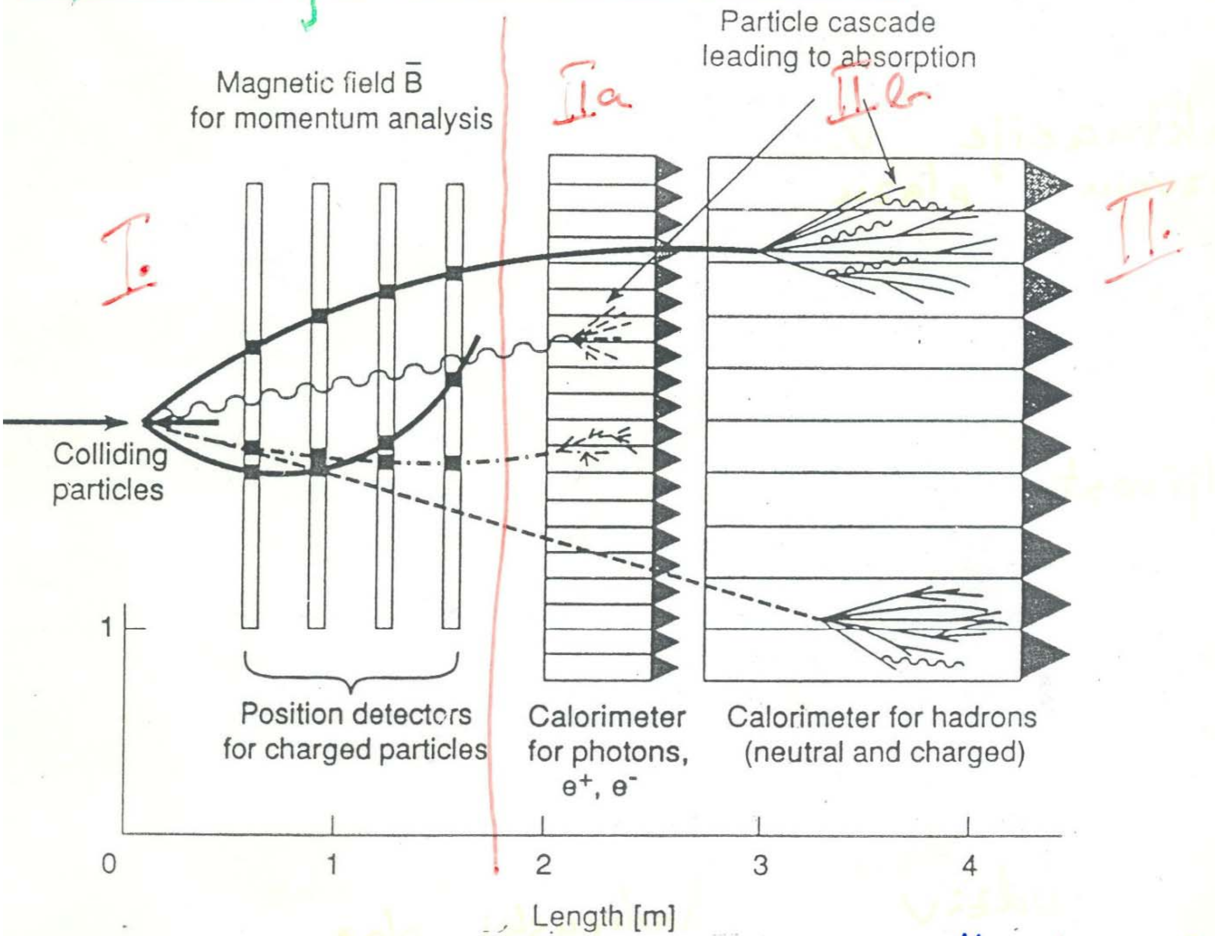
Merjenje energije - osnove kalorimetrije

a) zakaj kalorimetri?
b) EM plaz → EM kalorimeter
c) ločljivost EM kalorimetrov
d) vzorčevanje
e) hadronski plaz → hadronski kalorimeter
f) ločljivost hadronskih kalorimetrov
g) identifikacija s. kalorimetri

2

a) zakaj kalorimetri?



eksperiment → meritev $p^\mu = (E, \vec{p})$

$\vec{p}, E$ ali $\vec{p}, m$ ali $\vec{p}, v$

I. – $p = eBr$ sledilni sistem

II. – meritev E s popolno absorbcijo in zaznavo odložene energije

kalorimeter II.a EM e, γ

II.b hadronski π, K, p, n

odziv kalorimetra

- energija } delca
- vrsta

absorbcija (npr. število sek. delcev – N)
statistični proces → $\bar{E}$, σ_E

povprečni odziv, ponovljivost – ločljivost

prednosti kalorimetra za visoke E

- $\frac{\sigma_E}{E} \propto \frac{\sigma_N}{N} = \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E}}$ | – $\frac{\sigma_p}{p} \propto p/L^2$

ločljivost se izboljšuje! | se slabša!

- $L \propto \ln E$ | – $L \propto \sqrt{p}$

velikost narašča počasneje!

- $e, \gamma, \pi^{\pm}, \pi^0, K^{\pm}, \overset{(-)}{K}{}^0, p, n$ | – le nabiti

izmeri vse delce

- pljusk: E_{jet} | – $\vec{p}_{jet} = \sum_{jet} \vec{p}_i$

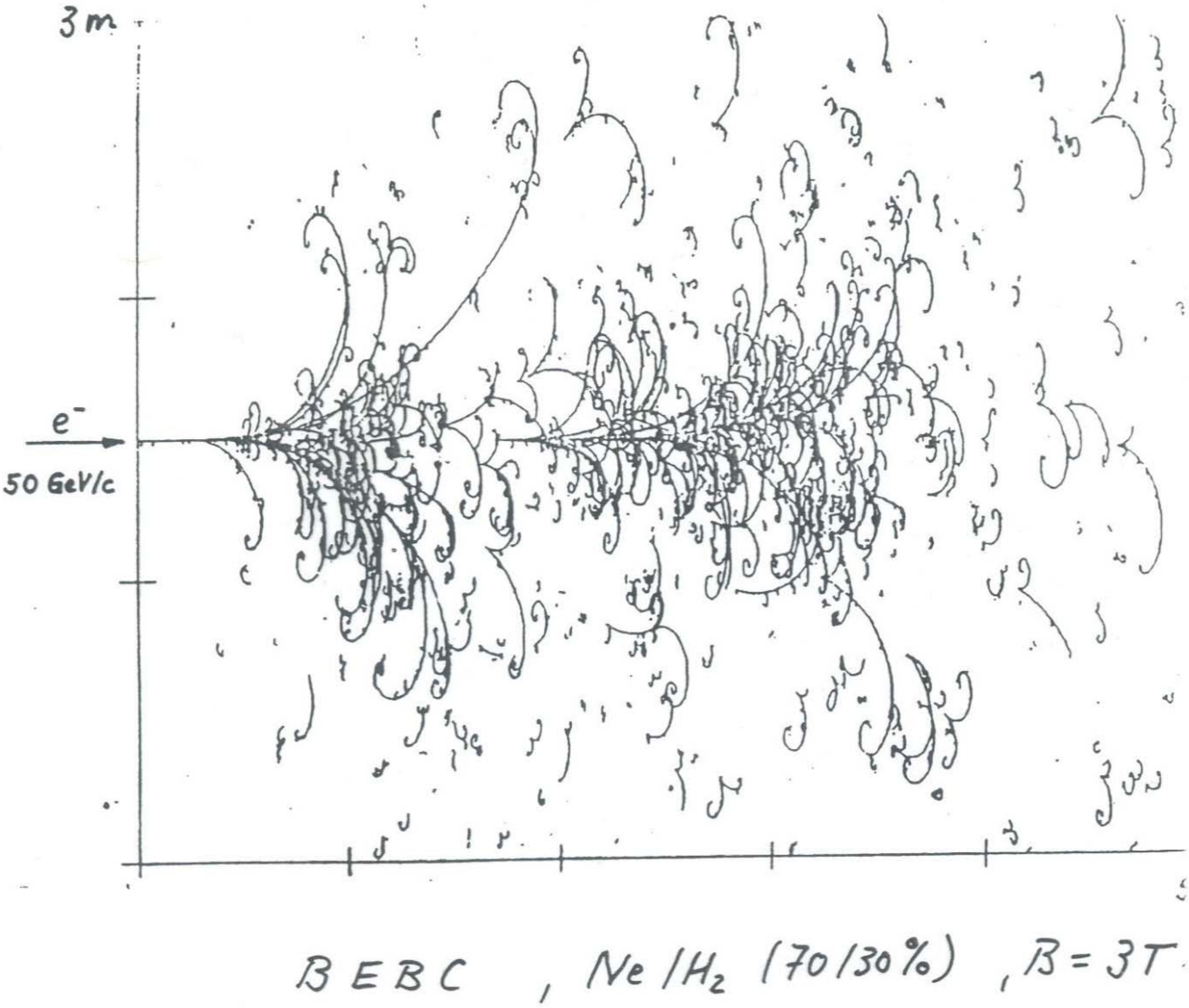
preprosta rekonstrukcija pljuskov
⇒ proženje

- hermetičnost
celoten dogodek ⇒ nevtrini, SUSY

III EM plaz

e ali γ z visoko energijo $E_0 >> E_c$

pari → zavorno sevanje → pari → .....



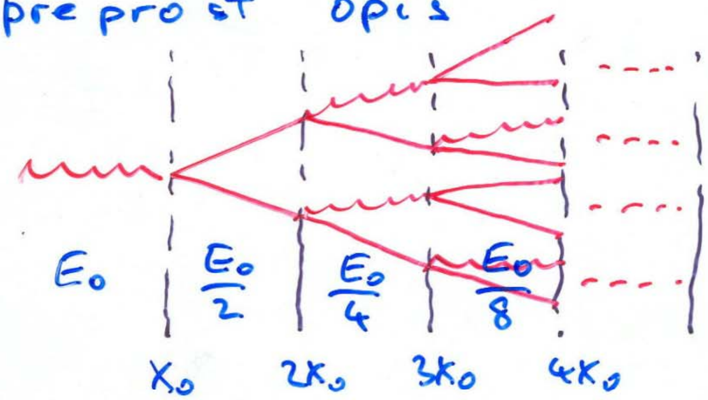
BEBC , Ne/H_2 (70/30%) , B = 3T

ELECTROMAGNETIC SHOWER DEVEL.

plaz raste dokler $e^{\pm}$ izgubljajo več energije z zavornim sevanjem kot z ionizacijo $- E_c$

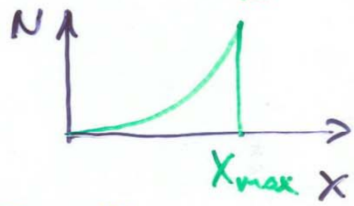
statistični proces

preprost opis



$$N = 2^{\frac{x}{X_0}}$$

$$E = \frac{E_0}{N}$$



maksimalna dolžina $E = E_c$

$$X_{max} = \frac{\ln \frac{E_0}{E_c}}{\ln 2} \qquad (44)$$

$$N_{max} = \frac{E_0}{E_c} \qquad (45)$$

dolžina (velikost detektorja) narašča kot $\ln E_0$ → kalorimetri

poznamo posamične procese ⇒

MC simulacija EM plazu

EGS (→ v GEANT)

longitudinalna oblika

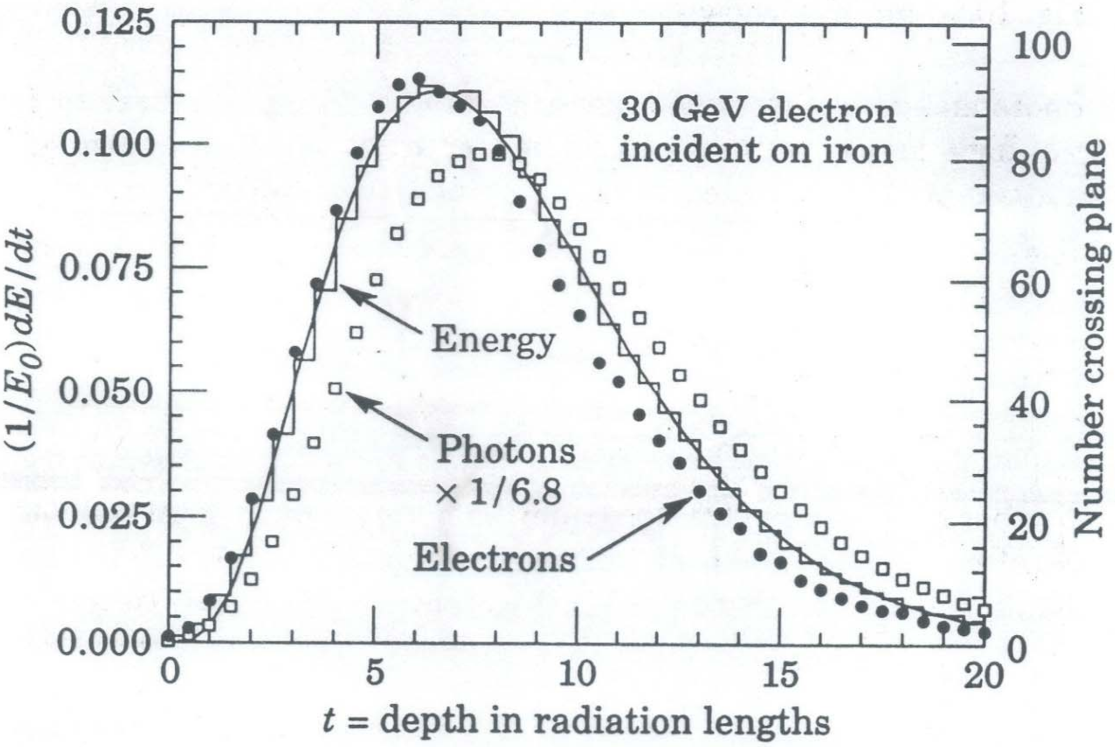
$$N = N_0 \left(\frac{x}{X_0}\right)^a e^{-b\frac{x}{X_0}} \qquad (49)$$

a, b : parametra, šibko odvisna od Z

zajetje 95% E_0

$$L\left(\frac{\Delta E}{E_0} = 95\%\right) \sim \left[\ln\left(\frac{E_0}{E_c} - 1\right) + 12\right] X_0 \qquad (50)$$

$\sim 21 X_0$ pri 100 GeV



analitični opis – Rossi '64
(Rossijeva aproksimacija B)

- $\frac{dE}{dx}_{ionizacija} = -\frac{E_c}{X_0} \neq f(E)$
- ni VCS, plaz v 1-D
- ni Comptonovega sipanja

vzdolžni profil

$$\frac{dE}{dt} = \frac{E_0\, b^{\alpha+1}}{\Gamma(\alpha+1)}\, t^{\alpha}\, e^{-bt} \qquad t = \frac{x}{X_0}$$

max pri $t_{max} = \frac{\alpha}{b} = \ln y_e^{\gamma} \mp 0{,}5$

$$y = \frac{E_0}{E_c}$$

skupna dolžina poti: $e^{\pm}$

$$T = y X_0 = \frac{E_0}{E_c} \cdot X_0$$

⇒ EM plaz odvisen le od

$$t = \frac{x}{X_0} \qquad y = \frac{E_0}{E_c}$$

$$\frac{1}{X_0} \sim \frac{\rho\, Z(Z+1)}{A} \cdot \frac{\ln(287/\sqrt{Z})}{716{,}4\ g\,cm^{-2}} \qquad E_c \sim \frac{600\,\mathrm{MeV}}{Z+1{,}2}$$

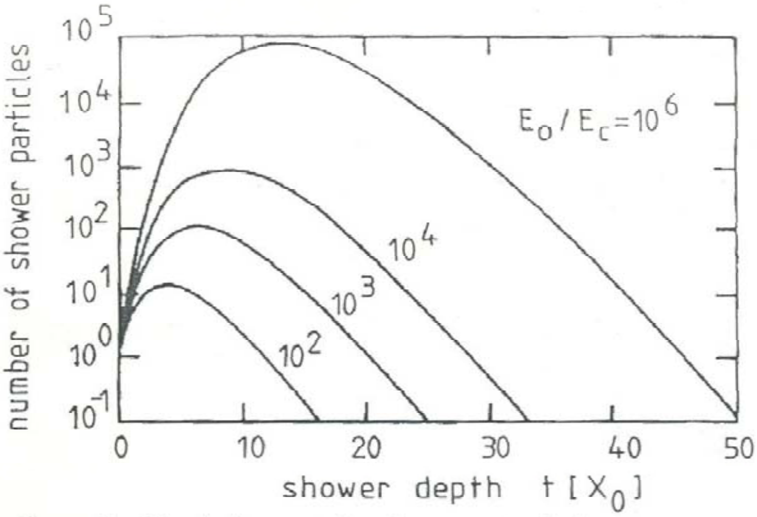


Fig. 7.21. Longitudinal shower development of electromagnetic cascades (E_c - critical energy) [509, 503].

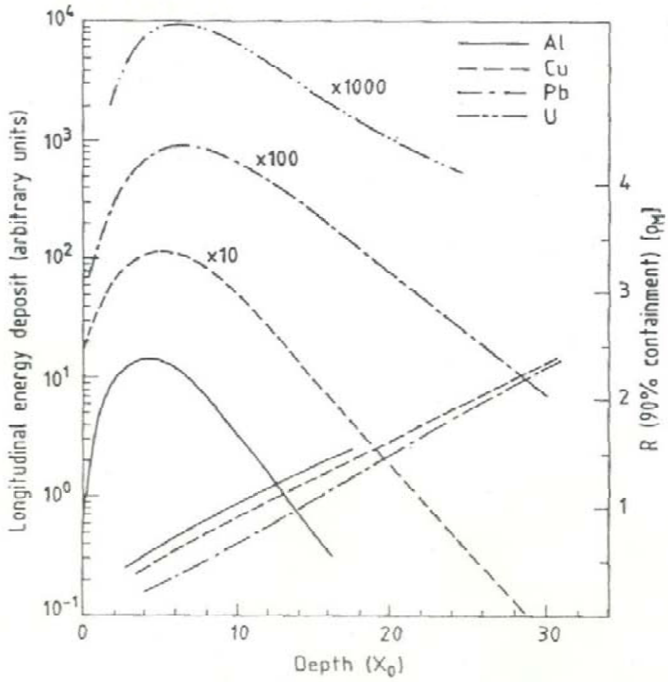


Fig. 3: Longitudinal shower development (left ordinate) of 6 GeV/c electrons in four very different materials, showing the scaling in units of radiation lengths X_0. On the right ordinate the shower radius for 90% containment of the shower is given as a function of the shower depth. In the later development of the cascade, the radial shower dimensions scale with the Molière radius $\varrho_M \sim 7A/Z$. [Al, Cu, and Pb, adapted from G. Bathow et al., Nucl. Phys. B20:592 (1970). Uranium data from G. Barbiellini et al., Ref. [127].

prečne dimenzije

začetek - zavorno sevanje $\vartheta \propto \left(\frac{E}{m_e}\right)^{-1} \sim 0$
- pari

kasneje - VCS

Moliere $\rho_M = X_0 \frac{21\,MeV}{E_c}$

različni materiali - str. 7, sl. 3., leva skala

vzdolžno širjenje plazu

1 GeV e^- na Al

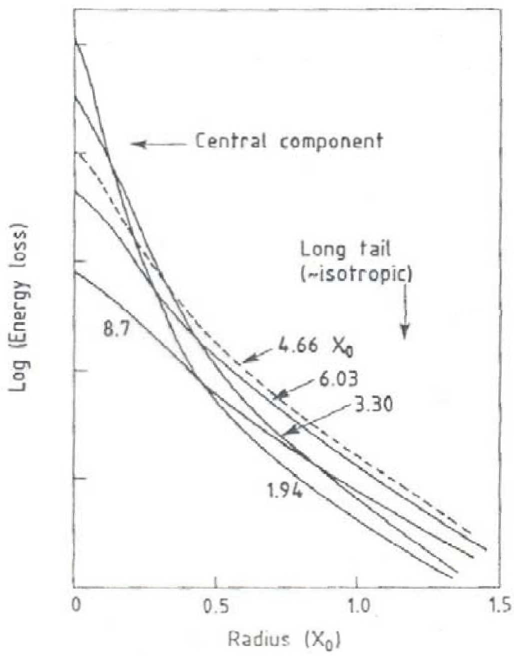


Fig. 4: Radial shower profile of 1 GeV electrons in aluminium; a pronounced central core, surrounded by 'halo', gradually widens with increasing depths of the shower [17].

c) ločljivost EM kalorimetrov

$E \rightarrow$ plaz $\rightarrow$ ionizacija (T)

$\rightarrow$ signal: detektiramo (T_v)
- naboj (Si, LAr)
- scint. fotone (NaJ, CsJ)
- Čerenkove -"- (Pb steklo)

prag za detekcijo $\eta \Rightarrow T_v < T$

$$T_v = F\left(\frac{\eta}{E_c}\right) \frac{E}{E_c} X_0$$

$$F\left(\frac{\eta}{E_c}\right) = \left(1 + \xi \ln \frac{\xi}{1{,}53}\right) e^{\xi}$$

$$\xi = 2{,}29 \frac{\eta}{E_c}$$

ocena $N = \frac{E}{\eta}$; $\frac{\sigma_E}{E} = \frac{1}{\sqrt{N}}$

Pb steklo $\eta \sim 0{,}7\ \mathrm{MeV}$; $\frac{\sigma_E}{E} = \frac{2{,}5\%}{\sqrt{E[\mathrm{GeV}]}}$

še statistika fotoelektronov

$2{,}5\% \rightarrow 4\%$

NaJ $E_c = 11{,}8\ \mathrm{MeV}$ $\frac{\eta}{E_c} = 0{,}04$

račun $$\left(\frac{\sigma_E}{E}\right)_{\text{intrinsic}} = \frac{0{,}7\%}{\sqrt{E(\mathrm{GeV})}}$$

(nedoseženi) cilj graditeljev EM kalorimetrov

10

ločljivost je slabša od $\left(\frac{\sigma_E}{E}\right)_{intrinsic}$

- statistika $\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}}$
- puščanje
- nehomogenosti
- kalibracija

} $\sigma_E \propto E$

- šum elektronike $\sigma_E = konst$

skupaj

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

nizke E — a, c

visoke E — b

druge parametri za cije

$\frac{\sigma_E}{E} \propto E^{-1/4}$ NaJ, CsJ

nehomogenosti v kristalu ($\sim a \oplus c$)

d) vzorčevanje

homogen detektor – cena
– zbiranje signala

Pb, W, Fe scintilator, LAr, MWPC
absorber (pasivni) & detektor

⇒ vzorčevalni kalorimeter

(+) absorber: – majhen X_0 – kompakten
– poceni
detektor: – segmentiran – profil plazu
– lažje zbiranje (svetloba, el. signal)

(–) dodatne fluktuacije – slabša $\frac{\sigma_E}{E}$

ocena: štejemo prehode skozi det. ravnine

$N = \frac{T}{d}$ d – razdalja med det. rav.

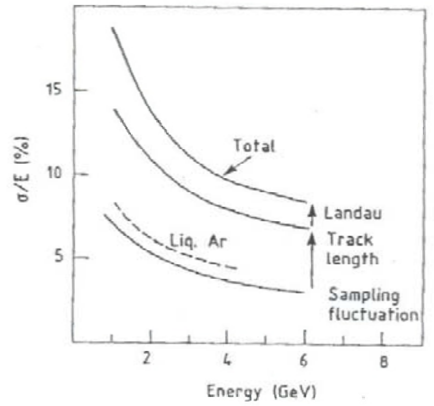
$N = \frac{E}{E_c}\frac{X_0}{d} = \frac{E}{\Delta E}$ ΔE – izguba v eni plasti

$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{N}} = \frac{1}{\sqrt{1000}}\sqrt{\frac{\Delta E\,(\mathrm{MeV})}{E\,(\mathrm{GeV})}} = 3{,}2\%\sqrt{\frac{\Delta E\,(\mathrm{MeV})}{E\,(\mathrm{GeV})}}$$

tipično: $d \sim X_0 \to \Delta E \sim E_c \sim 10\,\mathrm{MeV} \Rightarrow \frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E\,[\mathrm{GeV}]}}$

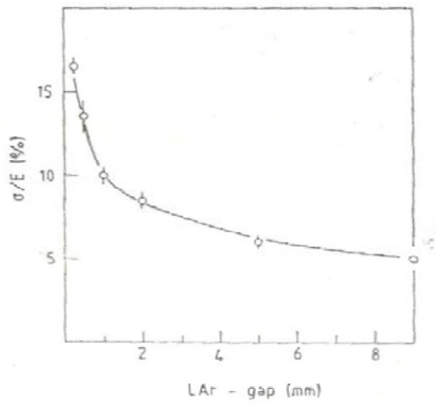
ločljivost poslabša

- VCS : $\langle d \rangle = \frac{d}{\langle \cos \vartheta \rangle}$
- zaradi parov e^+e^- $N_{eff} < N$
- plinski detektor: - sipanje v ravnino detektorja; - fluktuacije (Landau) } 10x slabše!



plin

Fig. 7b: Contributions of sampling, path length, and Landau fluctuations to the energy resolution of a lead/MWPC sampling calorimeter. The latter contribute approximately equally (~ 12% at E = 1 GeV), and combined quadratically with the sampling fluctuations (~ 7%) they account for the overall resolution of ~ 18%/√E [14].



LAr

Fig.7a: Energy resolution versus thickness of the active liquid-argon layer for 1 GeV electrons in an iron/argon sampling calorimeter.

12a

Table 28.5: Resolution of typical electromagnetic calorimeters. E is in GeV.

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	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

e) hadronski plaz → HCAL

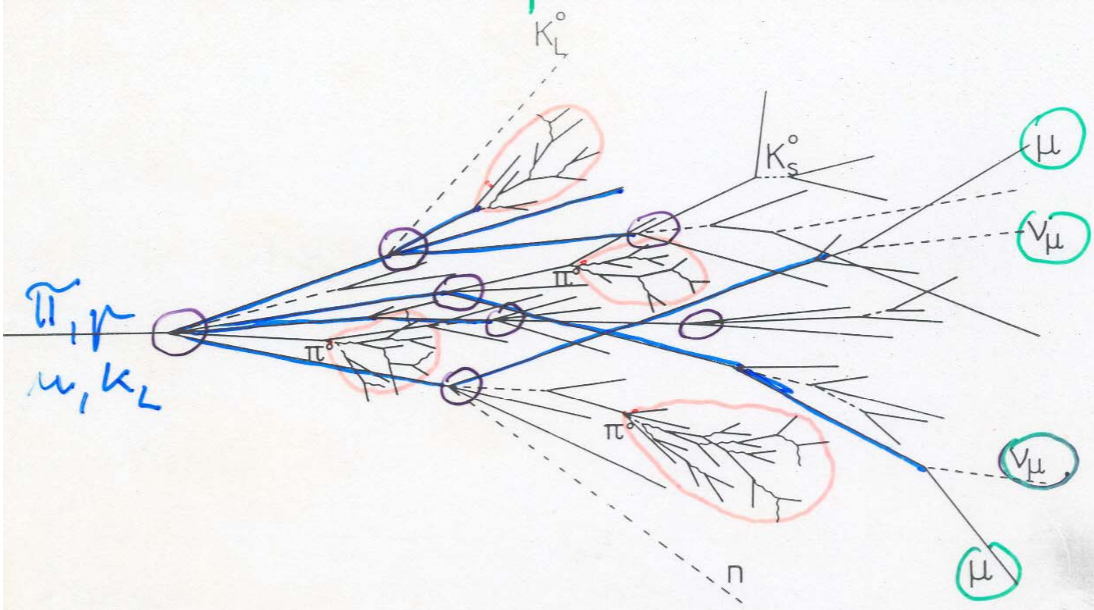


Fig. 7.32. Sketch of a hadron cascade in an absorber.

Razdelitev energije ($f(E)$, tipično za 10 GeV)

~50% visokoenergijski hadroni (~pioni)

π^+ π^- ↓ hadronski plaz (λ_I) ↓

π^0 lokalni EM plaz ↓ $\gamma\gamma$ (X_0)

~30% počasni nukleoni → signal?

$T_v < T$

~20% vzbujena jedra → p, n, γ 1–~30 MeV

~ $\frac{5\%}{\ln E[\mathrm{GeV}]}$ razpad $\pi^\pm \to \mu^\pm \overset{(-)}{\nu}$ pobegnejo raznolikost procesov

⇒ več možnosti za fluktuacije

→ slabša ločljivost

karakteristična dolžina

$\pi^+ \pi^-$ (hadroni) interakcijska dolžina

$$\rho \lambda_I \sim 35 A^{1/3} \frac{g}{cm^2}$$

$$t = \frac{x}{\lambda_I}$$

$\pi^0 \to 2\gamma \to$ EM plaz X_0

	λ_I [cm]	X_0 [cm]
NaJ	41	2,6
BGO	23	1,1
Fe	17	1,76
Pb	18,5	0,56
U	12	0,32

⇒ Fe tipičen absorber v hadronskih kalorimetrih

+ cena
+ povratni jarem magneta

maksimum plazu pri

$$t_{max} \sim 0,2 \ln(E[\mathrm{GeV}]) + 0,7$$

15

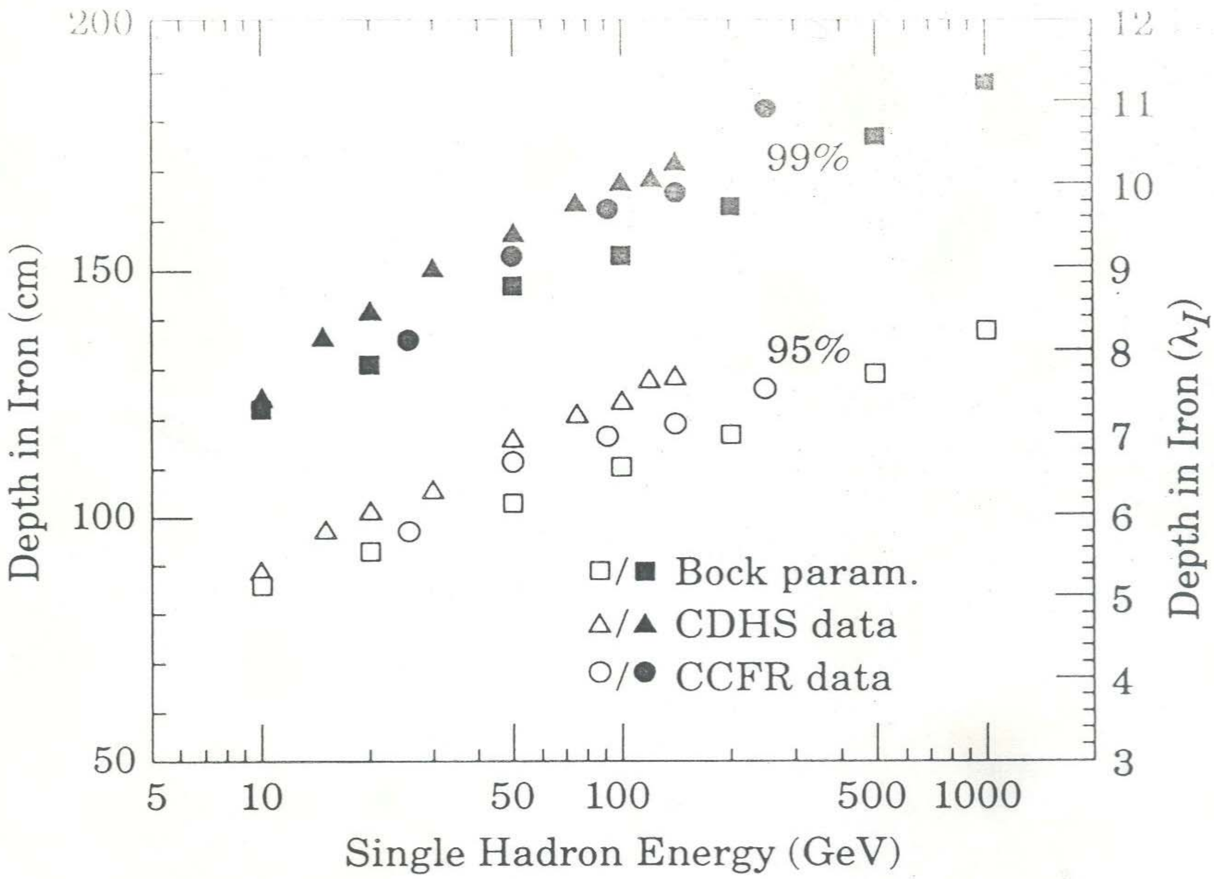


Figure 24.2: Required calorimeter thickness for 95% and 99% hadronic cascade containment in iron, on the basis of data from two large neutrino detectors and the parametrization of Bock *et al.* [44].

dolžina plazu ?

a) 95% energije v povprečju (ugaša kot $e^{-t/\lambda_{att}}$)

$$t_{95} \approx t_{max} + 2{,}5\,\lambda_{att}$$

$$\lambda_{att} \sim (E\,[GeV])^{0{,}13}$$

b) 95% energije v 95% primerov

$$t_{95/95} \sim t_{95} + 3$$

fluktuacije

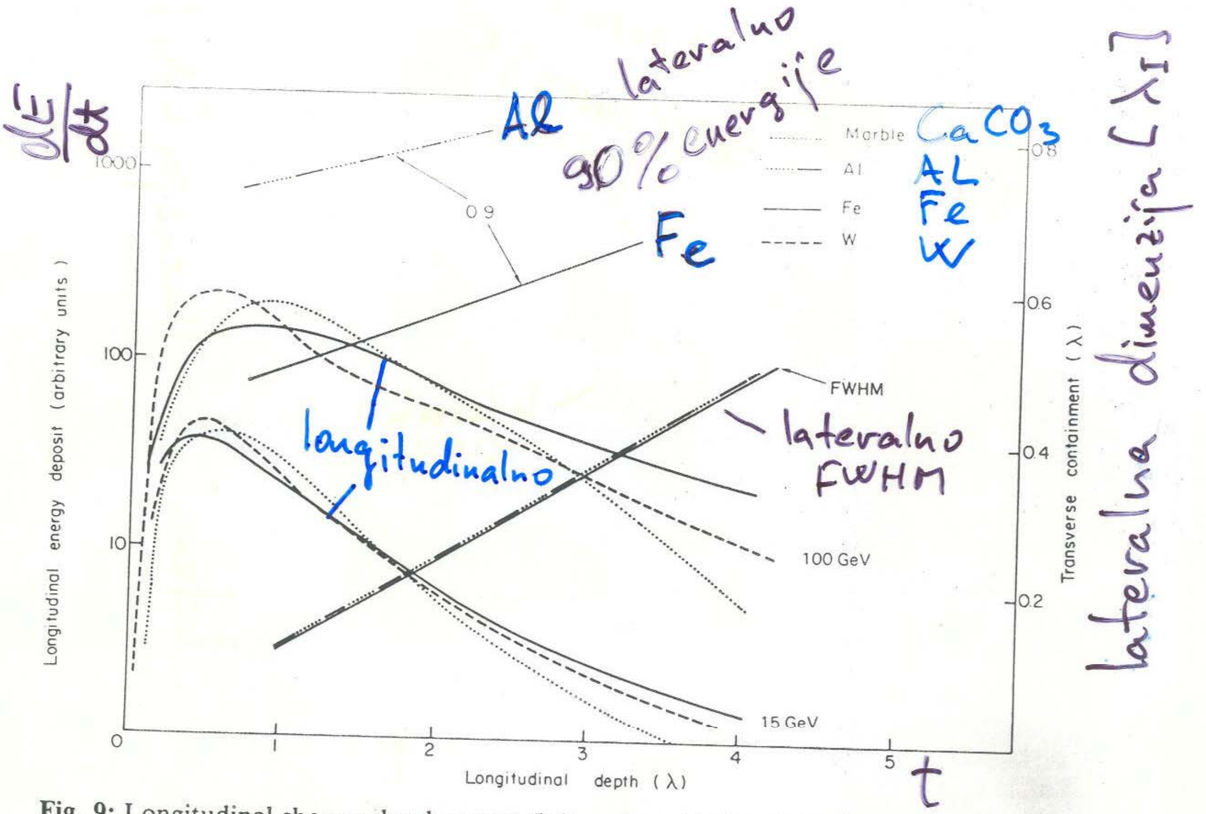


Fig. 9: Longitudinal shower development (left ordinate) induced by hadrons in different materials, showing approximate scaling in absorption length λ. The shower distributions are measured from the vertex of the shower and are therefore more peaked than those measured with respect to the face of the calorimeter. For the transverse distributions as a function of shower depth, scaling in λ is found for the narrow core (FWHM) of the showers. The radius of the cylinder for 90% lateral containment is much larger and does not scale in λ. [10 GeV/c π's: B. Friend et al., Nucl. Instrum. Methods 136:505 (1976)]. Note that marble and aluminium have almost identical absorption and radiation lengths [Marble: M. Jonker et al., Nucl. Instrum. Methods 200:183 (1982); Fe: M. Holder et al., Nucl. Instrum. Methods 151:69 (1978); W: D.L. Cheshire et al., Nucl. Instrum. Methods 141:219 (1977)].

lateralna dimenzija

- narašča s t
- FWHM (sredica) se umeri z λ_I
- 90% E (repi) ni umerjen z λ_I

MC simulacije - opis mnogo slabši kot za EM plaz (EGS)
(GHEISHA, FLUKA)

razlike med različnimi MC

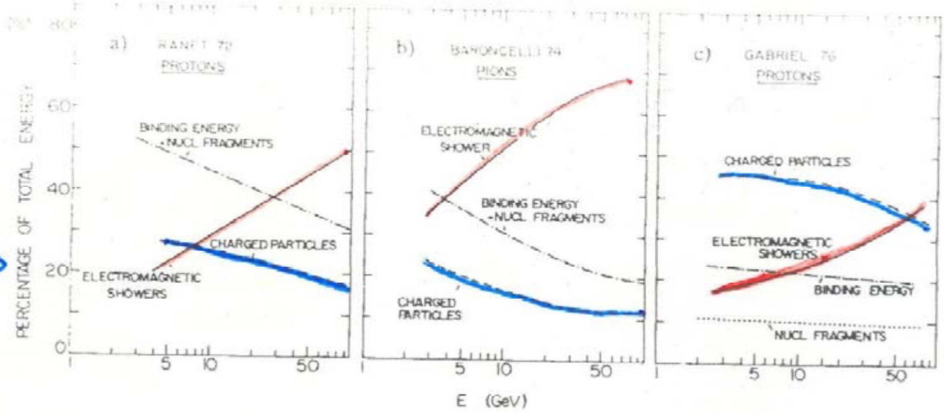


Fig. 8: Relative contributions of the most important processes to the energy dissipated by hadronic showers, as evaluated from three representative Monte Carlo calculations [25].

atmosfera

hadronski EM

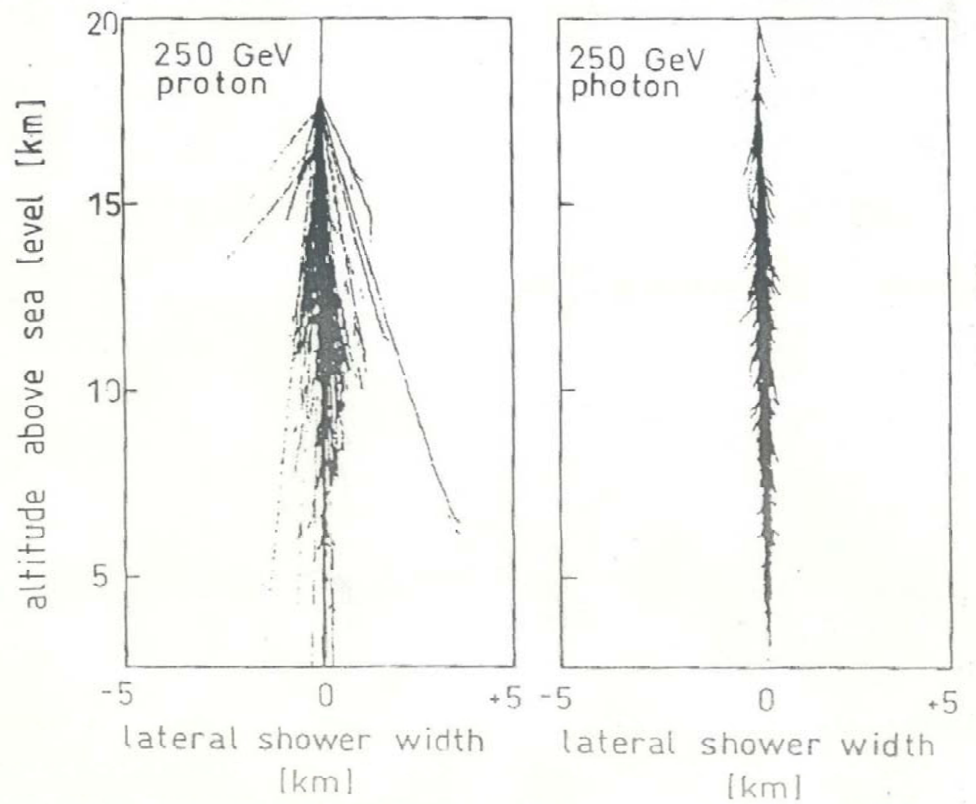


Fig. 7.34. Monte Carlo simulations of the different development of hadronic and electromagnetic cascades in the earth's atmosphere, induced by 250 GeV protons and photons [542].

f) ločljivost hadronskih kalorimetrov

omejitev

fluktuacije v razvoju plazu

- EM (π^0) ↑
- nevtroni ↓
- fragmenti ↓

→ ločljivost mnogo slabša kot pri EM

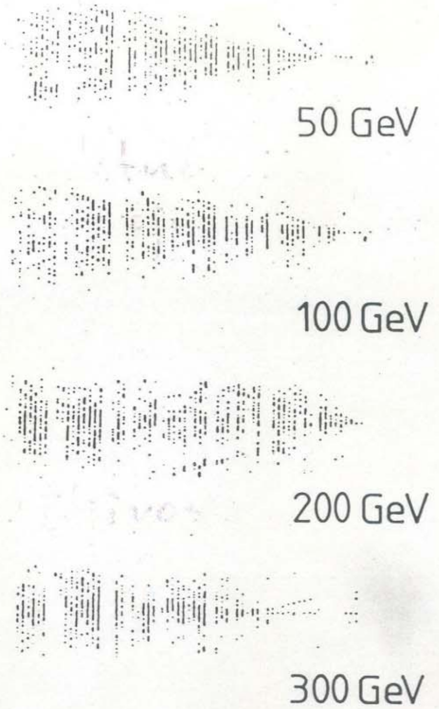
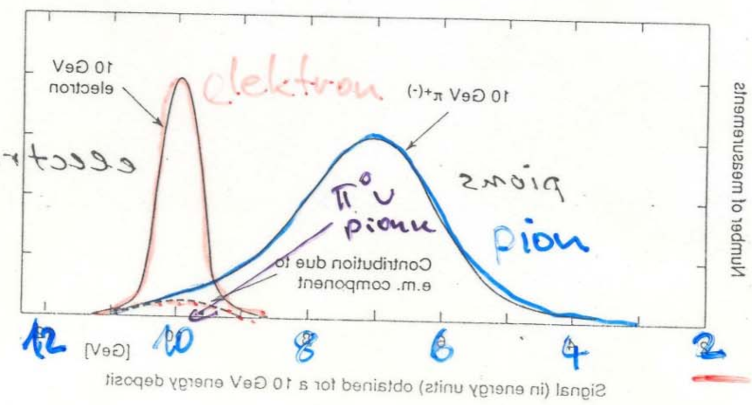


Fig. 7.42 b. Digital pattern of high energy hadron cascades (50 - 300 GeV) a flash-chamber calorimeter [560].

e/h odziv (meritev e/π)

hadronski plaz $R_e \to \pi^0$, $R_h \to$ ostalo



$\frac{e}{h} > 1$

$\pi = e R_e + h R_h$ $\qquad e = e \cdot 1$

↑ delež π^0

število π^0 $(E > 2,5\,GeV)$

$n_{\pi^0} \approx 5 \ln(E[GeV]) - 4,6$

n_{π^0} majhno (~ 7 pri 10 GeV) $\sigma_{n_{\pi^0}} \sim \sqrt{n_{\pi^0}}$ velike fluktuacije R_e med dogodki

$e/h \neq 1$ $(\sim 1,4)$

- $e/\pi = f(E)$ nelinearnost
- odziv nesimetričen (rep) $\Rightarrow \frac{\sigma_E}{E} = a \oplus \frac{b}{\sqrt{E}}$
- ločljivost slabša $\frac{\sigma_E}{E}_{intrinsic} \gtrsim \frac{45\%}{\sqrt{E(GeV)}}$

rešitev: kompenzacija $\frac{e}{h} \rightarrow 1$

$\left(\frac{\sigma_E}{E}\right)_{e/h=1,\ intrinsic} \sim \frac{20\%}{\sqrt[2]{E(GeV)}}$ + ni repov!

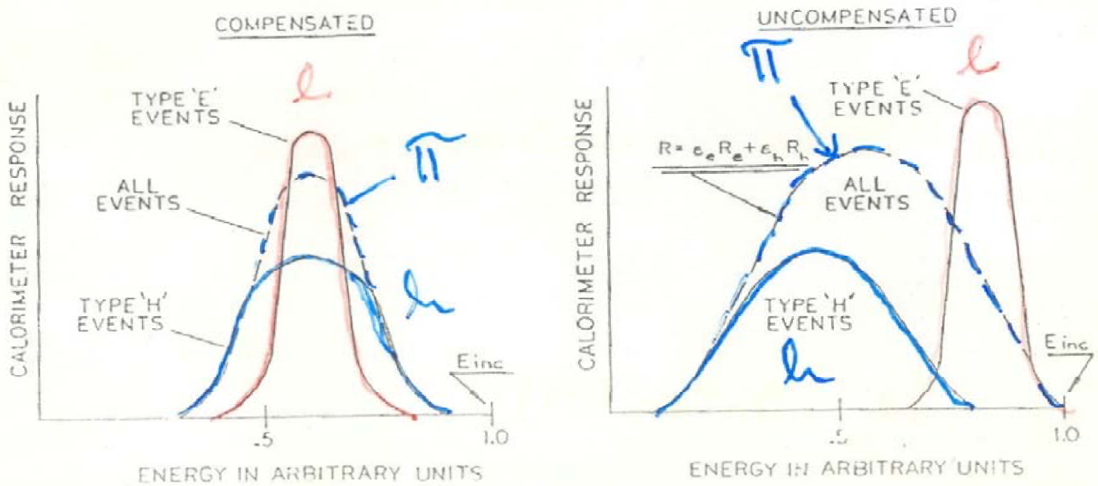


Figure 7: Schematic illustration of the effect of compensation on calorimeter response.

Kompenzacija: a) dvig h } hardware
b) zmanjšanje e }
c) meritev R_e in R_h dogodek po dogodek in uteževanje (software)

a) in b) le v vzorčevalnih kalorimetrih

dvig h - detekcija nevtronov
fisija (^{238}U) → n, γ
nitek Z (H) → $\Delta E = E_n$

zmanjšanje e - absorber velik Z
(fotoefekt nizkoenergijskih γ
→ ~ 40% energije EM plazu)
- aktivna snov majhen Z
(prozorna za nizkoen. γ)

$e/h \sim 1$ Pb / scintilator = 4:1

U / scintilator = 1:1

ločljivost zaradi vzorčevanja

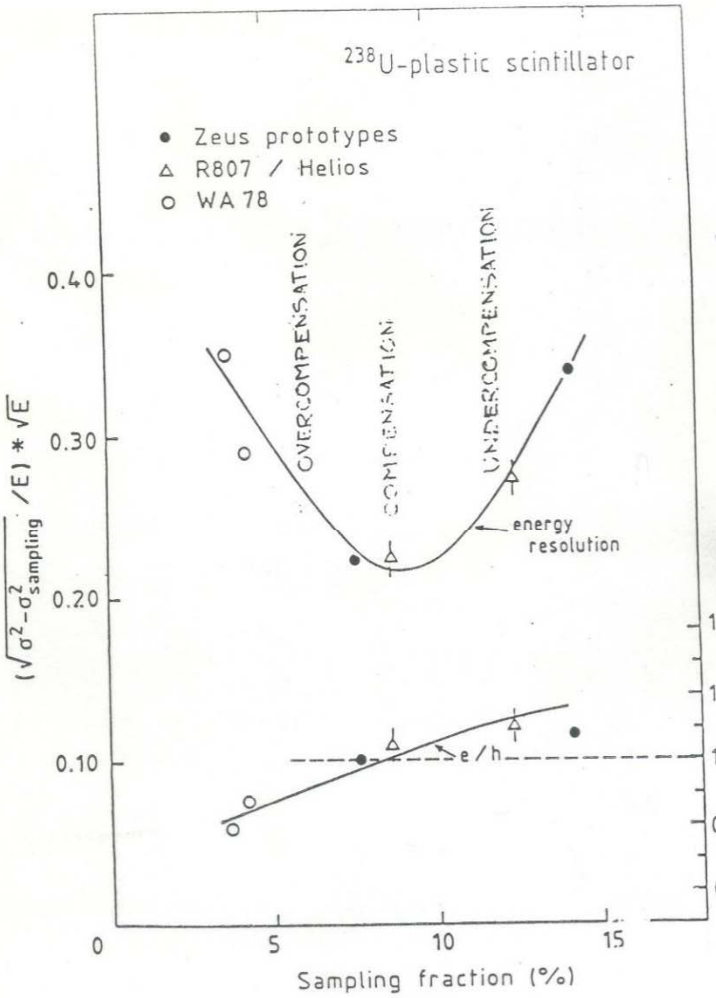
$$\left(\frac{\sigma_E}{E}\right)_{sample} \sim 9\% \sqrt{\frac{\Delta E\,[\mathrm{MeV}]}{E\,[\mathrm{GeV}]}}$$

(c.f. 3,2% za EM)

<< 45% / $\sqrt{E}$
↓
hadronski kalorimetri vzorčevalni

Kompenzacija z variacijo razmerja U / scintilator

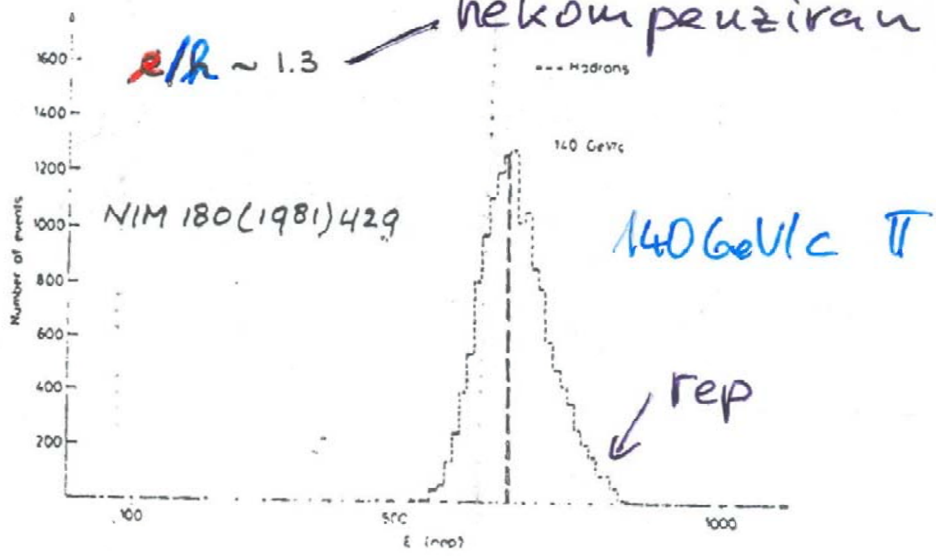
σ(E) AND e/h AS FUNCTION OF SAMPLING FRAC
(U - SCINTILLATOR CAL.)



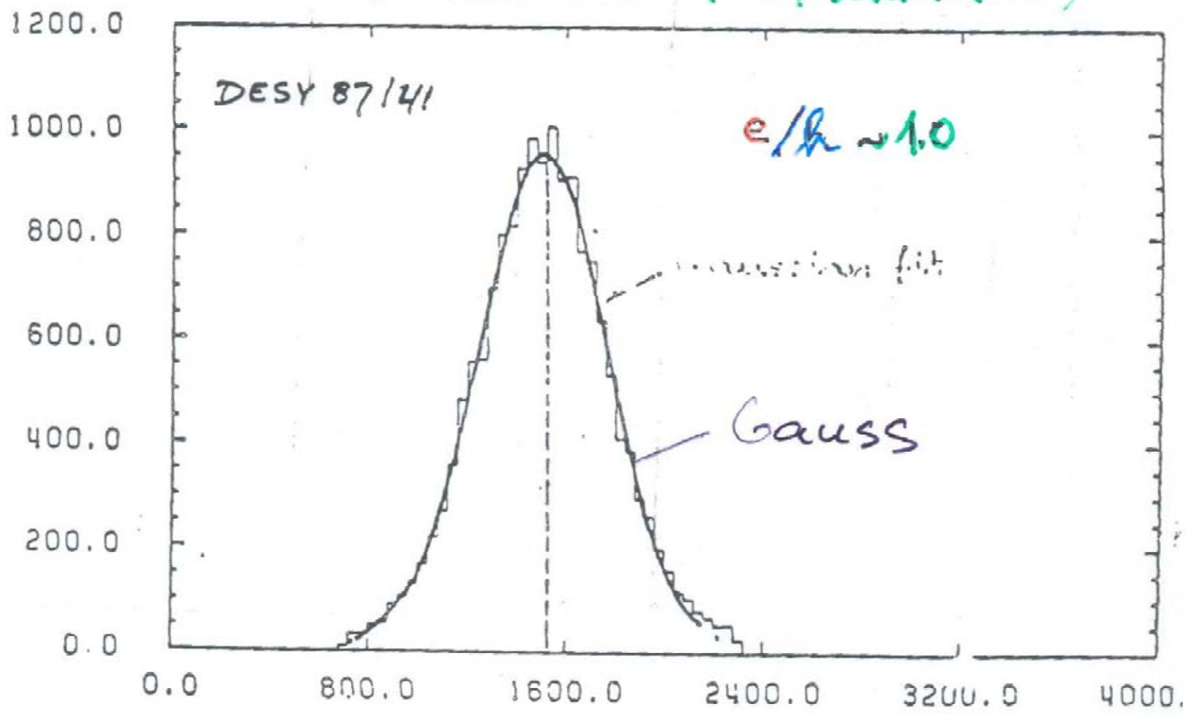
optimum blizu $\frac{20\%}{\sqrt{E}}$ – teoretična meja

! možnost pre-kompenzacije ($e/h < 1$)

HADRONIC LINE SHAPE



Kompenziran (U / scintilator)



Kompenzacija z uteževanjem
(R_e in R_h iz longitudinalnega profila plazu)

100 GeV π

$\frac{\sigma_E}{E} = \frac{80\%}{\sqrt{E}}$

uteži

$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}}$

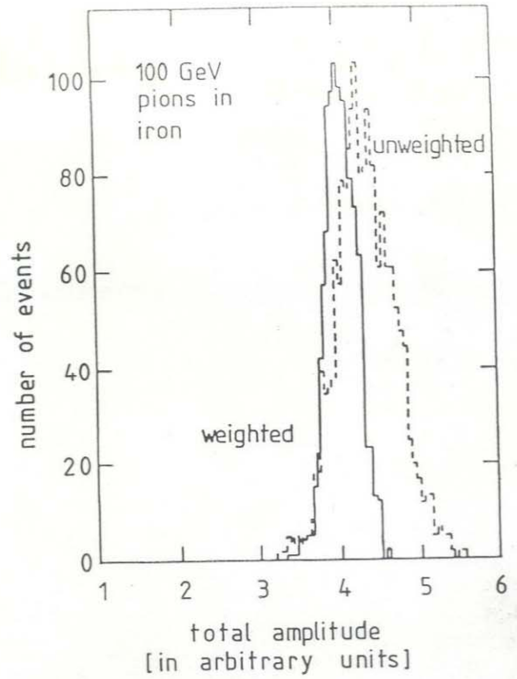


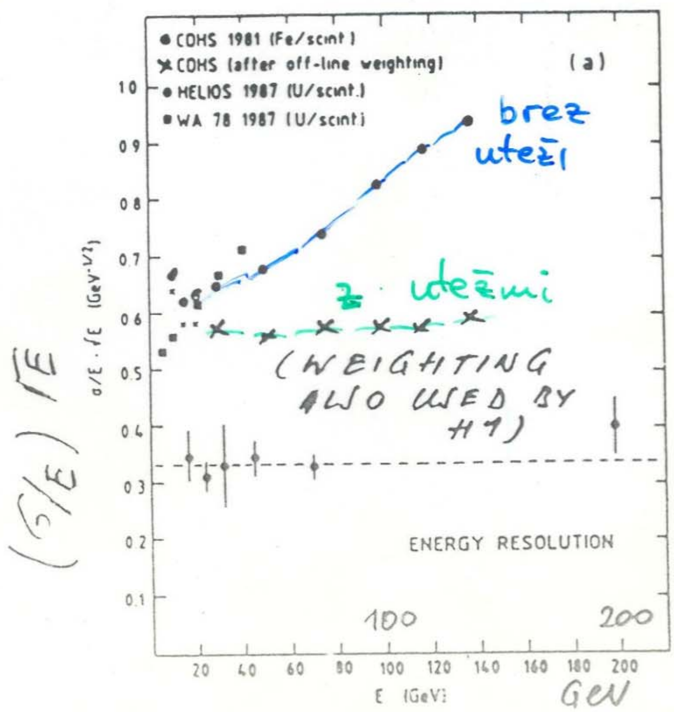
Fig. 7.45. Amplitude distribution for 100 GeV pions in an iron streamer-tube calorimeter with and without weighting factors [518]. The weighting factor was optimized for an incident energy of 100 GeV.

brez uteži

$\frac{\sigma_E}{E} \propto E^{-\alpha}$ $\alpha < 1/2$

z utežmi

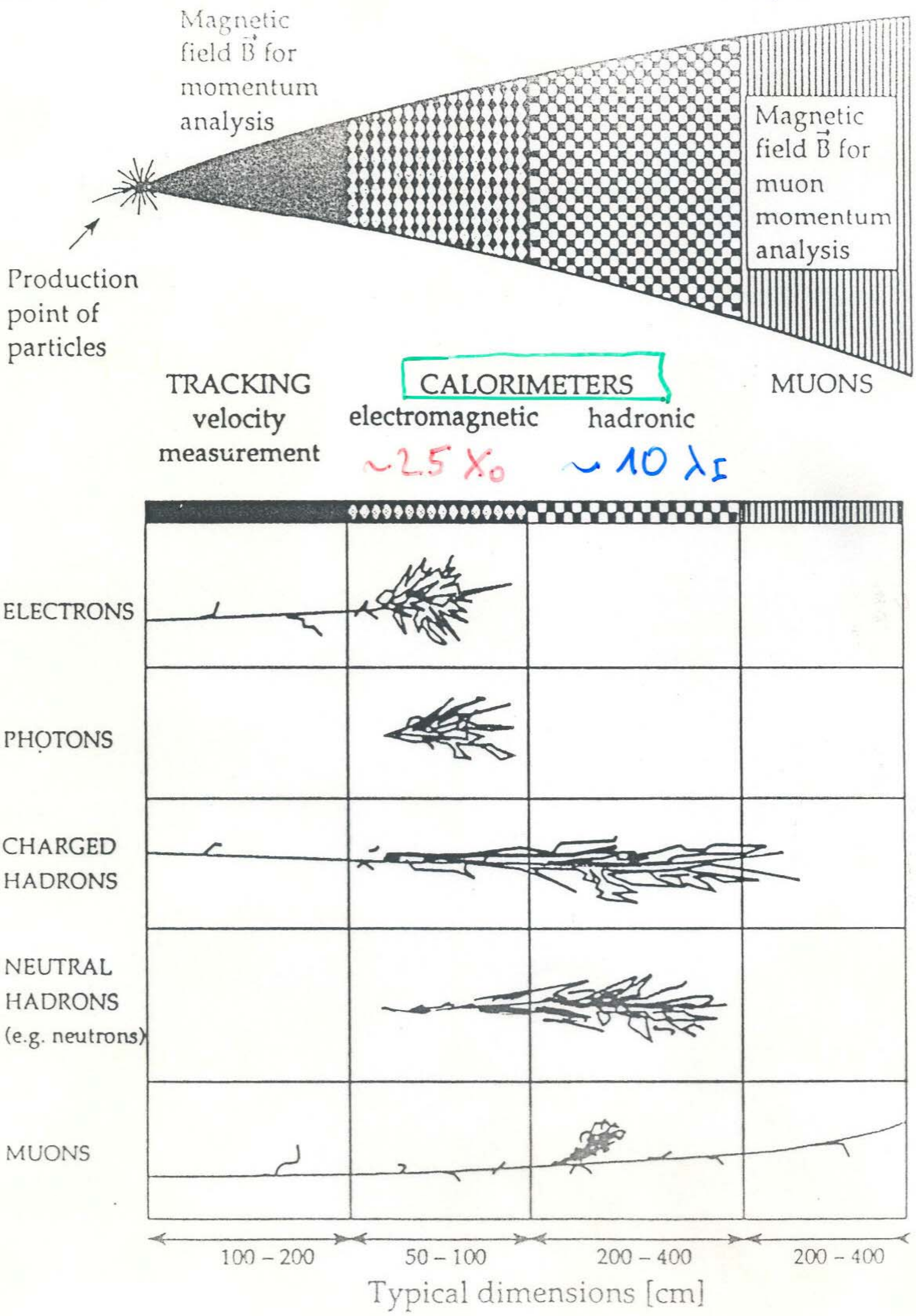
$\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}}$



g) identifikacija s kalorimetri

24

Osnova: različne interakcije e γ π p n K μ



e γ ⟺ hadroni

X_0 ⟷ λ_I

$$\frac{X_0}{\lambda_I} \doteq \frac{180\,A}{35\,Z^2\,A^{1/3}} \sim 8\,Z^{-4/3}$$

0,6 zrak
0,1 Fe
0,02 Pb

velik Z za EM kalorimeter

⇒ dobro ločevanje EM in hadronskega dela plazu

→ $e^{\pm}/\pi^{\pm}$ ločevanje (npr. za $H \to Z^0 Z^0$, $\hookrightarrow e^+e^-$)

omejitev 1. interakcija $\pi^{\pm} N \to \pi^0 N$
izmenjava naboja
verjetnost $10^{-2}-10^{-3}$

γ ⟺ π^0 ločevanje (npr. za $H \to \gamma\gamma$)

$\pi^0 \to 2\gamma$ pod majhnim kotom

⇒ zelo fino deljen prvi del ($\sim 2X_0$) EM kalorimetra → pre shower

26

Literatura

C. Grupen : Particle Detectors, Cambridge UP 1996
PDG : Review of Particle Physics, 1996, 2000
C. Fabjan : Calorimetry in HEP
U. Amaldi : Fluctuations in Calorimetry Measurements
v T. Ferbel: Experimental Techniques in HEP, Addison-Wesley 1987

H.J. Hilke : Particle Detectors, CERN Academic Training 1992
C. Fabjan : Calorimetry, ICFA '95, Ljubljana 1995