Concepts for Experiments at Future Colliders I

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Recapitulation of the previous lecture

Signal formation in a semiconductor detector

- The charge measured at the electrodes of a semiconductor detector, denoted as Q, is the induced charge generated by the movement of liberated charge carriers (q).
- The calculation of the induced charge involves the use of the Shockley-Ramo theorem, which we will not derive today.
- Today, we present a simplified derivation:
  - Work done by the electric field on q: $qE(x)dx$.
  - Change in the electric field in a capacitor: $\frac{Q}{C}dQ = UdQ$.
  - Due to conservation of energy, $qE(x)dx = UdQ$.
  - In a plate capacitor with plate spacing D, $E = \frac{U}{D}$, leading to the equation

$$dQ = \frac{q}{D}dx$$

    for the infinitesimal induced charge dQ.

Recapitulation of the previous lecture

Signal formation in a semiconductor detector

Temporal evolution of the induced charge

- Average velocity of electrons and holes:

$$v_{e/h} = \frac{q_{e/h}}{m_{e/h}} E \tau_{e/h},$$

  where τ is the mean time between two collisions of charge carriers in the lattice.

- Electric field in a pn junction from a p-substrate with an n$^+$-doped side:

$$E = -\frac{eN_A}{\epsilon} x.$$

$\Rightarrow$

$$v_{e/h} = \frac{dx_{e/h}}{dt} = \pm \frac{e^2 N_A}{\epsilon} x_{e/h} = C_{e/h} x_{e/h},$$

hence

$$x_{e/h}(t) = x_0 e^{C_{e/h} t}.$$

Signal Formation in a Semiconductor Detector

Temporal Evolution of the Induced Charge

- $Q_{e/h}(t) = \int\limits_0^t \frac{q_{e/h}}{D} v(t')dt' = \frac{q_{e/h}}{D} x_0 (e^{C_{e/h}t} - 1).$

Leo 1994

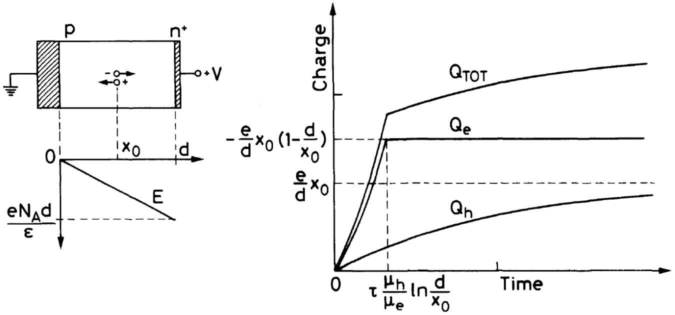
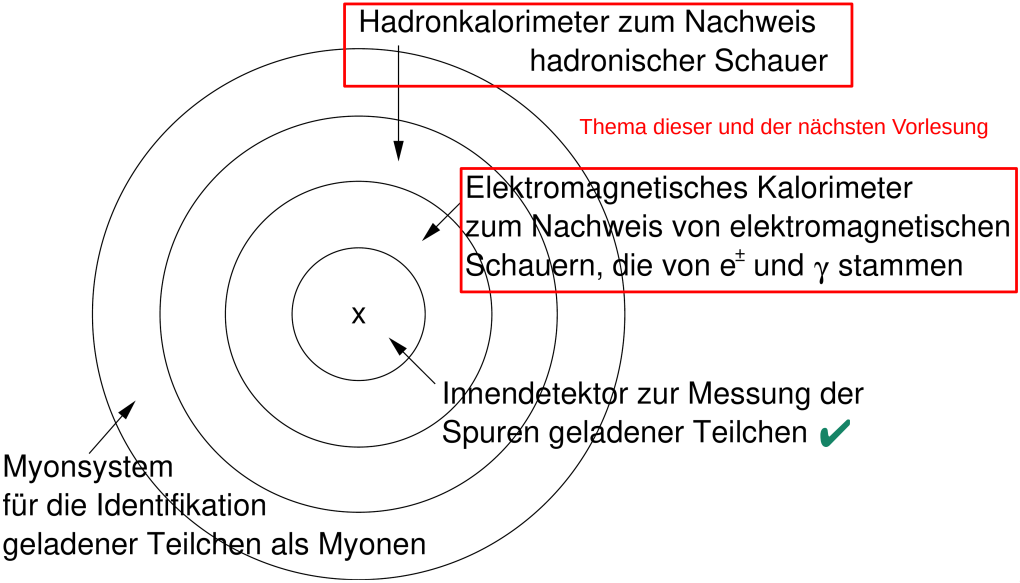


Fig. 10.10. Signal pulse shape due to a single electron-hole pair in an np junction

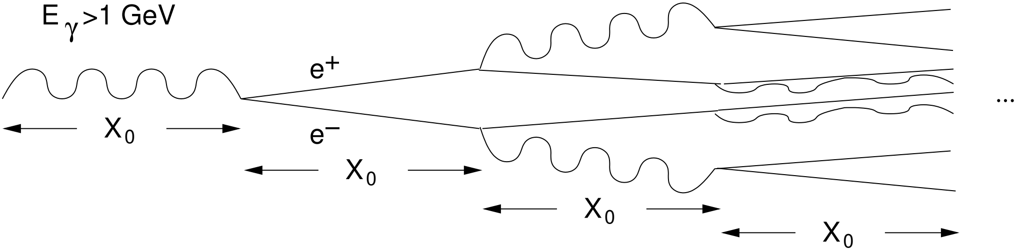
- $C_e > 0,\ q_e < 0.$
- $C_h < 0,\ q_h > 0.$

Structure of a hadron collider experiment



Recapitulation of the previous lecture

Electron photon showers



- After a distance $n \cdot X_0$: 2^n particles with energy $E_n \approx \frac{E_\gamma}{2^n}$.
- End of the cascade (shower), if $E_n = E_k$: $n = \frac{\ln \frac{E_\gamma}{E_k}}{\ln 2}$.
- Shower length: $n \cdot X_0 = X_0 \cdot \frac{\ln \frac{E_\gamma}{E_k}}{\ln 2}$.

Example

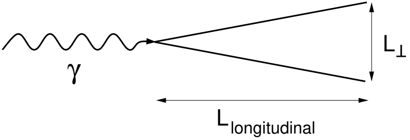
- $E_\gamma = 100$ GeV.
- Material: iron, d.h. $X_0 \approx 2$ cm, $E_k \approx 20$ MeV.

$\Rightarrow$ $n = 12$, d.h. ~ 4000 particles.

Shower length: $L_{longitudinal} \approx 24$ cm.

Transverse size of an electron photon shower

The full treatment with massive electrons and positrons leads to the following result.

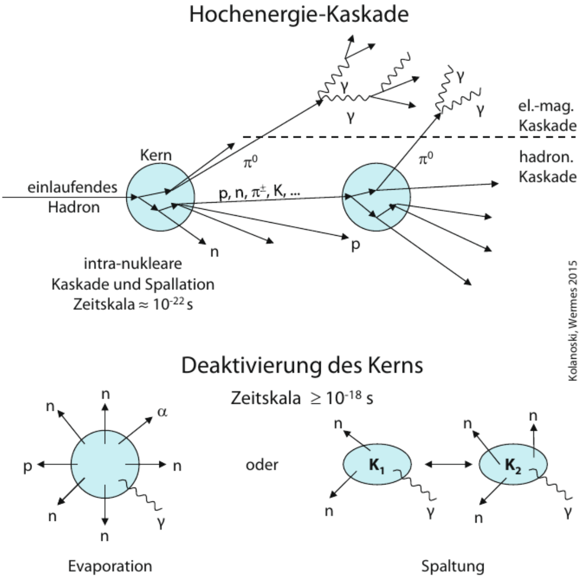


$$L_\perp \approx 4R_M = 4X_0 \frac{21,2 \text{ MeV}}{E_k}$$

R_M: Molière radius

- The transvers size of the shower $L_\perp$ is independent of $E_{\gamma/e^\pm}$.
- $L_{T,Fe} = 4 \cdot 1,8$ cm $\cdot \frac{21{,}2\text{MeV}}{30{,}2\text{MeV}} \approx 5$ cm.
- Characteristic for electromagnetic showers: small transverse size which is independent of $E_{\gamma,e^\pm}$.
- The number of generated particles is a measure for $E_{\gamma,e^\pm}$ and proportional to $E_{\gamma,e^\pm}$.

Hadron showers



Similar behaviour like electromagnetic showers:

- Shower length proportional to $\lambda_A \approx 35\ \mathrm{g\,cm}^{-2} \frac{A^{1/3}}{\rho} \gg X_0$.
- Transverse size independent of the energy of the primary hadron: λ_A.
- But much stronger variations of the shower size than in case of electromagnetic showers.

Recapitulation of the previous lecture

Shower components and shower fluctuations

Contributions to the energy E_{dep} deposited in a block of material

$$E_{dep} = (\underbrace{f_{em} + \underbrace{f_{ion} + f_n + f_\gamma + f_B}_{=:f_h}}_{=1 \text{ per definitionem}})E_{dep}$$

- f_{em}. Fraction of the energy deposited by photons from π^0 decays. As neutral pions are created again and again, f_{em} increases with the particle multiplicity in the cascade, hence with the energy of the incoming hadron.
- f_{ion}. Fraction of the energy deposited by a charged shower particle by ionization.
- f_n. Fraction of the energy deposited by neutrons via elastic scattering or nuclear reactions.
- f_γ. Fraction of the energy deposited by photons which are created in nuclear reactions. $E_\gamma \sim$ keV...MeV $\Rightarrow$ energy transfer by Compton scattering or photoelectric effect. This contribution can occur with a large delay $\gtrsim \mu$s.
- f_B. The binding energy which is required to break up a nucleus is not measured and does not contribute to the calorimeter signal. One has a similar situation with neutrinos which are usually take into account in f_B.

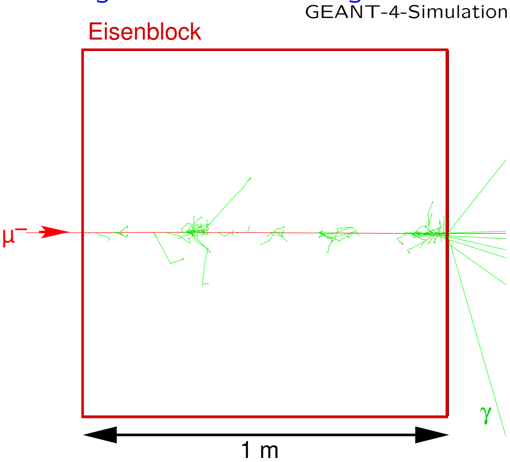
Shower components and shower fluctuations

Contribution of the energy E_{dep} deposited to a block of matter

$$E_{dep} = \underbrace{(f_{em} + \underbrace{f_{ion} + f_n + f_\gamma + f_B}_{=:f_h})}_{=1 \text{ per definitionem}} E_{dep}$$

- f_{em} varies strongly in a hadronic shower between 0 and 1 if no or only neutral pions are generated in the first interactions.
- The composition of the hadron component is independent of the type and energy of the incoming hadron.

Passage of muons through matter

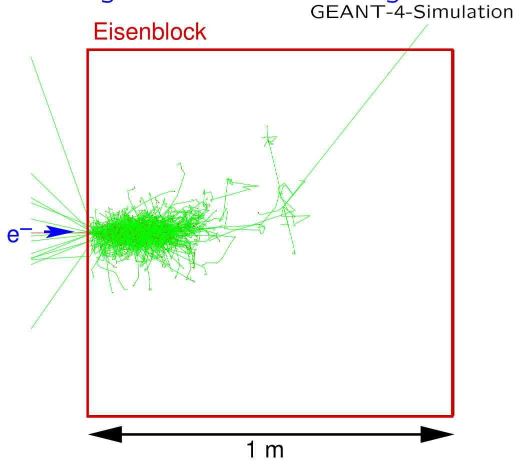


- Muon energy: 10 GeV.
- Muons: only electroweak interaction.
- Muons are heavy particles.

⇒ Small energy loss by excitation and ionization of iron atoms.

⇒ Muon passes the entry iron block.

Passage of electrons through matter



- Electron energy: 10 GeV.
- Electrons: only electroweak interaction.

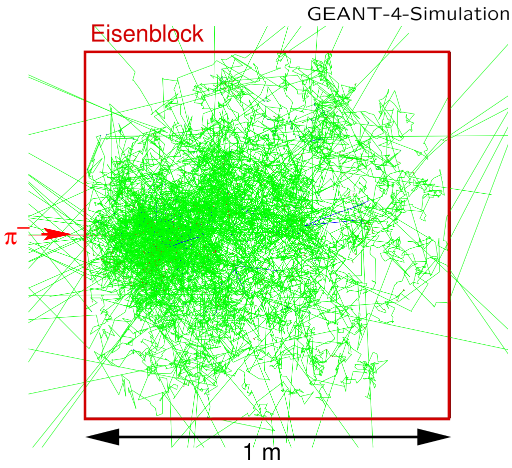
⇒ Large energy loss mainly by bremsstrahlung.

⇒ Evolution of an electron photon shower.

⇒ The electrons is stopped in the iron block.

Recapitulation of the previous lecture

Passage of pions through matter



- Pion energy: 10 GeV.
- Charged pions: electroweak and strong interaction.
- Charged pions are heavy charged particles.

⇒ Small energy loss by excitation and ionization of iron atoms.

⇒ But development of a hadron shower.

⇒ As the strong interaction is short range, the shower almost completly fill the iron block.

⇒ The block is just thick enough to stop the pion.

Calorimeter types

Nomenclature

Passive medium:	Material in which the shower develops.
Aktive medium:	Material in which the electronically detectable signals of the shower particles are created.

Two types of calorimeters

- Homogeneous calorimeters, in which the active material also serves as passive material.
- Inhomogeneous calorimeters or sampling calorimeters with alternating layers of active and passive materials.

Hadron calorimeters are always sampling calorimeters in order to limit their size. There are homogeneous and inhomgeneous electromagnetic calorimeters.

Recapitulation of the previous lecture

Longitudinal segmentation of a calorimeter

- Electromagnetic calorimeters are segmented longitudinally in order to be able to measure the longitudinal shower shape. This allows for the discrimination of showers initiated by electrons from showers initiated by pions which are longer than electron showers.
- In hadron calorimeters, the longitudinal segementation is important for the discrimination of the different shower components.

Recapitulation of the previous lecture

Tailcatcher, Presampler, lateral structure

Tailcatcher

This is a longitudinal extension of a calorimeter for the rough measuremetner of the shower tails to minimize detection losses.

Presampler

This is used in front of an electromagnetic calorimeter to identify if a shower initiated by a photon started before the calorimeter.

Lateral structure

The lateral segmentation has to be chosen small enough to separate neighbouring shower. So the segmentation is given by the Moliére radius for electromagnetic calorimeters and by the nuclear interaction length for hadron calorimeters.

Energy resolution and linearity

Energy resolution

- The energy measurement in a calorimeter consist of the detection of the shower particles. The measured energy is proportional to the number of detected shower particles N leading to $\frac{\delta E}{E} = \frac{\delta N}{N} = \frac{1}{\sqrt{N}}$.
- In a real calorimeter contributions to the energy resolution from detector noise and mechanical and electronic non-uniformities must be taken into account:

$$\frac{\delta E}{E} = \frac{a}{\sqrt{E}} \oplus \underbrace{\frac{b}{E}}_{El.\ noise} \oplus \underbrace{c}_{Non-uniformities}$$

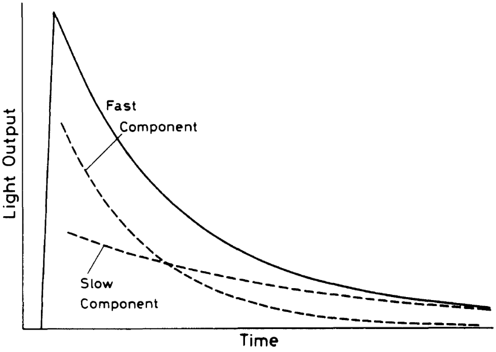
Linearity

Not only $\frac{\delta E}{E}$ is important, but also that the measureed signal depends linearly on E.

Scintillation counters

- Scintillation counters are important detectors for the active part of a calorimeter.
- Materials which emit a small flash of light when hit by radiation are used in scintillation counters.
- Important properties of the signal of a scintillation counter:
  - Above a certain minimum energy deposition, the amount of scintillation light is proportional to the deposited energy (in good approximation).
  - Fast response, i.e. the light signal is created a short time after the energy deposition.

- Scintillators are luminescent materials.
- If the emission of light happens within 10 ns, the process is called fluorescence.
- If the emission of light is delayed, the process is called phosphorescence.



- The time evolution of the light emission can be approximated by the superposition of two exponential distributions:

$$N_\gamma = A\exp\left(-\frac{t}{\tau_f}\right) + B\exp\left(-\frac{t}{\tau_s}\right);$$

τ_f Time constant of fast component.
τ_s Time constant of the slow component.

Requirements for scintillation counters

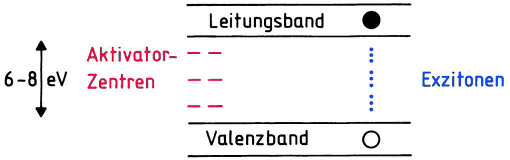
Good scintillation counters should have the following properties.

- High efficiency for the conversion of the deposited energy into scintillation light.
- The scintillator should be transparent for the scintillation light in order to allow for the transmission of the scintillation light.
- Emission of the scintillation light in a wavelength region for which efficient light detectors exist.
- Dominating fast component τ_f.

Anorganic scintillators

- Most of the anorganic scintillators are cristall of alkali halides mixed with small amounts of so-called activator impurities.
- Examples: NaI(Tl), CsI(Tl), $Bi_4Ge_3O_{12}$, $PbWO_4$.
- Many anorganic scintillators are hygroscopic, e.g. NaI, and have to be protected from humidity.
- CsI of BGO are examples of non- or weakly hygroscopic materials.

Scintillation mechanism in anorganic scintillators



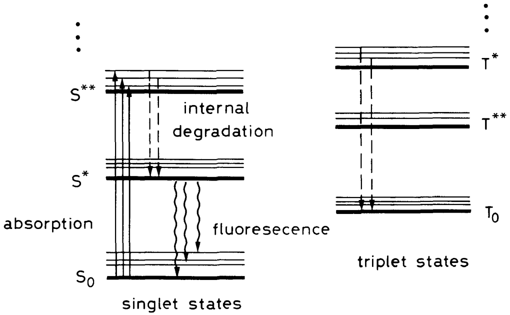
- Ionizing radiation can excite electrons into the conduction or exciton band.

- Light emitted in transition of electroncs from the conduction into the valence band is non-visible.
- Visible light is emitted in transitions from activator levels.
- Free holes of holes of excitons can ionize activator atoms. If an electron hit this atom, it can fill an excited activator state and return to the ground state by the emission of visible light.

Organic scintillators

- Organic scintillators are aromatic hydrocarbons containing bound or condensated benzen ring structures.
- Organic scintillators have a small time constant in the ns range.
- The scintillation light is emitted in transitions of free valence electrons in π orbitals of the molecules.

Szintillation mechanism in organic scintillators



- Excitation of electron energy or vibrational level by ionizing radiation.
- Radiationless transition from a singlet excitation S^{**} into S^{*}. within <10 ps.
- Large probability for a transition from S^{**} into a lower vibrational level.

$\Rightarrow$ The scintillator is transparent for the emitted light because the vibrational level is above the ground state S_0.

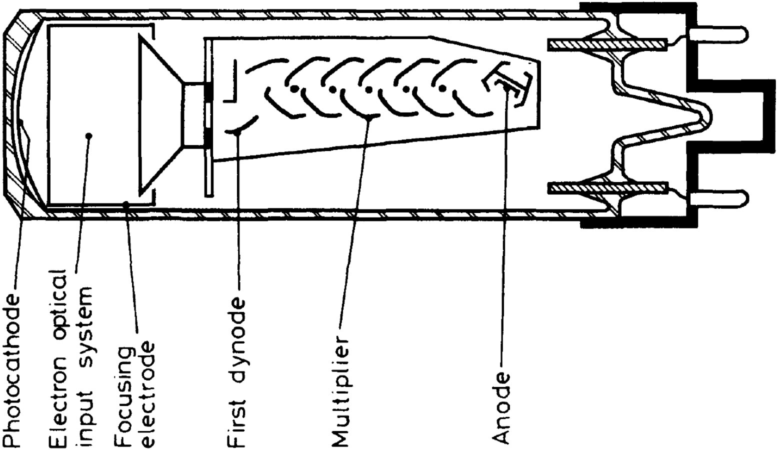
- Similar inner transitions from the excited triplet states.
- $T_0 \rightarrow S_0$ suppressed due to selection rules.
- $T_0 + T_0 \rightarrow S^* + S_0 +$phonons, afterwards emission of scintillation light as described above.

Plastic scintillators

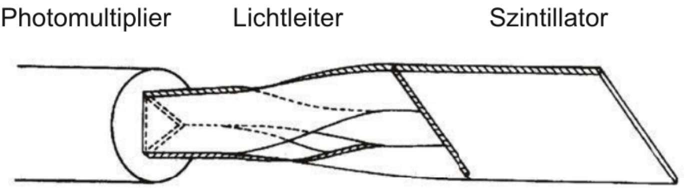
- Plastic scintillators are organic scintillators containe in a solid plastic.
- Frequently used plastics: polyvinyltoluene, polyphenylbenzene, polystyrene.
- Frequently used scintillators:
  - p-terphenyle ($C_{18}H_{14}$).
  - PDB ($C_{20}H_{14}N_2O$).
  - PPO ($C_{15}H_{11}NO$).

Photomultipliers

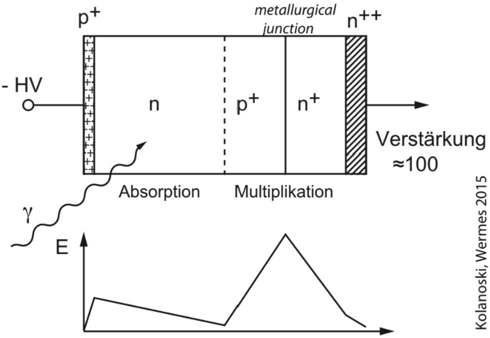
- Photomultipliers are widely used for the detection of scintillation light.
- Yet they need a log of space and cannot be easily operated in large magnetic field. Hence several experiments used avalanche photodiodes or silicon photomultipliers. These two technologies will not be covered in the lecture due to lack of time.
- Schematic drawing of a photomultiplier.



Typical structure of a scintillation counter



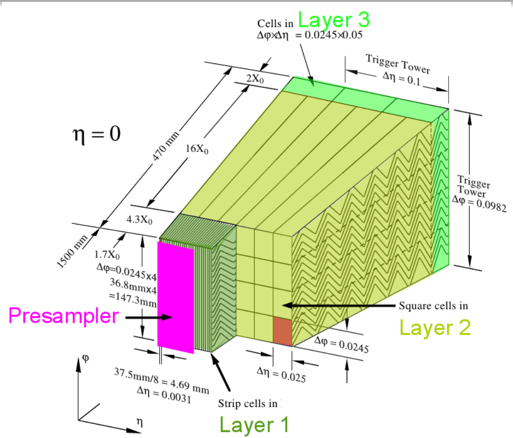
Avalanche photo diodes

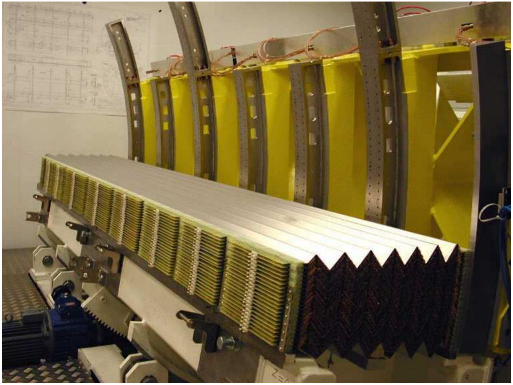


- Disadvantages of PMTs:
  - Use a lot space.
  - Operation in large magnetic fields difficult.
- Alternative chosen by CMS: Avalanche photo diodes (APDs):
  - Semiconductor photo detectors.
  - Doping profile leads to a region with a large electric field in which the electrons created by the impinging photons are multiplied.

Liquid argon as active medium

- Liquid argon is also used as active medium in calorimeters.
- Thanks to the large density of argon in liquid phase, many electrons are created by ionization radiation.
- In order to collect these electroncs, the liquid argon is contained between electrodes put under high voltage to collect the ionization charge.

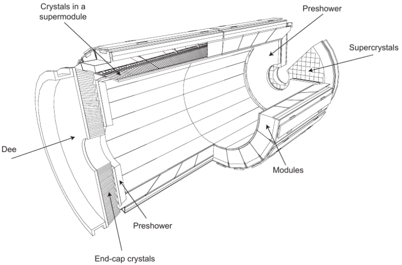


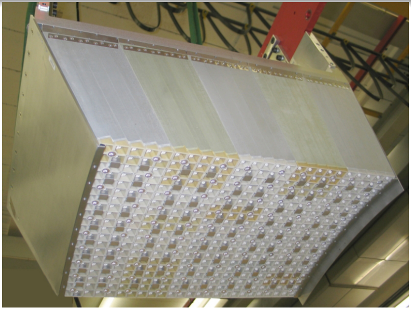


- Inhogeneous accordeon calorimeter with lead as passive material and liquid argon as active material.
- Accordeon structure to maximize the primary ionization path.
- Energy resolution:

$$\frac{\delta E}{E} = \frac{9\%}{\sqrt{E[\text{Gev}]}} \oplus 0,2\%$$

Electromagnetic calorimeter of the CMS experiment





- Homogeneous $PbWO_4$ calorimeter.
- Detector material: scintillation $PbWO_4$ crystalls with high radiation hardness in order to maximize the energy resolution for photons:

$$\frac{\delta E}{E} = \frac{2,8\%}{\sqrt{E[\text{Gev}]}} \oplus \frac{120\ \text{MeV}}{E} \oplus 0,3\%$$

- Disadvantages:
  - No longitudinal segmentation $\Rightarrow$ poor angular resolution.
  - Small light yield requires read-out electronics with very high gain: avalanche photo diodes in the barrel, photomultipliers in the end caps.

Typical structure of hadron calorimeters

- Hadron calorimeters are sampling calorimeters.
- Choice of passive material with λ_A not too different from X_0 to achieve a similar development of the hadronic and electromagnetic shower components.
- Good absorber: iron (X_0=1,8 cm, λ_A=17 cm).
- Alternative approach: compensating calorimeter.
  Choice of absorbers with high Z (uranium, lead, wolfram) to suppress the signal yield for the electromagnetic component with respect to the hadronic component.

Calorimeter signals of electrons and hadrons

- Signal of a pion:

$$S(\pi) = (f_{em} \cdot \epsilon_{em} + f_h \cdot \epsilon_h) \cdot E,$$

(ϵ: detection efficiency).

- Signal of an electron:

$$S(e) = \epsilon_{em} \cdot E$$

- $\frac{e}{p}$ ratio:

$$\frac{S(e)}{S(\pi)} = \frac{\epsilon_{em} \cdot E}{(f_{em} \cdot \epsilon_{em} + f_h \cdot \epsilon_h) \cdot E} = \frac{\frac{\epsilon_{em}}{\epsilon_h}}{1 - f_{em}(1 - \frac{\epsilon_{em}}{\epsilon_h})},$$

hence $\frac{S(e)}{S(\pi)}$=1, if $\epsilon_{em} = \epsilon_h$.

- Energy resolution:

$$\frac{\delta E}{E} = \frac{a}{\sqrt{E}} \oplus b\left(\frac{\epsilon_{em}}{\epsilon_h}\right);$$

$a \sim 50\%$, hence much larger than for electromagnetic calorimeters.

- The value of $\frac{\epsilon_{em}}{\epsilon_h}$ also influences the linearity of the calorimeter.