Calorimeters

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JLab Summer Detector/Computer Lectures

http://www.jlab.org/~gen/talks/calor_lect.pdf

Outline

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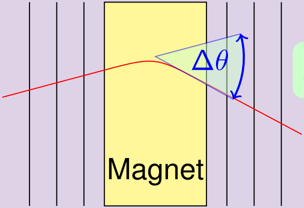
What is a calorimeter?

Particle detection main goal: measure 3-momenta $\vec{P}$

Magnetic spectrometers

- Coordinate detectors
- Magnetic field

Charged particles ($e^{\pm}$, $\pi^{\pm}$ etc)



$\Delta\theta \propto \frac{Bd\ell}{P}$

Momentum resolution:

$\boxed{\sigma(P)/P \propto P}$ (for large P)

Calorimeters

Detectors thick enough to absorb nearly all of the particle's energy released via cascades (showers)

Neutral (γ, n) and charged particles

The energy goes mainly into heat.

- "True" C. - E_o (heat)
- "Pseudo" C. - $\mathcal{O}(E_o)$: ionization, Cherenkov light

Poisson process: $N_e \propto E_0$,

$\sigma N_e = \sqrt{N_e}$ and $\boxed{\frac{\sigma E}{E} \propto \frac{1}{\sqrt{E}}}$

"True" Calorimeters

"True" calorimeters measure the temperature change of the absorber: $\Delta T = \frac{E_0}{c \cdot M} \sim \frac{1 \cdot 10^{10} eV \cdot 1.6 \cdot 10^{-19} J/eV}{10^3 J/kg \cdot 1 kg} \approx 10^{-12} K$ too low!

- High particle flux
  - History: W. Orthmann - 1μW sensitivity; 1930, with L. Meitner they measured the mean energy (6% accuracy) of β from ^{210}Bi $\Rightarrow$ W.Pauli's neutrino hypothesis.
  - Precise beam current measurements (SLAC-1970s, JLab-2003)
- Ultra-cold temperatures (low C), superconductivity - new detectors for exotic particle search, like "dark matter" candidates.

"Pseudo" Calorimeters

"Pseudo" calorimeters detect $\mathcal{O}(E_o)$: ionization, Cherenkov light

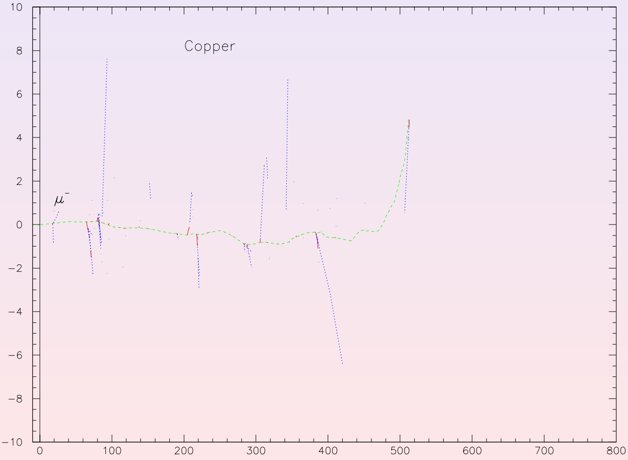
- History: N.L. Grigorov 1954 - idea, 1957 - implementation in cosmic ray studies (Pamir, 3900 m). Layers of an absorber and layers of proportional counters - counting the number of particles in the shower (calibration needed).
- Starting in 1960s - revolution in compact electronics $\Rightarrow$ affordable ADC (Analog-to-Digital Converters). New accelerators - various types of calorimeters with $\sim 10 \rightarrow 10^5$ ADC channels.

Applications

- detecting neutrals
- good energy resolution at high energies
- fast signals for trigger
- particle identification ($e^{\pm}/h$)

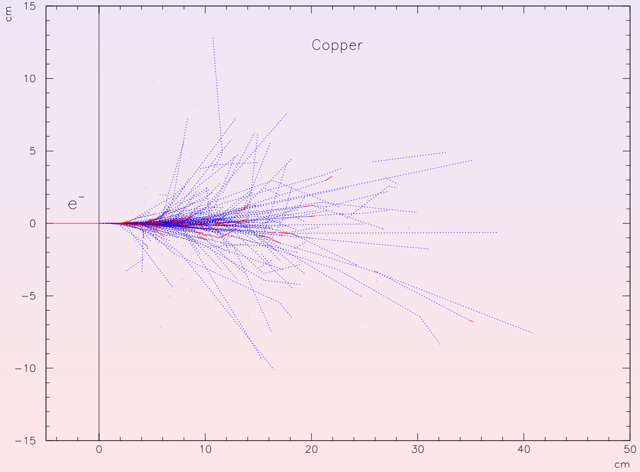
Muon in Medium

Trajectory of 8 GeV μ^- in copper. The coordinates are in cm.



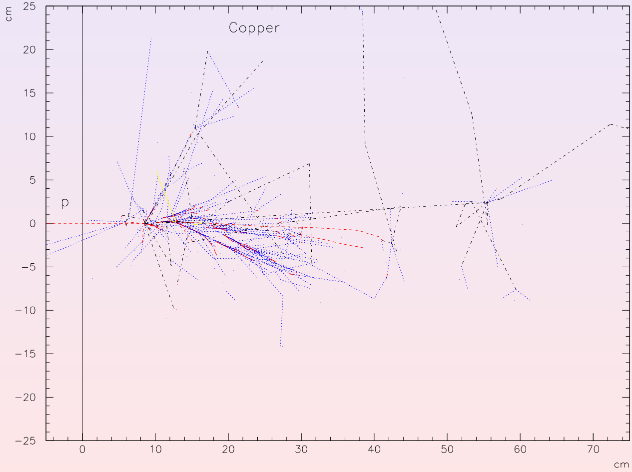
Electron in Medium

Trajectory of 8 GeV e^- in copper. The coordinates are in cm.



Proton in Medium

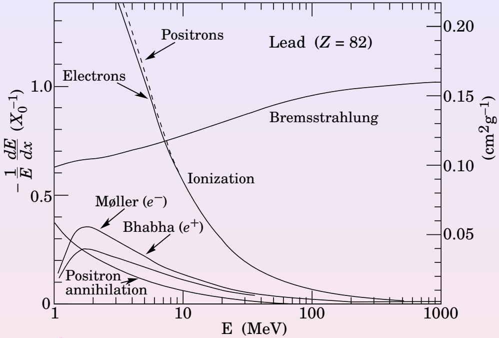
Trajectory of 8 GeV proton in copper. The coordinates are in cm.



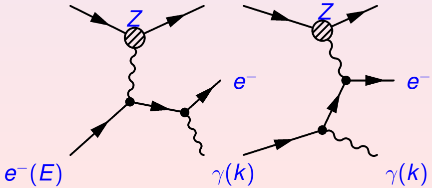
$e^{\pm}$ interactions

Energy loss in medium

- Bremsstahlung
  $e^{\pm}Z \rightarrow e^{\pm}\gamma Z$
- Ionization
- Bhabha/Møller scattering
  $e^{\pm}e^{-} \rightarrow e^{\pm}e^{-}$
- e^{+} annihilation



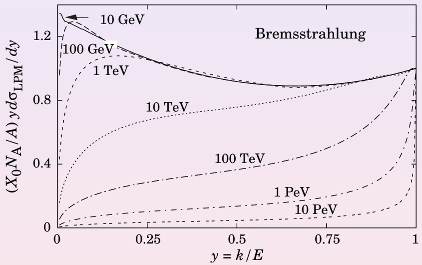
Bremsstrahlung

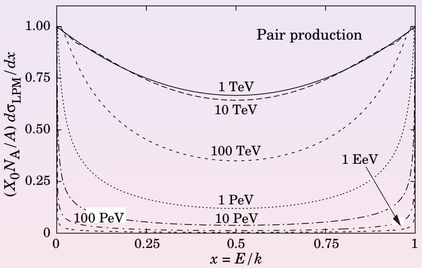


$$\sigma \propto \frac{Z^2}{m^2} \Rightarrow \frac{\sigma_\mu}{\sigma_e} \approx 2 \cdot 10^{-5}$$

$$\boxed{\frac{dN_\gamma}{dk} \propto \frac{1}{k}} \quad \boxed{\frac{dE_\gamma}{dk} = c(k)}$$

Bremsstrahlung and Pair Production

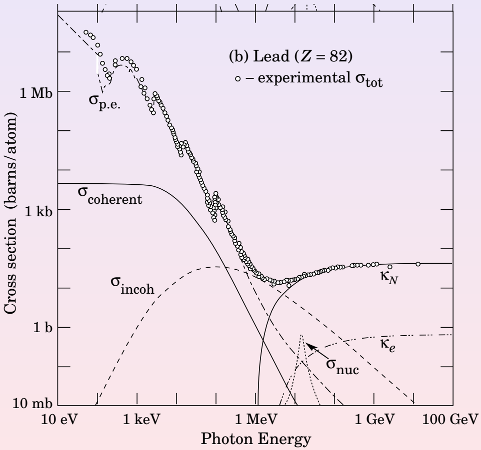




γ interactions

Interaction in medium

- Pair production
  $\gamma Z \rightarrow e^+ e^- Z$ (K_N)
- Pair production
  $\gamma e^- \rightarrow e^+ e^- e^-$ (K_e)
- Compton scattering
  $\gamma e^- \rightarrow \gamma e^-$ ($\sigma_{incoherent}$)
- Rayleigh scattering
  ($\sigma_{coherent}$)
- Photonuclear absorption
  (σ_{nuc})
- Atomic photoeffect ($\sigma_{p.e.}$)



Scaling of Material Properties

Radiation length

X_0 - the material thickness for a certain rate of EM:

$e^{\pm}$: $\boxed{\frac{dE_{loss}}{dx} \simeq \frac{E}{X_0}}$

γ: $\boxed{\lambda_{e^+e^-} \simeq \frac{9}{7} \cdot X_0}$

Derived from EM calculations:

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

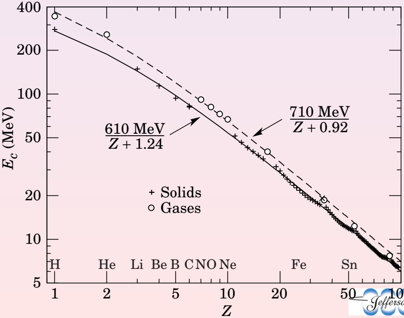
Critical Energy

E_c: cascade stops

Losses: Ionization $=$ Radiation

B.Rossi: $\frac{dE_{ioniz}}{dx}\Big|_{E_c} \simeq \frac{E}{X_0}$

$E_c \simeq \frac{610(710)\ MeV}{Z+1.24(0.92)}$ solids(gasses)



Electromagnetic Showers

Photons and light charged particles ($e^{\pm}$) interact with matter:

- electrons radiate $e^{\pm} \rightarrow e^{\pm}\gamma$
- photons convert $\gamma \rightarrow e^{+}e^{-}$

A cascade develops till the energy of the particles go below a certain limit.

The charged particles of the cascade ($e^{\pm}$) leave detectable signals.

Electromagnetic Shower: longitudinal development

Scaling variables:

$t = \frac{x}{X_0} \quad y = \frac{E}{E_c}$

Simple model

A simple example of a cascade: $\times 2$ at $\Delta t = 1$.

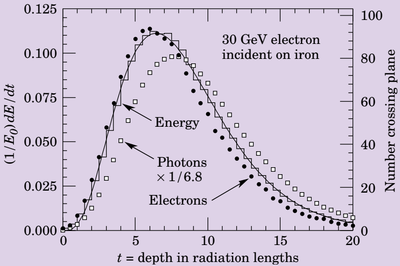
$E(t) = \frac{E_0}{2^t} \Rightarrow t_{max} = ln\frac{E_0}{E_c}/ln\,2$

$\boxed{t_{max} \propto ln(\frac{E_0}{E_c})}$

Detectable signal:

$L_{charged} \propto E_0/E_c$

Simulation: EGS4, GEANT



$t_{max} \simeq ln(y) + \begin{cases} -0.5 & e^- \\ +0.5 & \gamma \end{cases}$

$t(>95\%) \simeq t_{max} + 0.08Z + 9.6$

Fluctuations: mid of cascade

$\sigma N \simeq N \Rightarrow t_{calor} \sim t(>95\%)$

Electromagnetic Shower: transverse size

Molière radius: $R_M = \frac{X_0 \cdot 21 MeV}{E_c}$
$R < 2 \cdot R_M$ contains 95% of the shower

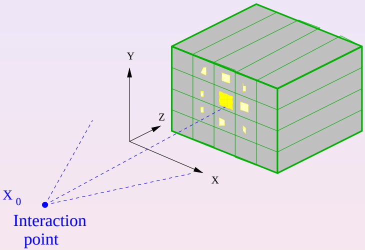
Properties of Materials

Material	Density g/cm^3	X_0 g/cm^2	X_0 cm	λ_I g/cm^2	Molière $R_M cm$	E_{crit} MeV	Refr. index
W	19.3	6.5	0.35	185.	0.69	10.6	
Pb	11.3	6.4	0.56	194.	1.22	9.6	
Cu	8.96	13.	1.45	134.	1.15	26.	
Al	2.70	24.	8.9	106.	3.3	56.	
C	2.25	42.	18.8	86.	3.5	111.	
Plastic	1.0	44.	42.	82.	6.1		1.58
H_2	0.07	61.	860.	50.	50.	360.	

Outline

Generic Calorimeter

A matrix of separate elements:



$$E = \sum_{i \in k \times k} \mathcal{E}_i$$

Typically $k = 3, 5$

$\mathcal{E}_i = \alpha_i \cdot A_i$

$x|y = f(.., x_i|y_i, E_i, ..)$

$\vec{X}_0 \Rightarrow$ direction

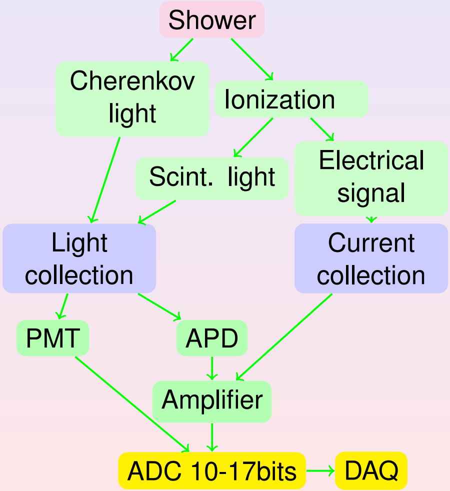
Measured:

- A_i - measured amplitudes
- α_i - calibration factors (slow variation)
- $x_i|y_i$ - module coordinates

Important parameters

- Energy resolution $\frac{\sigma E}{E}$
- Linearity
- Coordinate resolution σx
- Time resolution
- Stability
- Specific requirements: radiation hardness. mag. field
- Cost

Generic Calorimeter



Important procedures

- Calibration: A_i - measured $\rightarrow E_i = \alpha_i \cdot A_i$.
  α_i have to be measured using particles of known energies.
- Monitoring of the calibration factors α_i using detector response to a simple excitation (ex: light from a stable source).

Homogeneous and Sampling Calorimeters

Consider: EM shower in plastic scintillator
Needed length $\sim 15 \cdot X_0 = 600\ cm$ - not practical!

Homogeneous calorimeters (EM)

Heavy active material, no passive absorber

- Best energy resolution
- Higher cost

Sampling calorimeters

Heavy material absorber and the active material are interleaved.
Features:

- Compact
- Relatively cheap
- Sampling fluctuations $\Rightarrow$ impact on $\frac{\sigma E}{E}$

Resolutions

Energy resolution

$$\frac{\sigma E}{E} = \alpha \oplus \frac{\beta}{\sqrt{E}} \oplus \frac{\gamma}{E}$$

- α - constant term (calibration)
- β - stochastic term (signal/shower fluctuations)
- γ - noise

Spatial resolution

$$\sigma X = \alpha_1 \oplus \frac{\beta_1}{\sqrt{E}}$$

Energy resolution

- Fluctuations of the track length (EM): $\frac{\sigma E}{E} \simeq \frac{0.005}{\sqrt{E}}$
- Fluctuations of the track length (HD): $\frac{\sigma E}{E} \simeq \frac{0.5}{\sqrt{E}}$, or $\simeq \frac{0.2}{\sqrt{E}}$ with compensation
- Statistics of the observed signal (EM): $\frac{\sigma E}{E} > \frac{0.01}{\sqrt{E}}$
- Sampling fluctuations (EM): $\frac{\sigma E}{E} \simeq \frac{\sqrt{E_c \cdot t}}{\sqrt{E}}$, where t is the layer thickness in X_0 (B.Rossi), $\sim \frac{0.1 \cdot \sqrt{t}}{\sqrt{E}}$ for lead absorber ($t > 0.2$)
- Noise, pedestal fluctuations $\frac{\sigma E}{E} < \frac{0.01}{E}$
- Calibration drifts $\frac{\sigma E}{E} \sim 0.01$ for a large detector
- Other ...

Spacial resolution

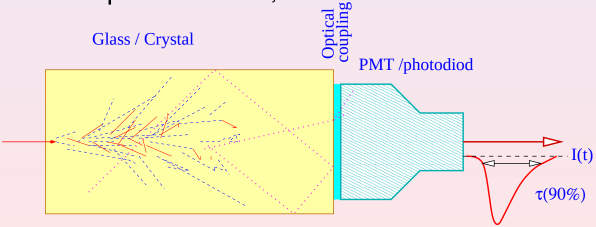
- Module lateral size $<$ shower size
- Calculating the shower centroid
- EM: $\sigma x > 0.05 \cdot R_M$
- HD: $\sigma x > 1 - 2cm$

Outline

Light Collecting Homogeneous EM Calorimeters

Heavy transparent materials (low X_0) are preferable $\Rightarrow$ compact, larger signal

- Heavy crystal scintillators: NaI, CsI, BGO, PbW etc: high light yield $\Rightarrow$ good resolution, expensive
- Heavy crystal Cherenkov detectors: PbF, etc: compact, radiation hard
- Lead glass (SiO $\rightarrow$ PbO) Cherenkov detectors: medium performance, affordable



Light collection 20 - 50%

Time resolution:

- Scintillation time
- Light bouncing
- Photodetector

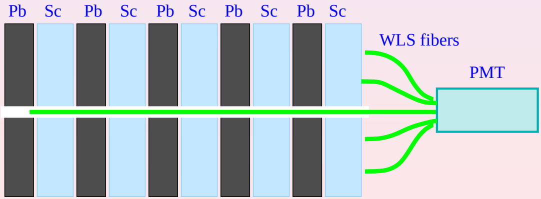
Typically:

$\tau(90\%) \sim 100$ ns for Cherenkov detectors

Light Collecting Sampling EM Calorimeters

Heavy absorber (Pb,Cu,W...) and a scintillator (plastic) or Cherenkov radiator (quartz fibers ...). Problem: how to collect the light? The most popular solutions for this moment:

- SPACAL (Pb, sc. fibers). The fibers can be bundled to the PM. Very good resolution. Difficult to manufacture.
- Sandwich with WLS fibers crossing through ("shashlik"). The fibers are bundled to the PM. Good resolution. Easy to build.



Time resolution:

- Scintillation time
- Photodetector time

Typically

$\tau(90\%) \sim 50$ ns

Light Detectors

Photomultiplier Tubes (PMT)

A vacuum vessel with a photocathode and a set of electrodes (dynodes) for electron multimplication.

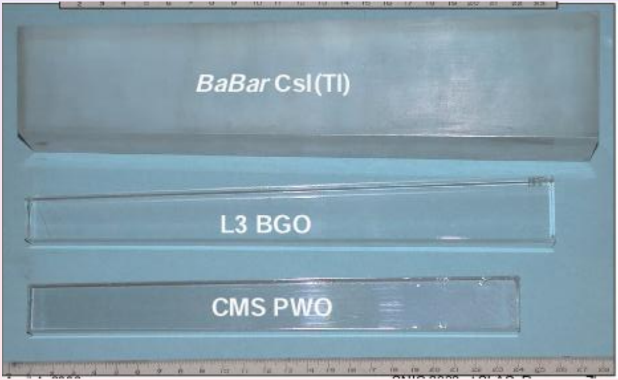
- Very high gain $\sim 10^5 - 10^7$
- Very low electronic noise
- Size: diameter 2-40 cm
- • Slow drift of the gain
- • Sensitive to the magnetic field
- • Relatively low QE$\sim$20%
- Radiation hard

Avalanche Photodiods (APD)

A silicon diod in avalanche mode and an electronic amplifier

- Gain $\sim 50 - 300$
- • High electronic noise
- • Size: $1 \times 2\ cm^2$
- • Very sensitve to the bias voltage
- Not sensitive to the magnetic field
- High QE$\sim$75% at 430 nm
- • Temperature sensitive -2%/K
- • Radiation hardness may be a problem

Crystals in big experiments



BaBar CsI(Tl) $\sim$ 10000

L3 BGO - $\sim$ 11000

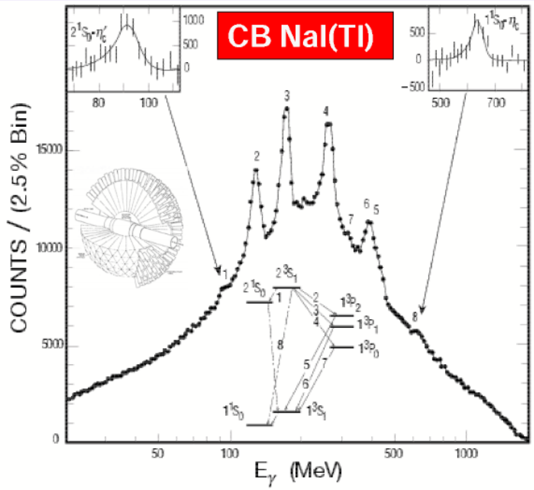
CMS PbWO - $\sim$ 80000

EM calorimeters with optical readout

Material	Density g/cm^3	X_0 cm	R_M cm	λ_I cm	Refr. index	τ ns	Peak λ nm	Light yield	$\frac{N_{p.e.}}{GeV}$	rad	$\frac{\sigma E}{E}$
Crystals											
NaI(Tl)**	3.67	2.59	4.5	41.4	1.85	250	410	1.00	10^6	10^2	$1.5\%/E^{1/4}$
CsI *	4.53	1.85	3.8	36.5	1.80	30	420	0.05	10^4	10^4	$2.0\%/E^{1/2}$
CsI(Tl)*	4.53	1.85	3.8	36.5	1.80	1200	550	0.40	10^6	10^3	$1.5\%/E^{1/2}$
BGO	7.13	1.12	2.4	22.0	2.20	300	480	0.15	10^5	10^3	$2.\%/E^{1/2}$
$PbWO_4$	8.28	0.89	2.2	22.4	2.30	5/39%	420	0.013	10^4	10^6	$2.0\%/E^{1/2}$
						15/60%	440				
						100/01%					
LSO	7.40	1.14	2.3		1.81	40	440	0.7	10^6	10^6	$1.5\%/E^{1/2}$
PbF_2	7.77	0.93	2.2		1.82	Cher	Cher	0.001	10^3	10^6	$3.5\%/E^{1/2}$
Lead glass											
TF1	3.86	2.74	4.7		1.647	Cher	Cher	0.001	10^3	10^3	$5.0\%/E^{1/2}$
SF-5	4.08	2.54	4.3	21.4	1.673	Cher	Cher	0.001	10^3	10^3	$5.0\%/E^{1/2}$
SF57	5.51	1.54	2.6		1.89	Cher	Cher	0.001	10^3	10^3	$5.0\%/E^{1/2}$
Sampling: lead/scintillator											
SPACAL	5.0	1.6				5	425	0.3	10^4	10^6	$6.0\%/E^{1/2}$
Shashlik	5.0	1.6				5	425	0.3	10^3	10^6	$10.\%/E^{1/2}$

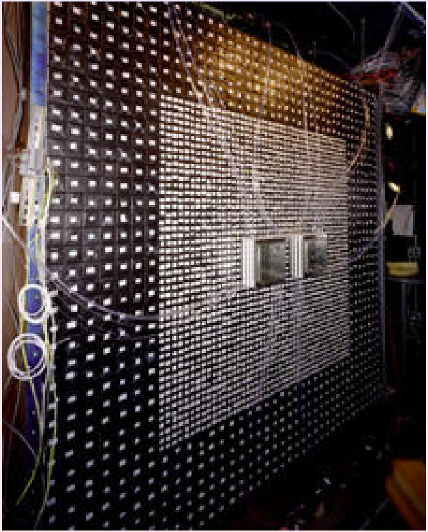
$*$ - hygroscopic

Crystal Ball (SLAC, DESY)



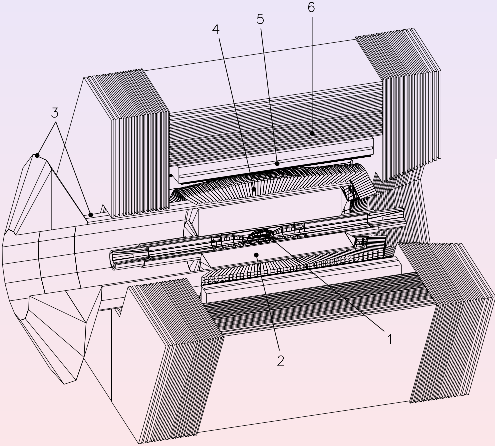
- $\sim$ 600 NaI crystals
- γ detection
- Charmonia spectra
  $\Rightarrow$ QCD tune!

KTeV (FNAL)

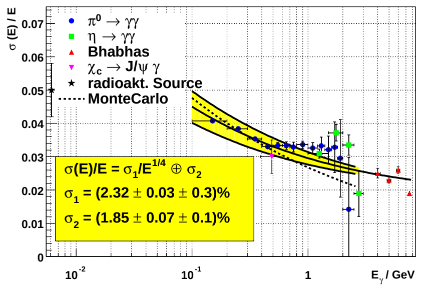


- 3256 CsI crystals
- $\pi^\circ \rightarrow \gamma\gamma$ detection
- $\sigma E/E \approx 2.0\%\sqrt{E} + 0.5\%$

BaBar (SLAC)

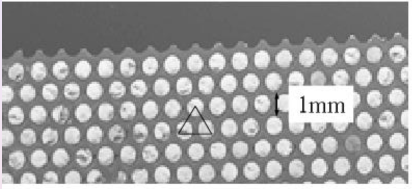


- $\sim$ 10000 CsI(Tl) crystals
- $\sigma E/E \approx 2.3\%/E^{1/4} + 1.9\%$



SpaCal (CERN, Frascatti)

scintillating fibers / lead matrix



- Fibers/lead 50% / 50% in volume
- $X_\circ = 1.2$ cm
- 5 g/cm^3

- CERN - original R&D
- KLOE (DAFNE) - 5000 PMTs
- KLOE $\sigma E/E \approx 5.7\%/E^{1/2}$
- KLOE $\sigma\tau \approx 50/E^{1/2} + 50$ ps

Front-End Electronics

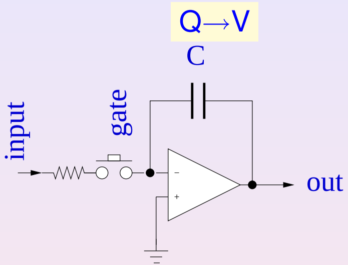
Requirements

- Resolution $\sim 10^{-3}$
- Dynamic range $> 10^{2}$: needed to measure the shower profile and the coordinates
- Differential linearity $<$1%
- Digitization speed ($>$10 MHz)
- Readout speed ($>$10 MHz)
- Cost

Existing generic solutions

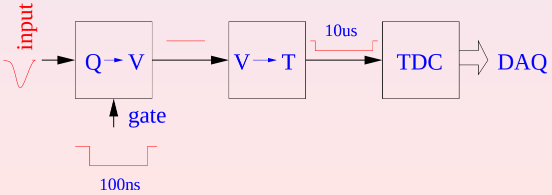
- Charge integrating ADC
- Flash ADC
- Combinations (pipeline ADC)

Charge Integrating ADC

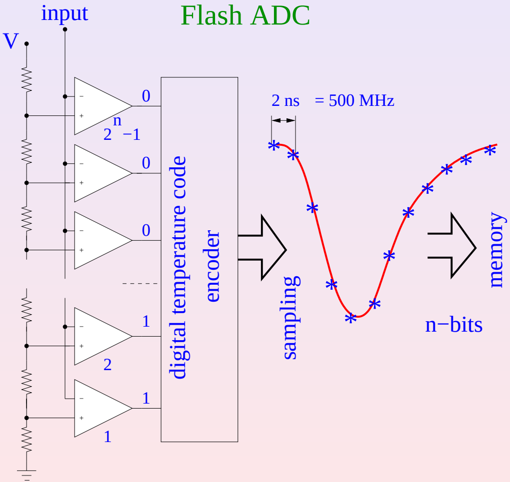


- Many products on the market
- Precise: 12-15 bits
- Gate must come in time $\Rightarrow$ long ($>$300-500 ns) delay for each channel is needed (cables)
- Slow conversion time $> 10\ \mu s \Rightarrow$ not suitable for trigger logic
- Problems at very high rate: pileup, deadtime
- Pedestal

Integrating ADC



Flash ADC



- Cost $\times 10$ of the QDC (100 MHz, 12 bits)
- Huge memory buffers needed
- Resolution n bits $\Rightarrow$ 2^n comparators
- No dead time
- No delay cables needed
- Pileup can be partially resolved
- Time resolution without extra discr.& TDCs
- Can be used in trigger logic

Calibration

The detector has to be calibrated at least once.

- Test beam
- Better: in-situ, using an appropriate process:
  - e^+e^- collider: Bhabha scattering $e^+e^- \to e^+e^-$, $e^+e^- \to e^+e^-\gamma$
  - LHC: $Z \to e^+e^-$ (1 Hz at low luminocity)
  - $h+h \to \pi^0 + X$, $\pi^0 \to \gamma\gamma$
  - RCS (JLab): $e^-p \to e^-p$

Procedure: for event n:

$$\mathcal{E}^{(n)} = \sum_{i \in k \times k} \alpha_i \cdot A_i^{(n)}$$

$$\chi^2 = \sum_n (E^{(n)} - \sum_{i \in k \times k} \alpha_i \cdot A_i^{(n)}) / \sigma_n$$

- System of linear equations
- $\Rightarrow N \times N$ matrix - nearly diagonal
- Easy to solve

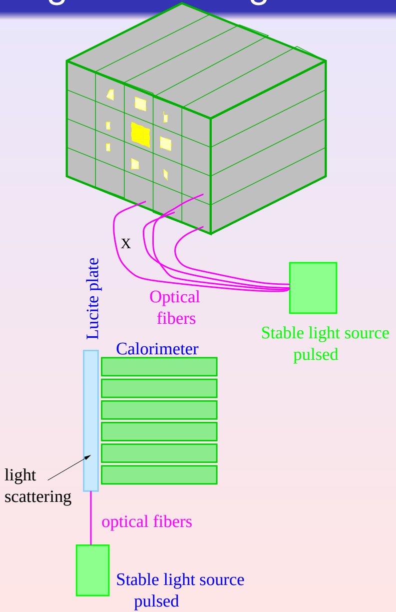
Monitoring

Instabilities:

- All avalanche-type devices tend to drift (PMT, gas amplification ...)
- Optical components may lose transparency
- Temperature dependence
- Many other sources of instability ...

Calibration is typically done once per many days of running $\Rightarrow$ signal monitoring in between is needed.

Light collecting devices



- Stable pulsed light source:
  - Xe flash lamp: 1% stability, $>$100 ns pulse
  - Laser: 2-5% stability, $\ll$1 ns pulse
  - LED: 1-3% stability in thermostate, $>$30 ns pulse
- Usually the light source has to be monitored
- Light distribution
- Material transparency: not easy to monitor (λ-dependence)
- Scintillation yield - no monitoring this way

Summary

Calorimeters are used for:

- Detecting neutrals
- Energy and coordinate measurements
- Trigger
- Separation of hadrons against $e^{\pm}, \gamma$ and muons

The calorimeters are of increasing importance with higher energies. They become the most important/expensive/large detectors in the current big projects (LHC, CLIC etc).

Summary (continued)

There are various techniques to build calorimeters for different resolution, price, radiation hardness and other requirements.

The typical energy resolutions are:

- EM: from $\frac{\sigma E}{E} \sim \frac{2\%}{\sqrt{E}} \oplus 0.3\%$ for scintillating crystals to about $\frac{\sigma E}{E} \sim \frac{10\%}{\sqrt{E}} \oplus 0.8\%$ for sampling calorimeters.
- HD calorimeters: $\frac{\sigma E}{E} \sim \frac{30{-}50\%}{\sqrt{E}} \oplus 3\%$

The coordinate resolutions could be about 1-3 mm for EM calorimeters and 20-30 mm for HD ones.

Outline

Charge collecting EM Calorimeters

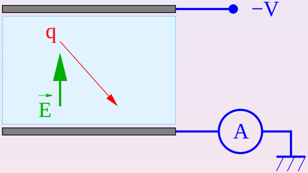
Ionization ⇒ electrical charge collected in electrical field. Sensitive to electro-negative contaminations. Active materials with electron/ion mobility:

- Solids: semiconductor (Si), no amplification, rad. soft/hard
- Liquids (no amplification, rad. very hard):
  - cryo Ar (sampling, impurities $<$ppm), Kr, Xe (impurities $<$ppb)
  - warm organic liquids (impurities $\ll$ ppb)
- Gas, sampling: low signals if no gas amplification used. Landau fluctuations.
  - High pressure (20-30 atm), no aplification, rad. hard, but low signals
  - gas wire chambers (with amplification), rad soft

Detector with no cascade-type amplification (like happens in wire chambers, PMT etc) have a much more stable calibration. But: low signals ⇒ amplifiers ⇒ sensitive to electronic noise.

Electrical Signal

Induced Charge: Ramo-Shockley Theorem



$$\boxed{I(t) = \frac{q\cdot(\vec{v}\cdot\vec{E})}{V}}$$

$$Q = \int I(t)dt = q$$

Ionization collection

Electrons and ions add to the signal.

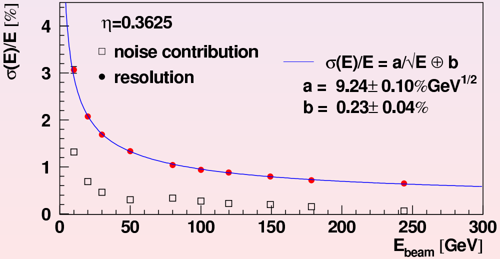
The velocities of electrons and ions are orders of magnitude different.

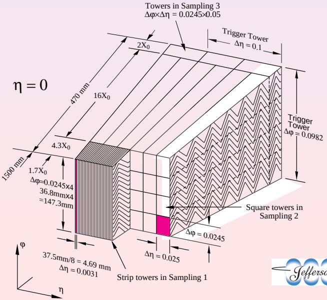
Liquid Argon Calorimeters

- $X_0 = 14$ cm - rather long $\Rightarrow$ SAMPLING
- $V_e = 3\ \mu\mathrm{m/ns}$ at 5 kV/cm
- $\sim 2 \cdot 10^6\ \mathrm{e^-/GeV}$ typically
- Widely used: H1 (Pb,Fe), D0 (U), SLD, ATLAS (Pb)
- Very stable (1%/year at SLD)

ATLAS (LHC)

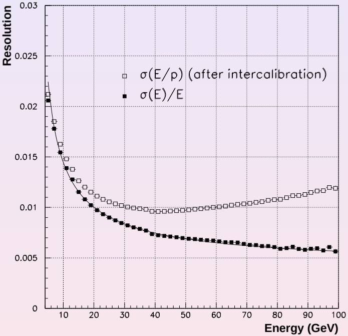
- “Accordion” structure
- 2 mm Pb, 3 mm LAr
- 2-5 kV on the gaps
- Amplifiers $\times 100$ noise $< 5000e^-$
- High capacitance $\Rightarrow$ noise

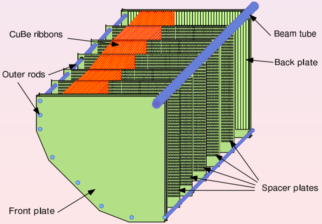


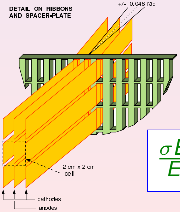


Liquid Krypton Calorimeters

- $X_0 = 4.5\ \mathrm{cm}$ - can be homogenous
- Signal $\sim \times 2$ of LAr
- Expensive
- Experiment NA-48: $\sim$4 m^3, homogeneous, thickness 27 X_0, 13k channels.



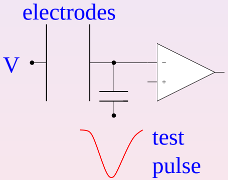




$$\frac{\sigma E}{E} = 0.4\% \oplus \frac{3.2\%}{\sqrt{E}} \oplus \frac{0.1\ \mathrm{GeV}}{E}$$

Monitoring: charge collecting devices

- Media purity (LAr ...) - general control
- Electrical pulse to monitor each electronic channel



- Very good stability (∼1%/year) reached in LAr detectors

Outline

Hadronic Shower

High energy nuclear interaction on a nucleus:

$h + A \rightarrow \sum_i h_i^{\pm,0} + \sum_i \pi_i^0$, and $\pi^0 \rightarrow \gamma\gamma$.

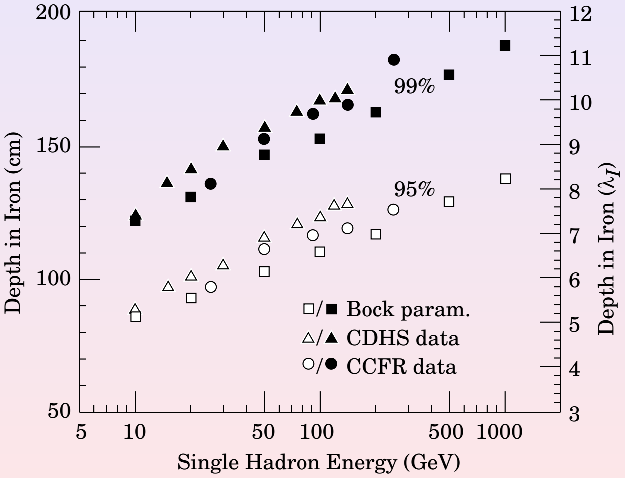
π^0 yield $N_{\pi^0}/N_{tot} \sim\ 0.1 \cdot ln\ E \quad \Rightarrow$ signal

- strong fluctuations depending on the first interaction
- a sizable amount of energy goes to nuclear excitation
- important parameter: response ratio e/h
  - $e/h \neq 1$ - non-linear with energy, poor resolution
  - $e/h = 1$ - "compensated" calorimeter

Scale: interaction length $\lambda_I\ \approx\ 35\ g/cm^2\ A^{1/3}$

Shower max: $x/\lambda_I = t_{max} \approx 0.2 \cdot ln(E/1GeV) + 0.7$

Hadronic Shower



Hadron Calorimeters

- SPACAL $\frac{\sigma E}{E} \simeq \frac{30\%}{\sqrt{E}} \oplus 3\%$
- L Ar $\frac{\sigma E}{E} \simeq \frac{52\%}{\sqrt{E}} \oplus 3\%$
- Tile $\frac{\sigma E}{E} \simeq \frac{60\%}{\sqrt{E}} \oplus 2\%$