SLUO LECTURE SERIES

Calorimetry I

LECTURE # 13

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SLUO Detector Techniques Series

Introduction

- Calorimeters are used to measure energy of neutral and charged particles
  - neutral particles cannot be momentum analyzed
  - electrons can be measured with better precision, and identified with a calorimeter
  - as energy increases
    - momentum measurements are less precise [$\sigma_p/p \sim p$]
    - energy measurements become more precise [$\sigma_E/E \sim 1/E^{1/2}$]
  - jets are often best measured by total absorption rather than measurement of individual particles

Introduction (cont.)

- Fundamental underlying principle: conservation of energy
  - convert energy of incident particle to detector response
    - ionization
    - Cerenkov radiation from charged particles
    - scintillation of excited molecules
    - acoustic energy
    - ....
- Details of this conversion complicate measurement
  - this is especially true for strongly interacting particles (hadrons)

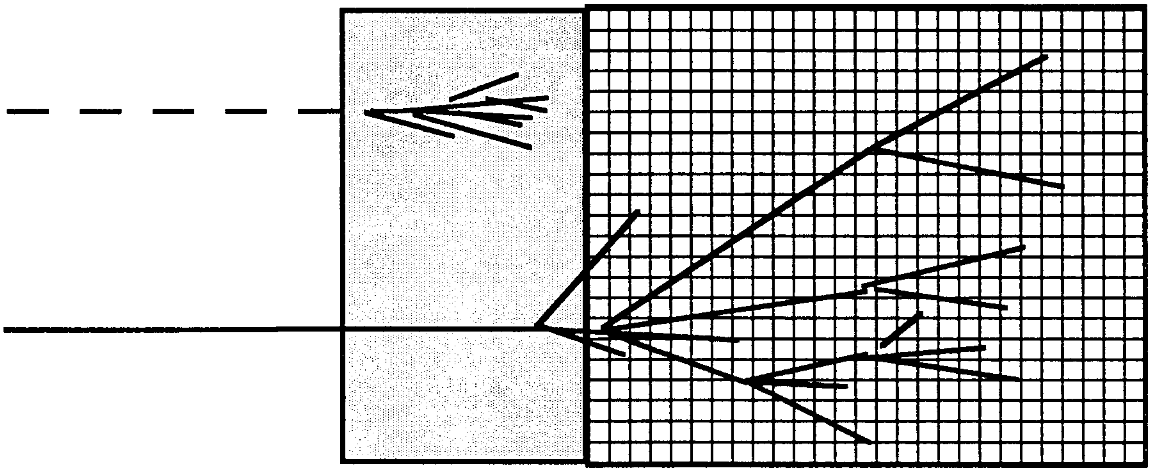
Outline

- Introduction
  - examples of important applications
- Electromagnetic showers
  - fundamental processes
  - characteristics of showers
- Electromagnetic Calorimeters
  - resolution
  - examples of calorimeters

- Next week: Hadron Calorimetry

EM and Hadronic Sub-detectors

- Calorimeters are subdivided into electromagnetic and hadronic sub-detectors
  - Electromagnetic interactions develop over shorter distances than hadronic interactions
  - Fundamental processes of signal generation differ, calling on different optimization



Evolution of Calorimeters

- Nuclear Physics
  - the advances of solid state detectors in the '50s broadened the technique of total absorption and energy measurement of nuclear radiation
- Cosmic Rays
  - 1958 - JETP 7, 348 (1958)

  Grigorov, Murzin and Rapoport

  report construction of first sampling calorimeter
- Particle Physics
  - First electromagnetic calorimeters, eventually hadronic calorimeters became essential components

Evolution of Calorimeters (cont.)

- Uranium/Compensation
  - in an effort to advance energy resolution, Willis et al introduced uranium calorimeters (1975) to "compensate" for the lost energy in nuclear collisions.
  - Zeus took the emerging understanding of the underlying mechanisms in hadronic showers to build the best hadronic calorimeter to date, uranium - scintillator
- High Precision Electromagnetic Calorimetry
  - Crystals have continued to advance
  - Other techniques, as well, are pushing the performance limits
    - e.g.. accordion liquid argon
    - scintillating fiber calorimeters

Evolution of Calorimeters (cont.)

- Today, calorimeters are in widespread use in particle physics
  - 4π detectors at colliders
    - energy measurements
    - particle identification
    - triggers
  - neutrino detectors at accelerators
  - underground proton decay detectors
  - underground neutrino detectors
- and in astrophysics
  - space-based detectors (--GLAST)
  - air showers

Examples of Calorimetry in Discovery

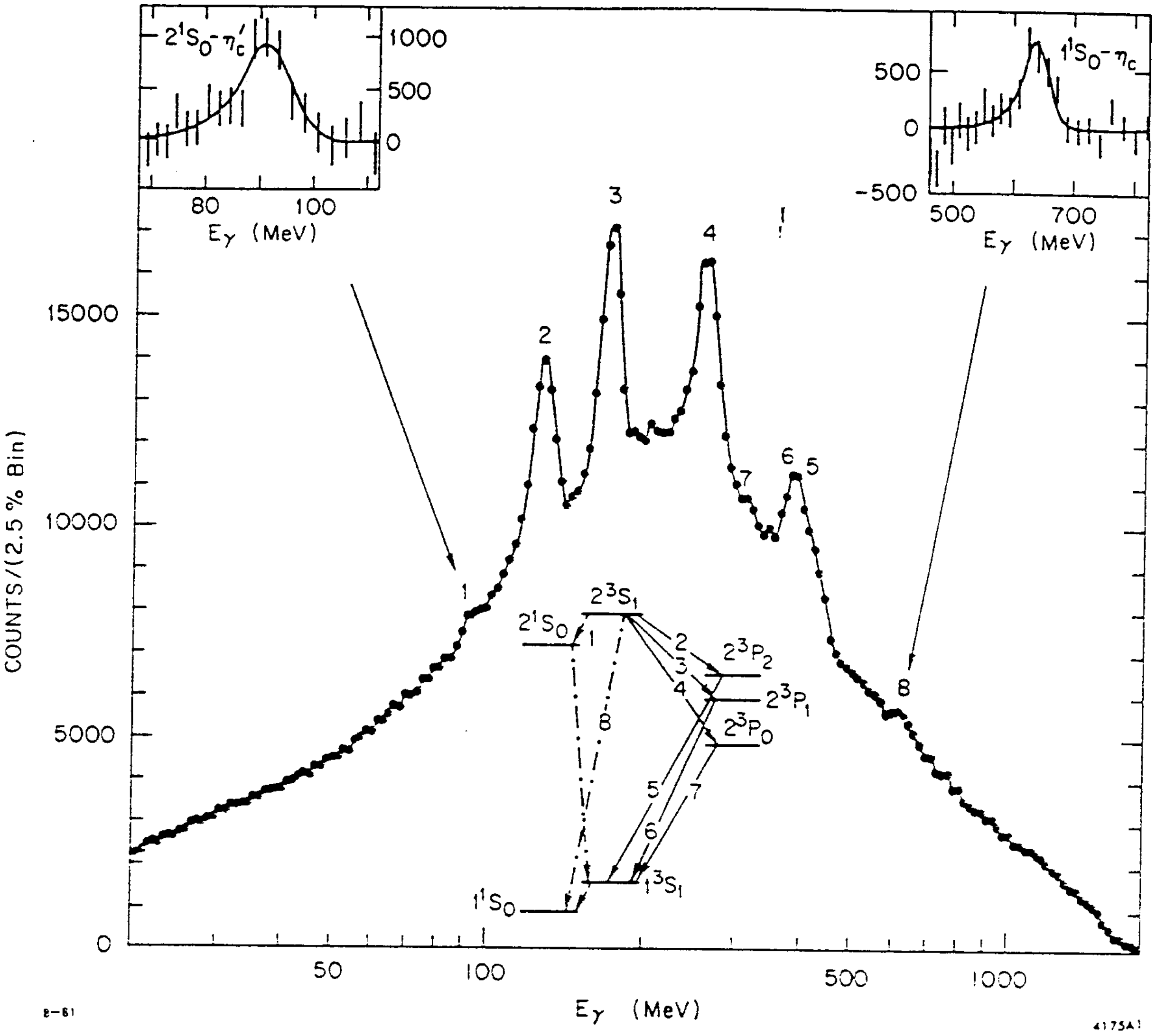
- Discovery of the anti-proton
  - Total absorption lead glass detector used to identify anti-proton annihilations.
- Discovery of the τ
  - Detection of electron-muon + missing energy events identified.
- Charm Spectroscopy
  - The radiative lines were studied in charmonium. (see figure)
- Discovery of the W
  - High transverse energy electron was detected and measured, and the recoiling neutrino was deduced and shown to balance the electron. (see figure)

Examples of Calorimetry in Discovery (cont.)

- Measurement of A_{LR}
  - The SLD Calorimeter provides the primary instrument for triggering and event tagging.
- W mass measurement
  - Di-jet events are reconstructed .
- e+e- -> γ + missing energy
  - Measurements of EM showers, combined with missing energy in the hadron calorimeter. (see figure)
- Higgs -> $\gamma\gamma$ (future?)
  - The preferred channel for discovery at LHC has an enormous background; high precision is demanded. (see figure)

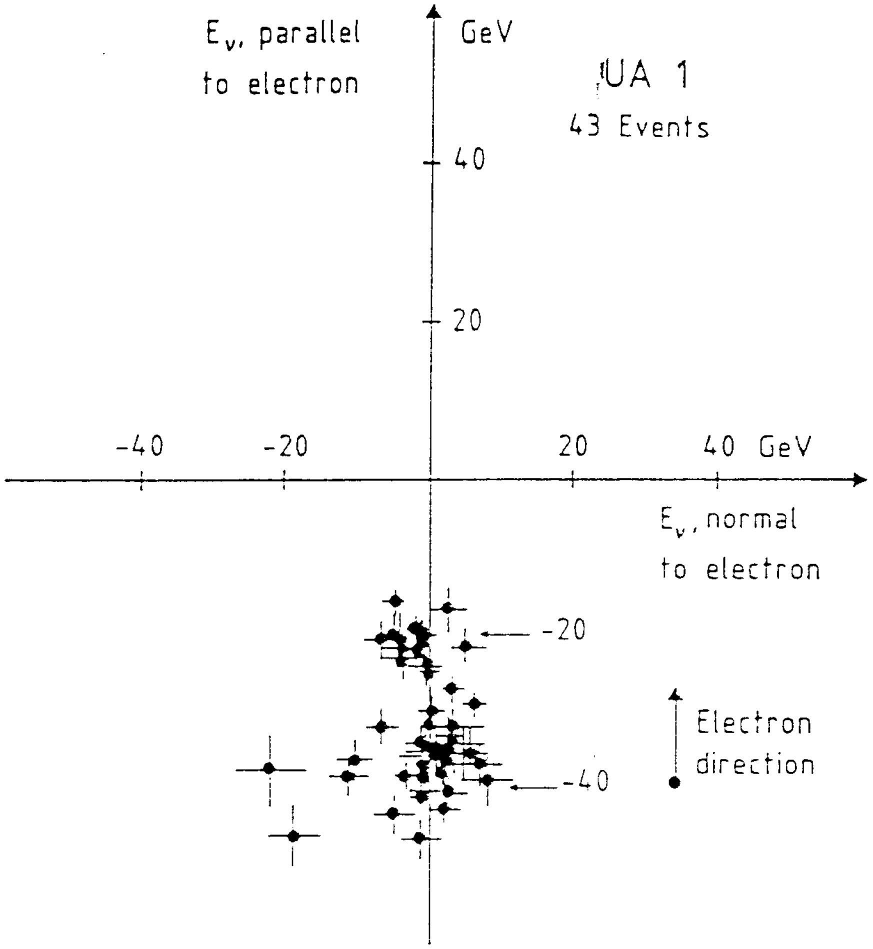
Charm Spectroscopy

- The Crystal Ball



Discovery of the W

- High transverse energy electron was detected and measured, and the recoiling neutrino was deduced and shown to balance the electron

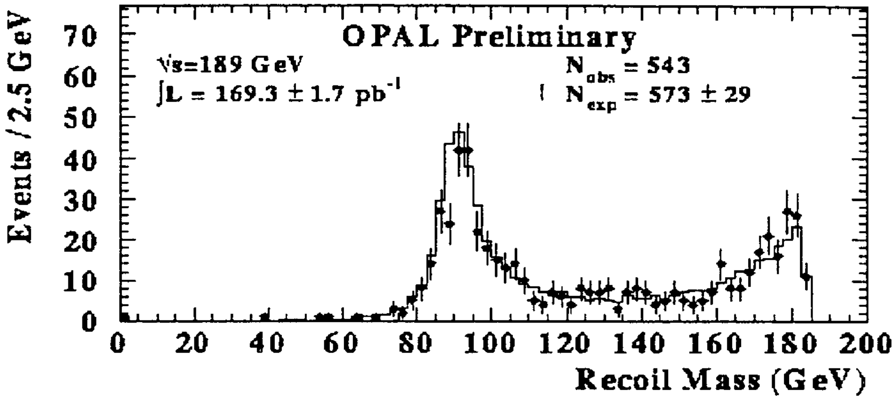


e+e- -> γ + missing energy

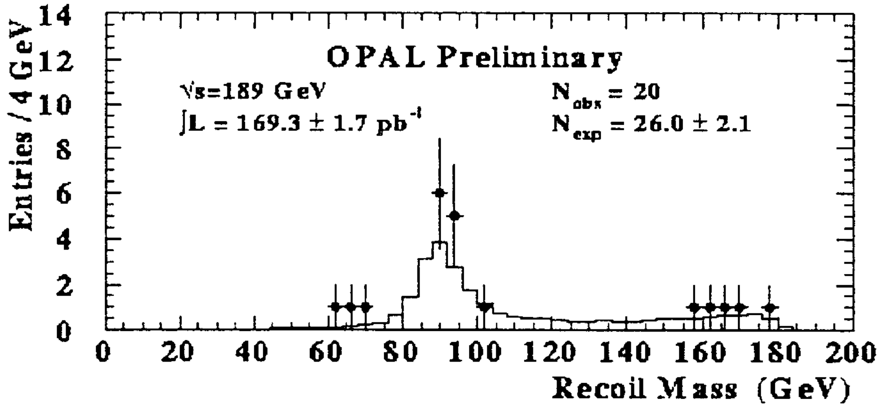
Photonic events with missing E_T

- Standard Model measurement $e^+e^- \to \nu\bar{\nu}\gamma(\gamma)$
- New physics : $\tilde{\chi}^0_2\tilde{\chi}^0_2$ ($\tilde{\chi}^0_1$ LSP), $\tilde{\chi}^0_1\tilde{\chi}^0_1$ (light $\tilde{G}$ LSP), $\nu^*\bar{\nu}^*$

Single photon recoil mass

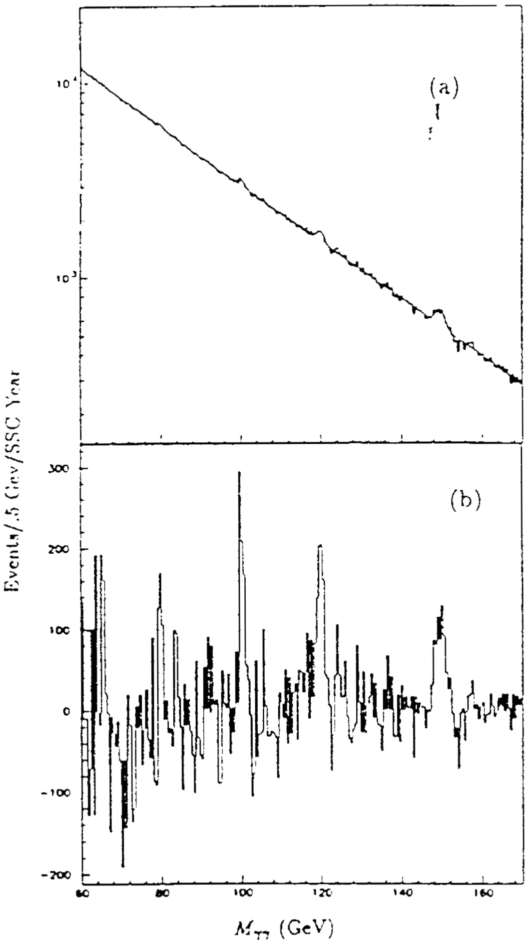


Acoplanar photons recoil mass



Higgs -> $\gamma\,\gamma$ at the LHC

- Outstanding EM resolution is needed to discover the Higgs -> $\gamma\,\gamma$ at a hadron collider (LHC)



Ideal Calorimeter

- excellent energy resolution
- stable calibration
- excellent position resolution
- large dynamic range
- excellent shower containment with multi-shower separation
- compact
- fast (high rate capability)
- operates in a magnetic field
- inexpensive
- robust

Compromise is always required

Electromagnetic and Hadronic Showers

- Electromagnetic
  - multiplication through pair production and bremsstrahlung
  - mean free path
    $9X_0/7$ for γ
    $X_0/\ln(E/k)$ for e
  - no invisible energy

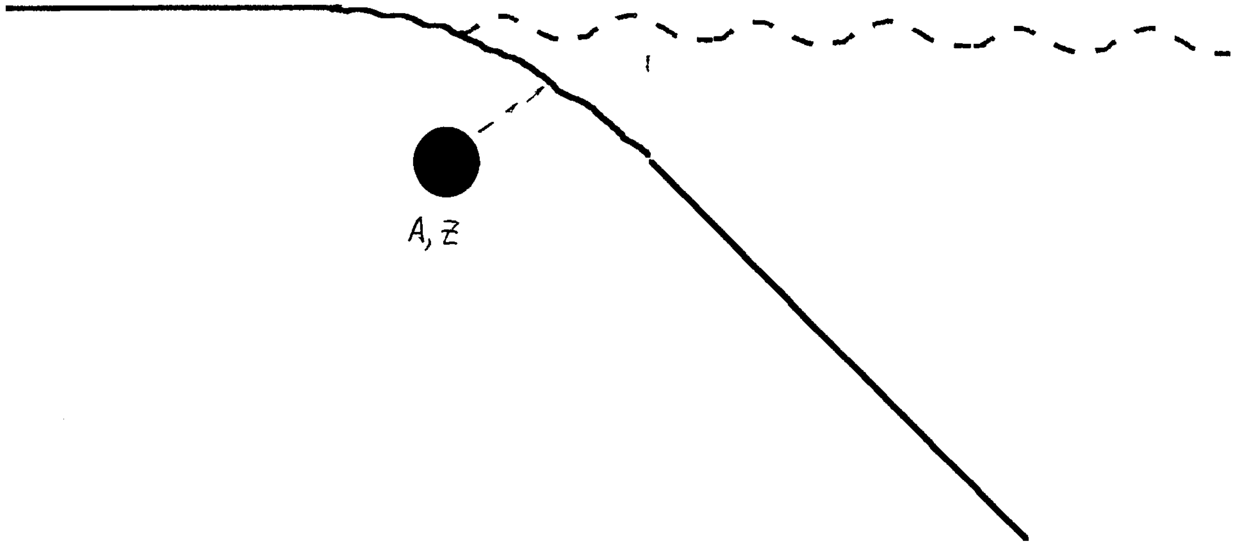
- Hadronic
  - multiplication through multiparticle production in nuclear interactions
  - mean free path
    $\sim \lambda$
  - nuclear binding energy and neutrinos invisible

Electromagnetic Showers

- In matter high energy electrons and photons interact primarily through electromagnetic interactions with the nucleus (and at lower energies with the atomic electrons)
- Electrons
  - Bremsstrahlung (nuclear)
- Photons
  - Compton scattering (atomic electrons)
  - pair production (nuclear)
  - photoelectric effect (atomic electrons)

Electromagnetic Showers: Electrons

- Bremsstrahlung

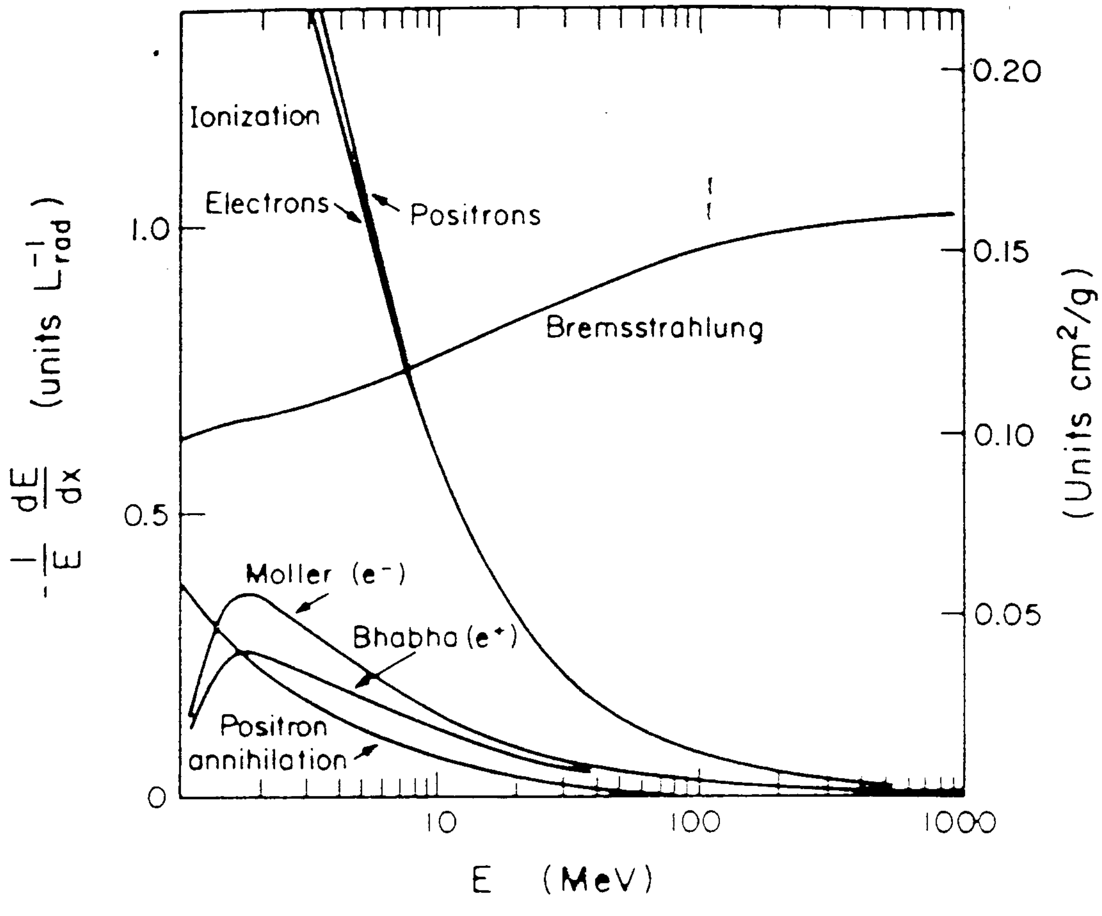


$$dE/dx|_{\text{brems}} \cong E/X_0$$

$$X_0 \sim \frac{716\ \text{gm cm}^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

Electromagnetic Showers: Electrons (cont.)

- Electron energy loss



Electromagnetic Showers: Electrons (cont.)

- Critical Energy (E_c)

At high energy, the energy loss of an electron from bremsstrahlung dominates over ionization loss.

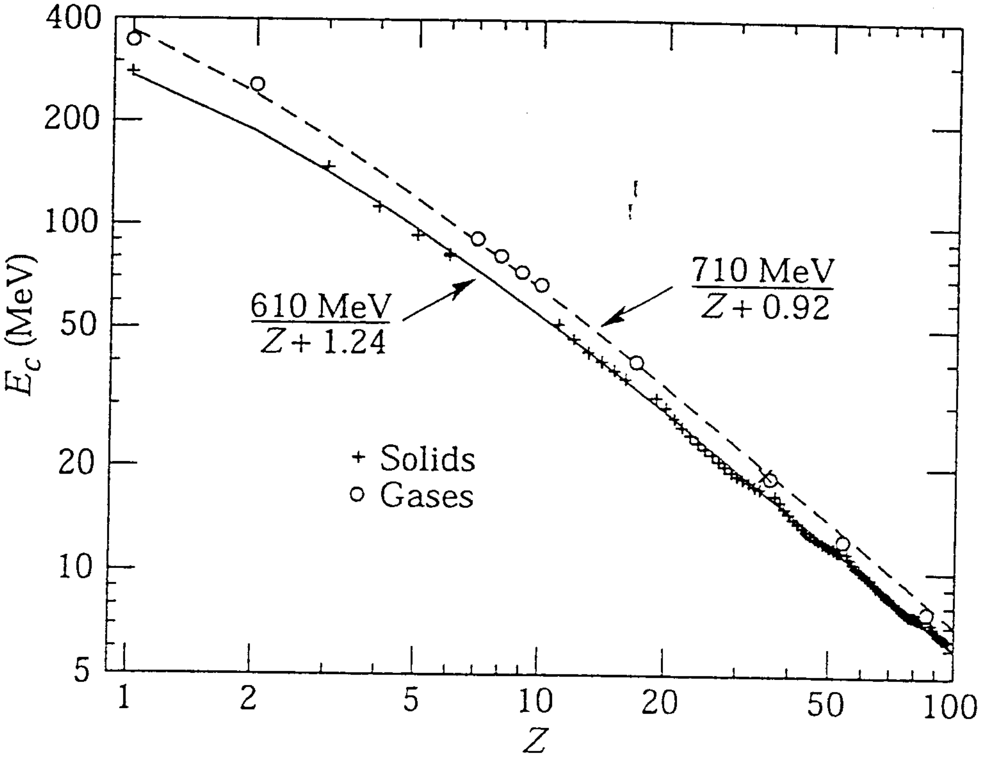
At a low enough energy, the ionization loss becomes important.

The energy at which ionization loss equals bremsstrahlung loss, is the critical energy (E_c)

(eg. $E_c \sim 7$ MeV for Lead -
see last and next transparencies)

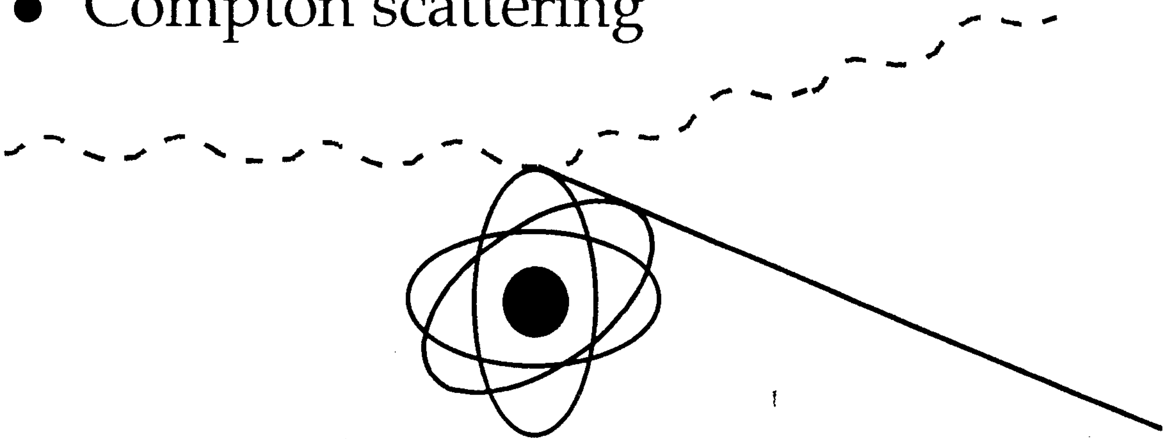
Electromagnetic Showers: Electrons (cont.)

- Critical energies of materials

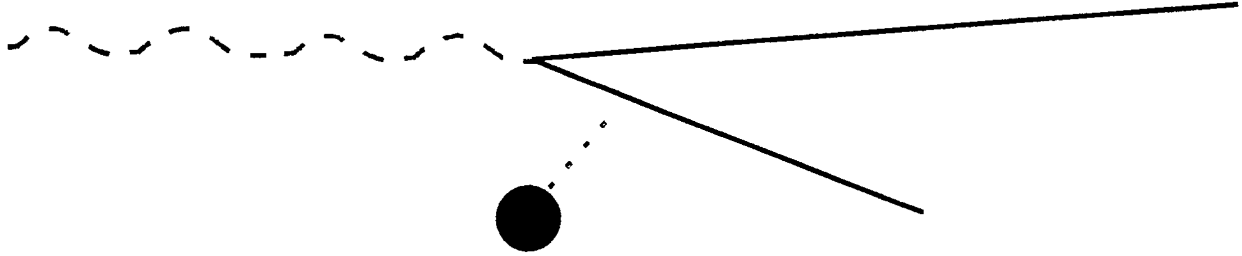


Electromagnetic Showers: Photons

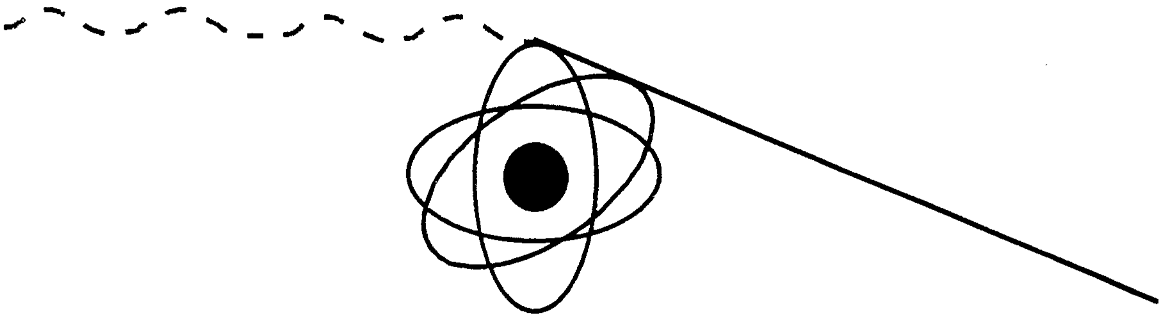
- Compton scattering



- pair production

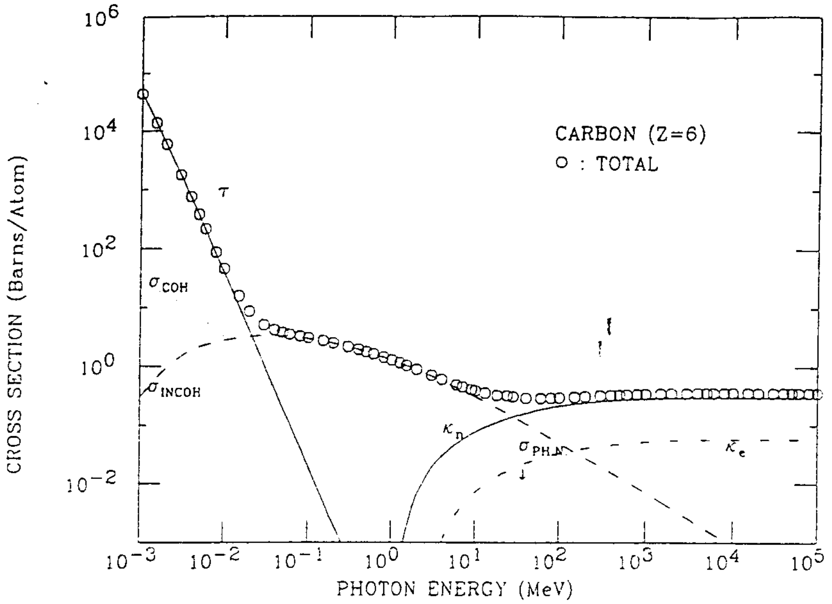


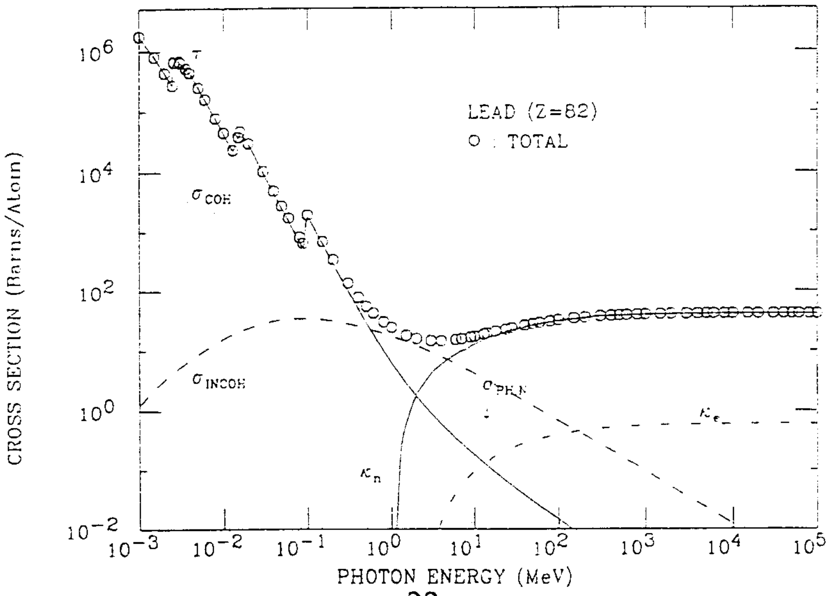
- photoelectric effect



Electromagnetic Showers: Photons (cont.)

Photon cross sections





Electromagnetic Showers

Many important properties of an EM shower can be understood by a simple model:

- after one radiation length a photon produces an $e^- e^+$ pair
- the electron and positron each emit one bremsstrhalung photon after another radiation length.

➔ This sequence leads to a cascading number of particles (N), which is

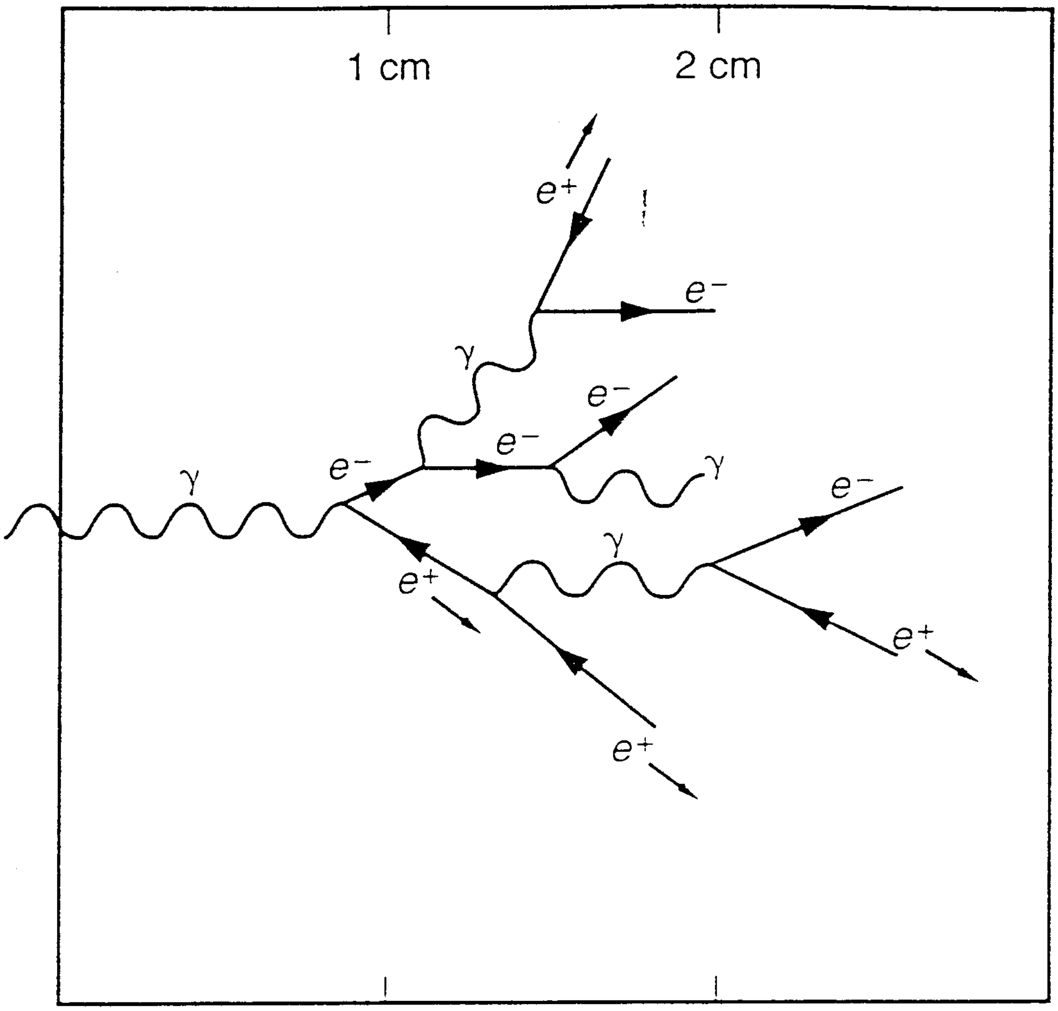
$$N(t) = 2^{t} \quad \text{(for t steps)}$$

➔ and each particle has an energy (E)

$$E(t) = E_0 / 2^{t}$$

Electromagnetic Showers

Illustration of simple model of shower



Electromagnetic Showers

- Longitudinal development scales with the radiation length (X_0)

  $X_0 \cong 180\ A / Z^2\ \mathrm{g/cm^2}$

  (higher Z materials have shorter radiation lengths)

- Transverse dimension scales with the Moliere radius (R_M)

  $R_M \cong 21\ \mathrm{MeV}\ X_0 / E_c$

  where $E_c \cong 550\ \mathrm{MeV} / Z$

Typical Scales for EM Calorimeters

Material	Atomic No.	Critical Energy (E_c)	Radiation Length (X_0)		Moliere Radius (R_M)
	(Z)	(MeV)	(g/cm^2)	(cm)	(cm)
Beryllium	**_4**	**116._**	**65.19**	**35.28**	**6.4**
Carbon	**_6**	**84._**	**42.70**	**18.8_**	**4.7**
Aluminum	**13**	**43._**	**24.01**	**8.9_**	**4.4**
Iron	**26**	**22._**	**13.84**	**1.76**	**1.7**
Copper	**29**	**20._**	**12.86**	**1.43**	**1.5**
Tungsten	**74**	**8.1**	**6.76**	**0.35**	**0.9**
Lead	**82**	**7.3**	**6.37**	**0.56**	**1.6**
Uranium	**92**	**6.5**	**6.00**	**0.32**	**1.0**

EM Showers: Longitudinal Development

- Electrons generate photons through bremsstrahlung and photons produce electrons and positrons through pair production
- The observed development depends on the minimum kinetic energy of an electron or a positron that can be detected (known as the cut-off energy).

This means the shower maximum will occur when the energy falls to E_c:

$$E_c = E_0 \,/\, 2^{\text{t-max}},$$

or

$$\text{t-max} \sim \ln (E_0 / E_c)$$

EM Showers: Longitudinal Development (cont.)

- Approximate formula ($t=x/X_0$):

$$dE/dt = E\, b^{\alpha+1}\, t^{\alpha}\, e^{-bt} / \Gamma(\alpha+1)$$

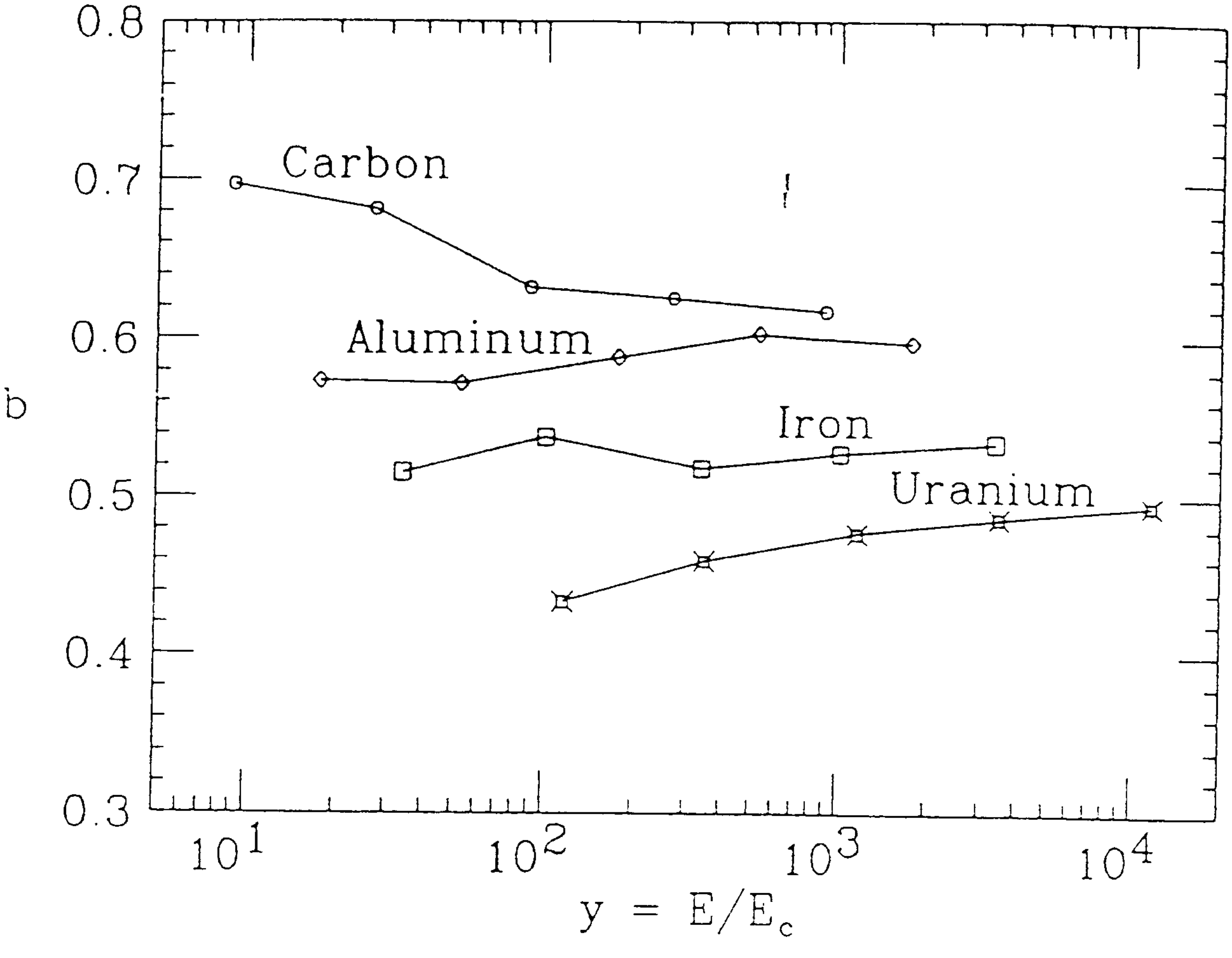
$b \sim 0.5$ (material dependent)
$\alpha = 0.5 \ln(E_0/E_c) - 1.1$
(+0.8 for γ)

so $t_{max} = \alpha / b \sim \ln(E_0/E_c)$ -

$$t_{95\%} \cong t_{max} + 0.08\, Z + 9.6$$

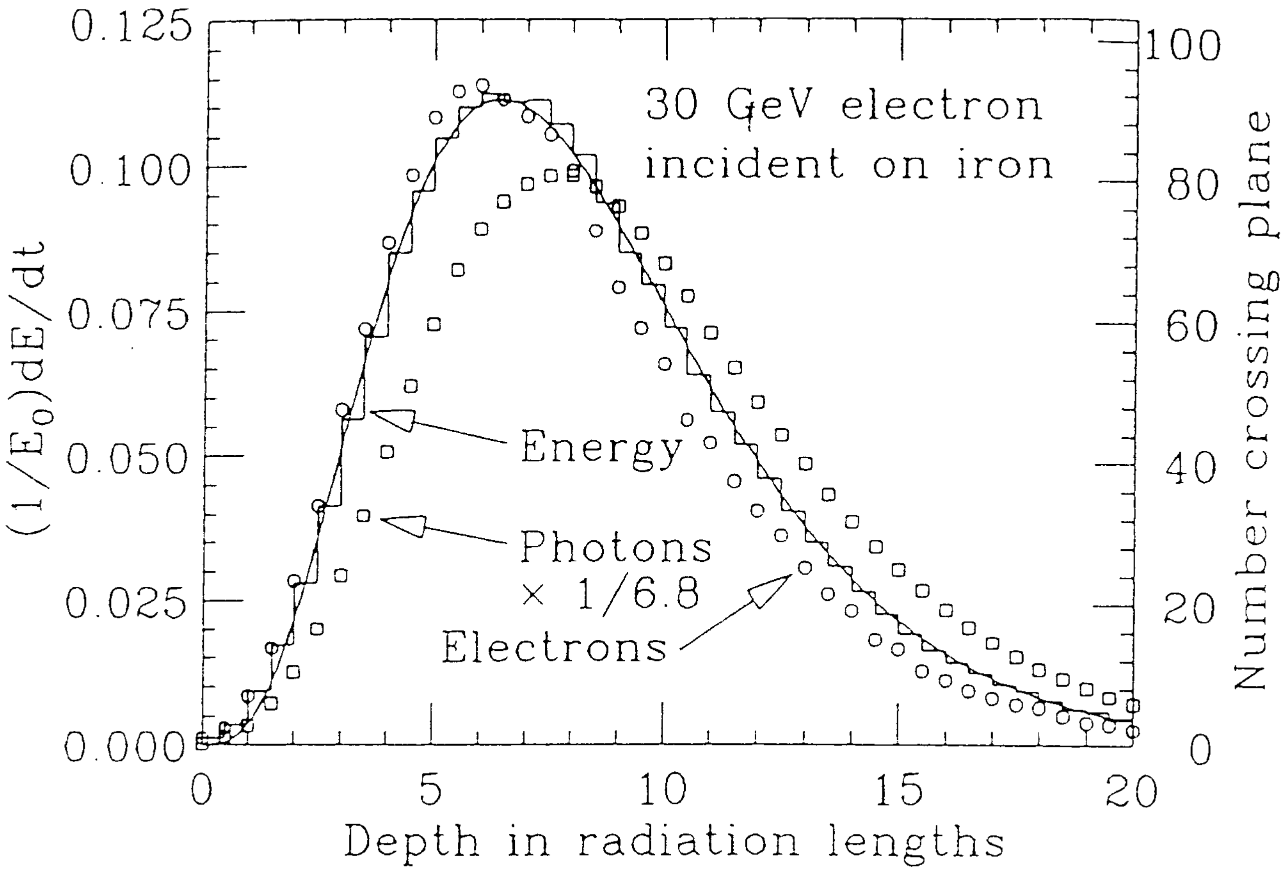
EM Showers: Longitudinal Development (cont.)

- Best fits are achieved with b adjusted for material and energy



Longitudinal development (cont.)

An example of longitudinal development (30 GeV electron induced shower in iron)



Longitudinal development (cont.)

- Effect of critical energy on longitudinal energy distribution
  - shower maximum
  - shower tail

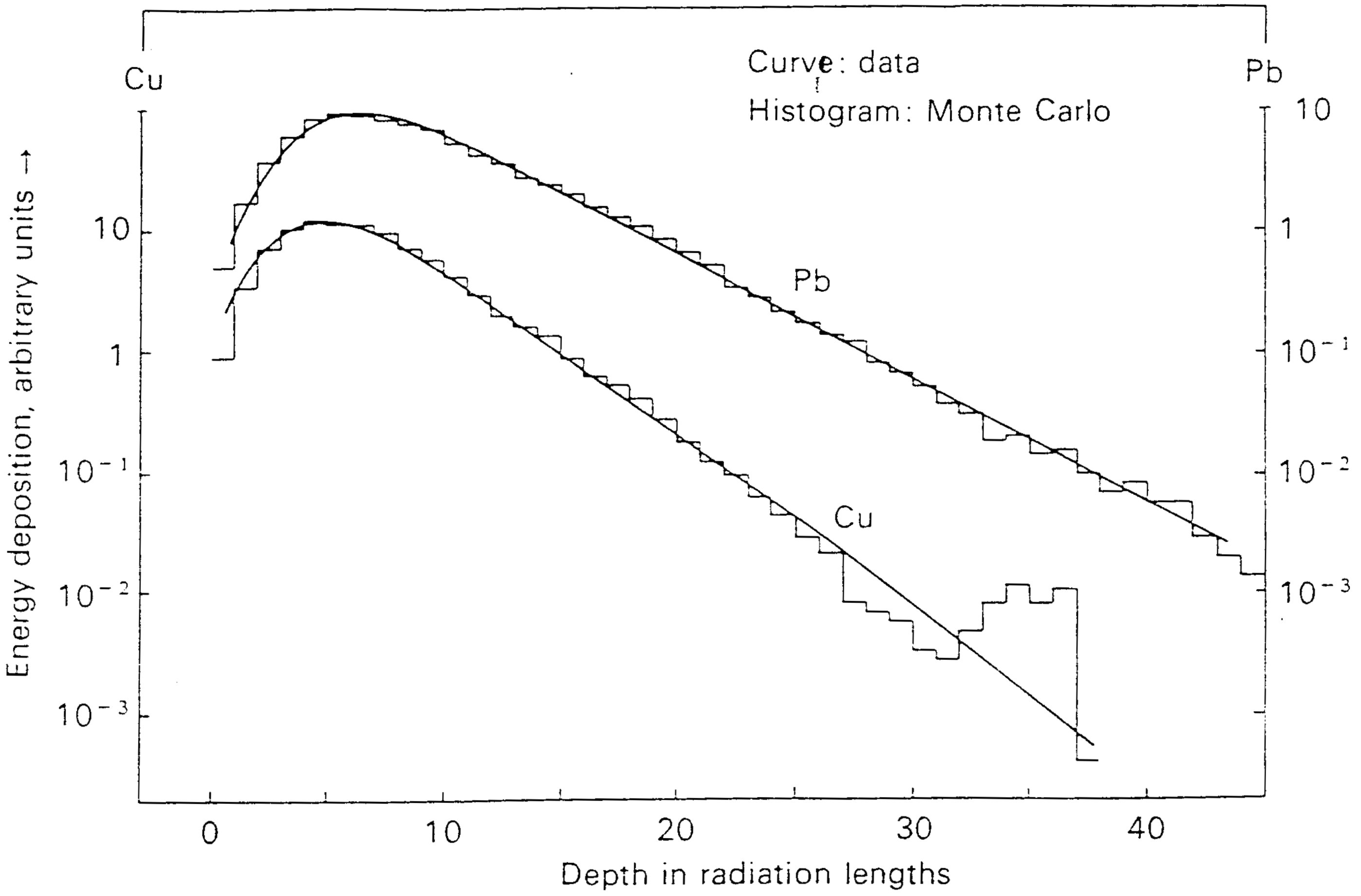
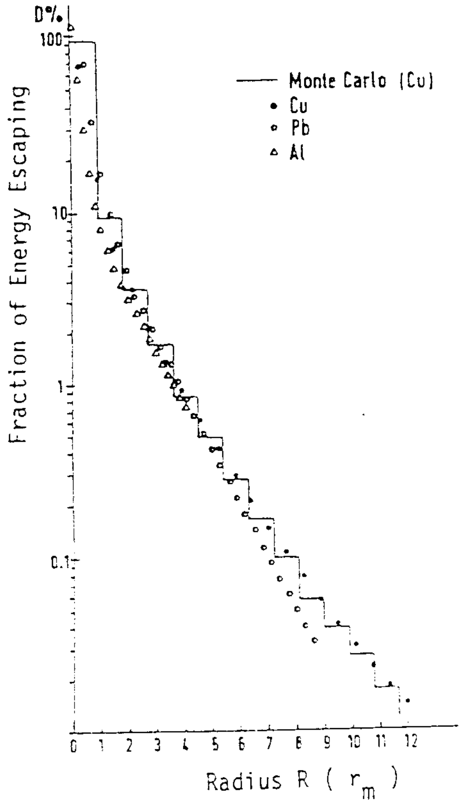


Figure 2.19 Longitudinal distribution of energy deposition in a 6-GeV electron shower (after Bathow *et al.* 1970).

Electromagnetic Showers: Radial distribution

- Scales with Moliere radius

  Al(Z=13) $R_M = 4.4$ cm
  Cu(Z=29) $R_M = 1.5$ cm
  Pb(Z=82) $R_M = 1.6$ cm
- ~90% of energy is within R_M, and ~95% of energy is within 2 R_M.



Electromagnetic Showers: Calorimetry

- The energy of the incident electron or photon is proportional to the total track length of the electrons and positrons in the EM shower
- Therefore, by measuring the electron+ positron track lengths, one measures a variable which is proportional to energy
- Measurements of:
  - Cerenkov radiation from e^- & e^+
  - scintillation from molecules in calorimeter
  - ionization of the detection medium

Electromagnetic Showers:

Calorimetry (homogeneous or sampling)

- Homogeneous calorimeter:

  calorimeters in which the shower is "observed" throughout the detector

  examples: lead glass, NaI, CsI, BGO, BaF

- Sampling calorimeter:

  calorimeters in which the shower is sampled by an "active" readout medium alternated with denser radiator material

  examples: scintillator sandwich, scintillating fiber, liquid argon, silicon, liquid scintillator

Electromagnetic Calorimetry:

homogeneous vs. sampling tradeoffs

- Homogeneous
    - better energy resolution
        - observation of full shower
    - limited spatial resolution
        - segmentation is limited to preserve energy resolution

- Sampling
    - limited energy resolution
        - sampling fluctuation
    - good spatial resolution
        - segmentation gives detailed shower shape information

Electromagnetic Showers: Fluctuations

- The measurement of energy will be limited in precision by fluctuations in the EM shower and in the measurement process
- The shape of an EM shower fluctuates only modestly, and resolution of an EM calorimeter is usually limited by other effects (assuming full containment has been achieved)
  - Dominant fluctuation in the shower is the depth of the first pair conversion.

EM Calorimeters: Energy Resolution

- Sampling Fluctuations (a)
- Noise (b)
- Pedestal Fluctuations (b)
- Nonuniformities (c)
- Calibration errors (c)
- Incomplete shower containment (leakage) (c)

$$\sigma/E = a/\sqrt{E} \oplus b/E \oplus c$$

EM Calorimeters: Energy Resolution (sampling fluctuations)

- The calorimeter is measuring total track length. This track length (S) will fluctuate as $S^{1/2}$ so that the energy measurement will have an error which scales as (since $E \sim S$)

$$\sigma / E \sim E^{-1/2}$$

- In a sampling calorimeter we have the further scaling law that the resolution will scale with the sampling thickness

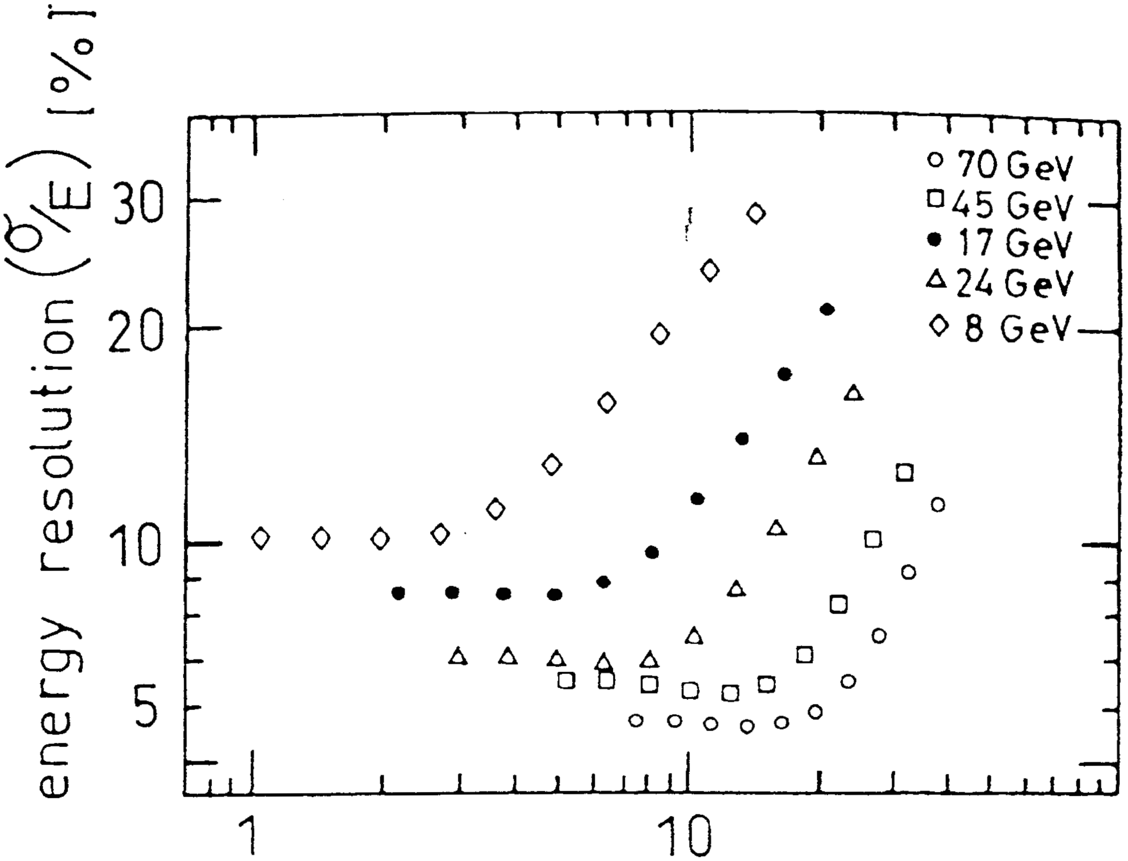
$$\sigma / E \sim t^{1/2} / E^{1/2}$$

- The limiting resolutions are

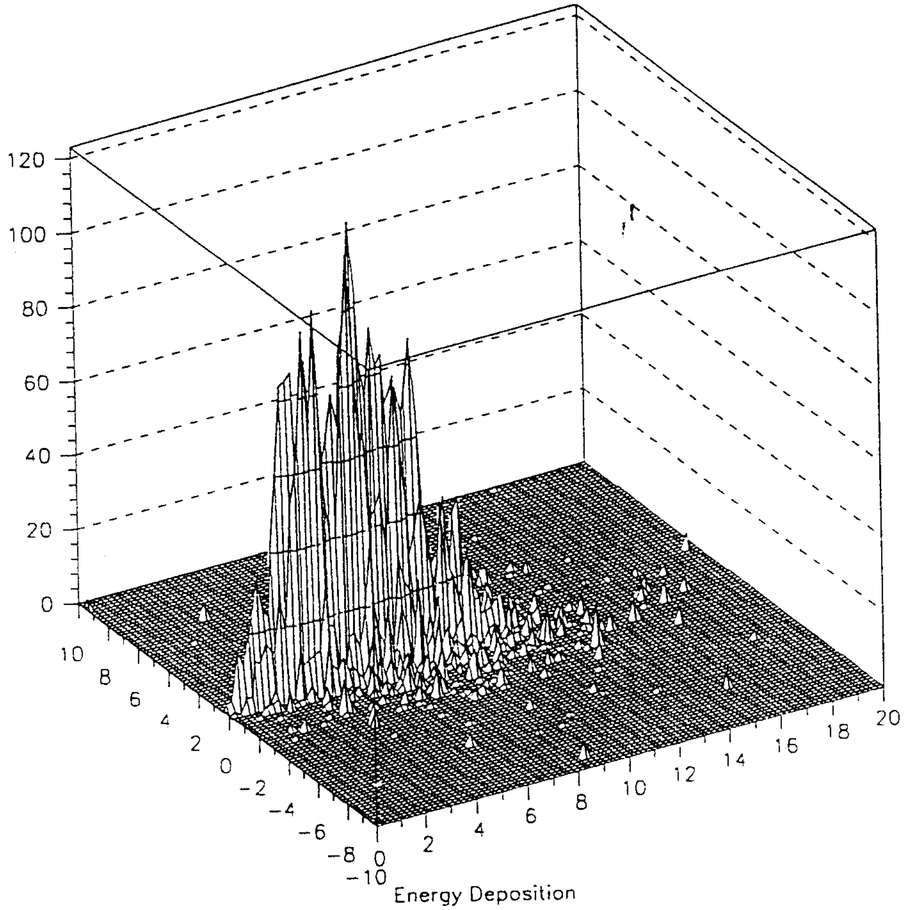
$$(\sigma / E)_{\text{shower}} \sim 0.005\, E^{-1/2}$$

$$(\sigma / E)_{\text{sampling}} \sim 0.04\, (1000\, \Delta E / E)^{1/2}$$

EM Calorimeters: Energy Resolution (longitudinal. leakage)



50 GeV
EM Shower



Examples of EM Calorimeters (pdg)

NaI(Tl)	2.7%/$E^{1/4}$
Lead Glass	5%/ $E^{1/2}$
Lead-liq. argon	7.5%/ $E^{1/2}$
Lead-scin. sand.	9%/ $E^{1/2}$
Lead-scin. spaghetti	13%/ $E^{1/2}$
Prop. wire chamber	23%/ $E^{1/2}$

- most of these resolutions must be added in quadrature with the appropriate constant term, typically on the order of 1%, or a bit smaller.
- Better resolution has been achieved with most advanced crystals (eg. CsI)

Position and Pointing Resolution

- The measurement of the impact point of a photon entering an EM calorimeter is limited by the transverse fluctuations in the shower, and the measurement errors of this measurement.
- This measurement involves determining the centroid of the shower as a function of depth in the calorimeter
- Typically, the achievable resolution is:

few mm / $E^{1/2}$

Position and Pointing Resolution (cont.)

- More challenging than position impact position measurement, is a measurement of the direction of the incident particle
  - This is particularly important at high luminosity colliders where multiple event occur within the same beam crossing (or readout window)
- Atlas has acheived about

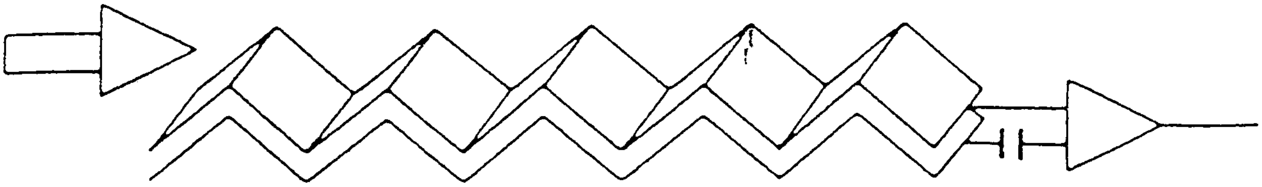
  40 mrad / E $^{1/2}$ (see figure)
- Position resolution often reflects on the electron identification performance

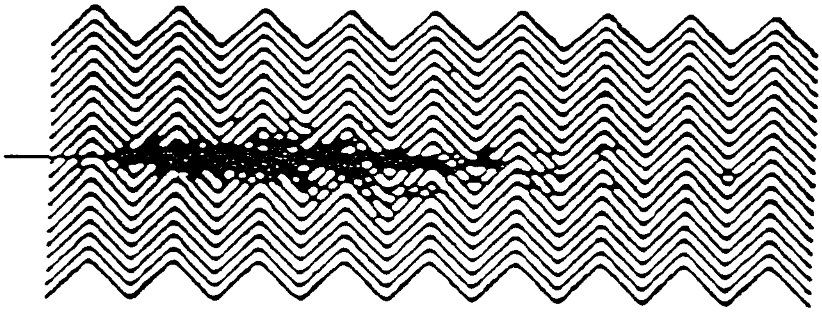
Examples of Recent Advances in EM Calorimeters

- Accordion liquid argon calorimeter
- Radiation resistant crystals
- Silicon luminosity monitors
- Scintillating Fiber
- CsI
  - CLEO
  - KTeV
  - BaBar (thallium doped)
  - BELLE (thallium doped)

Accordion Liquid Argon Calorimeter

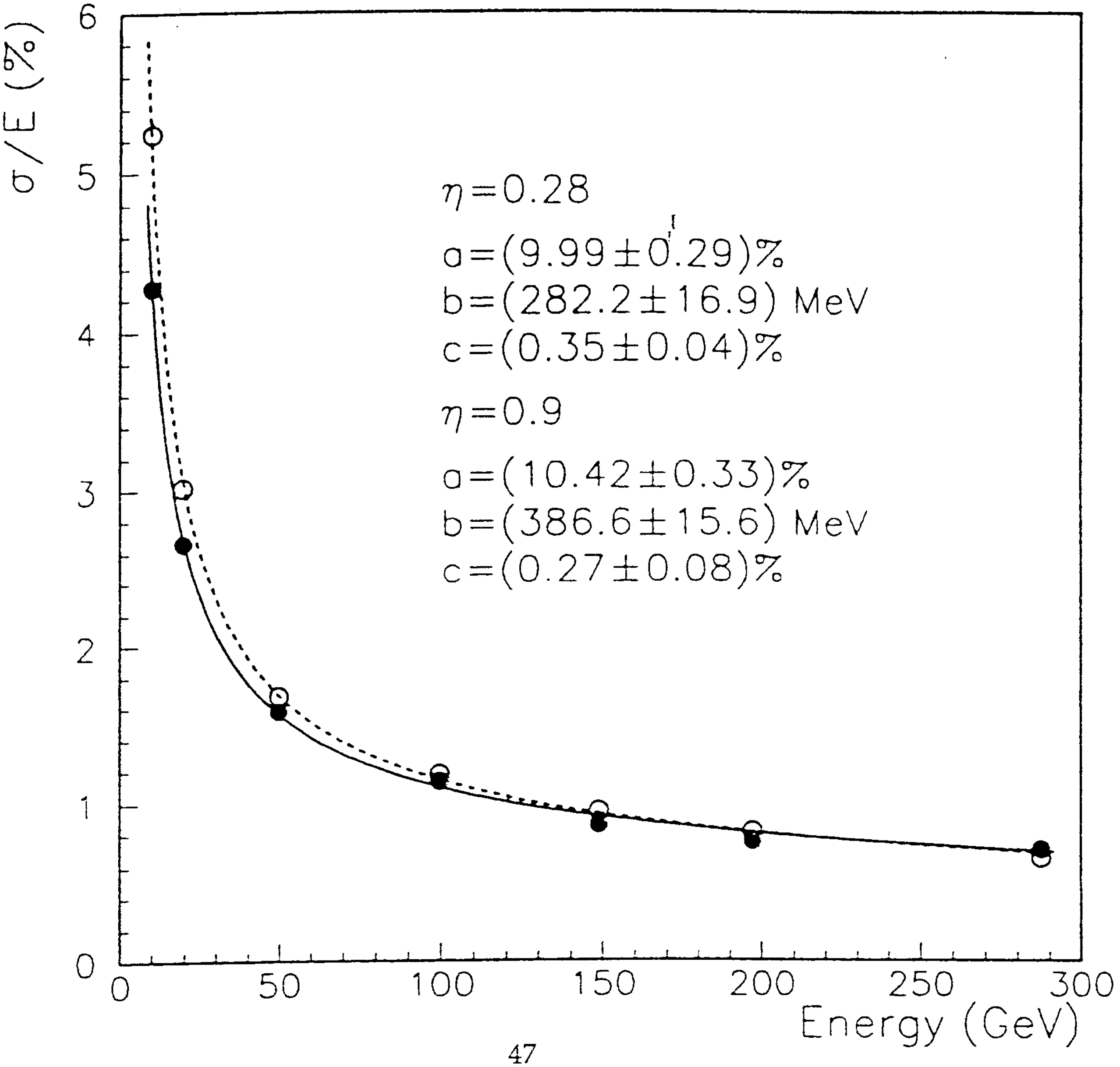
- fast readout
    - combines electrode and transmission line
- amenable to very fine readout





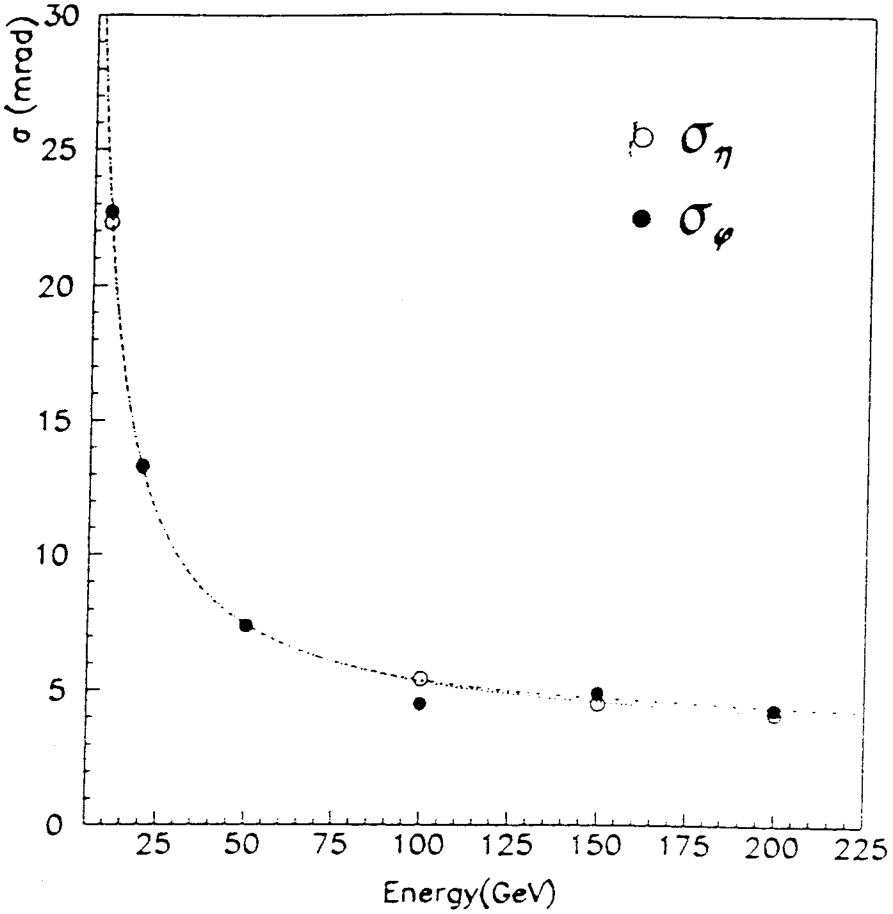
Accordion Liquid Argon Calorimeter (cont.)

- Excellent performance has been demonstrated in beam tests



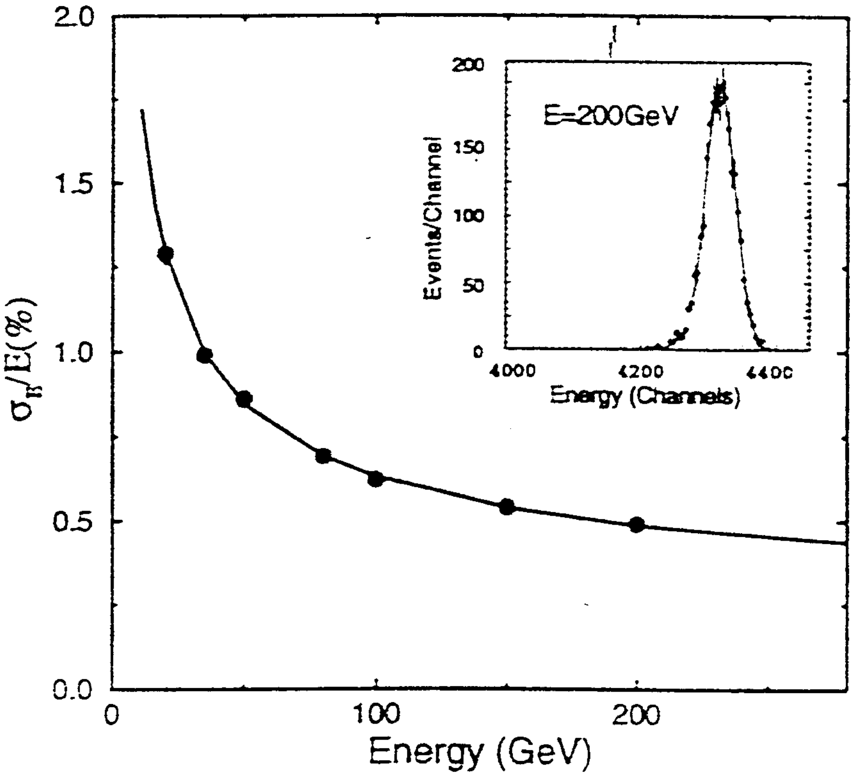
Accordion Liquid Argon Calorimeter (cont.)

- Atlas measures the position of the shower at front and back of calorimeter to get a vector



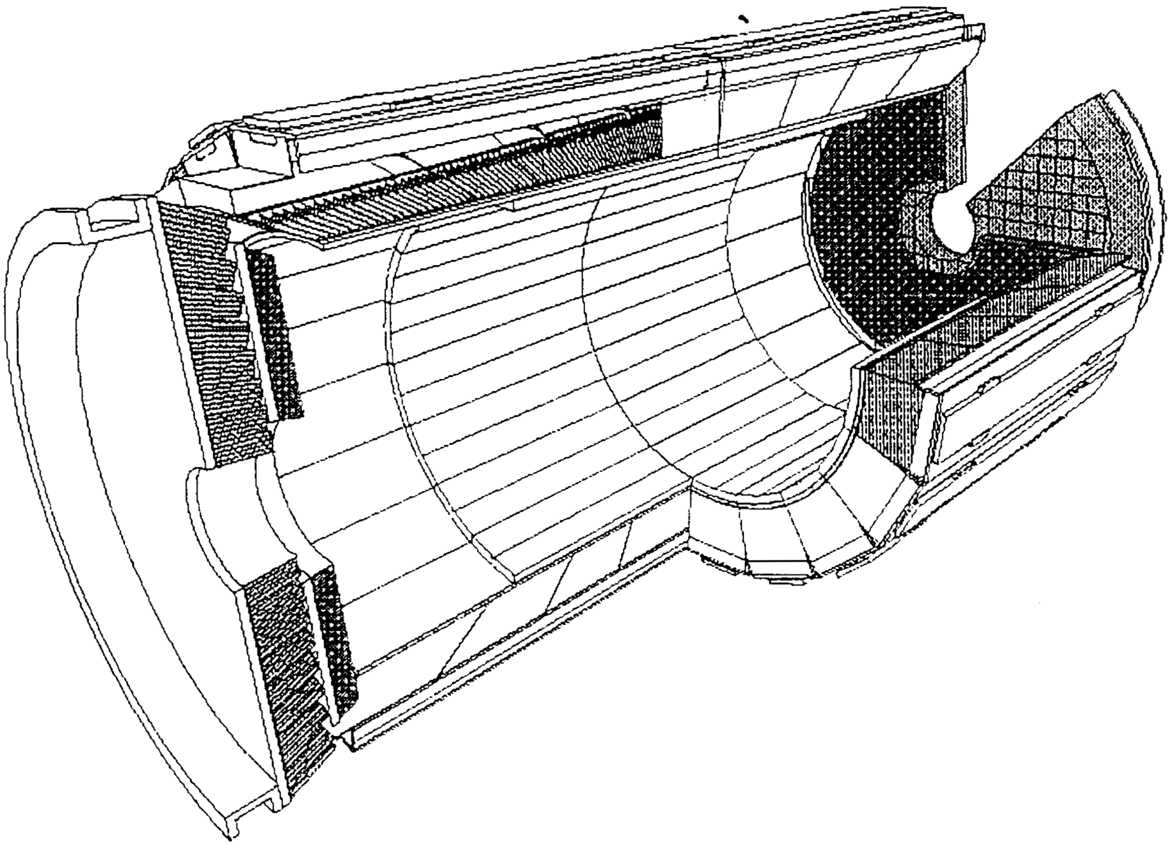
Liquid Krypton (in ATLAS tests)

- better sampling fraction
- double to signal
- saturated drift velocity



Radiation resistant Crystal Calorimeters

- CMS Plans a 83,000 crystal calorimeter in the hostile environment of the LHC
  - 1 krad/day



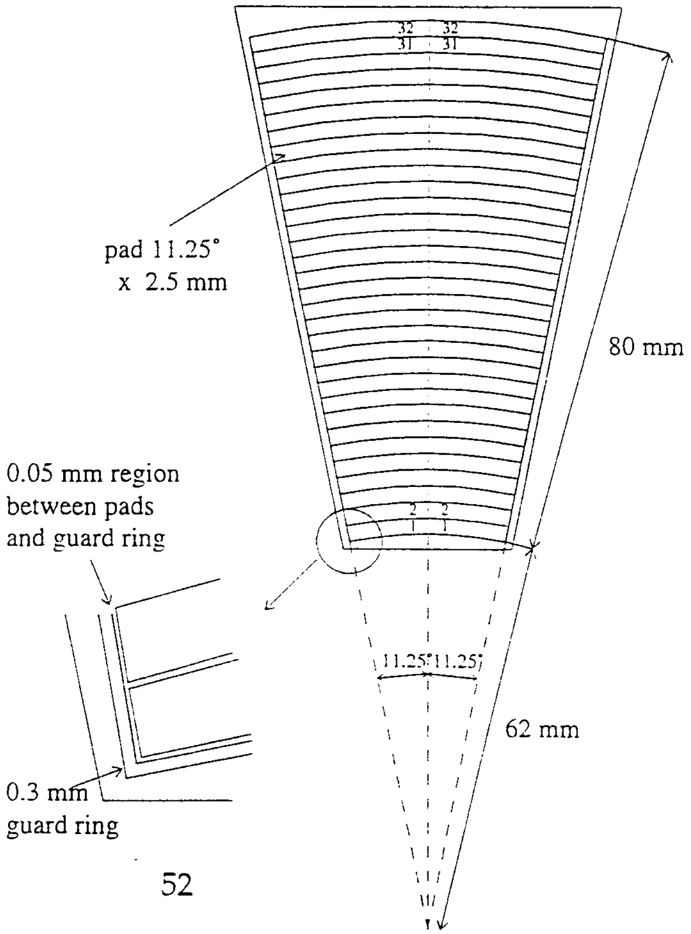
Radiation resistant Crystal Calorimeters (cont.)

- $PbWO_4$ (Lead Tungstate)
  - very dense
  - fast
  - intrinsically rad hard
- Radiation damage mechanism now better understood
  - scintillation light yeild is not significantly damaged by radiation
  - predominant radiation damage effect is radiation induced absorption
- Rad-hard crystal R&D continues

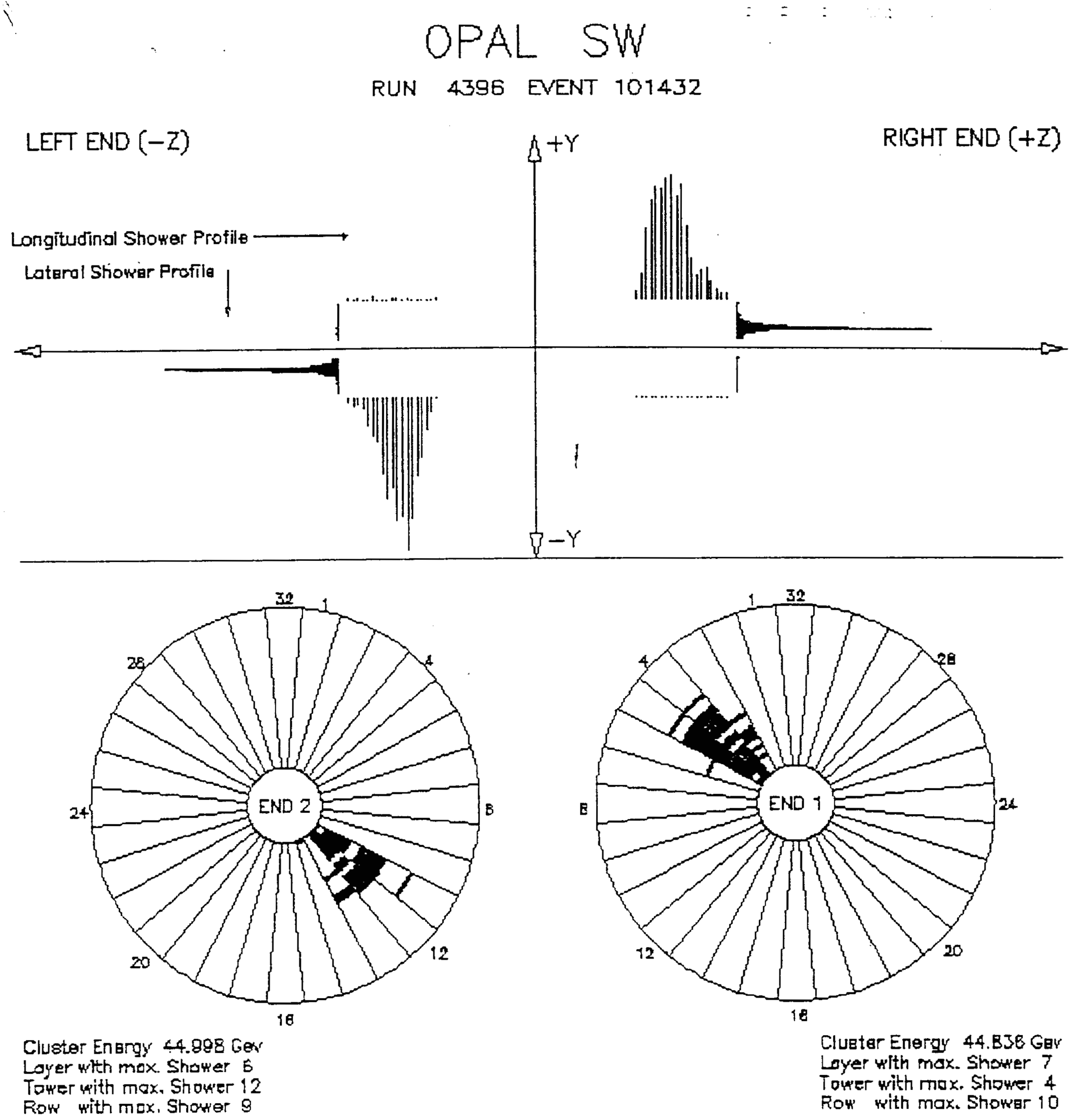
Silicon Calorimetry: Luminosity Monitors

- SLD built first silicon luminosity monitor (installed in 1991); it has provided reliable performance.
- OPAL improved on the design with a silicon calorimeter that achieves < 0.04% luminosity measurement

Silicon Wedge



Silicon Calorimetry: OPAL Luminosity Monitor (cont.)


OPAL SW

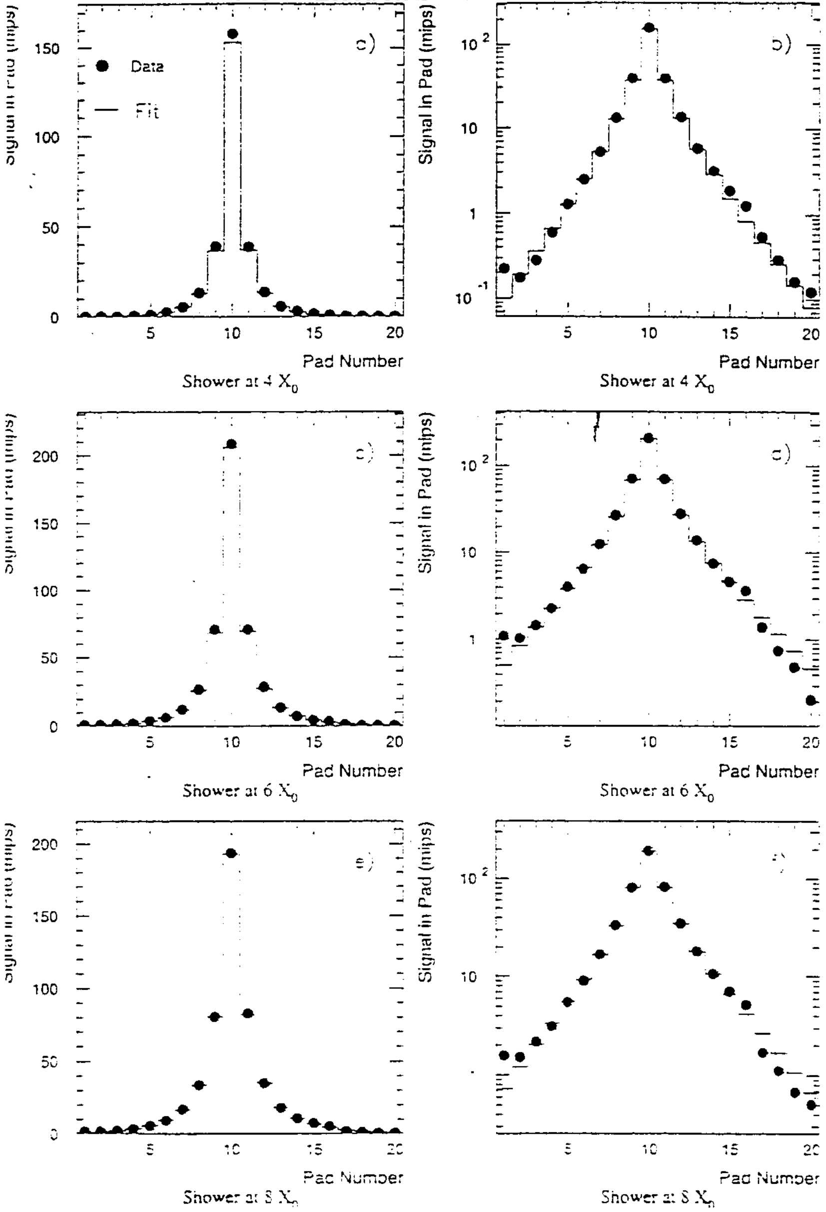
RUN 4396 EVENT 101432

Cluster Energy 44.898 Gev
Layer with max. Shower 6
Tower with max. Shower 12
Row with max. Shower 9

Cluster Energy 44.836 Gev
Layer with max. Shower 7
Tower with max. Shower 4
Row with max. Shower 10

Silicon Calorimetry: OPAL Luminosity Monitor (cont.)

45 GeV Electron Lateral Shower Profiles



Scintillating Fiber EM Calorimeters

- Latest application - KLOE:
  - scintillating fiber (1 mm diameter) -lead calorimeter at DAFNE, the phi factory at Frascati
  - Fiber:Lead:Glue = 50:40:10
  - Beam test performance:

$$\sigma/E = (4.96 \pm 0.01)\% / \sqrt{E}$$

  - Very fast:

$$\sigma_T = 71.7 \pm 1.0 \text{ psec} / \sqrt{E}$$

Cesium Iodide

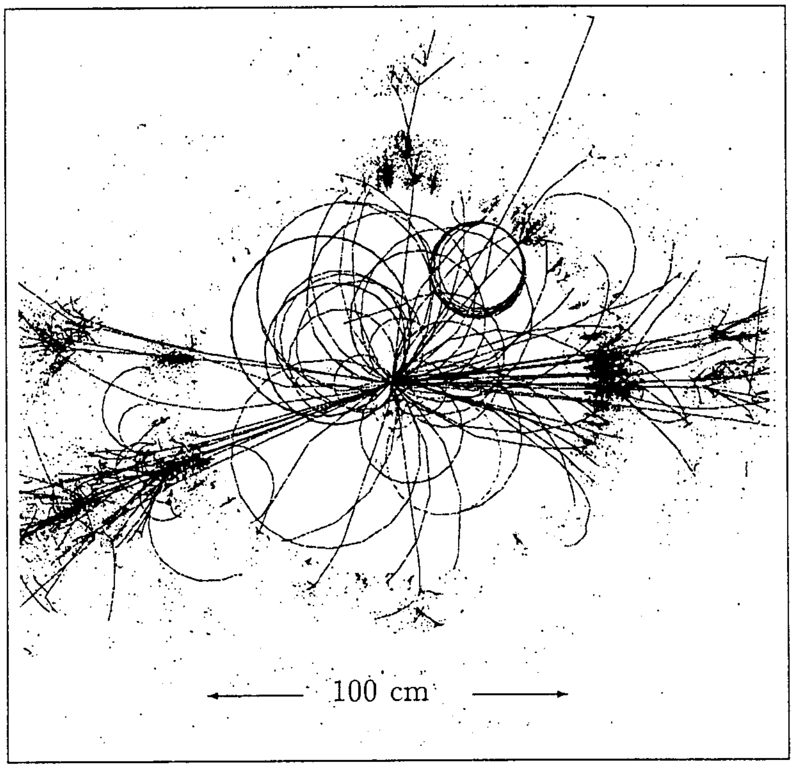
- CLEO has an excellent history with CsI and BaBar and BELLE will soon.
- KTeV has completed physics run with CsI
  - outstanding performance has been achieved.

$$\sigma / E = 2\% / \sqrt{E} \oplus 0.2\% \oplus 0.4\%$$

  - The π/e rejection is 680/1, based on a shape χ^2

Compact, Highly Segmented Calorimeter for the NLC

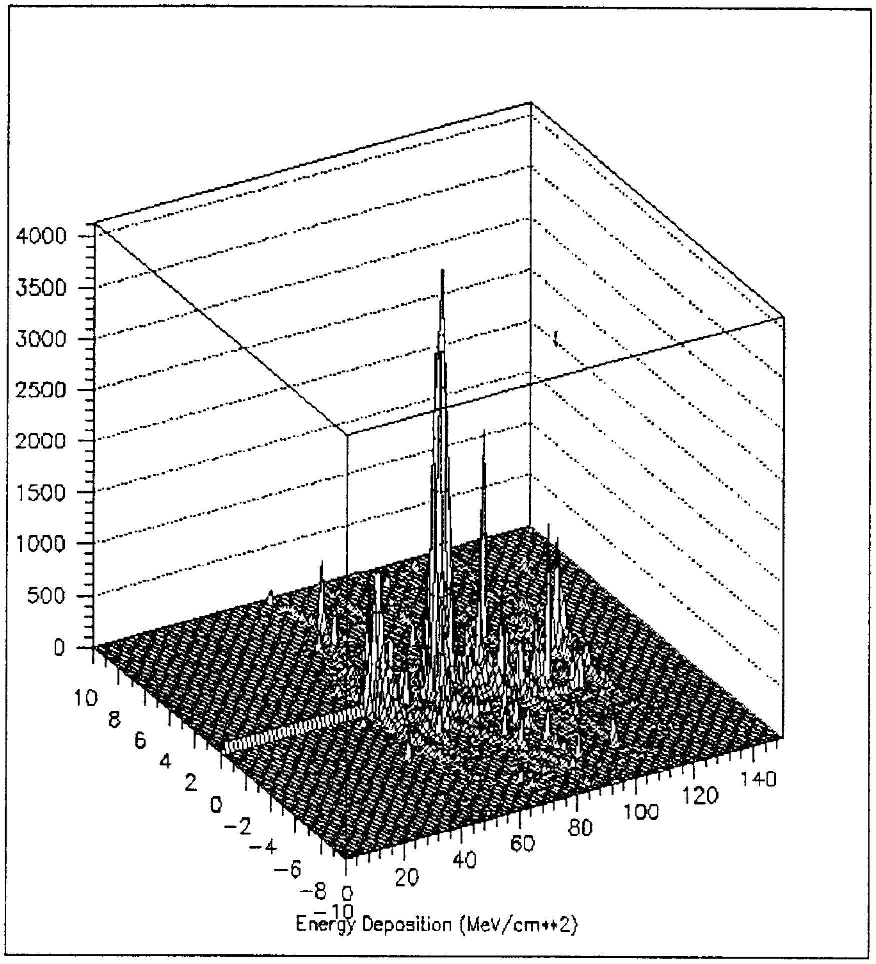
- Highly segmented silicon/tungsten EM calorimeter for the NLC
  - motivated by desire to separate EM showers from charged tracks in the jet environment
  - 4 million readout cells, very dense



Summary

- Electromagnetic Showers are very well understood theoretically.
- Electromagnetic Calorimeters are continuing to advance many varieties. For example:
  - crystals
  - accordion liquid argon
  - silicon sampling
  - scintillating fibers
- Optimization is always a trade-off between competing constraints.

100 GeV
Hadronic Shower



Hadronic Showers

- Hadronic Showers are much more complex than EM showers, and hadron resolution is more limited (eg. the best performance of hadron calorimeters is ~ 30% / $E^{1/2}$)
- Next week - Hadronic Calorimetry

References

- William J. Willis, New Directions in Calorimetery, in Techniques and Concepts of High-Energy Physics VIII, edited by Thomas Ferbel (1995).
- C.W.Fabjan et al, Iron Liquid-argon and Uranium liquid-argon Calorimeters for Hadron Energy Measurements, NIM 141, 61 (1977).
- Ugo Amaldi, Fluctuations in Calorimetry Measurements, Physica Scripta 23, 409 (1981).