Calorimetry *in high energy physics*

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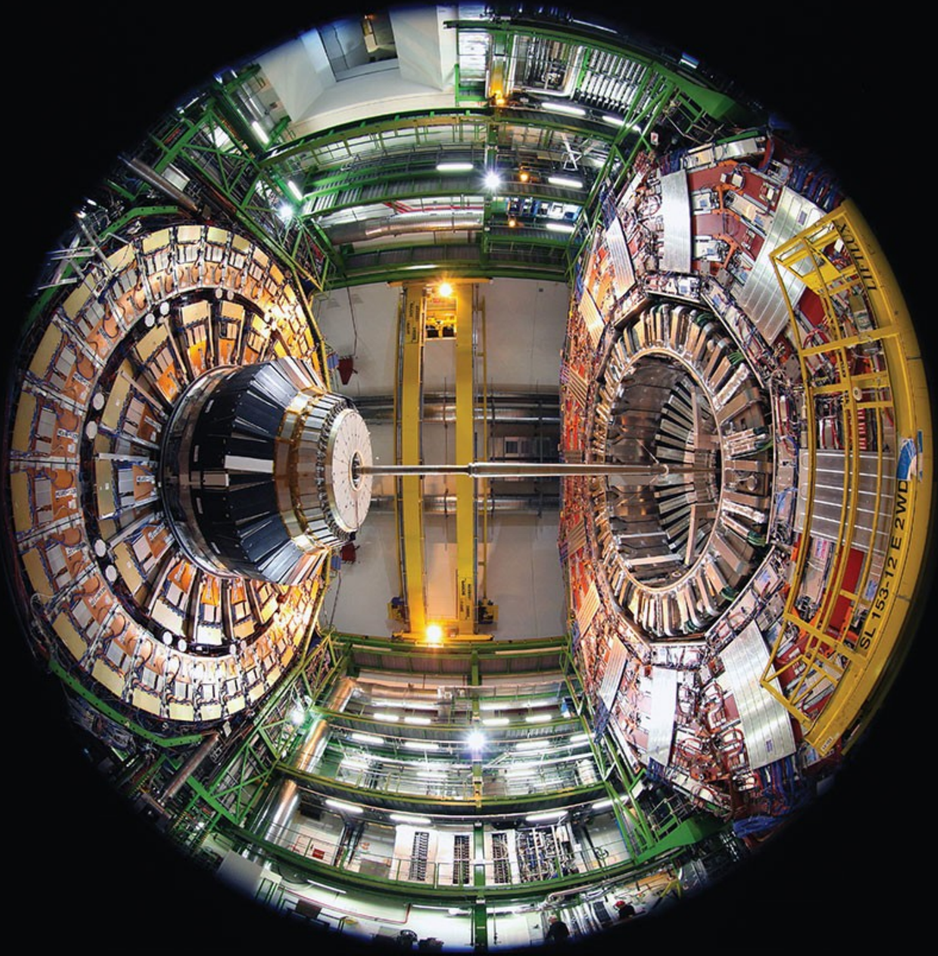


Lecture plan

- 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

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

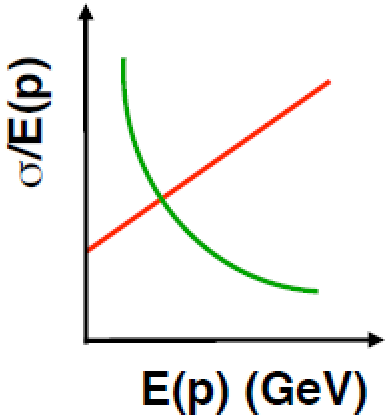
Energy reconstruction & calibration

An example: CMS HGCAL

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

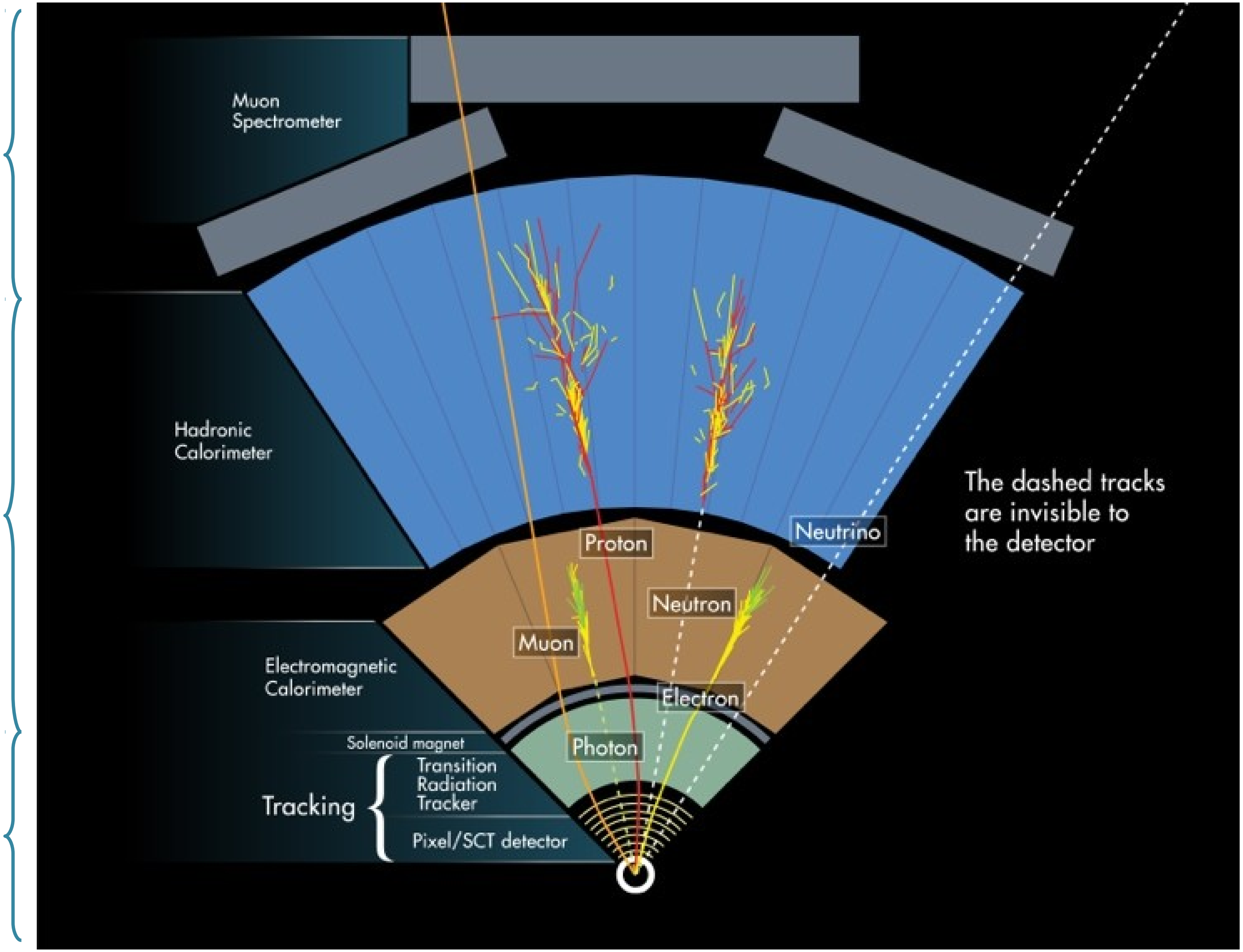
$$\frac{\sigma(p)}{p} = ap \oplus b$$

Calorimetry

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

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

Typical HEP detectors

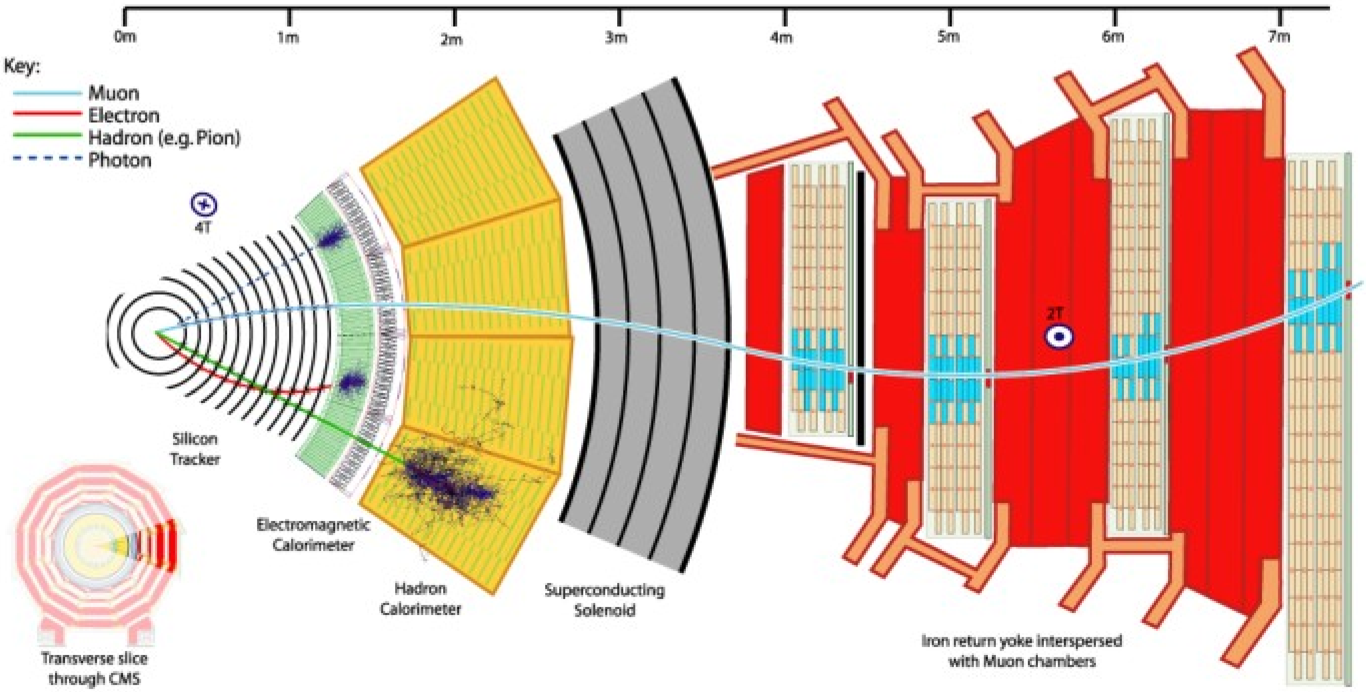


Muon spectrometer

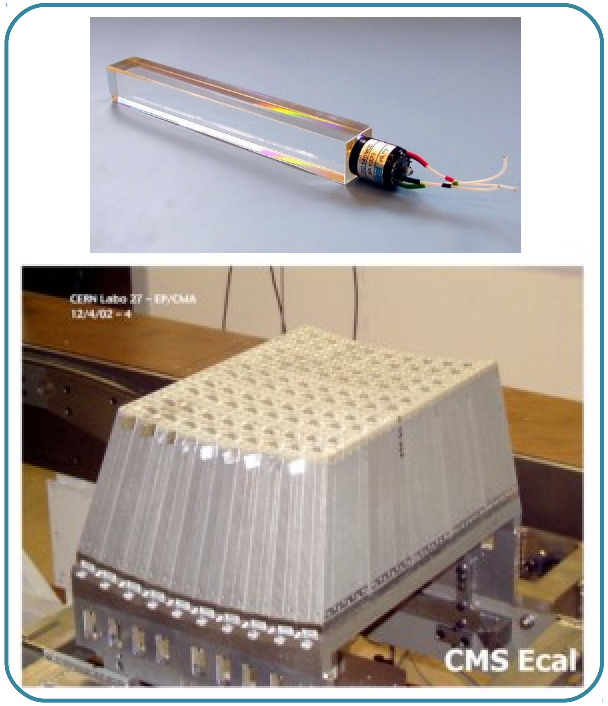
Calorimeters

Trackers

Example 1: CMS ECAL



CMS ECAL crystal and module

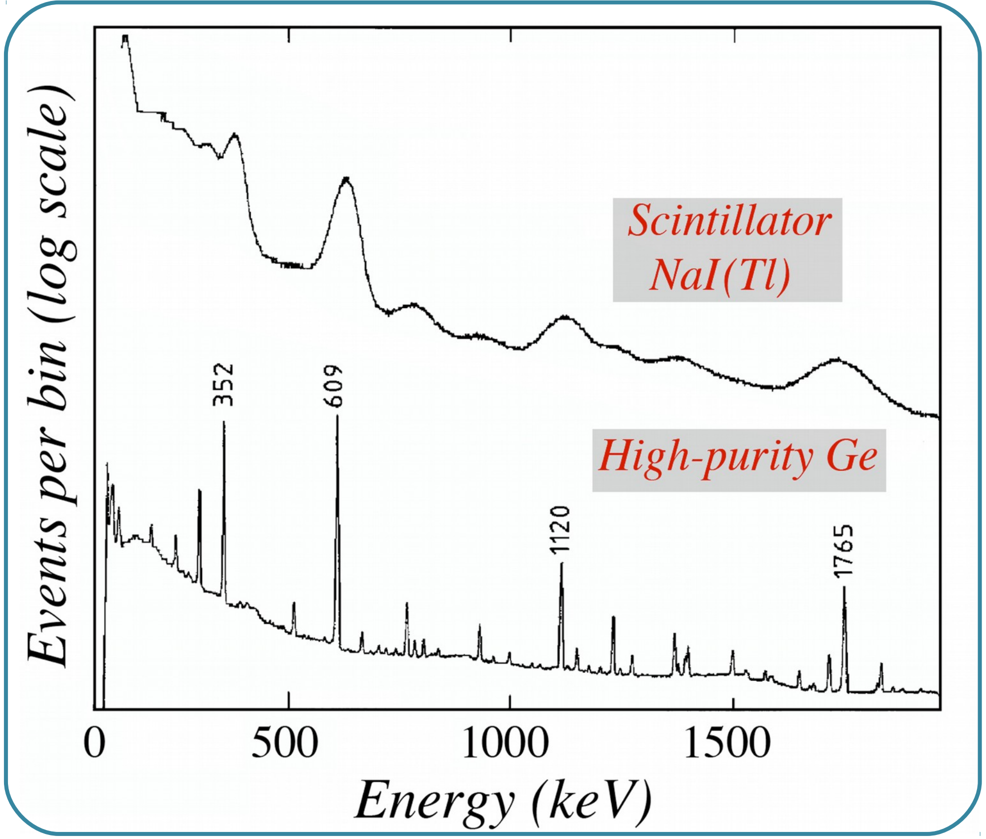


- CMS: typical **onion-like** detector **structure**
  - ○ Tracking + magnet (curvature of charged particles)
  - ○ EM and hadronic calorimeters
- CMS ECAL
  - ○ **Scintillating crystals** + **photodiodes**

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)

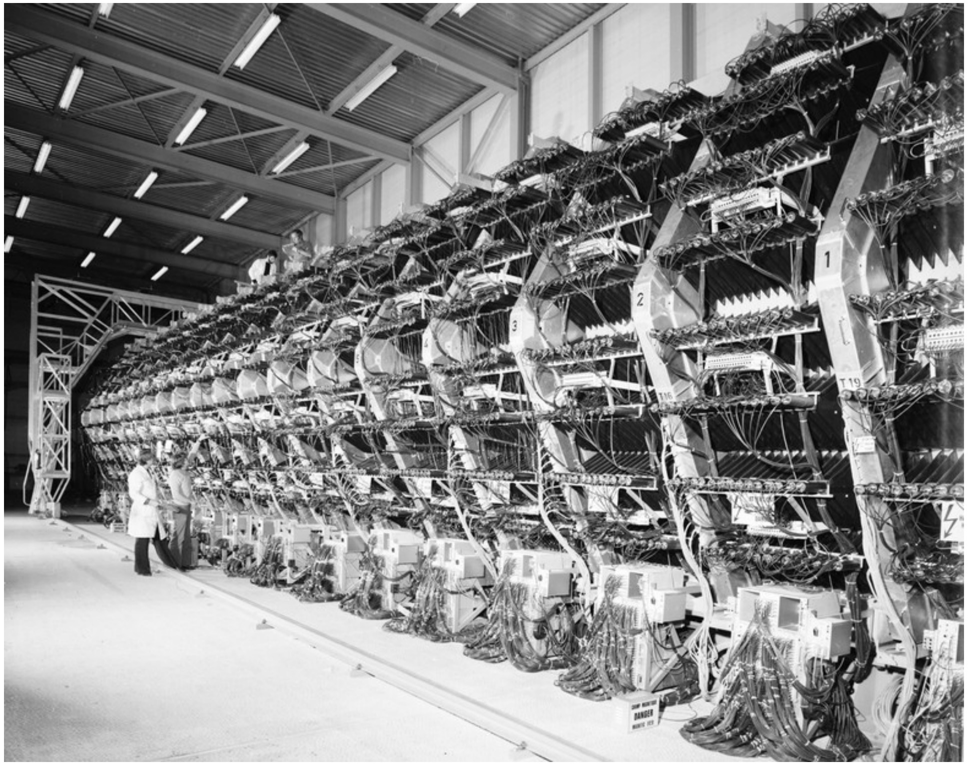
Energy resolution is important



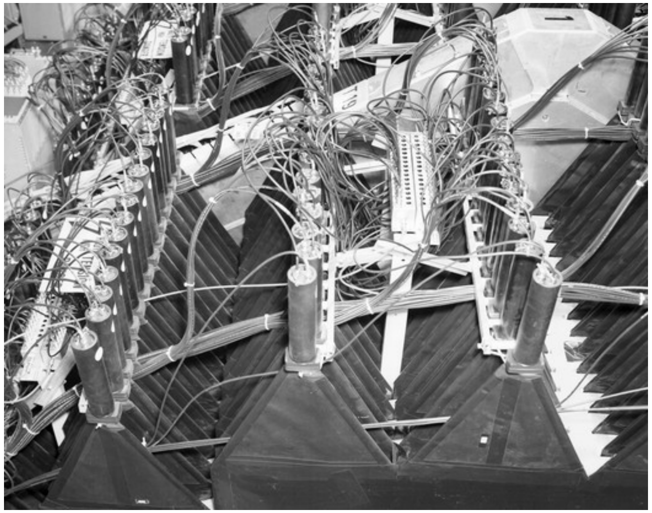
Neutrino experiments at SPS (CERN)

- 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

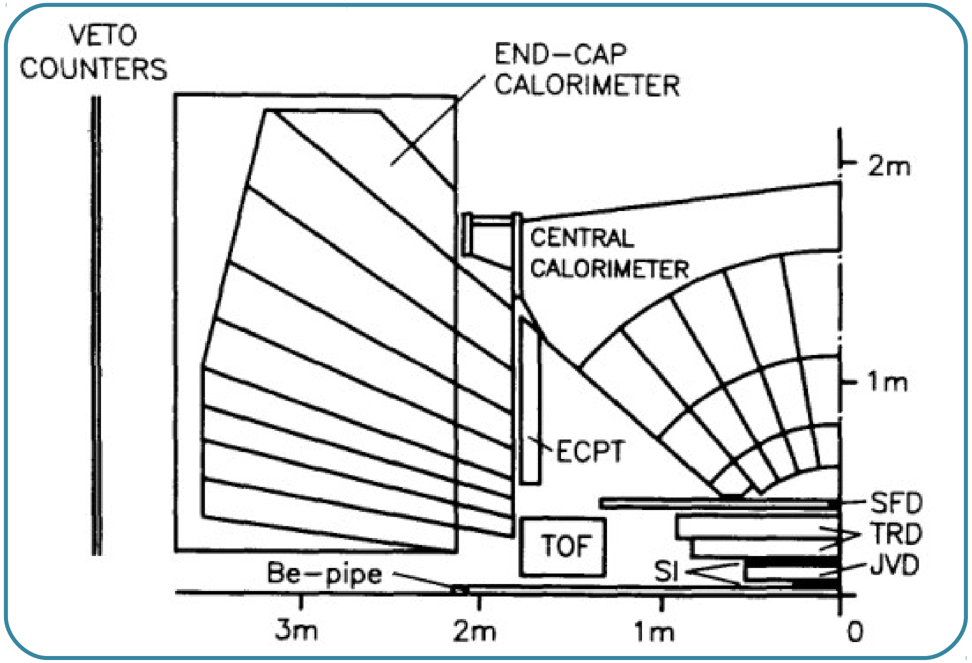


UA1 and UA2

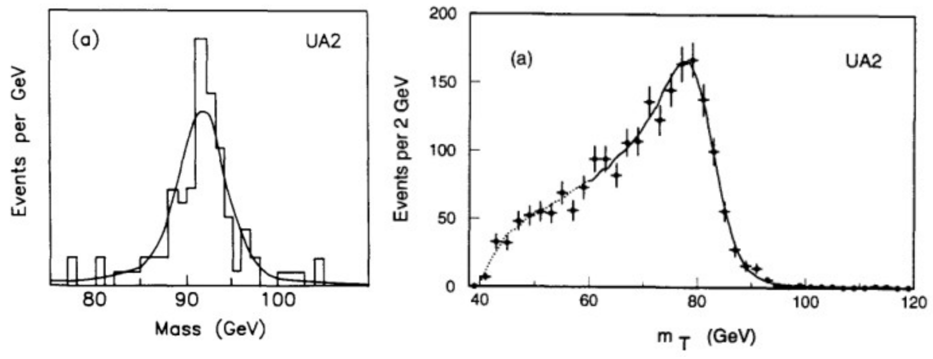
- UA1 & UA2 = Experiments at the SppS (CERN)
- UA2 (1981-1990)
  - More focused on calorimetry
  - **Lead (or Iron) + scintillator**
- Discovery of the **W and Z bosons**

UA2 detector

UA2 cross-section

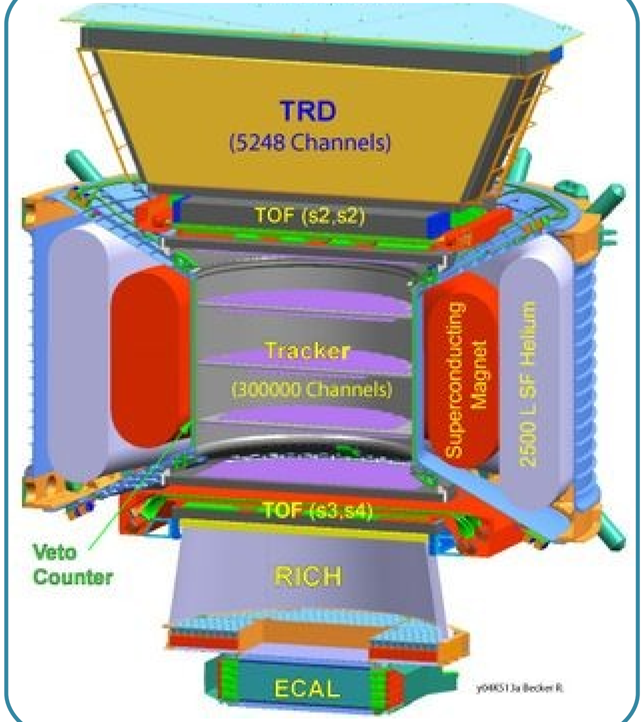


Z mass & W transverse mass



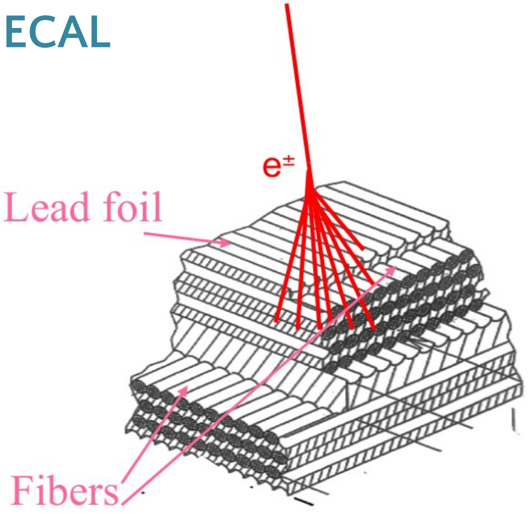
AMS

AMS cross-section



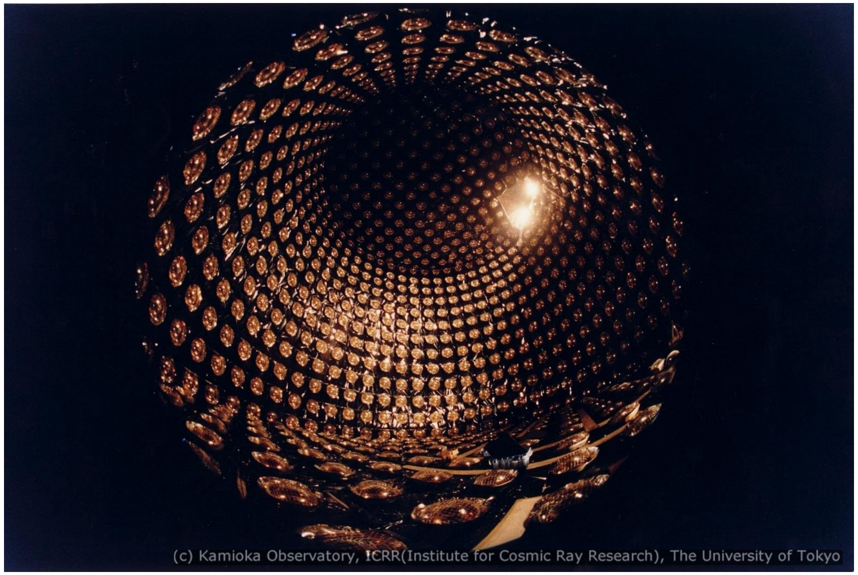
- AMS: experiment on the International Space Station
- Search presence of **antimatter and dark matter**
- Electromagnetic calorimeter
  - Measure high energy electrons/positrons
  - Discriminate against protons

ECAL

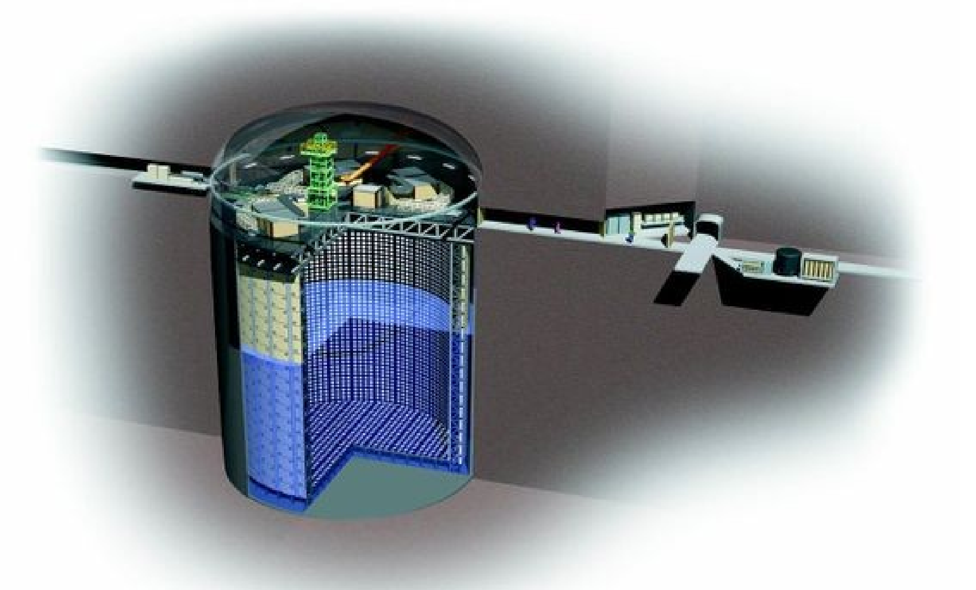


(Super-)Kamiokande

Super-Kamiokande



(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo



- **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**

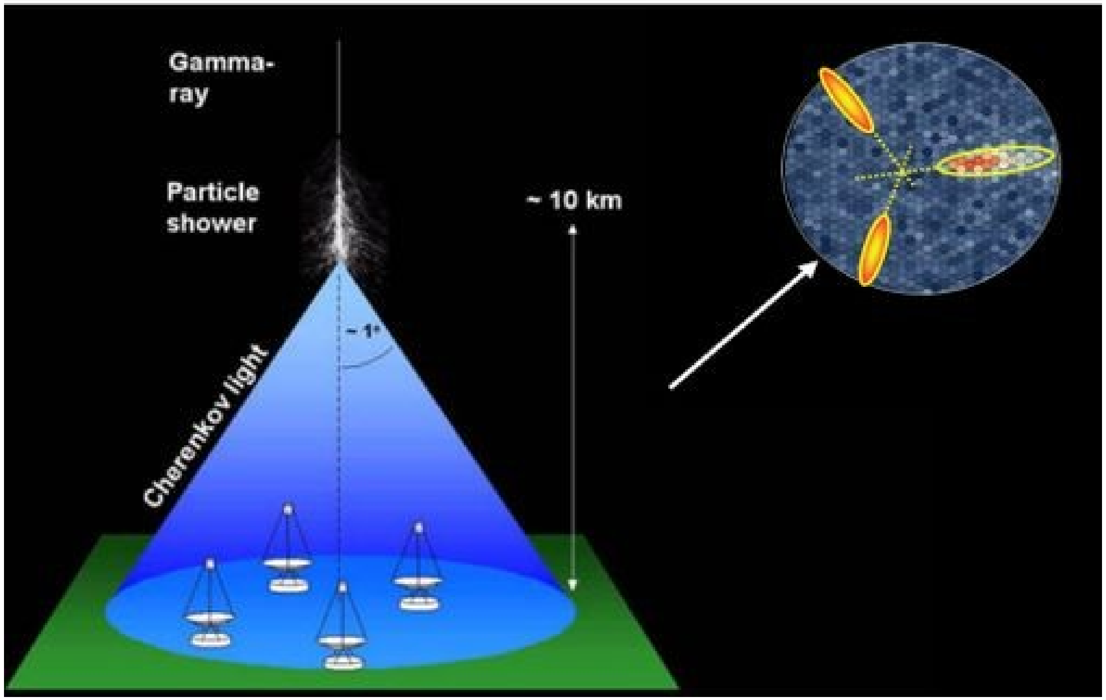
Large PMT

HESS

The 5 HESS telescopes

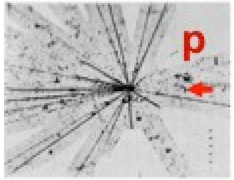
- Explore cosmic gamma rays
  - ○ Interaction with the **atmosphere**
  - ○ Emission of **Cerenkov light**
- Telescopes record this Cerenkov light on the ground

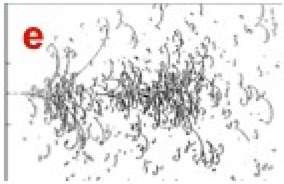
Detection principles



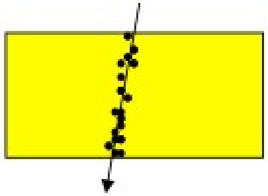
Calorimeter: principles

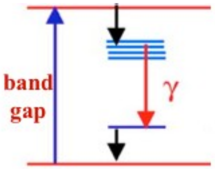
Particles interact with matter
Depends on particle and material

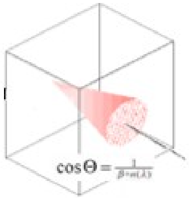




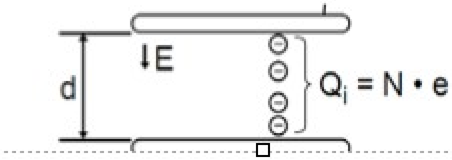
Energy lost transferred to detectable signal
Light, electric signal, etc.

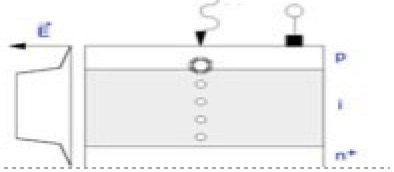




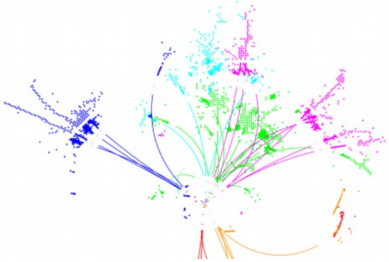


Signal collected and acquired
In the end: digitized signal





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
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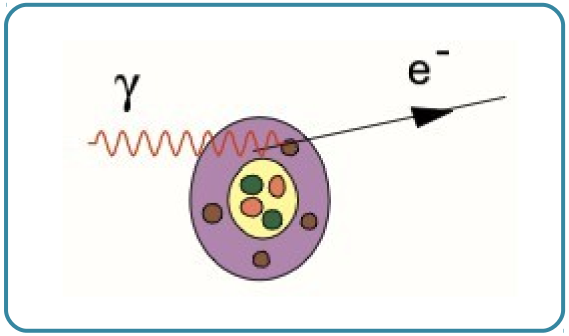
- An example: CMS HGCAL

Electromagnetic interactions with matter

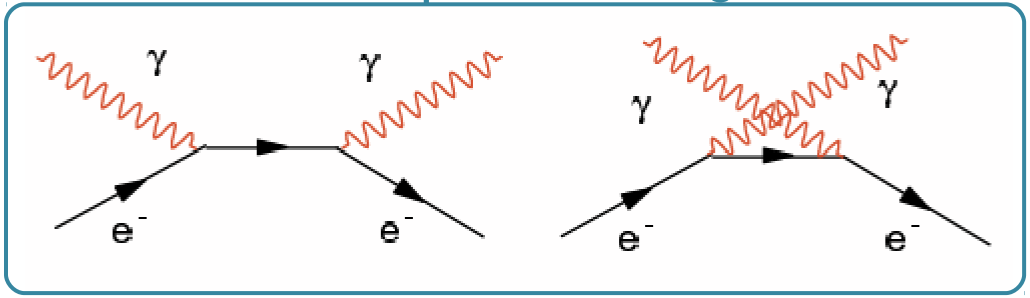
Photons | **Electrons**

Low energy

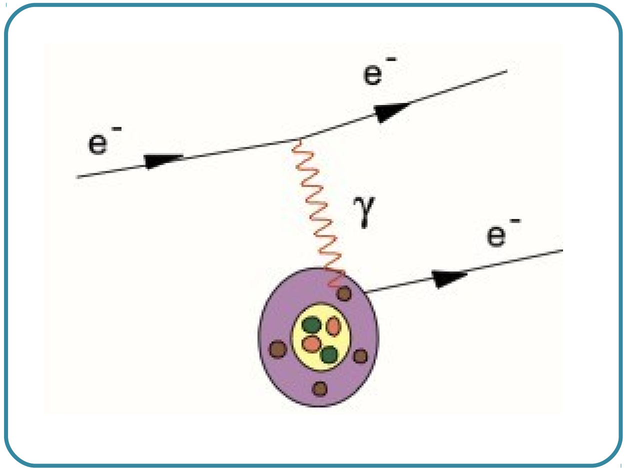
Photoelectric effect



Compton scattering

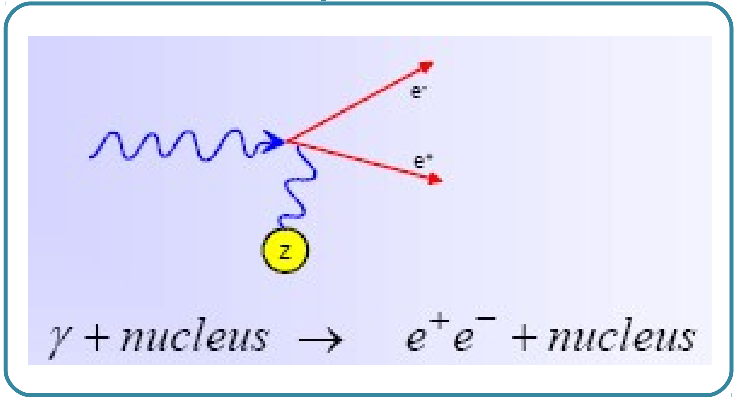


Ionisation



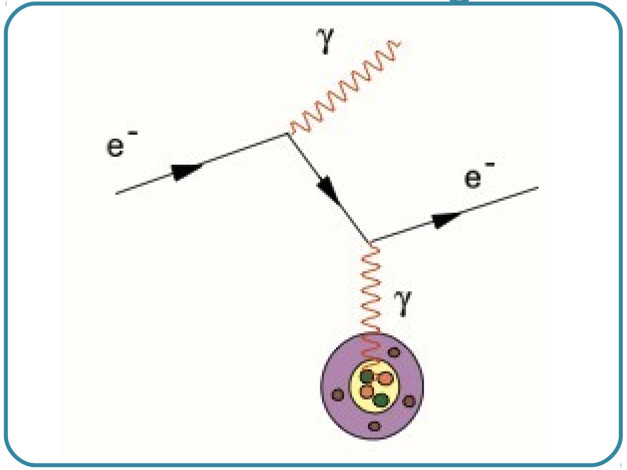
High energy

Pair production



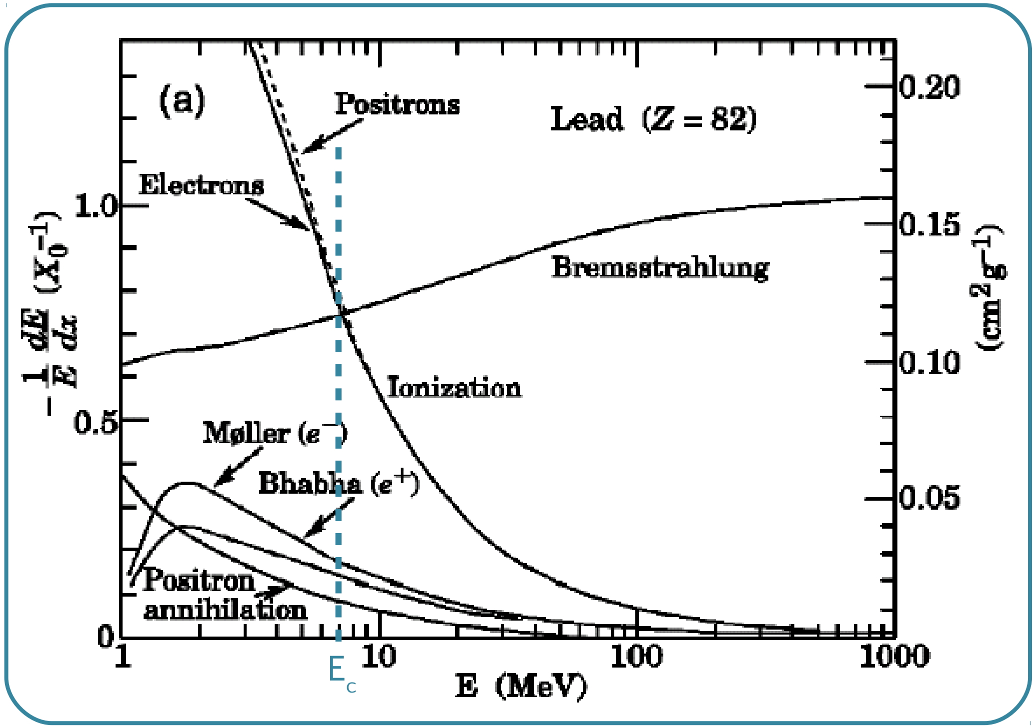
$$\gamma + nucleus \rightarrow e^+e^- + nucleus$$

Bremsstrahlung

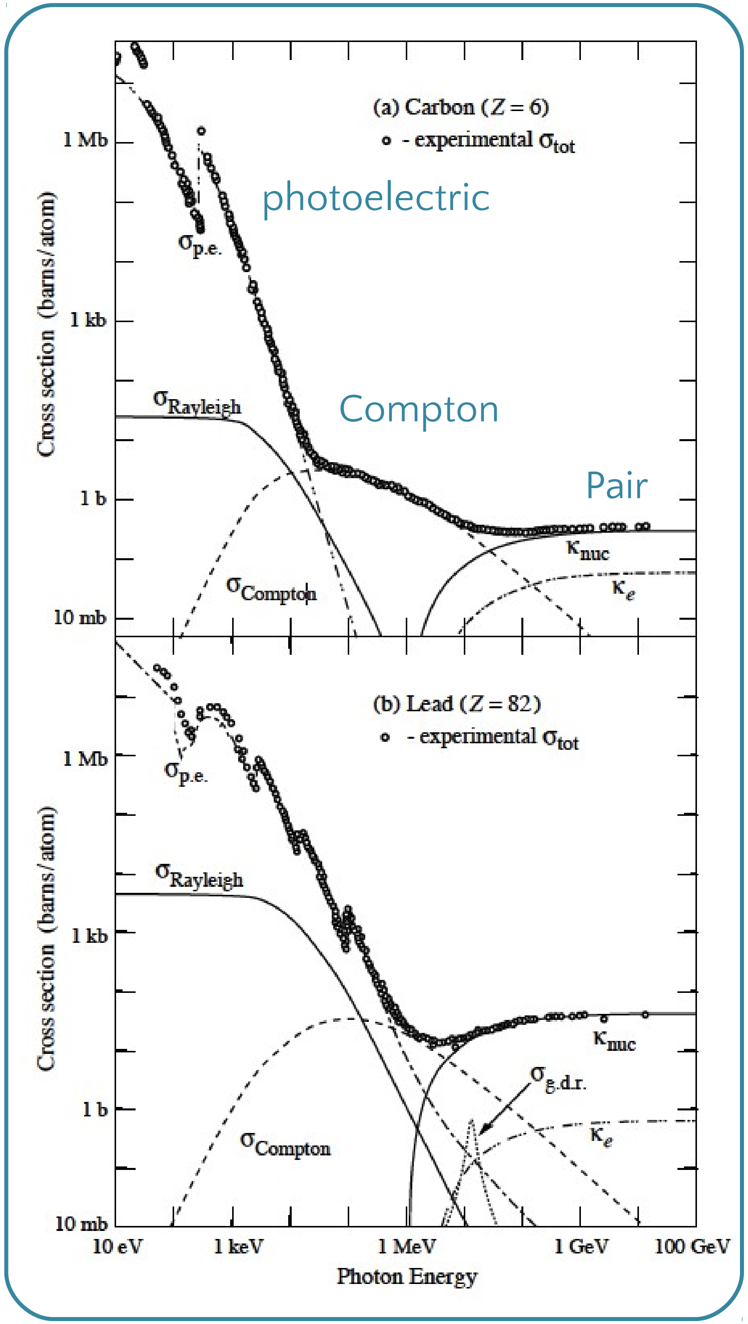


Dominant processes

Electrons



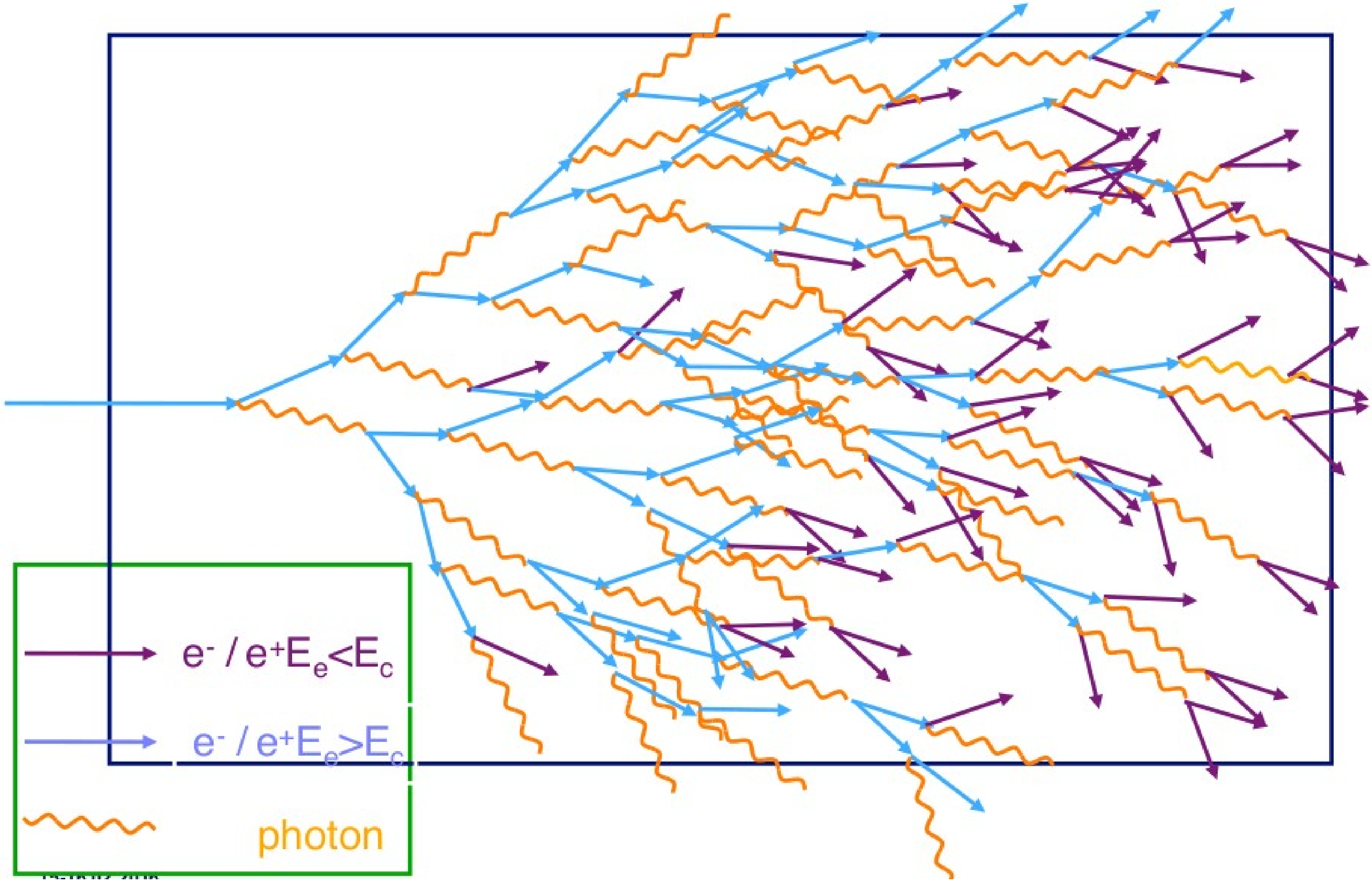
Photons



- 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

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

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

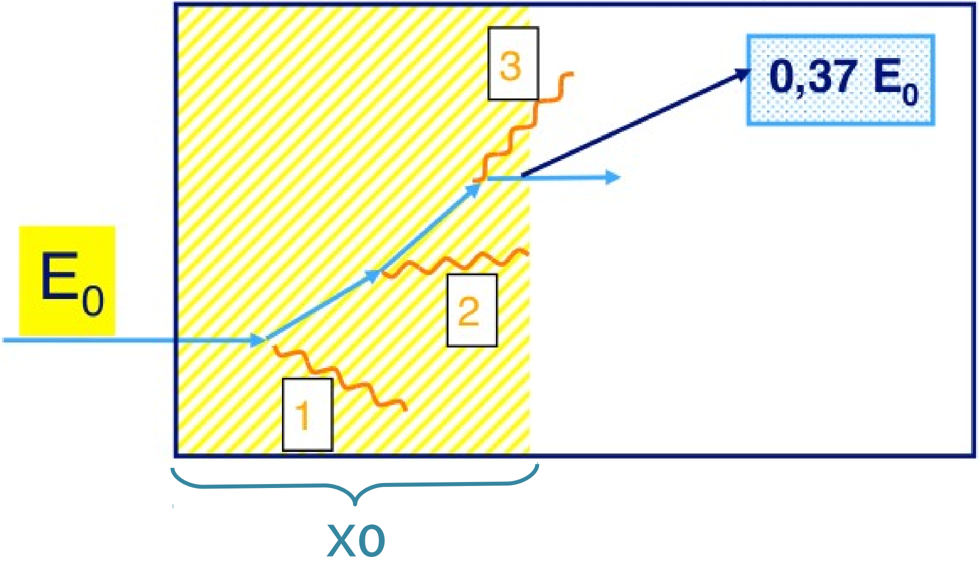
$$x(E_0/2)=X_0\ln(2)$$

Pair prod. probability

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

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

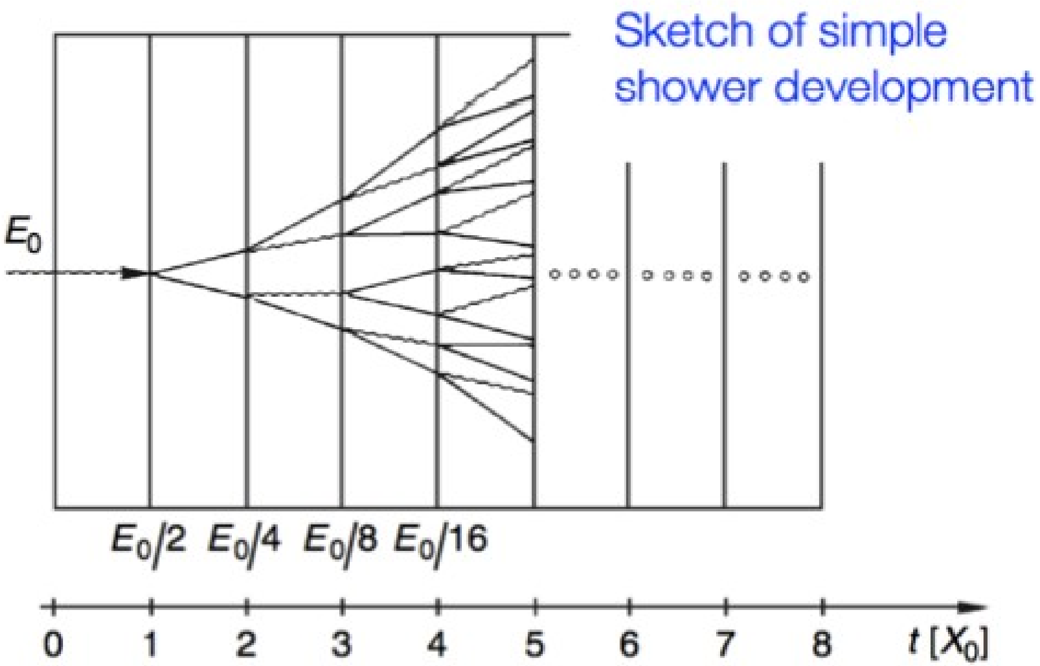
Radiation length X_0



- $X_0\approx\frac{180\,A}{Z^2}\,g.cm^{-2}$
- 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×X_0**
- Photons convert in about **9/7×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"



$t = x / X_0$

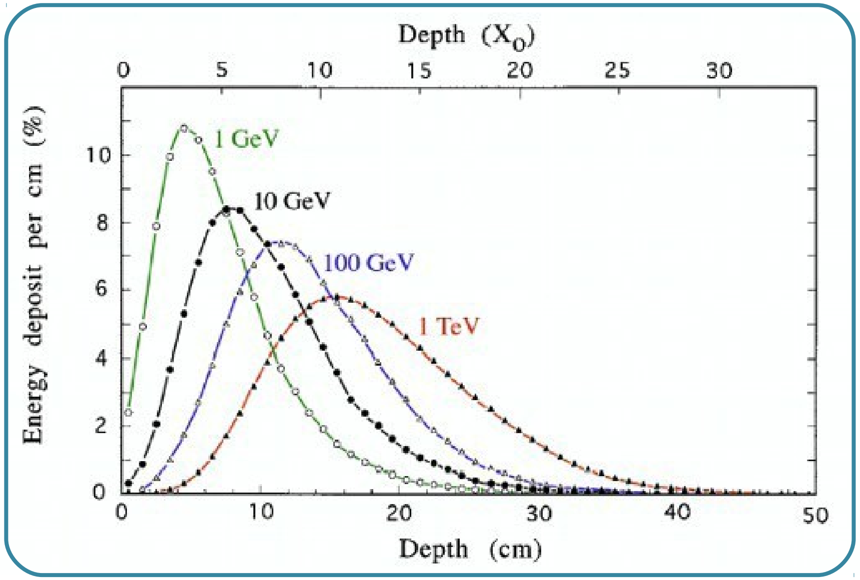
Some EM shower properties

- 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**

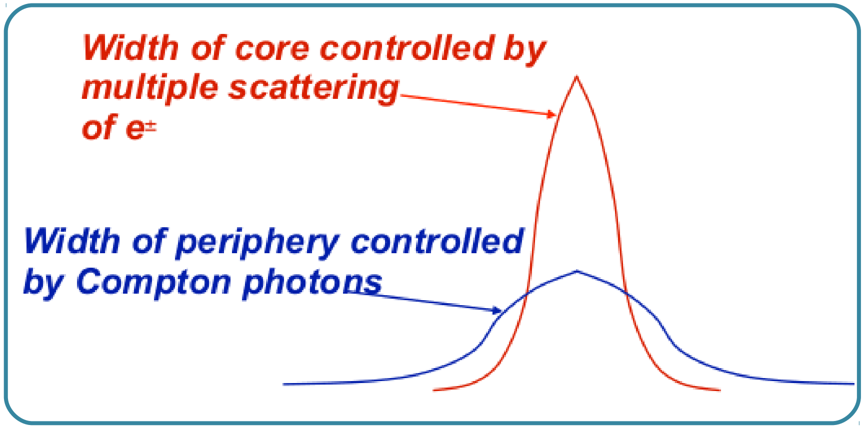
$$R_M = \frac{21\,MeV \times X_0}{E_c} \approx \frac{7\,A}{Z}\,g.cm^{-2}$$

  - ○ **Tails at larger angles**
    - – Isotropic Compton scattering
    - – Beyond shower max

Longitudinal profile



Lateral profile

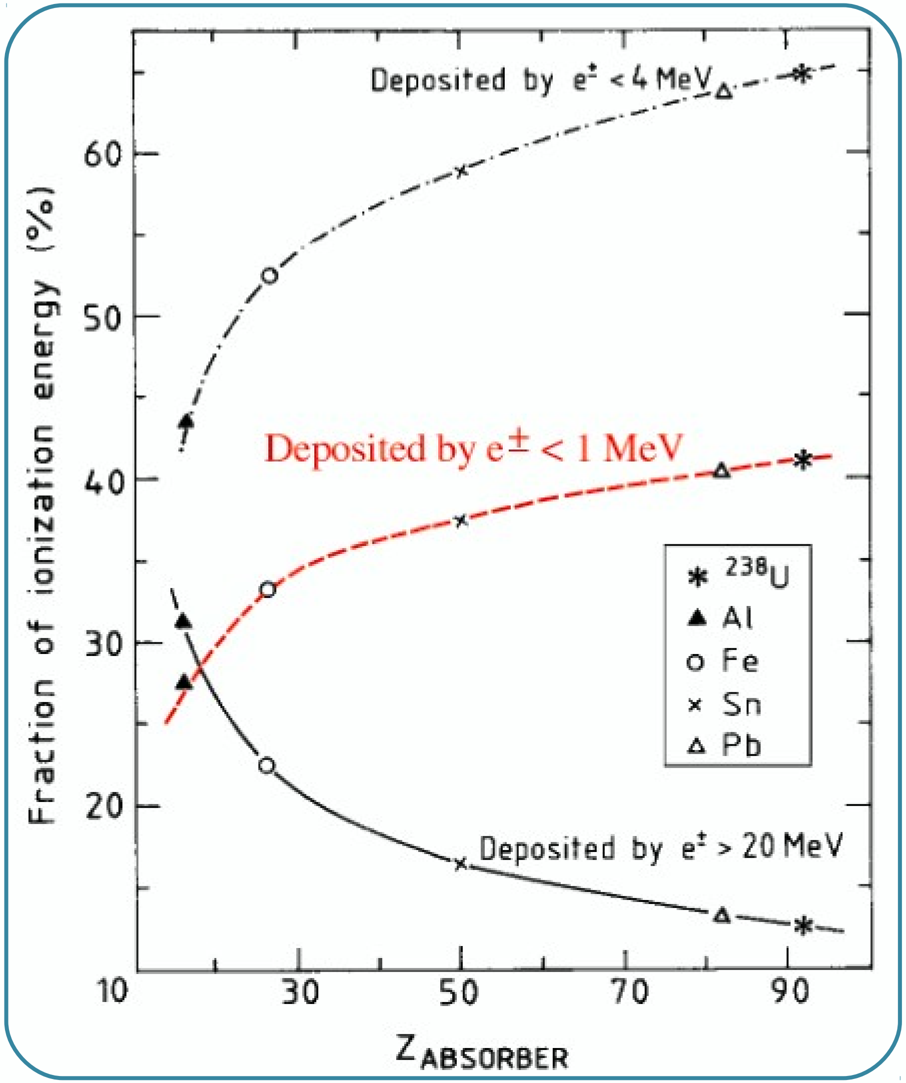

Width of core controlled by multiple scattering of e±

Width of periphery controlled by Compton photons

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)

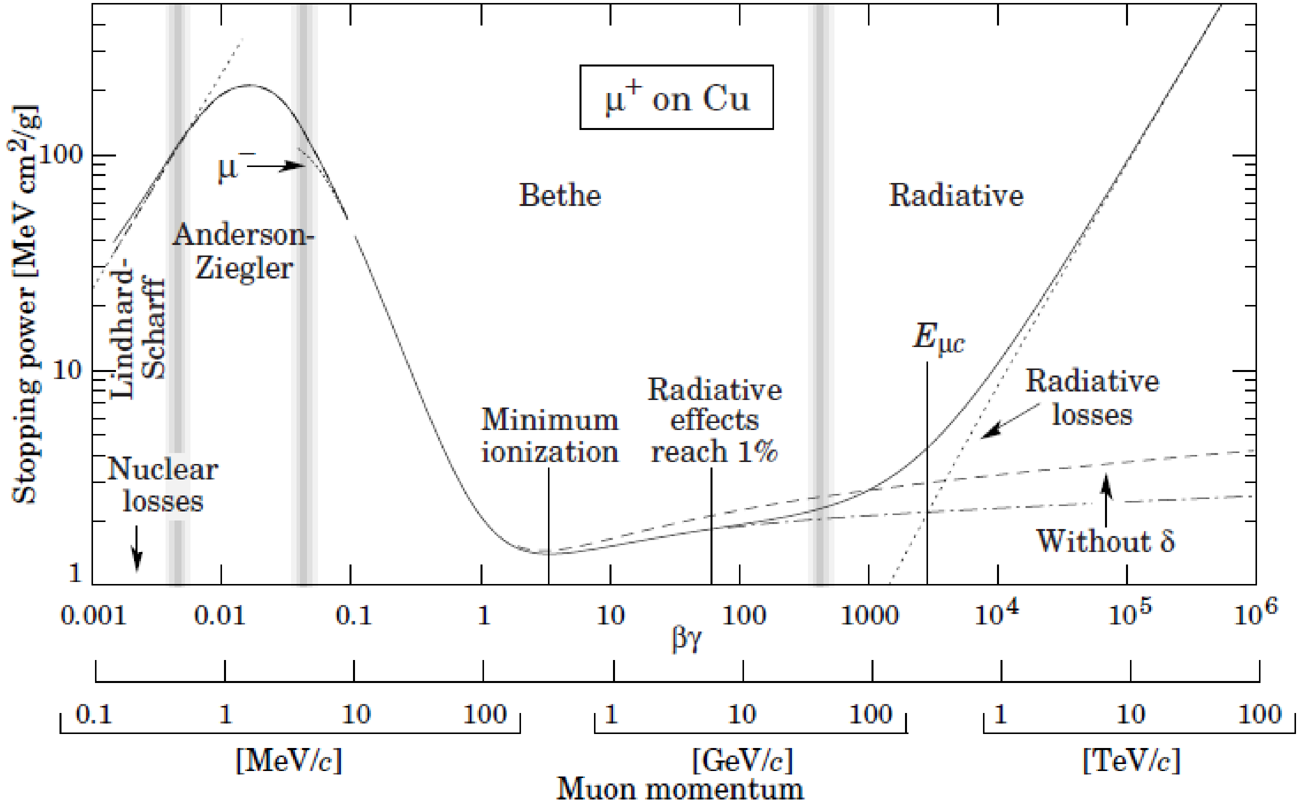
$$R_M = \frac{21\,MeV \times X_0}{E_c} \approx \frac{7\,A}{Z}\,g.cm^{-2}$$

- 95% lateral containment

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

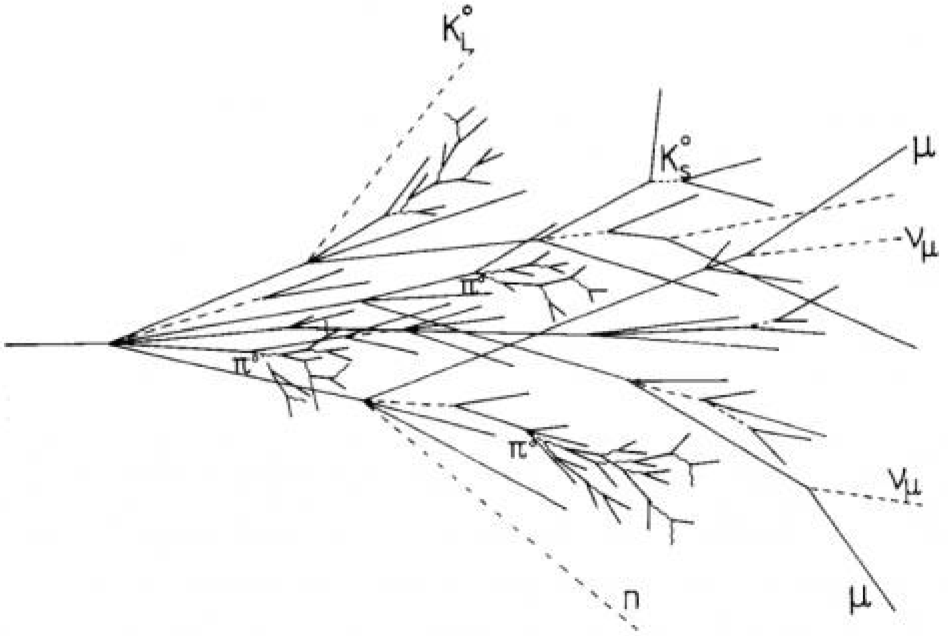
The case of the muon

- 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



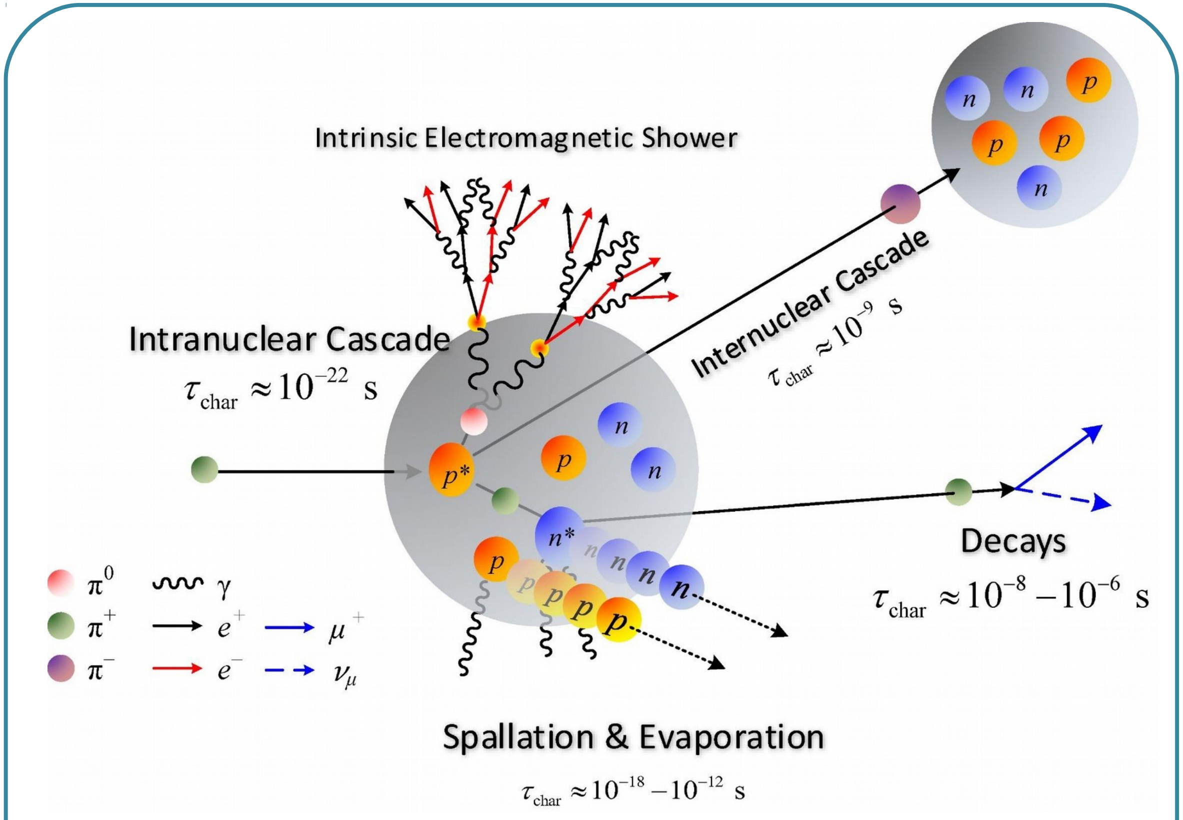
Hadronic showers

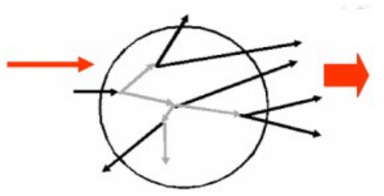
- Cascade of particles **initiated by a hadron**
  - Strong interaction in addition to EM interaction
- **Many processes** involved
  - Ionisation
  - Hadron production (fragmentation, etc.)
  - Charge exchange
    - $\pi\, n \rightarrow \pi^0\, p$
  - Spallation, fission
  - Nuclear de-excitation
 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



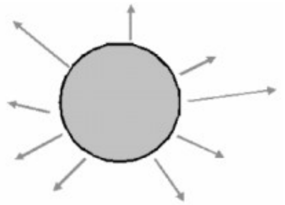
Hadronic interactions

Hadronic shower evolution





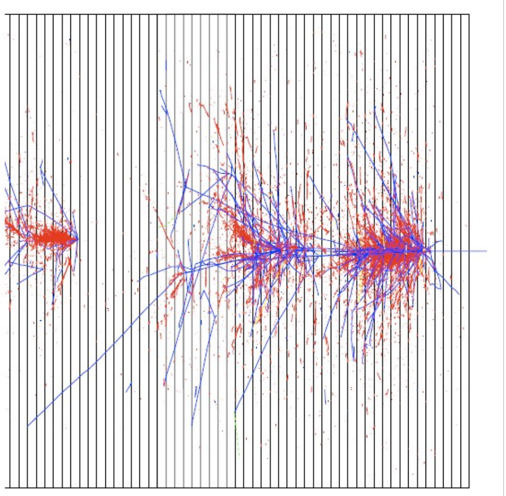
Intranuclear cascade
Incoming direction
Fast



Evaporation
Isotropic
Slow

- 1) **Hard collision**
  - ○ Can travel long distance before 1^{st} 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

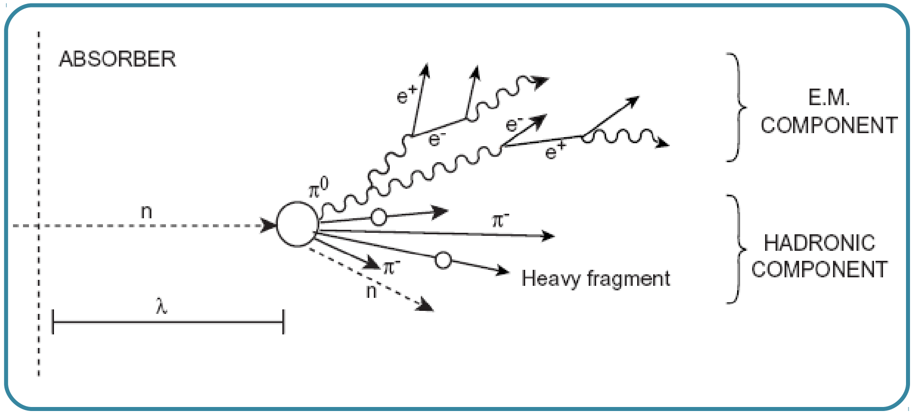
- Contributions
  - ○ Electrons & photons
  - ○ **Neutral pions** (e.g. $\pi^0 \rightarrow \gamma\gamma$)
- About 1/3 of π^0 produced at each nuclear interaction
- On average, **EM fraction increases with energy**

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

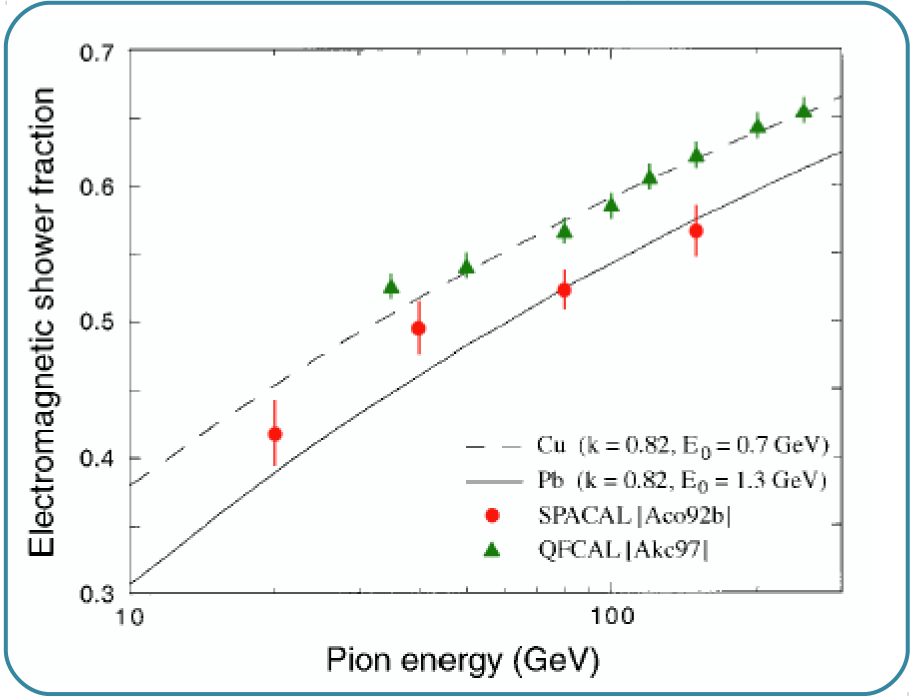
E_0 = average energy needed for π^0 production

k is related to the average multiplicity of π^0 produced at each interaction

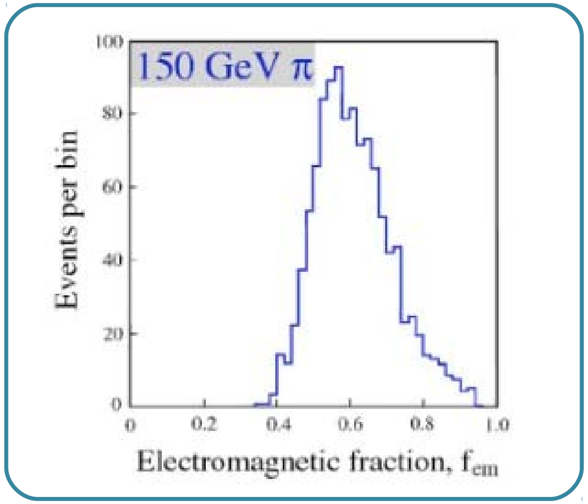
First hadronic interaction



EM fraction vs energy



Fluctuations in EM fraction



Non-EM components

Non-EM energy breakdown

Numbers for Lead

56% ionizing particles

2/3 are protons (from spallation)

<E> ~ 50-100 MeV

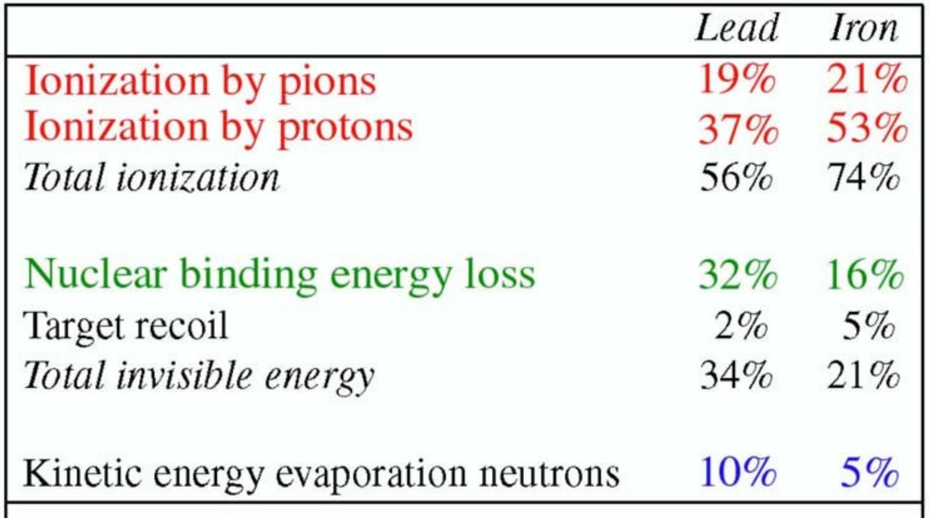
34% invisible

Break-up of nuclei

10% neutrons

Very soft (typically a few MeV)

On average 37n per deposited GeV



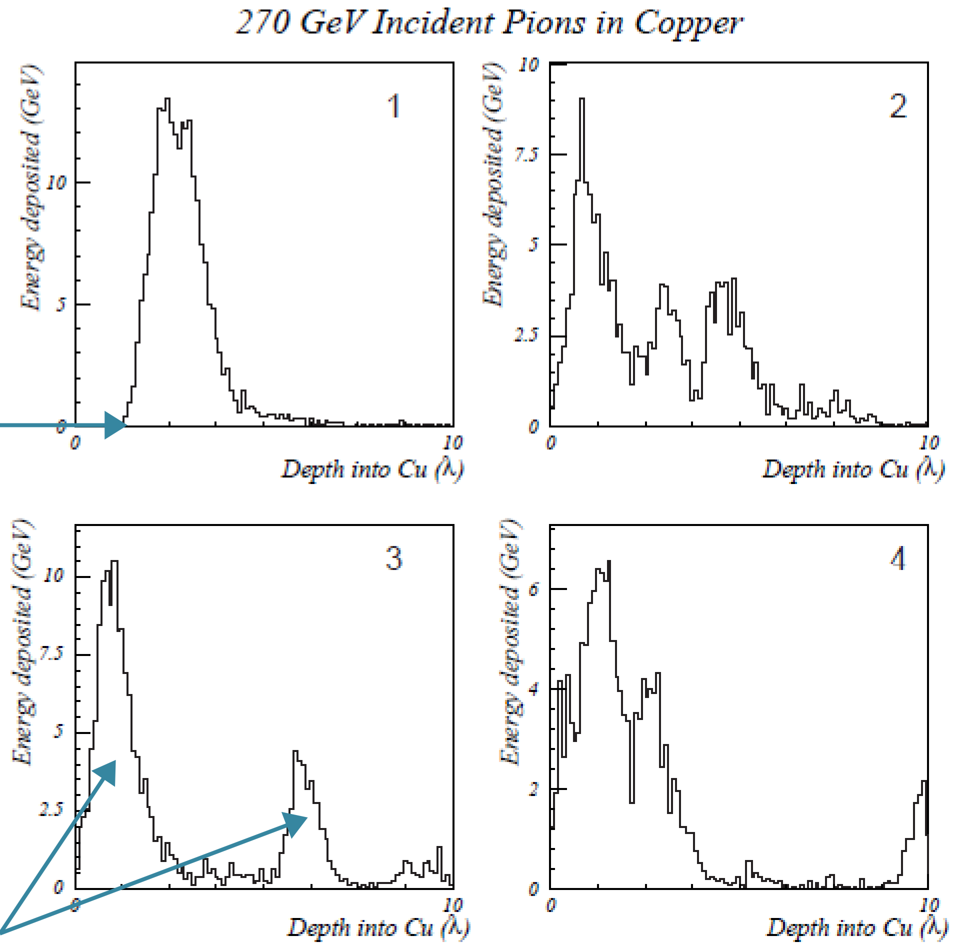
	Lead	*Iron*
Ionization by pions	19%	21%
Ionization by protons	37%	53%
Total ionization	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
Total invisible energy	34%	21%
Kinetic energy evaporation neutrons	10%	5%

- 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 1^{st} 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

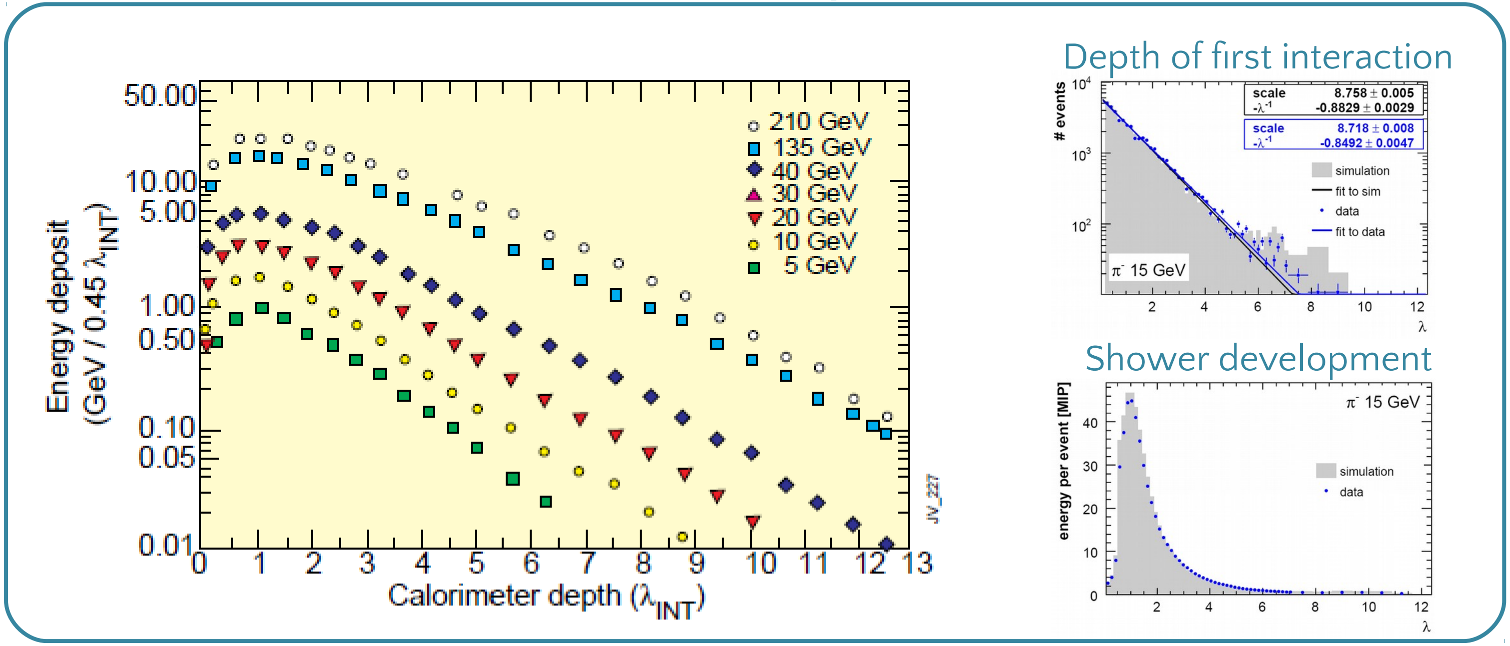
Longitudinal profile

- 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



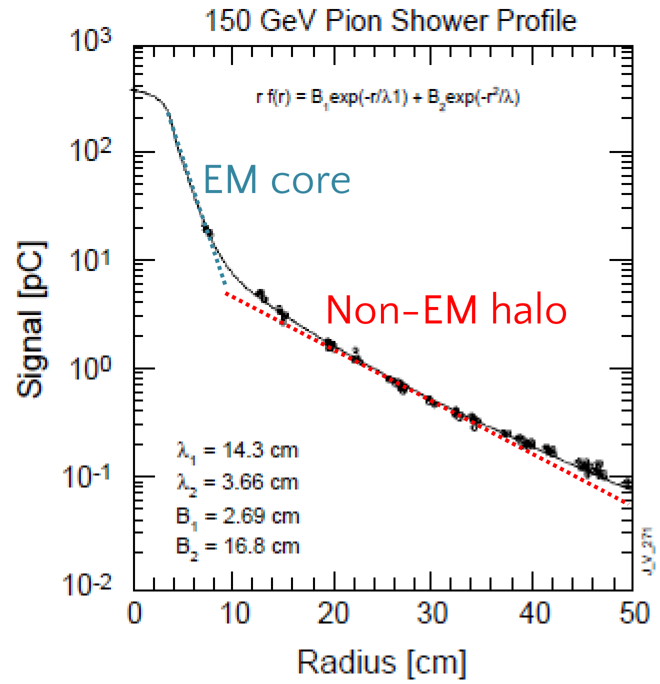
Depth of first interaction

Shower development

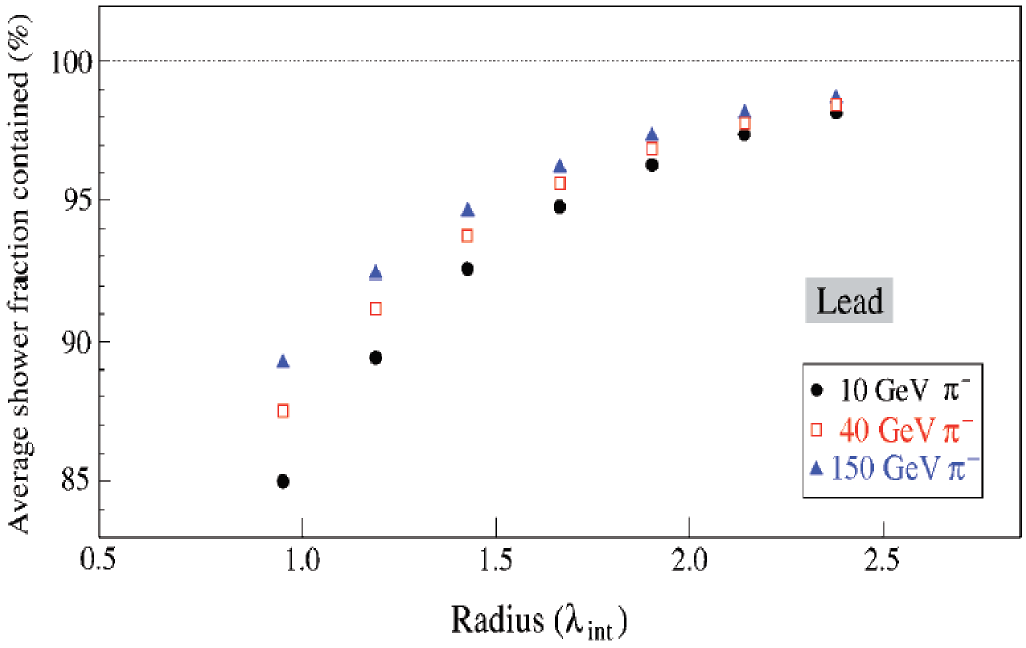
Lateral profile

- 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

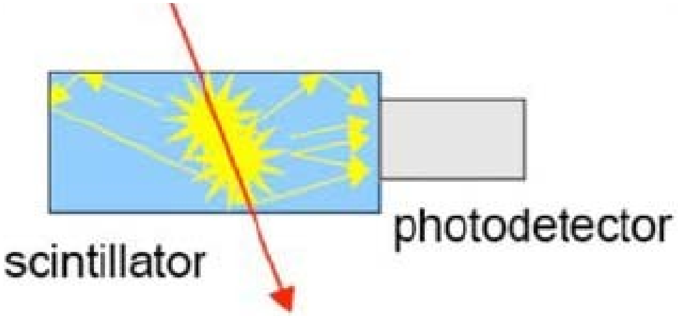


Lecture plan

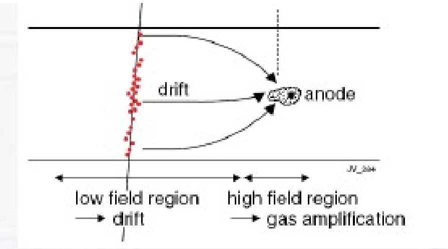
- What is a calorimeter in HEP?
- Detection techniques
- Electronics readout and trigger
- Beyond calorimetry: Particle Flow
- Electromagnetic and hadronic showers
- Calorimeter response & resolution
- Energy reconstruction & calibration
- An example: CMS HGCAL

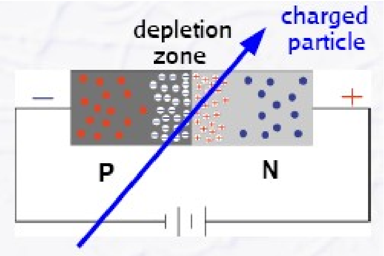
Measurement principles

- 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



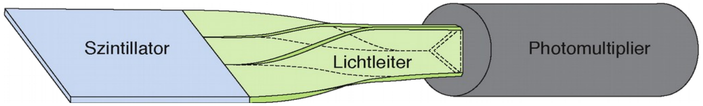


- One can also measure (very small) temperature increase
  - ○ e.g. Bolometers
  - ○ Not presented here

Scintillators

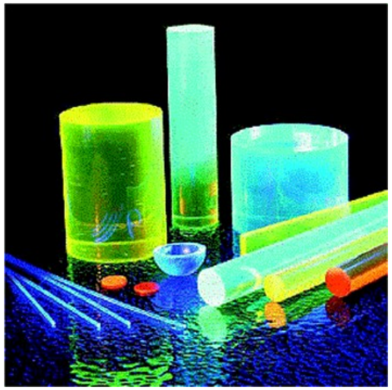
- **Excited atoms or molecules** in scintillating medium
  - De-excitation and emission of light (visible, UV, sometimes X-rays)
  - Propagation of light (wavelength shifters can be used, light guides)
  - Conversion into electric signal (photo-detector)

Light production and collection



- 2 types of scintillating material
  - **Organic** (plastics or liquids)
  - **Inorganic** (crystals)

Various scintillators

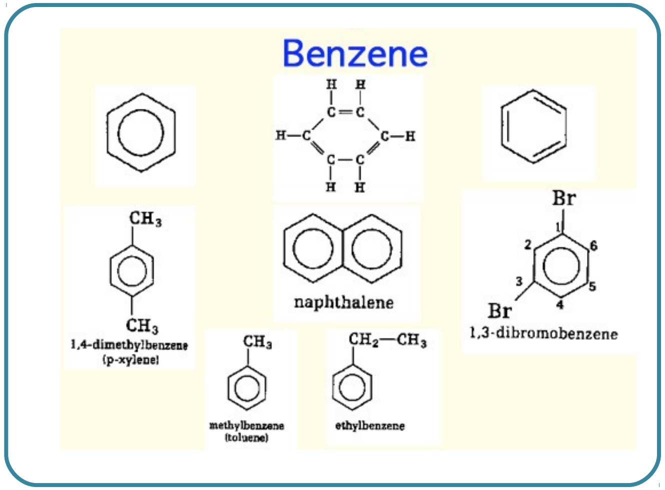


CMS PbWO4 crystal

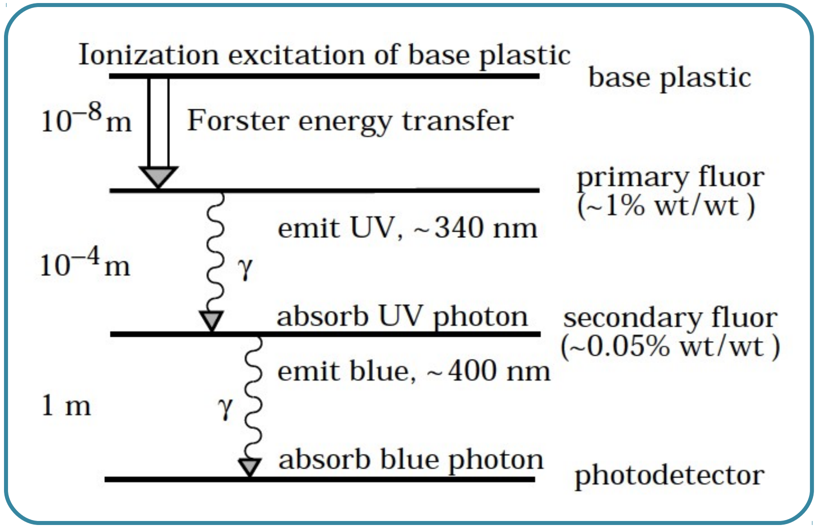
Organic scintillators

- Organic crystals, organic liquids, plastic scintillators
  - **Aromatic hydrocarbon** compounds (containing carbon rings)
  - Base/solvent + fluor (= fluorescent emitter, not fluorine)
- 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



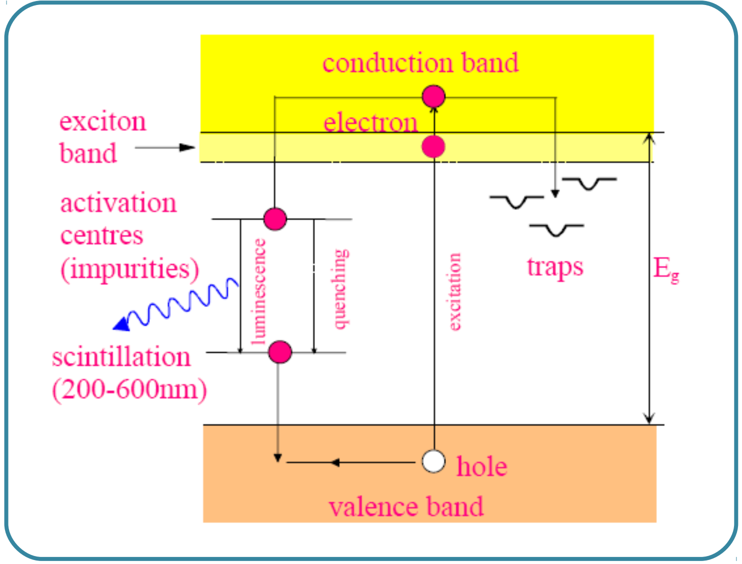
Inorganic scintillator

- **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**

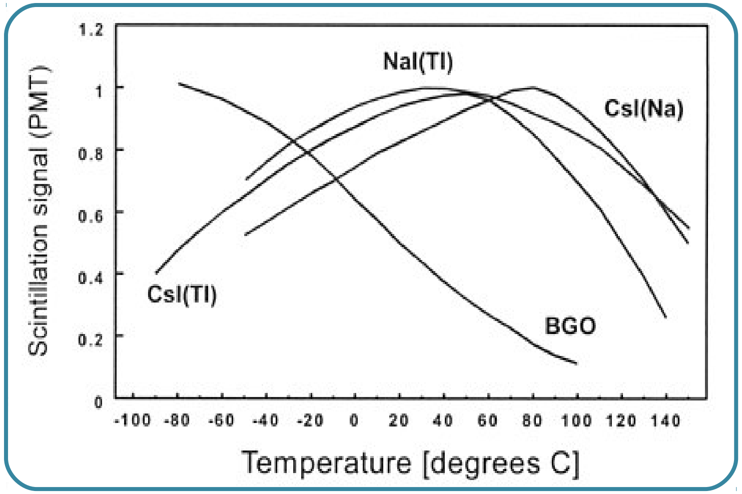
Material	Form	λ_{max} (nm)	τ_f (ns)	ρ (g/cm^3)	Photons per MeV
NaI(Tl) (20°C)	crystal	415	230	3.67	38,000
pure NaI (-196°C)	crystal	303	60	3.67	76,000
$Bi_4Ge_3O_{12}$ (20°C)	crystal	480	300	7.13	8,200
$Bi_4Ge_3O_{12}$ (-100°C)	crystal	480	2000	7.13	24,000
CsI(Na)	crystal	420	630	4.51	39,000
CsI(Tl)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

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

Light emission process



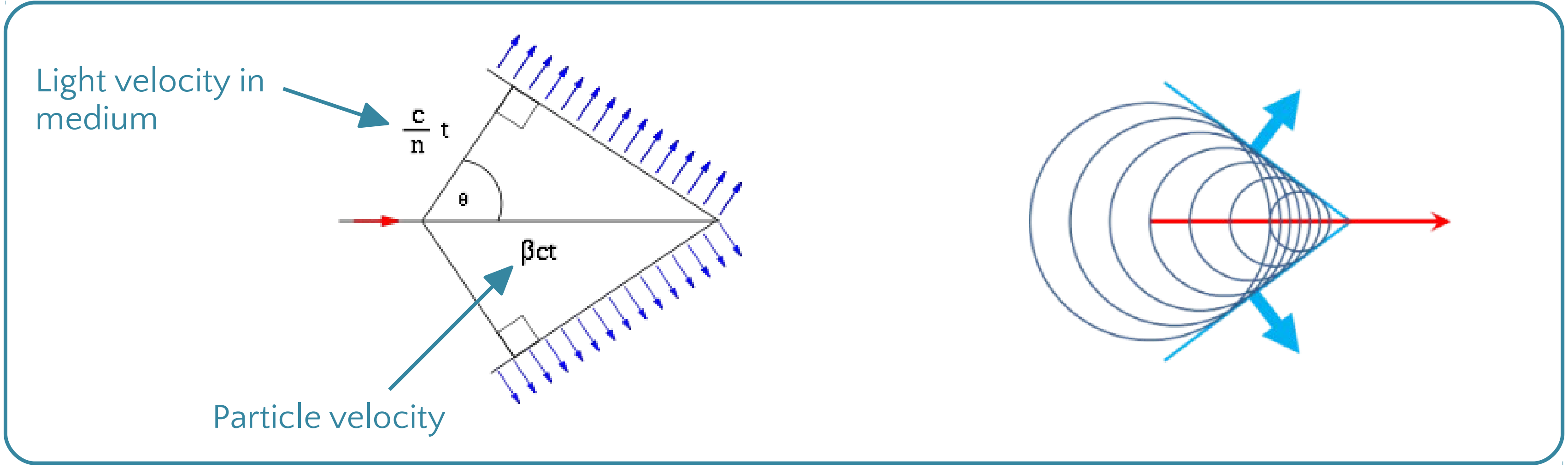
Light yield vs temperature



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



Light velocity in medium

Particle velocity

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

Medium refractive index

$\beta = v_p / c$

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

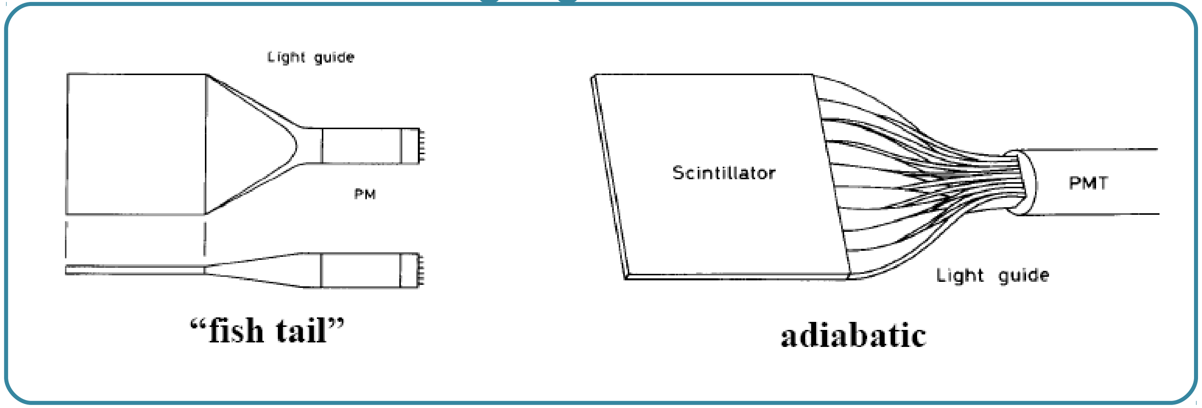
Spectrum in $1/\lambda^2$

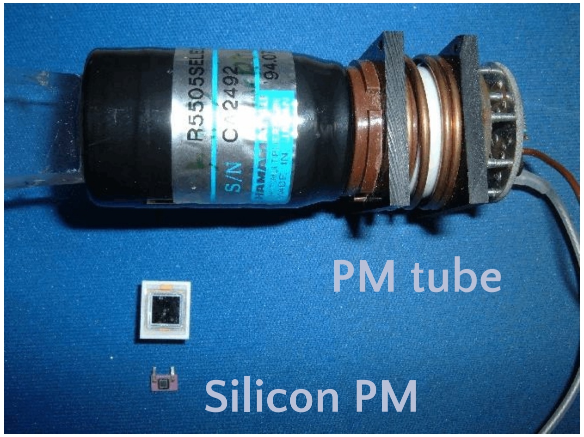
→ appears blue/violet in the visible spectrum

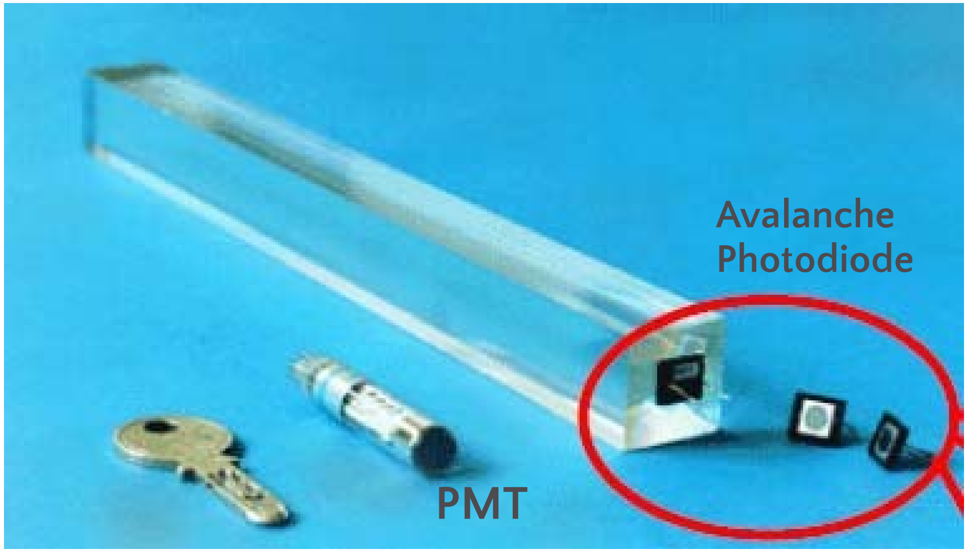
Photodetectors

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

Light guides





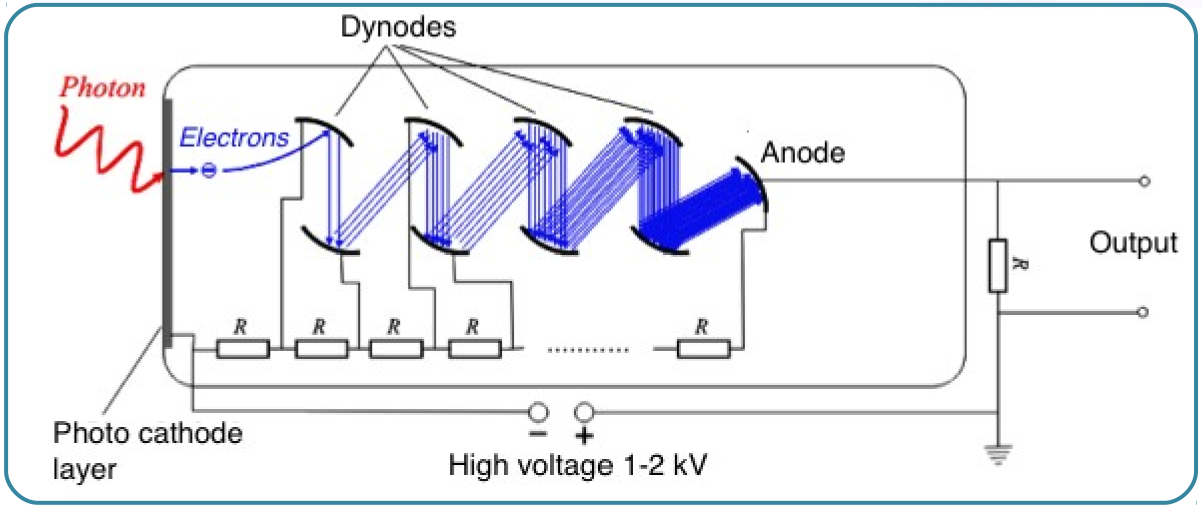


Large PMT

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

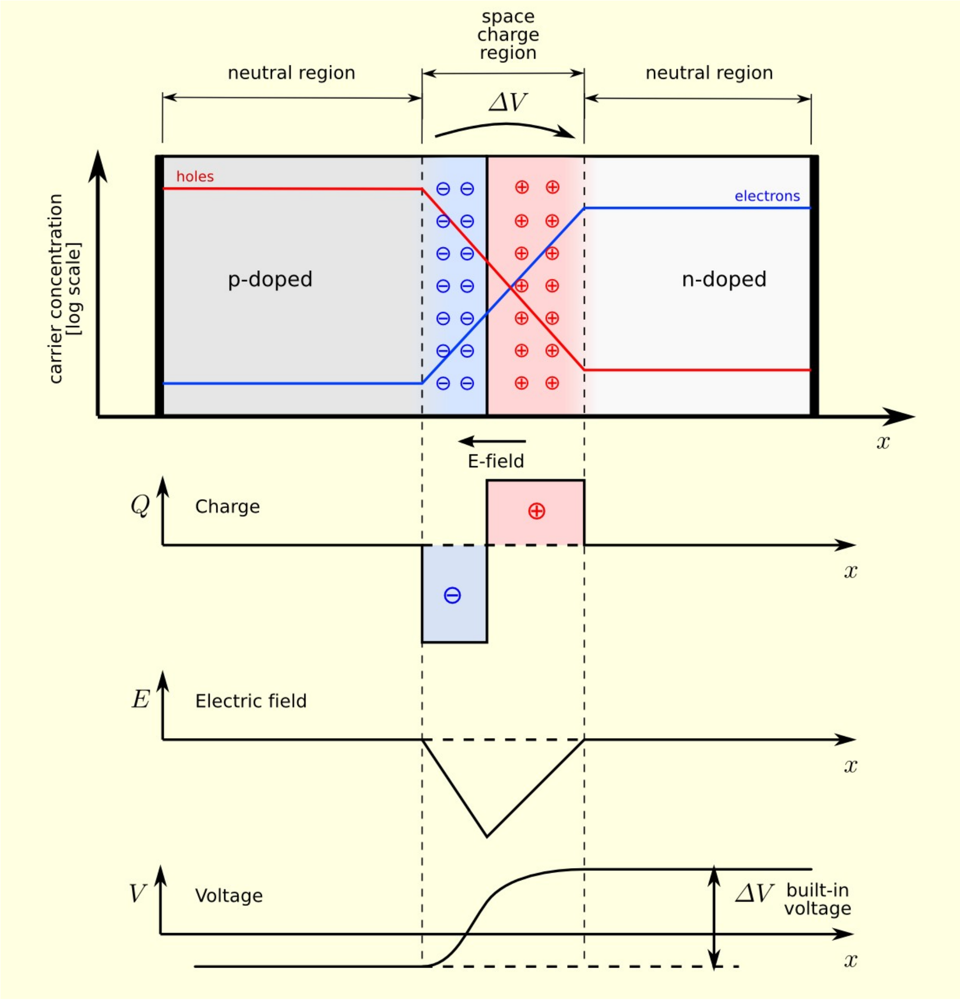
Varieties of PMT



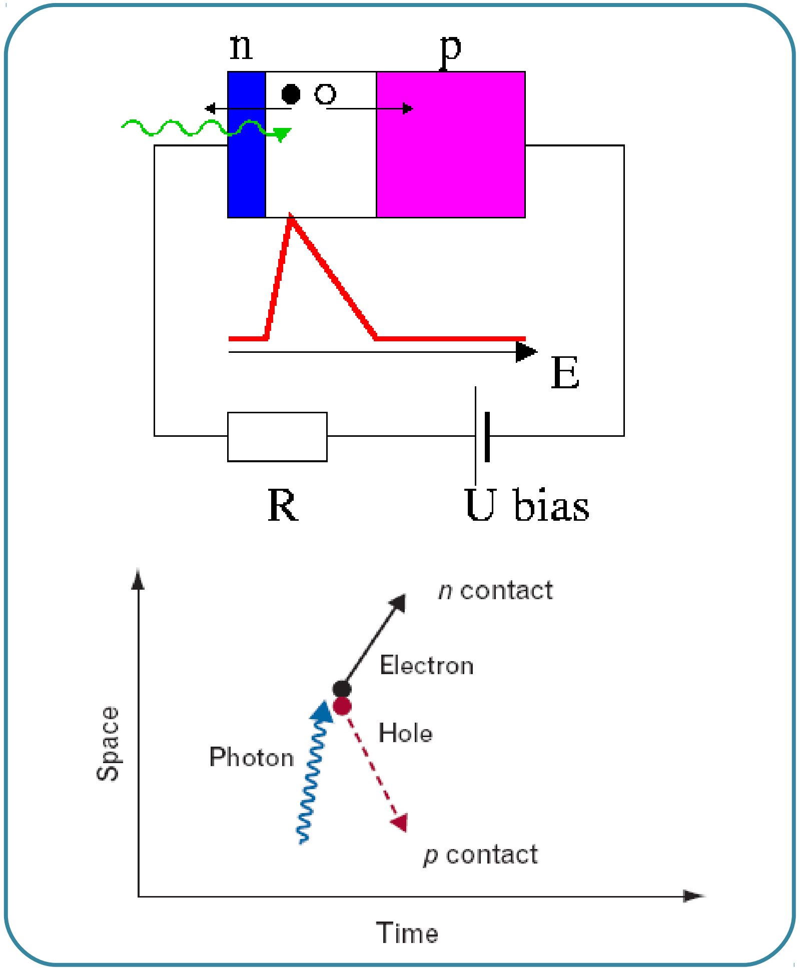
Signal amplification

PN diodes

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



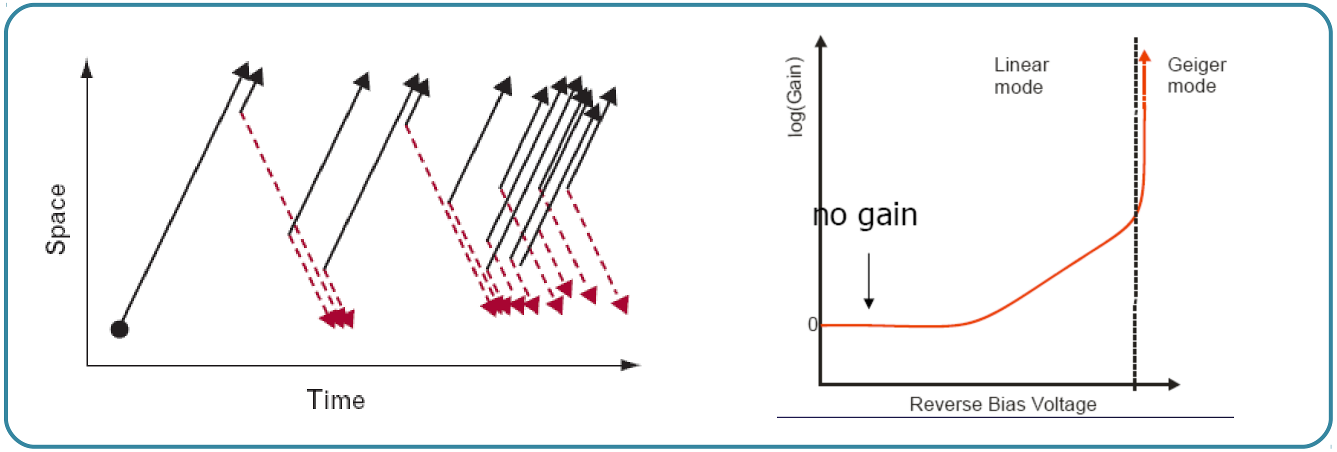
Photodetector based on PN diode



Silicon PM, Avalanche Photo Diodes

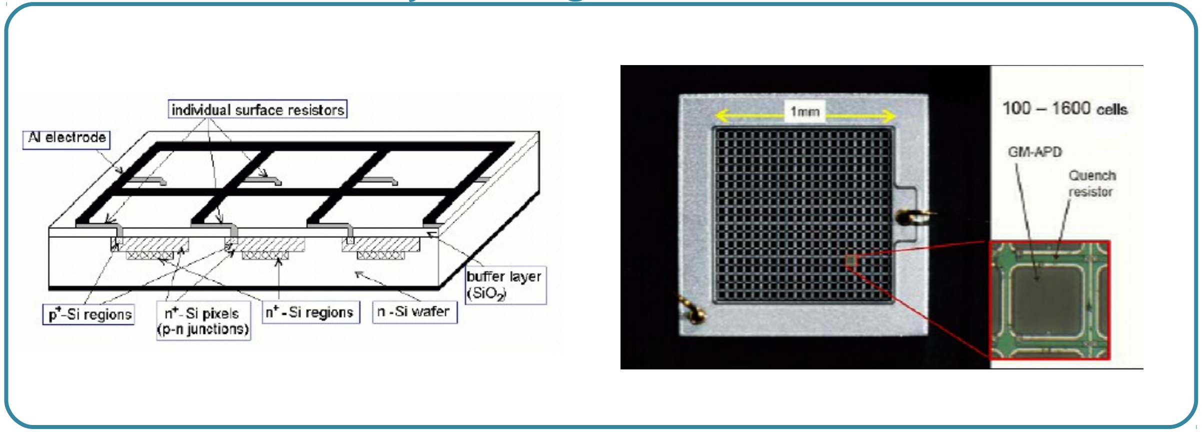
- Applying a **high reverse voltage**
  - Creates electron-hole multiplication

PN diode in avalanche mode



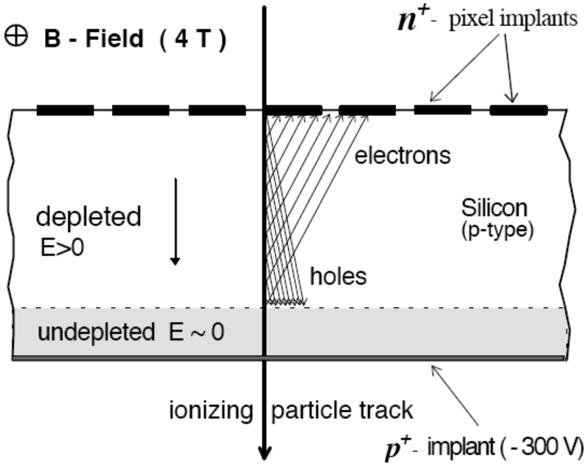
- Linear mode = **Avalanche Photo Diode** (APD)
- **Geiger mode** (or "Single Photon") APD
  - Above breakdown voltage
  - Binary mode
  - → Arrays of G-APD = Silicon PM

Array of Geiger mode APD

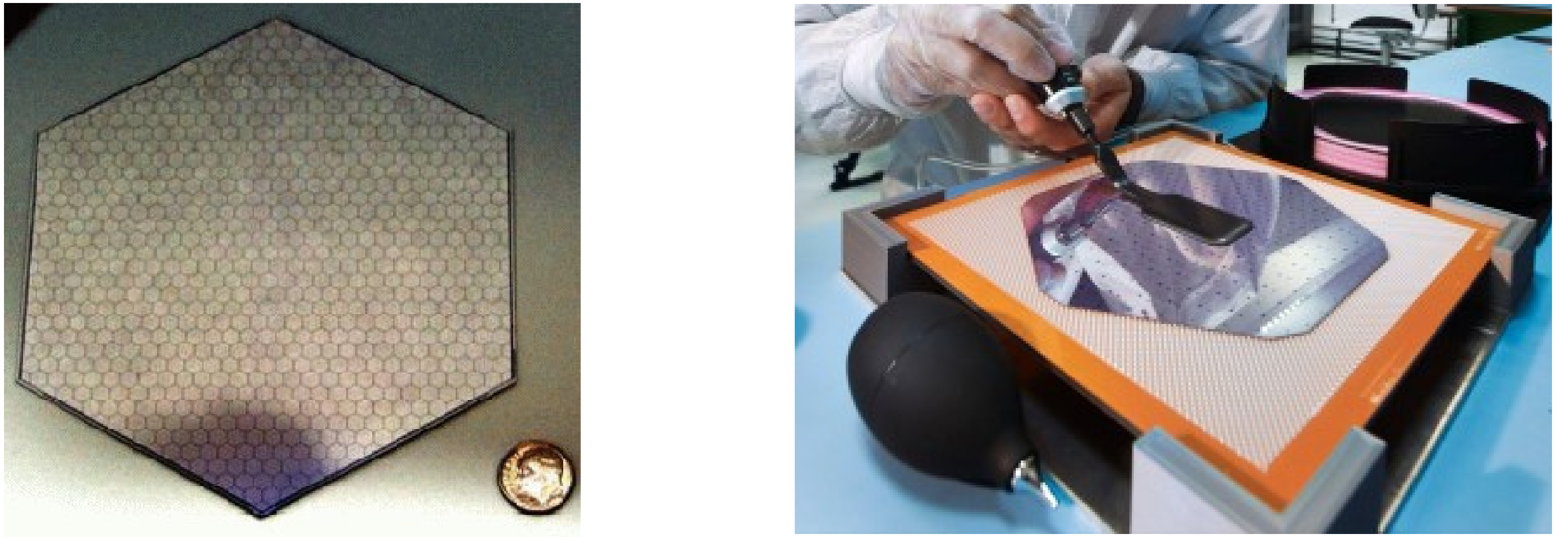


Direct charge collection with semiconductor detectors

- 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

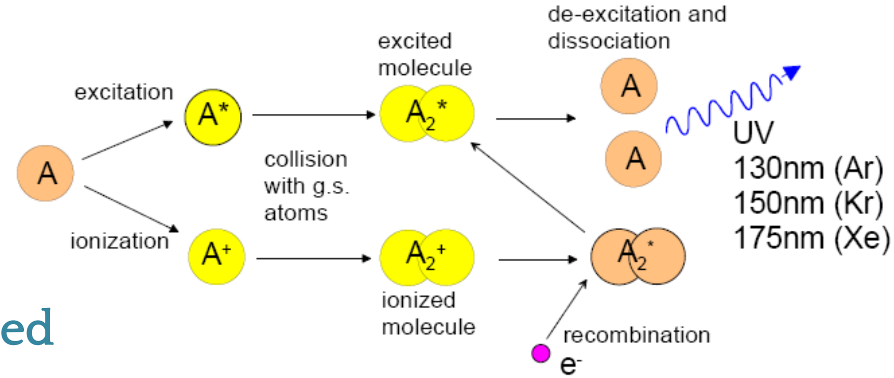


Silicon sensors with hexagonal cells

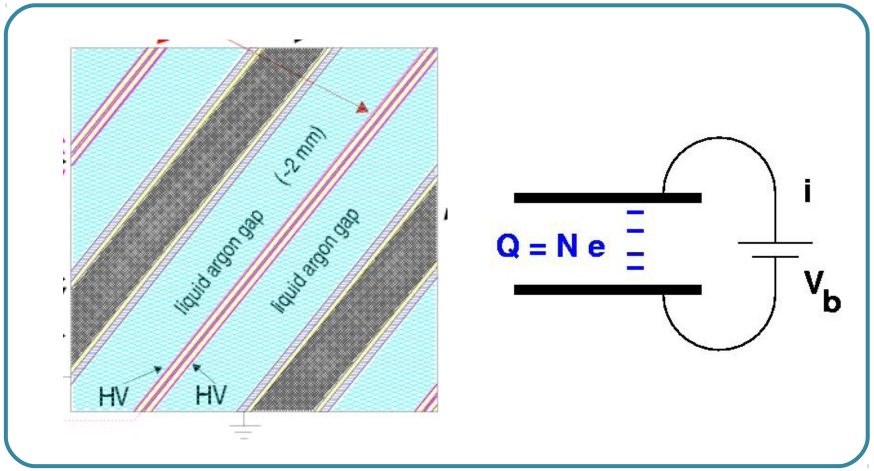


Direct charge collection with noble liquids

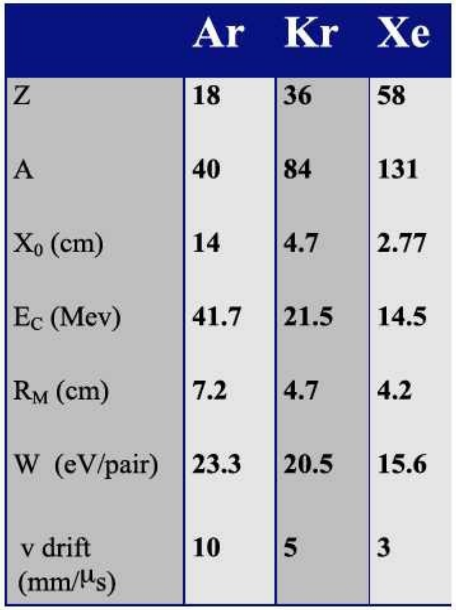
- Two processes in noble liquids
  - Molecule **excitation** → UV light emission
  - Molecule **ionization** → electron and ion drift
- Dense material
  - Lots of charge → **no charge amplification needed**
  - Good stability, good homogeneity



Charge collection



Noble liquids characteristics

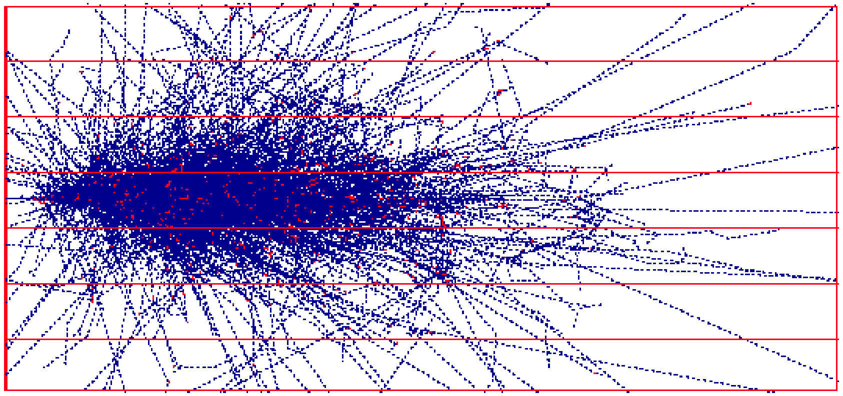


	Ar	Kr	Xe
Z	18	36	58
A	40	84	131
X_0 (cm)	14	4.7	2.77
E_C (Mev)	41.7	21.5	14.5
R_M (cm)	7.2	4.7	4.2
W (eV/pair)	23.3	20.5	15.6
v drift (mm/µs)	10	5	3

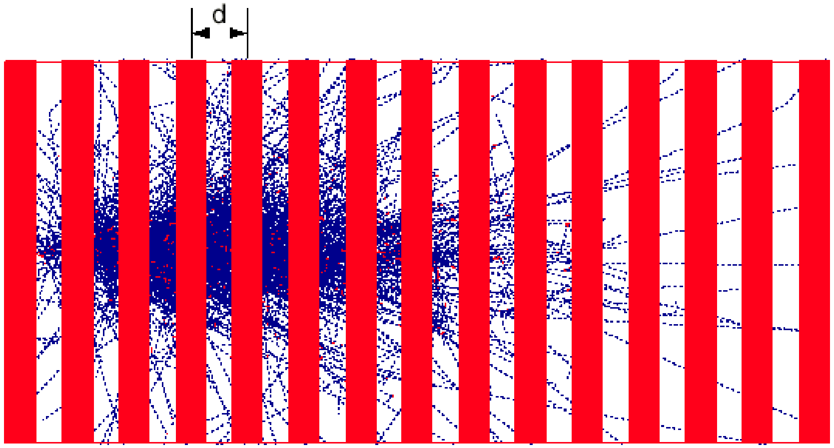
- Similar principles can also be used in gas detectors
  - But low density, so amplification needed → less stable
  - Larger detectors

Two calorimeter types

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



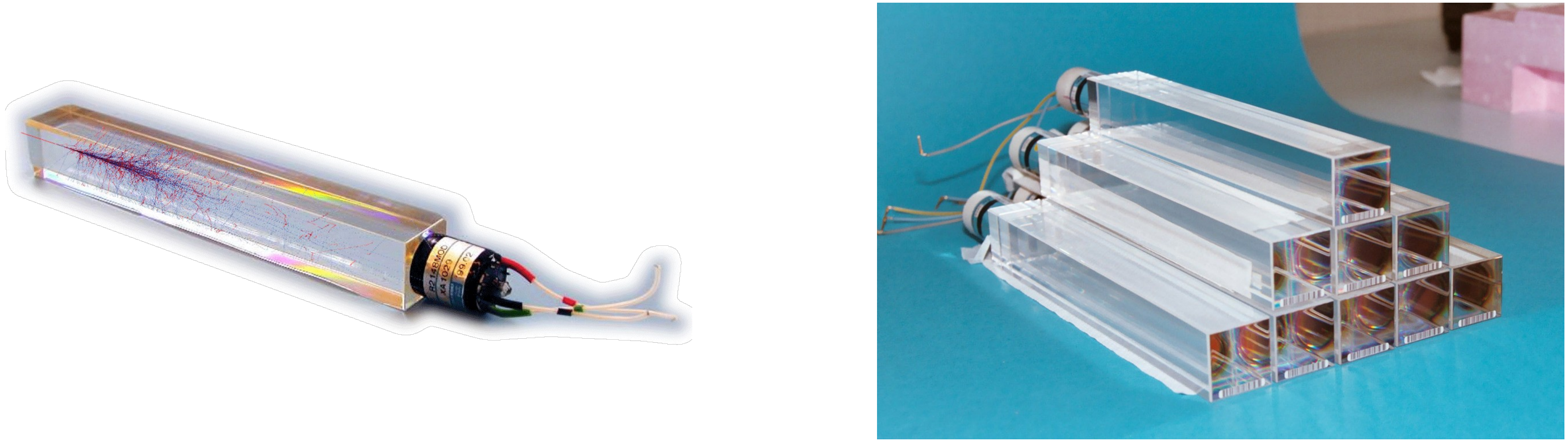
- Sampling calorimeter
  - **Two materials**
    - One for shower development (**absorber**)
    - One for signal collection (detectors / **active material**)
  - Only energy deposited in active material is collected
    - The shower is sampled



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



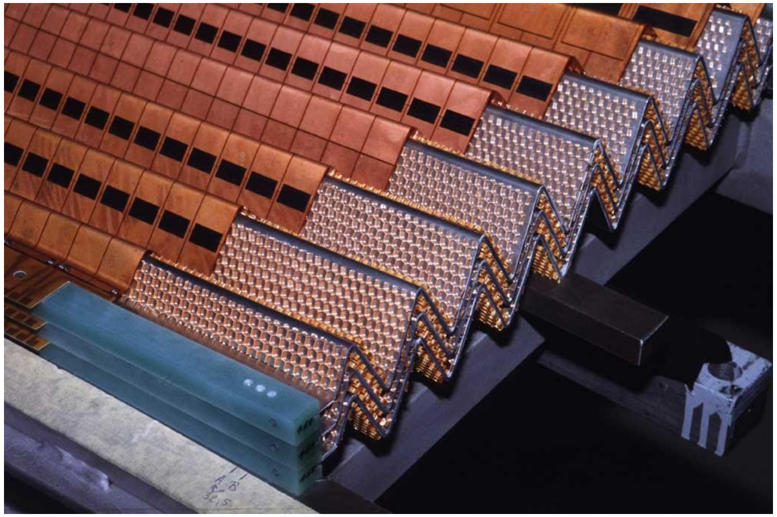
Sampling calorimeter

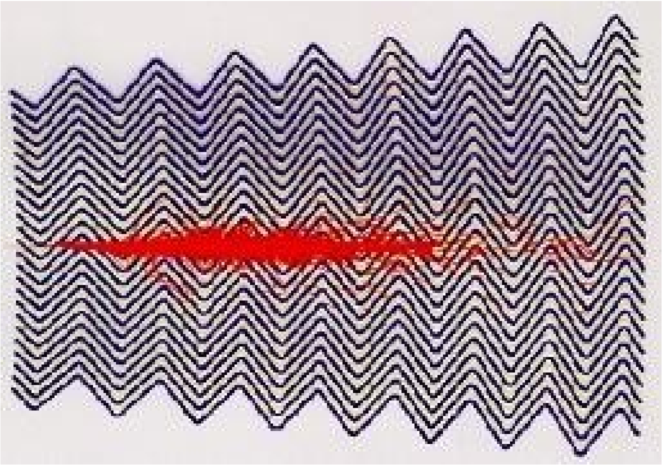
- Absorber with high-density material
- Interleaved with active readout devices
- Lower cost than homogeneous calorimeters
- And can have longitudinal segmentation
- But
  - Only part of the shower energy is collected
  - Fluctuation of energy deposited in active layers
    - Proportional to number of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

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

    - (And less charges deposited compared to homogeneous calorimeters)

ATLAS Liquid Argon ECAL

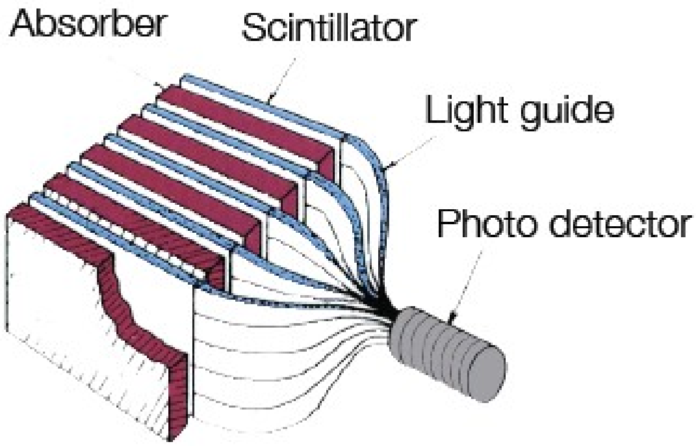




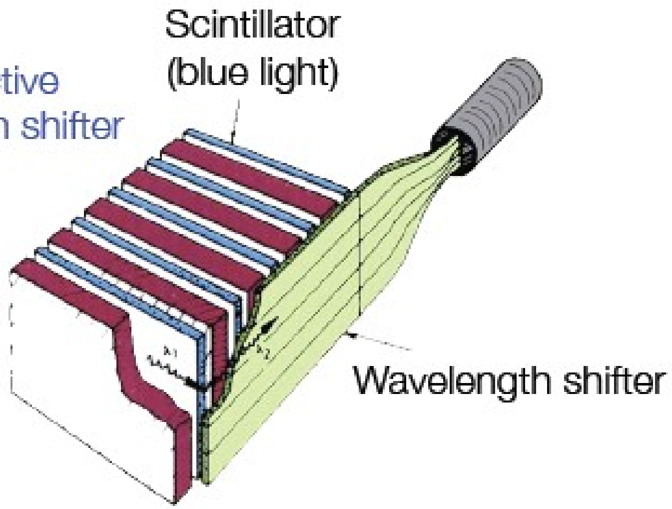
Some types of sampling calorimeters

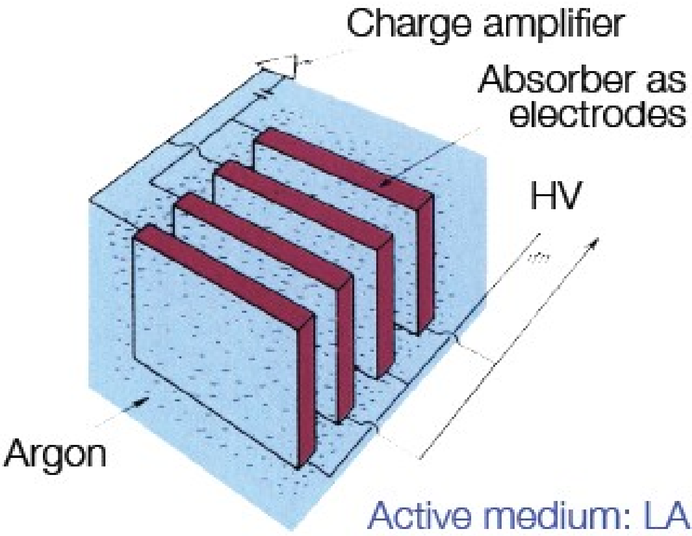
Possible setups

Scintillators as active layer;
signal readout via photo multipliers



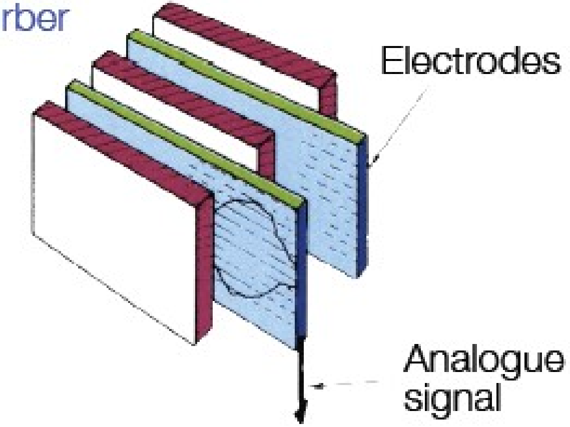
Scintillators as active
layer; wave length shifter
to convert light





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

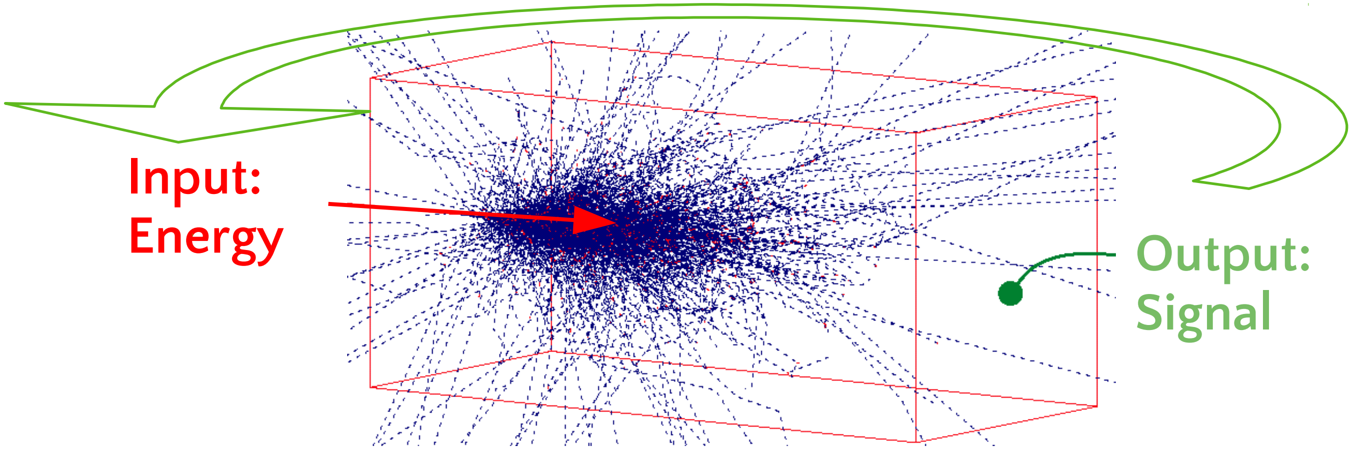
Energy reconstruction & calibration

Beyond calorimetry: Particle Flow

An example: CMS HGCAL

Measurement of showers

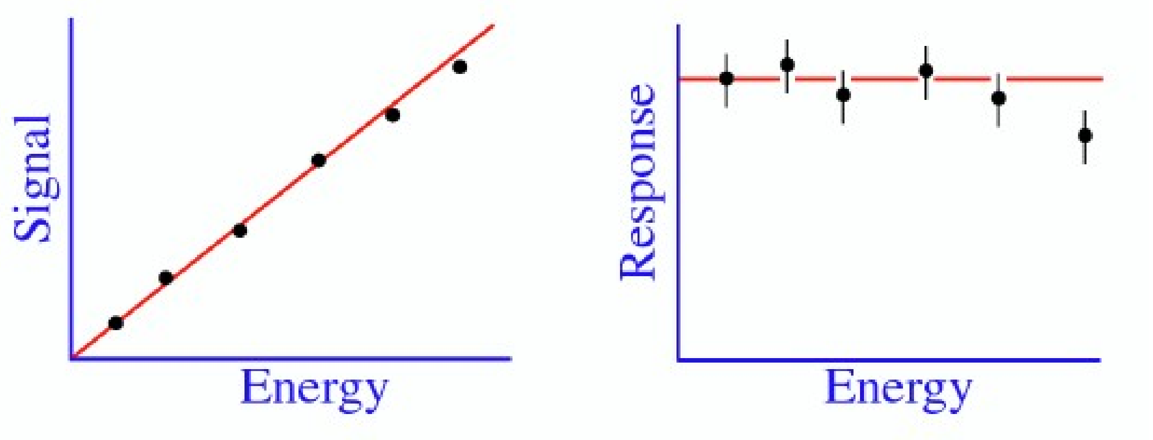
- From collected signal back to the energy of the particle



- 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

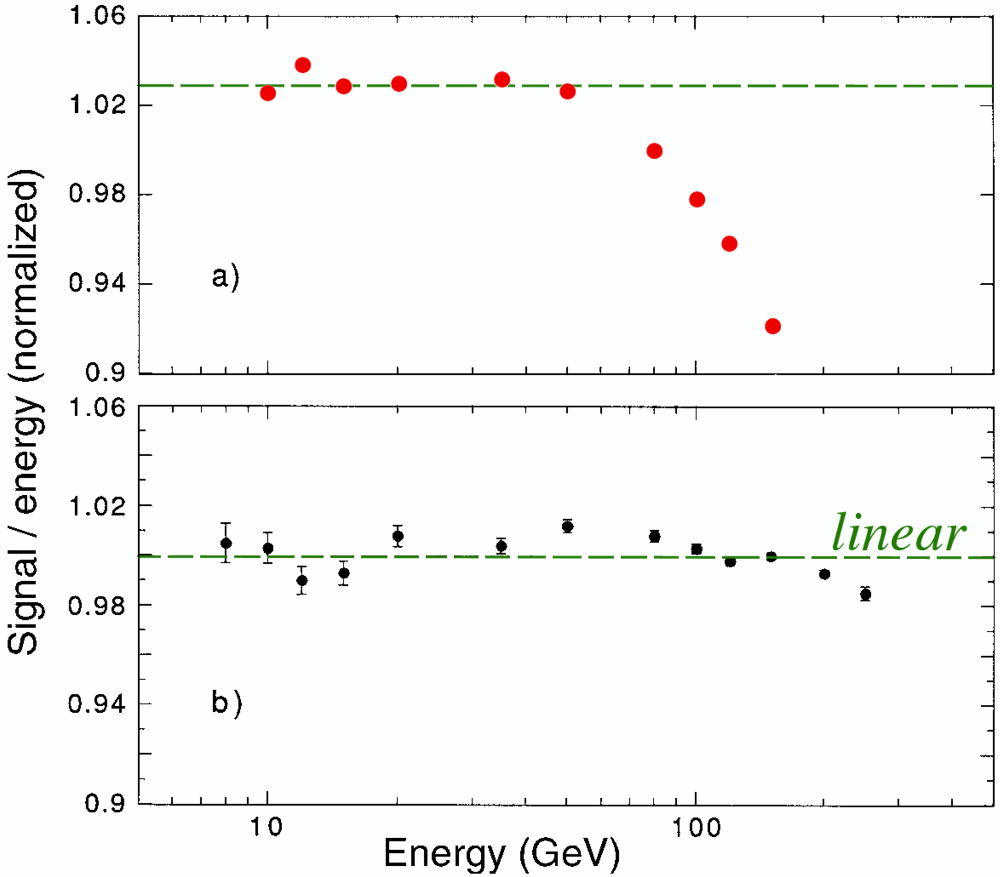
- Response: average signal per unit of deposited energy
- A linear calorimeter has a constant response
  - The signal is proportional to the deposited energy



- 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



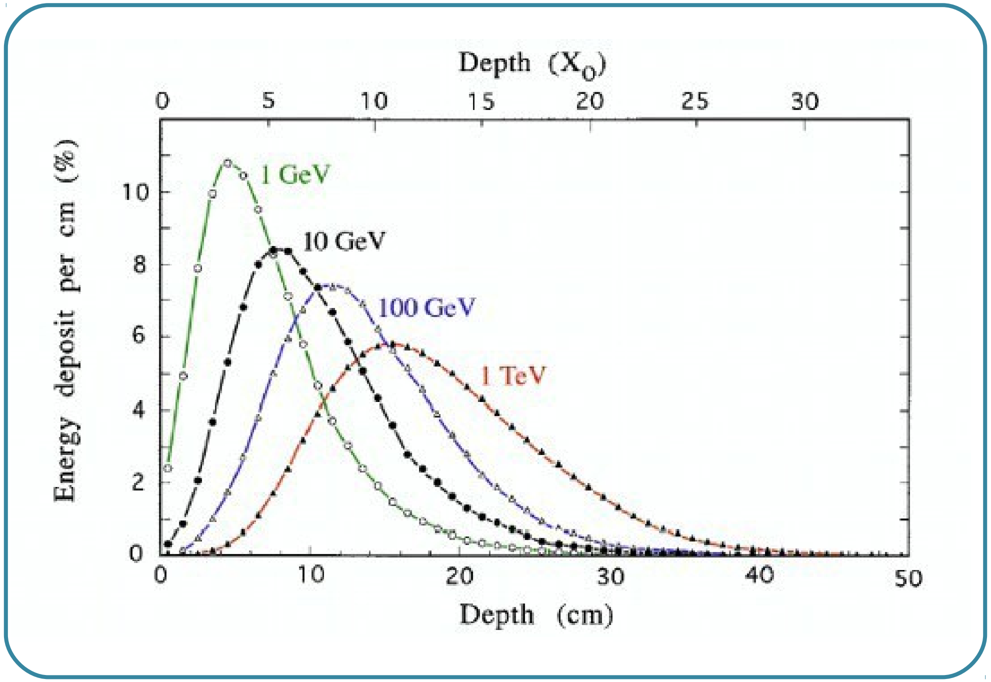
PMT saturation in QFCAL calorimeter

After correction of this saturation

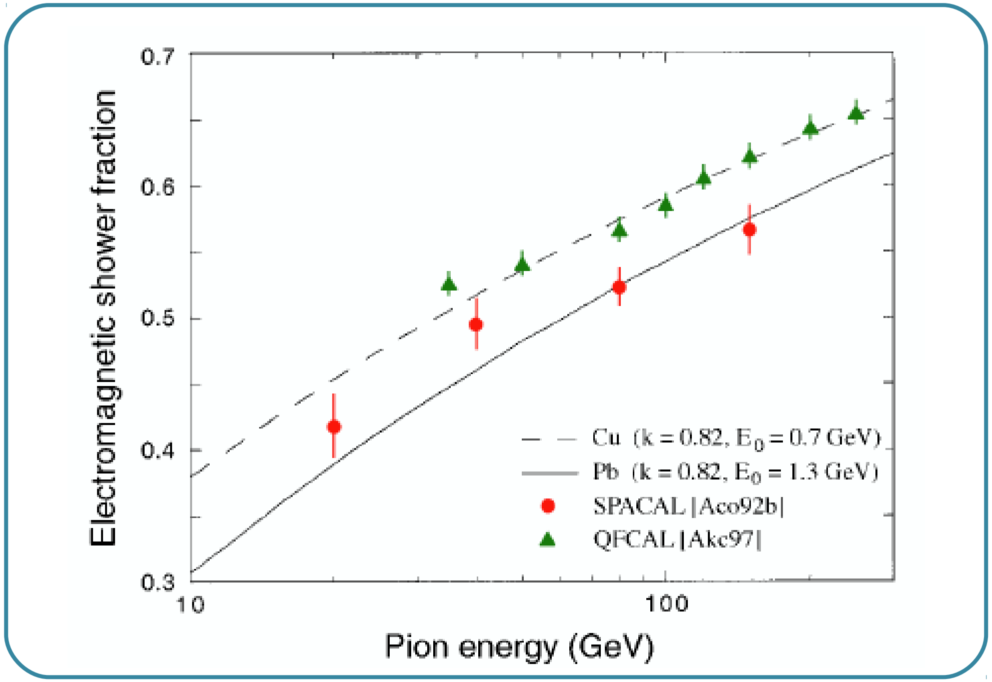
Sources of non-linearity (2/2)

- 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



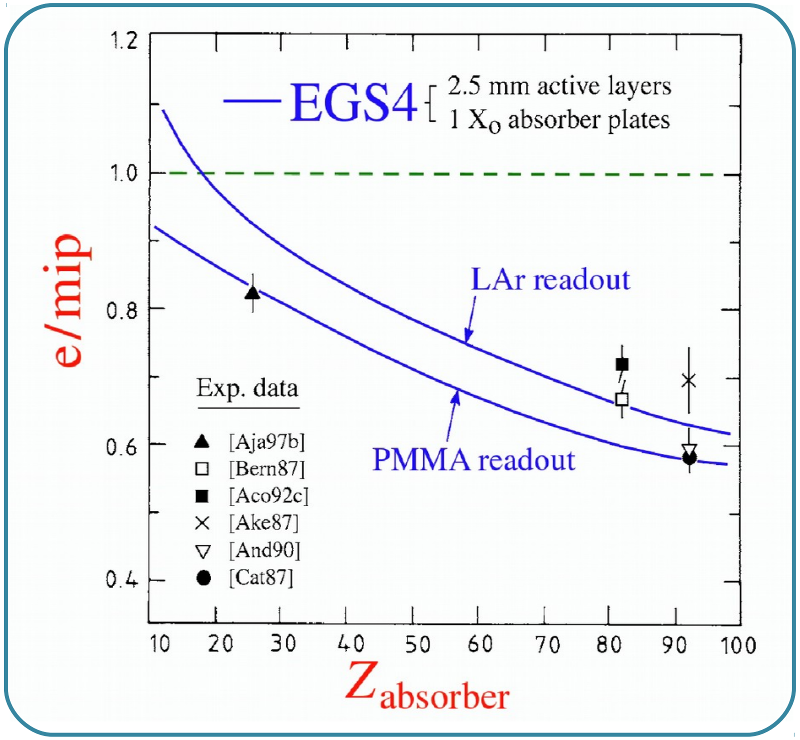
EM fraction vs energy



Sampling: EM vs mip response

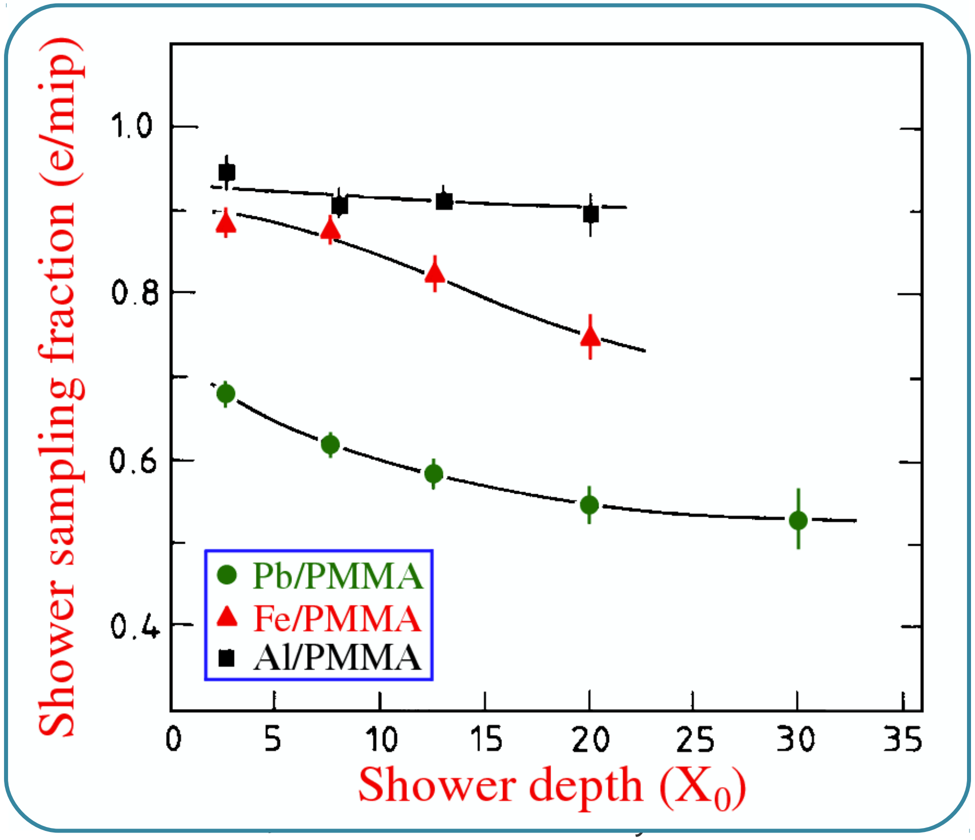
- **Homogeneous** calorimeters
  - ○ Same deposit mechanisms for EM showers and mips → same response (**e/m=1**)
- But **EM showers are not sampled like mips** by sampling calorimeters
  - ○ Photoelectric effect $\sigma_{pe} \propto Z^5$
  - ○ Soft photons are very inefficiently sampled due to the Z 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

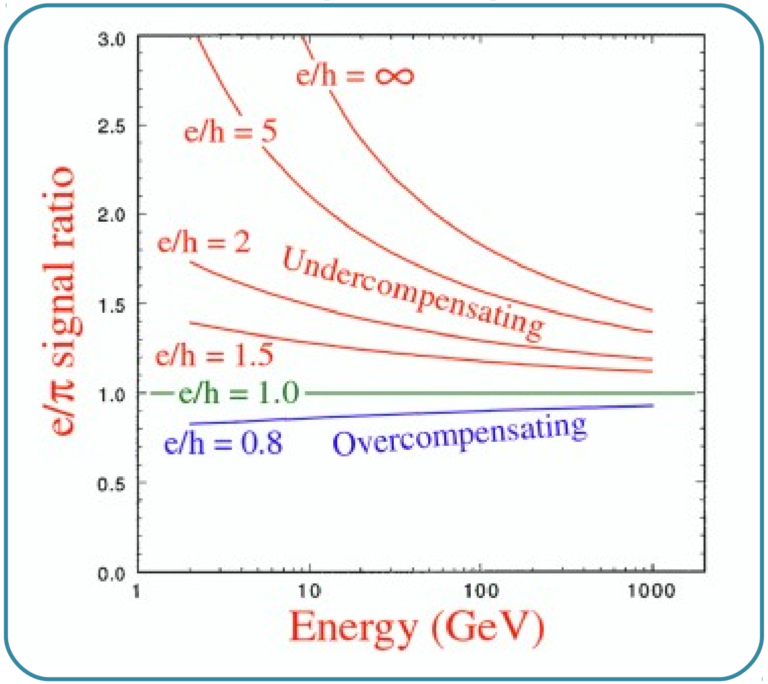
Hadronic response and compensation

- 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

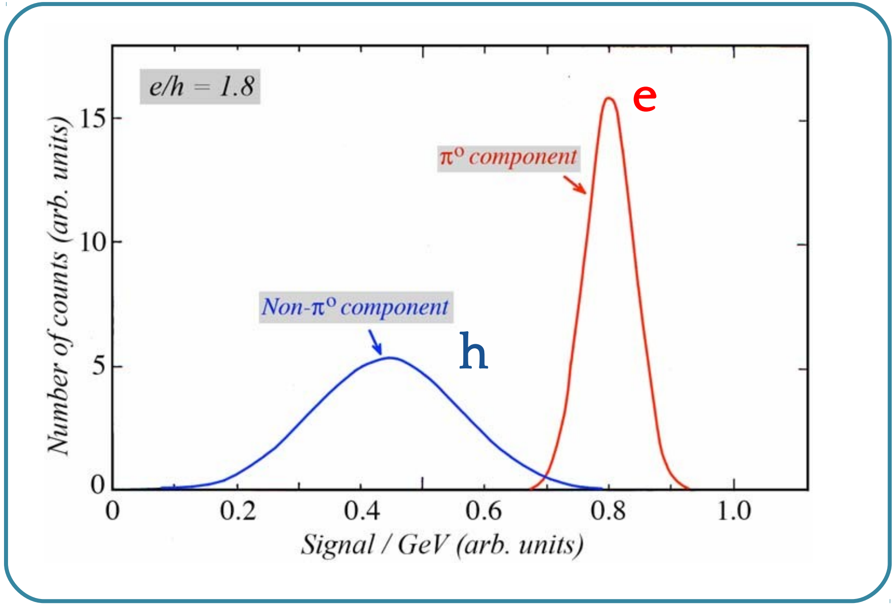
- Non-linearity determined by e/h

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

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

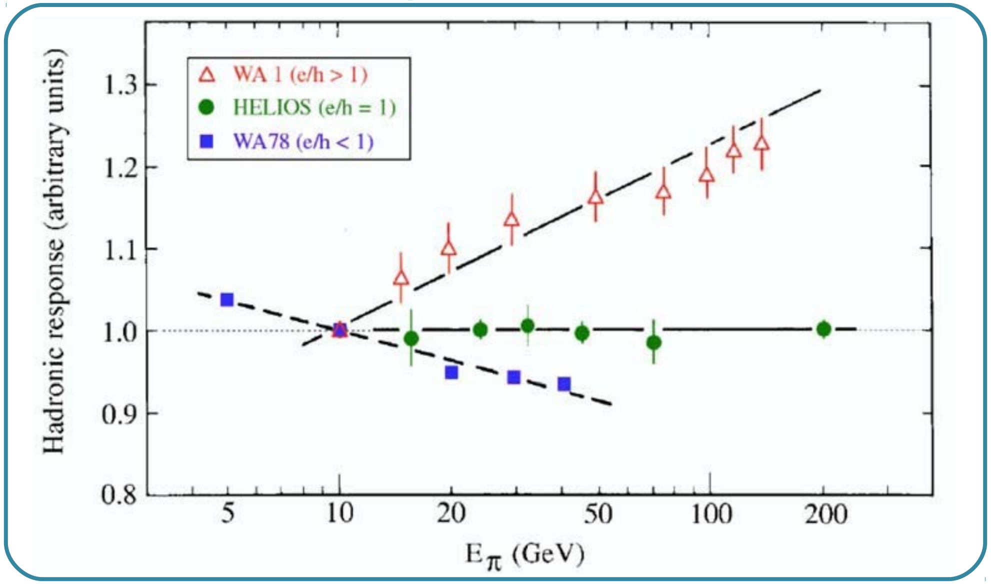
$$e/h=1\Rightarrow\frac{\pi(E1)}{\pi(E2)}=1$$

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}

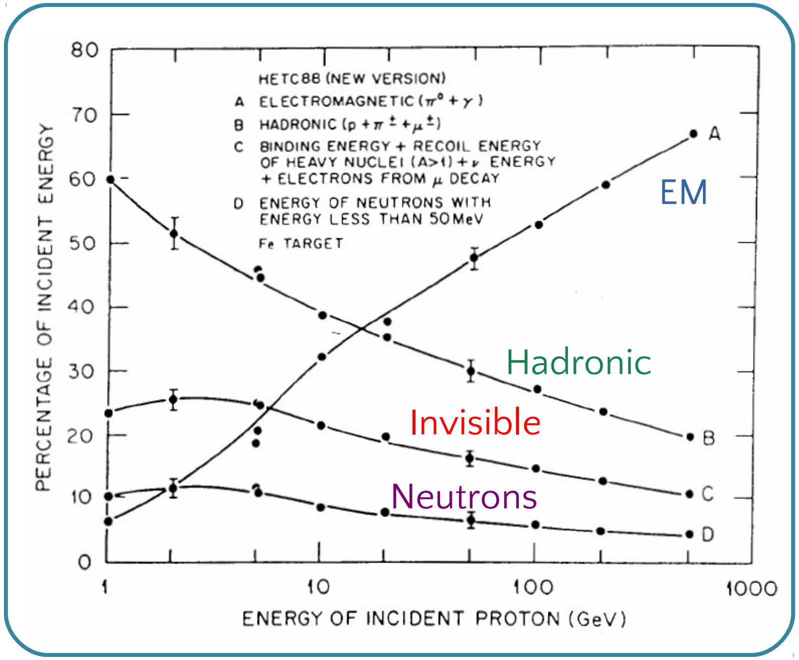
$$e/h = \frac{\overset{<1}{e/m}}{\underbrace{f_{rel}\cdot rel/m}_{=1} + \underbrace{f_p\cdot p/m}_{>1} + \underbrace{f_n\cdot n/m}_{>1} + \underbrace{f_{inv}\cdot inv/m}_{=0}}$$

= 1 (similar to mip in their ionization loss)

> 1 (more efficient sampling)
But saturates

> 1 (through elastic scattering)

Sharing of energy between components



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

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

$$\left.\begin{array}{l}\text{1 MeV neutron deposits 98\% in } H_2\\ \text{mip deposits 2.2\% in } H_2\end{array}\right\} \text{n/mip = 45}$$

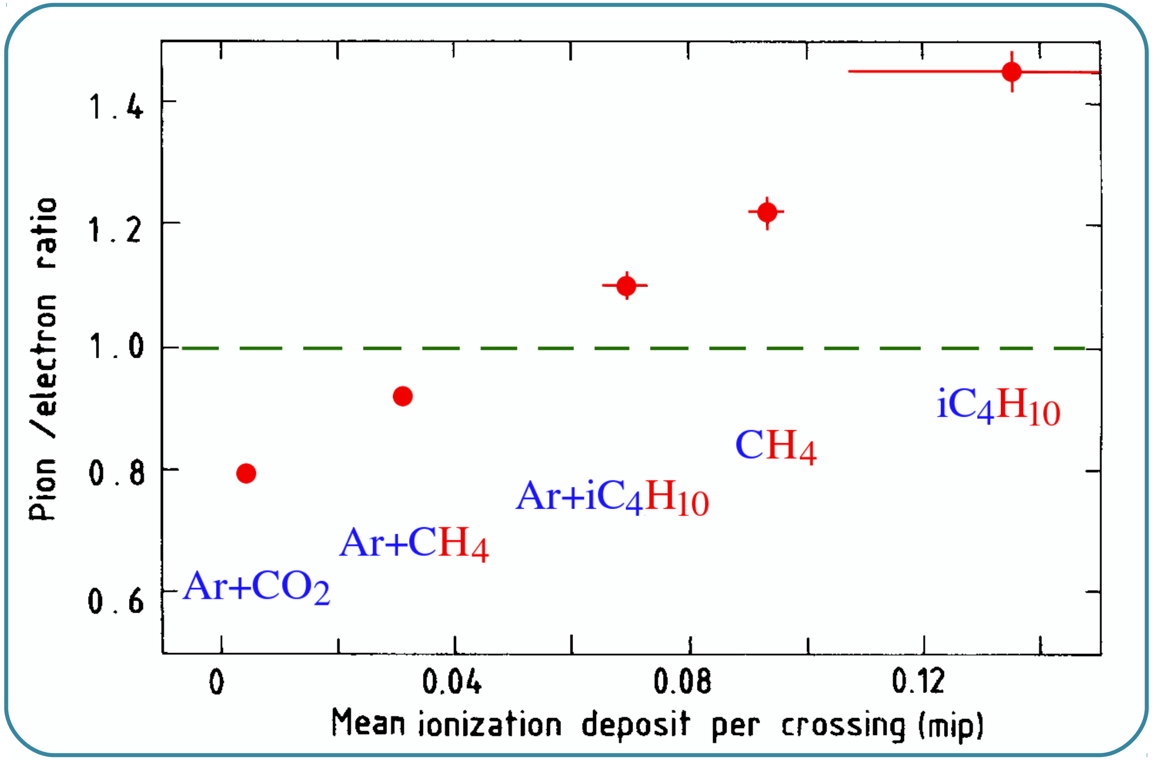
- The relative n/mip response can be further increased by changing the sampling
- Pb / H_2 calorimeter structure with 90/10 sharing
  - 1 MeV neutron deposits 87% in H_2
  - mip deposits 0.25% in H_2

$$\left.\begin{array}{l}\text{1 MeV neutron deposits 87\% in } H_2\\ \text{mip deposits 0.25\% in } H_2\end{array}\right\} \text{n/mip = 350}$$

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

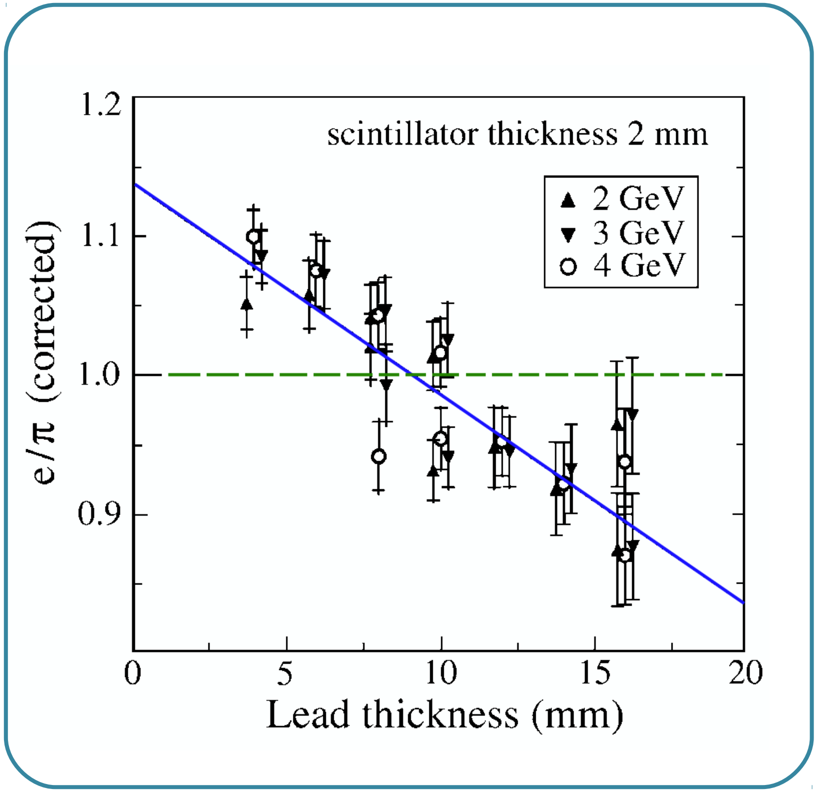
π/e for several materials, with different energy deposits by slow neutrons (Uranium / gas calorimeter with different gas mixtures)



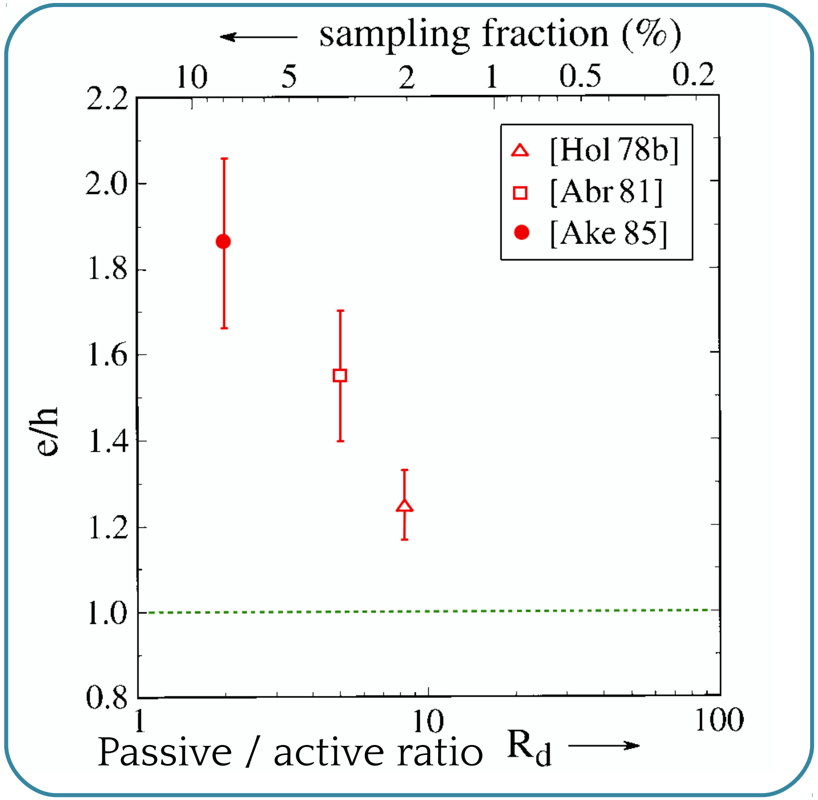
Tuning neutron response with sampling fraction

- 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



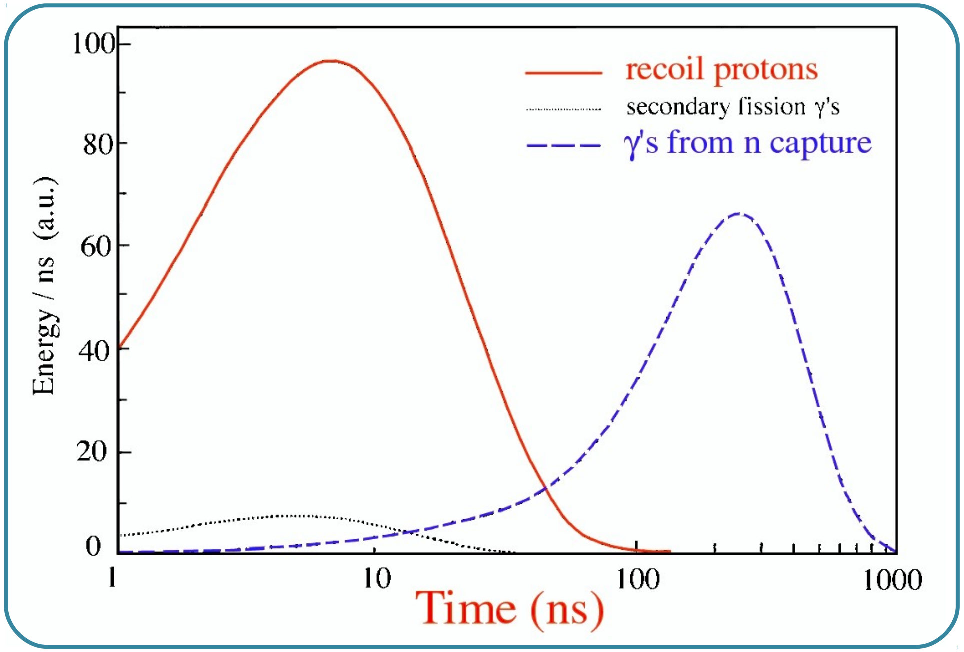
e/h for Fe / Scint calorimeters



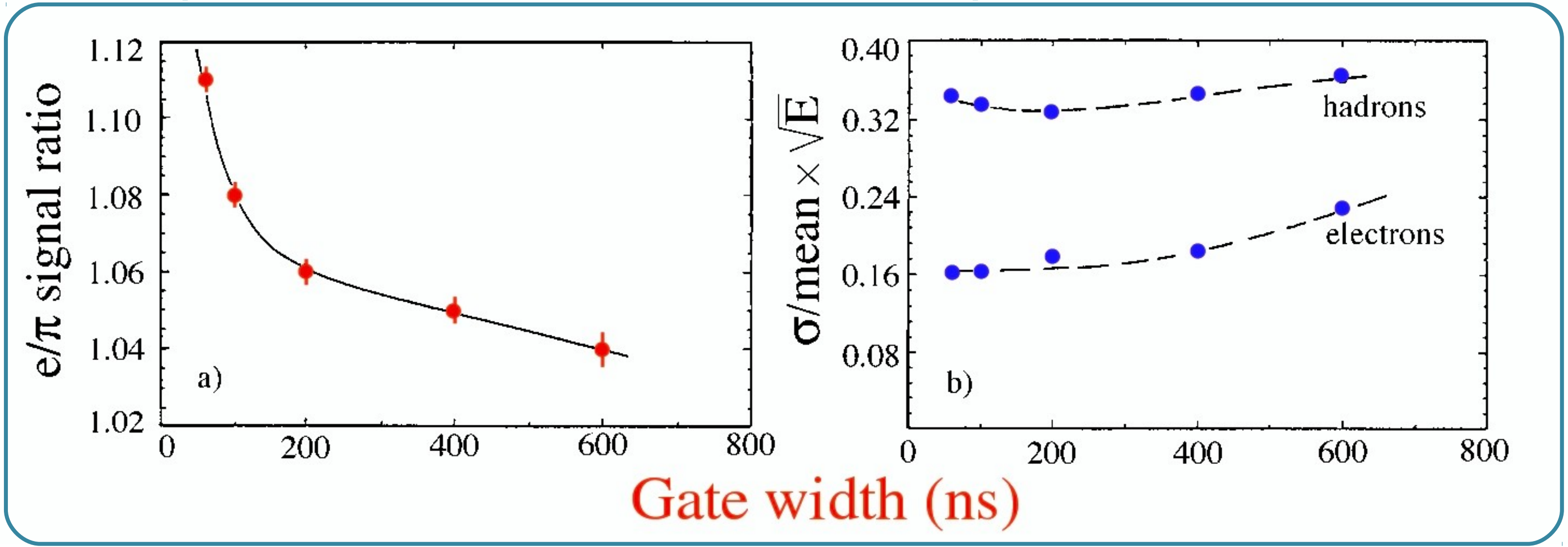
Energy released by slow neutrons

- 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



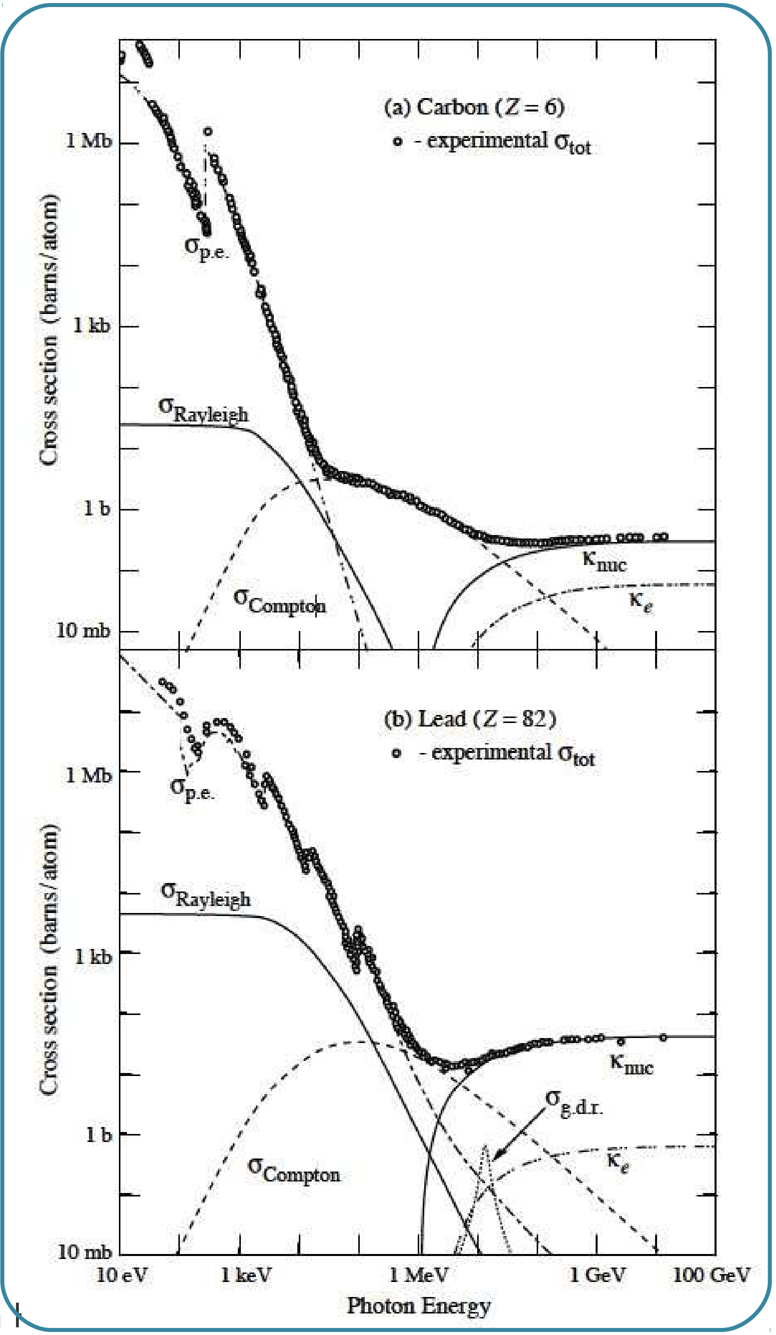
Impact of charge integration time on compensation and resolution



Decreasing EM response and compensation recipe

- Electrons and photons are sampled less efficiently when using **high-Z absorber**
  - ○ Photoelectric effect cross section $\propto Z^5$
  - ○ Photons < 1MeV captured in absorber
- Recipe for compensating hadron calorimeter
  - ○ Sampling 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

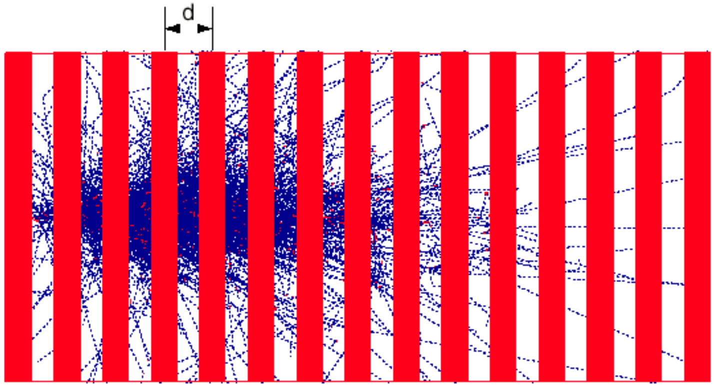
- Calorimeter's energy resolution is determined by fluctuations
- Input energy **E ∝ N number of secondary particles**
  - Poisson distribution of N → $\sigma(E)/E \propto \sqrt{N}/N \propto 1/\sqrt{E}$
  - Although in reality only a fraction can be detected (threshold effects)
- Other types of fluctuations
  - 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

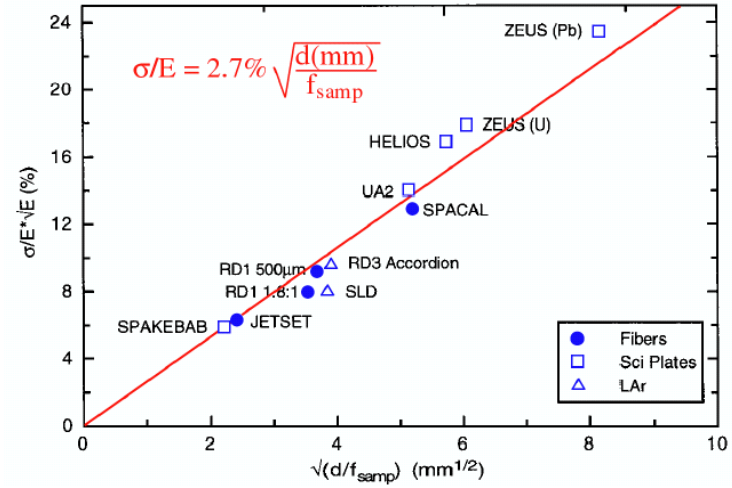
$$f_{samp} = \frac{E^{mip}_{loss\,in\,active}}{E^{mip}_{total\,loss}}$$

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



Thicker active layer → worse resolution
Lower sampling → worse resolution

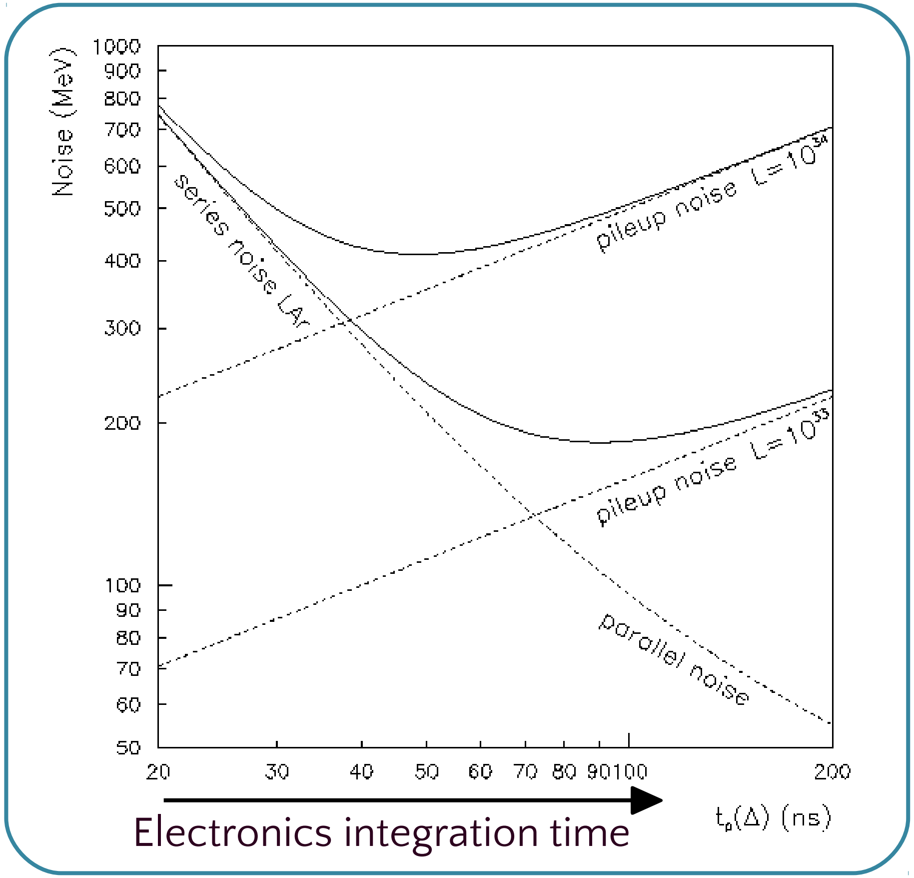
$$\frac{\sigma(E)}{E} \propto \sqrt{\frac{d_{active}}{f_{samp}}} \frac{1}{\sqrt{E}}$$



Noise

- 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)

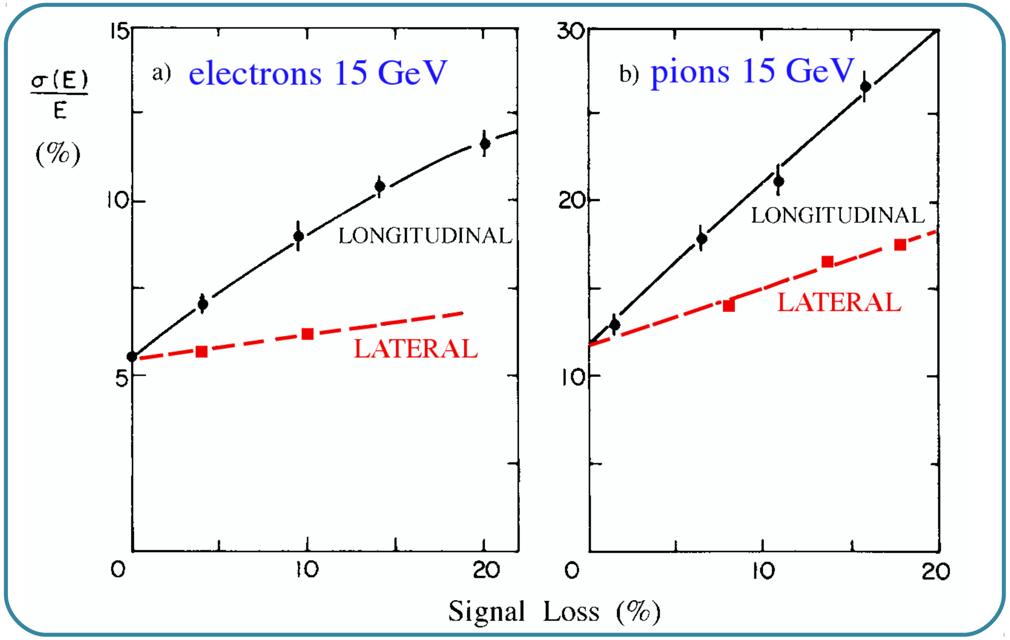


Leakage

- 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

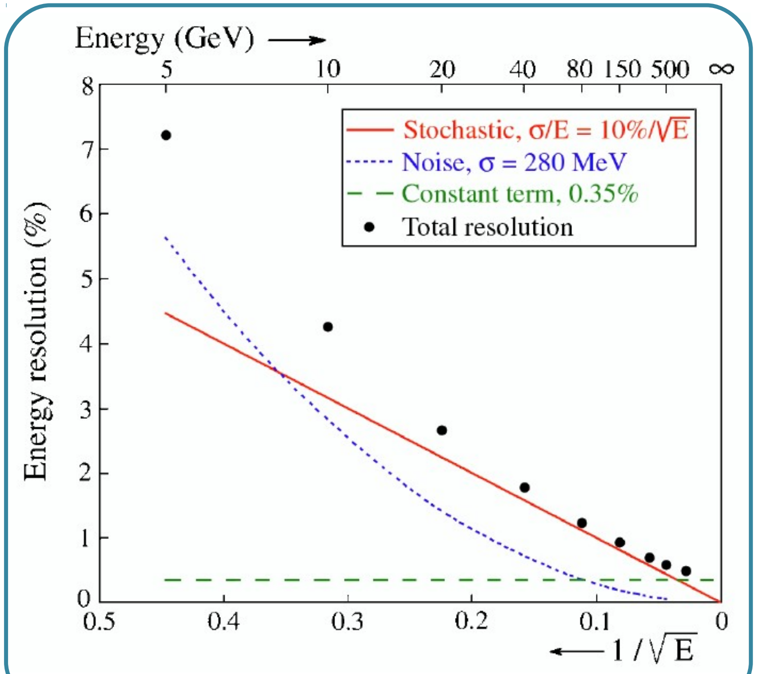
$$\frac{\sigma(E)}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C$$

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

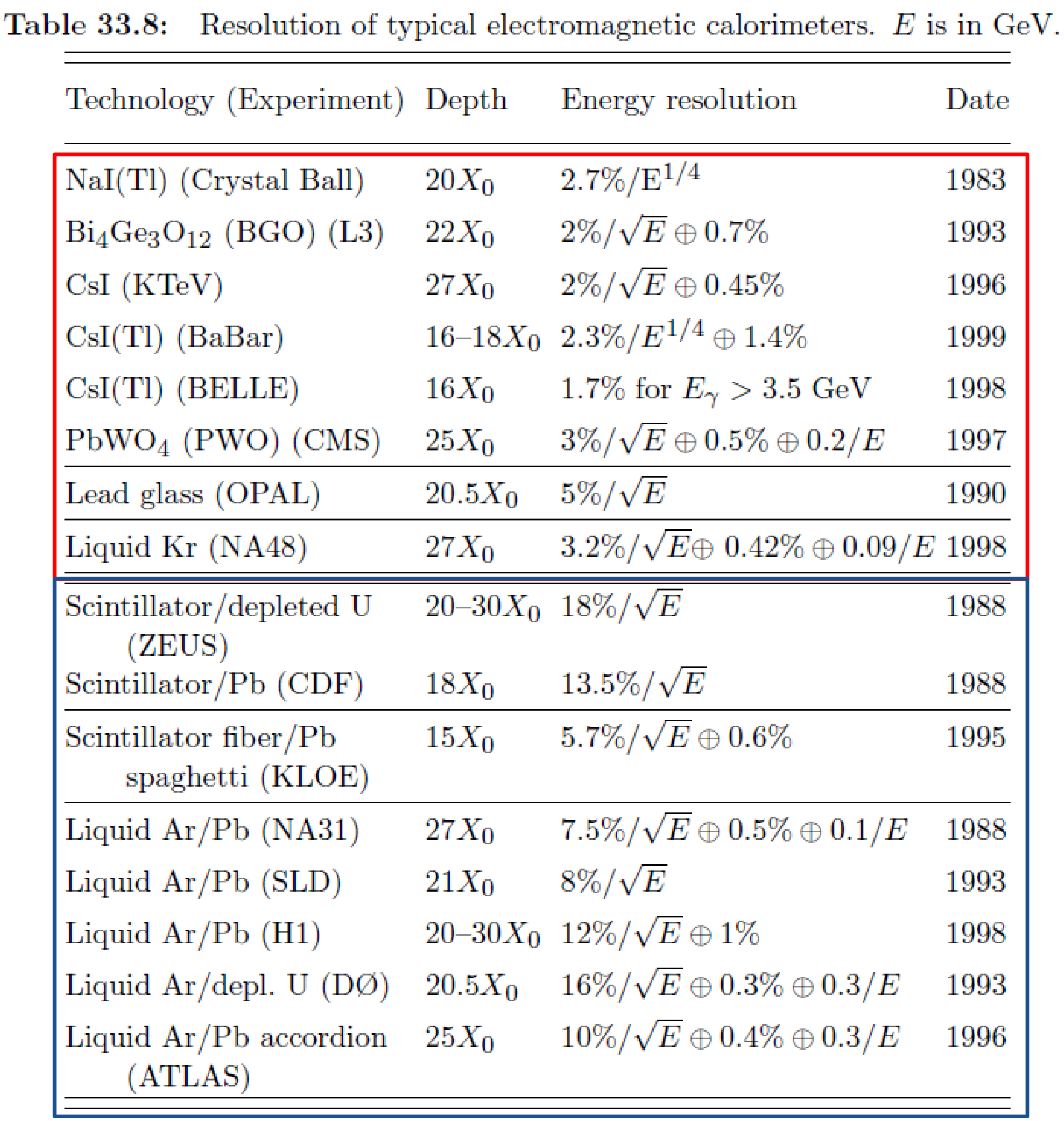


Table 33.8: Resolution of typical electromagnetic calorimeters. E is in GeV.

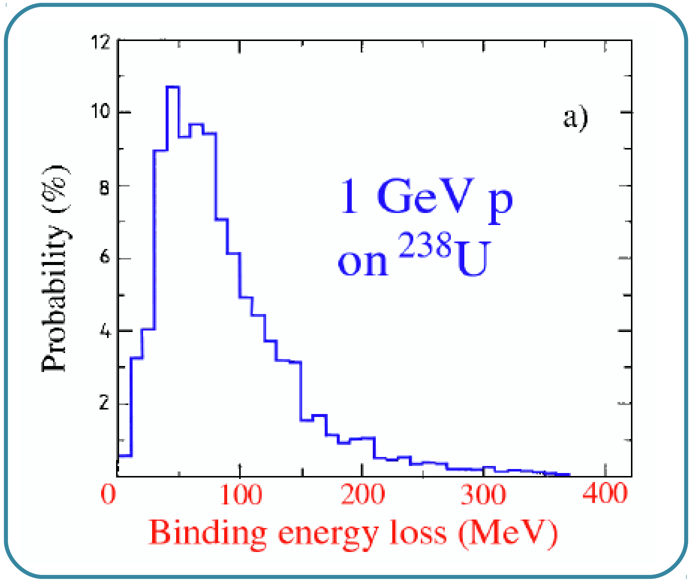
Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl)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

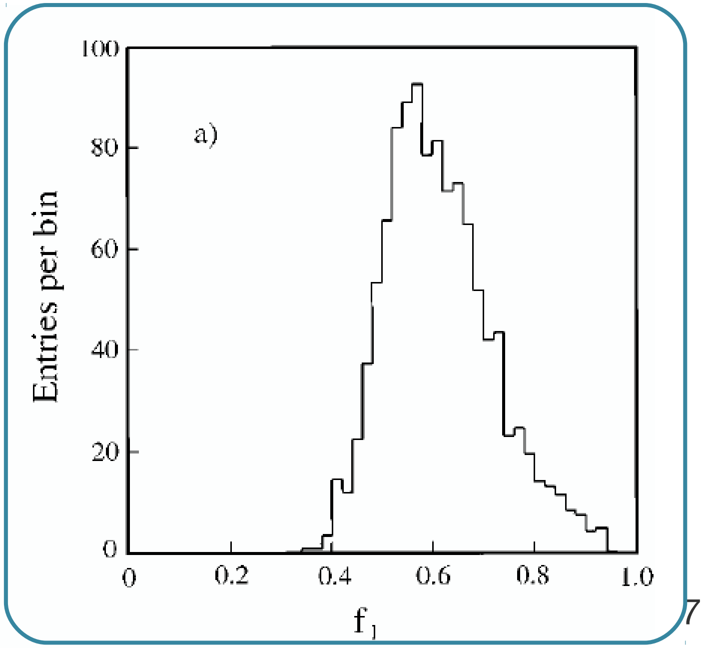
Homogeneous

Sampling

Fluctuations in hadron showers

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

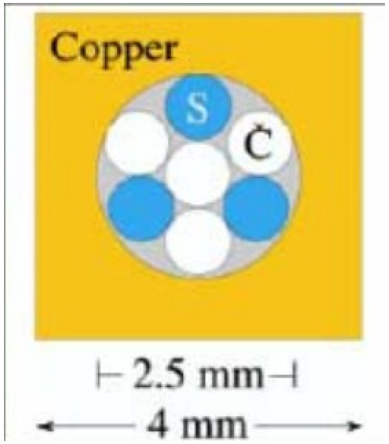

Binding energy loss for 1 GeV proton in Uranium


EM fraction of 150GeV π showers in SPACAL

Measurement of the EM fraction with Dual Readout

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

Conceptual design of a dual readout calorimeter

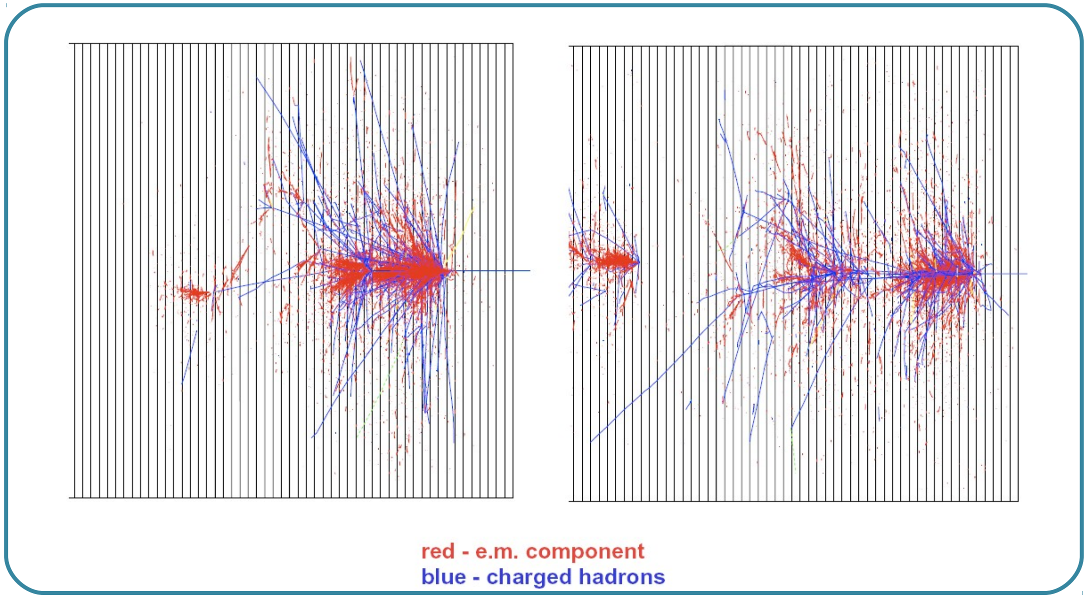


DREAM prototype

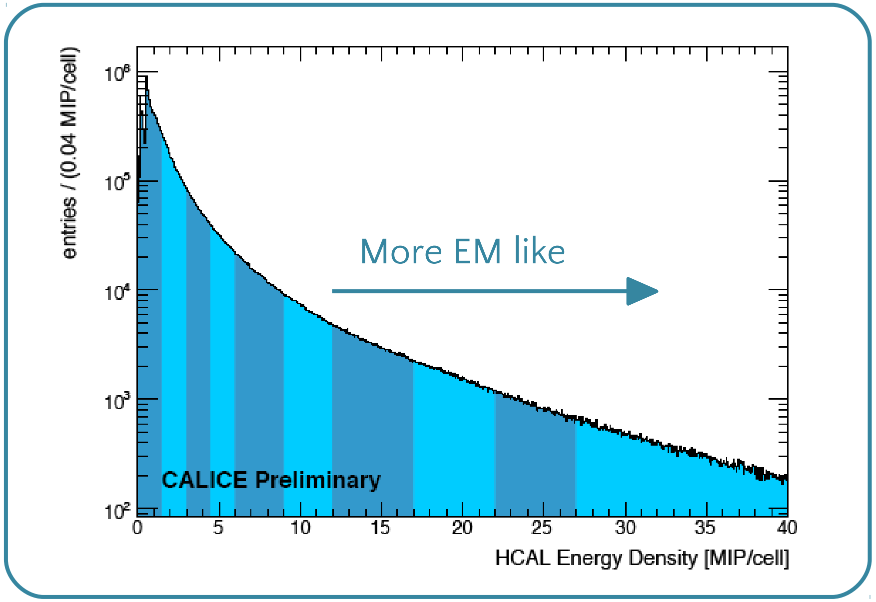
Measurement of the EM fraction indirectly

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

EM and hadronic components in showers



Cell energy density



Lecture plan

What is a calorimeter in HEP?

Electromagnetic and hadronic showers

Detection techniques

Calorimeter response & resolution

Electronics readout and trigger

Energy reconstruction & calibration

Beyond calorimetry: Particle Flow

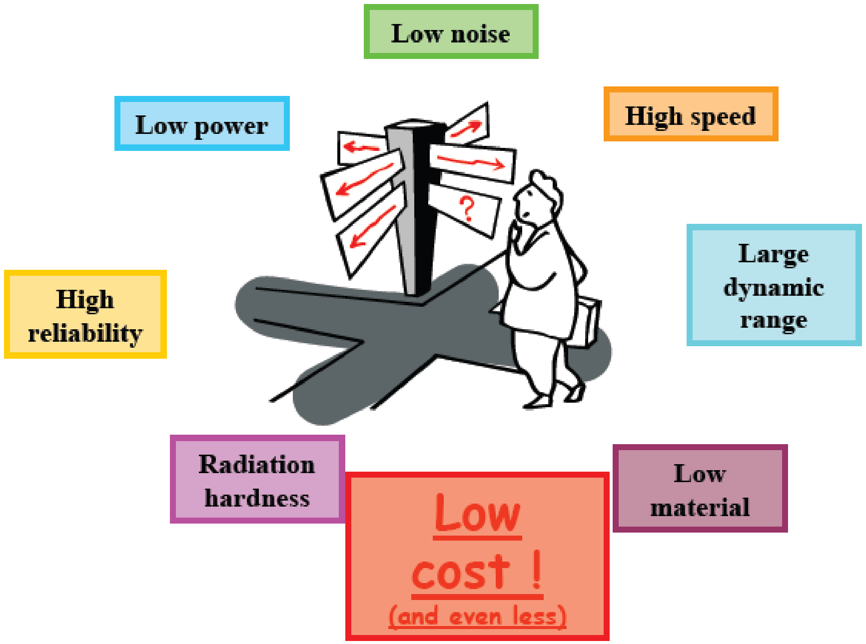
An example: CMS HGCAL

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



Low noise

Low power

High speed

Large dynamic range

High reliability

Radiation hardness

Low material

Low cost !

(and even less)

Data acquisition

Detector

signal

Readout electronics

Reduced data

Trigger system

accept/reject

Full data

Buffer

DAQ system

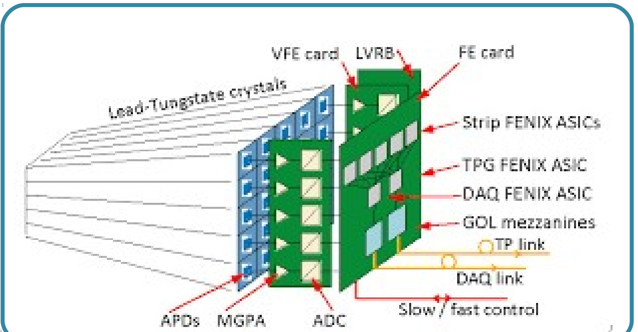
event

- 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

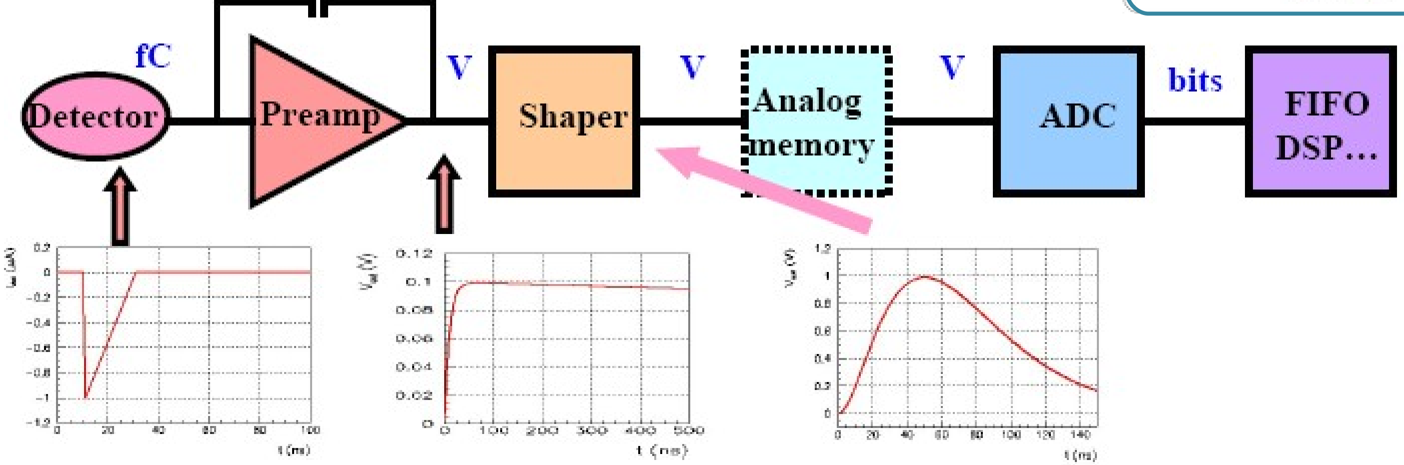
Readout electronics

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

CMS ECAL FE electronics



Typical front-end electronics chain

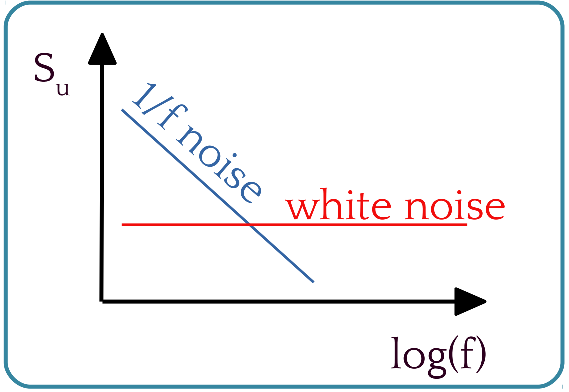


- Very small signals (fC)
  - Amplification needed
  - Optimisation of S/N (shaper)
- Need time to decide to keep the event or not → memory
- Conversion from analogue signal to digital values (ADC pulse sampling)

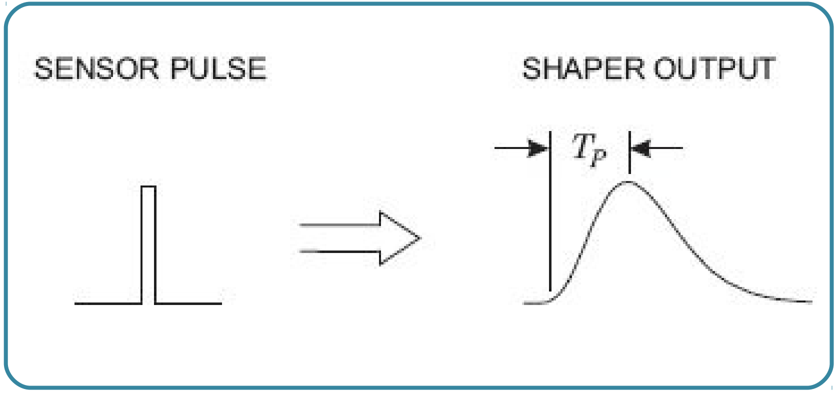
Pulse shaping

- 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

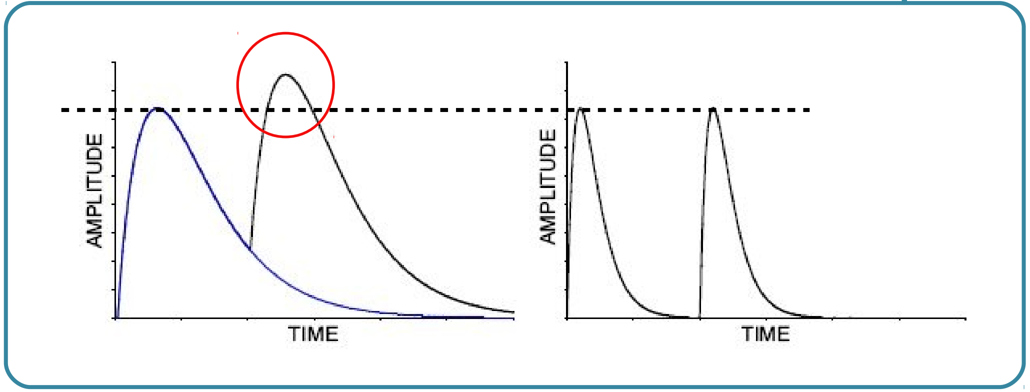
Noise spectrum



Shaper output



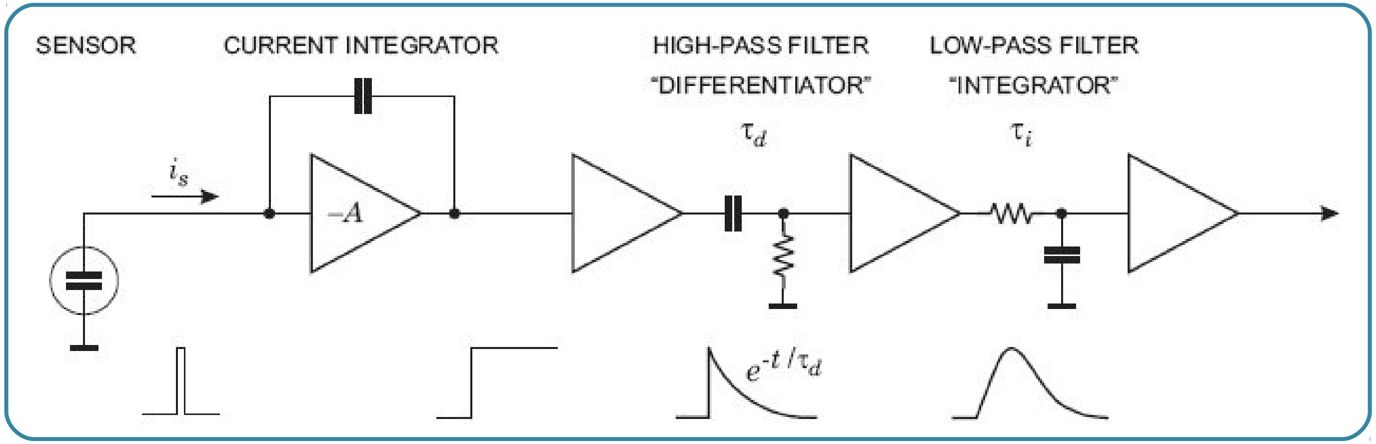
Pulse overlap



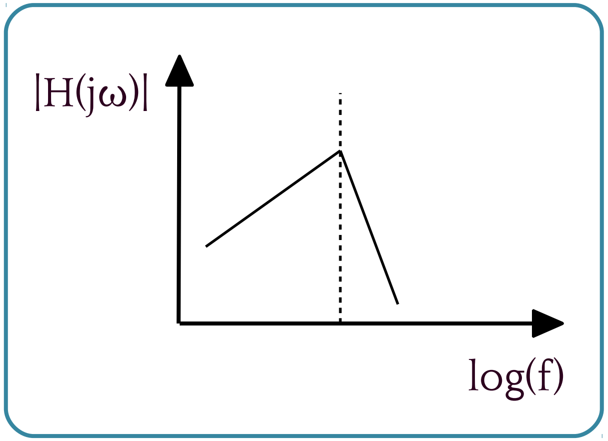
CR–RC shaper

- 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

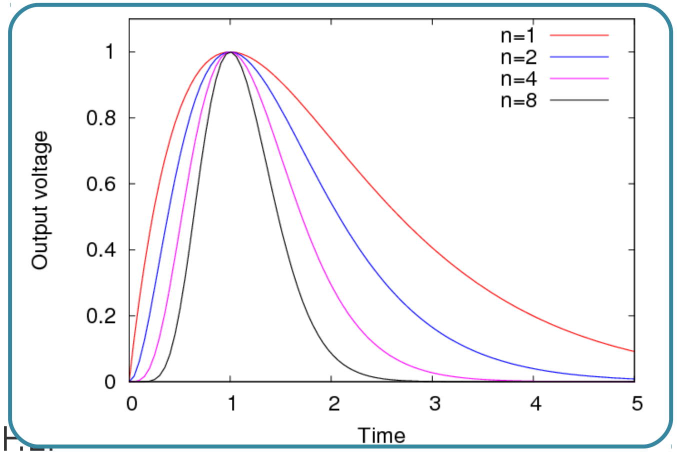
Integrator + RC–RC chain



RC–(RC)^n transfer function



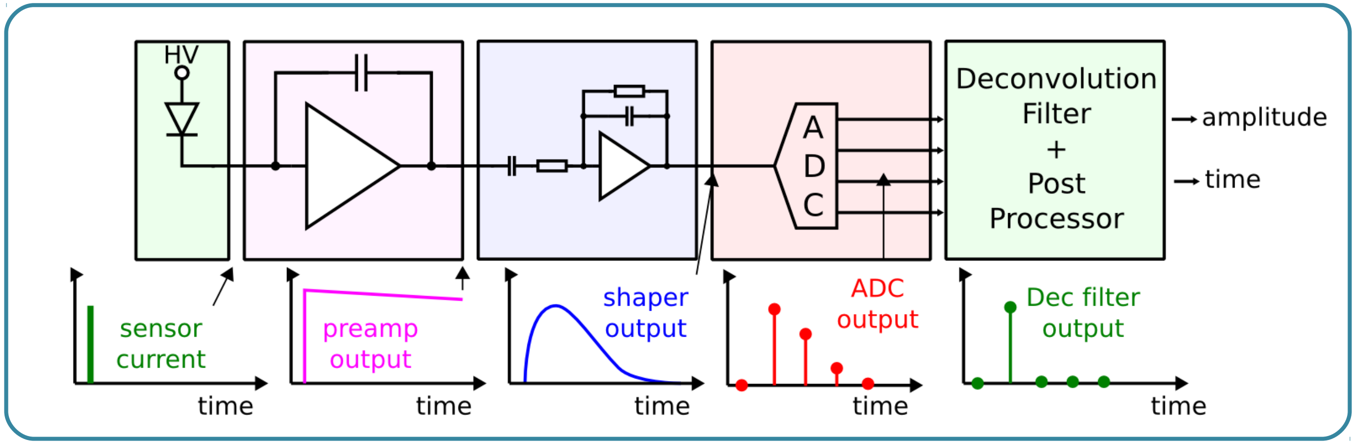
Impact of filter order



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

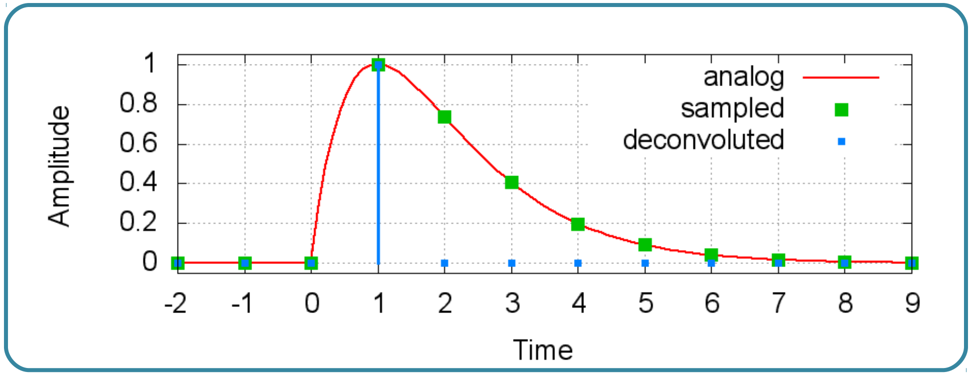
Amplitude measurement

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**

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

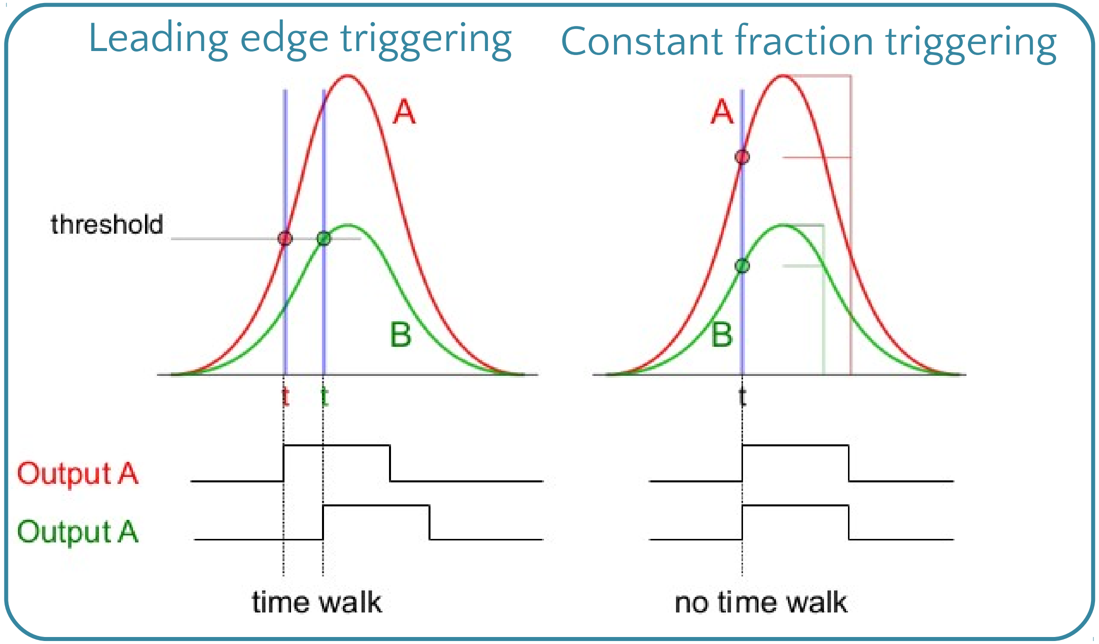


    - – Weights w_i can be optimized with various techniques
    - – Takes into account noise characteristics and known pulse shape
  - ○ **Peak finder** to find maximum

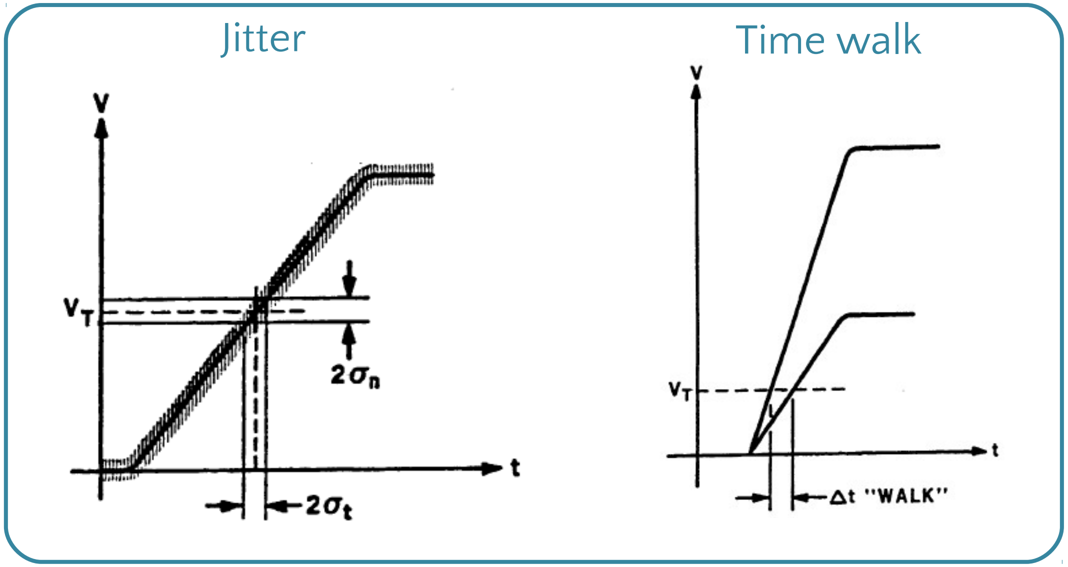
Time measurement

- 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



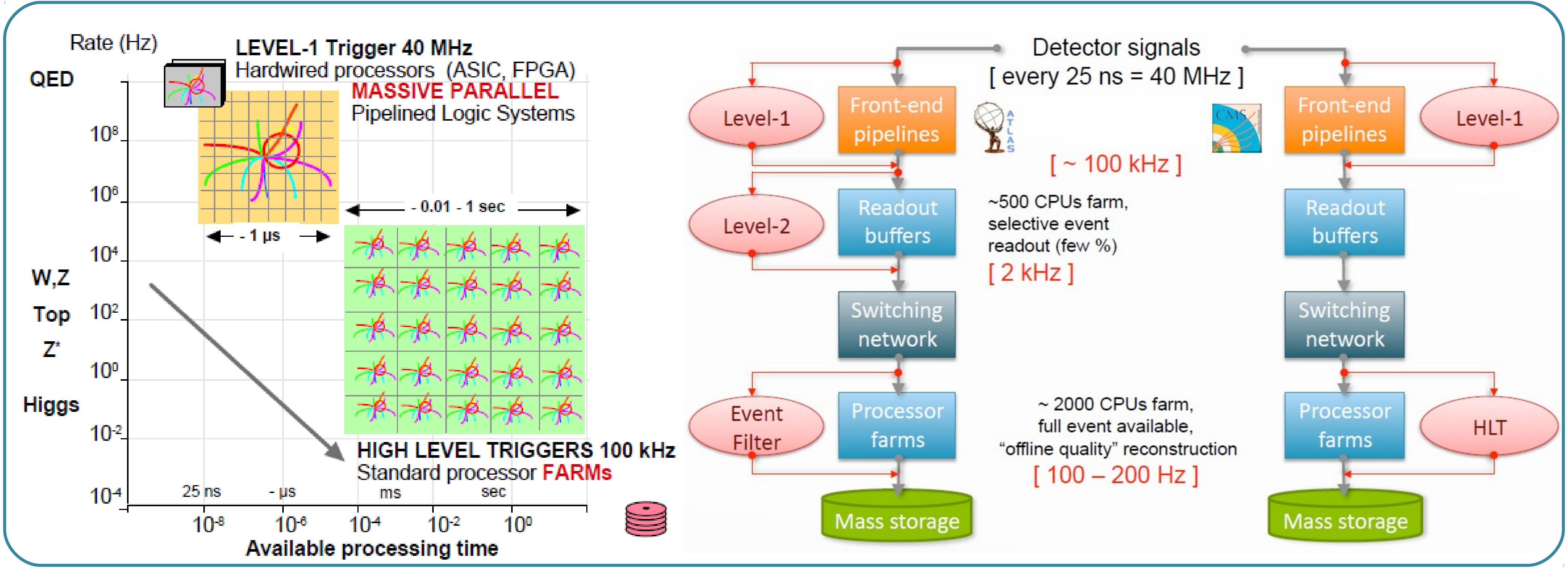
Measurement degraded by



Trigger

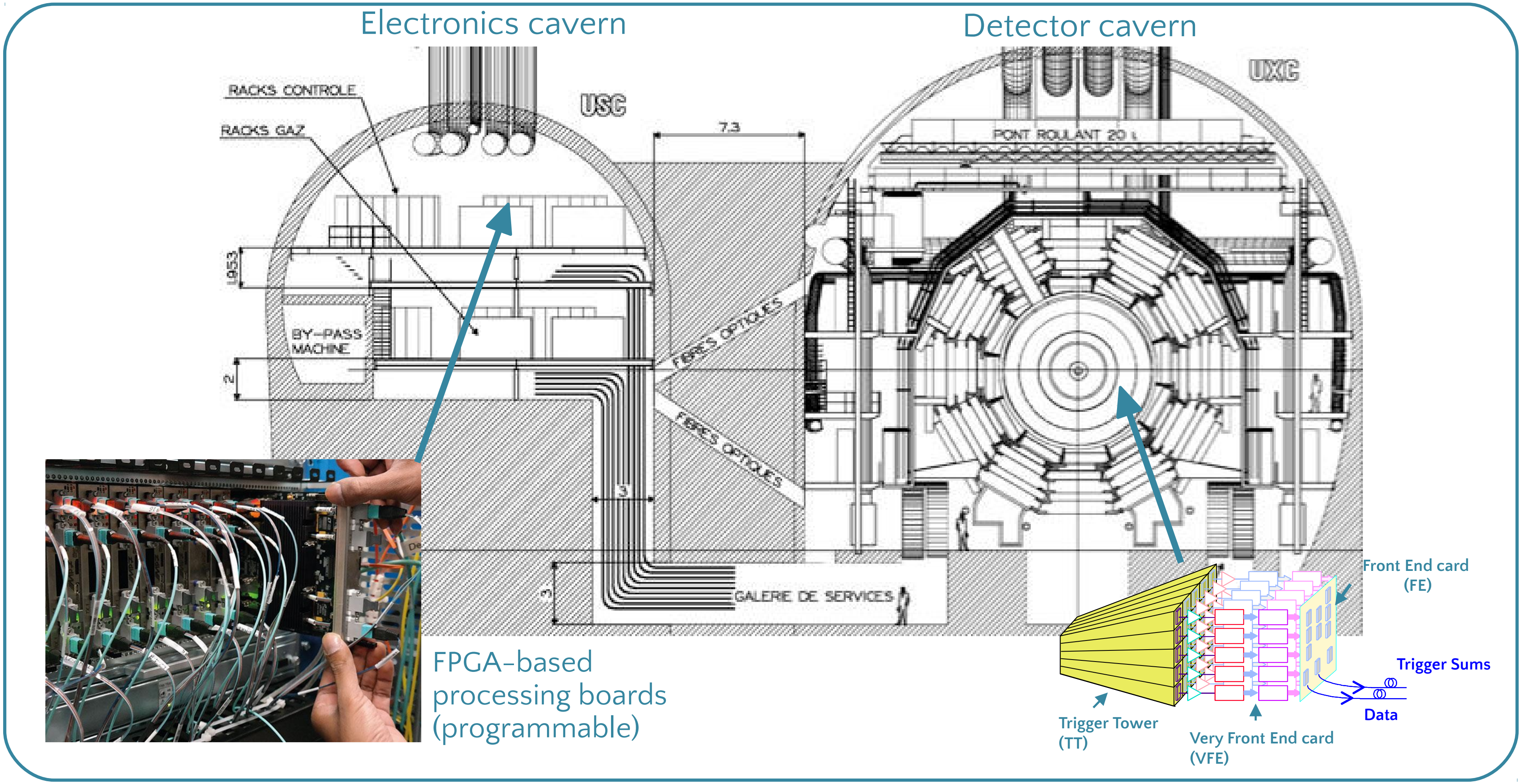
- In many cases it is impossible to store or transfer all the data from a calorimeter
  - e.g. at the LHC
- Need fast **trigger system to eliminate uninteresting events**
  - Trade-off between high performance (signal efficiency / background rejection)
  - And fast decision / low latency
- One solution: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



Electronics cavern

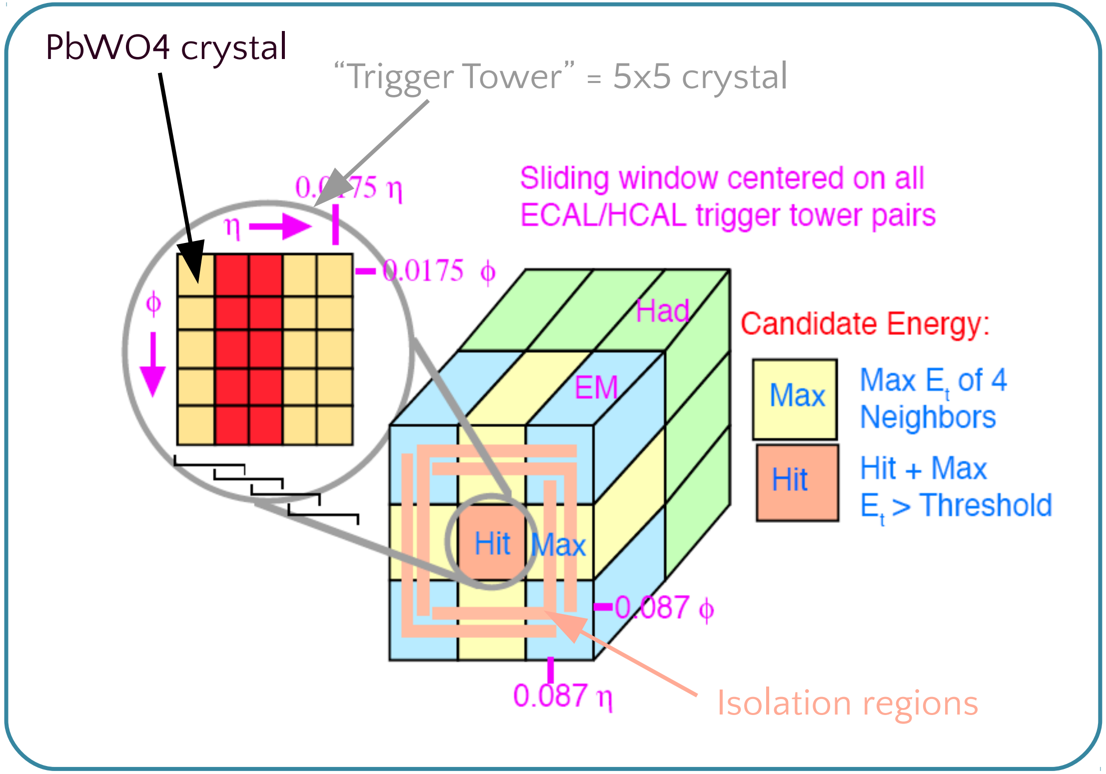
Detector cavern

FPGA-based processing boards (programmable)

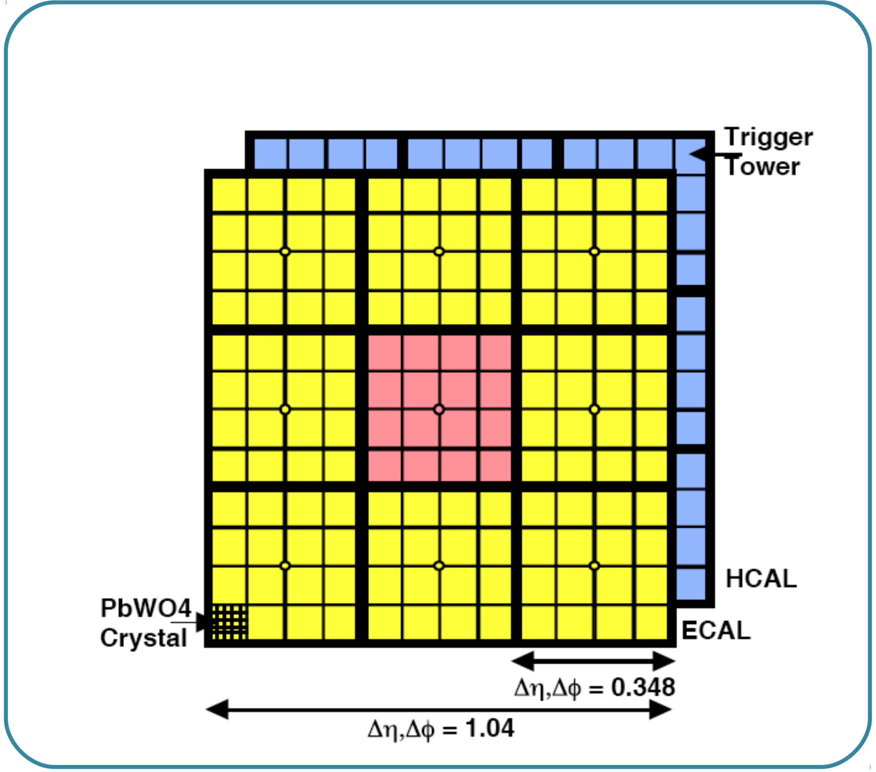
Calorimeter trigger objects, examples (CMS, Run 1)

- 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

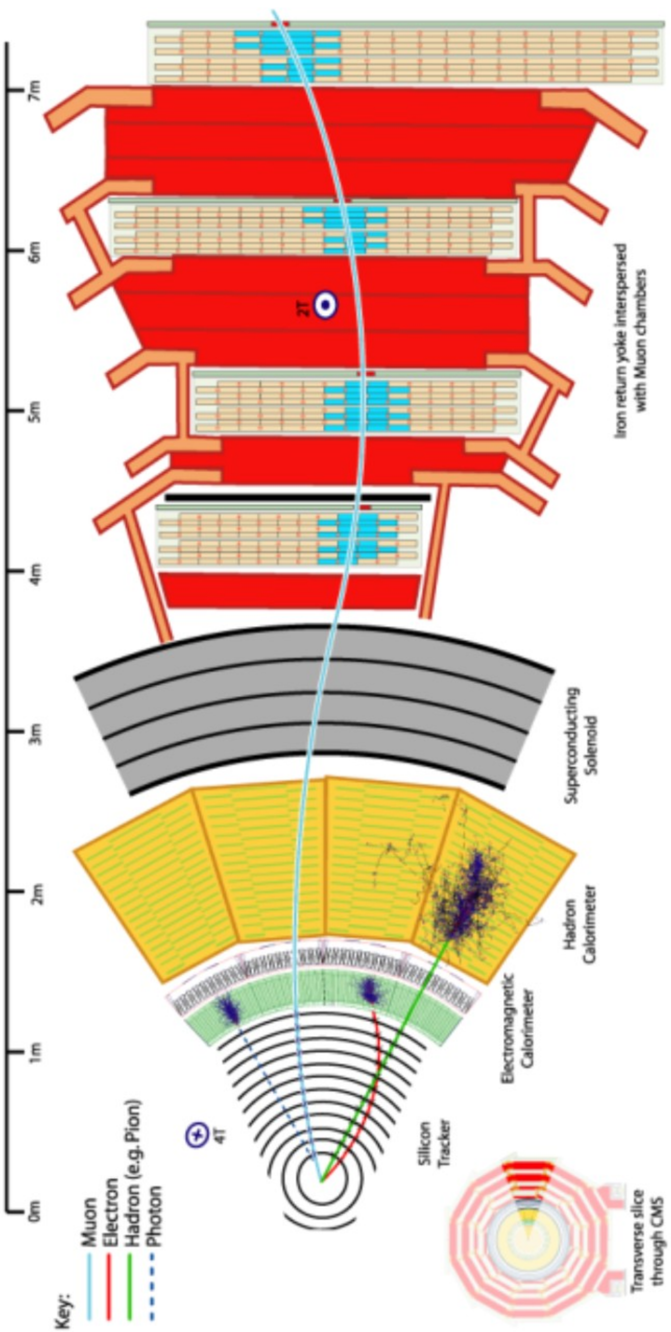
Energy reconstruction & calibration

Beyond calorimetry: Particle Flow

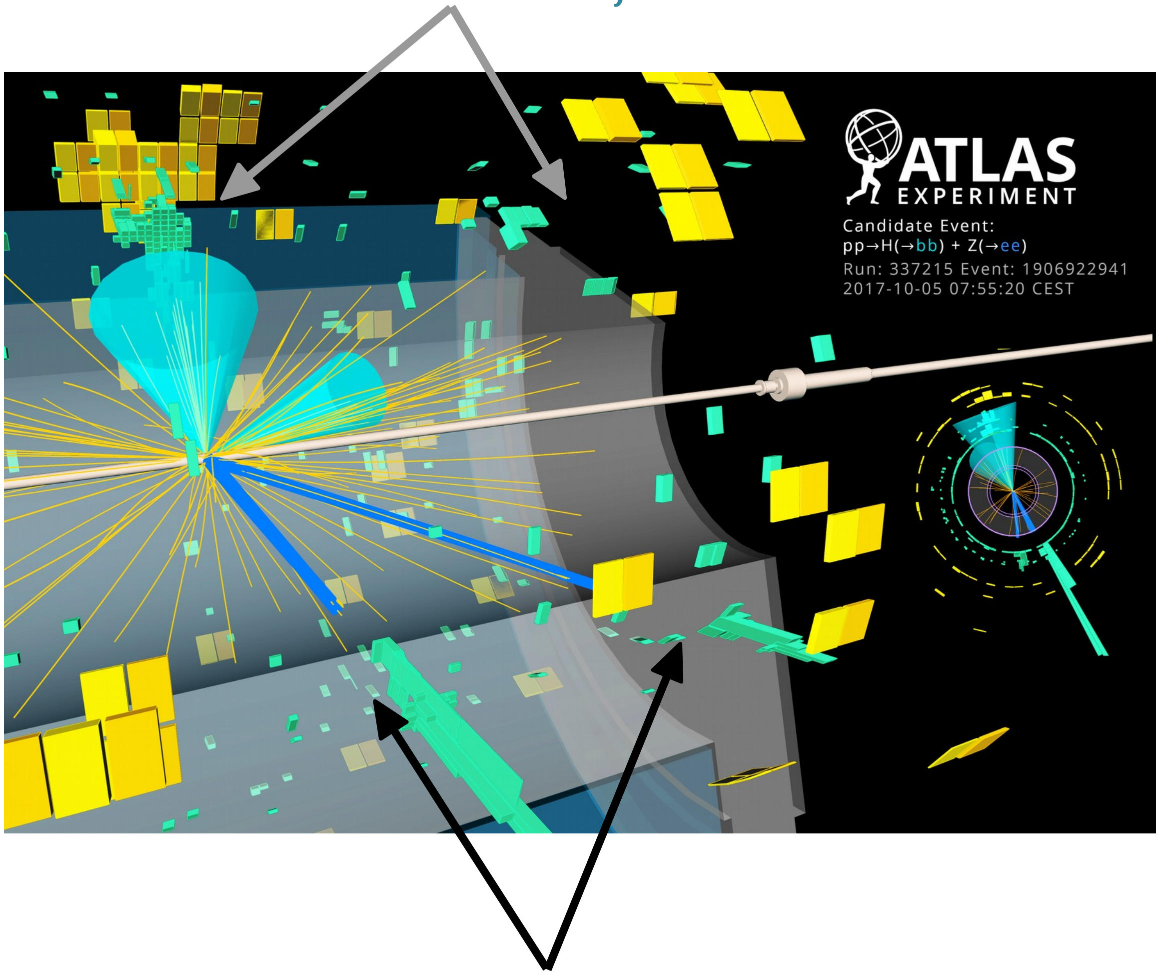
An example: CMS HGCAL

Reconstructing particles in calorimeters

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



Reconstructed jets

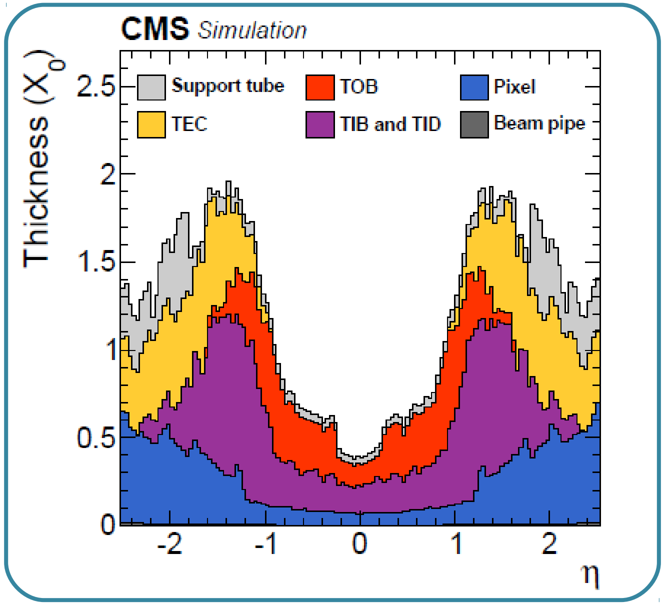


Reconstructed electrons

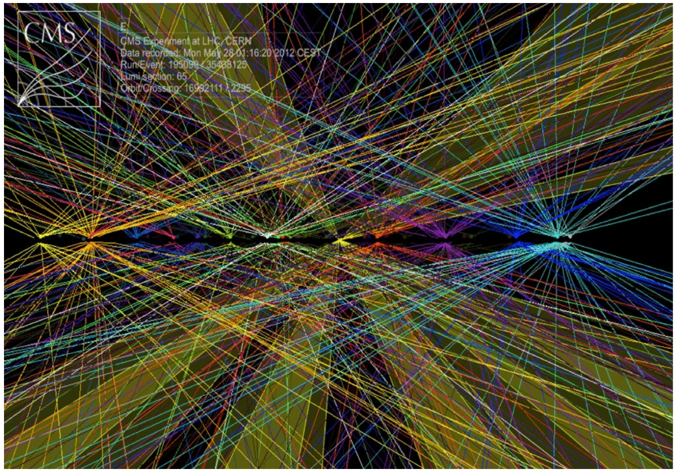
Real-life conditions

- 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

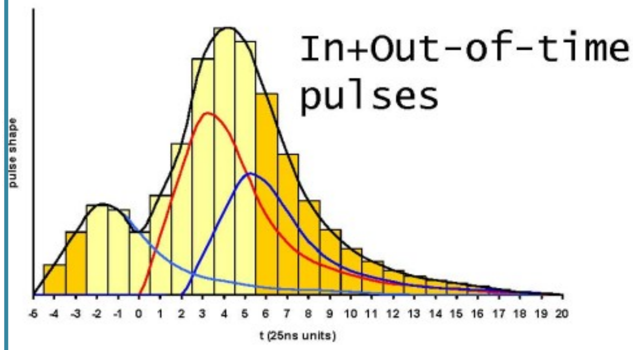
Material in front of the CMS calorimeters



Tracks from multiple simultaneous interactions

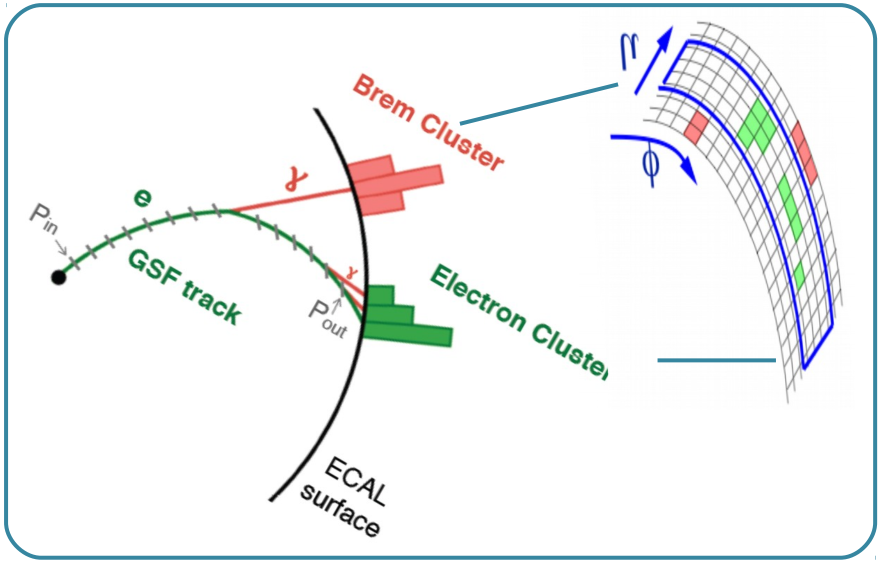


Energy deposited from consecutive interactions

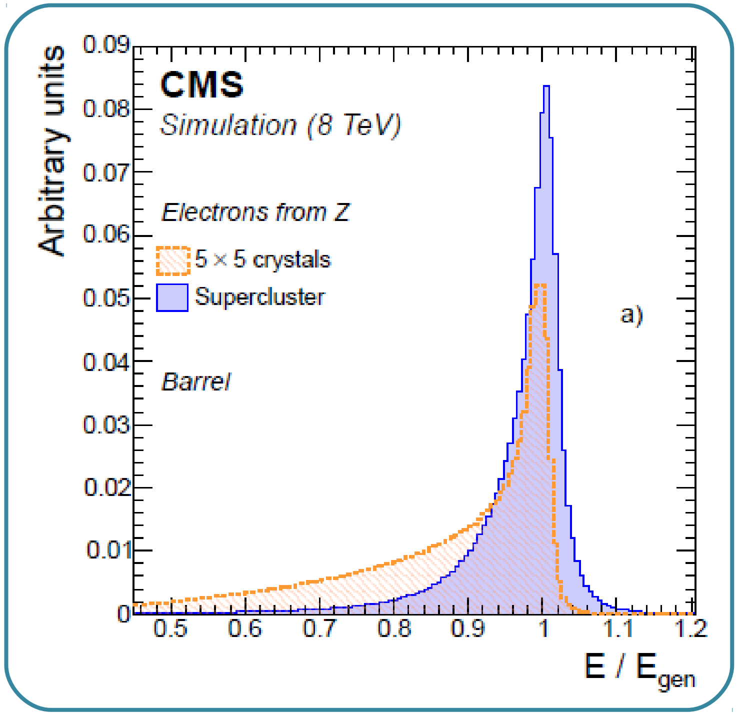


Electrons and photons reconstruction

- 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

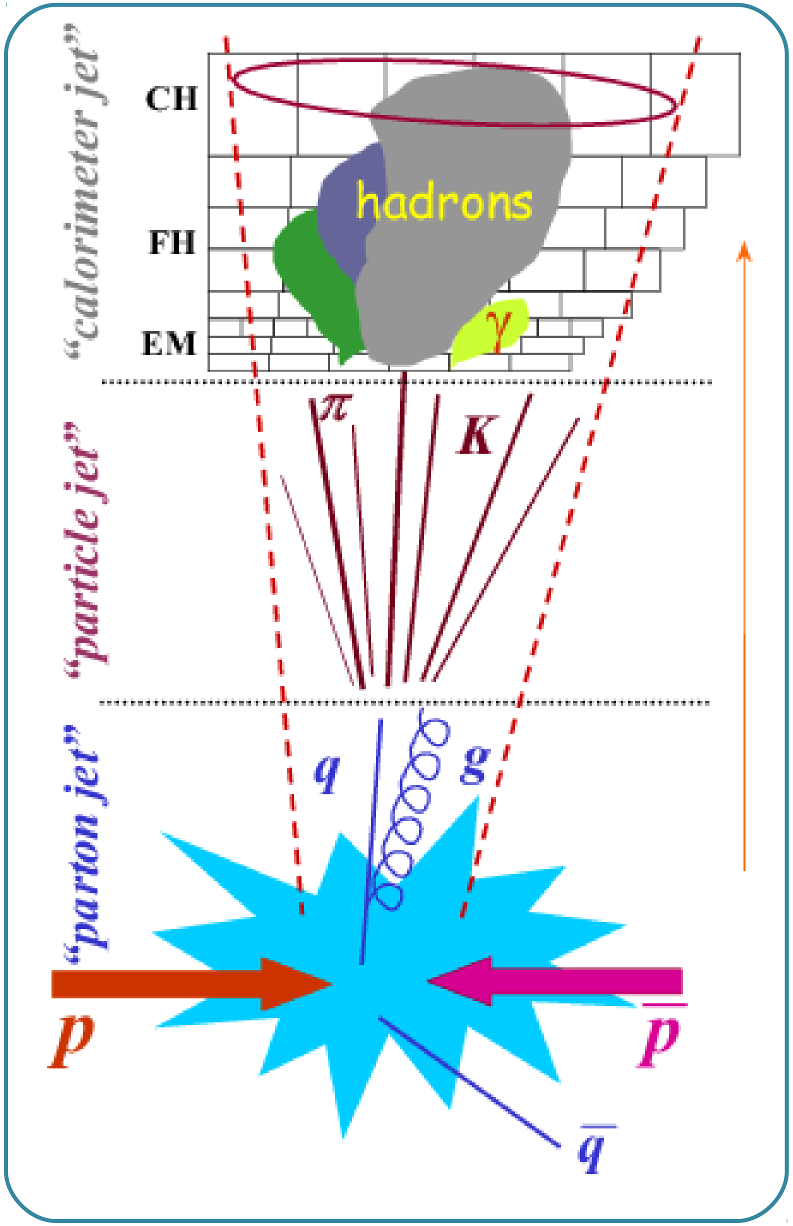


Impact of grouping distant clusters



- 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)

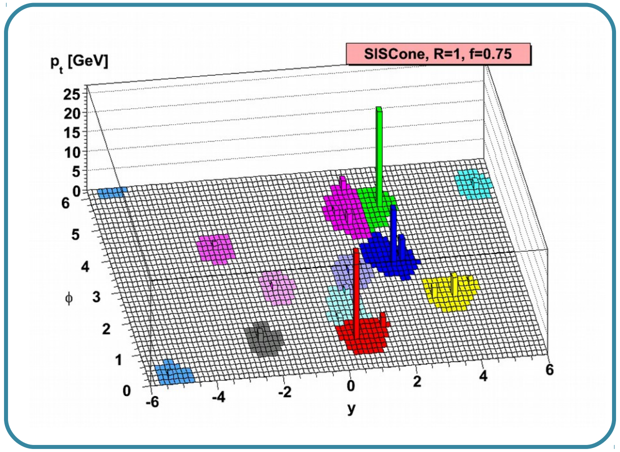
Jet algorithms

- 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**

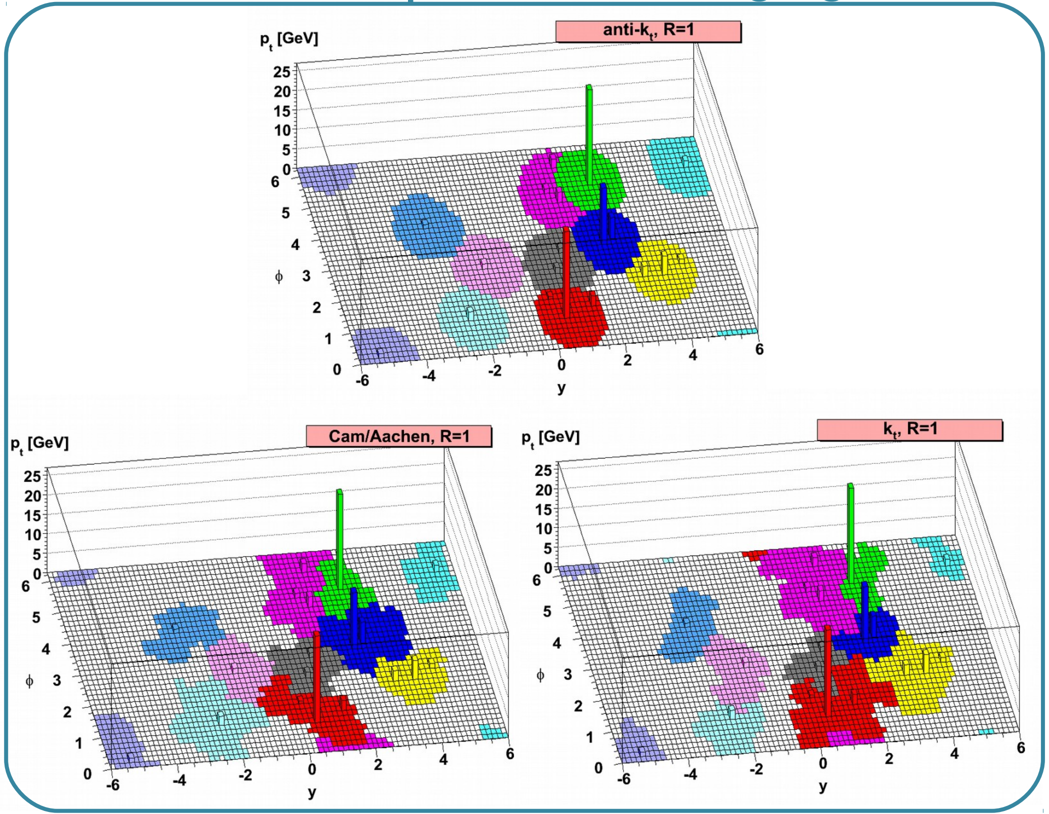
$$d_{ij}=min\left(\frac{1}{p_{Ti}^2},\frac{1}{p_{Tj}^2}\right)\times\frac{R_{ij}^2}{R}$$

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

Example of cone algorithm



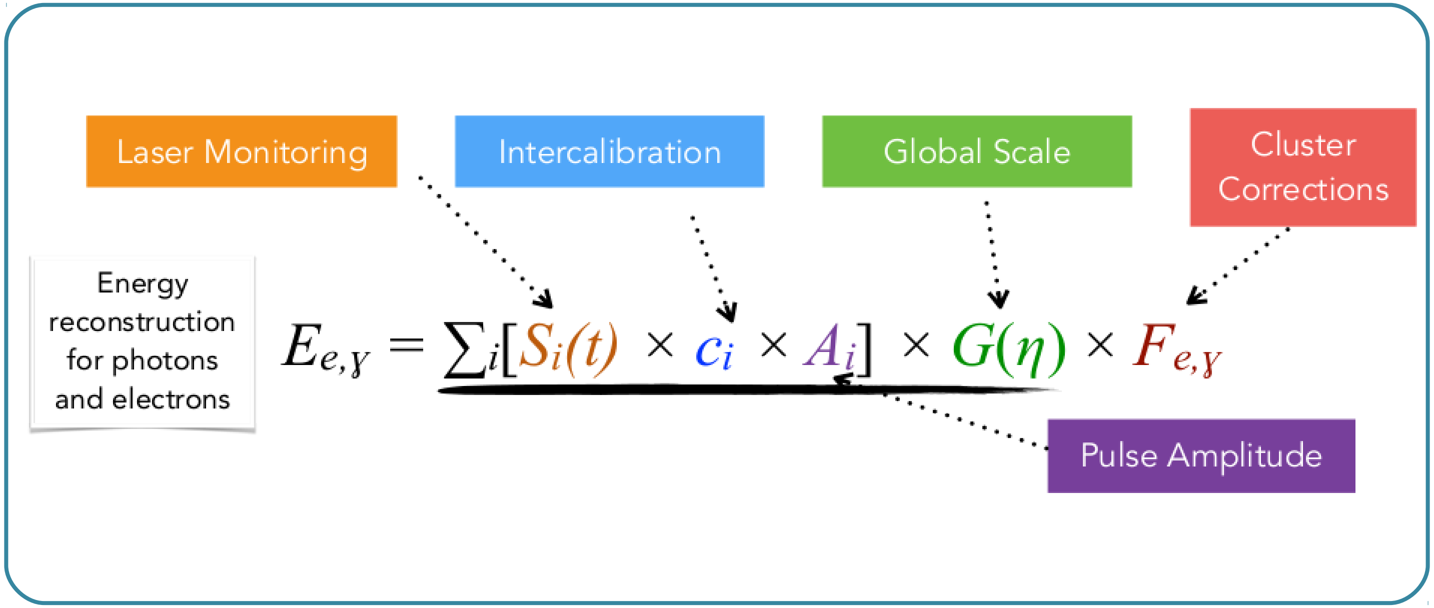
Most common sequential clustering algorithms



Calorimeter calibration / energy reconstruction

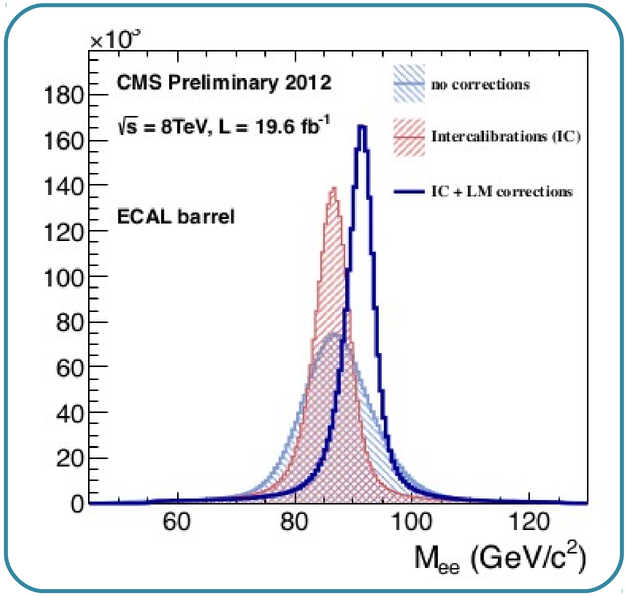
- Typical calibration components
  - ○ Pulse amplitude → energy (charge → energy deposited, can include sampling fraction)
  - ○ Response effects from monitored parameters
  - ○ Intercalibration (looking at differences of response in different places)
  - ○ Leakage corrections (energy outside of cluster)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

Example in CMS ECAL

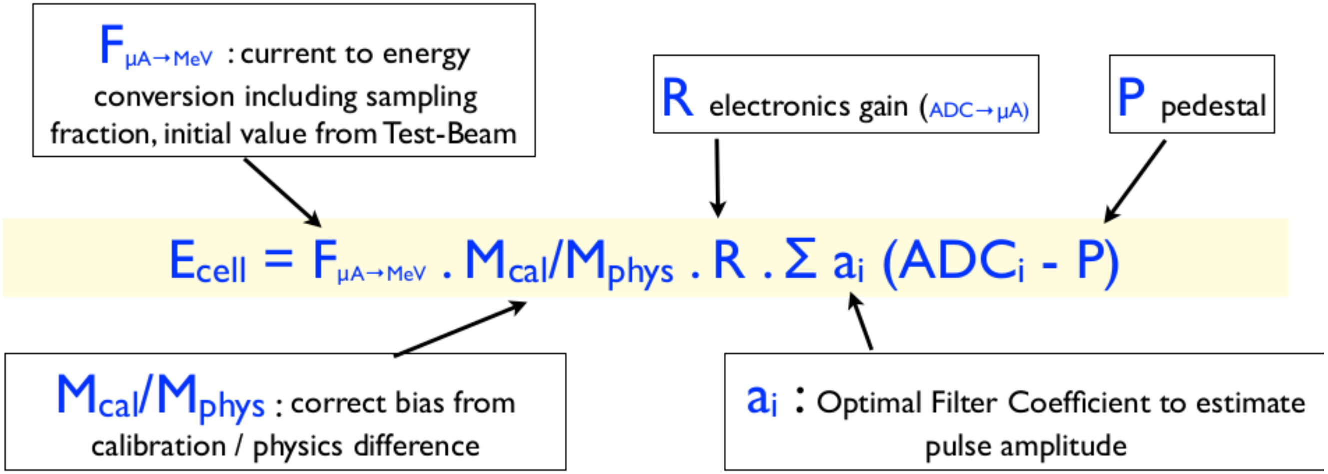


$$E_{e,\gamma} = \sum_i [S_i(t) \times c_i \times A_i] \times G(\eta) \times F_{e,\gamma}$$

Impact of intercalibration and laser monitoring



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

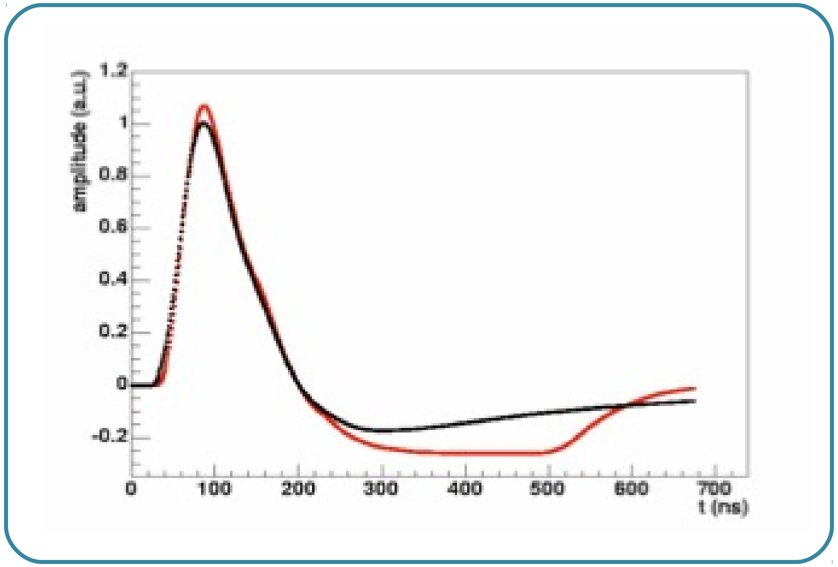
$$E_{cell} = F_{\mu A \to MeV} \,.\, M_{cal}/M_{phys} \,.\, R \,.\, \Sigma\, a_i \,(ADC_i - P)$$

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

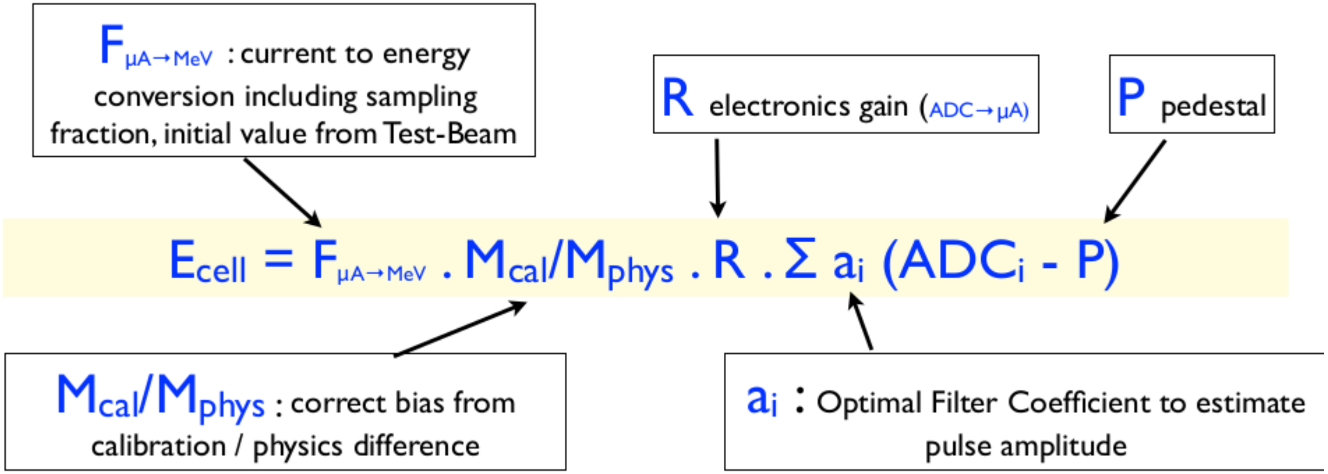
a_i : Optimal Filter Coefficient to estimate pulse amplitude

- 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



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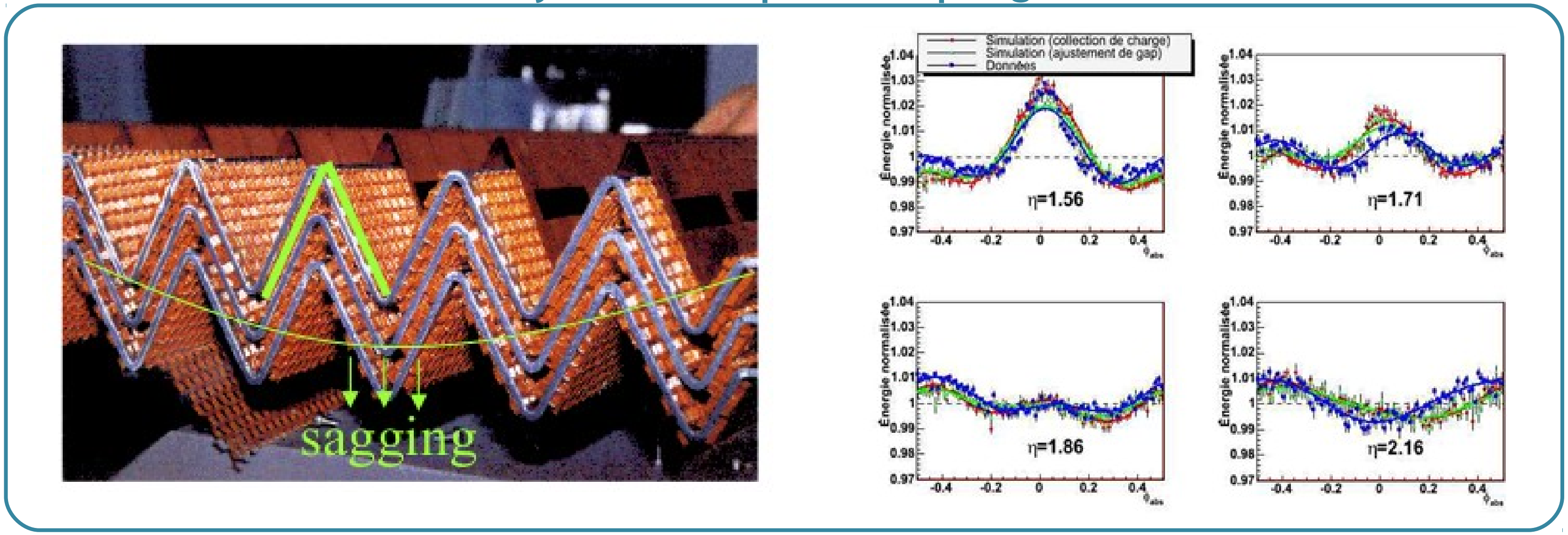
a_i : Optimal Filter Coefficient to estimate pulse amplitude

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

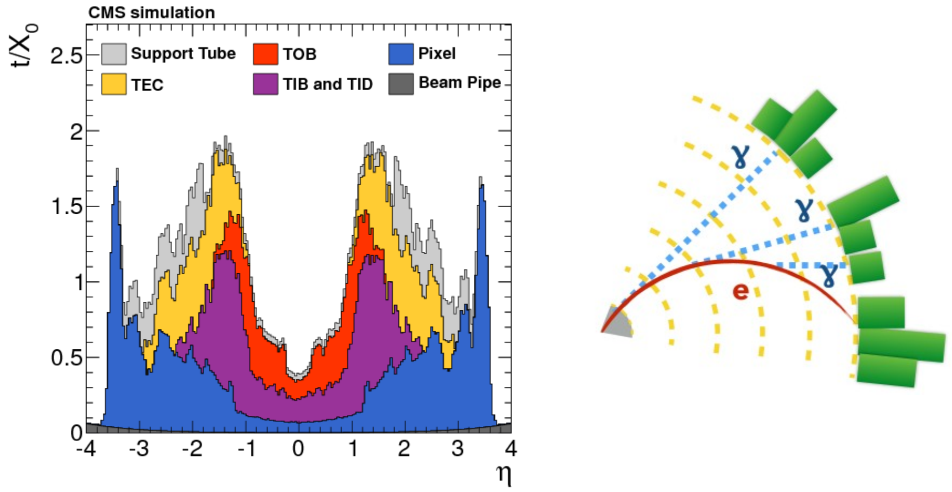
Gravity effects impact sampling fraction



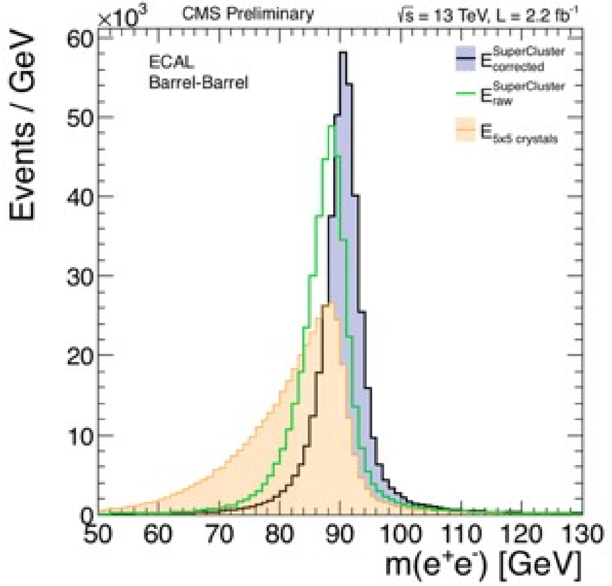
Cluster energy corrections

- 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



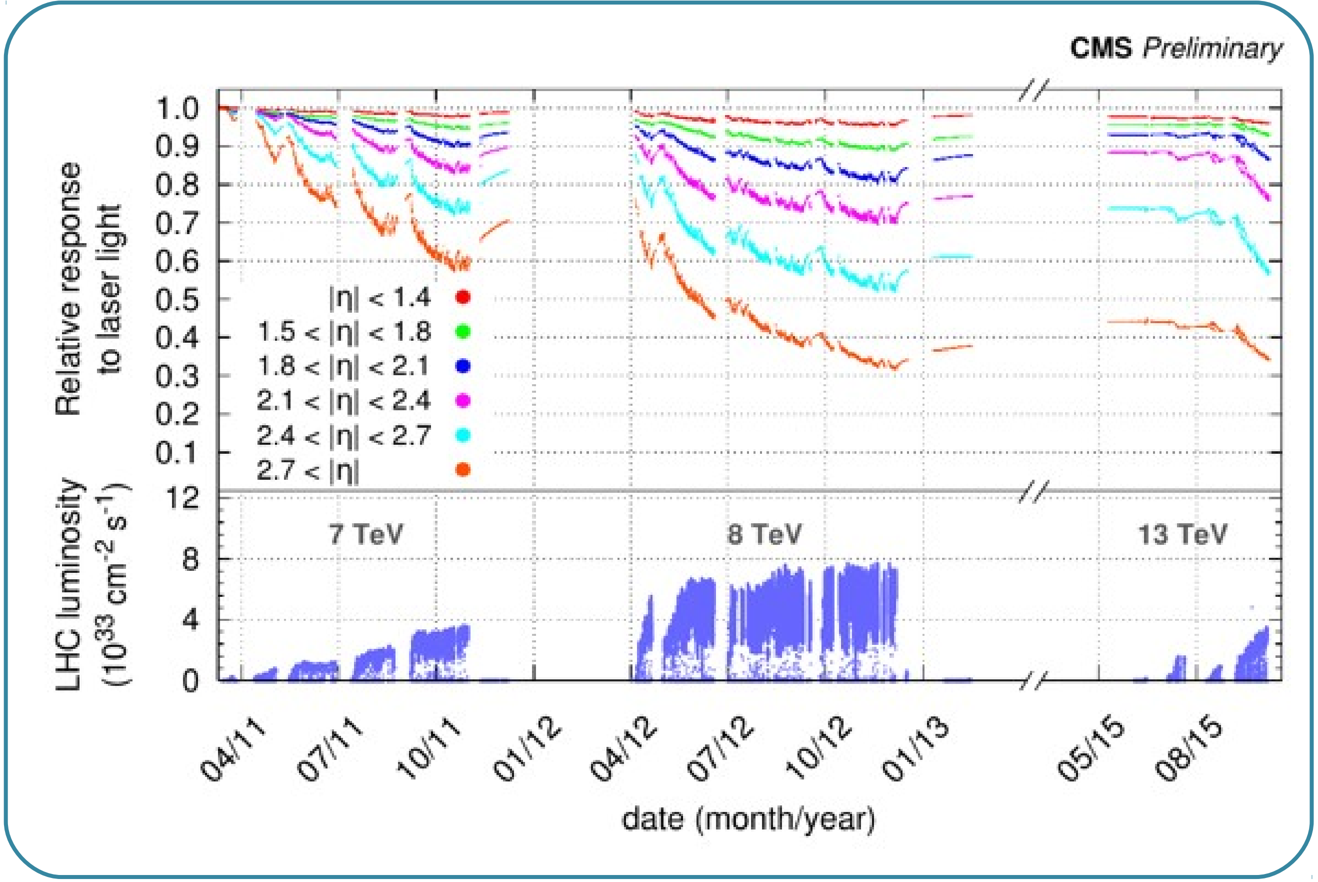
Impact of clustering and corrections on reconstructed Z mass



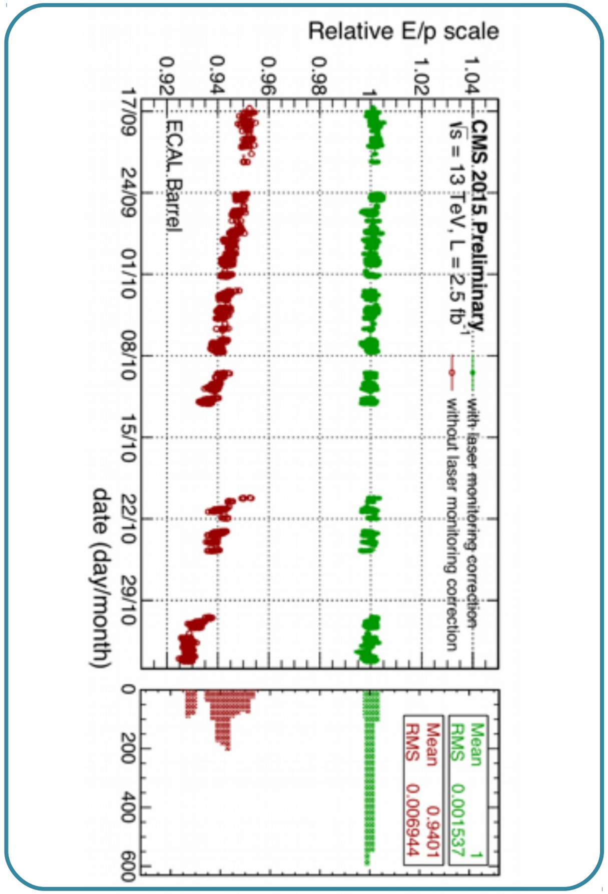
Monitoring

- 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)



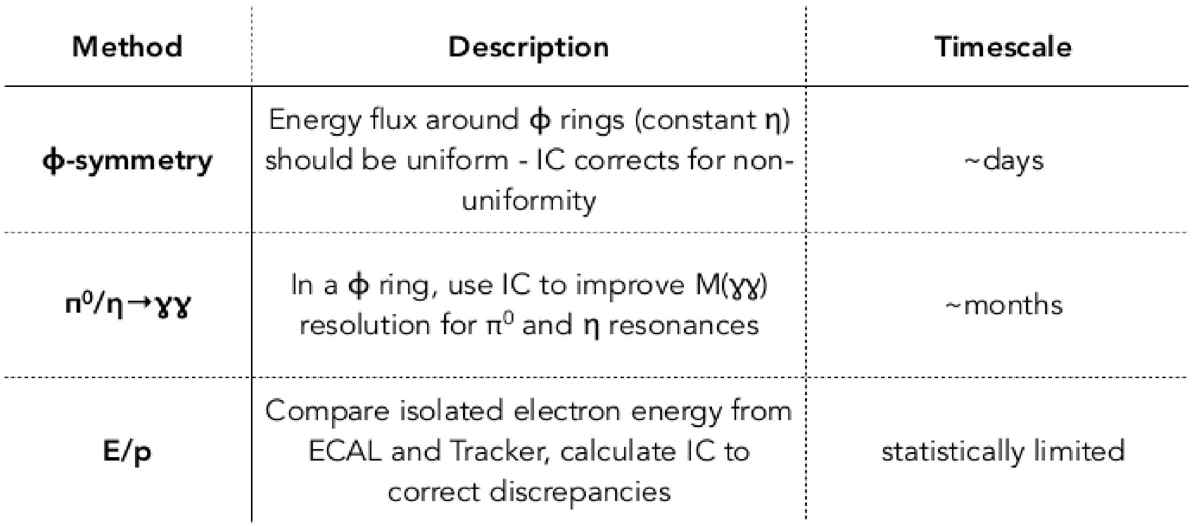
Effect of monitored crystal response on reconstructed electron energy



Intercalibration

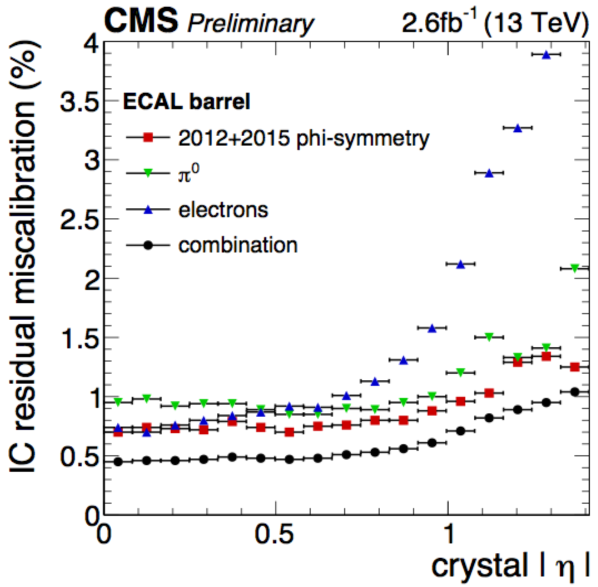
- There are always local effects which cannot be perfectly simulated nor measured
- Need to equalize the response of each sensor one to an other
  - In situ (e.g. using collision data) intercalibration
- In general, several methods are combined
  - Using detector symmetries
  - Using "standard candles"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

Intercalibration methods used in CMS ECAL



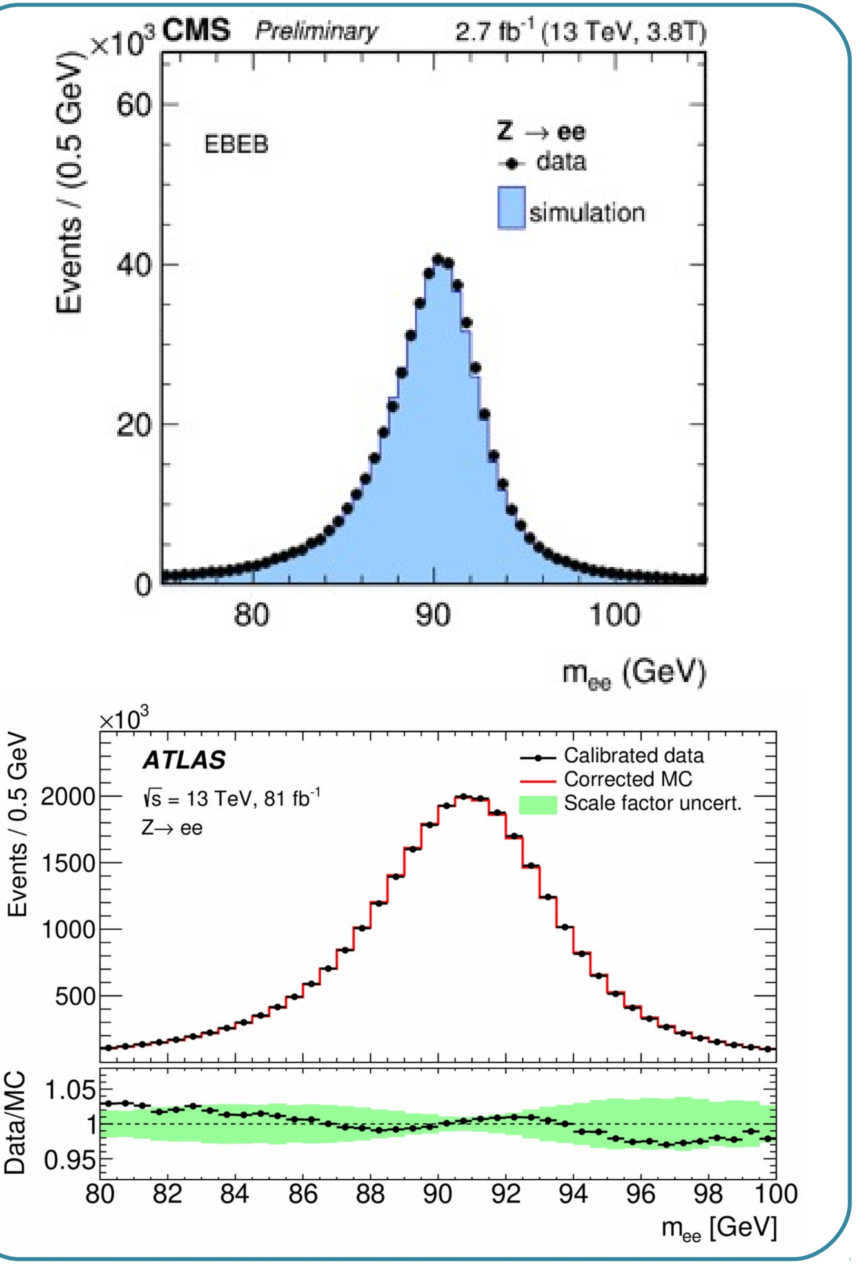
Method	Description	Timescale
ϕ-symmetry	Energy flux around ϕ rings (constant η) should be uniform - IC corrects for non-uniformity	~days
$\pi^0/\eta \to \gamma\gamma$	In a ϕ ring, use IC to improve M(γγ) resolution for π^0 and η resonances	~months
E/p	Compare isolated electron energy from ECAL and Tracker,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

Precisions obtained with each intercalibration methods



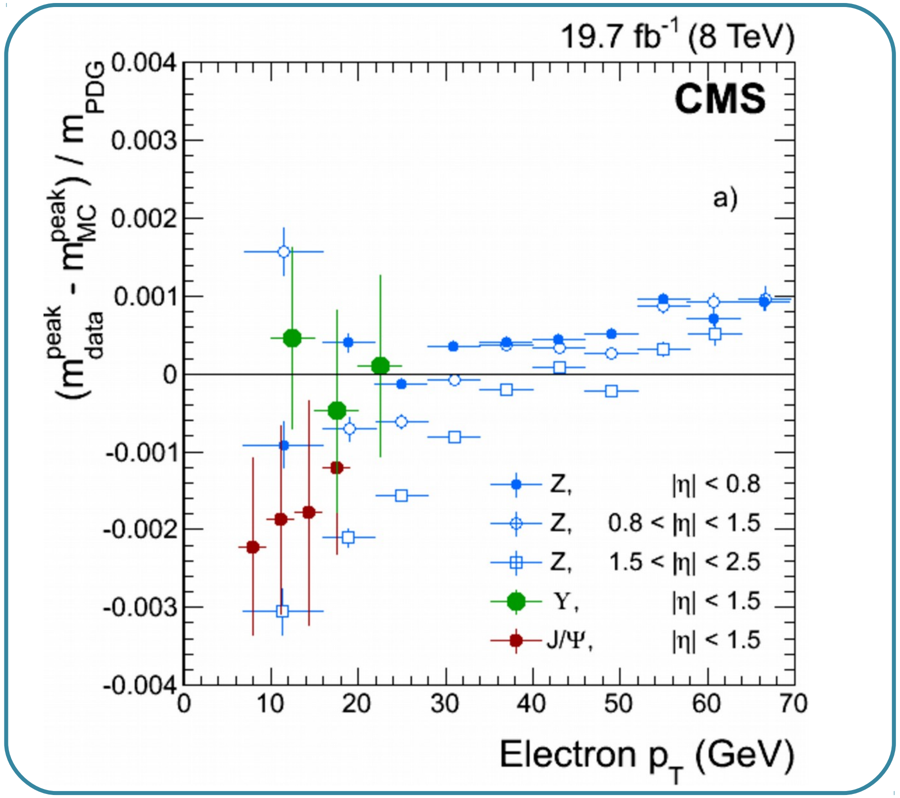
Absolute calibration

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

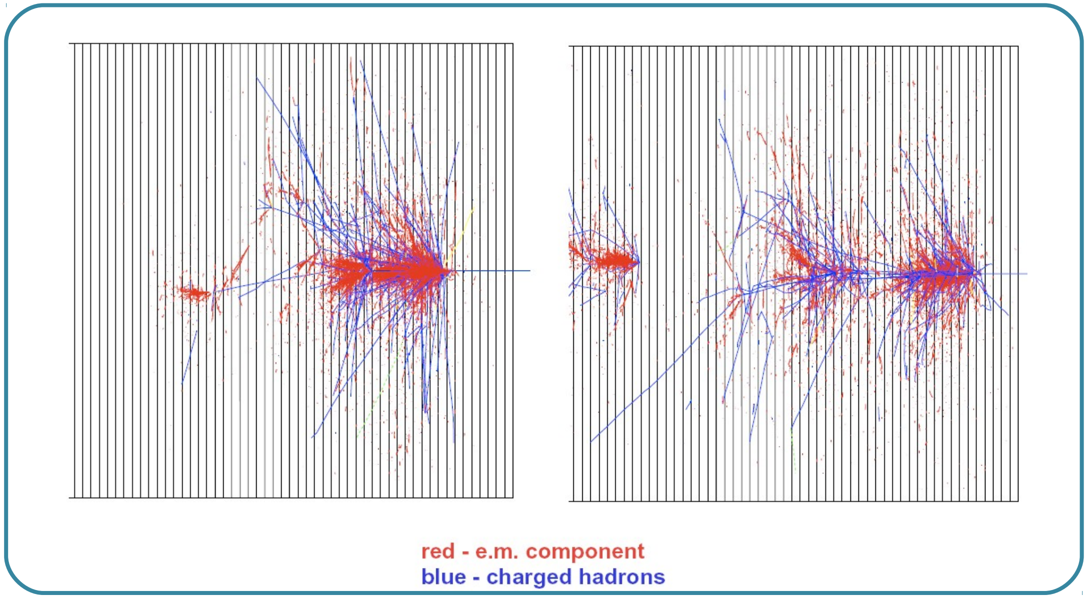
Linearity check with different resonances



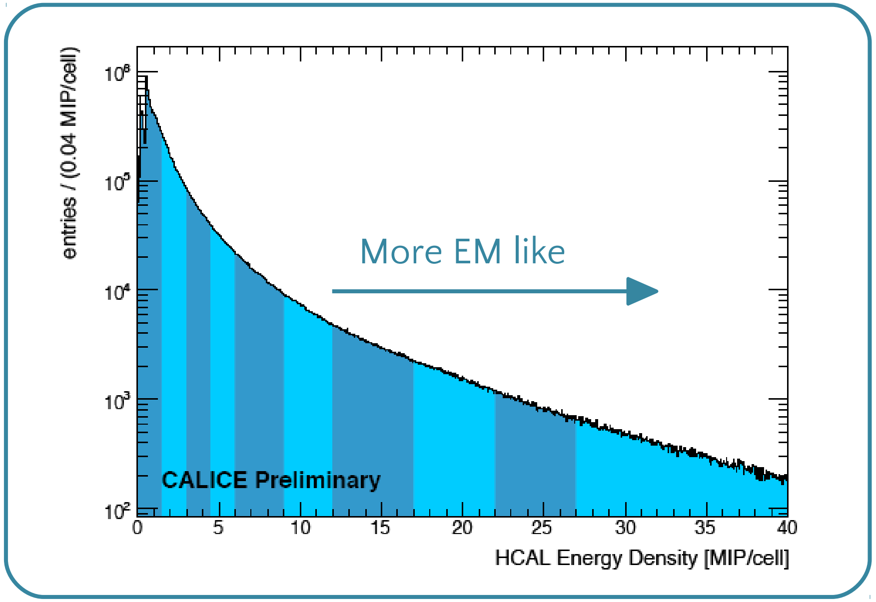
Jet energy measurement

- 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

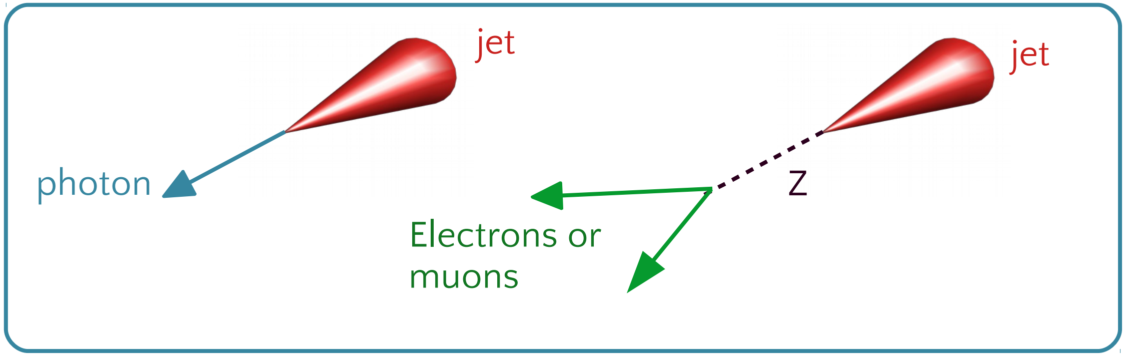


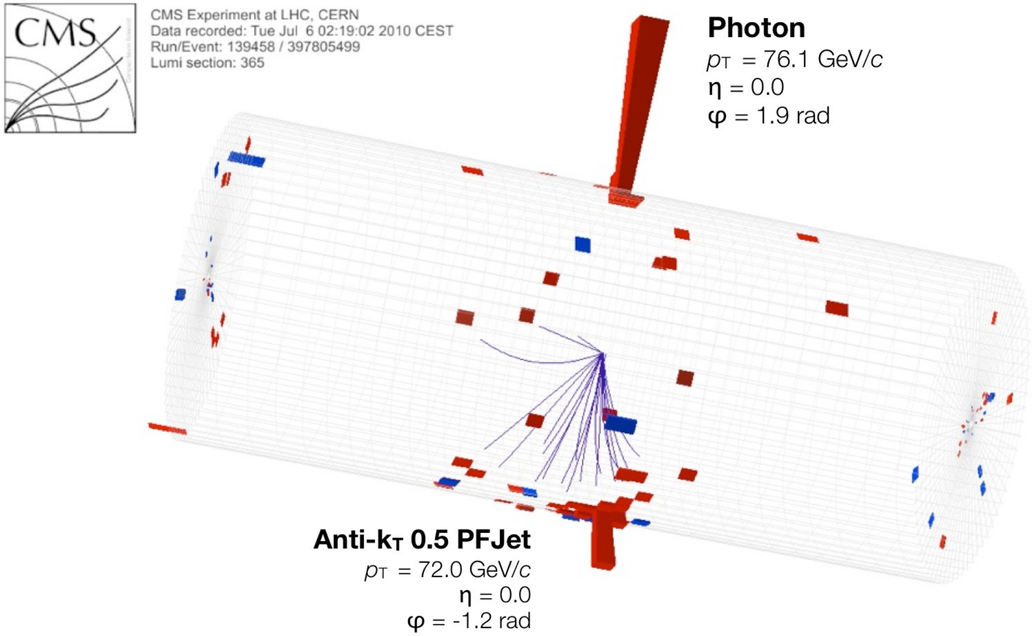
Cell energy density



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**

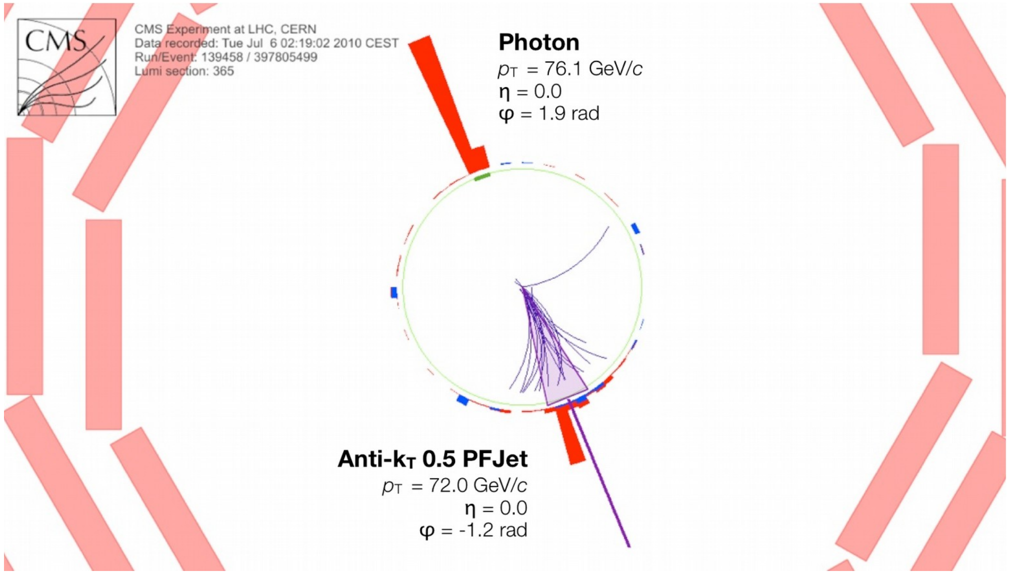




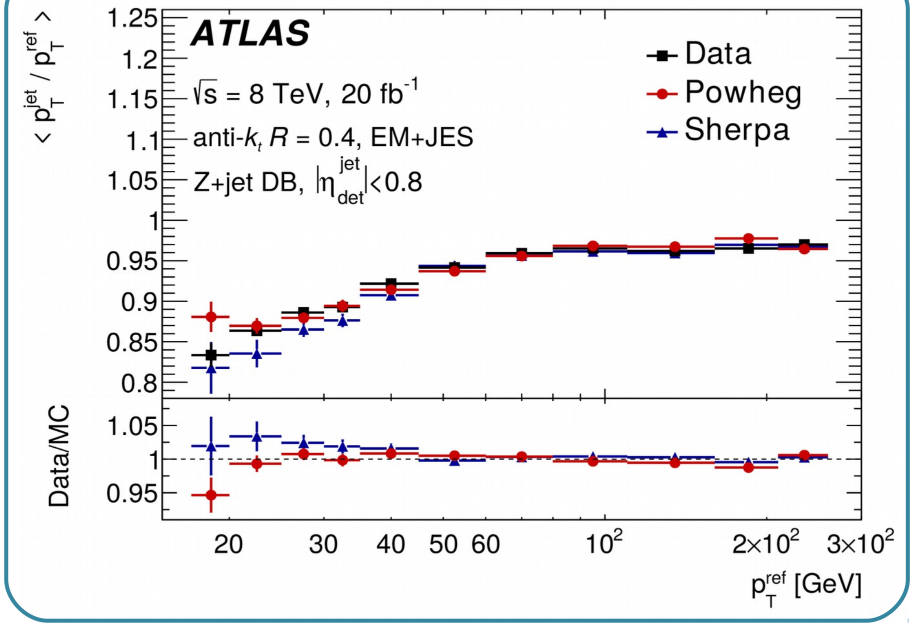
Jet in situ calibration

- 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

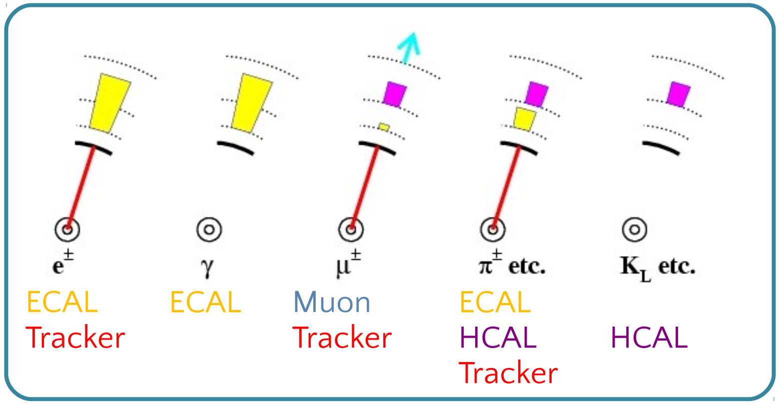
Energy reconstruction & calibration

An example: CMS HGCAL

Reconstruction beyond calorimeters

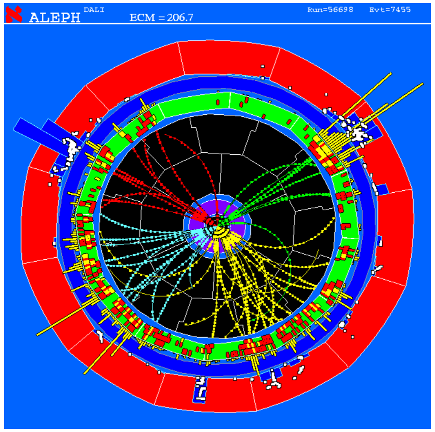
- Electrons, photons, hadrons, etc. produce different signatures in the different subdetectors
  - ○ Photon: mainly ECAL
  - ○ Electron: ECAL + tracker
  - ○ Charged hadrons: all calorimeters + tracker
  - ○ Neutral hadrons: all calorimeters
  - ○ Muons: Mainly muon chambers + tracker

Signatures from different particles

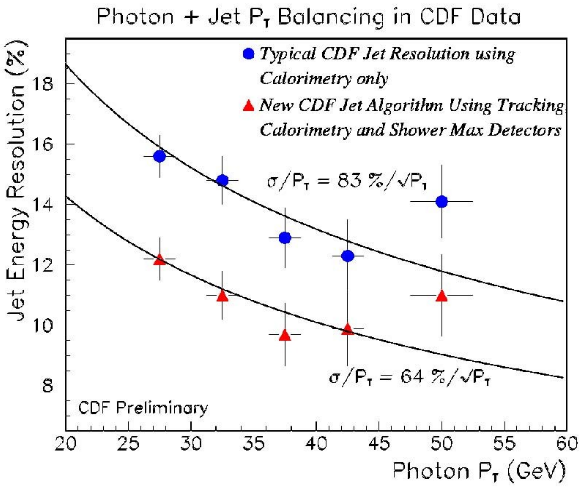


- The idea is to **combine the information from all subdetectors**
  - ○ Can better identify objects and measure / calibrate their energy
- Pioneered in ALEPH at LEP (90's) and used later in other detectors

WW → 4q in ALEPH



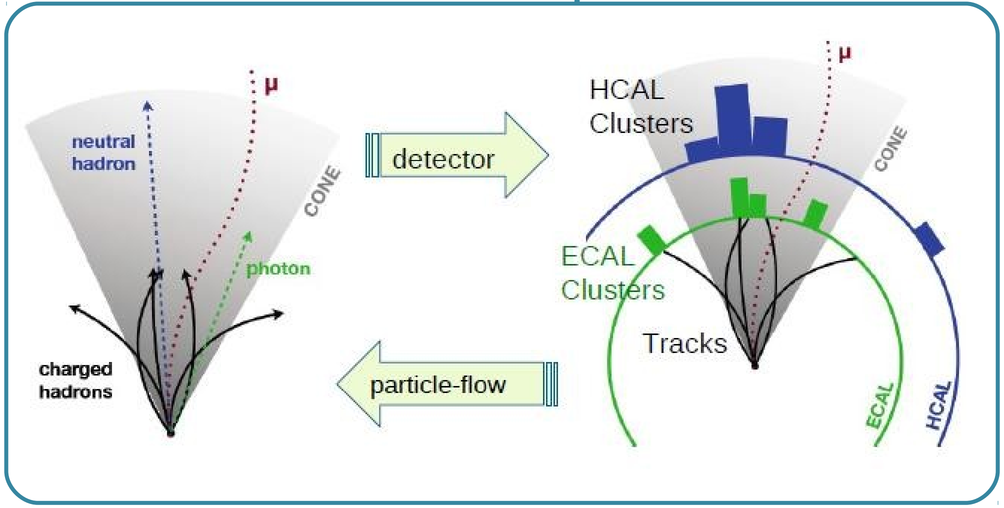
Improvement in jet energy resolution in CDF



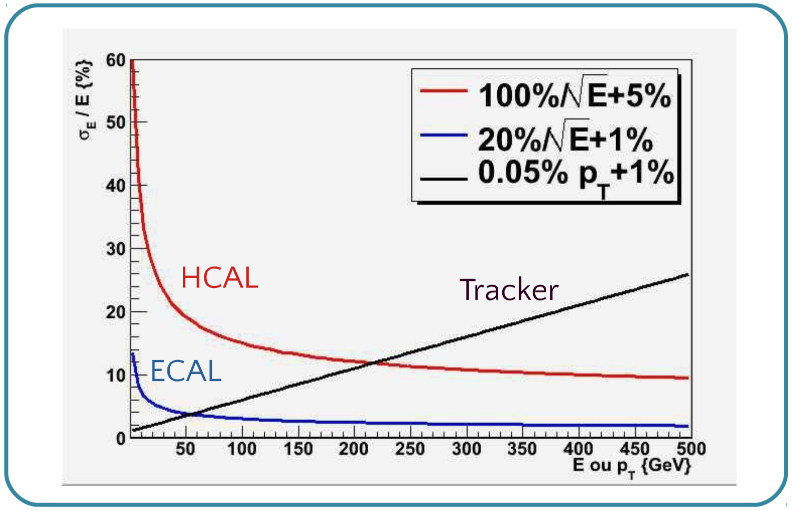
Particle Flow

- **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

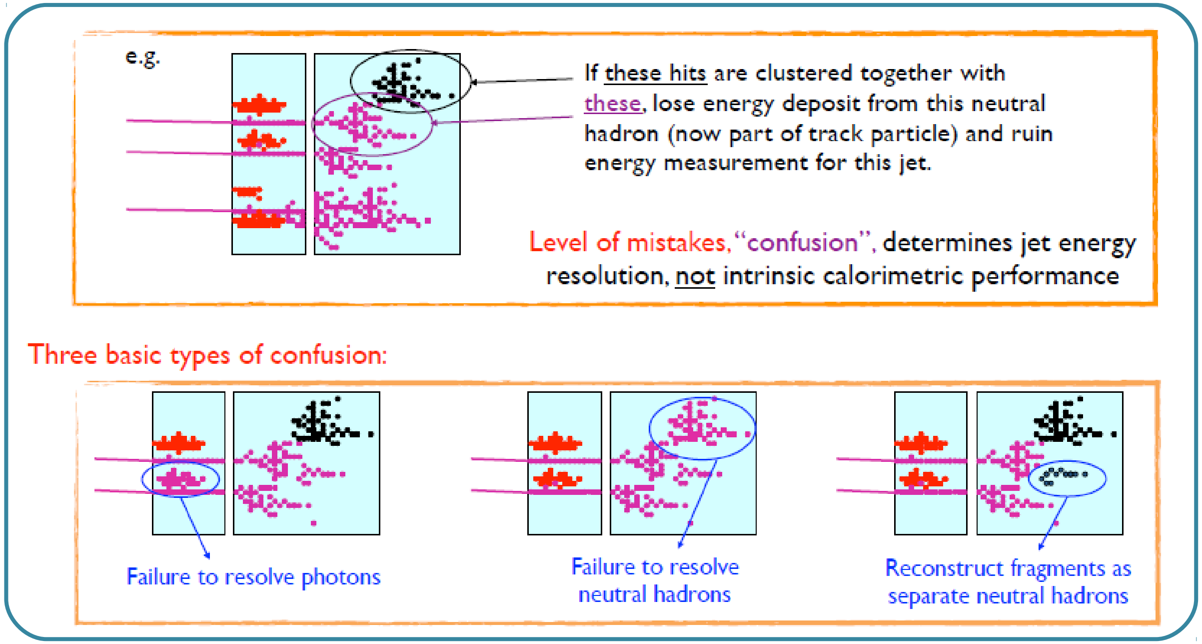
- Jet energy resolution (forgetting correlations):

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

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



e.g.

If these hits are clustered together with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

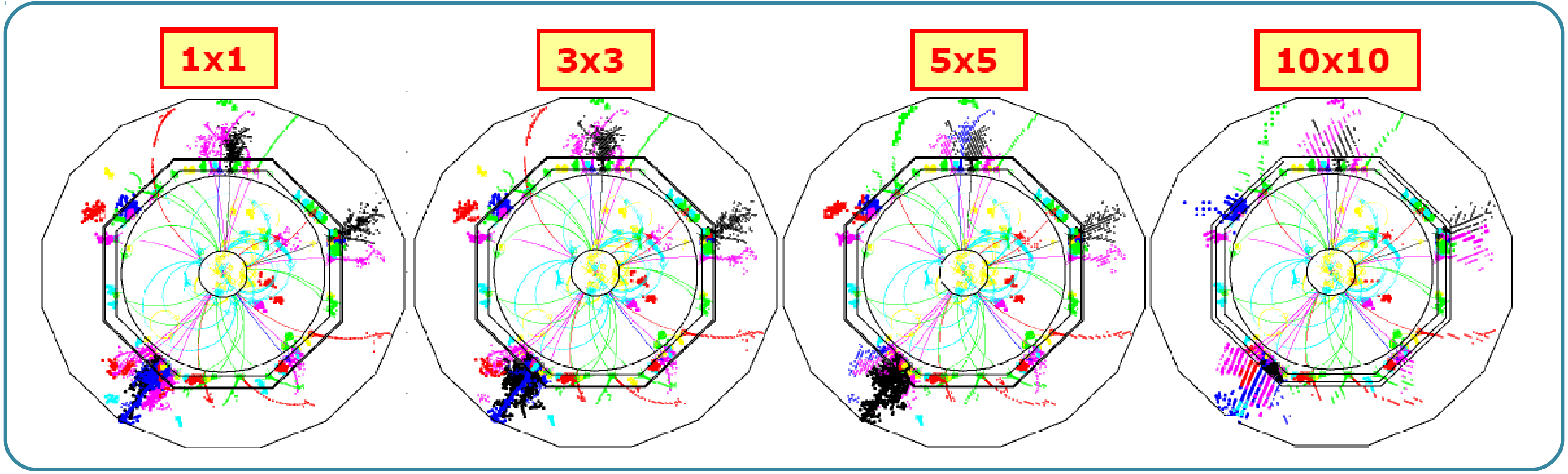
Level of mistakes, "confusion", determines jet energy resolution, not intrinsic calorimetric performance

Three basic types of confusion:

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

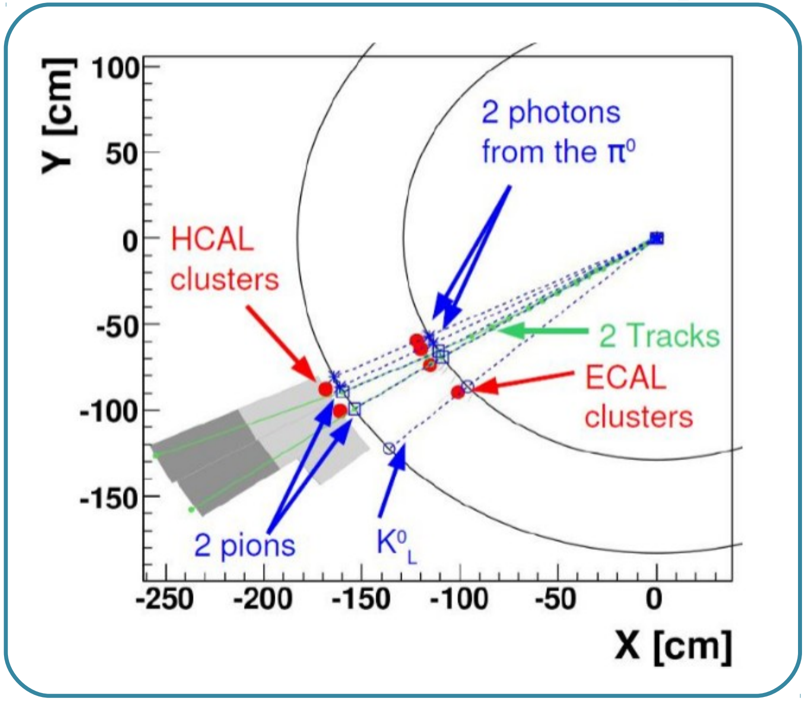
Impact of HCAL granularity



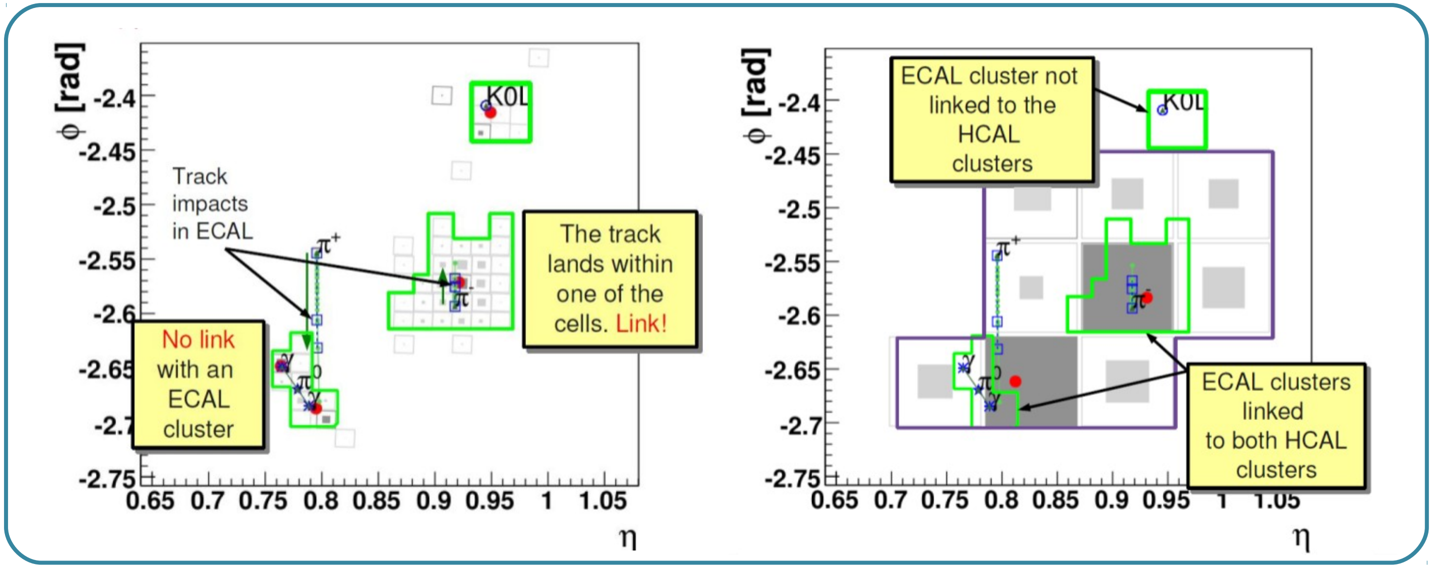
Particle Flow in CMS

- 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



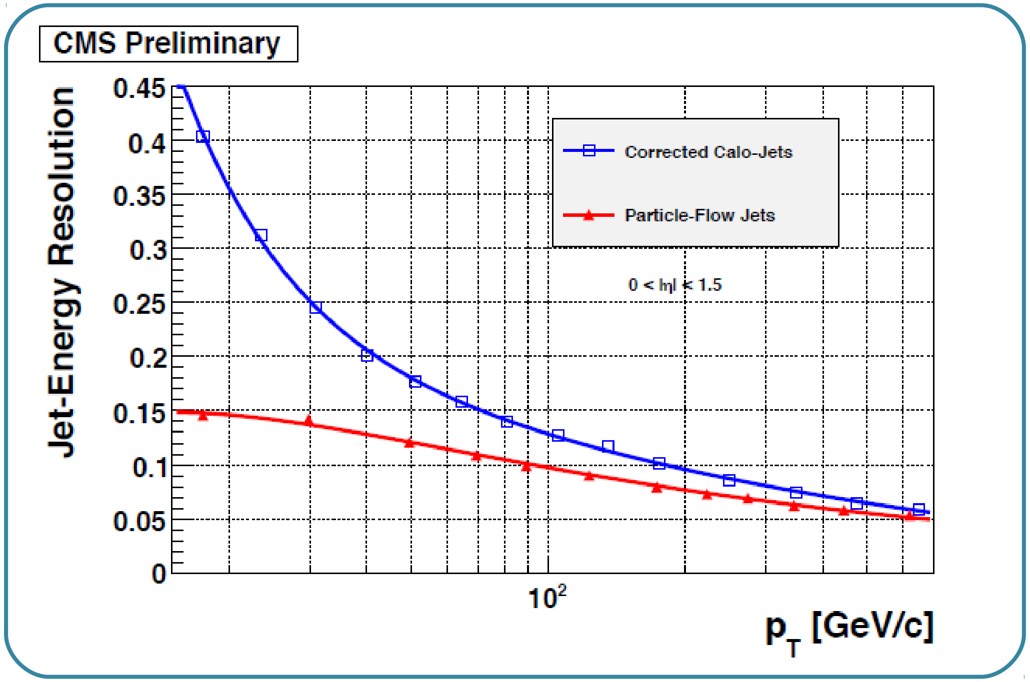
ECAL and HCAL surfaces



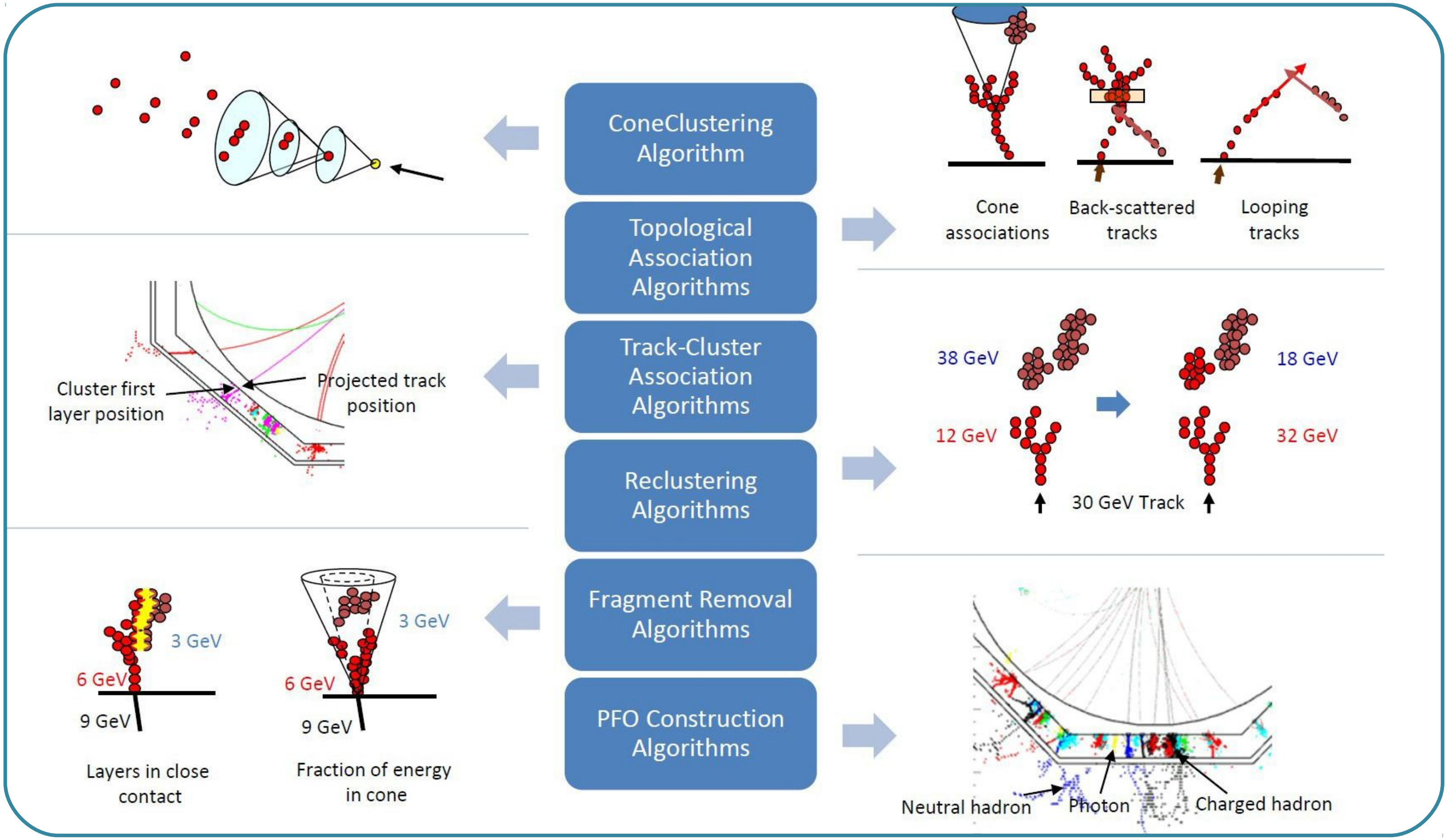
Particle Flow in CMS

- 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



ConeClustering Algorithm

Topological Association Algorithms

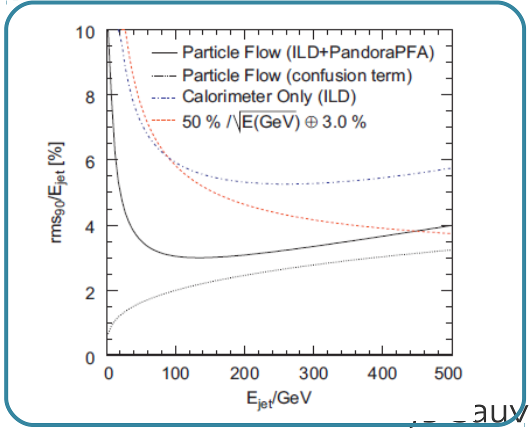
Track-Cluster Association Algorithms

Reclustering Algorithms

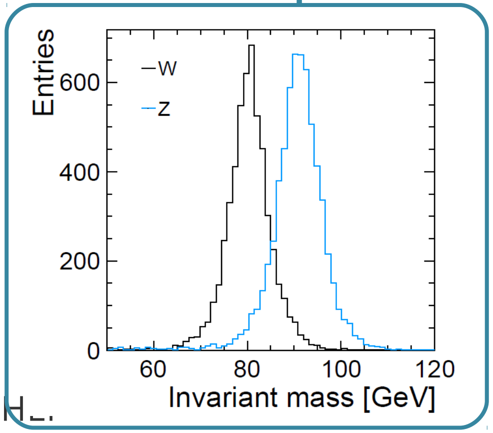
Fragment Removal Algorithms

PFO Construction Algorithms

Impact on jet energy resolution



W-Z mass separation



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Beyond calorimetry: Particle Flow

Electromagnetic and hadronic showers

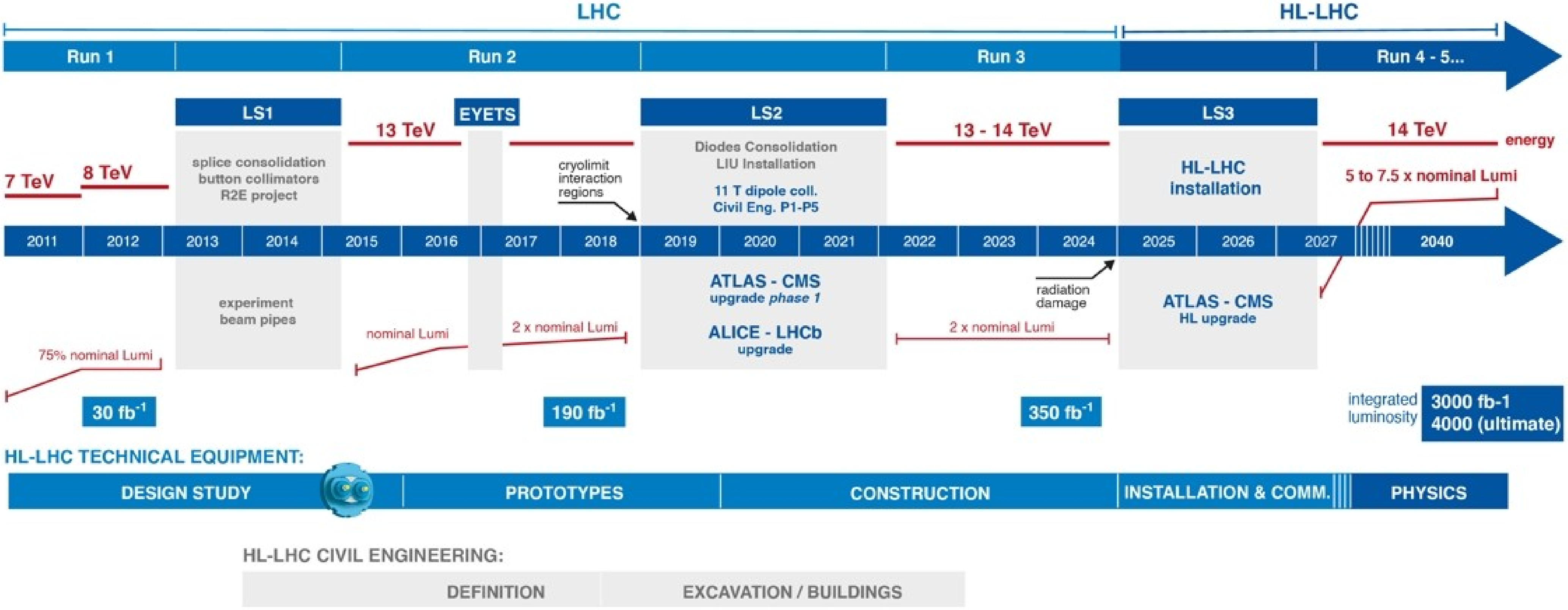
Calorimeter response & resolution

Energy reconstruction & calibration

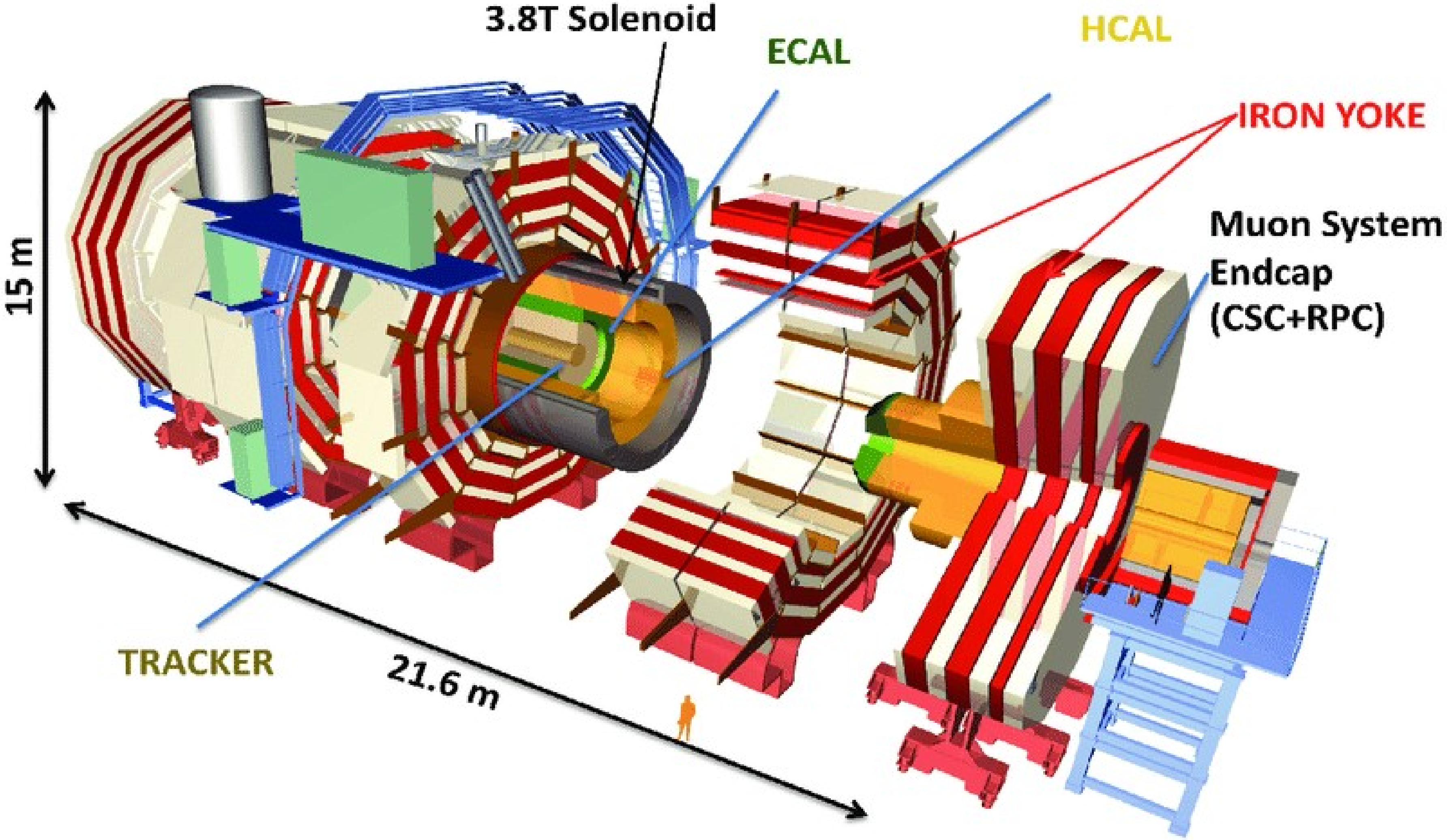
An example: CMS HGCAL

High Luminosity LHC

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

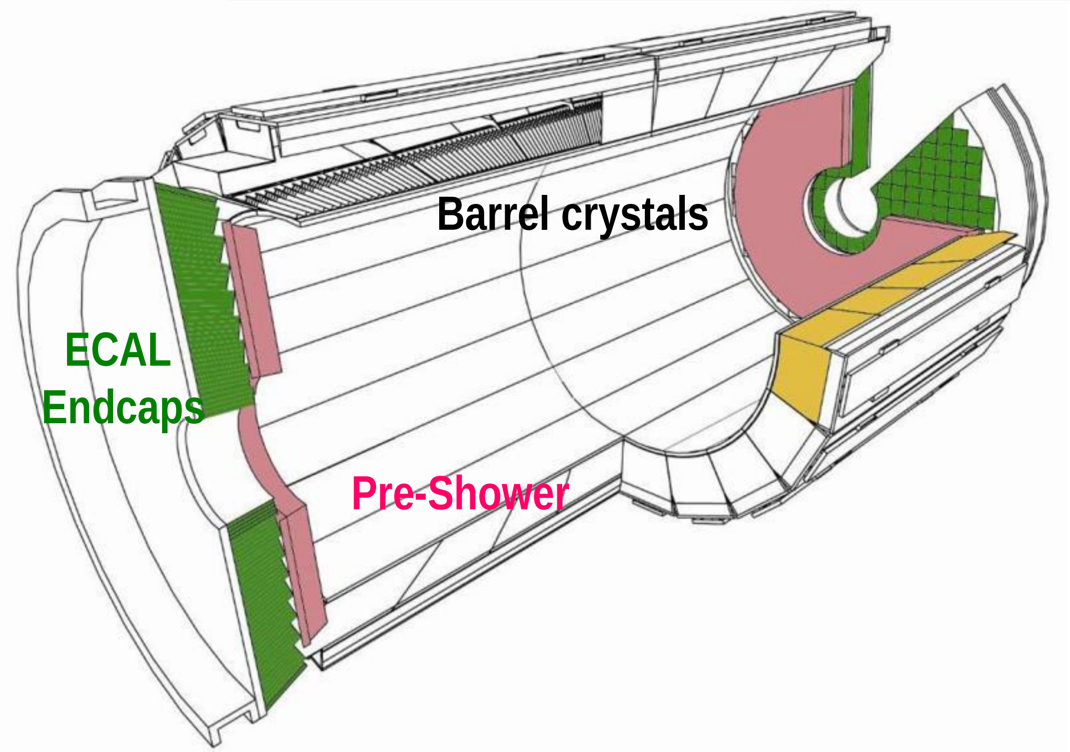


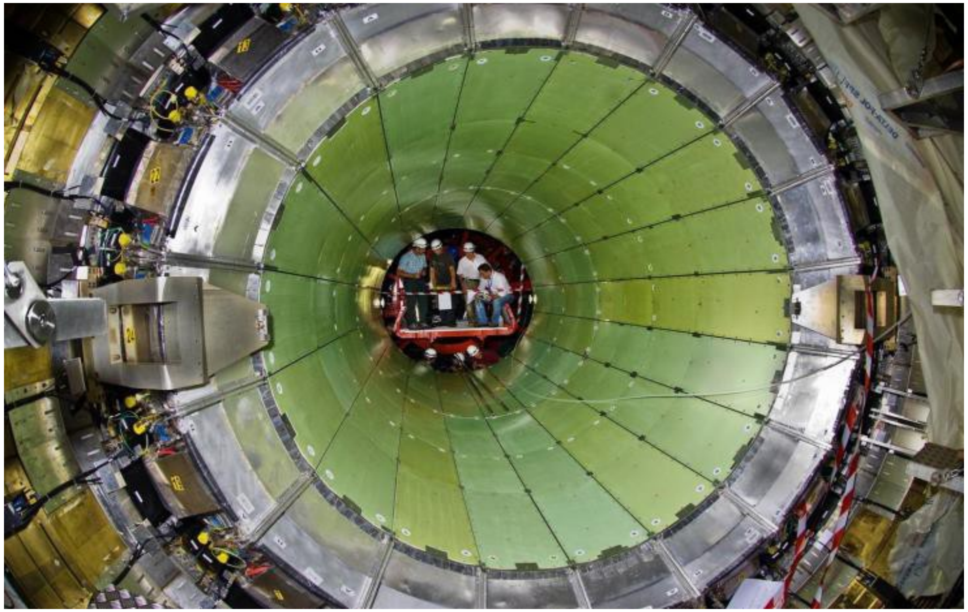
CMS


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

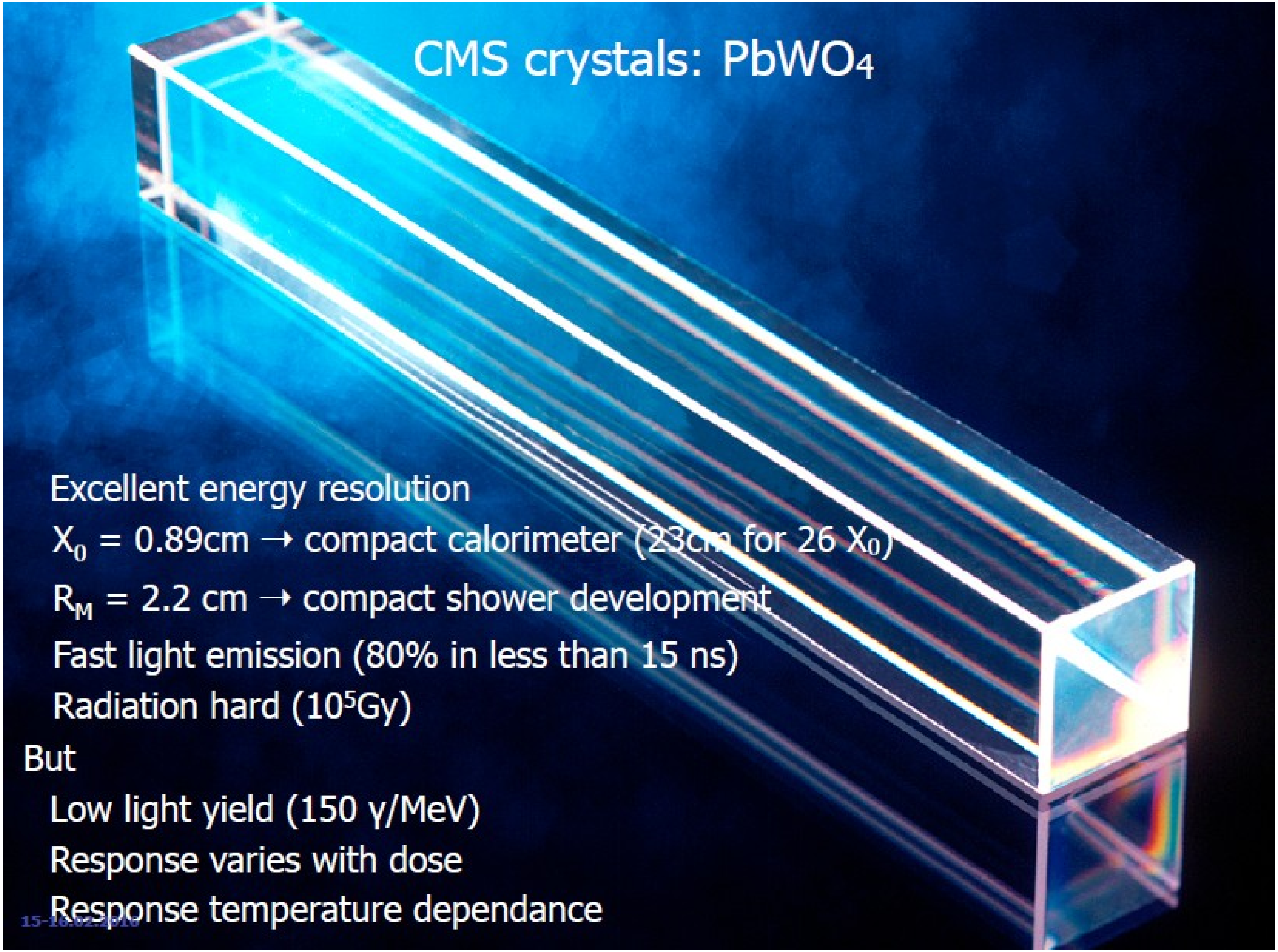




- Barrel ($|\eta|<1.48$), ~67 t
- 61200 crystals over 36 super-modules

- 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 crystals: $PbWO_4$

- Excellent energy resolution
- X_0 = 0.89cm → compact calorimeter (23cm for 26 X_0)
- R_M = 2.2 cm → compact shower development
- Fast light emission (80% in less than 15 ns)
- Radiation hard (10^5Gy)

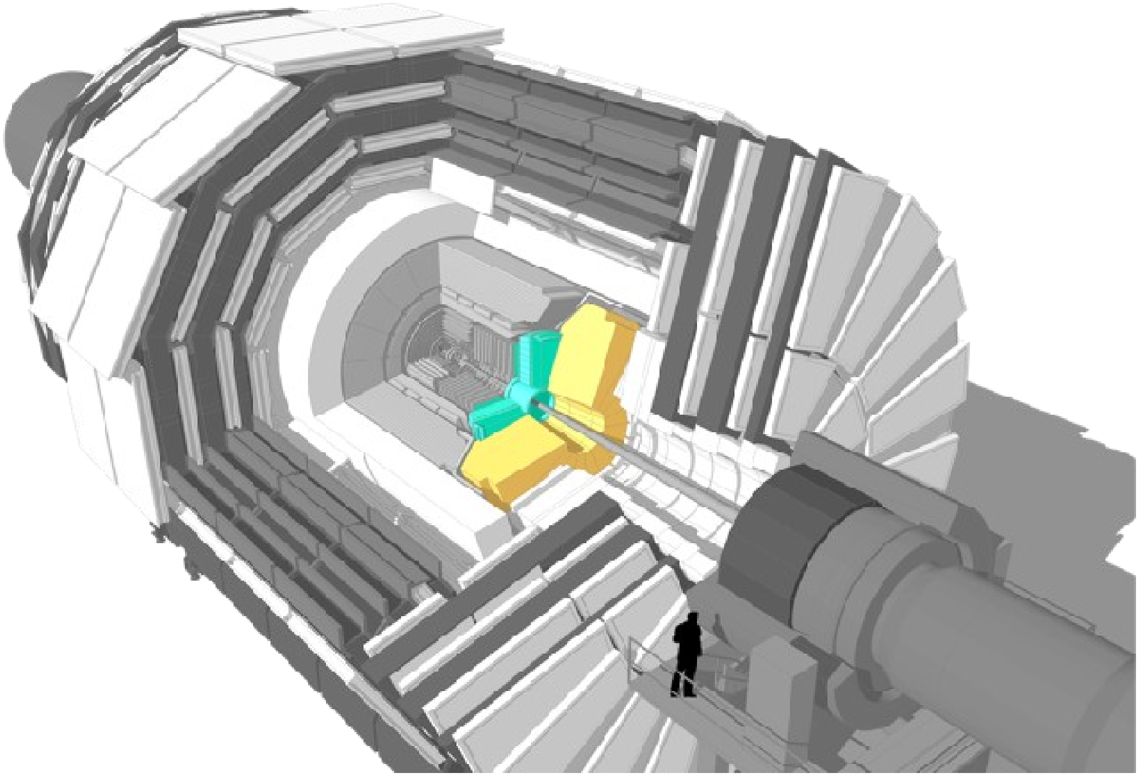
But

- Low light yield (150 γ/MeV)
- Response varies with dose
- Response temperature dependance

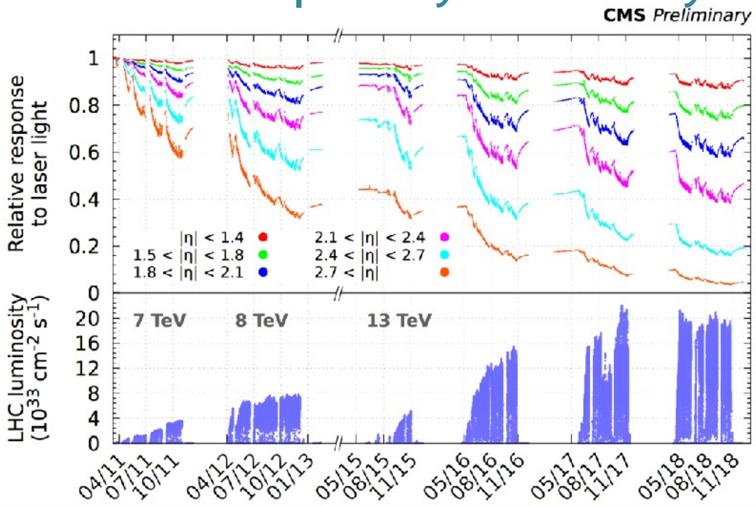
15-16.02.2010

CMS endcap calorimeters for HL-LHC

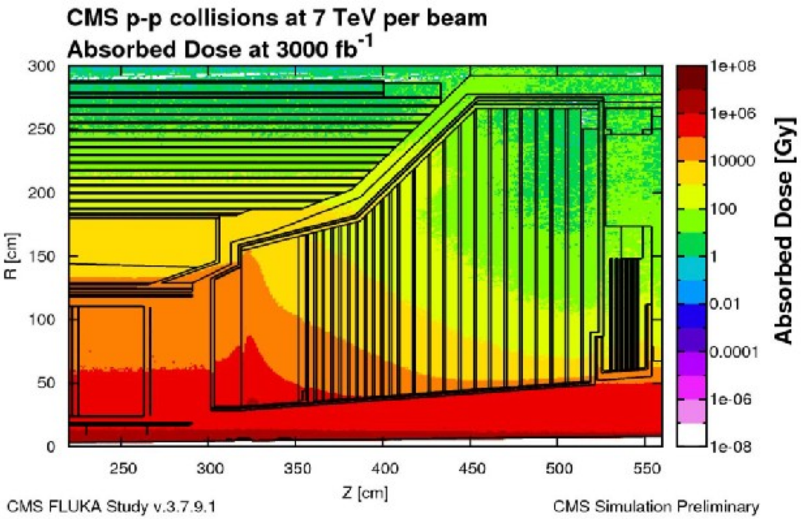
- CMS endcap calorimeters will need to be replaced
  - ECAL crystals and HCAL scintillators suffer from **irreparable radiation damage** after 500 fb^{-1}



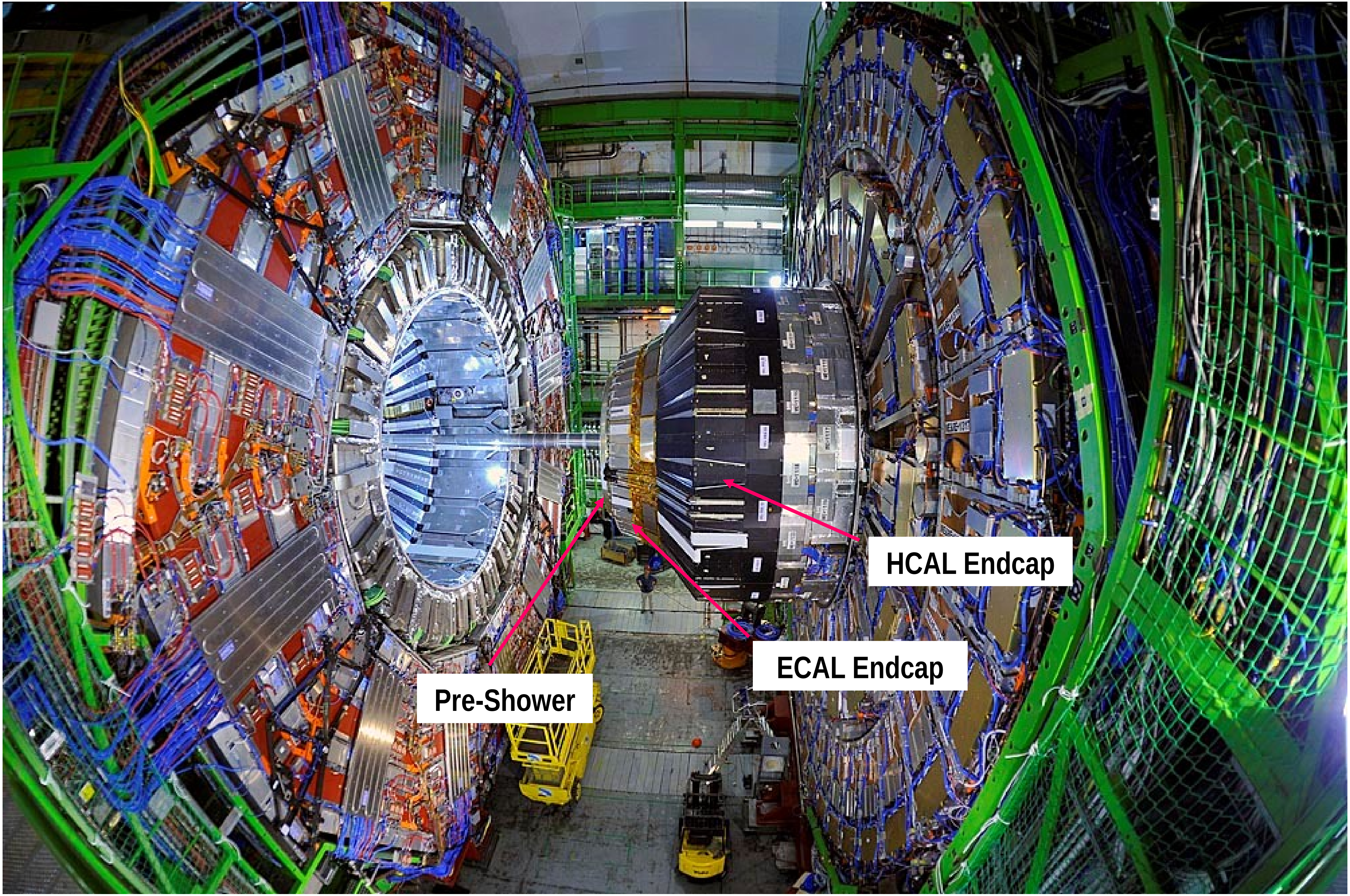
Loss of transparency of ECAL crystals



Absorbed dose at the end of HL-LHC



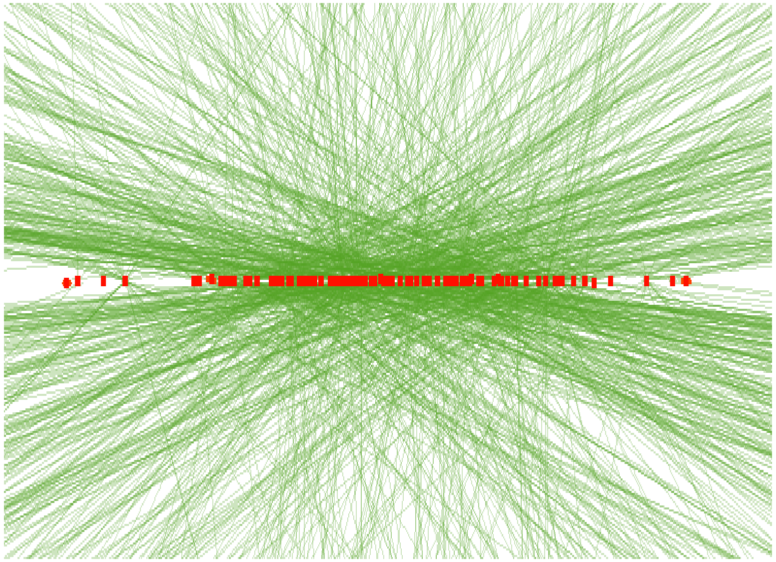
CMS endcap



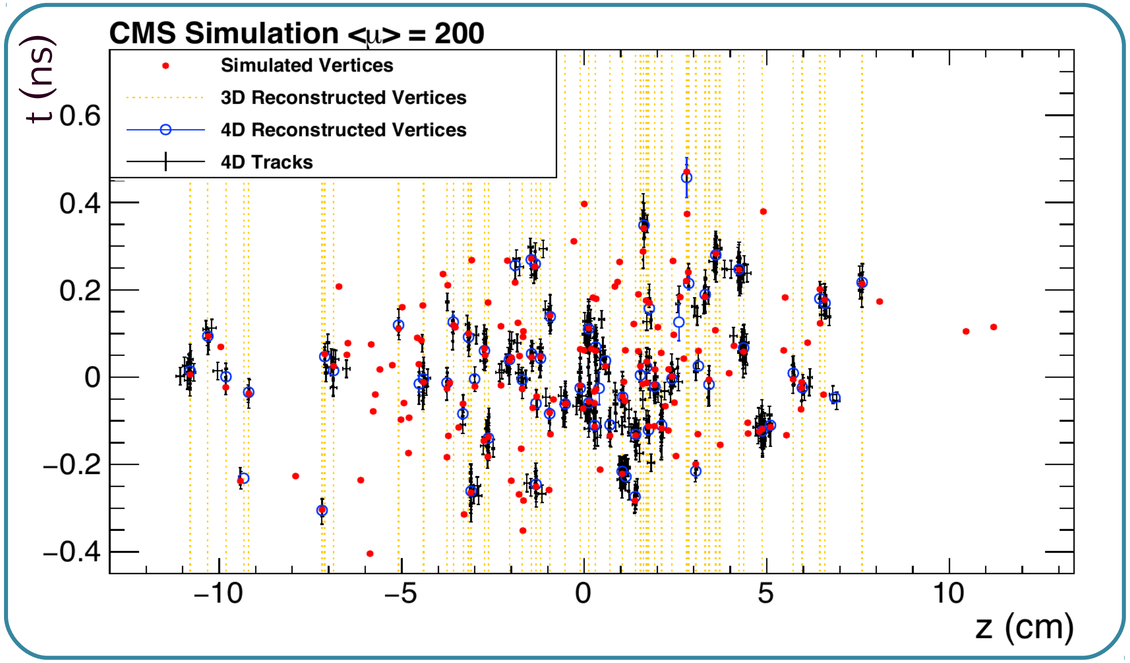
Challenges: pile-up (PU)

- 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

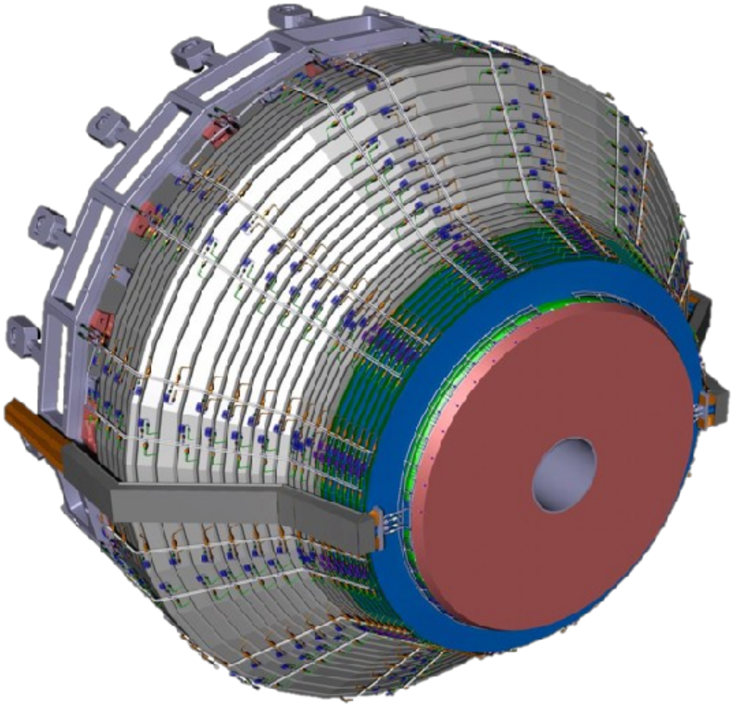


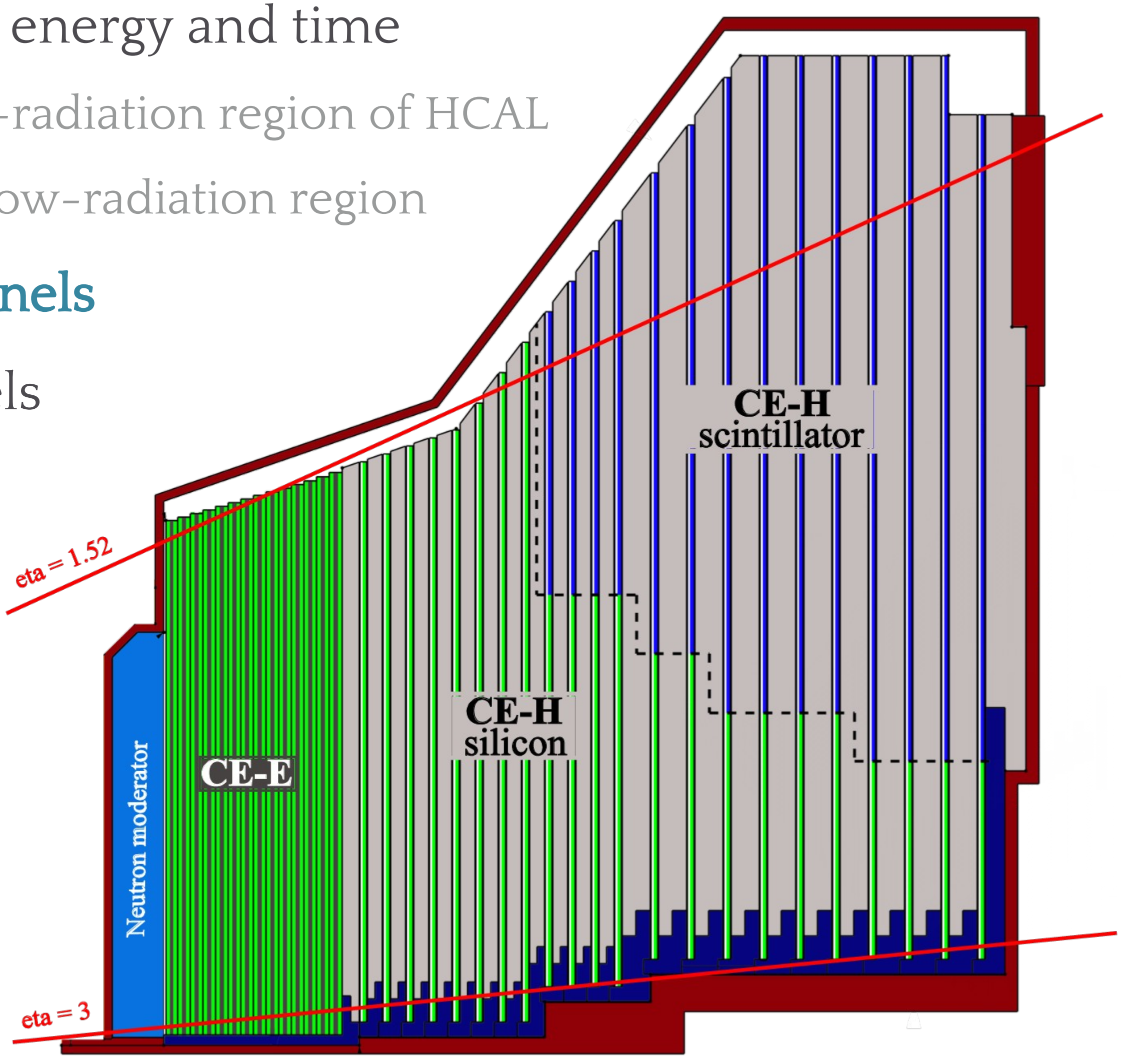
Space-time view of interaction vertices



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





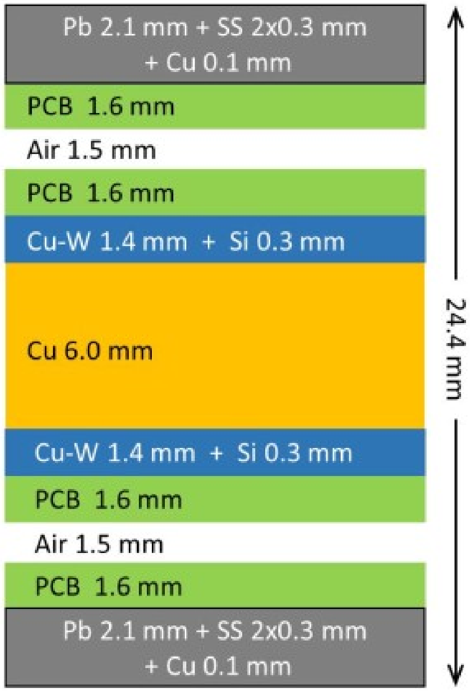
ECAL (CE-E):
28 layers, 25 X_0, 1.3 λ
Pb, Cu, CuW absorbers

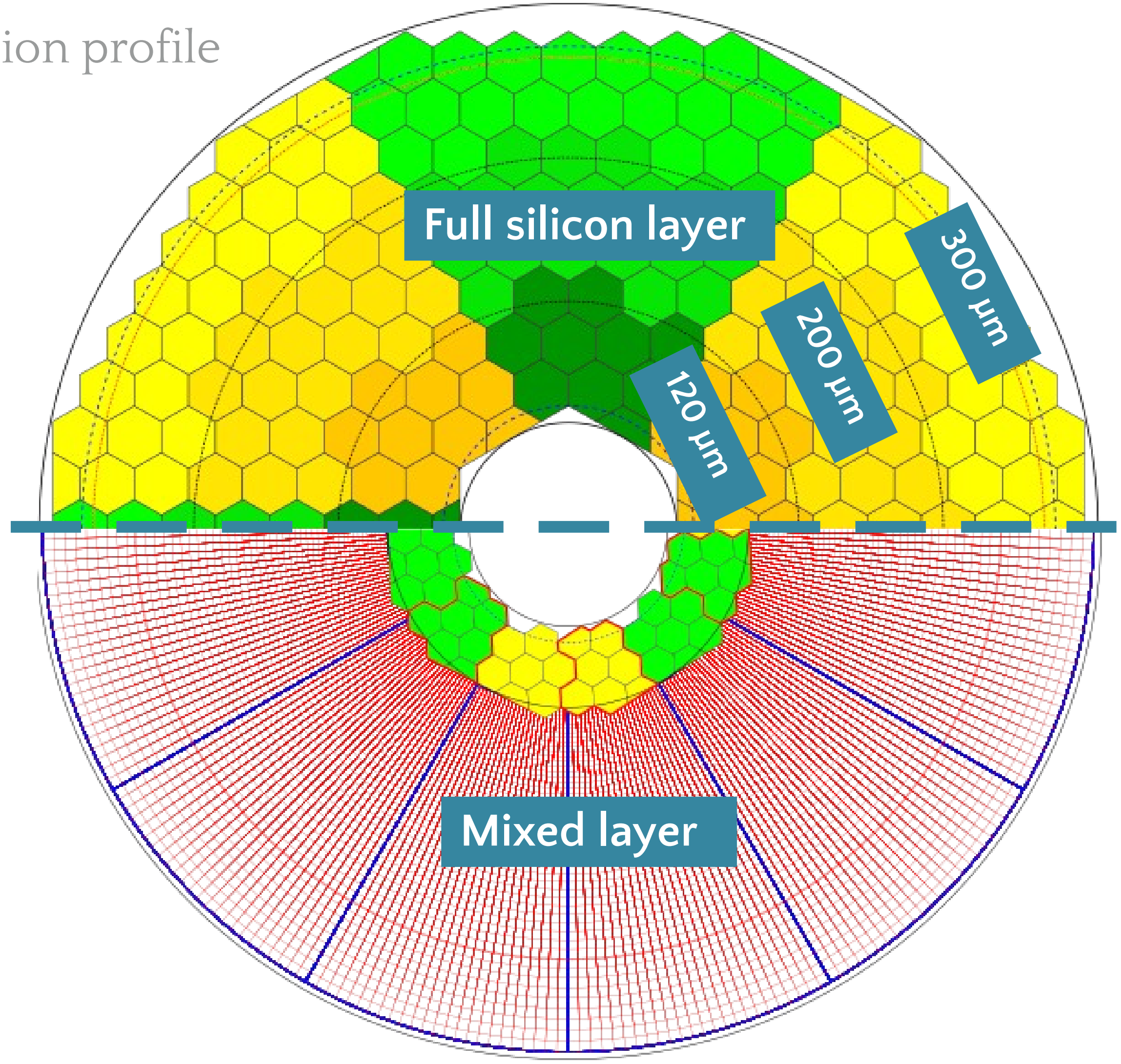
HCAL (CE-H):
22 layers, 8.5 λ
Steel, Cu absorbers

Layer structure

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

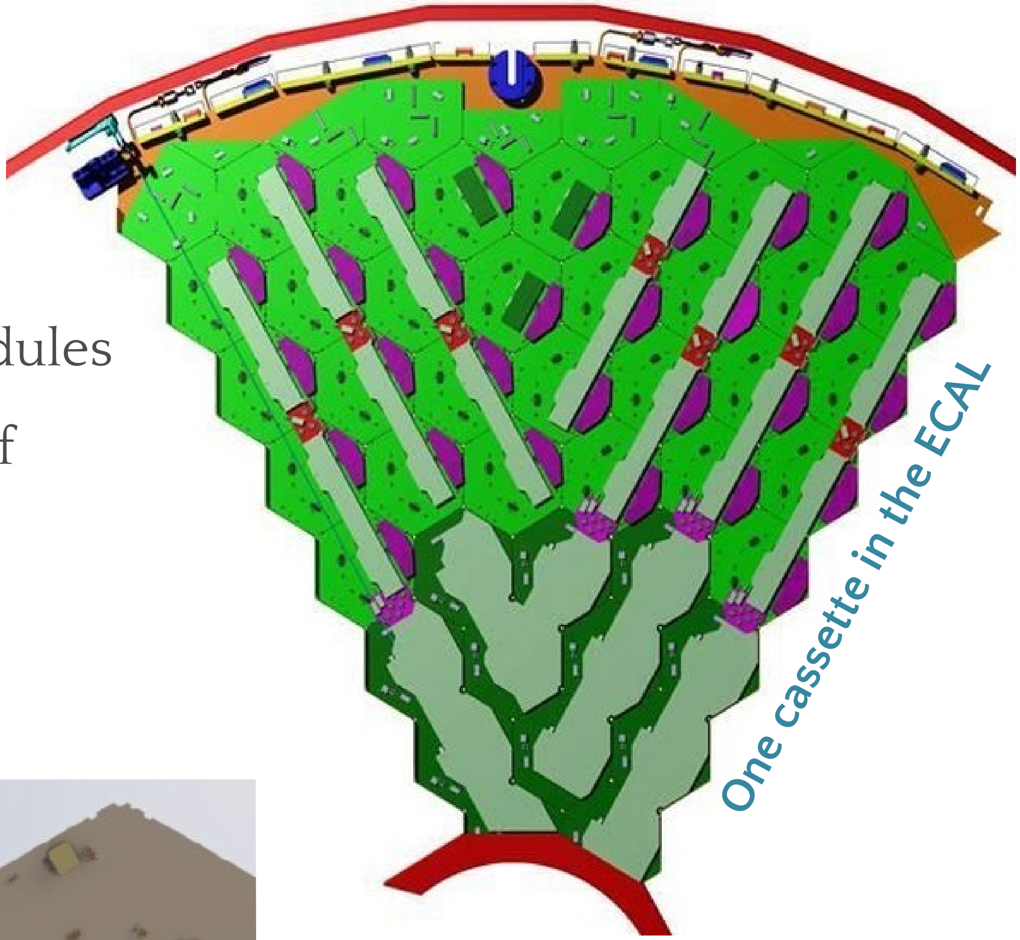
ECAL layer structure in depth

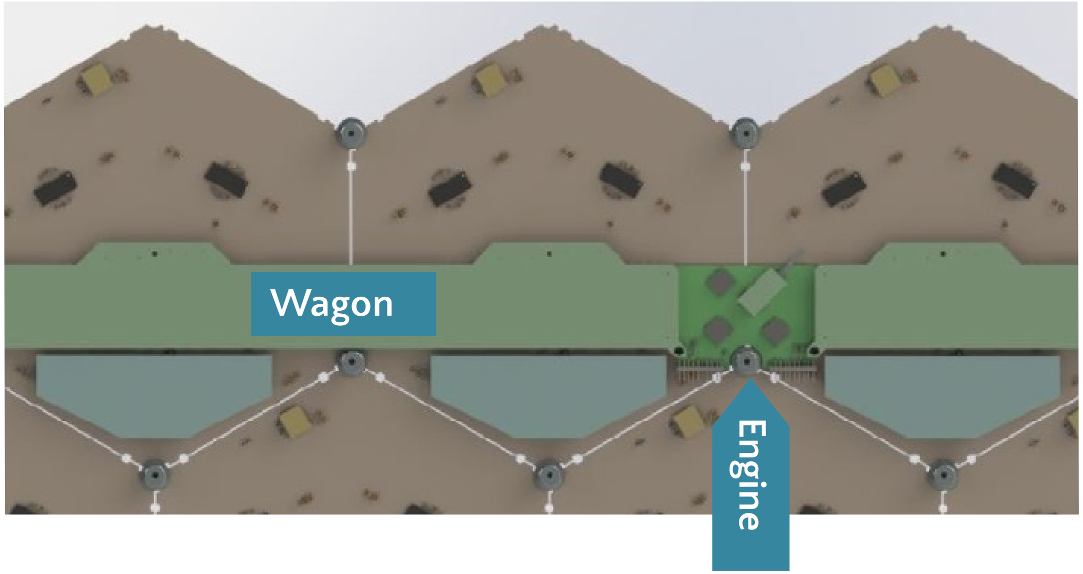




Layer components

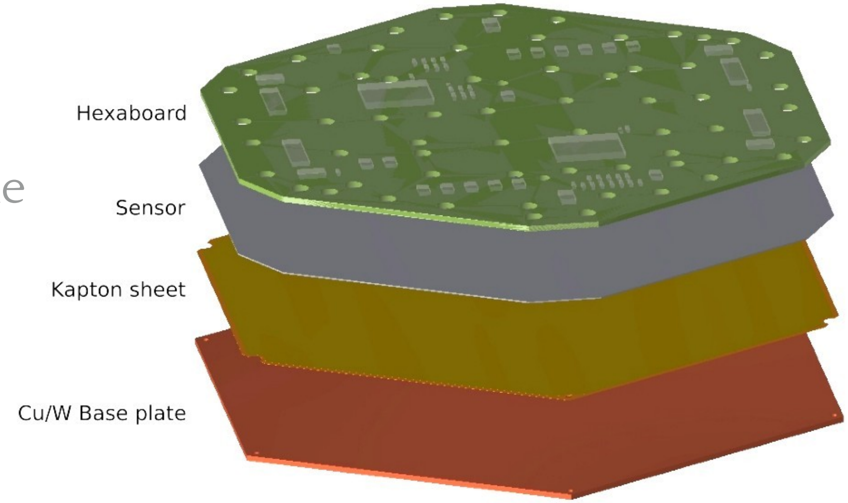
- Detector is organized into **cassettes** made of a cooling plate with **modules mounted on it**
- Frontend electronics located on the modules
- Readout and control through a system of engine/wagon **motherboards**



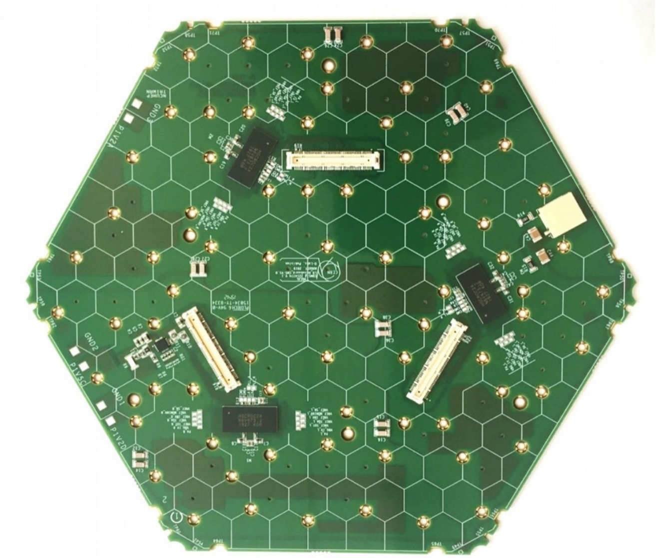


Silicon modules

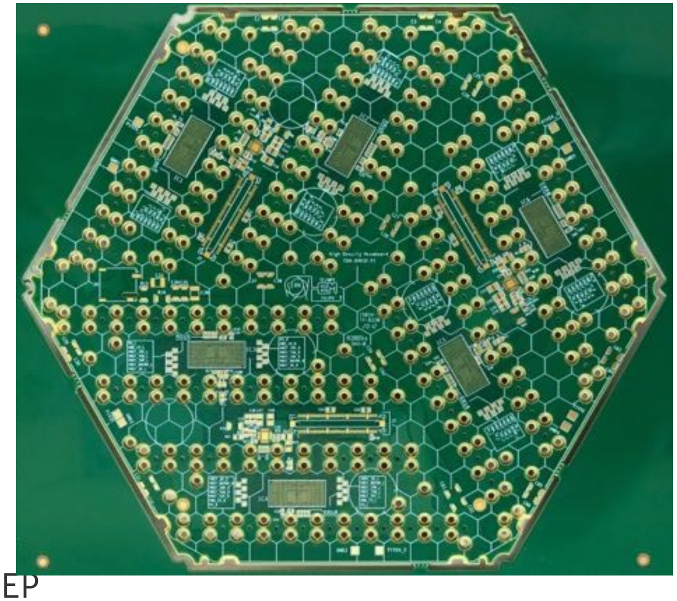
- Stack of **sensor**, readout **PCB** (Printed Circuit Board) and **baseplate**
  - ○ Several HGCROC (HGC readout chip) ASICs on the board
- "High density" and "Low density" modules
  - ○ **0.5 cm^2 cell** area in the highest radiation region
  - ○ **1.1 cm^2** otherwise



Low density module
192 channels
3 readout chips

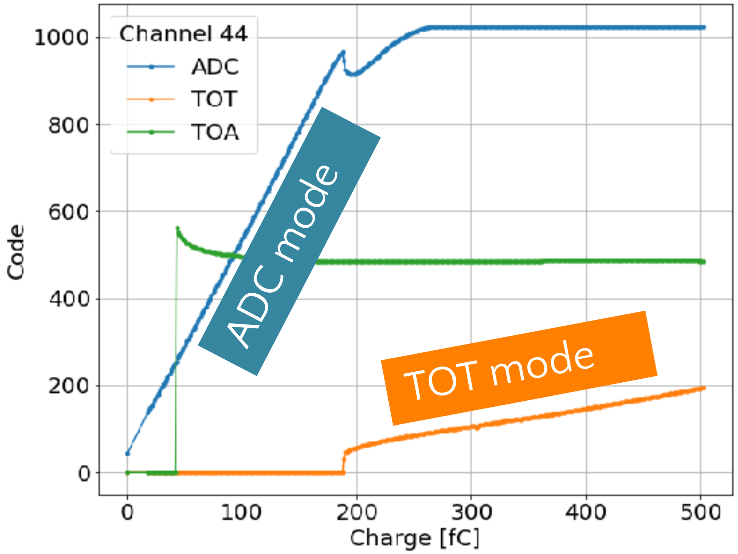


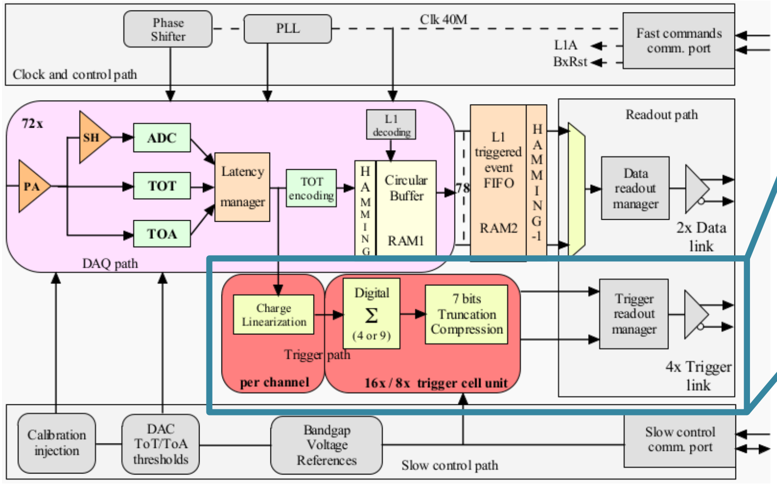
High density module
432 channels
6 readout chips

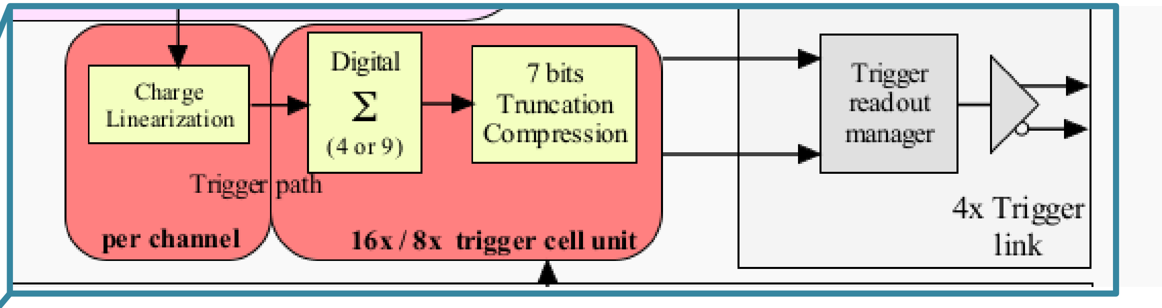


The readout chip (HGCROC)

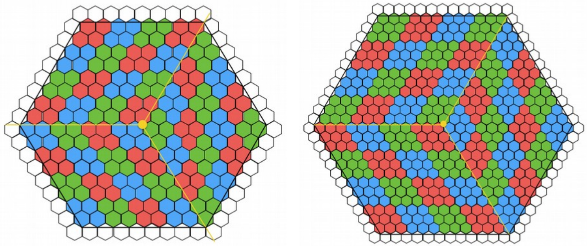
- ASIC amplifying, shaping, digitizing collected charges
  - ○ Two modes: "**ADC**" (low charges) & "**TOT**" (high charges)
  - ○ Data buffered before read out
- Trigger path
  - ○ ADC and TOT **linearization**
  - ○ Sums of channels → **Trigger cells**
  - ○ Energy **compression**







Trigger cells in low and high density modules

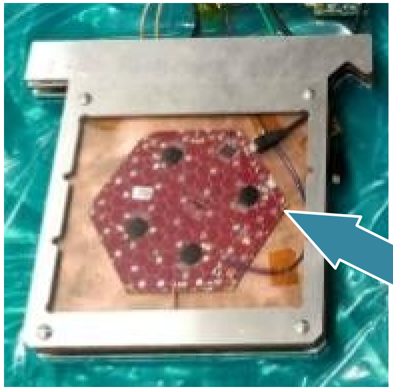


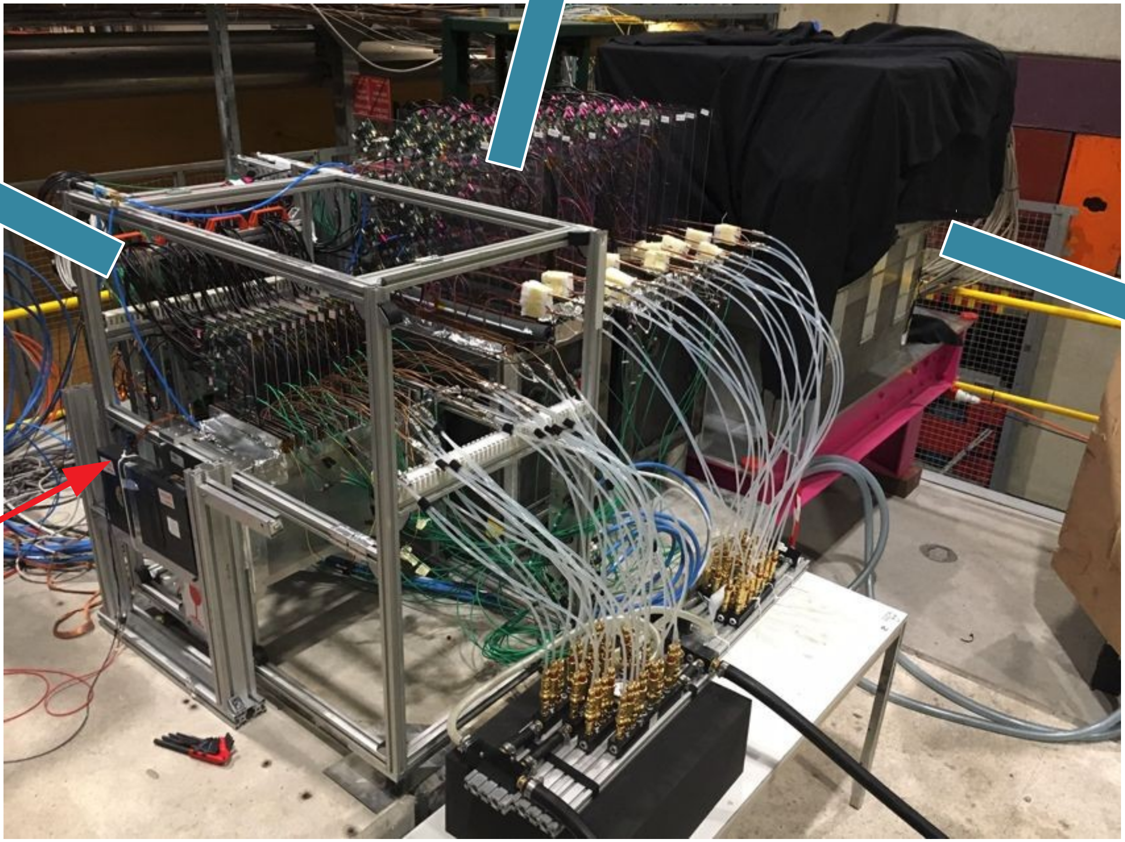
HGCAL prototype in beam test experiments

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

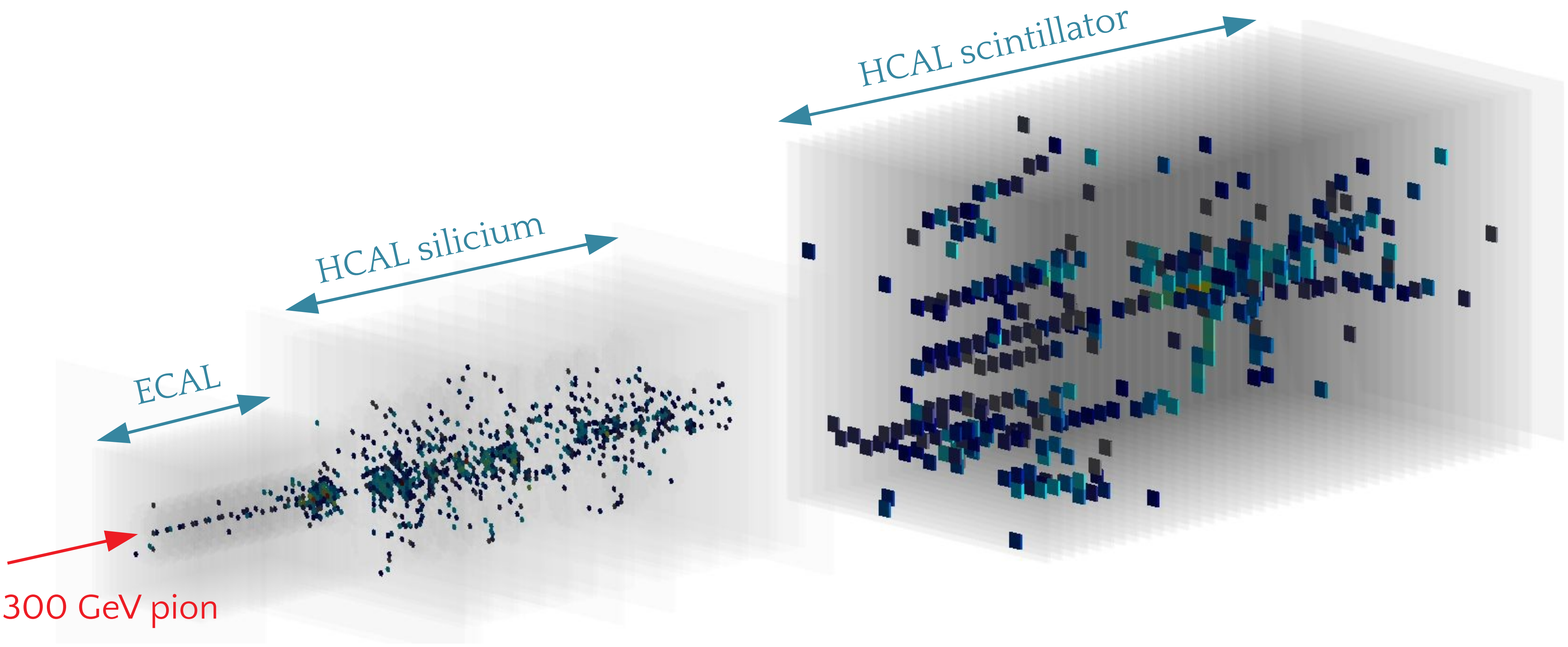
- CE-H
  - ○ Daisy arrangement of the modules
  - ○ Steel absorber
  - ○ 3.4 L

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





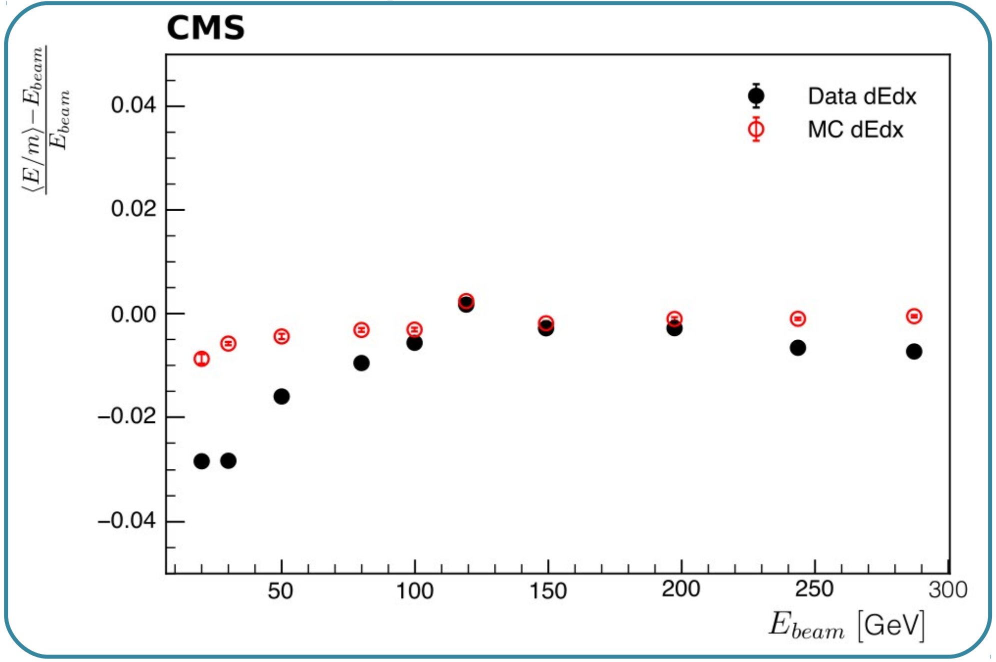
Display of pion shower



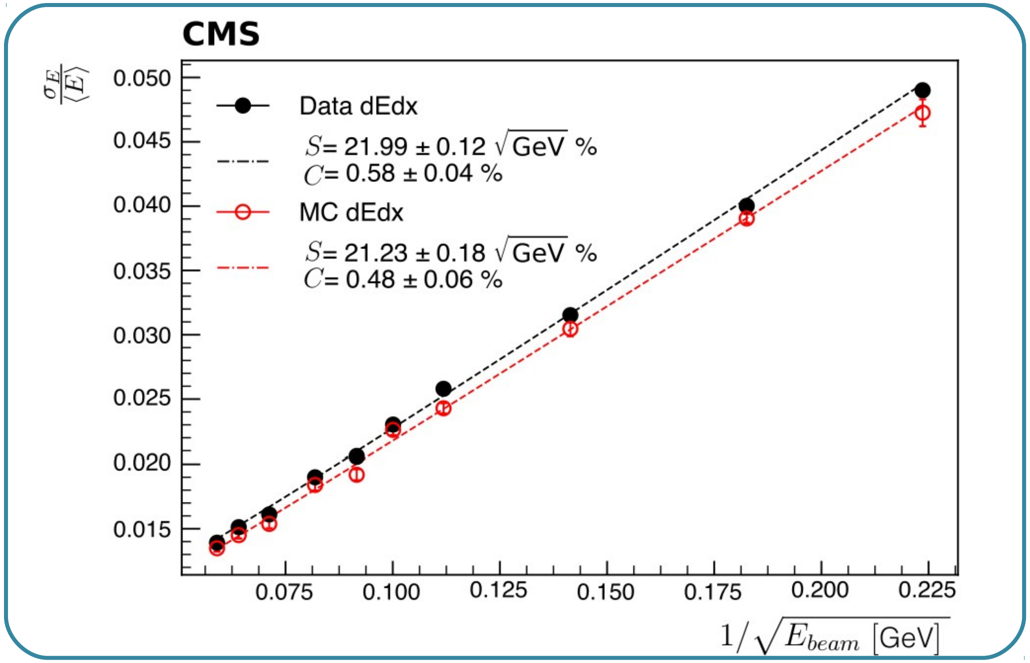
Electromagnetic showers reconstruction

- 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



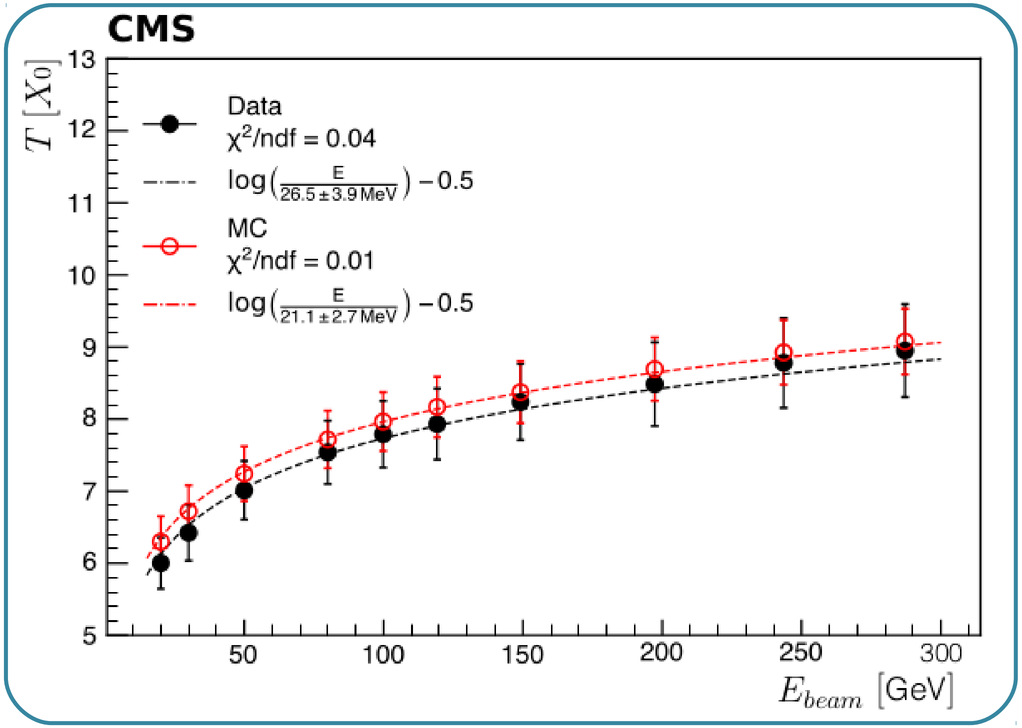
Resolution



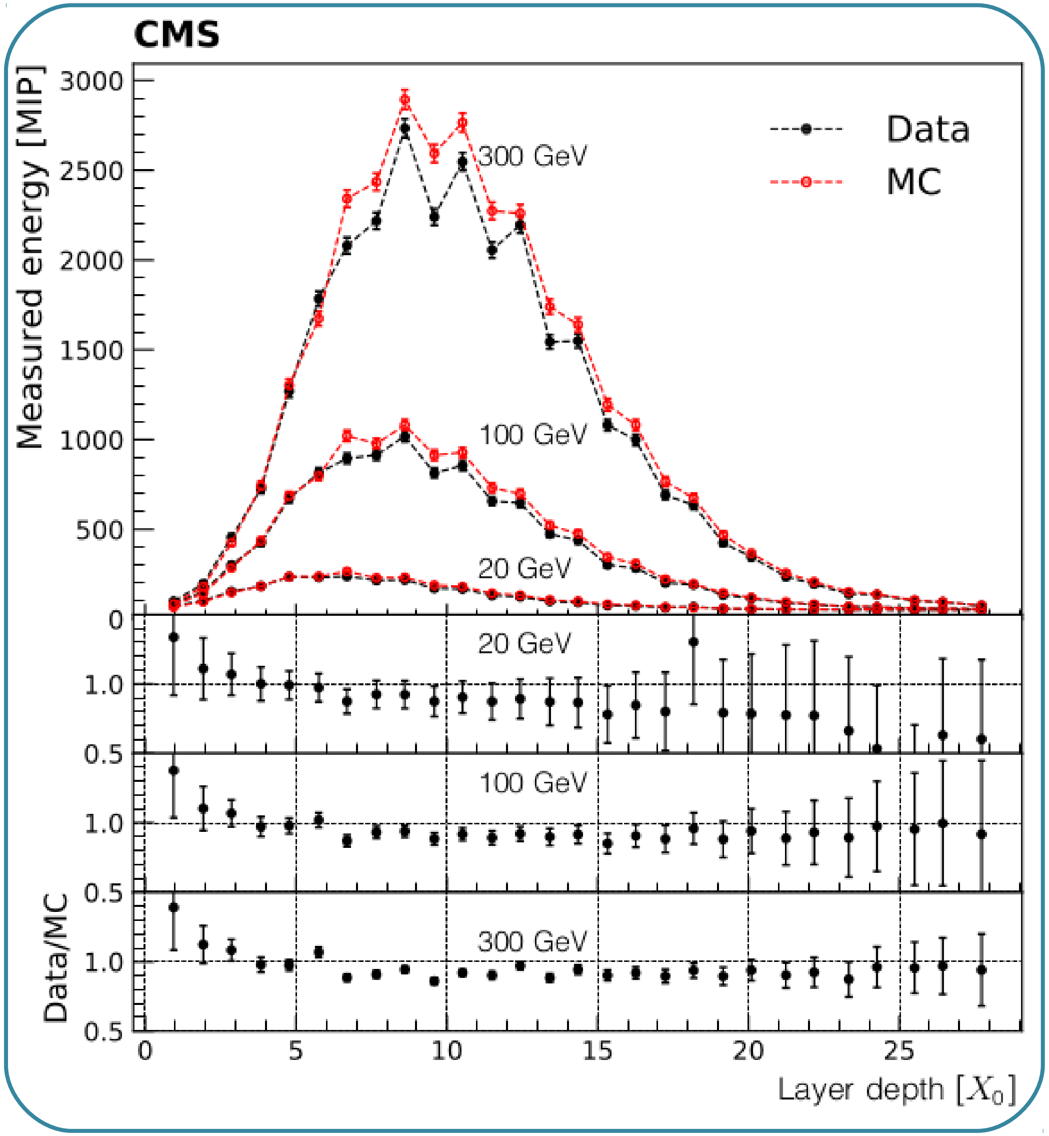
Electromagnetic shower profile

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

Shower maximum



Longitudinal profile



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