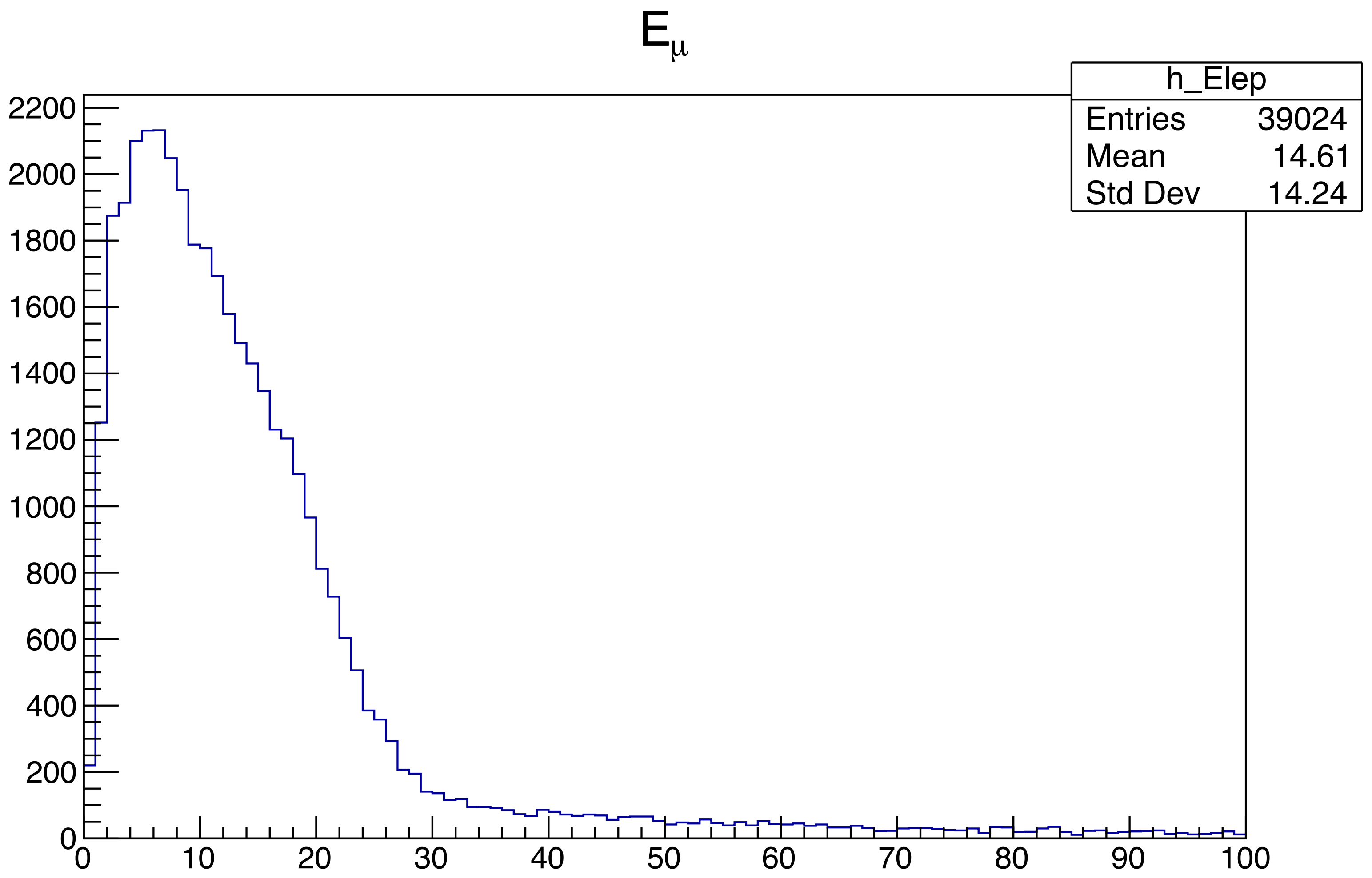
Video of the lecturer





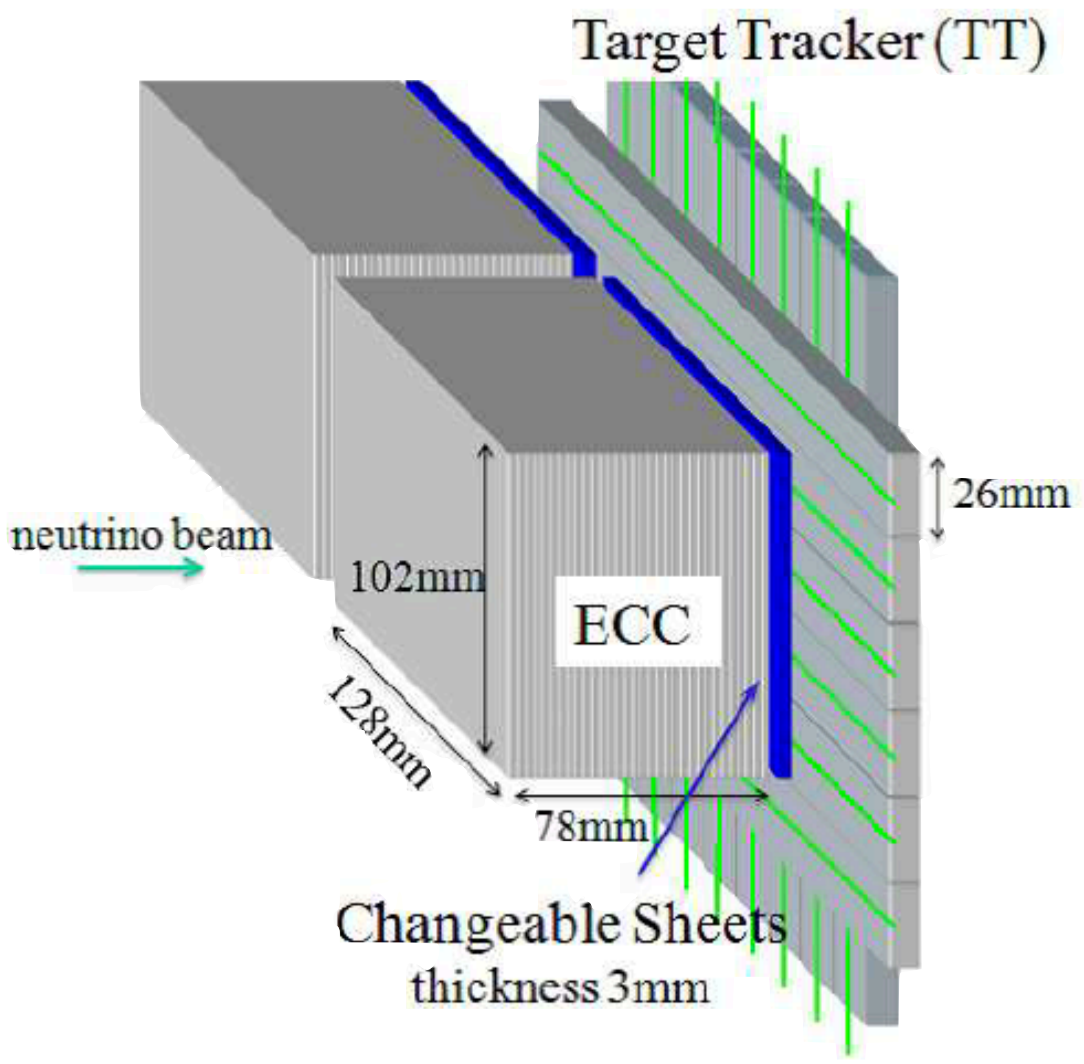
ν_μCC events with at least one reconstructed muon

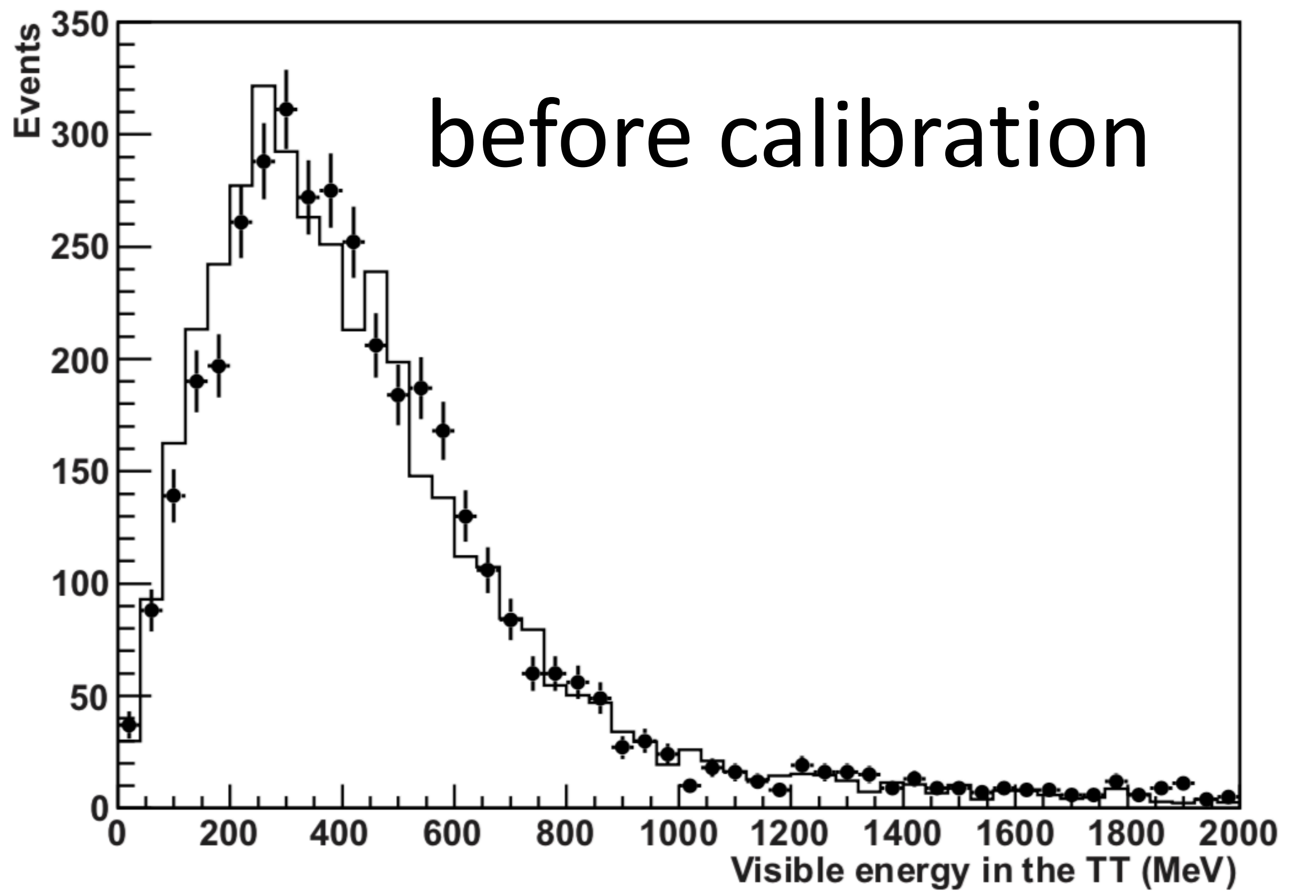




Measuring neutrino energy in OPERA

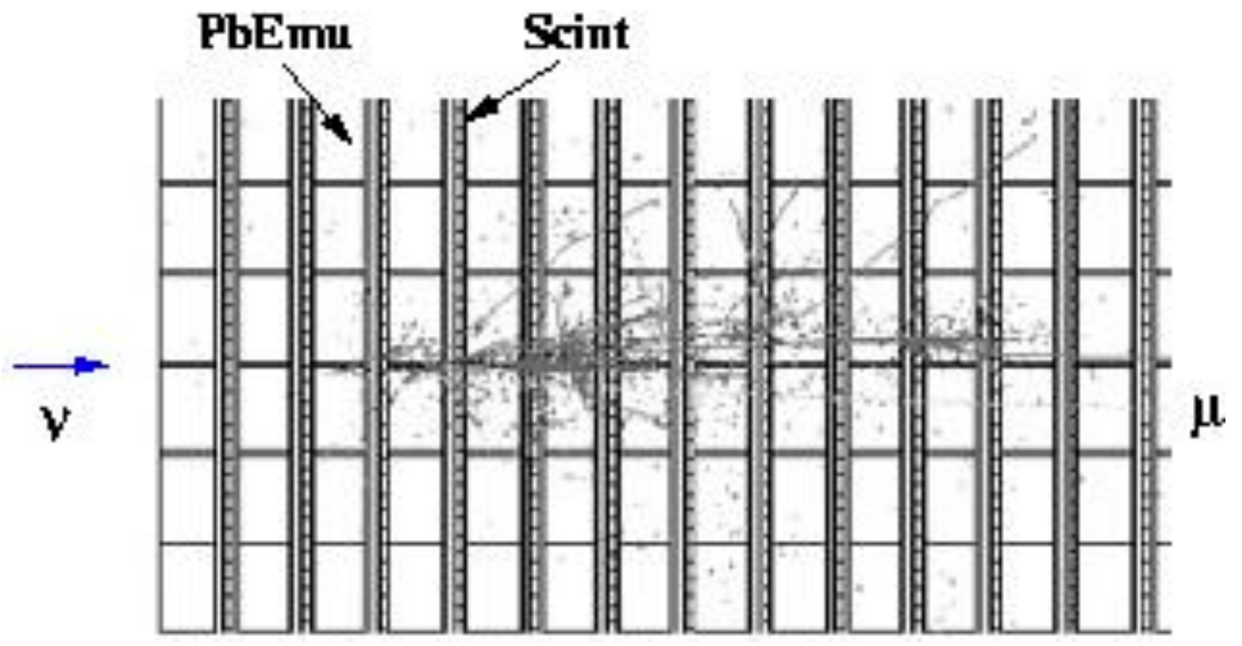
Video of the lecturer

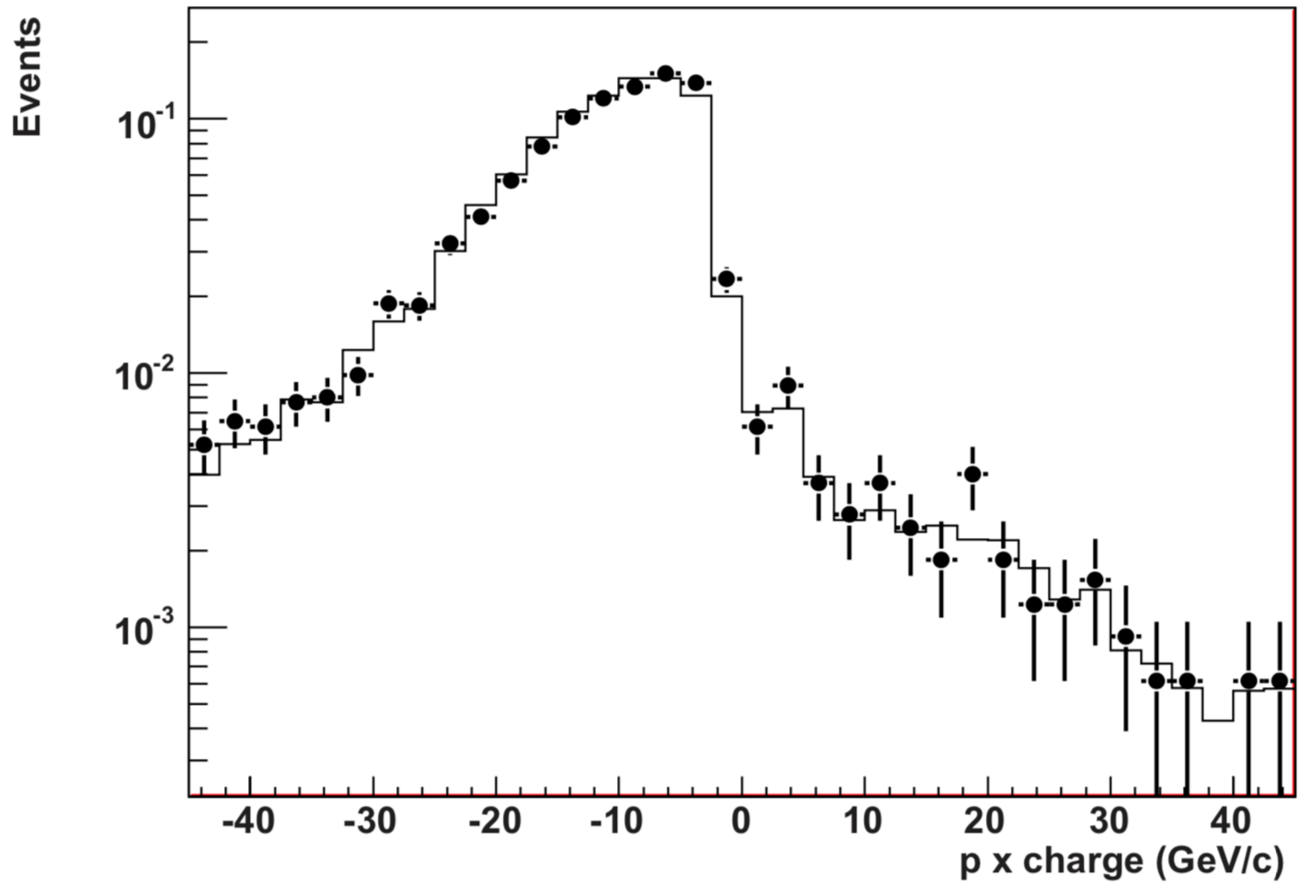




Energy deposit (before calibration) in the TT for events with at least one reconstructed muon.

Dots with error bars correspond to data and solid lines to MC.

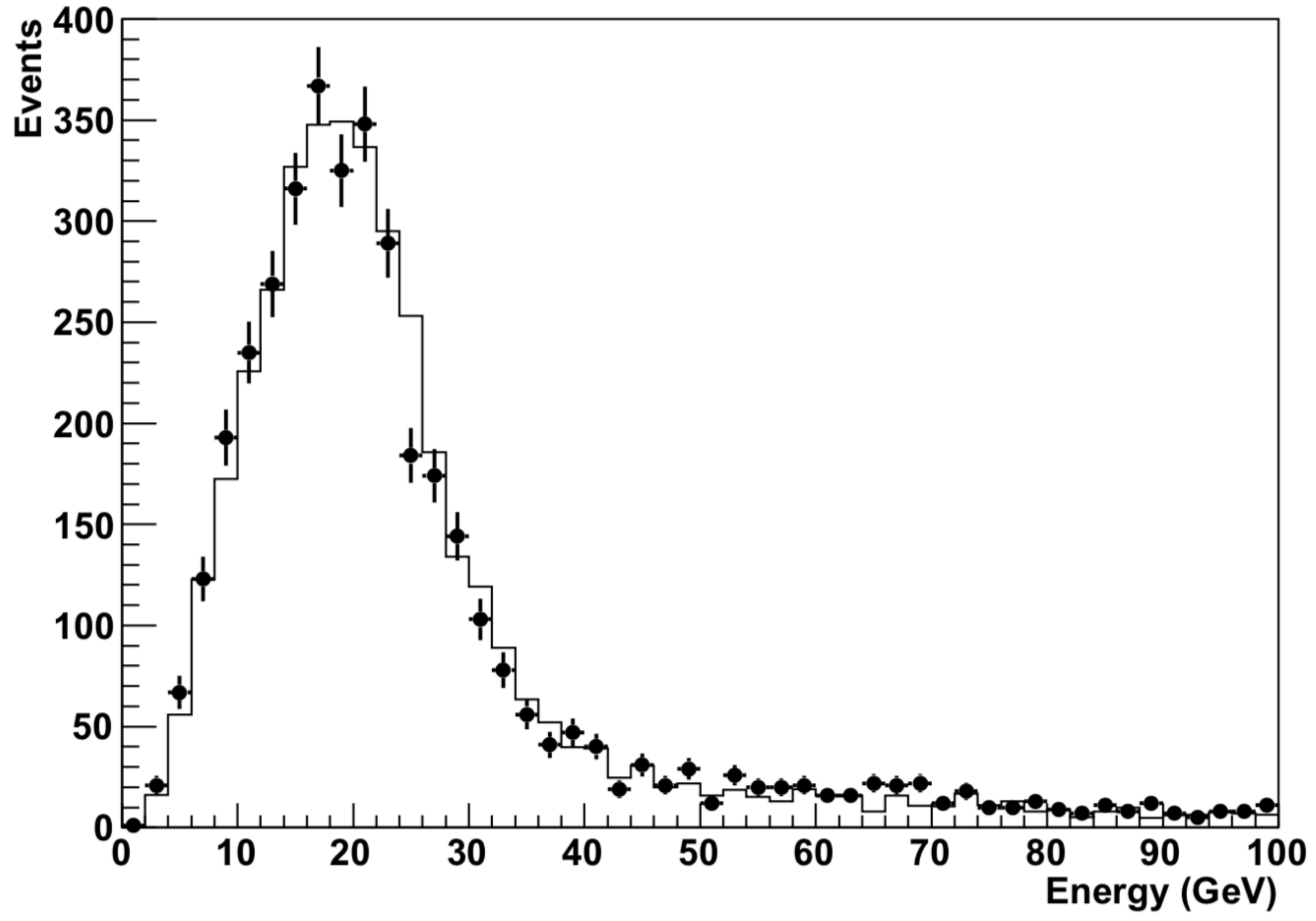




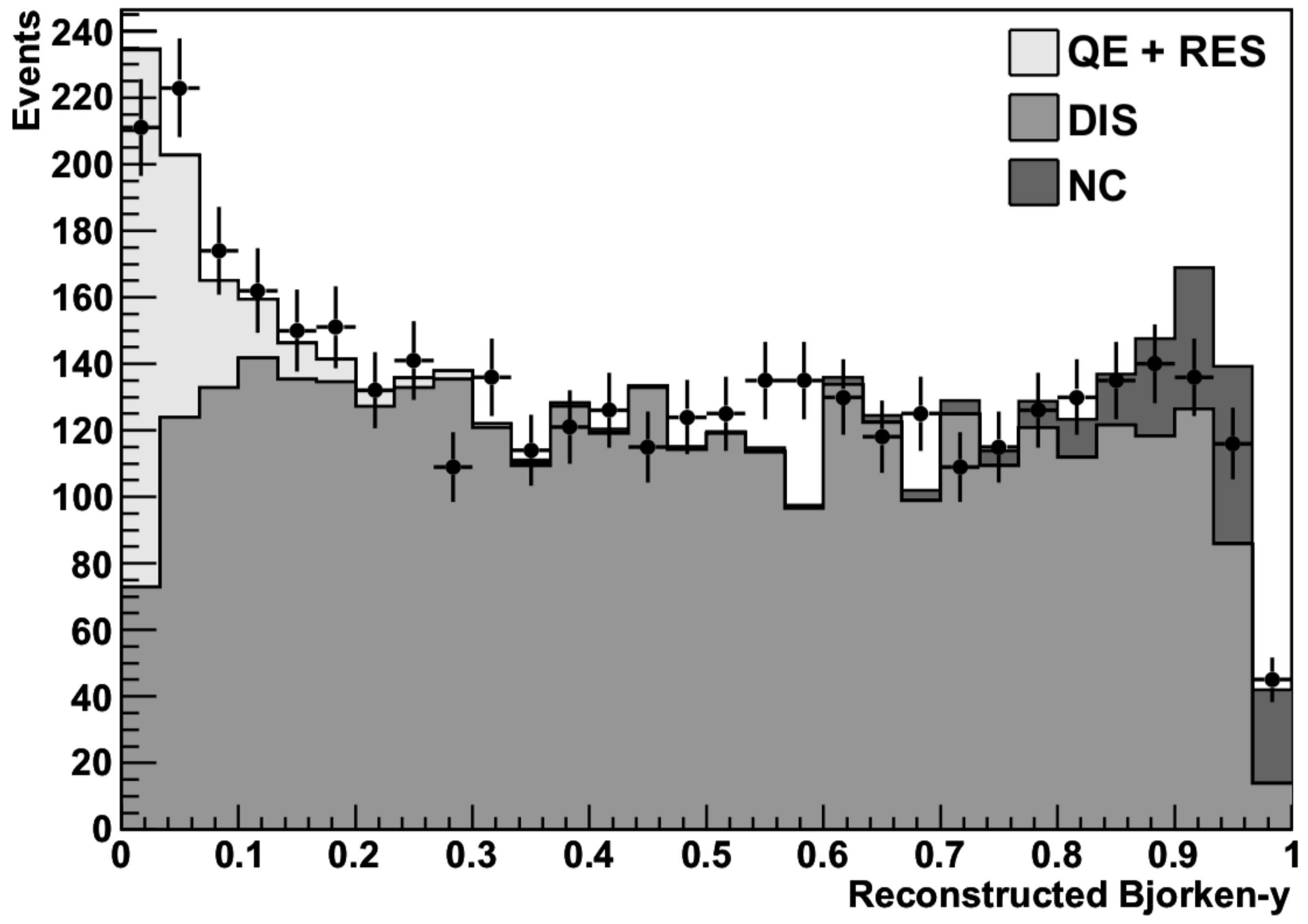
Muon charge comparison (momentum × charge): data (black dots with error bars) and MC (solid line) are normalized to 1.

Measuring neutrino energy in OPERA

Video of the lecturer



Total reconstructed energy for events with at least one identified muon for data (dots with error bars) and MC (solid line). The MC distribution is normalized to data.



$$y_B = 1 - \frac{E_\mu}{E_{\nu_\mu}} = \frac{E_{had}}{E_\mu + E_{had}}$$

Bjorken-y variable reconstructed in data (dots with error bars) and MC (shaded areas) for all the events with at least one muon.

The MC distributions are normalized to data.

Measuring the energy with the SND detector

- The Scattering and Neutrino detector operating at the LHC in Run3 (2022-2024)
- Combining electromagnetic (Emulsion + SciFi) and hadronic calorimeter (SciFi + Scintillating bars)

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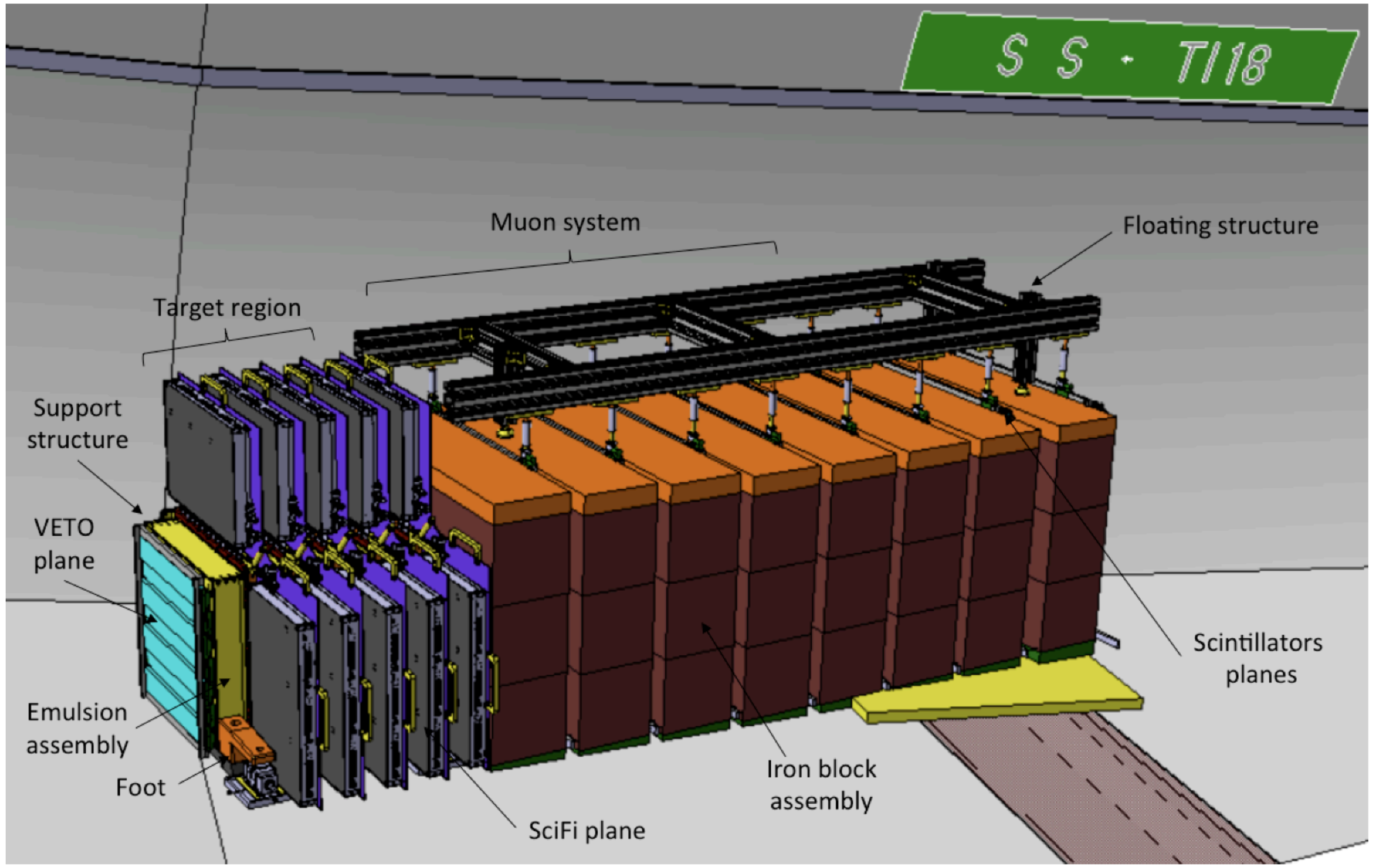
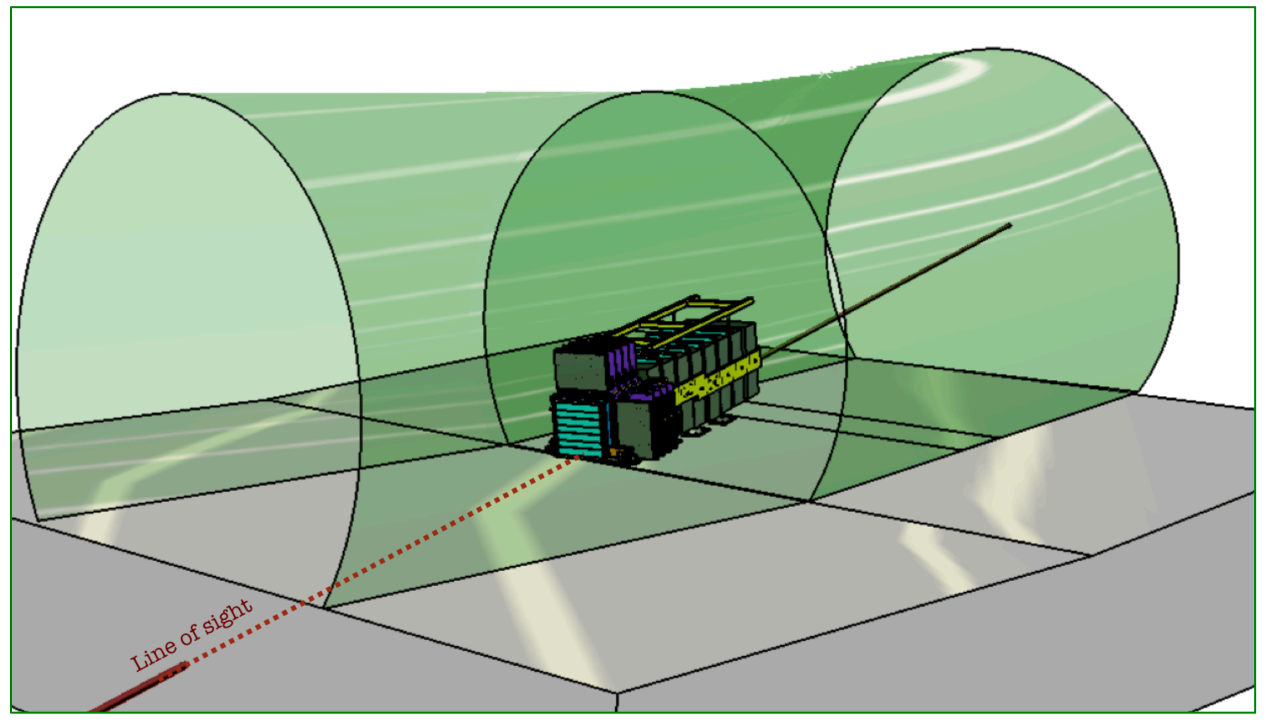
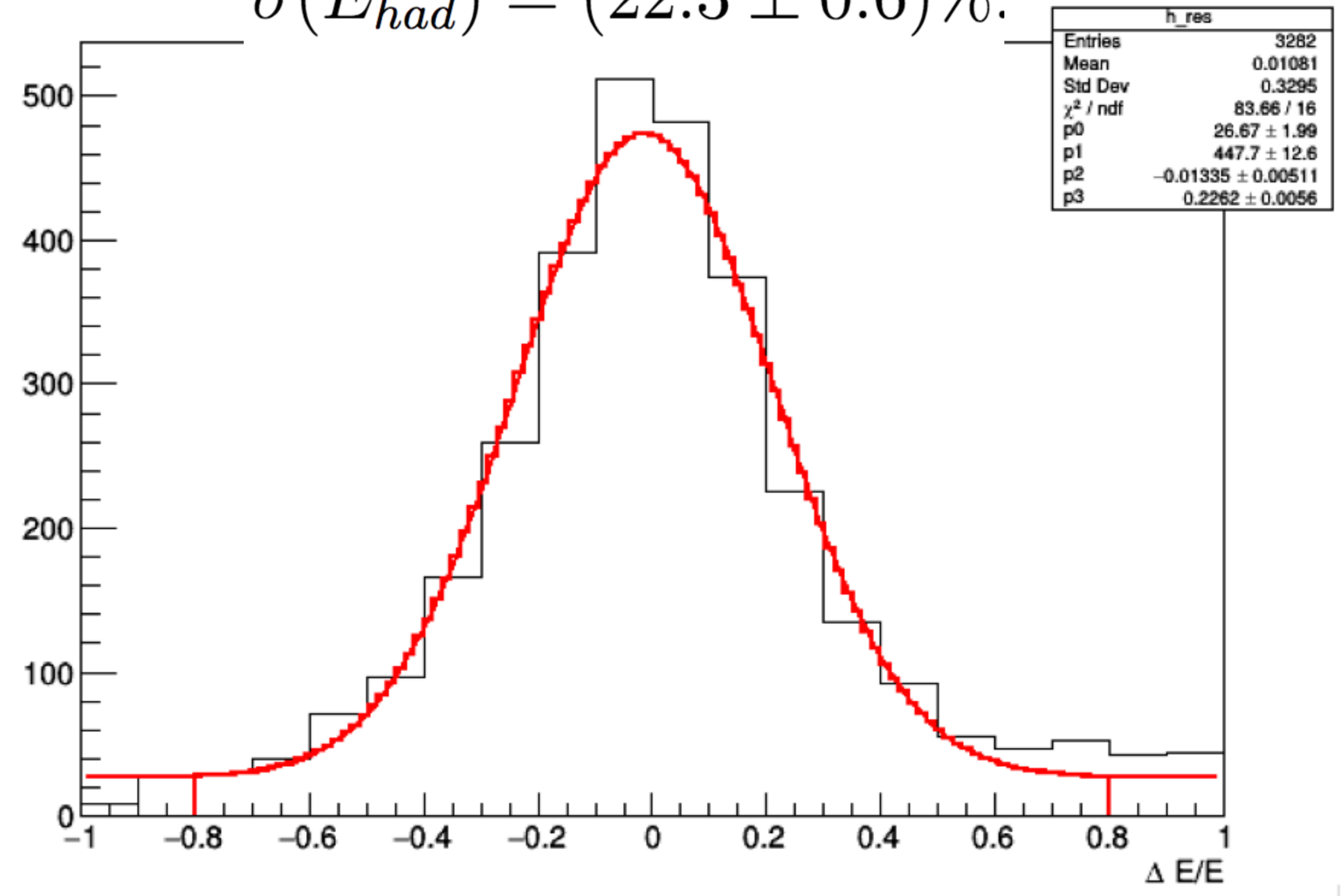




$$\sigma(E_{had}) = (22.3 \pm 0.6)\%.$$



Conclusion

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The story of modern calorimetry is a textbook example of physics research driving the development of an experimental method.

The long quest for precision electron and photon spectroscopy explains the remarkable progress in new instrumentation techniques, for both sampling and homogeneous calorimeters.

The study of jets of particles as the macroscopic manifestation of quarks has driven the work on hadronic calorimeters.

Calorimeters largely used also in neutrino physics

Quiz

Explain how one can measure the neutrino energy

Explain what is the main difference in the measurement of the energy for an electron neutrino and a muon neutrino

Homework

CMS and ATLAS experiments at CERN use large electromagnetic calorimeters to detect decay products of the Higgs boson and to measure its mass.
In the following, you may take the mass of the Higgs boson to be 125 GeV.

(i) In particle physics, the invariant mass M of the system is equal to the mass in the rest frame and can be calculated from the system energy E and its momentum p as measured in any frame, by the energy-momentum relation $M^2 = E^2 - p^2$, in natural units where c = 1.

Show that the invariant mass, M, of two photons is given by $\mathbf{M^2_{\gamma\gamma} = 2E_1E_2(1-\cos\theta)}$, where E_1 and E_2 are the energies of the two photons and θ is the angle between the directions of flight of these photons.

Hint: You may rewrite the energies of the two photons in terms of their momenta.

Homework

(ii) Assuming the angular resolution is accurate enough that its error can be neglected, show that the fractional mass resolution is given by

$$\frac{\sigma_{M_{\gamma\gamma}}}{M_{\gamma\gamma}} = \frac{1}{2}\left[\left(\frac{\sigma_{E_1}}{E_1}\right)^2 + \left(\frac{\sigma_{E_2}}{E_2}\right)^2\right]^{1/2}$$

where M is the error on the two photon invariant mass, and $E_{1,2}$ are the errors on the photon energies $E_{1,2}$.

(iii) The fractional calorimeter energy resolution is given by $$\frac{\sigma_E}{E} = \left[\left(\frac{a}{\sqrt{E}}\right)^2 + b^2\right]^{1/2}$$

where energy E is measured in GeV and the coefficients a and b depend on the calorimeter construction: a is ~3% for the CMS calorimeter and ~10% for the ATLAS calorimeter. The coefficient b is ~0.5% for the both calorimeters. Consider the Higgs boson decaying into two photons of equal energies $E_1 = E_2 = 50$GeV. Estimate the absolute mass resolution in GeV for the Higgs mass reconstructed in the CMS and ATLAS calorimeters.