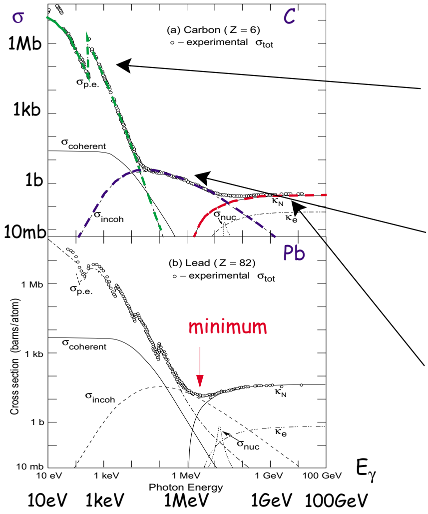
Part III

- Scintillators
- Photodetectors
- Cherenkov detectors
- Transition radiation detectors
- Calorimeters
  - shower development
  - electromagnetic calorimeters
  - hadronic calorimeters

Interaction of Photons with Matter



Three effects are important:

- Photoeffect: $\gamma + \text{atom} \rightarrow e^- + \text{atom}^+$

$$\sigma_{Ph} \propto \frac{Z^5}{E^{3.5}}$$

- Comptoneffect: $\gamma + \text{atom} \rightarrow \gamma + e^- + \text{atom}^+$

$$\sigma_{Compton} \propto \frac{\ln E}{E} \cdot Z$$

- Pairproduction: $\gamma + \text{nucl.} \rightarrow e^+ + e^- + \text{nucl.}$

$$\sigma_{Pair} \propto Z^2 \quad \text{für} \quad E_\gamma \gg 2m_ec^2$$

Intensity Attenuation

- Intensity attenuation: $I(x) = I_0 \cdot \exp(-\mu x)$,

  with mass absorption coefficient $\mu = \frac{N_A \cdot \sigma}{A}$ [cm^{-1}]

  strongly energy dependent

- connection between radiation length and high energy limit for pair production:

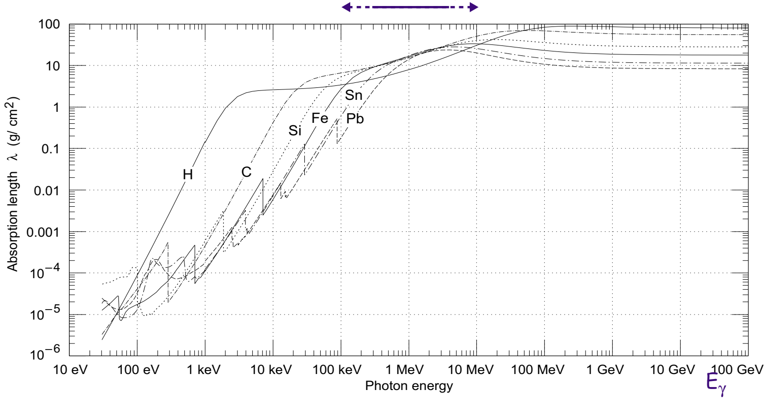
$$\sigma|_{E \gg 1\,\mathrm{GeV}} = \frac{7}{9} 4\alpha r_e^2 Z^2 \ln\frac{183}{Z^{1/3}} \approx \frac{7}{9} \cdot \frac{A}{N_A} \cdot \frac{1}{X_0}$$

$\Rightarrow I(x) = I_0 \cdot \exp\left(-\frac{7}{9}\frac{x}{X_0}\right)$ probability for pair production after traversing one X_0 is ≈54%.

Photon Absorption Length λ

Definition of mass absorption coefficient: $\lambda = \frac{1}{(\mu/\rho)}$ [g cm^{-2}] with $\mu = \frac{N_A \cdot \sigma}{A}$

$\sigma_{Ph} \propto \frac{Z^5}{E^{3.5}}$ $\sigma_{Compton} \propto \frac{\ln E}{E} \cdot Z$ $\sigma_{Pair} \propto Z^2$

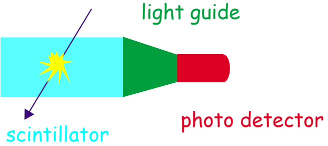


Scintillation Detectors

Phenomenon of scintillation known since long. Extensive use only after invention of photomultiplier in 1944. Since then significant development of this technology.

Advantage for detection of particles and photons:

- simplicity and robustness
- signal speed
- high density → large signals
  ⇒ good time and energy measurement



Now also scintillating fibres available ⇒

- position resolution as well

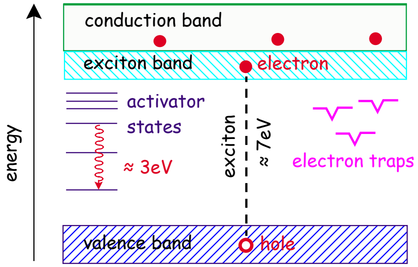
There are different mechanisms in:

- anorganic crystals
- organic substances

Inorganic Crystals

Example: Sodium-Iodide

- NaI insulator with bandgap of 7eV
- replace ≈ 0.1% of sodium atoms with so-called activators: thallium atoms ⇒
  - shift of light energy into visible regime: (advantageous for detection via photo cathode)
  - enhanced light yield
  - reduced re-absorption
- exciton creation by charged particles

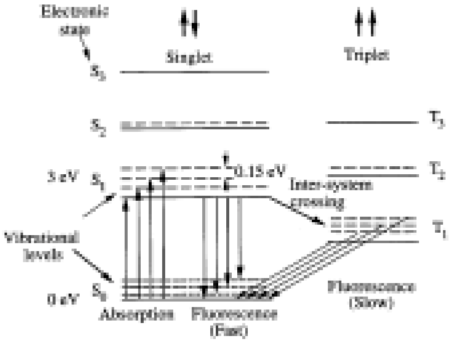


- excitons move in crystal until they reach activator
- energy release by photon emission (3eV ⇒ λ ≈ 400nm)
- for this wavelength the material is transparent
- decay time τ ≈ 230 ns

Organic Scintillators

Mechanism

- Excited vibrational modes of molecules de-excite by emission of UV light.
- This UV light is then transformed into visible light by so called wave length shifters that are added to the material.



Mono crystals

- Napthalen ($C_{10}H_8$)
- Anthrazen ($C_{10}H_{10}$)
- p-Terphenyl ($C_{58}H_{14}$)

Liquid- and plastic- scintillators

- consist of organic substance (polystyrol) plus scint. molecules (≈1%)
- in addition: secondary fluor compounds as wavelength shifters

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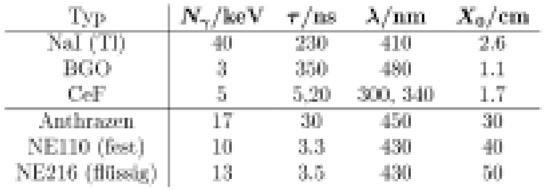
Comparison Organic vs Inorganic Scintillators



	Typ	N_γ/keV	τ/ns	λ/nm	X_0/cm
Inorganic	NaI (Tl)	40	230	410	2.6
	BGO	3	350	480	1.1
	CeF	5	5,20	300, 340	1.7
Organic	Anthrazen	17	30	450	30
	NE110 (fest)	10	3.3	430	40
	NE216 (flüssig)	13	3.5	430	50

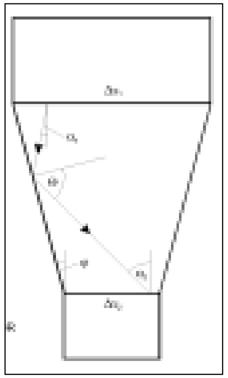
Inorganic crystals

- well suited for calorimetric applications (high light yield and small radiation length)

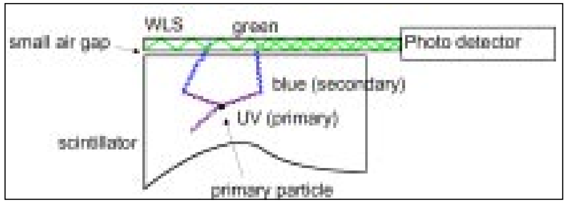
Plastic scintillators

- fast particle registration (trigger)

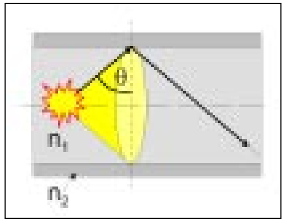
Light Collection



plexiglas lightguide



wavelength shifter bars



total reflection
in optical fibres

Conversion of Scintillation Light

Scintillation light must be converted into electrical signal .

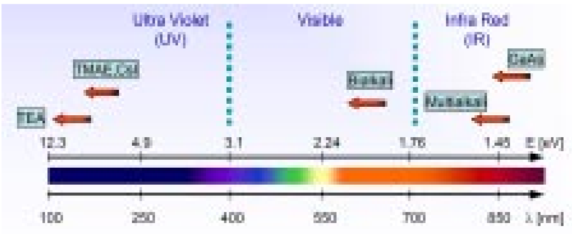
Requirement

- high sensitivity, i.e. high "quantum efficiency": Q.E. = $N_{photoelectrons} / N_{photon}$

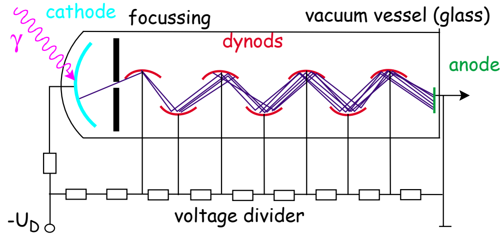
Commonly used photo detectors

- gas based systems
  - e.g. RICH detectors
- vacuum based systems
  - photomultiplier
- solid state detectors
  - photodiodes etc.

Threshold for photo-emission of various materials

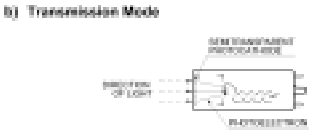


Photomultiplier

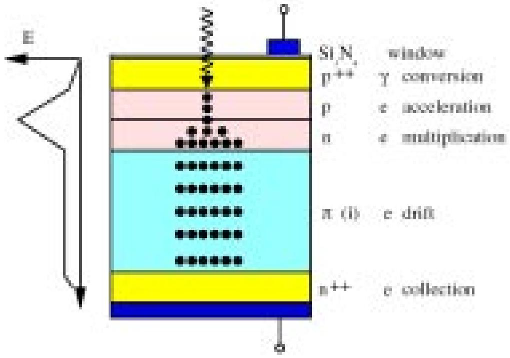


Example: 10 dynodes, each with gain factor $g = 4$

$$\Rightarrow \text{total gain } M = \prod_{i=1}^{N} g_i = 4^{10} \approx 10^6$$



Avalanche Photo Diode APD



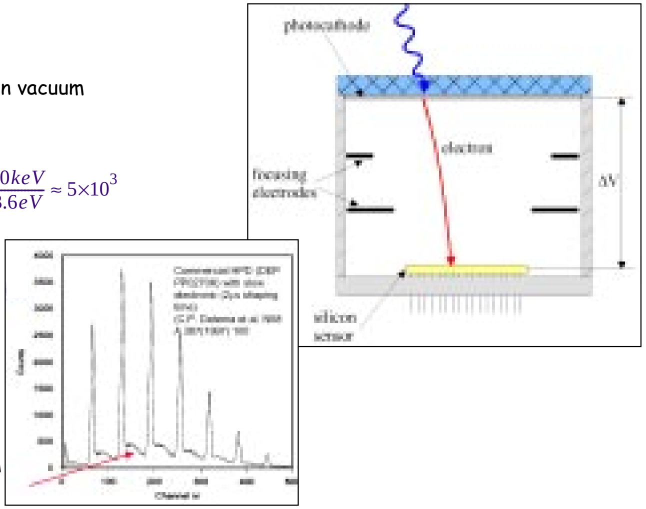
- large reverse bias voltage of 100-200 V
- high internal electric field leads to avalanche formation
- typical gain $G \approx 100 - 1000$

Hybrid Photo Diode HPD

Combination of:

- photocathode
  - like in PMT
- acceleration region in vacuum
  - ΔV = 10 - 20 kV
- silicon detector
  - Gain $G = \frac{e\Delta V}{W_{Si}} = \frac{20keV}{3.6eV} \approx 5\times10^3$
  - Poisson statistics with $\bar{n} = 5000$

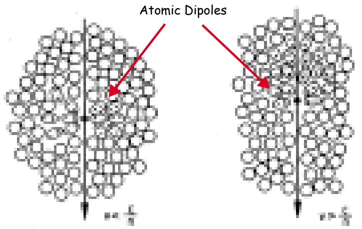
⇒ extremly good pulse height resolution. Single photon counting.



Backscattering from silicon surface

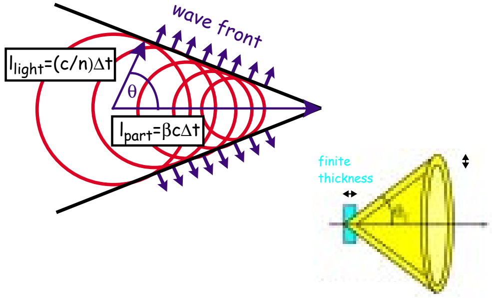
Cherenkov Radiation

- If particle velocity is larger than speed of light in medium:
  - asymmetric polarisation of medium
  - emission of Cherenkov light



- Opening angle of emission cone:

$$\cos(\theta_c) = \frac{(c/n)\cdot\Delta t}{\beta c\cdot\Delta t} = \frac{1}{\beta\cdot n}$$

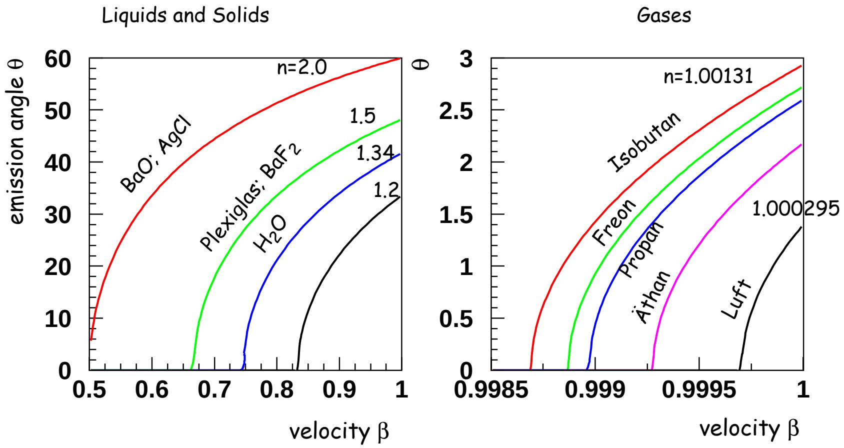


- threshold at $\beta_{thr} = \frac{1}{n}$ (i.e. $\theta_C \cong 0$)
- maximum opening angle:

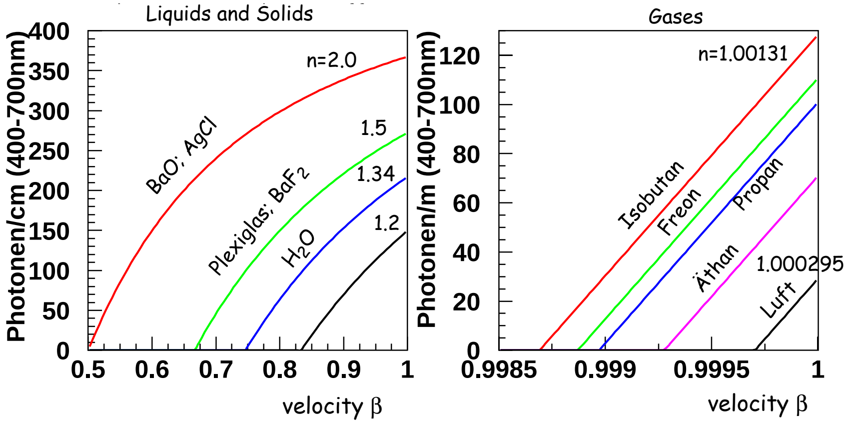
  $\theta_{max} = arc\cos\left(\frac{1}{n}\right)$ (für $\beta \approx 1$)
- photon yield small (λ~400-700nm):

  $dN/dx = 500\sin^2\theta_C\ [\mathrm{cm}^{-1}]$

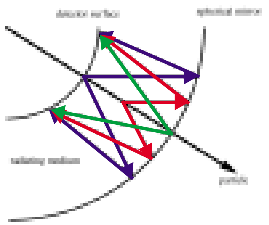
Cherenkov Angle vs β

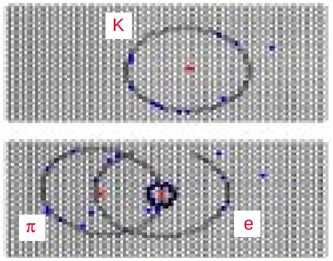


Photon Yield vs β

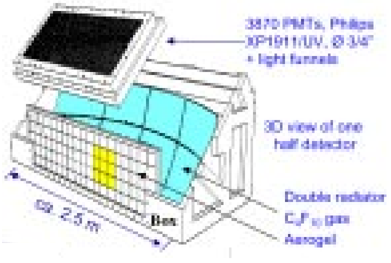


Example: Ring Imaging Cherenkov Counter RICH

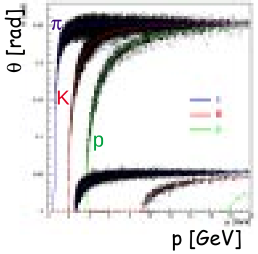




Hermes RICH detector

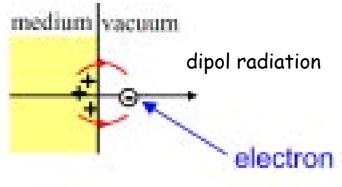


particle identification



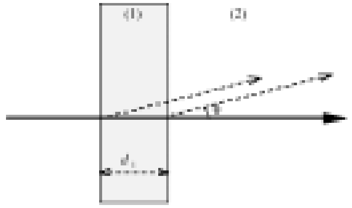
Transition Radiation

Even below the threshold for Cherenkov-radiation photons can be emitted when charged particles cross boundaries between media with different dielectric constants.



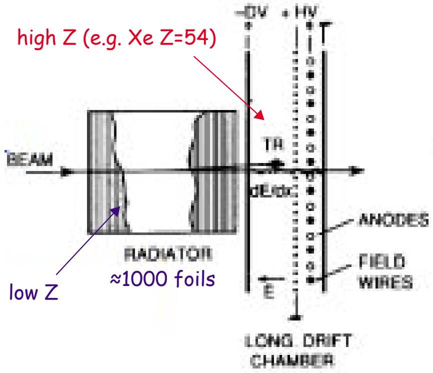
Radiated energy per boundary:

- $W = \frac{1}{3}\alpha\frac{h}{2\pi}\omega_p\gamma \propto \gamma$, i.e. only significant for highly relativistic particles ($e^{\pm}$)
- X-ray photons are emitted in a forward cone; $\theta \propto 1/\gamma$
- → transition radiation only occurs very close to the track



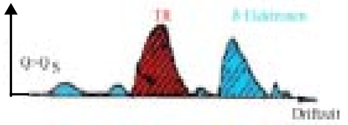
Transition Radiation Detectors

high Z (e.g. Xe Z=54)



≈1000 foils

low Z



TR hits characterised by:

- large amplitude
- occur preferentially at start of the track

Application:

- distinguish high energetic electrons from pions
- discrimination possible for momenta from about 1 GeV/c to ~100 GeV/c

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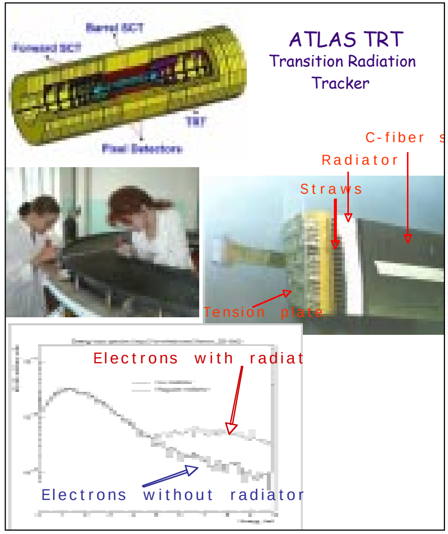
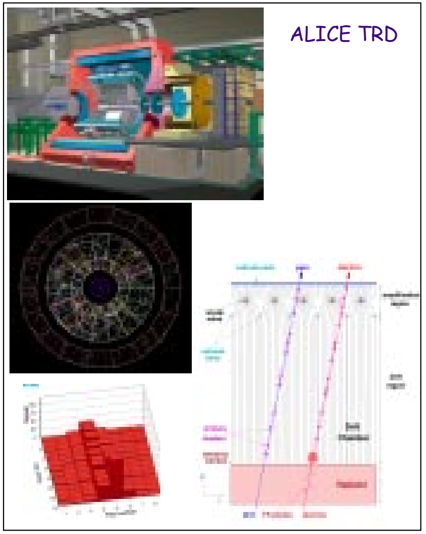
Use of Transition Radiation Detectors at LHC


ATLAS TRT
Transition Radiation Tracker


ALICE TRD

Intermediate Summary

Scintillators
- inorganic crystals (NaI, CsI, BGO, $PbWO_4$, ...)
  - energy loss by ionisation → transfer to luminiscent centers → radiate photons
  - high light yield, small radiation length → calorimeters
- organic (polystyrene, polyvinyltoluene, ...)
  - molecules get excited → energy released as optical photons → Fluors act as wavelength shifter
  - lower light yield, but faster signals → trigger counters

Conversion of Scintillation Light
- photo multiplier
- solid-state photon detectors (APD, HPD, SiPM, ...)

Energy loss processes other than ionisation (used for particle identification)
- Cherenkov radiation
  - threshold effect $\beta_{thr} = n^{-1}$, if particle moves faster than light in medium; but small light yield
- Transition radiation
  - fast particles radiate if they cross boundaries → sensitivity to γ ; but small light yield

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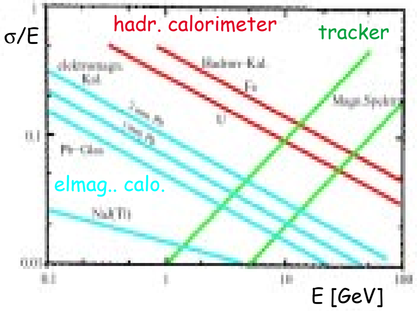
Why do we need Calorimeters ?

Recall: for tracking in magnetic field we have
- $\frac{\sigma(p_T)}{p_T} \propto \frac{p_T}{L^2}$
- momentum (energy) measurement degrades linearly with increasing energy
- size of detector $L \propto \sqrt{E}$
- only detection of charged particles

In contrast (as we will see) for calorimeters:
- $\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}}$
- detection of
  - photons
  - neutral hadrons

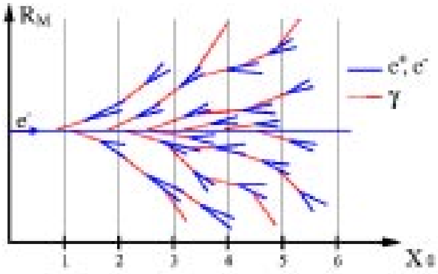
⇒ for high energy detectors calorimeters are indispensable components



Electromagnetic Shower Development

Interaction of photons and electrons above 10 MeV dominated by
- pairproduction $\gamma \to e^+e^-$
- Bremsstrahlung $e^\pm \to e^\pm\,\gamma$

which are both characterised by X_0 . Alternating sequence leads to shower which stops if energy of particles < E_c .

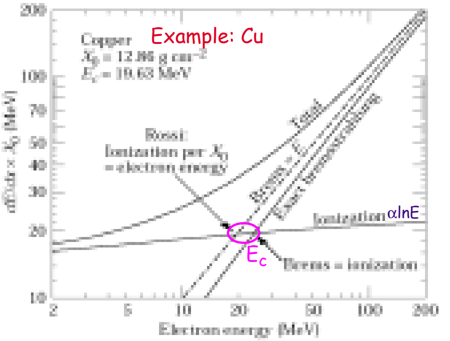


Simple model for shower development initiated by photon of energy $E_0 = E_\gamma$:
- within $\approx 1\,X_0$ γ produces e^+e^- pair
- assume symmetric energy sharing $E_e = E_\gamma/2$
- e^+e^- radiate photon after $\approx 1\,X_0$ $E_\gamma = E_e/2$
- ⇒ number of particles at depth $t = x/X_0$: $N(t) = 2^t$ with energy $E(t) = E_0 \cdot 2^{-t}$
- multiplication continues until energy falls below critical energy : $E_c = E_0 \cdot 2^{-t_{MAX}}$
- from then on shower particles are only absorbed. Position of shower maximum: $t_{MAX} = \frac{\ln E_0/E_c}{\ln 2} \propto \ln E_0$

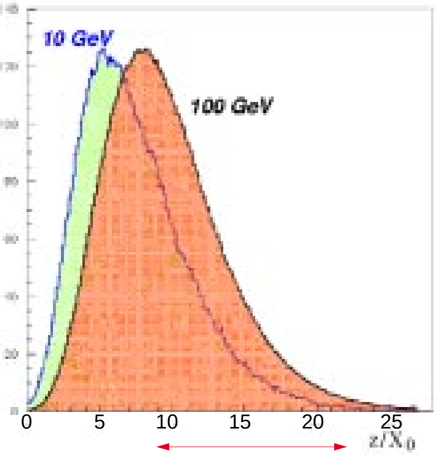
Energy Loss of Electrons

In addition to energy loss by ionisation high energy particles also loose energy due to interaction with the Coulomb field of the nuclei: Bremsstrahlung

Due to their small mass this effect is especially prominent for electrons (positrons):
- $-dE/dx \propto Z^2 \cdot E/m^2$
- it is useful to introduce radiation length X_0
- energy attenuation: $E = E_0 \exp\left(\frac{-x}{X_0}\right)$
- approx.: $X_0 = \frac{716\text{g cm}^{-2}A}{Z(Z+1)\,\ln(287/\sqrt{Z})}$
- critical energy E_c:
$$\frac{dE_{Brems}}{dx} = \frac{dE_{collision}}{dx}$$
- approximately: $E_c = \frac{610\text{MeV}}{Z + 1.24}$

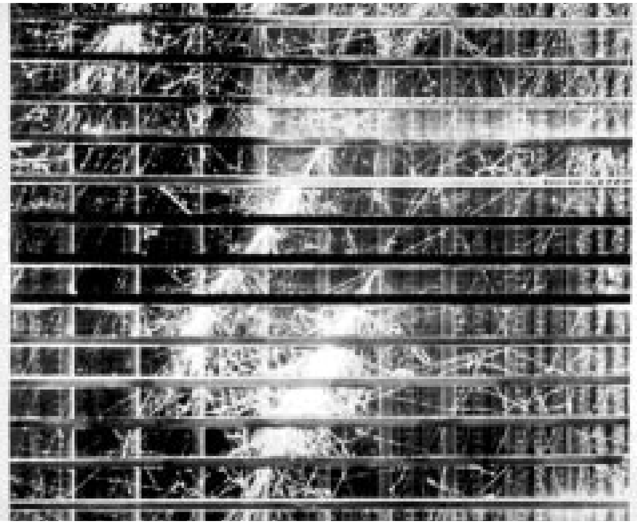


Shower Depth vs Energy



typical range of depth for EM calorimeter

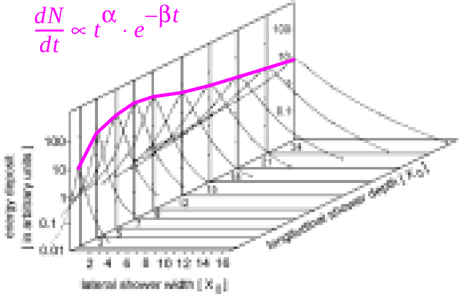
Example: μ-induced Shower



Shower Development

Multiple scattering of the e± causes a broadening of the shower also in the transverse direction:

- contribution from electrons with $E \cong E_c$ dominates
- ⇒ the shower width can be characterized by the so-called Moliere-Radius $R_M = \frac{21\text{MeV}}{E_c} X_0$
- meaning: 90(95)% of shower energy is contained in cylinder with radius R_M ($2R_M$) around the shower axis



$$\frac{dN}{dt} \propto t^{\alpha} \cdot e^{-\beta t}$$

Shower Containment:

- transverse: $R_{95\%} = 2R_M$
  - Example lead glass: $R_M = 1.8X_0$ ¯ 3.6 cm ⇒˚$R_{95\%}$ ¯ 7 cm
- longitudinal: $L_{95\%} = t_{MAX} + 0.08 \cdot Z + 9.6\ [X_0]$ [with $t_{MAX} = \ln(E_0/E_c)/(\ln 2)$]
  - Example: 100 GeV e- in lead glass (E_c=11.8 MeV ⇒˚ t_{MAX} ¯ 13, $L_{95\%}$ ¯ 23)

Stochastic Fluctuations

- Number of particles at shower maximum increases linearly with initial energy: $N_{MAX} = N(t_{MAX}) = E_0/E_c$
- Total number of particles in the shower $N_{tot} \propto N_{MAX} = E_0/E_c$
- If response of calorimeter is proportional to number of shower particles it acts as a linear device for energy measurements
- Even for a perfect detector there are intrinsic statistical limitations for the energy resolution:
  - total track length $T \propto N_{tot} \cdot X_0 \propto \frac{E_0}{E_c} \cdot X_0$
  - detectable track length $T_{det} = F(\xi) \cdot T$ with $\xi = E_{cut}/E_c$ [above energy threshold E_{cut}]
  - ⇒ for relative energy resolution $\frac{\sigma(E)}{E} = \frac{\sigma(T_{det})}{T_{det}} = \frac{1}{\sqrt{T_{det}}} \propto \frac{1}{\sqrt{E}}$

Energy Resolution

In general the energy resolution of a calorimeter can be parametrised as:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

Stochastic Term

- stochastic fluctuations in shower development
- sampling fluctuations in case of sampling calorimeter
- photo-electron statistics

Constant Term

- inhomogeneities dead material
- non-linearities
- leakage
- inter-calibration between individual cells

Noise Term

- electronic noise
- radioactivity
- pile-up

Calorimeter Types

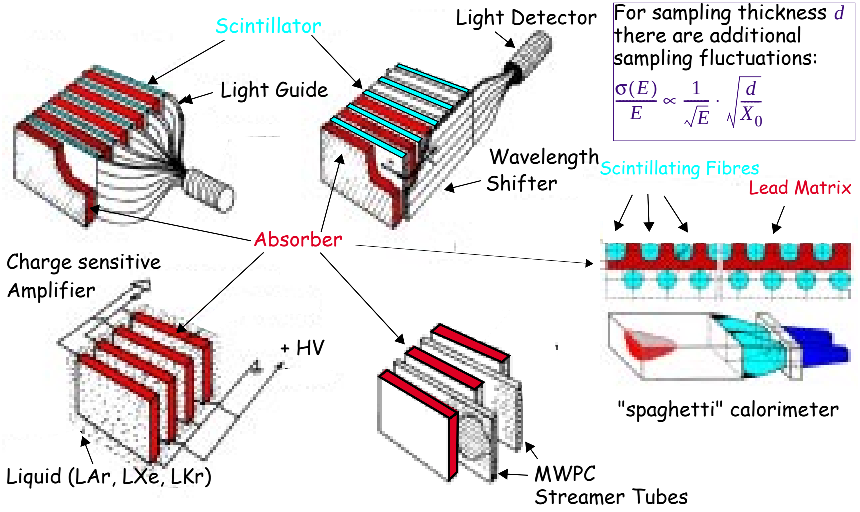
Homogeneous calorimeters:

- detector = absorber
- good energy resolution
- limited spatial resolution (particularly in longitudinal direction)
- only used for electromagnetic calorimetry

Sampling calorimeters:

- detectors and absorber are separated $\Rightarrow$ only fraction of the energy is sampled
- heavy absorber material: compact design
- energy resolution limited by sampling fluctuations
- good spatial resolution due to segmentation
- can be used for electromagnetic and hadronic calorimetry

Examples for Sampling Calorimeters

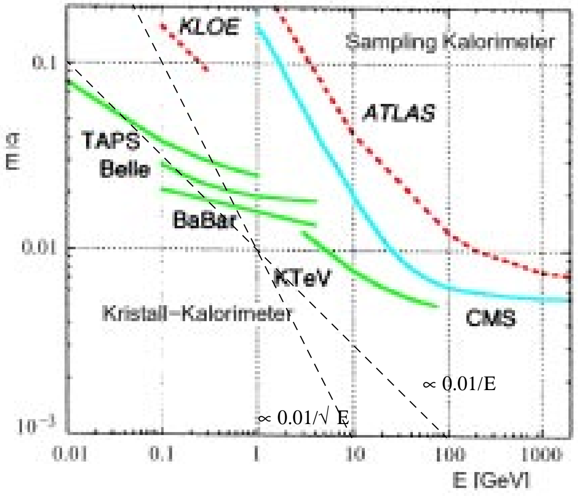


For sampling thickness d there are additional sampling fluctuations:

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}} \cdot \sqrt{\frac{d}{X_0}}$$

"spaghetti" calorimeter

Comparison of various Calorimeters (Electromagnetic)



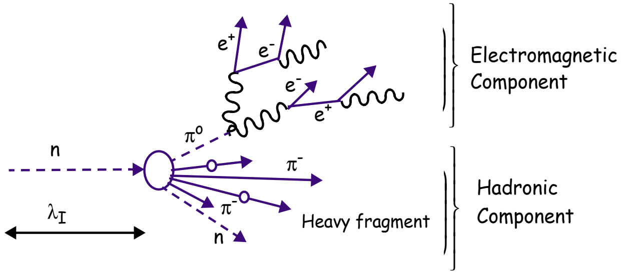
Hadron Calorimeters

High energy hadrons also develop showers in an absorber

Shower development much more complicated than in EM case

Components in shower

- hadronic
- electromagnetic
  - mainly due to π^0
- invisible
  - nuclear excitation
  - neutrons
  - neutrinos



Typical length scale given by nuclear interaction length λ_i:

$$N(x) = N_0 \cdot \exp\left(-\frac{\rho}{\lambda_I}x\right)$$

⇒ hadronic showers are much longer and much wider than electromagnetic showers

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Hadronic Interactions

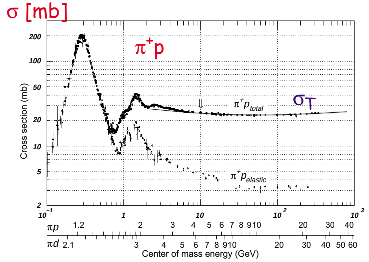
For high energies the hadronic cross section is

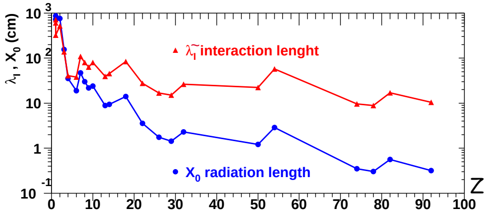
- ≈ constant as function of energy
- ≈ independent of hadron type

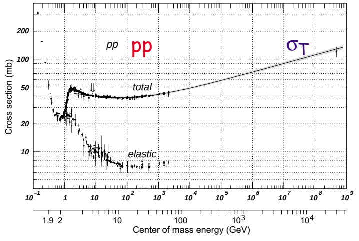
Material dependence of total cross section is given by: $\sigma_A = \sigma_p \cdot A^{2/3}$

⇒ Characterize hadronic interactions by hadronic interaction length $\tilde{\lambda}_I = \frac{A}{N_A \rho \cdot \sigma_A}$ [cm]

[in table: $\lambda_I = \tilde{\lambda}_I \cdot \rho \propto A^{1/3}$ [g/cm^2]]







Compensation

Problem

- the fraction of the different components fluctuate significantly
- the signal response of electromagnetic and hadronic component are in general different i.e. $\varepsilon_{em} \neq \varepsilon_{had}$
- for good performance one needs to compensate for this effect. Two possibilities:
- hardware compensation
  - careful choice of absorber & active material and their thickness
    - increase ε_{had} : Uranium [neutrons and soft γ: fission] or increase neutron eff. w/ hydrogenous comp.
    - decrease ε_{em} : reduce sensitivity to low-energy γ by using high Z absorber and low Z detector
  - example: ZEUS calorimeter: Uranium (depleted) / scintillator [3.3/2.6 mm]
- software compensation
  - if readout granularity of detector is sufficiently high one can distinguish between electromagnetic and hadronic component and correct by software weighting
  - example: H1 calorimeter: liquid argon (LAr) with steel [≈ 45000 cells]

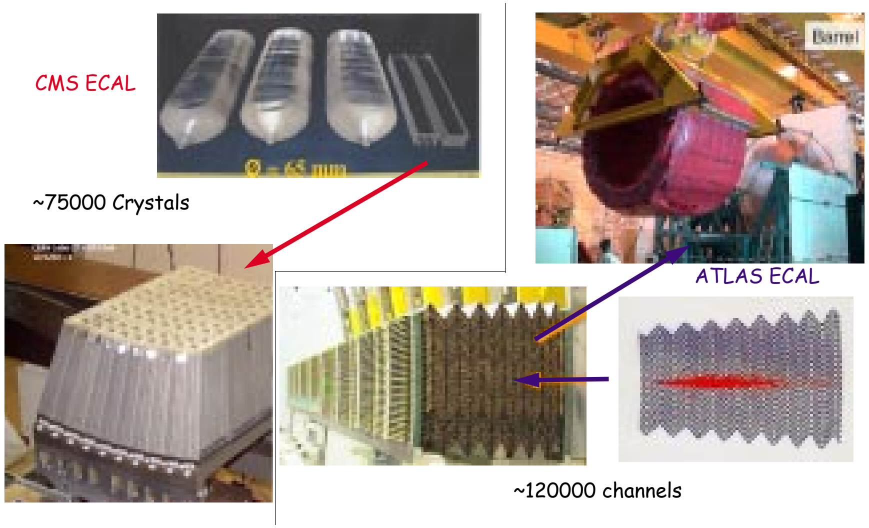
- due to the large intrinsic fluctuations hadronic calorimeters in general have worse resolution compared to electromagnetic calorimeters → typical values:

$$\frac{\sigma(E)}{E} \propto \frac{35 - 50\ \%}{\sqrt{E}}$$

Examples for Calorimeters

Experiment	Kind	Absorber	Active material	Resolution	Type
ZEUS	em	Uranium	Scintillator	18% / √E	sampling
ZEUS	had	Uranium	Scintillator	35% / √E	sampling
H1	em	Pb	LAr	12% / √E	sampling
H1	had	Steel	LAr	50% / √E	sampling
H1 SpaCal	em	Pb	Scintill. Fibre	7.5% / √E	sampling
NA48	em	LKr	LKr	3.5% / √E	homogeneous
BaBar	em	CsI	CsI	2.3% / $E^{1/4}$	homogeneous
ATLAS	em	Pb (Cu)	LAr	10% / √E	sampling
ATLAS	had	Iron (Cu)	Scintillator	47% / √E	sampling
CMS	em	$PbWO_4$	$PbWO_4$	4% / √E	homogeneous
CMS	had	Brass	Scintillator	115% / √E	sampling

LHC Calorimeters under Construction



CMS ECAL

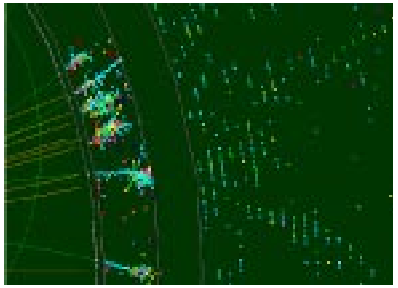
~75000 Crystals

ATLAS ECAL

~120000 channels

Calorimeter R&D for ILC @ DESY

- At Linear Collider expect final states with heavy bosons: W, Z, H
- Have to reconstruct their hadronic decay modes → multi jet events
- Challenge: need jet resolution of 30% / √E
- Expect ~60% of total energy in charged particles (tracker) , 20% in photons (ECAL), 10% in neutral hadrons (HCAL) and 10% in neutrinos ⇒ new concept of particle flow:
  - reconstruction of individual particles
  - separation of particles (charged and neutral)
- Detector requirements:
  - excellent tracking, in particular in dense jets
  - excellent granularity in the ECAL
  - “no” material in front of ECAL
  - good granularity in the HCAL
  - excellent linking between tracker – ECAL – HCAL
  - excellent hermeticity
- Prototype tests ongoing at CERN



Summary on Calorimeters

High energy particles develop showers:

- e, γ → electromagetic showers, relevant quantities: E_c, X_0
  shower development:
  - longitudinal $t_{max} \propto \log E$
  - transverse Moliere Radius
- hadrons (π, n, p, ...) → hadronic showers, characteristic quantity: λ_I
  - shower development much more complicated than in em case

Many effects contribute to energy resolution

- dominant dependence from stochastic fluctuations: $\frac{\sigma}{E} \propto \frac{1}{\sqrt{E}}$
- ⇒ calorimeters complementary to tracking detectors
- typical resolutions
  - electromagnetic: $\frac{\sigma}{E} \approx \frac{4-10\%}{\sqrt{E}}$; hadronic: $\frac{\sigma}{E} \approx \frac{35-50\%}{\sqrt{E}}$