Calorimetry in HEP

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esi European Scientific Institute
esipap European School of Instrumentation in Particle & Astroparticle Physics
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l'X ÉCOLE POLYTECHNIQUE
IP PARIS

Lecture plan

- What is calorimeter in HEP?
- Electromagnetic and hadronic showers
- Detection techniques
- Calorimeter response & resolution
- Electronics readout and trigger
- Energy reconstruction & calibration
- Beyond calorimetry: Particle Flow
- An example: CMS HGCAL

Reference

- The following lecture was built upon several lectures and books
- Lectures
  - C. Ochando, *Lectures on Calorimetry*, ESIPAP 2019
  - I. Wingerter-Seez, *Calorimetry: Concepts and Examples*, ESIPAP 2016
  - E. Garutti, *The art of calorimetry*
  - R. Wigmans, *Calorimetry*, EDIT 2011
  - V. Boudry, *La Calorimetrie*, Ecole du detecteur a la mesure 2013
  - D. Cockerill, *Introduction to Calorimeters*, Southampton Lecture 2016
  - A. Zabi, *Instrumentation for High Energy Physics*, TES-HEP 2016
  - P. Janot, *Particle-Flow event reconstruction from LEP to LHC*, EDIT 2011
- Books
  - R. Wigmans, *Calorimetry, Energy measurement in Particle Physics*, Oxford science publication
  - C. Gruppen & B. Shwartz, *Particle detectors*, Cambridge monographs on particle physics, nuclear physics and cosmology

A few words about myself

- Physicist at the Laboratoire Leprince-Ringuet
  - Located at the Ecole polytechnique, in the south of Paris
- PhD thesis in ATLAS during the LHC Run 1 data taking period
  - Jet energy calibration
  - Z+jets cross section measurements
- In CMS since 2012
  - Higgs measurements ($H \rightarrow ZZ^* \rightarrow$ 4 leptons, $H \rightarrow \tau\tau$)
  - Electron energy reconstruction
  - Phase 1 calorimeter trigger upgrade
  - High Granularity Calorimeter (CMS endcap calorimeter Phase 2 upgrade)

Lecture plan

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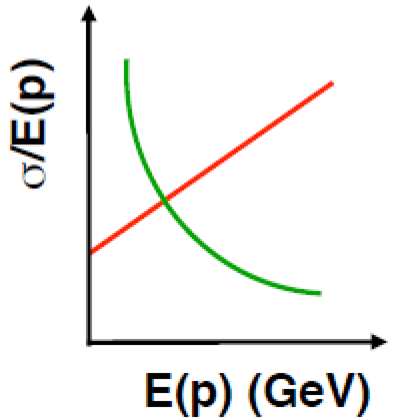
What is a calorimeter (in HEP)?

- Originally a "calorimeter" is an instrument measuring heat ("calor" in latin) produced by some reactions (chemical or physical)
  - In HEP it is quite different
- Detection of particles through **total absorption** in a block of matter
- Complementary to tracking detectors
  - Trackers measures charged particle bending
  - Calorimeters **measure absorbed energy**

Resolution



Tracking

$$\frac{\sigma(p)}{p} = ap \oplus b$$

Calorimetry

$$\frac{\sigma(E)}{E} \approx \frac{a}{\sqrt{E}}$$

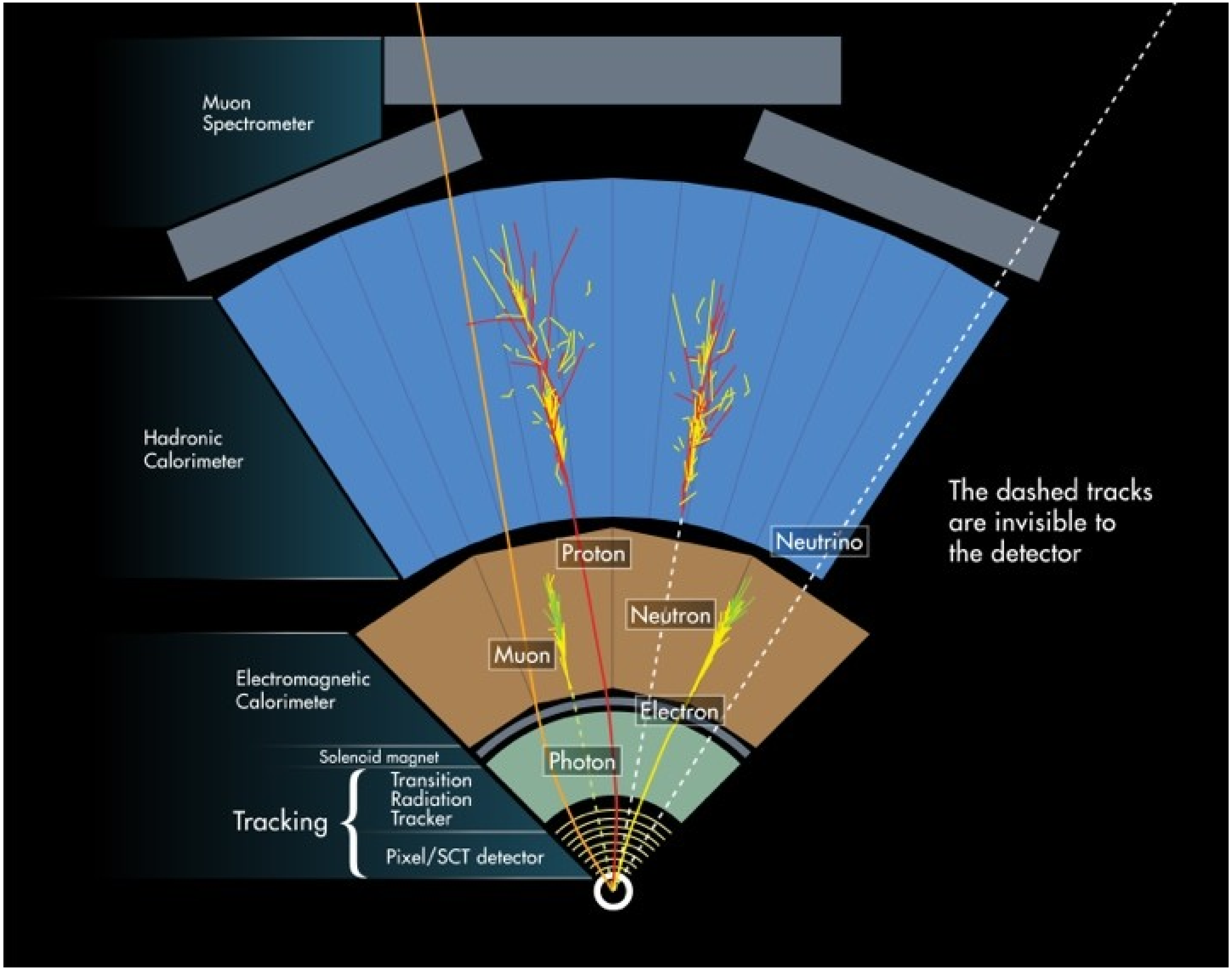
- Calorimeters can **measure both charged and neutrals**

Typical HEP detectors

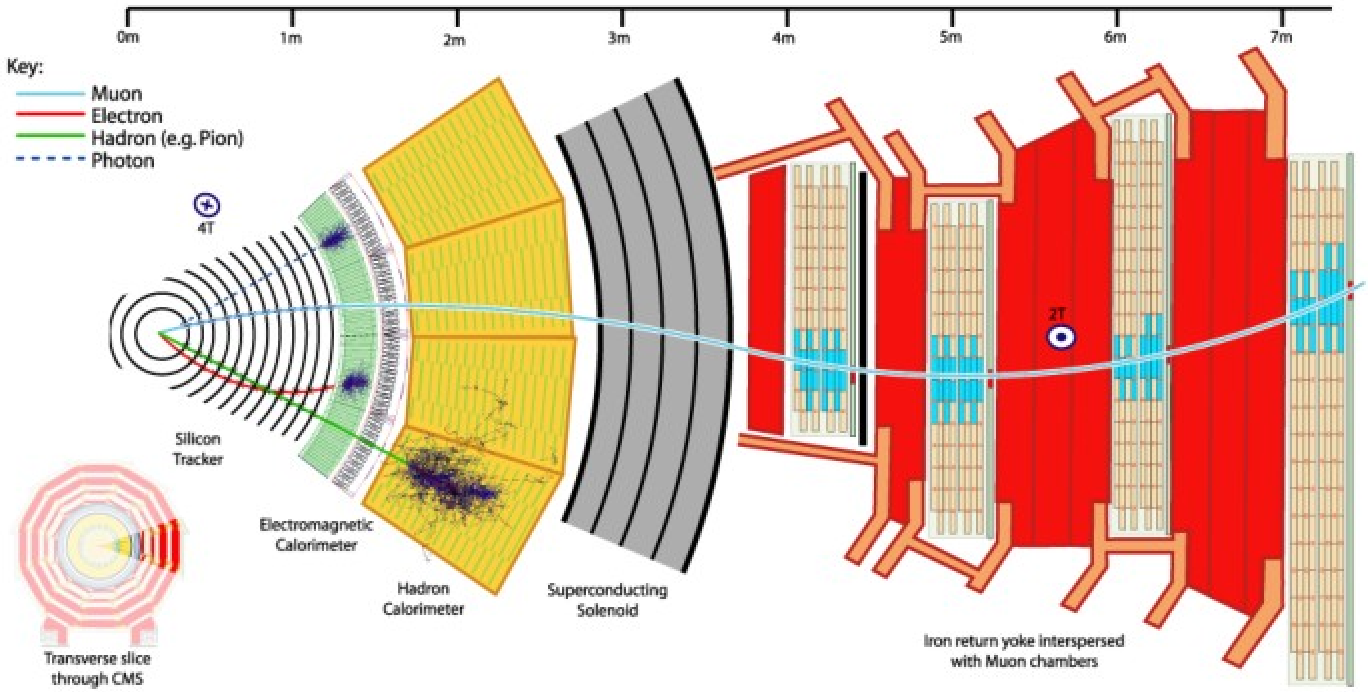
Muon spectrometer

Calorimeters

Trackers



CMS ECAL



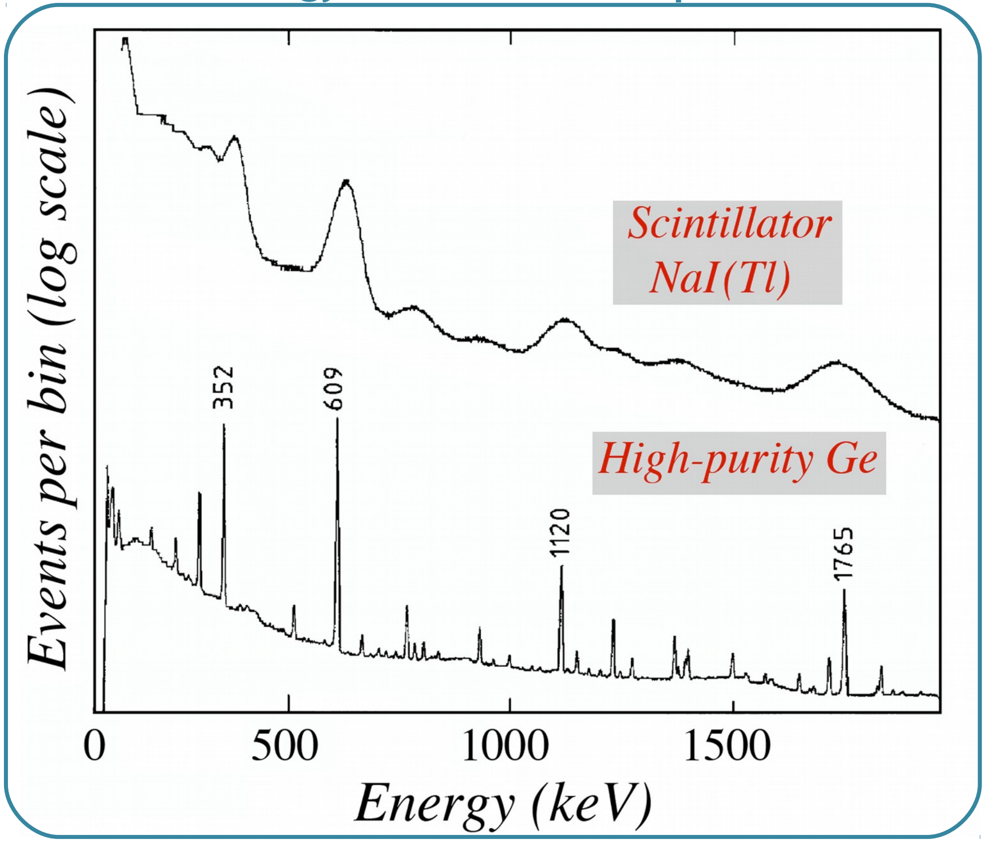
- CMS: typical Onion-like detector structure
  - Tracking + magnet (curvature of charged particles)
  - EM and hadronic calorimeters
- CMS ECAL
  - Scintillating crystals + photodiodes

CMS ECAL module

Back to the origins: Nuclear radiation detectors

- Late 40's
  - **Scintillating crystals** + Photomultiplier tubes (PMT)
  - First calorimeters used in the detection of nuclear decays (α, β, γ)
- In the 60's
  - First **semiconductor detectors** (silicon and germanium)

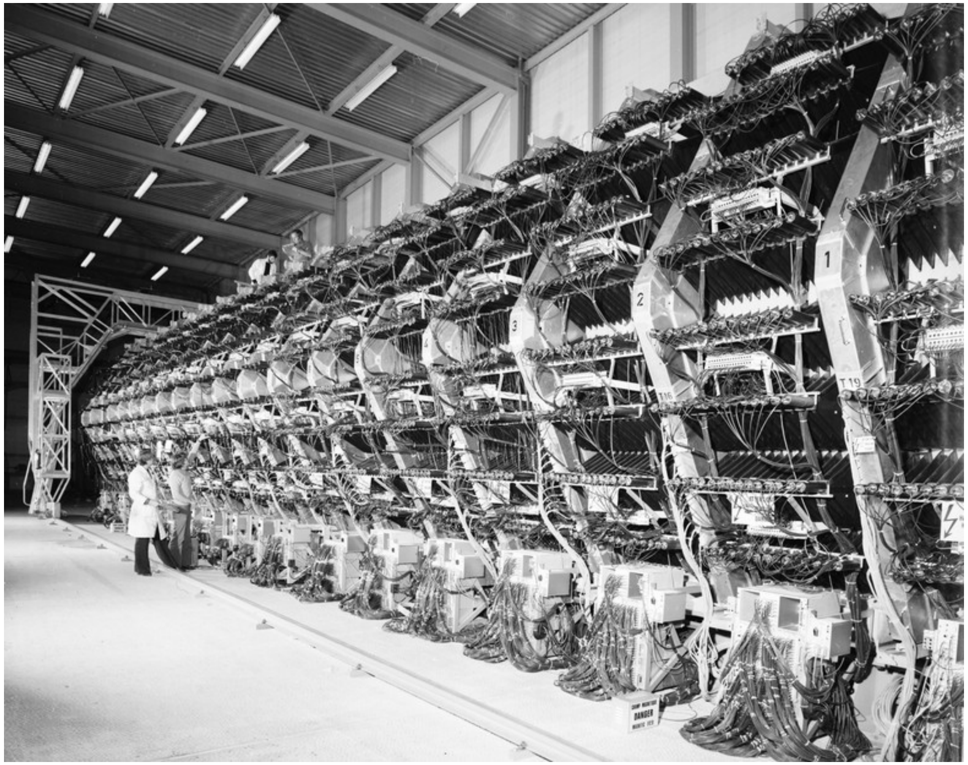
Energy resolution is important



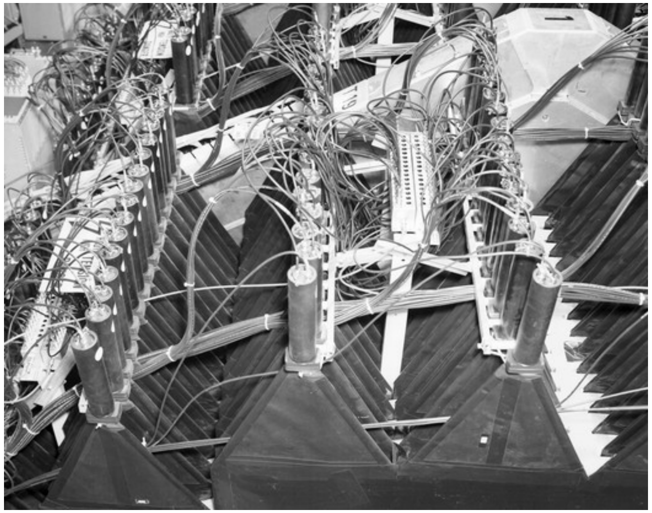
Neutrino experiments at SPS (CERN)

- In the 70's – 80's
  - Deep inelastic **neutrino interactions**
  - Weakly interacting
  - Instrumented mass of ~1 kTon
  - Intense beams
- WA1
  - Slabs of (magnetized) **Iron**
  - Interleaved with **plastic scintillators**
  - + wire chambers in the rear to track muons

WA1 experiment



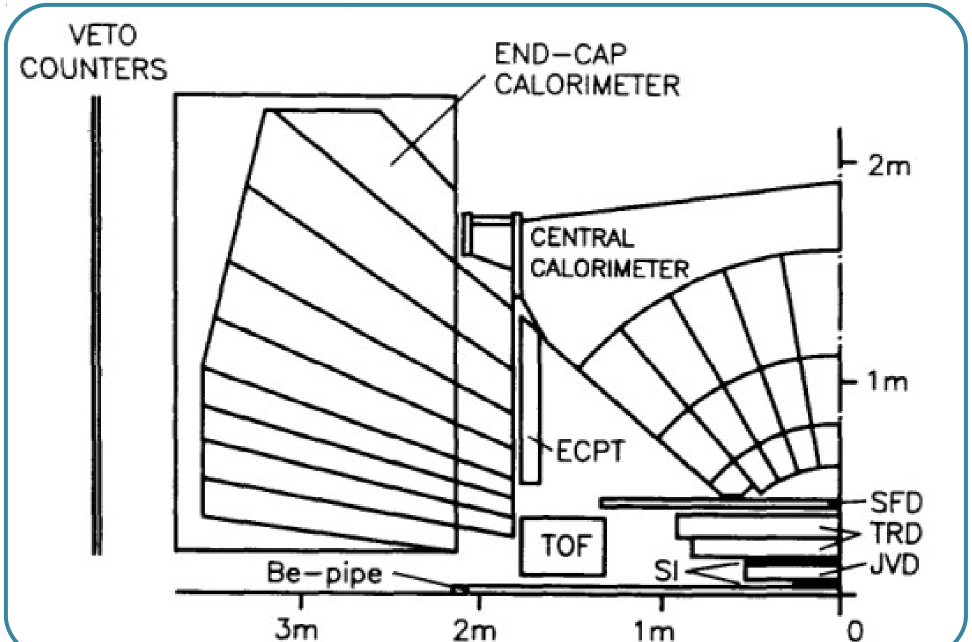
Scintillators + PMT



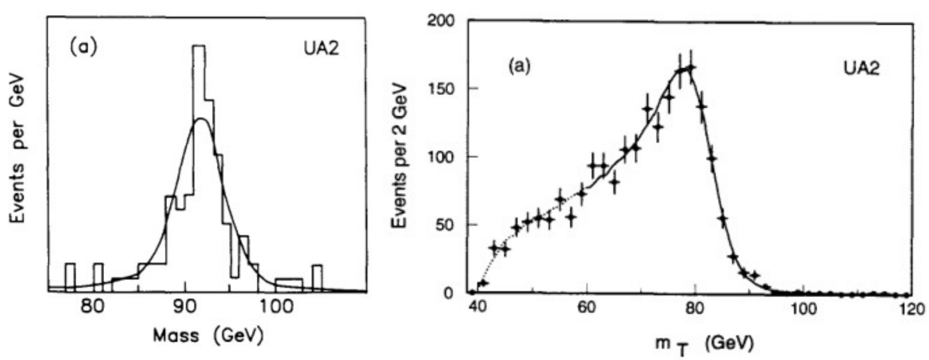
- UA1 & UA2 = Experiments at the SppS (CERN)
- UA2 (1981-1990)
  - More focused on calorimetry
  - Lead (or Iron) + scintillator
- Discovery of the W and Z bosons

UA2 detector

UA2 cross-section

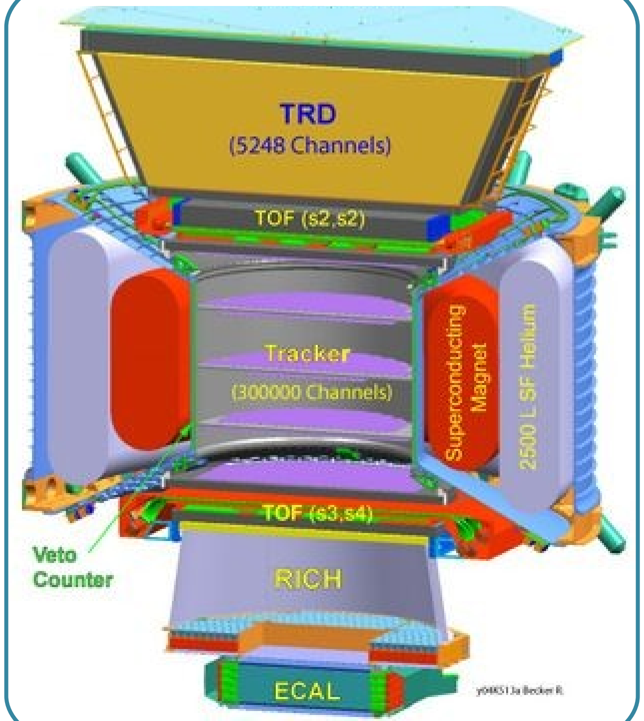


Z mass & W transverse mass

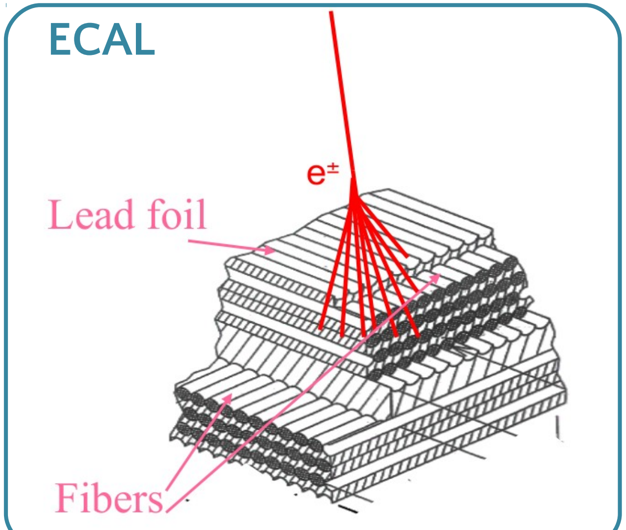


AMS

AMS cross-section

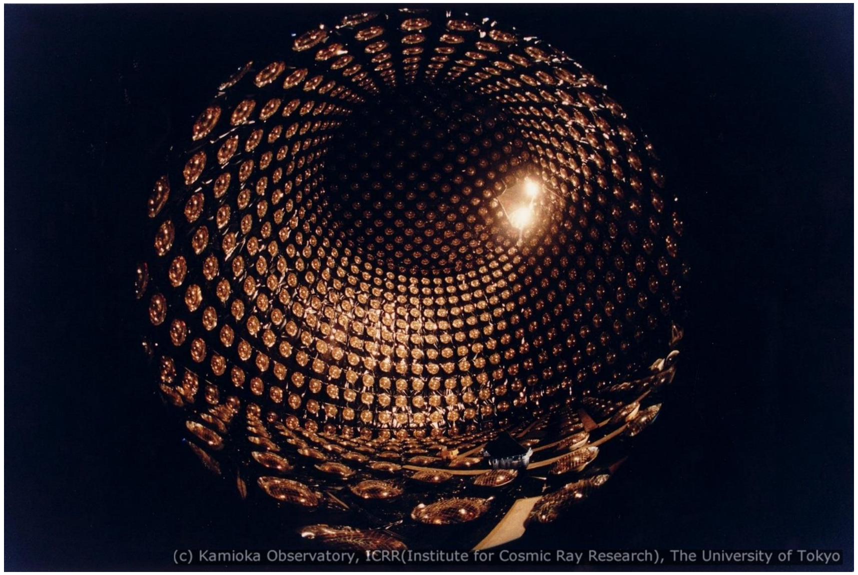


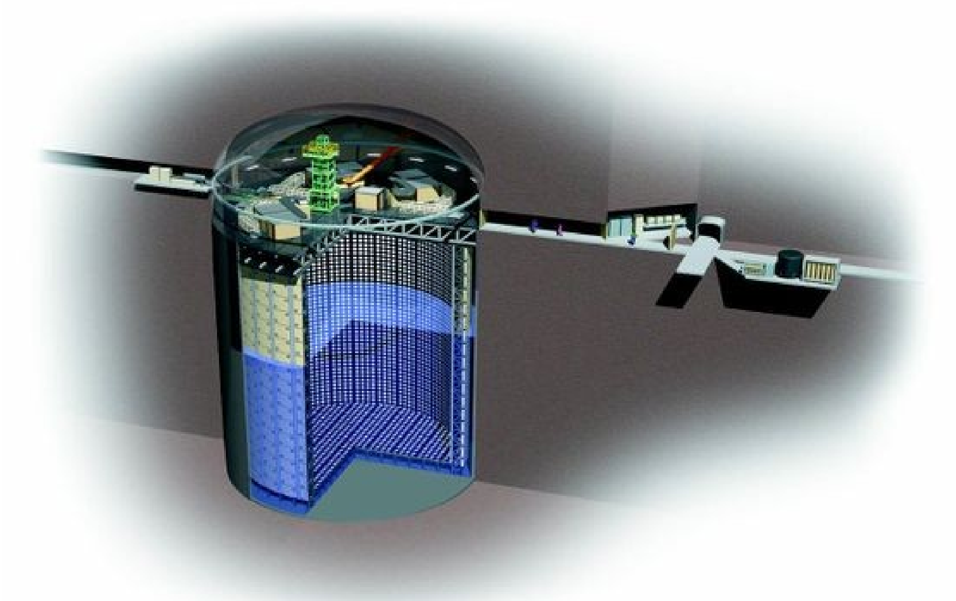
- AMS: experiment on the International Space Station
- Search presence of **antimatter and dark matter**
- Electromagnetic calorimeter
  - Measure high energy electrons/positrons
  - Discriminate against protons



(Super-)Kamiokande

Super-Kamiokande





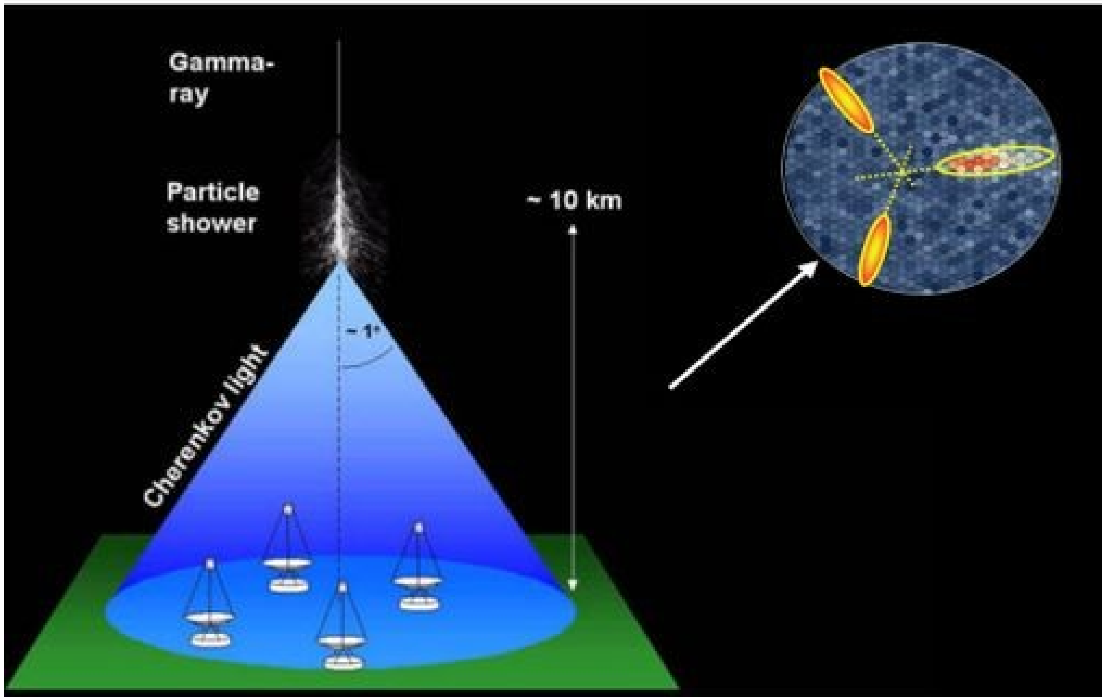
- Water tank (> 2140 t) placed in underground mine
- Surrounded by 1k photomultipliers
- Scattering of neutrinos with electron or nuclei of water → Cerenkov light
- 1990's:
  - Measurement of solar neutrinos flux deficit
- Followed by Super-Kamiokande
  - Discovery of **neutrino oscillation**

Large PMT

The 5 HESS telescopes

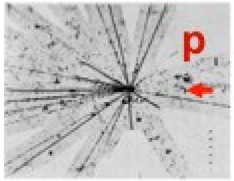
- Explore cosmic gamma rays
  - Interaction with the **atmosphere**
  - Emission of **Cerenkov light**
- Telescopes record this Cerenkov light on the ground

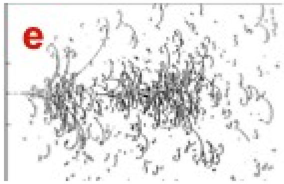
Detection principles



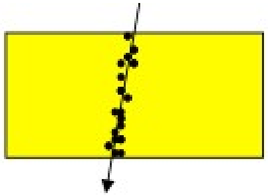
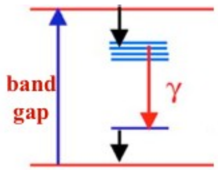
Calorimeter: principles

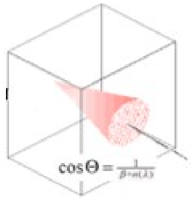
Particles interact with matter
Depends on particle and material



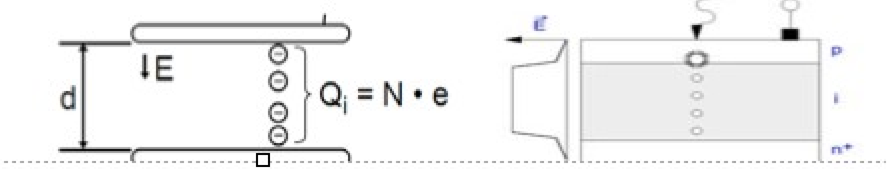


Energy lost transferred to detectable signal
Light, electric signal, etc.

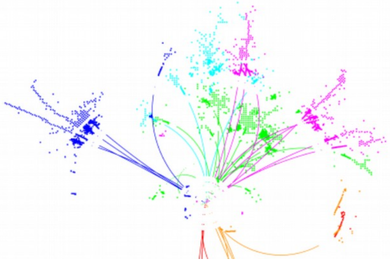





Signal collected and acquired
In the end: digitized signal



Calibration and reconstruction
Infer initial particle energy, position and type



Everything together
Build an experimental setup
Many constraints to be satisfied

Lecture plan

What is a calorimeter in HEP?

Detection techniques

Electronics readout and trigger

Beyond calorimetry: Particle Flow

Electromagnetic and hadronic showers

Calorimeter response & resolution

Energy reconstruction & calibration

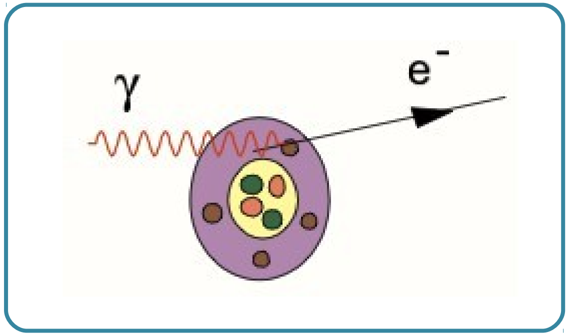
An example: CMS HGCAL

Electromagnetic interactions with matter

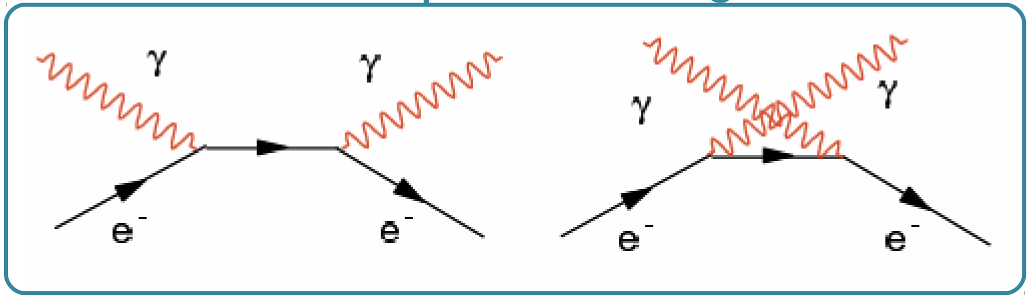
Photons | Electrons

Low energy

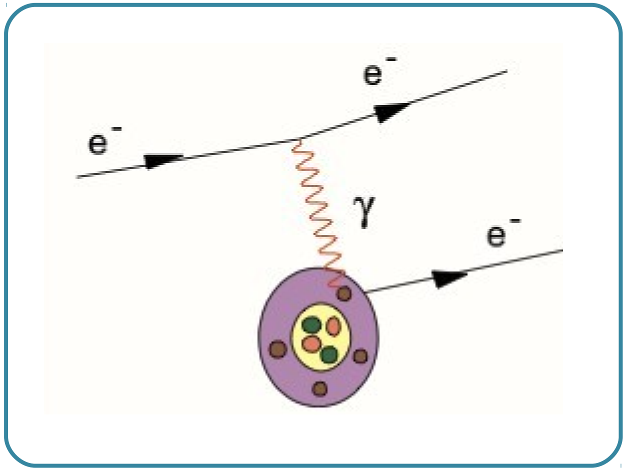
Photoelectric effect



Compton scattering

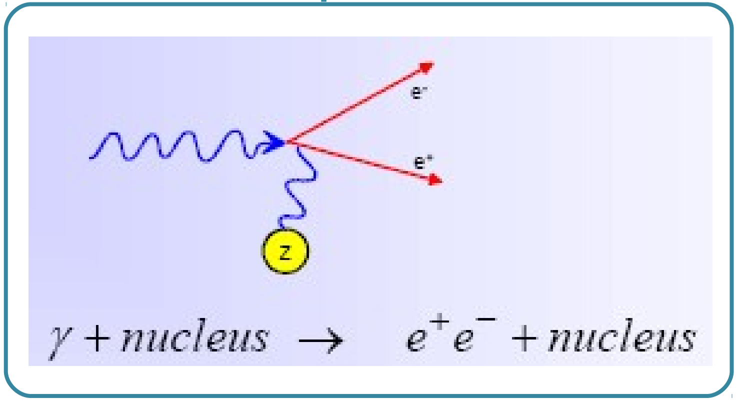


Ionisation

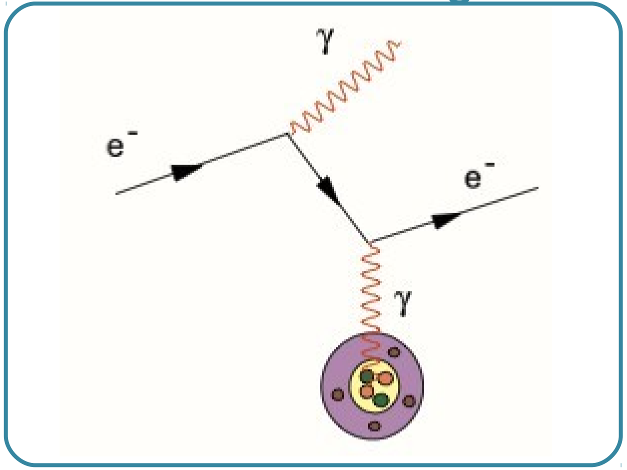


High energy

Pair production

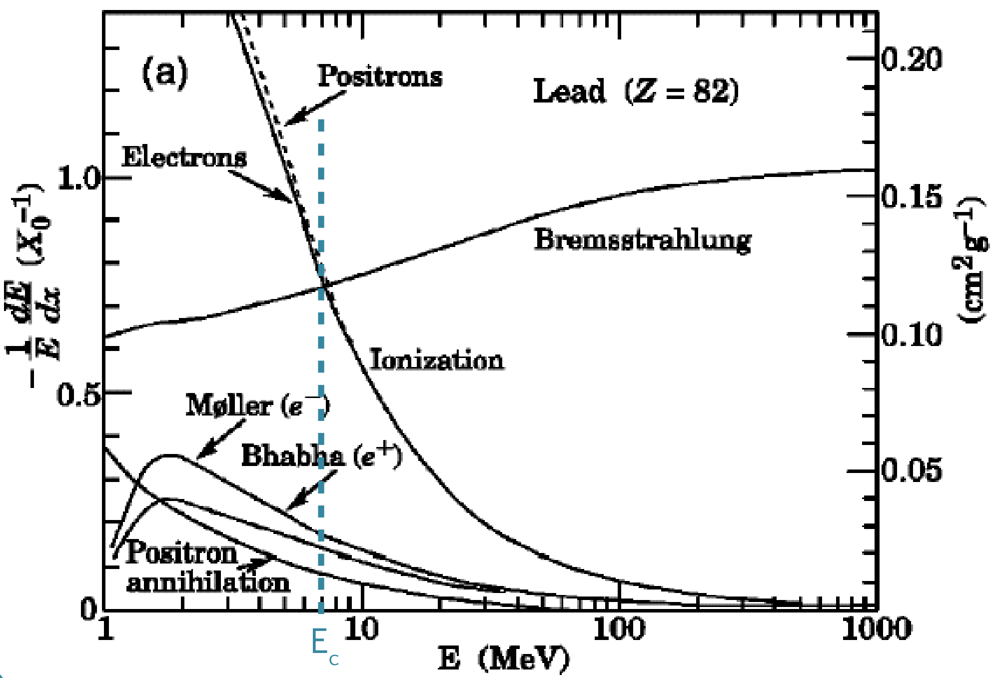


Bremsstrahlung

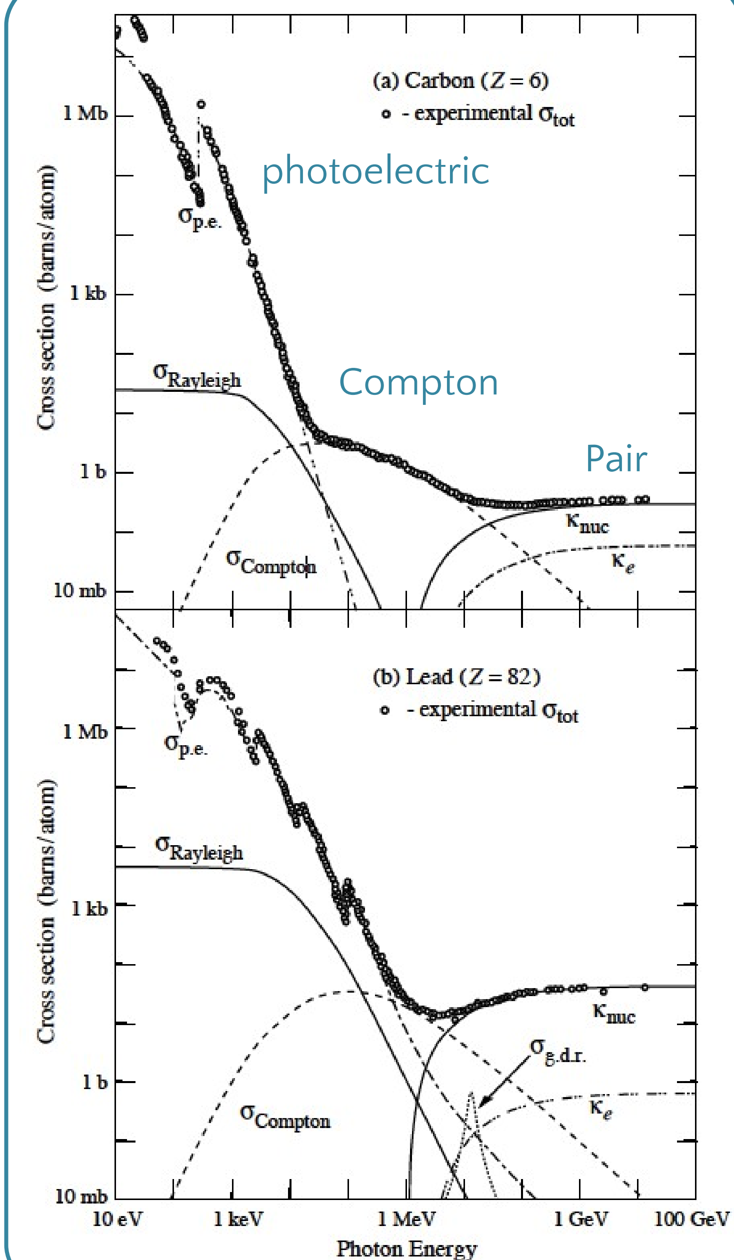


Dominant processes

Electrons



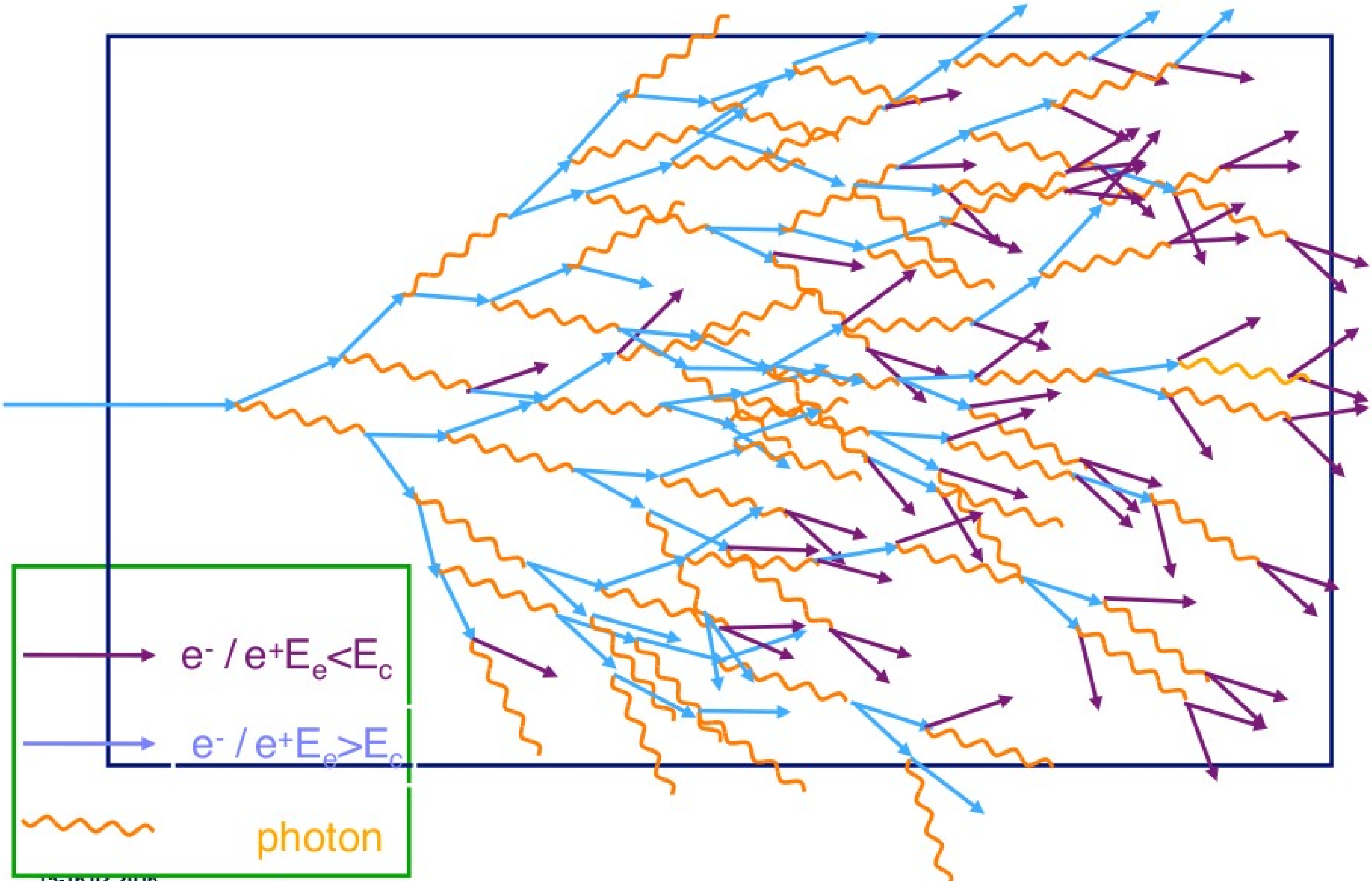
Photons



- High energy electrons: **Bremsstrahlung**
- High energy photons: **Pair creation**
- Below critical energy
  - Energy loss through **ionisation / excitation** of the medium

Shower development

- High energy particle creates a **cascade** of lower energy electrons and photons
  - Through bremsstrahlung and pair production
- When the **critical energy** is reached, secondary particles are slowly **stopped** (electrons) or **absorbed** (photons)



Energy loss and mean free path

Two dominant processes: Bremsstrahlung and pair production

Electron energy loss

$$-\left(\frac{dE}{dx}\right)_{rad}=\frac{E}{X_0}$$

$$E=E_0 e^{-x/X_0}$$

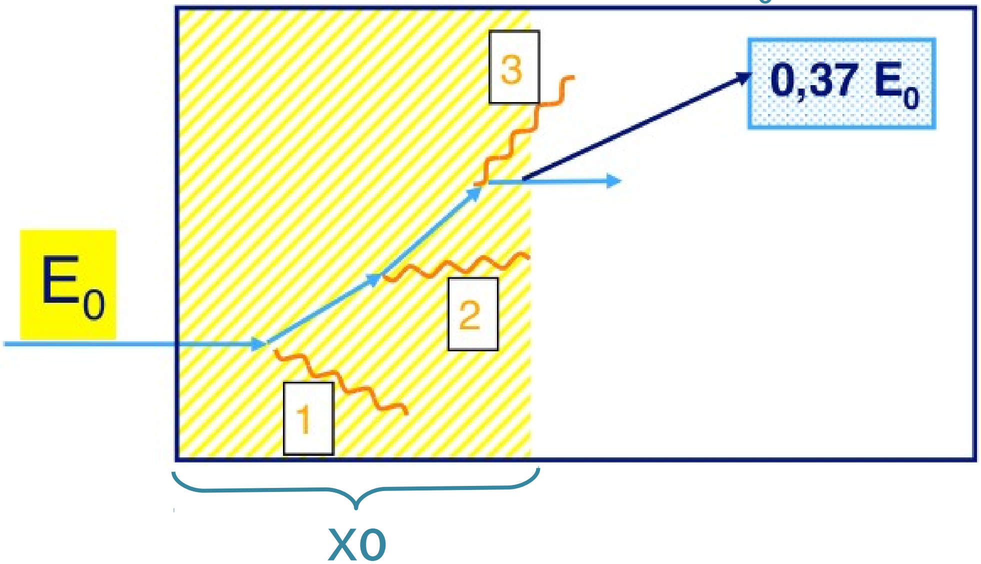
$$x(E_0/2)=X_0\ln(2)$$

Pair prod. probability

$$\frac{dw}{dx}=\frac{1}{\lambda_{pair}}e^{-x/\lambda_{pair}}$$

$$\lambda_{pair}=\frac{9}{7}X_0$$

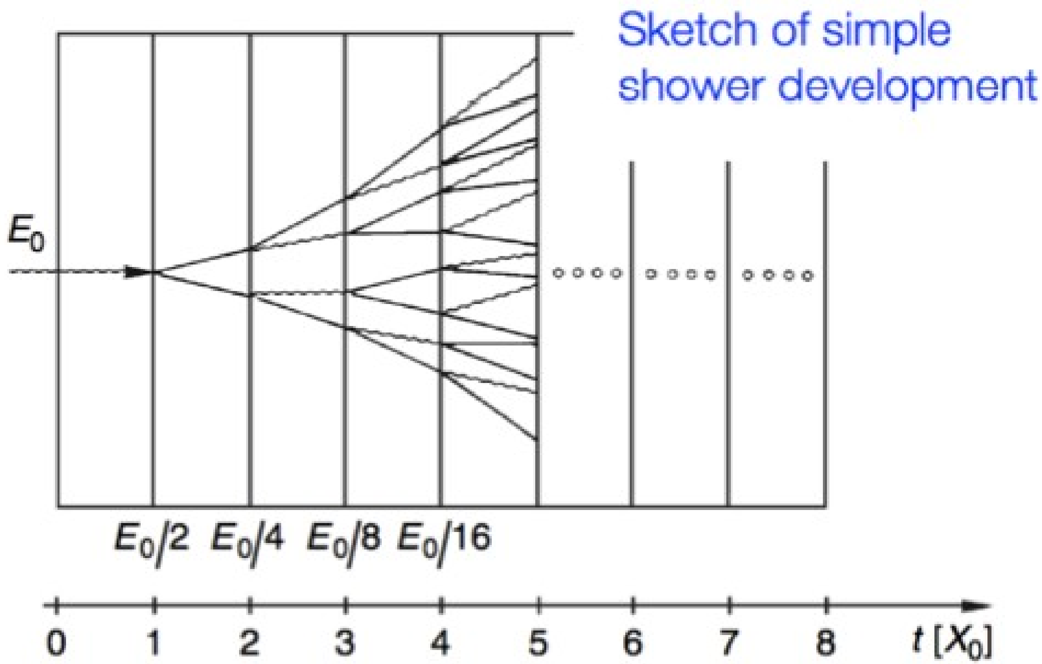
Radiation length X_0



- $X_0\approx\frac{180\,A}{Z^2}\,g.cm^{-2}$
- X_0 expressed in **cm or g.cm^{-2}**
  - Conversion between the two with the material density
- Electrons loose half of their energy in about **$2/3\times X_0$**
- Photons convert in about **$9/7\times X_0$**

Simplistic shower model

- $x(E_0/2)=X_0\ln(2)$ and $\lambda_{pair}=\frac{9}{7}X_0$, and the average roughly equals to X_0
- So we consider that, on average
  - One **particle duplication occurs every X_0** (e → eγ or γ→ ee)
  - With **equal sharing of energy** between the two produced particles
- Stops at the critical energy **$E = E_c$**
  - Reaches **maximum number of particles** = "shower maximum"



$t=x/X_0$

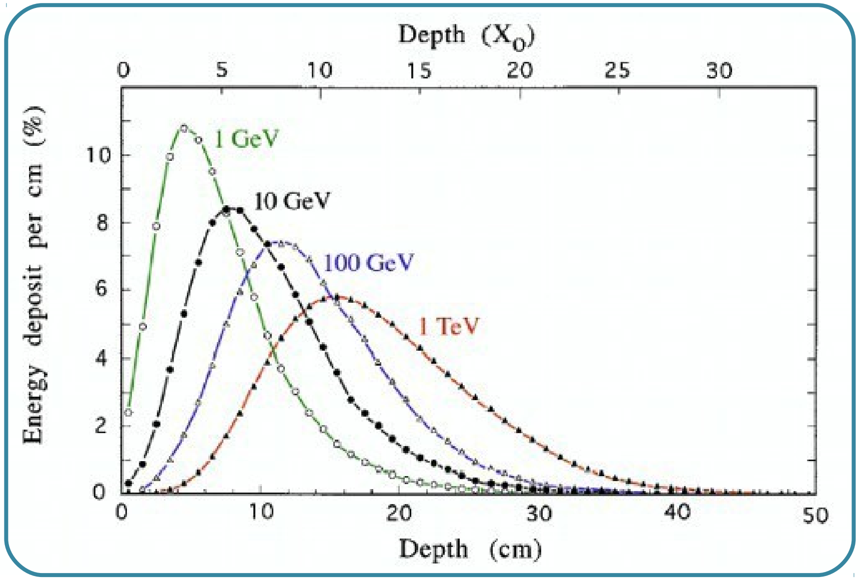
Some EM shower properties

- Number of particles proportional to the initial energy
  - Energy per particle after depth t: $E = E_0 \cdot 2^{-t}$
  - Shower maximum $t_{max} \propto \ln(E_0/E_c)$ (X_0 units)
- Shower lateral extent
  - Narrow core
    - Early stage of the shower
    - 90% of shower contained in "Moliere" radius

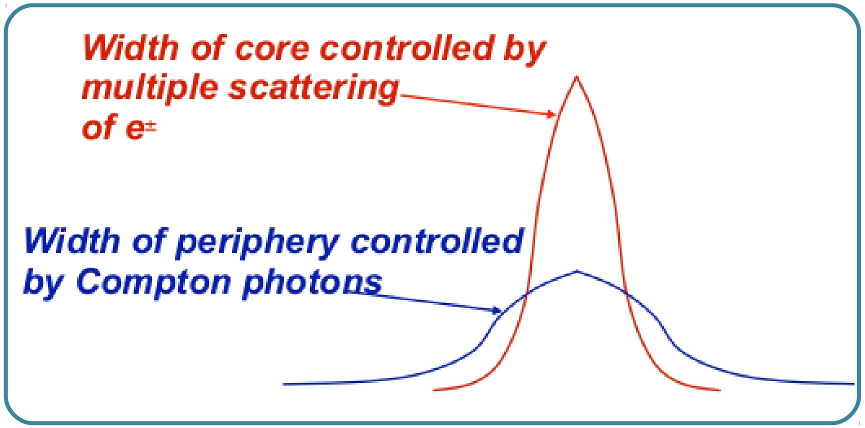
$$R_M = \frac{21\, MeV \times X_0}{E_c} \approx \frac{7\, A}{Z}\, g.cm^{-2}$$

  - Tails at larger angles
    - Isotropic Compton scattering
    - Beyond shower max

Longitudinal profile



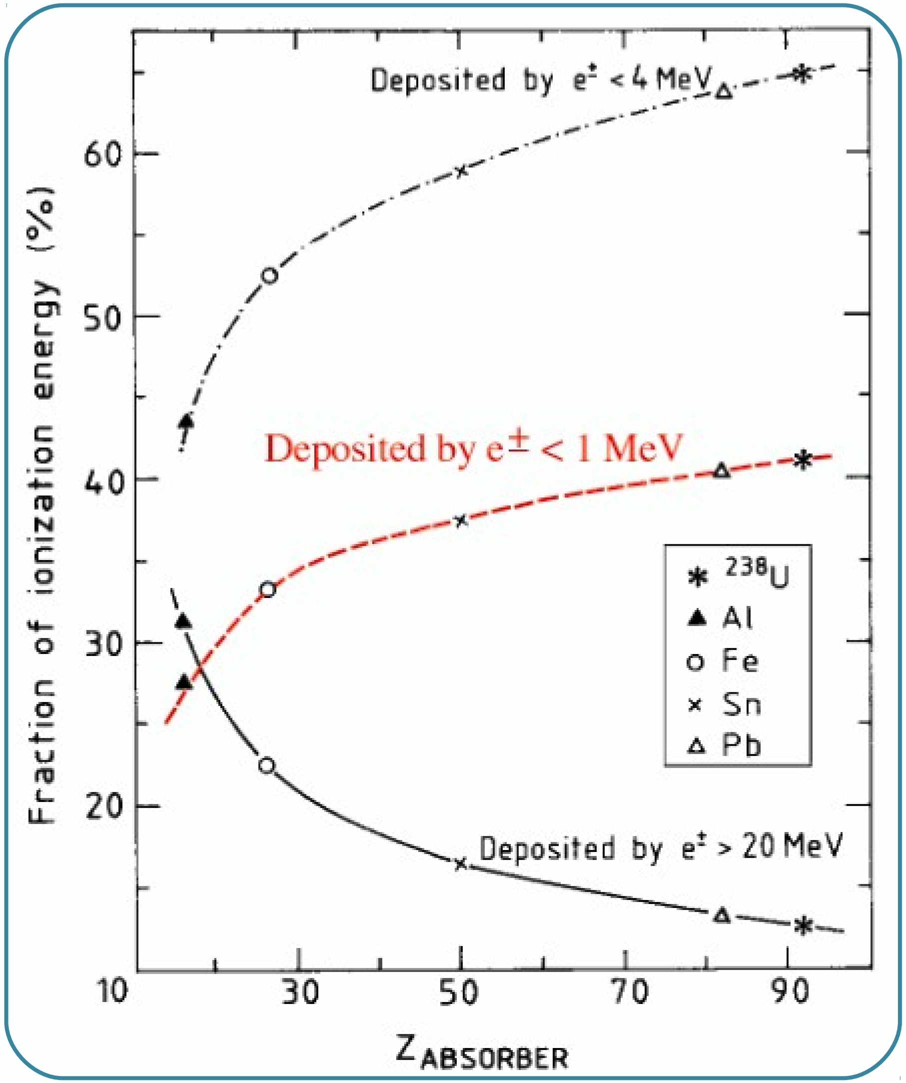
Lateral profile



Importance of low energy particles

- Shower development driven by high-energy particles
- But phenomena at **$E < E_c$ are important for calorimeter** properties
  - In lead 40% of the energy deposited by electrons < 1MeV

Fractions of deposited energy for 10 GeV EM showers



Useful quantities

- **Critical energy** for solids & liquids

$$E_c = \frac{610\,MeV}{Z+1.24}$$

- Critical energy for gaz

$$E_c = \frac{710\,MeV}{Z+0.92}$$

- **Radiation length** (approximate formulas)

$$X_0 \approx \frac{180\,A}{Z^2}\,g.cm^{-2}$$

$$X_0 \approx \frac{716.4\,A}{Z(Z+1)\ln(287/\sqrt{Z})}\,g.cm^{-2}$$

Compound:

$$\frac{1}{X_0} = \sum \frac{m_j}{X_j}$$

m_j = fraction of material by mass
X in g.cm^{-2}

Mixture:

$$\frac{1}{X_0} = \sum \frac{v_j}{X_j}$$

v_j = fraction of material by volume
X in cm

- **Shower maximum** (X_0 units)

$$t_{max} = \ln(E_0/E_c) - \begin{matrix} 1 & \text{(electrons)} \\ 0.5 & \text{(photons)} \end{matrix}$$

- 95% longitudinal containment (X_0 units)

$$L(95\%)/X_0 = t_{max} + 0.08\,Z + 9.6$$

- **Moliere radius** (same as X_0 for compound/mixture)

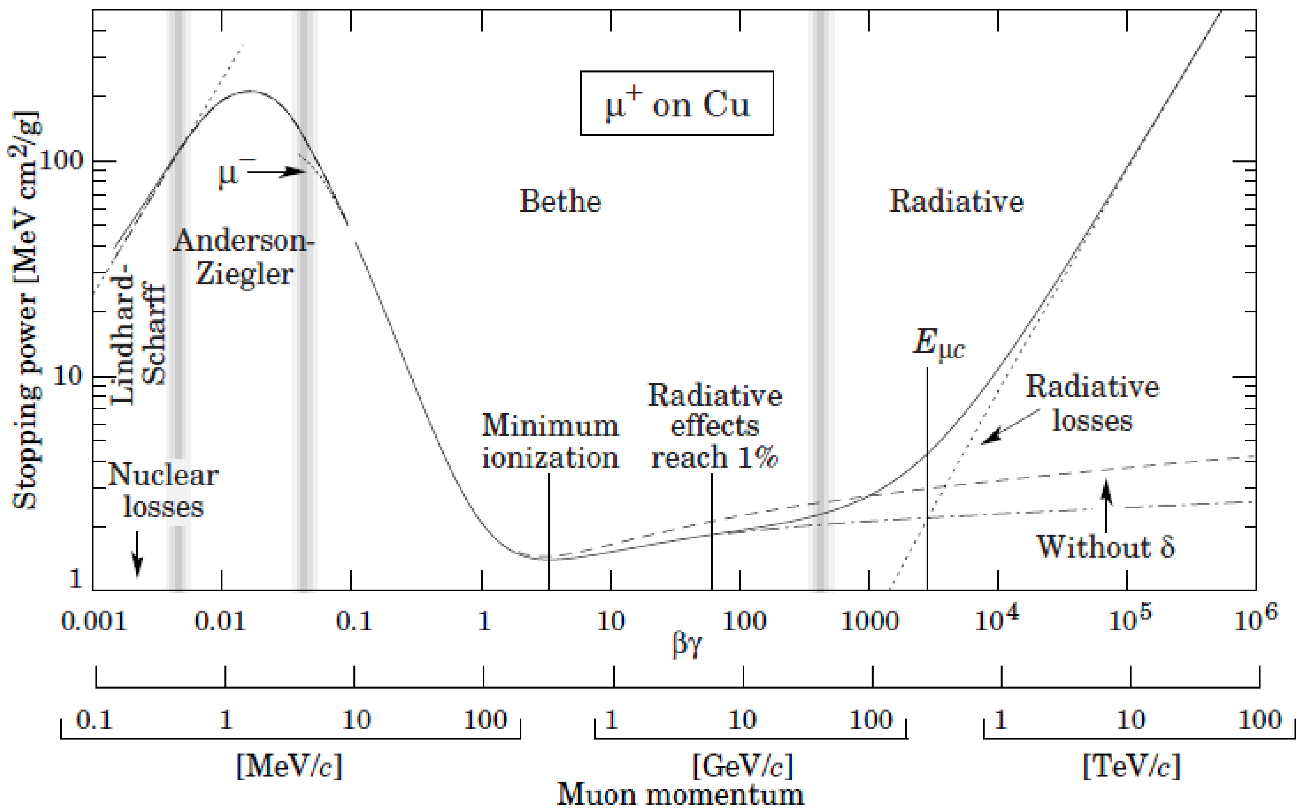
$$R_M = \frac{21\,MeV \times X_0}{E_c} \approx \frac{7\,A}{Z}\,g.cm^{-2}$$

- 95% lateral containment

$$R(95\%) = 2\,R_M$$

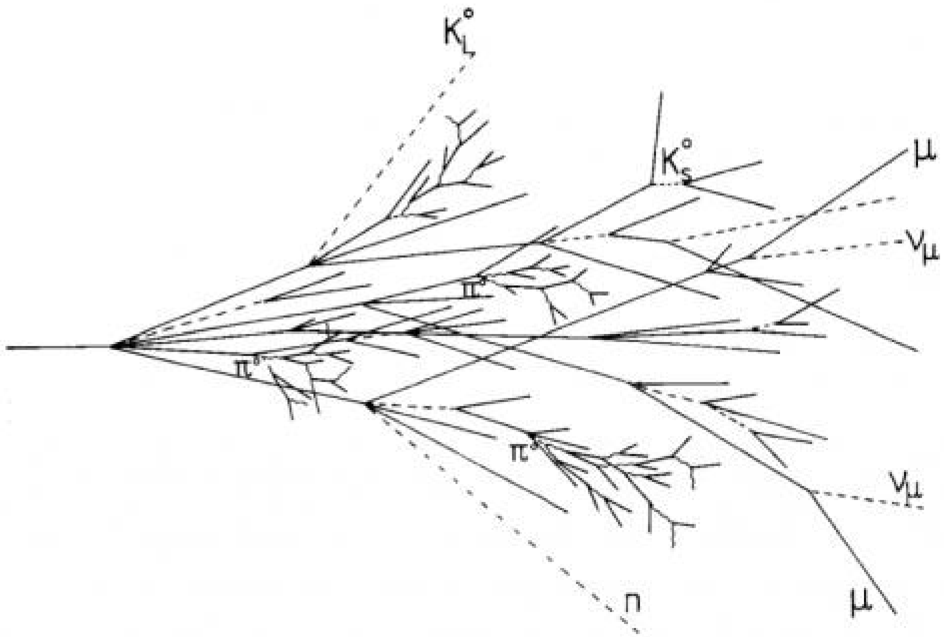
The case of the muon

- Muons are charged leptons, like electrons, but much heavier
  - $m_\mu / m_e \sim 200$
- Loss of energy by brem $-\left(\frac{dE}{dx}\right)_{brem} \propto \frac{E}{m^2}$
- Main mechanism for muons is ionization → **no shower**
  - Very small energy deposits
  - Radiation only above the TeV scale



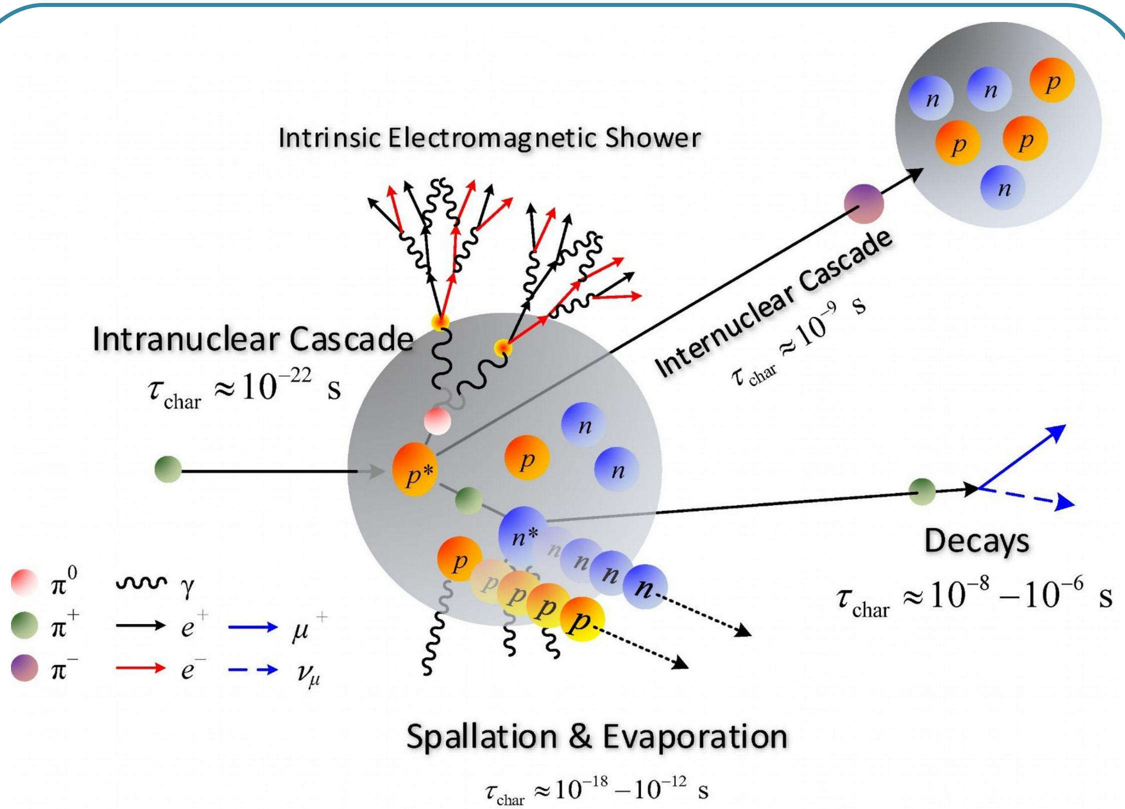
Hadronic showers

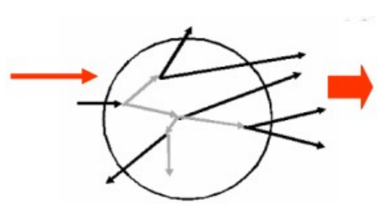
- Cascade of particles **initiated by a hadron**
  - Strong interaction in addition to EM interaction
- **Many processes** involved
  - Ionisation
  - Hadron production (fragmentation, etc.)
  - Charge exchange
    - $\pi\, n \rightarrow \pi^0\, p$
  - Spallation, fission
  - Nuclear de-excitation
  - Pion decay
  - …



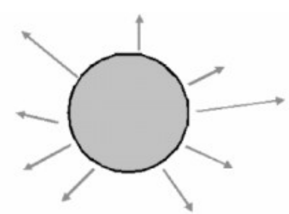
Hadronic interactions

Hadronic shower evolution





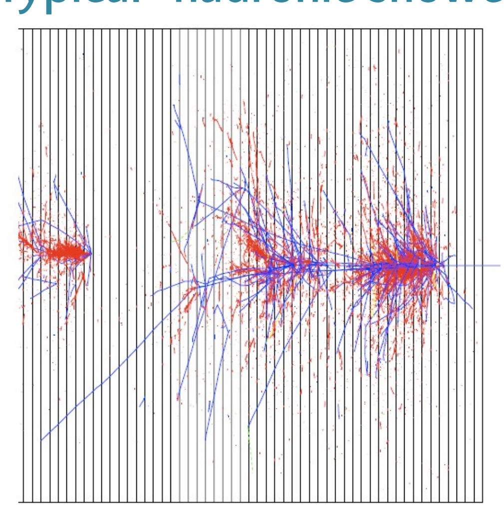
Intranuclear cascade
Incoming direction
Fast



Evaporation
Isotropic
Slow

- 1) **Hard collision**
  - Can travel long distance before 1st interaction
  - Similar to a MIP
- 2) **Spallation**
  - Intra-nuclear cascade
  - Frees protons and neutrons
  - Nucleus excitation and de-excitation (evaporation)

"Typical" hadronic shower



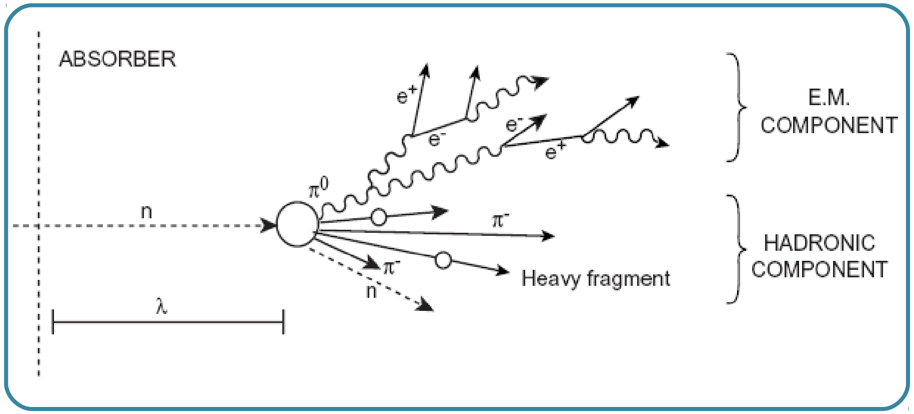
Electromagnetic component

- Contributions
  - Electrons & photons
  - **Neutral pions** (e.g. $\pi^0 \to \gamma\gamma$)
- About 1/3 of π^0 produced at each nuclear interaction
- On average, **EM fraction increases with energy**

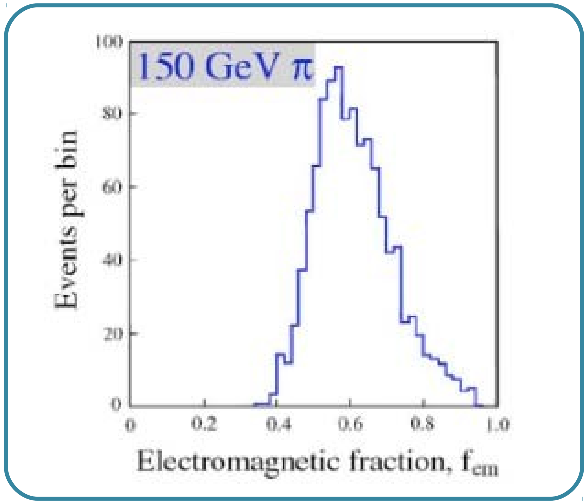
$$\langle f_{em} \rangle = \langle E_{EM} / E_{tot} \rangle = 1 - (E / E_0)^{k-1}$$

E_0 = average energy needed for π^0 production
k is related to the average multiplicity of π^0 produced at each interaction

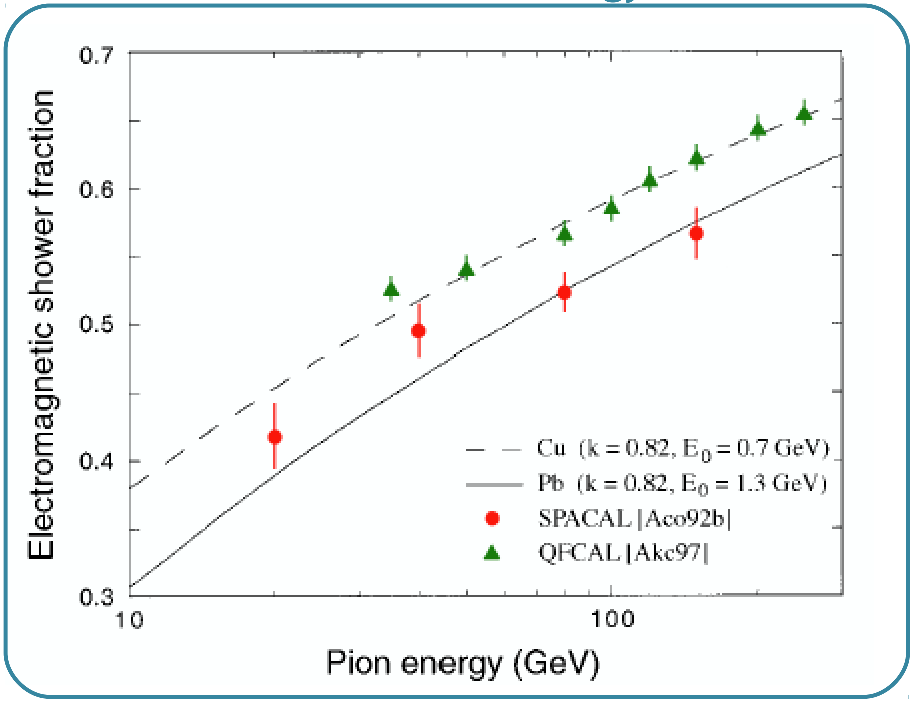
First hadronic interaction



Fluctuations in EM fraction



EM fraction vs energy



Non-EM components

Non-EM energy breakdown

Numbers for Lead

56% ionizing particles
2/3 are protons (from spallation)
<E> ~ 50-100 MeV

34% invisible
Break-up of nuclei

10% neutrons
Very soft (typically a few MeV)
On average 37n per deposited GeV

	Lead	*Iron*
Ionization by pions	19%	21%
Ionization by protons	37%	53%
Total ionization	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
Total invisible energy	34%	21%
Kinetic energy evaporation neutrons	10%	5%

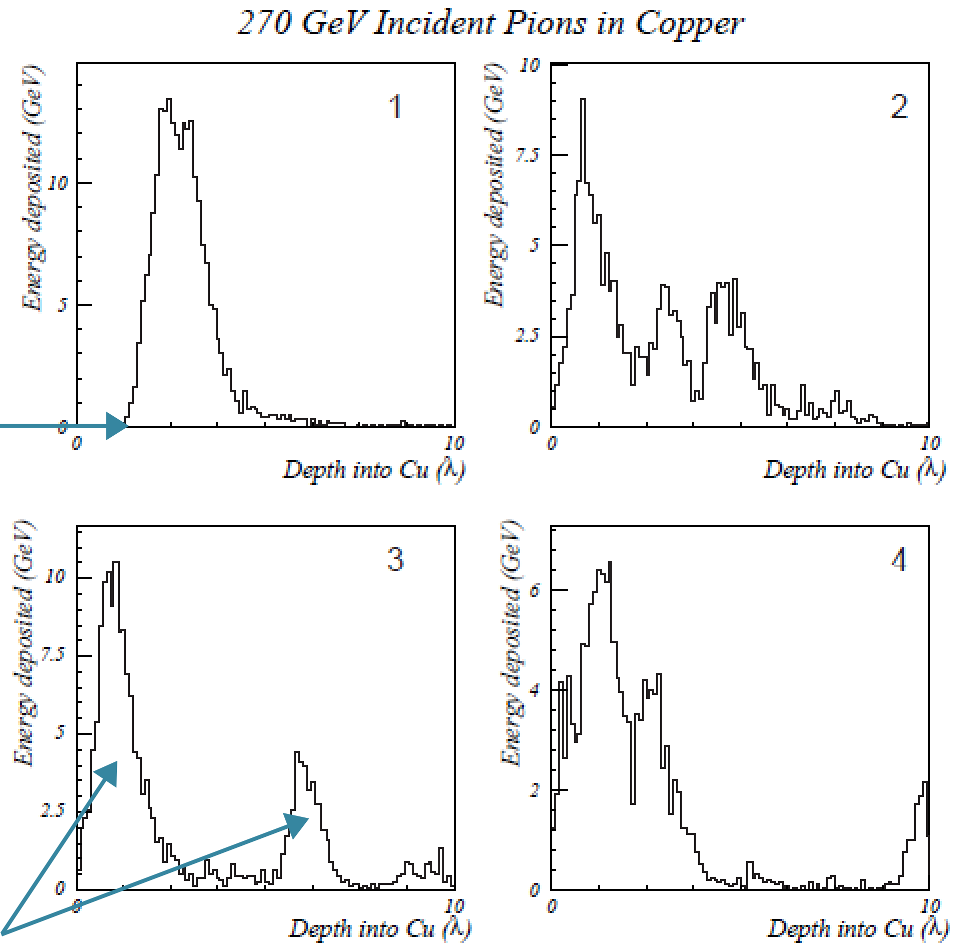
- A large part of energy losses is **invisible**
  - Energy used to release protons and neutrons from nuclei
  - Kinetic energy carried by recoil nuclei
- Also significant fraction in **evaporation neutrons**
  - Elastic scattering (large energy transfer for small nuclei, e.g. Hydrogen)
  - Neutron capture (sizeable energy, but late w.r.t. main shower component)

Shower development

- A hadronic shower doesn't have a profile which can be parameterized
- The size of the 1st interaction will essentially determine the EM fraction

Examples of longitudinal development

A pion can travel a significant distance before the first interaction happens



π_0 production in consecutive hadronic interactions

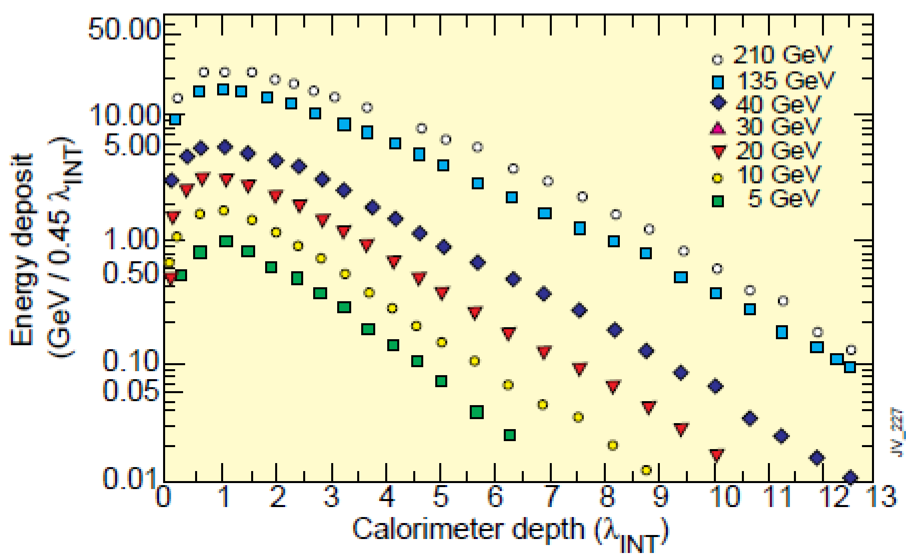
Longitudinal profile

- Hadronic shower governed by the **interaction length** $\lambda_{\text{int}} \propto A^{1/3}$
  - Mean free path between inelastic interaction
- Depth to contain shower increases with ln(E)
  - Similarly to EM showers
- But convolution of two components
  - Depth of the first interaction
  - Shower development

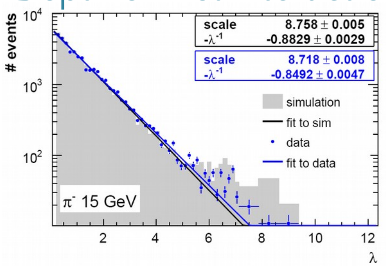
Examples of radiation and interaction length

	Z	ρ (g.cm-3)	E_c (MeV)	X_0 (cm)	λ_{int} (cm)
Air				30 420	~70 000
Water				36	84
$PbWO_4$		8.28		0.89	22.4
C	6	2.3	103	18.8	38.1
Al	13	2.7	47	8.9	39.4
L Ar	18	1.4		14	84
Fe	26	7.9	24	1.76	16.8
Cu	29	9	20	1.43	15.1
W	74	19.3	8.1	0.35	9.6
Pb	82	11.3	6.9	0.56	17.1
U	92	19	6.2	0.32	10.5

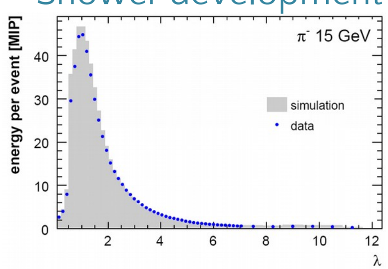
Longitudinal profile



Depth of first interaction



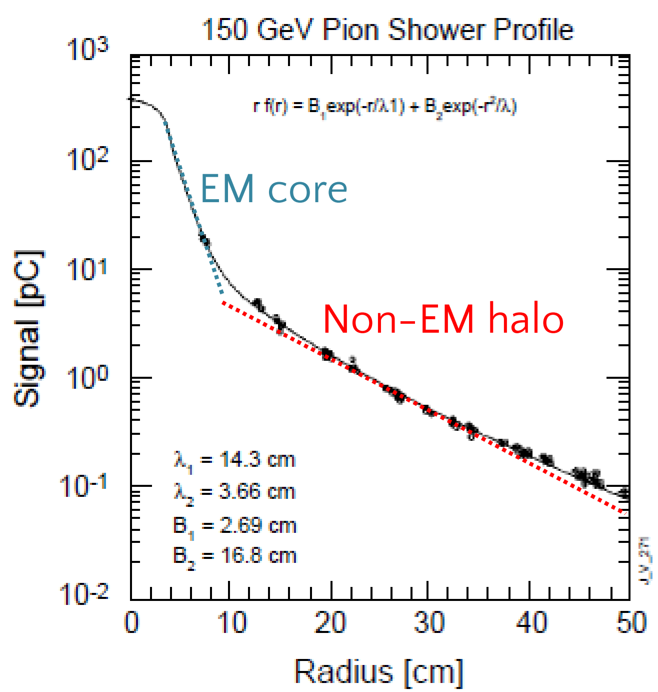
Shower development



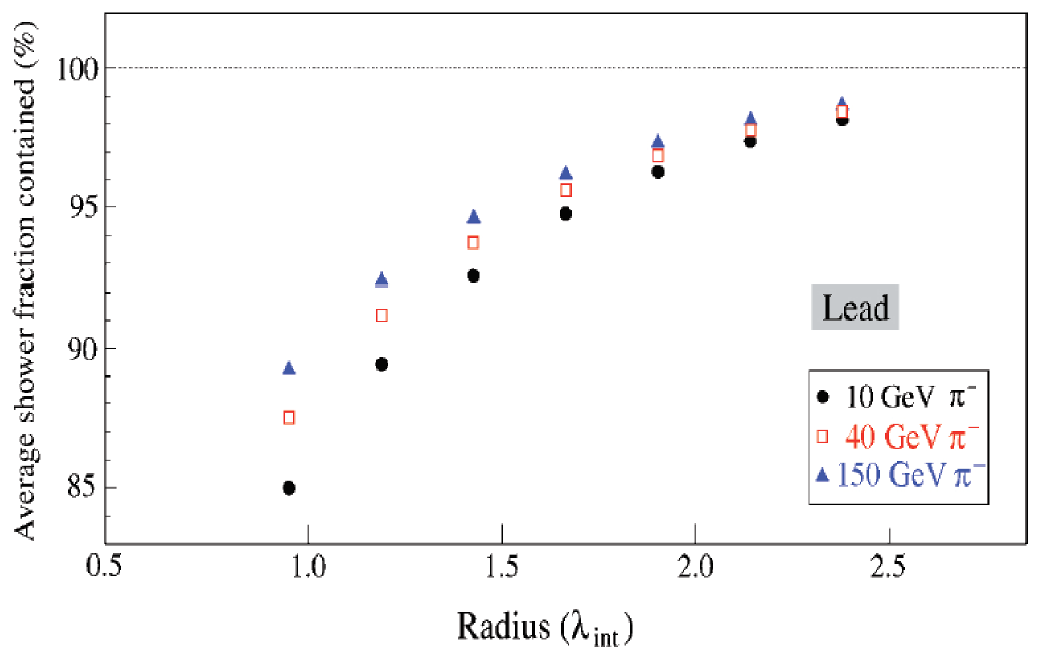
Lateral profile

- Lateral shower development has two components
  - Electromagnetic core
  - Non-EM halo (mainly non-relativistic shower particles)
- EM shower core prominently present in the initial stages
- Energy dependence of the lateral containment is directly related to the EM fraction dependence

Lateral profile



Lateral containment

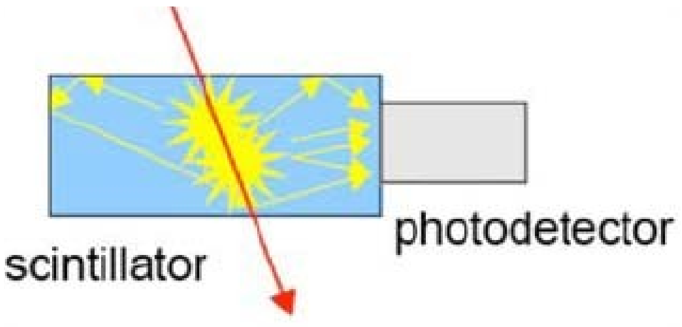


Lecture plan

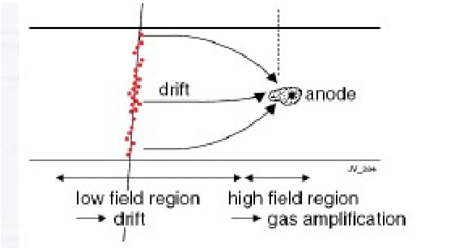
- What is a calorimeter in HEP?
- **Detection techniques**
- Electronics readout and trigger
- Beyond calorimetry: Particle Flow
- Electromagnetic and hadronic showers
- Calorimeter response & resolution
- Energy reconstruction & calibration
- An example: CMS HGCAL

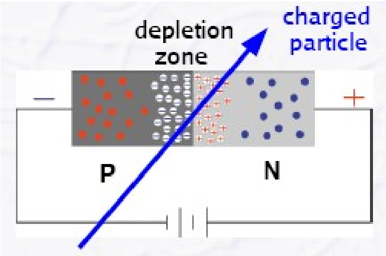
Measurement principles

- Convert ionisation **energy to light**
  - Scintillator (organic, inorganic)
- And then convert **light to electric current**
  - Photomultipliers, photodiodes, etc.



- Directly **collect charges**
  - From ionisation in gaz or noble liquids
  - From electron/hole pairs in semiconductors



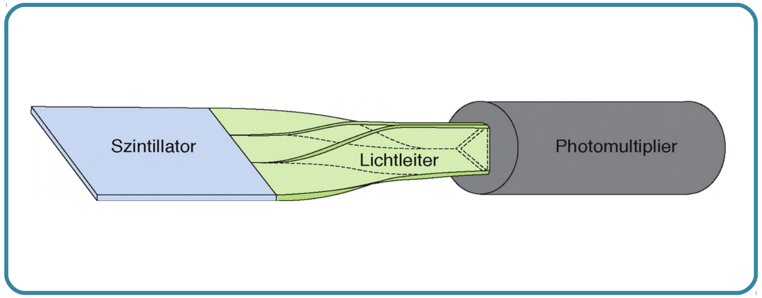


- One can also measure (very small) temperature increase
  - e.g. Bolometers
  - Not presented here

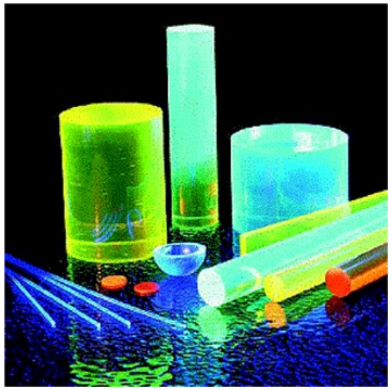
Scintillators

- **Excited atoms or molecules** in scintillating medium
  - De-excitation and emission of light (visible, UV, sometimes X-rays)
  - Propagation of light (wavelength shifters can be used, light guides)
  - Conversion into electric signal (photo-detector)

Light production and collection

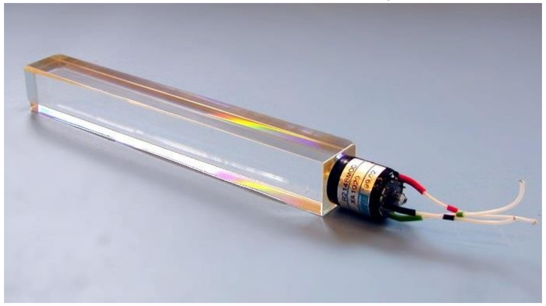


Various scintillators



- 2 types of scintillating material
  - **Organic** (plastics or liquids)
  - **Inorganic** (crystals)
- 2 types of light emission
  - Fluorescence: prompt (ns → µs)
  - Phosphorescence: emission over long period (µs → ms)

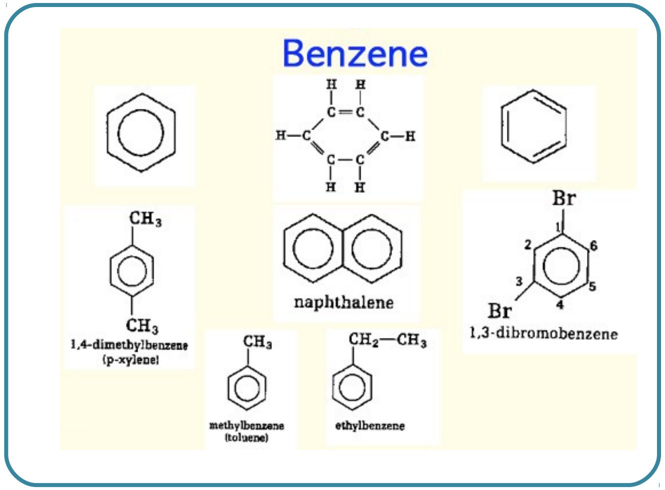
CMS PbWO4 crystal



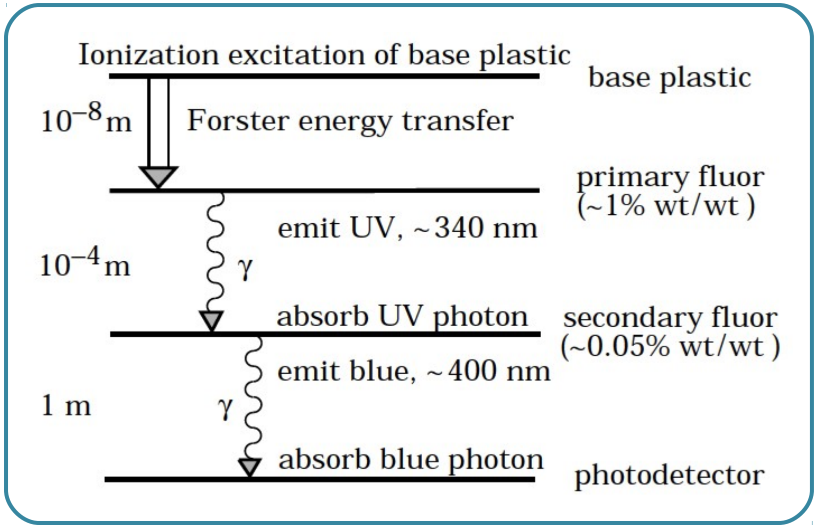
Organic scintillators

- Organic crystals, organic liquids, plastic scintillators
  - Aromatic hydrocarbon compounds (containing carbon rings)
  - Base/solvent + fluor
- Transition of electrons between molecular levels → scintillation
  - Fast: few ns
  - Fluorescent UV light
- UV light absorbed in most organic material
  - Second fluorescent material for conversion in visible light
  - a.k.a. wavelength shifter
- Usually made of low Z / low density material
  - → more volume
  - But inexpensive

Aromatic hydrocarbons



De-excitation process



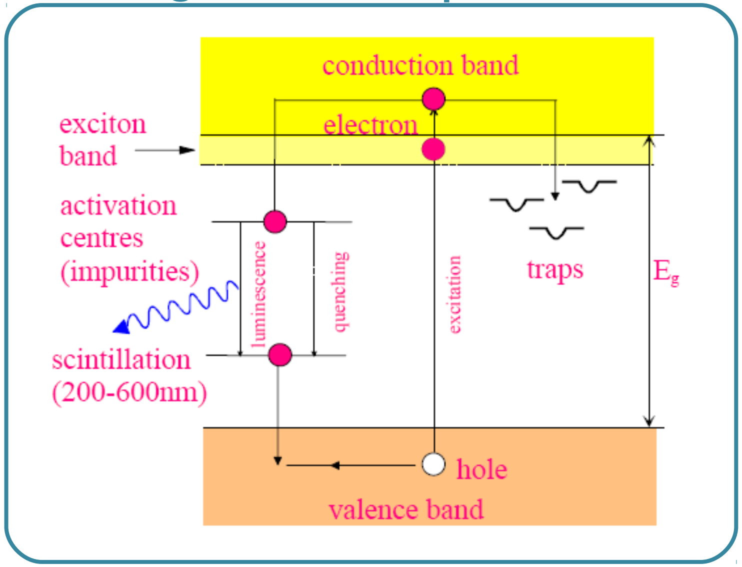
Inorganic scintillator

- **Crystalline structure**
  - Energy bands
  - Ionizing particles create free electrons and holes
  - Excites activation centres (impurities or doping)
  - Decay → light emission
- Slower than organic scintillator (> 100 ns)
- But **high Z / high density**

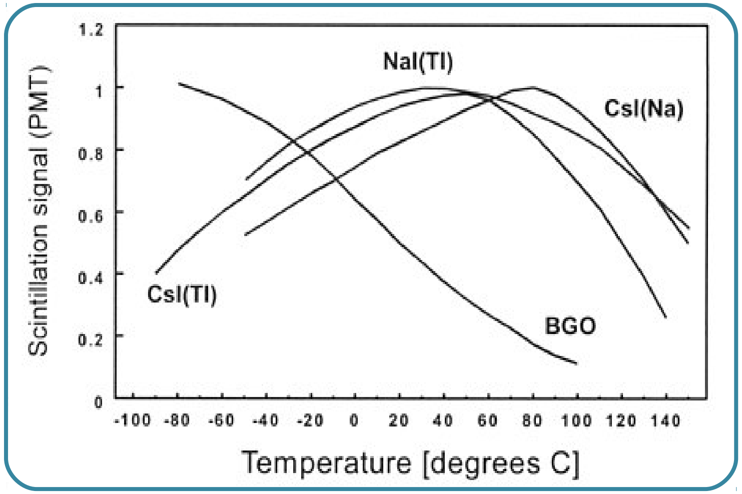
Material	Form	λ_{max} (nm)	τ_f (ns)	ρ (g/cm^3)	Photons per MeV
NaI(Tl) (20°C)	crystal	415	230	3.67	38,000
pure NaI (-196°C)	crystal	303	60	3.67	76,000
$Bi_4Ge_3O_{12}$ (20°C)	crystal	480	300	7.13	8,200
$Bi_4Ge_3O_{12}$ (-100°C)	crystal	480	2000	7.13	24,000
CsI(Na)	crystal	420	630	4.51	39,000
CsI(Tl)	crystal	540	800	4.51	60,000

- Light output depends on temperature
  - Needs good control and monitoring

Light emission process



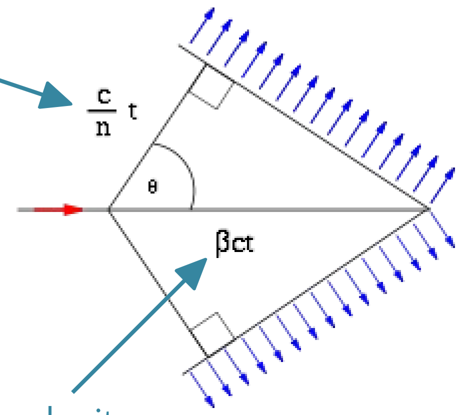
Light yield vs temperature

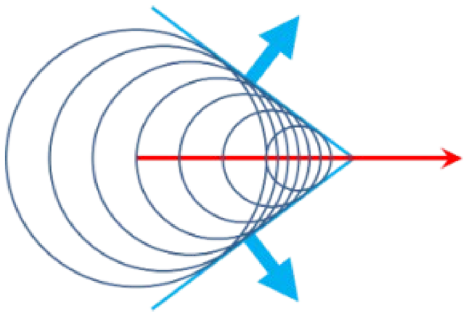


A bit on the Cerenkov effect

- Collective effect when charged relativistic particle passes through matter at a speed higher than the speed of light (in the medium)

Principle

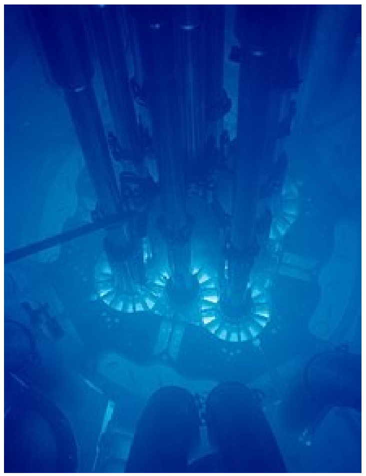




- Propagation angle $\cos(\theta) = \frac{1}{n\beta}$

Medium refractive index → n; $\beta = v_p / c$ → β

- Very **small loss of energy** from the incoming particle
  - e.g. ~400 eV / cm for a particle with β≃1 in water

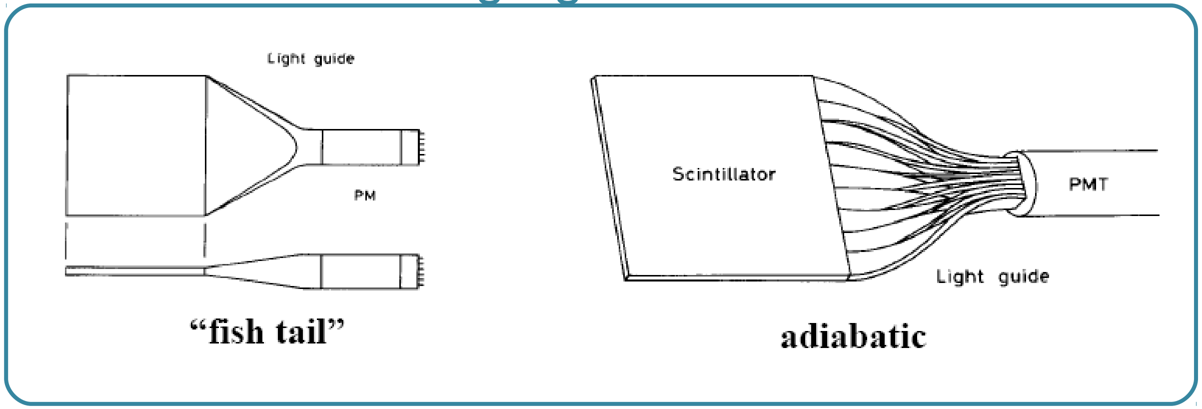


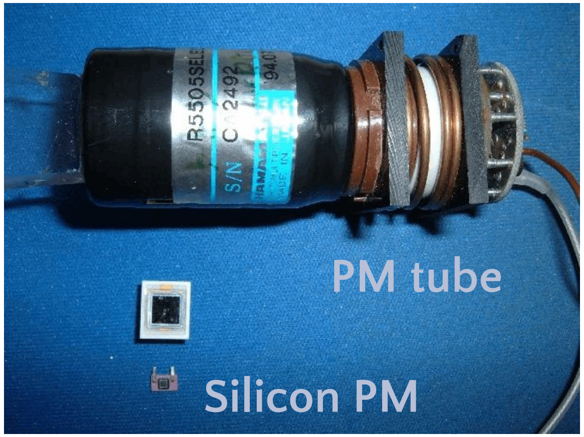
Spectrum in $1/\lambda^2$
→ appears blue/violet in the visible spectrum

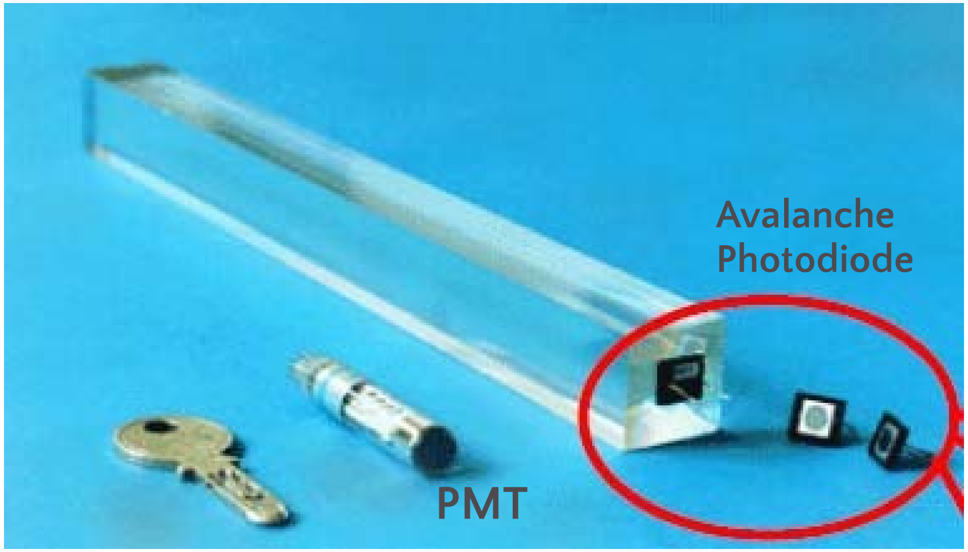
Photodetectors

- Conversion of scintillation (or Cerenkov) light to electric signals

Light guides





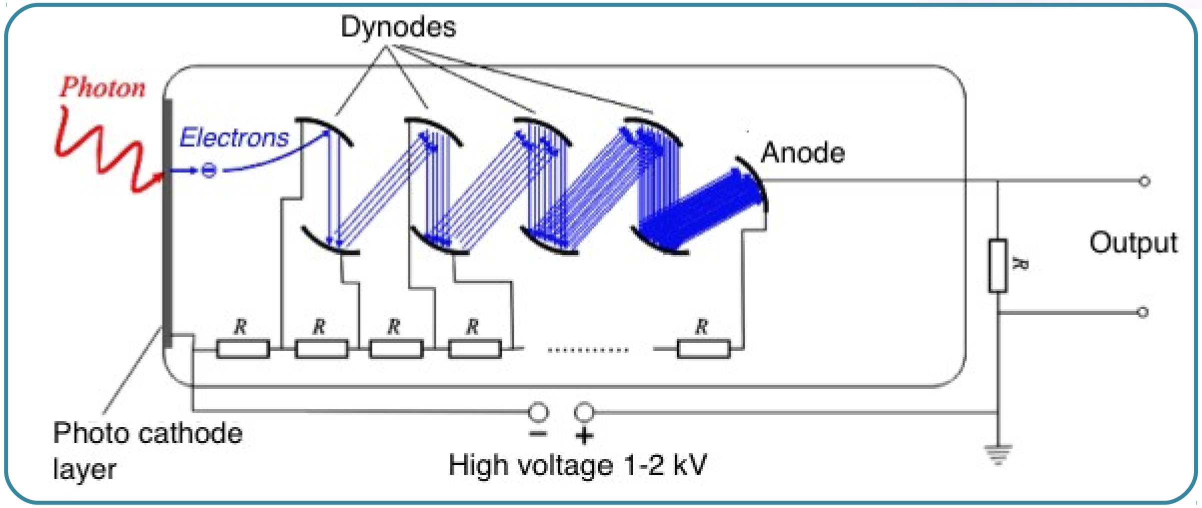


Large PMT

Photomultipliers

- Photons hit a **photo cathode** → electrons (photoelectric effect)
- **High voltage** to accelerate the produced electrons
- Succession of dynodes to **amplify the signal**
  - Produces secondary electrons
- Can reach high amplification gains (10^4 – 10^7)
- But several drawbacks
  - Bulky
  - Expensive,
  - Sensitive to magnetic fields

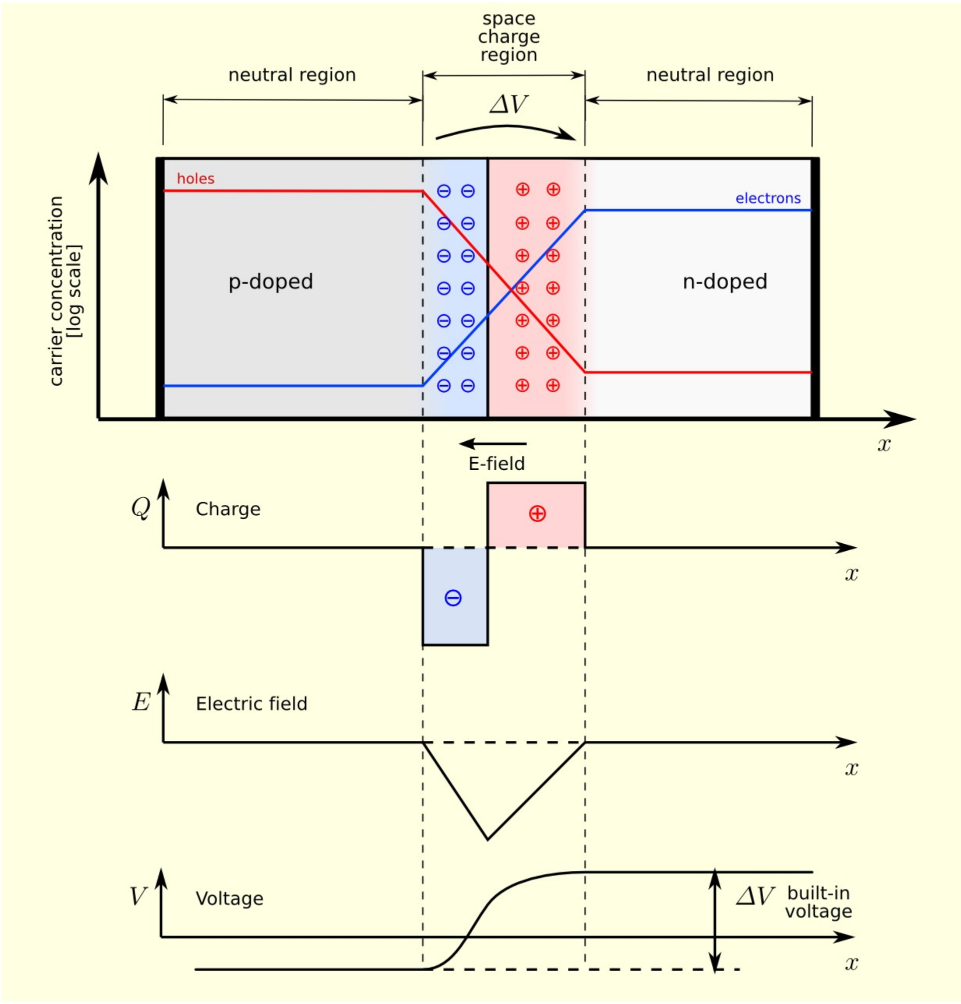
Varieties of PMT



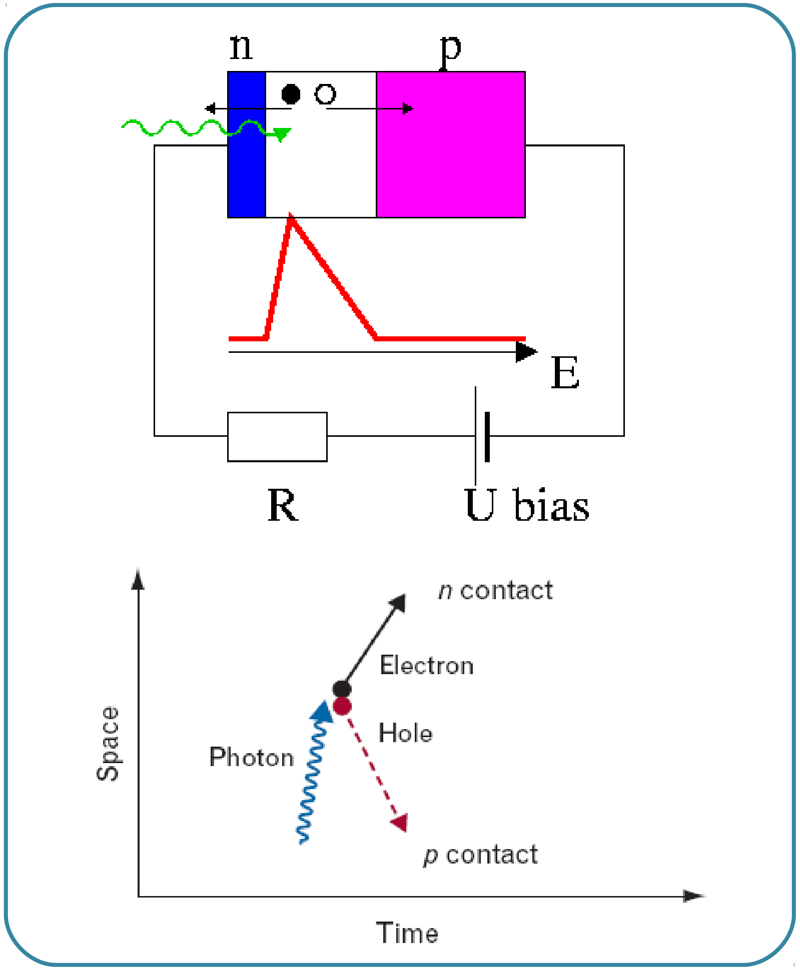
Signal amplification

PN diodes

- Semiconductor based photo detectors are more used nowadays
- Based on **PN diodes with reverse bias**
  - Photon creates electron-holes pair in the depletion region



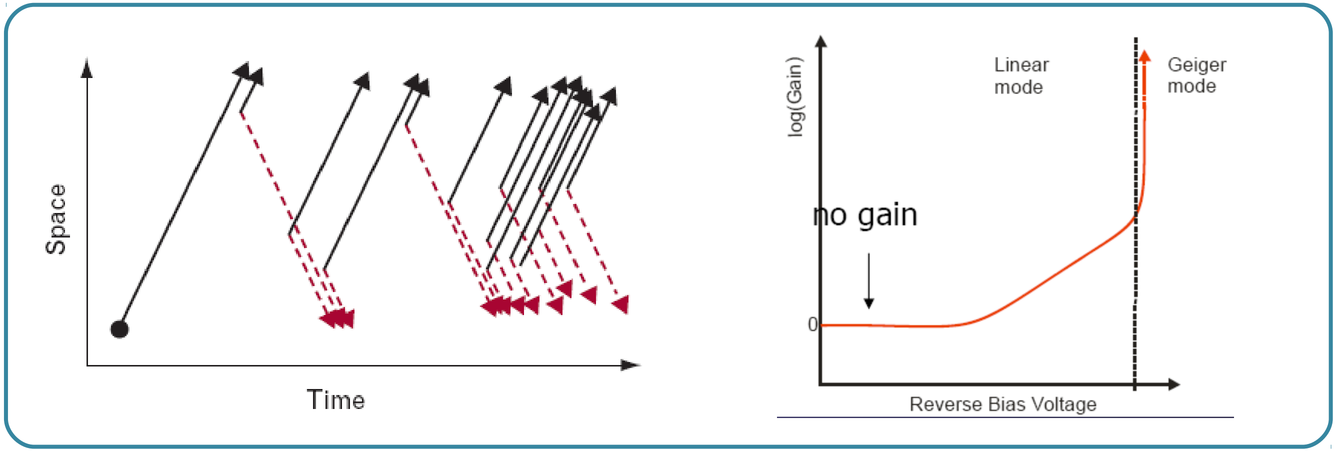
Photodetector based on PN diode



Silicon PM, Avalanche Photo Diodes

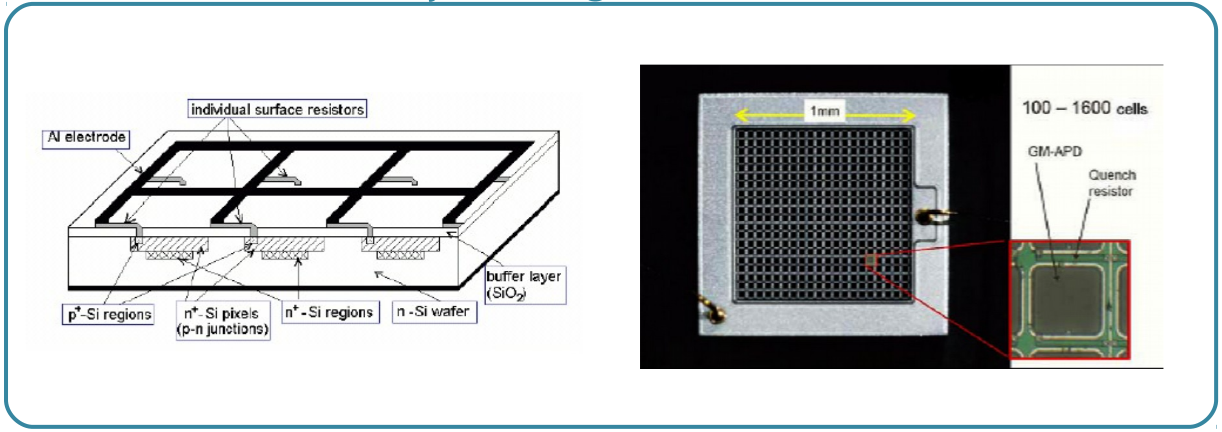
- Applying a **high reverse voltage**
  - Creates electron-hole multiplication

PN diode in avalanche mode



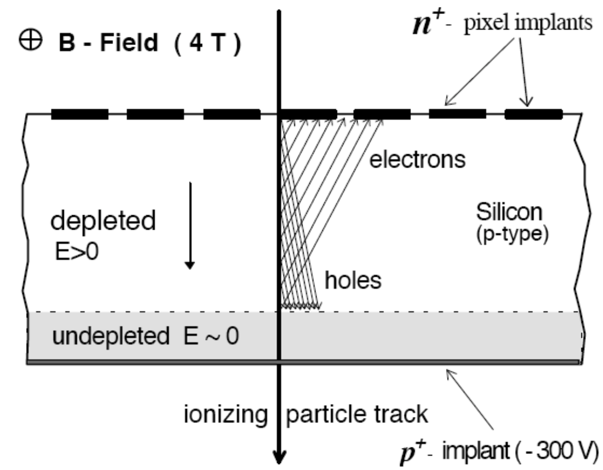
- Linear mode = **Avalanche Photo Diode** (APD)
- **Geiger mode** (or "Single Photon") APD
  - Above breakdown voltage
  - Binary mode
  - → Arrays of G-APD = Silicon PM

Array of Geiger mode APD

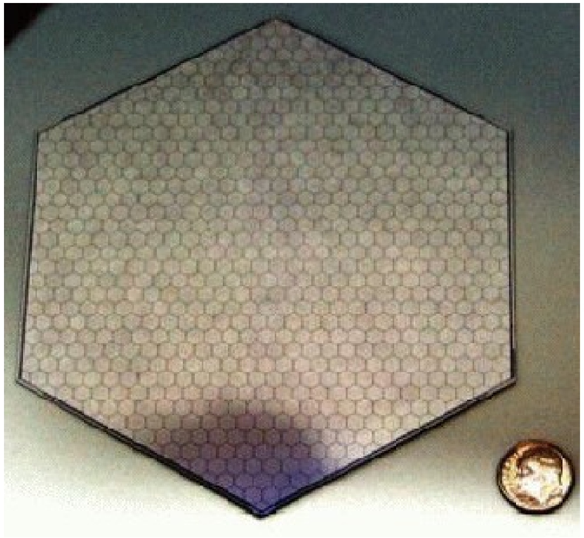


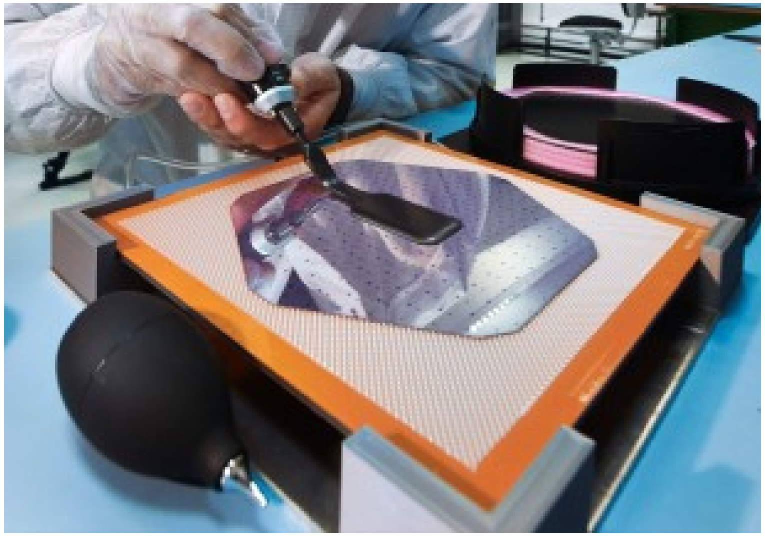
Direct charge collection with semiconductor detectors

- Silicon detectors can also **collect charges from ionization**
  - Also used for tracking
- An electron can create many electron-hole pairs
  - About 9000 e-h created / 100 microns
- Thin: few 100 microns thickness
- High bias voltage: few 100V



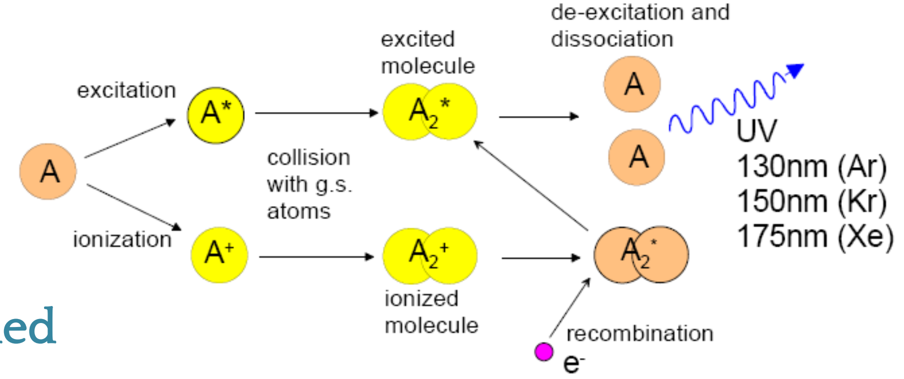
Silicon sensors with hexagonal cells



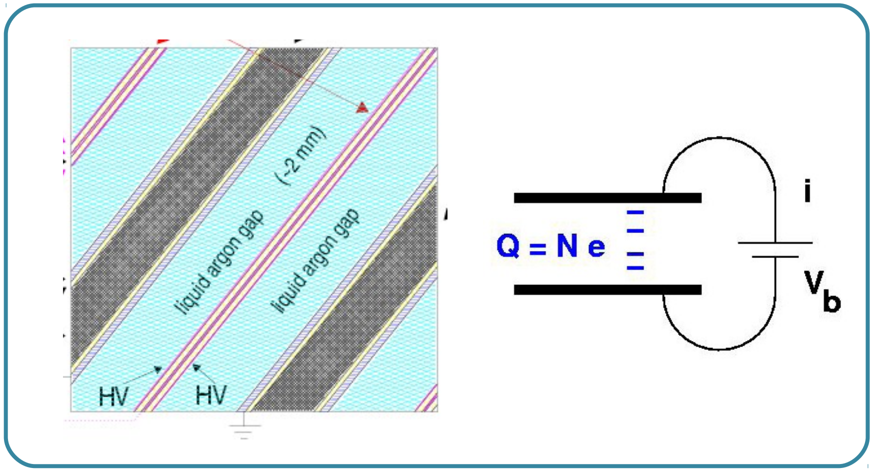


Direct charge collection with noble liquids

- Two processes in noble liquids
  - Molecule **excitation** → UV light emission
  - Molecule **ionization** → electron and ion drift
- Dense material
  - Lots of charge → **no charge amplification needed**
  - Good stability, good homogeneity



Charge collection



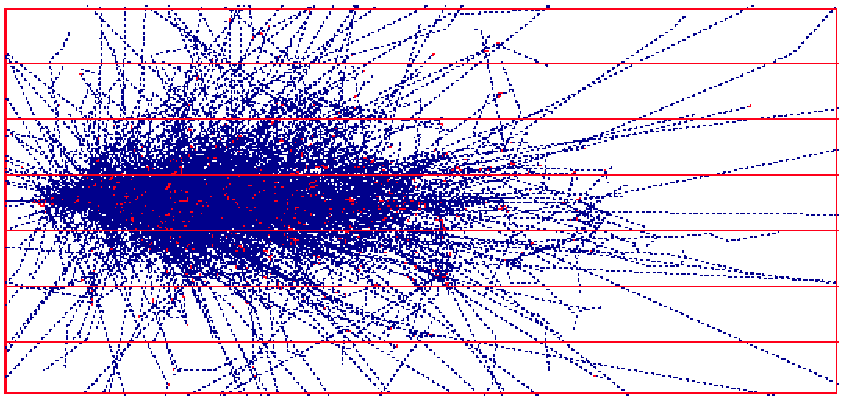
Noble liquids characteristics

	Ar	Kr	Xe
Z	18	36	58
A	40	84	131
X_0 (cm)	14	4.7	2.77
E_C (Mev)	41.7	21.5	14.5
R_M (cm)	7.2	4.7	4.2
W (eV/pair)	23.3	20.5	15.6
v drift (mm/μs)	10	5	3

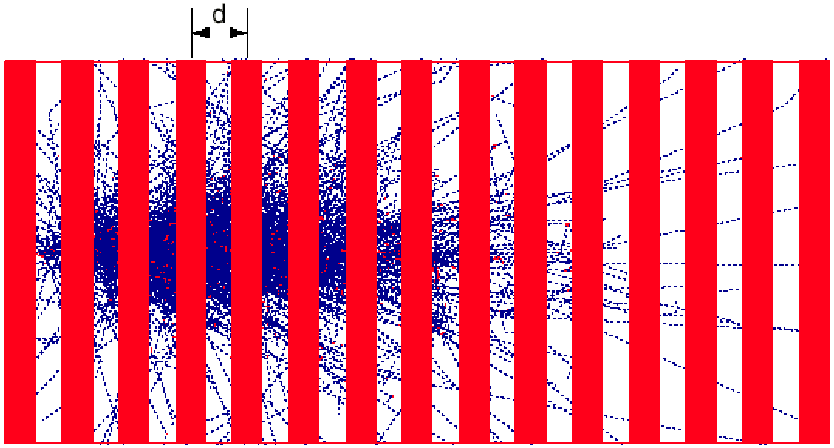
- Similar principles can also be used in gas detectors
  - But low density, so amplification needed → less stable
  - Larger detectors

Two calorimeter types

- Homogeneous calorimeter
  - **Single medium** for
    - Shower development (dense material)
    - Signal collection
  - "All" energy deposited is collected



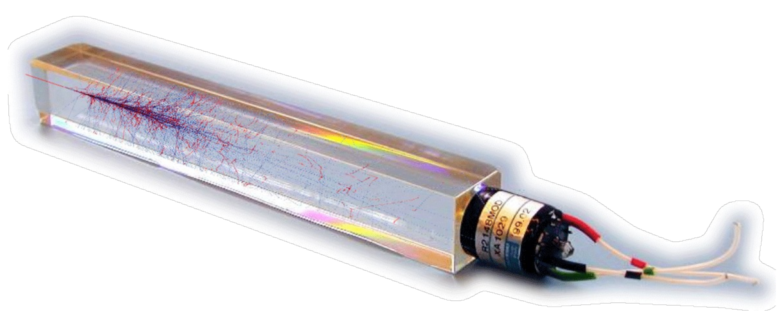
- Sampling calorimeter
  - **Two materials**
    - One for shower development (**absorber**)
    - One for signal collection (detectors / **active material**)
  - Only energy deposited in active material is collected
    - The shower is sampled

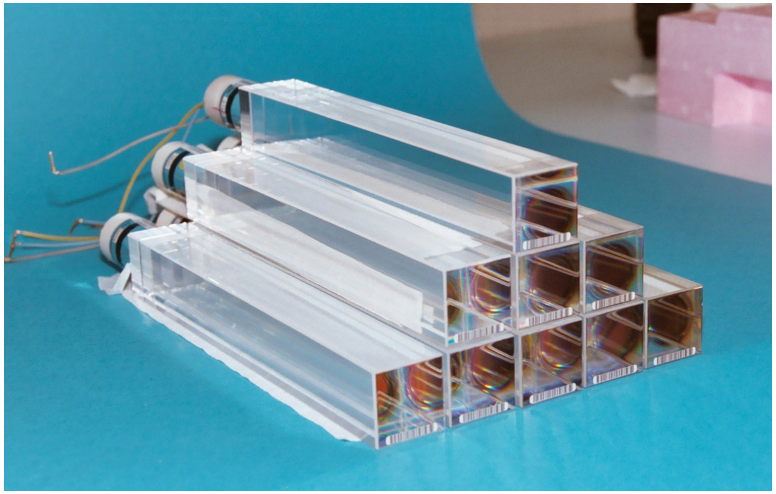


Homogeneous calorimeters

- Based on **scintillating crystals** with high density and high Z
- Very good energy resolution and linearity
- But
  - Very expensive
  - Radiation damages can be a problem
  - No longitudinal (depth) segmentation

CMS ECAL PbWO4 crystals





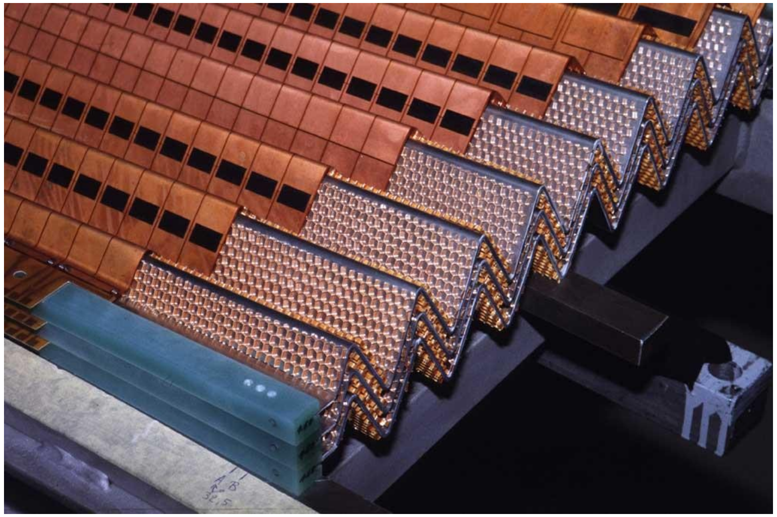
Sampling calorimeter

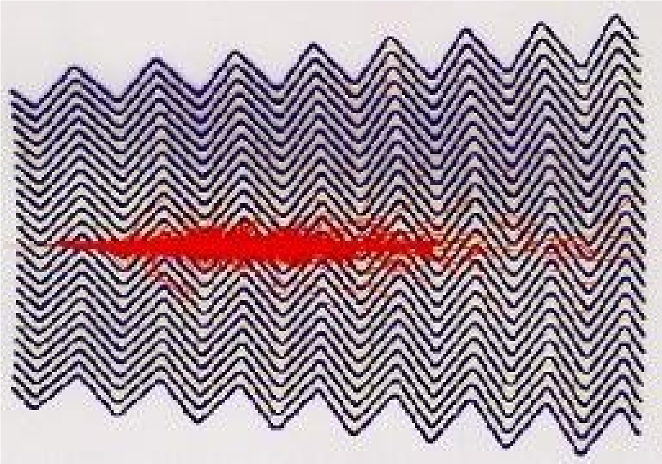
- Absorber with high-density material
- Interleaved with active readout devices
- Lower cost than homogeneous calorimeters
- And can have longitudinal segmentation
- But
  - Only part of the shower energy is collected
  - Fluctuation of energy deposited in active layers
    - Proportional to number of charged particles

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{n_{ch}}}$$

    - (And less charges deposited compared to homogeneous calorimeters)

ATLAS Liquid Argon ECAL

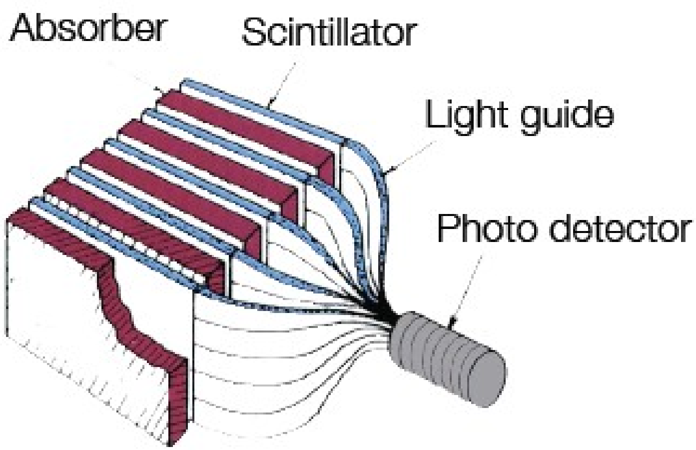




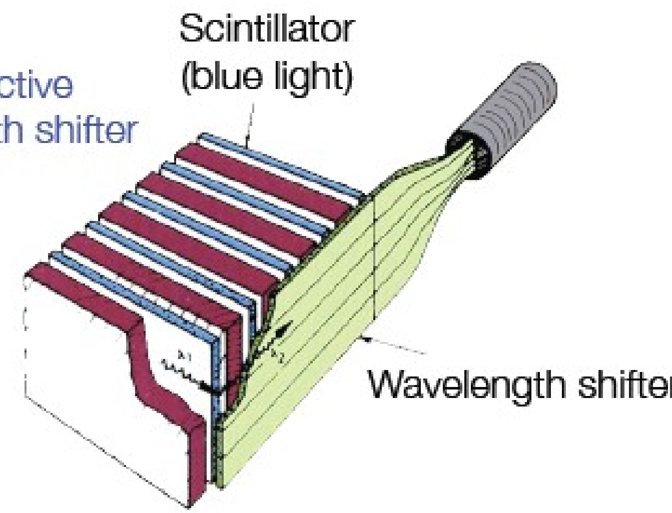
Some types of sampling calorimeters

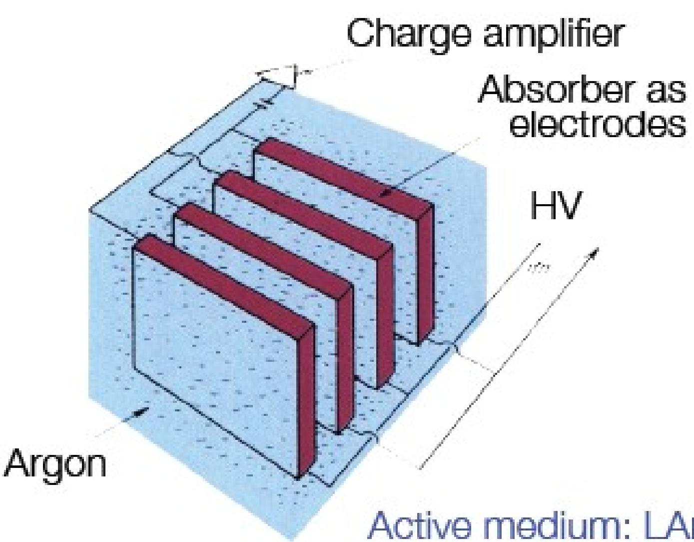
Possible setups

Scintillators as active layer;
signal readout via photo multipliers



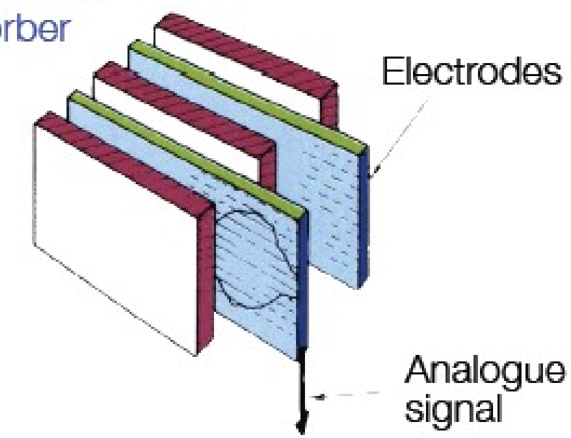
Scintillators as active layer; wave length shifter to convert light





Active medium: LAr; absorber embedded in liquid serve as electrods

Ionization chambers between absorber plates



Lecture plan

What is calorimeter in HEP?

Electromagnetic and hadronic showers

Detection techniques

Calorimeter response & resolution

Electronics readout and trigger

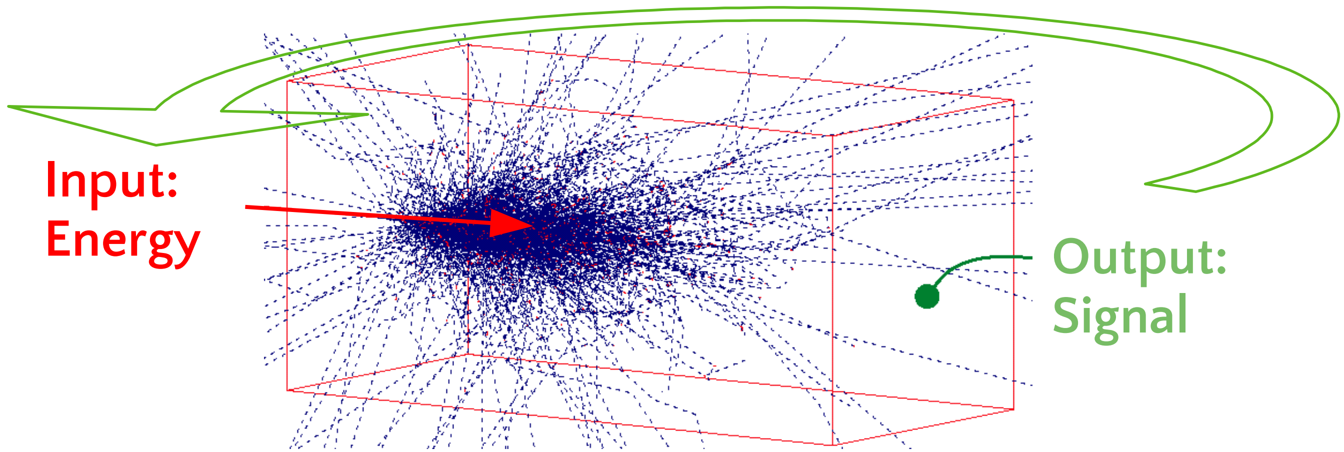
Energy reconstruction & calibration

Beyond calorimetry: Particle Flow

An example: CMS HGCAL

Measurement of showers

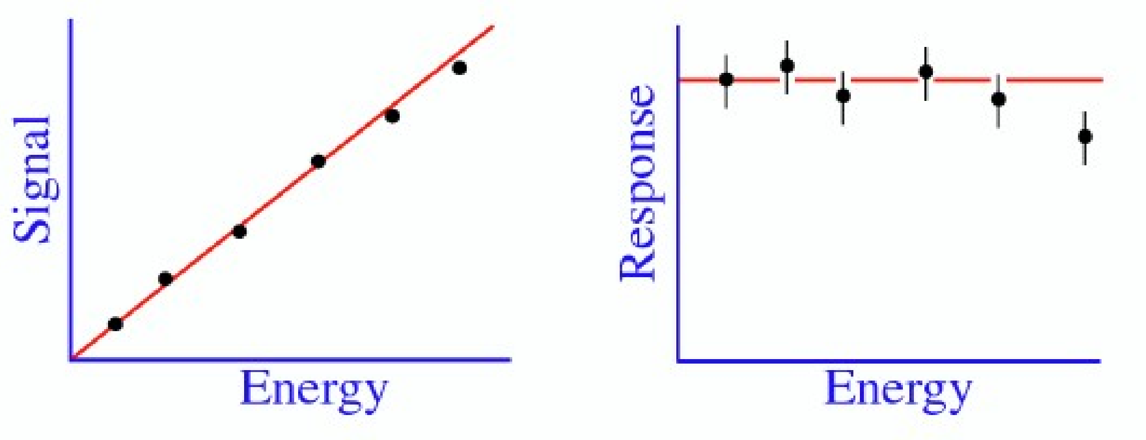
- From collected signal back to the energy of the particle



- Average signal collection → **response** of the calorimeter to the input energy
  - Ideally proportional to the input energy (linearity)
  - Homogeneous and sampling calorimeters behave differently
  - The response differs between EM and hadronic showers
- Fluctuations of the collected signal → calorimeter **resolution**
  - For a given energy there are shower to shower variations of the signal
  - Contributions to these fluctuations differ with the energy

Calorimeter response

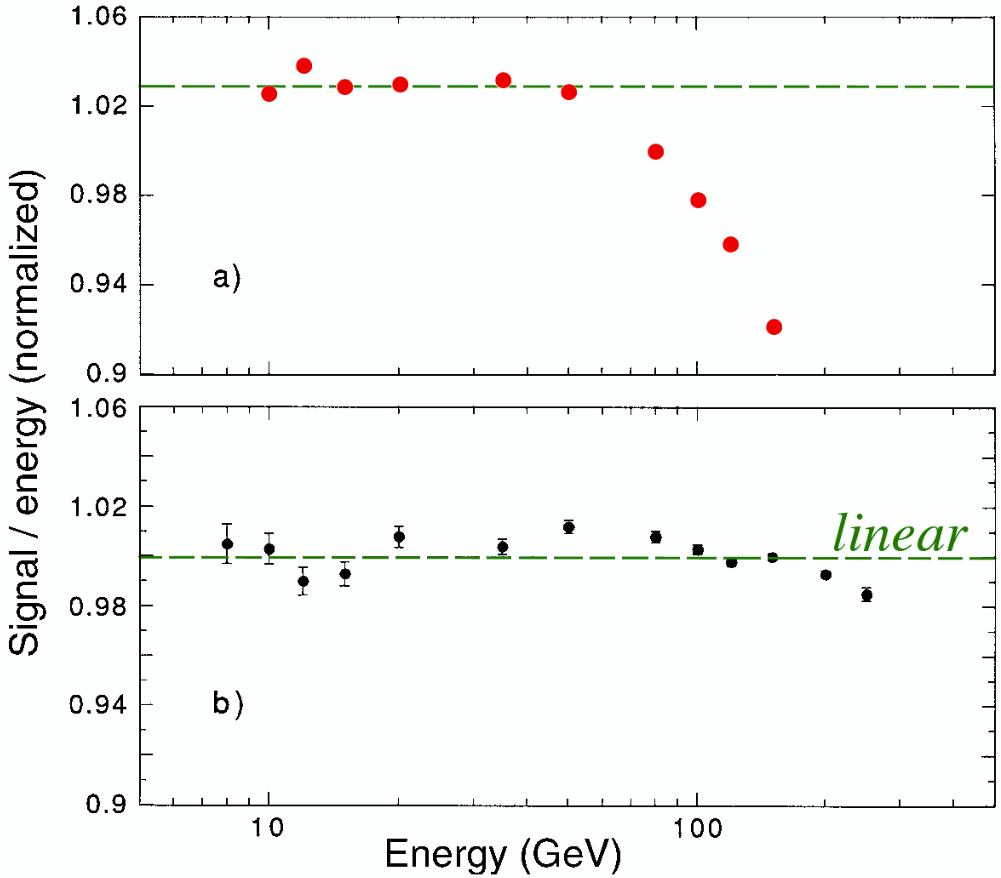
- Response: average signal per unit of deposited energy
- A linear calorimeter has a constant response
  - The signal is proportional to the deposited energy



- In general electromagnetic calorimeters are linear
  - All energy deposited through ionization / excitation of absorber
- Hadronic calorimeters are not

Sources of non-linearity (1/2)

- Instrumental effects
  - e.g. saturation of scintillators, photo-detectors, electronics



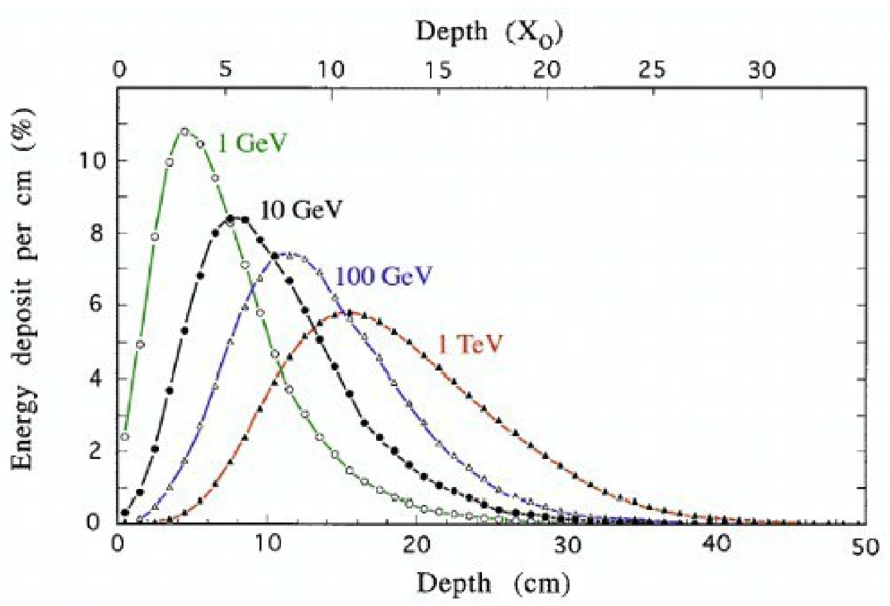
PMT saturation in QFCAL calorimeter

After correction of this saturation

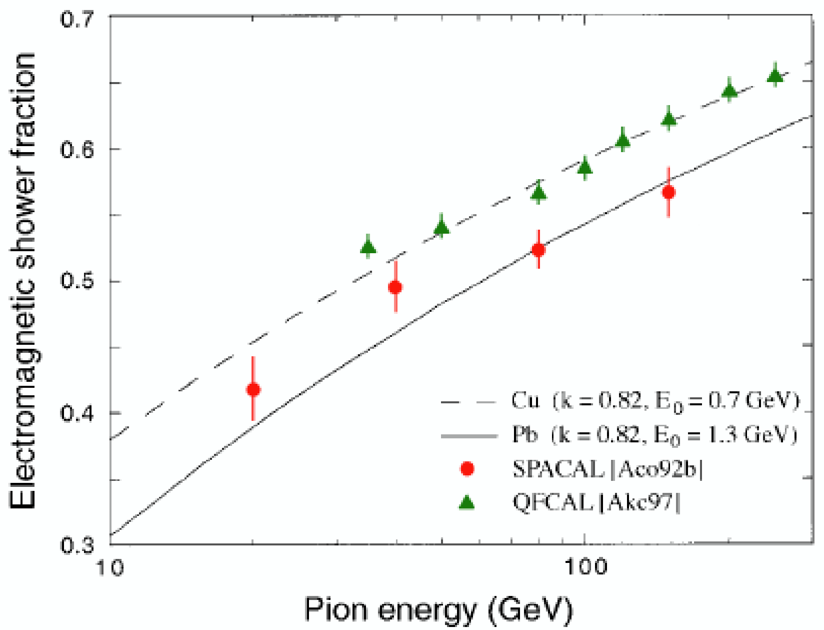
Sources of non-linearity (2/2)

- Non-linearity appears if response depends on something that varies with energy
  - e.g. if deposited energy counts differently depending on depth
    - Since **depth increases with energy**
  - Electromagnetic and hadronic energies count differently
    - And **EM fraction increases with energy** → non linear hadronic calorimeter response
- Energy **leakage**

Longitudinal profile vs energy



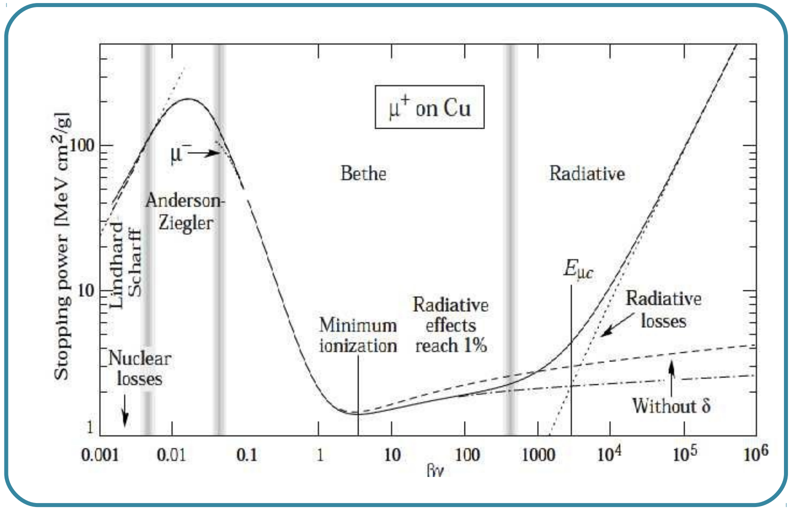
EM fraction vs energy



Sampling: EM vs mip response

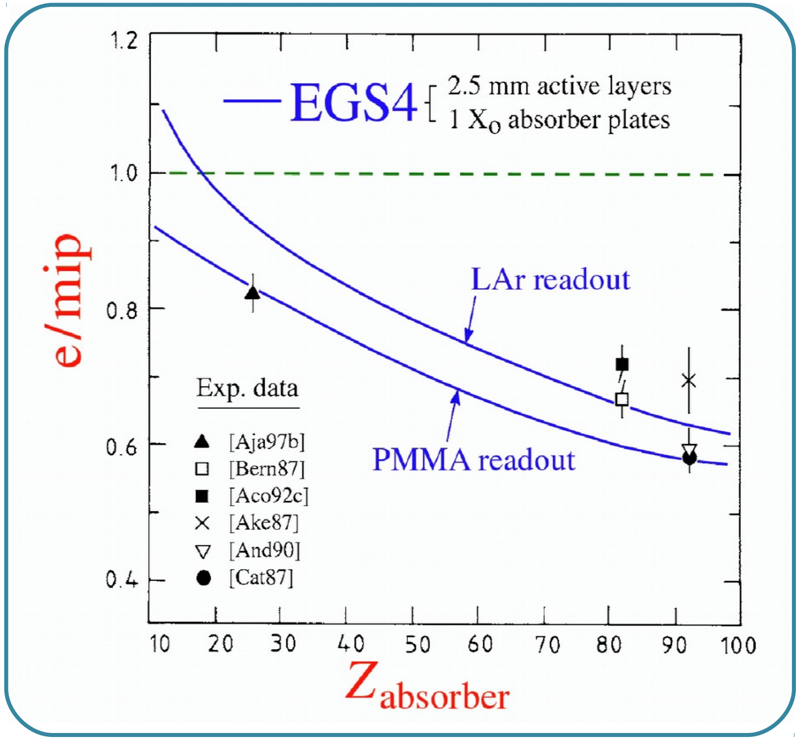
- **Homogeneous** calorimeters
  - Same deposit mechanisms for EM showers and mips → same response (**e/m=1**)
- Sampling fractions defined for a minimum ionizing particle (mip)

$$f_{samp} = \frac{E_{mip}^{loss\ in\ active}}{E_{mip}^{total\ loss}}$$



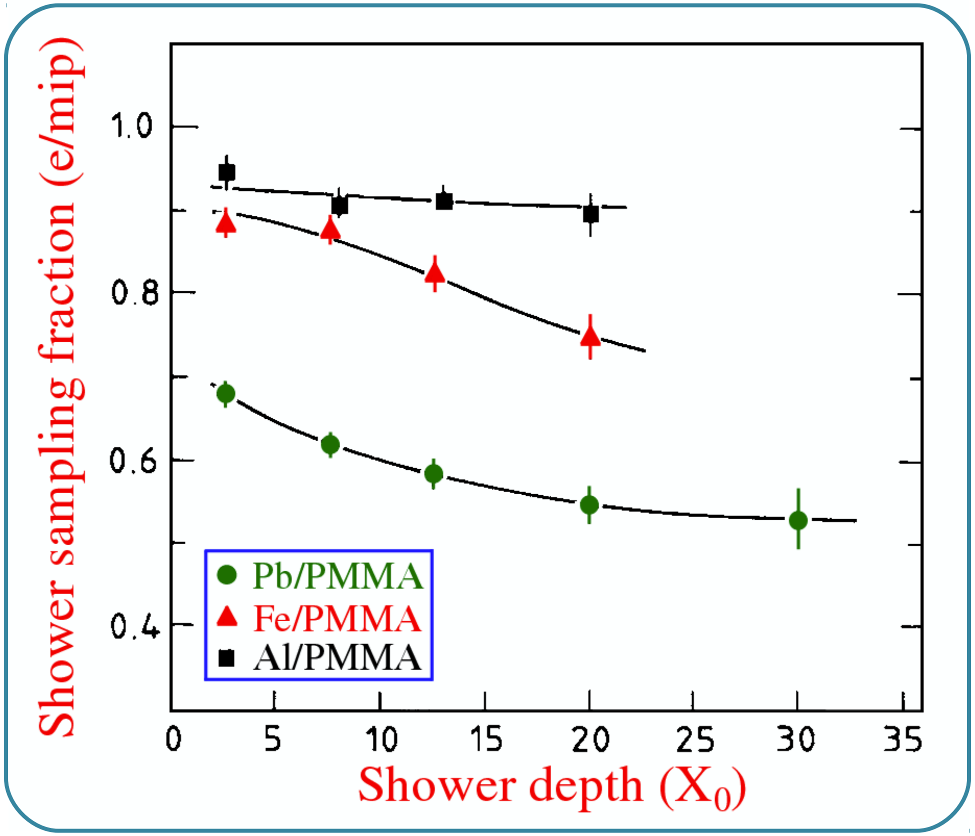
- But **EM showers are not sampled like mips**
  - Photoelectric effect $\sigma_{pe} \propto Z^5$
  - Soft photons are very inefficiently sampled due to the Z asymmetry between absorber and detector
  - Only photoelectrons produced near the boundary (<1mm) between active and passive material produce a signal
- **Sampling** calorimeters: **e/m < 1** (or << 1)

e/m vs absorber Z



Sampling: e/m dependence with shower depth

- e/m changes as the shower develop
- Because the shower composition evolves
  - Early phase: relatively fast shower particles (pairs)
  - Tails: dominated by Compton and photoelectric electrons
- Longitudinally segmented calorimeter
  - Must calibrate differently vs depth



e/m vs shower depth

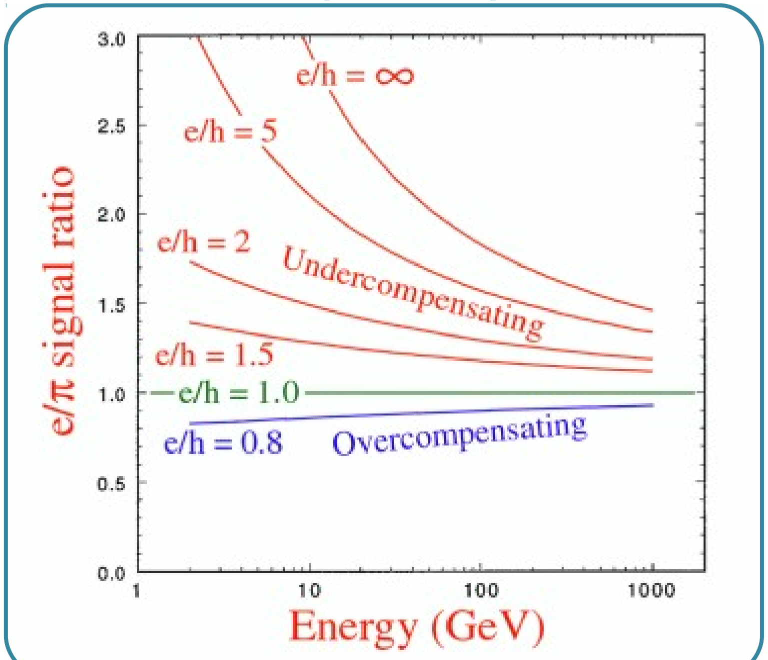
Hadronic response and compensation

- Response to the hadronic part usually smaller than to the EM part
  - e/h > 1
  - Invisible nuclear binding energy, escaping muons and neutrinos
  - Saturation effects, etc.
- e = h → compensating calorimeter
  - Can be obtained in non-homogeneous calorimeters
  - Homogeneous calorimeters are in general non-compensating
- e/h not directly measurable
  - Uses pion response

$$e/\pi = \frac{e}{f_{EM}e + (1 - f_{EM})h} = e/h \frac{1}{1 + f_{EM}(e/h - 1)}$$

- EM fraction increases with E → non linearity

Non-compensation effect on electron vs pion responses



Non-linearity and e/h

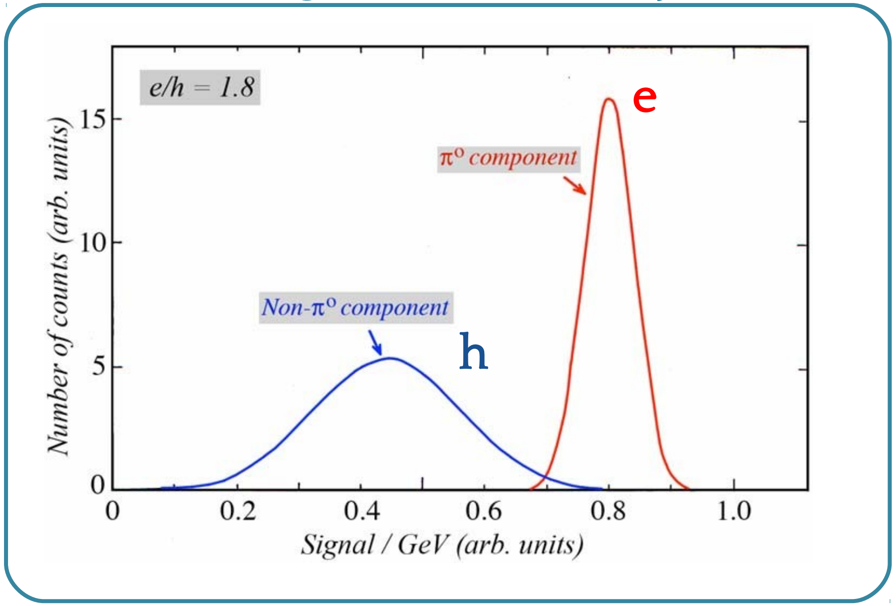
- Non-linearity determined by e/h

$$\frac{\pi(E_1)}{\pi(E_2)} = \frac{f_{EM}(E_1) + [1 - f_{EM}(E1)] \cdot e/h}{f_{EM}(E_2) + [1 - f_{EM}(E2)] \cdot e/h}$$

  - Assuming linearity for EM showers
  - And e/h constant with energy

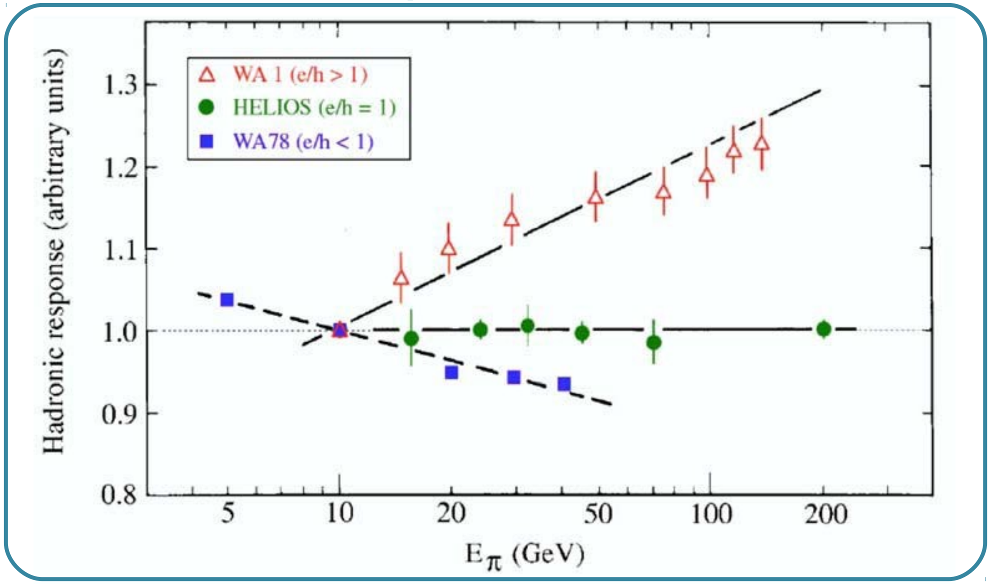
$$e/h = 1 \Rightarrow \frac{\pi(E1)}{\pi(E2)} = 1$$

The origin of non linearity



- Inversely: measurement of non-linearity is one method to determine e/h

Pion responses vs energy



Compensation

- Non-electromagnetic shower energy components
  - **Ionization** by charged pions (relativistic shower component) → f_{rel}
  - **Spallation protons** (non-relativistic shower component) → f_p
  - Kinetic energy carried by **evaporation neutrons** → f_n
  - The energy used to **release protons and neutrons from nuclei**, and the kinetic energy carried by **recoil nuclei** do not lead to a signal → f_{inv}

$$e/h = \frac{e/m}{f_{rel} \cdot rel/m + f_p \cdot p/m + f_n \cdot n/m + f_{inv} \cdot inv/m}$$

e/m: < 1

rel/m: = 1 (similar to mip in their ionization loss)

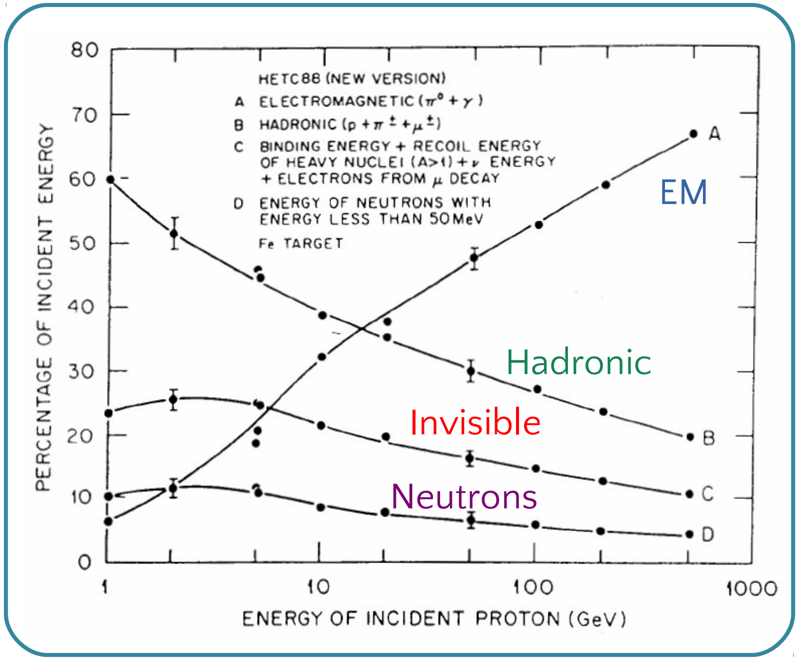
p/m: > 1 (more efficient sampling) But saturates

n/m: > 1 (through elastic scattering)

inv/m: = 0

- **Compensate invisible energy with neutron response**
  - Neutrons correlated with binding energy loss
- **Reduce e/m** further

Sharing of energy between components



Increasing neutron response

- Elastic scattering higher with light nucleus: $f_{elastic} = 2A/(A+1)^2$
  - 0.5 for Hydrogen
  - 0.005 for Lead
- Recoil protons can be measured
- Pb / H_2 calorimeter structure with 50/50 sharing
  - 1 MeV neutron deposits 98% in H_2
  - mip deposits 2.2% in H_2

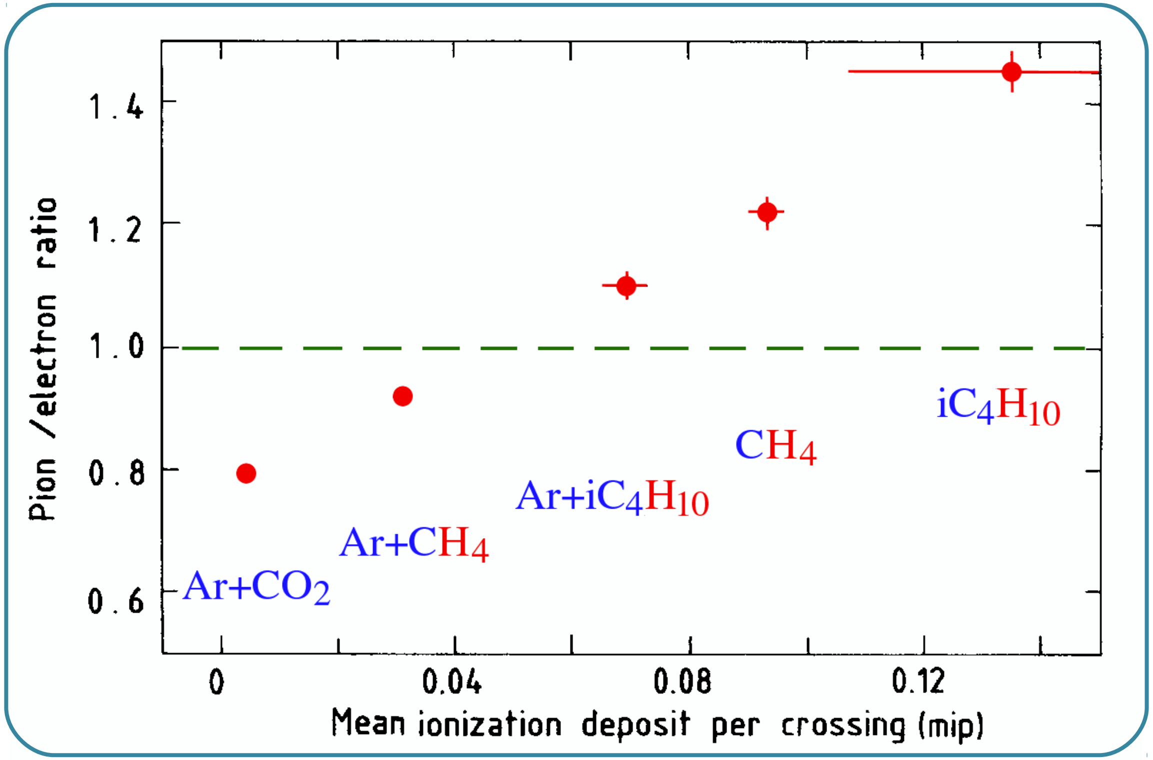
  } n/mip = 45
- Pb / H_2 calorimeter structure with 90/10 sharing
  - 1 MeV neutron deposits 87% in H_2
  - mip deposits 0.25% in H_2

  } n/mip = 350

Tuning neutron response with active material

- The key to boost hadronic response is to use **hydrogenous active material**
- The response can be tuned using more or less hydrogeneous material

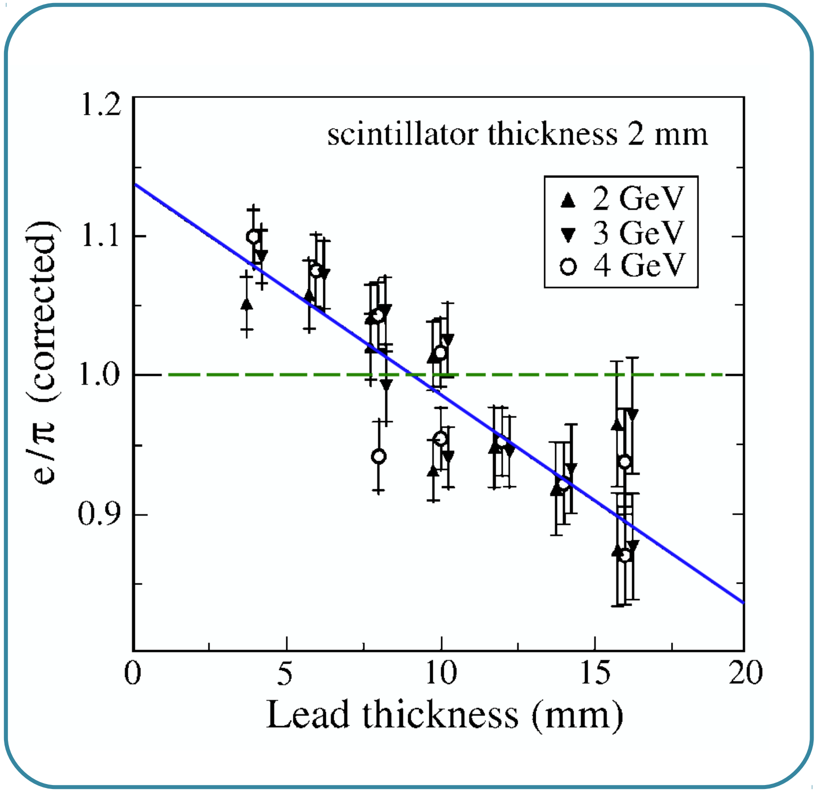
π/e for several materials, with different energy deposits by slow neutrons (Uranium / gas calorimeter with different gas mixtures)



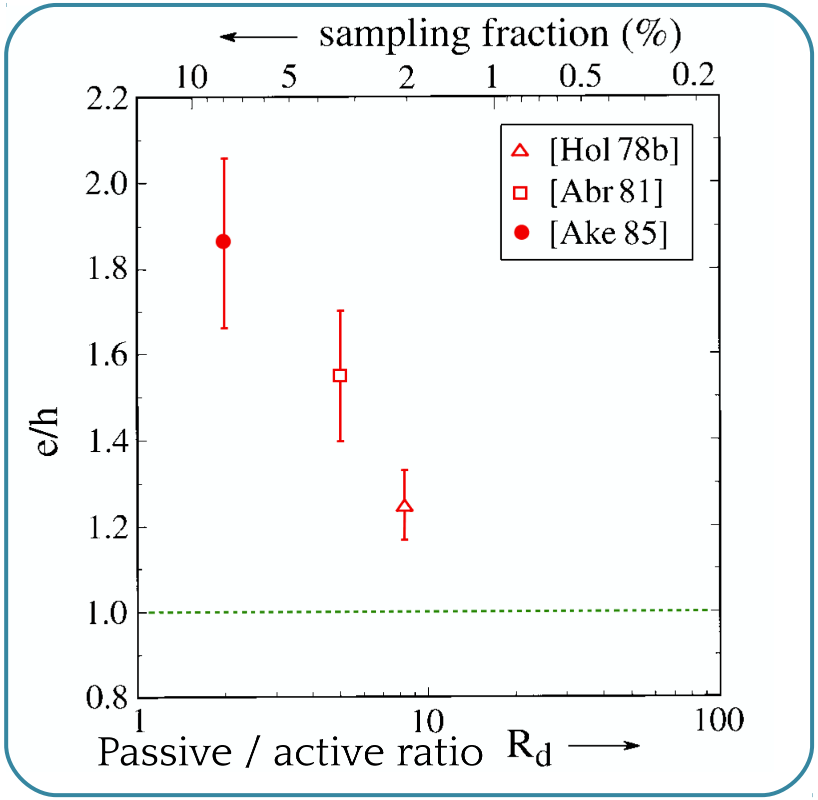
Tuning neutron response with sampling fraction

- Finer tuning can be obtained by **adjusting the sampling frequency**
- Works best with Lead and Uranium
  - e.g. a ratio of 4:1 gives compensation for Pb/Scint
- In principle also possible with iron, but only a few neutrons generated
  - Ratio > 10:1 needed → deterioration of longitudinal segmentation

e/π for Pb / Scint calorimeters



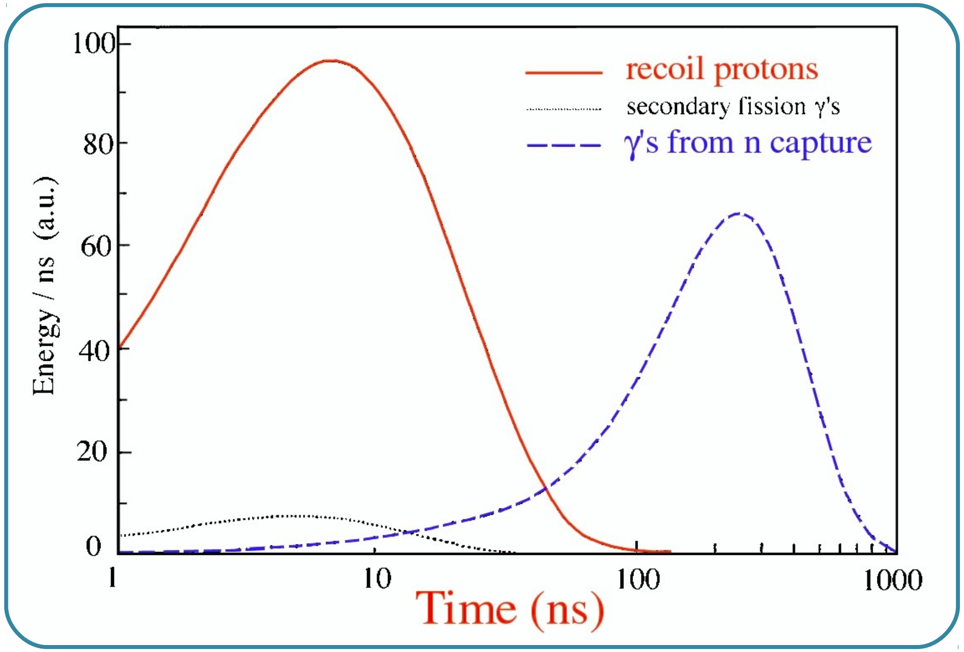
e/h for Fe / Scint calorimeters



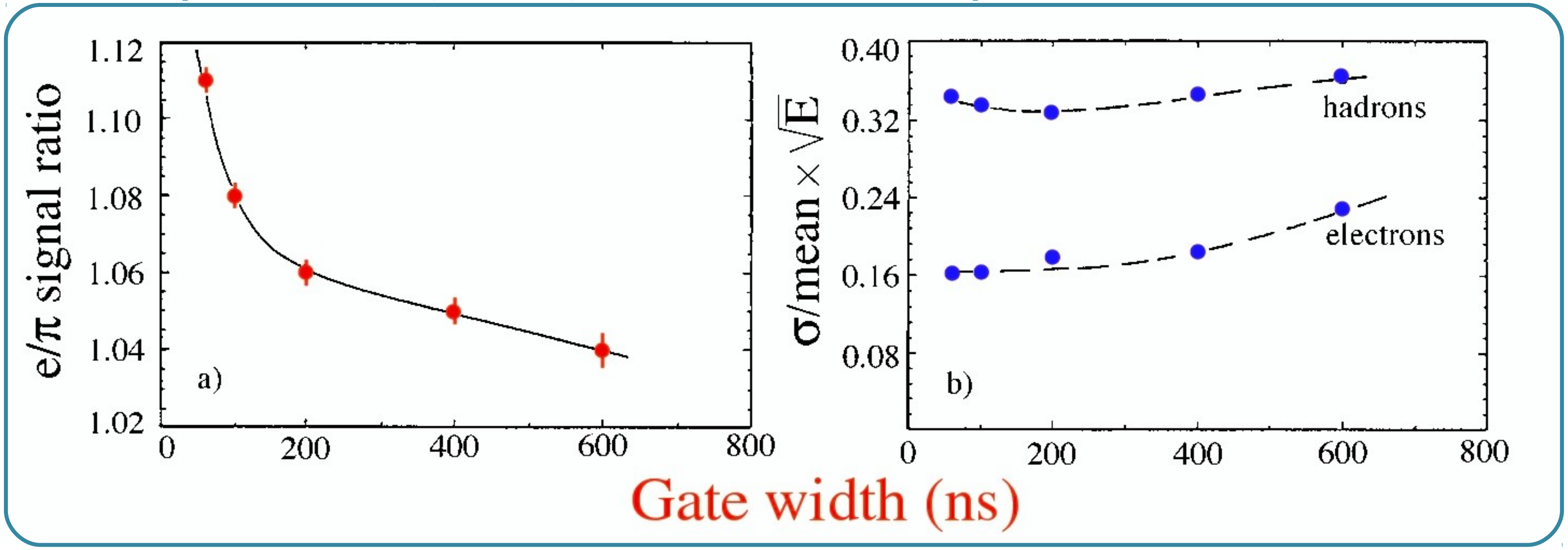
Energy released by slow neutrons

- Large fraction of neutron energy captured and released after 100 ns
- Needs **long integration time** to collect this energy
- Trade-off between compensation and noise integration (resolution degradation)

Time structure of neutron-induced processes in U / Scint calorimeter



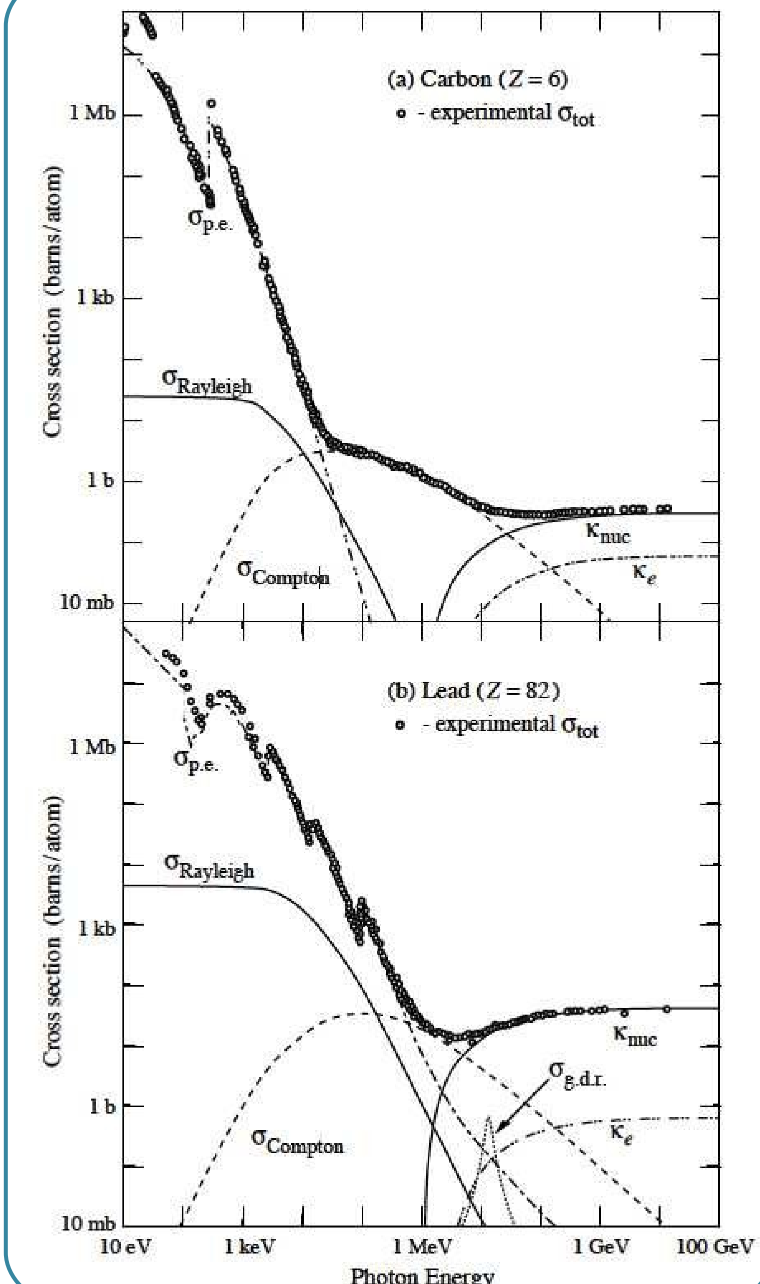
Impact of charge integration time on compensation and resolution



Decreasing EM response

- Electrons and photons are sampled less efficiently when using **high-Z absorber**
  - Photoelectric effect cross section ∝ Z^5
  - Photons < 1MeV captured in absorber
- Recipe for compensating hadron calorimeter
  - High Z absorber
  - Hydrogenous active medium
  - Precisely tuned sampling fraction

Cross sections in Carbon and Lead



Pros & cons of compensating calorimeters

- Pros
  - Same energy scale for electrons, hadrons and jets
  - Just need to calibrate with electrons
  - Excellent hadronic resolution
  - Linearity, Gaussian response distribution
- Cons
  - Small sampling fraction → EM energy resolution limited
  - Compensation relies on detecting neutrons
    - Large integration volume
    - Long integration time (~50 ns) → noise integration

Energy resolution

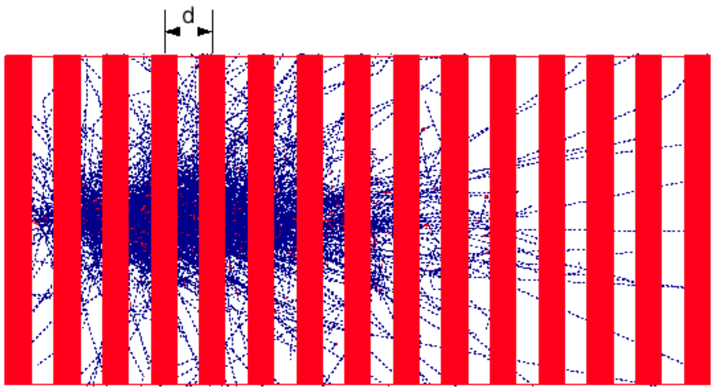
- Calorimeter's energy resolution is determined by **fluctuations**
- Input energy **E ∝ N number of secondary particles**
  - Poisson distribution of N → $\sigma(E)/E \propto \sqrt{N}/N \propto 1/\sqrt{E}$
  - Although in reality only a fraction can be detected (threshold effects)
- Other types of fluctuations
  - 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
  - Lower sampling → less particles collected → larger fluctuations
- **Active layer thickness**
  - Large fraction of low energy electrons (< 1MeV) produced in absorber
  - Traveling a small distance in active material

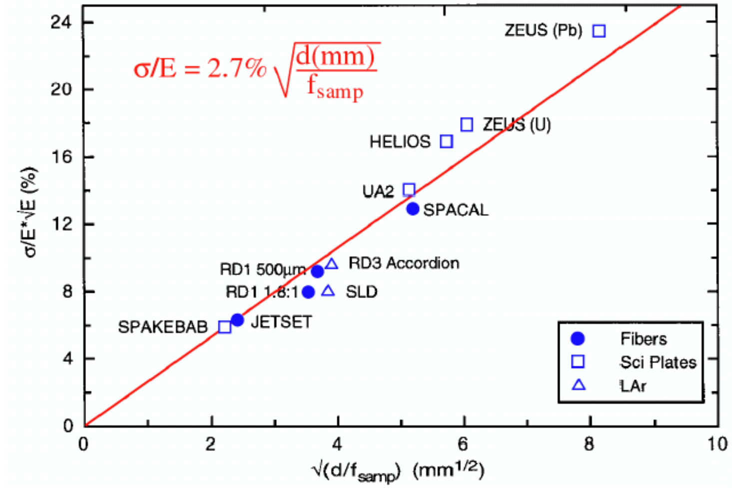
$$f_{samp} = \frac{E^{mip}_{loss\,in\,active}}{E^{mip}_{total\,loss}}$$

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



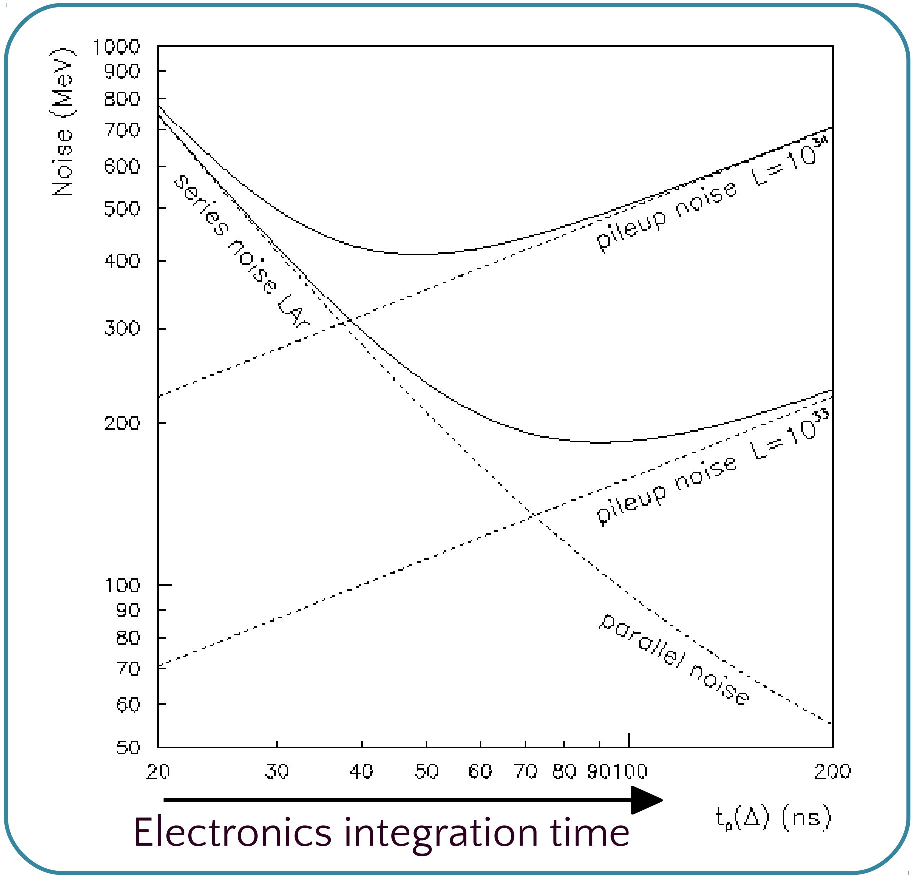
Thicker active layer → worse resolution
Lower sampling → worse resolution

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



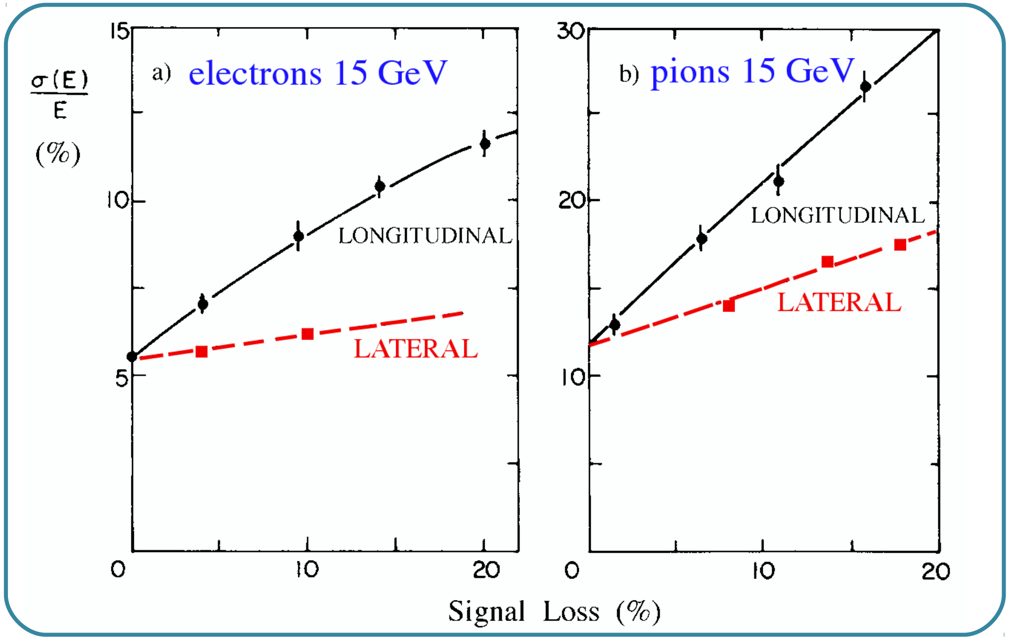
- Noise fluctuations are constant in energy
  - → Impact resolution in 1/E (mainly low energy)
- Usually comes from the **electronics readout** system
- But at hadron colliders
  - Contributions from **pile-up interactions**
  - = fluctuations due to multiple low energy collisions

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

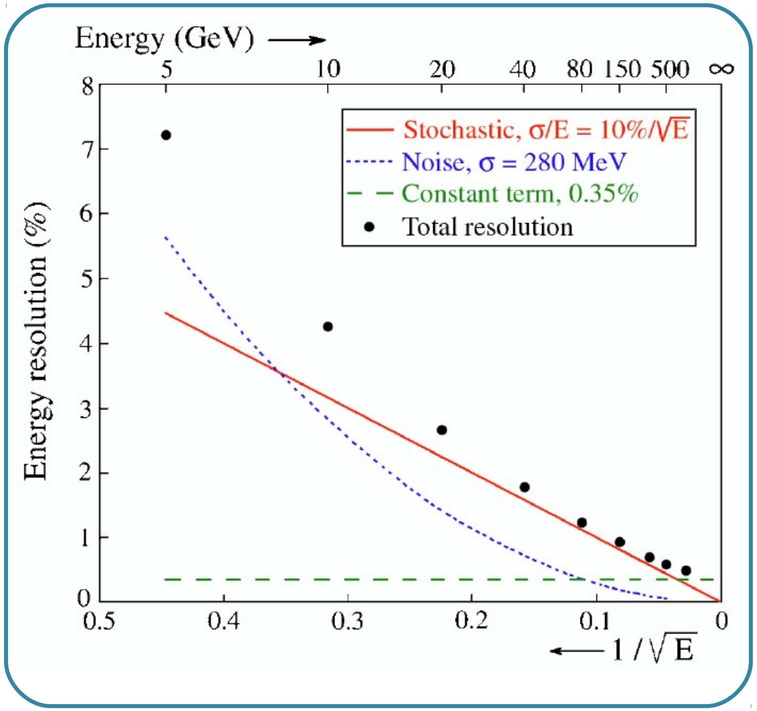
$$\frac{\sigma(E)}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C$$

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)	$16\text{–}18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	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)	$20\text{–}30X_0$	$18\%/\sqrt{E}$	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)	$20\text{–}30X_0$	$12\%/\sqrt{E} \oplus 1\%$	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

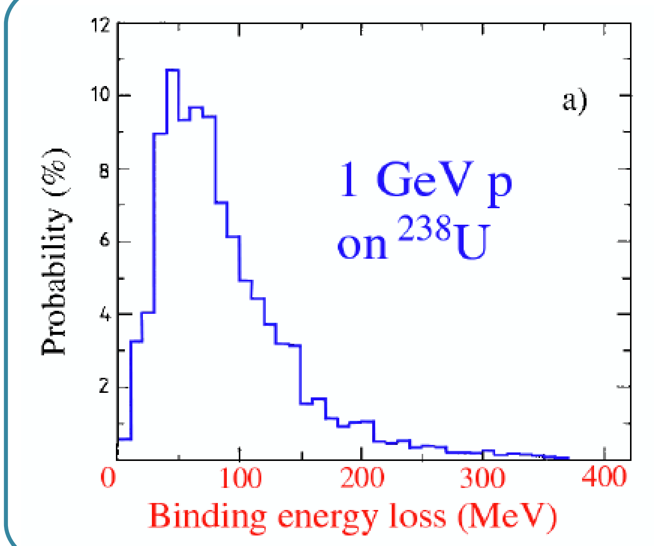
Homogeneous

Sampling

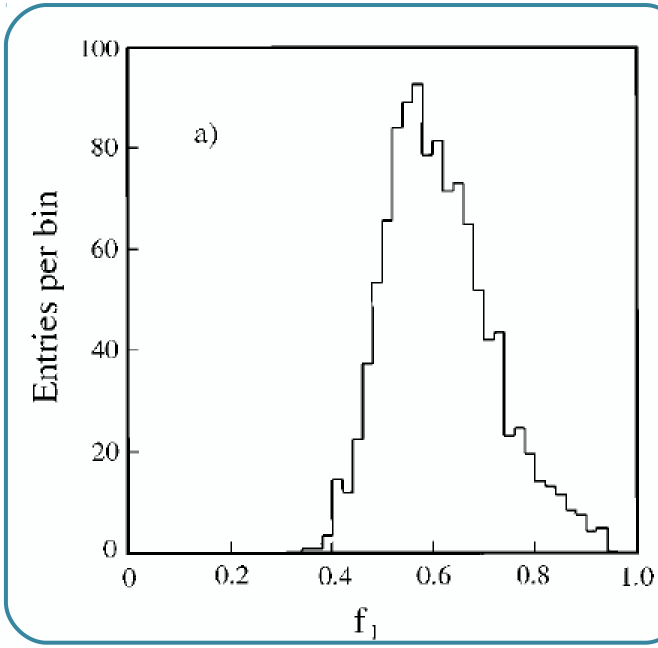
Fluctuations in hadron showers

- 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 $e/h \neq 1$
  - 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



Lecture plan

What is a calorimeter in HEP?

Electromagnetic and hadronic showers

Detection techniques

Calorimeter response & resolution

Electronics readout and trigger

Energy reconstruction & calibration

Beyond calorimetry: Particle Flow

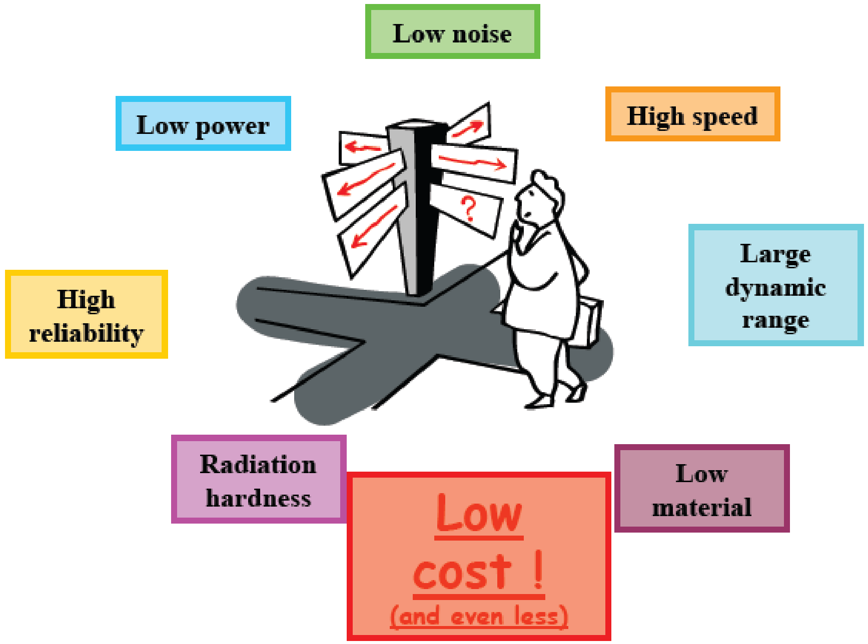
An example: CMS HGCAL

Signal acquisition

- Determine energy deposited and event time in detector
- Detector signal = short current pulse
  - Thin silicon detector (10-300 μm): 100ps-30ns
  - Thick (-cm) Si or Ge detector: 1-10μs
  - Scintillator + PMT/APD: 100ps – 10μs

Energy proportional to collected charge $$E \propto Q_s = \int i_s(t)\,dt$$

- Necessary to **integrate detector signal current**
- Small signal → need **amplification**
- But many requirements & constraints



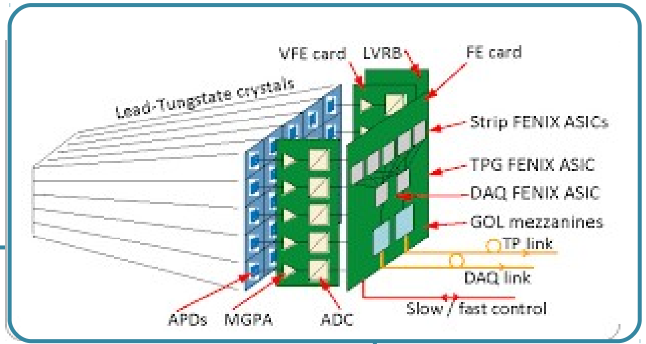
Data acquisition

- Signal is **converted to digital** values
- Put in **buffers** until it is read out by the DAQ (data acquisition) system and **transferred to mass storage** (disk, tape)
- In many cases, all the data cannot be stored or transferred
  - → **Trigger system**
  - Real-time processing of events on reduced data
  - Accept / reject decision

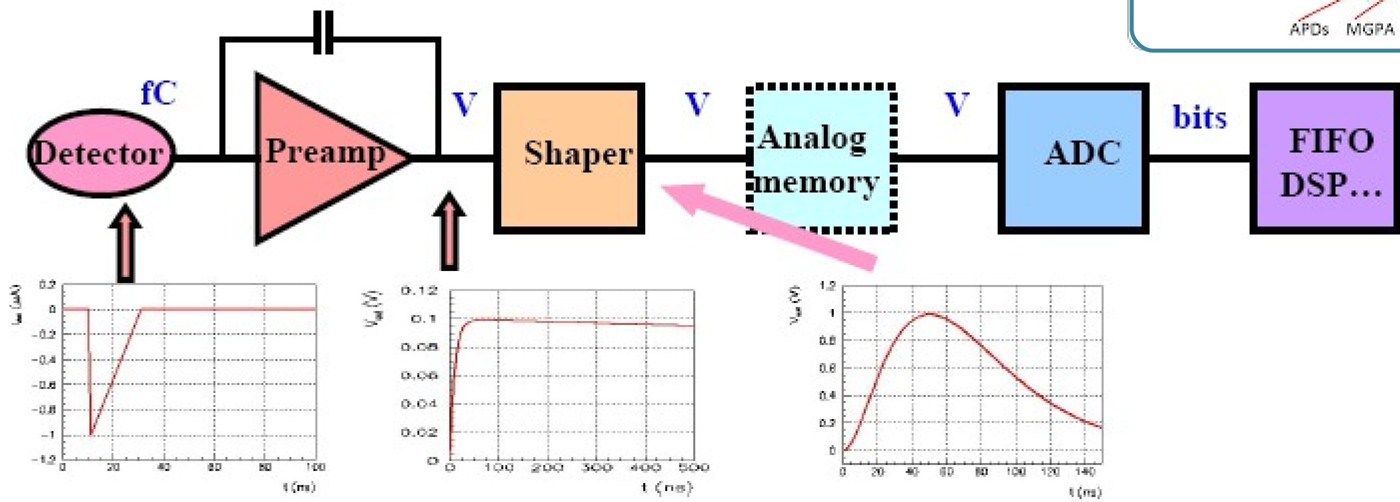
Readout electronics

- Located on detector (front-end electronics)
- Most front-ends follow a similar architecture

CMS ECAL FE electronics



Typical front-end electronics chain

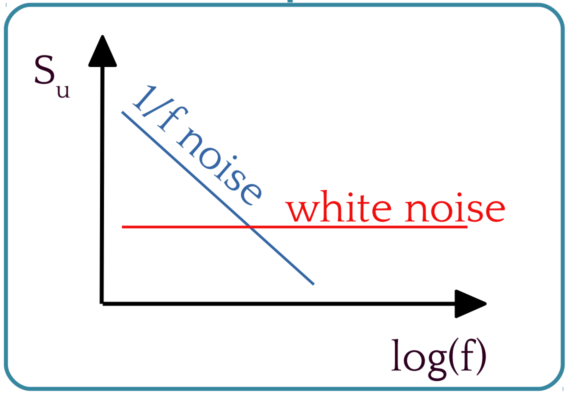


- Very small signals (fC)
  - Amplification needed
  - Optimisation of S/N (shaper)
- Need time to decide to keep the event or not → memory
- Conversion from analogue signal to digital values (ADC pulse sampling)

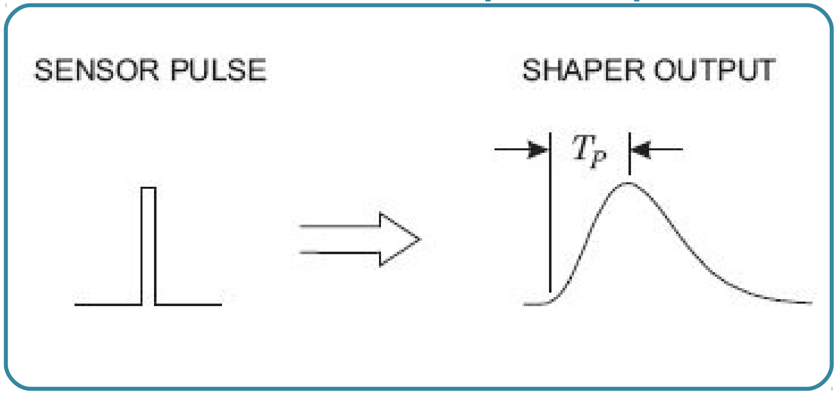
Pulse shaping

- Goal = **increase S/N ratio**
- Cut low frequency and high frequency noise
  - Limit bandwidth
  - Shaping = filtering
- **Limited frequency band** with characteristic time consistent with the input pulse
- In case of successive signal pulses
  - Shaped pulse need to be short enough
  - Avoid signal overlap
- Two conflicting effects
  - Filter noise
  - Avoid overlap

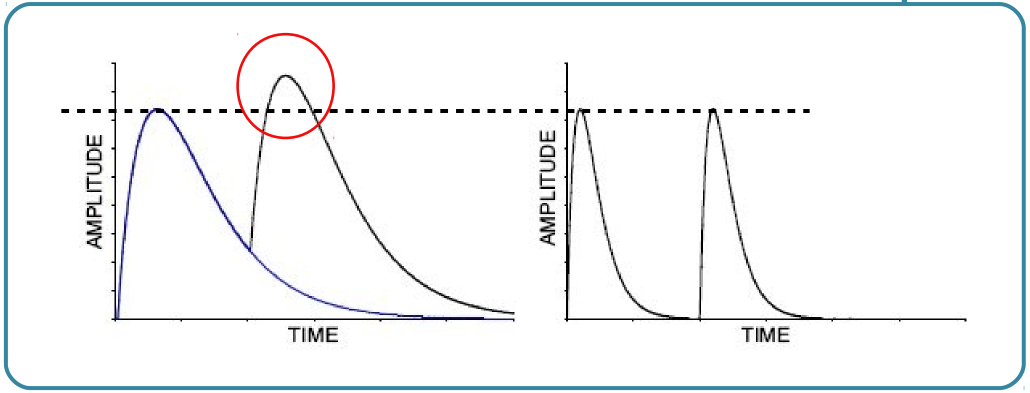
Noise spectrum



Shaper output



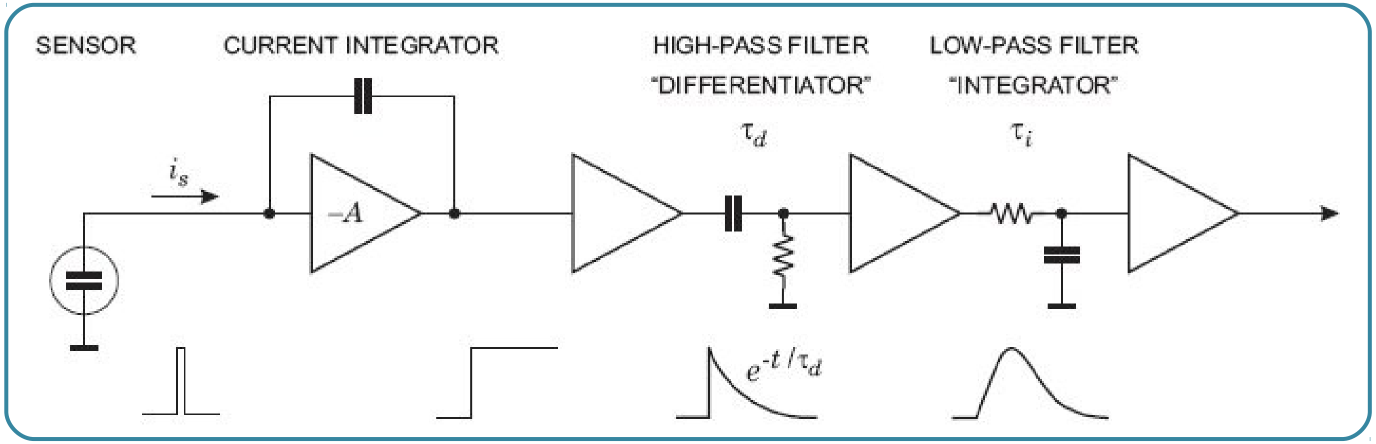
Pulse overlap



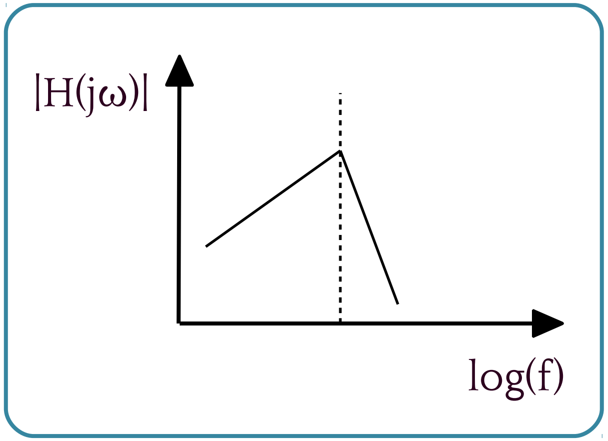
CR-RC shaper

- CR circuit = "**differentiator**" = high-pass filter
  - Sets the duration of the pulse
- RC circuit = "**integrator**" = low-pass filter
  - Increases the rise time to limit high-frequency noise

Integrator + RC-RC chain

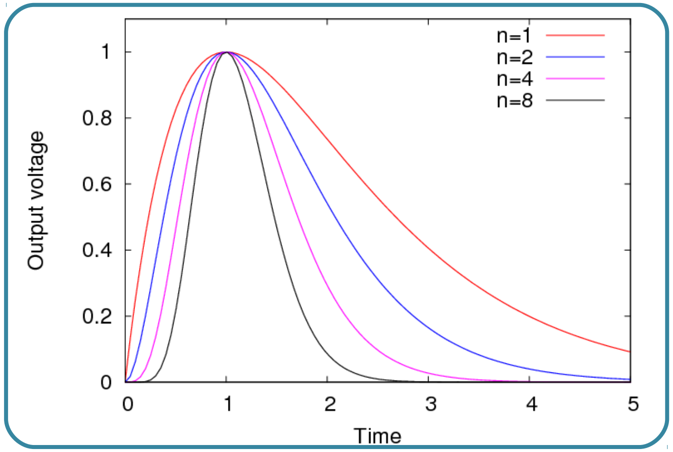


RC-(RC)^n transfer function



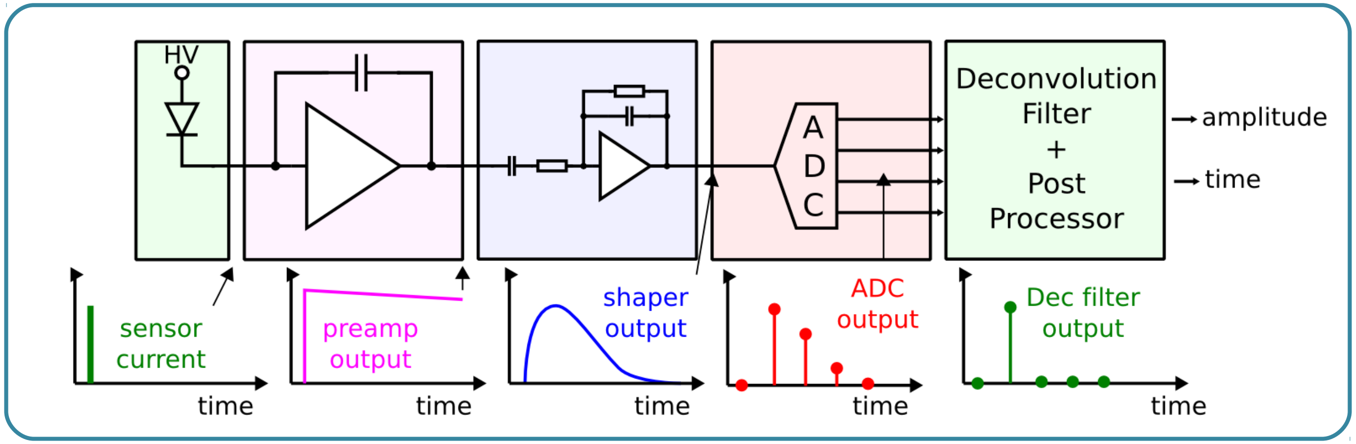
- Can also have additional RC or CR steps
  - e.g. CR-(RC)^2
  - CR-(RC)^n approximates Gaussian shape

Impact of filter order

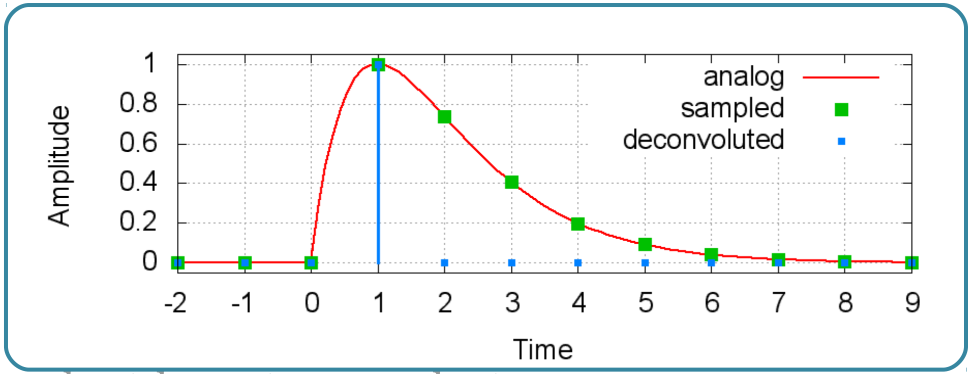


Amplitude measurement

After the shaping



- Pulse at output shaper = convolution of input signal and readout chain response
- Can perform **deconvolution** of the two, using the sampled pulse values
- Usually done in two steps



  - **Linear digital filter**

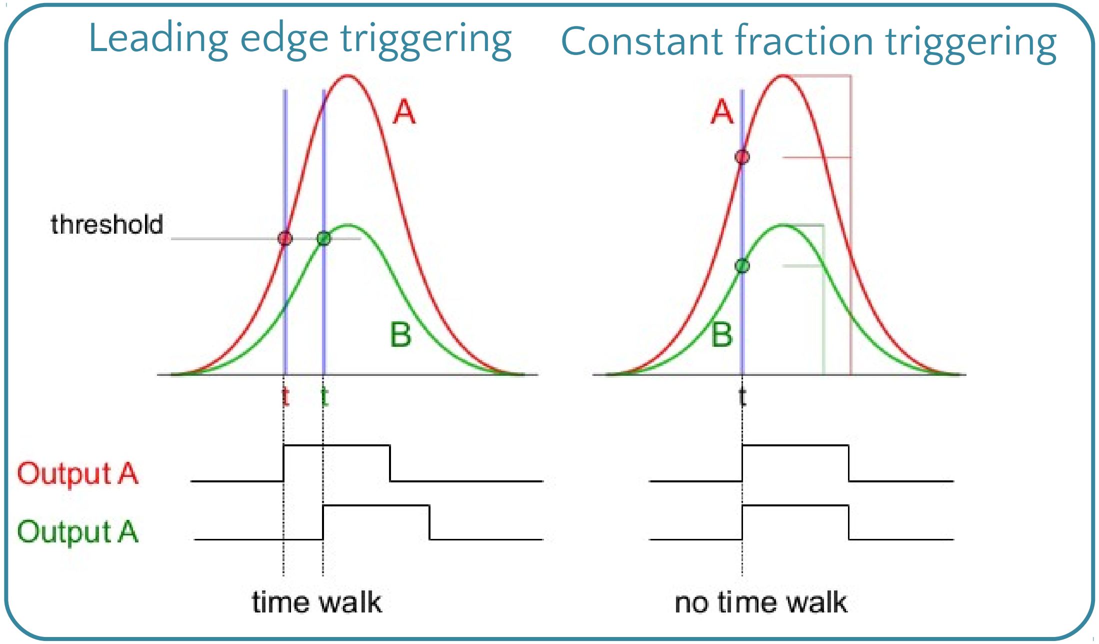
$$\hat{A} = \sum_{0 \leq i < N} w_i \times S_i$$

    - Weights w_i can be optimized with various techniques
    - Takes into account noise characteristics and known pulse shape
  - **Peak finder** to find maximum

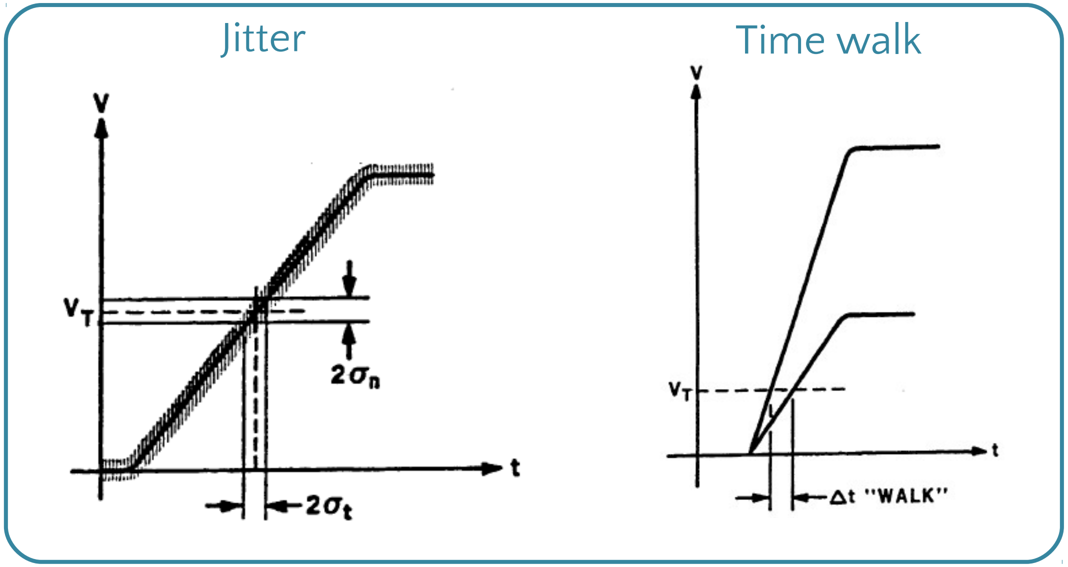
Time measurement

- Time measurement based on discriminators
  - Compare voltage level of signal with a given level (threshold)
- Often discriminator output depends on the signal amplitude
  - = Time walk
- Slope to noise ratio characterizes the time measurement
- Measurement affected by
  - Jitter: due to high-frequency noise
  - Time walk (can eventually be corrected)
- Ideally needs
  - Fast rise time of the pulse
  - Low noise

Discriminator techniques



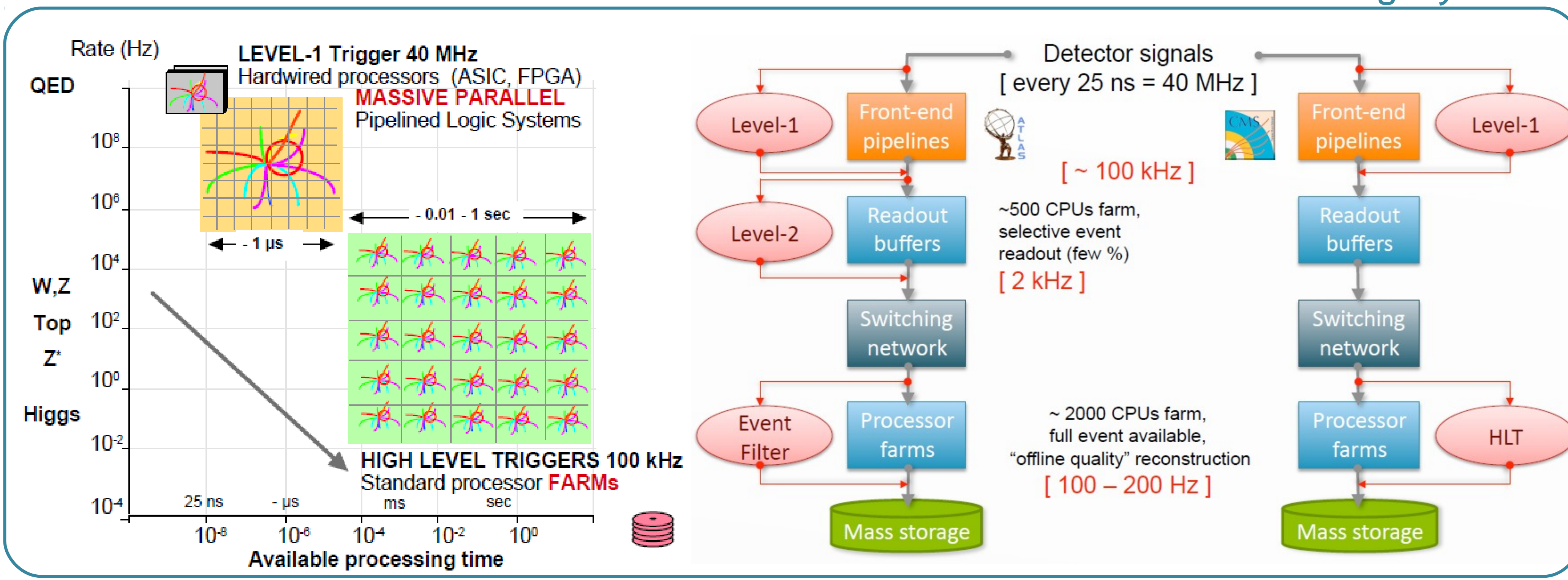
Measurement degraded by



Trigger

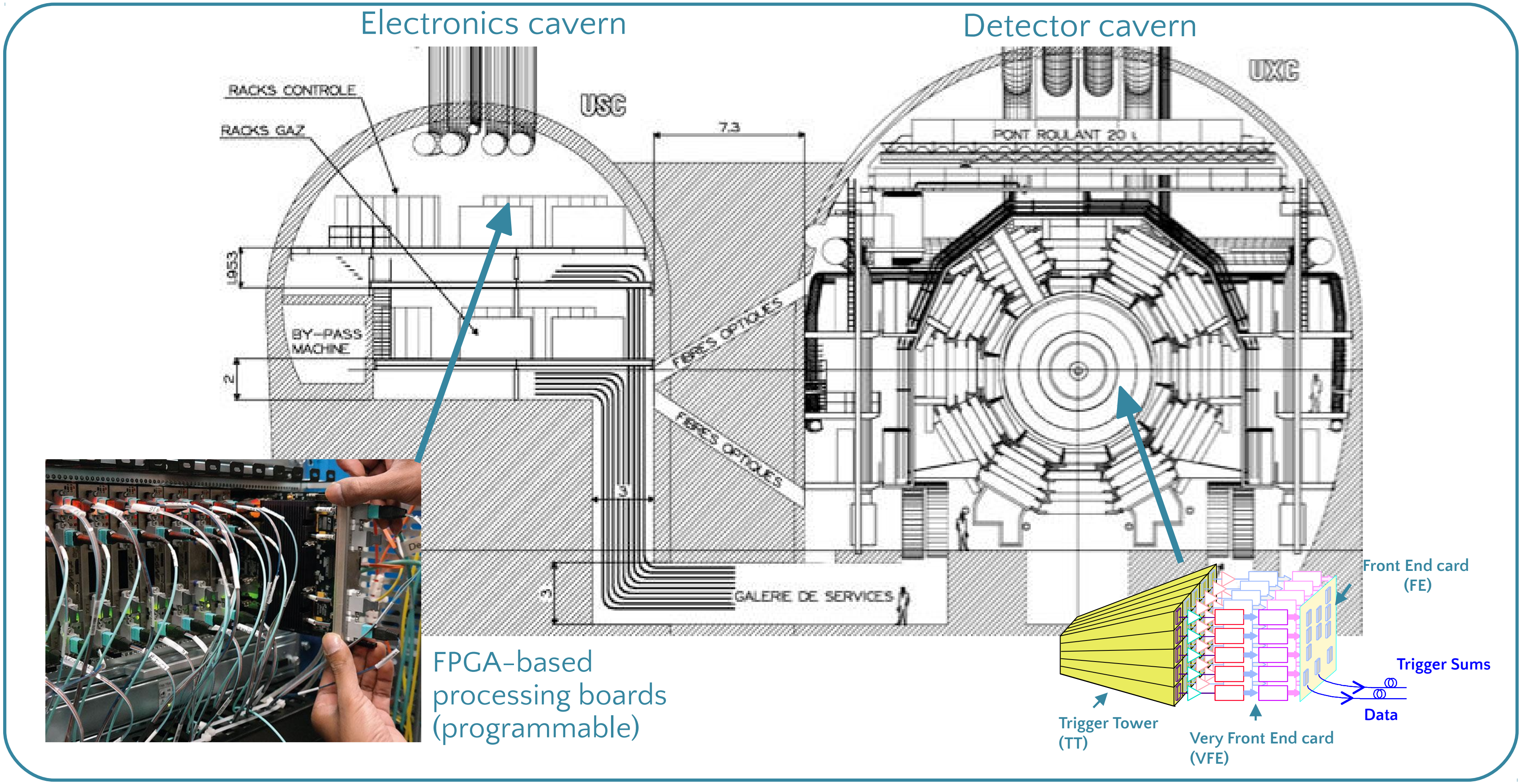
- In many cases it is impossible to store or transfer all the data from a calorimeter
  - e.g. at the LHC
- Need fast **trigger system to eliminate uninteresting events**
  - Trade-off between high performance (signal efficiency / background rejection)
  - And fast decision / low latency
- One solution: **multi-stage system**

Rate reduction in multi-stage systems



Off-detector electronics

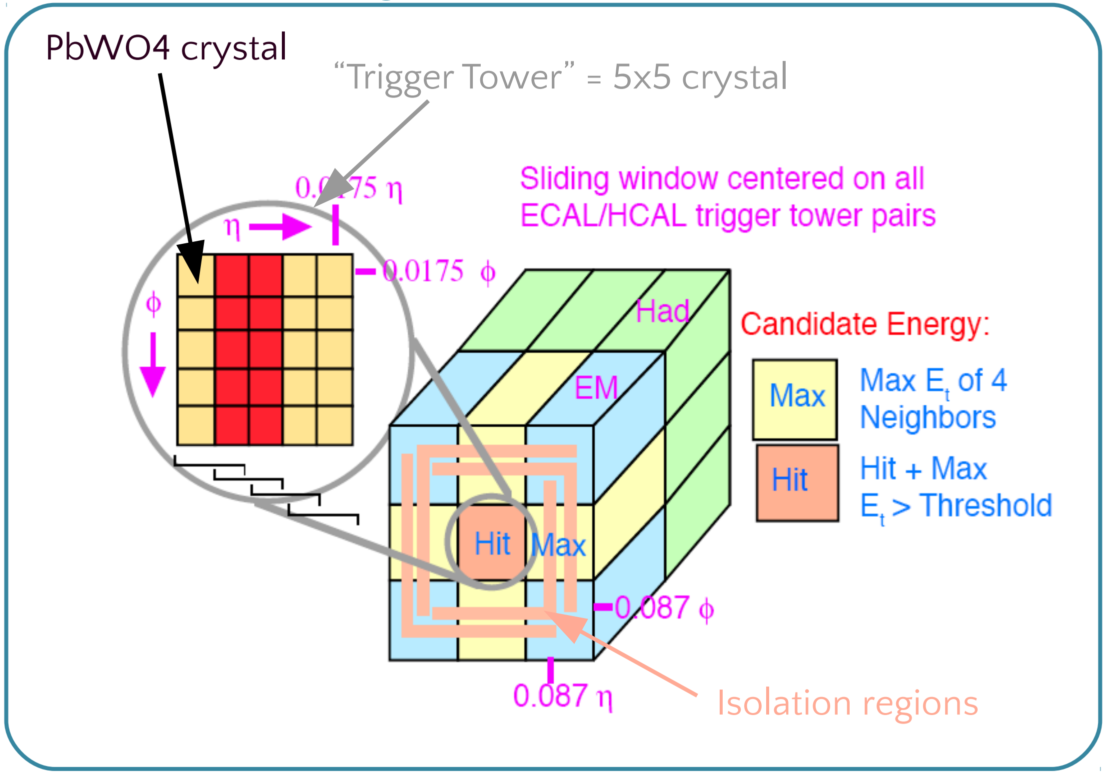
- **First trigger level** (L1) processing : hardware based (ASIC, FPGA)
  - **Data simplification / coarsification** on-detector (in **front-end electronics**)
  - Reconstruction and decision making off-detector (in **back-end electronics**)
  - Linked with optical fibers



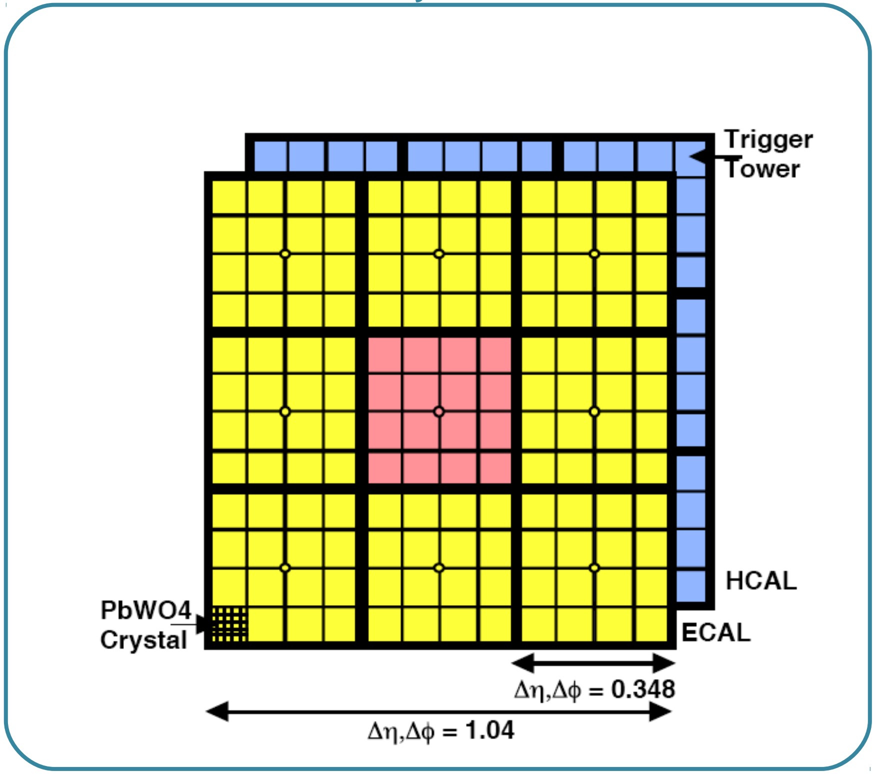
Calorimeter trigger objects, examples (CMS, Run 1)

- Coarse granularity
  - Cannot send the full granular data out of the calorimeter
- Simple reconstruction and identification of the showers
  - Faster
- Apply cut on the (transverse) energy of these objects

Electromagnetic shower reconstruction



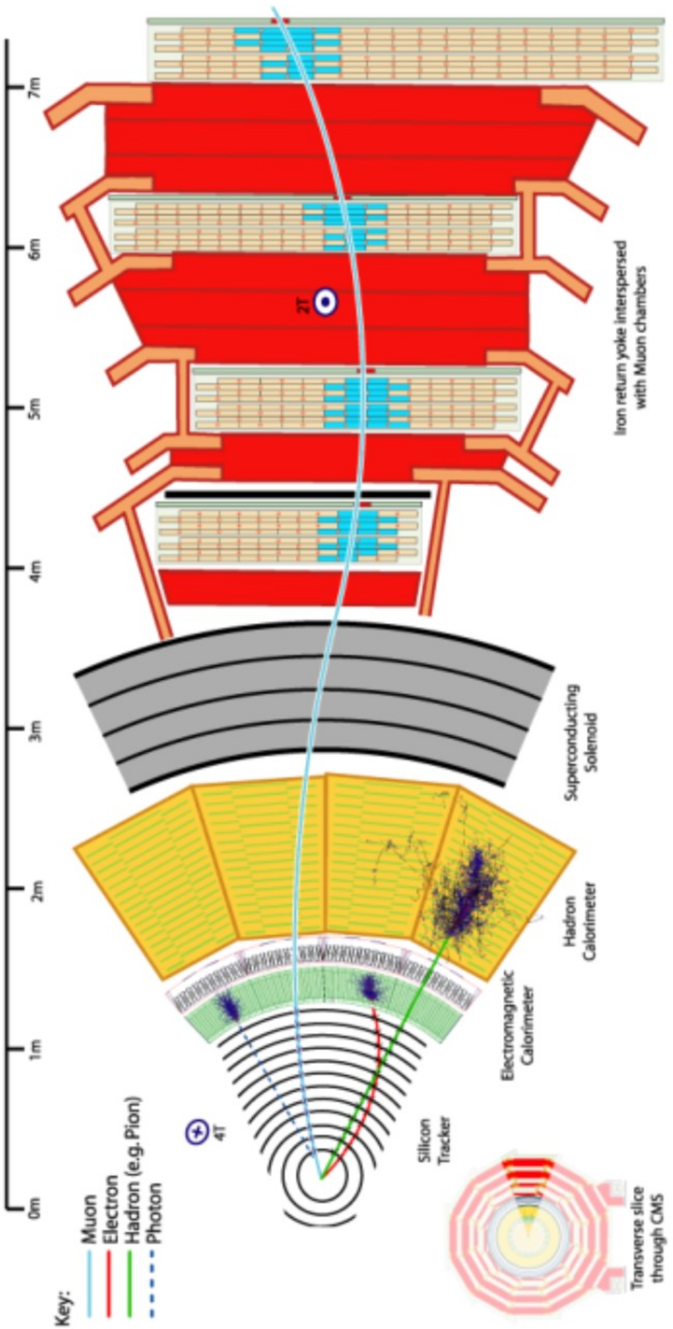
Hadronic shower (jet) reconstruction



Lecture plan

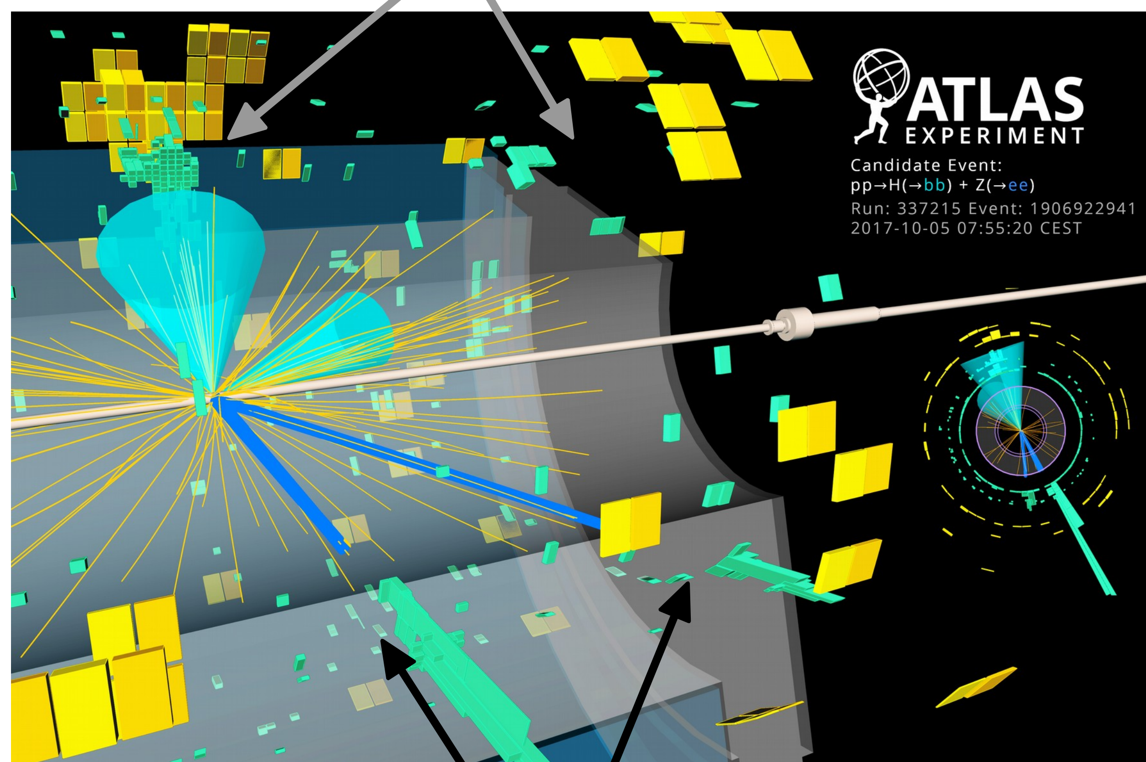
- What is a calorimeter in HEP?
- Electromagnetic and hadronic showers
- Detection techniques
- Calorimeter response & resolution
- Electronics readout and trigger
- **Energy reconstruction & calibration**
- Beyond calorimetry: Particle Flow
- An example: CMS HGCAL

Reconstructing particles in calorimeters



- Focus on objects at colliders
  - Electrons and photons
  - Hadronic jets

Reconstructed jets

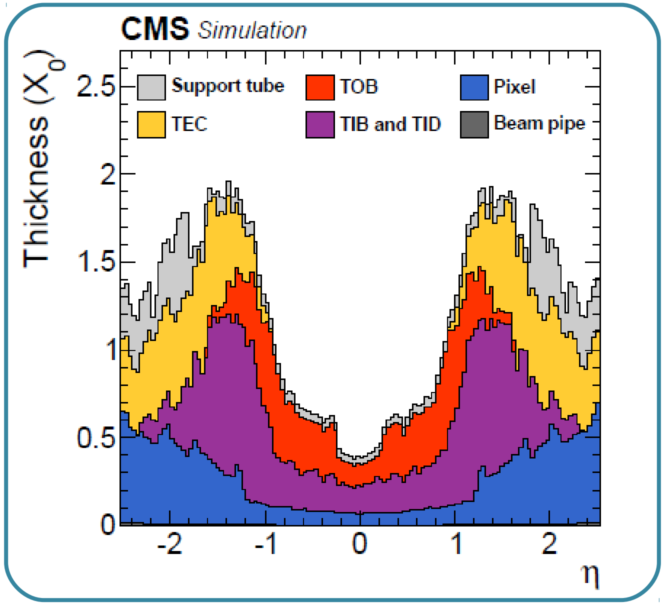


Reconstructed electrons

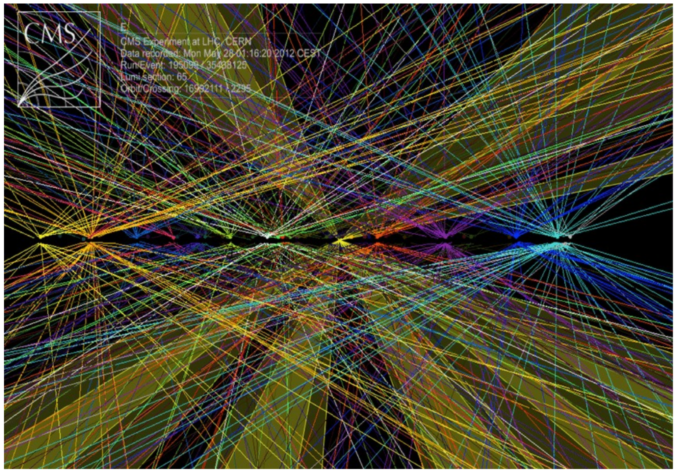
Real-life conditions

- 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
  - **Radiations**, Pile-up (in-time and out-of-time)
  - ...
- Degrades performance compared to standalone devices or test beams

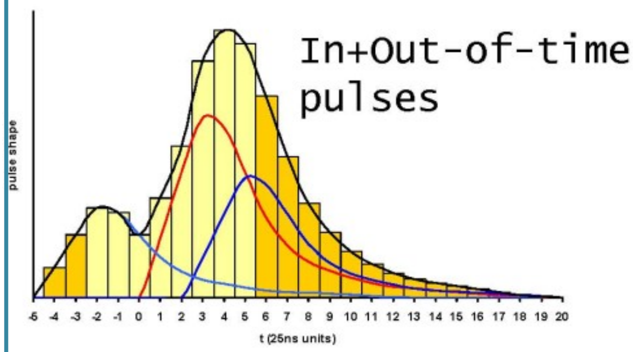
Material in front of the CMS calorimeters



Tracks from multiple simultaneous interactions

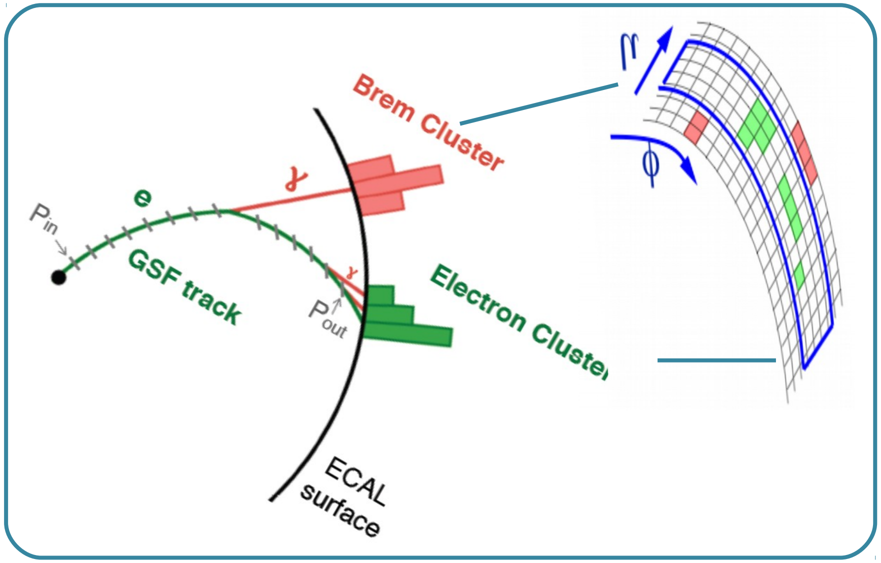


Energy deposited from consecutive interactions

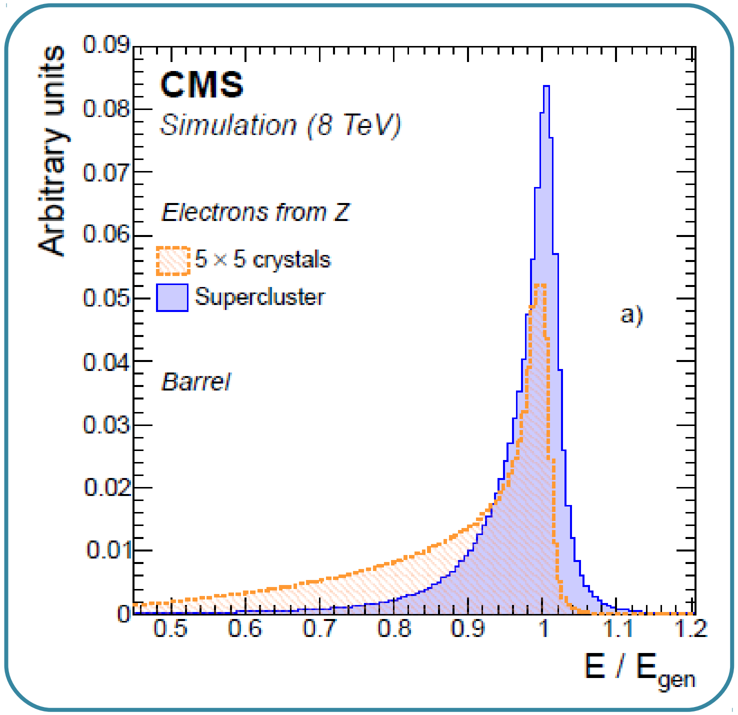


Electrons and photons reconstruction

- Material in front of the calorimeter (cables, cooling, mechanical support, etc.)
  - **Electrons initiate showers before reaching the ECAL** (e.g. 40-80%)
  - Photons convert (e.g. 20-40%) in e^+e^- pairs
- Magnetic field → **radiated energy spread along phi**
  - One electron / photon can produce several distinct showers

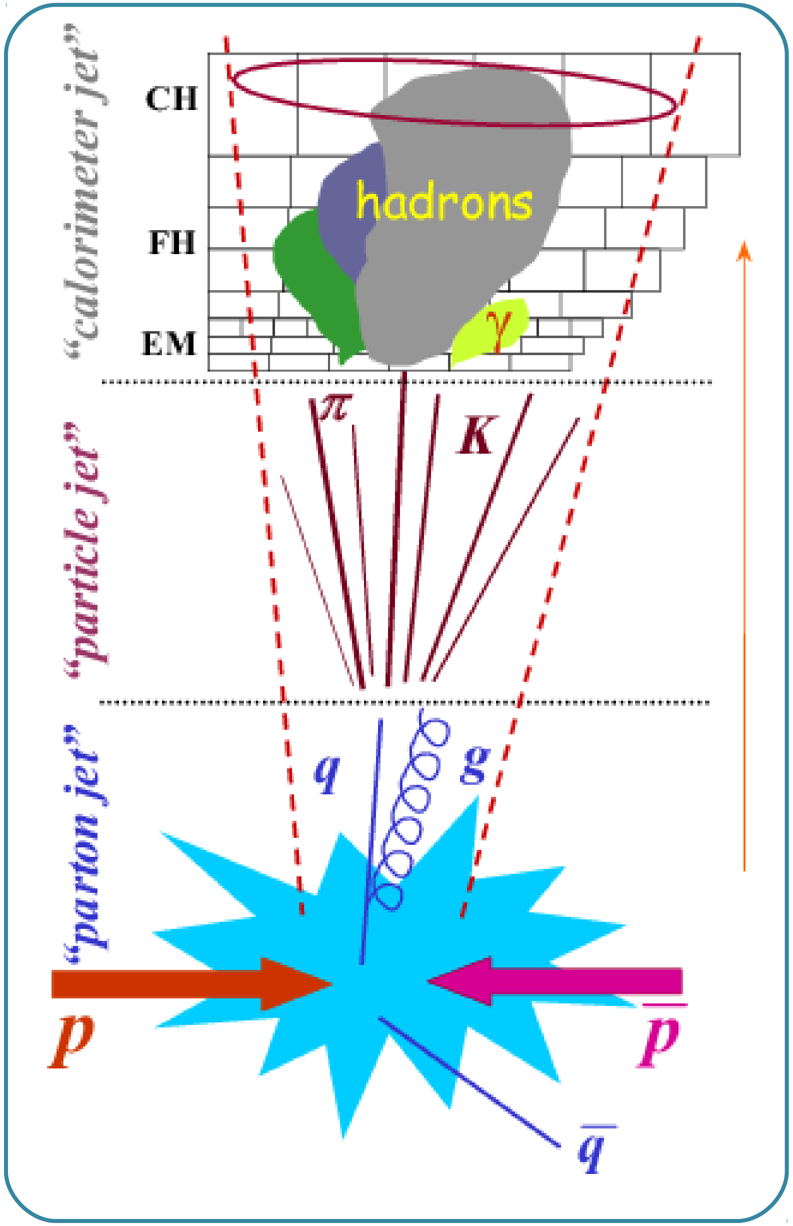


Impact of grouping distant clusters



- Reconstruction algorithms need to
  - **Cluster topologically connected deposits**
  - **Associate distant clusters** together

From single hadrons to jets



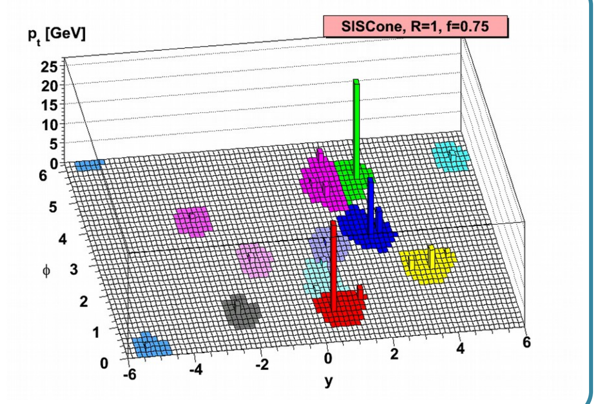
- Quarks and gluons (a.k.a. partons) can be produced from collisions (e.g. protons)
- They produce secondary partons
  - Parton shower
- These partons turns into **collimated hadrons**
  - Hadronization
- This set of collimated hadrons is called a "**jet**"
  - Each hadron will shower in a calorimeter
  - A jet will create a set of overlapping showers
- Jets are reconstructed in two steps
  - **Clustering** of topologically connected deposits
  - **Grouping clusters** together with distance-based association (creates cone-like objects)

- Usually inputs are clusters of energy deposits
  - But can be any vector-like object
- Two main classes of algorithms
  - **Cone algorithms** (older)
  - **Sequential clustering** algorithms (used nowadays)
- Sequential algorithms based on a distance
  - Most commonly used: **anti-kt**

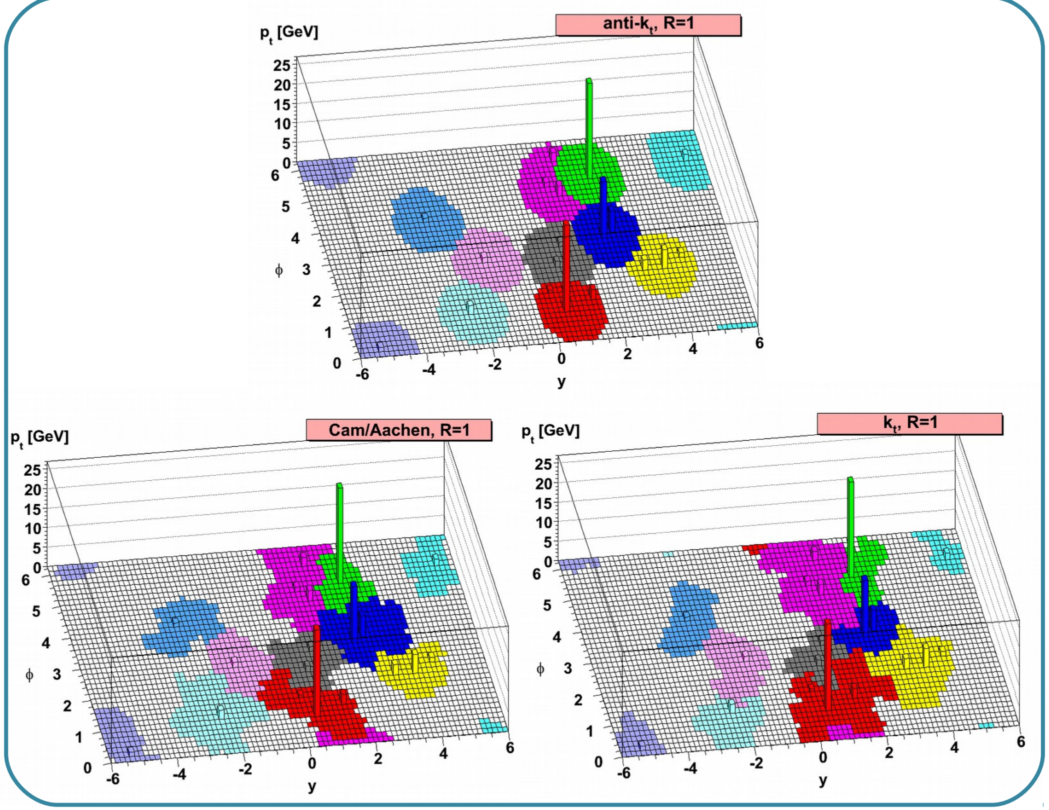
$$d_{ij} = min\left(\frac{1}{p_{Ti}^2}, \frac{1}{p_{Tj}^2}\right) \times \frac{R_{ij}^2}{R}$$

  - Cluster first hard objects → very stable
  - Some others more sensitive to the jet substructure

Example of cone algorithm



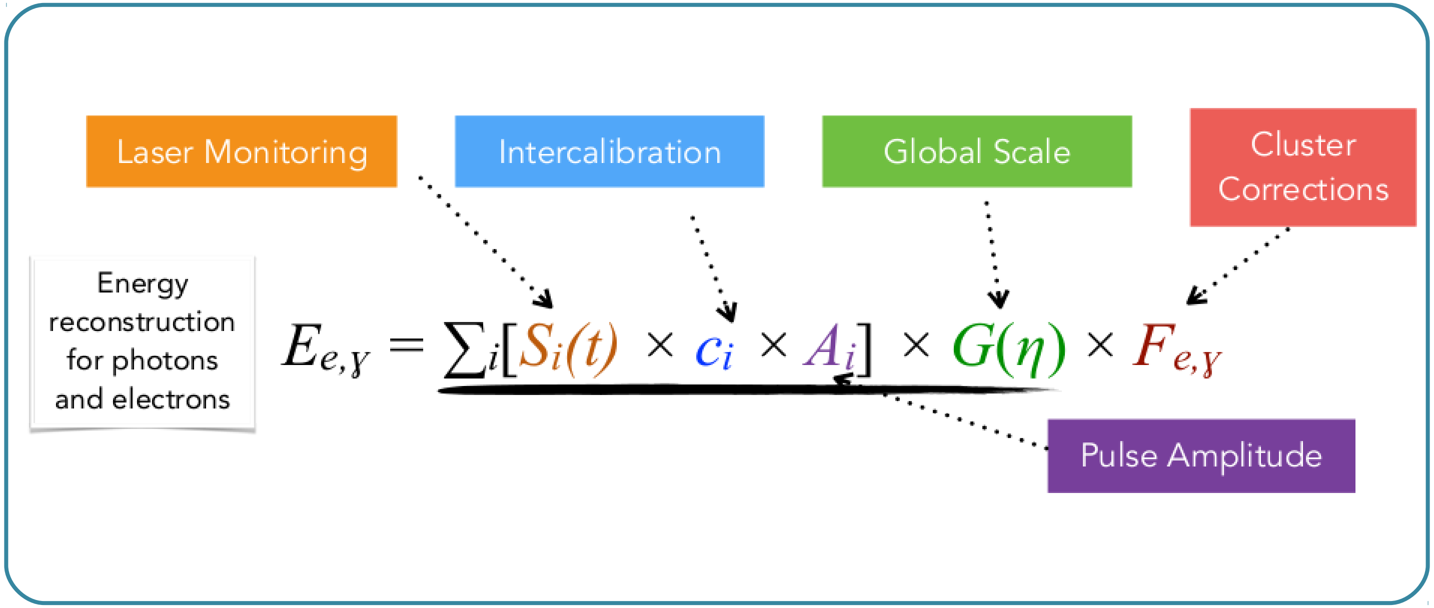
Most common sequential clustering algorithms



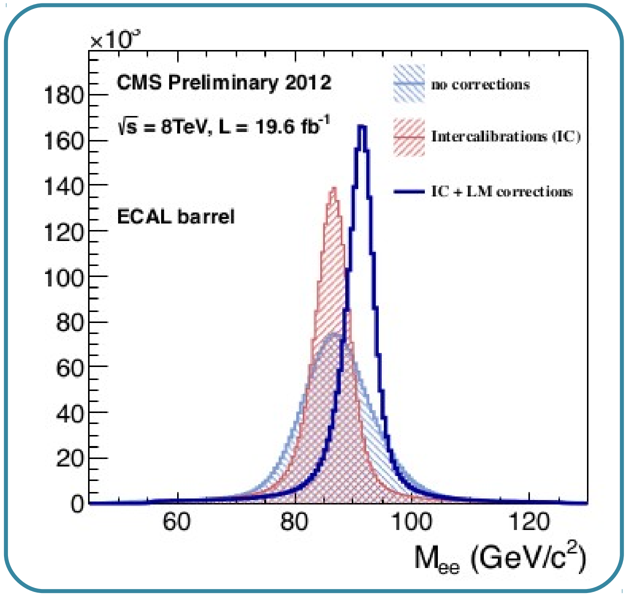
Calorimeter calibration / energy reconstruction

- Typical calibration components
  - Pulse amplitude → energy (charge → energy deposited, can include sampling fraction)
  - Response effects from monitored parameters
  - Intercalibration (looking at differences of response in different places)
  - Leakage corrections (energy outside of cluster)
  - Absolute energy scale correction

Example in CMS ECAL



Impact of intercalibration and laser monitoring



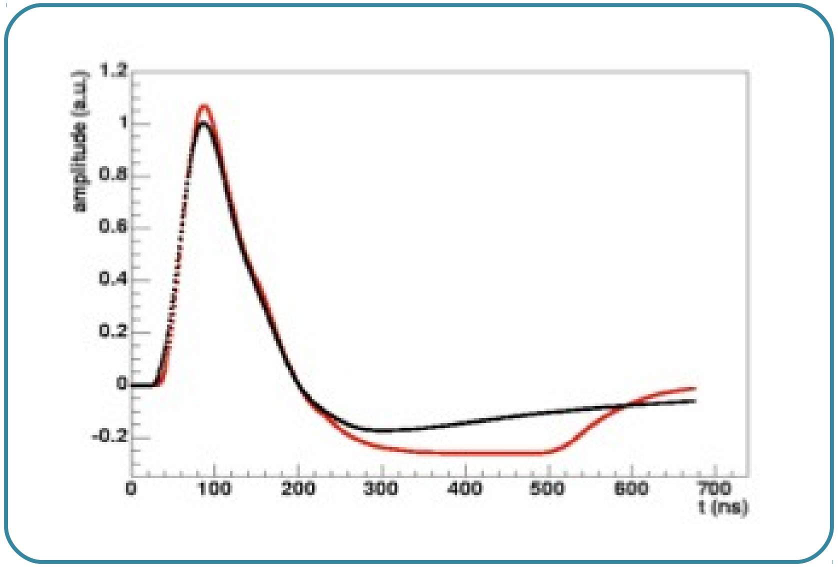
Pulse calibration

$$E_{cell} = F_{\mu A \to MeV} \,.\, M_{cal}/M_{phys} \,.\, R \,.\, \Sigma\, a_i\,(ADC_i - P)$$

- $F_{\mu A \to MeV}$: current to energy conversion including sampling fraction, initial value from Test-Beam
- R electronics gain ($ADC \to \mu A$)
- P pedestal
- M_{cal}/M_{phys} : correct bias from calibration / physics difference
- a_i : Optimal Filter Coefficient to estimate pulse amplitude

- Correct the electronics chain response
  - Linear filtering of ADC samples (seen before)
- Can **derive the response by injecting known signal** (with dedicated calibration circuits)
  - Differences between calibration pulses and physics pulses need to be taken into account

Calibration and physics pulses differences



Pulse calibration

$F_{\mu A \to MeV}$: current to energy conversion including sampling fraction, initial value from Test-Beam

R electronics gain ($ADC \to \mu A$)

P pedestal

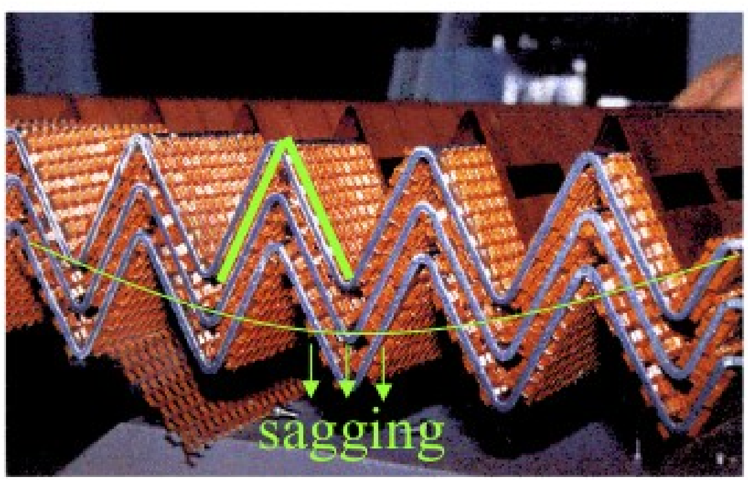
$$E_{cell} = F_{\mu A \to MeV} \,.\, M_{cal}/M_{phys} \,.\, R \,.\, \Sigma\, a_i\, (ADC_i - P)$$

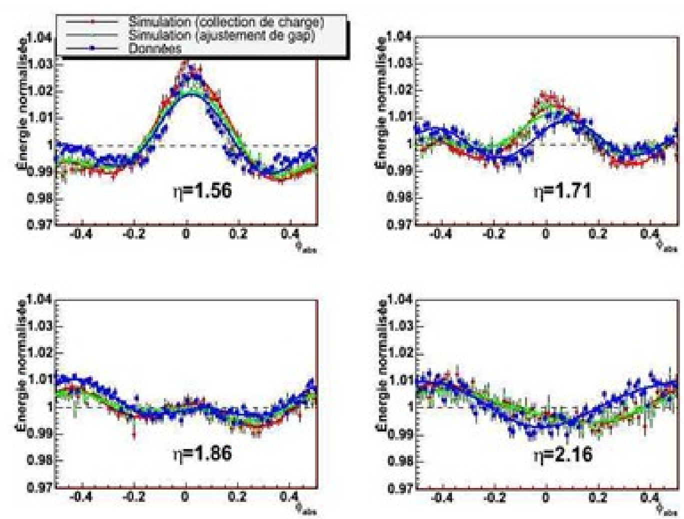
M_{cal}/M_{phys} : correct bias from calibration / physics difference

a_i : Optimal Filter Coefficient to estimate pulse amplitude

- Take into account sampling fraction in case of sampling calorimeters
- Local **variations of the sampling fraction** need to be understood as precisely as possible

Gravity effects impact sampling fraction

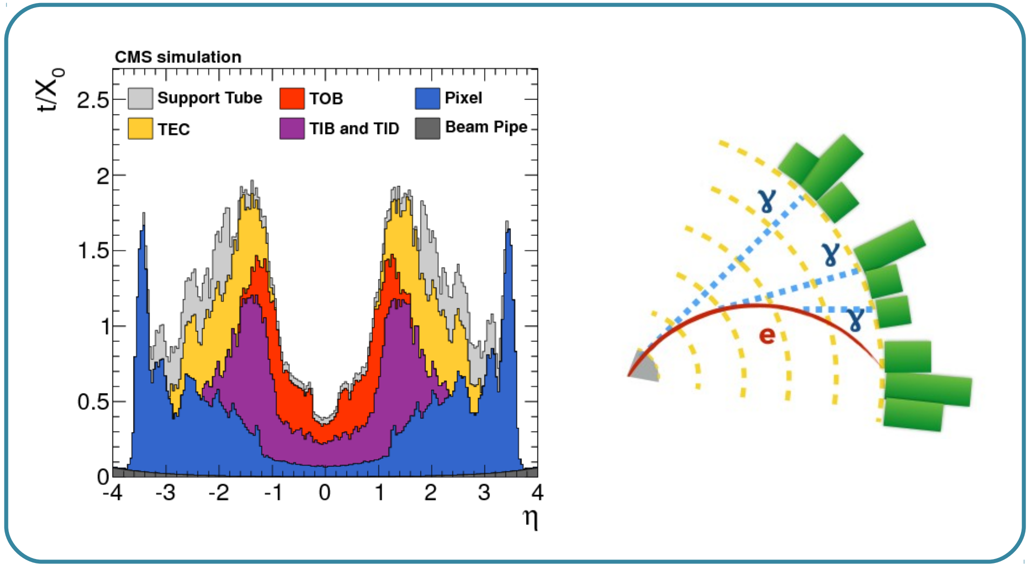




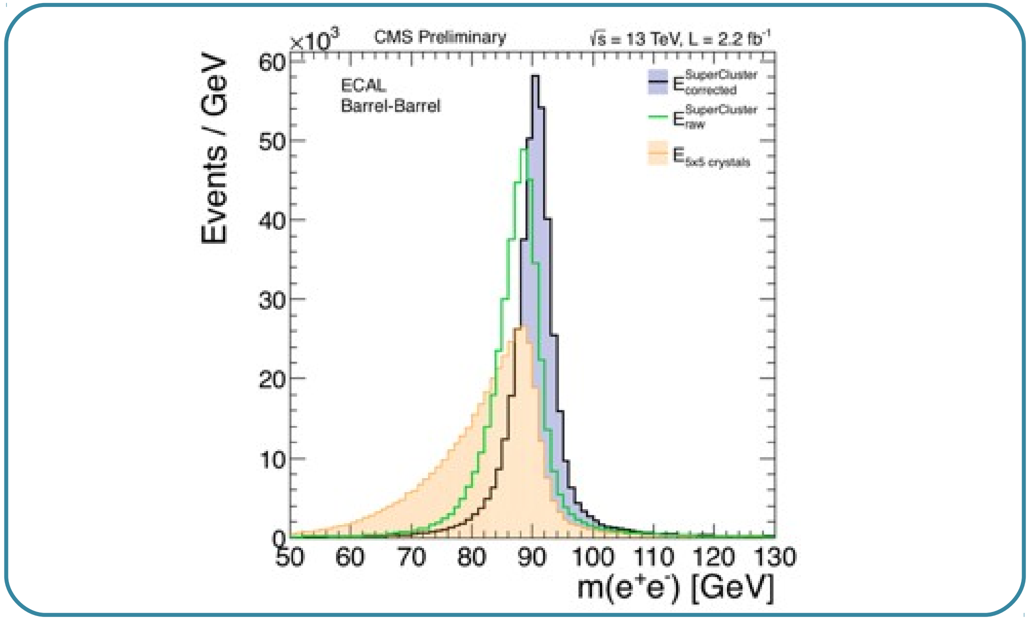
Cluster energy corrections

- Several sources of energy **reconstruction inefficiencies**
  - Threshold applied (e.g. to reduce noise impact)
  - Unclustered energy (linked to calorimeter depth, cluster size, interactions with material in front of the calorimeter)
- Remaining **noise** propagating to the final reconstructed cluster
- Requires reconstruction algorithms optimizations
- And corrections to take into account the remaining effects
  - Derived from detailed detector simulations

Material in front of the CMS ECAL



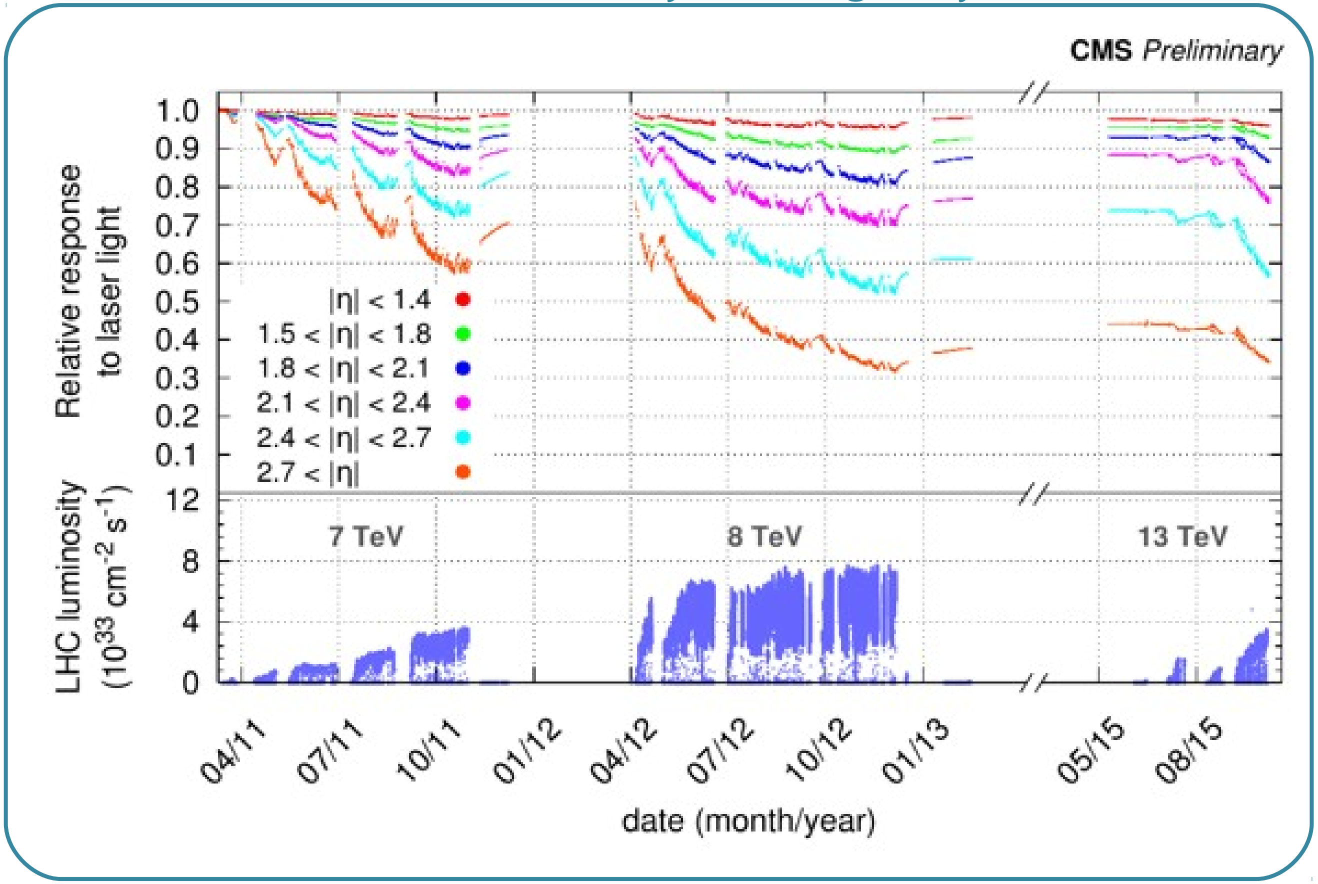
Impact of clustering and corrections on reconstructed Z mass



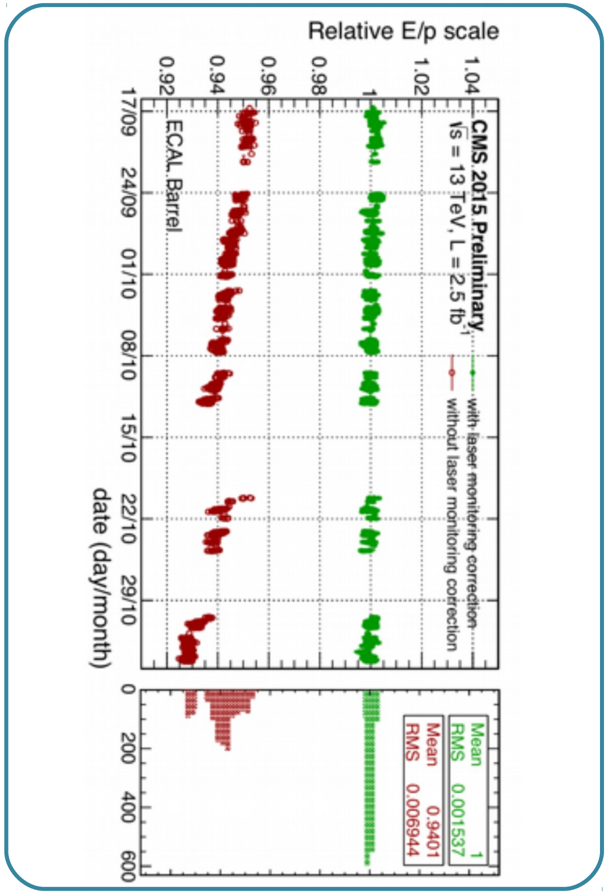
Monitoring

- Some parameters affecting the detector response **change with time**
  - Temperature, radiation effects (e.g. light attenuation), etc.
- These parameters are **monitored** and the response is corrected accordingly

CMS ECAL PbWO4 crystal loss of transparency monitored with a laser system (light injection)



Effect of monitored crystal response on reconstructed electron energy



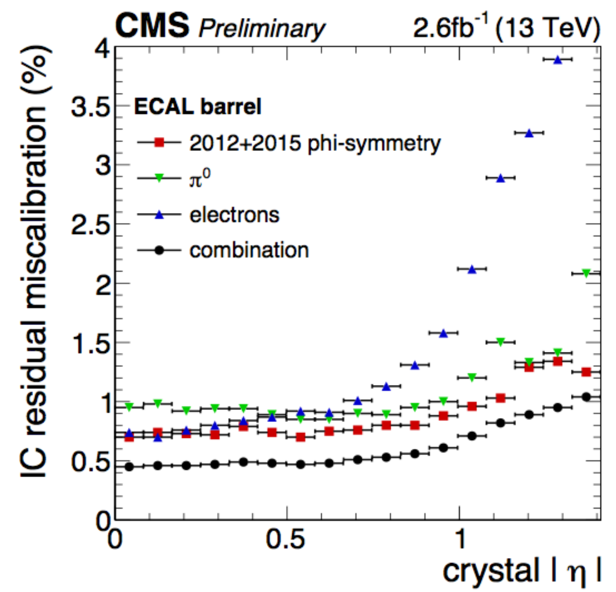
Intercalibration

- There are always local effects which cannot be perfectly simulated nor measured
- Need to equalize the response of each sensor one to an other
  - In situ (e.g. using collision data) intercalibration
- In general, several methods are combined
  - Using detector symmetries
  - Using "standard candles" (e.g. known resonances)
  - Comparing with other sub-detectors

Intercalibration methods used in CMS ECAL

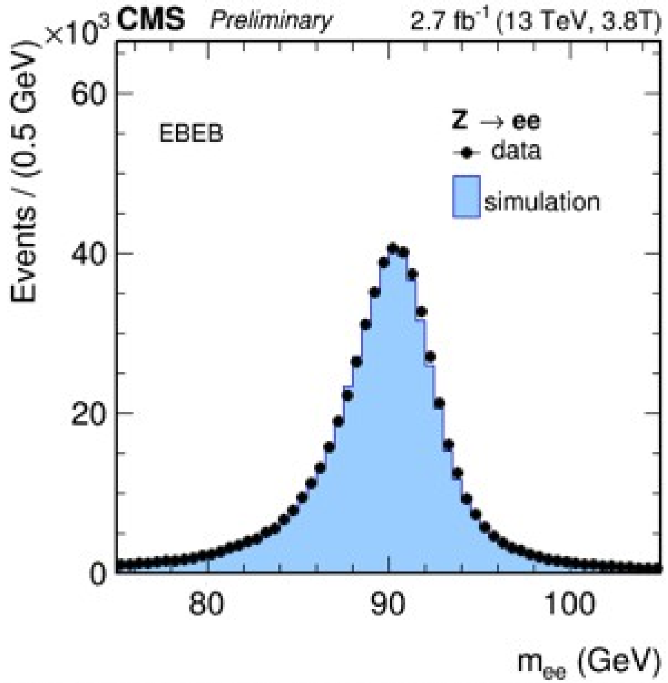
Method	Description	Timescale
ϕ-symmetry	Energy flux around ϕ rings (constant η) should be uniform - IC corrects for non-uniformity	~days
$\pi^0/\eta \to \gamma\gamma$	In a ϕ ring, use IC to improve M(γγ) resolution for π^0 and η resonances	~months
E/p	Compare isolated electron energy from ECAL and Tracker, calculate IC to correct discrepancies	statistically limited

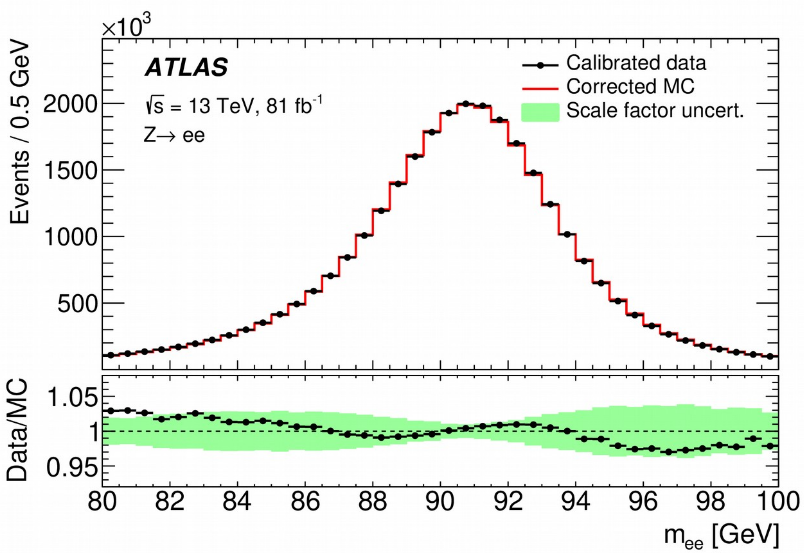
Precisions obtained with each intercalibration methods



Absolute calibration

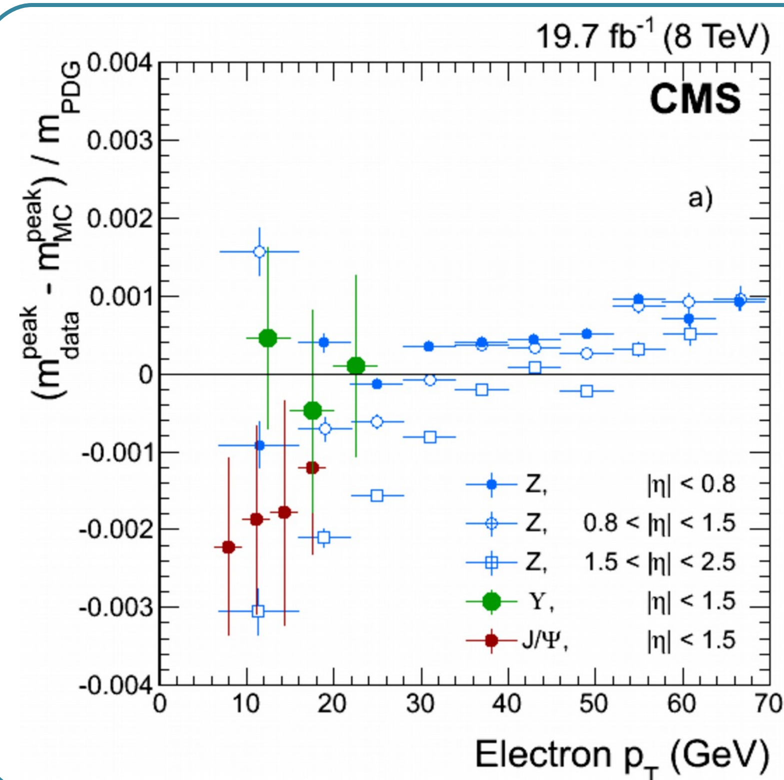
Comparisons of Z peak obtained in data and simulation (CMS and ATLAS)





- Calibration factors to set the **overall scale**
  - In situ, based on standard candles (e.g. Z→ee)
  - Match data Z peak lineshape to simulation

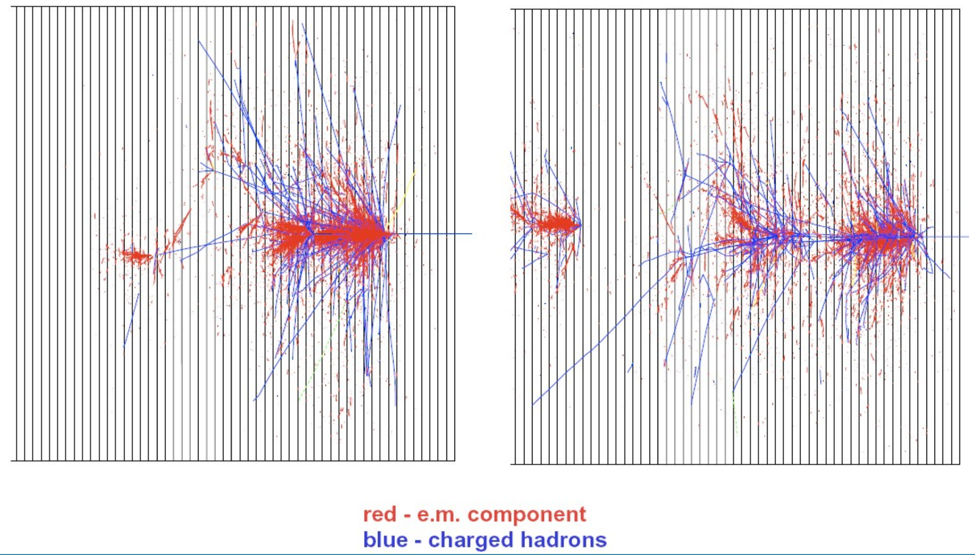
Linearity check with different resonances



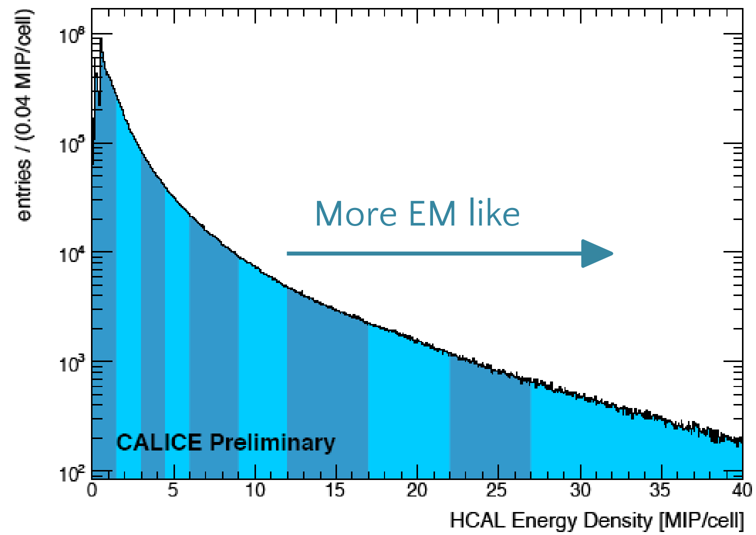
Jet energy measurement

- Similar techniques are used to calibrate jets made of hadron showers
- Additional techniques for non-compensating calorimeters
  - Need to **measure or estimate the EM fraction**
  - Apply different weights according to the EM fraction
  - Called "**software compensation**"
- EM shower are narrow and dense and hadronic showers are more diffuse
  - → Apply weights according to energy density

EM and hadronic components in showers

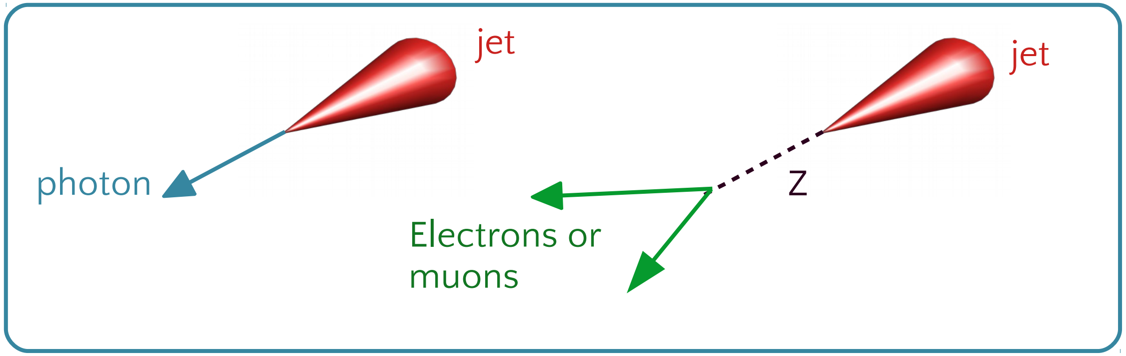


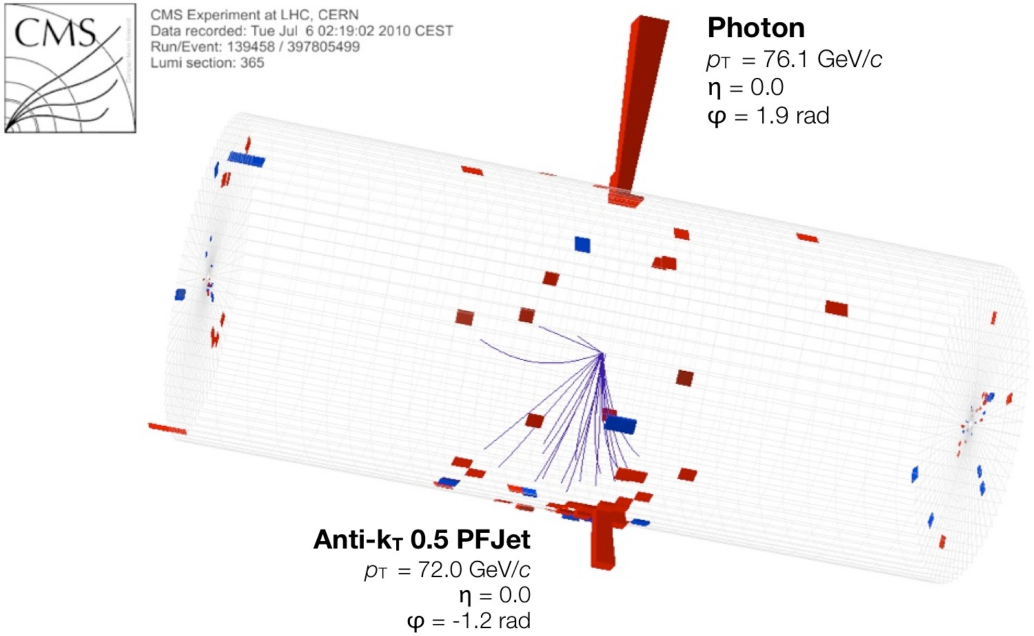
Cell energy density



Jet in situ calibration

- The jet energy resolution is poorer compared to other particles
  - Electrons, photons, muons
- Use the **recoil between a jet and precisely measured objects**

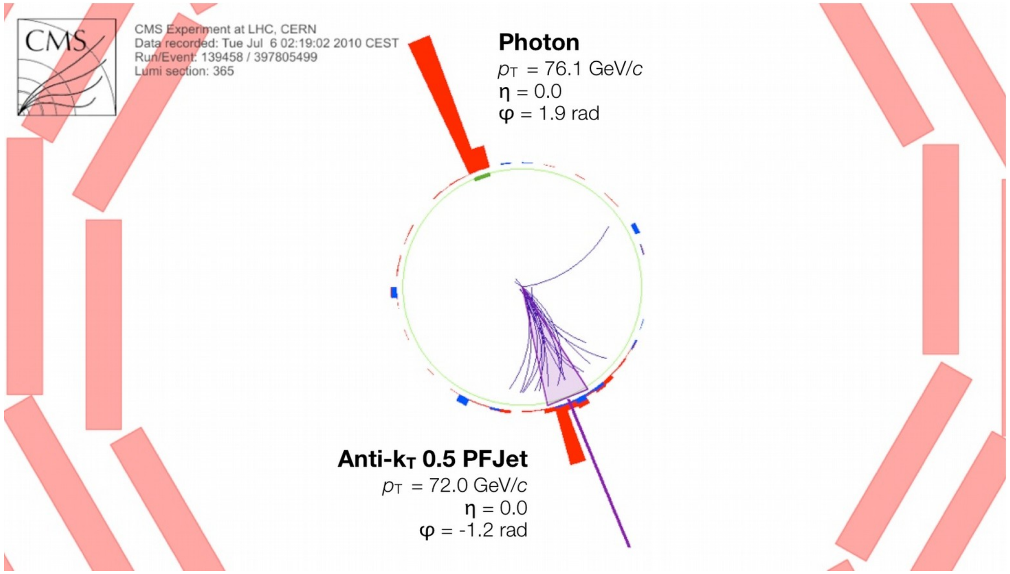




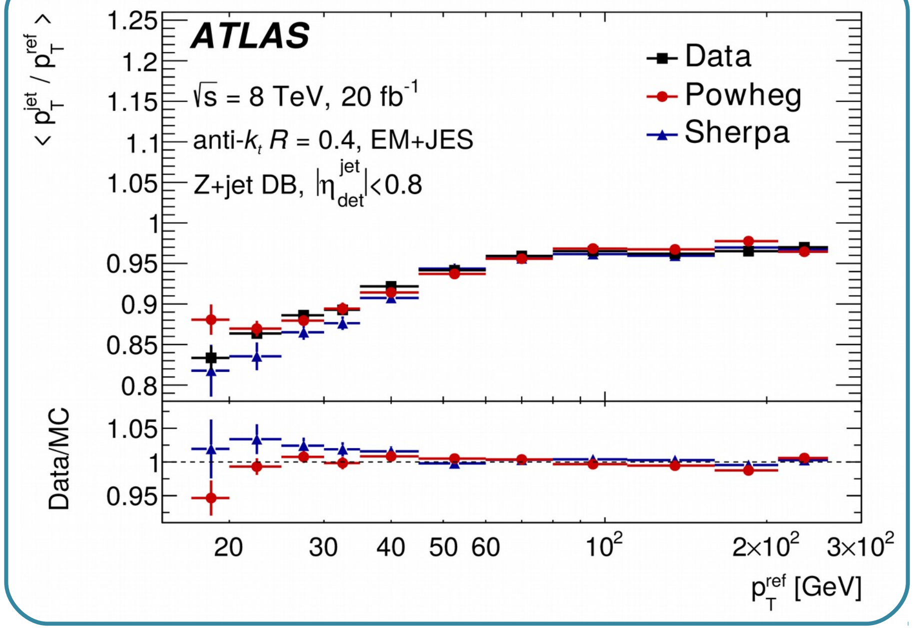
Jet in situ calibration

- In the transverse plane, objects in an event are recoiling one against the others
- One corrects for discrepancies in data and simulation

Recoil of a photon and a jet in the transverse plane



P_T "balance" in data and simulation



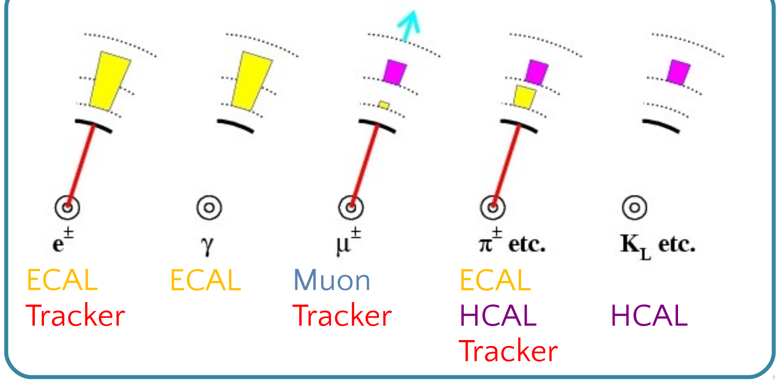
Lecture plan

- What is a calorimeter in HEP?
- Detection techniques
- Electronics readout and trigger
- **Beyond calorimetry: Particle Flow**
- Electromagnetic and hadronic showers
- Calorimeter response & resolution
- Energy reconstruction & calibration
- An example: CMS HGCAL

Reconstruction beyond calorimeters

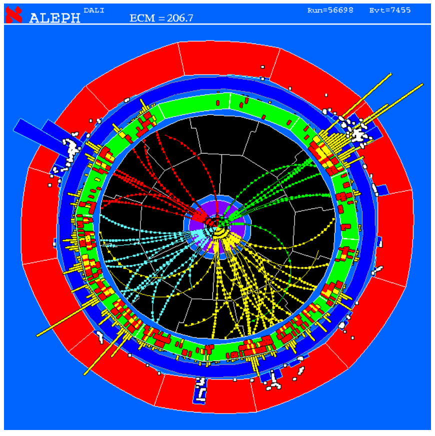
- Electrons, photons, hadrons, etc. produce different signatures in the different subdetectors
  - Photon: mainly ECAL
  - Electron: ECAL + tracker
  - Charged hadrons: all calorimeters + tracker
  - Neutral hadrons: all calorimeters
  - Muons: Mainly muon chambers + tracker

Signatures from different particles

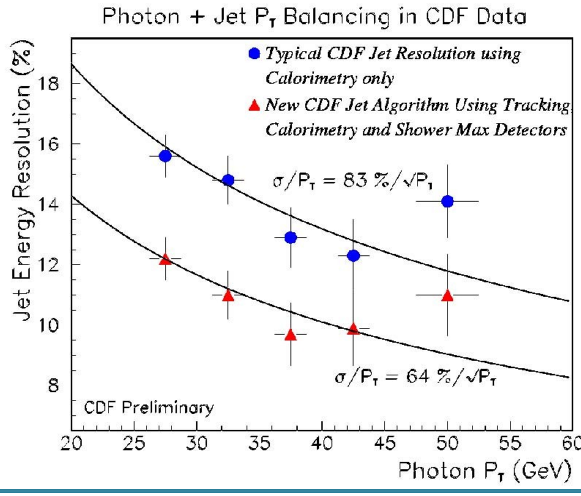


- The idea is to **combine the information from all subdetectors**
  - Can better identify objects and measure / calibrate their energy
- Pioneered in ALEPH at LEP (90's) and used later in other detectors

WW → 4q in ALEPH



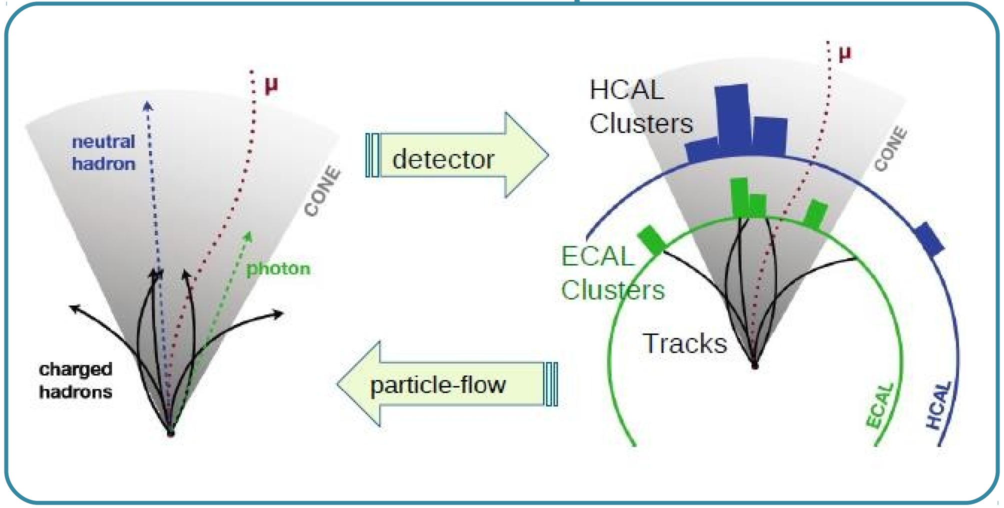
Improvement in jet energy resolution in CDF



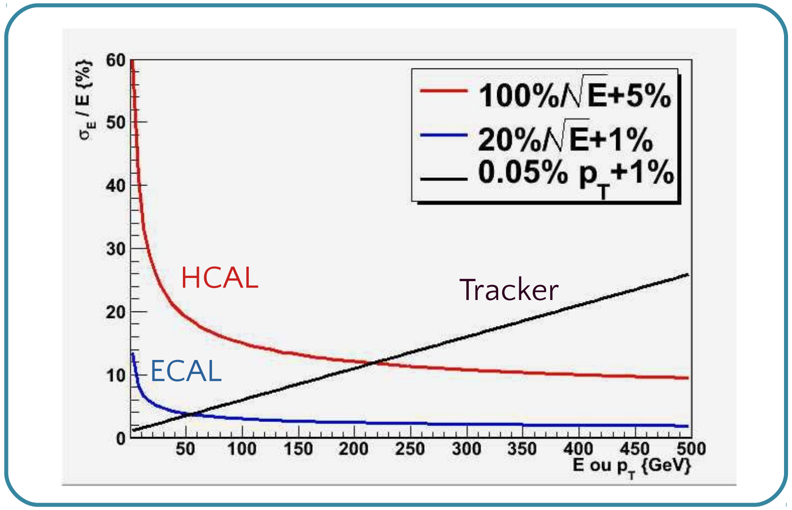
Particle Flow

- **Sub-detectors are complementary**, which is why combining them brings something more
- The ultimate goal is to **reconstruct each individual particle**
  - In particular particles within a jet
  - Charged hadrons and low p_T electrons better measured with the tracker
  - Photons measured by the ECAL
  - Neutral hadrons can only be measured by the HCAL
- Better identify EM and hadronic components (can apply **software compensation**)
- Can have a global description of collision events (pile-up, jet substructure, etc.)

From detector to particles



Typical resolutions



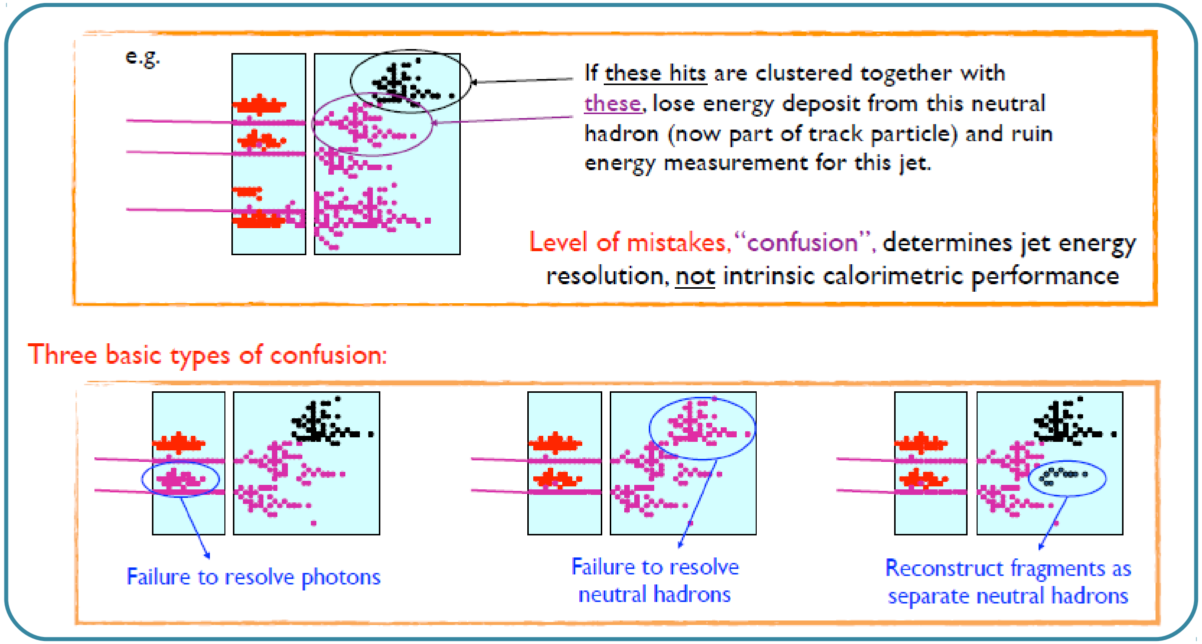
Particle Flow challenges

- Jet energy resolution (forgetting correlations):

$$\sigma^2_{jet} = \sigma^2_{h^{+-}} + \sigma^2_{\gamma} + \sigma^2_{h^0} + \boxed{\sigma^2_{confusion} + \sigma^2_{threshold} + \sigma^2_{losses}}$$ Reconstruction contributions

  - **Threshold**: energy cuts applied
  - **Losses**: imperfect reconstruction
  - **Confusion**: wrong identification of energy deposits (plays a major role)
- Need an efficient linking procedure between sub-detectors
  - Avoid **double counting** of energy
  - Avoid to apply **wrong calibration** weights

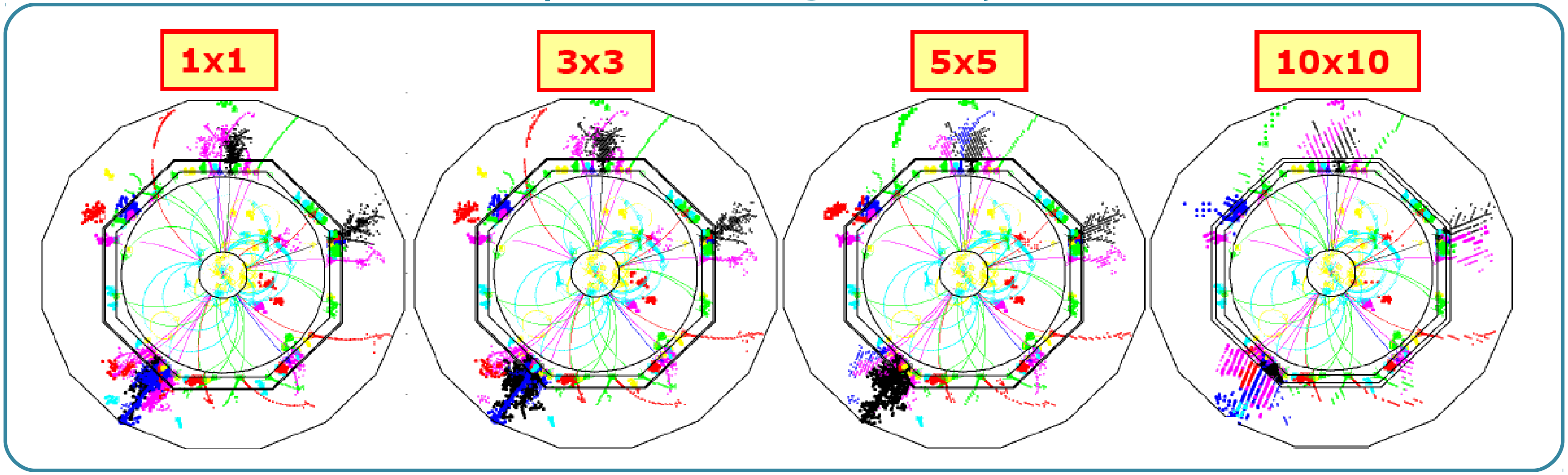
Confusion effects



Particle Flow ingredients

- Good separation of particles
  - High magnetic field integral (B×R)
  - High granularity
- Low amount of material before the calorimeters
  - Light tracker, calorimeters inside the coil
- Small Moliere radius (dense calorimeters)
  - Minimize overlaps between showers
- Efficient tracking

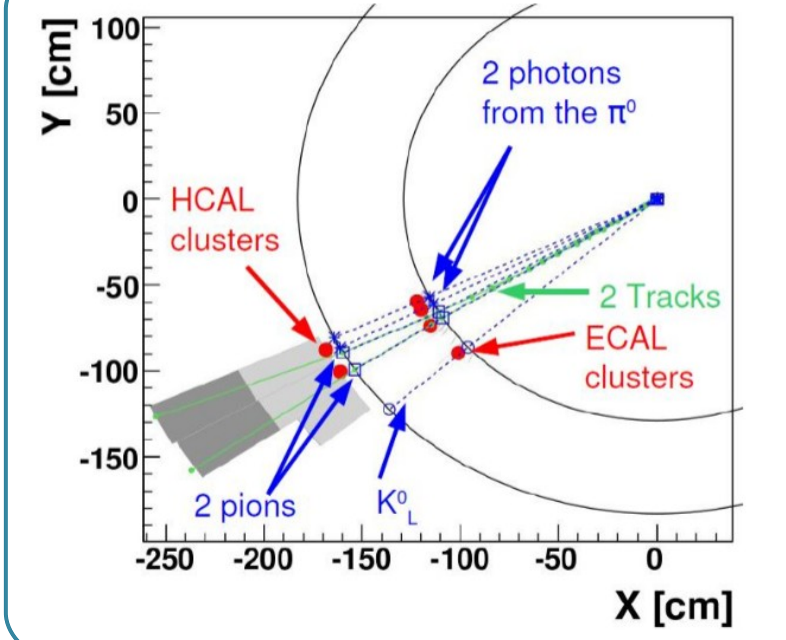
Impact of HCAL granularity



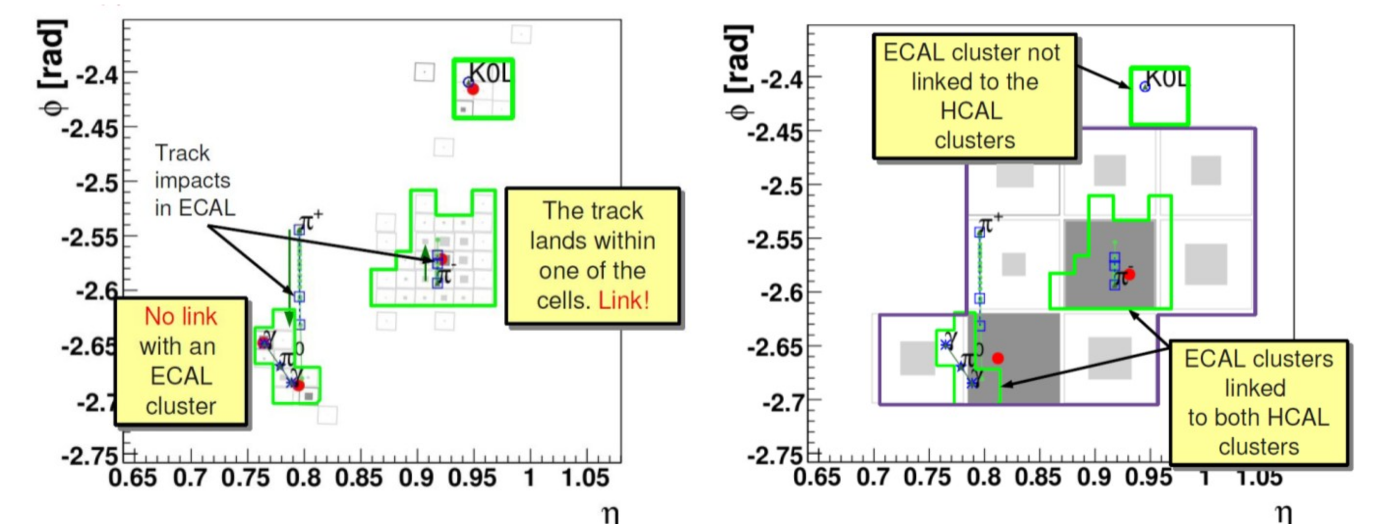
Particle Flow in CMS

- CMS not designed for Particle Flow
- Though meets several of the criteria for a good PF
  - Large field integral: B×R = 4.9 T.m
  - Excellent ECAL resolution, granularity and small Moliere radius
  - Excellent tracking

A jet containing π^+, π^-, π^0, K_L^0



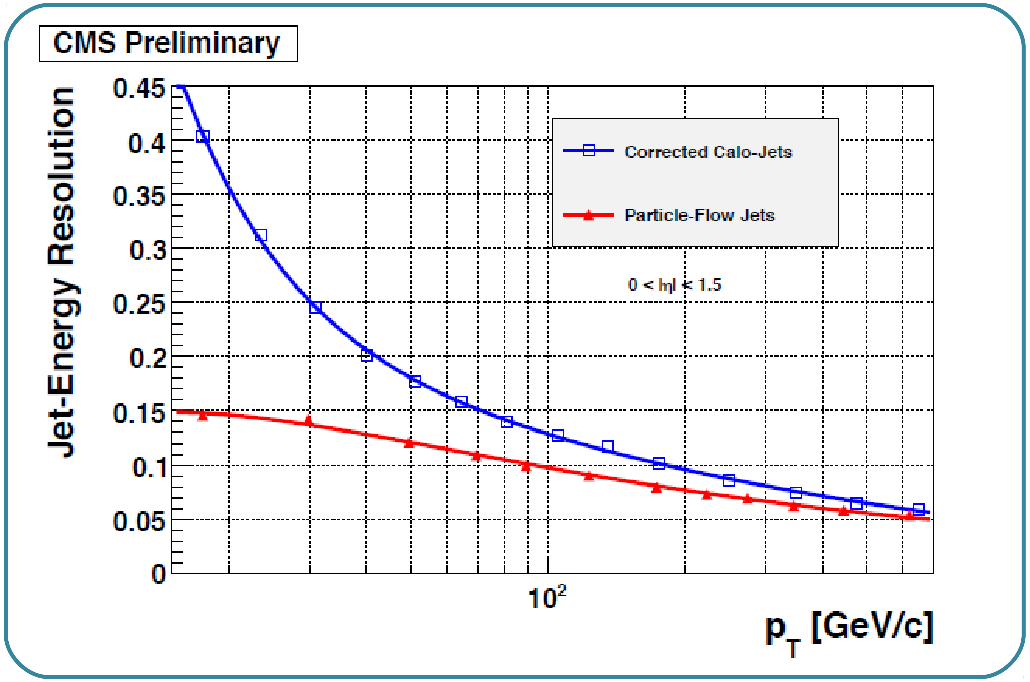
ECAL and HCAL surfaces



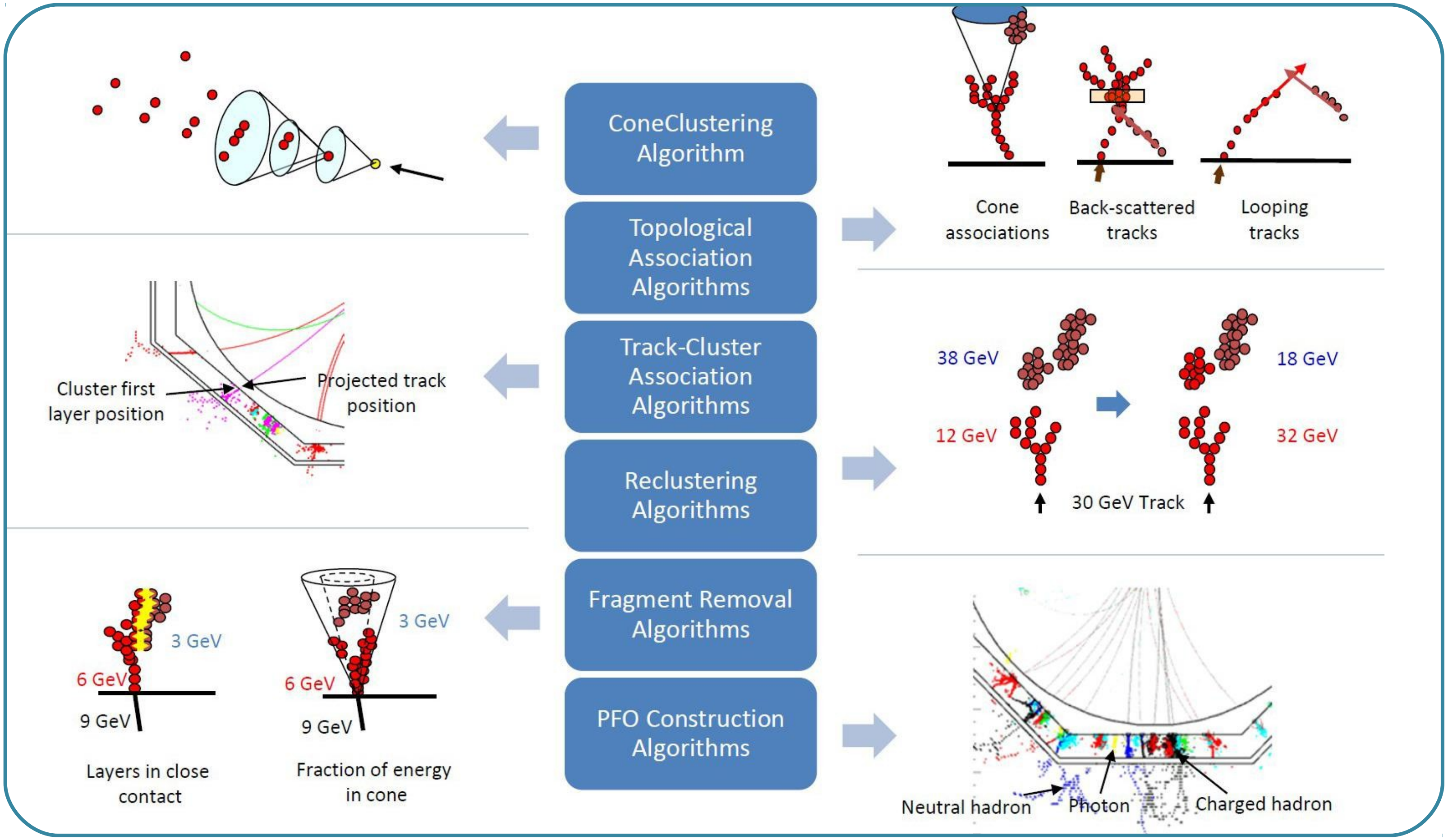
Particle Flow in CMS

- Particle Flow **improved jet energy resolution** significantly
  - In particular at low p_T
  - Where the tracker contribution is important
- But considerable challenges
  - Up to $2X_0$ of tracker material
  - Pile-up and very high density of particles

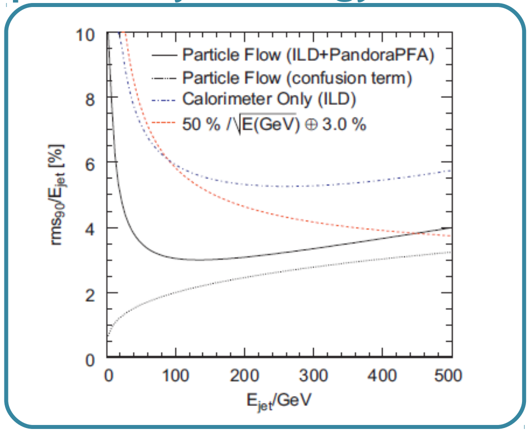
Improvement in jet energy resolution from PF



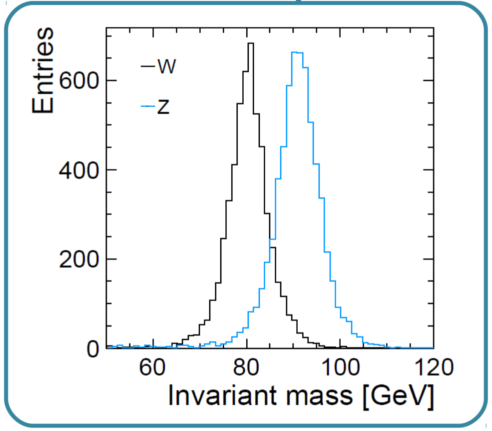
Particle Flow at the ILC



Impact on jet energy resolution



W-Z mass separation



Lecture plan

- What is a calorimeter in HEP?
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- Beyond calorimetry: Particle Flow
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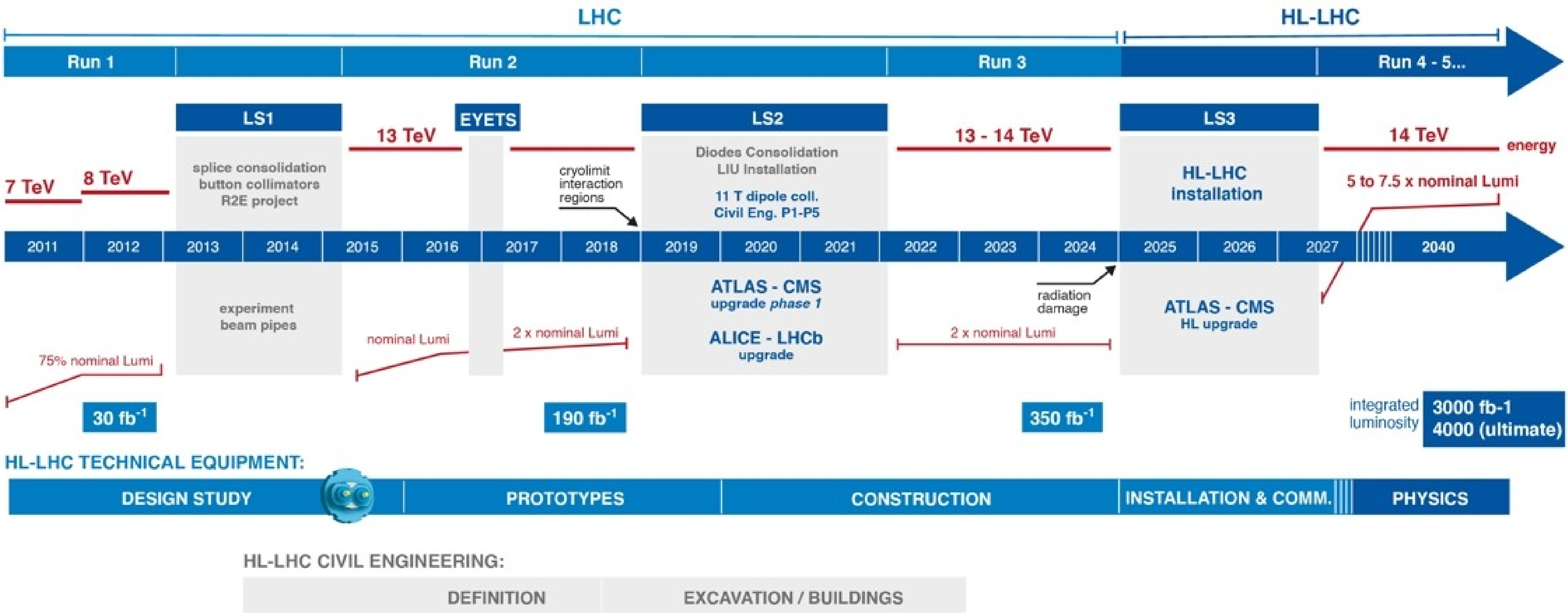
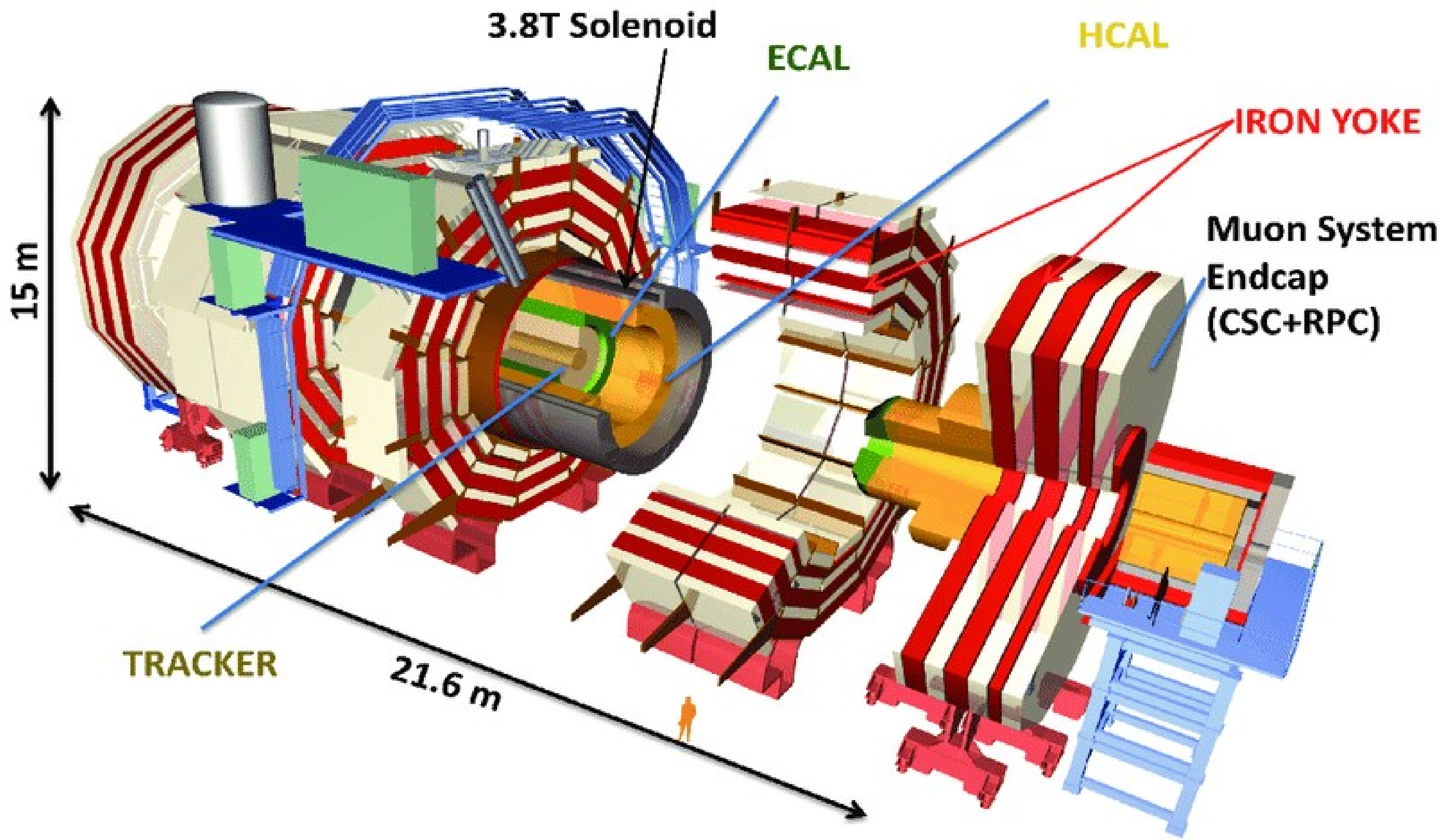
- Energy reconstruction & calibration
- **An example: CMS HGCAL**

High Luminosity LHC

- Luminosity upgrade of the LHC
  - Starting in **2027**
  - Installation in 2025-2027
- Together with an **upgrade of the detectors**

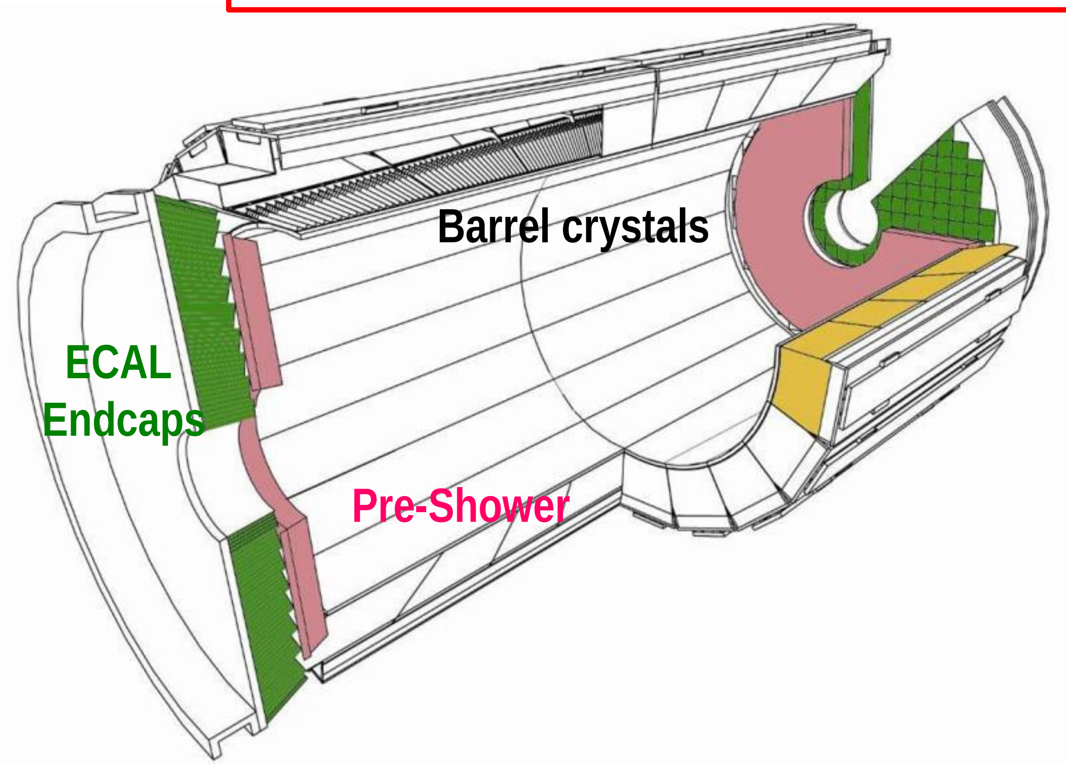


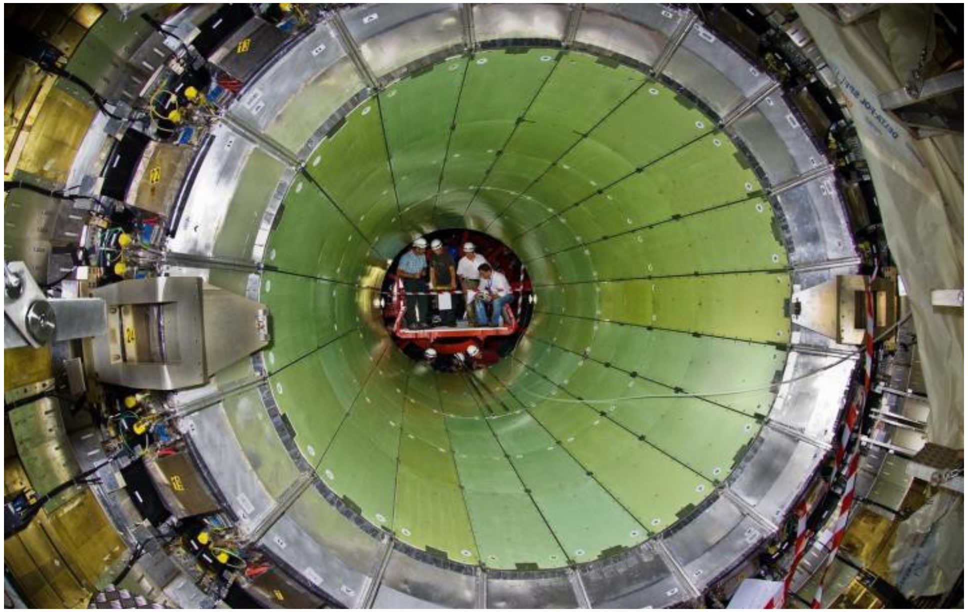
CMS


3.8T Solenoid
ECAL
HCAL
IRON YOKE
Muon System
Endcap
(CSC+RPC)
15 m
TRACKER
21.6 m

CMS ECAL

Homogenous calorimeter made from 75848 $PbWO_4$ scintillating crystals

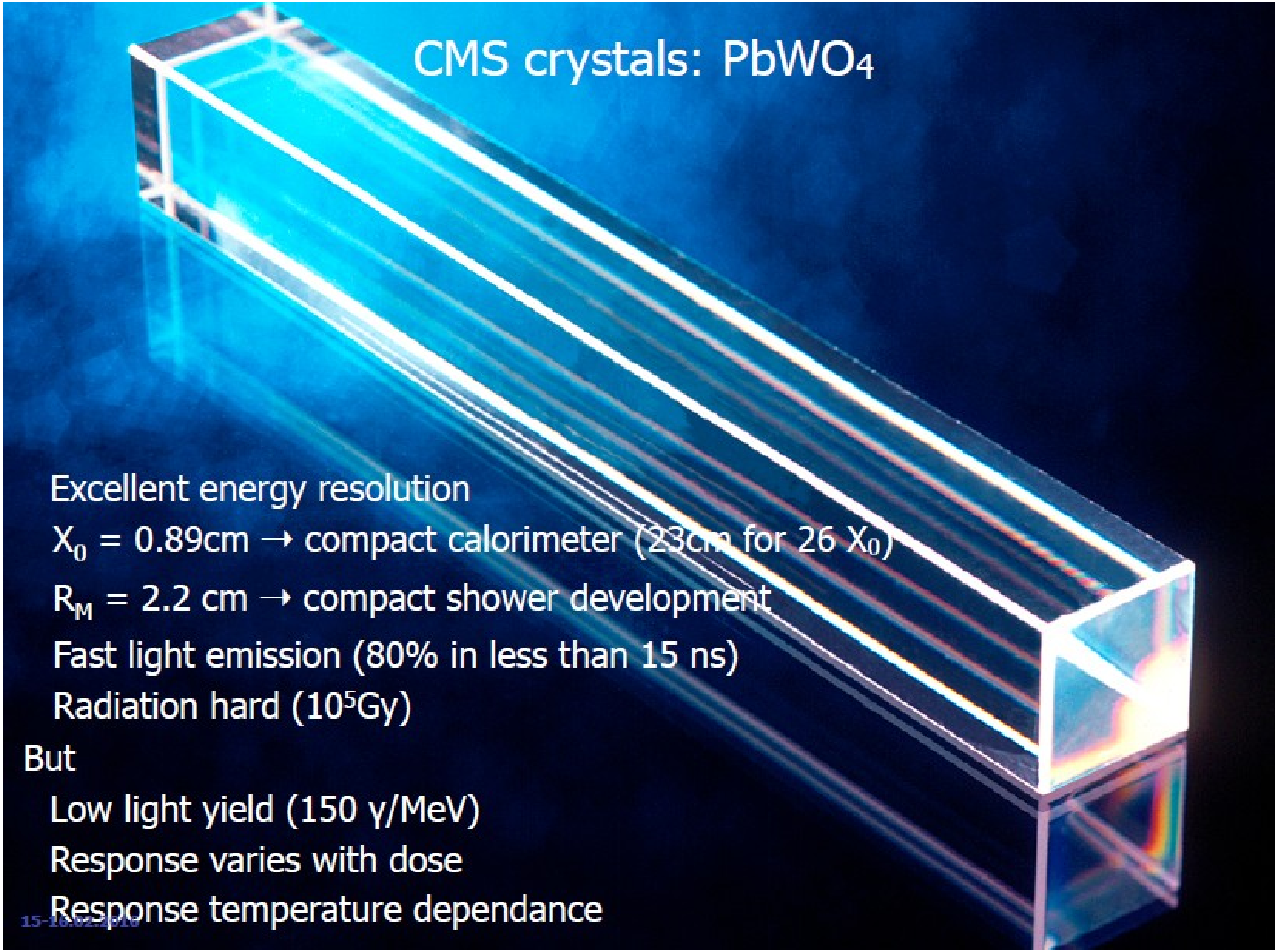




- Barrel ($|\eta|<1.48$), ~67 t
- 61200 crystals over 36 super-modules

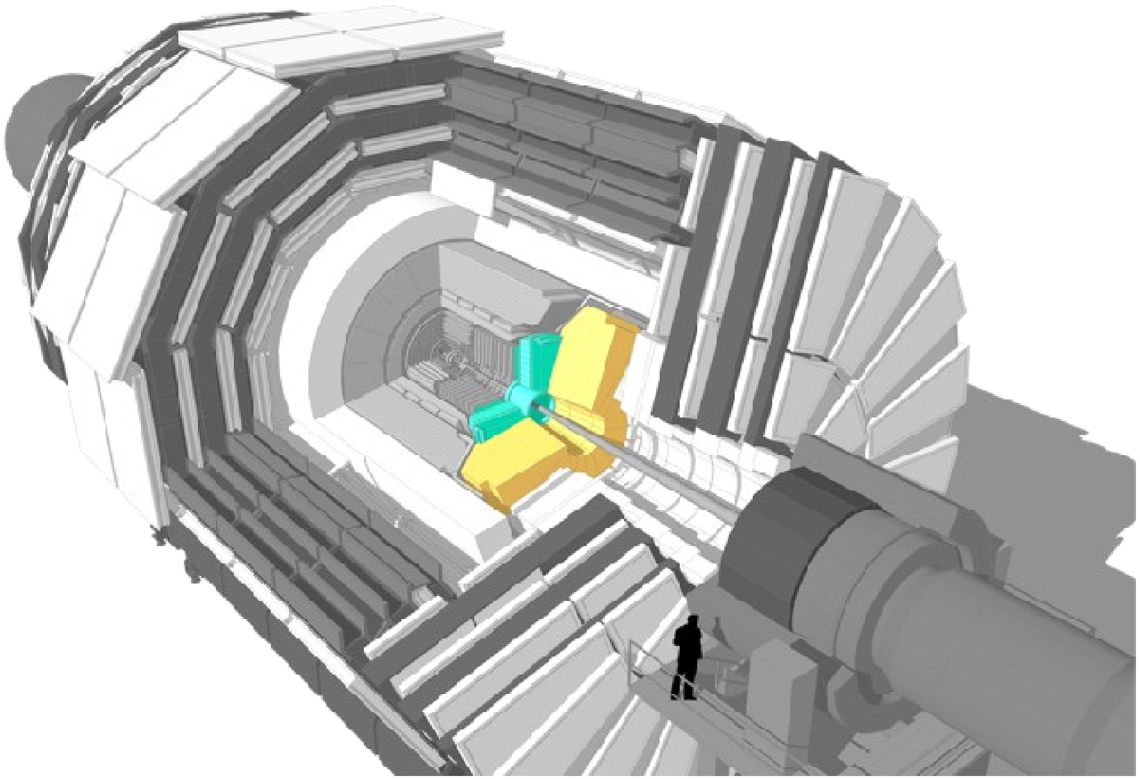
- Endcaps ($1.48<|\eta|<3$), ~23 t
- 14648 crystals over 4 Dees (2 per endcap)
- Preceded by Pb/Si Pre-Shower

Material: inorganic scintillator

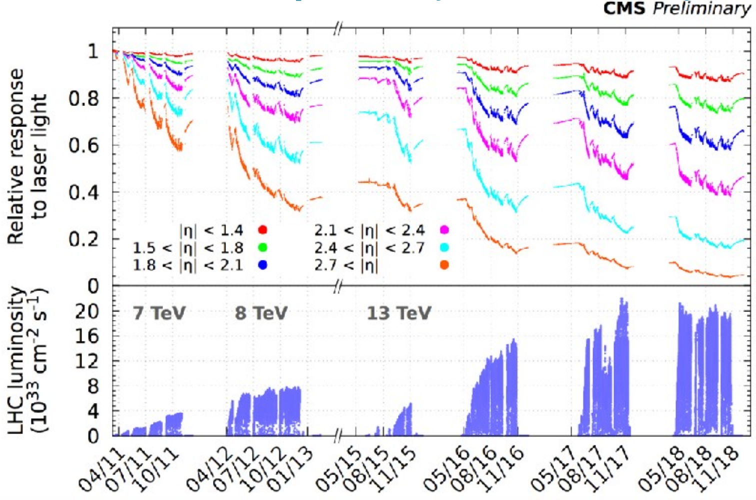


CMS endcap calorimeters for HL-LHC

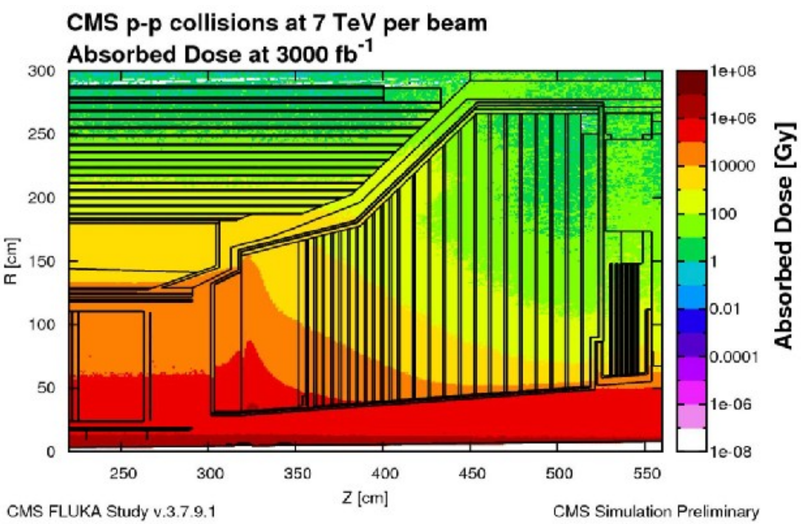
- CMS endcap calorimeters will need to be replaced
  - ECAL crystals and HCAL scintillators suffer from **irreparable radiation damage** after 500 fb^{-1}



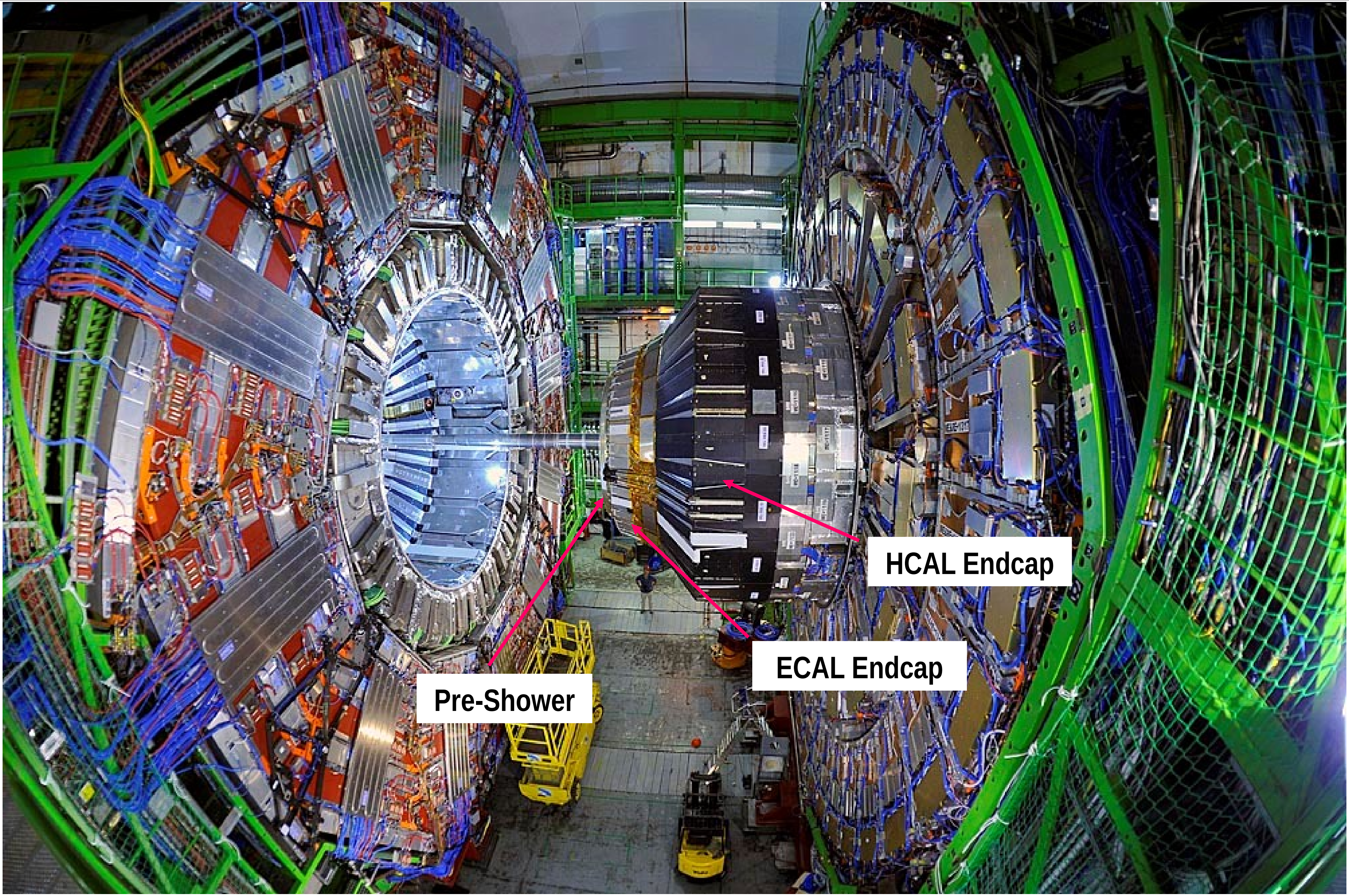
Loss of transparency of ECAL crystals



Absorbed dose at the end of HL-LHC

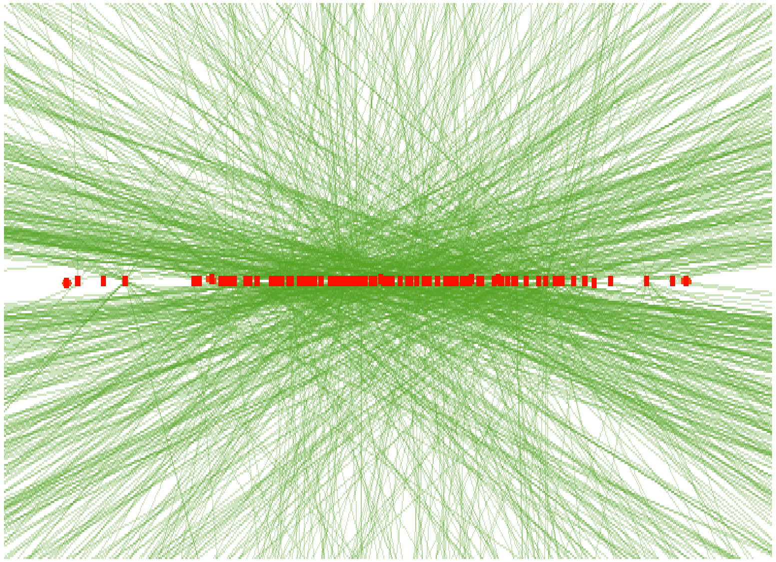


CMS endcap

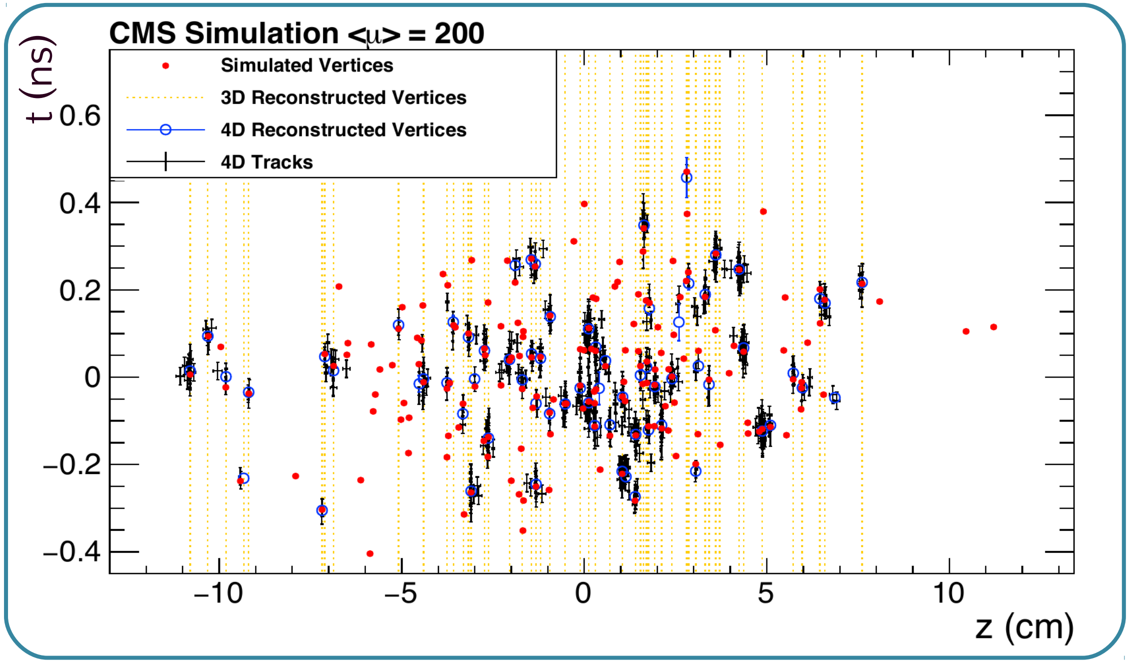


- HL-LHC nominal parameters
  - **140-200 quasi simultaneous interaction** each bunch crossing
- Needs detectors that can survive high radiation but can also disentangle all these simultaneous interactions
  - Needs **high granularity**
  - And **precise timing information**

140 PU interactions event

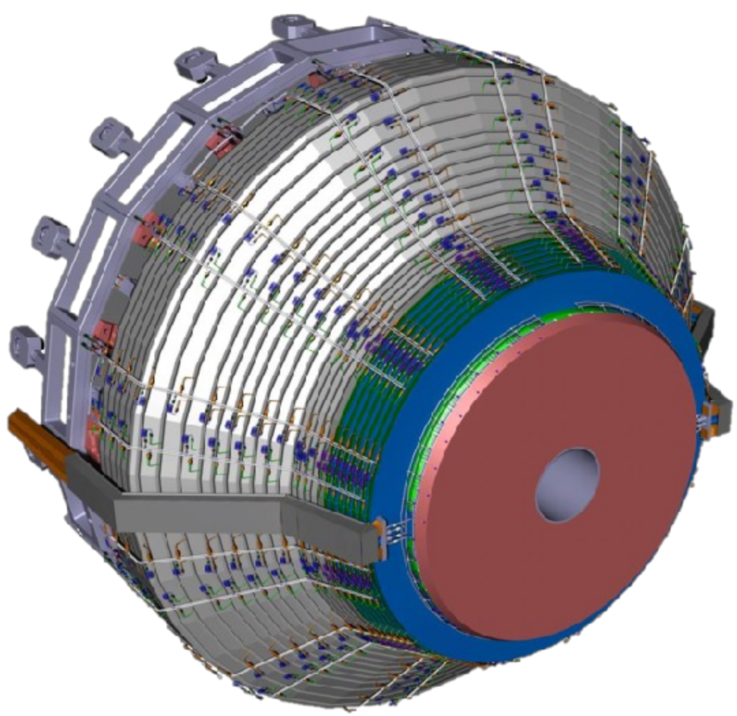


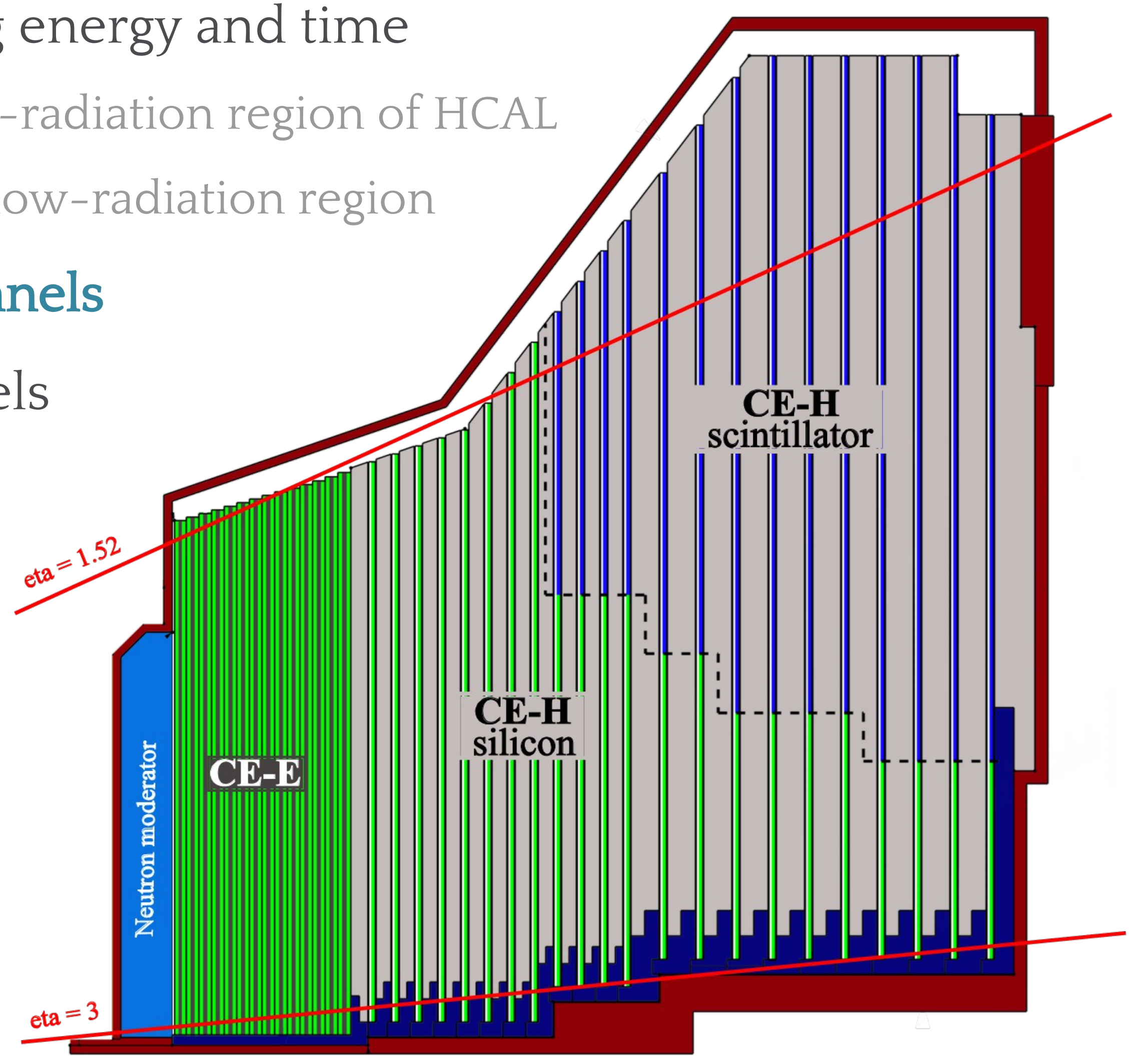
Space-time view of interaction vertices



HGCAL overview

- Radiation hard detector measuring energy and time
  - **Silicon sensors** in ECAL and highest-radiation region of HCAL
  - **Scintillating tiles + SiPM** readout in low-radiation region
- 620 m² of silicon sensors, **6M channels**
- 400 m² of scintillator, 240k channels



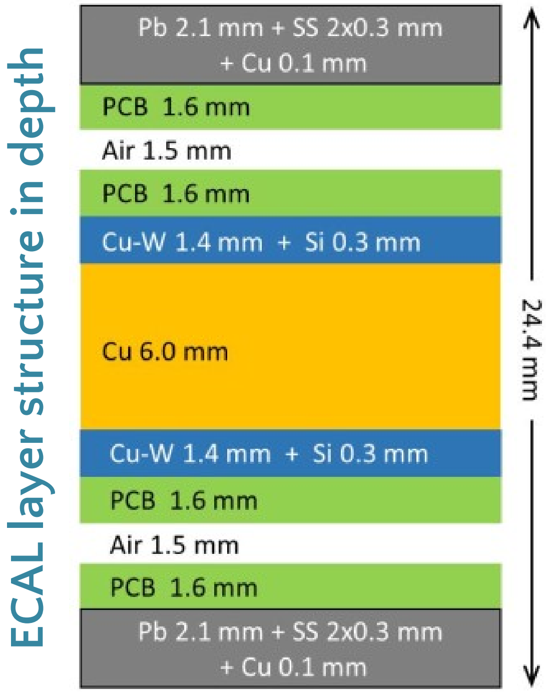


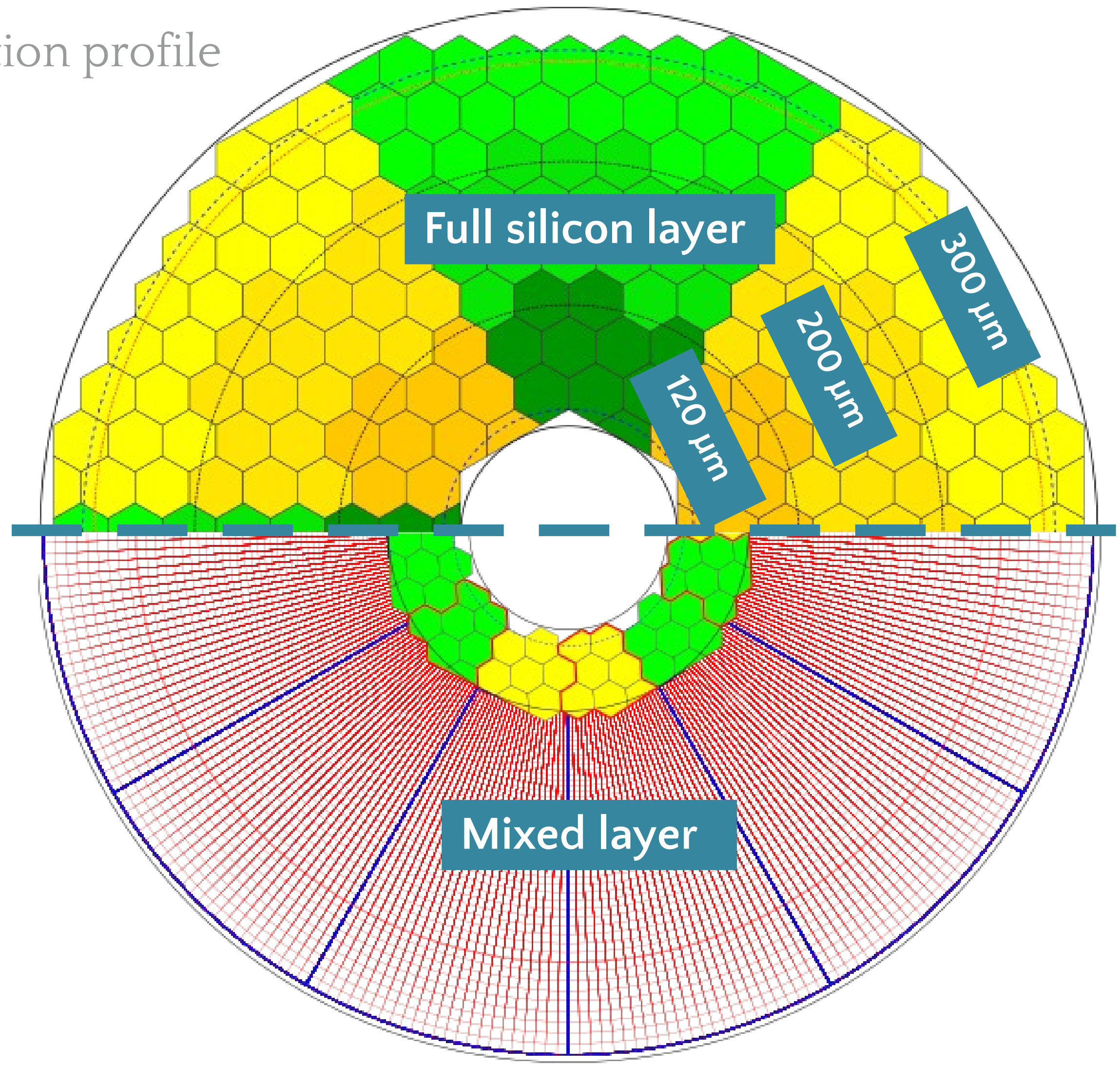
ECAL (CE-E):
28 layers, 25 X_0, 1.3 λ
Pb, Cu, CuW absorbers

HCAL (CE-H):
22 layers, 8.5 λ
Steel, Cu absorbers

Layer structure

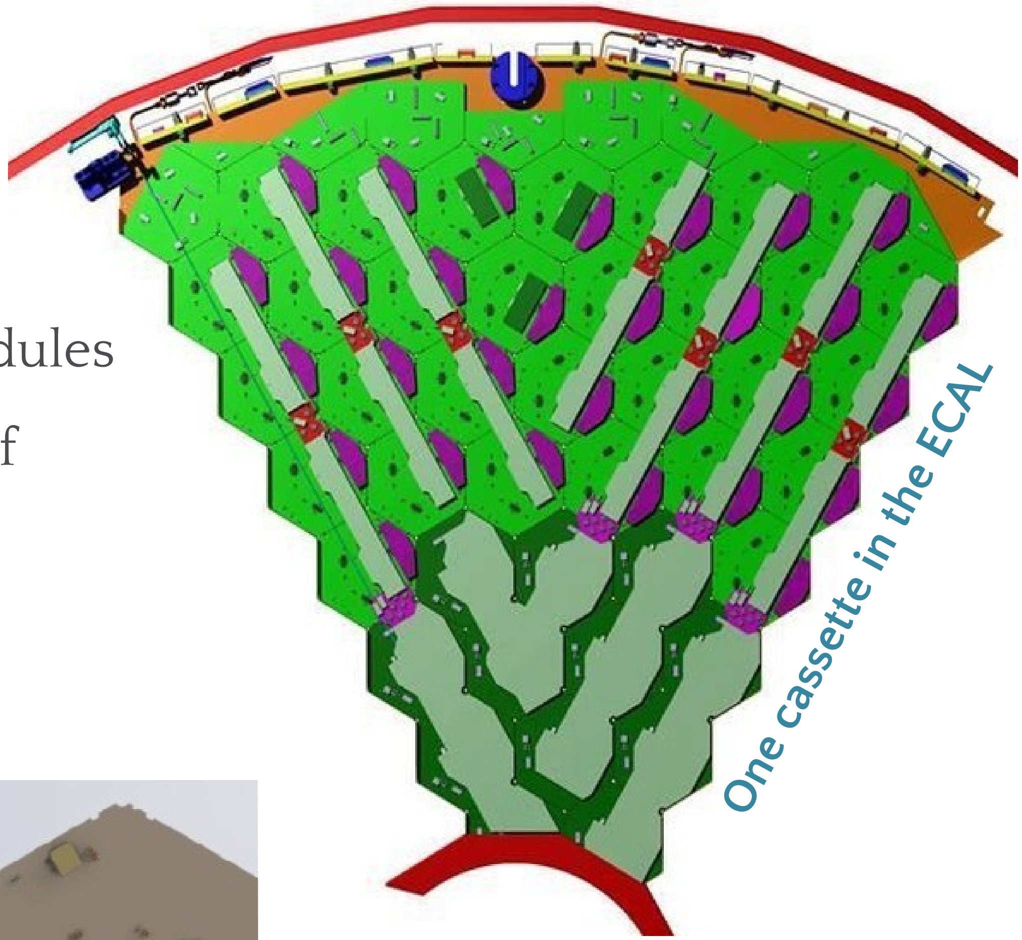
- Silicon
  - 8" **hexagonal wafers**
  - Three thicknesses following radiation profile
    - 120, 200 & 300µm
- Scintillator
  - **Tile size varies with eta (1.5°)**

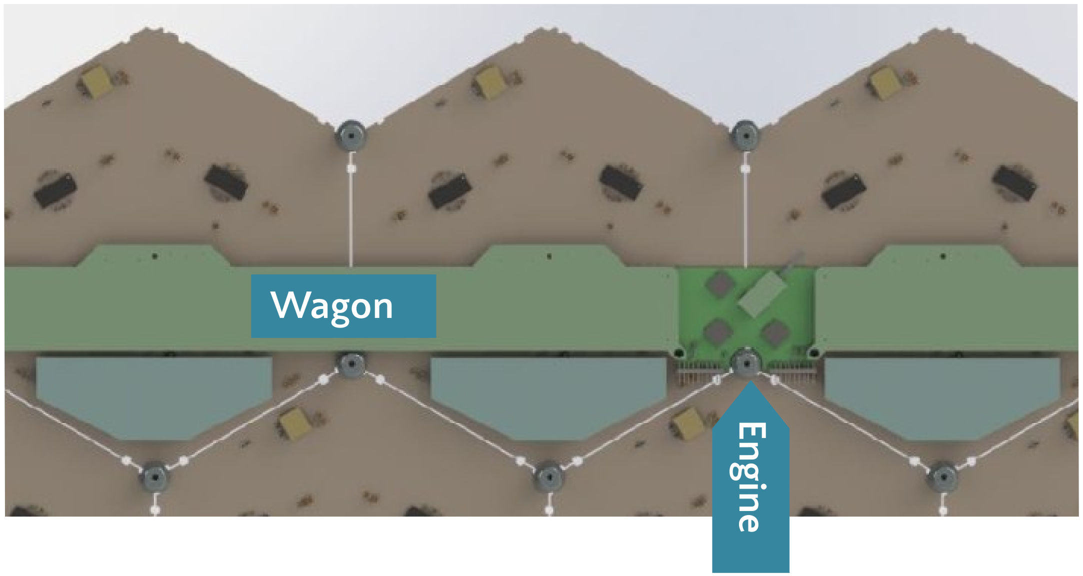




Layer components

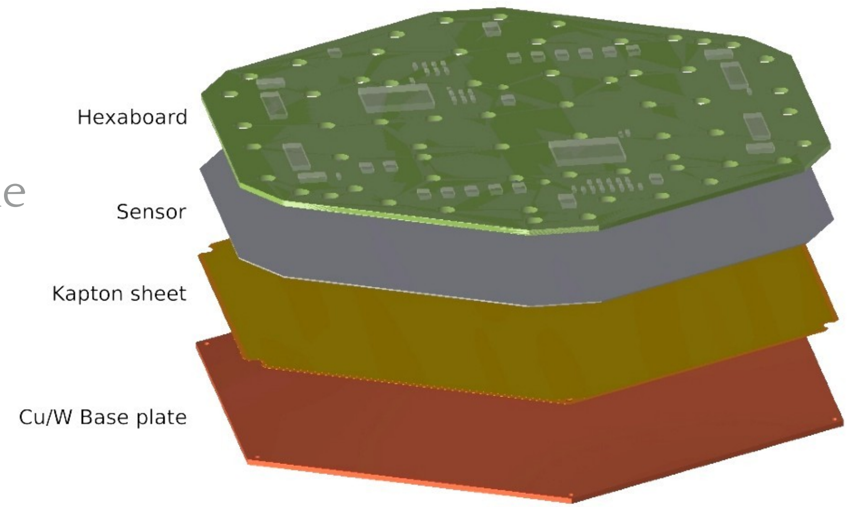
- Detector is organized into **cassettes** made of a cooling plate with **modules mounted on it**
- Frontend electronics located on the modules
- Readout and control through a system of engine/wagon **motherboards**



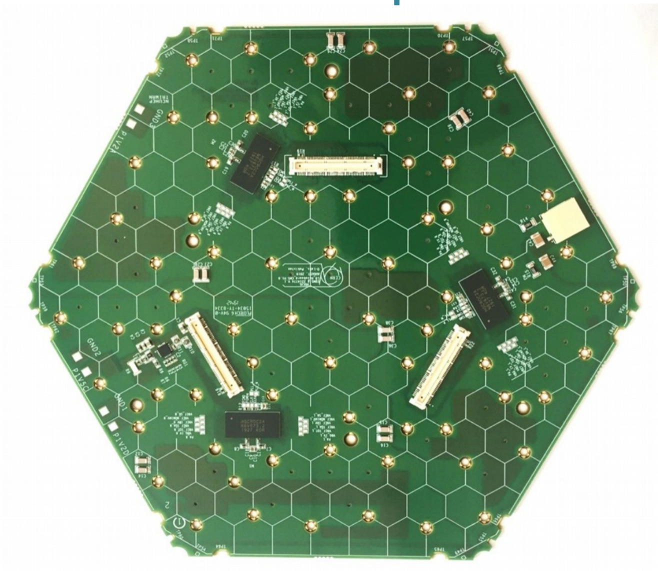


Silicon modules

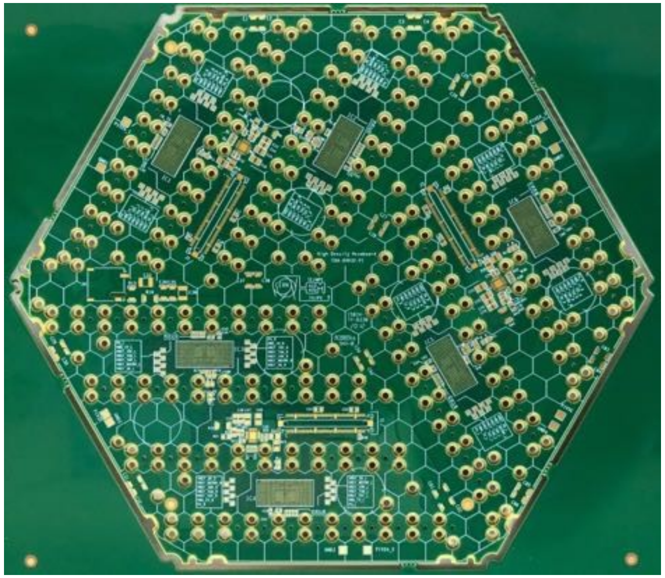
- Stack of **sensor**, readout **PCB** (Printed Circuit Board) and **baseplate**
  - Several HGCROC (HGC readout chip) ASICs on the board
- "High density" and "Low density" modules
  - **0.5 cm^2 cell** area in the highest radiation region
  - **1.1 cm^2** otherwise



Low density module
192 channels
3 readout chips

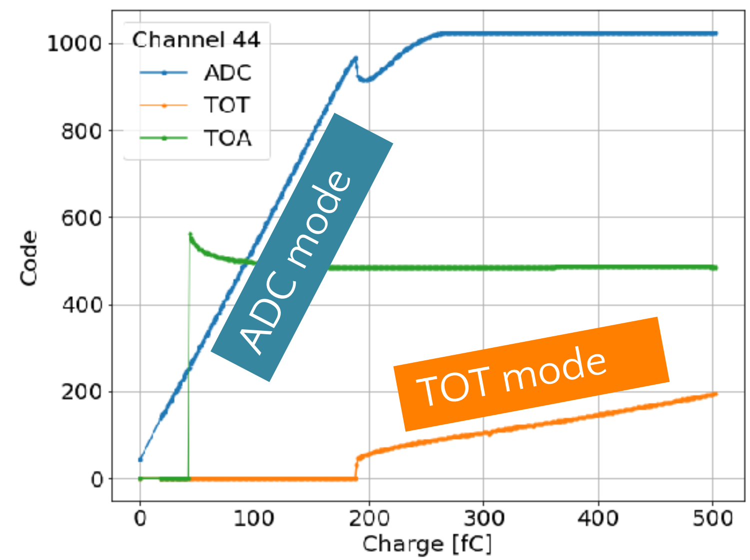


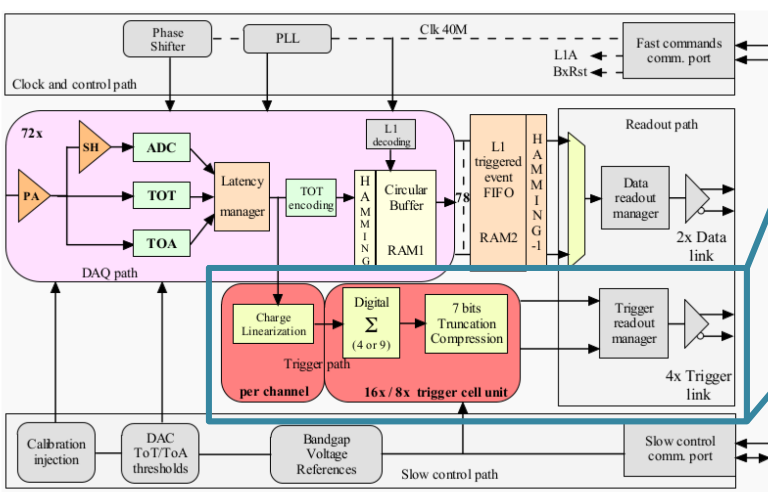
High density module
432 channels
6 readout chips

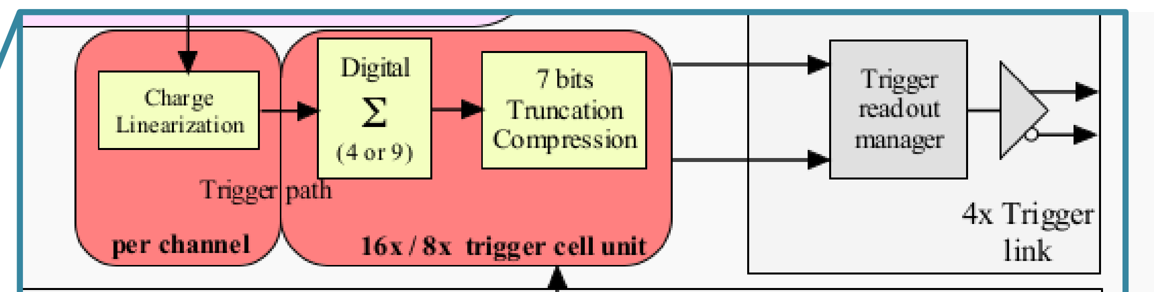


The readout chip (HGCROC)

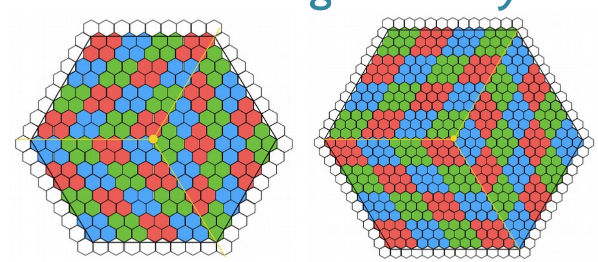
- ASIC amplifying, shaping, digitizing collected charges
  - Two modes: "**ADC**" (low charges) & "**TOT**" (high charges)
  - Data buffered before read out
- Trigger path
  - ADC and TOT **linearization**
  - Sums of channels → **Trigger cells**
  - Energy **compression**





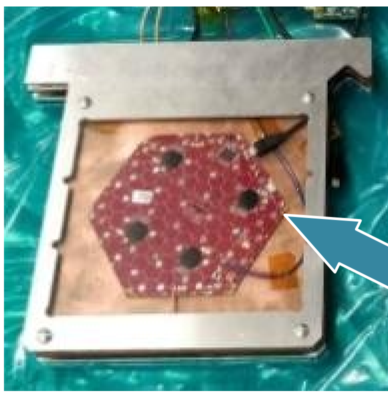


Trigger cells in low and high density modules

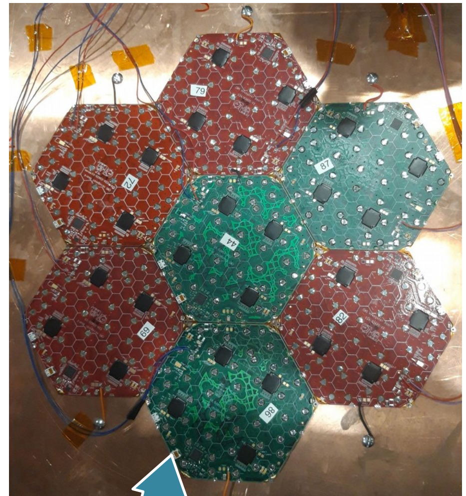


HGCAL prototype in beam test experiments

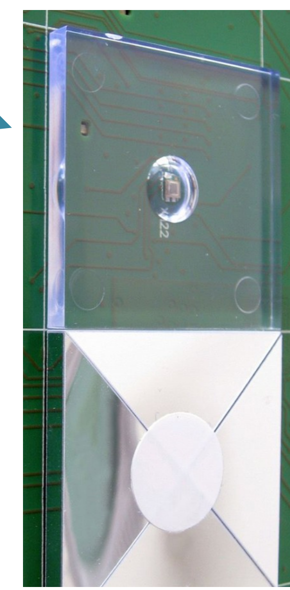
- CE-E
  - Double sided mini-cassettes
  - Lead absorber
  - 26 X0, 1.4 L

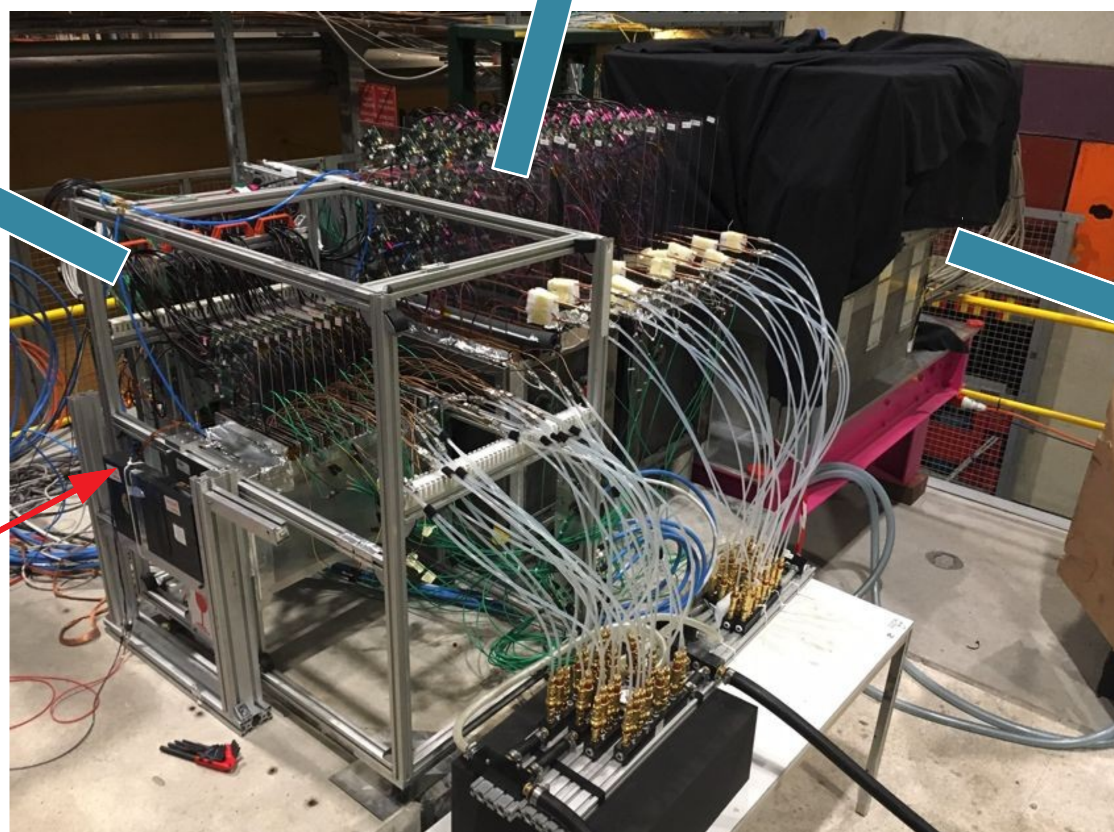


- CE-H
  - Daisy arrangement of the modules
  - Steel absorber
  - 3.4 L

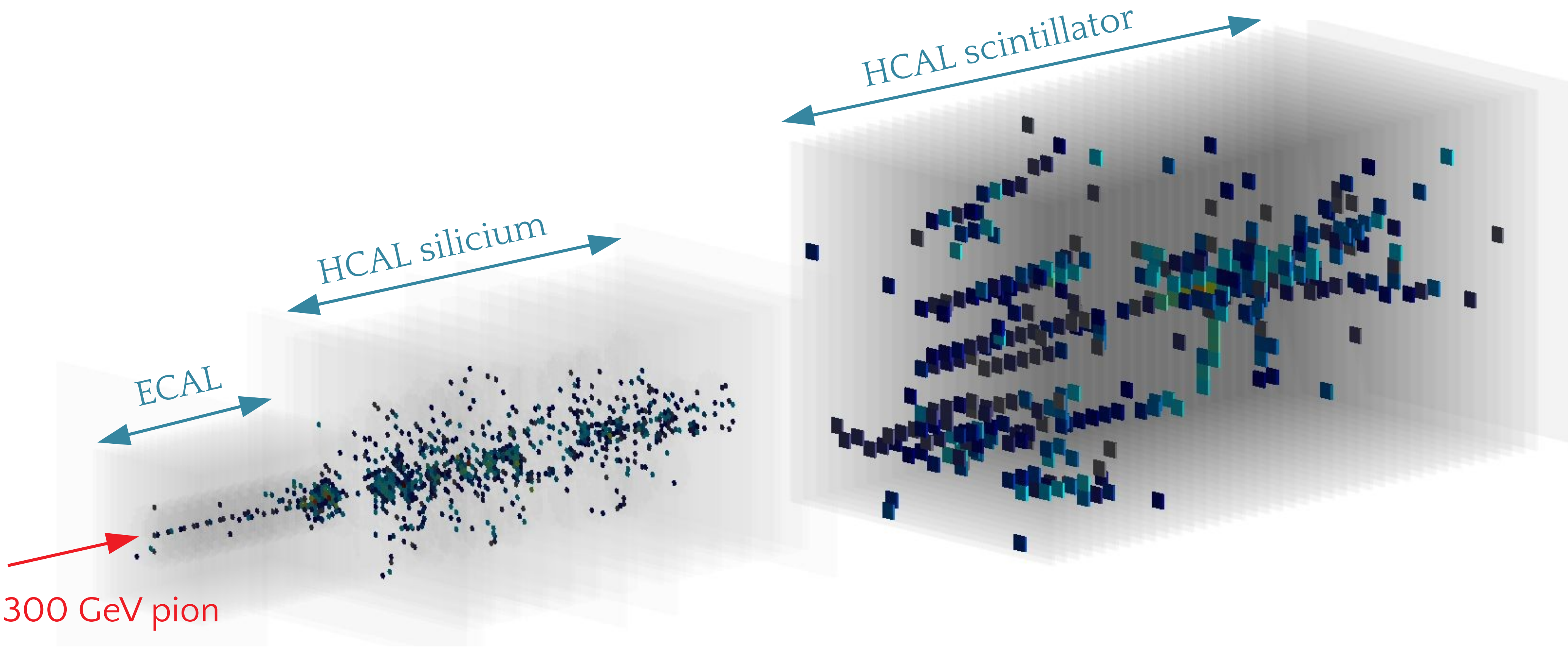


- CALICE AHCAL
  - Scintillator + SiPM
  - Steel absorber
  - 4.4 L





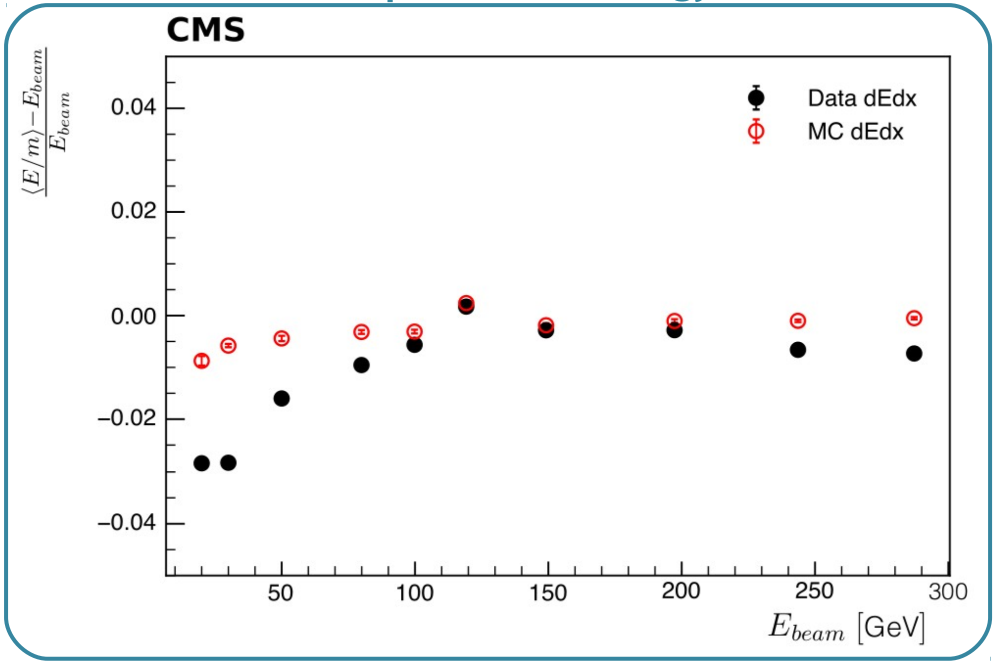
Display of pion shower



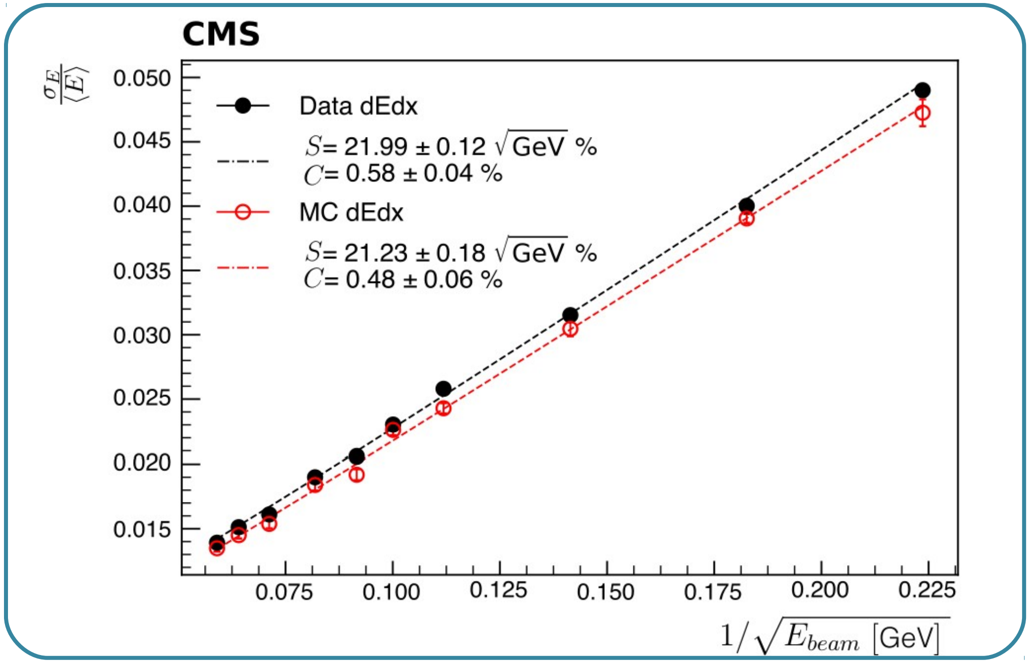
Electromagnetic showers reconstruction

- Response to electromagnetic showers
  - Good linearity
  - Small drop of response for lower energy showers
- Resolution: stochastic term around 22%
- Simulation slightly optimistic

Response vs energy



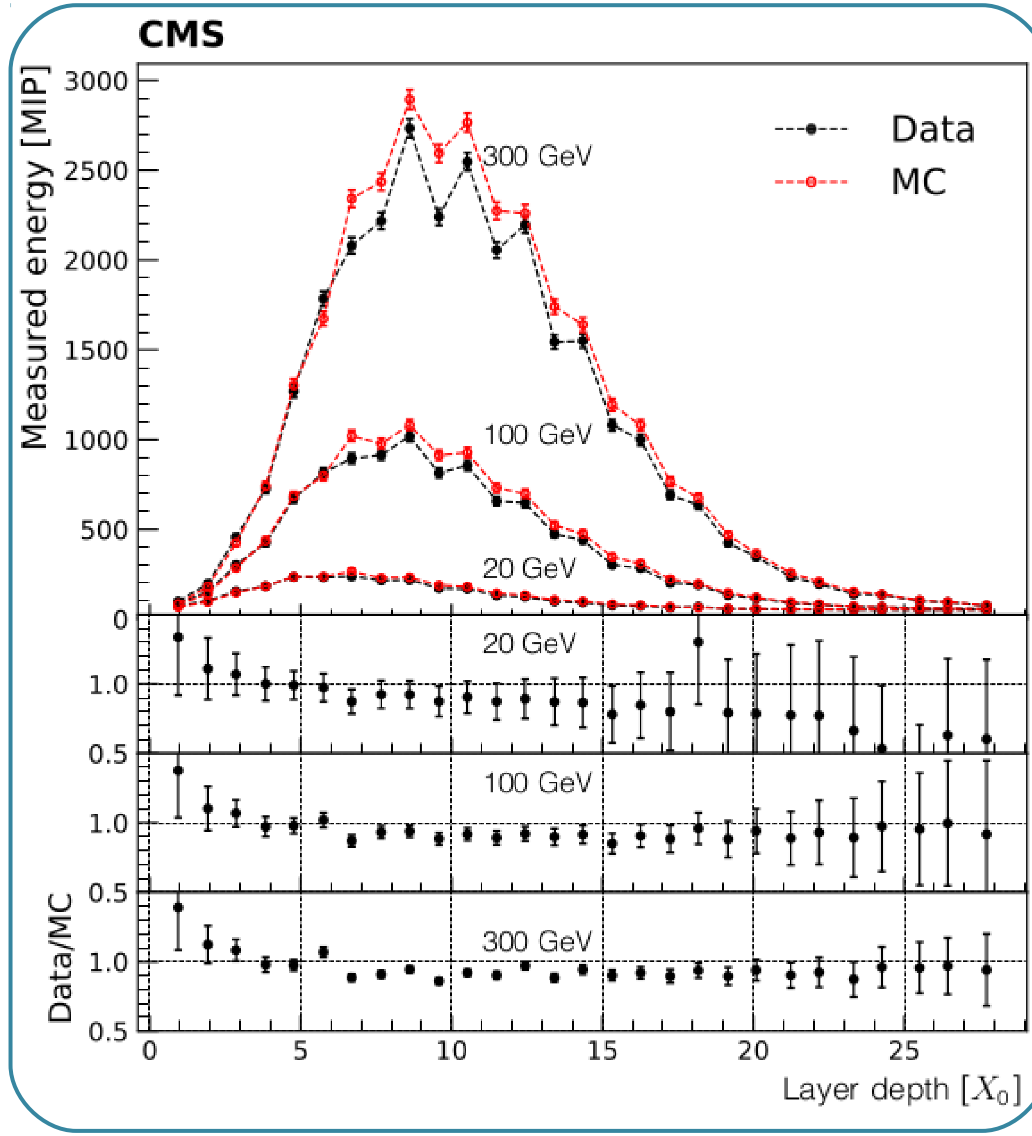
Resolution



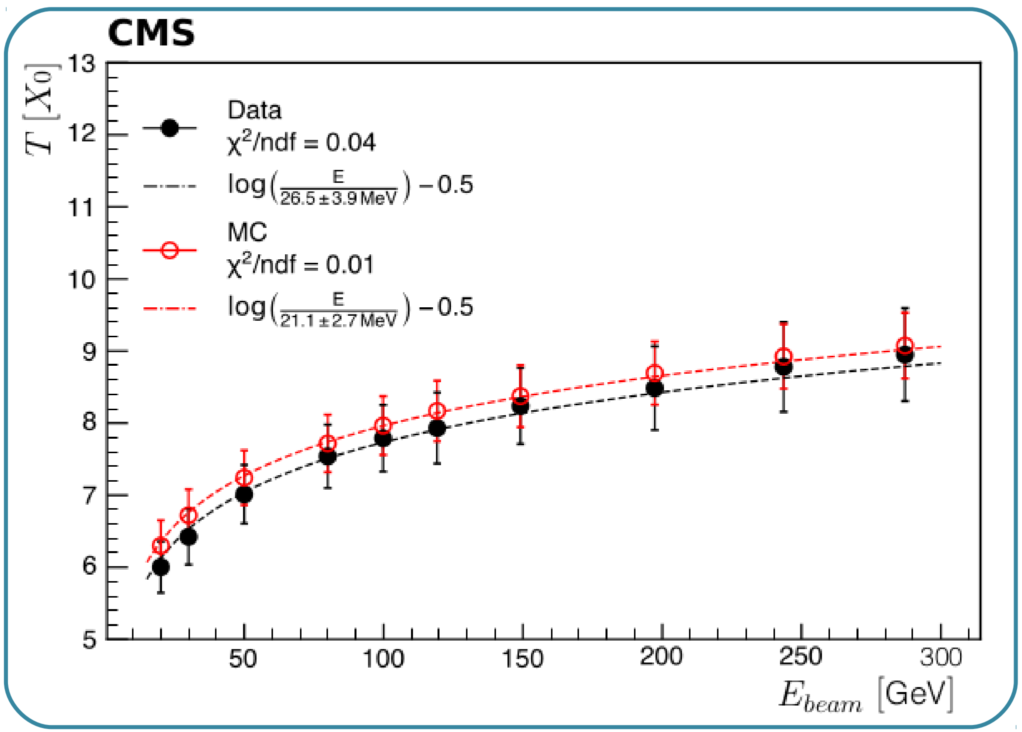
Electromagnetic shower profile

- Logarithmic dependency of the shower depth
- Fine structure of the profile due to **variations of absorber thicknesses** from one active layer to an other

Longitudinal profile



Shower maximum



Hadronic shower reconstruction

- First a calibration based on electrons in the ECAL part and pions in the HCAL part
- As expected, non linear response for hadronic showers
  - This is a **non compensating calorimeter**
  - Need more sophisticated calibration techniques (e.g. software compensation)

Pion shower non linearity