SLUO LECTURE SERIES

Calorimetry II

LECTURE # 14

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January 14, 1999

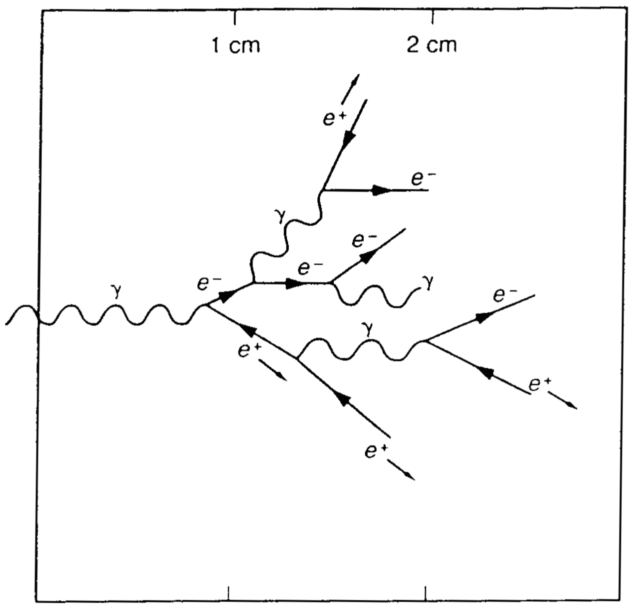
Outline

- Hadronic Showers
  - components
    - electromagnetic, hadronic, binding energy losses, etc.
  - properties
    - longitudinal and transverse distributions
  - fluctuations
  - resolution of calorimeters
    - compensation
  - examples of calorimeters

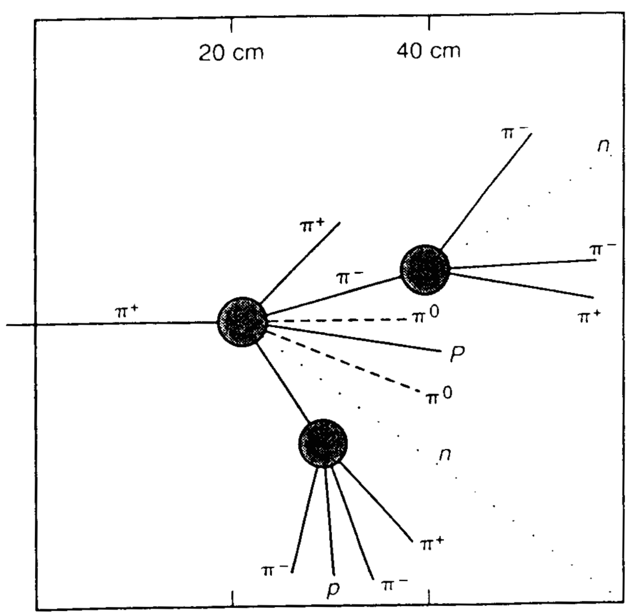
Hadron Calorimetry

- Hadron Calorimeters, as electromagnetic calorimeters, measure the energy of the incident particle(s) by fully absorbing the energy of the particle(s) and providing a measurement of the absorbed energy.
- Hadronic Showers are more complicated than electromagnetic showers, significantly reducing the optimal precision

Electromagnetic and Hadronic Showers



Huston



100 GeV Hadronic Shower

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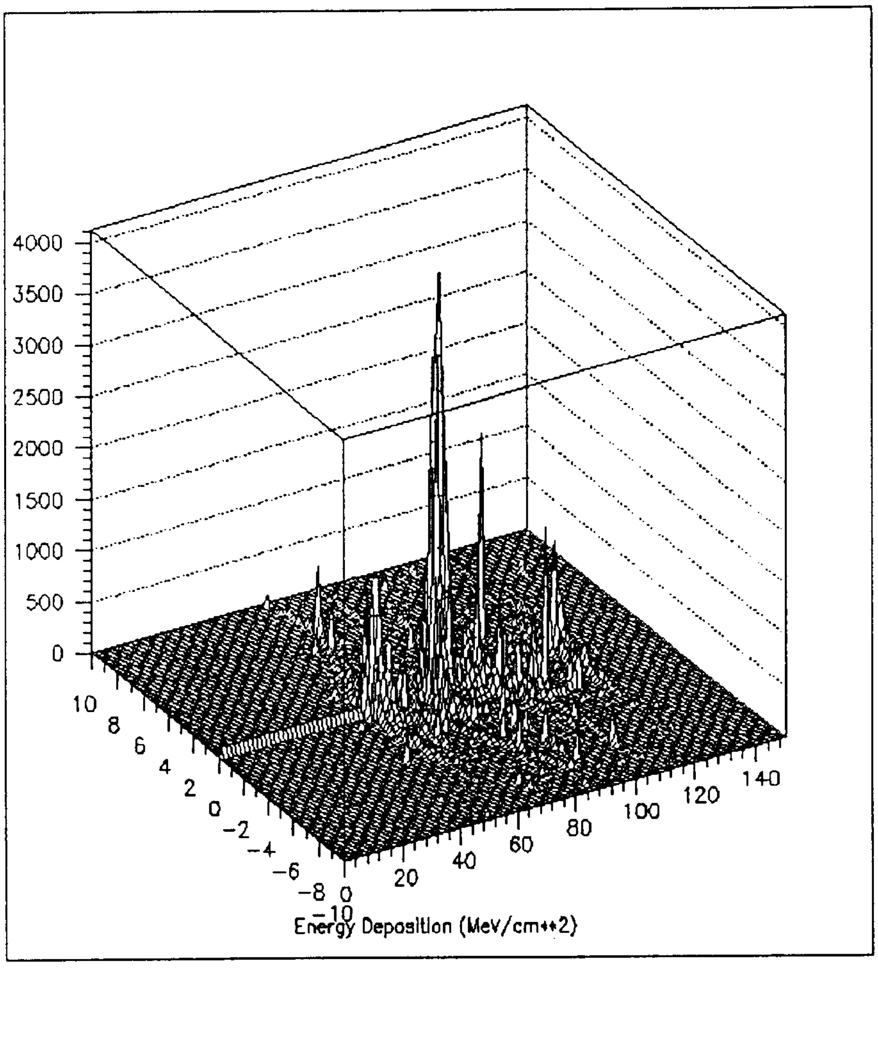


Furuno

Hadronic Showers

- The strongly interaction particle will interact (inelastically) with a nucleus according to the nuclear cross section:

$$\lambda_I \approx 35 \text{ g cm}^{-2} \ A^{1/3}$$

survival (without interacting)

$$= e^{-\lambda_I x / \rho}$$

Hadronic Showers

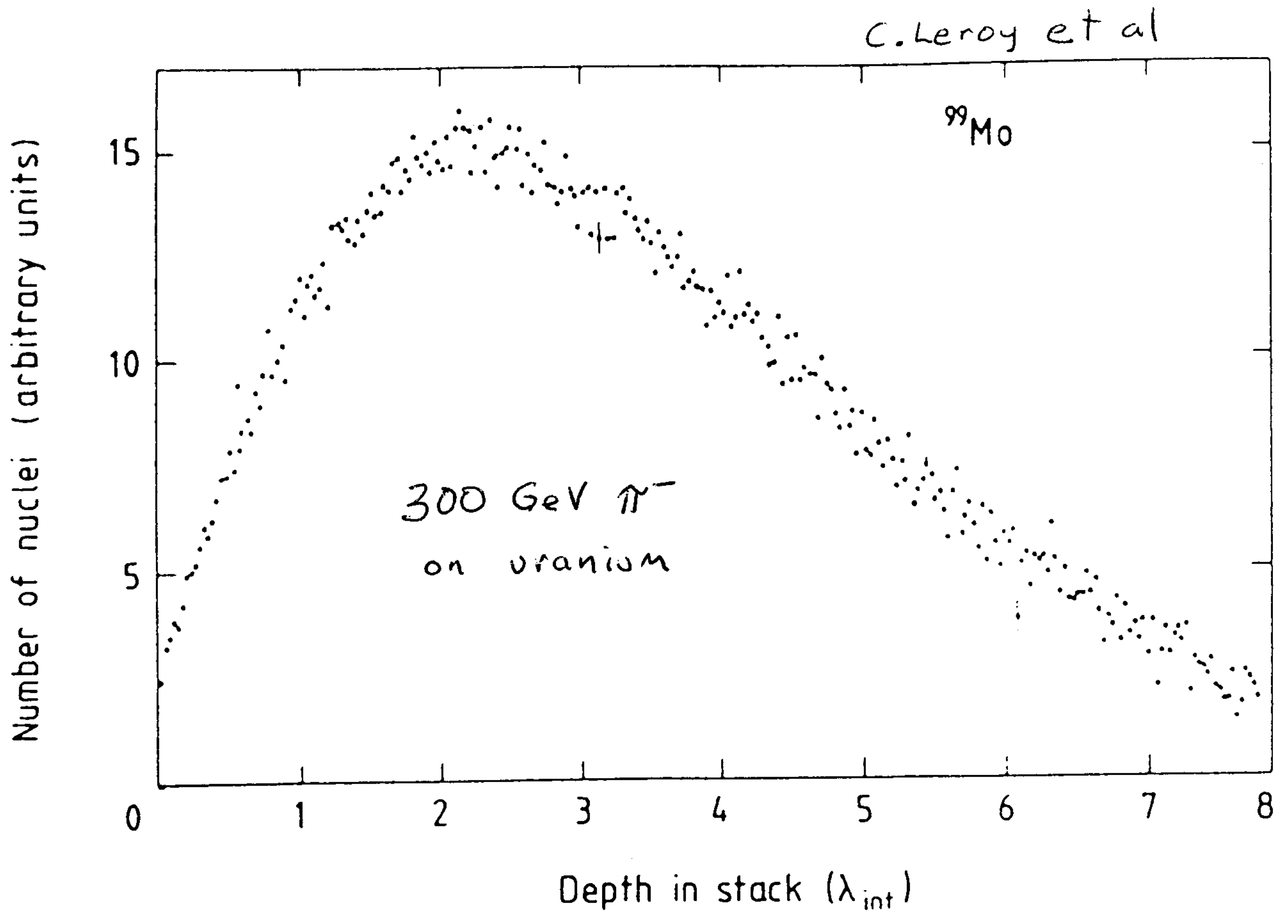
- The nuclear interaction length is longer than the radiation length, defining the fundamental scale of the hadronic shower

Material	Atomic No. (Z)	Radiation Length (X_0) (g/cm^2)	(cm)	Interaction Length (λ) (g/cm^2)	(cm)	X_0/λ
Beryllium	**_4**	**65.19**	**35.28**	**75.2**	**40.7**	**1.2**
Carbon	**_6**	**42.70**	**18.8_**	**86.3**	**38.1**	**2.0**
Aluminum	**13**	**24.01**	**8.9_**	**106.4**	**39.4**	**4.4**
Iron	**26**	**13.84**	**1.76**	**131.9**	**16.8**	**9.5**
Copper	**29**	**12.86**	**1.43**	**134.9**	**15.1**	**15.1**
Tungsten	**74**	**6.76**	**0.35**	**185._**	**9.6**	**27.4**
Lead	**82**	**6.37**	**0.56**	**194._**	**17.1**	**30.5**
Uranium	**92**	**6.00**	**0.32**	**199._**	**10.5**	**33.2**

The higher Z materials separate hadronic & EM interactions more fully ⬆

Hadronic Showers: Longitudinal Development

- The longitudinal development is characterized by the nuclear interaction length

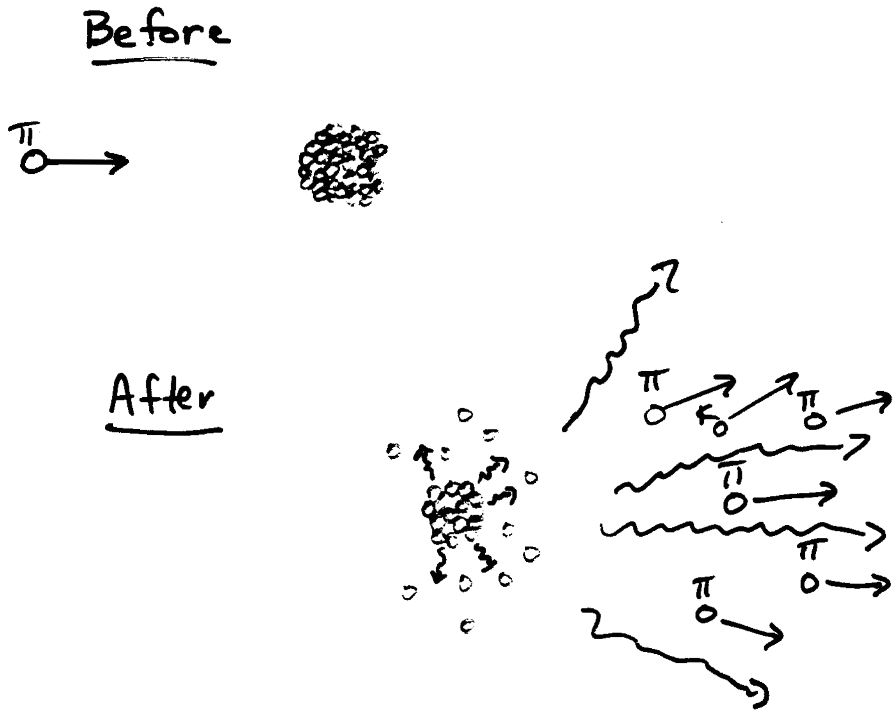


Hadronic Showers

- As a strongly interacting particle (hadron) passes through matter, it eventually initiates a nuclear interaction, and starts a nuclear shower.
- The initial interaction will be characterized by:
  - meson (π, K, ...) production.
  - emission of nucleons and low energy gammas by the interacting nucleus.
  - absorption of energy to release bound nucleons by the nucleus (binding energy is ~ 8 MeV/ nucleon)

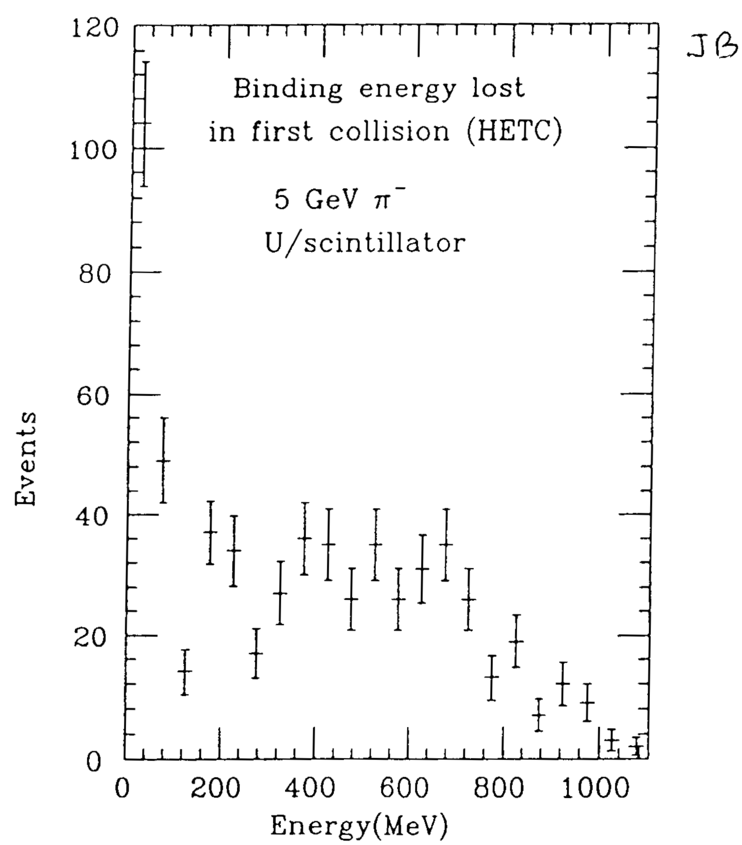
Hadronic Showers

- Intial interaction



Hadronic Showers

- Binding energy lost in <u>first interaction</u> of a 5 GeV π^- on a uranium-scintillator calorimeter
  - average = 380 MeV (or 7.6% of incident energy)



Hadronic Showers: Cascade of Interactions

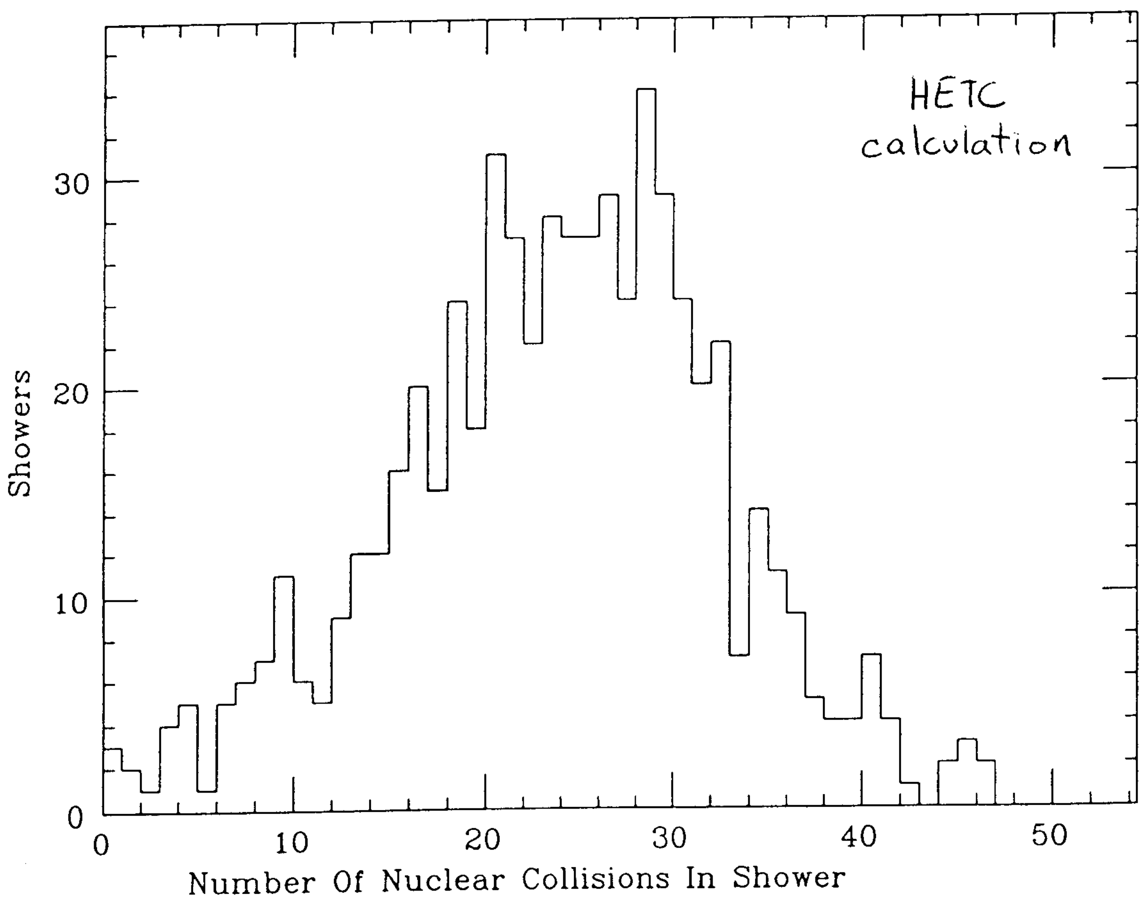
- In hadronic showers, we have many particle types, which have different processes
  - π^0 s
    - decay "instantly" to $\gamma\gamma$, which intitiate electromagnetic showers
    - roughly 1/3 of the mesons of the initial interaction
  - charged mesons
    - secondary interactions
    - decays (producing neutrinos & μ's, which escape with their energy)
  - nucleons from nuclear break-up & evapor.
    - protons - lose energy through ionization, can range out before interacting
    - neutrons - chargeless, and therefore will not range out - transport energy
  - gammas from nuclear excitation
    - interact electromagnetically

Hadronic Showers: Cascade of Interactions (cont.)

- The distribution of the number of nuclear interactions in a shower initiated by a 5 GeV π^- on a uranium-scintillator calorimeter.

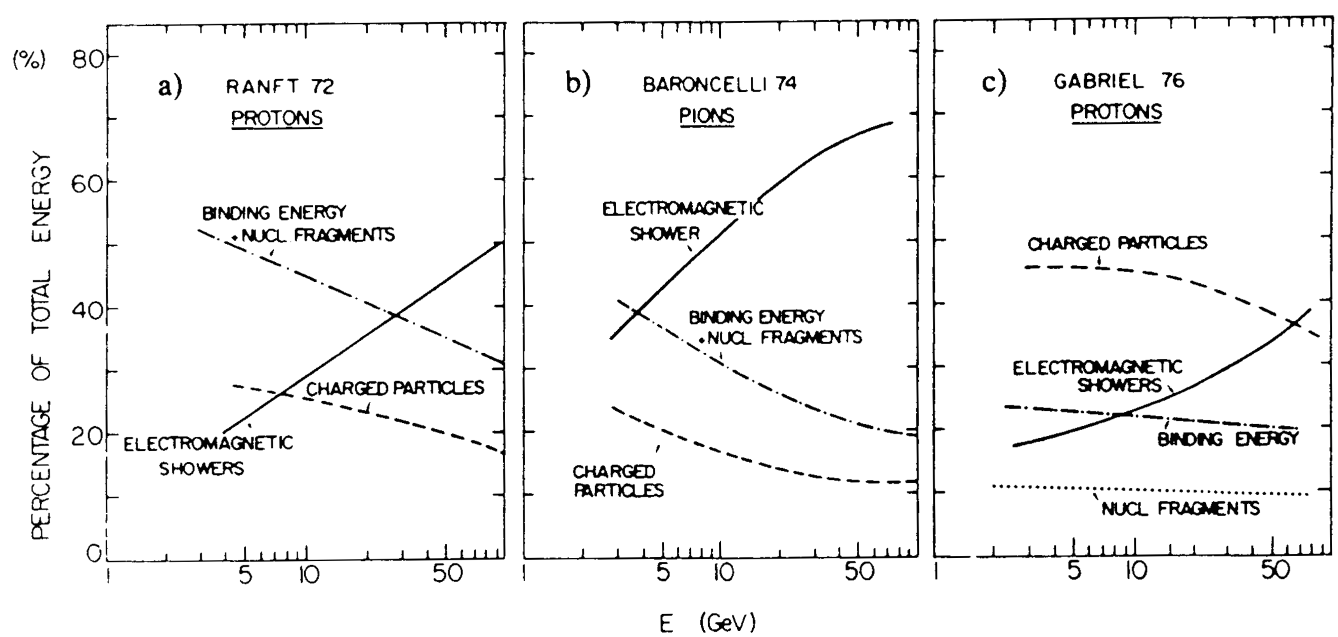
  (neutrons are cut-off at 20 MeV)

  - average = 24

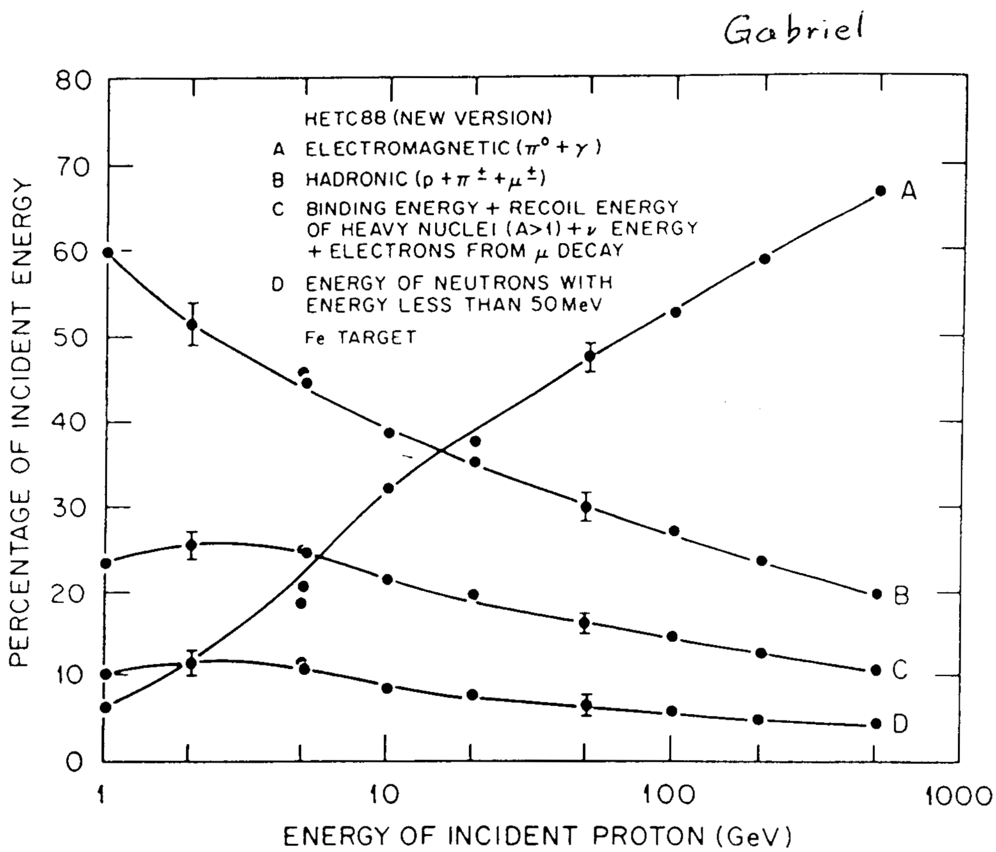


Hadronic Showers: Cascade of Interactions (cont.)

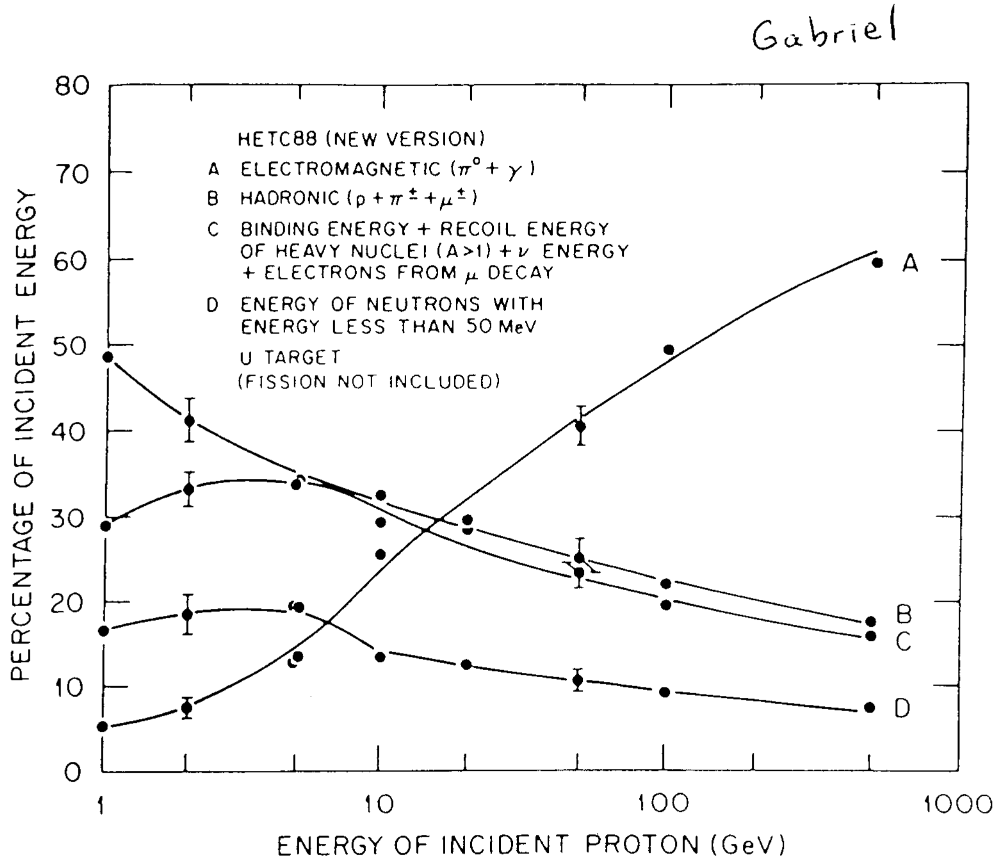
- With 30% of the meson production at the initial interaction (on average) going into electromagnetic showers (π^0->$\gamma\gamma$), and similar fractions on subsequent interactions, the fraction of the shower which is electromagnetic will increase with energy.



Hadronic Showers: Energy Fractions (Fe)

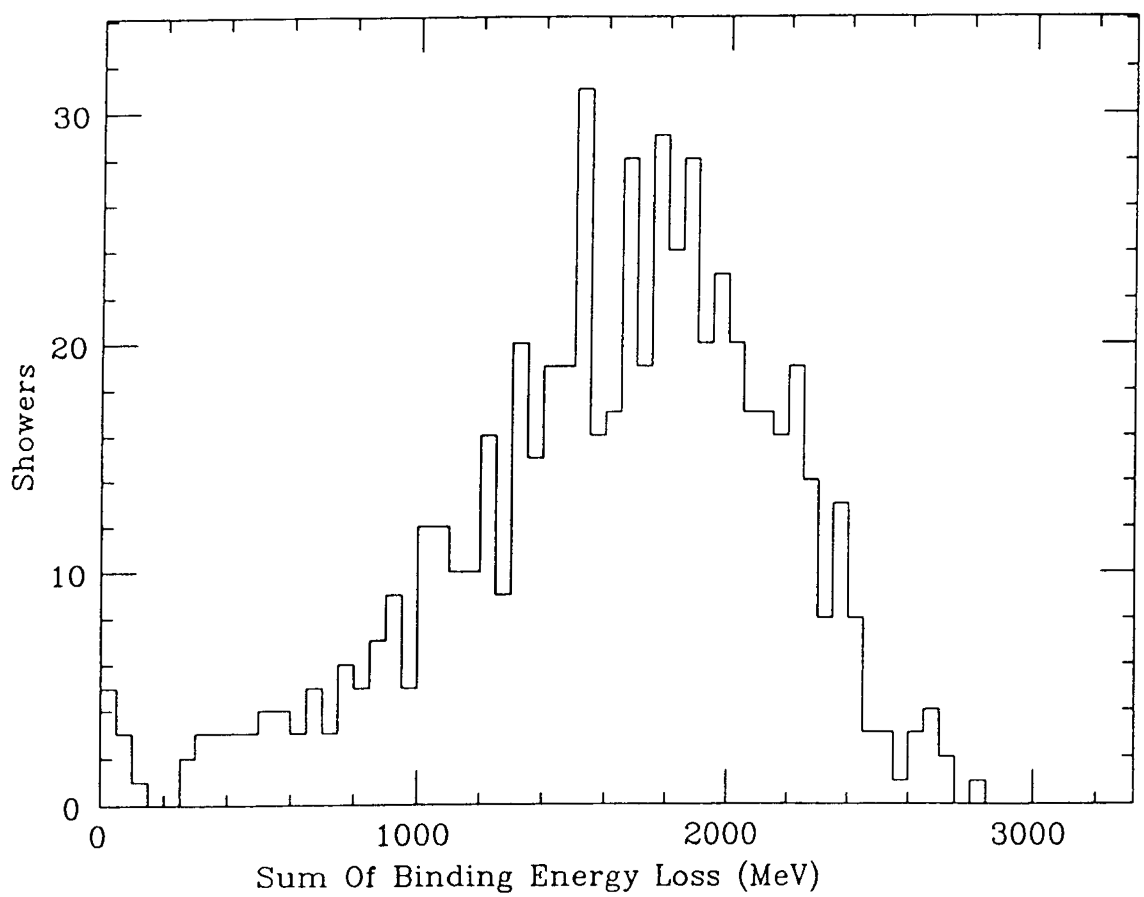


Hadronic Showers: Energy Fractions (U)

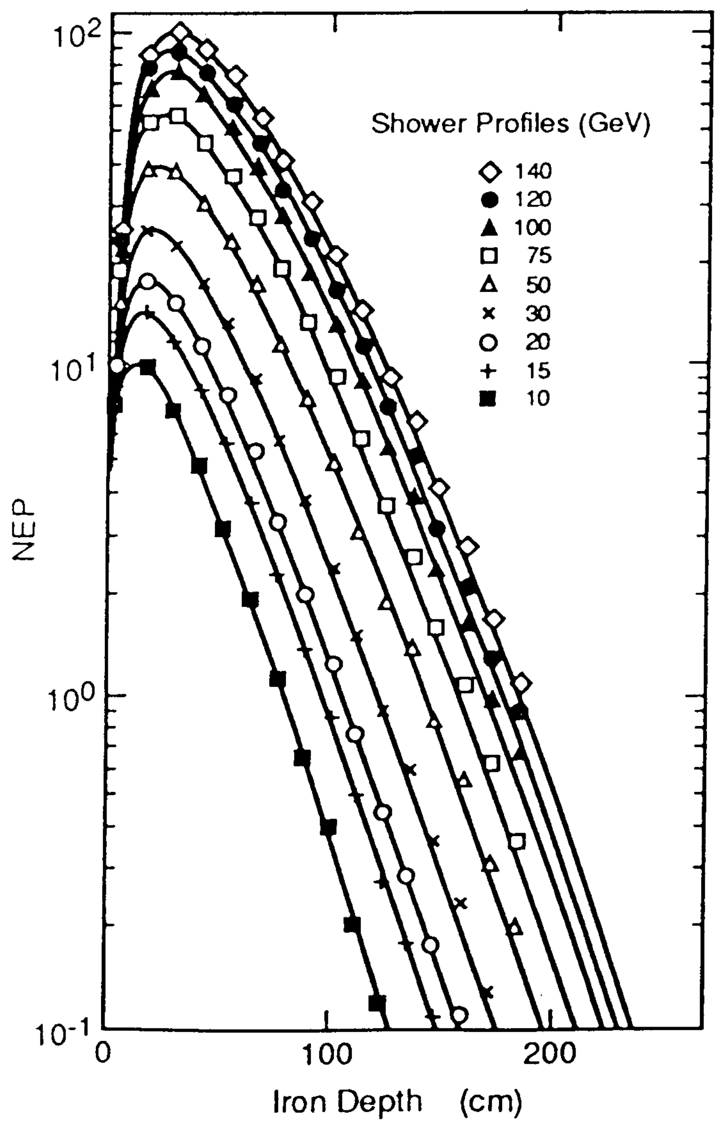


Hadronic Showers: Cascade of Interactions (cont.)

- Binding energy lost in a 5 GeV π^- incident on a uranium-scintillator calorimeter.
  - average = 1600 MeV (32% of incident energy)



Hadronic Showers: Longitudinal Development



Hughes

Hadronic Showers: Long. Development (cont.)

- The curves on the previous transparency are fit to the Bock parametrization (NIM 186, 533 (1981))

$$dE = \kappa[\underbrace{\omega s^{-\alpha}\ \exp(-\beta s)}_{EM} + \underbrace{(1-\omega)t^{-\alpha}\ \exp(-\delta t)}_{HAD}]$$

$(s = z/1.76\ \text{cm})$
$(t = z/19.5\ \text{cm})$

$\omega = 1.03 - 0.365 \log E\ (\text{GeV})$

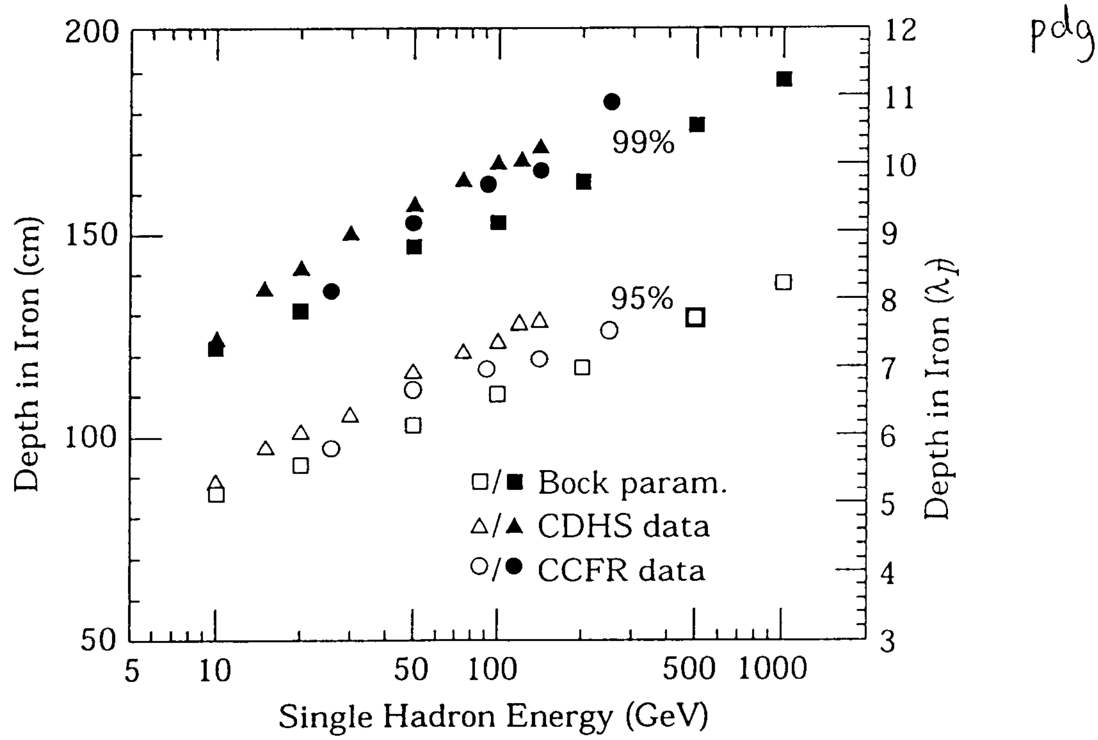
$\alpha = 0.214 - 0.984 \log E\ (\text{GeV})$

$\beta = 0.29$

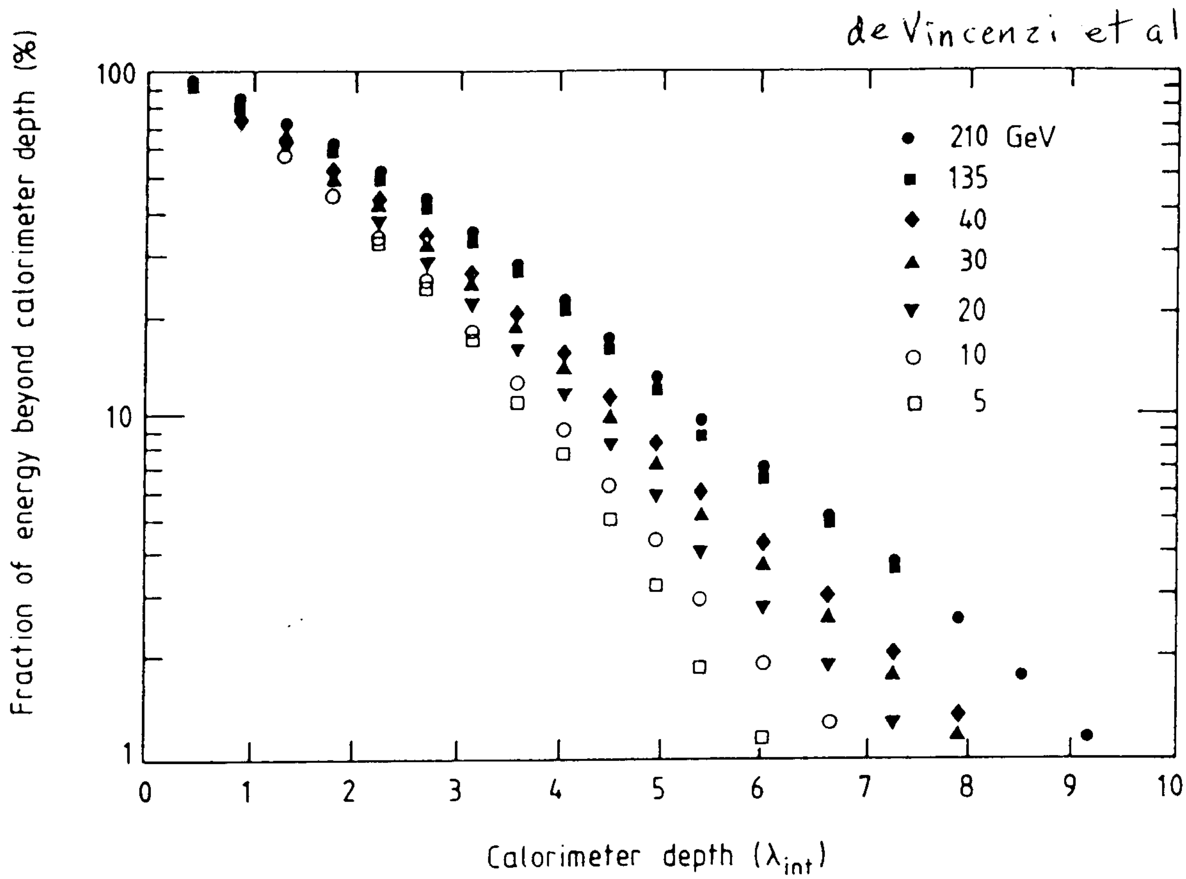
$\delta = 0.978$

E. Hughes

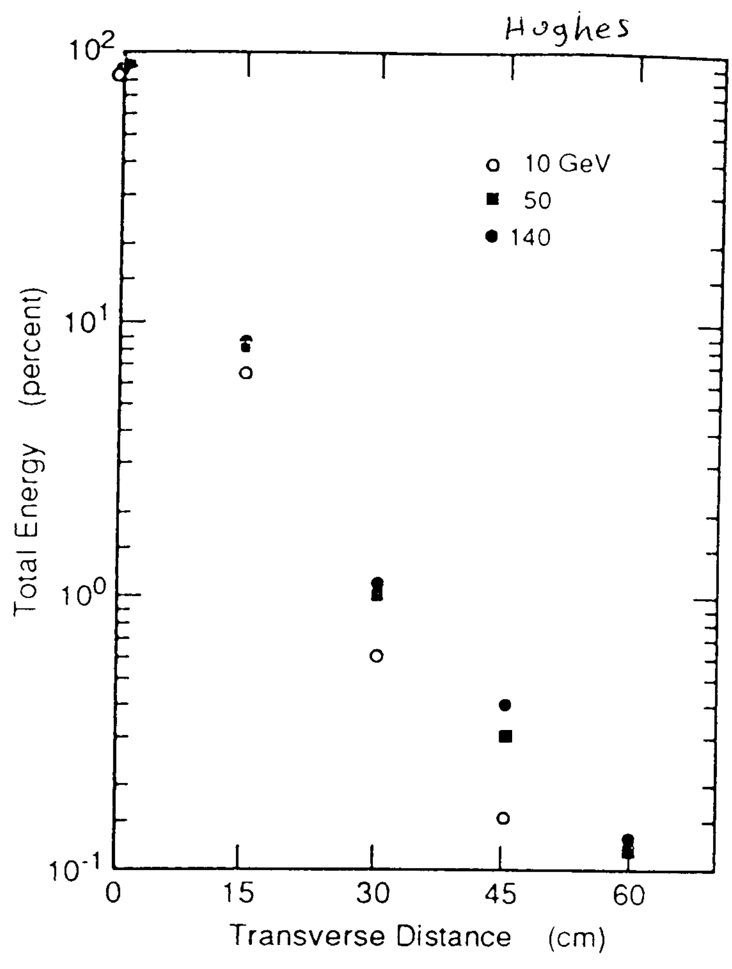
Hadronic Showers: Long. Development (cont.)



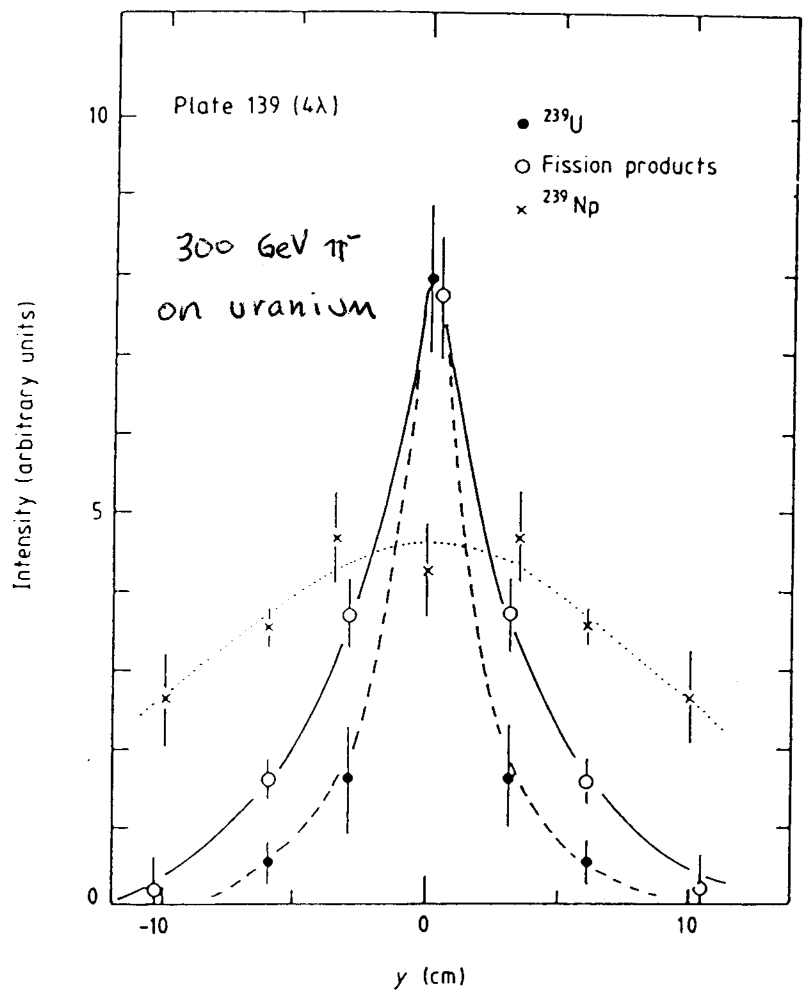
Hadronic Showers: Long. Development (cont.)



Hadronic Showers: Transverse Distribution



Hadronic Showers: Trans. Distribution (cont.)

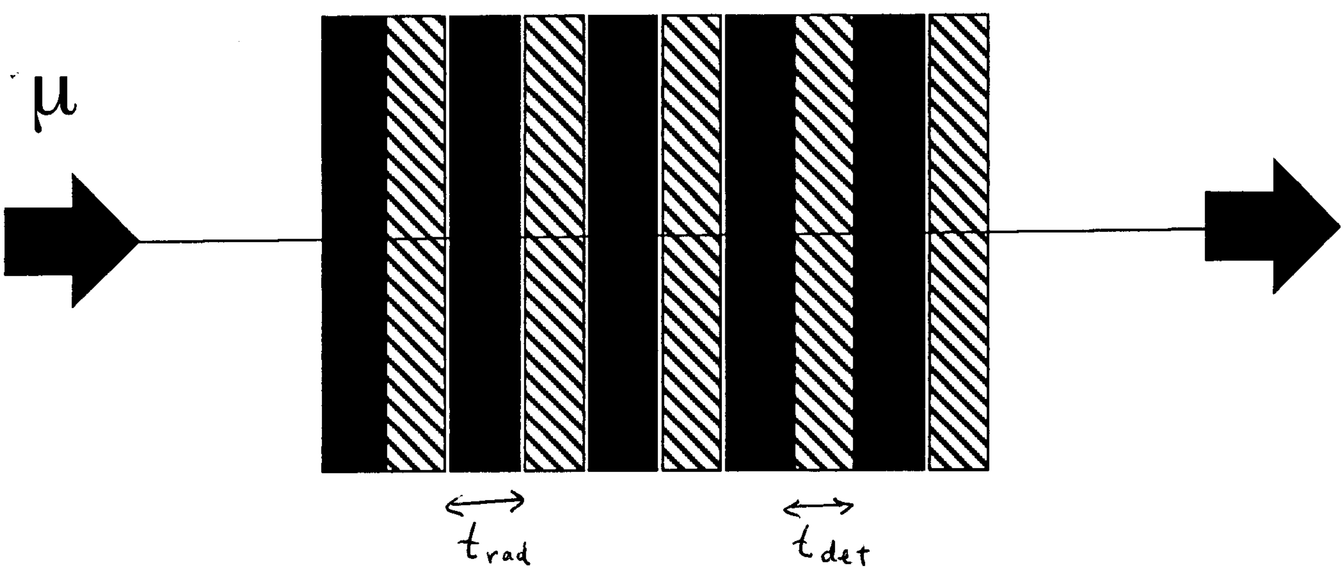


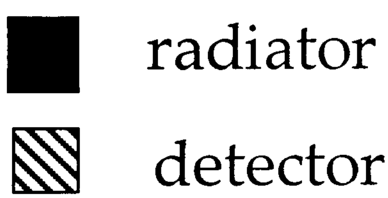
Leroy et al.

Electromagnetic Sampling Inefficiencies

Consider a Sampling Calorimeter

- Calibrate the energy in the calorimeter using muons





$$\frac{E_{det}}{E_{tot}} = \frac{\left.\frac{dE}{dx}\right|_{det} t_{det}}{\left.\frac{dE}{dx}\right|_{det} t_{det} + \left.\frac{dE}{dx}\right|_{rad} t_{rad}}$$

Electromagnetic Sampling Inefficiencies (cont.)

- The interaction of low energy photons differs from material to material (see next transparency)
- Therefore, an electromagnetic cascade will not deposit its energy in the same proportion between the high Z radiator material andthe lower Z material of the sensitive layers
- Typical examples:
  - Fe or Cu radiator:

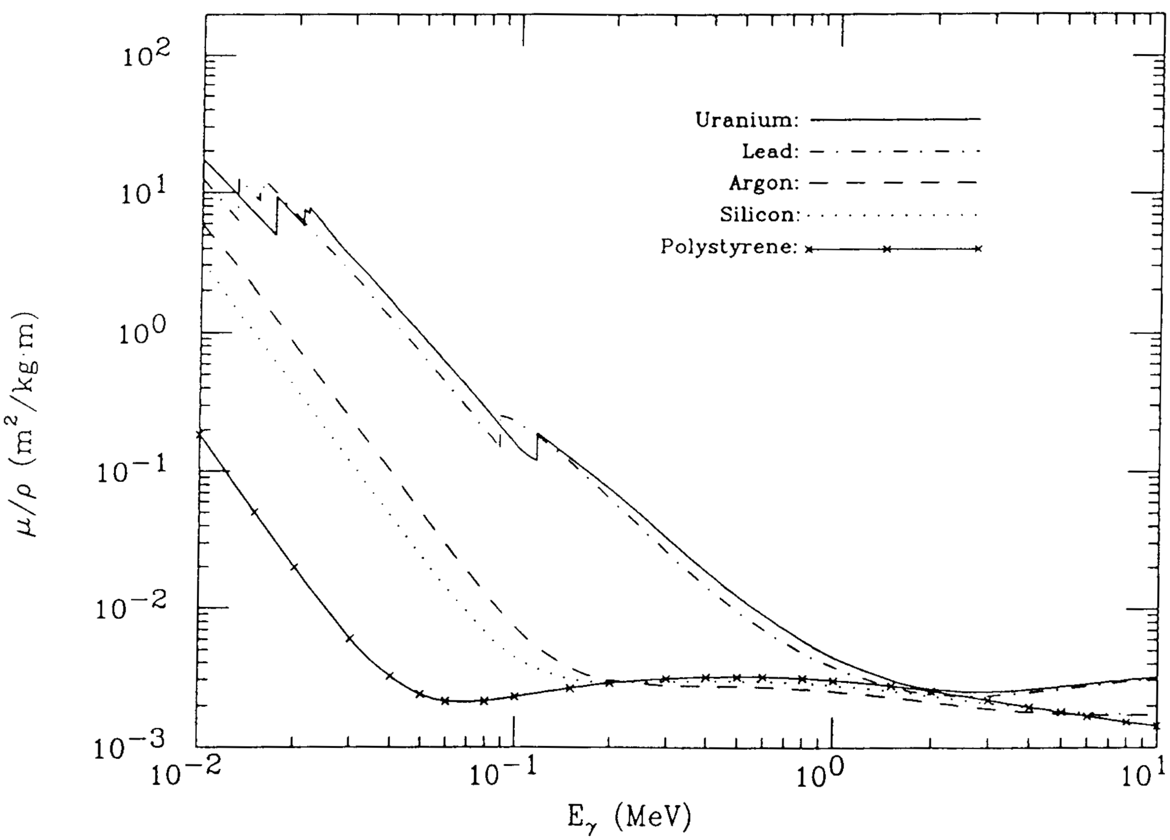
    $e/\mu \sim 0.9 - 1$
  - Pb radiator

    $e/\mu \sim 0.7 - 0.8$
  - U radiator

    $e/\mu \sim 0.6 - 0.7$

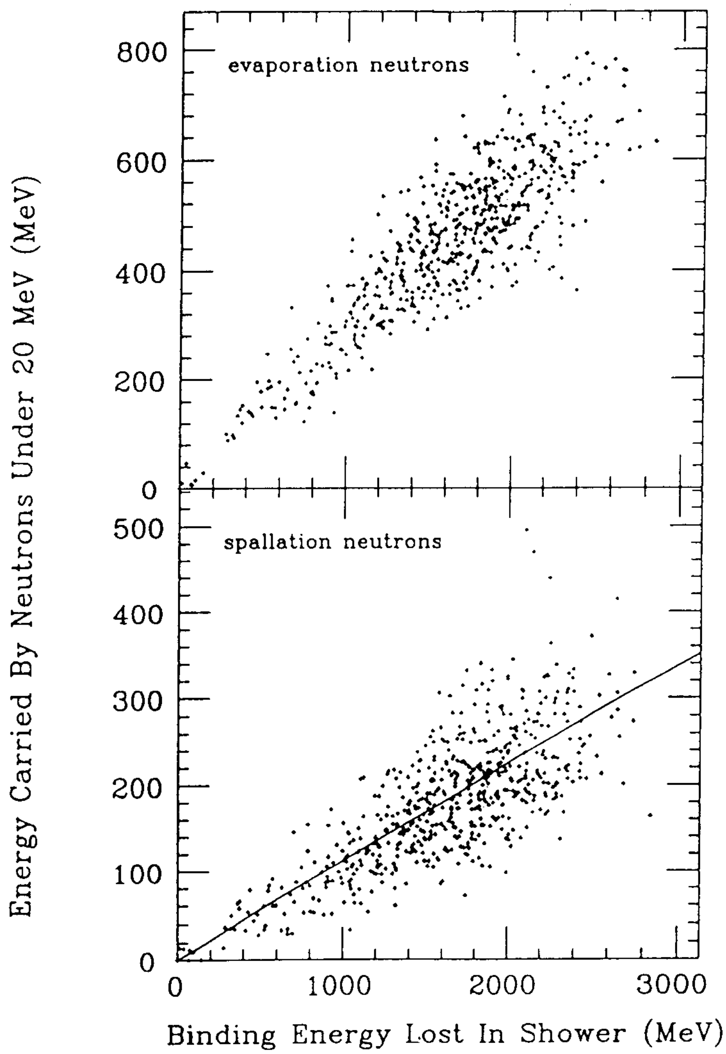
Electromagnetic Sampling Inefficiencies (cont.)

The electromagnetic sampling inefficieny results from the rise in low energy photon absorption in high Z materials below 1 MeV



Hadronic Showers: The role of neutrons

- Neutrons carry information on the nuclear binding energy releases



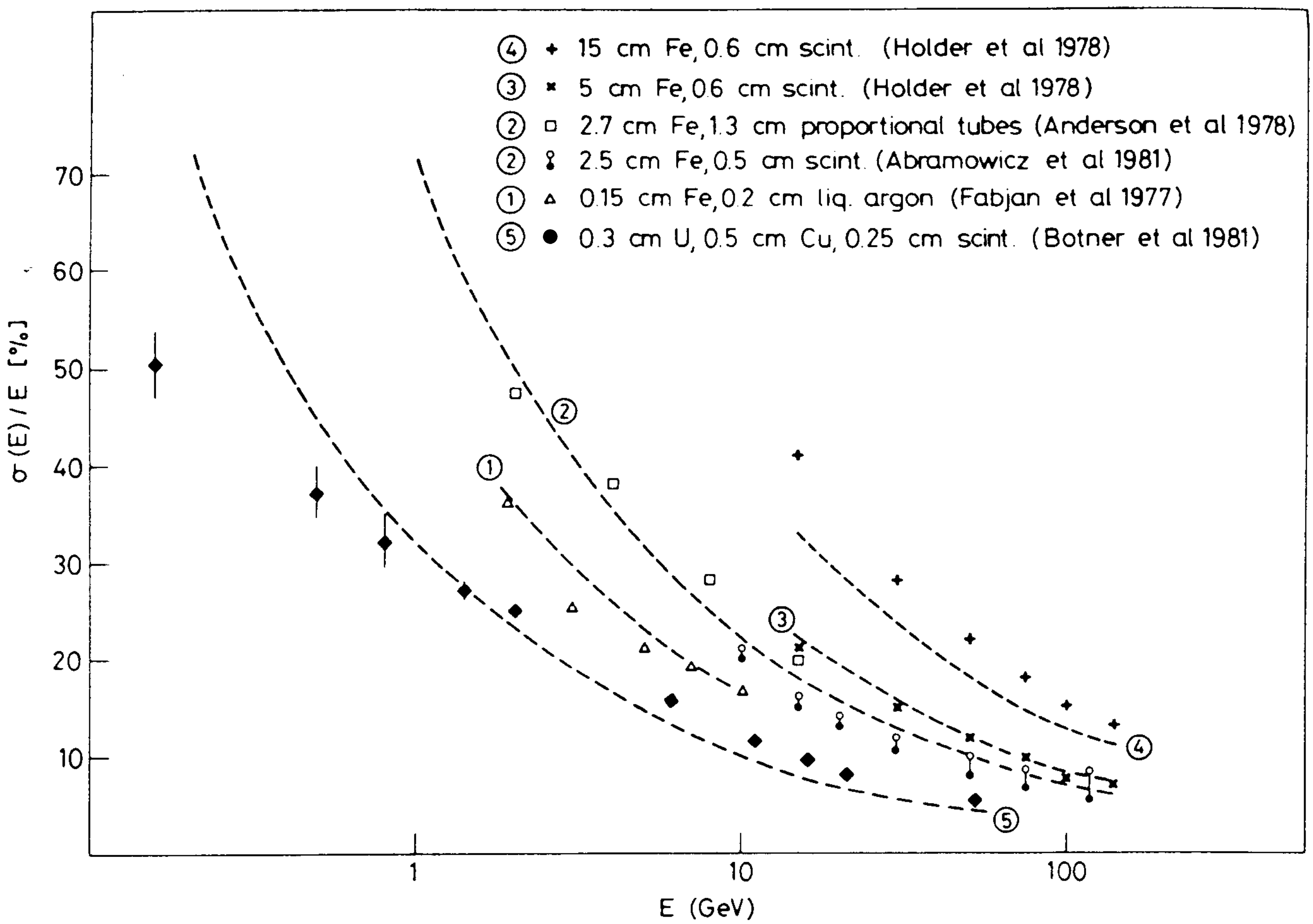
MORSE calculation

Hadronic Showers: Fluctuations

- EM vs. non-EM components
- nuclear binding energy losses
- sampling
- leakage of ionizing particles
- leakage of non-ionizing particles
- saturation of the detector response
  - or non-linear response of the detector
- noise
- non-uniformities of the detector
- time dependence of the various components: eg. EM or neutrons

Sampling Fluctuation in Hadronic Calorimeters

Fabjan

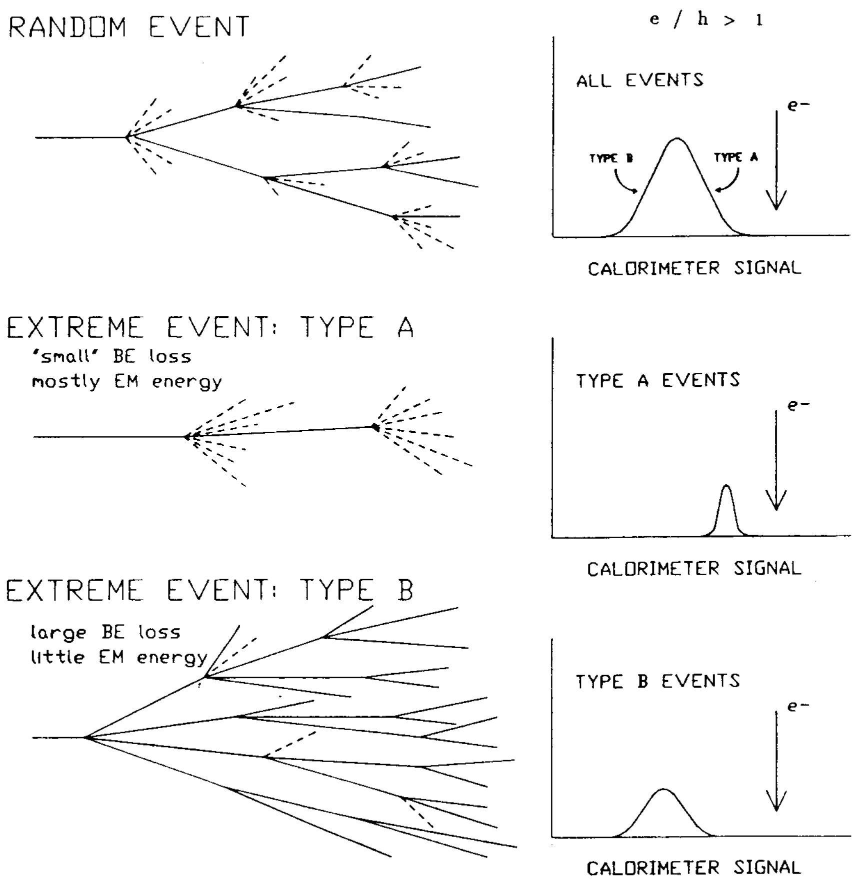


Hadronic Showers: Resolution

- The most important fluctuation: binding energy losses
- However, binding energy losses are correlated with fraction of the shower energy which goes into electromagnetic energy
  - if this is large, there will be fewer nuclear interactions, and less binding energy lost
  - if it is small, there are more nuclear interactions, and more binding energy lost
- The binding energy losses are large and variable, and are a fundamental obstacle to the best resolution

Hadronic Showers: Resolution

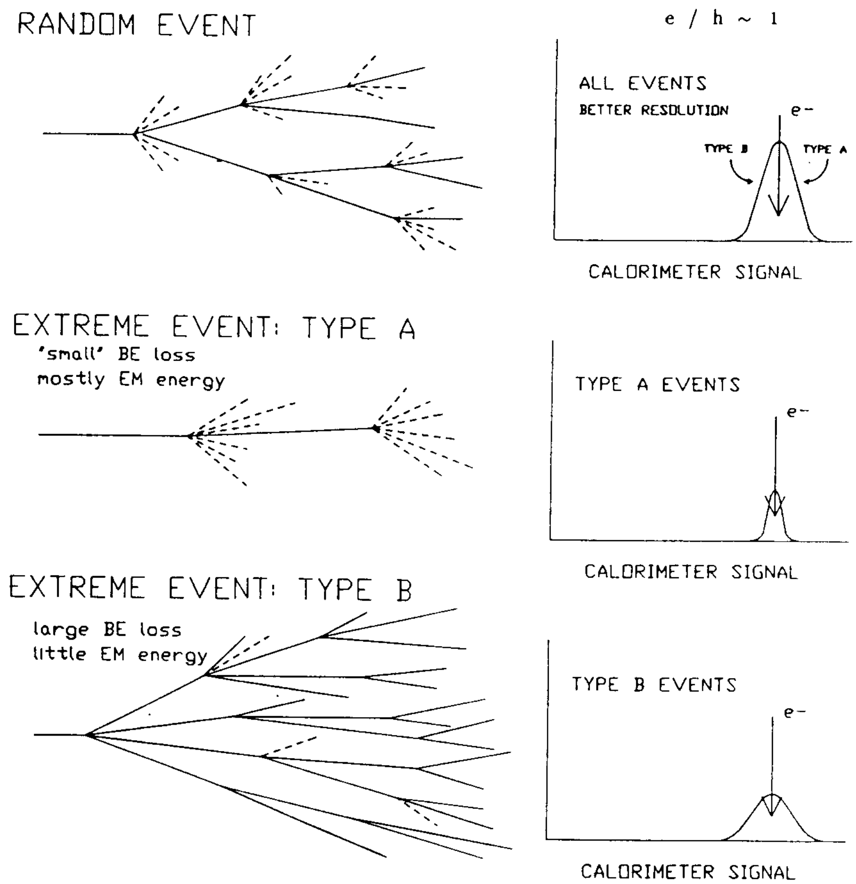
- Illustration of fluctuations in energy measurement



In order to achieve optimal resolution, one needs to equalize the response of type A and type B events

Hadronic Showers: Resolution

- Illustration of fluctuations for calorimeter with equalized response



This is referred to as <u>compensation</u>.
Also notice that e / h = 1.

Hadronic Showers: Compensation

Compensation

- A dominant factor in the resolution of a hadron calorimeter is the unequal response to electromagnetic energy deposition and hadronic energy deposition
  - the fluctuations in the proportion of energy deposited from either harms resolution
- one can reduce this fluctuation by equalizing the electromagnetic and hadronic response:

$$e / h = 1$$

Compensation: Approaches

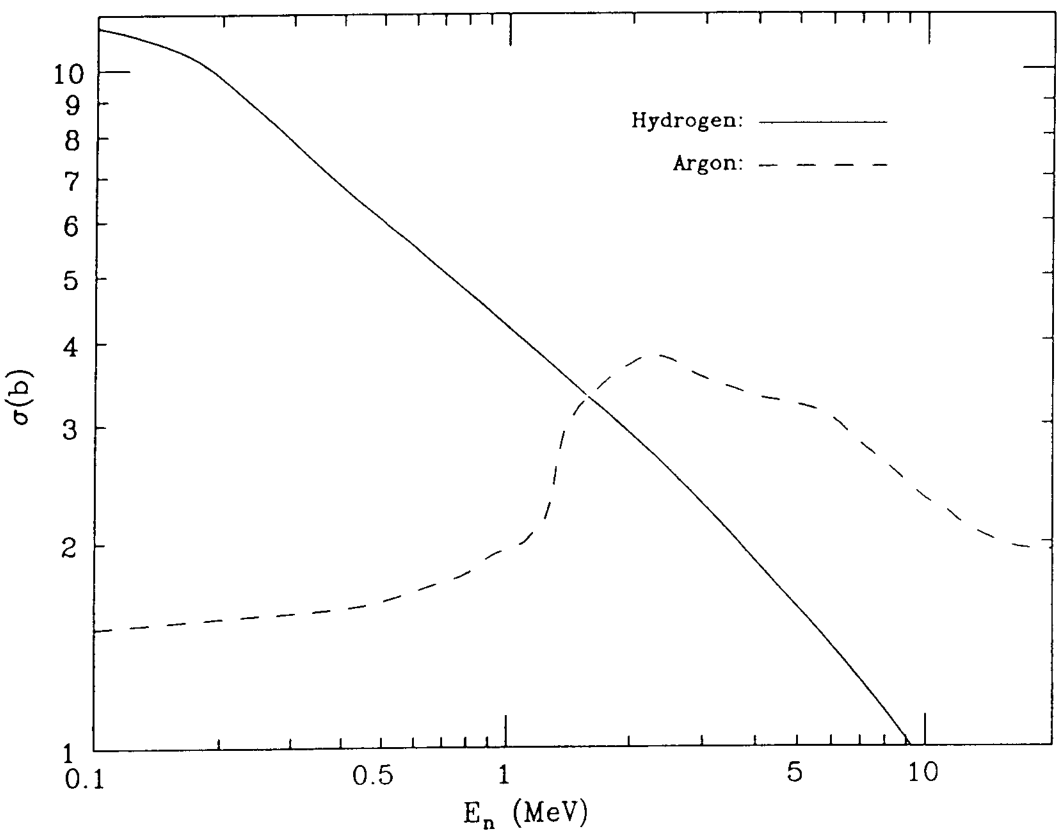
- The electromagnetic and non-electromagnetic components of the hadronic shower can be equalized in response with a variety of techniques (Willis, 1995):
  - Amplify the nuclear signal
    - amplify the nuclear energy itself
    - favor the nuclear signal in sampling
  - Attenuate the EM signal
  - Measure the hadronic/EM ratio in each event and correct
    - by spatial character
    - by temporal character
    - by differential response of two detectors

Hadronic Calorimetry: Compensation

- Uranium/Scintillator Calorimeters
  - Electromagnetic Sampling inefficiencies reduce the EM response
  - Neutron response in the scintillator recovers the binding energy losses
    - WHY?
    - Recall the neutrons carry energy which is proportional to the binding energy losses
    - Neutrons preferentially scatter off hydrogen, and transfer a lot of energy to hydrogen when they scatter. (see next transparency)

Uranium/Scintillator Calorimeters (cont.)

- 1. The nuclear scattering cross sections in hyrdogen and argon

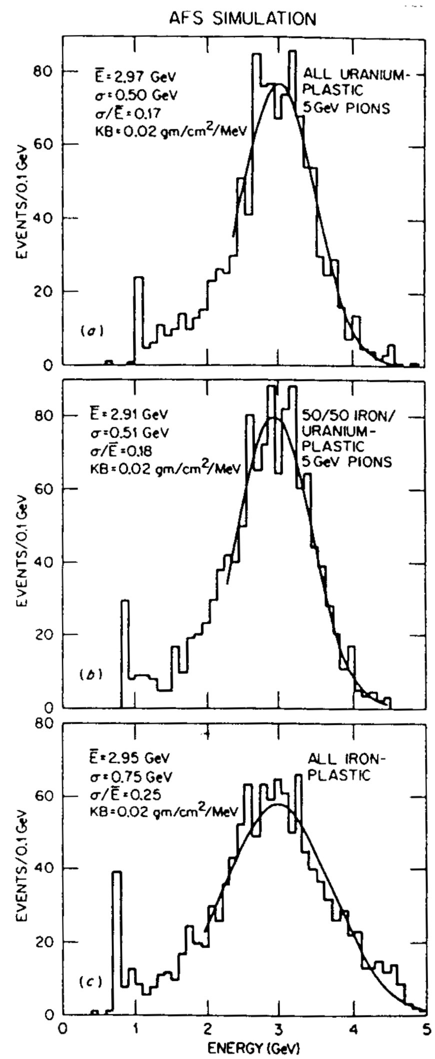


2. The max recoil energy for non-rel neutron:

$$E_{Rmax} = 4A\,E_n / (1+A)^2$$

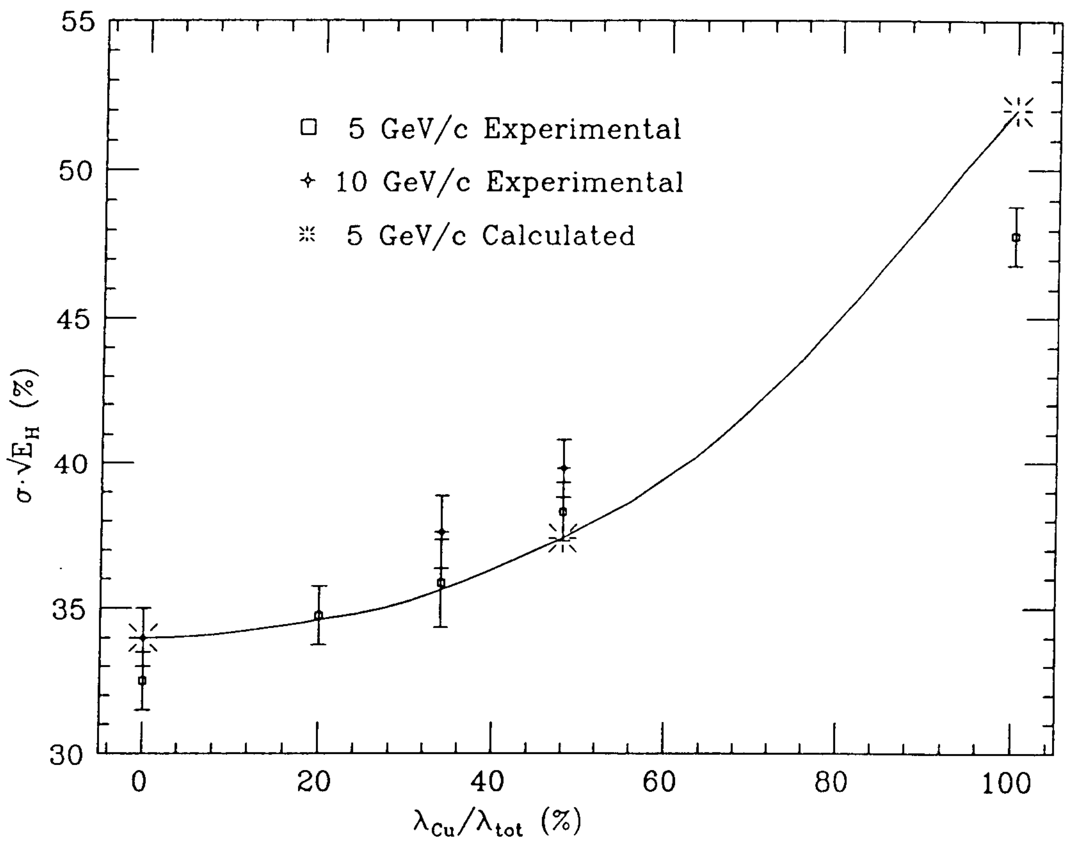
The Original U/Scintillator Compensating Calorimeter (AFS)

- Simulation confirmed the importance of (NIM A238, 489 (1985).):
  - electromagnetic sampling inefficienies
  - neutron detection



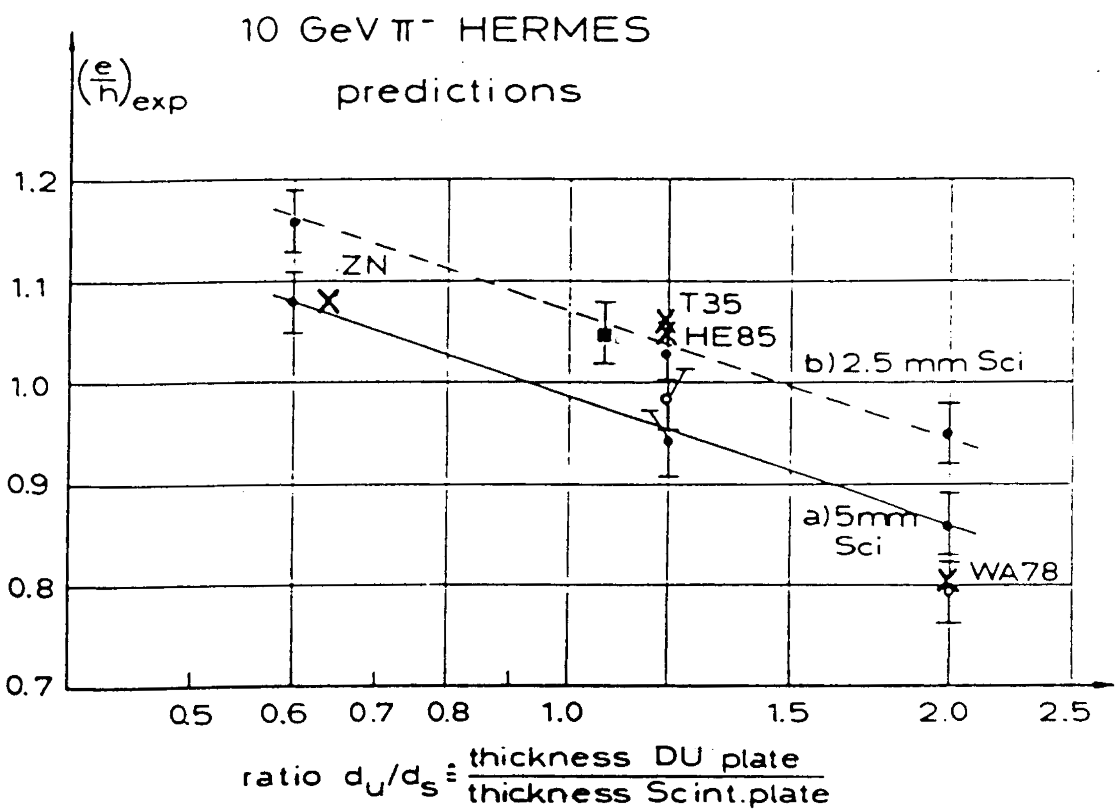
The Original U/Scintillator Compensating Calorimeter (AFS)

AFS made measurements with several mixtures of Cu and U and the simulations (NIM A238, 489 (1985).) reproduced them well



Compensating Calorimetry: Uranium/Scintillator

- The mix of uranium and scintillator must be just right to achieve the compensation condition (e/h = 1).

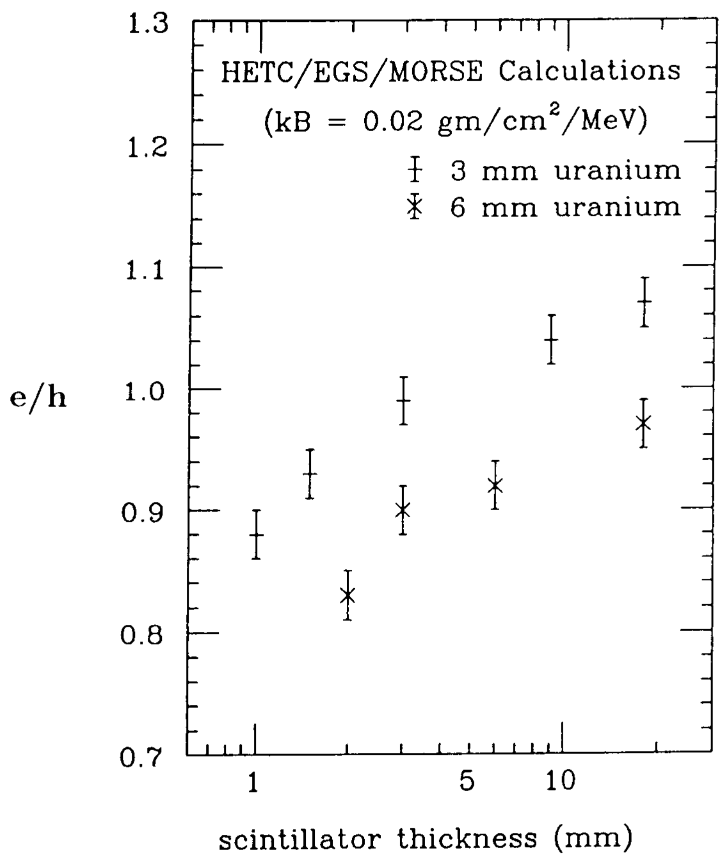


This was discovered by H. Bruckmann

(Caltech Workshop, 1985, CALT-68-1305)

Compensating Calorimetry: Uranium/Scintillator

- Calculations

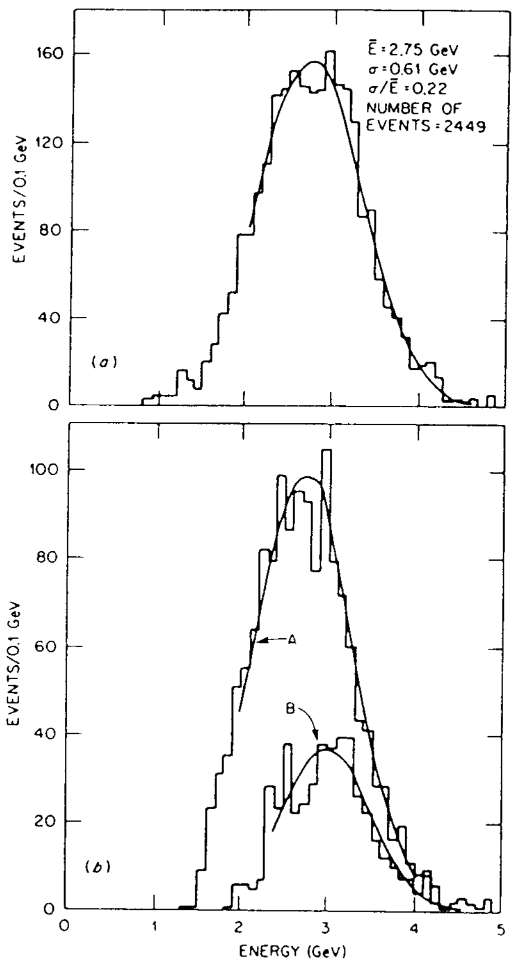


Uranium-Liquid Argon

- Uranium-Liquid Argon does not achieve full compensation:
  - the electromagnetic sampling inefficiency does reduce the electron signal
  - neutron signal is not amplified
    - neutron cross sections are small
    - maximum energy transfer is small
    - high density energy deposition is saturated
  - Partial Compensation

Uranium-Liquid Argon Simulations

HEXAGONAL URANIUM-IRON-LIQUID ARGON CALORIMETER
5 GeV PROTONS

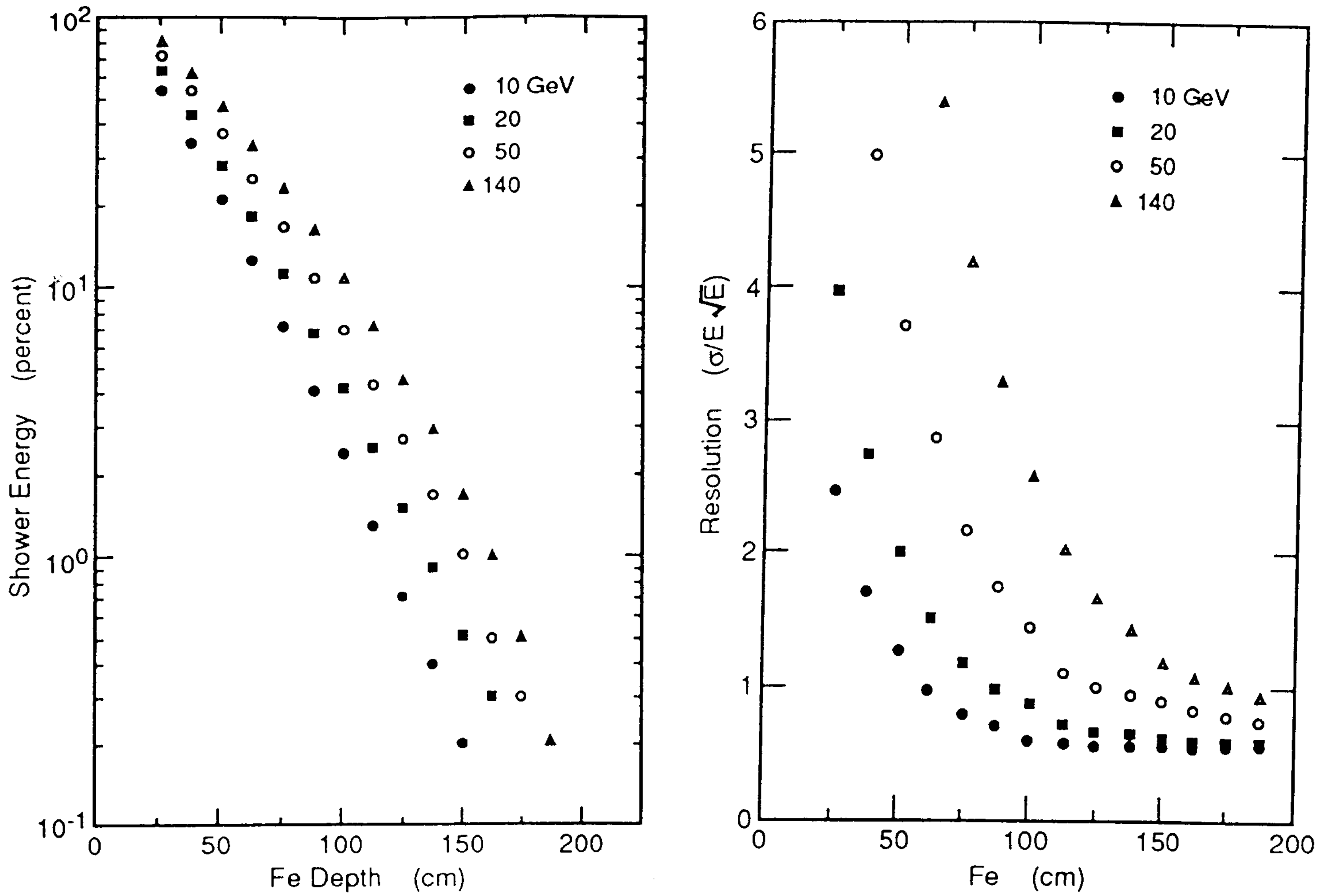


A- FIRST INTERACTION IN MODULE A
Ē = 2.71 GeV, σ = 0.57 GeV, σ/Ē = 0.21
NUMBER OF EVENTS = 1425

B- FIRST INTERACTION IN MODULE B
Ē = 3.00 GeV, σ = 0.50 GeV, σ/Ē = 0.16
NUMBER OF EVENTS = 462

Hadron Calorimeters: Leakage and Tail Catchers

E. Hughes



Particle Identification with Calorimetry

Different particles interact differently in the calorimeter

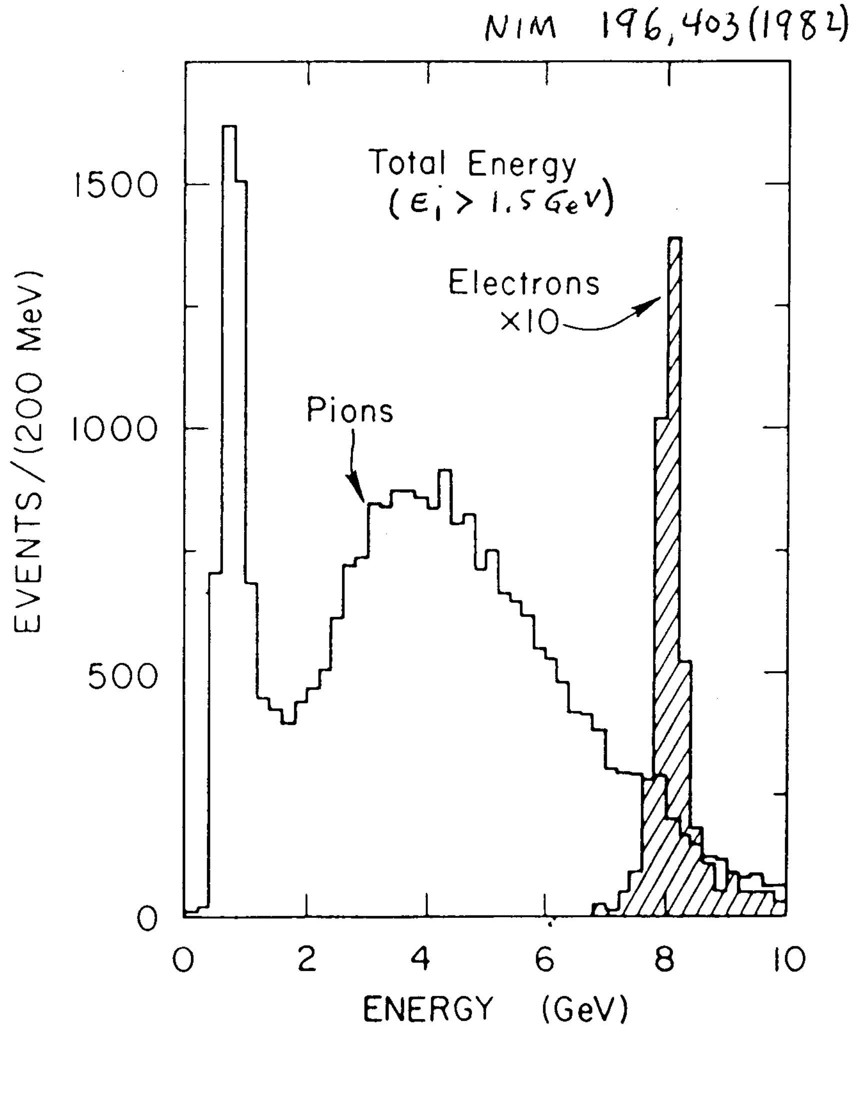
- Electron identification
  - identified by early shower (EM)
  - background from charge exchange
    - π^- N -> π^0 X early in calorimeter
    - discrimination of 100-1000
- Photon identification
  - EM shower with charged track entering
  - background from meson decays to photons
- Muons
  - isolated, min-I tracks
  - punchthrough
- Neutrinos
  - missing energy

Particle Identification with Calorimetry (Electrons)

- Electrons can be identified by discriminating <u>against</u> hadronic showers:
  - match momentum measurement with energy measurement (E/p)
  - transverse shower limited to few Moliere radii
  - energy in calorimeter starts early (in few radiation lengths)
  - energy in calorimeter ends early (~20 radiation lengths) - little leakage (no hadronic energy)
  - pulse height of shower large near shower max

Electron Identification with Calorimetry

Pb-glass at SLAC Hybrid Facility



Add position and shape cuts

π^- reject.	e^- accept
1.5×10^{-3}	82%
1.5×10^{-4}	50%

Trigger

- Calorimeters often provide a significant trigger input:
  - fast
  - inclusive or exclusive
  - low backgrounds with thresholds

- Example: SLD

Simulations Tools

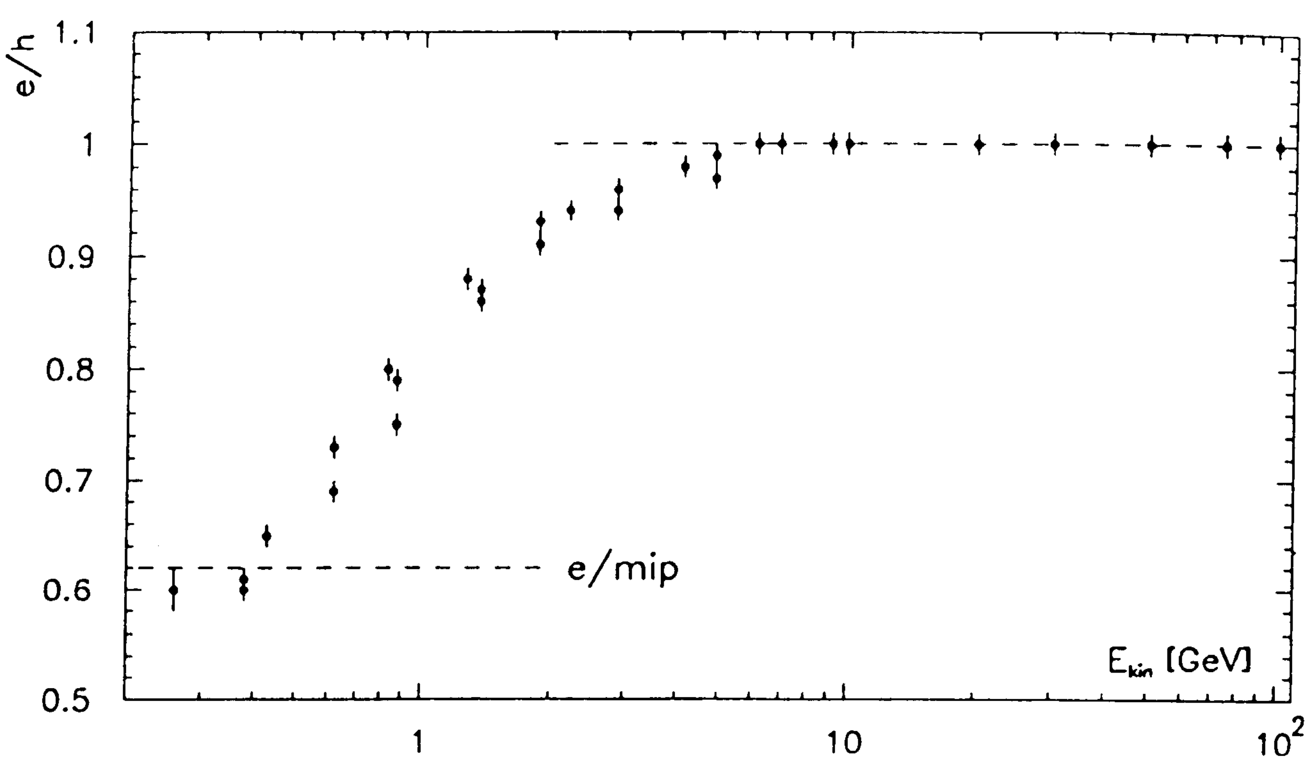
- Electromagnetic Showers
  - EGS
    - W.R. Nelson, H. Hirayama, and D.W.O. Rogers, SLAC Report-165
  - GEANT
    - R. Brun, GEANT 3.15 Manual
- Hadronic Showers
  - CALOR
    - T.A. Gabriel et al, CALOR89, ORNL/TM-11185
  - Gheisha
    - H. Fesefeldt, The simulation of hadronic showers, PITHA 85/02 (Aachen, 1985)
  - FLUKA
    - P.A. Aarnio, FLUKA 89 Users Guide, 1990
  - GEANT
    - R. Brun, GEANT 3.15 Manual

The Calorimeters of the Collider Experiments

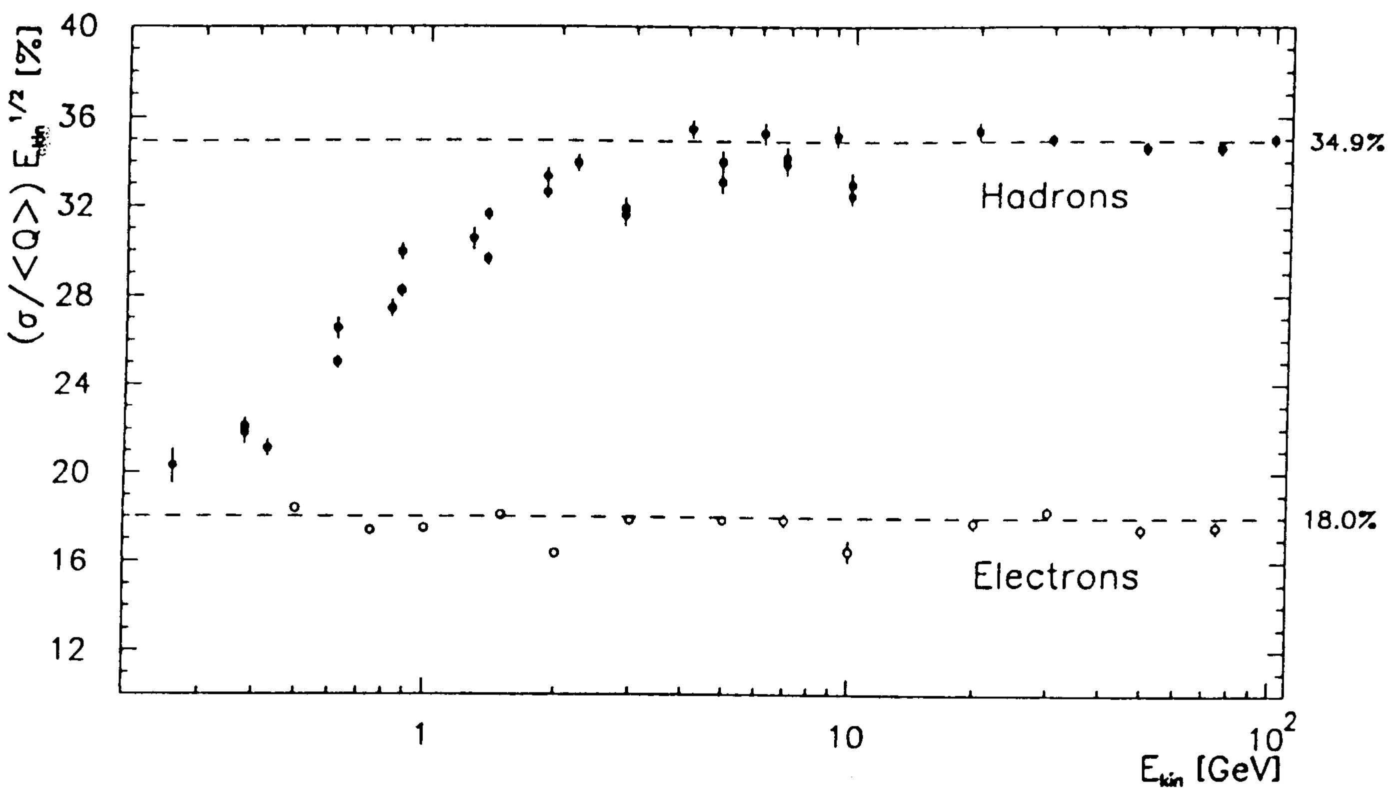
Exp.	EM cal	Had cal
SLD	Pb/LArgon	Pb/LAr + Fe/gas
ALEPH	Pb/Al tubes	Pb/plastic tubes
DELPHI	Pb/TPC	Fe/plastic tubes
L3	BGO	U/brass tubes
OPAL	Pb-glass	Fe/prop chambers
H1	Pb/LArgon	Pb/LArgon
ZEUS	U/scin	U/scin
ATLAS	Pb/LAr(acc.)	Pb/Scin
CMS	PbWO4 crystals	Cu/Scin

ZEUS Calorimeter

- Shortly after the understanding of compensation was established, ZEUS capitalized on this and built the best possible hadron calorimeter (U/Scin)



ZEUS Calorimeter



Atlas Forward Calorimeter

- Very forward region important to maintain detection of all energy in events and enable SUSY searches
- Very high radiation region
- Atlas: Liquid argon with a tungsten rod in a hole in a tungsten block

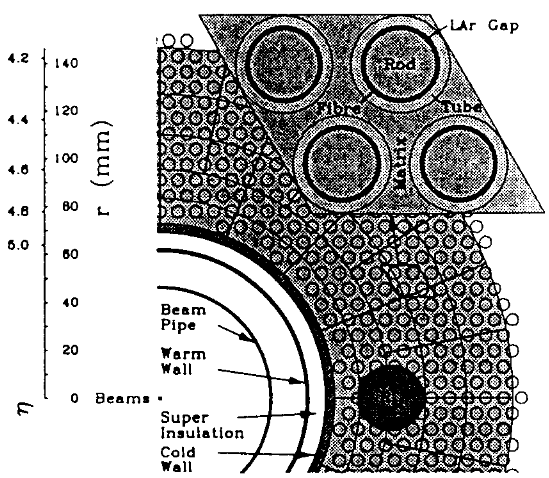
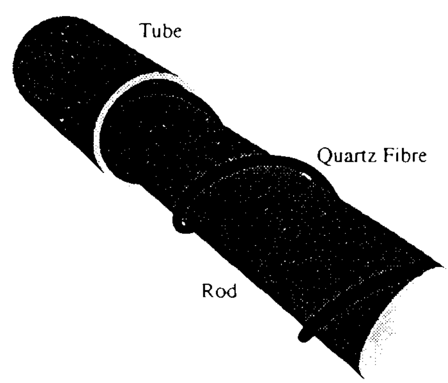
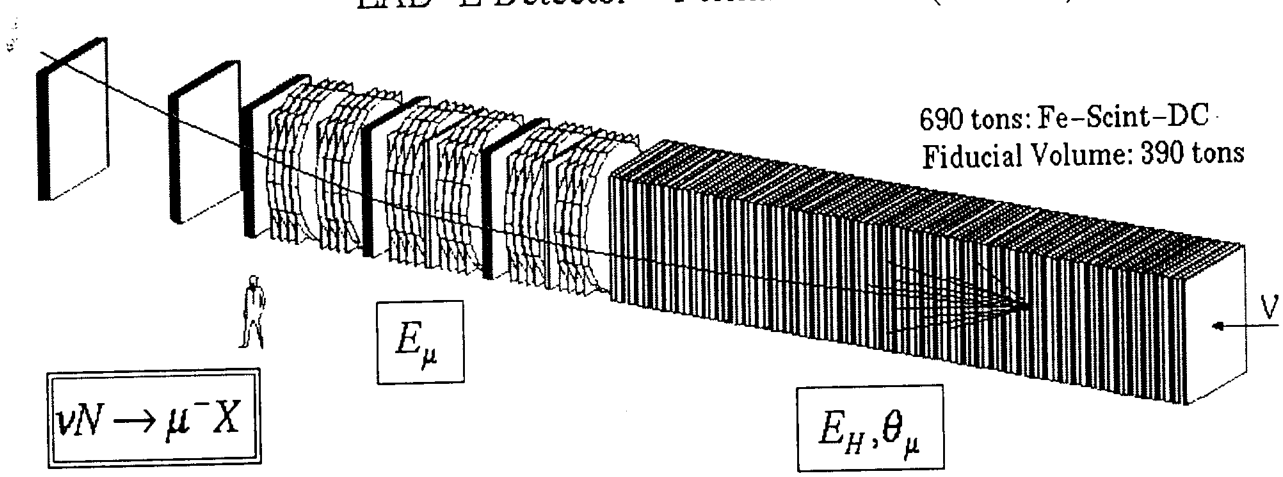


Figure 2.19: Front face of the e.m. module in the region of the beam pipe. The circle labelled R_M indicates the Molière radius for e.m. showers. The insert at the upper right shows the detail of four tube electrodes embedded in the absorber matrix.



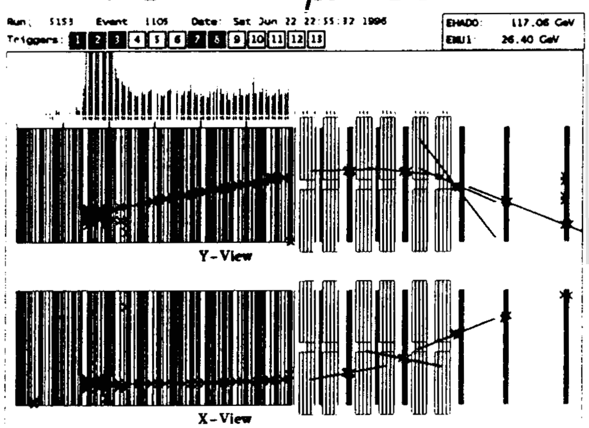
Neutrino Detector (NuTeV)

LAB-E Detector - Fermilab E815 (NuTeV)

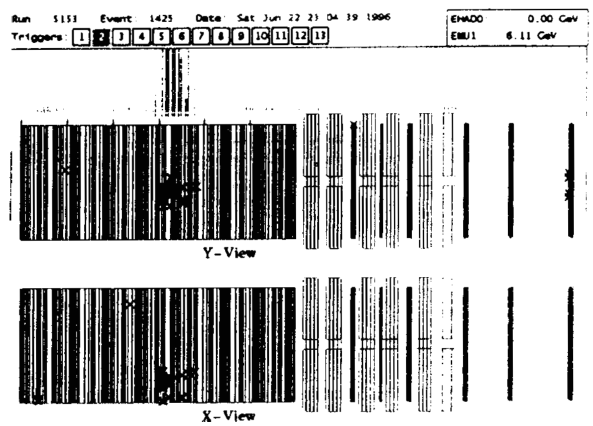


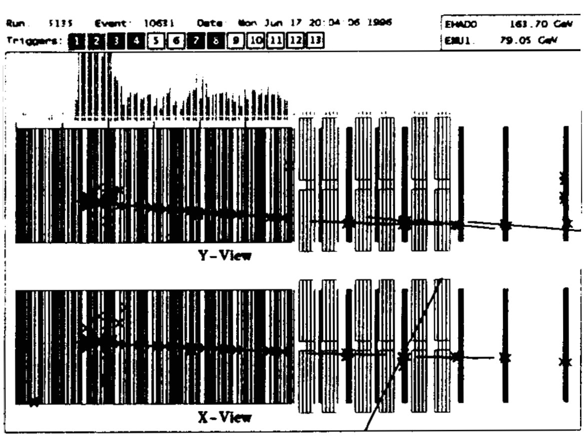
Neutrino Detector (NuTeV) (cont.)

$$\nu N \rightarrow \mu^- X$$

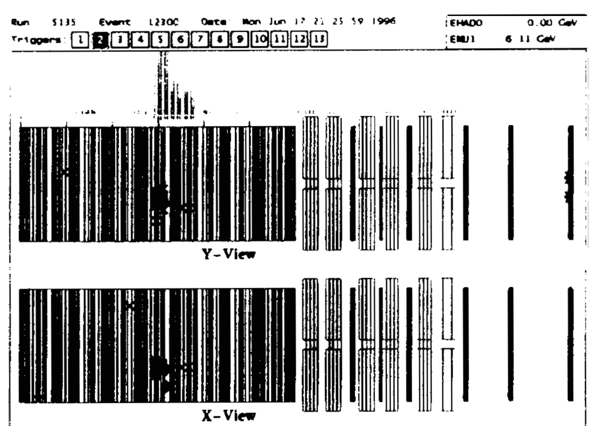


$$\nu N \rightarrow \nu X$$





$$\overline{\nu} N \rightarrow \mu^+ X$$

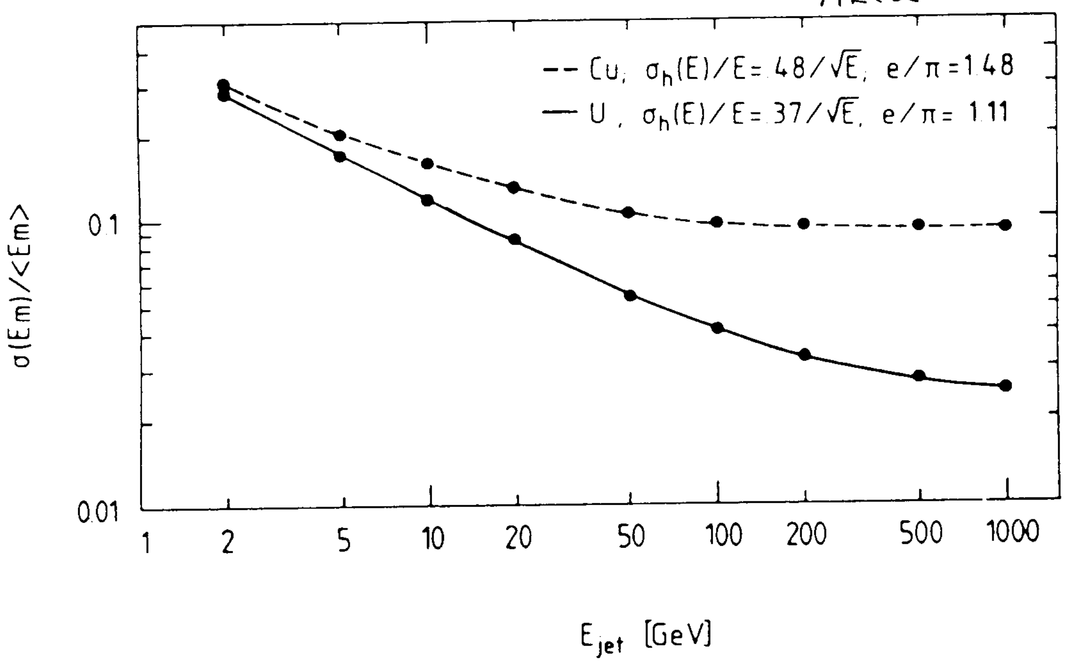


$$\overline{\nu} N \rightarrow \overline{\nu} X$$

Jet Resolution

- Just as with single particles, achieving e/h ~ 1 is important for jets:

Akesson et al



Summary

- In these two lectures we have only scratched the surface on calorimetry in high energy physics.
- It is still an advancing field, despite the significant advances in recent years.
- Many publications report new ideas and tests (see the series of International Conference on Calorimetry in High Energy Physics, for example).

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