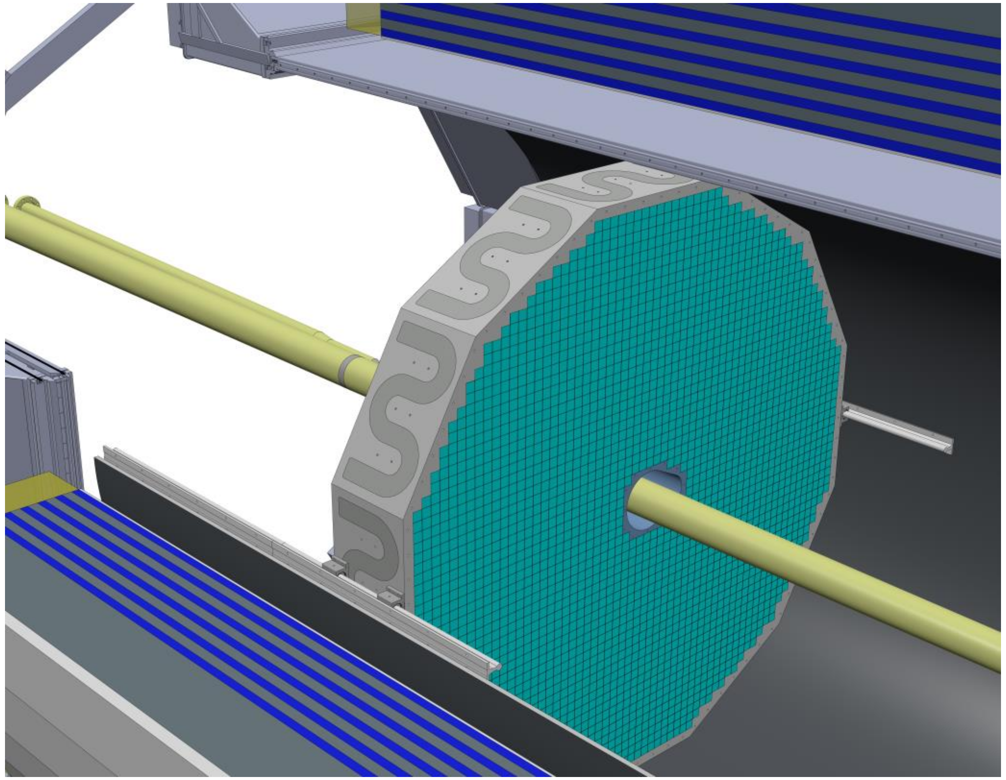


Calorimetry
(Lecture 1)

2nd European EIC School

Carlos Muñoz Camacho
IJCLab

Benicassim, June 25-26 (2025)

With material from E. Chudakov, H. Klest, F. Sefkow, F. Simon and many others..

Outline

1. **Calorimetry in high energy physics**

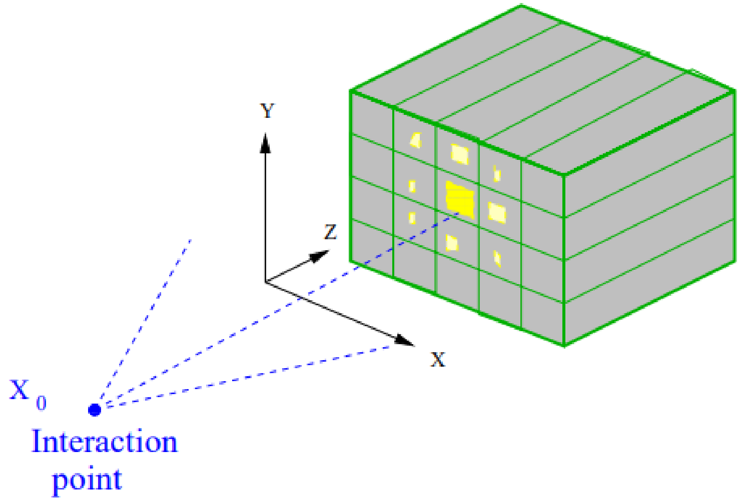
2. Calorimetry at EIC (ePIC detector)

3. New trends in calorimetry (R&D avenues)

1. Introduction
2. Basic Principles of Particle Interaction
3. Calorimetric Measurements: Response, Resolution, and Capabilities
4. Calorimeter Types
5. Conceptual Refinements
6. Summary and recap

Introduction

- Calorimeters measure particle energy via total absorption.
- Essential for detecting both charged and neutral particles.
- Key components in all modern high-energy physics detectors.
- Complement tracking detectors, especially for photons and neutrinos.



Measured:

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

Calorimeters vs. Tracking Detectors

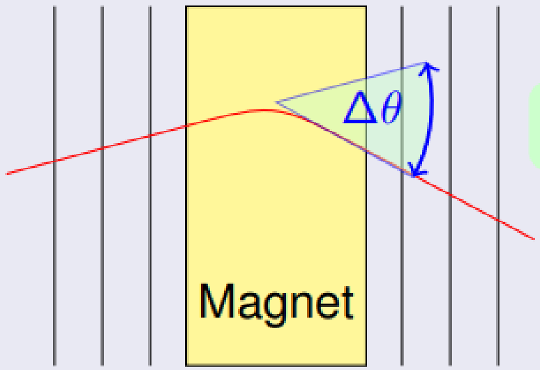
Particle detection main goal: measure 4-momenta P

- Tracking: precise momentum measurement for charged particles.
- Calorimeters: total energy measurement, including neutrals.
- Calorimeters are destructive; tracking is non-invasive.
- Complementary roles for full event reconstruction.

Magnetic spectrometers

- For charged particles
- Coordinate detectors
- Magnetic field

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



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

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

Momentum resolution:

$\frac{\sigma(P)}{P} = \frac{\sigma(\Delta\theta)}{\Delta\theta} \propto P$ (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.

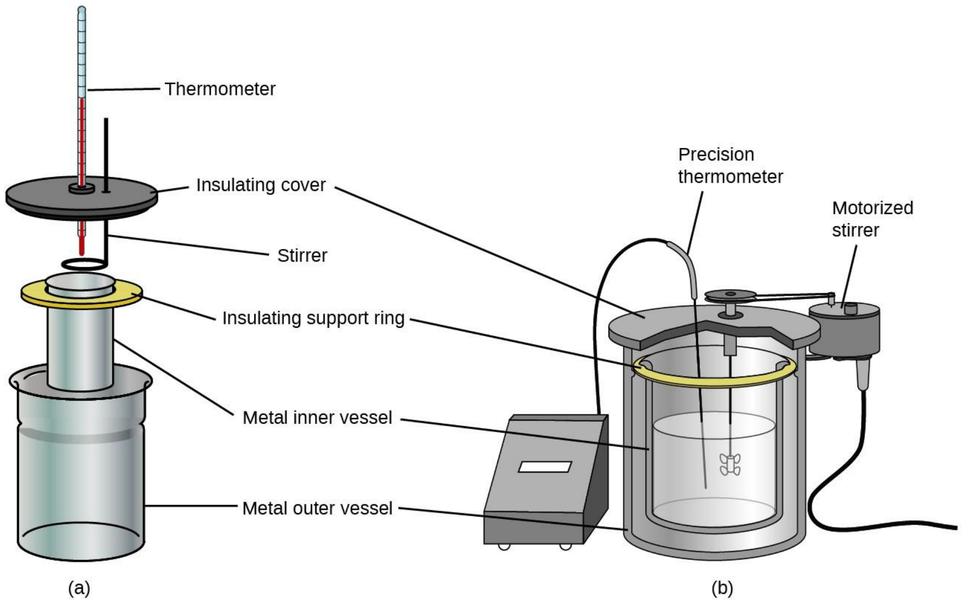
- "True" C. - E_o (heat)
- "Pseudo" C. - $\mathcal{O}(E_o)$: ionization, Cherenkov light

Poisson process: $N_e \propto E_0$,
$\sigma N_e = \sqrt{N_e}$ and $\frac{\sigma E}{E} \propto \frac{1}{\sqrt{E}}$

Thickness needed for full absorption:

$t \propto ln(E)$

Real calorimeters



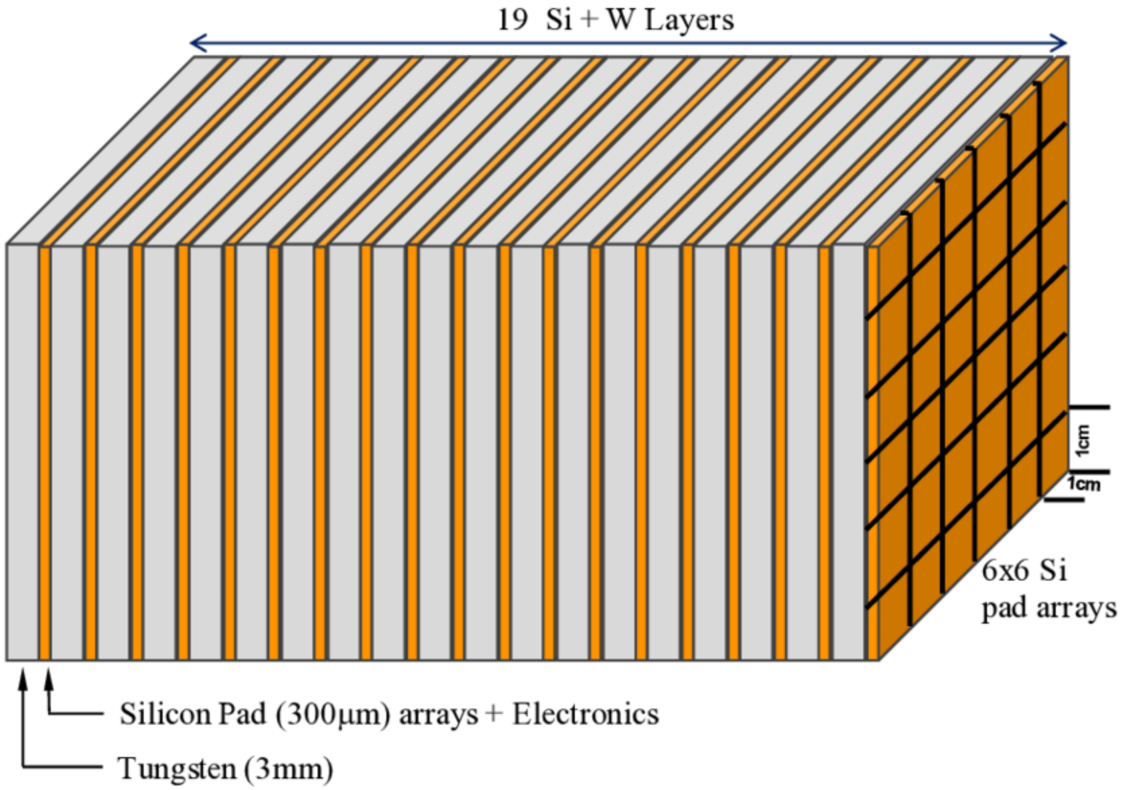
"True" calorimeters measure the temperature change of the absorber:

$$\Delta T = \frac{E_0}{c \cdot M} \sim \frac{1 \cdot 10^{10} eV \cdot 1.6 \cdot 10^{-19} J/eV}{10^3 J/kg/K \cdot 1 kg} \approx 10^{-12} K \text{ too low!}$$

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

Role in Collider and Fixed-Target Experiments

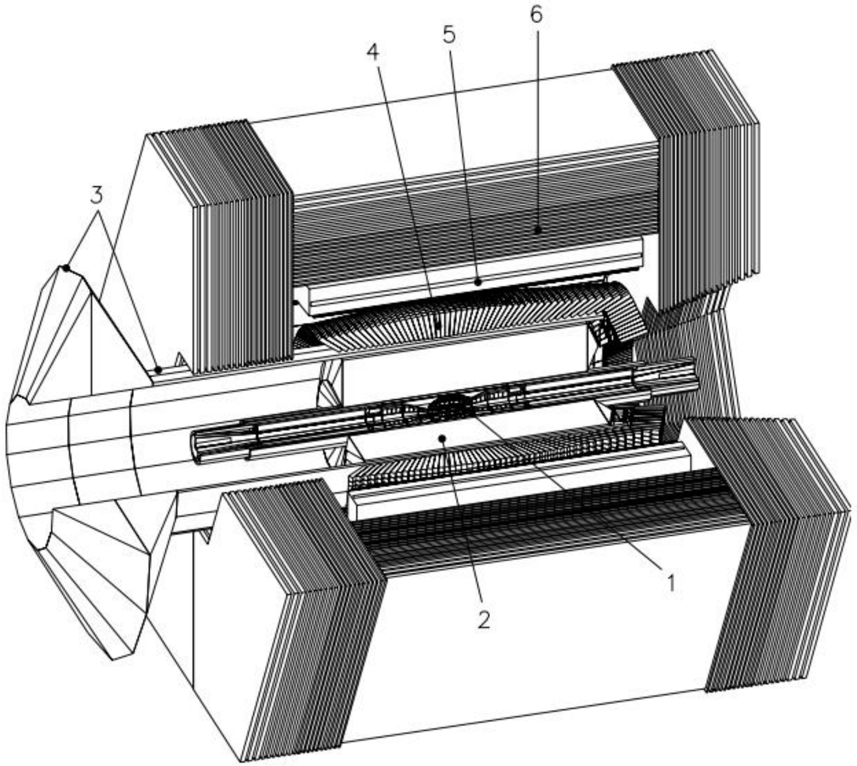
- Ubiquitous in HEP: ATLAS, CMS, LHCb, neutrino experiments.
- Crucial for jet energy, missing energy, and particle ID.
- Applicable in fixed-target setups and beam experiments.
- Also used in test beams and beam diagnostics.



Components of a silicon-tungsten sampling calorimeter consisting of 19 alternating layers of silicon pad detectors (individual pad area of 1 cm^2) and tungsten plates (1 X_0 thick).

Detecting Neutral Particles

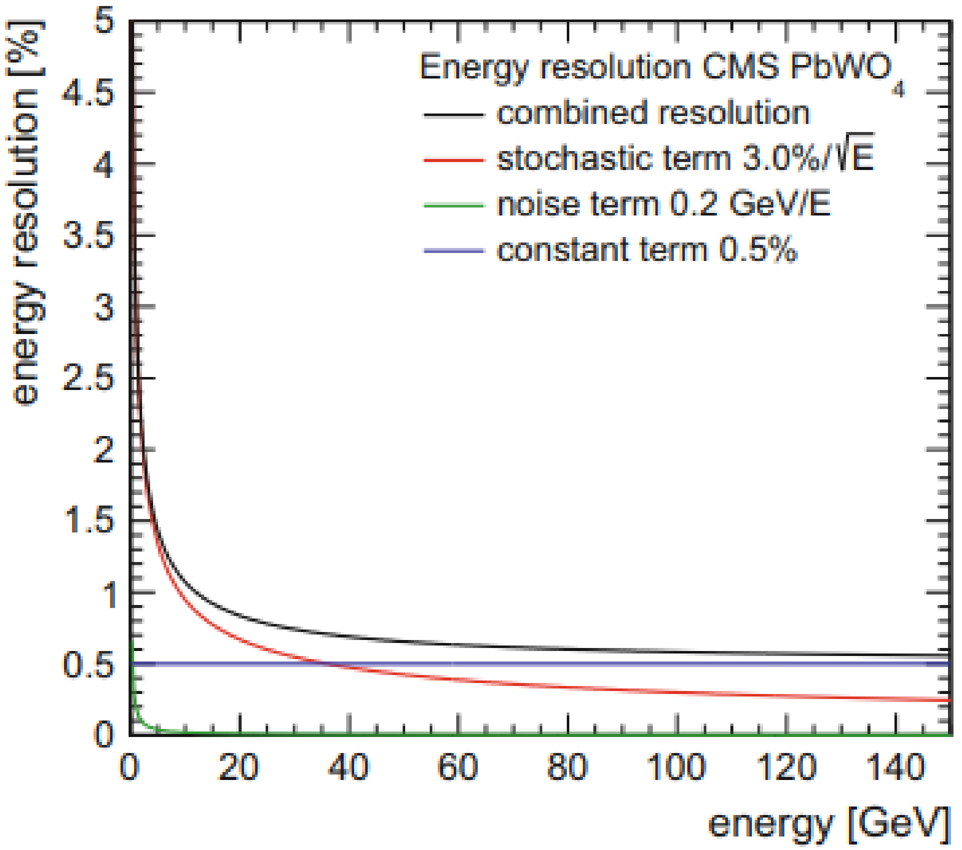
- Neutral particles do not ionize: need calorimetry.
- Photons initiate EM showers via pair production.
- Neutrons interact via nuclear collisions and capture.
- Neutrinos inferred via missing energy.



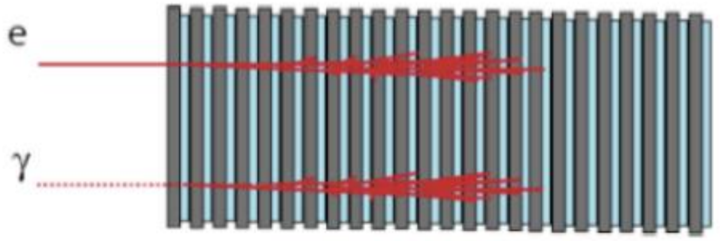
BABAR at SLAC

Motivation for High-Energy Use

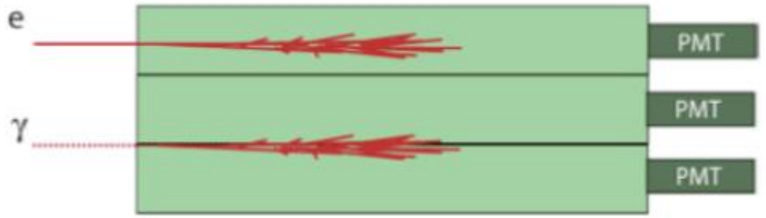
- Calorimeters improve with energy ($\sigma/E \sim 1/\sqrt{E}$).
- Logarithmic scaling in size makes them efficient at TeV scale.
- Magnetic tracking becomes impractical at very high energies.
- Excellent for multi-TeV jet and lepton detection.



Full vs. Partial Energy Measurement



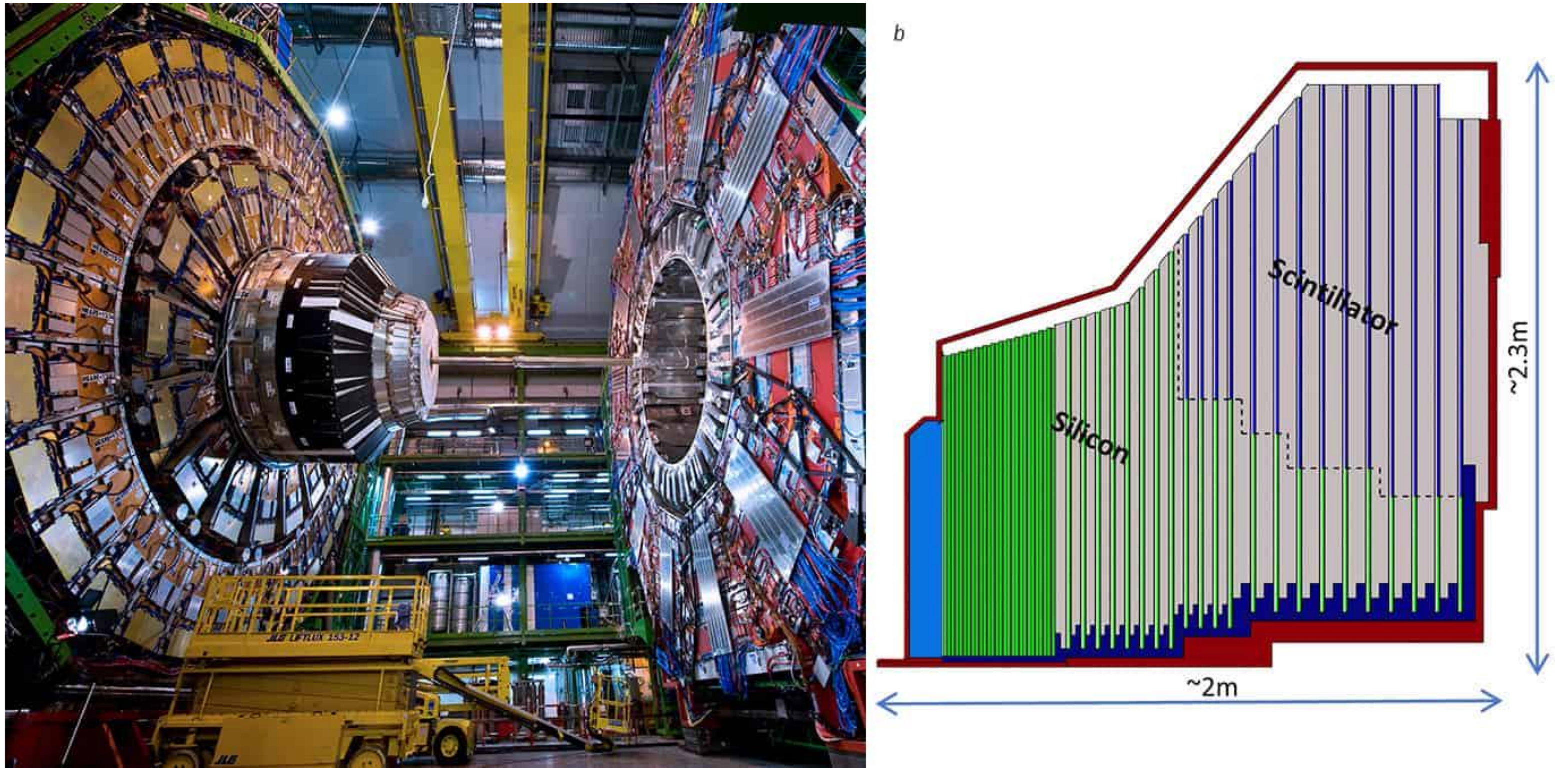
- Ideal: full absorption = full energy measurement.
- Real: signal ≠ total energy due to losses.
- Energy converted into scintillation light, ionization, etc.
- Design aims to maximize signal per unit energy deposited.

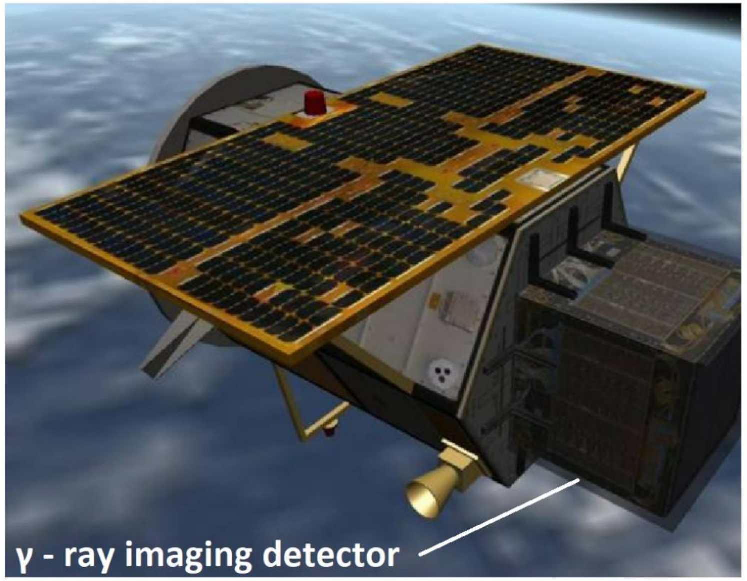


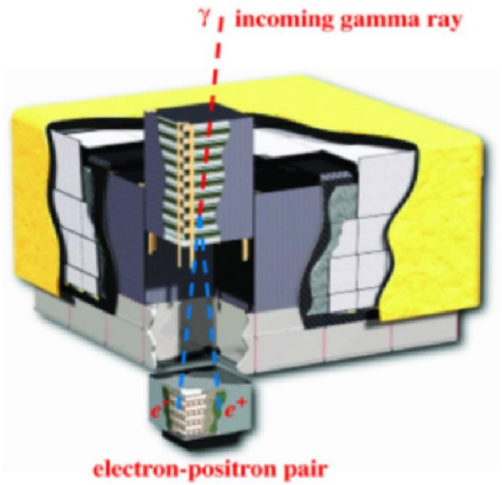
Complexity of Calorimeter Systems

- Multi-material, highly segmented designs.
- Active and passive components arranged in layers.
- Readout electronics, cooling, support all tightly integrated.
- Tailored to experiment geometry and radiation conditions.

a b







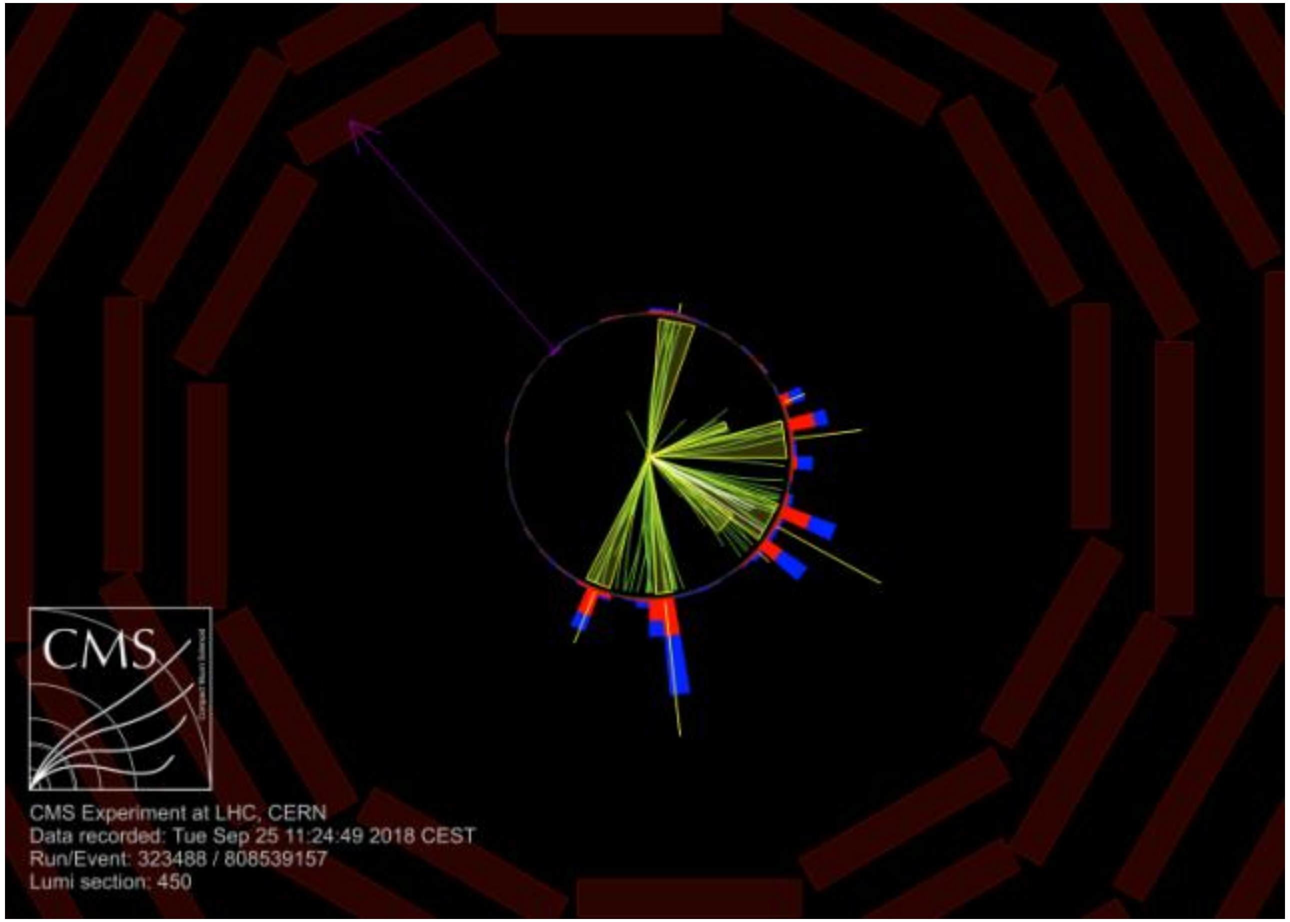
- PET scanners and SPECT: medical imaging via calorimetry.
- Space calorimeters: gamma-ray and cosmic ray detection.
- Industrial and homeland security scanning systems.
- Synergies with material science and radiation dosimetry.

Physics Goals of Calorimetry

- Measure energy of EM and hadronic showers.
- Identify electrons, photons, π^0, and jets.
- Support jet reconstruction and missing transverse energy (MET).
- Enable fast timing for pile-up suppression.

Missing Energy and Neutrinos

- MET calculated via energy imbalance in transverse plane.
- Requires hermetic calorimetry: ECAL + HCAL + coverage.
- Neutrinos don’t interact, but we “see” them through MET.
- Used in searches for SUSY, dark matter, W/Z decays.



Transition to Particle Interactions

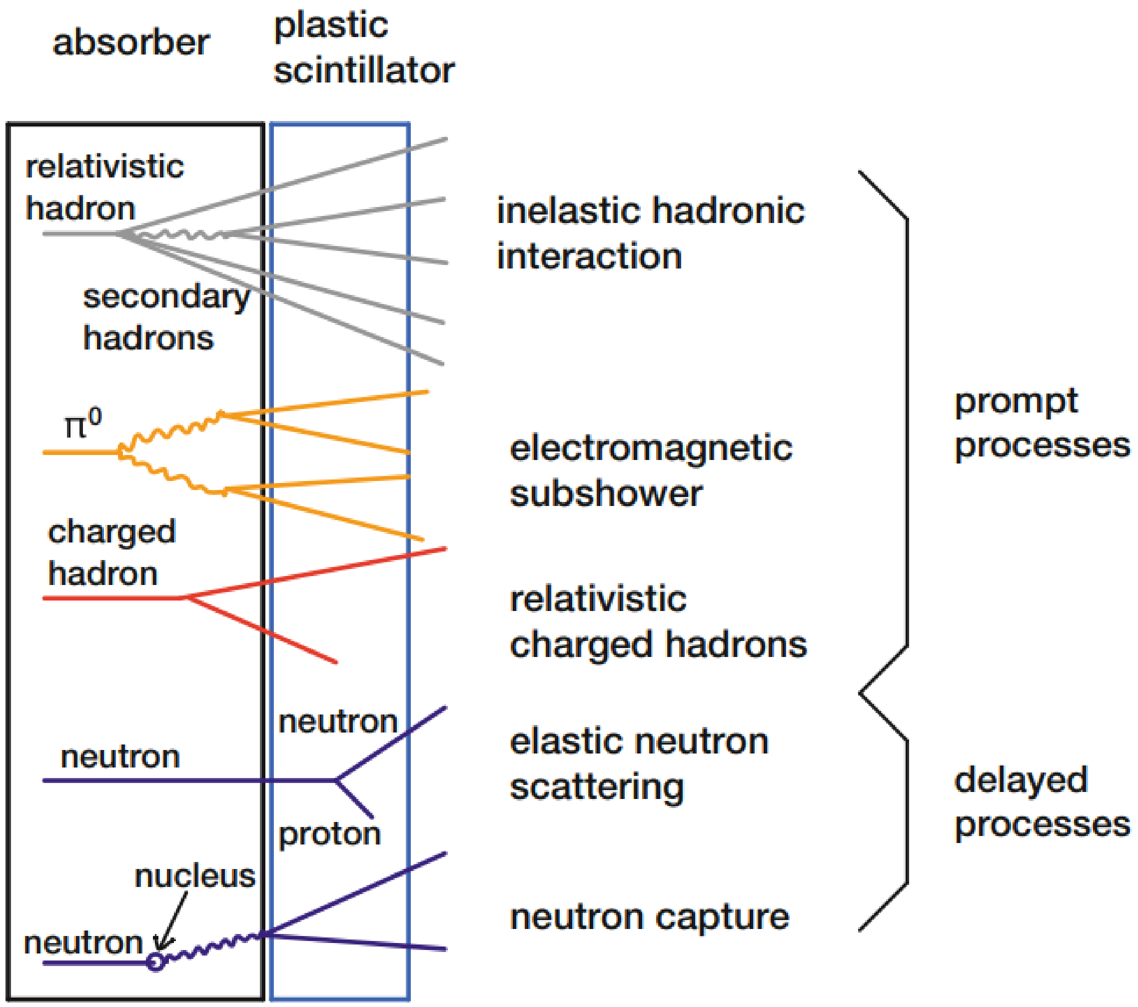
- Next: how particles deposit energy in materials.
- Types: EM, hadronic, nuclear, ionization.
- Understanding interactions = understanding signal formation.
- Prepares ground for resolution and design discussions.

Particle type → interaction mode → calorimeter response.

Particle interactions

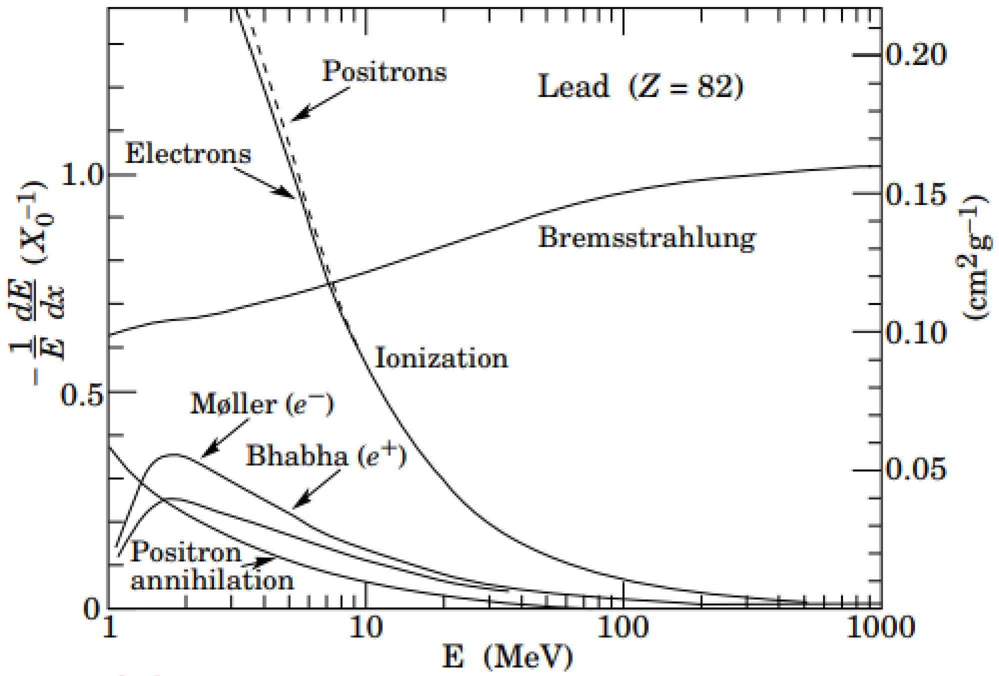
Key Interactions in Calorimeter Materials

- Charged particles ionize and excite atoms.
- Neutral particles interact via nuclear forces.
- EM interactions dominate for e± and γ; hadrons undergo nuclear collisions.
- Interaction depth and shower types depend on material.



Electrons and Positrons

- Lose energy via bremsstrahlung and ionization.
- Bremsstrahlung dominates above critical energy (E_c).
- Results in electromagnetic showers.
- Showers develop over radiation lengths (X_0).



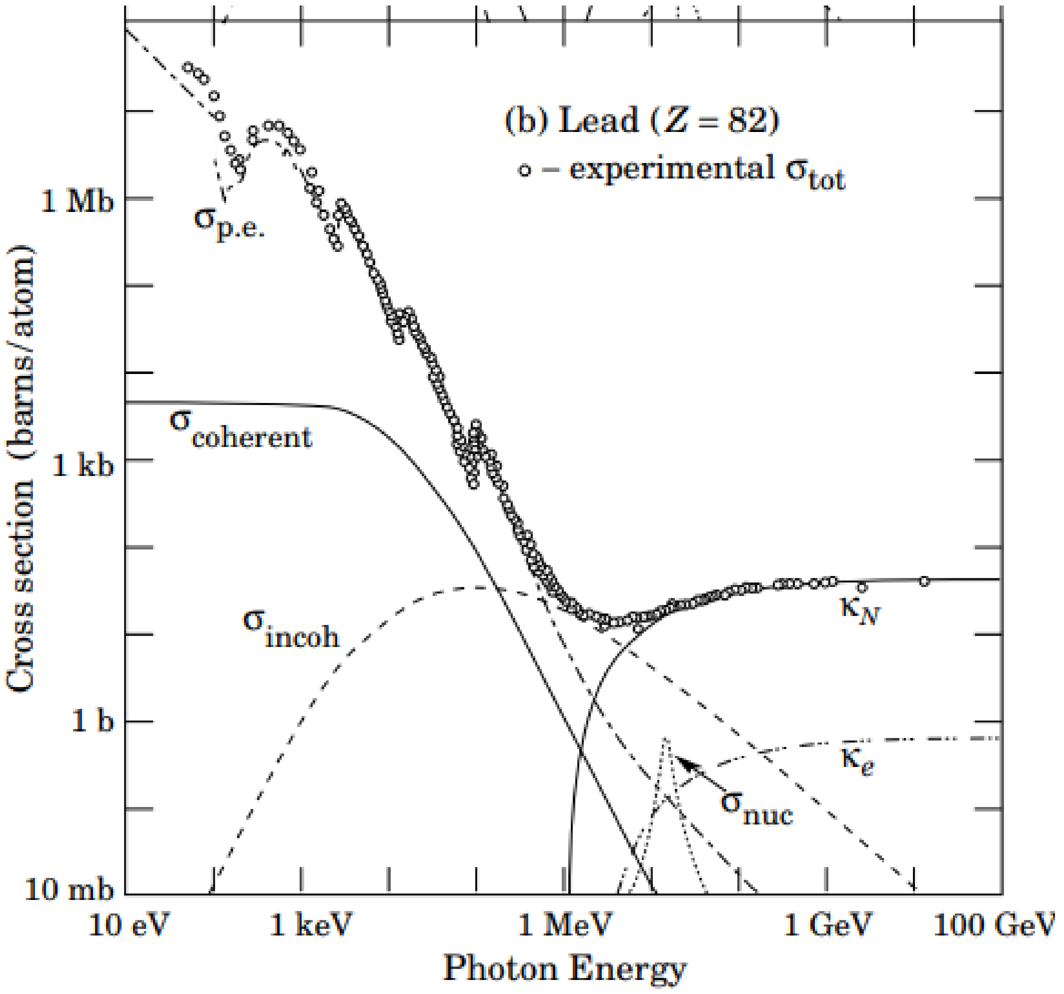
The energy loss due to bremsstrahlung is proportional to the energy of the e±

$$\frac{dE}{dx} = -\frac{E}{X_0}$$

- X_0 (radiation length mean path length of an e± until its energy is reduced to E/e by bremsstrahlung
- X_0 depends on $1/Z^2$ of the material and on the particle mass squared m^2

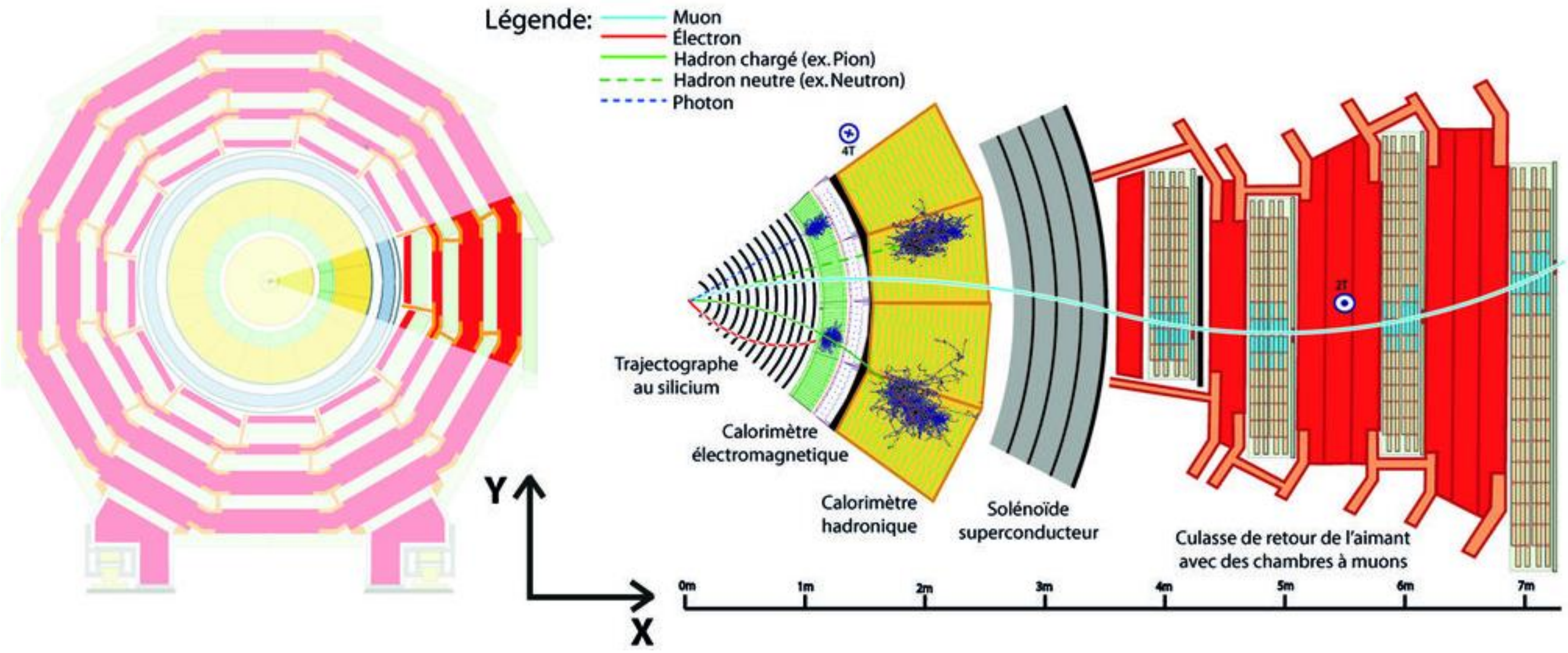
Photons

- 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 $(\sigma_{p.e.})$



Muons

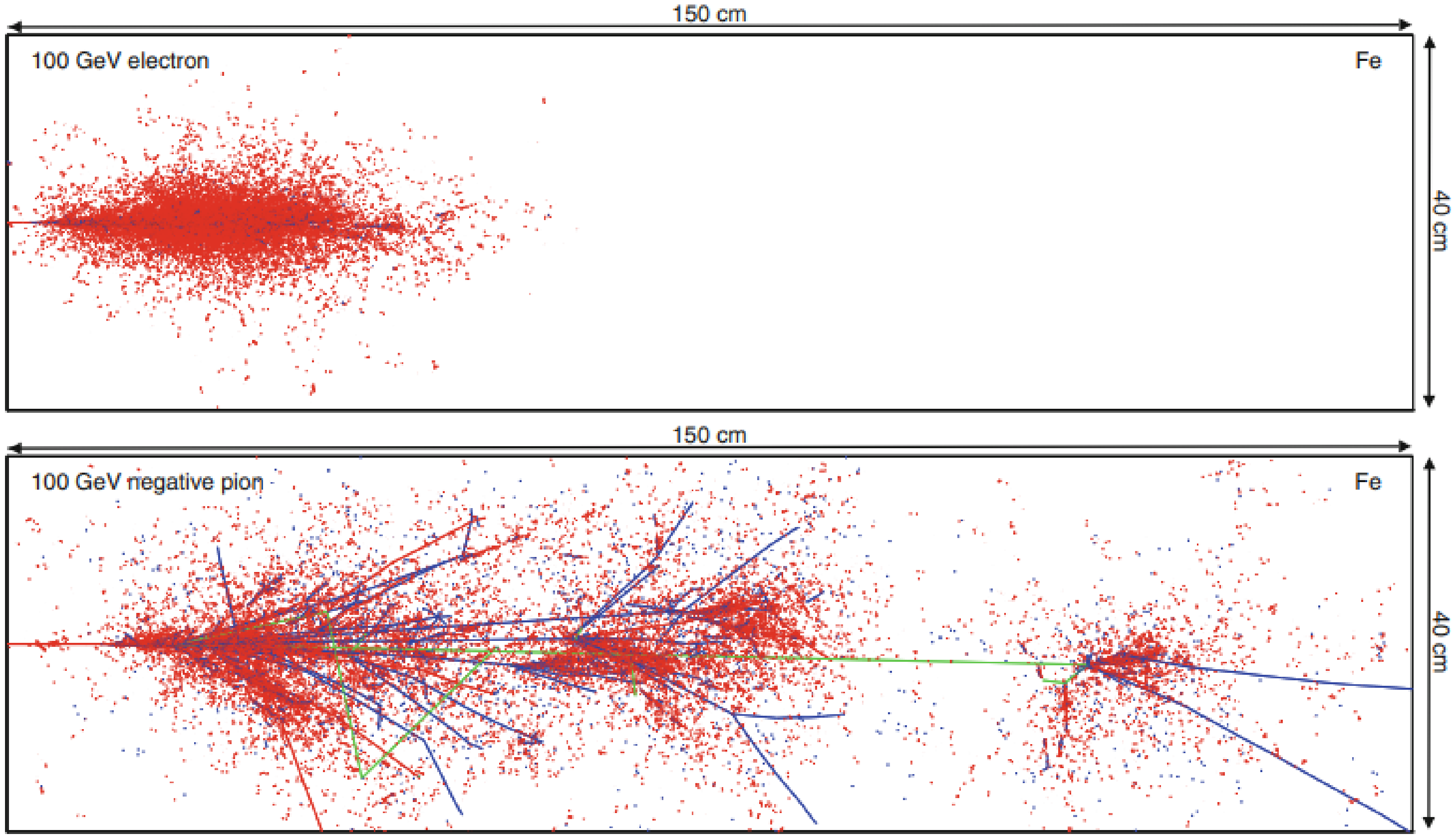
- Minimum ionizing particles (MIPs).
- Interact weakly, penetrate deeply.
- Useful for alignment and calibration.
- Minimal energy deposition in calorimeters.



CMS detector

Hadrons

- Undergo strong interactions with nuclei.
- Produce secondary particles, mostly pions.
- Induce complex hadronic showers.
- Contain both EM and hadronic components.



GEANT4 simulation:

Only charged particles (blue, positive; red, negative) and

selected neutral particles (green, excluding photons, neutrons, and neutrinos) are shown

Hadronic cascade: interaction length

- Charged hadrons continuously lose energy due to ionization processes.
- Due to the high particle masses, bremsstrahlung is of no importance.
- Main energy loss for highly energetic hadrons: inelastic strong interactions with atomic nuclei.
- Leads to subsequent collisions of the struck nucleon with other nucleons within the nucleus (intra-nuclear cascade).
- Pions (π0, π±) and other hadrons can be produced (and can escape the nucleus)
- Residual nucleus very likely be in an excited state and undergo a de-excitation process
- Part of the deposited energy is converted into nuclear binding energy which is **not observable**

Nuclear interaction length, λ_I: mean free path length of protons before undergoing an inelastic interaction

In Pb, for example, X_0 = 5.6 mm, but λ_I = 18 cm

- ➢ Compared to electromagnetic interactions, the hadronic interactions → larger scale
- ➢ Greater material depth is required for hadronic than for electromagnetic calorimeters

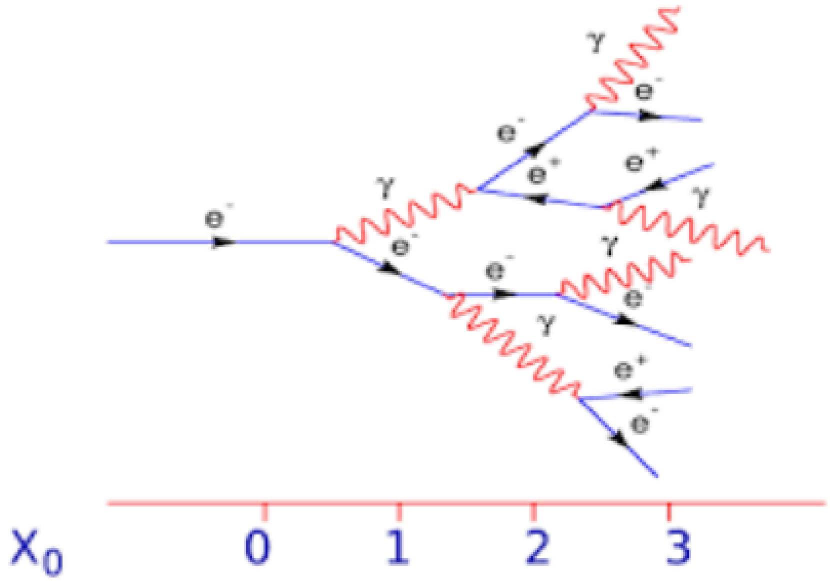
Material properties

Material	Density g/cm^3	X_0 g/cm^2	X_0 cm	λ_I g/cm^2	λ_C g/cm^2	Molière $R_M cm$	E_{crit} MeV	Refr. index
W	19.3	6.76	0.35	192.	134.	0.93	7.97	
Pb	11.3	6.37	0.56	200.	137.	1.60	7.43	
Cu	8.96	12.9	1.44	137.	84.	1.57	19.4	
Fe	7.87	13.8	1.76	132.	82.	1.72	21.0	
Al	2.70	24.	8.9	107.	69.	4.41	42.7	
C	2.21	42.7	19.3	86.	59.	5.0	81.7	
Plastic Sc.	1.03	43.7	42.4	81.	58.	$\approx$ 11.	82.	1.58
H_2	0.071	63.	890.	52.	43.	68.	271.	

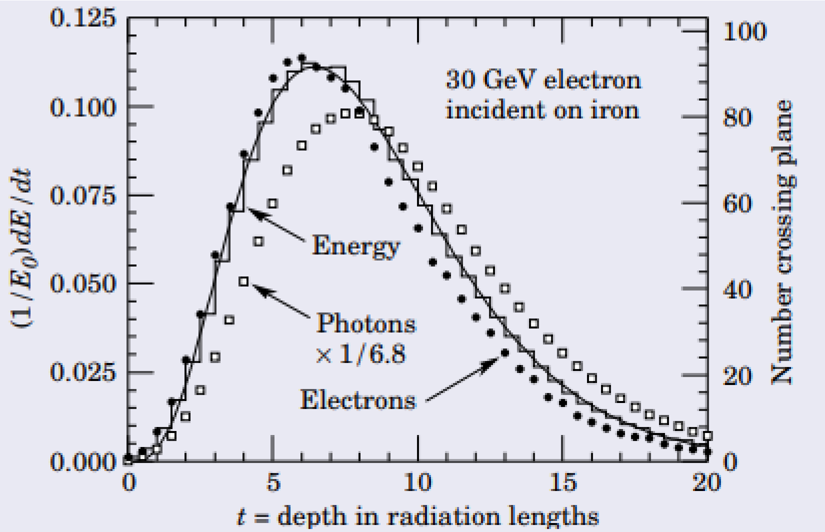
EM Shower Development

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

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



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



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

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

Transverse development:

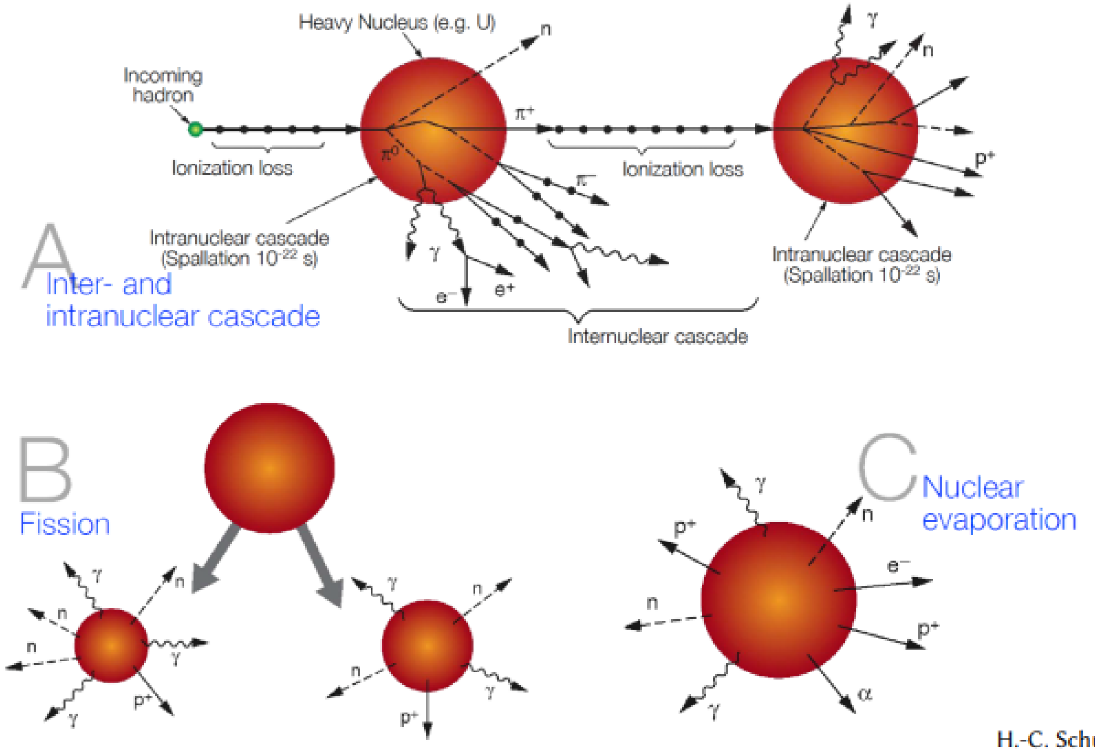
Molière radius: $R_M = \frac{X_0 \cdot 21 MeV}{E_c}$

$R < 2 \cdot R_M$ contains 95% of the shower

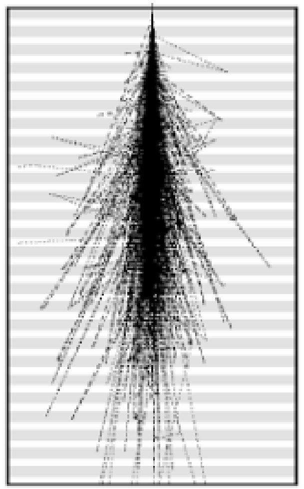
A cascade develops till the energy of the particles go below a certain limit.
The charged particles of the cascade (e$^{\pm}$) leave detectable signals.

- Involve nuclear collisions and pion production.
- Produce secondary EM sub-showers via $\pi^0 \rightarrow \gamma\gamma$.
- Highly fluctuating and less predictable.

- multi-particle production, typically mesons ($\pi^{\pm}$, π^0, K, ...)
- Important: $\sim \frac{1}{3}$ of secondaries are π^0s, which decay immediately via $\pi^0 \rightarrow \gamma\gamma$. $\Rightarrow$ EM shower inside hadronic shower!
- This happens every interaction $\Rightarrow$ EM fraction increases w/energy
- Nuclei breakup leading to spallation neutrons/protons



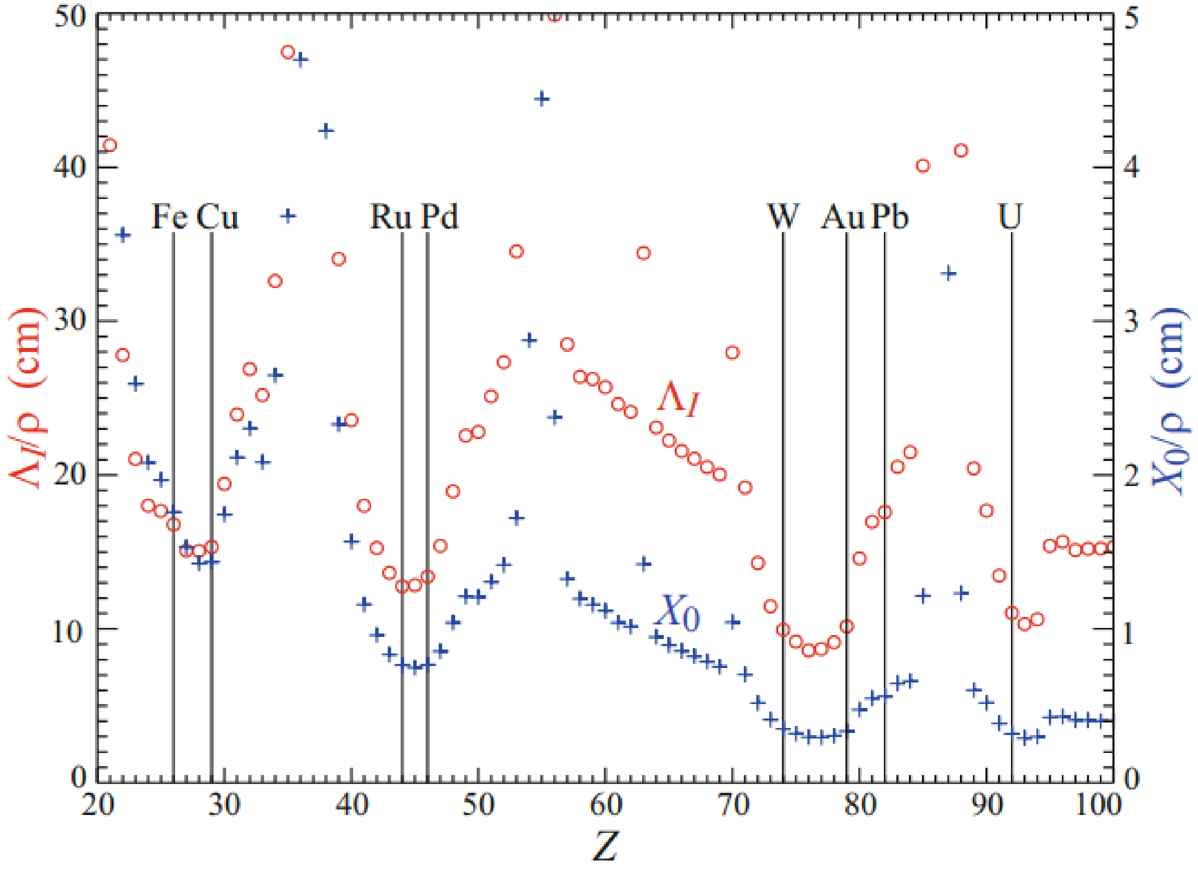
had. shower



H.-C. Schultz-Coulon

Summary: Particle Interactions

- Interaction types define calorimeter response.
- Determines shower type, containment, and readout needs.
- Foundation for resolution and performance models.



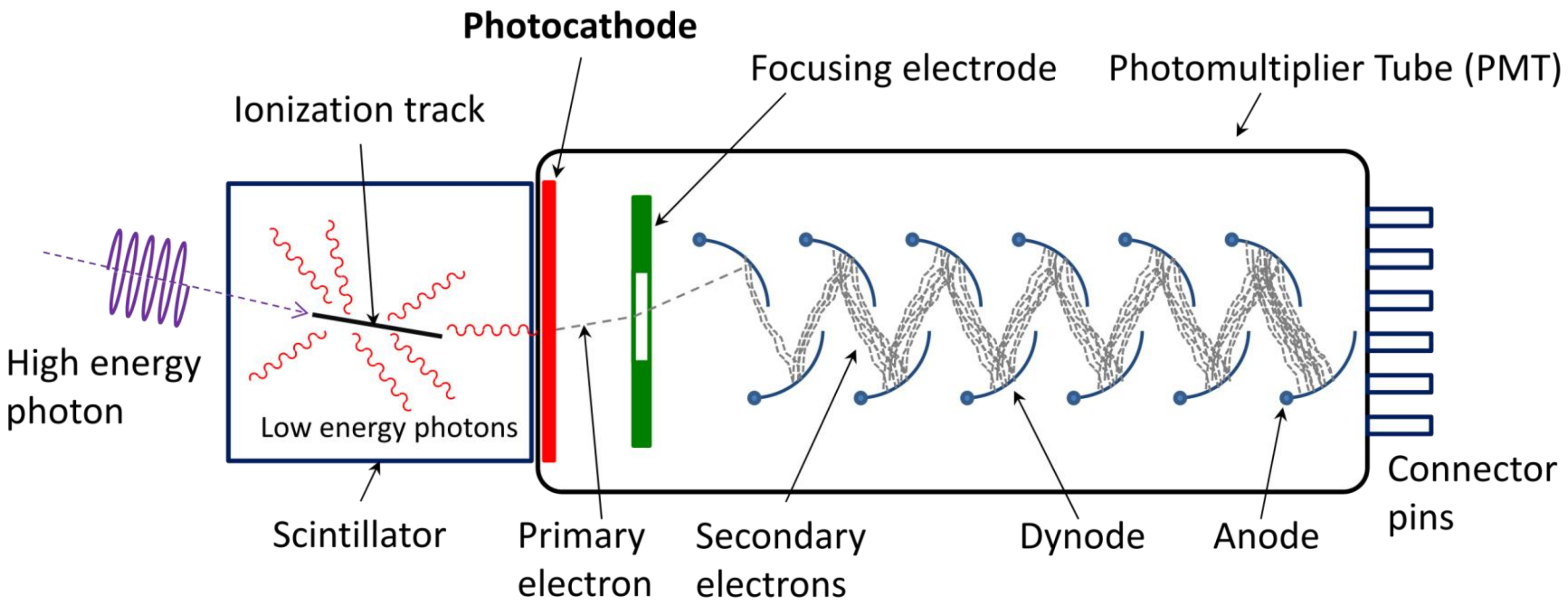
- ➢ Compact detectors: minima in λI/ρ and X0/ρ.
- ➢ For hadronic calorimeters, the ratio of λI and X0 influences the sampling of electromagnetic sub-showers wrt length scale of the hadronic cascade.
- ➢ Region of Ru and Pd : high cost.

- ✓ Lead and tungsten typical choices for EMCals
- ✓ Steel, copper, and brass for hadronic calorimeters
- ✓ Tungsten, lead, and uranium also used for specific hadron calorimeters

Calorimetric Measurements: Response, Resolution, and Capabilities

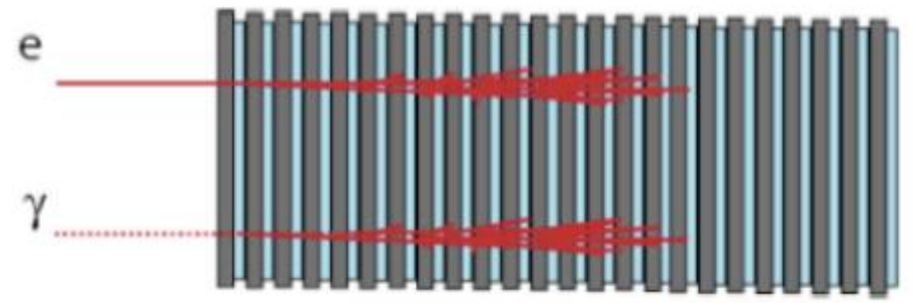
Signal Formation in Active Materials

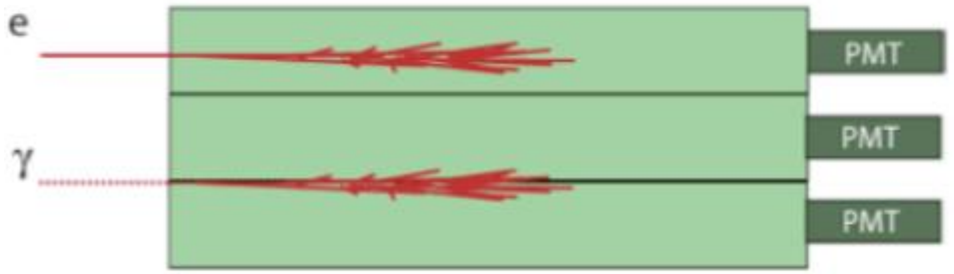
- Energy deposit excites or ionizes atoms in active medium.
- Common mechanisms: scintillation, ionization, Cherenkov radiation.
- Signal proportional to energy deposited (ideally).
- Detector choice affects linearity, speed, and resolution.



Homogeneous vs. Sampling Calorimeters

- Homogeneous: entire volume is active (e.g., crystal calorimeters).
- Sampling: layers of absorber and active material.
- Sampling fraction affects resolution and linearity.
- Tradeoff between performance, cost, and radiation length.



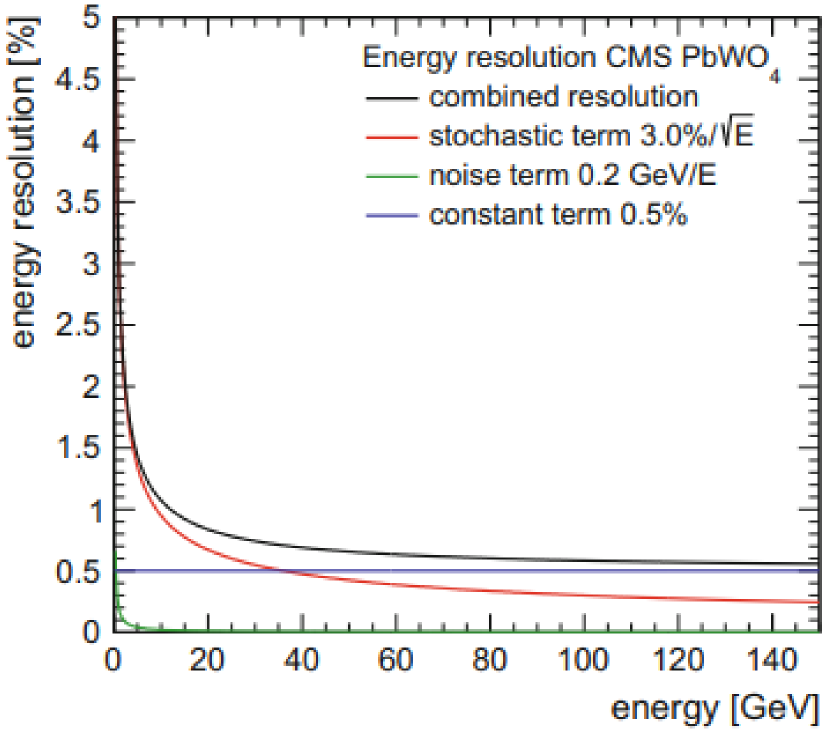


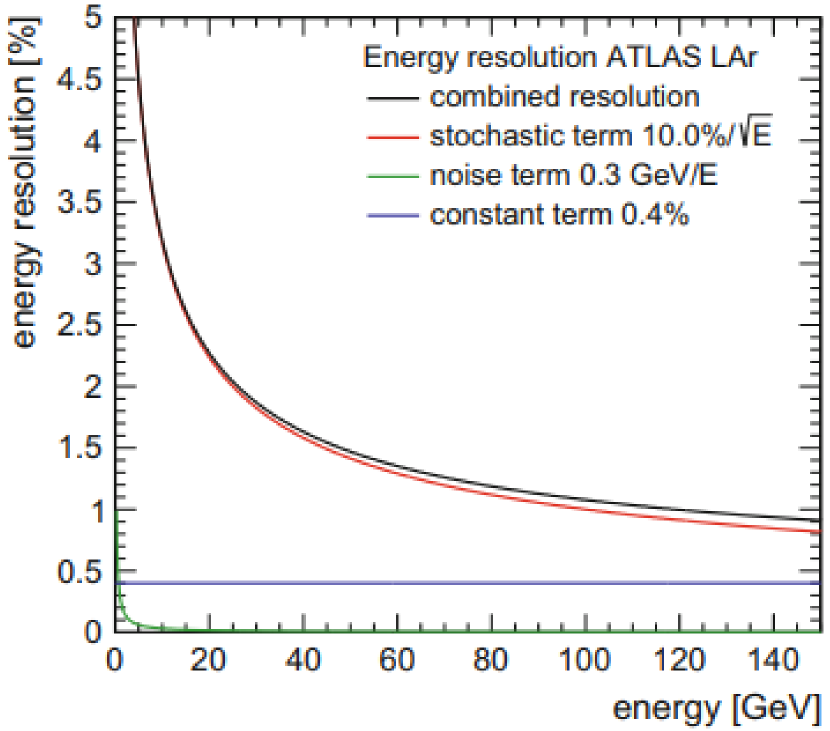
Active Media Examples:

- Scintillators: plastic, inorganic (e.g., $PbWO_4$).
- Noble liquids: LAr, LXe (ionization + scintillation).
- Silicon pads for precision and granularity.
- Gas detectors for digital/semi-digital HCALs.

Resolution Components

- Stochastic term ($A/\sqrt{E}$): shower fluctuations.
- Noise term (B/E): electronics, pile-up.
- Constant term (C): calibration, geometry.
- Combined in quadrature: $\sigma/E = A/\sqrt{E} \oplus B/E \oplus C$.





Spatial resolution

- Depends on granularity and Molière radius.
- ECALs optimized for photon/electron separation.
- Shower overlap in jets affects resolution.
- Crucial for high pile-up environments.

Molière radius: $R_M = \frac{X_0 \cdot 21 MeV}{E_c}$

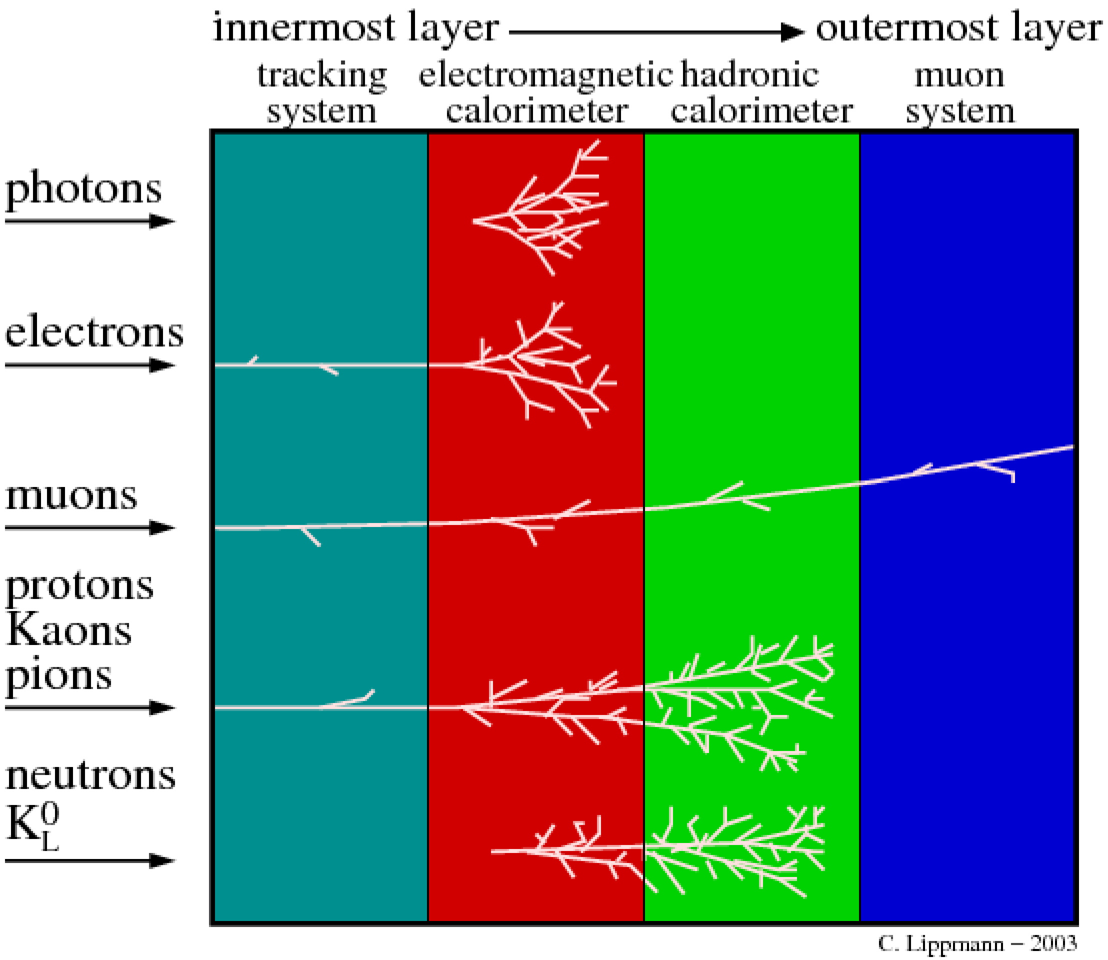
$R < 2 \cdot R_M$ contains 95% of the shower

Timing resolution

- High-resolution timing suppresses pile-up.
- Fast media (e.g., Si, LYSO) achieve ~10-50 ps.
- Enables 4D tracking with calorimeters.
- Used in HL-LHC upgrades.

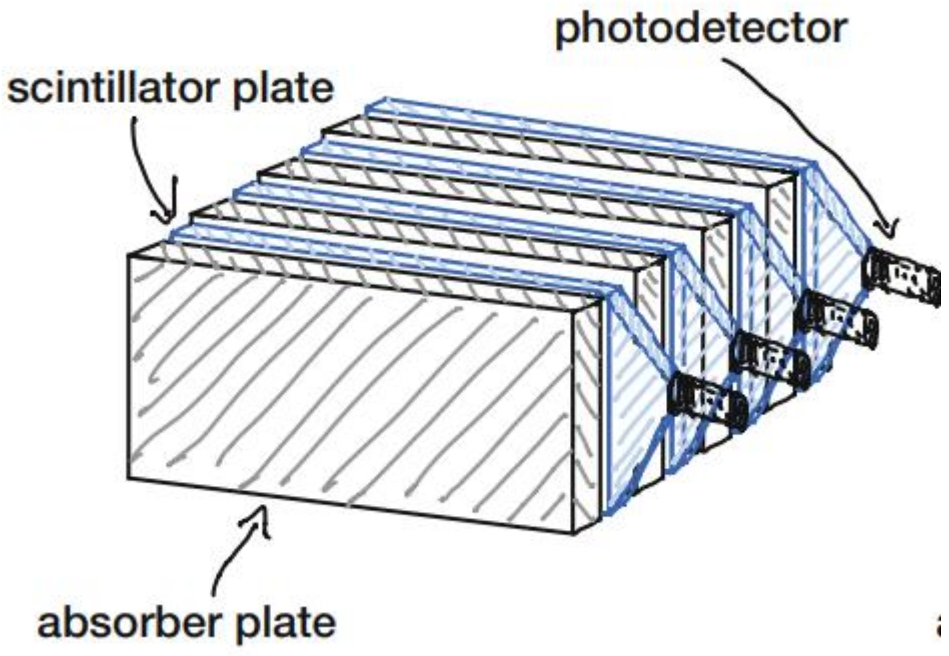
Particle identification

- Shower shape, depth, width → ID electrons vs. hadrons.
- Use in jet/e/γ separation.
- ECAL vs HCAL ratios and transverse profiles.
- Machine learning aids in classification.



Longitudinal Segmentation

- Enables shower shape analysis and timing layers.
- LAr and HGCAL use multiple longitudinal segments.
- Improves particle ID and pile-up rejection.



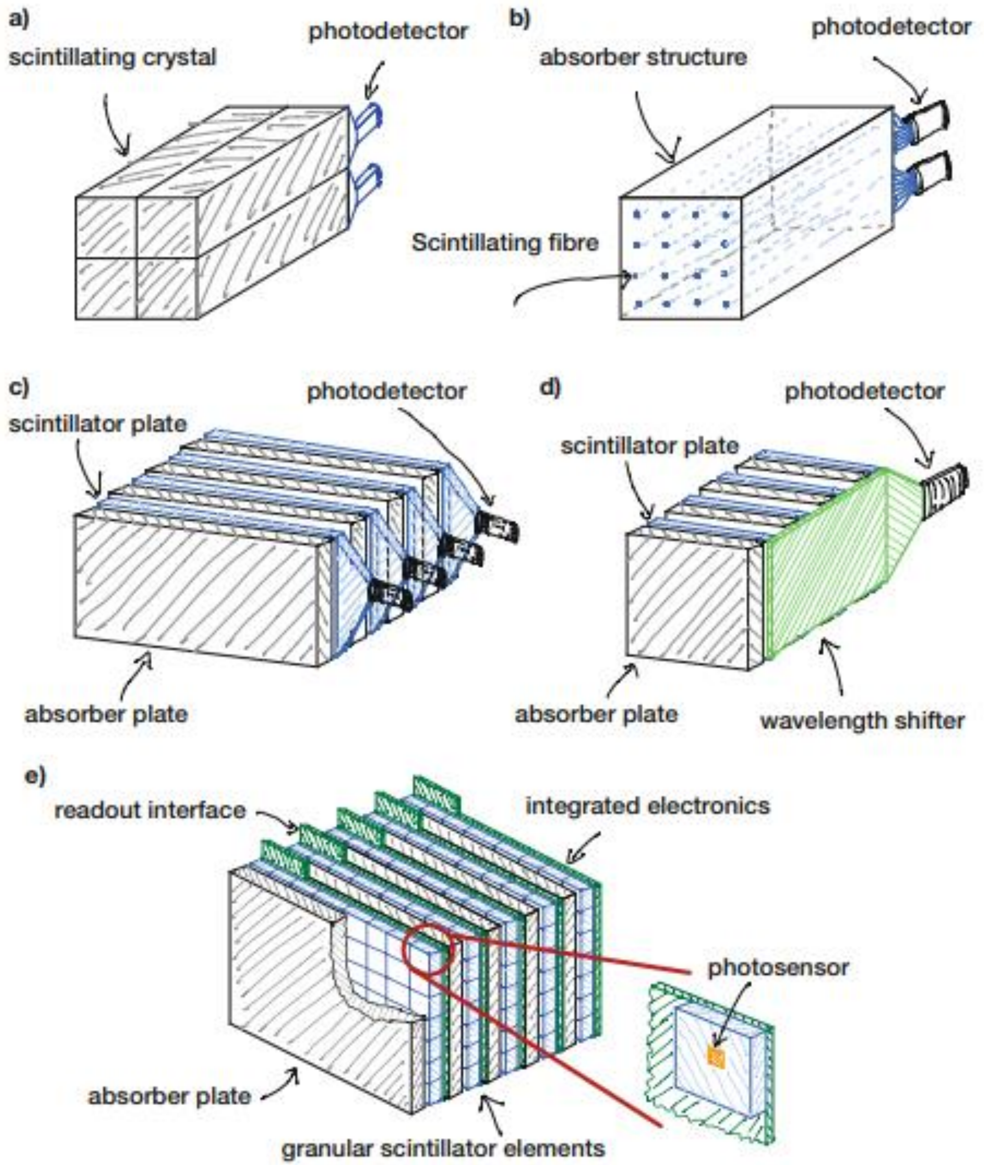
Summary: Calorimetric Performance

- Performance tied to resolution, granularity, timing.
- Tradeoffs between cost, complexity, and precision.
- Understanding measurement is key to using calorimeter data.

Calorimeter types

Calorimeter Classification Overview

- Homogeneous vs sampling calorimeters.
- Active vs passive media.
- EM vs hadronic calorimeters.
- Digital, analog, dual-readout distinctions.

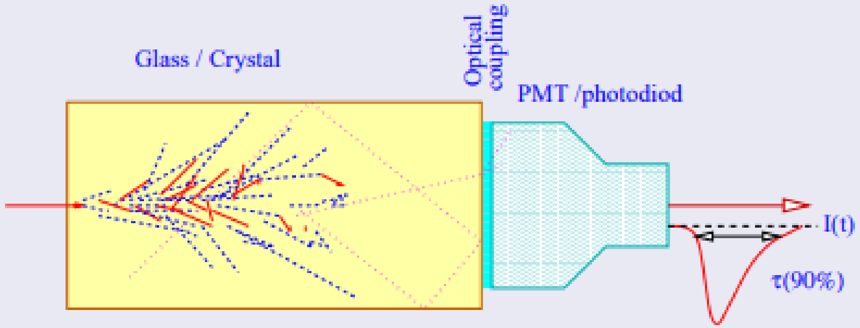


Homogeneous Calorimeters

- Entire volume is sensitive (e.g., crystals).
- Excellent energy resolution.
- Expensive, limited scalability.
- Example: CMS ECAL ($PbWO_4$ crystals).

Heavy active material, no passive absorber

- Best energy resolution
- Higher cost

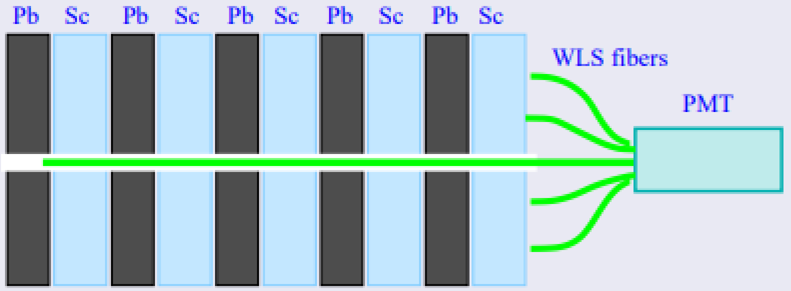


Sampling calorimeters

- Alternating layers of absorber and active material.
- Widely used in hadronic calorimetry.
- Lower resolution but scalable and affordable.
- Example: ATLAS Tile Calorimeter.

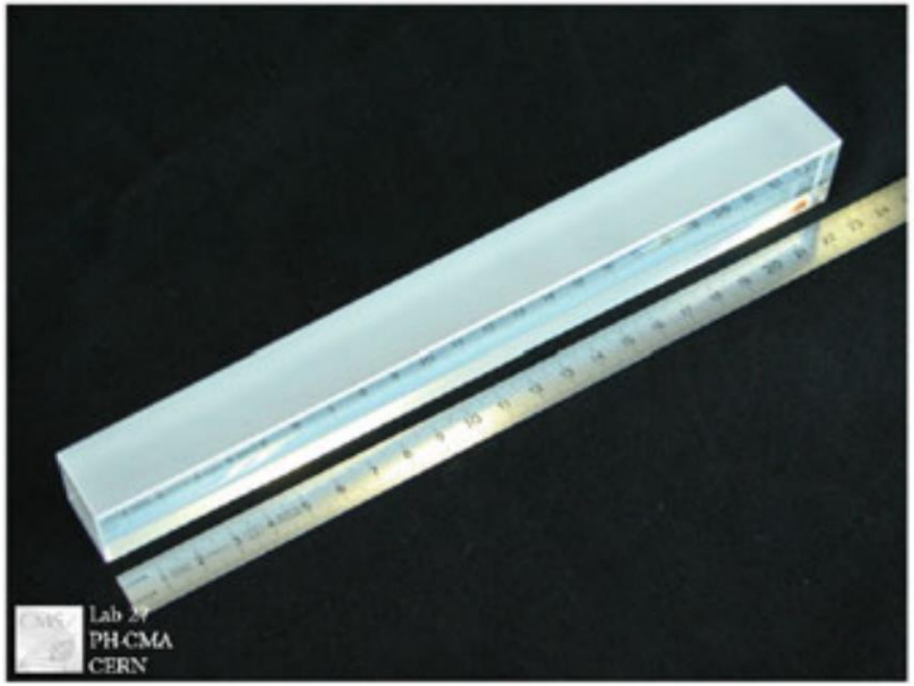
Heavy material absorber and the active material are interleaved.
Features:

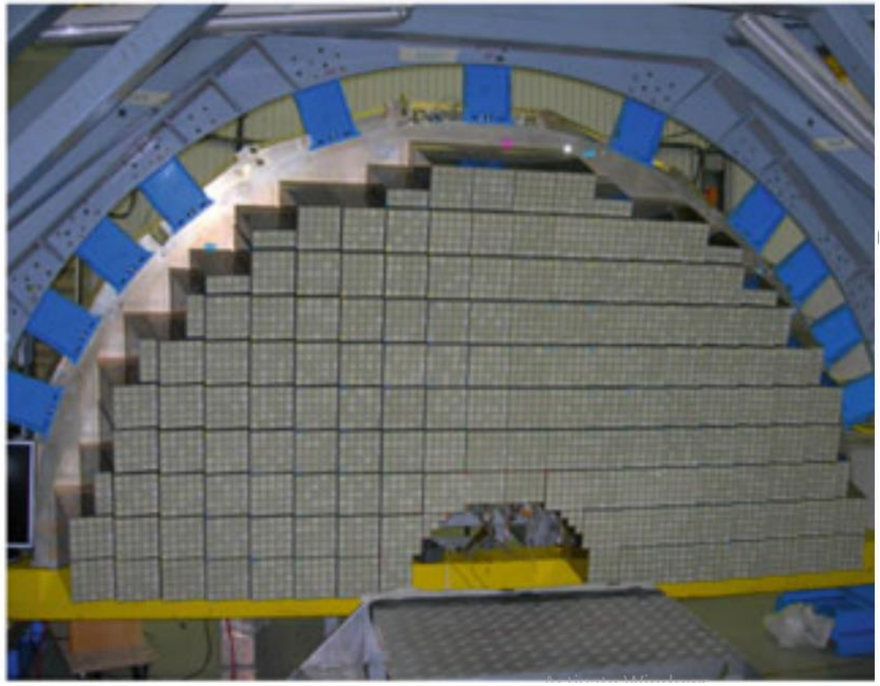
- Compact
- Relatively cheap
- Sampling fluctuations ⇒ impact on $\frac{\sigma E}{E}$



Scintillating calorimeters

- Use plastic or inorganic scintillators.
- Emit light when particles deposit energy.
- Read out by PMTs or SiPMs.
- High light yield and fast response.

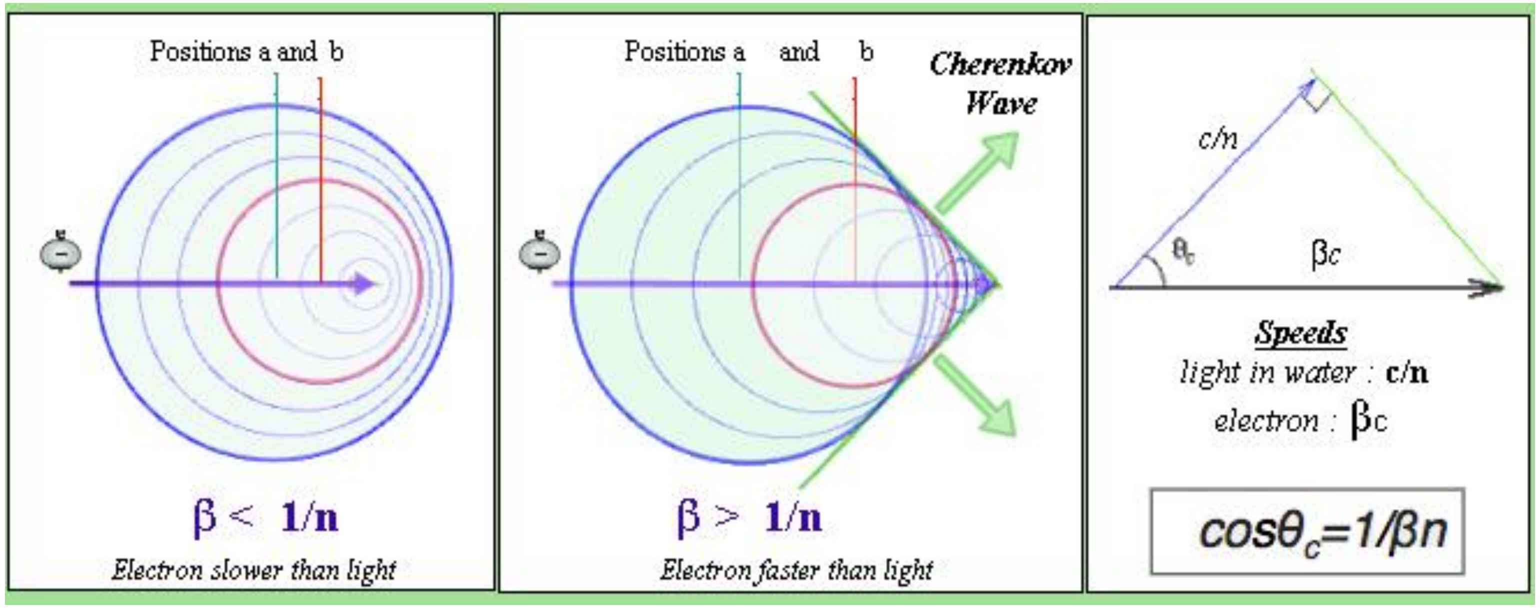




CMS EM Calorimeter

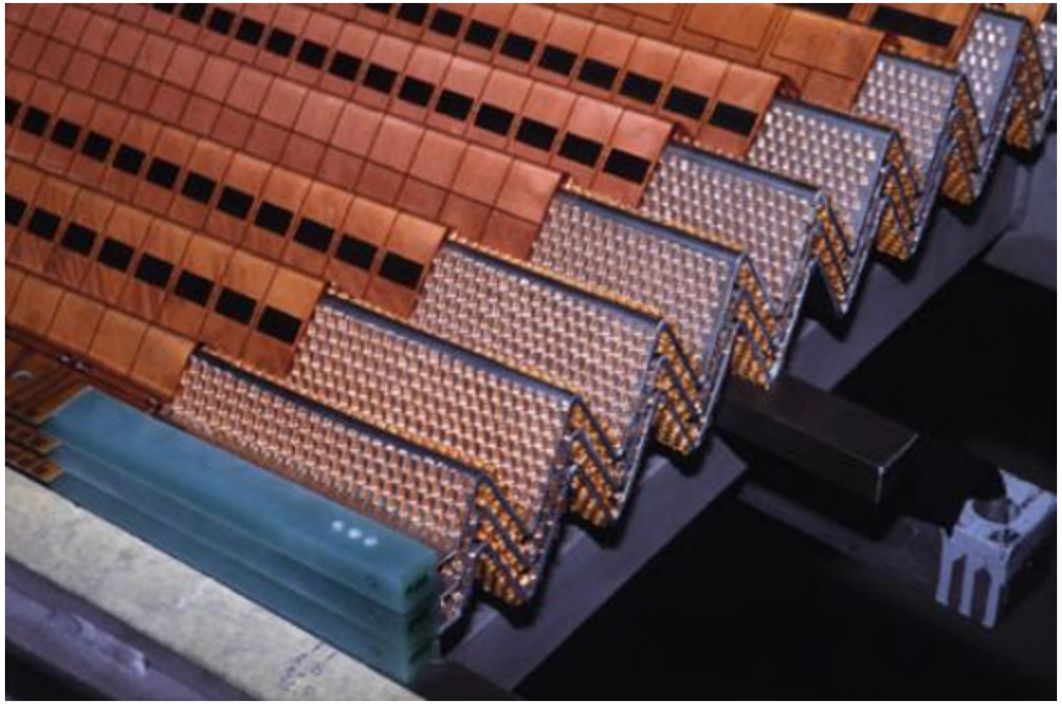
Cherenkov-Based Calorimeters

- Use fast Cherenkov light from charged particles.
- Materials: quartz fibers, lead glass.
- **Intrinsically fast, low light yield.**
- Used in dual-readout systems.



Liquid Argon Calorimeters

- Use ionization in cryogenic LAr as signal.
- Excellent linearity, stable over time.
- Used in ATLAS EM calorimeter.
- Requires cryogenic systems.



Sampling structure of the ATLAS liquid argon EM calorimeter, showing the accordion-shaped lead absorber sheets, spacers for the argon gaps, and the pick-up electrodes

- PMTs: traditional, large, high gain.
- SiPMs: compact, magnetic field resistant.
- Coupling via fibers or direct contact.

Photomultiplier Tubes (PMT)

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

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

Avalanche Photodiods (APD)

A silicon diod in avalanche mode and an electronic amplifier

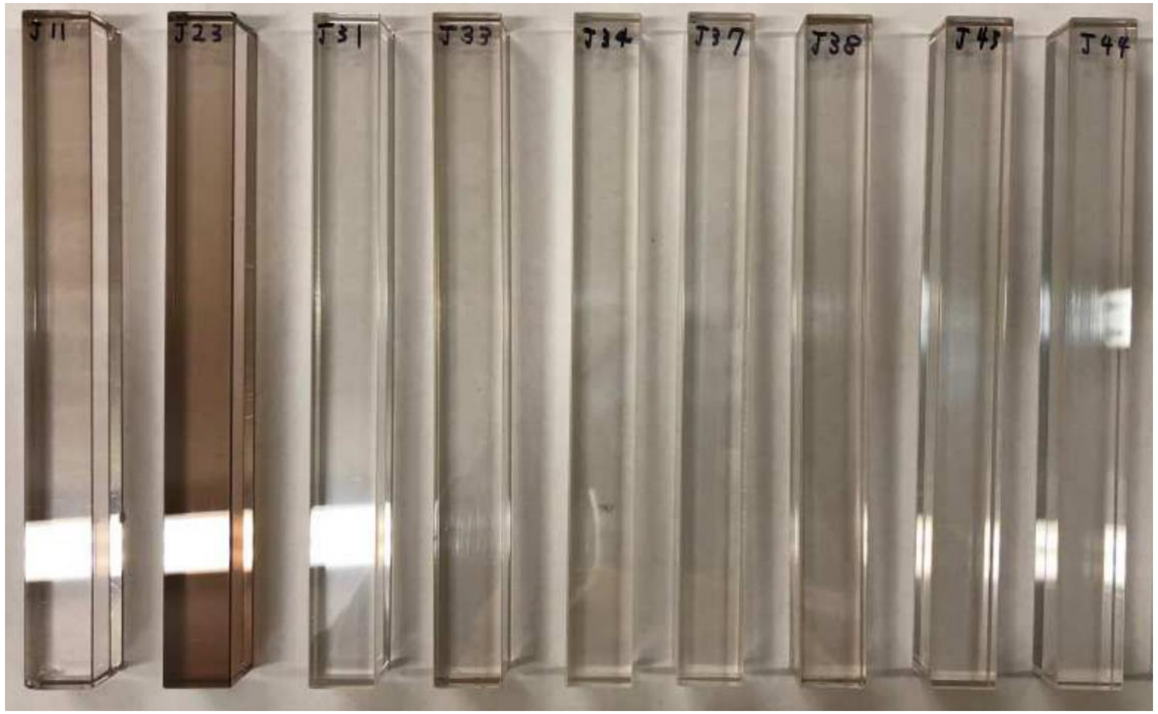
- Not sensitive to magnetic field
- High QE$\sim$75% at 430 nm
- • Gain $\sim 50 - 300$
- • High electronic noise
- • Size: 1×2 cm^2
- • Sensitve to the bias voltage
- • Temperature sensitive -2%/K
- • Radiation hardness may be a problem

Silicon Photomultiplier (SiPM)

- Not sensitive to magnetic field
- High gain $\sim 10^6$
- • Radiation hardness
- • Non linear

Radiation Hardness Considerations

- Material and electronics degrade under high dose.
- LHC environments demand long-term tolerance.
- Si, LYSO, and LAr show good performance.



Design considerations

- Full angular coverage needed for MET
- Gaps between modules affect performance.
- Overlap and modularity design considerations.
- Balance cost, resolution, and mechanical constraints.
- Tailored to experiment: e.g., ILC vs LHC.
- Tradeoffs: depth vs granularity, speed vs signal.

Simulations play a crucial role in calorimeter design

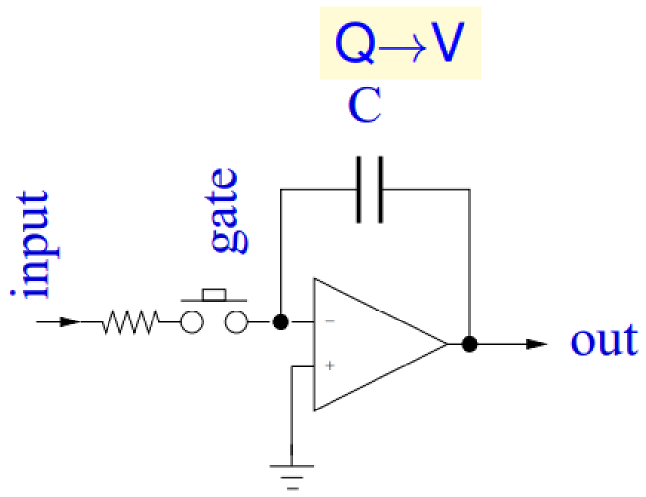
Front-end electronics

Requirements

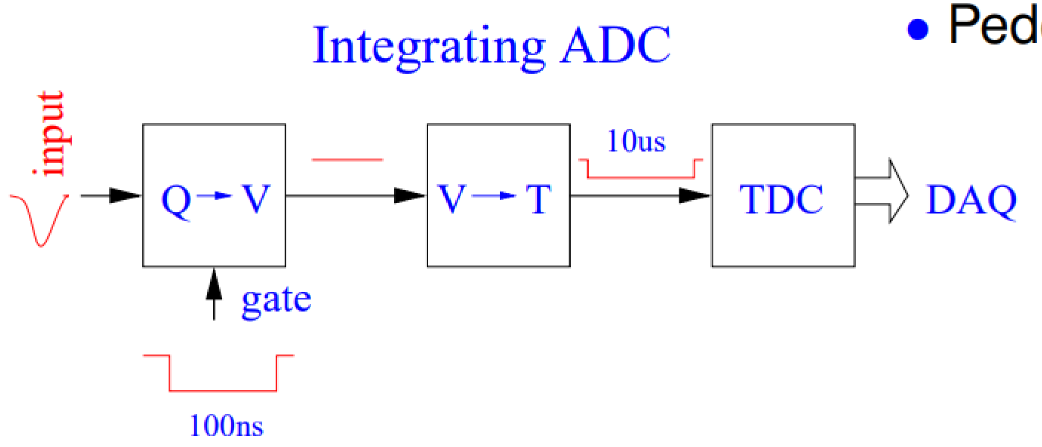
- Resolution $\sim 10^{-3}$
- Dynamic range $> 10^2$: needed to measure the shower profile and the coordinates
- Differential linearity $<$1%
- Digitization speed ($>$1 MHz)
- Readout speed ($>$100 kHz)
- Cost

Existing generic solutions

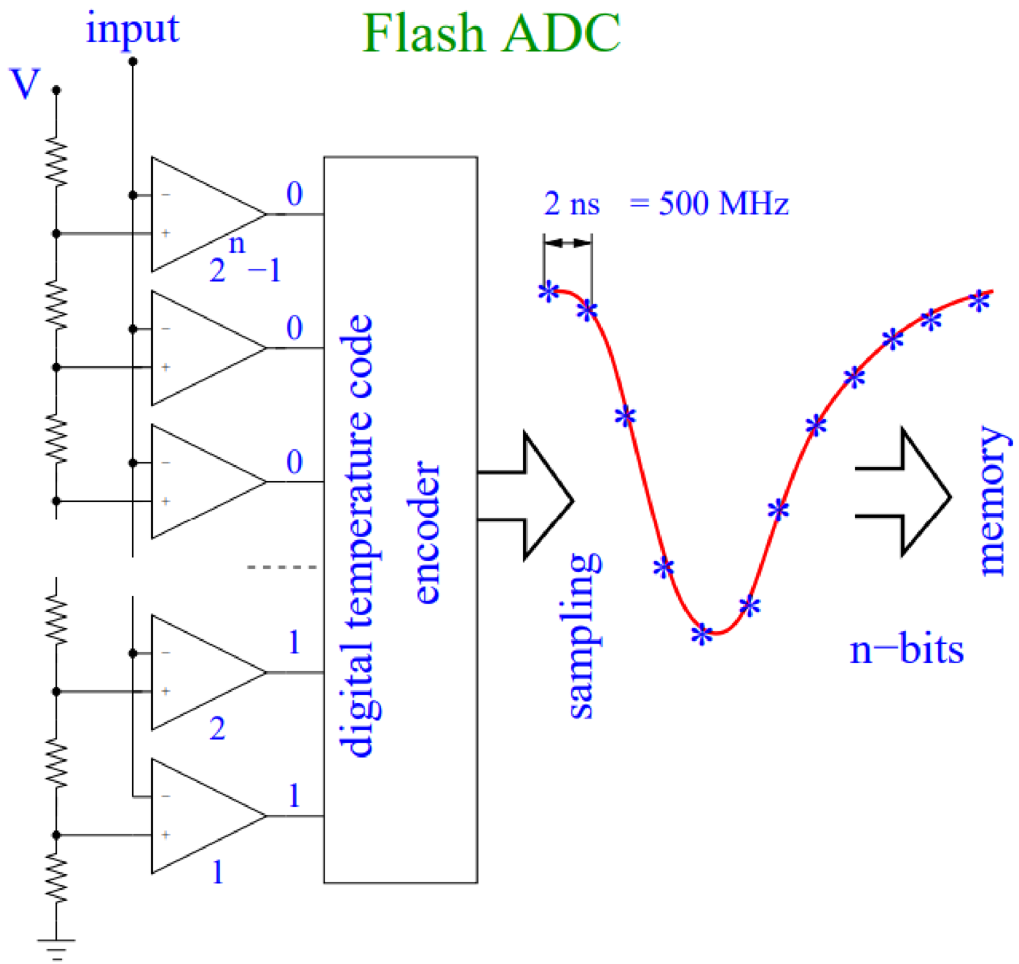
- Charge integrating ADC
- Flash ADC
- Combinations (pipeline ADC)



- Many products on the market
- Precise: 12-15 bits
- Gate must come in time ⇒ 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



Flash ADC



- Cost ×10 of the QDC (250 MHz, 12 bits)
- Huge memory buffers needed
- Resolution n bits ⇒ 2^n comparators
- Pipeline readout - no dead time
- No delay cables needed
- Pileup can be partially resolved
- Timing resolution without extra discr.& TDCs
- FPGA computing - trigger logic
- Became the mainstream

JLab: 12 bit fADC-250MHz, 16ch in a VXS/VME module

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 luminosity)
  - $h+h \to \pi^0+X$, $\pi^0 \to \gamma\gamma$
  - RCS (JLab): $e^-p \to e^-p$

Procedure: for event n:

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

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

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

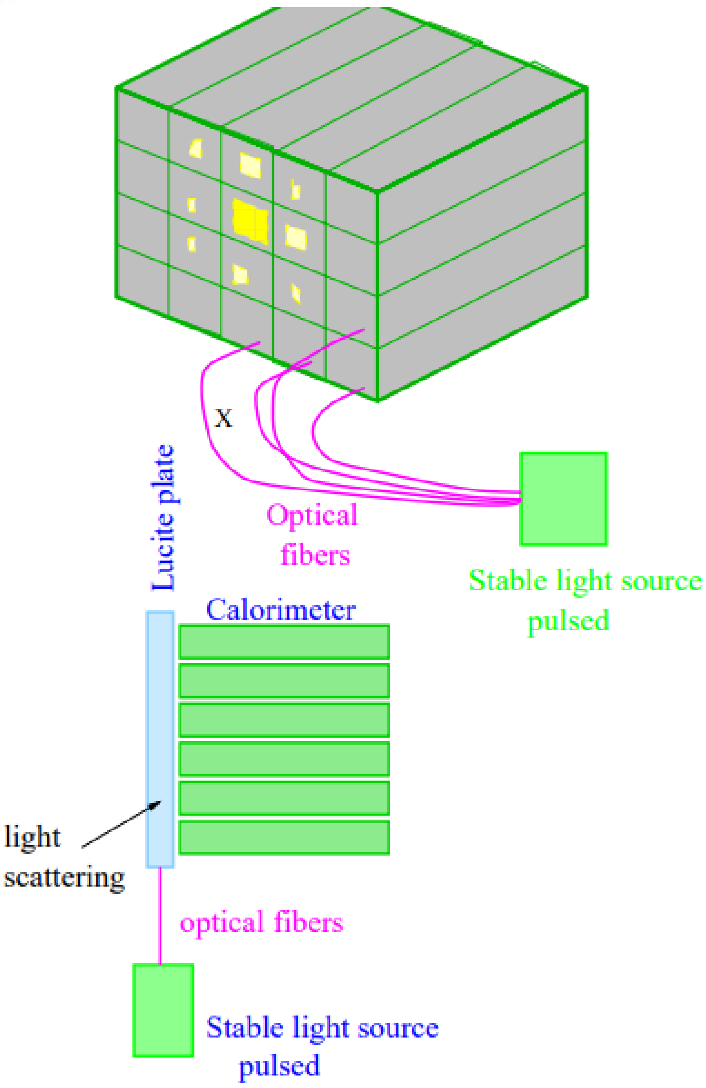
Detector response monitoring

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.

Monitoring systems



- Stable pulsed light source:
  - Xe flash lamp: 1% stability, >100 ns pulse
  - Laser: 2-5% stability, ≪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: calorimeter technologies

- Broad range of designs tailored to physics goals.
- No “best” calorimeter — depends on application.
- Advances driven by materials, electronics, computing.