



6 Calorimeters

Detectors for Particle Physics

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6 Calorimeters

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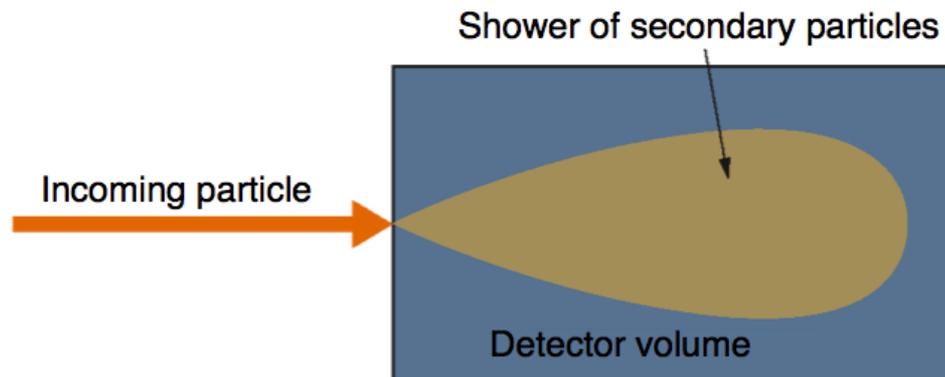
6.1 Calorimeters Principles

General



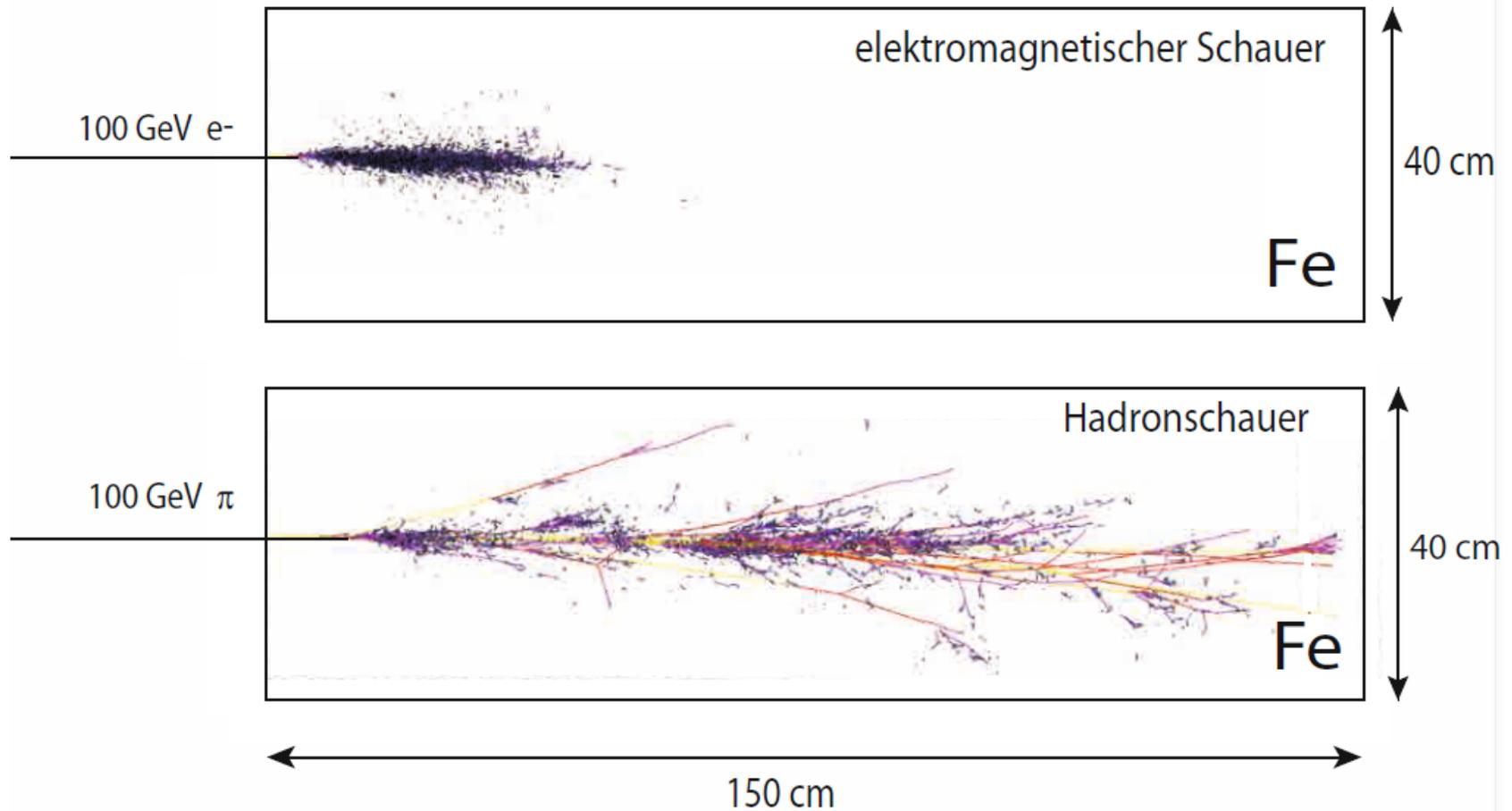
- A calorimeter is a detector which fully absorbs the particles. The signals produced are a measure for the energy of the particle.
- The particle initiates a particle shower. Each secondary particle deposits energy and produces further particles until the full energy is absorbed.

The composition and the dimensions of these showers depend on the type and energy of the primary particle (e^\pm , photons or hadrons).



6.1 Calorimeters Principles

Particle showers



6.1 Calorimeters Principles

Calorimeter signals



- The energy of the particle can be deposited in several ways:
 - Heat (hence the historical name calorimeter)
 - Ionization
 - Excitation of atoms
 - Cherenkov light
 - ...
- Depending on the type of the calorimeter one of these effects is measured and a signal deduced
- For a “practical” calorimeter

Calorimeter signal \propto deposited energy \propto energy of primary particle

6.1 Calorimeters Principles

Properties



Calorimeters are very important components of every detector in particle physics. The reasons are:

- Calorimeters measure also energy and direction of **neutral particles**.
- Calorimetry is based on a statistical process. A particle produces on average N secondary particles, where N is proportional to the energy. The energy resolution is dominated by statistical fluctuations of N
→ **the relative energy resolution improves with increasing energy**.
- The necessary thickness of a calorimeter scales only with the logarithm of the particle energy.
- Calorimeters can be used to **identify particle types** due to their shower shapes
- Calorimeters are important components for the **trigger system** at hadron colliders. Within a few ns complex information on particle energy, particle direction, topology of the event, and possible missing energy is available!

6.1 Calorimeters Principles

Different calorimeter types



- Two different calorimeters by construction:
 - Homogeneous Calorimeters
 - Sampling Calorimeters
- Two different applications:
 - Electromagnetic calorimeters measure the energy of electrons, positrons and photons
 - Hadronic calorimeters measure the energy of hadrons

6.1.1 Homogeneous Calorimeters



- In a homogenous calorimeter the detector material is at the same time the absorbing material and the detector.
- Examples for different signal exploited:

Signal	Material
Scintillation	BGO*, BaF ₂ , CeF ₃ , PbWO ₄
Cherenkov light	Lead glass
Ionization	Liquid noble gasses (Ar, Kr, Xe), Germanium (in nuclear physics)

* Bismuth Germanate Bi₄Ge₃O₁₂

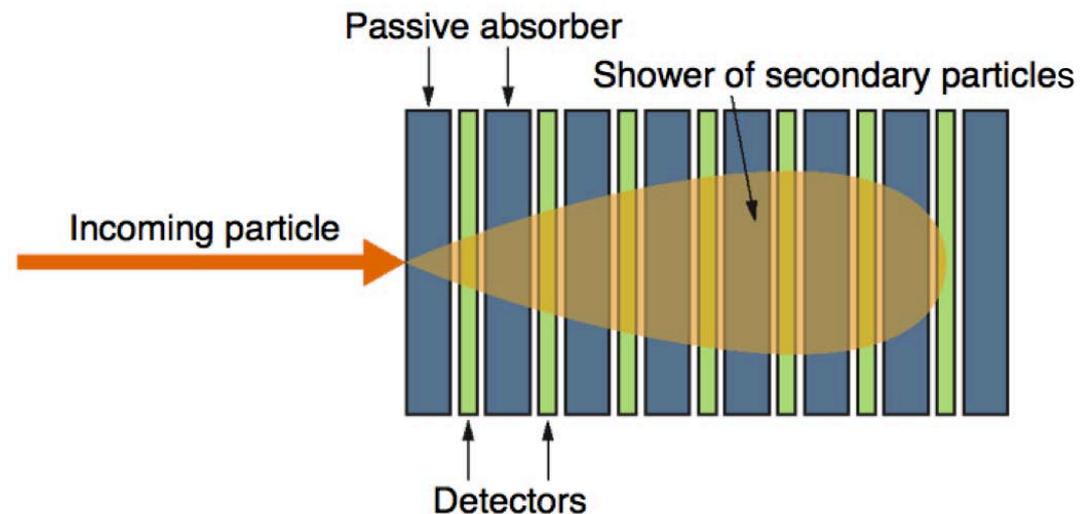
- Advantage: Best possible energy resolution achievable
- Disadvantage: Expensive
- Homogenous calorimeters are only used as electromagnetic calorimeters (e.g. to measure energy of e[±] and photons – see later).

6.1.2 Sampling Calorimeters



- A sampling calorimeter consists of alternating layers of passive absorbers and active detectors.
- Typical absorbers are materials with high density, e.g.: Fe, Pb, U
- Typical active detectors:
 - Plastic scintillators
 - Silicon detectors
 - Noble liquid ionization chambers
 - Gas detectors

Principle of a sampling (sandwich) calorimeter:



6.1.2 Sampling Calorimeters

Properties



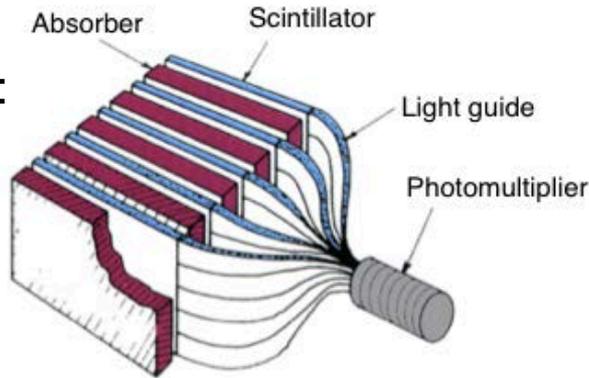
- Advantages:
 - Can optimally choose the absorber and detector material independently and according to the application.
 - By choosing a very dense absorber material the calorimeters can be made very compact.
 - The passive absorber material is cheap
- Disadvantages:
 - Only part of the particles energy is deposited in the detector layers and measured
 - ⤵ Energy resolution is worse than in homogeneous calorimeter (“Sampling-Fluctuations”).

6.1.2 Sampling Calorimeters

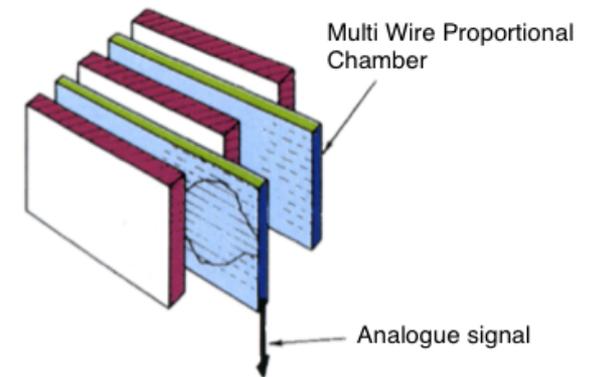
A few examples for different detectors



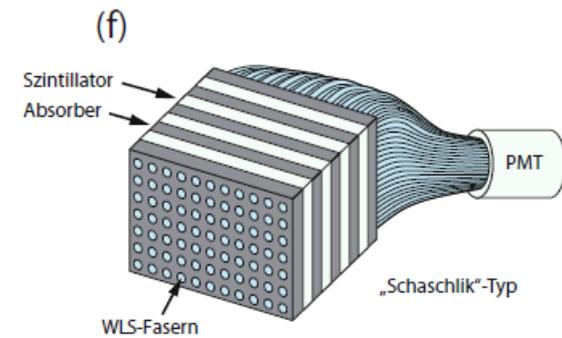
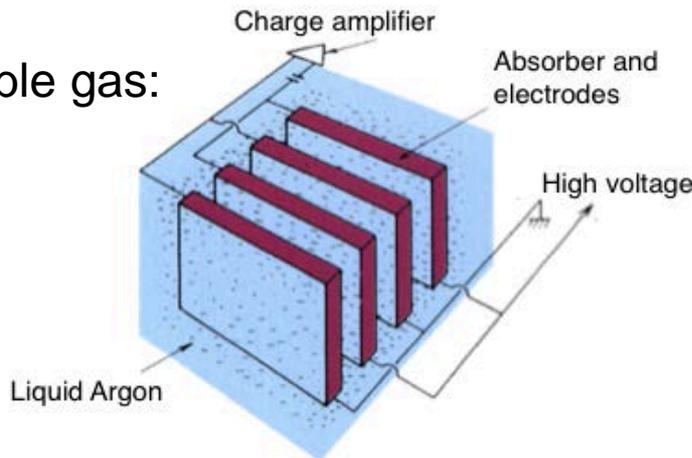
Scintillator plates:



Proportional chambers:



Liquid noble gas:



Kolanoski, Wermes 2015

W. Lucha, M. Regler, *Elementarteilchenphysik*, Verlag Paul Sappi, 1997

6.2 Electromagnetic Calorimeters

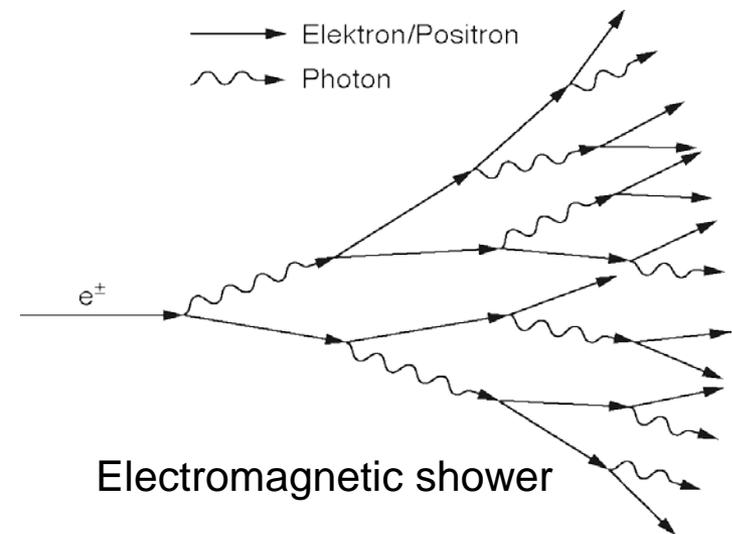


- Electromagnetic calorimeters measure the energy of **electrons, positrons and photons**.
- High energy electrons, positrons and photons interact via **Bremsstrahlung and pair production** (see chapter “Particle Interaction with Matter”).

→ shower development scales with radiation length X_0

→ energy loss is fast, e.m. calorimeters are not very thick

- E.m. calorimeters exist as homogeneous and as sampling calorimeters.



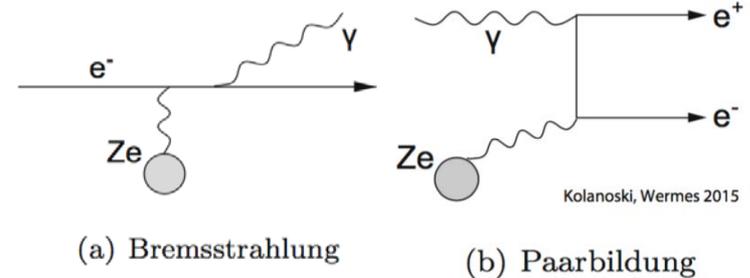
6.2.1 Electromagnetic Showers

Simple Model



- Bremsstrahlung and pair production are considered

- Cross section $\sigma \propto Z^2$
 - $X_0 \propto 1/Z^2$



- Critical Energy E_k

- where energy loss by bremsstrahlung equal ionization $N_{tot} \approx \frac{E_0}{E_k}$,

- Total length $s=t \cdot X_0$ $N = 2^t$, $E = \frac{E_0}{2^t}$

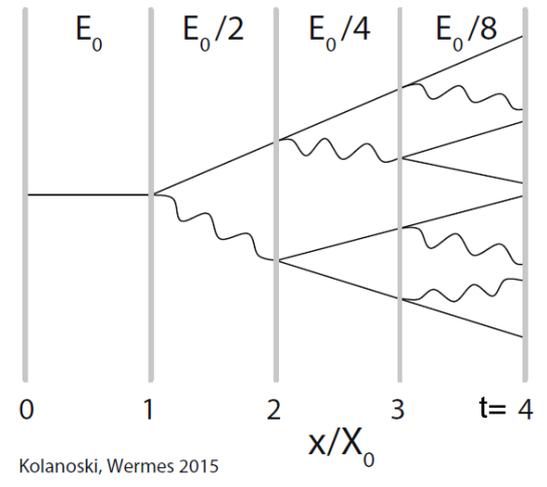
$$E = E_k = \frac{E_0}{2^{t_{max}}}$$

$$N_{max} = \frac{E_0}{E_k},$$

$$t_{max} = \frac{\ln E_0/E_k}{\ln 2}$$

Message:

- N scales linear with energy,**
- t_{max} logarithmic**



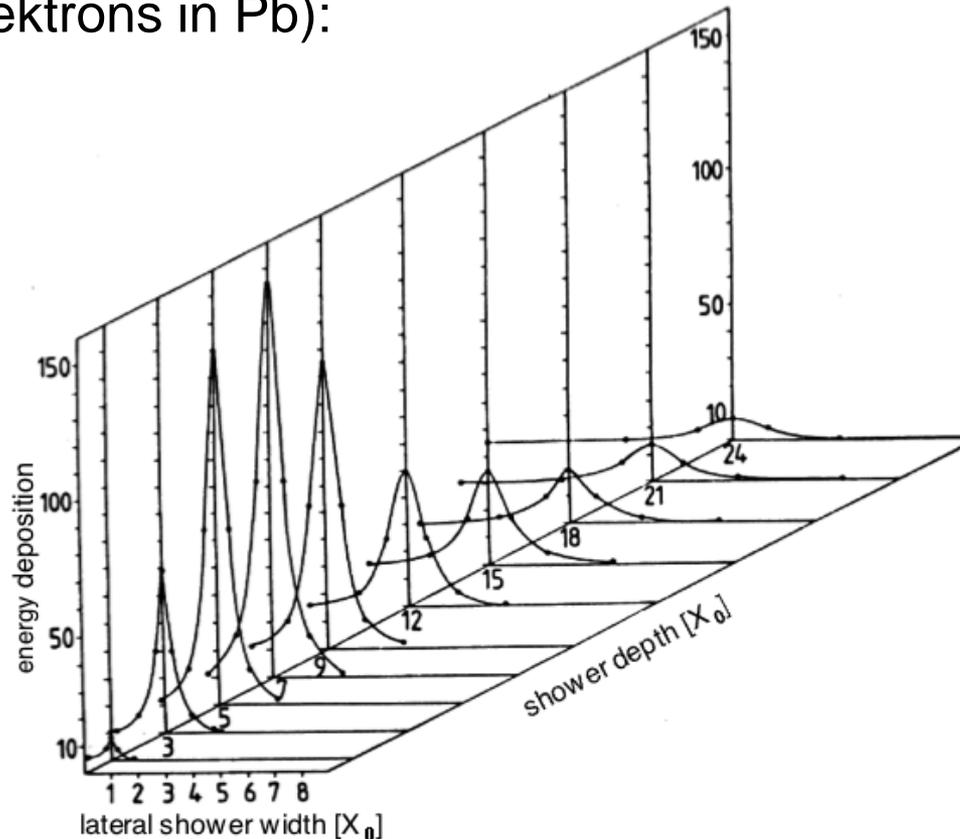
Rossi "approximation B" (1952), simplification by Heitler

6.2.1 Electromagnetic Showers

Shower shape



Longitudinal und transversal e.m. shower development
(6 GeV/c electrons in Pb):



C. Grupen, *Teilchendetektoren*, B.I. Wissenschaftsverlag, 1993

6.2.1 Electromagnetic Showers

Radiation length X_0 , Molière radius ρ_M



- The spatial extension of a shower depends on the material. Using the radiation length and the Molière radius a material independent description of an electromagnetic shower is possible:
 - Longitudinal dimension: radiation length X_0
 - transversal (lateral) dimension: Molière radius ρ_M
- **Radiation length X_0** is the distance in which the projectile loses 1/e ($\approx 63.2\%$) of its energy due to radiation.
- The **Molière radius ρ_M** is a measure of the transversal deviation of an electron with energy E_c after traversing one radiation length:

$$\rho_M = \frac{\sqrt{\frac{4\pi}{\alpha}} m_e c^2}{E_c} = \frac{21 [\text{MeV}]}{E_c [\text{MeV}]} \cdot X_0$$

The critical energy E_c is the energy at which the loss through ionization equals the loss through bremsstrahlung.

Reminder: Radiation Length



- Definition: The radiation length X_0 is the distance in which the energy of the particle is reduced by $1/e$ ($\approx 63.2\%$) due to bremsstrahlung.

- Approximation:

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

- Mean free path length for photons from pair production:

$$\lambda_{\text{Paar}} \approx \frac{9}{7} X_0$$

6.2.1 Electromagnetic Showers

Parametrisation – 1



A useful tool to understand electromagnetic showers is simulation (Monte Carlo method). A popular program is EGS (Electron Gamma Shower Package*)

- Parametrisation of the longitudinal e.m. shower profile (in a homogeneous calorimeter):

$$\frac{dE}{dt} = E_0 t^a \frac{b^{a+1}}{\Gamma(a+1)} \cdot \exp(-bt)$$

- t ... shower depth in units of X_0
- E_0 ... energy of incident particle
- Γ ... Euler's Gamma function: $\Gamma(z) = \int_0^{\infty} \exp(-x) \cdot x^{z-1} dx$
- a, b ... fit parameters (in first approximation $b \sim 0.5$, $a = bt_{peak}$)

- Position of the shower maximum in units of X_0 :

$$t_{max} = \ln\left(\frac{E_0}{E_c}\right) + B$$

$B = -0.5$ for e^\pm and $B = +0.5$ for γ

- Number of e^\pm at the shower maximum:

$$N_{peak} = 0.3 \frac{E_0}{E_c} \cdot \left[\ln\left(\frac{E_0}{E_c}\right) - C \right]^{-\frac{1}{2}}$$

$C = 0.37$ for e^\pm and $C = 0.31$ for γ

* <http://www.slac.stanford.edu/egs/>

6.2.1 Electromagnetic Showers

Parametrisation - 2



- Important for the design of calorimeter is, first of all, the longitudinal dimension of the shower.

About 95% of the energy of the incident particle is contained within the depth T (semi empirical formula*):

$$T(95\%) = t_{\max} + 0.08Z + 9.6$$

Z ... Atomic number of detector material

Rule of thumb: need about $25 X_0$

- In the transversal plane 95% of a shower is contained within 2 Molière radii:

$$R(95\%) = 2\rho_M$$

- The transversal shower profile has a central core in which most of the energy is deposited. This core is surrounded by a halo. The width of the core is determined by small angle scattered e^\pm , whereas the halo develops due to low energy photons, which fly a long distance in the detector.

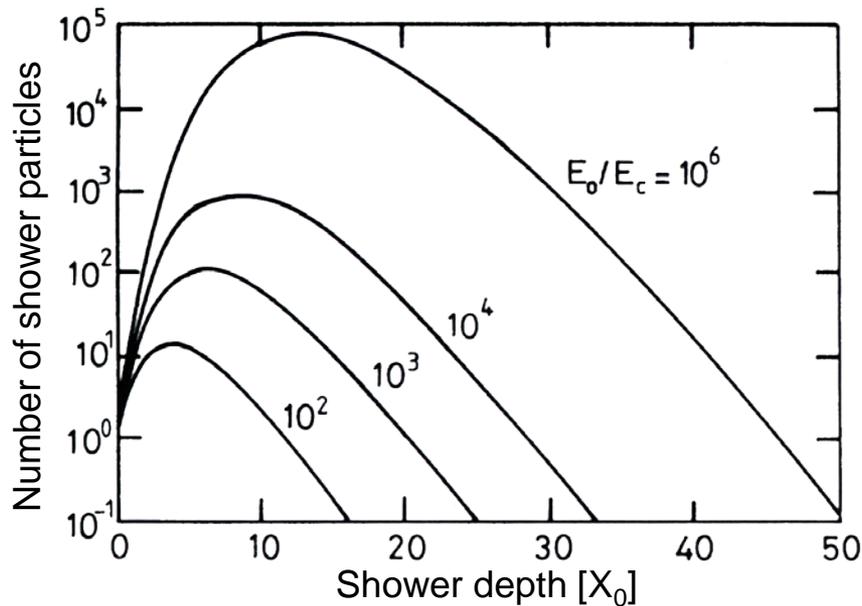
* From C. Leroy, F.-G. Rancoita, Rep.Prog.Phys. **63**, 505–606 (2000)

6.2.1 Electromagnetic Showers

Shower Profiles



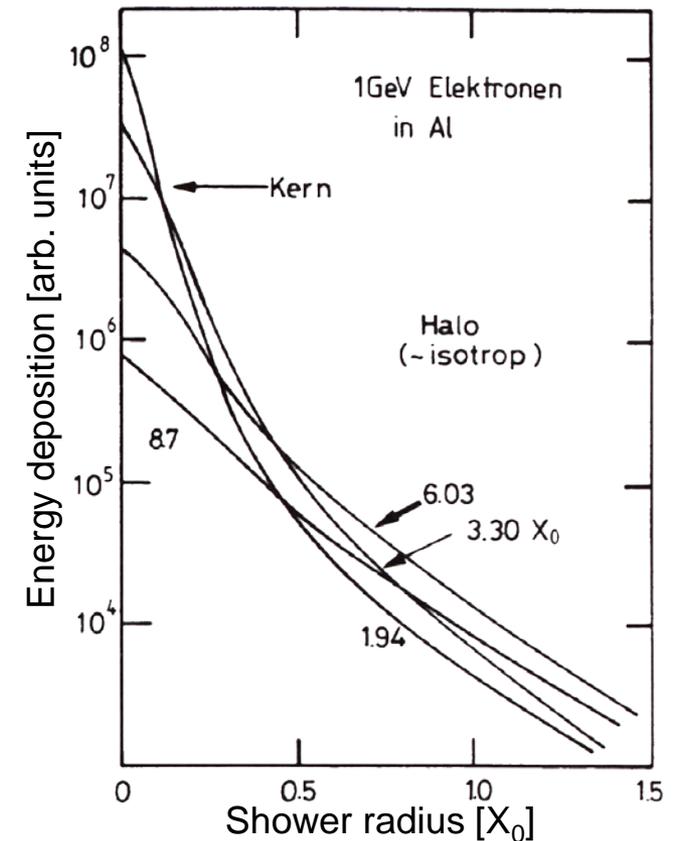
Longitudinal e.m. shower profile
for different incident energies:



(E_0 ... energy of the incident particle
 E_c ... critical energy)

Both plots: C. Grupen, *Teilchendetektoren*,
B.I. Wissenschaftsverlag, 1993

Transversal e.m. shower profile
at different shower depths:



6.2.1 Electromagnetic Showers

Shower dimensions



The shower dimensions scale with the radiation length X_0 (longitudinal) and the Molière radius ρ_M (lateral):

Material	X_0 [cm]	ρ_M [cm]	E_c [MeV]
Fe	1.76	1.77	21–27
Pb	0.56	1.60	7.4
U	0.32	1.00	6.8
W	0.35	0.92	8
Polystyrol	42.9	8.25	80–109
Ar	14	7.2	41.7
Si	9.36	5.28	37.6
BGO	1.12	2.33	10.2
H ₂ O	36.10	10.9	70

C. Leroy, F.-G. Rancoita, *Physics of Cascading Shower Generation and Propagation in Matter: Principles of High-Energy, Ultrahigh-Energy and Compensating Calorimetry*, Rep.Prog.Phys. **63**, 505–606 (2000)

6.1.3 Energy Resolution General

Intrinsic resolution



In an ideal homogeneous calorimeter with infinite dimensions the energy resolution is determined by the statistical fluctuations of the number of shower particles N :

$$\frac{\sigma(E)}{E} \propto \frac{\sigma(N)}{N} \approx \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

σ ...Standard deviation

E ...Particle energy

Maximal number of “detectable” particles is given :

$$N_{\max} = E/\eta$$

E is the energy of the primary particle and η is the threshold energy of the detector, i.e. the minimal energy to produce a single detectable secondary particle.

Examples for the threshold energy:

- Ge (Si) detectors: $\eta \approx 2.9$ eV (3.6 eV)
- Gas detectors: $\eta \approx 30$ eV
- Plastic scintillators: $\eta \approx 100$ eV

6.1.3 Energy Resolution General

Sampling Fluctuations

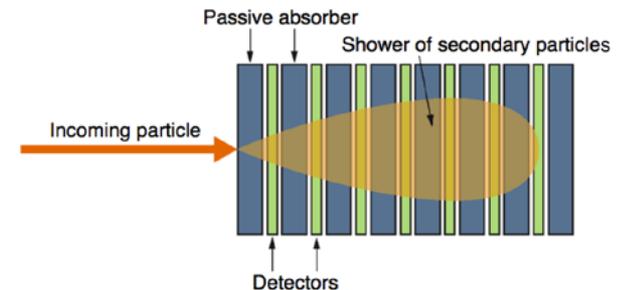


Sampling fluctuations:

In sampling calorimeters only a small part of the deposited energy is measured.

- The fractions of how much energy is deposited in the absorber and in the detector varies from event to event → these fluctuations cause a worsening of the energy resolution
- Important is the number of charged secondary particles traversing the detector layers N_{det}

→ The fluctuation of this number is another contribution to the total energy resolution



$$\left(\frac{\sigma(E)}{E} \right)_{\text{sampling}} \approx \frac{\sqrt{N_{\text{det}}}}{N_{\text{det}}} = \sqrt{\frac{\Delta E}{E}}$$

E ... Energy of the primary particle

ΔE ... mean energy loss in one layer of absorber

6.1.3 Energy Resolution General

Additional contributions in sampling calorimeters

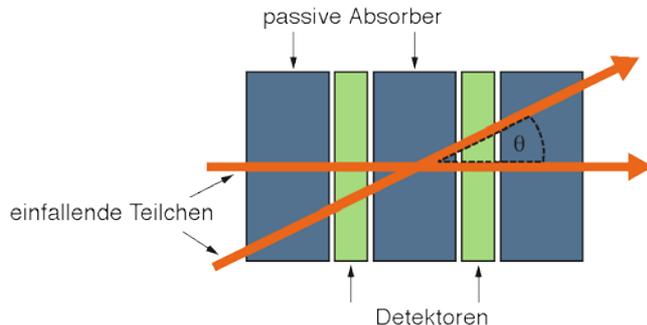


Landau fluctuations:

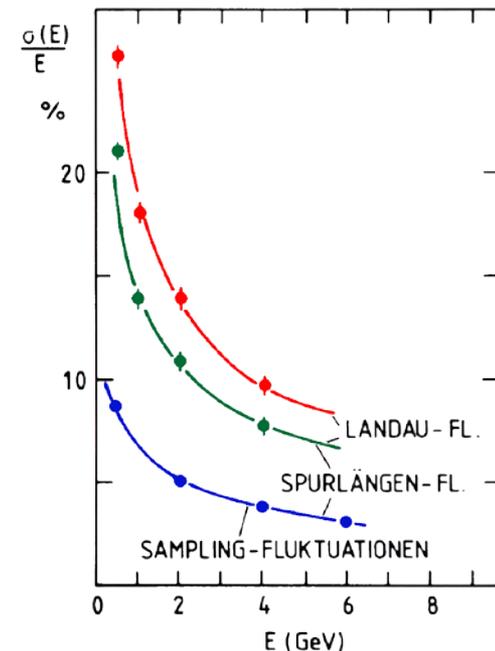
In case of thin detector layers due to the asymmetric energy loss distribution (Landau instead of Gaussian distribution), e.g. important in gas and silicon detectors.

Track length fluctuations:

Secondary particles are scattered and cross the detector planes under various angles. From event to event the total track length of secondary particles fluctuates → contribution to the energy resolution.



Calculation for an e.m. calorimeter (1 mm Pb, 5 mm scintillators):



K. Kleinknecht, Detektoren für Teilchenstrahlung, Teubner 1992

6.1.3 Energy Resolution General

General parameterization



The energy resolution of a calorimeter can be parameterized using:

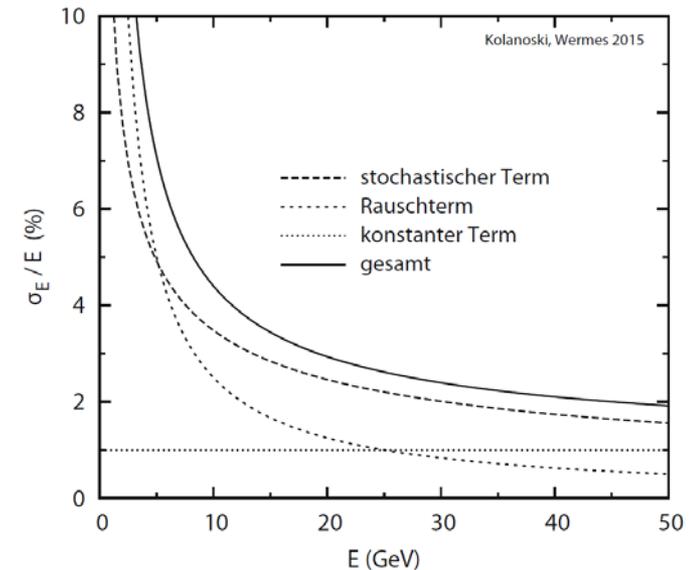
$$\frac{\sigma(E)}{E} \approx \sqrt{\left(\frac{c_1}{\sqrt{E}}\right)^2 + \left(\frac{c_2}{E}\right)^2 + c_3^2}$$

E Particle energy in GeV

c_1, c_2, c_3 ...Empirical, detector dependent constants or fit parameters

- the intrinsic resolution is $\propto 1/\sqrt{E}$
- the term $\propto 1/E$ is mainly due to electronic noise (+ pile up noise in high luminosity environments)
- the constant term is caused by inhomogeneous response, calibration errors, dead channels, longitudinal leakage, etc.

At high energies the constant term dominates the energy resolution!



6.2.2 E.M. Energy Resolution

Examples e.m. calorimeters



Homogeneous calorimeters:

Experiment	Material	Energy resolution (E in GeV)
NA48	Liquid Kr	$4.8\%/\sqrt{E} \oplus 0.22\%$
BELLE	CsI(Tl)	$0.8\%/\sqrt{E} \oplus 1.3\%$
CMS	PbWO ₄	$2.7\%/\sqrt{E} \oplus 0.55\%^*$

Sampling calorimeters:

Experiment	Detector	Detector thickness [mm]	Absorber material	Absorber thickness [mm]	Energy resolution (E in GeV)
UA1	Scintillator	1.5	Pb	1.2	$15\%/\sqrt{E}$
SLD	liquid Ar	2.75	Pb	2.0	$8\%/\sqrt{E}$
DELPHI	Ar + 20% CH ₄	8	Pb	3.2	$16\%/\sqrt{E}$
ALEPH	Si	0.2	W	7.0	$25\%/\sqrt{E}$
ATLAS	liquid Ar		Pb		$10\%/\sqrt{E} \oplus 0.7\%^*$
LHCb	Scintillator		Fe		$10\%/\sqrt{E} \oplus 1.5\%^*$

* Design values

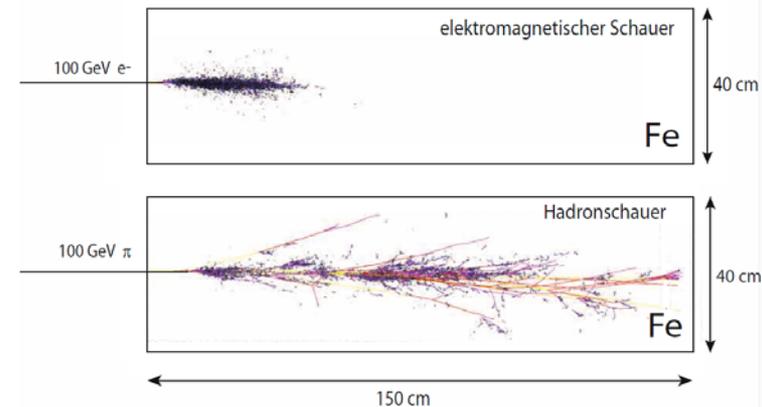


Hadron Calorimeters

6.3 Hadron Calorimeters



- Hadron calorimeters measure the energy of **charged and neutral hadrons**.
- Shower development similar to e.m. calorimeters. However the interactions are hadronic interactions
 - shower development scales with nuclear absorption length λ_a
 - hadron calorimeters need to be much “thicker”
- Hadron calorimeters exist only as sampling calorimeters.
- In an experimental set-up the e.m. calorimeter is therefore always in front of the hadron calorimeter



6.3.1 Hadronic Showers

General



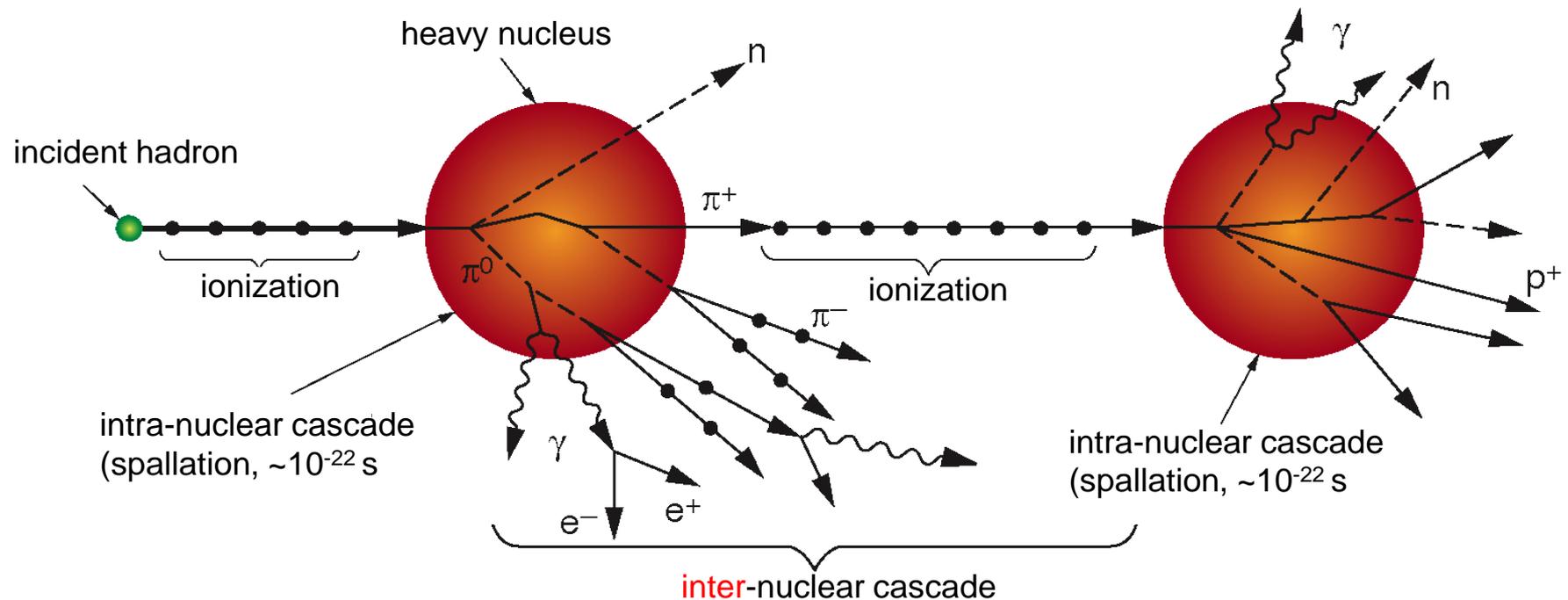
- Hadronic showers are a series of *inelastic hadronic interactions* of a primary particle with the nuclei of the target material. Produced secondary particles undergo further inelastic interactions and produce more particles.
- Due to the multitude of possible processes the development of a hadronic shower is considerably more complicated compared to an electromagnetic shower.
- *Elastic interactions* do not produce secondary particles, and hence do not contribute to the hadronic shower.
- In between the inelastic interactions with the nuclei and at the end of the shower (where the energy becomes too low for the interactions with the nucleus) the shower particles lose their energy due to ionization and excitation of atoms.

6.3.1 Hadronic Showers

Hadronic interactions



- **Intra-nuclear cascade:** Components of the nucleus receive enough energy to interact with each other and to produce pions or other hadrons.
- **Inter-nuclear cascade:** Particles escaping the nucleus hit another nucleus.



6.3.1 Hadronic Showers

Hadronic interactions - 2



- Inelastic interactions of high energy hadrons:
 - Production of mesons (π , K, ...) and baryons (n, p, ...)
 - Spallation
 - Excitation of nuclei
 - Nuclear fission
- The neutral mesons decay into photons and initiate an electromagnetic shower within the hadronic shower!

6.3.1 Hadronic Showers

Spallation



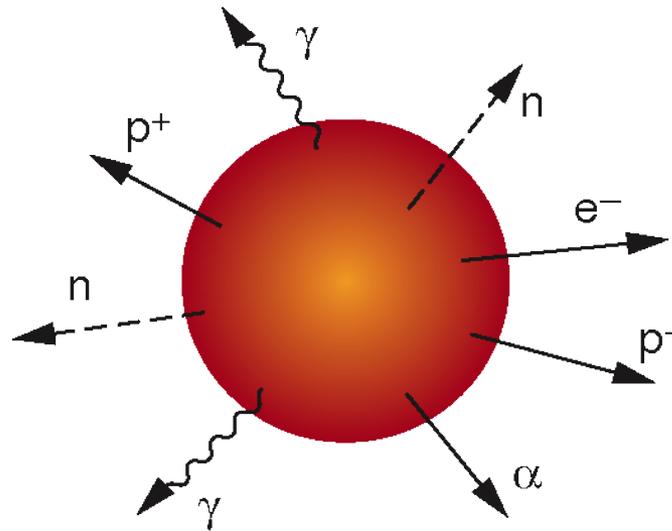
- Spallation is the transformation of a nucleus caused by an incident, high energetic, hadronically interacting particle. During spallation a large number of elementary particles, α -particles, and possibly larger debris of the nucleus are emitted.
- Spallation is the most probable process when a hadron hits a nucleus.
- Following spallation the target nucleus is in an excited state and releases further particles or undergoes fission.
- The secondary particles from the spallation process have mostly enough energy to itself interact with a nucleus.

6.3.1 Hadronic Showers

Nuclear excitation, nuclear evaporation process



- **Nuclear evaporation:** excited nuclei emit particles until the remaining excitation energy is below the binding energy of the components in the nucleus.
- Highly excited nuclei lose most of their excitation energy in typically $\sim 10^{-18}$ s.

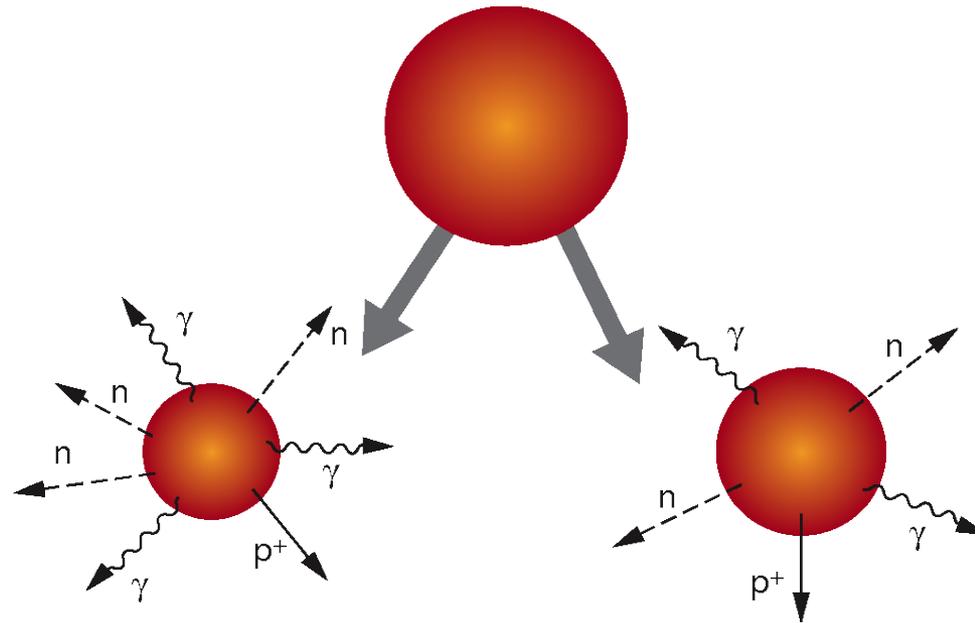


6.3.1 Hadronic Showers

Fission



- In heavy elements, e.g. ^{238}U , fission may occur following spallation or due to the capturing of slow neutrons. The nucleus decays in two (possibly 3) approximately equal debris. Additionally photons and neutrons are emitted and if enough excitation energy remains further hadrons are emitted.

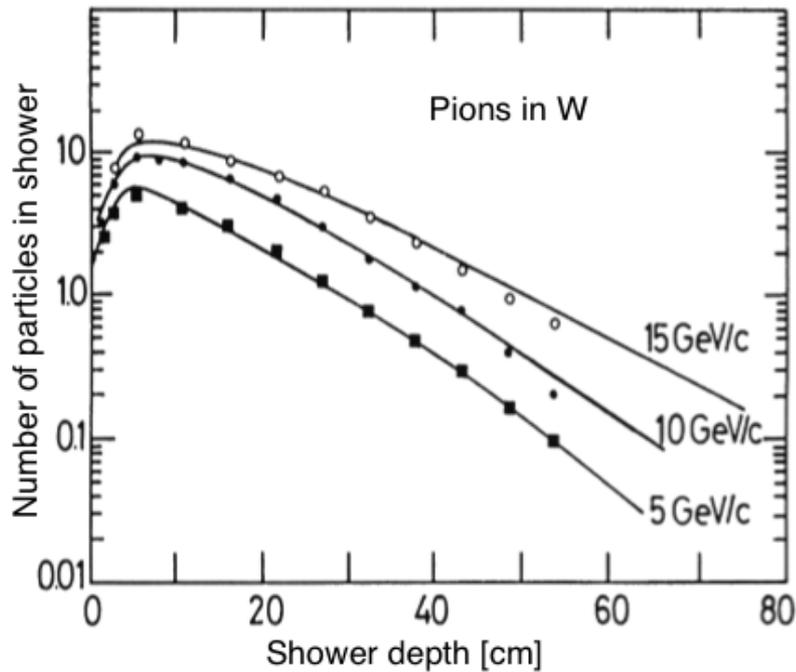


6.3.1 Hadronic Showers

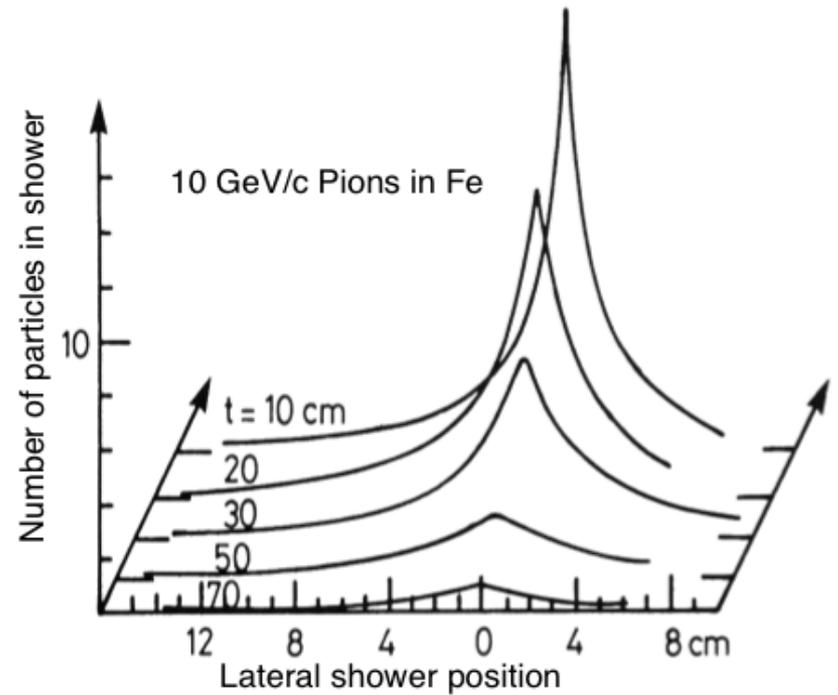
Shower shape



Longitudinal shower development, charged pions in W for 3 different energies:



Longitudinal und transversal shower development, 10 GeV/c Pionen (π^-) in Fe:



C. Grupen, *Teilchendetektoren*, B.I. Wissenschaftsverlag, 1993

6.3.1 Hadronic Showers

Parametrisation



Similar to electromagnetic showers also hadronic showers are simulated by Monte Carlo methods* to achieve a parametrisation, even if it is much more complex.

- Example for the parametrisation of the longitudinal shower profile:

$$\frac{dE}{ds} = K \left[w t^a \cdot \exp(-bt) + (1 - w) \cdot l^c \cdot \exp(-dl) \right]$$

(first term e.m. component, second term hadronic component)

t ... e.m. shower depth in units of X_0

l ... hadronic shower depth in units of the nuclear absorption length λ_a

w ... weighting factor e.m. and hadronic component

a, b, c, d ... experimentally determined fit parameters

(depend logarithmically from the energy of the incident particle: $a = a_1 + a_2 \cdot \ln(E)$)

- The shower maximum is at:

$$t_{\max}(\lambda_a) \approx 0.2 \cdot \ln E[\text{GeV}] + 0.7$$

* e.g.: FLUKA (<http://www.fluka.org/>), GHEISHA or CALOR.

6.3.1 Hadronic Showers

Dimensions



- Hadronic shower dimensions described by the **nuclear absorption length λ_a** .
- 95% of a shower is contained in approximately $7.6 \lambda_a$ (about 80 cm U).
Rule of thumb: $10 \lambda_a$ required
- 95% of the total energy is deposited in a cylinder with radius λ_a .
The transversal profile consists of a high energy core (FWHM¹ $0.1 - 0.5 \lambda_a$) and a halo of low energy particles.

¹ Full Width Half Maximum

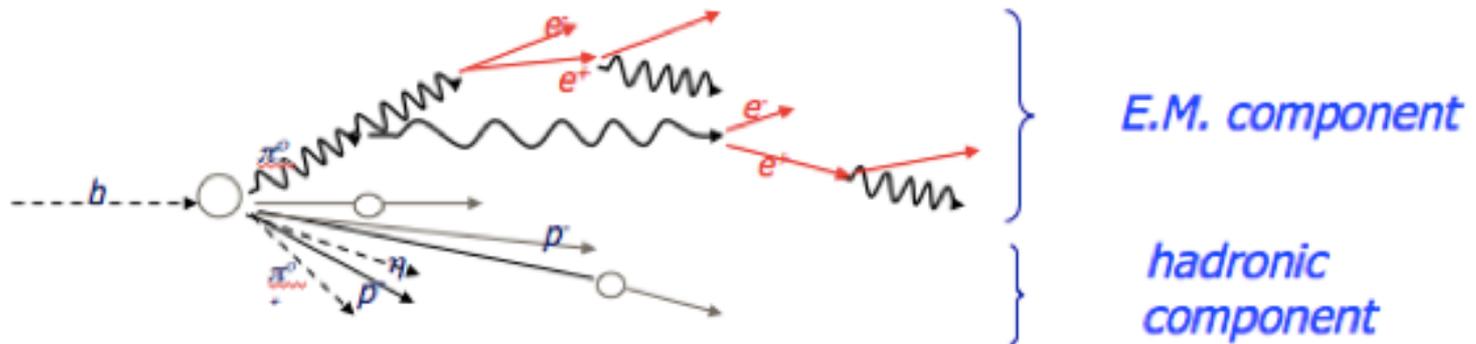
Material	λ_a [cm]
Fe	16.8
Pb	17.1
U	10.5
Cu	15.1
Al	39.4
W	9.6
Polystyrol	79.5
Ar	83.7
Si	45.5

6.3.2 Shower Components

Neutral mesons and the internal e.m. shower



- The neutral mesons produced in the hadronic shower may decay via the electromagnetic interaction, and hence initiate a purely e.m. shower within the hadronic shower

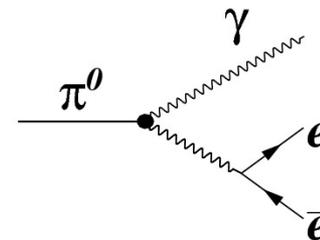


- Pion decay

$$\pi^0 \rightarrow \gamma_1 + \gamma_2,$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu,$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu.$$



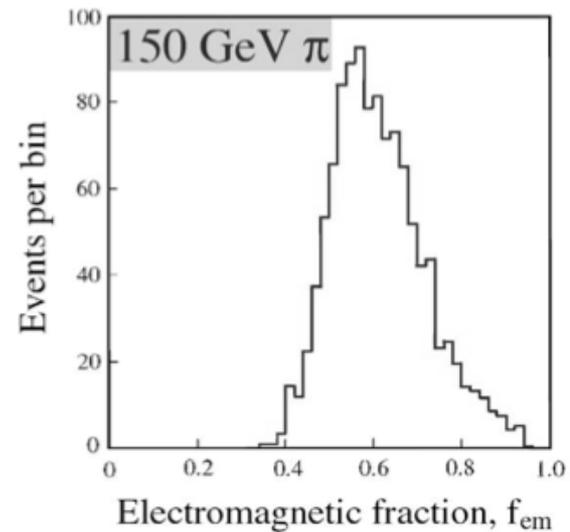
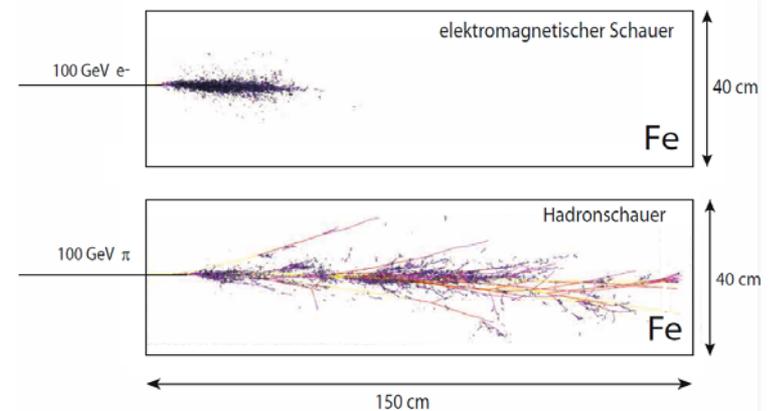
6.3.2 Shower Components

Neutral mesons and the internal e.m. shower



- **The fraction of the shower energy which goes into the e.m. shower is determined at the first interactions (beginning of the shower).**

→ large variation from event to event
→ worsening of the energy resolution
(energy resolution does not improve with $1/\sqrt{E}$)



R. Wigmans, EDIT, CERN, 2011

6.3.2 Shower Components

Neutral mesons and the internal e.m. shower



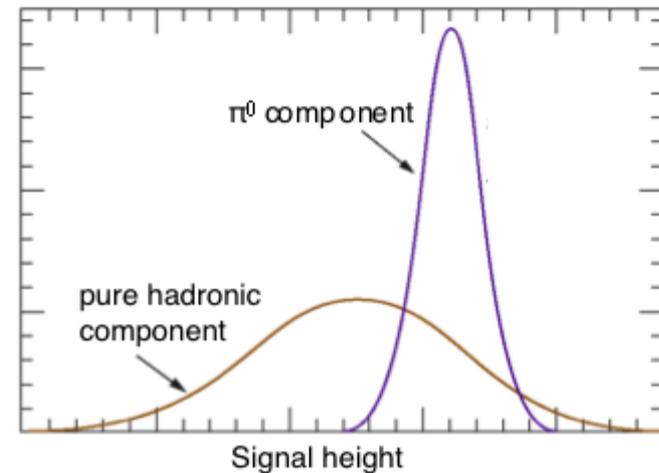
- The absorption of the purely hadronic shower involves energy loss processes which do not create measurable signals:
 - Nuclear binding energy
 - Production of neutrinos and high energy muons
 - Kinetic energy of debris of nuclei

No such energy loss mechanism in the e.m. shower

→ response of calorimeter

to purely e.m. component larger than
to purely hadronic component.

- e/h response ratio figure of merit of a hadron calorimeters:
a priori $e/h > 1$
ideal calorimeter has $e/h=1$



6.3.2 Shower Components

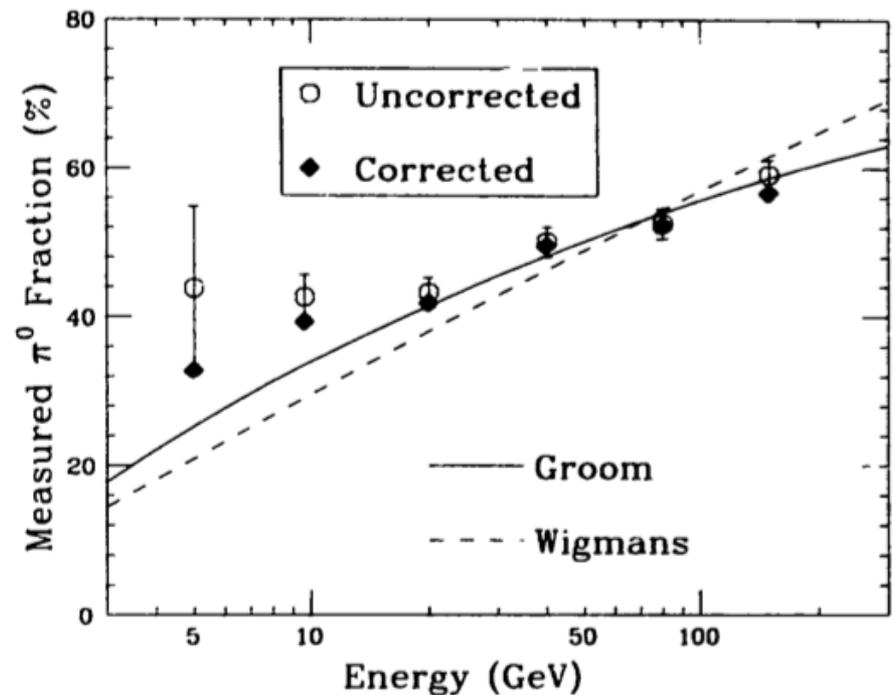
Neutral mesons and the internal e.m. shower



- The mean fraction of e.m. showers increase with particle energy
→ non-linearity of the calorimeter

$$\langle f_{em} \rangle \approx 0.1 \cdot \ln E \text{ [GeV]}$$

R. Wigmans, Nucl. Instr. Methods A 265 (1988) 273



D. Acosta e al., Nucl. Instr. Methods A 316 (1992) 184

6.3.3 Compensation

Recipe - 1



Calorimeters with equal response to the e.m. and hadronic shower components $e/h = 1$ are called **compensating calorimeters**.

A very simplified cooking recipe to achieve compensation:

- Use absorber material with large Z and detectors with low Z . Due to the migration effect of photons (cross section $\propto Z^5$) they preferentially interact in the absorber. \rightarrow reduce e
- Use ^{238}U as absorber. Induced fission occurs, the binding energy is released and debris of nuclei are produced (including neutrons). \rightarrow increase h (To achieve compensation the use of ^{238}U is neither mandatory nor sufficient.)
- **Efficient detection of neutrons in the shower.** This requires detector materials with large fraction of “free” protons (Hydrogen atoms). Elastic scattering of neutrons on protons transfers large energy and the recoiling protons produce large signals. \rightarrow increase h
- Optimised thicknesses of absorber and detector layers.

6.3.3 Compensation

Recipe - 2



- To achieve compensation the influence of the electronics signal integration time need to be considered.

Some processes (e.g. neutron capture with subsequent γ emission) have long time constants (> 100 ns). Using short integration times such signals are no longer measured.

- **Software compensation:**

In fine segmented calorimeters the e.m. showers deposit large signals in a small number of cells compared to hadronic showers. By down weighting cells with large signals software compensation is achieved

→ does not work at trigger level

→ problematic for jets

6.3.3 Compensation

Calculation of e/h



- To estimate the expected e/h ratio of a calorimeter one usually looks at the response of individual shower components in relation to the response of a mip.
- A possible approach:

$$\frac{e}{h_{int}} = \frac{e/mip}{f_{ion} \cdot ion/mip + f_n \cdot n/mip + f_\gamma \cdot \gamma/mip}$$

f_{ion}, f_n, f_γ fraction of the energy transferred into ionisation, neutrons, photons
 $e/mip, n/mip, \gamma/mip, ion/mip$... response of e^\pm , neutrons, photons, ionisation loss in units of a mip signal.

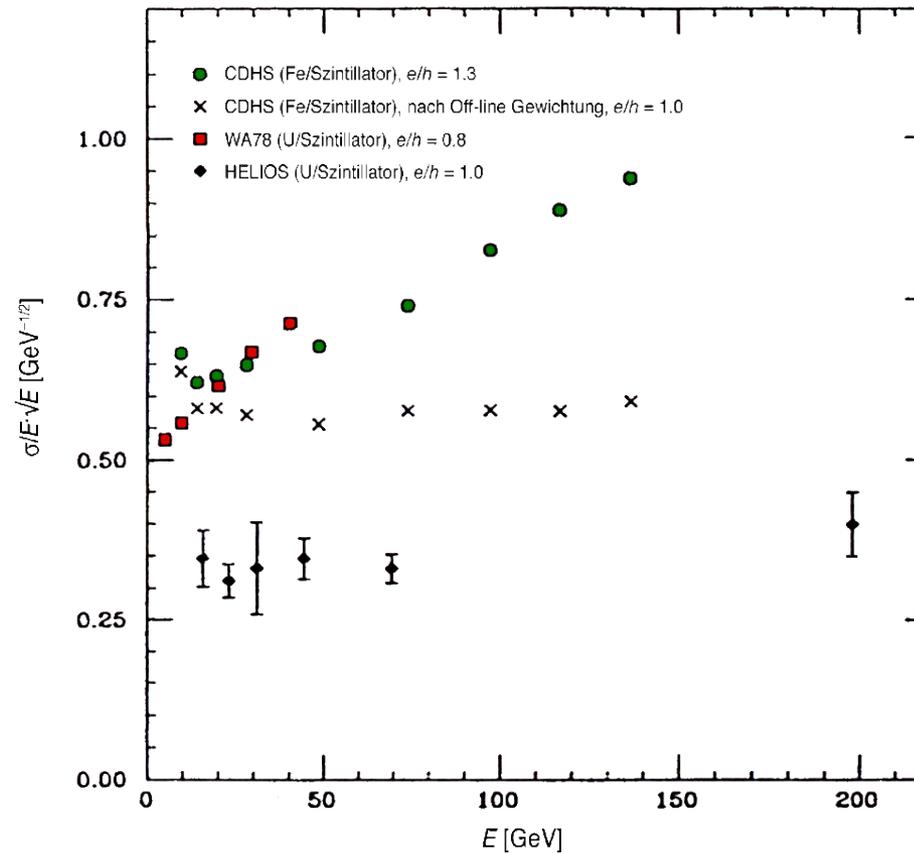
These fractions depend on the choice of the active material, the absorber material, and the relative thicknesses.

6.3.4 Energy Resolution

Examples – 1



Energy resolution of compensating and non-compensating hadron calorimeters:



6.3.4 Energy Resolution

Examples – 2



Experiment	Detectors	Absorber material	e/h	Energie resolution (E in GeV)
UA1 C-Modul	Scintillator	Fe	≈ 1.4	$80\%/\sqrt{E}$
ZEUS	Scintillator	Pb	≈ 1.0	$34\%/\sqrt{E}$
WA78	Scintillator	U	0.8	$52\%/\sqrt{E} \oplus 2.6\%^*$
D0	liquid Ar	U	1.11	$48\%/\sqrt{E} \oplus 5\%^*$
H1	liquid Ar	Pb/Cu	$\leq 1.025^*$	$45\%/\sqrt{E} \oplus 1.6\%$
CMS	Scintillator	Brass (70% Cu / 30% Zn)	$\neq 1$	$100\%/\sqrt{E} \oplus 5\%$
ATLAS (Barrel)	Scintillator	Fe	$\neq 1$	$50\%/\sqrt{E} \oplus 3\%^{**}$
ATLAS (Endcap)	liquid Ar	Brass	$\neq 1$	$60\%/\sqrt{E} \oplus 3\%^{**}$

* After software compensation

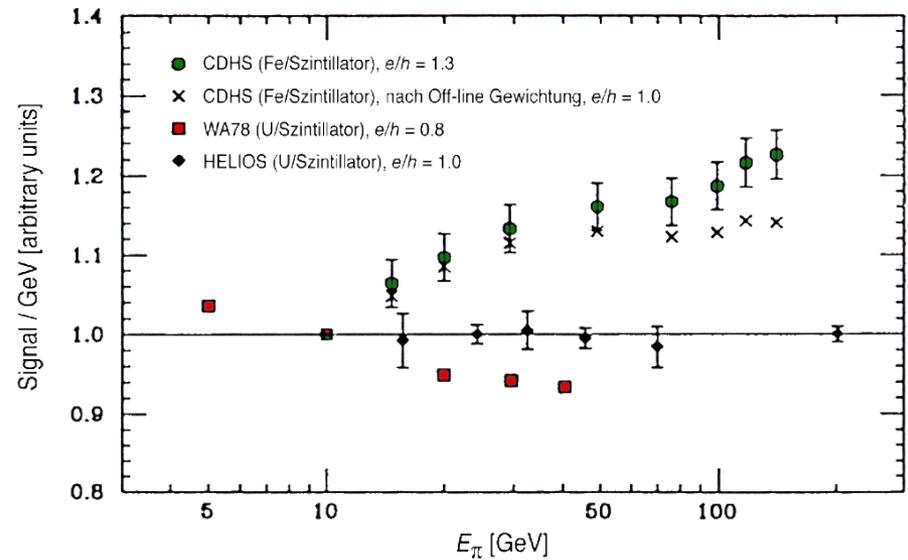
** Design values

6.3.5 Linearity



- The e.m. fraction is energy dependent and hence non-compensating calorimeters are non-linear.
- Compensating calorimeters are linear over a large energy range. Below 2 GeV non-linearities appear due to low energy hadrons losing their energy by ionisation only $\rightarrow e/h$ drops below 2 GeV

Linearity of compensating and non-compensating hadron calorimeters:



6.4 Particle Flow Method



Reconstruct all particles and combine the information from tracking with the measurements in the electromagnetic and hadron calorimeter

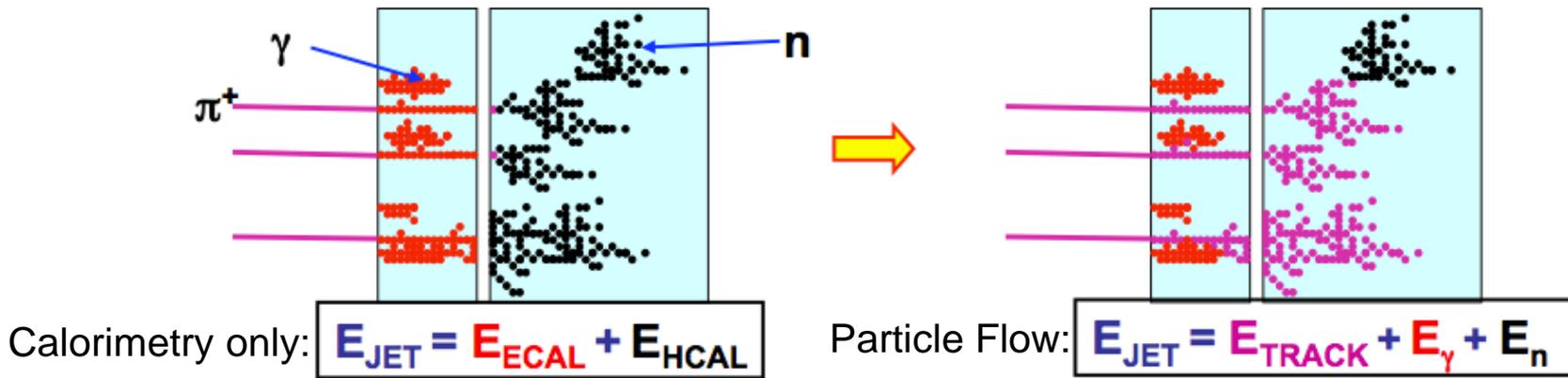
- Momenta of charged particles measured in the tracker
 - Energy of photons measured in the electromagnetic calorimeter
 - Energies of neutral hadrons measured in the em. and had. calorimeter
- **Requires very fine granularity of the calorimeters**

Particles in jets	Fraction of energy in jets	Detectors	Single particle resolution*
Charged particles	65 %	Tracker	$\sigma_{pt}/p_t \sim 1\% p_t$
Photons	25 %	E.m. calorimeter	$\sigma_E/E \sim 2,8\%/\sqrt{E}$
Neutral Hadrons	10 %	E.m. and had. calorimeter	$\sigma_E/E \sim 100\%/\sqrt{E}$

The table lists values of a typical experiment, e.g. CMS.

6.4 Particle Flow Method

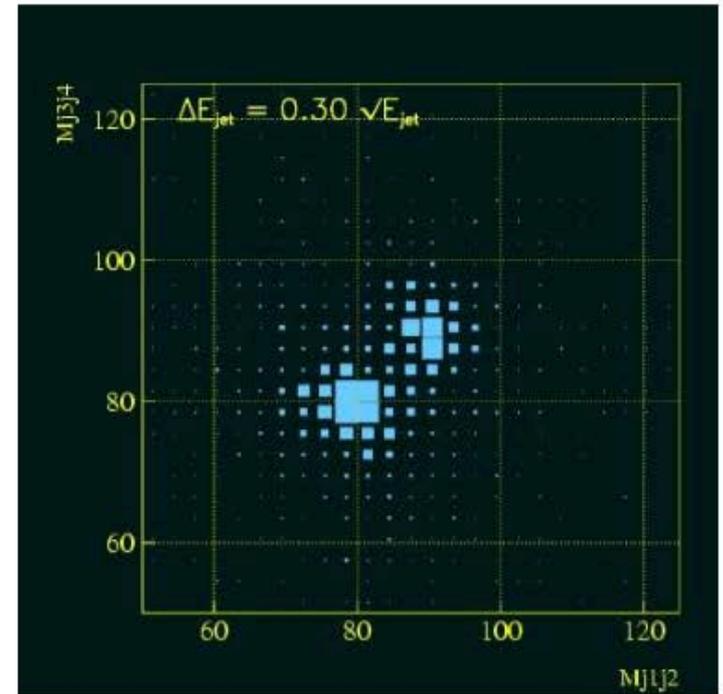
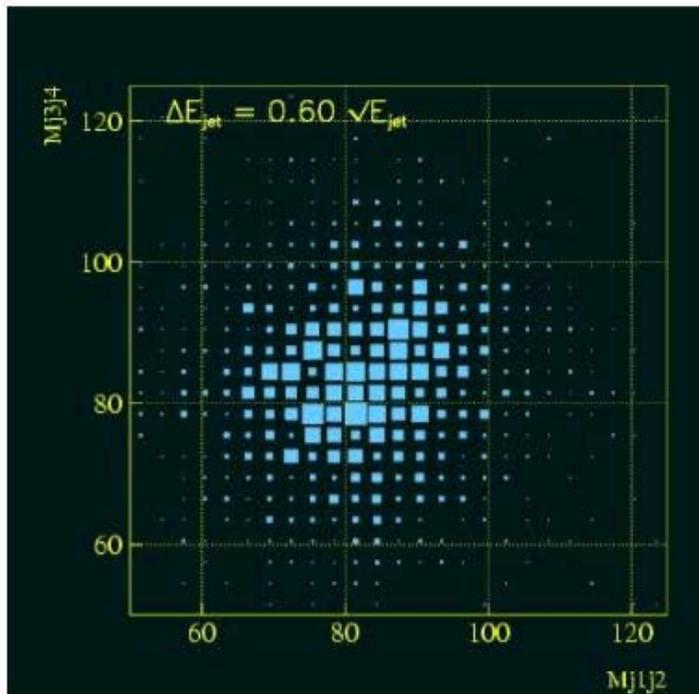
Jet energy measurement



→ improves measurement of jet energy, missing transfers energy MET, tau identification.

Particle Flow Method

Example: ILC

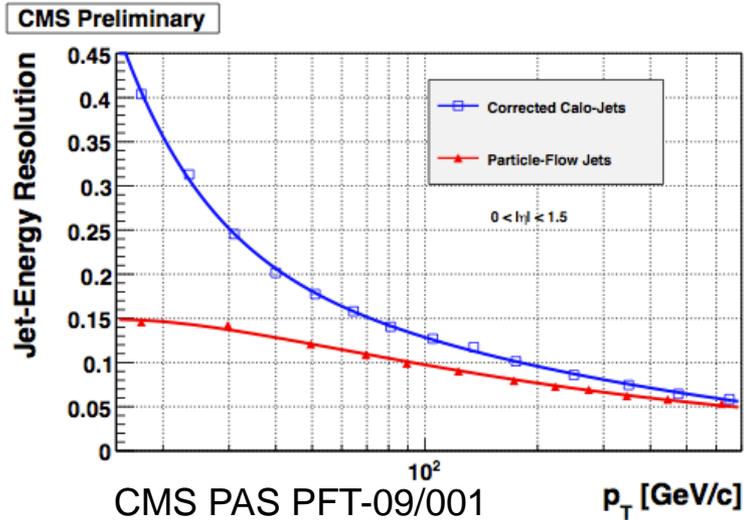


6.4 Particle Flow Method

Example CMS: Particle Flow vs. pure Calorimetry

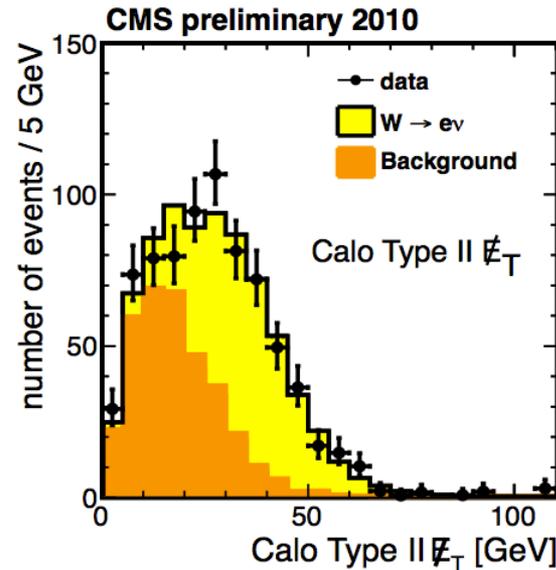


Jet energy resolution (MC):

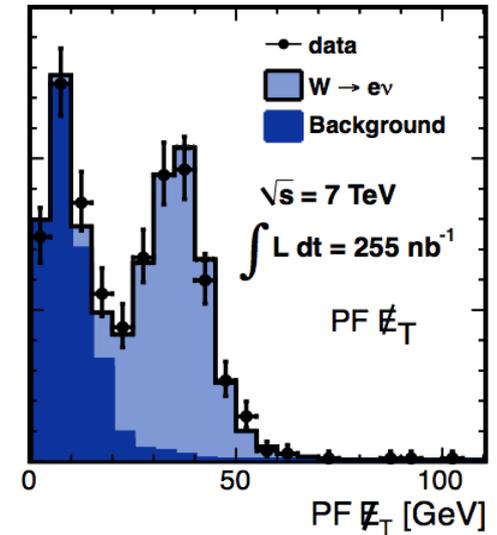


MET distribution in $W \rightarrow e\nu$ candidate events (Data and MC):

Calorimeter MET:



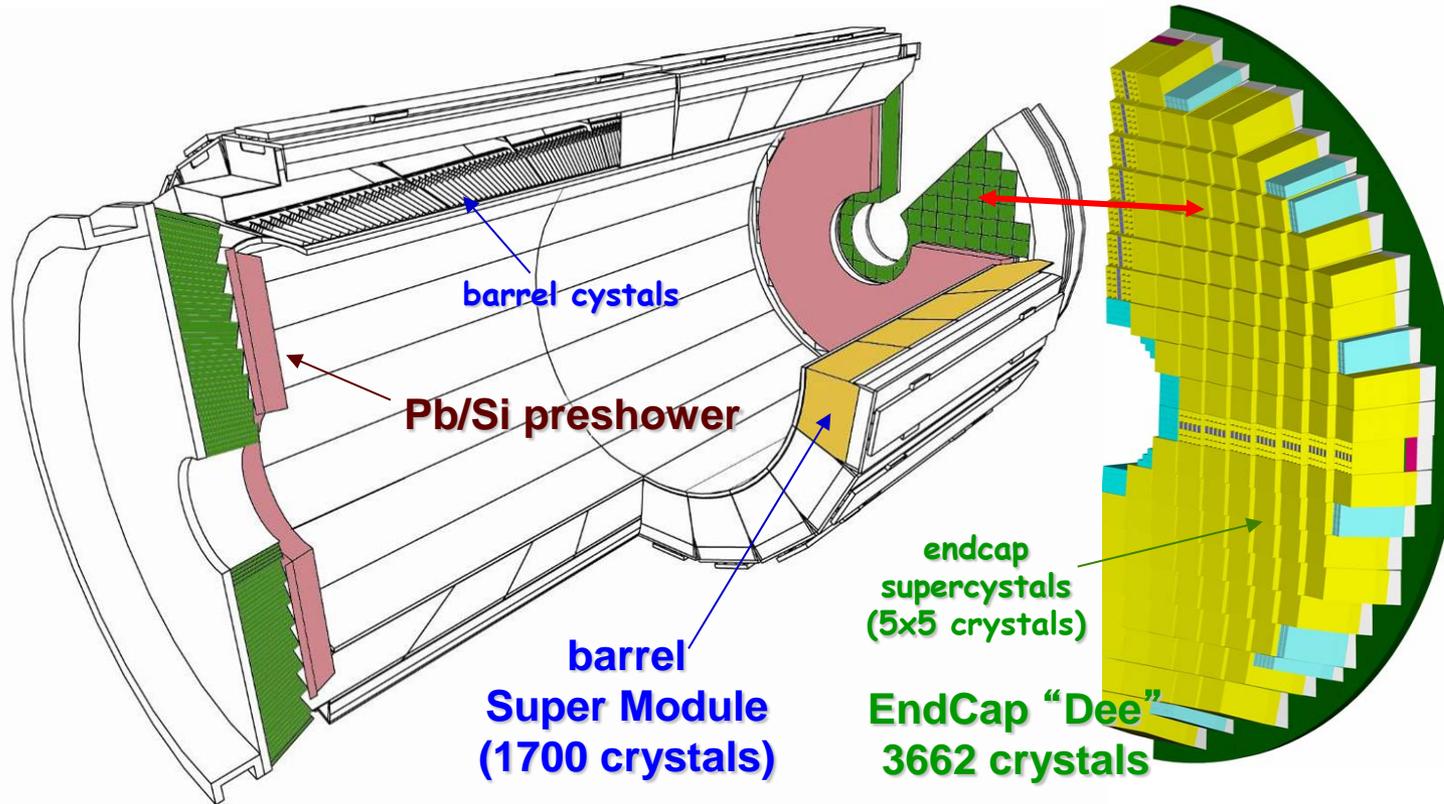
Particle Flow MET:



CMS PAS JME-10-005

6.5 Calorimeter Examples

The PbWO_4 calorimeter of CMS - 1



Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals ($2 \times 2 \times 23 \text{cm}^3$)

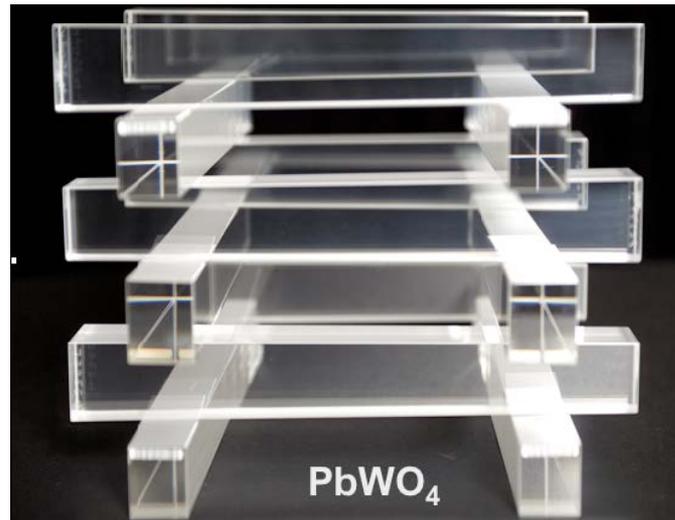
EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals ($3 \times 3 \times 22 \text{cm}^3$)

6.5 Calorimeter Examples

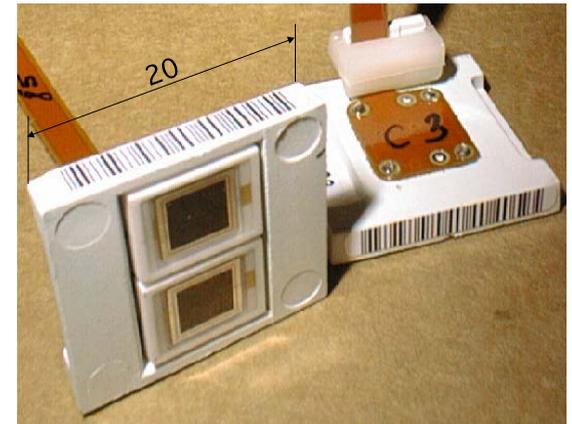
The PbWO₄ calorimeter of CMS - 2



Endcap-Ingot:



Barrel: Avalanche photodiodes (APD)
Two 5x5 mm² APDs/crystal
Amplification: 50 QE: ~75% at I_{peak}= 420 nm



Endcaps: - Vacuum phototriodes (VPT)
Better radiation resistance compared to APDs
Active area ~ 280 mm²/crystal
Amplification 8 -10 (B=4T) Q.E.~20% at 420 nm

Result from test beam:

$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\text{GeV})}} \oplus \frac{125}{E(\text{MeV})} \oplus 0.3\%$$

6.5 Calorimeter Examples

CMS – HCAL - 1



Absorber: Brass (70% Cu / 30% Zn)
Thickness 50.5 mm, 56.5 mm

Detector: Plastic Scintillator
(Kuraray SCSN81),
Thickness 3.7 mm



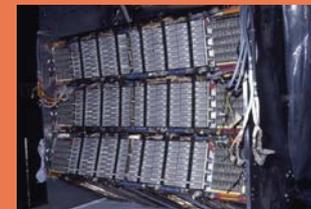
Used over a million World War II brass shell casements from the Russian Navy.



Half-Barrel des CMS
Hadron Kalorimeters:

6.5 Calorimeter Examples

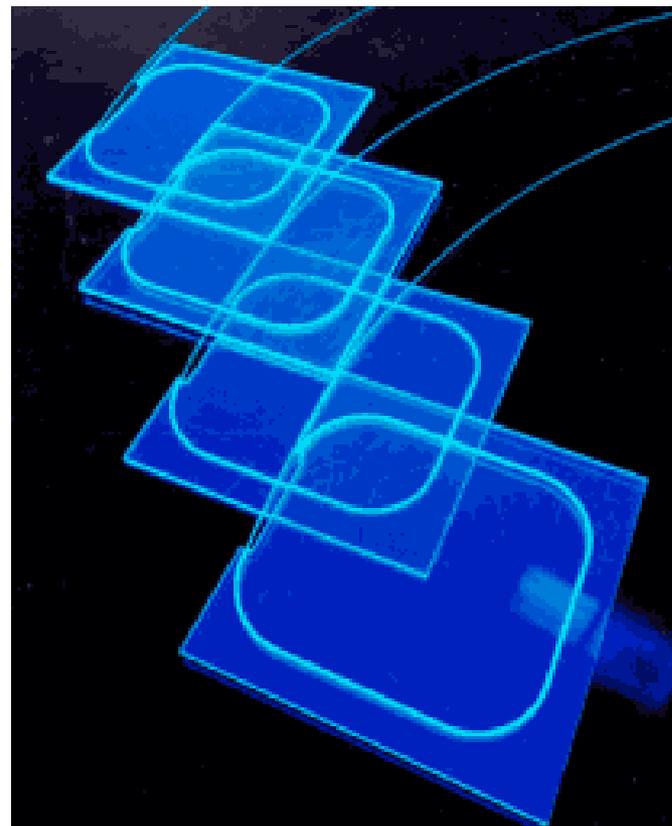
CMS – HCAL - 1



Plastic scintillators with embedded wave length shifting fibers:

Light from the scintillator is emitted at 410-425 nm (blue-violet). The fibers absorb the light and re-emit it at 490 nm (green).

Hybrid Photodiodes are used to convert light into electrical signals.



Energy resolution about $100\%/\sqrt{E} \oplus 5\%$

6.5 Calorimeter Examples

”Spaghetti”-Calorimeter (Scintillating Fiber Calorimeter)



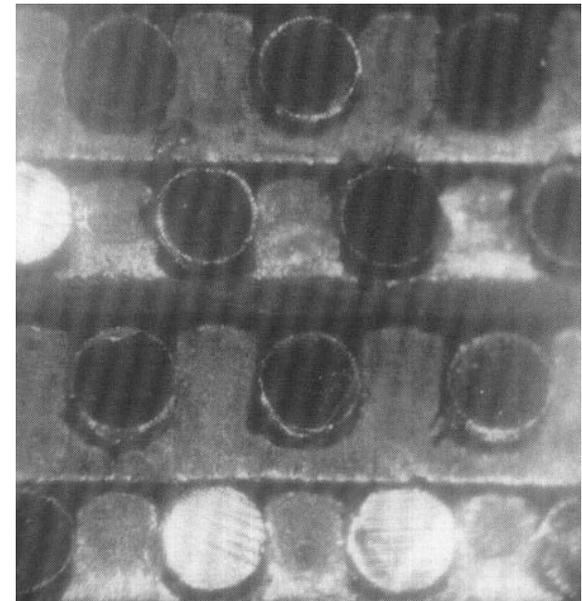
- In this type of calorimeter parallel bundles of scintillating fibers are embedded in an absorber matrix (e.g. Pb). Fiber diameter typically 0.5–1 mm.
- Advantages: cheap, compensation possible, excellent hermeticity of the detector
- Disadvantage: no longitudinal segmentation
- Prototypes: 1 mm thick fibers in Pb matrix, distance between fibers 2.22 mm

→ energy resolution:

$$\sigma(E)/E (e.m.) = 15.7\%/\sqrt{E} \oplus 2\% \text{ and}$$

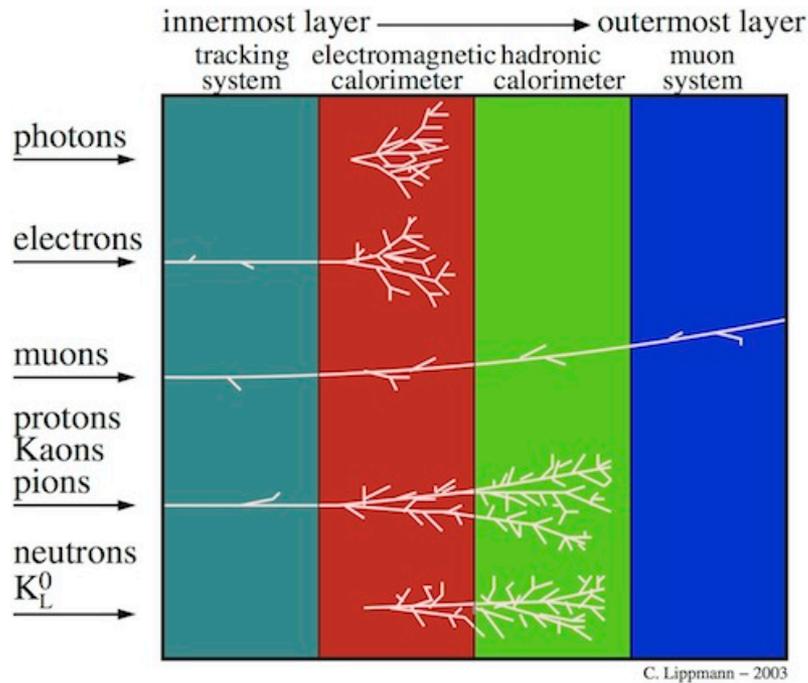
$$\sigma(E)/E (hadron.) = 33.3\%/\sqrt{E} \oplus 2.2\%.$$

Scintillating fibers in Pb matrix:

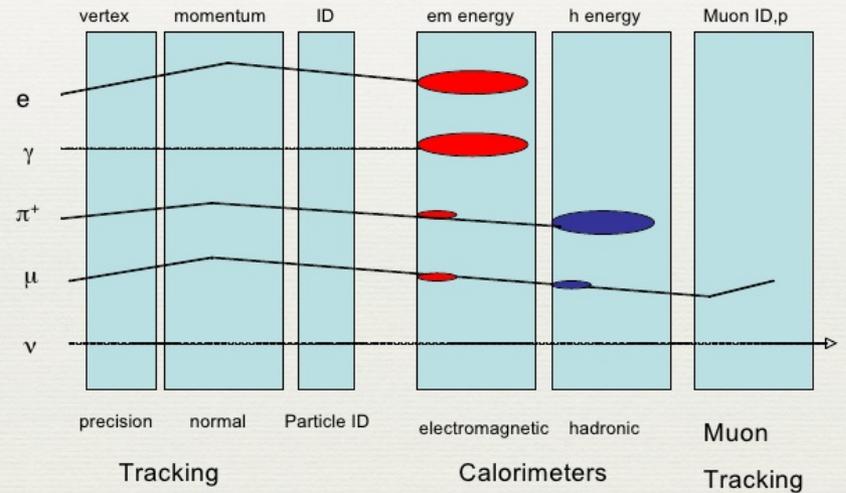


Nucl. Instr. Methods A., **386**, 397–408 (1997)

Experiment principles



Particle Identification

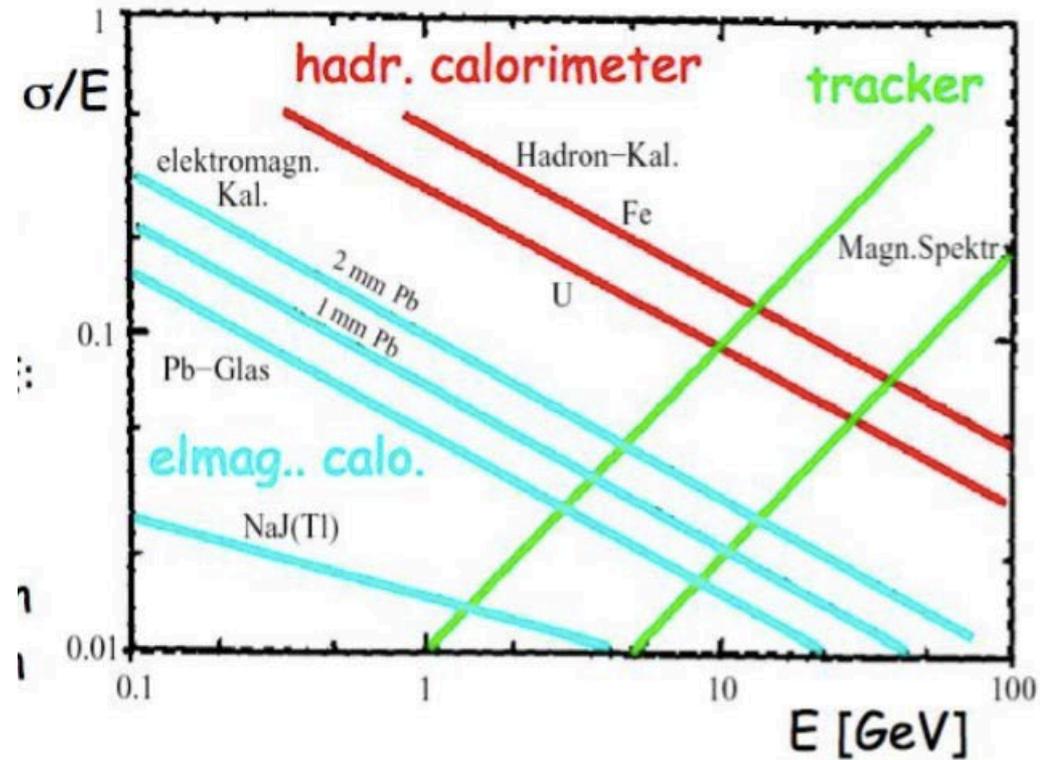


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Tracker and calorimeter resolution



- Tracker $\sigma(p)/p \approx p$
- Calorimeter $\sigma(E)/E \approx 1/E$





THE END.