Calorimetry in High-Energy Nuclear and Particle Physics Experiments

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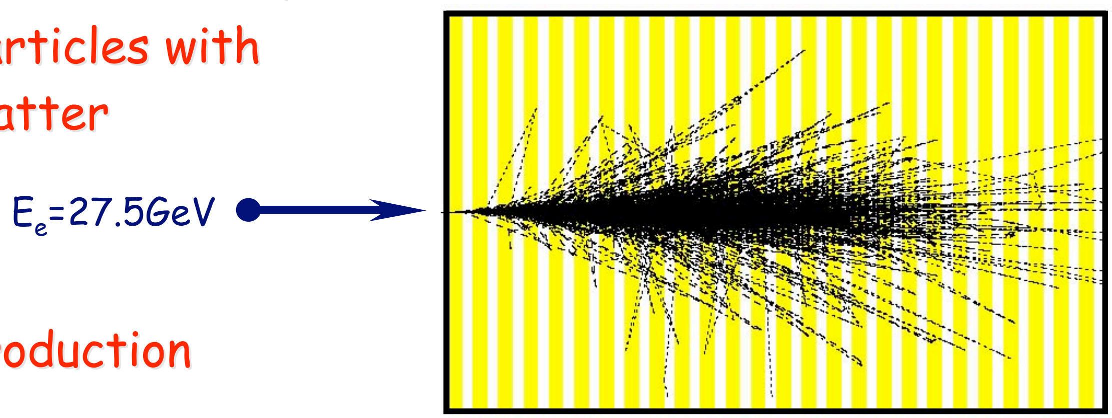
Outline

- Hadronic showers
- Electromagnetic showers
- Electromagnetic calorimeters
- Interactions of particles with matter
- Hadronic calorimeters

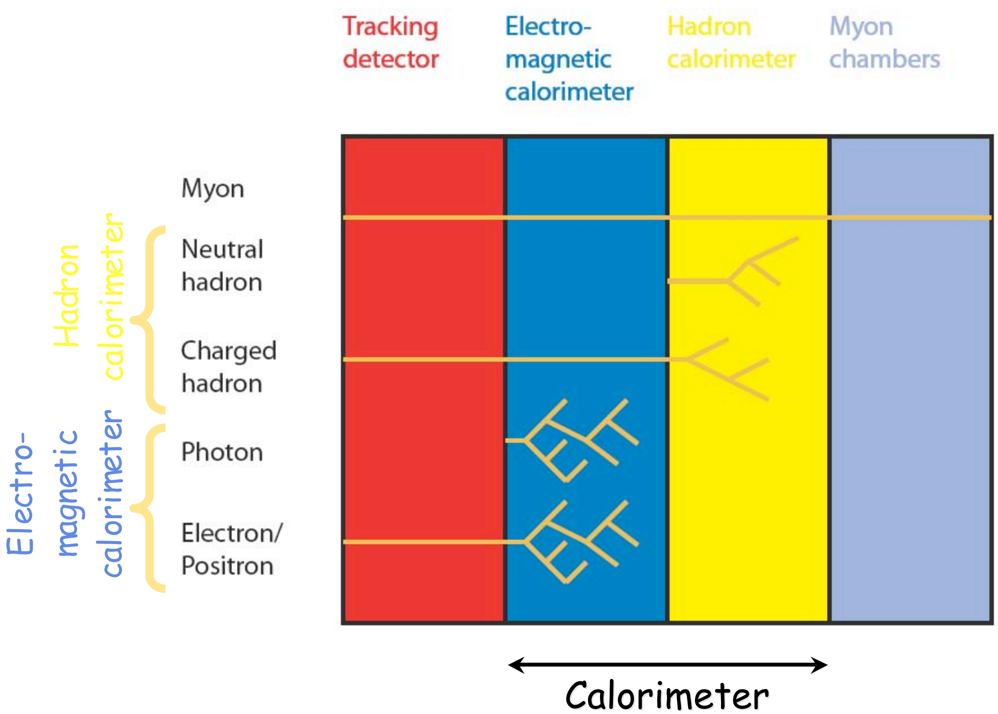


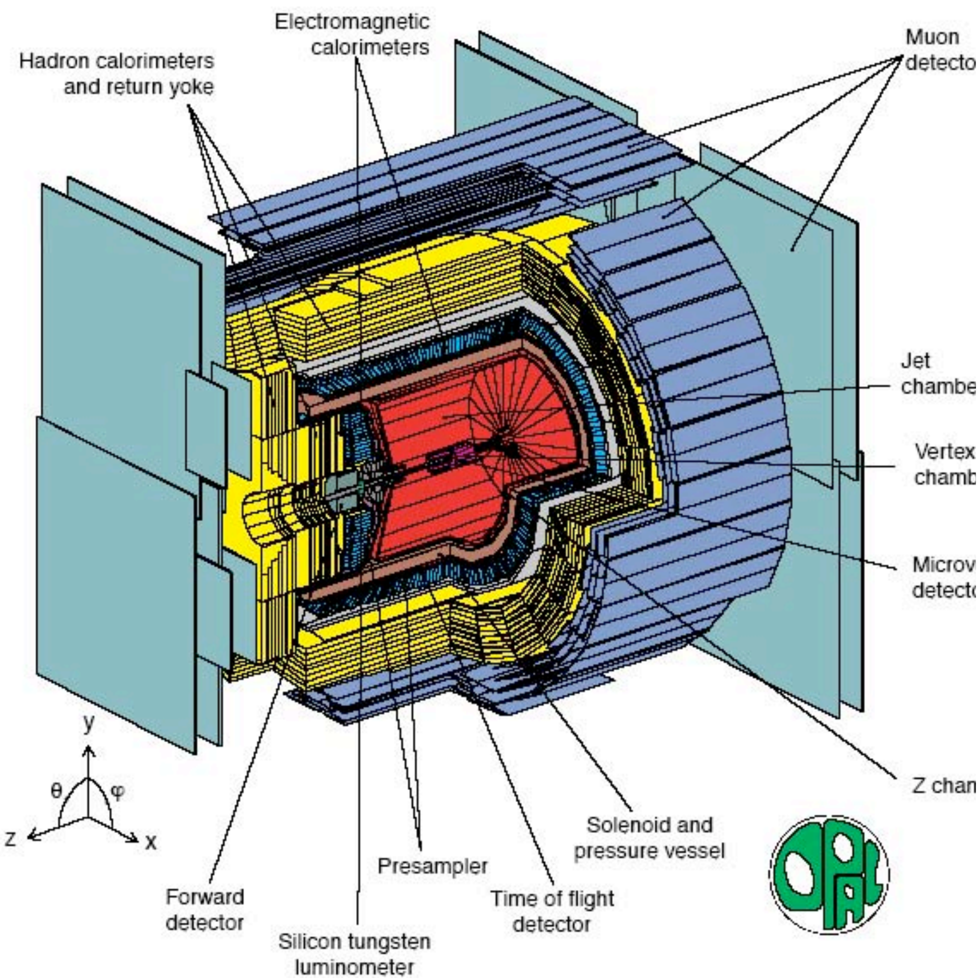
- Introduction
- Summary

Introduction

- **Definition and importance of calorimetry**
  - Measure p_μ of final-state particles in high-energy particle collisions
  - Calorimeter: Prime device to measure energy (E) of high-energy particles through total absorption

$$p_\mu = (E, \vec{p})$$

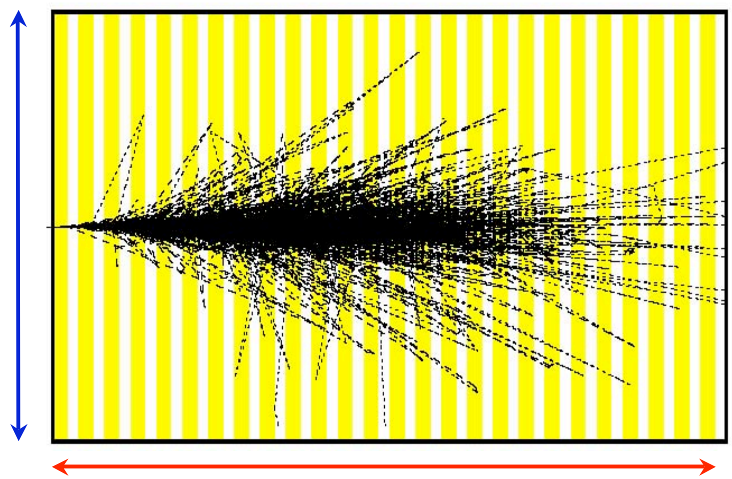




Introduction

Basic properties of calorimeters

- Conceptual idea of calorimeter principle: Shower formation of decreasingly lower-energy particles
- Small fraction of deposited energy is converted into a measurable signal depending on the type of instrumented materials being used:
  - Scintillation light
  - Cherenkov light
  - Ionization charge
- Important: Calorimeter has to be large enough (long./trans. dimension) to contain the full shower
- Unique properties of calorimeters:
  - Energy resolution of well designed calorimeters improve with increasing energy: $\sigma_E/E \propto 1/\sqrt{E}$
  - Longitudinal dimension necessary to absorb energy E scales logarithmically with energy E: $\propto \ln E$

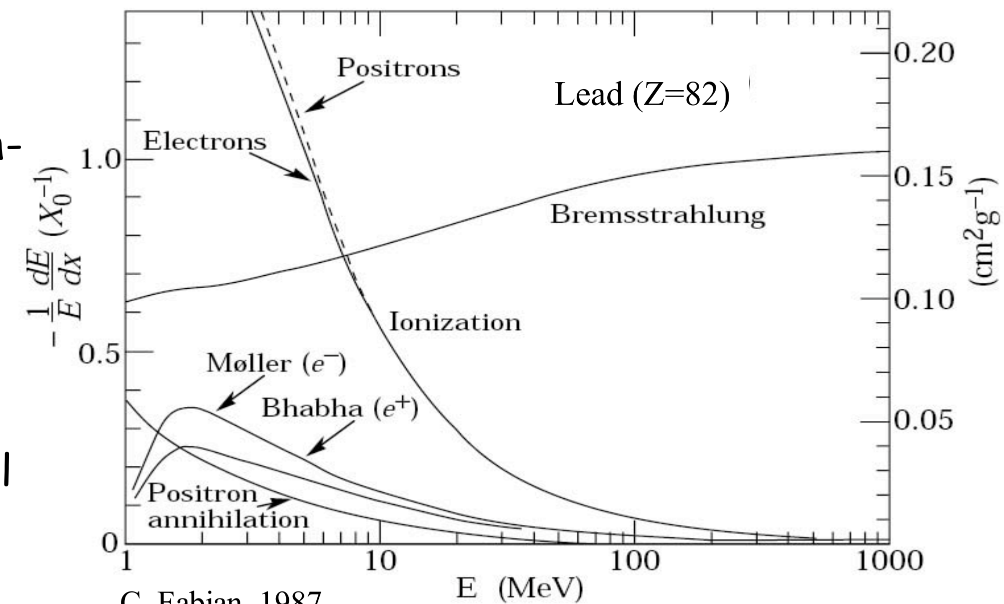


- Segmentation allows to measure impact position of incident particle
- Fast time response, depending on type of instrumented materials, allows to accept high event rate: Trigger input
- Response depends on particle type (trans./long. shower formation): Means of electron/hadron separation

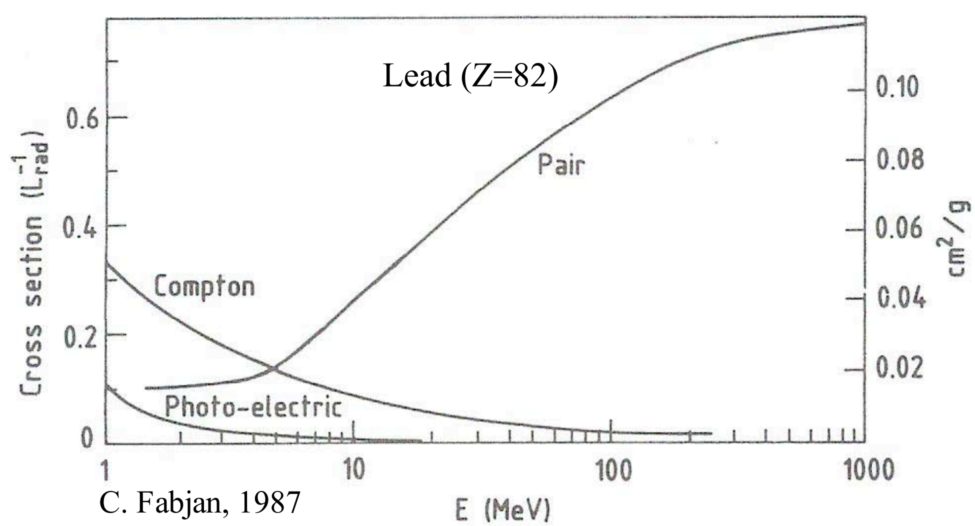
Interaction of particles with matter

Overview of interaction processes

- Particles created in the collision of high-energy particle beams experience electromagnetic and/or nuclear interactions in the detector material they pass through
- Understanding these processes are vital for the design of any detector system!
- Main processes for charged particles:
  - Ionization
  - Cherenkov radiation
  - Bremsstrahlung
- Main processes for photons:
  - Photoelectric effect
  - Compton scattering
  - Pair production



C. Fabjan, 1987



C. Fabjan, 1987

Interaction of particles with matter

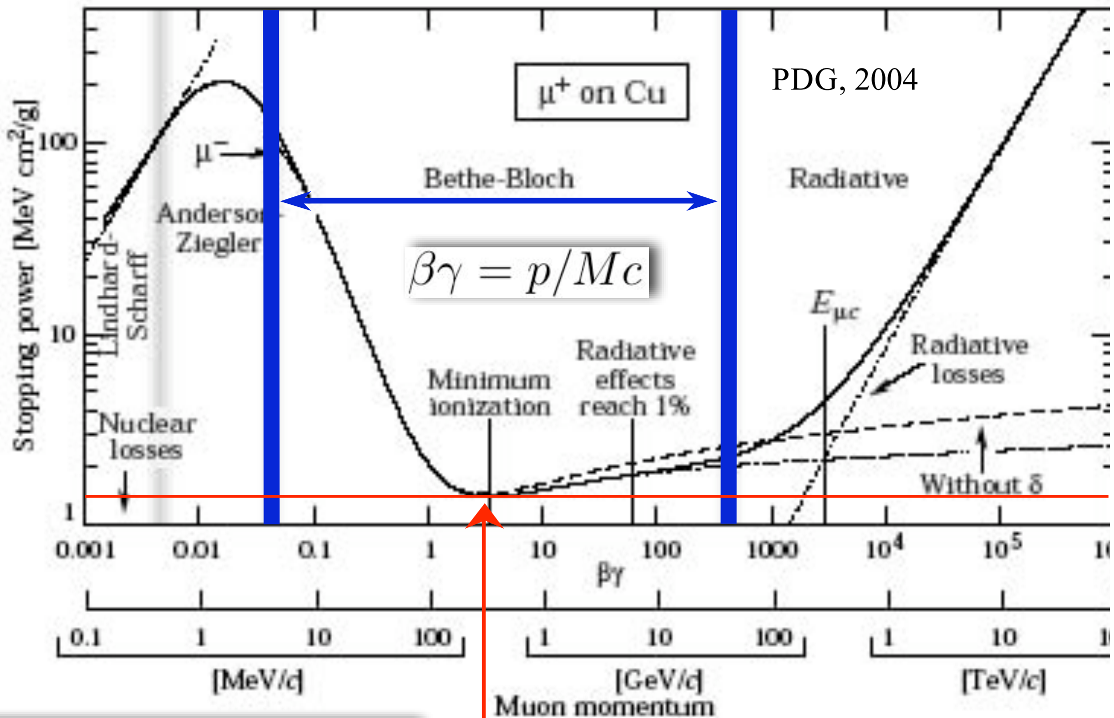
Ionization

- Bethe-Bloch equation: Mean energy (or stopping power)

  -dE/dx in units of:

  (MeV/cm)/(g/cm³)=(MeV cm²/g)

  -dE/x for charged particles: M » m_e



$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}\right]$$

Minimum at approx.: $\beta\gamma \approx 3$

(-dE/dx of relativistic particles: Close to minimum-ionizing particle (MIP)

with:

$$T_{max} = \frac{2m_ec^2\beta^2\gamma^2}{1+2\gamma_e m_e/M + (m_e/M)^2}$$

$$K = 4\pi N_A r_e^2 m_e c^2$$

Note:

1. Density (δ) and shell (C) corrections at high and low energies, respectively
2. -dE/dx for electrons modified due to the kinematics, spin and identity of the incident electron with the medium electrons

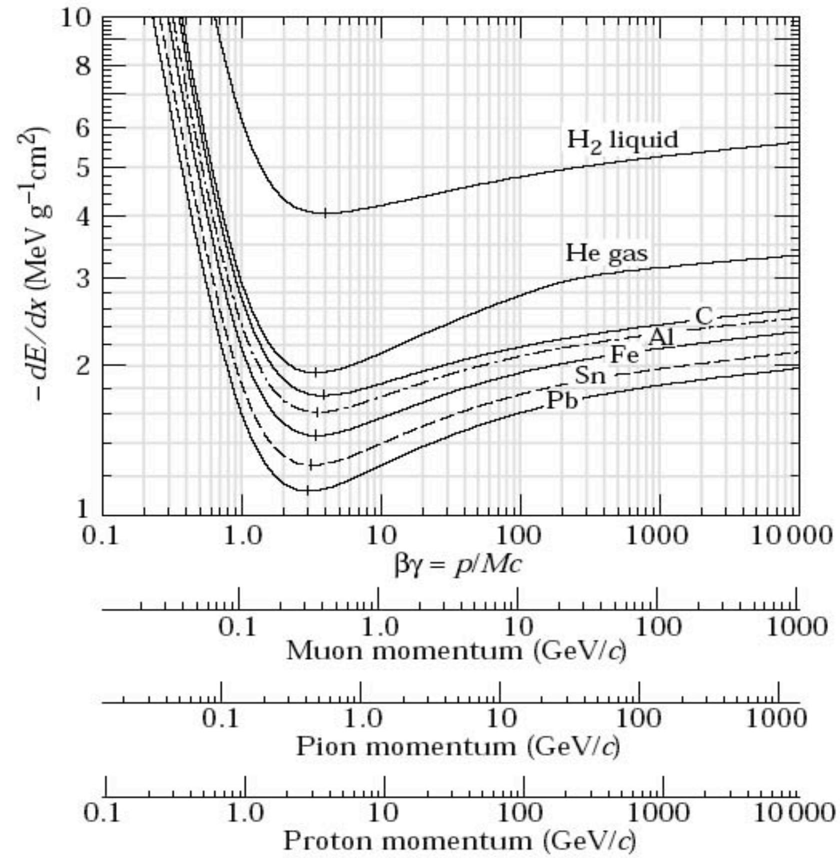
Interaction of particles with matter

- **Ionization**

Material	Z	A	Z/A	dE/dx min ($MeVcm^2/g$)	Density (g/cm^3)
H_2 (liquid)	1	1.008	0.992	4.034	0.0708
He	2	4.002	0.500	1.937	0.125
C	6	12.01	0.500	1.745	2.27
Al	13	26.98	0.482	1.615	2.70
Cu	29	63.55	0.456	1.403	8.96
Pb	82	207.2	0.396	1.123	11.4
W	74	183.8	0.403	1.145	19.3
U	92	238.0	0.387	1.082	19.0
Scint.			0.538	1.936	1.03
BGO			0.421	1.251	7.10
CsI			0.416	1.243	4.53
NaI			0.427	1.305	3.67

- Medium dependence

- Weak dependence on the medium, since $Z/A \approx 0.5$:

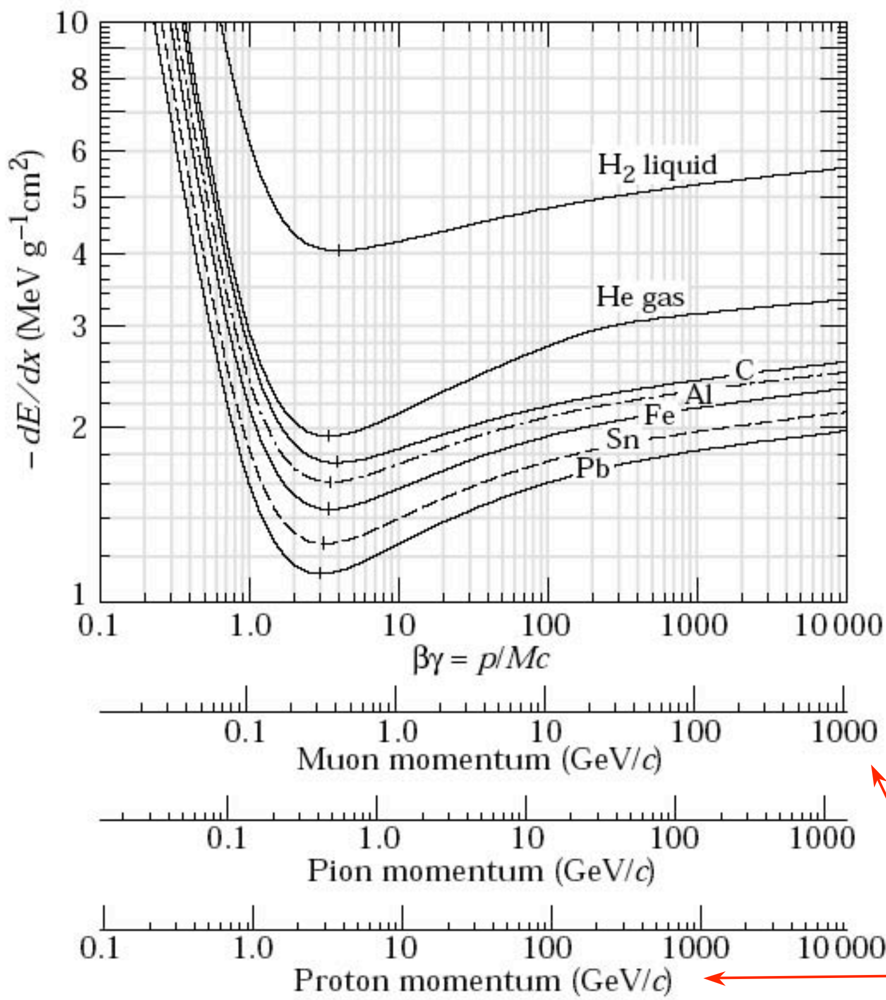


PDG, 2004

- Scintillator: $dE/dx|_{min} \approx 2MeV/cm$
- Tungsten: $dE/dx|_{min} \approx 22MeV/cm$

Interaction of particles with matter

- **Ionization**
  - Particle mass dependence



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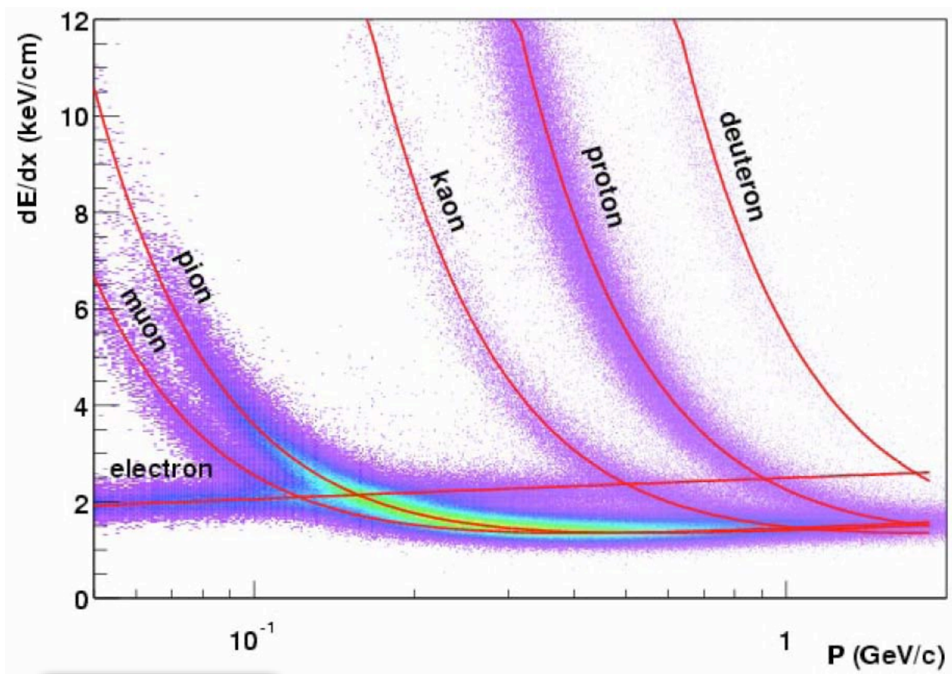
- STAR Time-Projection Chamber (TPC):

10% Methan / 90% Argon (2mbar above athm. pressure)



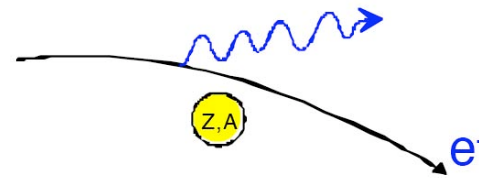
$$p = \beta\gamma Mc$$

- Minimum in $\beta\gamma \approx 3$ occurs for fixed momentum p at different locations depending on particle mass: Means of particle identification at low momentum p!
- Example: $M_p/M_\mu \approx 10$

Interaction of particles with matter

Bremsstrahlung

- Radiation of real photons in the Coulomb field of the nuclei of the absorber: Mean energy loss due to Bremsstrahlung



$$\frac{dE}{dx} = -4\alpha \frac{\rho N_A}{A} Z(Z+1) r_e^2 \ln(183 Z^{-1/3}) E \propto \frac{E}{m_e^2}$$

Note: Effect plays only a role for $e^{+/-}$ and ultra-relativistic muons (> 1 TeV) ($(m_\mu/m_e)^2 \approx 4 \cdot 10^4$)

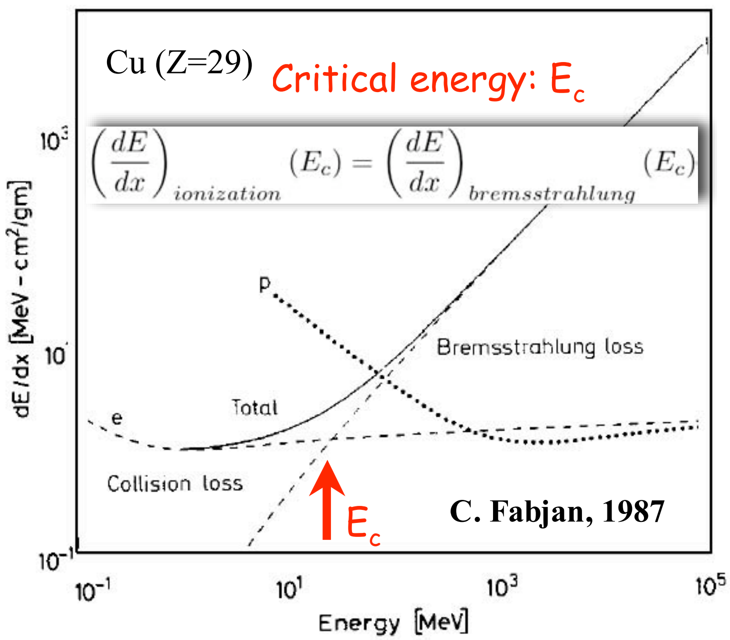
- Definition of radiation length X_0:

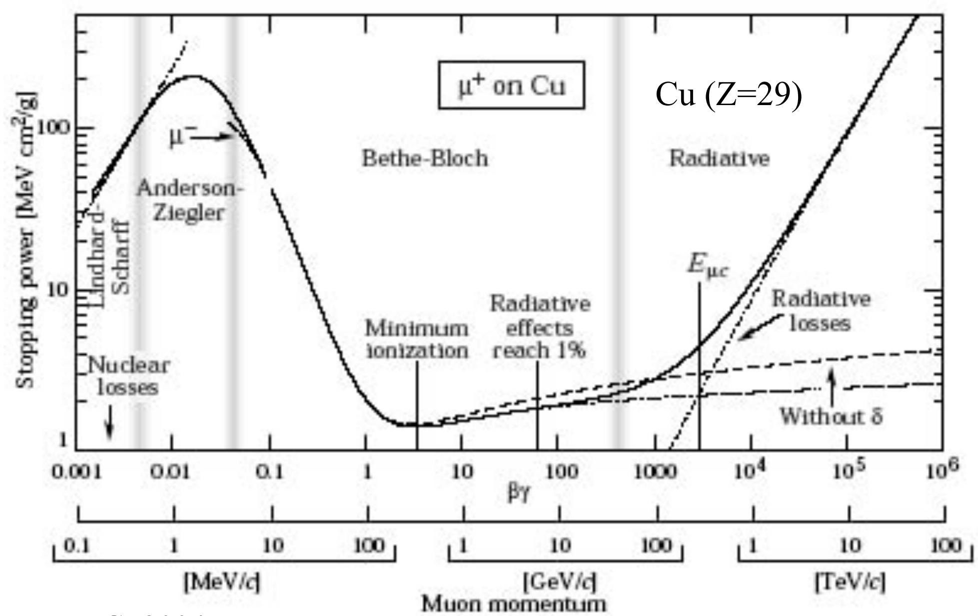
$$-\frac{dE}{dE} = \frac{dx}{X_0}$$

$$\frac{1}{X_0} = 4\alpha \frac{\rho N_A}{A} Z(Z+1) r_e^2 \ln(183 Z^{-1/3})$$

Critical energy: E_c

$$\left(\frac{dE}{dx}\right)_{ionization}(E_c) = \left(\frac{dE}{dx}\right)_{bremsstrahlung}(E_c)$$





PDG, 2004

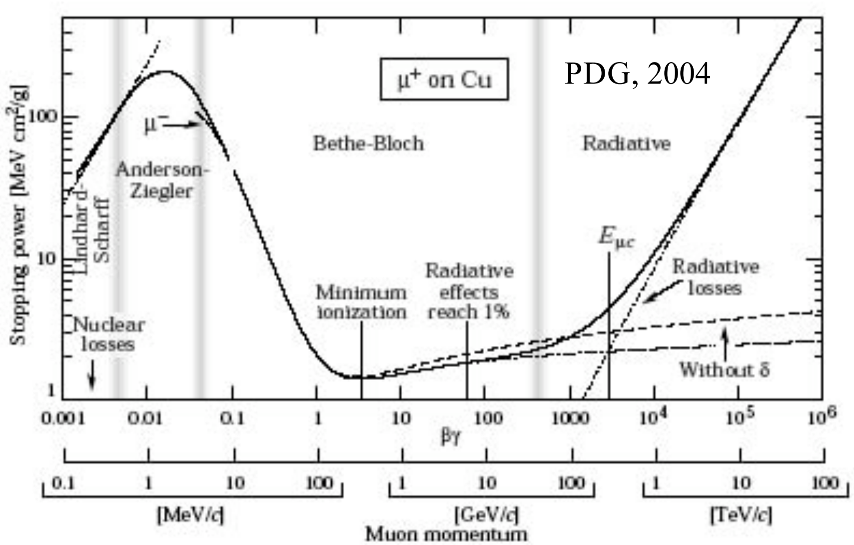
Interaction of particles with matter

- **Bremsstrahlung**
  - Material dependence in radiation length X_0
  - Critical energy:

$$E_c \approx \frac{800MeV}{Z+1.2}$$

$$E_c(e^- \text{ for Cu } Z=29) \approx 20MeV$$

$$E_c(\mu^- \text{ for Cu } Z=29) \approx 800GeV$$



Material	Z	A	Z/A	X_0 (cm)	Density (g/cm^3)
H_2 (liquid)	1	1.008	0.992	866	0.0708
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Interaction of particles with matter

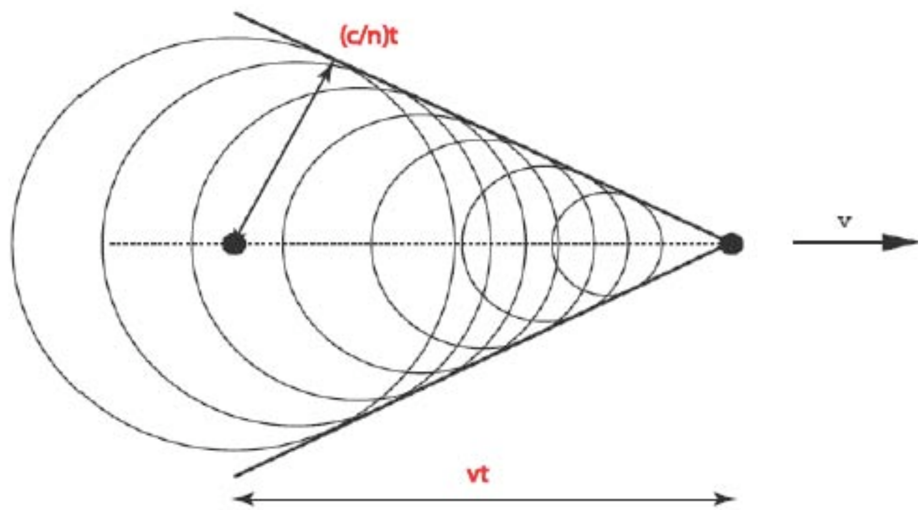
Cherenkov radiation

- Definition: Cherenkov radiation arises when a charged particle in a material moves faster than the speed of light in that same medium:

$$\beta c = v = c/n$$

- Condition for Cherenkov radiation to occur:

$$\cos\theta_c = \frac{1}{\beta n} \qquad v_{particle} > c/n$$



- Energy emitted per unit path length:

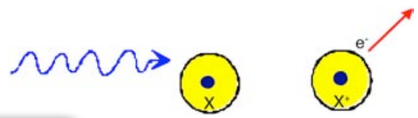
$$\frac{dE}{dx} = 4\pi^2 e^2 \int_{\beta n > 1} \frac{1}{\lambda^3}\left(1 - \frac{1}{\beta^2 n^2}\right) d\lambda$$

- Example: Lead-glass (Passive absorber material = Active detector material) calorimeter (Type SF5):
  - Density: $\rho = 4.08 g/cm^3$
  - Radiation length: $X_0 = 2.54cm$
  - Index of refraction: $n = 1.67$

Interaction of particles with matter

Interactions of photons with matter

- Photoelectric effect



$$\gamma + X \rightarrow e^- + X^+$$

For $E\gamma \ll m_e c^2$ and the fact that for $E\gamma$ above the K shell, almost only K electrons are involved one finds:

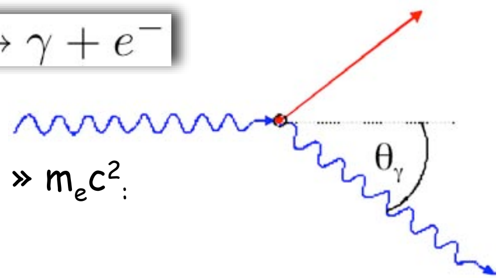
$$\sigma_{photo} = \sqrt{\left(\frac{32}{\epsilon^7}\right)} \alpha^4 Z^5 \sigma_{th}$$

$$\sigma_{th} = \frac{8}{3}\pi r_e^2$$

$$\epsilon = \frac{E_\gamma}{m_e c^2}$$

- Compton scattering

$$\gamma + e^- \rightarrow \gamma + e^-$$



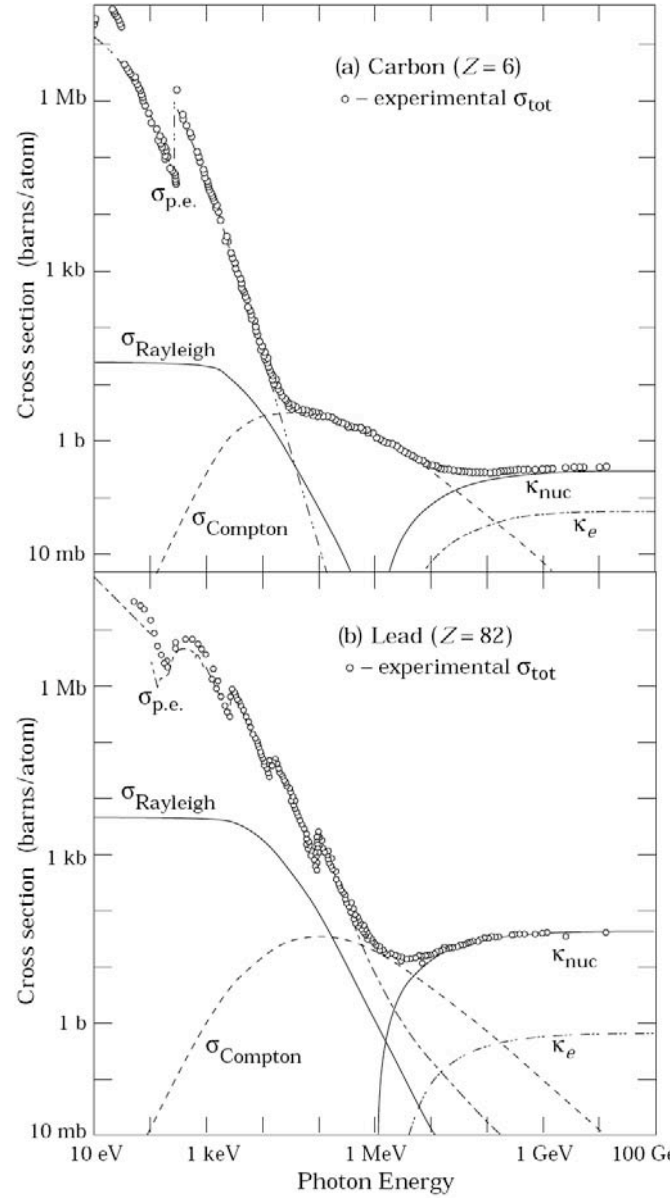
Assume electrons as quasi-free and $E\gamma \gg m_e c^2$:

$$\sigma_c = \frac{3}{8}\sigma_{th}\frac{1}{\epsilon}\left\{\ln(\epsilon) + \frac{1}{2}\right\}$$

(Klein-Nishina)

$$E_\gamma' = E_\gamma \frac{1}{1 + \epsilon(1 - \cos\theta_\gamma)}$$

Atomic Compton cross-section: $\sigma_c^{atomic} = Z\sigma_c$



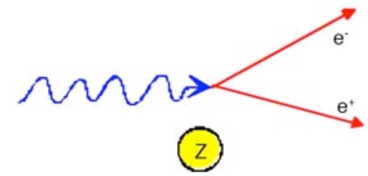
PDG, 2004

Interaction of particles with matter

- **Interactions of photons with matter**

  - Pair production

$$\sigma_{pair} = 4\alpha Z(Z+1)r_e^2\left[\frac{7}{9}\ln(183Z^{-1/3}) - \frac{1}{54}\right]$$



$$\frac{1}{\lambda_{pair}} = \frac{N_A\rho}{A}\sigma_{pair} \approx \frac{7}{9}4\alpha\frac{\rho N_A}{A}Z(Z+1)r_e^2\ln(183Z^{-1/3}) = \frac{7}{9}\frac{1}{X_0}$$

$$\frac{1}{\lambda_{pair}} \approx \frac{7}{9}\frac{1}{X_0}$$

  - Absorption coefficient

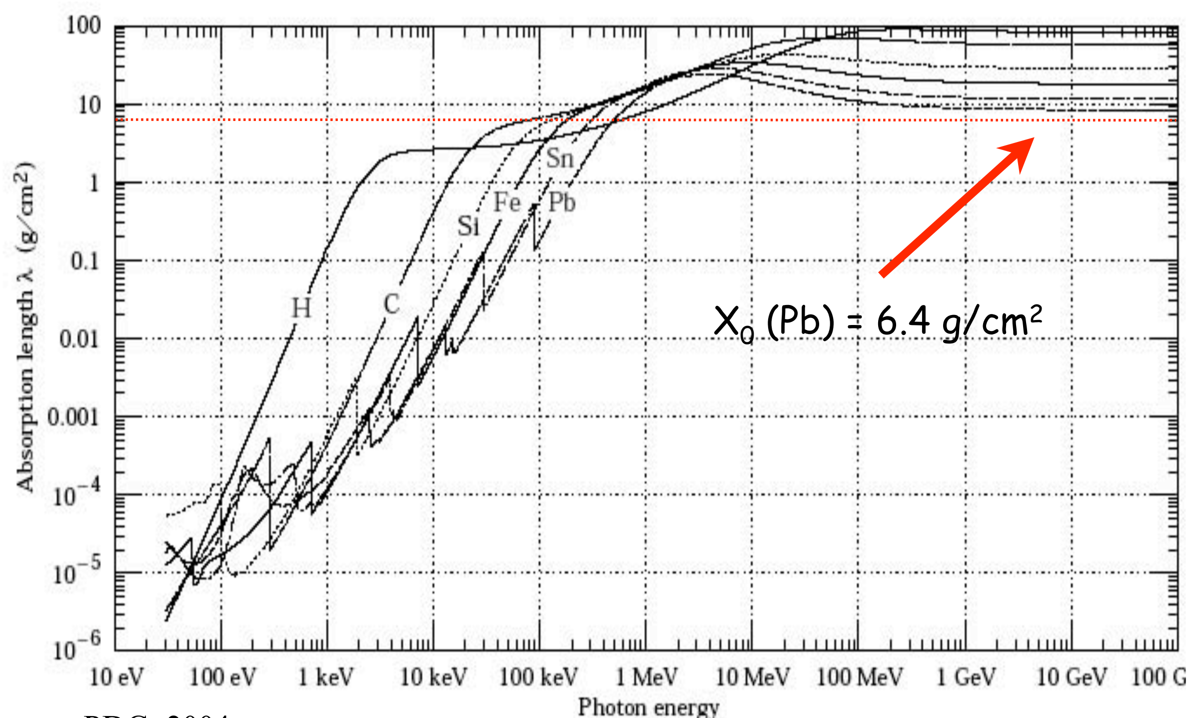
Total probability for γ interaction in matter:

$$\sigma = \sigma_{photo} + Z\sigma_c + \sigma_{pair}$$

Probability per unit length or total absorption coefficient (Inverse of absorption length λ of γ):

$$\mu = \sigma\left(\frac{N_A\rho}{A}\right)$$

$$I = I_0 e^{-\mu x}$$

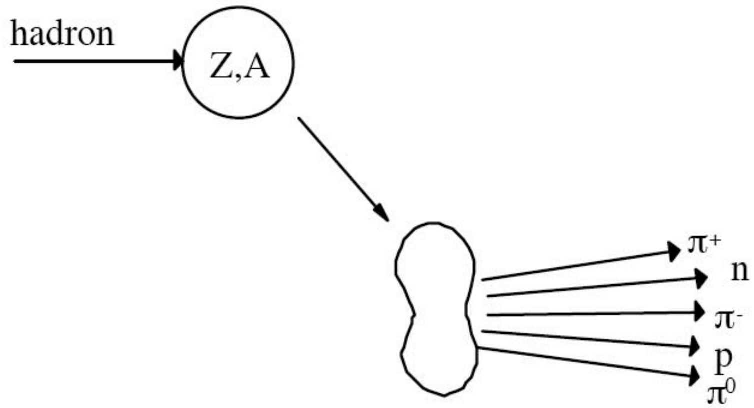


PDG, 2004

Interaction of particles with matter

- **Nuclear interactions**

  - The interaction of energetic hadrons (charged or neutral) is determined by various nuclear processes:



Multiplicity $\propto$ ln(E)

P_t < 1 GeV/c

  - Excitation and finally breakup of nucleus: nuclear fragments and production of secondary particles

  - For high energies (> 1GeV) the cross-sections depend only little on the energy and on the type of the incident particle (p, π, K, …)

  - Define in analogy to X_0 a hadronic interaction length λ_I:

$$\lambda_I = \frac{A}{N_A \sigma_{total}} \propto A^{\frac{1}{3}}$$

Interaction of particles with matter

- Comparison of nuclear interaction length (in cm) and radiation length (in cm)

Material	Z	A	Z/A	X_0 (cm)	λ_I (cm)	Density (g/cm^3)
H_2 (liquid)	1	1.008	0.992	866	718	0.0708
He	2	4.002	0.500	756	520	0.125
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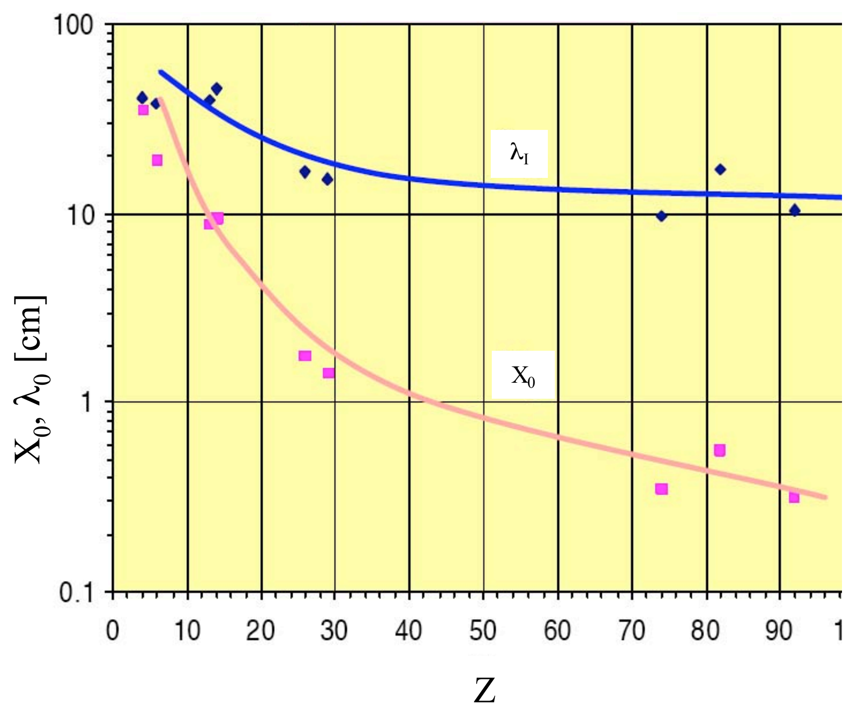
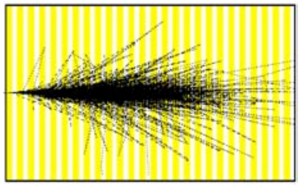
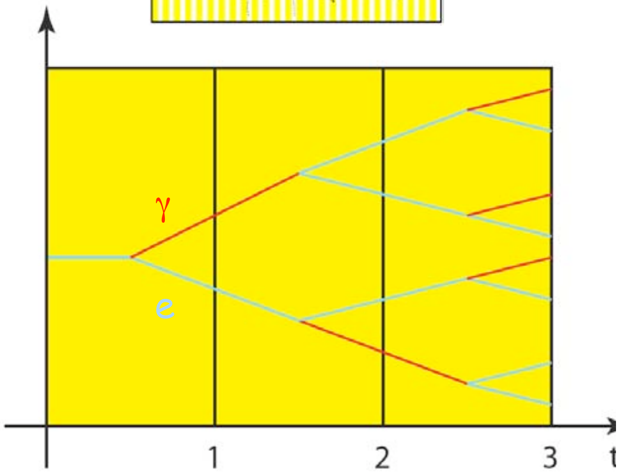


Electromagnetic showers

Electromagnetic shower development

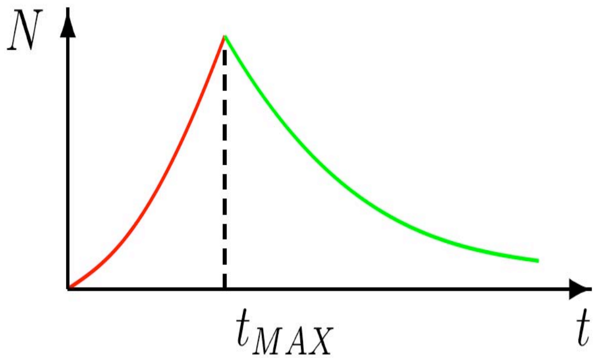
- Simple qualitative model for shower development (Heitler)
  - Consider only: bremsstrahlung and pair production
  - Each electron with $E > E_c$ travels $1X_0$ and then gives up half of its energy to a bremsstrahlung photon
  - Each photon with $E > E_c$ travel $1X_0$ and then undergoes pair production with each created particle receiving half of the energy of the photon
  - Electrons with $E < E_c$ cease to radiate and lose remaining energy through ionization
  - Neglect ionization losses for $E > E_c$





Total number of particles after t X_0:

$$N(t) = 2^t = e^{t \ln 2}$$



Average energy of shower particle at depth t:

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

$$E(t) = E_c \qquad t_{max} = \ln(E_0/E_c)/\ln 2 \propto \ln(E_0)$$

$$N_{max} = e^{t_{max} \ln 2} = E_0/E_c$$

After $t=t_{max}$: ionization, compton effect and photoelectric effect!

Electromagnetic showers

Longitudinal shower profile

- Size of shower grows only logarithmically with E
- Rossi's approximation B (Analytical description of shower development):

quantity	incident electron	incident photon
t_{max}	$\ln y - 1$	$\ln y - 0.5$
t_{med}	$t_{max} + 1.4$	$t_{max} + 1.7$
N_{max}	$\frac{0.3y}{\sqrt{\ln y - 0.37}}$	$\frac{0.3y}{\sqrt{\ln y - 0.31}}$

- Longitudinal profile:

$$\frac{dE}{dt} = E_0 \frac{b^{\alpha+1}}{\Gamma(\alpha+1)} t^{\alpha} e^{-bt}$$

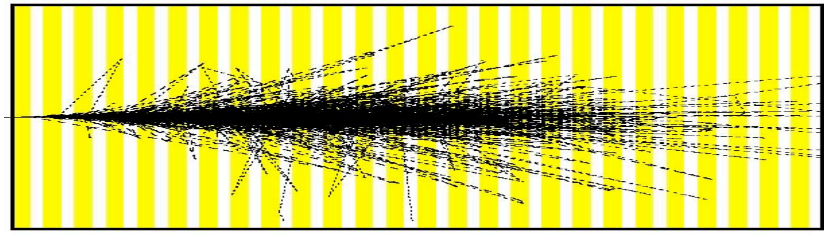
- 95% shower containment:

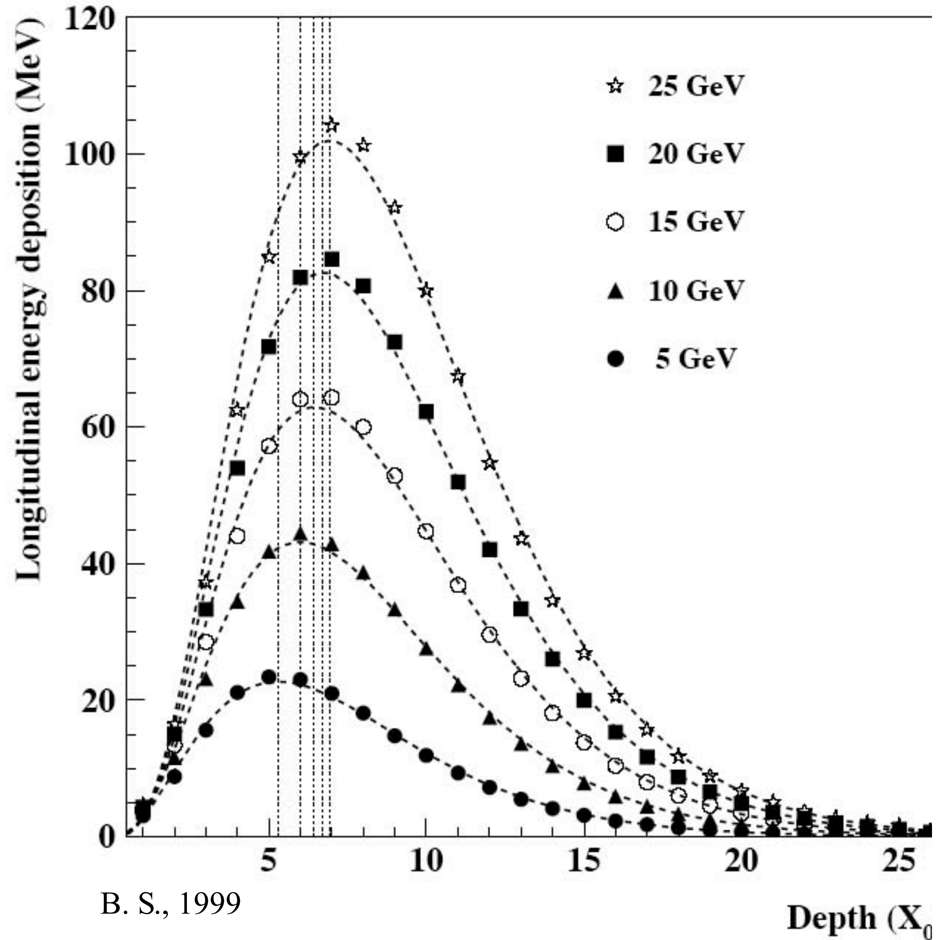
$$t_{max} = \alpha / b$$

$$t_{max}(25GeV \text{ for W}) \approx 7$$

$$L(95\%) \approx t_{max} + 0.08Z + 9.6$$

$$L(95\% \text{ for W}) \approx 22$$





Electromagnetic showers

Transverse shower profile

- Contributions to widening of shower:
  - Opening angle between e^-/e^+ for pair production
  - Emission of bremsstrahlung photons
  - Multiple scattering, dominant for the low-energy part of shower
- Transverse shower structure:
  $$\left(\frac{dE}{dr}\right) = \frac{1}{N}\left\{e^{-\sqrt{r/\lambda_1}} + C_{12}e^{-r/\lambda_2}\right\}$$
  - High-energy core
  - Low-energy halo
- Gradual widening of shower scales with Molière radius R_M: $E_S \approx 21\,\mathrm{MeV}$

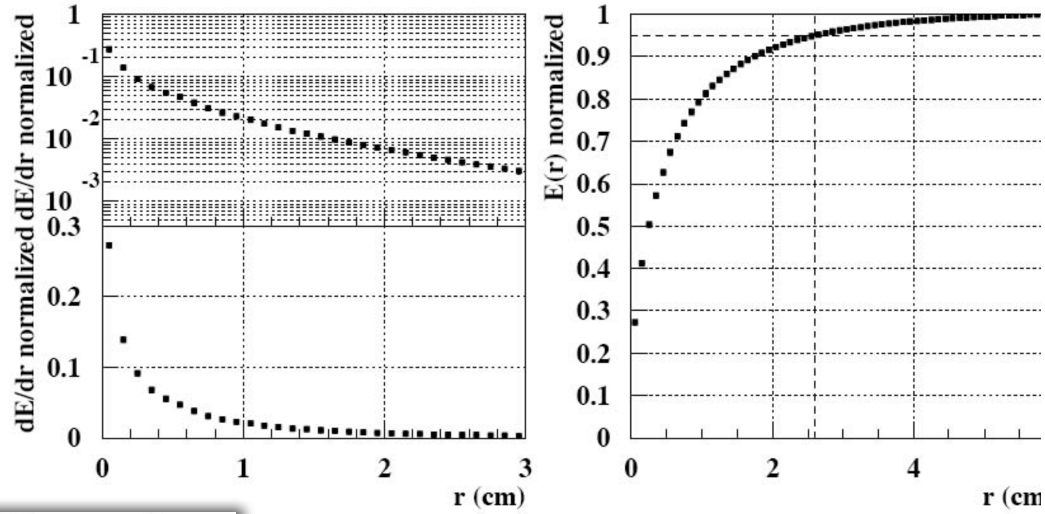
$$R_M \approx 7\frac{A}{Z} \qquad R_M \approx E_S\frac{X_0}{E_c}$$

- 95% shower containment:

$$R(95\%) \approx 2R_M$$

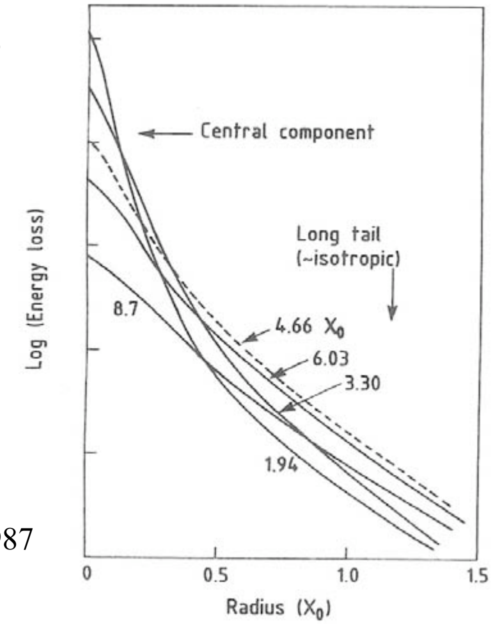
$$\text{For W}: R(95\%) \approx 2R_M = 2\,\mathrm{cm}$$

B. S., 1999



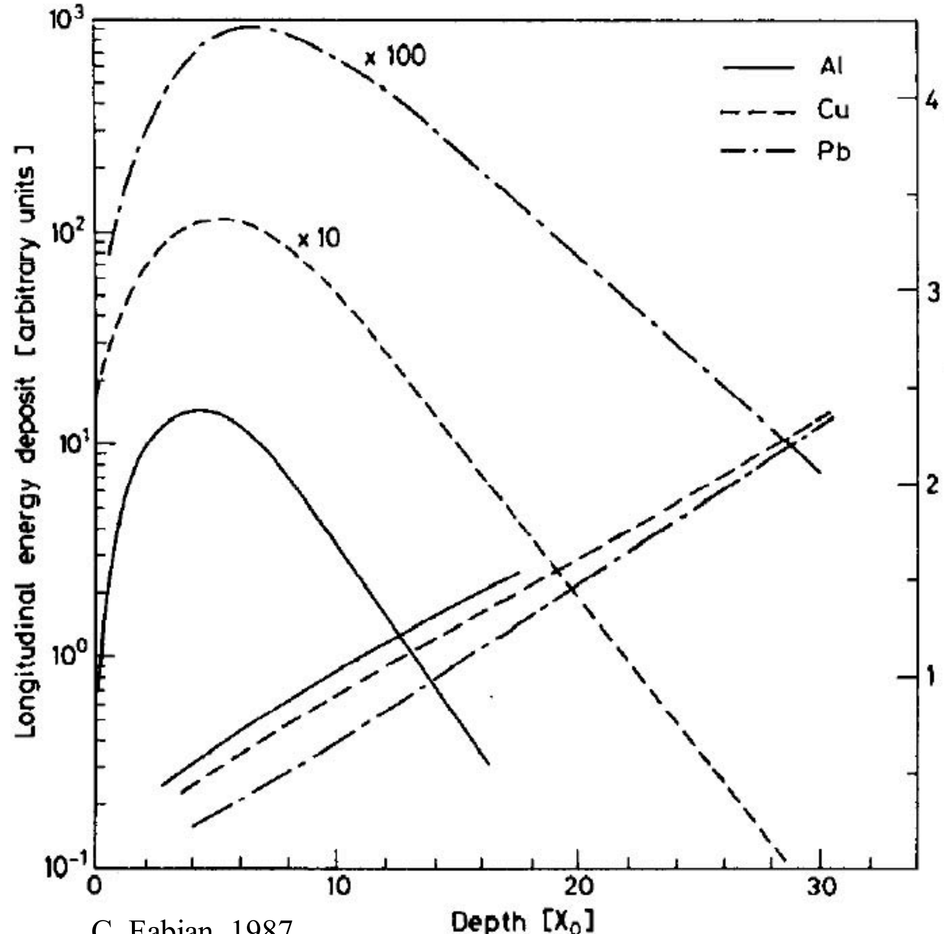
Electromagnetic showers

- Shower profile



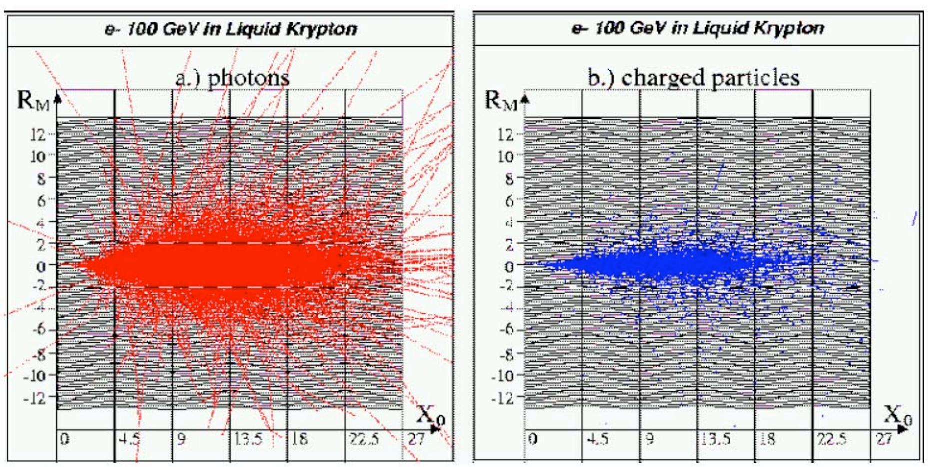
C. Fabjan, 1987

6GeV electrons in different materials:



C. Fabjan, 1987

MC simulation:



D. Wegener, 2001

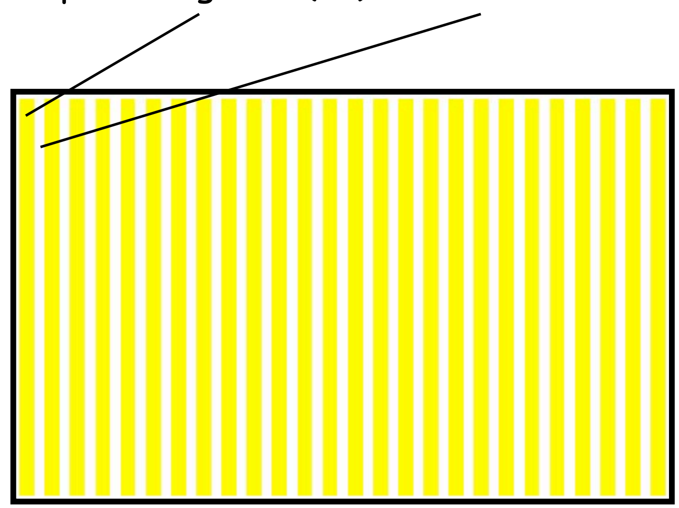
Electromagnetic showers

Calorimeter types

- Homogeneous calorimeter
  - Detector=Absorber
  - Good energy resolution
  - Limited position resolution (particularly in longitudinal direction)
  - Only used for electromagnetic calorimetry
- Sampling calorimeter
  - Detectors (active material) and absorber (passive material) separated: Only part of the energy is sampled
  - Limited energy resolution
  - Good position resolution
  - Used both for electromagnetic and hadron calorimeter

Example: Pb-glass

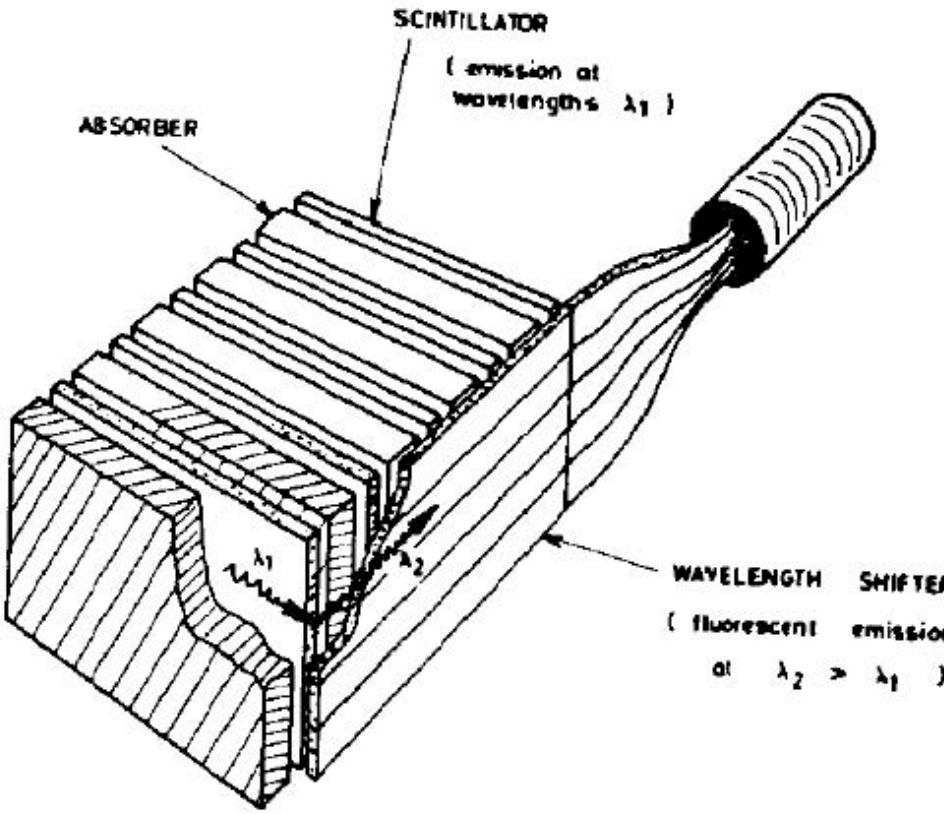
Example: Tungsten (W) - scintillator



Electromagnetic showers

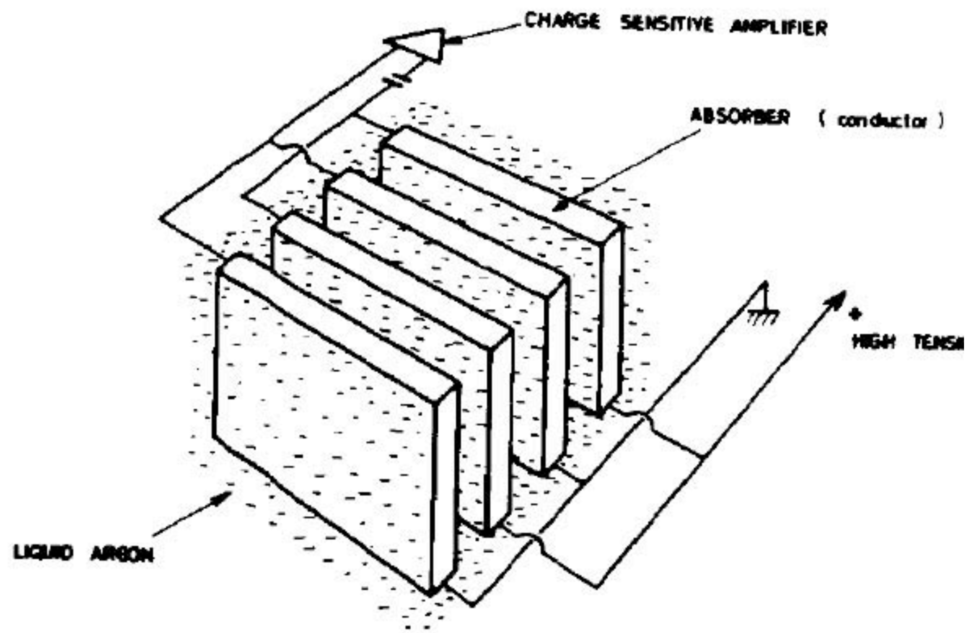
- Basic readout types for sampling calorimeters

  - Metal-scintillator sandwich structure



C. Fabjan and T. Ludlam, 1987

  - Metal-liquid argon ionization chamber



C. Fabjan and T. Ludlam, 1987

Electromagnetic showers

Scintillators

- General comments
  - Concept: Small fraction energy lost by a charged particle can excite atoms in the scintillation medium. A small percentage of the energy released in the subsequent deexcitation can produce visible light
  - Inorganic (e.g. crystals: BGO, CsI, $PbWO_4$) and organic scintillator are known
  - Organic scintillators: Organic crystals and liquid scintillators and plastic scintillators
- Plastic scintillators
  - Wide-spread use as trigger counters and in the calorimeter sampling structures as active detector material
  - Example: Rough design numbers for a plastic scintillator coupled to a photomultiplier tube (PMT):
    - Energy loss in plastic (MIP): 2MeV/cm
    - Scintillation efficiency: 1photon/100eV
    - Collection efficiency: 0.1
    - Quantum efficiency: 0.25

Number of photoelectrons: ~500

With a PMT gain of 10^6 one would collect 80pC!

Electromagnetic showers

Energy resolution: General considerations

- Intrinsic fluctuations
  - Track length T: Total length of all charged particle tracks within a calorimeter
  - Total detectable track length:

$$z = 4.58 \frac{Z}{A}\frac{E_{min}}{E_c}$$

$$F(z) = e^z\left[1 + z\ln(z/1.526)\right]$$

$$T = F(z)\frac{E_0}{E_c}$$

  - Number of energy depositions above minimum detectable energy E_{min} :

$$N_{max} = E_0/E_{min}$$

  - Intrinsic resolution:

$$(\sigma_E/E)_{intrinsic} \sim \sigma_{N_{max}}/N_{max} = 1/\sqrt{N_{max}} \propto 1/\sqrt{E_0}$$

  - Illustrative example: Pb-glass

$$E_{min} \simeq 0.7MeV \text{ for } E_0 = 1GeV$$

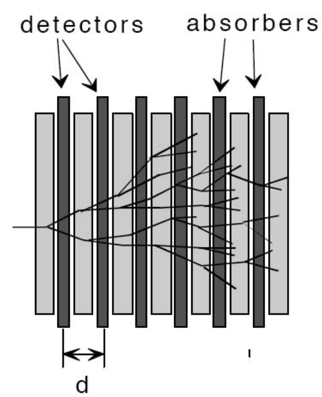
$$N_{max} = 1000/0.7 = 1500$$

⇒ Resolution: few percent!

- Intrinsic sampling fluctuations
  - In a sampling calorimeter, one determines not the total track length T but only a fraction of it depending on the thickness of passive and active absorber plates
  - Number of crossings:
  - Sampling resolution:

$$N_x = \frac{T_d}{d} = F(z)\frac{E_0}{E_c d}$$

$$(\sigma_E/E)_{sampling} \sim \sigma_{N_x}/N_x = 1/\sqrt{N_x}$$



Electromagnetic showers

- Energy resolution: General considerations

  - Instrumental effects

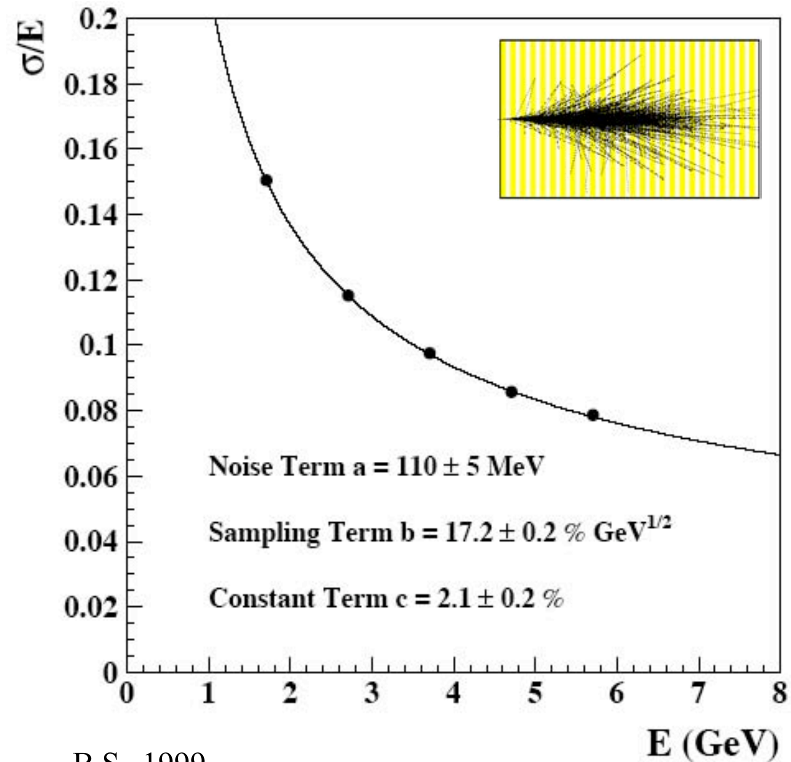
    - Effects other then the intrinsic resolution components are accounted for as follows:

$$\left(\frac{\sigma_E}{E}\right) = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

Stochastic term

Constant term (Imperfections in calorimeter design and calibration)

Noise term (e.g. electronic noise)



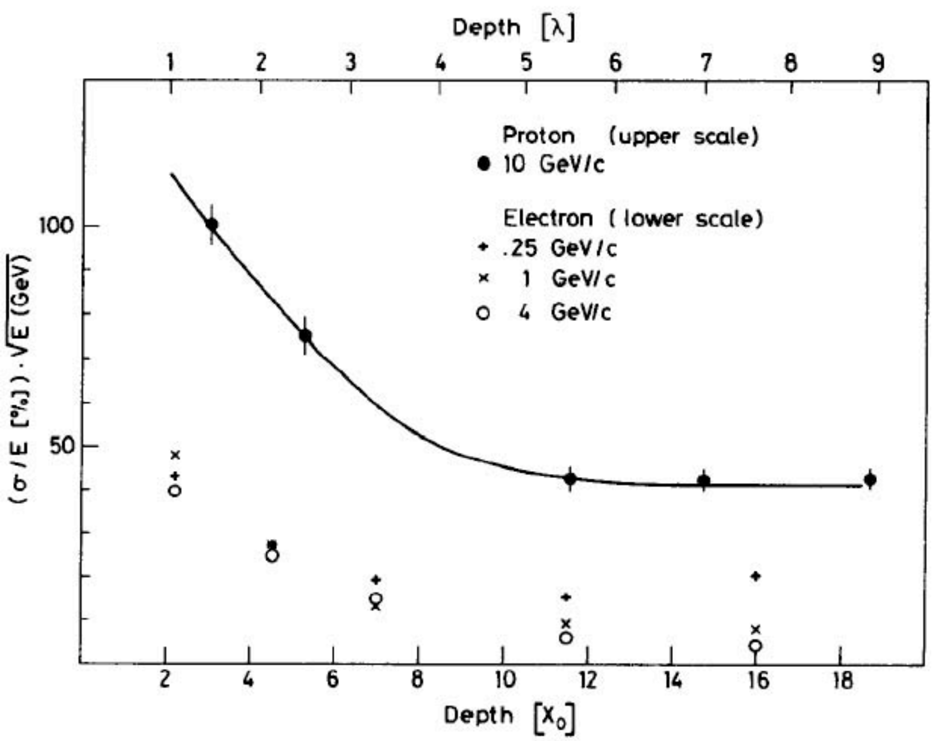
B.S., 1999

  - Additonal contributions to the energy resolution

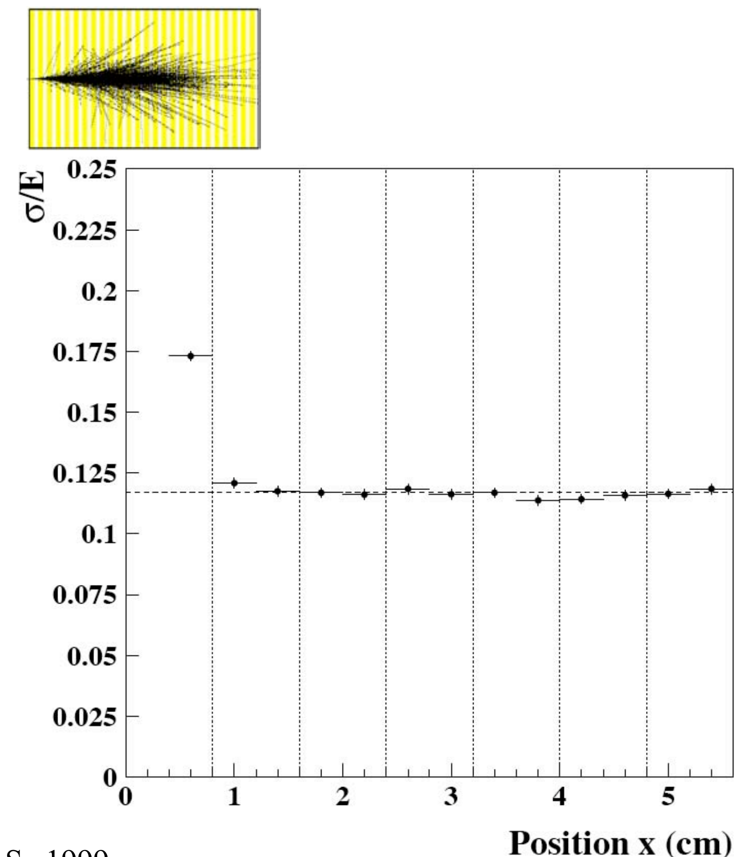
    - Longitudinal shower leakage
    - Transverse shower leakage
    - Dead material effects

Electromagnetic showers

- Energy resolution: Limitations
  - Longitudinal and transverse shower leakage



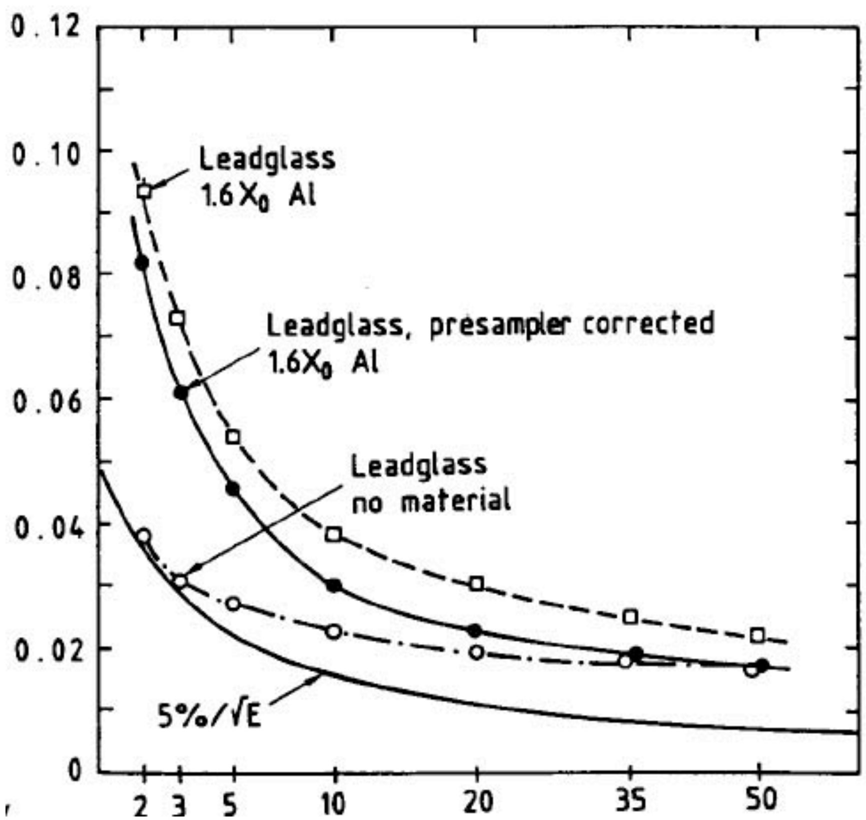
C. Fabjan and T. Ludlam, 1987



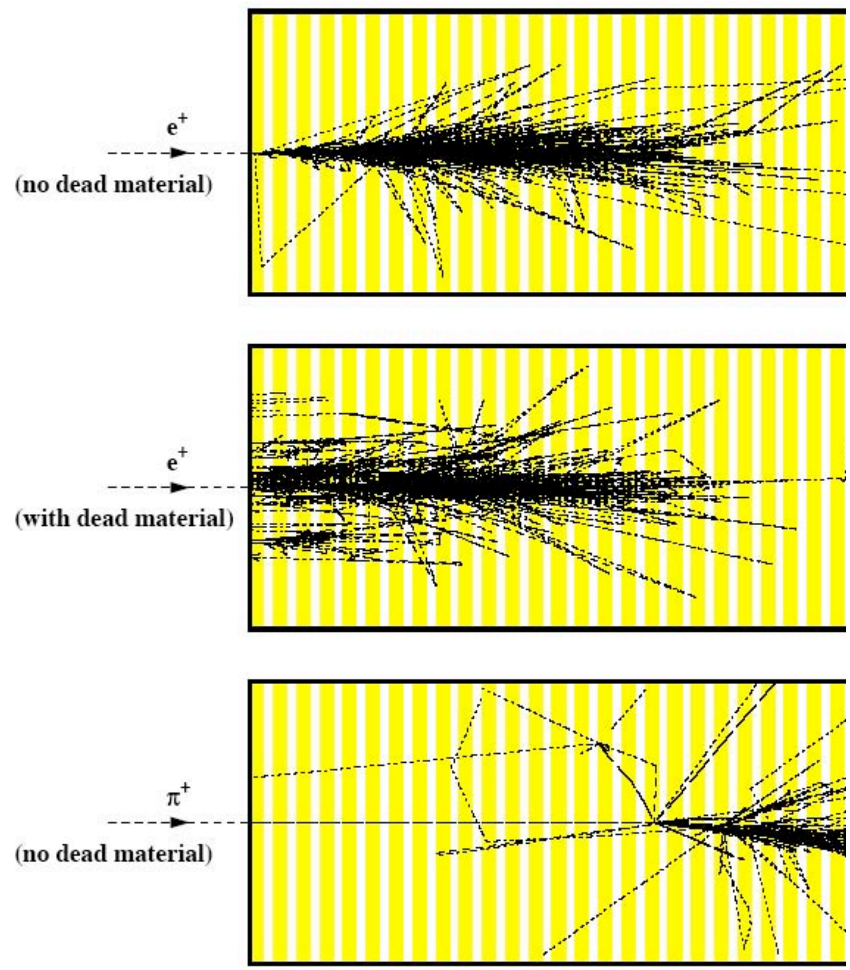
B.S., 1999

Electromagnetic showers

- Energy resolution: Limitations
  - Dead material effects



OPAL collaboration, C. Beard et al. NIM A 286 (1990) 117.

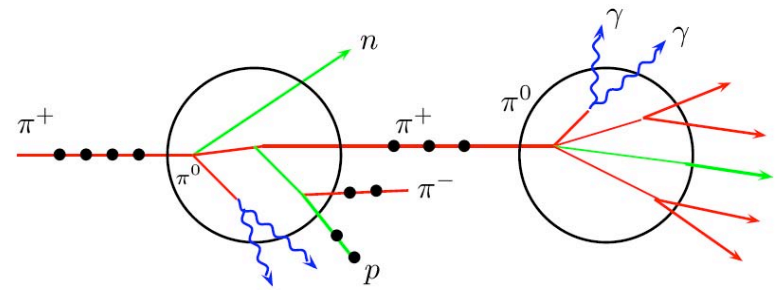


Hadronic showers

Hadronic shower development

- General comment: Complexity of of hadronic and nuclear processes produce multitude of effects that determine the functioning and performance of hadron calorimeters
  - Many channels compete in the development of hadronic showers
  - Larger variations in the deposited and visible energy
  - More complicated to optimize
- Sizeable electromagnetic (e) besides hadronic (h) shower contribution mainly from π^0 decay (1/3 of pions)
- Invisible energy due to delayed emitted photons in nuclear reactions, soft neutrons and binding energy
- Visible energy smaller for hadronic (h) than for electromagnetic (e) showers: Ratio of response e/h > 1
- Larger intrinsic fluctuations for hadronic than electromagnetic showers
- Improvements: Increase visible energy to get e/h=1: Compensation (Compensation for the loss of invisible energy)!
- Discussed instr. effects for e showers also hold for h showers

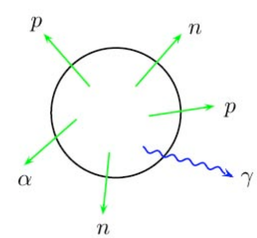
Step 1: Production of energetic hadrons with a mean free path given by the nuclear interaction length:



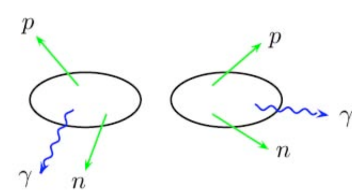
dE/dx nuclear cascade dE/dx nuclear cascade

Step 2: Hadronic collisions with material nuclei (significant part of the primary part of primary energy is consumed in nuclear processes):

Evaporation



Evaporation followed by evaporation



Hadronic showers

Hadronic shower profile

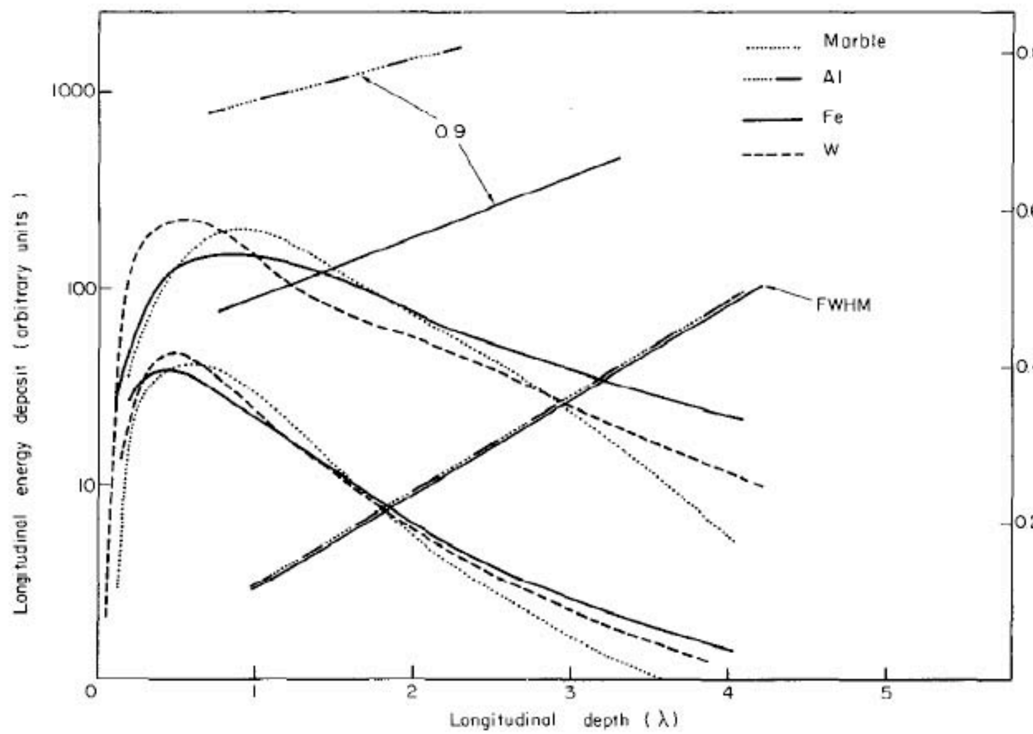
- Longitudinal and transverse shower shape characterized by λ_I
- Hadronic showers are much longer and broader then electromagnetic showers: Means of e/h separation
- Longitudinal containment:

$$t_{95\%} = a \ln E + b$$

$$t_{max}(\lambda_I) = 0.2 \ln E + 0.7$$

$$Fe : a = 9.4, b = 39, E = 100GeV : t_{95\%} = 80cm$$

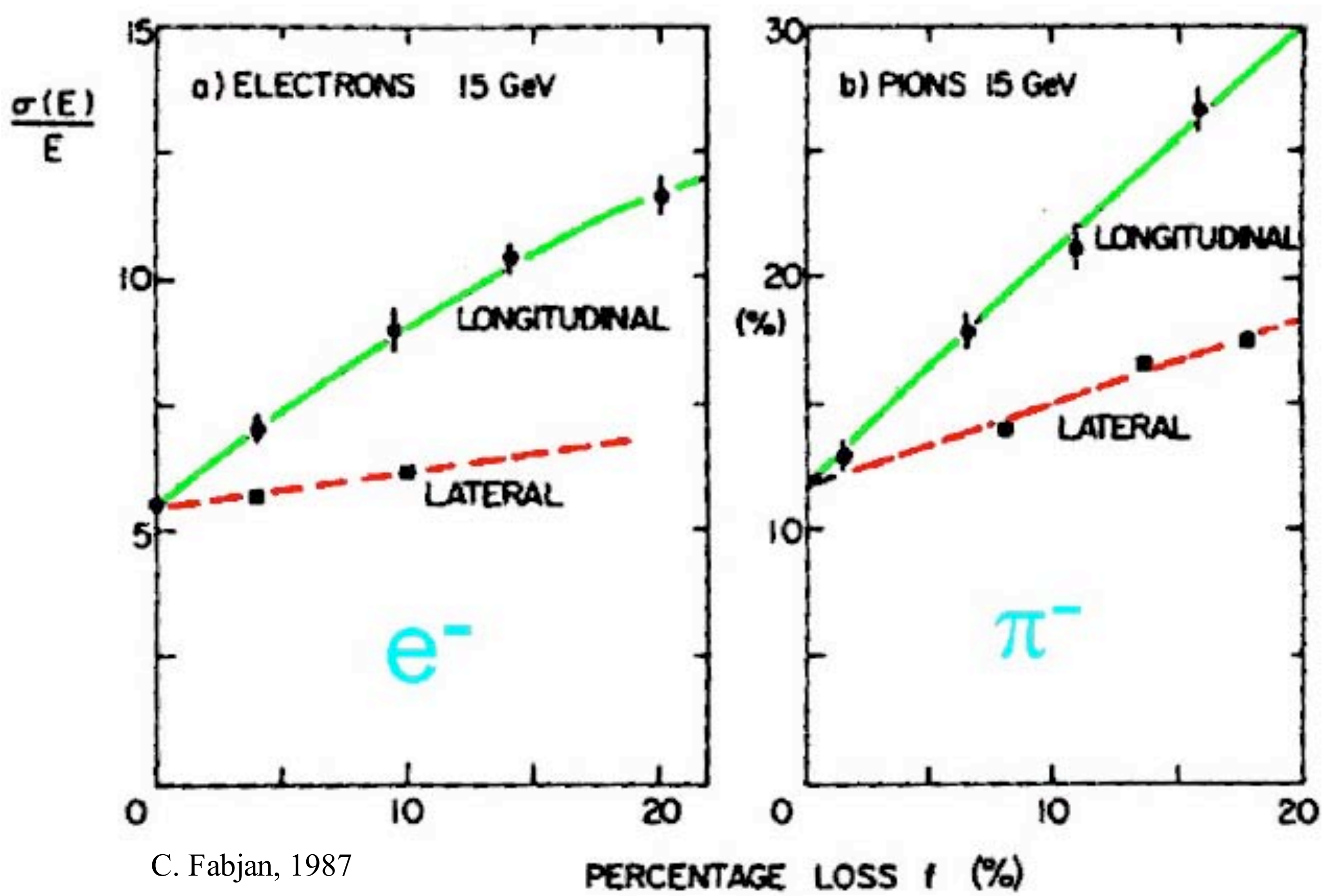
- Transverse containment:
  - 95% of shower contained with a cylinder of radius λ_I
  - Example: 16.7 cm for Fe



C. Fabjan, 1987

Hadronic showers

- Energy resolution: Example of longitudinal and transverse shower leakage



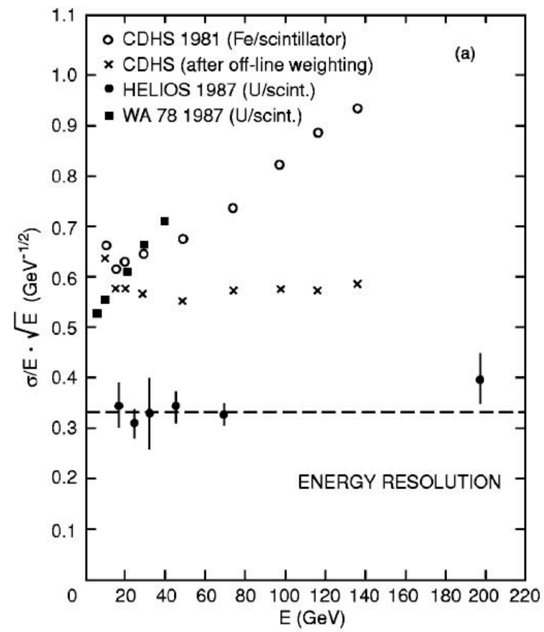
C. Fabjan, 1987

- Longitudinal leakage more serious than transverse shower leakage!

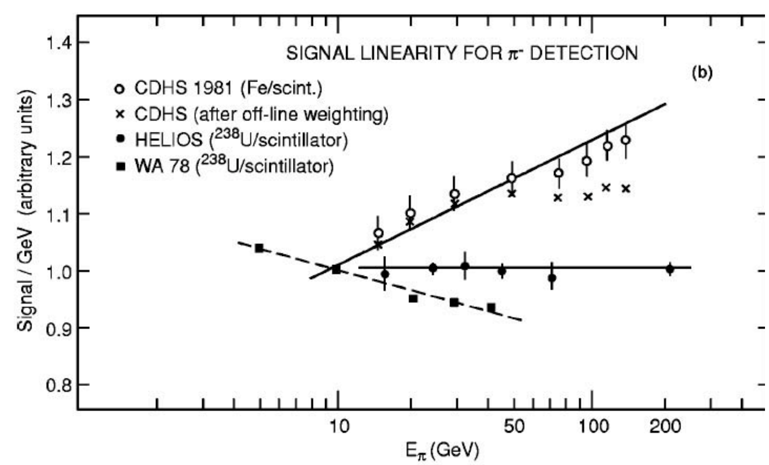
Hadronic showers

Energy resolution: Concept of compensation

- Compensation for loss of invisible energy: e/h=1
- Noncompensating detectors show deviations from scaling in $1/\sqrt{E}$ and non-linearity in signal response
- How can compensation be achieved?
  - Reduce e and increase h component
  - High-Z material such as U will absorb larger fraction of energy of electromagnetic part of shower: Smaller signal in active part from e contribution!
  - For the hadronic part, low energy neutrons are not affected by U. Interaction of n with hydrogen (large n-p cross section): Recoil proton produced in active part contributes to calorimeter signal thus larger signal in active part from h contribution
  - The amount of electromagnetic reduction and neutron amplification is set by the ratio of absorber to active material: Tuning this ratio yields compensation!
  - Other techniques: Software compensation (H1 Liquid Ar calorimeter)



C. Fabjan and F. Gianotti, 2003



C. Fabjan and F. Gianotti, 2003

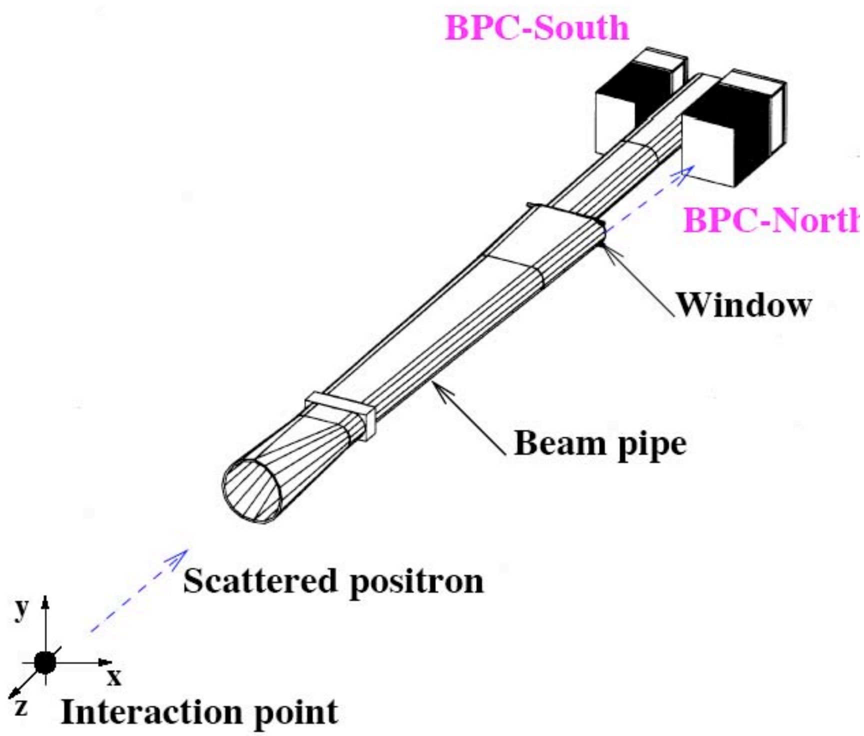
Electromagnetic and hadronic calorimeters

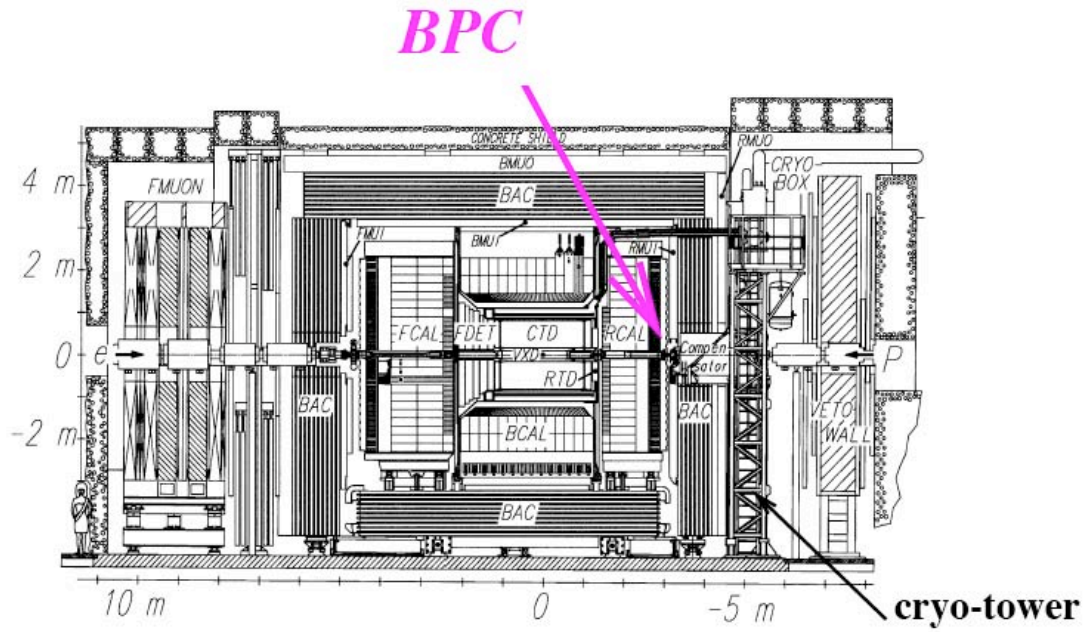
- **Overview**

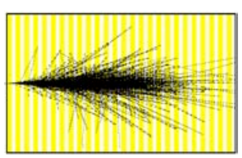
Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

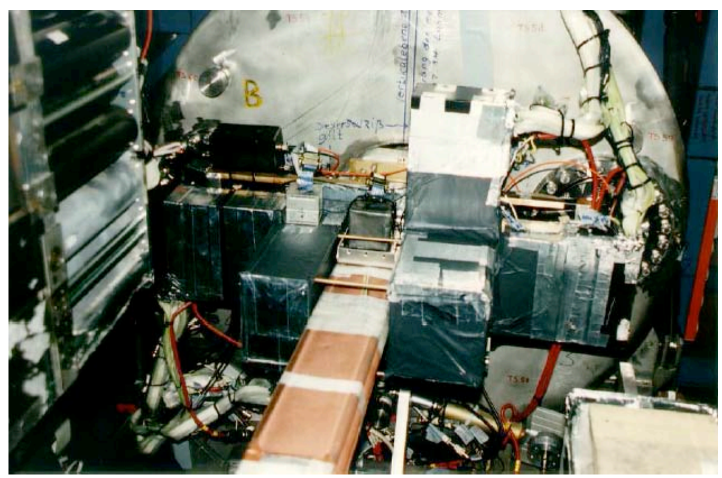
Electromagnetic calorimeter

- Sampling calorimeter: ZEUS Beam Pipe Calorimeter (BBC) at ep collider HERA
  - Overview



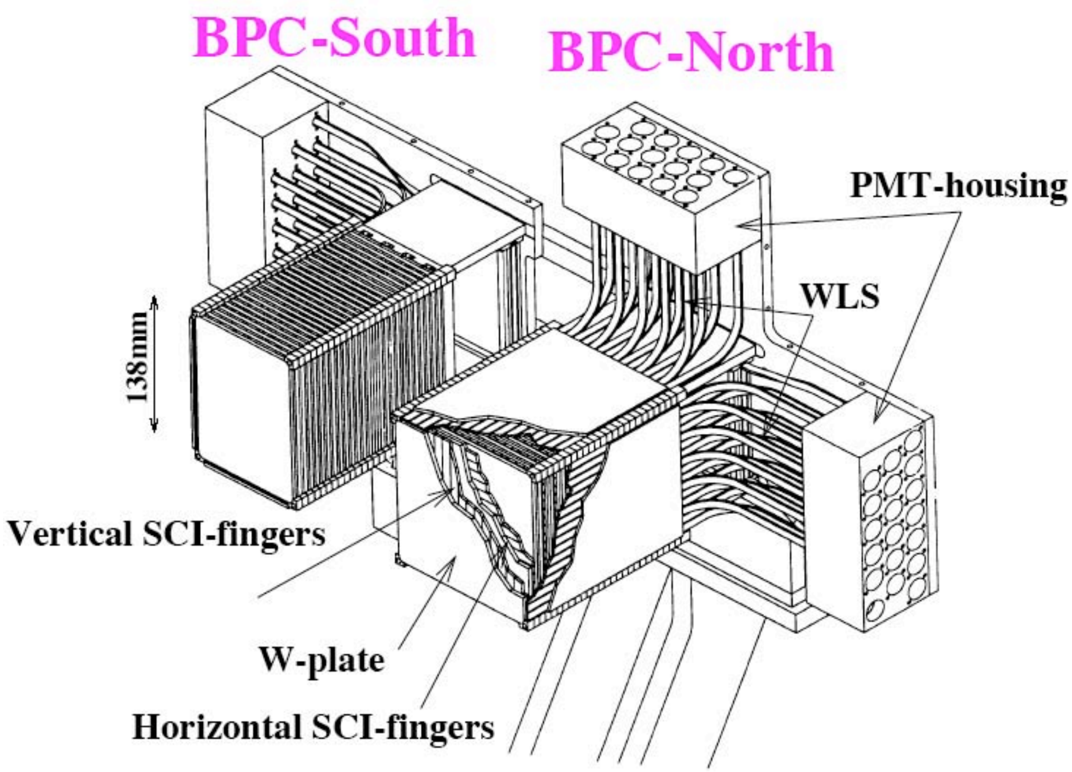


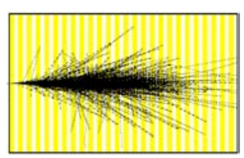




Electromagnetic calorimeter

- Sampling calorimeter: ZEUS Beam Pipe Calorimeter (BBC) at ep collider HERA

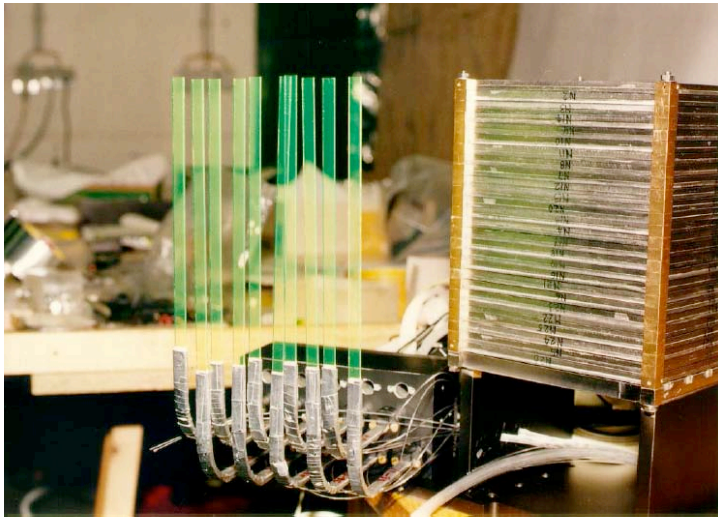


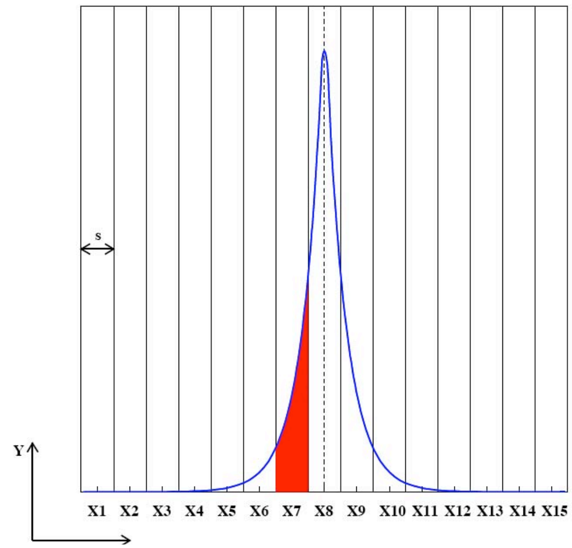


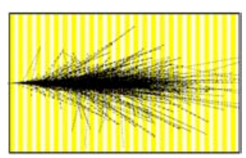
- Specifications:
  - Tungsten-scintillator electromagnetic-sampling calorimeter
  - Depth: 24 X_0
  - Alternating horizontal and vertical oriented 8 mm wide scintillator fingers
  - Energy resolution: 17%/√E
  - Accuracy of energy calibration 0.5%
  - Uniformity: 0.5
  - Position resolution: < 1 mm
  - Alignment: 0.5 mm
  - Time resolution: < 1 ns

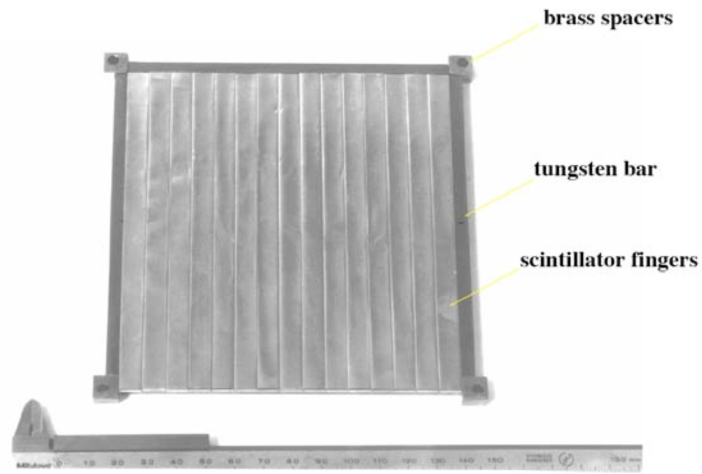
Electromagnetic calorimeter

- Sampling calorimeter: ZEUS Beam Pipe Calorimeter (BBC) at ep collider HERA
  - Layout



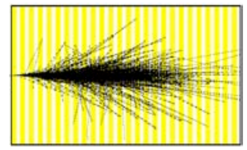


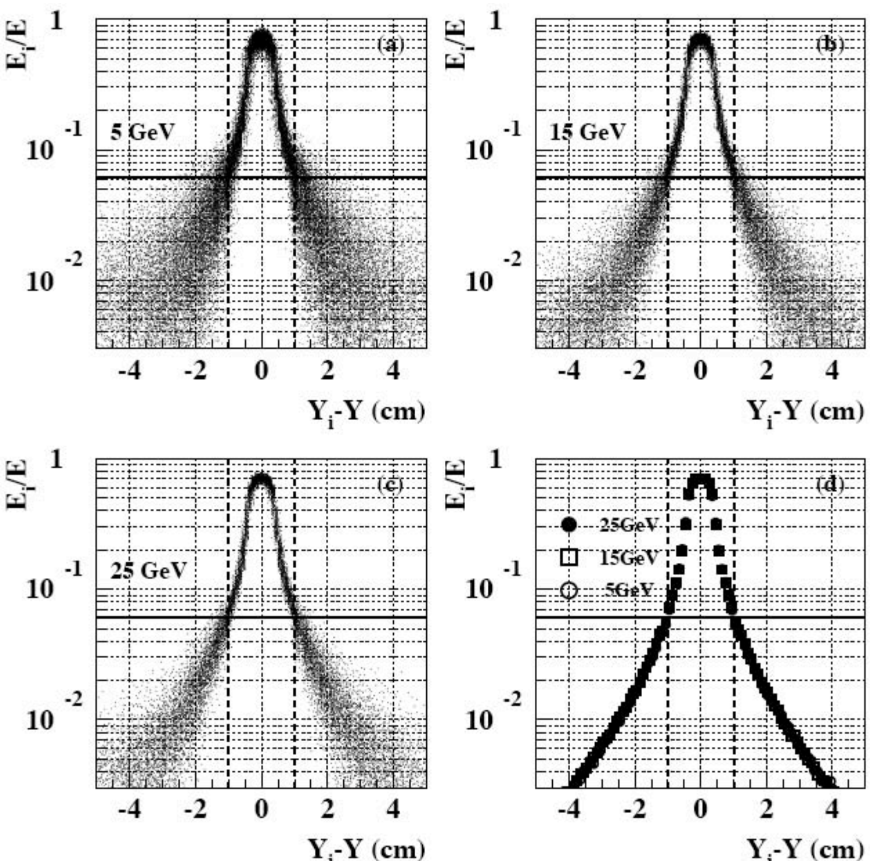




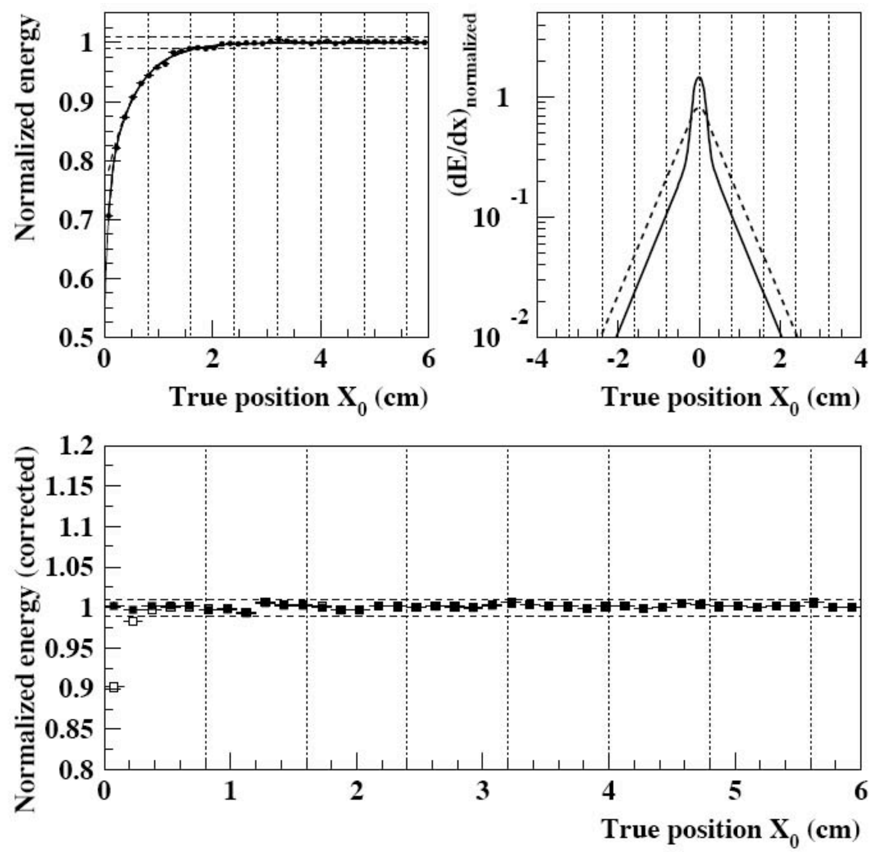
Electromagnetic calorimeter

- Sampling calorimeter: ZEUS Beam Pipe Calorimeter (BBC) at ep collider HERA
  - Transverse shower profile (MC study)





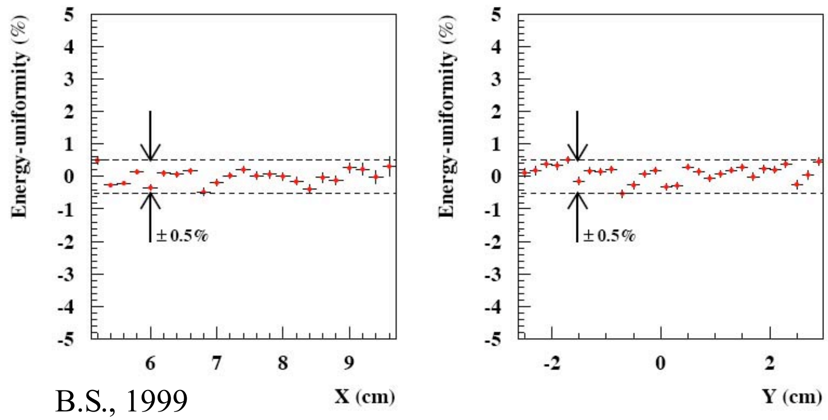
B.S., 1999



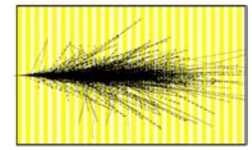
B.S., 1999

Electromagnetic calorimeter

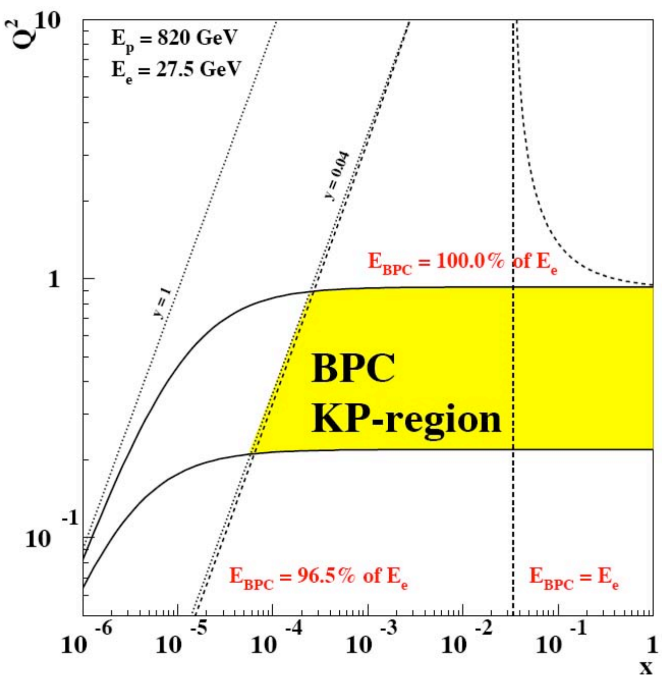
- Sampling calorimeter: ZEUS Beam Pipe Calorimeter (BBC) at ep collider HERA
  - Uniformity



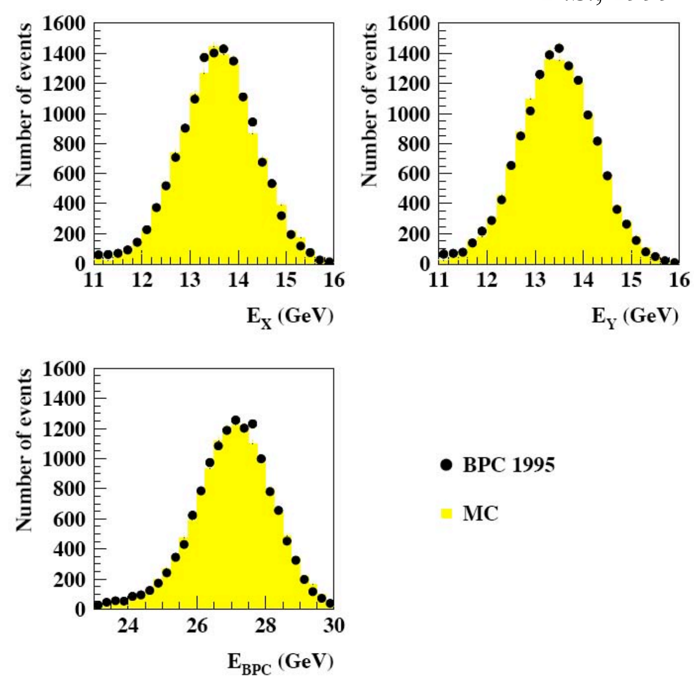
B.S., 1999



  - Energy scale

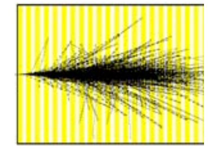


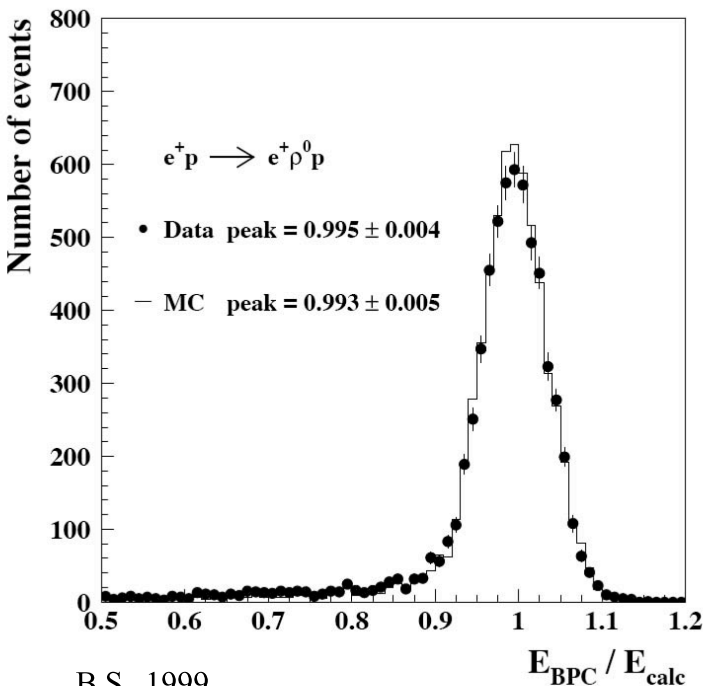
B.S., 1999



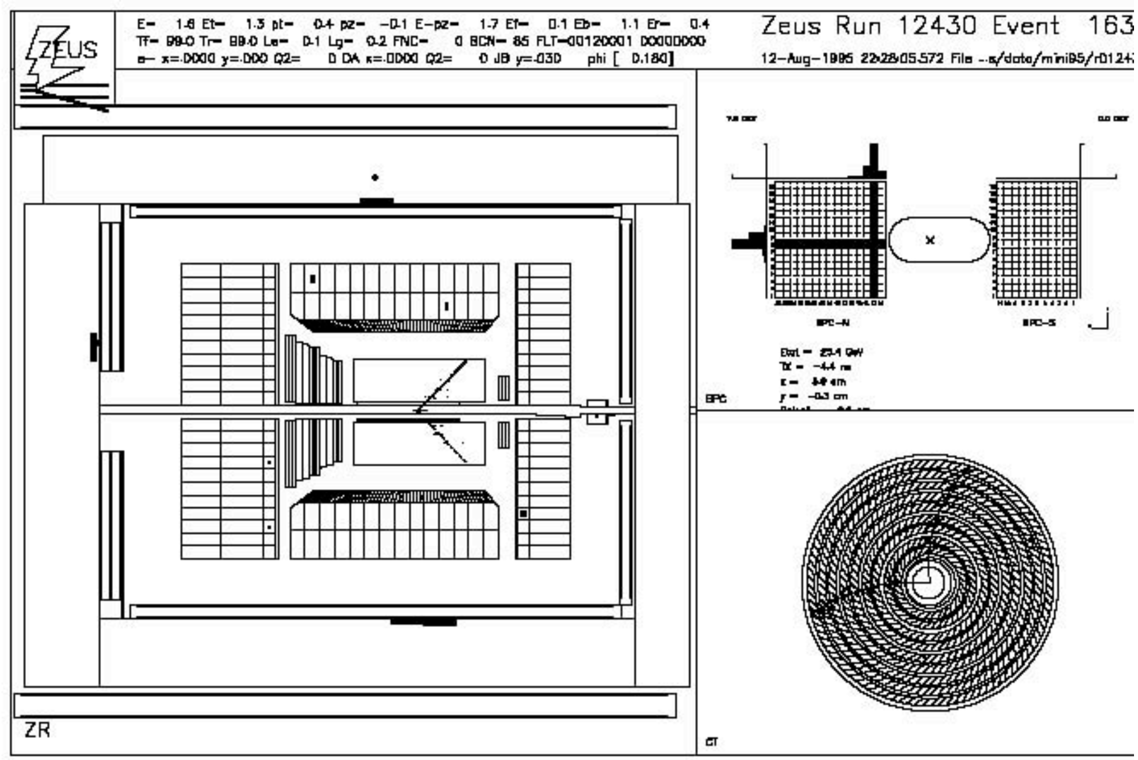
Electromagnetic calorimeter

- Sampling calorimeter: ZEUS Beam Pipe Calorimeter (BBC) at ep collider HERA
  - Uncertainty of energy scale



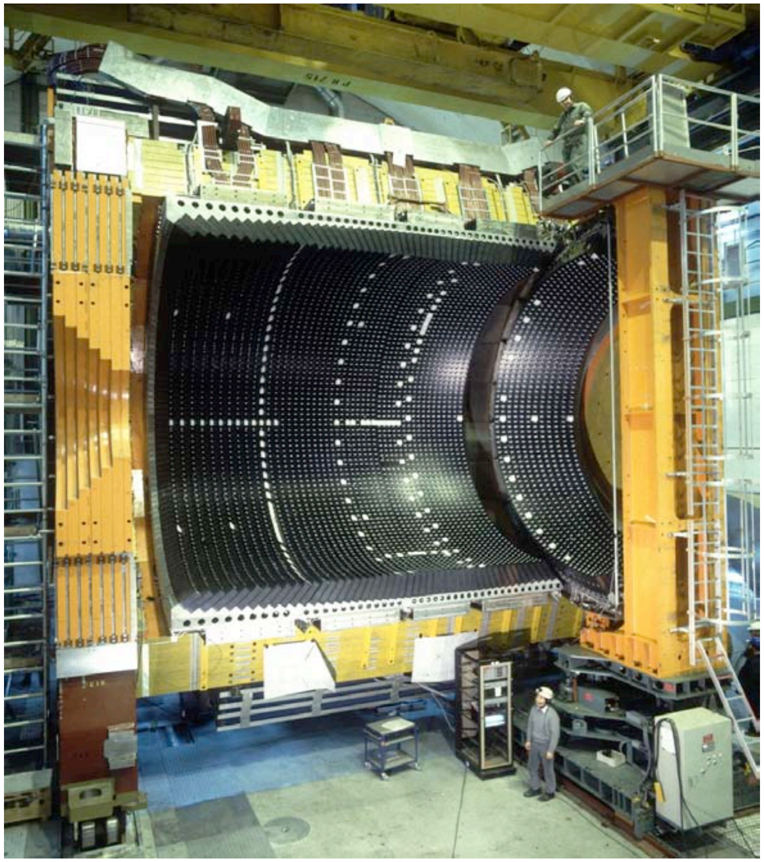


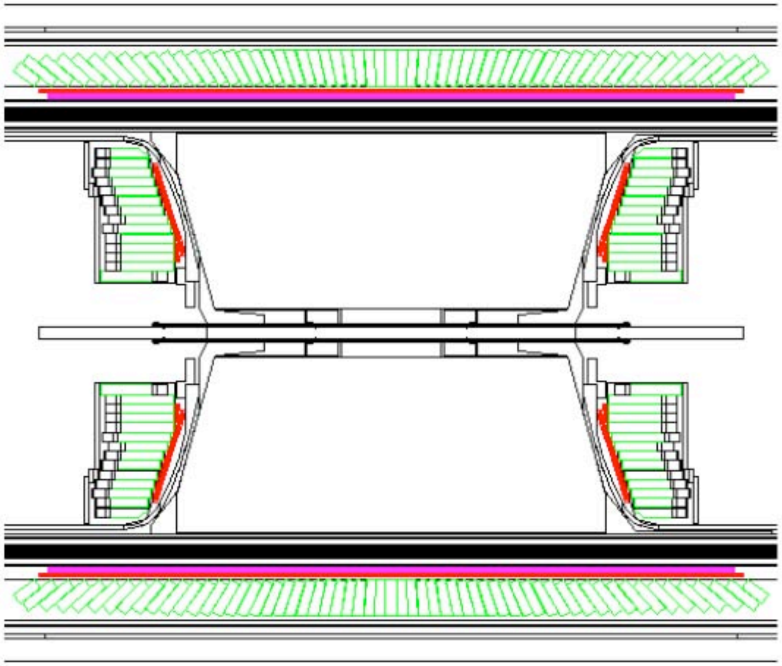
B.S., 1999



Electromagnetic calorimeter

- Homogeneous calorimeter: OPAL Pb-glass calorimeter at e^+e^- collider LEP
  - Layout



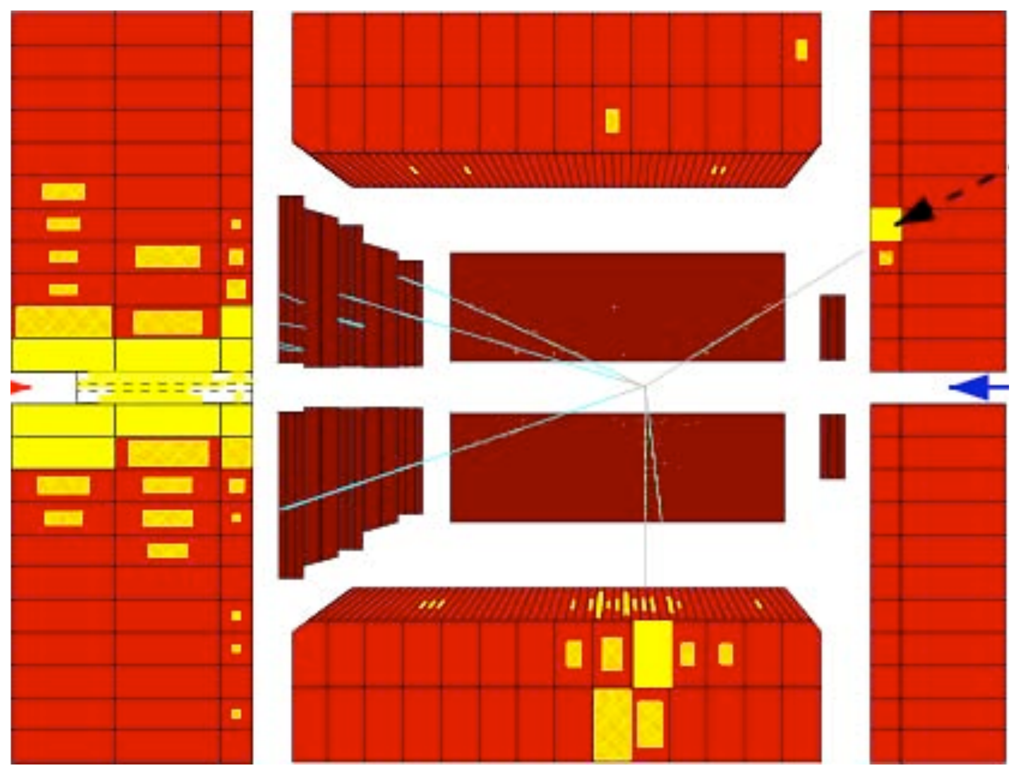


OPAL collaboration, C. Beard et al. NIM A 305 (1991) 275.

- 10572 Pb-glass blocks ($24.6X_0$)
- Energy resolution: $\frac{\sigma_E}{E} = \frac{6\%}{\sqrt{E}} \oplus 0.002$
- Spatial resolution: 11mm at 6GeV

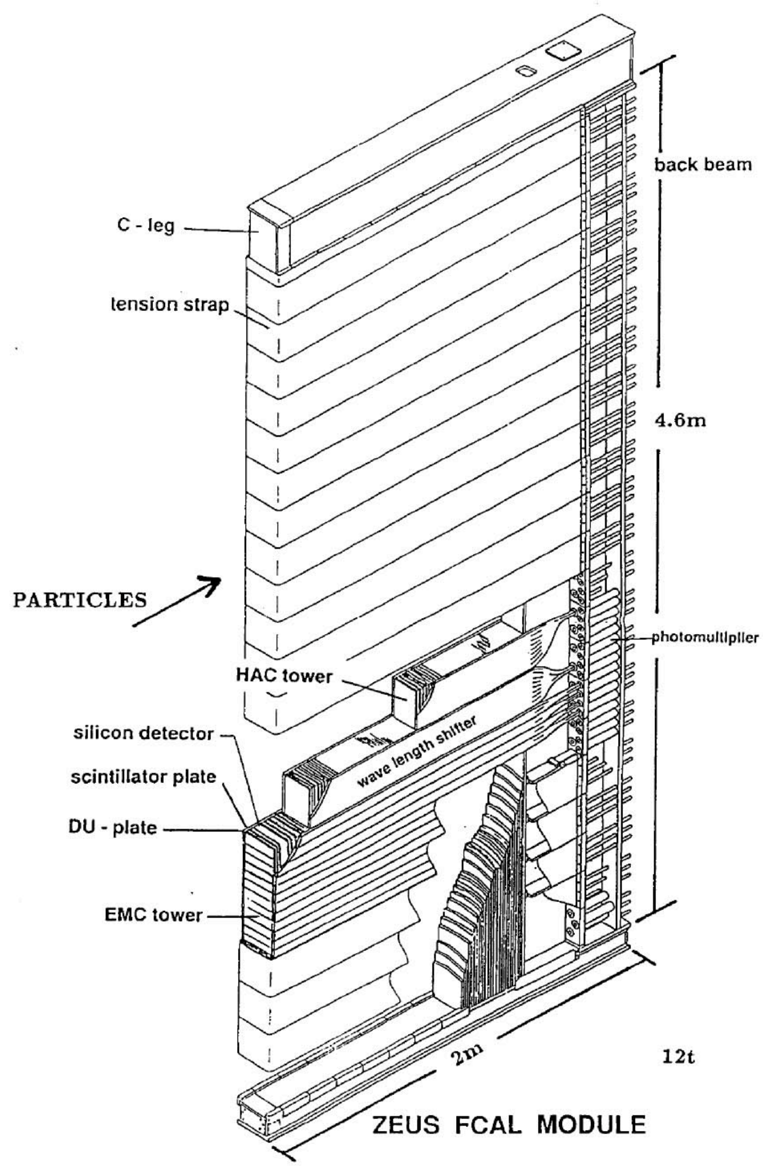
Hadronic calorimeter

- ZEUS Uranium Calorimeter at ep collider HERA
  - 3 Sections: Uranium Calorimeter
    - Forward (FCAL) (7λ): 2.2° - 39.9°
    - Barrel (RCAL): 36.7° - 129.1°
    - Rear (RCAL) (4λ): 128.1° - 176.5°
  - F/RCAL modules 20cm width
  - Original beam pipe hole: 20 x 20 cm^2
  - Compensating: e/h = 1.00 ± 0.02 (3.3mm U/2.6mm SCI)



Hadronic calorimeter

- **ZEUS Uranium Calorimeter at ep collider HERA**
  - Linear response to electrons and hadrons
  - Energy resolution
    - Electrons: $\frac{\sigma_E}{E} = \frac{18\%}{\sqrt{E}}$
    - Hadrons: $\frac{\sigma_E}{E} = \frac{35\%}{\sqrt{E}}$
  - Timing resolution: $\sigma_t = \frac{1.5}{\sqrt{E}}$ ns



Summary

- **Review**
  - Calorimeter: Prime device to measure energy (E) of high-energy particles through total absorption
  - Conceptual idea of calorimeter principle: Shower formation of decreasingly lower-energy particles
  - Electromagnetic calorimetry:
    - Underlying shower processes (QED) well understood: Completely governed by pair production and bremstrahlung above 1GeV
    - Transverse and longitudinal shower dimension: Characterized by radiation length
    - Homogeneous and sampling calorimeter types
  - Hadronic calorimetry:
    - Complexity of of hadronic and nuclear processes produce multitude of effects that determine the functioning and performance of hadron calorimeters: Electromagnetic and hadronic component
    - Transverse and longitudinal shower dimension: Characterized by nuclear interaction length
    - Sampling calorimeter types
    - Crucial step: Compensation for invisible energy in nuclear reactions: Achieve $e/h = 1$ by tuning the ratio of the passive/active sampling layer thickness $\Rightarrow$ Improvement in energy resolution: ZEUS U/SCI calorimeter: $35\%/\sqrt{E}$

Summary

- **Literature**
  - Textbooks
    - R. Fernow, Experimental particle physics, Cambridge University Press, Cambridge
    - W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer, New Yor
    - R. Wigmans, Techniques in calorimetry, Cambridge University Press, Cambridge
    - T. Ferbel, Experimental Techniques in High-Energy physics, Addison-Wesley, Menlo Pa
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    - C. Fabjan and T. Ludlam, Ann. Rev. Nucl. Part. 32 (1982) 32.
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    - R. Wigmans, Ann. Rev. Nucl. Part. Sci. 41 (1991) 133.
    - B.S., EPJdirect C2 (1999) 1.