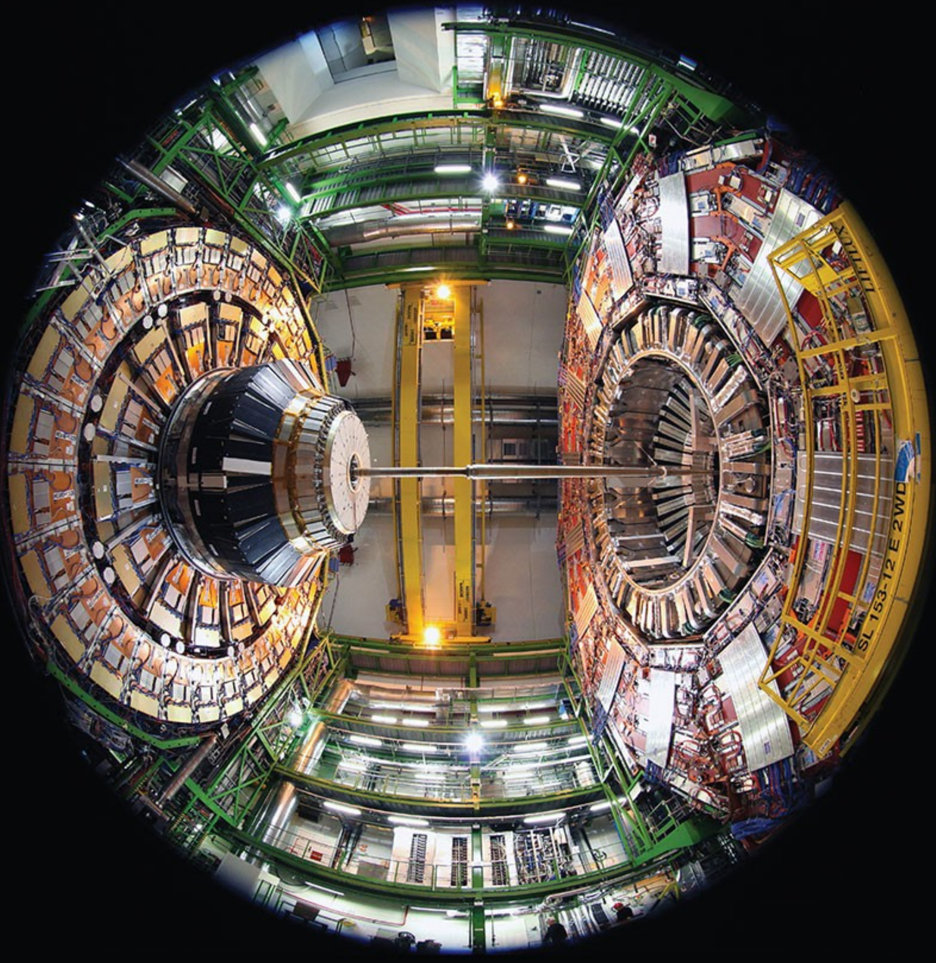
Calorimetry in high energy physics

Part 4



J.-B. Sauvan

Laboratoire Leprince-Ringuet
CNRS / École polytechnique

Lecture plan

What is calorimeter in HEP?

Electromagnetic and hadronic showers

Detection techniques

Calorimeter response & resolution

Closing remarks

Energy resolution

- Calorimeter's energy resolution is determined by **fluctuations**
- Input energy **E ∝ N number of secondary particles**
  - Poisson distribution of N → $\sigma(E)/E \propto \sqrt{N}/N \propto 1/\sqrt{E}$
  - Although in reality only a fraction can be detected (threshold effects)
- Other types of fluctuations
  - Signal quantum fluctuations (e.g. photoelectron statistics)
  - Sampling fraction
  - Shower leakage
  - Instrumental effects (electronic noise, light attenuation, non-uniformity, etc.)
  - Hadronic-specific fluctuations (EM fraction, invisible energy)

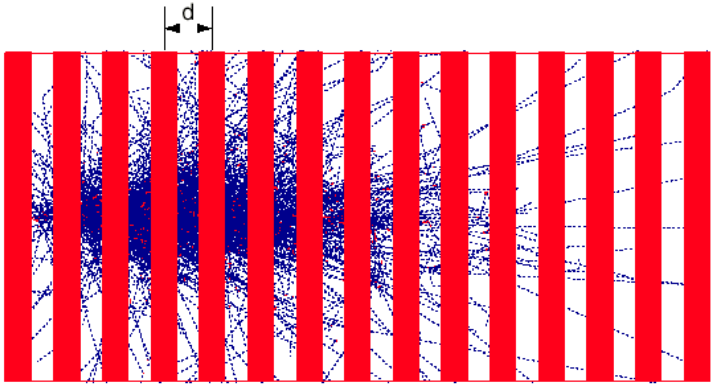
Sampling fluctuations

- Two aspects in sampling fluctuations
- **Sampling fraction**: fraction of energy deposited in active material **by a mip**
  - ○ Lower sampling → less particles collected → larger fluctuations

$$f_{samp} = \frac{E^{mip}_{loss\,in\,active}}{E^{mip}_{total\,loss}}$$

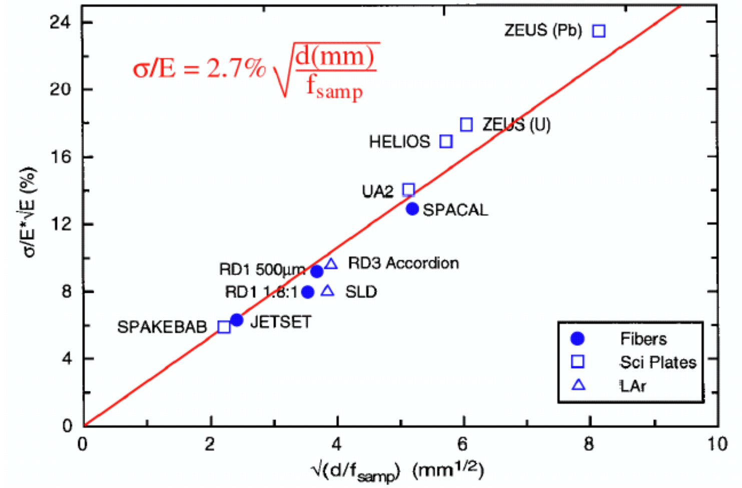
$$f_{samp} = \frac{d_{active}\times(dE/dx)^{mip}_{active}}{d_{absorber}\times(dE/dx)^{mip}_{absorber}+d_{active}\times(dE/dx)^{mip}_{active}}$$

- **Active layer thickness**
  - ○ Large fraction of low energy electrons (< 1MeV) produced in absorber
  - ○ Traveling a small distance in active material



Thicker active layer → worse resolution
Lower sampling → worse resolution

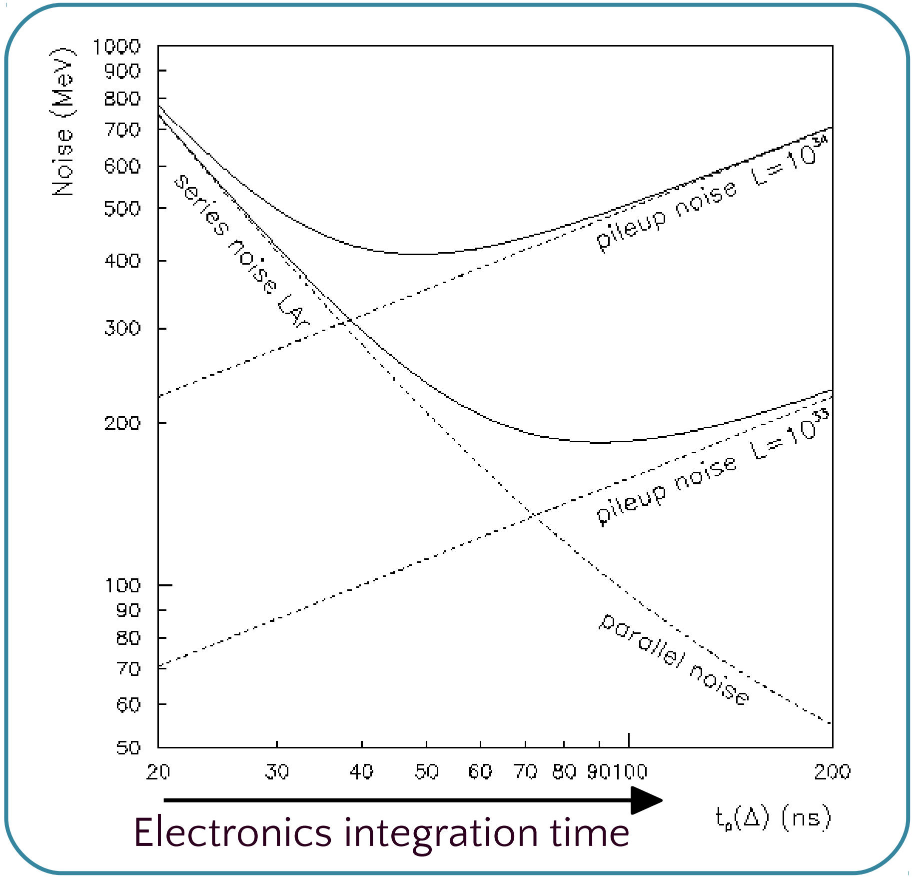
$$\frac{\sigma(E)}{E} \propto \sqrt{\frac{d_{active}}{f_{samp}}}\frac{1}{\sqrt{E}}$$



Noise

- Noise fluctuations are constant in energy
  - → Impact resolution in 1/E (mainly low energy)
- Usually comes from the **electronics readout** system
- But at hadron colliders
  - Contributions from **pile-up interactions**
  - = fluctuations due to multiple low energy collisions

Electronic noise vs pile-up noise (ATLAS LAr calorimeter)

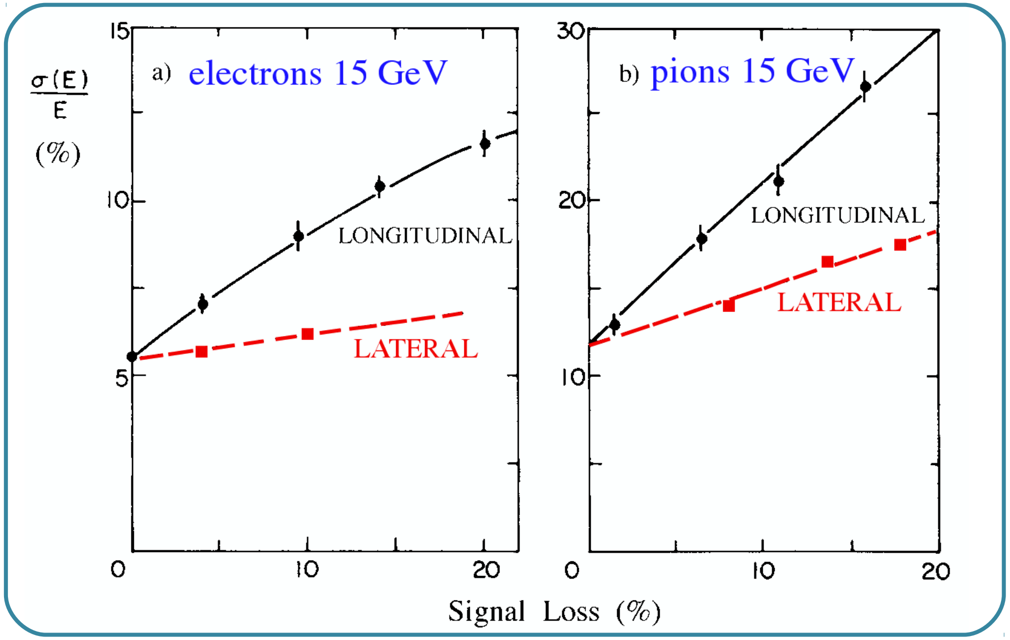


Leakage

- Energy from secondary particles escaping measurement
  - Non-Poissonian fluctuations

- **Longitudinal** leakage (rear of the detector)
  - A detector is never infinitely deep
  - Dangerous since increases as log(E)
  - Alleviated if calorimeter "sufficiently" deep

- **Lateral** leakage
  - One tends to limit the lateral size over which the signal is integrated
  - Need to limit integration of channels with low S/N
  - Need to limit integration of nearby showers



Contribution of leakage fluctuations to energy resolution

Energy resolution: parametrization

Stochastic

Constant

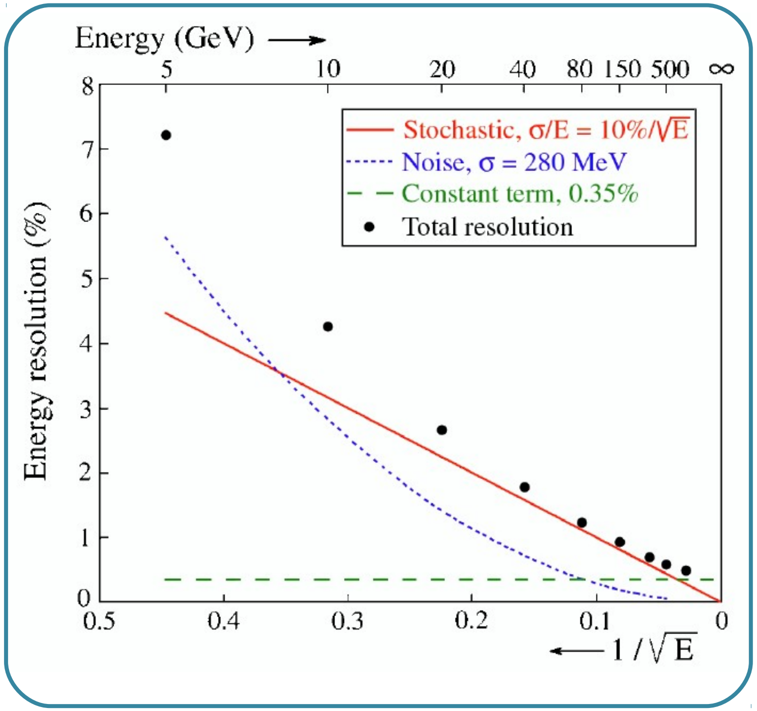
$$\frac{\sigma(E)}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C$$

Noise

$\oplus$ = quadratic sum

- Stochastic term
  - Everything with a **Poisson-like** statistics
  - Intrinsic particle fluctuations, sampling, quantum fluctuations
- Noise term
  - Internal (e.g., electronics) and external (e.g. pile-up) noise
- Constant term
  - Fluctuations due to **leakage**
  - Imperfections in construction, **non-uniformity**
    - Local variations of temperature, light attenuation, material thicknesses, etc.

Energy resolution in EM ATLAS barrel calorimeter



Homogeneous vs sampling calorimeters

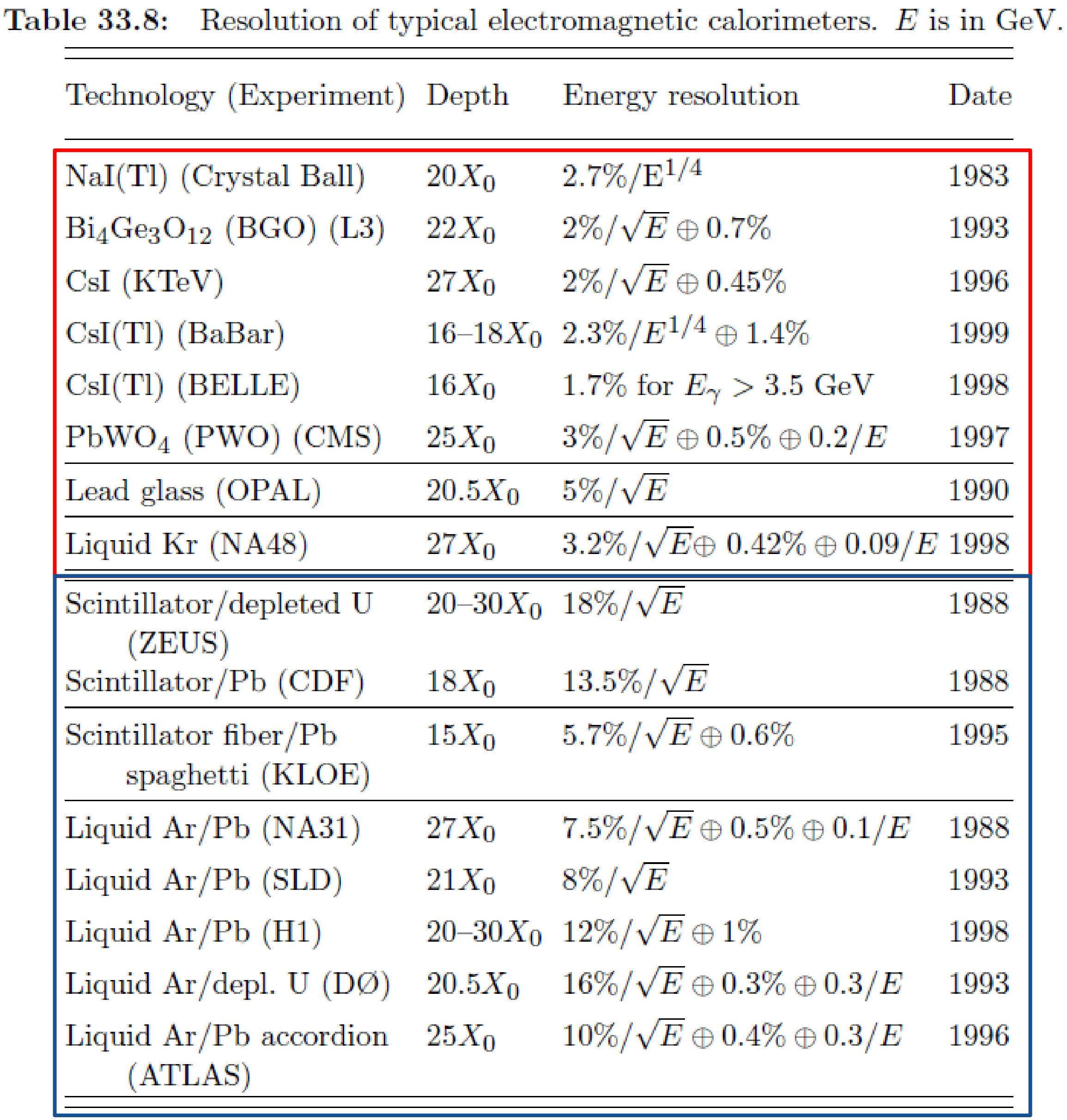


Table 33.8: Resolution of typical electromagnetic calorimeters. E is in GeV.

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$\mathrm{Bi_4Ge_3O_{12}}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$\mathrm{PbWO_4}$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

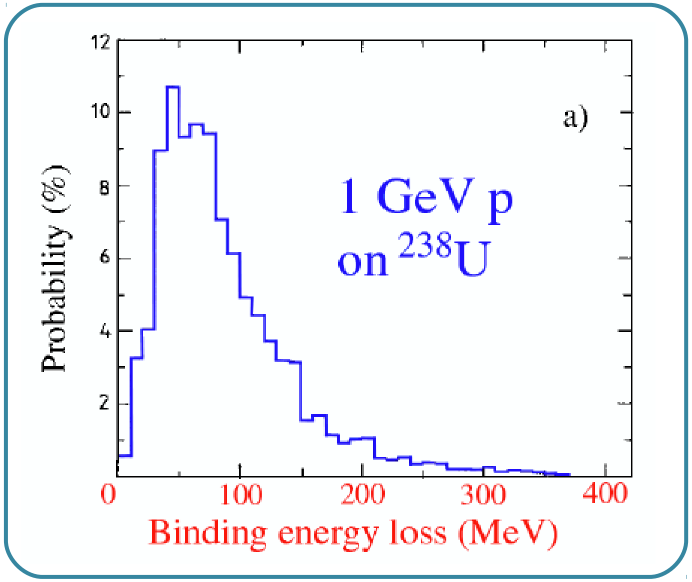
Homogeneous

Sampling

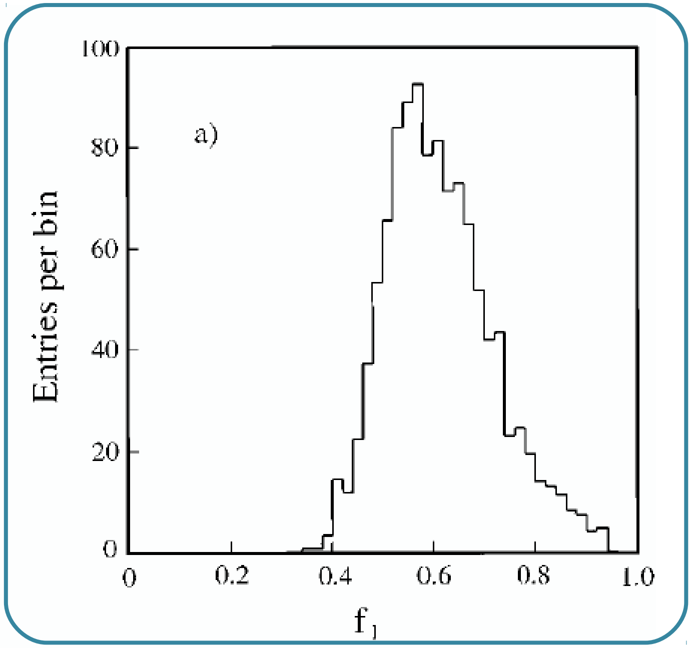
Fluctuations in hadron showers

- Same types of fluctuations as in EM showers +
- **Fluctuations in visible energy**
  - ○ Fluctuations in losses due to nuclear binding energy
  - ○ Note: Correlation with the number of neutrons produced in spallation reactions
- **Fluctuation in the EM shower fraction**
  - ○ Dominating effect in most hadron calorimeters, where e/h ≠ 1
  - ○ Due to the irreversibility of π_0 production → asymmetry in EM fraction distribution
  - ○ Ideally need to measure the EM fraction for each shower

Binding energy loss for 1 GeV proton in Uranium



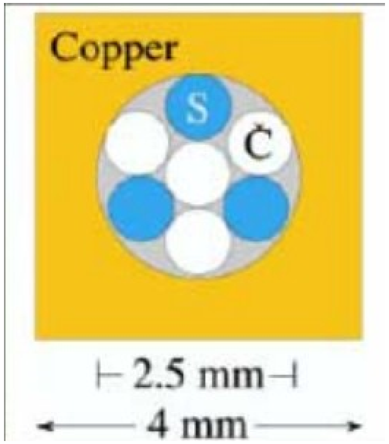
EM fraction of 150GeV π showers in SPACAL



Measurement of the EM fraction with Dual Readout

- For non-compensating calorimeters
  - Can improve the resolution by **measuring the EM fraction**
  - Largest source of fluctuations
- Can be done with **Dual Readout**
  - DREAM prototype exploring this idea
- Combination of **quartz fibers** and scintillator fibers
  - Quartz fibers only sensitive to EM component
  - Collecting **Cerenkov light emitted by electrons**
- Allows to measure separately the EM and hadronic components of the shower

Conceptual design of a dual readout calorimeter

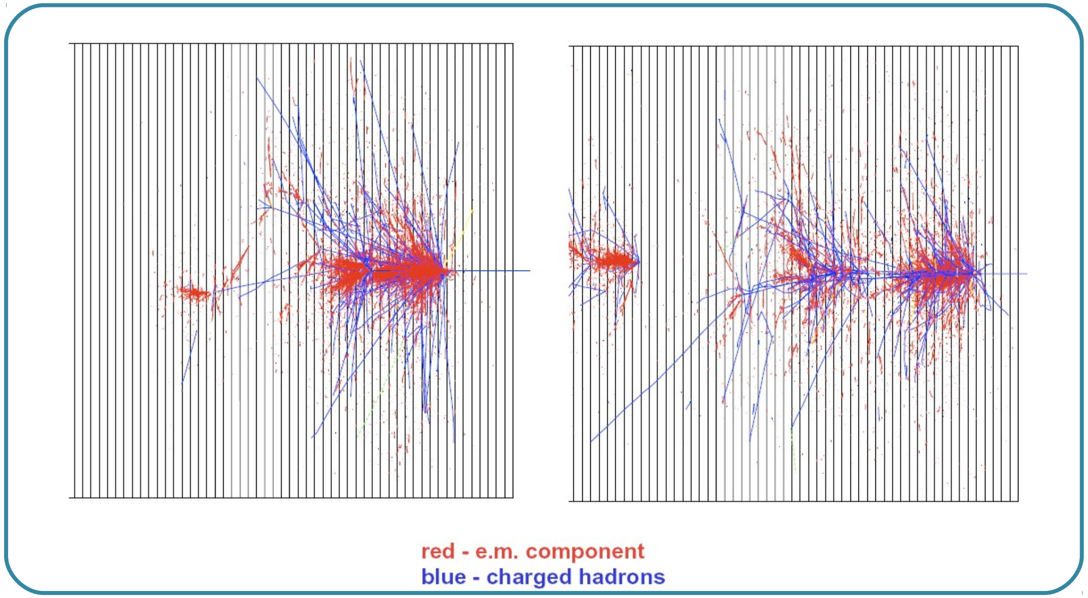


DREAM prototype

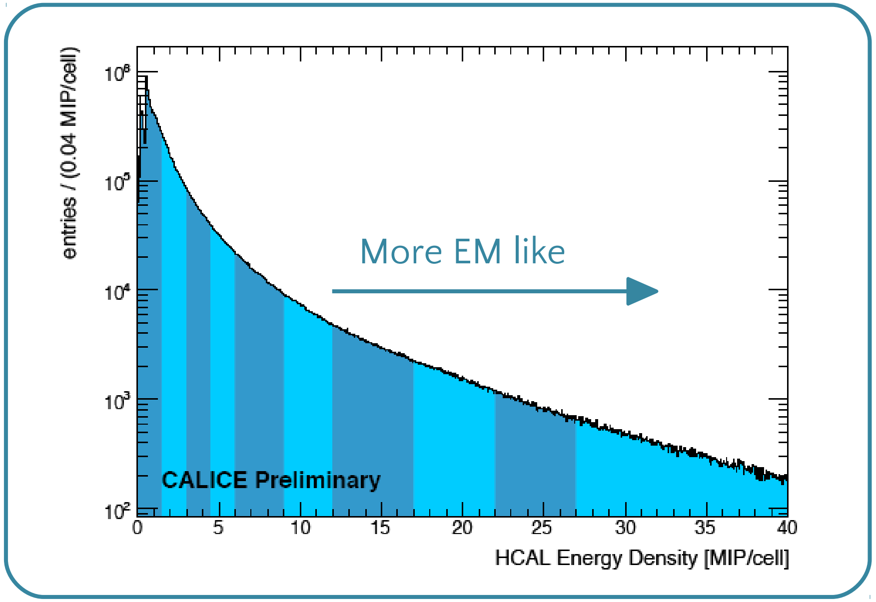
Measurement of the EM fraction indirectly

- One can also **infer** the shower components indirectly
  - And apply different calibrations according to the type of energy deposit (EM or hadronic)
- General idea: EM shower are narrow and dense while hadronic showers are more diffuse
  - → Apply weights according to energy density
- Requires calorimeters with **high-granularity** and **fine segmentation**

EM and hadronic components in showers



Cell energy density



Lecture plan

What is calorimeter in HEP?

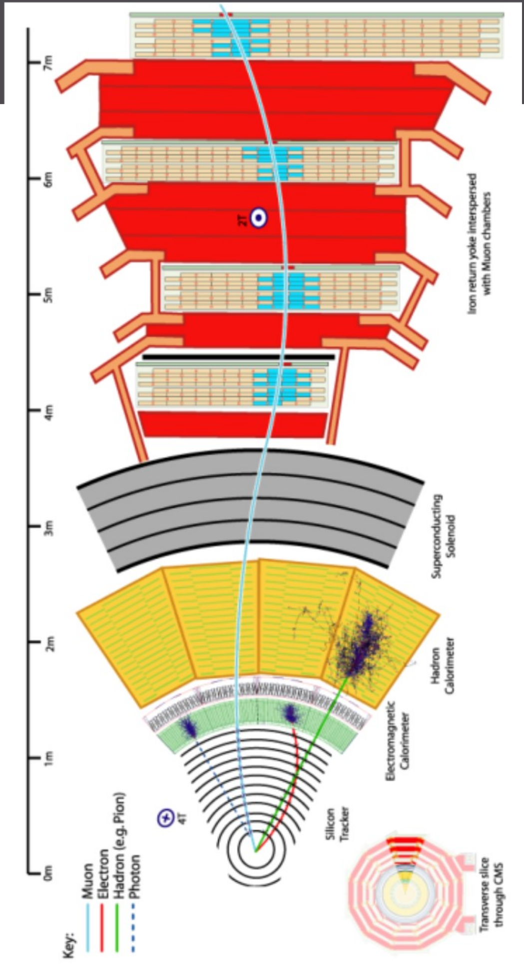
Electromagnetic and hadronic showers

Detection techniques

Calorimeter response & resolution

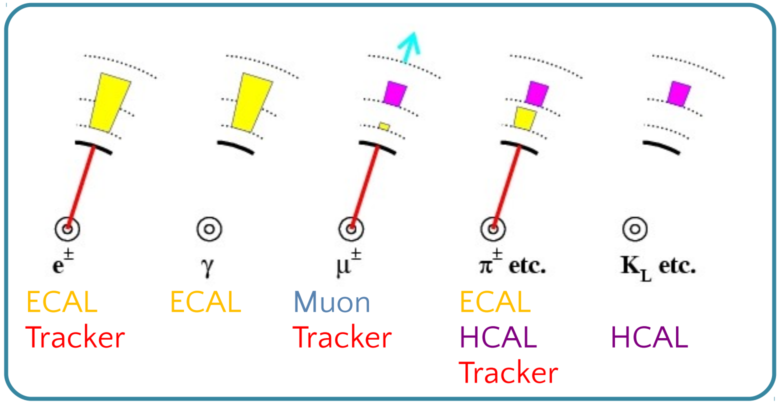
Closing remarks

Closing remarks (1/2)



- In the end a calorimeter is used for
  - ○ Measuring particle energies as precisely as possible (needs a **linear response and a good resolution**)
  - ○ **Identifying particles/showers**, in particular electrons/photons and hadrons
- Many parameters can be optimized
  - ○ Type of calorimeter, material, segmentation, granularity, etc.
- The perfect calorimeter doesn't exist (yet)
  - ○ But one can **combine calorimeter measurements with information from other subdetectors** (e.g. trackers)
  - ○ And make use of their complementary measurements
  - ○ Strategy used in **"Particle Flow"** reconstruction algorithms

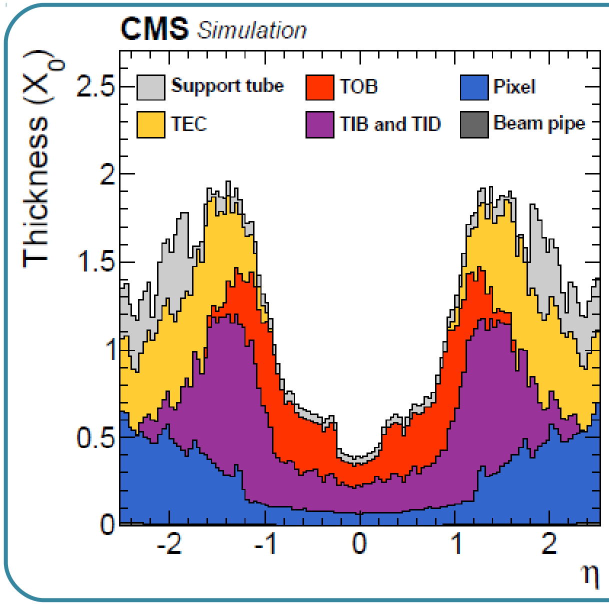
Signatures from different particles



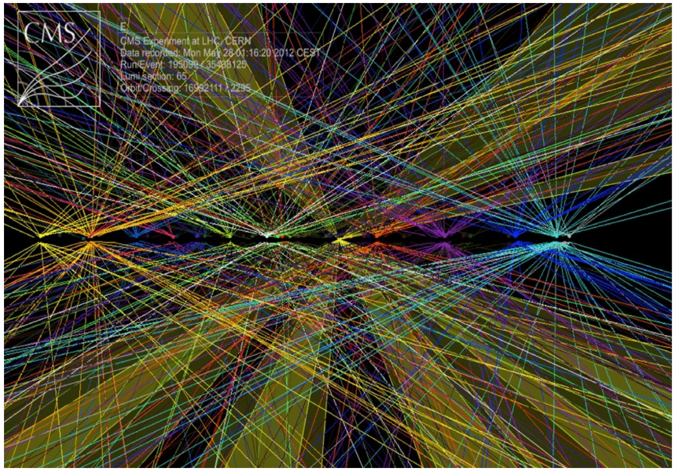
Closing remarks (2/2)

- Real conditions of a full detector in its environment are harsh
  - ○ Very **high number of calorimeter channels** (100k to several millions)
  - ○ **Magnetic field** (impact on photodetectors, electronics, mechanics)
  - ○ **Material** in front of the calorimeter (mechanical structure, other sub-detectors)
  - ○ **Radiations**, Pile-up (in-time and out-of-time)
  - ○ …
- Degrades performance compared to standalone devices or test beams
- Needs to be taken into account when designing/optimizing a calorimeter

Material in front of the CMS calorimeters



Tracks from multiple simultaneous interactions

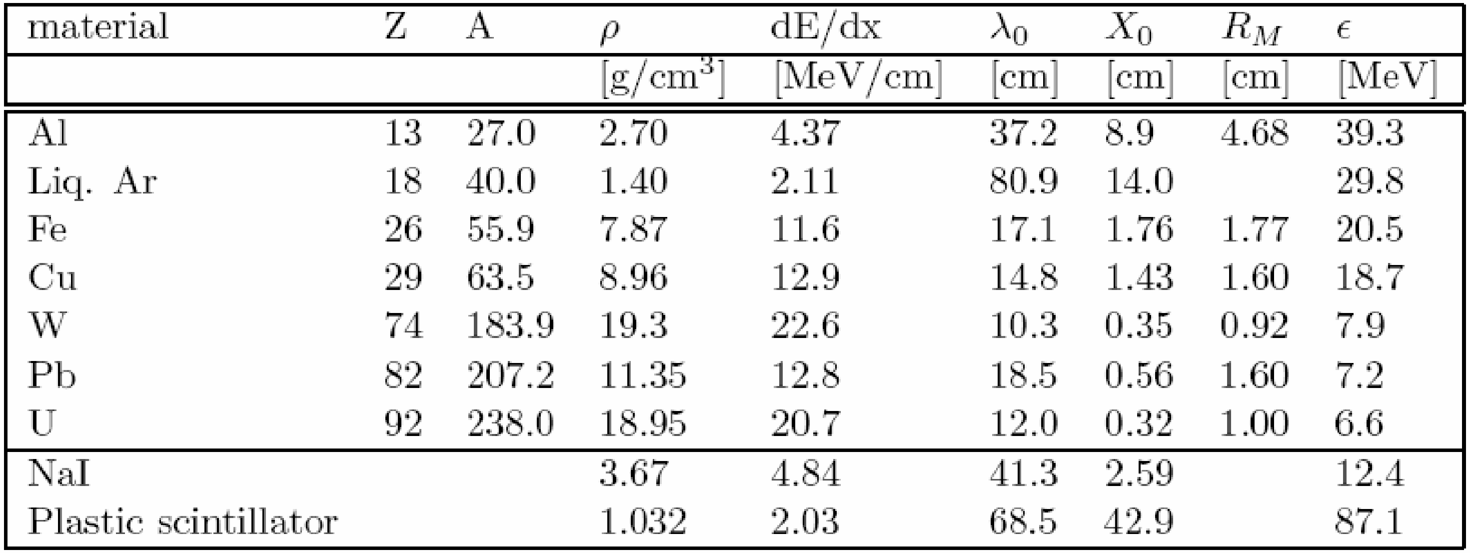


Exercises

- In the next two slides are a few exercises related to the resolution of calorimeters
- The solutions can be found on the ESIPAP Indico page

Energy resolution – Sampling term

- We consider a sampling calorimeter using Lead as absorber and Plastic Scintillator as active material, with the following properties:
  - 5 mm thick lead plates
  - 3 mm thick scintillator tiles
  - A resolution of 16% / √E (sampling term)
- Compute the sampling fraction of this calorimeter
- What is the sampling fraction that would be required to get a sampling term of 13% / √E ?
- Consequently, what is the lead plate thickness that would be required, if we use the same scintillator thickness as before (3mm)?



material	Z	A	ρ	dE/dx	λ_0	X_0	R_M	ϵ
			[g/cm^3]	[MeV/cm]	[cm]	[cm]	[cm]	[MeV]
Al	13	27.0	2.70	4.37	37.2	8.9	4.68	39.3
Liq. Ar	18	40.0	1.40	2.11	80.9	14.0		29.8
Fe	26	55.9	7.87	11.6	17.1	1.76	1.77	20.5
Cu	29	63.5	8.96	12.9	14.8	1.43	1.60	18.7
W	74	183.9	19.3	22.6	10.3	0.35	0.92	7.9
Pb	82	207.2	11.35	12.8	18.5	0.56	1.60	7.2
U	92	238.0	18.95	20.7	12.0	0.32	1.00	6.6
NaI			3.67	4.84	41.3	2.59		12.4
Plastic scintillator			1.032	2.03	68.5	42.9		87.1

Energy resolution – Comparison of two EM calorimeters

- We are comparing the resolutions of the ATLAS and CMS EM calorimeters, as measured in test beams:

CMS

$$\frac{\sigma(E)}{E} = \frac{0.03}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{0.3}{E(\mathrm{GeV})} \oplus 0.005$$

ATLAS

$$\frac{\sigma(E)}{E} = \frac{0.1}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{0.3}{E(\mathrm{GeV})} \oplus 0.007$$

- Fill the following table for both calorimeters. And comment these numbers.

	10 GeV	1 TeV
Stochastic [%]		
Noise [%]		
Constant [%]		
$\sigma(E)$ / E [%]		